QCD and the XYZs

Tom Steele, University of Saskatchewan
CAP Congress, June 2015

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References

- R.T. Kleiv, TGS, Ailin Zhang, Ian Blokland
  Phys. Rev. D87 (2013) 125018 [arXiv:1304.7816]
- Wei Chen, Hong-ying Jin, R.T. Kleiv, TGS, Meng Wang, Qing Xu
  Phys. Rev. D88 (2013) 045027 [arXiv:1305.0244]
- Wei Chen, R.T. Kleiv, TGS, B. Bulthuis, D. Harnett, J. Ho, T. Richards, Shi-Lin Zhu
  JHEP 09 (2013) 019 [arXiv: 1304.4552]
- Wei Chen, TGS, Meng-Lin Du, Shi-Lin Zhu
  Eur. Phys. J C74 (2014) 2773 [arXiv:1308.5060]
- Wei Chen, TGS, Shi-Lin Zhu
  Journal of APCosPA 2 (2014) 13 [arXiv: 1403.7457]
- Wei Chen, TGS, Hua-Xing Chen, Shi-Lin Zhu
  arXiv:1501.03863
- Wei Chen, TGS, Hua-Xing Chen, Shi-Lin Zhu
  arXiv:1505.05619

Outline

- Overview of XYZ states and possible interpretations
- Overview of QCD sum-rule methods
- Selected QCD sum-rule results:
    - $Z_c^+,\ J^{PC}=1^{+-}$ molecular states
    - Closed-charm tetraquark states
    - Charmonium hybrids
    - Mixed Molecular-Hybrid scenario for X(3872)
    - Diquarks and Tetraquark Scenario
- Summary

Limit discussion to charm (closed flavour) sector

What are the XYZ Mesons?

- Charmonium-like and bottomonium-like states that defy standard interpretations
- Decay into final states containing $\bar{c}c$ or $\bar{b}b$ pair
- Many such states (more than 25) discovered/confirmed since 2003 by BaBar, Belle, BES, CDF, CMS, CLEO, LHCb
- Denoted as X, Y, Z states in literature; PDG 2014 only uses X
- No sign that discovery is slowing
- Production of heavy pair from vacuum suppressed; assumed in initial state
- Charged states $Z_c^+(3900),\ Z_1^+(4050),\ Z_2(4250),\ Z_c^+(4050),\ Z_c^+(4200),\ Z^+(4430)$
  evidence for four-quark states $\bar{c}cu\bar{d}$

recent Belle results: arXiv: 1410.7641, PRD90 (2014)

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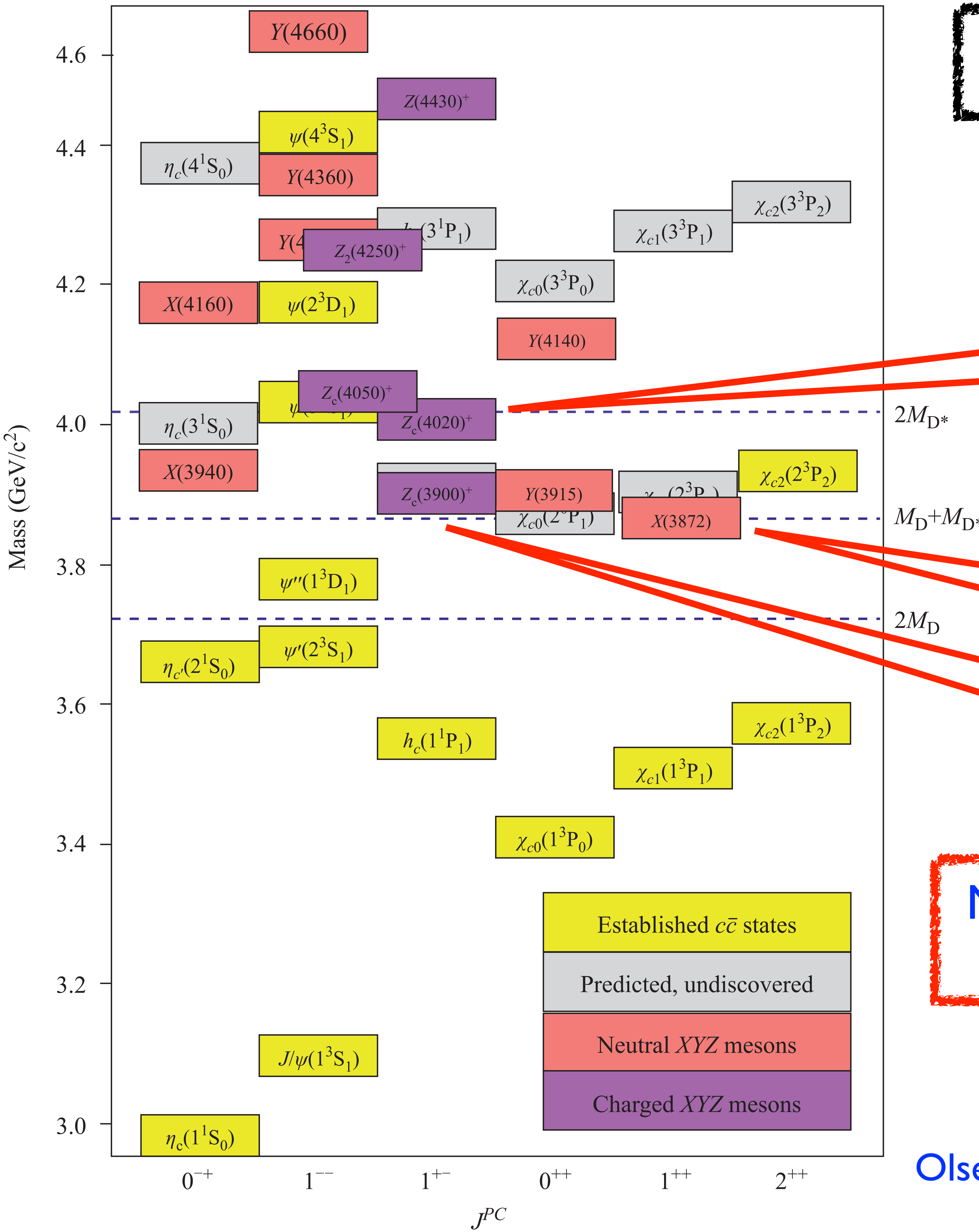
XYZ Overview



neutral partner: isotriplet

likely isosinglet

neutral partner: isotriplet

Most widths 100 MeV or less,
Z(4200), Z(4430) widest

Olsen, Front. Phys. 10 (2015) 101401

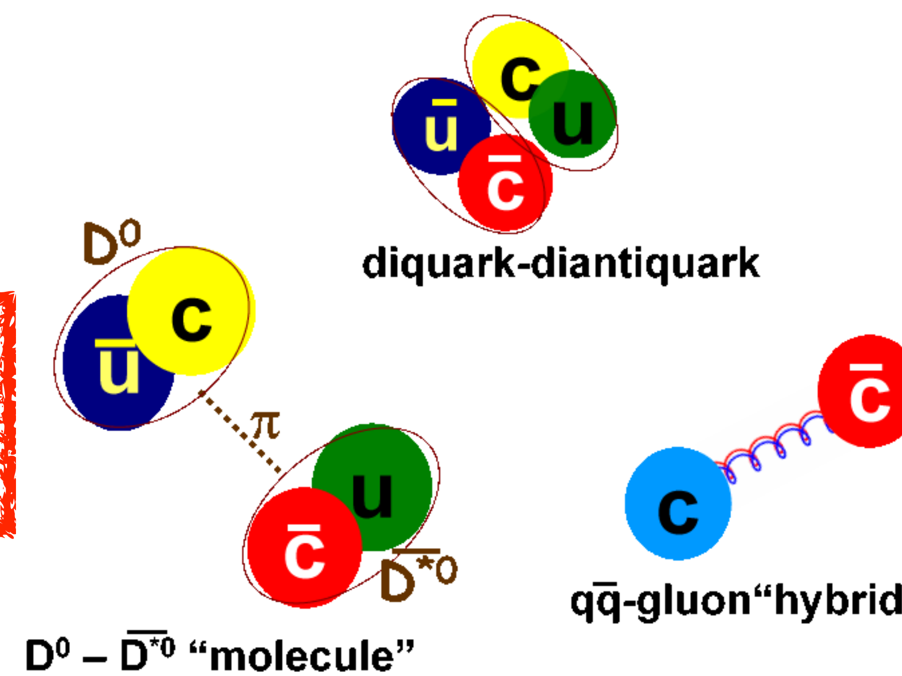
Interpretations of XYZs

- Charmonium (needs to be ruled out first)
- Hybrids: mesons with gluonic excitation (colourless quark-antiquark-glue state), can have conventional or exotic J^{PC}
- Four-Quark scenarios

  Also used to interpret light-quark scalar sector

  - Molecules: meson-meson bound state
  - Tetraquarks: diquark-antidiquark state (diquark colour triplet just like quarks)
  - Hadrocharmonium: tightly bound $\bar{c}c$ pair in light meson cloud
- Mixed scenarios: when pure interpretations fail

Four-Quark scenarios have different internal quark configurations



Godfrey & Olsen, Ann.Rev.Nucl.Part.Sci.58 (2008) 51

QCD Sum-Rules

- Basic concept similar to lattice QCD: study correlation functions of (local) currents J(x) with quantum numbers of state

Local operator obscures internal structure

$$\Pi\left(Q^2\right) = i \int d^4x\, e^{iq\cdot x} \left\langle 0 \middle| T\left[J(x)J(0)\right] \middle| 0 \right\rangle$$

- Classify states |M> by coupling to current $\langle 0|J|M\rangle \neq 0$
- Currents are probes of spectrum and might not overlap with desired state
- Apply Borel transform to correlation function's dispersion relation
- Laplace sum-rules relate QCD prediction to hadronic spectral function

$$\mathcal{R}_k\left(\tau, s_0\right) = \frac{1}{\pi}\int_{t_0}^{s_0} t^k \exp(-t\tau)\rho^{\rm had}(t)\, dt$$

- Both lattice and QCD sum-rules predict mass from exponential decays (in distance for lattice, in Borel-transformed momentum space for sum-rules)
- Sum-rules contain power-law contributions from QCD condensates (non-perturbative inputs)

$Z_c^+,\ J^{PC}=1^{+-}$ Molecular States

W Chen, TGS, H-X Chen, S-L Zhu
arXiv:1505.05619

- Experimental evidence of a landscape of charged states (spin of Z_1 and Z_2 ?)

$$Z_c^+(3900),\ Z_1^+(4050),\ Z_2(4250),\ Z_c^+(4050),\ Z_c^+(4200),\ Z^+(4430)$$

- Can form eight independent $J^{PC}=1^{+-}$ "molecular" currents (4 singlet-singlet and 4 octet-octet) for QCD sum-rule analysis e.g.,

$$J_{1\mu}^{(\mathbf{1})}=(\bar{q}_a\gamma_5 Q_a)(\bar{Q}_b\gamma_\mu q_b)+(\bar{q}_a\gamma_\mu Q_a)(\bar{Q}_b\gamma_5 q_b)$$

$D\bar{D}^*$

$$J_{1\mu}^{(\mathbf{8})}=(\bar{q}_a\gamma_5\lambda^n_{ab}Q_b)(\bar{Q}_c\gamma_\mu\lambda^n_{cd}q_d)+(\bar{q}_a\gamma_\mu\lambda^n_{ab}Q_b)(\bar{Q}_c\gamma_5\lambda^n_{cd}q_d)$$

- Can Fierz transform the eight molecular currents into tetraquark currents (4 triplet-triplet and 4 sextet-sextet)

Local operators obscure information on internal structure Zhang, Huang, TGS PRD76 (2007)

- Calculate QCD sum-rule for correlation function at leading loop-order, dominant non-perturbative effects from quark and mixed condensate

$Z_c^+,\ J^{PC}=1^{+-}$ QCD Sum-Rule Analysis

- QCD input parameters

$$m_c(m_c) = (1.23 \pm 0.09)\mathrm{GeV}\,,\ m_b(m_b) = (4.20 \pm 0.07)\mathrm{GeV}\,,$$
$$\langle \bar{q} g_s \sigma \cdot G q \rangle = -M_0^2 \langle \bar{q} q \rangle\,,\ M_0^2 = (0.8 \pm 0.2)\mathrm{GeV}^2$$
$$\langle \bar{q} q \rangle = -(0.23 \pm 0.03)^3 \mathrm{GeV}^3\,,\ \langle g_s^2 GG \rangle = (0.88 \pm 0.14)\mathrm{GeV}^4$$

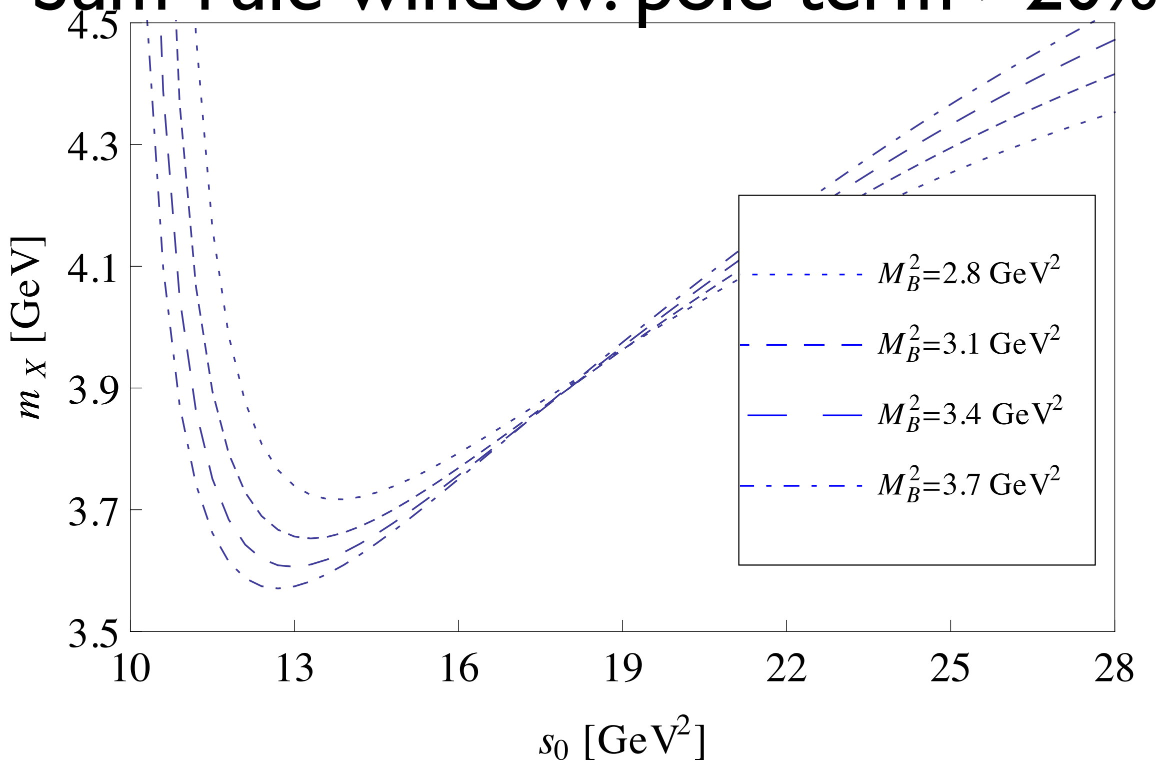
- Single narrow resonance plus QCD continuum model, predict mass M_X via

$$M_X^2 = \frac{\mathcal{R}_1(\tau, s_0)}{\mathcal{R}_0(\tau, s_0)}$$

critical point of ratio

- Narrow width approximation very good since $\tau\,\Gamma\,M_X$ is small

- Sum-rule window: pole term >20%, highest dimension condensates <5%



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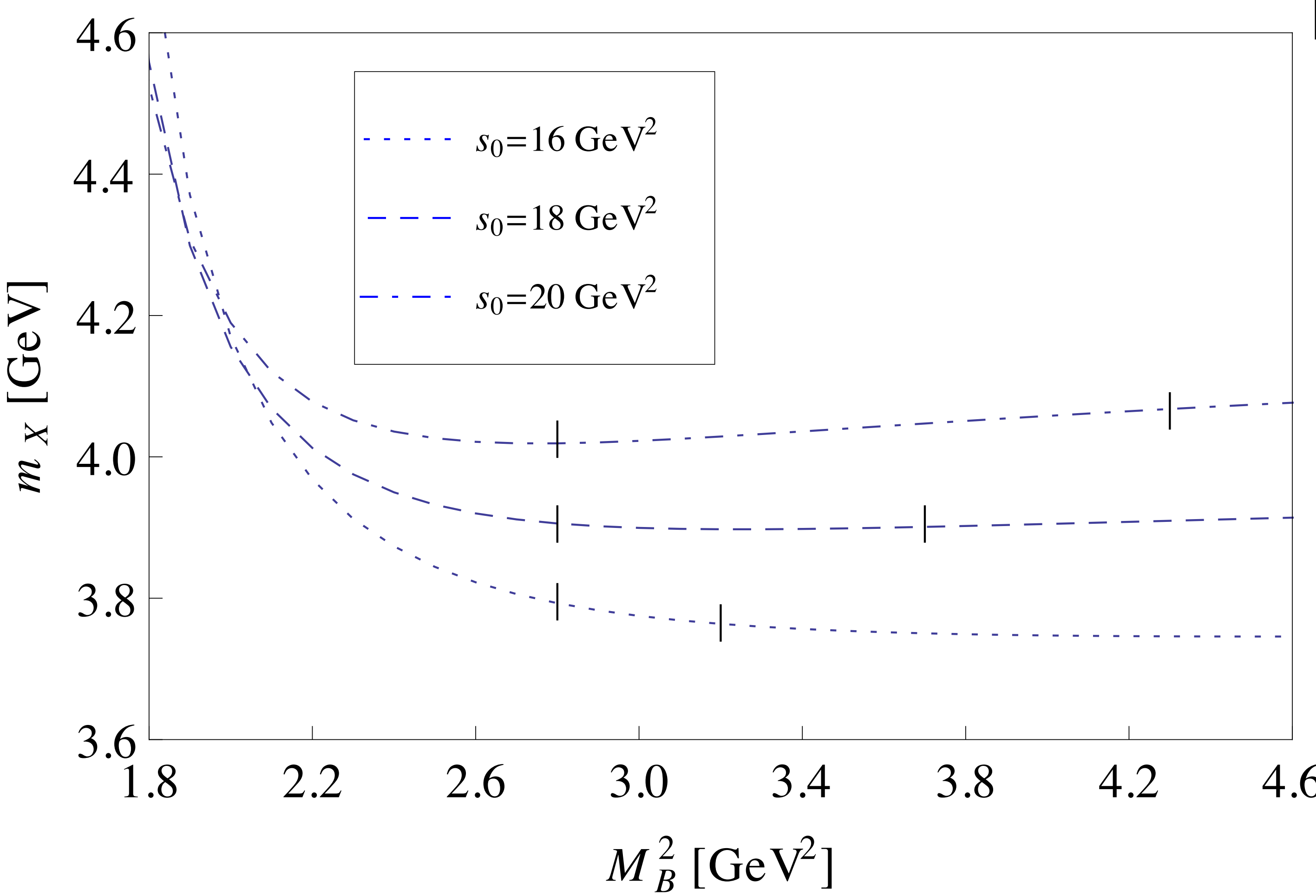
$Z_c^+,\ J^{PC}=1^{+-}$ Molecular Mass Spectrum

Current	s_0 (GeV^2)	M_X (GeV)
$J_{1\mu}^{(\mathbf{1})},\ D\bar{D}^*$	21	4.22 ± 0.14
$J_{2\mu}^{(\mathbf{1})},\ D_0^*\bar{D}_1$	—	—
$J_{3\mu}^{(\mathbf{1})},\ D^*\bar{D}^*$	20	4.04 ± 0.12
$J_{4\mu}^{(\mathbf{1})},\ D_1\bar{D}_1$	20	4.02 ± 0.15
$J_{1\mu}^{(\mathbf{8})}$	18	3.90 ± 0.12
$J_{2\mu}^{(\mathbf{8})}$	—	—
$J_{3\mu}^{(\mathbf{8})}$	18	3.85 ± 0.11
$J_{4\mu}^{(\mathbf{8})}$	20	4.03 ± 0.18

$Z_c(4200)$ → $J_{1\mu}^{(\mathbf{1})},\ D\bar{D}^*$

$Z_c(3900)$, $Z_c(4020)$, $Z_c(4050)$ → $J_{3\mu}^{(\mathbf{1})}$ / $J_{4\mu}^{(\mathbf{1})}$

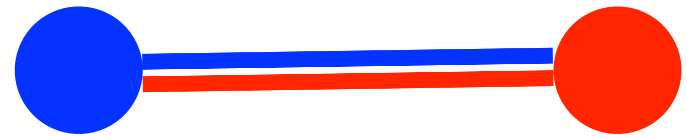


Landscape of charged and neutral Z_c molecular states

W Chen, TGS, H-X Chen, S-L Zhu
arXiv:1505.05619

Charmonium Hybrids

W Chen, Kleiv, TGS, Bulthuis, Harnett, Richards, Ho, S-L Zhu, JHEP09 (2013)



- Mesons with gluonic excitation (quark-antiquark-glue) form colourless states
- Can have conventional J^{PC} and mix with quark-antiquark mesons
- Can have non-standard J^{PC} like 1^{-+} with clear exotic signature
- Unique decay signatures (e.g. S-wave meson pairs suppressed) Isgur et al, PRL54 (1985)
- Y(4260) has been interpreted as hybrid candidate S-L Zhu, PLB625 (2005)
- Bag model and lattice QCD: supermultiplet structure, odd parity states lighter

Comprehensive QCD sum-rule analysis for exotic and conventional quantum numbers

Charmonium Hybrid QCD Sum-Rule Analysis

- Construct hybrid interpolating currents for exotic and conventional J^{PC}

$$J_\mu = g_s \bar{Q} \frac{\lambda^a}{2} \gamma^\nu G^a_{\mu\nu} Q\,, \qquad J^{PC} = 1^{-+}, 0^{++}\,,$$

$$J_\mu = g_s \bar{Q} \frac{\lambda^a}{2} \gamma^\nu \gamma_5 G^a_{\mu\nu} Q\,, \qquad J^{PC} = 1^{+-}, 0^{--}\,,$$

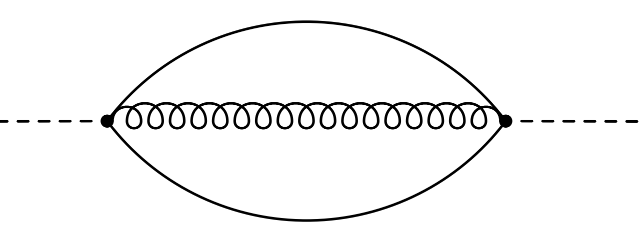
opposite parity
$G \to \tilde{G}$

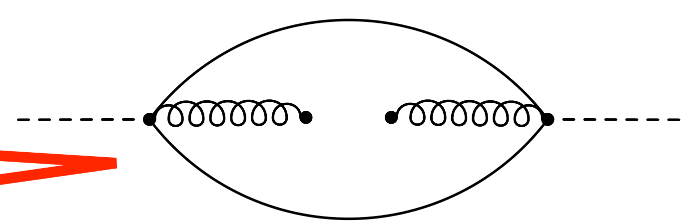
$$J_{\mu\nu} = g_s \bar{Q} \frac{\lambda^a}{2} \sigma^\alpha_\mu \gamma_5 G^a_{\alpha\nu} Q\,, \qquad J^{PC} = 2^{-+}, 1^{++}, 1^{-+}, 0^{-+}$$

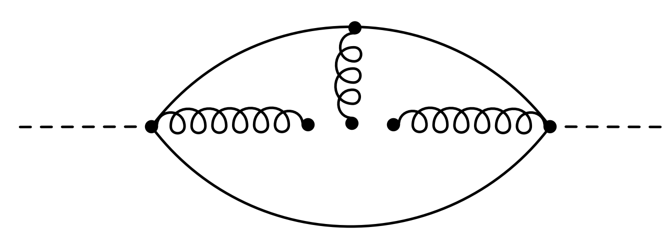
- Leading order correlator (QCD sum-rule) up to dim-six gluonic condensates

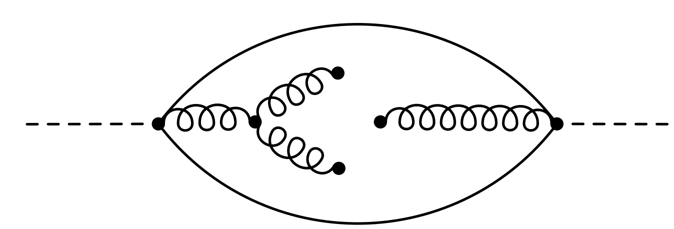
- Same methodology as molecular states: stability analysis of sum-rule ratio in sum-rule window of validity

$$M_X^2 = \frac{\mathcal{R}_1(\tau, s_0)}{\mathcal{R}_0(\tau, s_0)}$$









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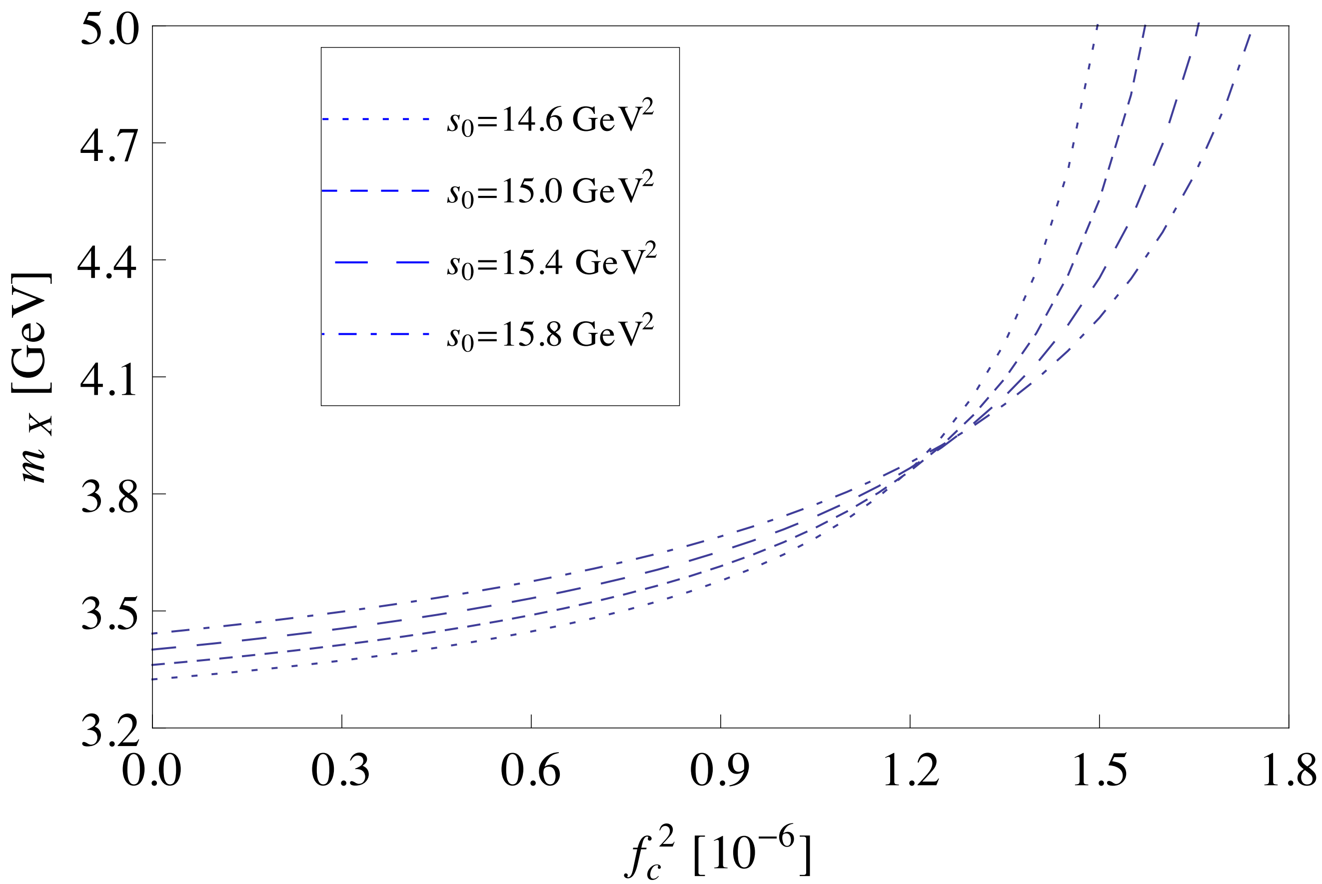
Charmonium Hybrid Mass Spectrum

- Supermultiplet structure based on parity
- 0^{--} anomalous: heaviest state
- For conventional J^{PC} mixing with charmonium would raise mass prediction (lower bound)
- No obvious alignment with observed XYZs

J^{PC}	$s_0(\text{GeV}^2)$	$m_X(\text{GeV})$
1^{--}	15	3.36 ± 0.15
0^{-+}	16	3.61 ± 0.21
1^{-+}	17	3.70 ± 0.21
2^{-+}	18	4.04 ± 0.23
0^{+-}	20	4.09 ± 0.23
2^{++}	23	4.45 ± 0.27
1^{+-}	24	4.53 ± 0.23
1^{++}	30	5.06 ± 0.44
0^{++}	34	5.34 ± 0.45
0^{--}	35	5.51 ± 0.50

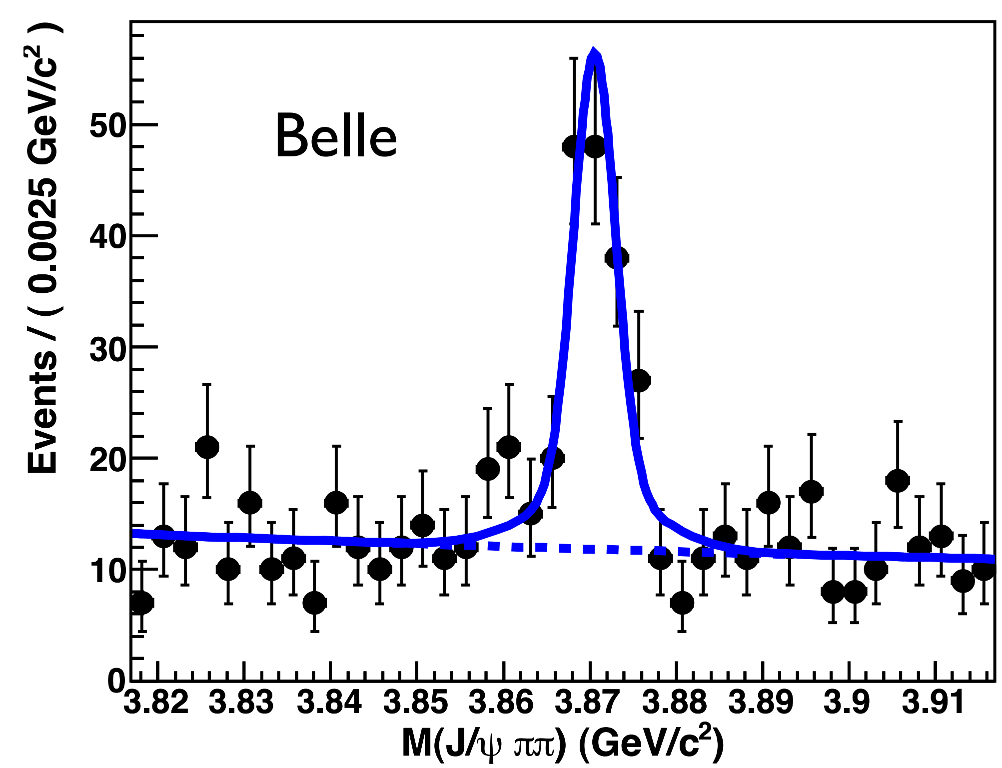


W Chen, Kleiv, TGS, Bulthuis, Harnett, Richards, Ho, S-L Zhu, JHEP09 (2013)

If hybrids present in XYZs might be within mixed states

The Enigmatic X(3872)

- Discovery by Belle, confirmed by CDF, D0, BaBar Belle PRL91 (2003)
- PDG mass 3871.69 ± 0.17 MeV and width Γ< 1.2 MeV
- LHCb settles quantum numbers: $J^{PC}= 1^{++}$ LHCb PRL110 (2013)
- Large isospin violation: $X \to \rho\, J/\psi$ and $X \to \omega\, J/\psi$ comparable (Belle/BaBar)
- Isospin not well understood: likely an isosinglet
- Molecular interpretation explains isospin violation but hard to describe radiative decays $X \to \gamma\, J/\psi$ Swanson PLB588 (2004)



Mixed scenario likely needed for X(3872)

Godfrey hep-ph/0605152
Coito et al EPJC71 (2011)

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Mixed Hybrid/Molecular Currents

- Mixed 1^{++} hybrid/molecular currents for QCD sum-rule analysis

$$J_\mu^h = \frac{1}{2} g \bar{c} \gamma^\nu \lambda^a \tilde{G}^a_{\mu\nu} c \,, \; \tilde{G}^a_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} G_a^{\alpha\beta} \,, \; J_\nu^m = \frac{1}{\sqrt{2}} \left(\bar{q}_a \gamma_5 c_a \bar{c}_b \gamma_\nu q_b - \bar{q}_a \gamma_\nu c_a \bar{c}_b \gamma_5 q_b \right)$$

$$J_\nu^\xi = \sqrt{1-\xi^2} J_\nu^m + \xi \sigma J_\nu^h$$

- Parameter $0<\xi<1$ interpolates between molecular and hybrid limits; σ is mass scale (set σ=1 GeV with no loss of generality)

Harnett, Kleiv, TGS, H-Y Jin, JPG39 (2012)
Lee et al arXiv:0803.1168

- Mixed current correlation function contains known hybrid-hybrid and molecular-molecular results; off-diagonal (hm) correlator must be calculated

$$\Pi^\xi_{\mu\nu}(q) = i \int d^4x \, e^{iq\cdot x} \langle 0 | T \left[\, J_\mu^\xi(x) \, J_\nu^\xi(0) \, \right] | 0 \rangle$$

$$\Pi^{\rm hm}_{\mu\nu}(q) = i \int d^4x \, e^{iq\cdot x} \langle 0 | T \left[\, J_\mu^{\rm h}(x) \, J_\nu^{\rm m}(0) \, \right] | 0 \rangle$$

1^{++} transverse part

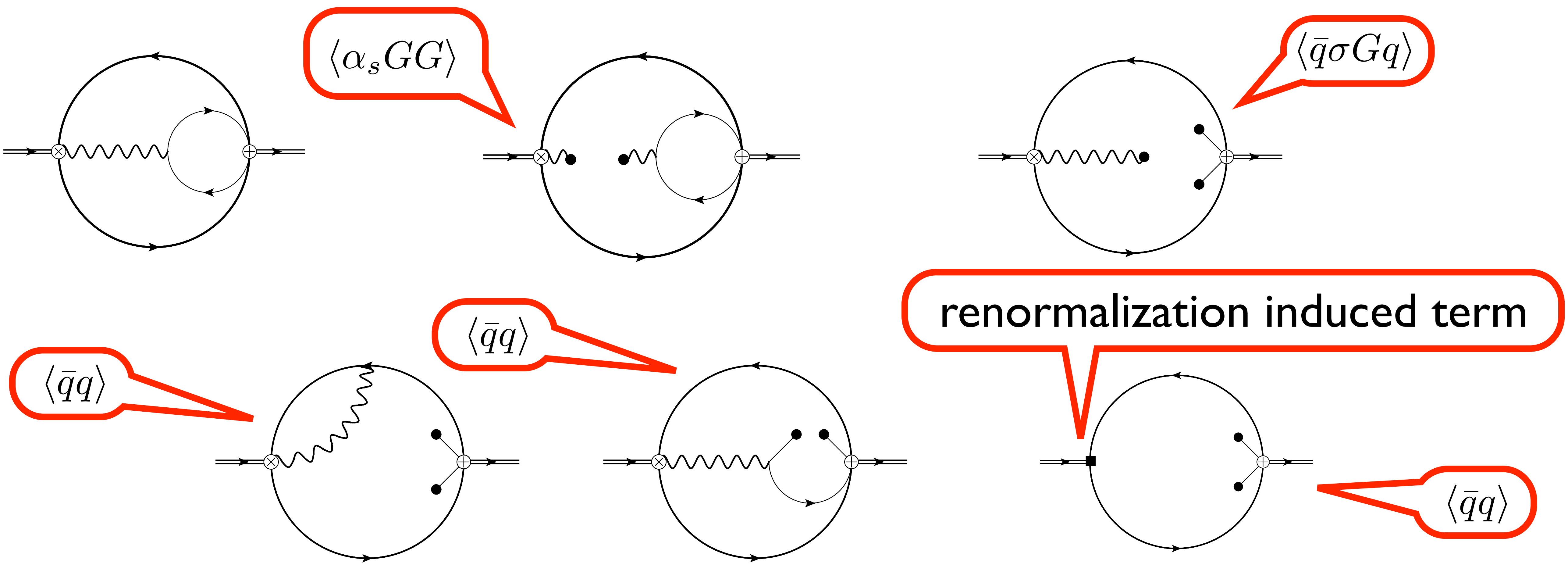
Molecule/Hybrid QCD Sum-Rule Analysis

- Mixed correlator subtle: need to renormalize hybrid (composite) operator

$$\left[J_\mu^h\right]_R = Z_1\left[J_\mu^h\right]_B + Z_2 m^2\left[\mathcal{O}_\mu\right]_B + \ldots\,,\;\; Z_1 = 1 + \frac{\alpha}{\pi}\frac{Z_{h1}}{\epsilon}\,,\;\; Z_2 = -\frac{10}{243}\frac{\alpha}{\pi}\frac{1}{\epsilon}$$

$$\mathcal{O}_\mu = \bar{c}\Gamma_\mu c\,,\quad \Gamma_\mu = \epsilon_{\mu\nu\alpha\beta}\left(\gamma^\nu\sigma^{\alpha\beta} + \gamma^\alpha\sigma^{\beta\nu} - \gamma^\beta\sigma^{\alpha\nu}\right)$$

- Leading order, condensates up to dimension five

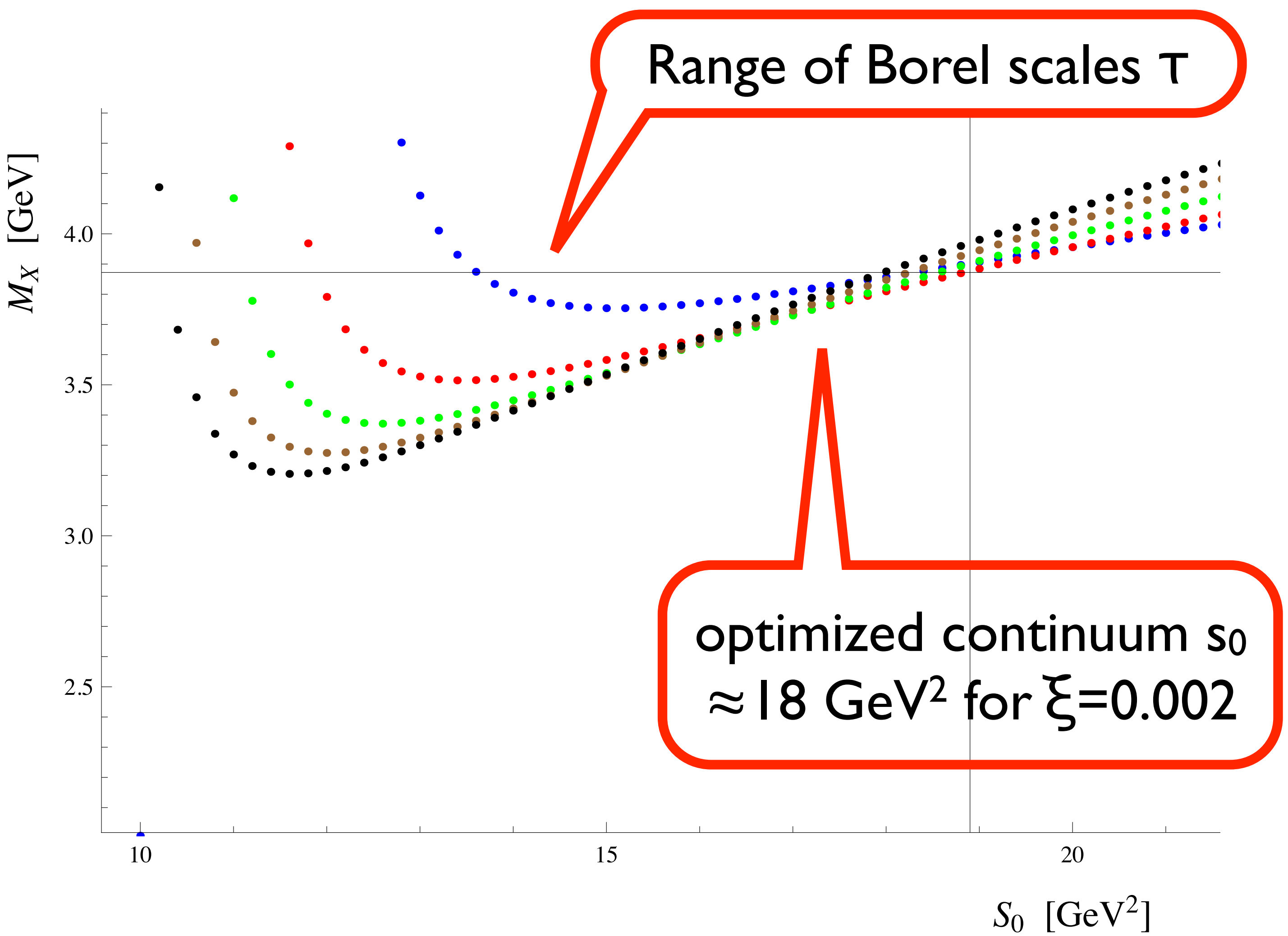


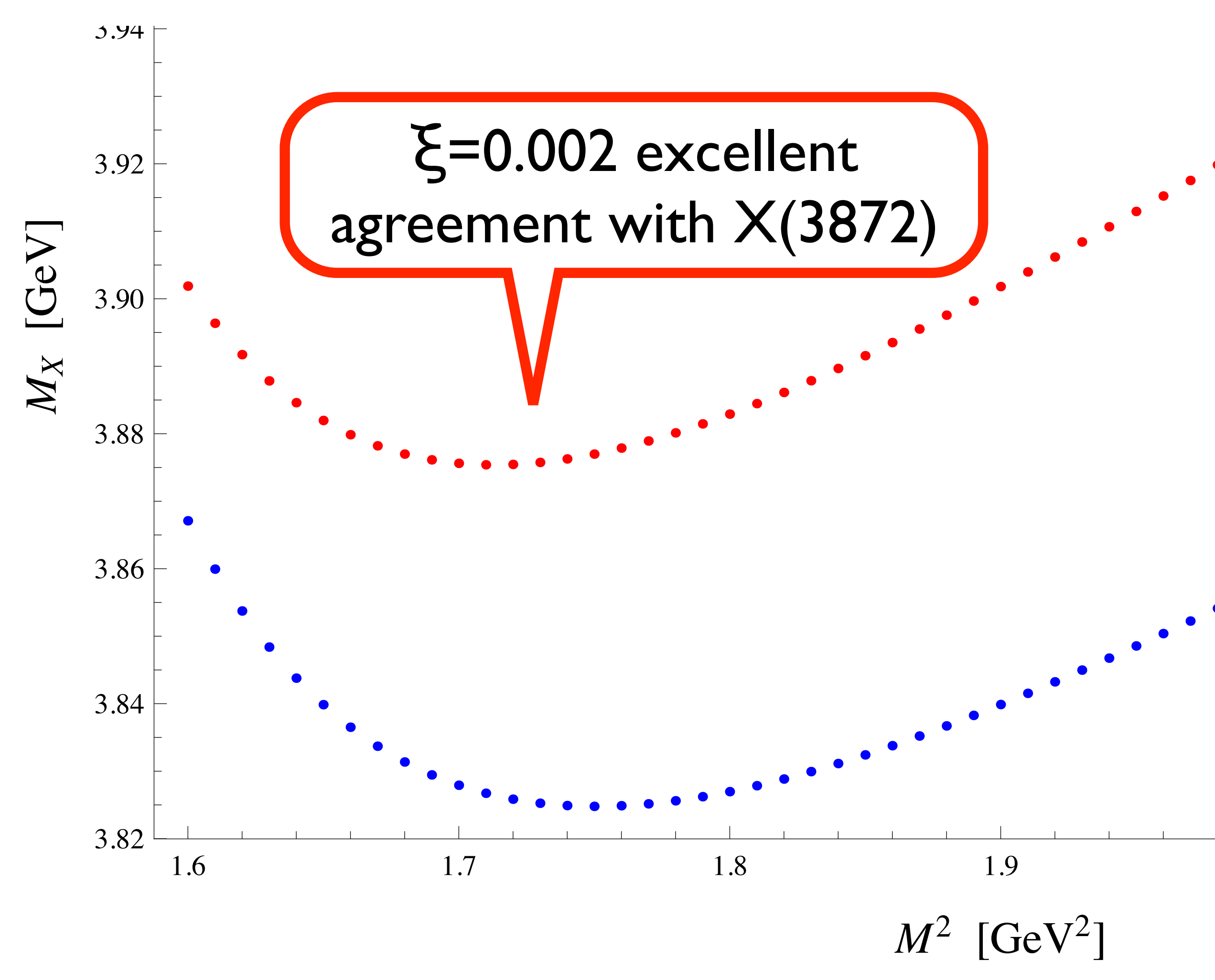
W Chen, H-Y Jin, Kleiv, TGS, M Wang, Q Xu, PRD88 (2013)

X(3872): Mixed Hybrid/Molecule

W Chen, H-Y Jin, Kleiv, TGS, M Wang, Q Xu, PRD88 (2013)

- Scan QCD sum rule for M_X over mixing parameter ξ (must optimize s_0)
- M_X increases as ξ increases from zero (pure molecule) until max at $\xi \approx 0.002$
- Viable scenario of X(3872) coupling to mixtures of hybrid/molecular currents
- Significant mixing (compare $\xi \approx 0.002$ to ratios of pure correlation functions)





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Internal Structure of Multiquark XYZs

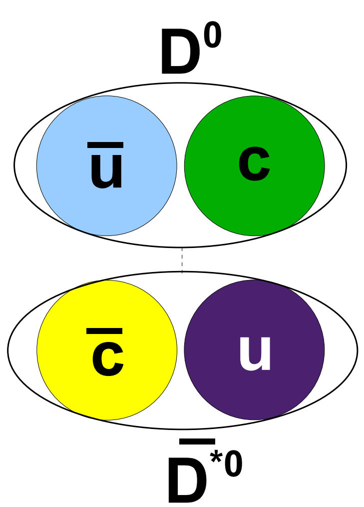
- Molecular and diquark scenarios of XYZs cluster quarks differently
- Diquarks are in colour triplet; experience colour force like quarks
- Two mixed neutral states $[cq]_{\bar{3}}[\bar{c}\bar{q}]_{3}$ (q=u,d)

Maiani et al PRD71 (2005)

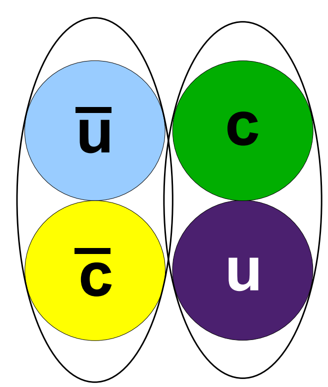
- Phenomenological input of constituent diquark mass $M_{[cq]} = 1933\,\mathrm{MeV}$
- Decay by "single switch" process $[cq]_{\bar{3}}[\bar{c}\bar{q}]_{3} \rightarrow [\bar{c}c]_{0}[\bar{q}q]_{0}$

tuned to X(3872) !!

J/ψ



D^0-$\bar{D}^{*0}$ "molecule"



antidiquark - diquark

Nielsen et al PhysRep497 (2010)

Can QCD say anything about internal structure? Diquark mass prediction provides indirect probe

Heavy-Light Diquarks

Kleiv, TGS, Zhang, Blokland, PRD87 (2013)

- Gauge dependent diquark currents for QCD sum-rule analysis

$$J_\alpha = \epsilon_{\alpha\beta\gamma} Q_\beta^T C \mathcal{O} q_\gamma\,;\;\; \mathcal{O} = \gamma_5\,, I\,, \gamma_\mu\,, \gamma_\mu\gamma_5 \;\; (J^P = 0^+,\; 0^-,\; 1^+,\; 1^-)$$

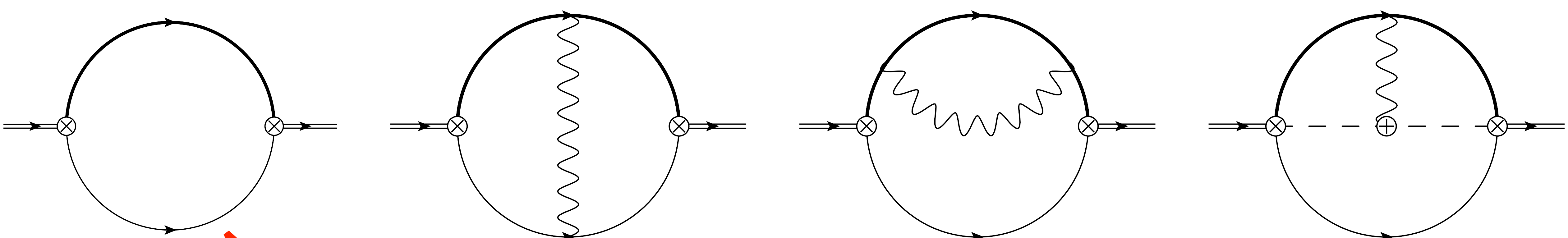
- Schwinger string extracts gauge invariant information from correlator

Dosch, Jamin, Stech, ZPC42 (1989)

$$\Pi\left(Q^2\right) = i\int d^4x\, e^{iq\cdot x}\langle 0|T\left[\, J_\alpha\left(x\right) S_{\alpha\omega}\left[x\,,0\right] J_\omega^\dagger\left(0\right)\,\right]|0\rangle$$

$$S_{\alpha\omega}\left[x\,,0\right] = P\exp\left[ig\frac{\lambda^a_{\alpha\omega}}{2}\int_0^x dz^\mu\;\; A^a_\mu\left(z\right)\right]$$

- Calculate correlator: next-to-leading perturbation theory



Include diquark renormalization
Kleiv, TGS, JPG38 (2011)

Schwinger string

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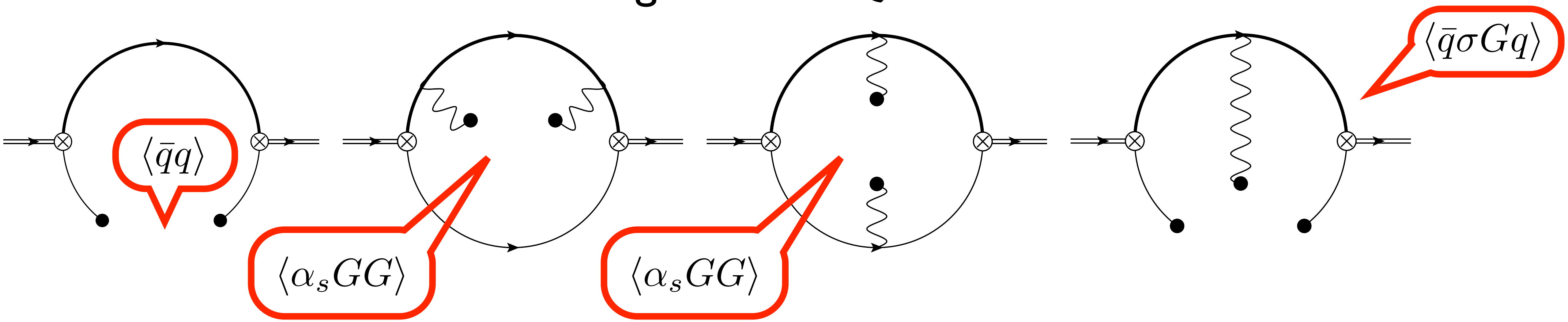
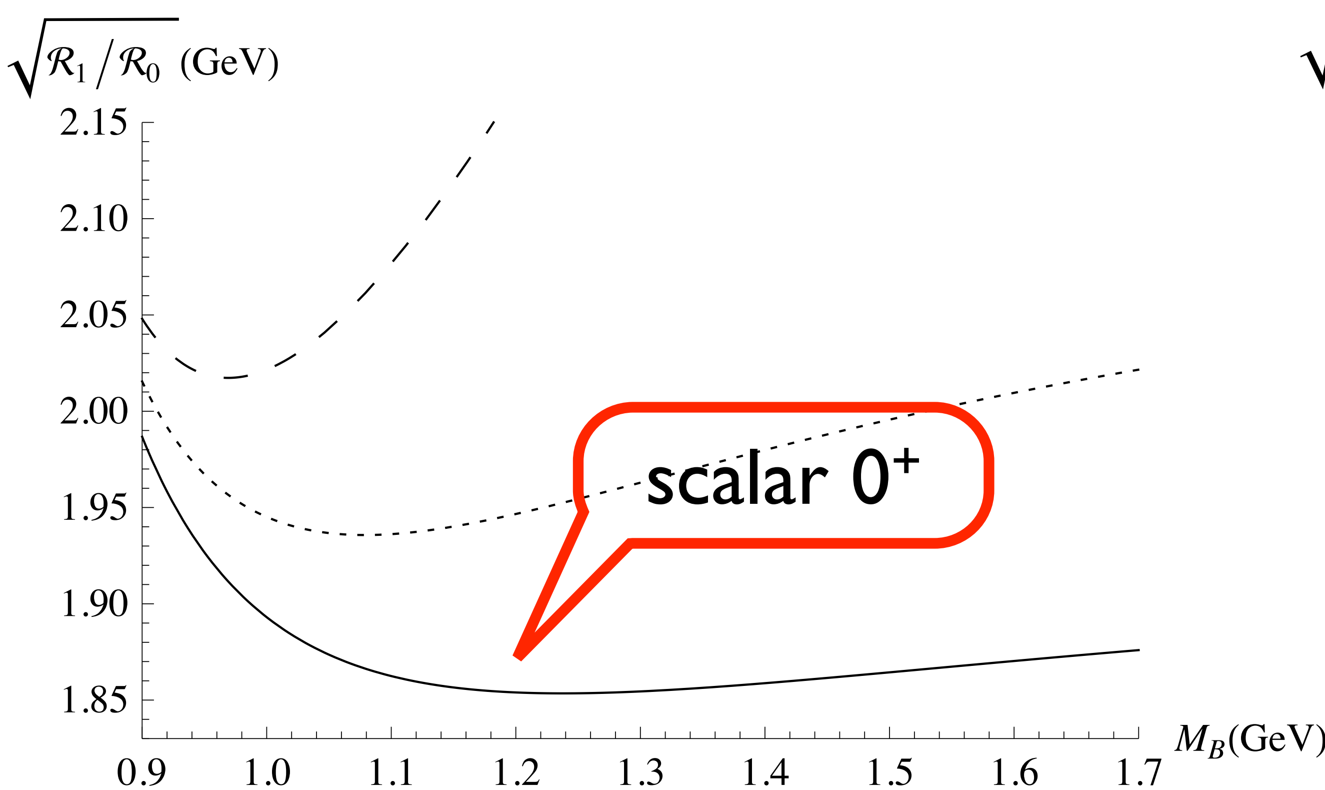
Heavy-Light Diquark Correlator

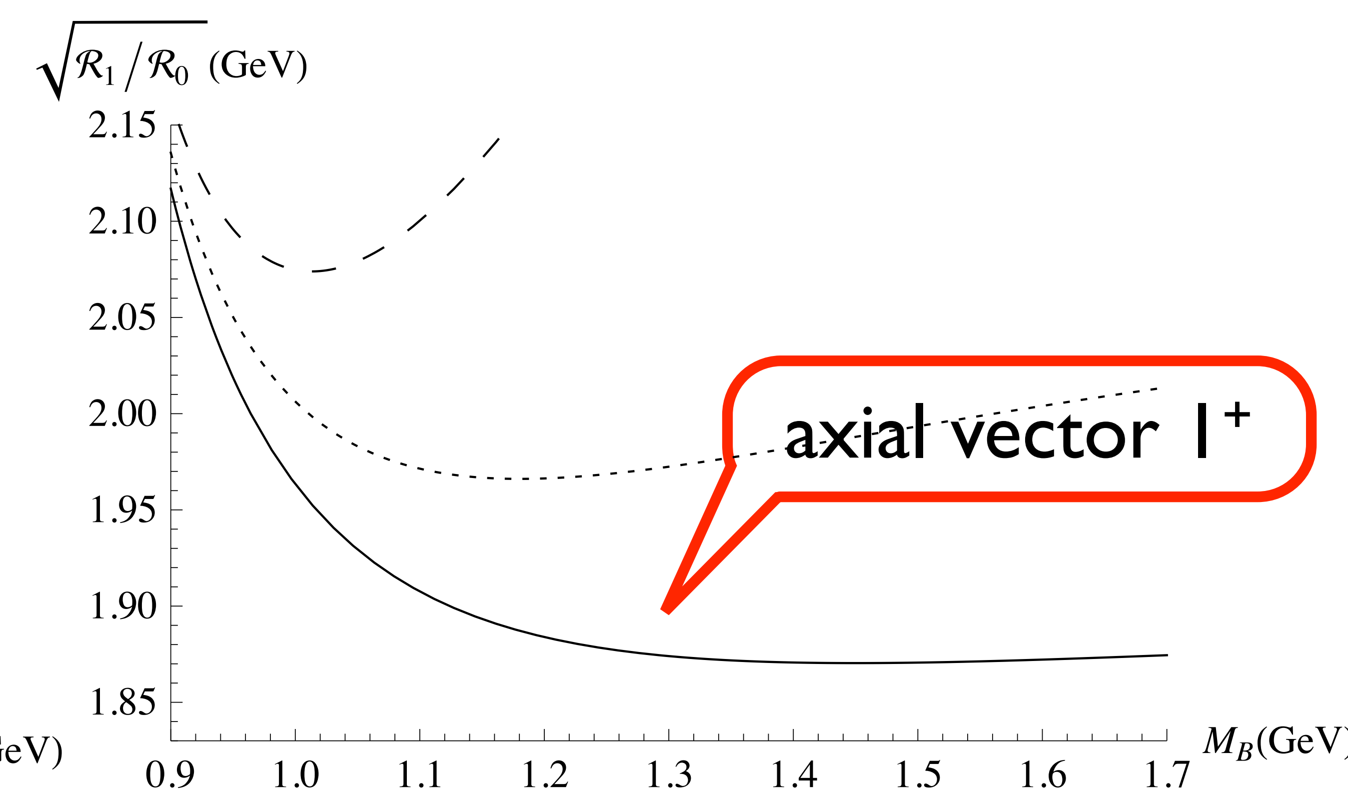
Kleiv, TGS, Zhang, Blokland, PRD87 (2013)

- Calculate correlator: leading-order in QCD condensates to dimension five



- Standard sum-rule analysis: only stable results for positive parity diquarks
  Jaffe: no negative parity "worse" diquarks





Charm-Light Diquark Mass

Kleiv, TGS, Zhang, Blokland, PRD87 (2013)

- [cq] positive parity diquark QCD sum-rule mass predictions nearly degenerate

$$M_s = 1.86 \pm 0.05\,\mathrm{GeV},\ \ M_a = 1.87 \pm 0.1\,\mathrm{GeV}$$

- Excellent agreement with tetrauqark model tuned to X(3872)

$$M_{[cq]} = 1933\,\mathrm{MeV}$$ Maiani et al PRD71 (2005)

Indirect QCD evidence supporting tetraquark model for XYZs

Additional results

Discussion

- Rich landscape of XYZ mesons observed that cannot be explained as charmonium states
- Many charged states now observed: multi-quark scenarios seem inevitable and provide unifying theme with light scalars
- Neutral partners for some charged states, completing isospin multiplets
- Open question: internal quark structure of multi-quark states (e.g. tetraquark versus molecular); difficult to answer with analyses based on local operators
- No evidence of pure charmonium hybrids amongst known XYZs; QCD evidence of viable mixed hybrid/multiquark states to resolve stubborn puzzles
- QCD can provide indirect evidence for multi-quark models (e.g., agreement between diquark mass predictions in QCD and tetraquark models)

Key challenge for QCD

compelling unifying theoretical framework for the XYZs

Thank you!

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Additional QCD Sum-Rule Results

- Bottomonium hybrids W Chen, Kleiv, TGS, Bulthuis, Harnett, Richards, Ho, S-L Zhu, JHEP09 (2013)

- Bottom/Charm hybrids W Chen, TGS, S-L Zhu, JPG 41 (2014)

- Open-flavour (bottom/charm) tetraquarks W Chen, TGS, S-L Zhu, PRD 89 (2014)

- Z_c(4200) decay widths $Z_c^+(4200) \to J/\psi\pi^+,\ \eta_c\rho^+,\ D^+\bar{D}^{*0}$

W Chen, TGS, H-X Chen,
S-L Zhu, arXiv:1501.03863

Summary