Exotic and excited-state radiative transitions in charmonium from lattice QCD

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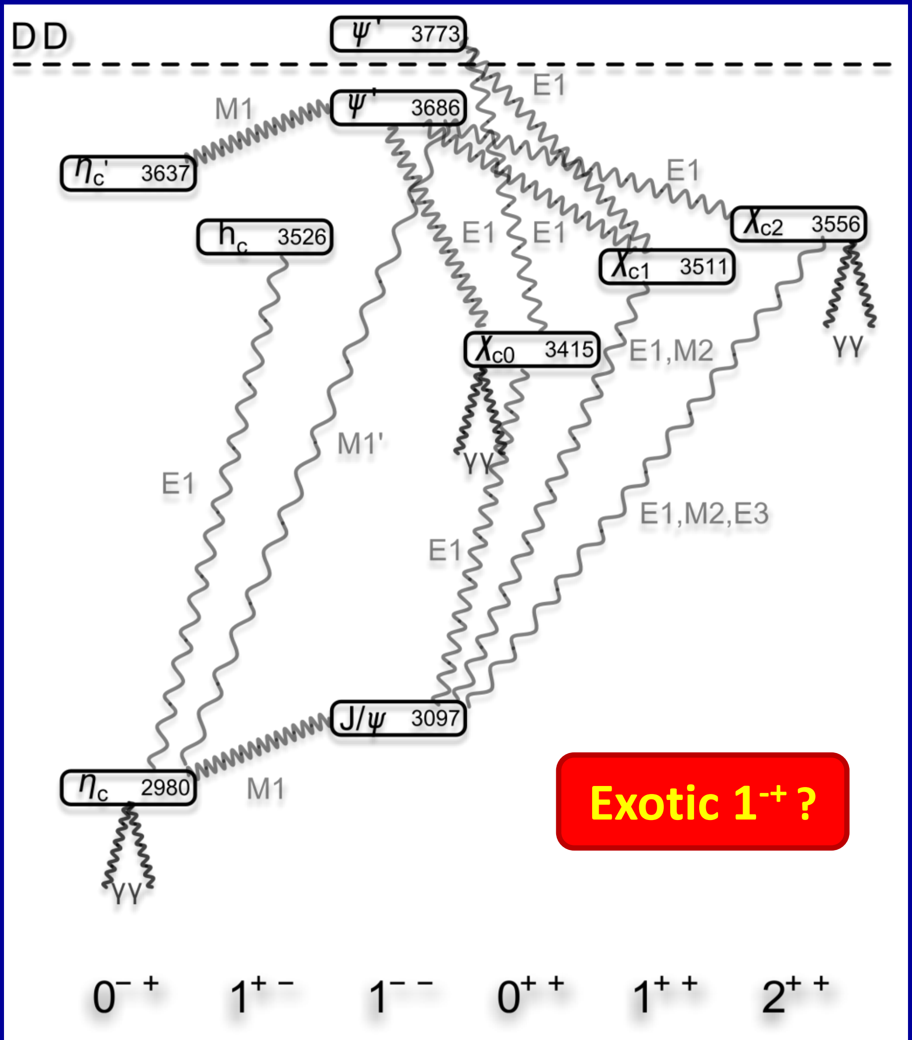
In collaboration with:
Jo Dudek, Robert Edwards, David Richards
and the *Hadron Spectrum Collaboration*

Outline

- Introduction and motivation
- Method
- Result highlights and interpretations
- Conclusions

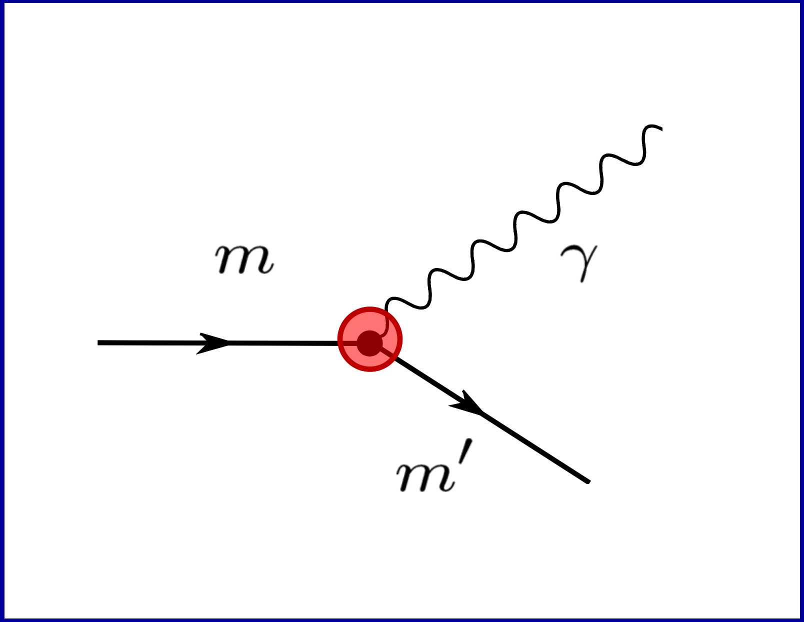
Charmonium radiative transitions



Exotic 1^{-+} ?

BABAR, Belle, BES, CLEO-c

Meson – Photon coupling



Broader Picture

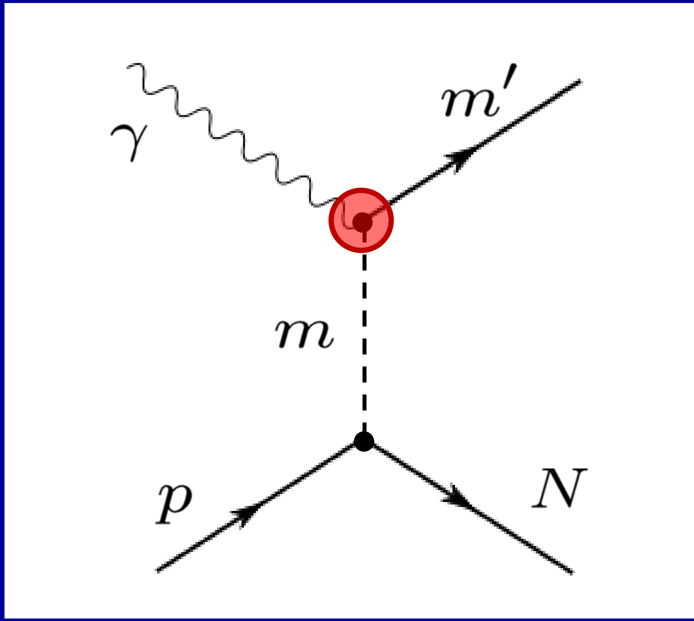
Develop Lattice QCD Techniques

Test in the charmonium system

Apply to lighter mesons…

Photoproduction at GlueX

Exotic 1^{-+} ?



For progress on the light meson spectrum see Jo Dudek's talk from Tuesday

Spectroscopy on the lattice

Calculate energies and matrix elements (Z) from correlation functions of meson interpolating fields

$$O = \bar{\psi}(x)\Gamma_i \overleftrightarrow{D}_j \overleftrightarrow{D}_k \ldots \psi(x)$$

$$Z_i^{(n)} \equiv < n|O_i|0 >$$

$$\begin{aligned} C(t) &= < 0|O_i(t)O_j(0)|0 > \\ &= \sum_n \frac{e^{-E_n t}}{2E_n} < 0|O_i(0)|n >< n|O_j(0)|0 > \\ &\xrightarrow[t\to\infty]{} \frac{Z_i^{(0)} Z_j^{(0)*}}{2E_0} e^{-E_0 t} \end{aligned}$$

Variational Method

Consider a large basis of operators → matrix of correlators $C_{ij}(t)$

Generalised eigenvector problem:

$$C_{ij}(t)v_j^{(n)} = \lambda^{(n)}(t)C_{ij}(t_0)v_j^{(n)}$$

Eigenvalues → energies

$$\lambda^{(n)}(t) \to e^{-E_n(t-t_0)}$$

$(t >> t_0)$

Eigenvectors → optimal linear combination of operators to overlap on to a state

$$\Omega^{(n)} \sim \sum_i v_i^{(n)} O_i$$

$Z^{(n)}$ related to eigenvectors

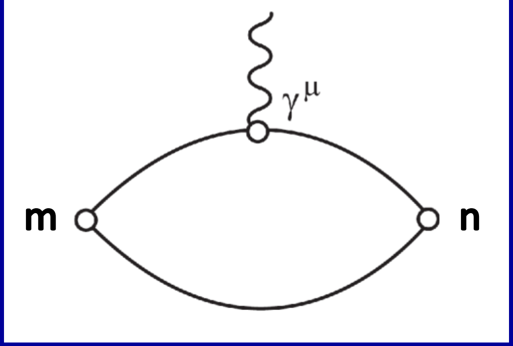
Photocouplings on the Lattice

Calculate from 3-point correlators:

$$C_{ij}(t_f, t, t_i) =< 0|O_i(t_f)\ \bar{\psi}(t)\gamma^\mu\psi(t)\ O_j(t_i)|0 >$$

$$\sim \sum_n \sum_m < 0|O_i(0)|n >< n|\bar{\psi}\gamma^\mu\psi|m >< m|O_j(0)|0 >$$
$$\times e^{-E_n(t_f-t)} e^{-E_m(t-t_i)}/(2E_n 2E_m)$$

Known from 2-point analysis



What we want: parameterize in terms of multipoles (~ form factors) and known factors

Multipoles

$$< n|\bar{\psi}\gamma^{\mu}\psi|m > \sim \sum_{k} K^{\mu}_{k,n,m}(\vec{p_i},\vec{p_f}) F_{k,n,m}(Q^2,t)$$

Multipoles

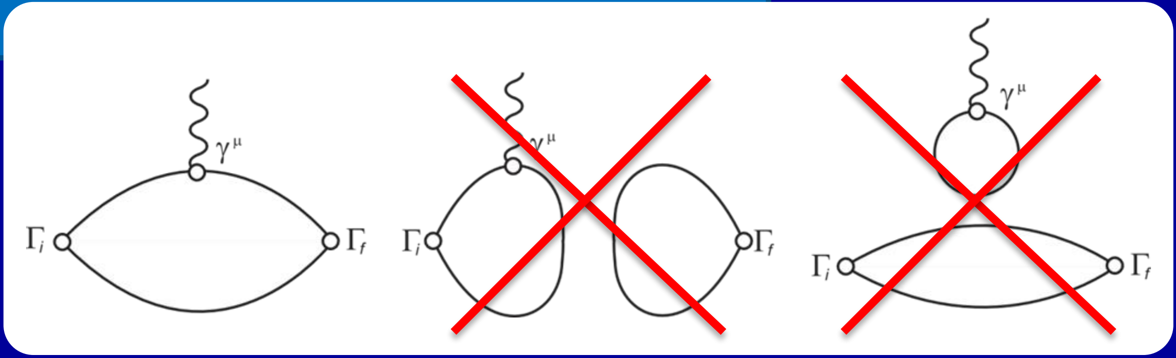
$J_i = J_f \otimes k \quad (k > 0)$

Experimentally measure multipoles at $Q^2 = 0$

Discrete momenta on the lattice

Charmonium radiative transitions

- Caveats:
  - Quenched (no quark loops; no light quarks at all)
  - One lattice spacing (a_t^{-1} = 6.05 GeV)
  - One volume ($L_s \approx$ 1.2 fm)
  - Only connected diagrams



Only a selection; results and details in
Dudek, Edwards & CT, PR **D79** 094504 (2009)

Also: Dudek et al PR **D77** 034501 (2008); Dudek & Rrapaj PR **D78** 094504 (2008)

Exotic 1^{-+} – Vector 1^{--}

Spectrum analysis: 1^{-+} η_{c1} state found at 4300(50) MeV

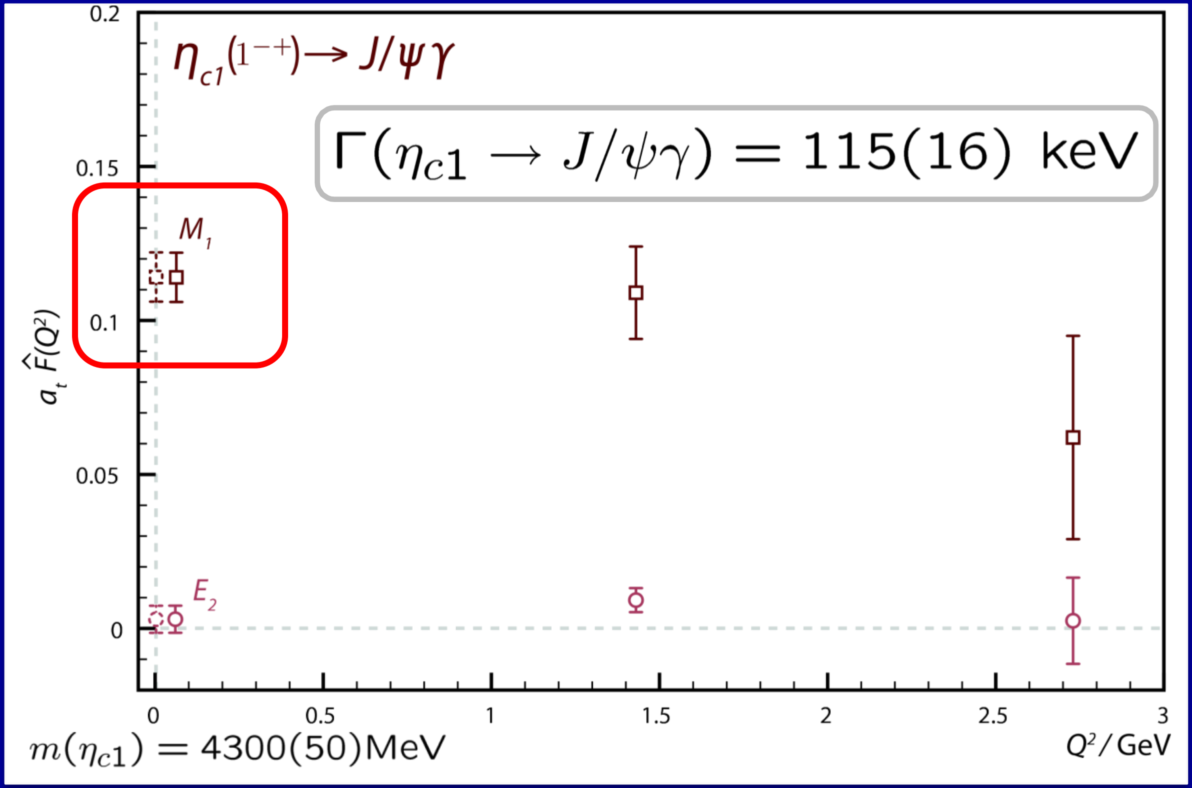
Exotic quantum numbers – can’t be fermion-antifermion pair

Can’t be a molecular/multi-quark state in **quenched** lattice calc.

→ Strongly suggests a hybrid

What about radiative transitions?

Exotic 1^{-+} – Vector 1^{--}



M_1 multipole dominates

Same scale as many measured conventional charmonium transitions

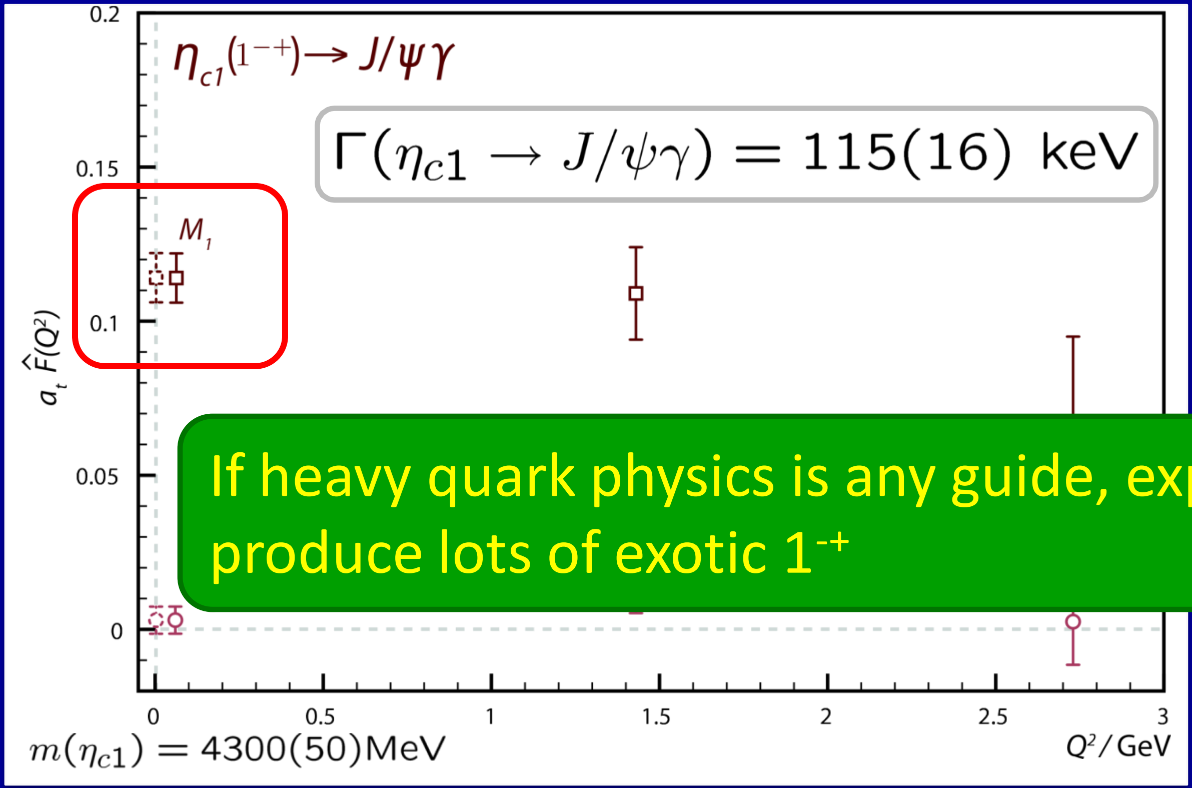
BUT very large for an M_1 transition

$\Gamma(J/\psi \to \eta_c\gamma) \sim 2$ keV

- Usually M_1 → spin flip (e.g. $^3S_1$→ $^1S_0$) → $1/m_c$ suppression
- Spin-triplet hybrid → extra gluonic degrees of freedom

  → M_1 transition without spin flip → not suppressed

Exotic 1^{-+} – Vector 1^{--}



M_1 multipole dominates

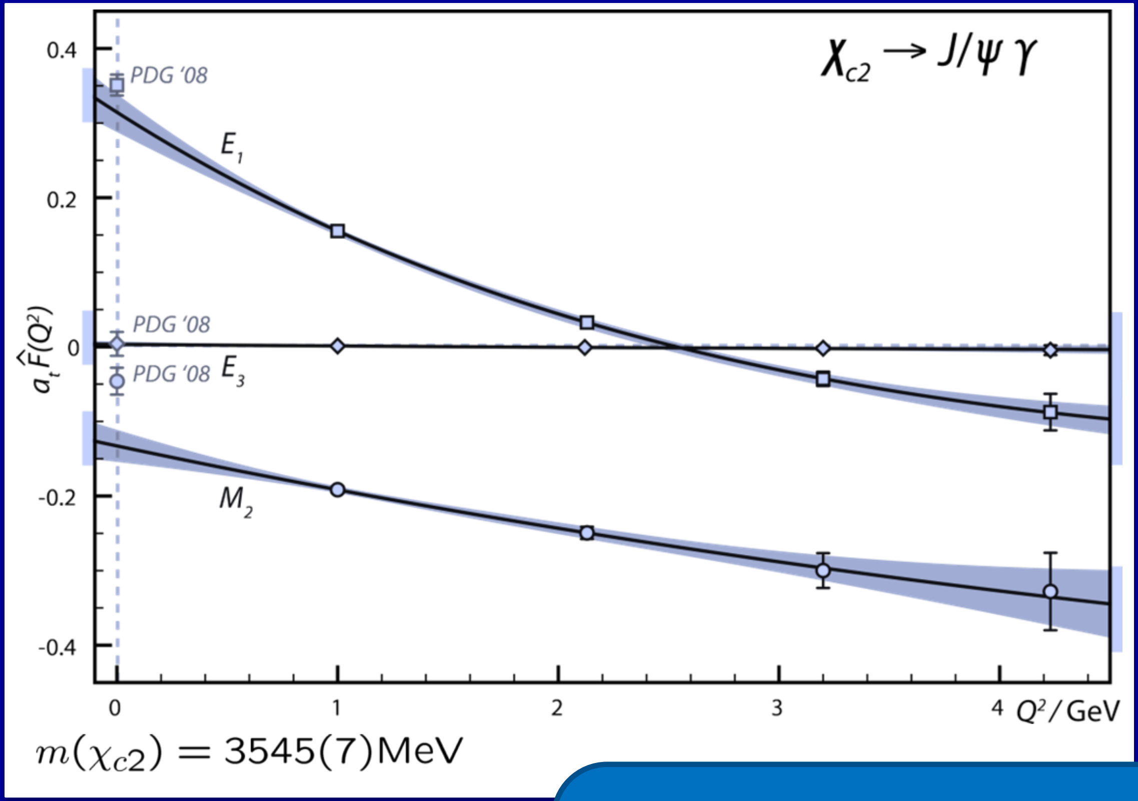
Same scale as many measured conventional charmonium transitions

$\Gamma(J/\psi \rightarrow \eta_c\gamma) \sim 2$ keV

If heavy quark physics is any guide, expect GlueX to produce lots of exotic 1^{-+}

- Usually M_1 → spin flip (e.g. ${}^3S_1$→ ${}^1S_0$) → $1/m_c$ suppression
- Spin-triplet hybrid → extra gluonic degrees of freedom
  → M_1 transition without spin flip → not suppressed

Tensor 2^{++} – Vector 1^{--}

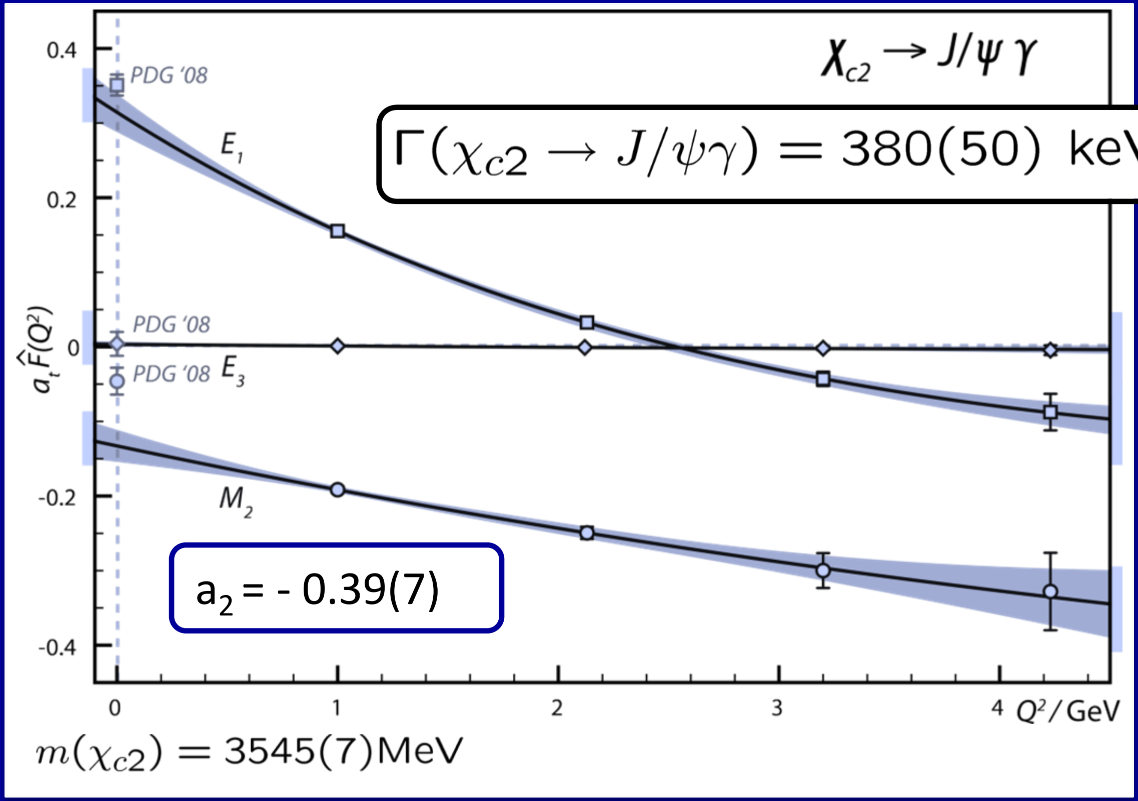


E_1, M_2, E_3

- Lattice: discrete set of allowed momenta
- Can't calculate at $Q^2 = 0$ and so extrapolate:

$$F_k(Q^2) = F_k(0)\left(1 + \lambda Q^2\right) e^{-\frac{Q^2}{16\beta^2}}$$

Tensor 2^{++} – Vector 1^{--}



E_1, M_2, E_3

PDG08: 406(31) keV

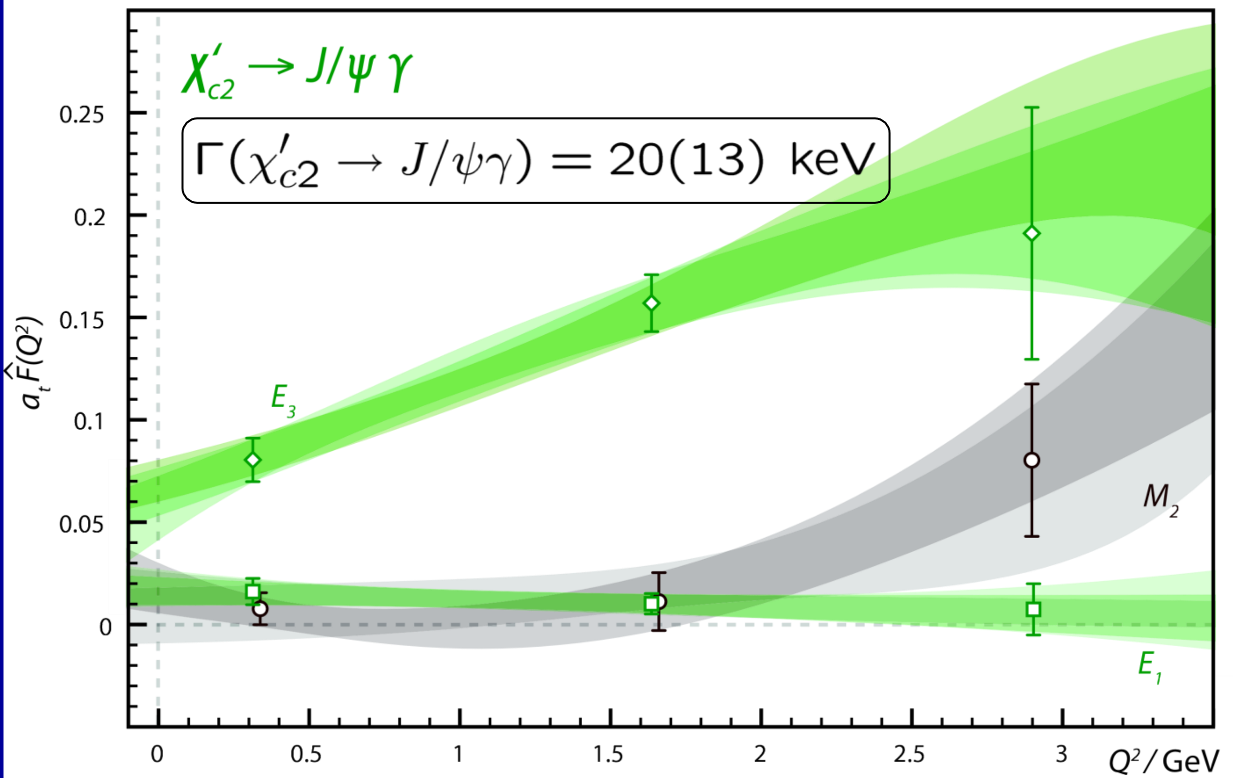
Quark models (1^3P_2)
~ 290 – 420 keV

$a_2 = M_2/\sqrt{(E_1^2+M_2^2+E_3^2)}$

PDG08: -0.13(5)
CLEO: -0.079(19)
[CLEO arXiv:0910.0046]

- Same hierarchy as expected: $|E_1(0)| > |M_2(0)| \gg |E_3(0)|$
- Ratio $|M_2/E_1|$ is considerably larger than experiment

Tensor 2^{++} – Vector 1^{--}

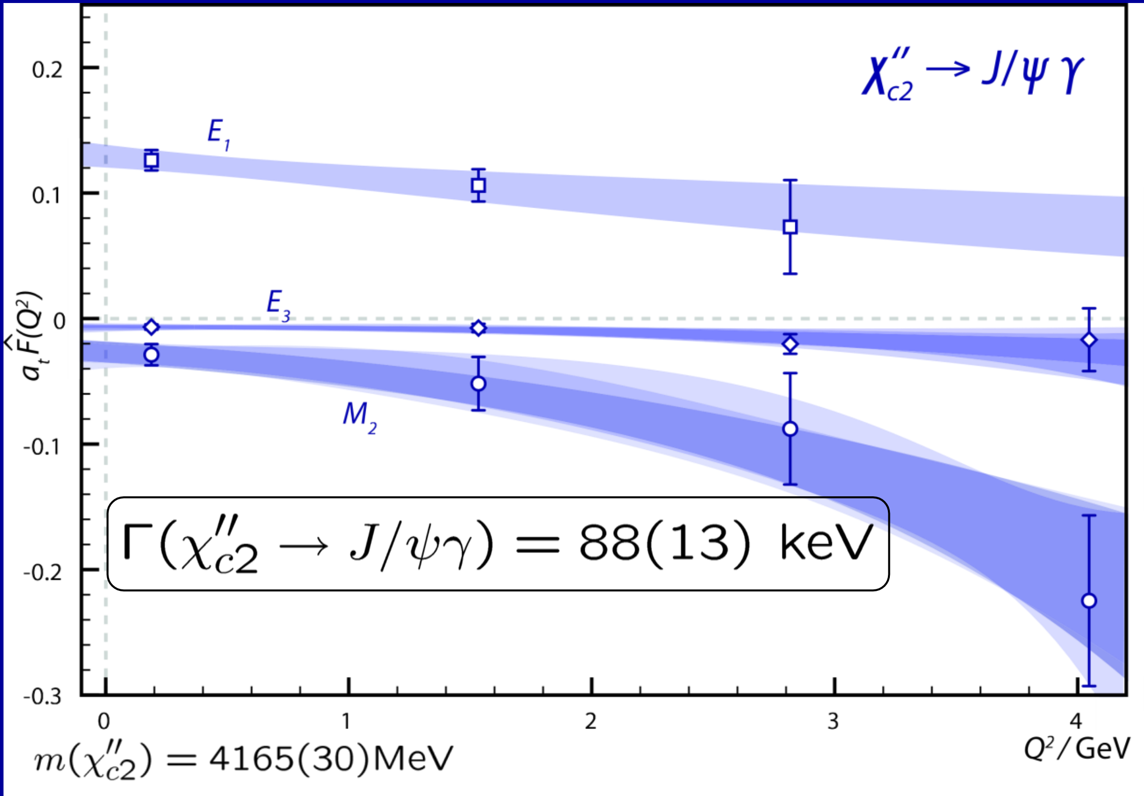


$m(\chi'_{c2}) = 4115(28)$MeV

E_1, M_2, E_3

Completely different hierarchy! $|E_3(0)| > |M_2(0)|\ ,\ |E_1(0)|$

Tensor 2^{++} – Vector 1^{--}



E_1, M_2, E_3

Quark models (2^3P_2)
~ 50 – 80 keV

Reverted to expected hierarchy: $|E_1(0)| > |M_2(0)| >> |E_3(0)|$

Tensor 2^{++} – Vector 1^{--}

Interpretation: **single quark transition** model

In general: $J_i = J_f \otimes k \quad (k > 0)$
E_1, M_2, E_3 (k = 1,2,3)

If only a single quark is involved ($^3\mathbf{P}_2 \rightarrow {}^3S_1$):
$j = 3/2 \rightarrow j = 1/2$
k = 1,2 only and $E_3 = 0$
$|E_1(0)| > |M_2(0)| >> |E_3(0)|$

If instead tensor is $^3\mathbf{F}_2$ ($^3\mathbf{F}_2 \rightarrow {}^3S_1$):
$j = 5/2 \rightarrow j = 1/2$
k = 2,3 only and $E_1 = 0$
$|E_3(0)| > |M_2(0)| >> |E_1(0)|$

Tensor 2^{++} – Vector 1^{--}

Interpretation: **single quark transition** model

In general: $J_i = J_f \otimes k \quad (k > 0)$

If onl

If ins

$|E_3(0)| > |M_2(0)| >> |E_1(0)|$

Interpretation:

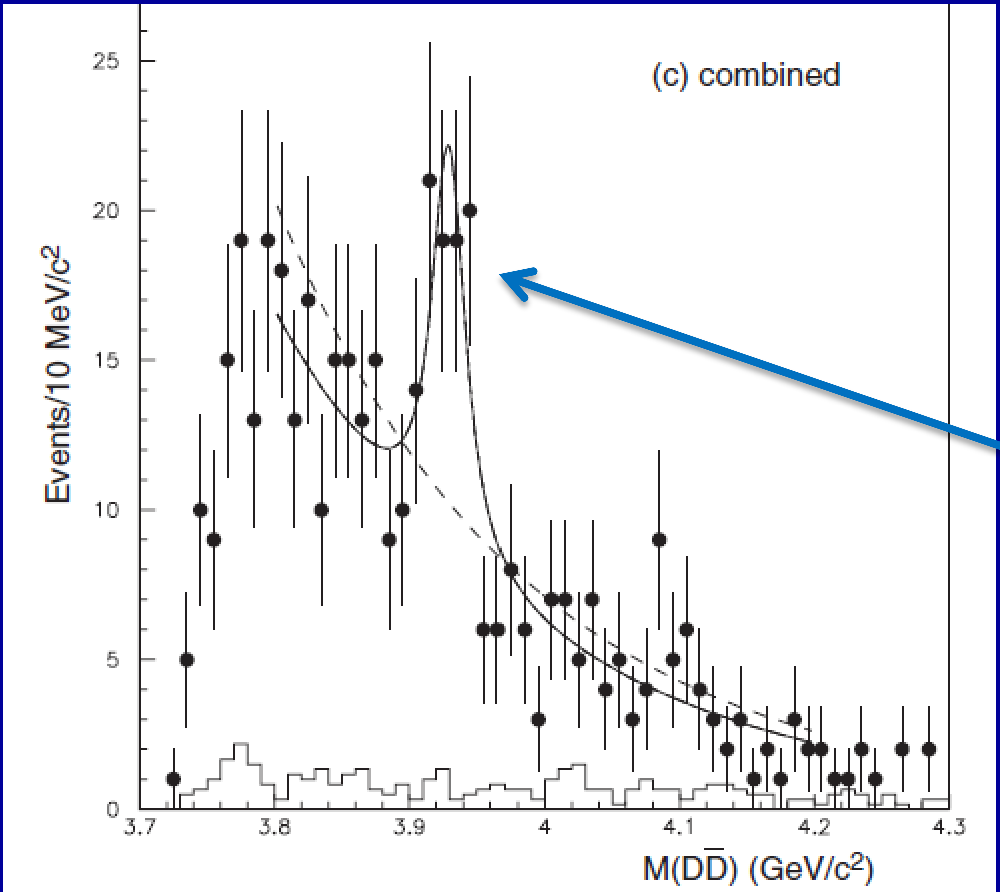
$\chi_{c2} - 1^3P_2$

$\chi'_{c2} - 1^3F_2$

$\chi''_{c2} - 2^3P_2$

Supported by spectrum analysis

Tensor 2^{++} – Vector 1^{--}



Belle [PRL 96 082003 (2006)]

Belle

$\gamma\gamma \rightarrow D\bar{D}$

χ'_{c2} ~ 3930 MeV

Needs lattice calc of two-photon coupling

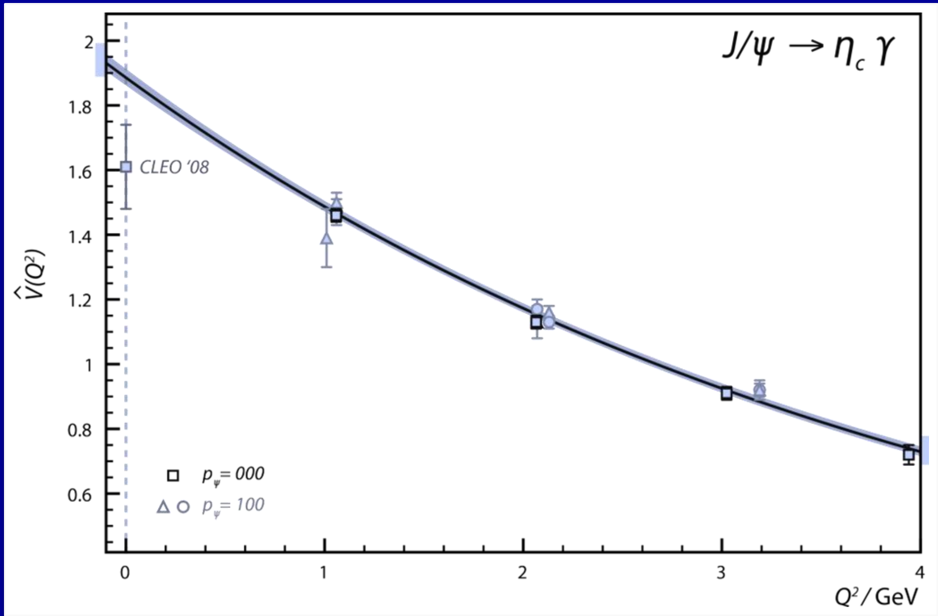
Vector 1^{--} – Pseudoscalar 0^{-+}

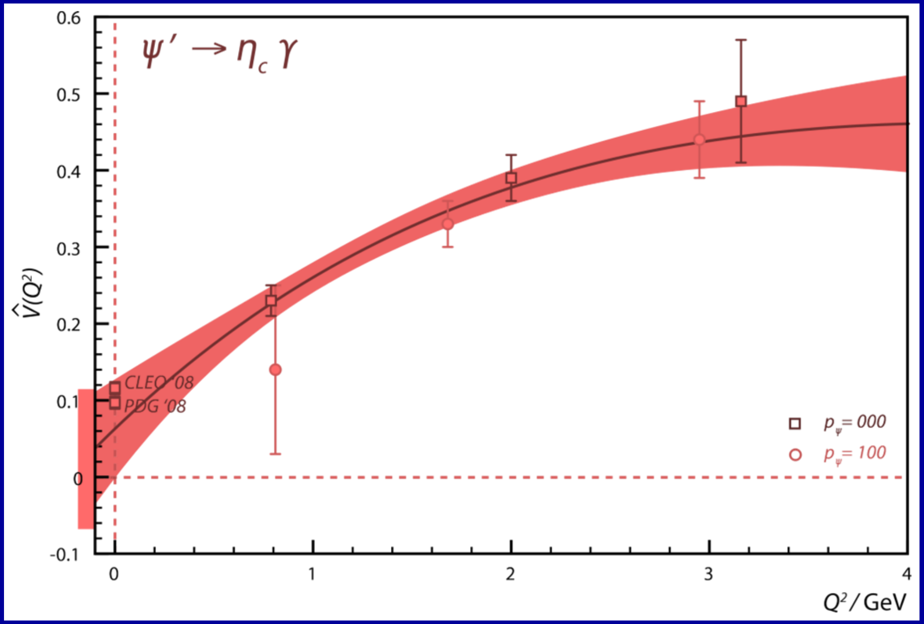
Spectrum results [PR **D77** 034501 (2008) , PR **D78** 094504 (2008)]:

Level	Mass / MeV	Suggested state	Model assignment
0	3106(2)	J/ψ	$1\,^3S_1$
1	3746(18)	$\psi'(3686)$	$2\,^3S_1$
2	3846(12)	$\psi_3(3^{--})$	lattice artifact
3	3864(19)	$\psi''(3770)$	$1\,^3D_1$
4	4283(77)	ψ('4040')	$3\,^3S_1$
5	4400(60)	Y	hybrid

Vector 1^{--} – Pseudoscalar 0^{-+}

Only M_1



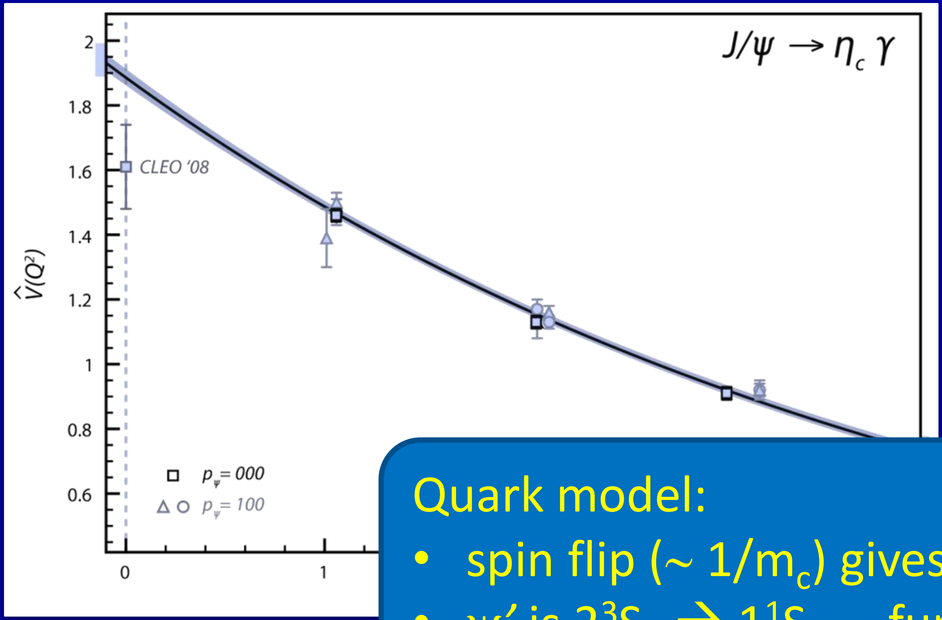


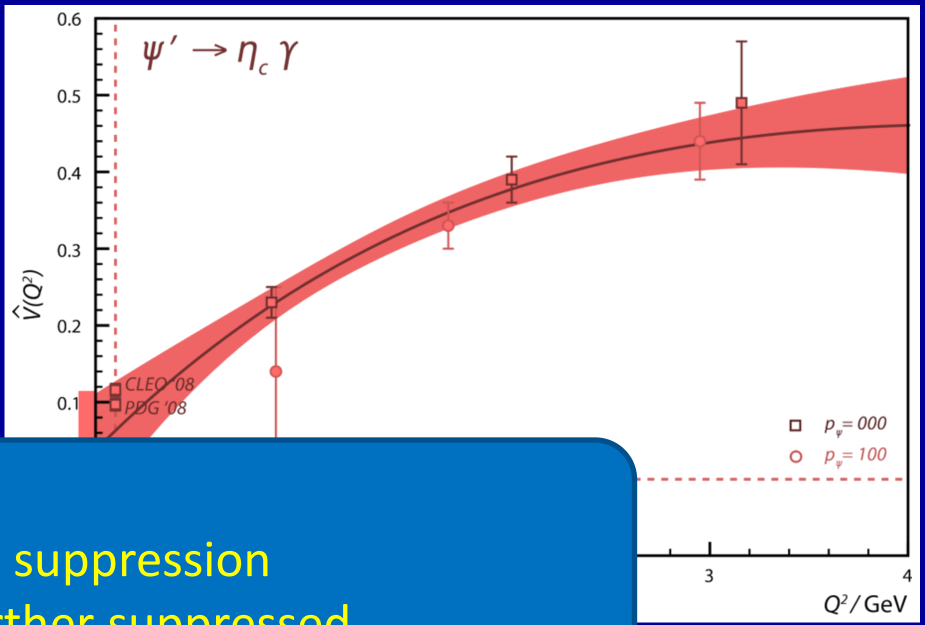
Γ / keV	Lattice	Exp.	Barnes, Godfrey, Swanson 'NR'	'GI'	Eichten et. al.
$J/\psi \to \eta_c\gamma$	2.51(8)	1.85(29) (CLEO-c)	2.9	2.4	1.92
$\psi' \to \eta_c\gamma$	0.4(8)	0.95(16) (PDG08) 1.37(20) (CLEO-c)	4.6, 9.7	9.6	0.91

[CLEO **PRL 102** 011801 (2009)]

Vector 1^{--} – Pseudoscalar 0^{-+}

Only M_1





Quark model:

- spin flip ($\sim 1/m_c$) gives suppression
- ψ' is $2^3S_1 \rightarrow 1^1S_0$ – further suppressed

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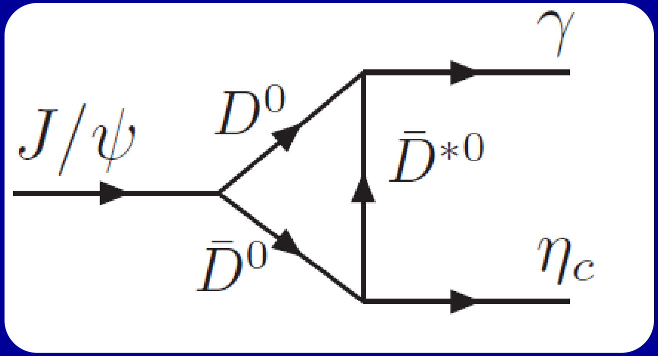
[CLEO **PRL 102** 011801 (2009)]

Vector 1^{--} – Pseudoscalar 0^{-+}

Loops

Li & Zhao [PL **B670** 55 (2008)]:
loop contributions in
vector – psuedoscalar transitions



→ Large loop contrib (~10 keV) to $\psi' \to \eta_c\gamma$

Interferes with ~10 keV bare amp. → ~1 keV (in line with experiment)

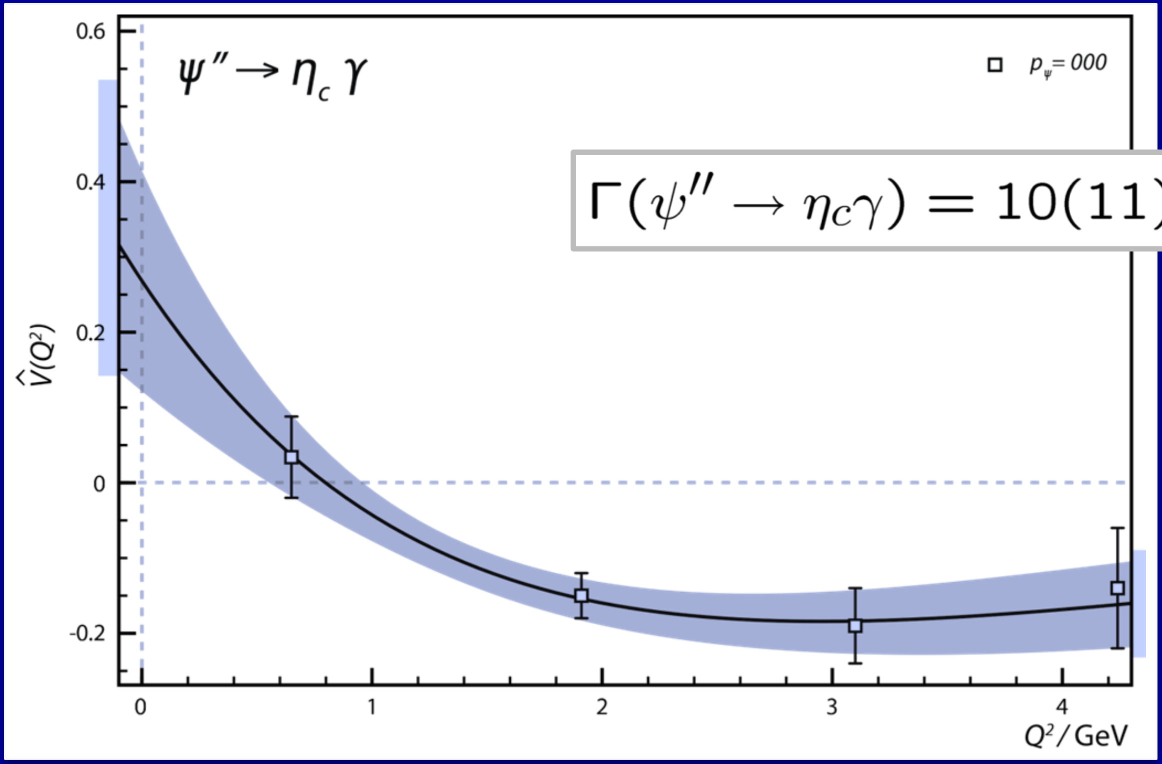
But no room for large loop contrib with 0.4(8) keV from quenched lattice

Actually loops calc has uncertainties from couplings an phases
E.g. use $\Gamma(D^{*0} \to D^0\gamma) \sim 800$ keV for $g_{D^*D\gamma}$ c.f. QM ≈ 30 keV

→ **Not** incompatible with lattice results

Vector 1^{--} – Pseudoscalar 0^{-+}

Only M_1

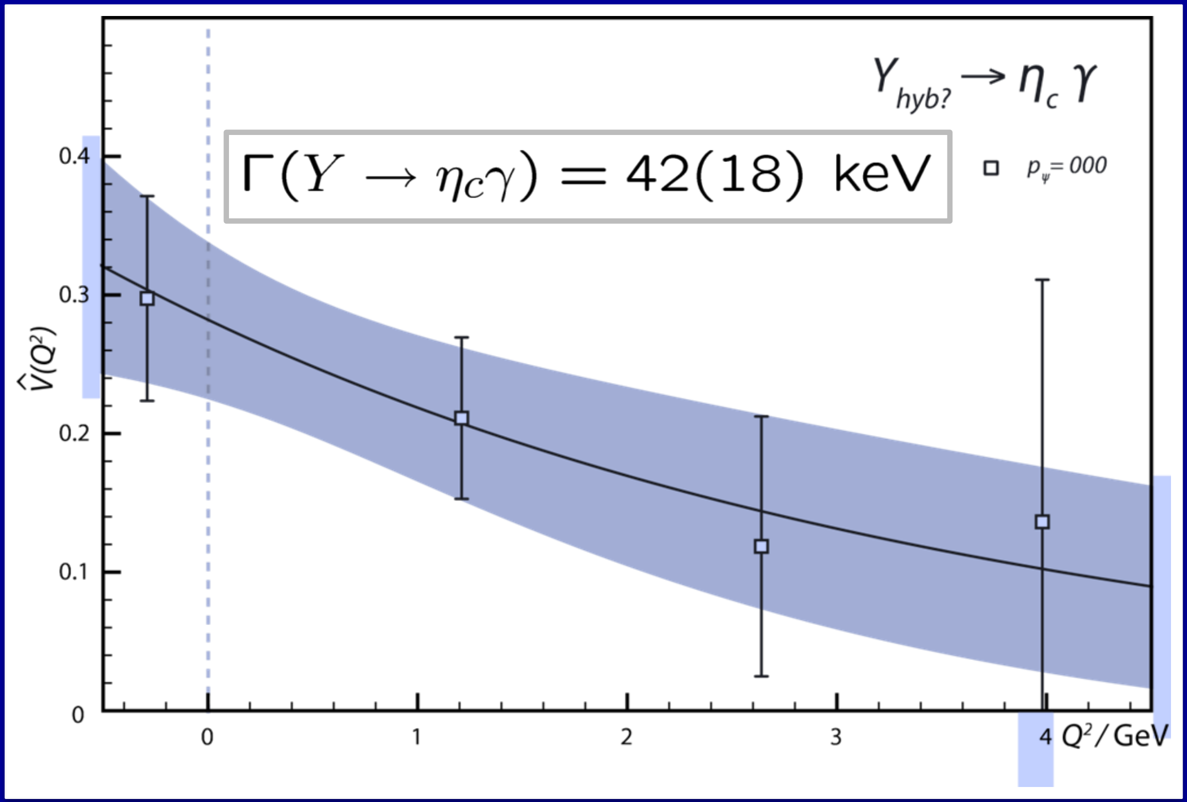


$$\Gamma(\psi'' \to \eta_c\gamma) = 10(11)\ \text{keV}$$

Quark model: $1^3D_1 \rightarrow 1^1S_0$ has same leading Q^2 behaviour as $2^3S_1 \rightarrow 1^1S_0$

Vector 1^{--} – Pseudoscalar 0^{-+}

Only M_1



Much larger than other $1^{--} \to 0^{-+}$ M_1 trans

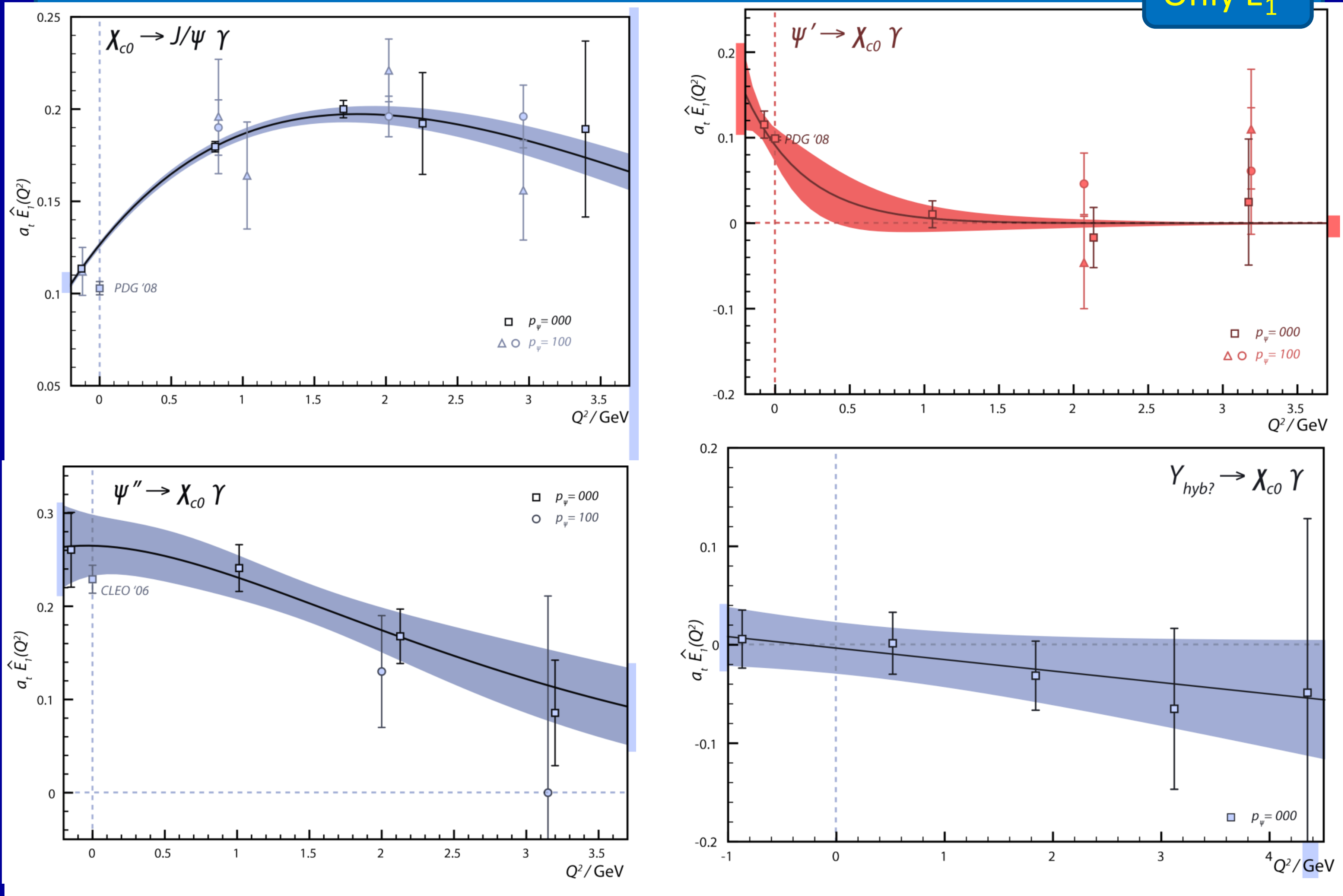
Spectrum analysis suggests a vector hybrid (spin-singlet)

Analogous to 1^{-+} hybrid to vector trans: M_1 with no spin flip

c.f. flux tube model 30 – 60 keV

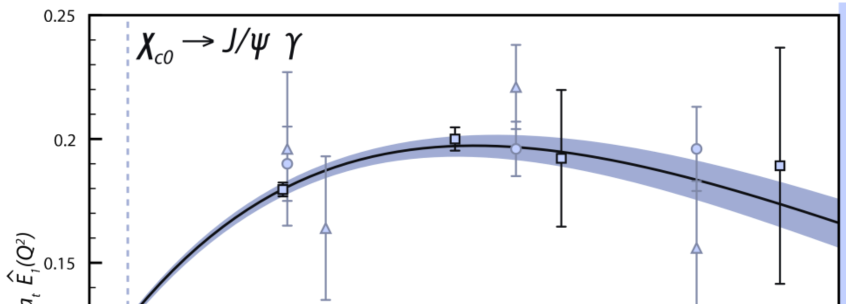
Scalar 0^{++} – Vector 1^{--}

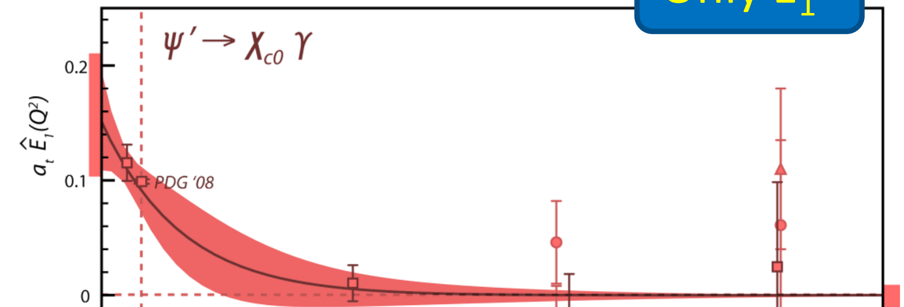
Only E_1



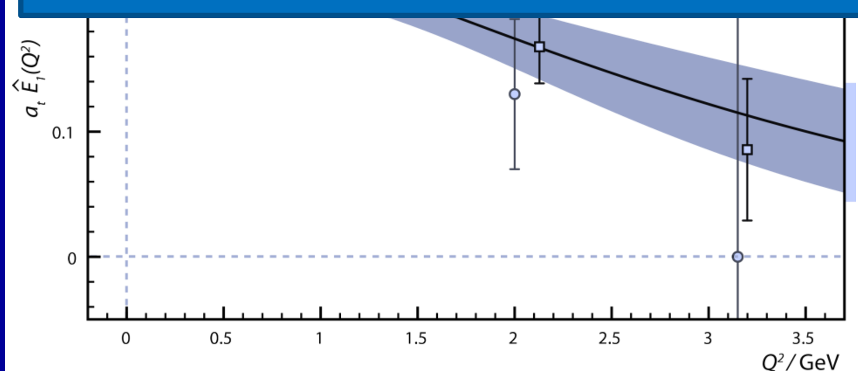
Scalar 0^{++} – Vector 1^{--}

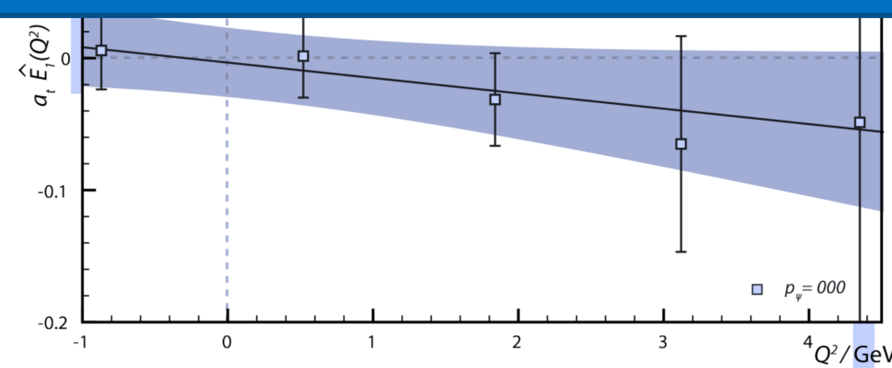
Only E_1





Γ / keV	Lattice	Exp. (PDG08)	Barnes, Godfrey, Swanson 'NR'	'GI'	Eichten et. al.
$\chi_{c0} \to J/\psi(1^3S_1)\gamma$	199(6)	131(14)	152	114	120, 105
$\psi'(2^3S_1) \to \chi_{c0}\gamma$	26(11)	30(2)	63	26	46, 38
$\psi''(1^3D_1) \to \chi_{c0}\gamma$	265(66)	199(26)	403	213	287
$\psi''(3^3S_1) \to \chi_{c0}\gamma$			0.27	0.63	
$Y \to \chi_{c0}\gamma$	$\lesssim 20$				





Summary and Outlook

Charmonium Summary

- **Method successful**: first calc. of excited meson rad. trans. on lattice
- **Hybrid photocoupling is large**: $\Gamma(\eta_{c1} \rightarrow J/\psi\gamma) \sim 100 \text{ keV}$
- M_1 transitions: $\psi \longrightarrow \eta_c\gamma$
- Non-exotic **vector hybrid candidate** $\Gamma(Y \rightarrow \eta_c\gamma) = 42(18) \text{ keV}$
- E_1, M_2, E_3 multipoles; 2^3P_2, 1^3F_2 states in $\chi_{c2} \longrightarrow J/\psi\gamma$
- Comparison with quark models

Outlook

- Systematically improvable
- Apply to lighter mesons (unquenched calc.)