Excited radiative transitions in charmonium from lattice QCD

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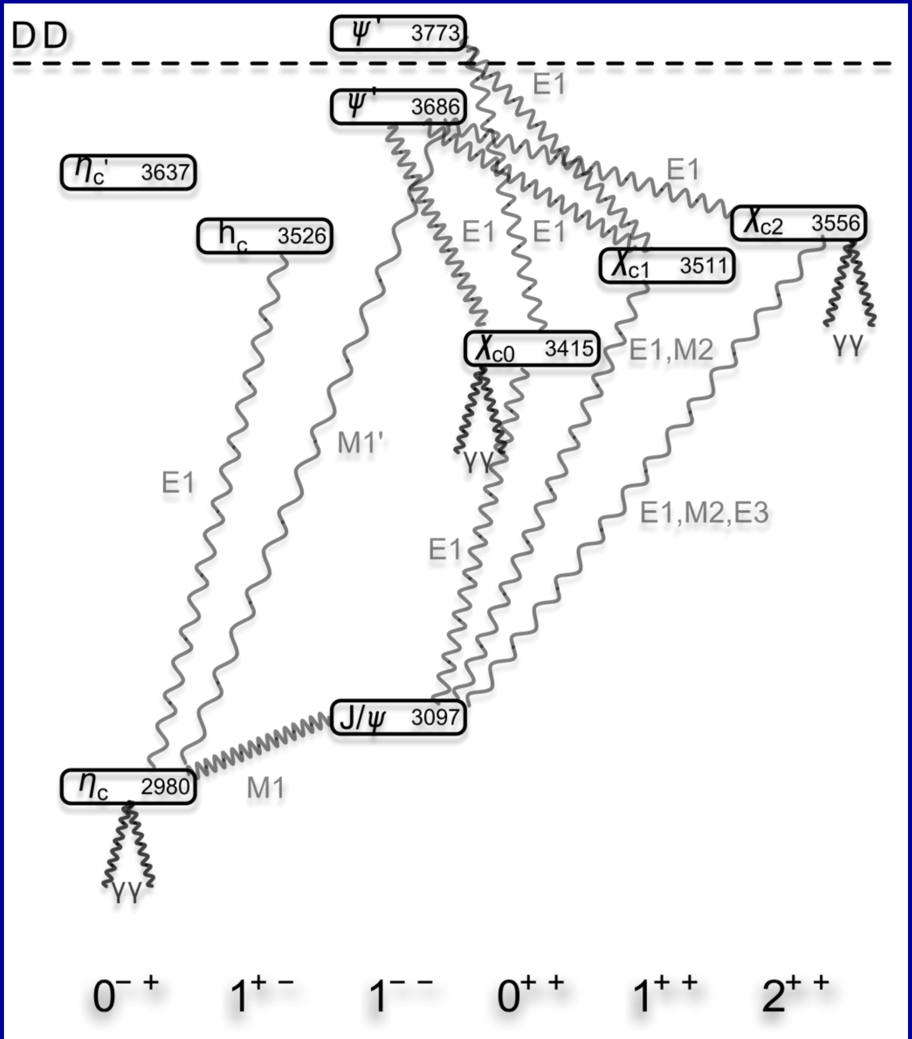
QWG Workshop, Fermilab, May 2010

With Jo Dudek and Robert Edwards
Previous work: Nilmani Mathur, David Richards and Ermal Rrapaj (and *Hadron Spectrum Collaboration)*

Outline

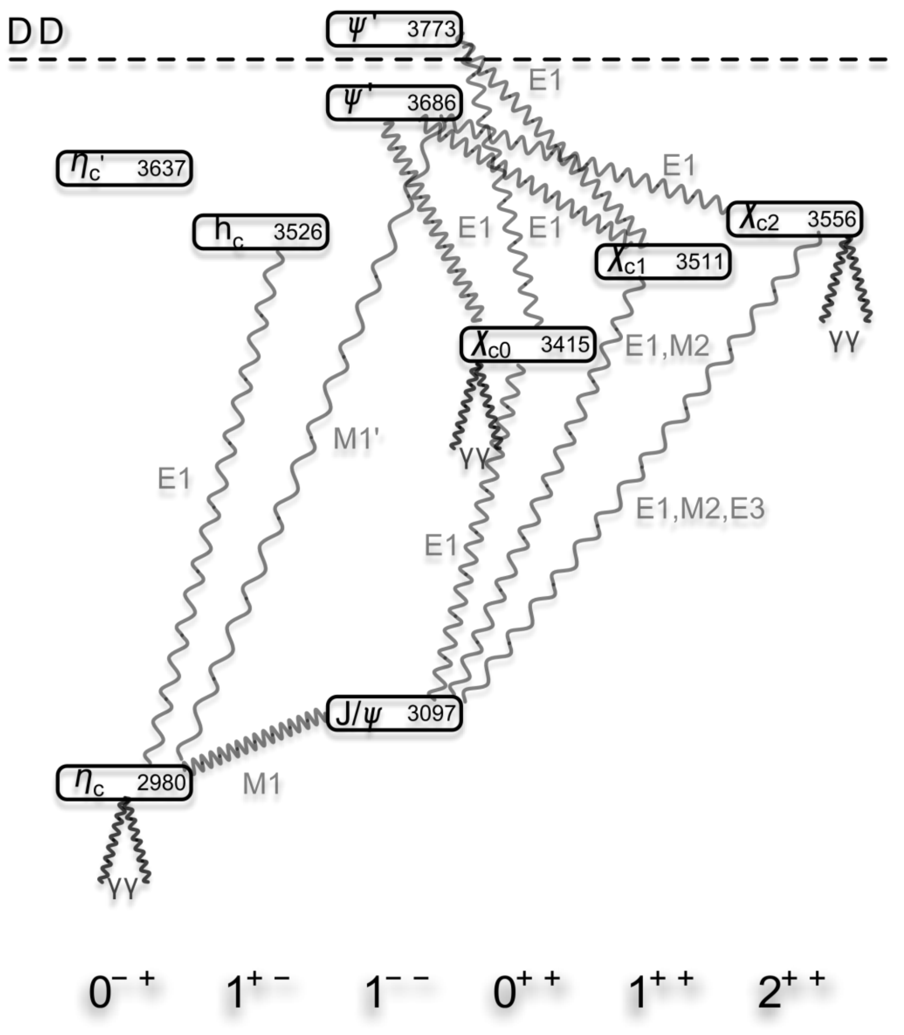
- Introduction and motivation
- Method
- Result highlights and interpretations
- Summary and outlook

Charmonium radiative transitions



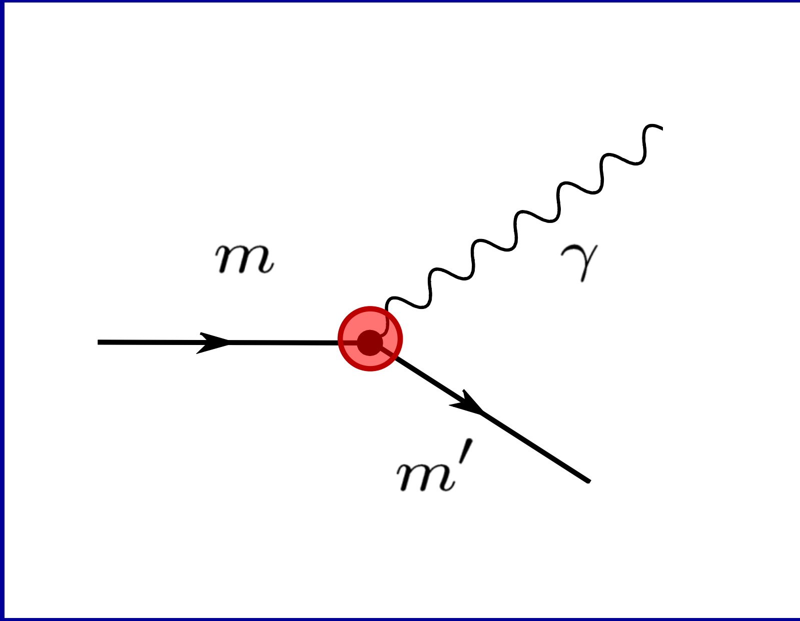
Below DD threshold radiative transitions have significant BRs

Charmonium radiative transitions

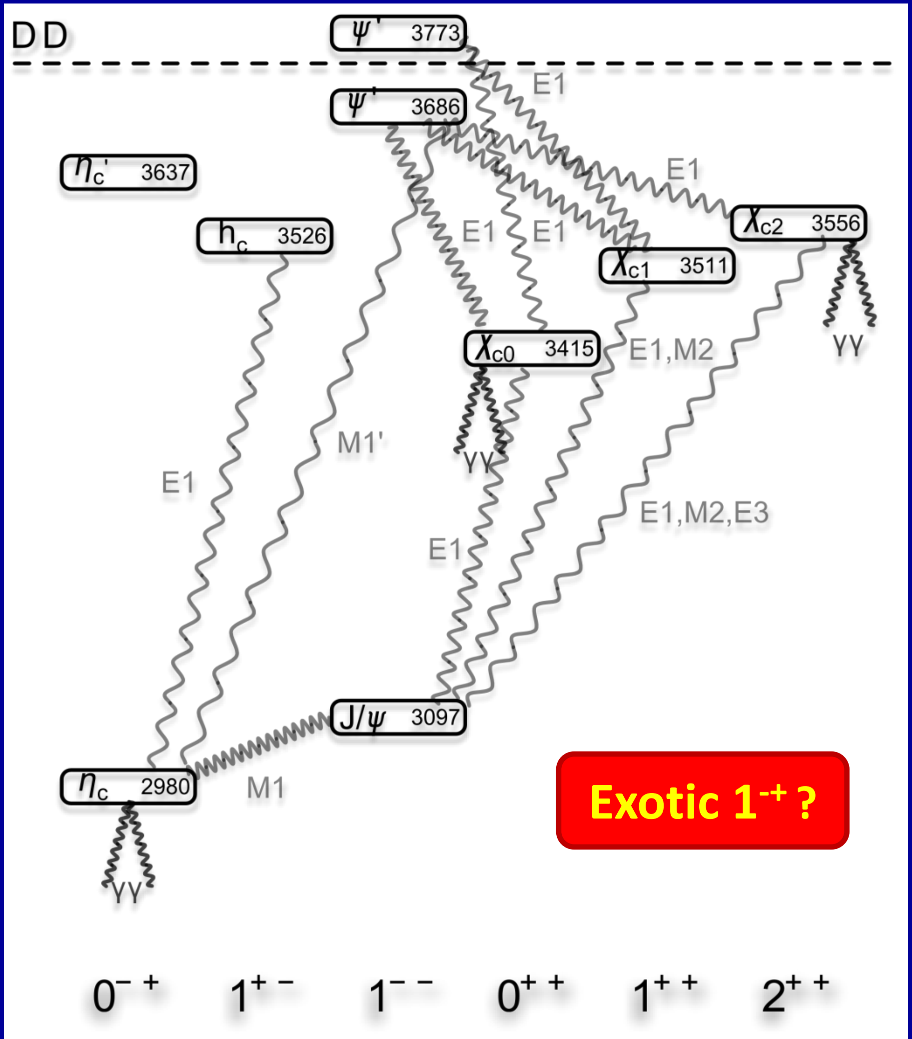


Below DD threshold radiative transitions have significant BRs

Meson – Photon coupling



Charmonium radiative transitions



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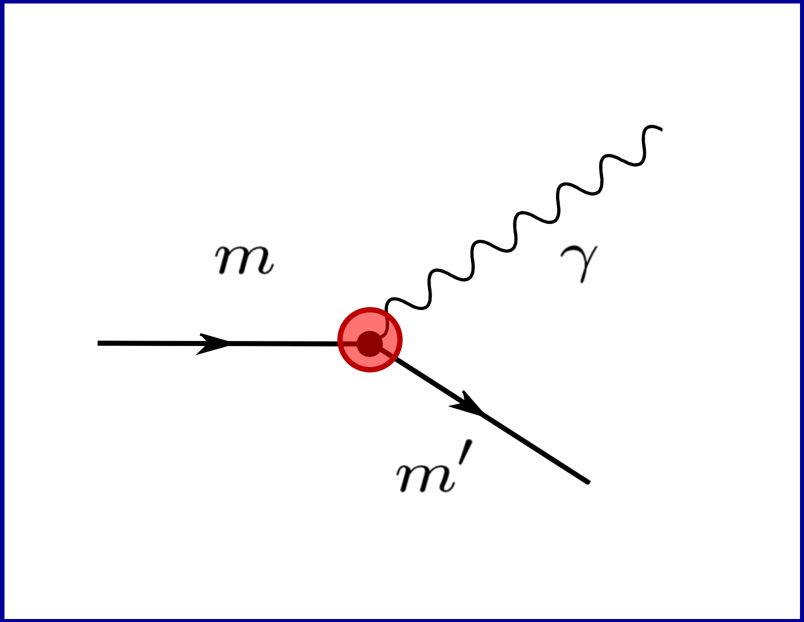
Meson – Photon coupling



Broader Picture

Develop Lattice QCD techniques

Test in the charmonium system

Apply to lighter mesons...

Broader Picture

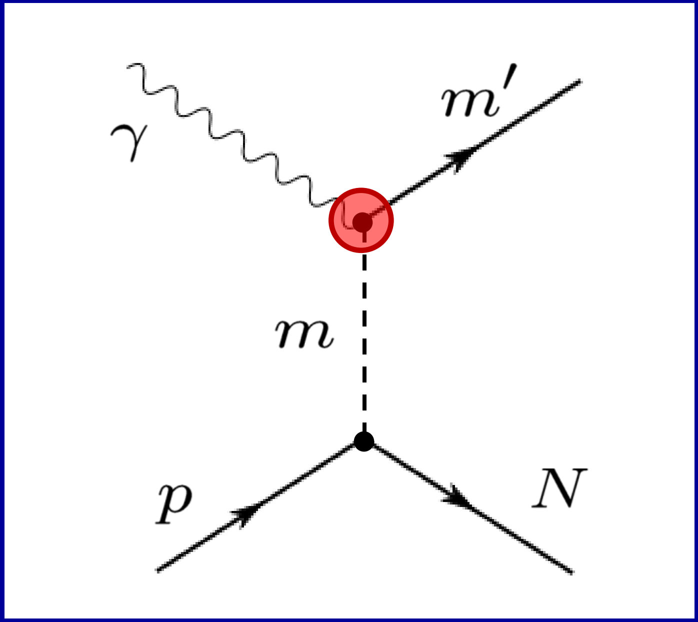
Develop Lattice QCD techniques

Test in the charmonium system

Apply to lighter mesons...

Photoproduction at GlueX
(JLab 12 GeV upgrade)

Exotic 1^{-+} ?



Progress on the light meson spectrum in Dudek et al
PRL103 262001 (2009) and arXiv:1004.4930.

Photocouplings on the lattice

Two-point correlation functions with a large basis of operators → energies and matrix elements (Z)

$$O(t) = \sum_{\vec{x}} e^{i\vec{p}\cdot\vec{x}} \; \bar{\psi}(x)\Gamma_i \overleftrightarrow{D}_j \overleftrightarrow{D}_k \ldots \psi(x)$$

$$C(t) = < 0|O_i(t)O_j(0)|0 >$$

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

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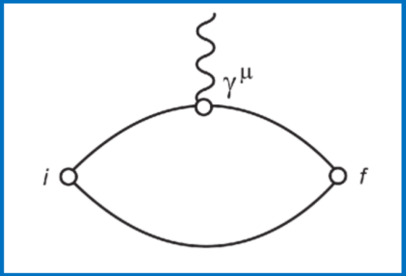
$$C(t) = < 0|O_i(t)O_j(0)|0 >$$

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

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

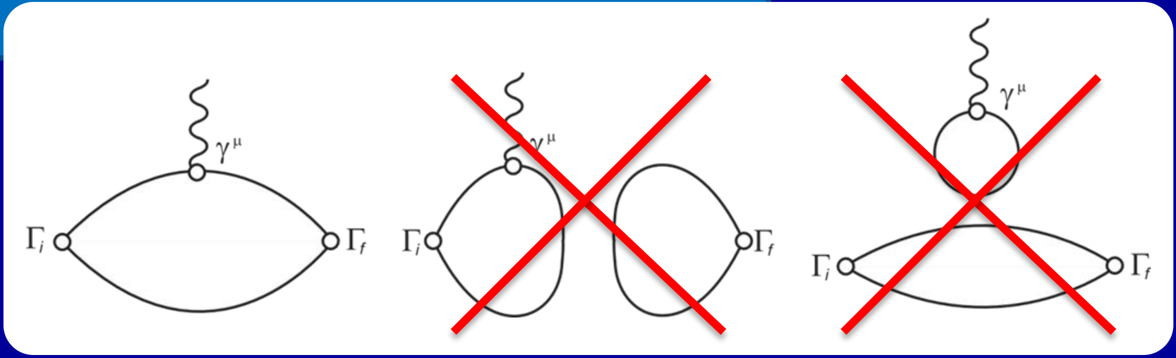
Photocouplings from three-point correlators

Need energies and Z's from two-point analysis



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 some highlights here; more 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^{-+}

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

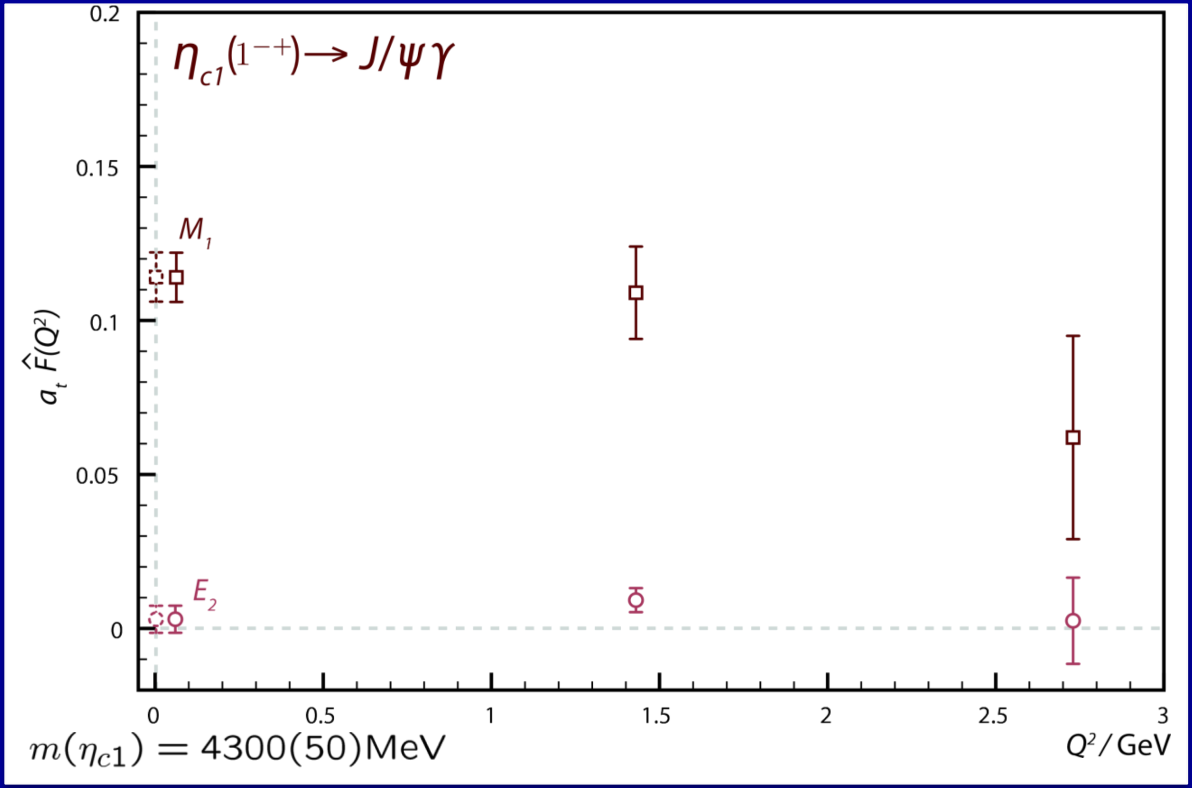
Exotic quantum numbers – can't be fermion-antifermion pair

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

→ Strongly suggests a hybrid

What about radiative transitions?

Exotic 1^{-+} – Vector 1^{--}



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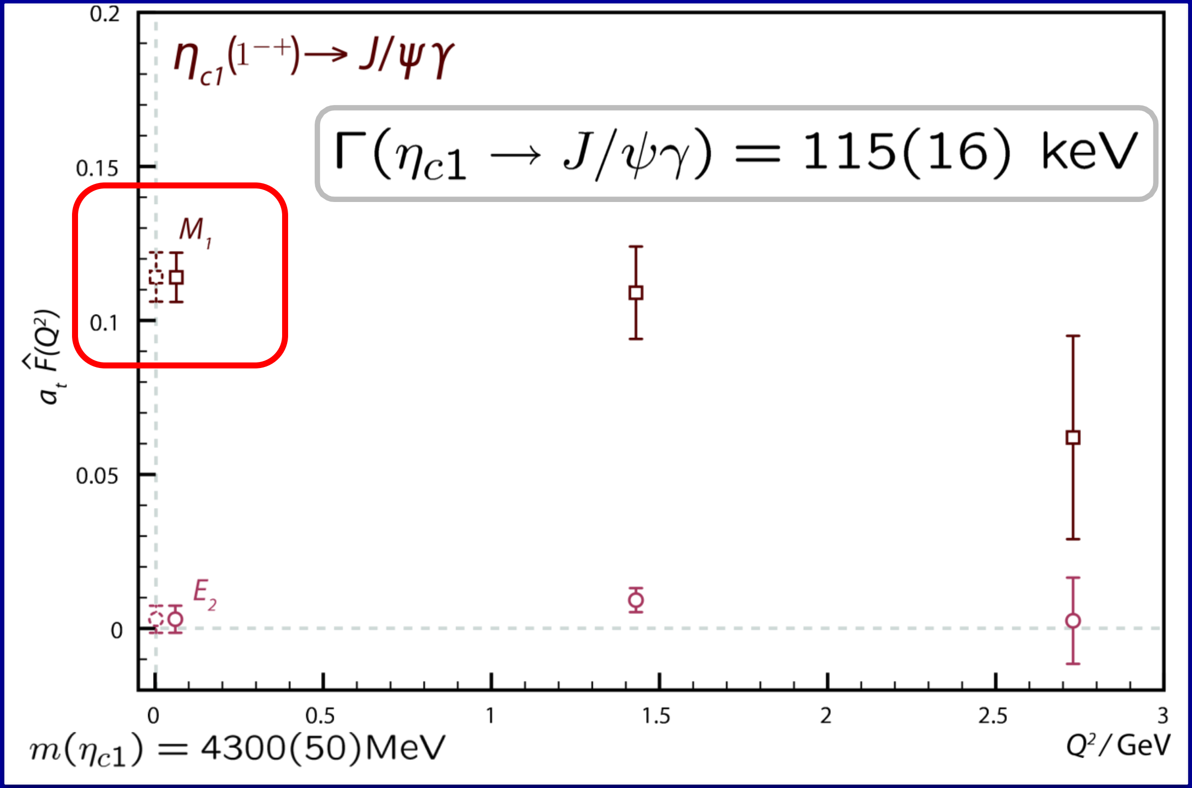


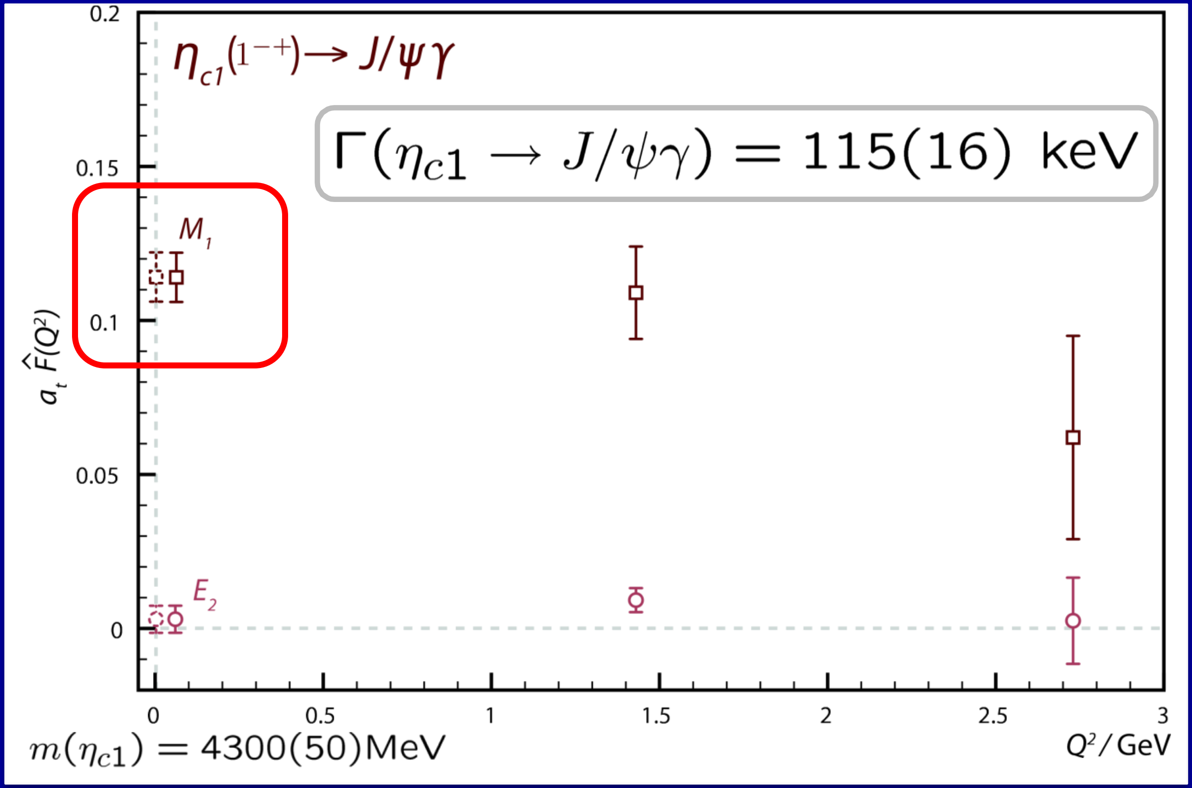
M_1 multipole dominates

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

Exotic 1^{-+} – Vector 1^{--}



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- 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

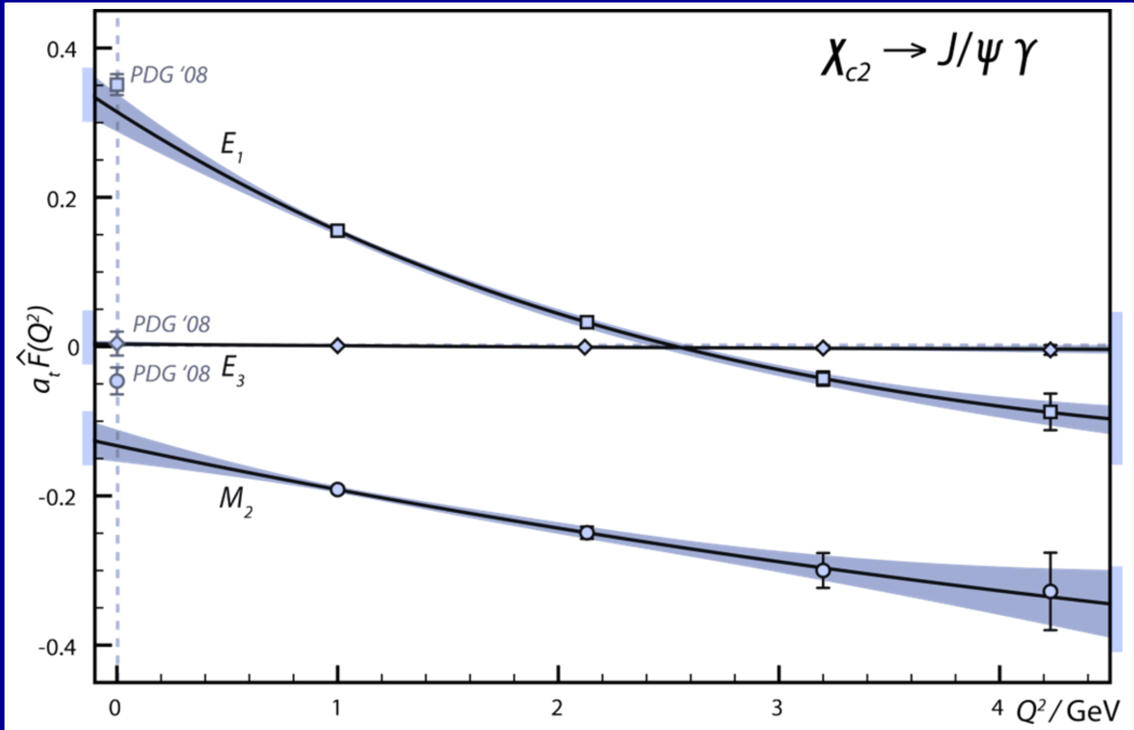
Three tensor states found in spectrum analysis:

$\chi_{c2} \approx 3545(7)$ MeV

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

$\chi''_{c2} \approx 4165(30)$ MeV

Tensor 2^{++} – Vector 1^{--}



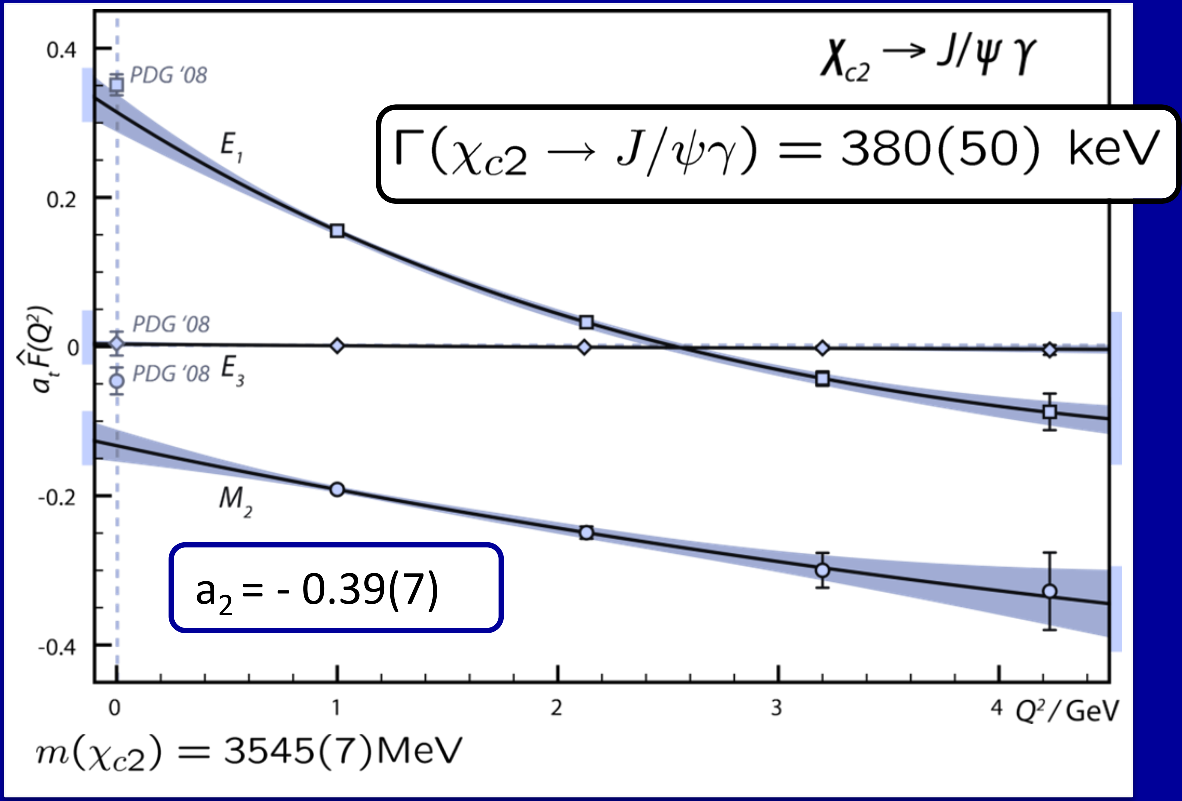
$m(\chi_{c2}) = 3545(7)\text{MeV}$

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^{--}

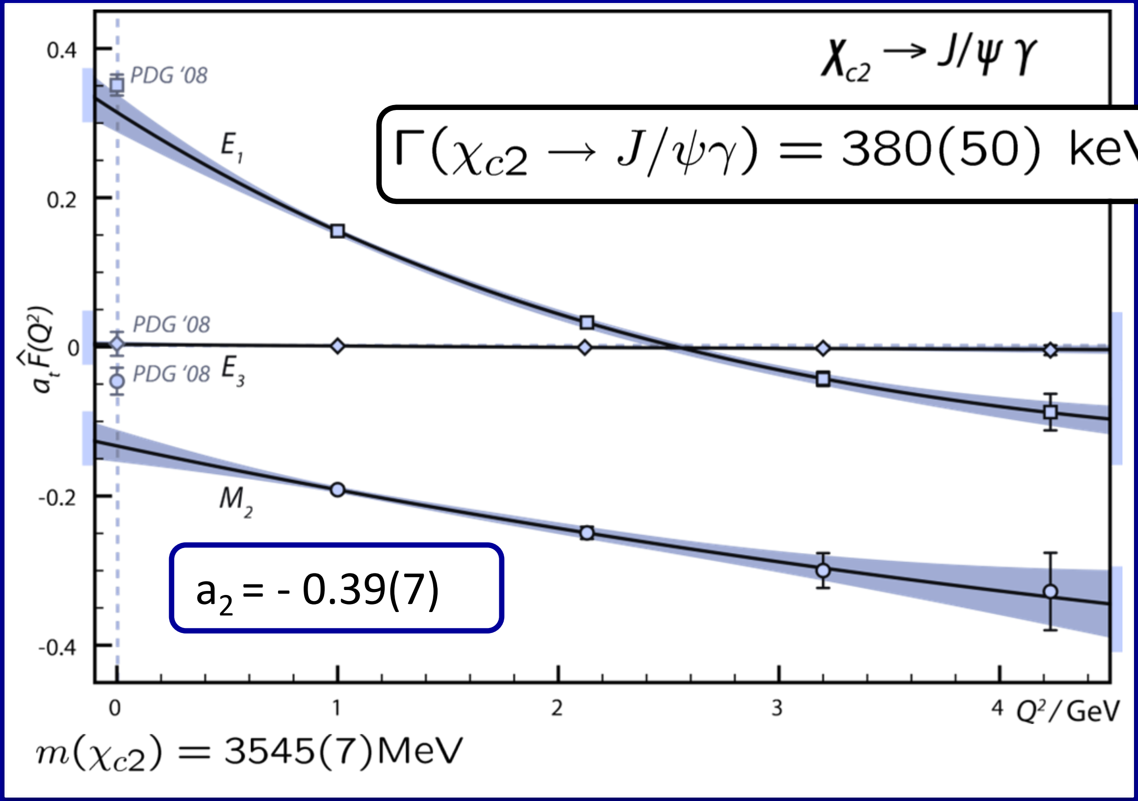


E_1, M_2, E_3

PDG08: 406(31) keV

Quark models (1^3P_2)
~ 290 – 420 keV

Tensor 2^{++} – Vector 1^{--}



E_1, M_2, E_3

PDG08: 406(31) keV

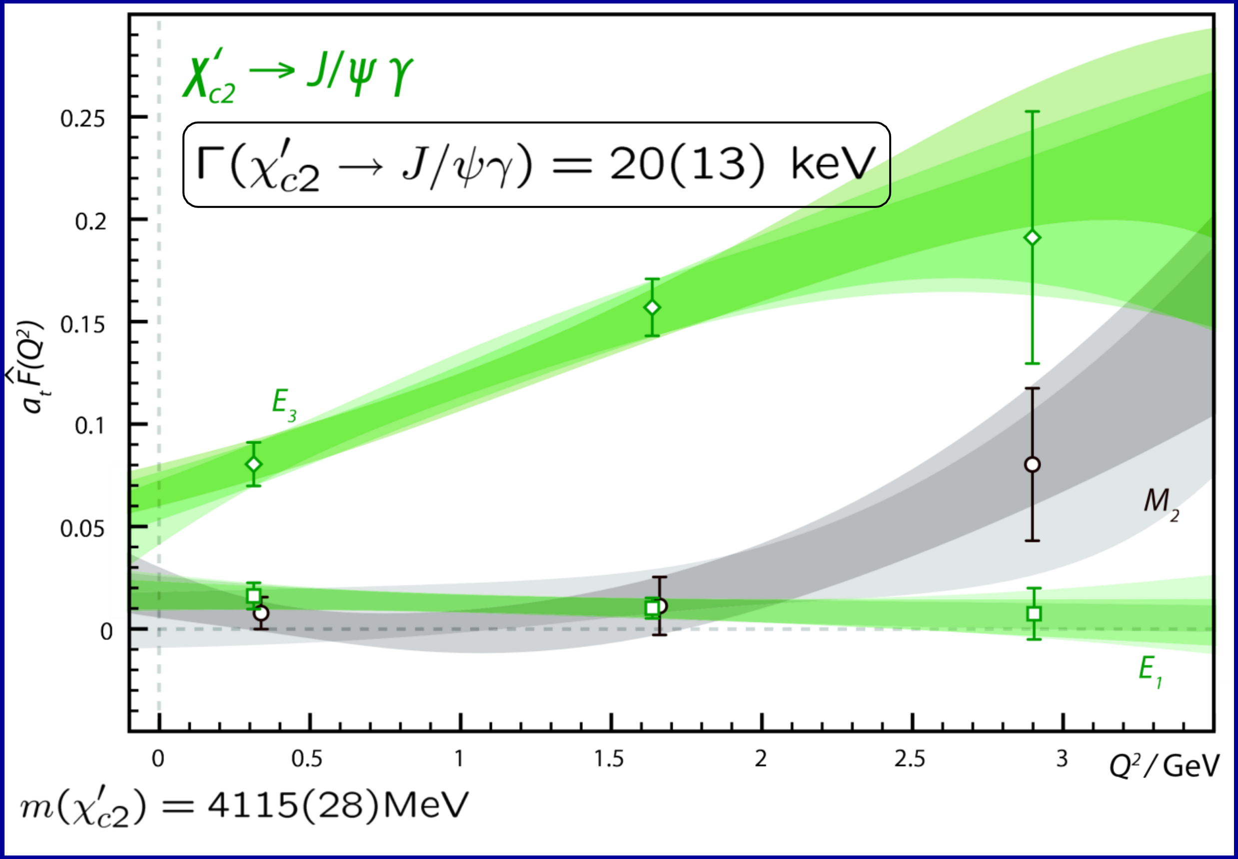
Quark models (1^3P_2)
~ 290 – 420 keV

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

PDG08: -0.13(5)
CLEO: -0.079(19)
[CLEO PRD80 112003 (2009)]

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

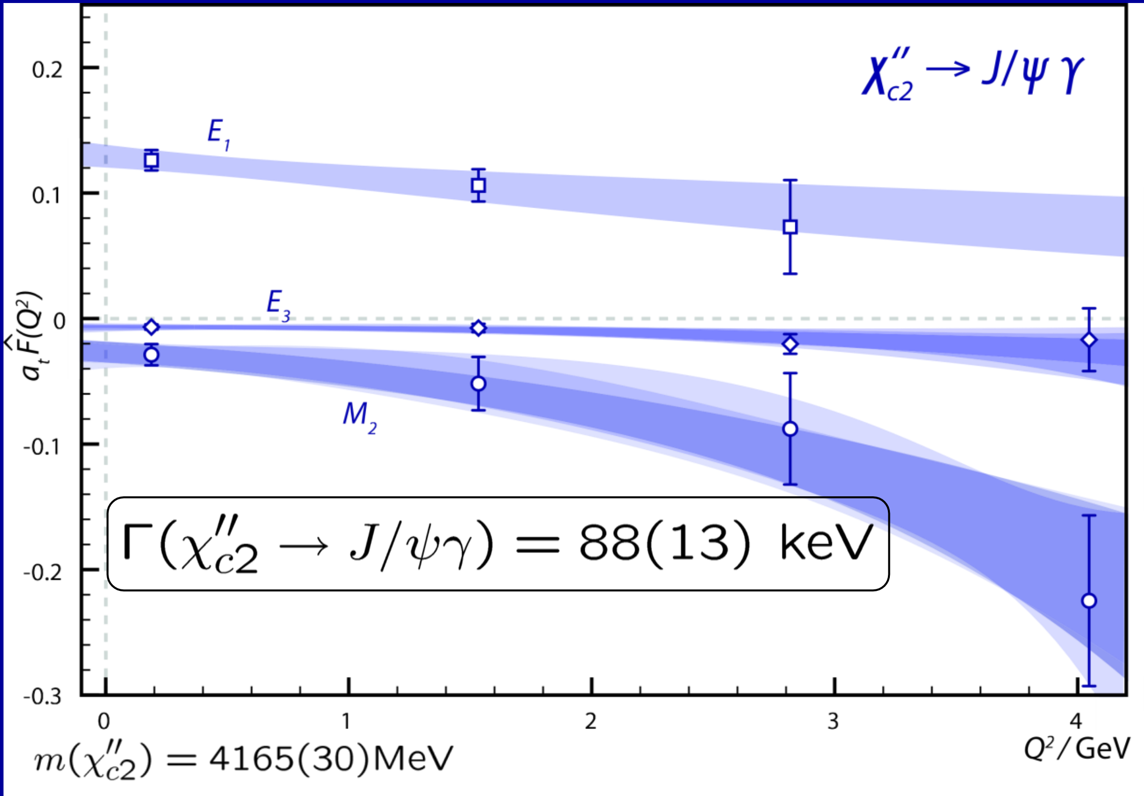
Tensor 2^{++} – Vector 1^{--}



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

Tensor 2^{++} – Vector 1^{--}

Interpretation: **single quark transition** model

In general: $J_i = J_f \otimes k \quad (k > 0)$
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If only a single quark is involved ($^3\mathbf{P_2} \rightarrow {}^3S_1$):
j = 3/2 → j = 1/2
k = 1,2 only and $E_3 = 0$
$|E_1(0)| > |M_2(0)| >> |E_3(0)|$

Tensor 2^{++} – Vector 1^{--}

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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:

If

If

Interpretation:

χ_{c2} – 1^3P_2

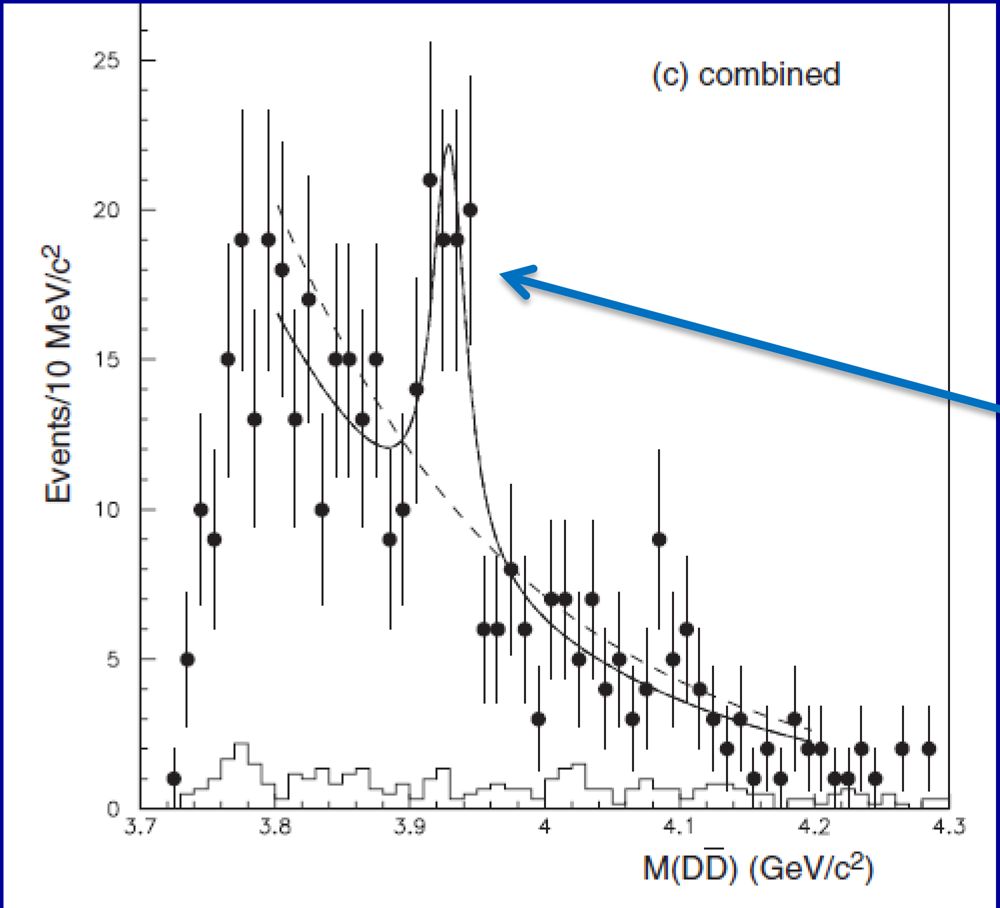
χ'_{c2} – 1^3F_2

χ''_{c2} – 2^3P_2

Supported by spectrum analysis

Squeezed in finite volume?
Mixing of 1F and 2P?

Tensor 2^{++} – Vector 1^{--}



Belle [PRL 96 082003 (2006)]

Belle

$\gamma\gamma \to D\bar{D}$

χ'_{c2} ~ 3930 MeV

Needs lattice calc of two-photon coupling [extension of Dudek and Edwards **PRL 97** 172001 (2006)]

Vector 1^{--} – Pseudoscalar 0^{-+}

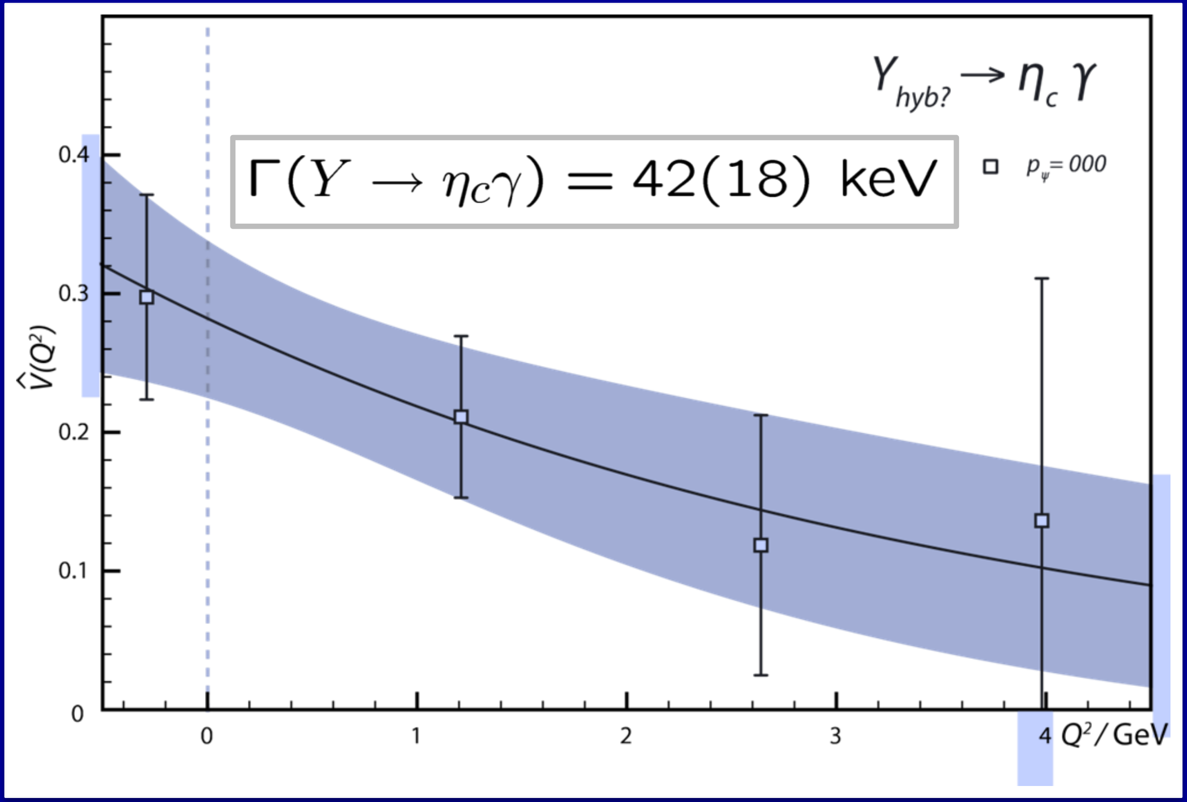
Spectrum results [PR **D77** 034501 (2008) , PR **D78** 094504 (2008)]:

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

Significant overlap with operator ~ [D_i , D_j] ~ F

Vector 1^{--} – Pseudoscalar 0^{-+}

Only M_1

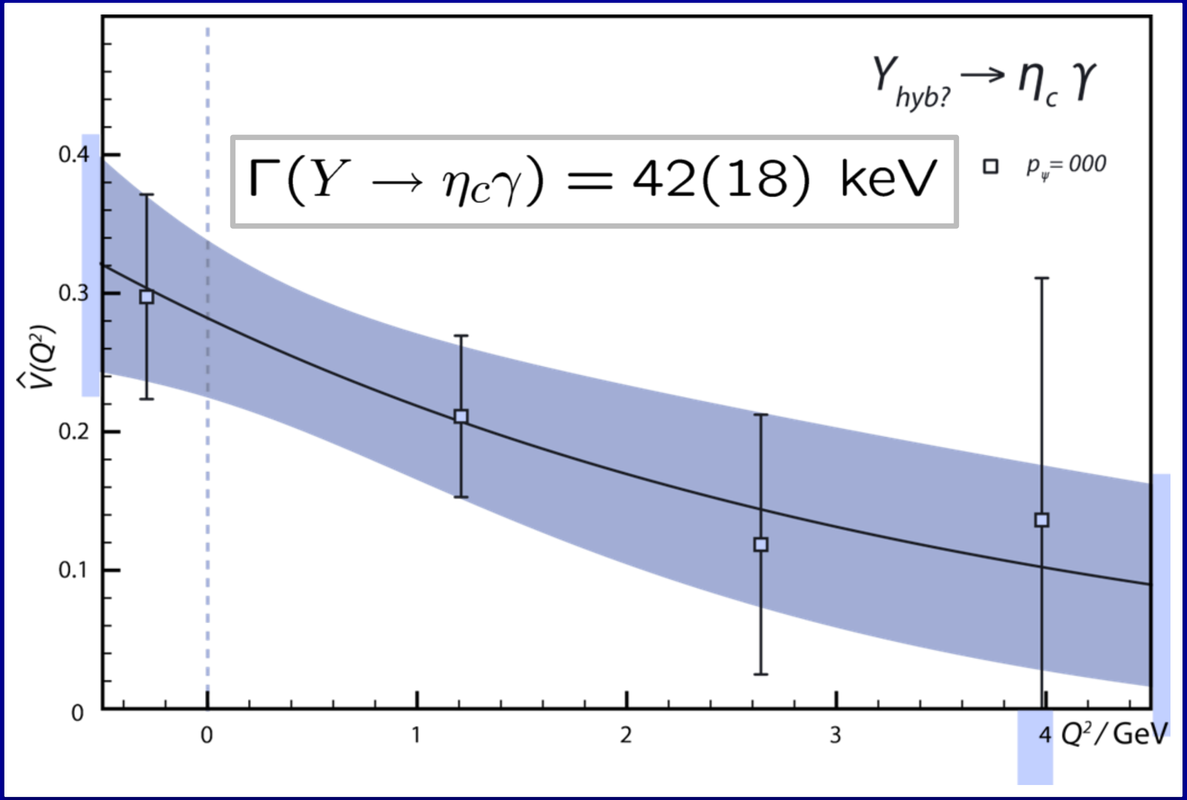


Much larger than other $1^{--} \to 0^{-+}$ M_1 transitions

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

Vector 1^{--} – Pseudoscalar 0^{-+}

Only M_1



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

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

Summary and Outlook

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 models

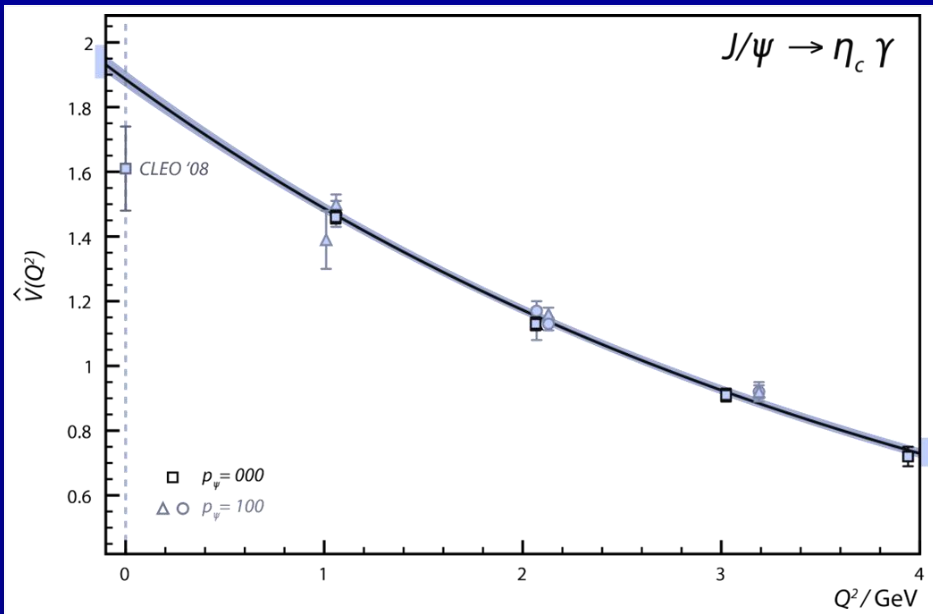
Outlook

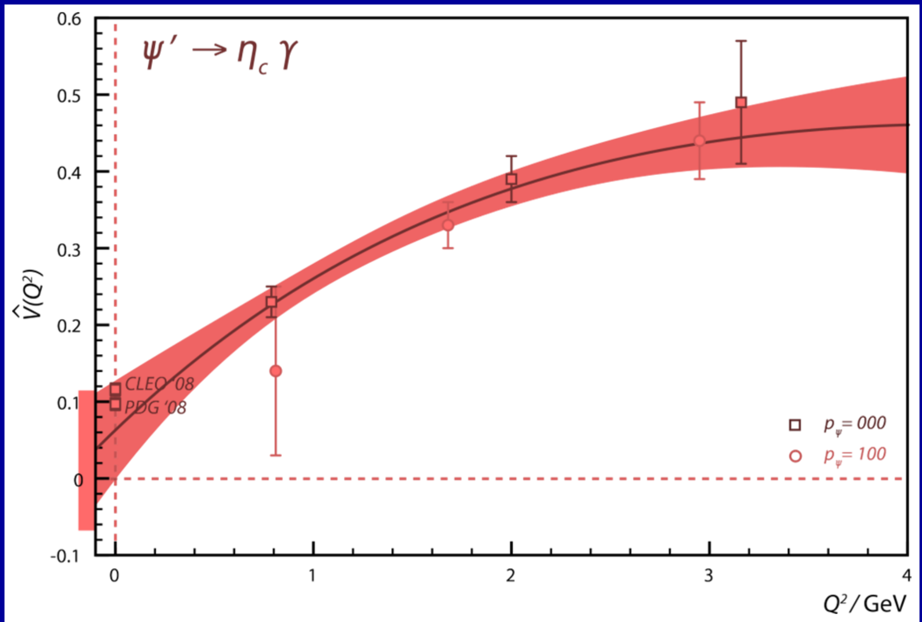
- Systematically improve (unquenched and using 'distillation')
- Apply to lighter mesons (spectrum results) + charmonium (in progress)

Extra Slides

Vector 1^{--} – Pseudoscalar 0^{-+}

Only M_1



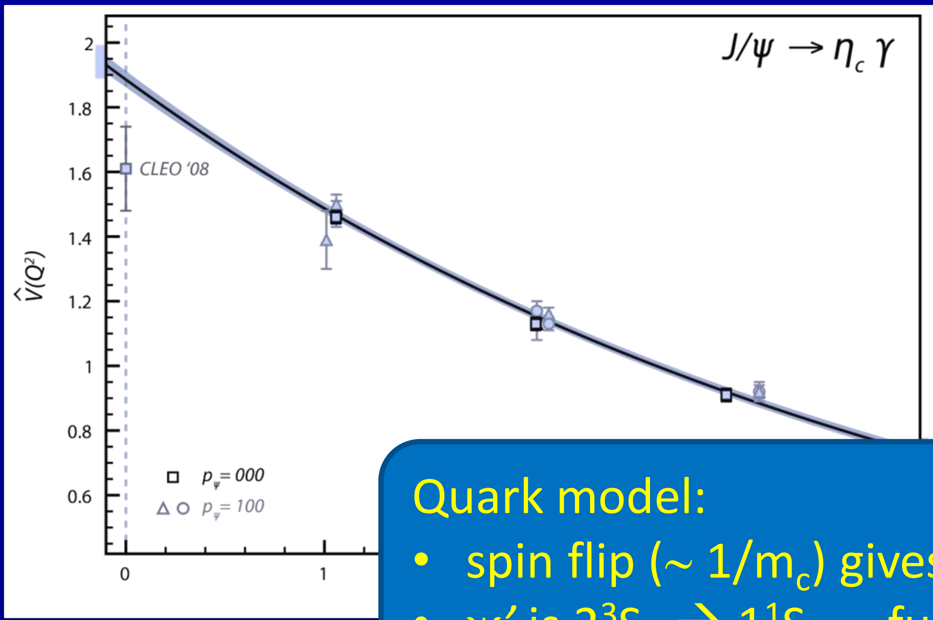


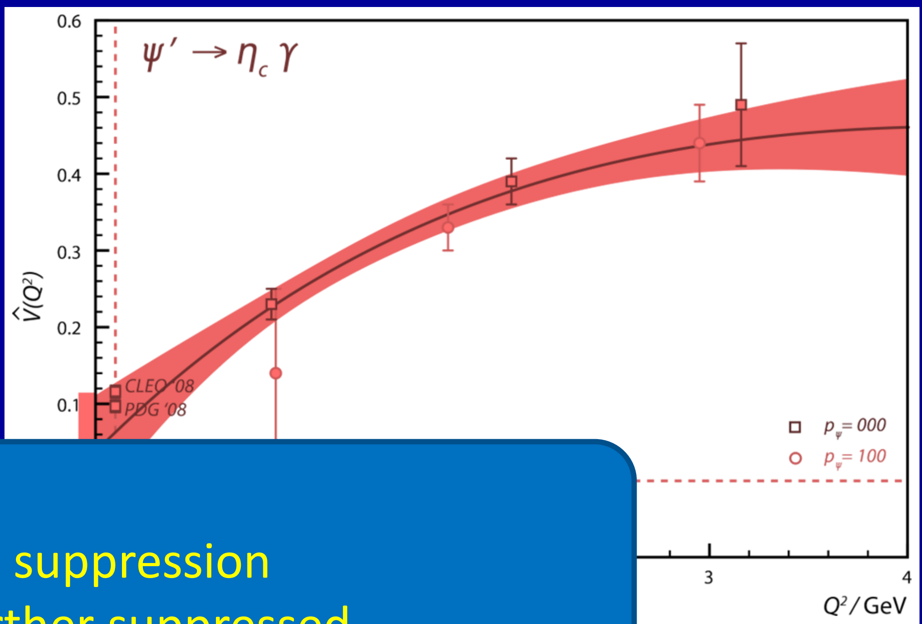
Γ / keV	Lattice	Exp.	Barnes, Godfrey, Swanson 'NR'	'GI'	Eichten et. al.
$J/\psi \to \eta_c\gamma$	2.51(8)	1.85(29) (CLEO-c)	2.9	2.4	1.92
$\psi' \to \eta_c\gamma$	0.4(8)	0.95(16) (PDG08) 1.37(20) (CLEO-c)	4.6, 9.7	9.6	0.91

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

Vector 1^{--} – Pseudoscalar 0^{-+}

Only M_1





Quark model:

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

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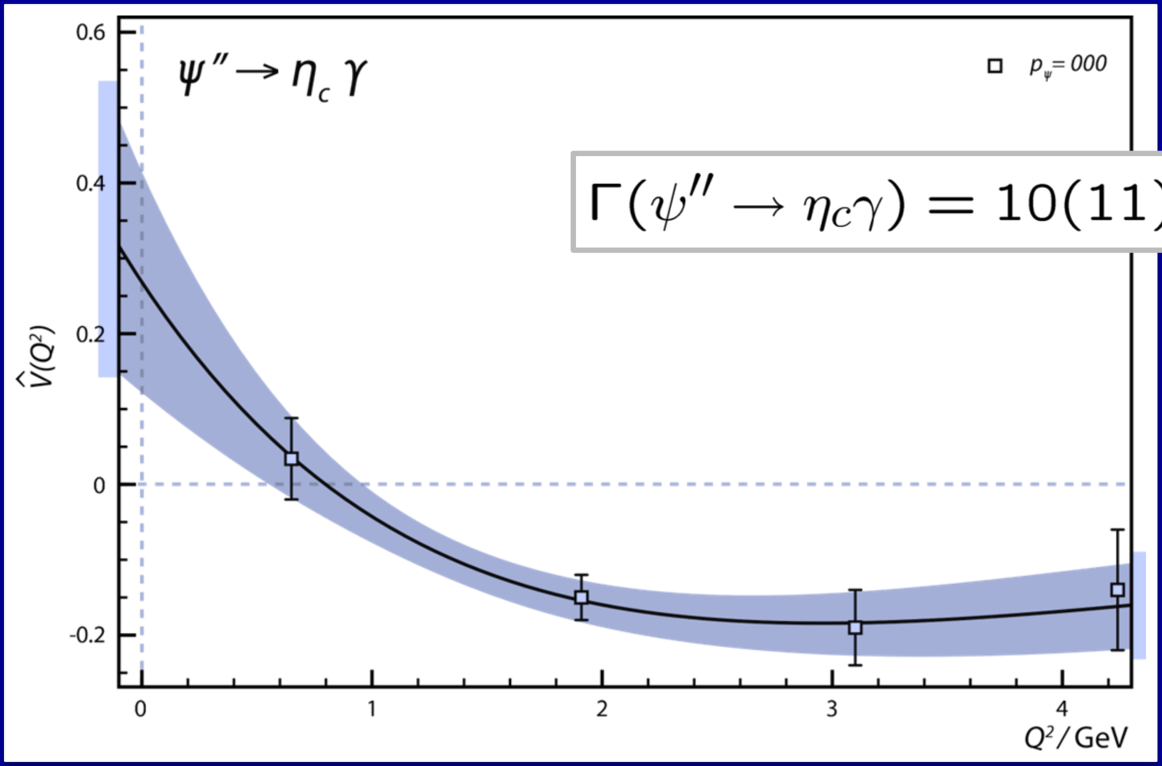
[CLEO **PRL 102** 011801 (2009)]

Vector 1^{--} – Pseudoscalar 0^{-+}

Only M_1

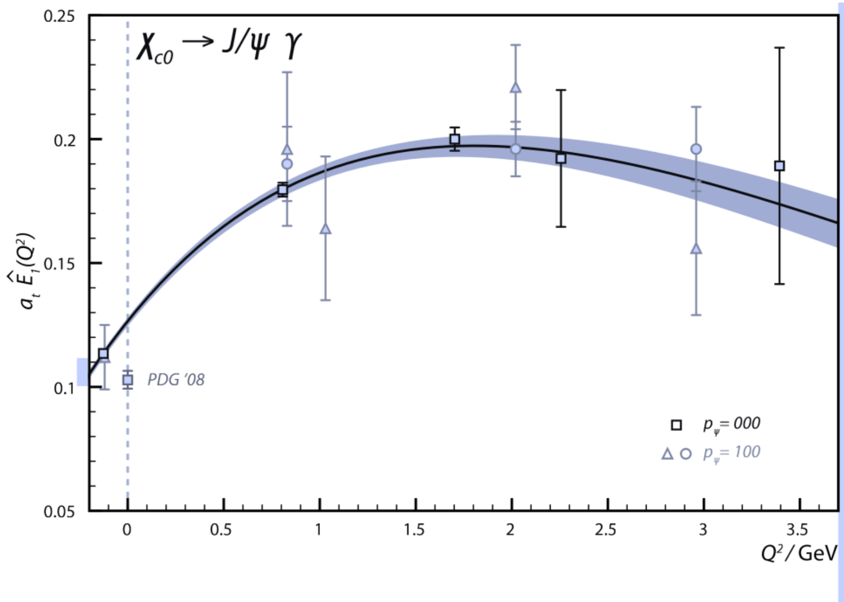


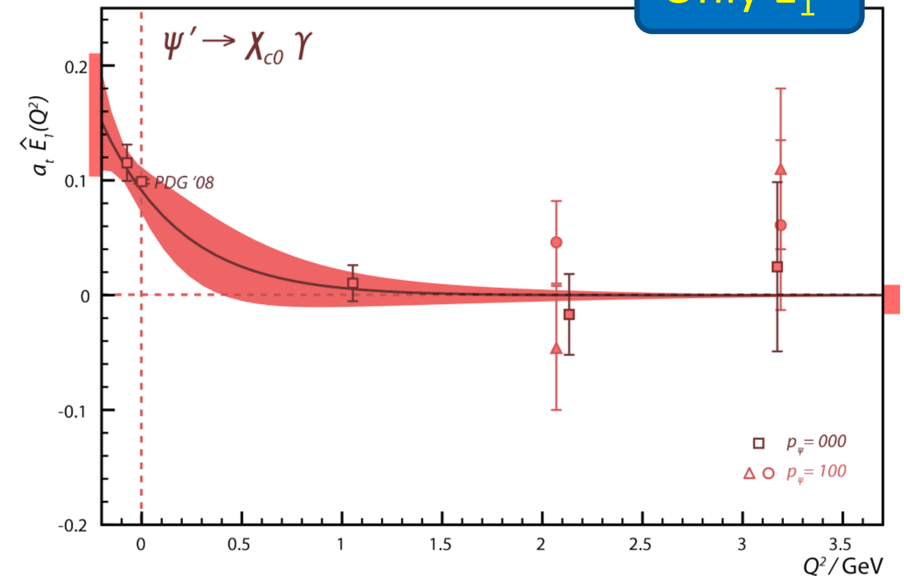
$$\Gamma(\psi'' \to \eta_c\gamma) = 10(11)\ \text{keV}$$

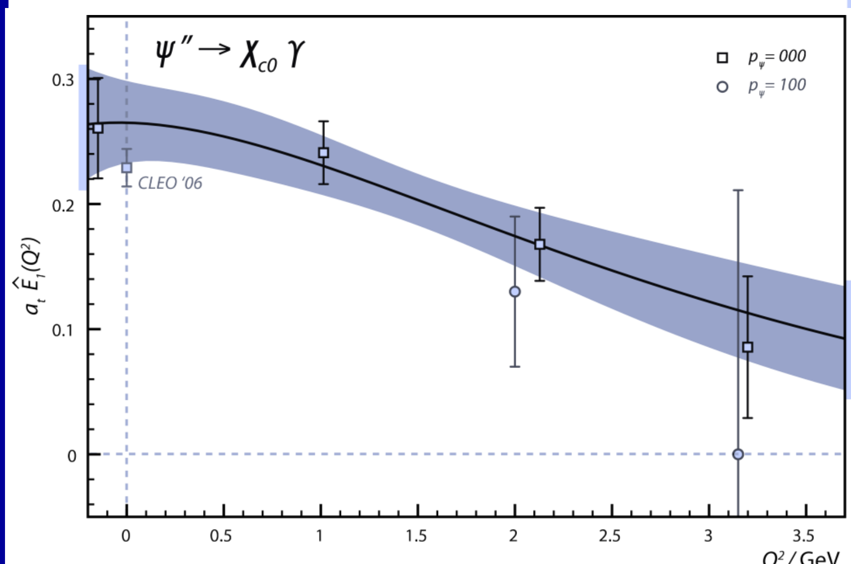
Quark model: $1^3D_1 \rightarrow 1^1S_0$ has same leading Q^2 behaviour as $2^3S_1 \rightarrow 1^1S_0$

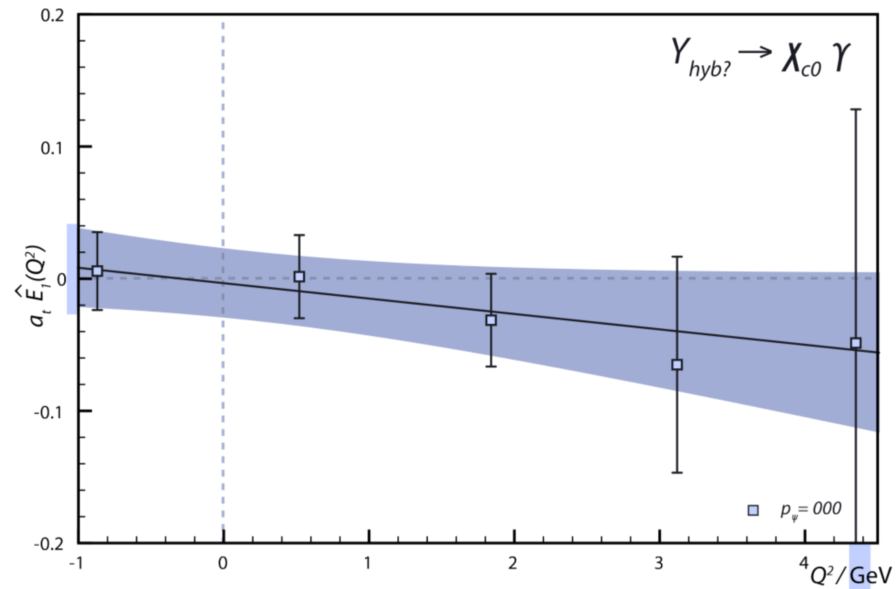
Scalar 0^{++} – Vector 1^{--}

Only E_1



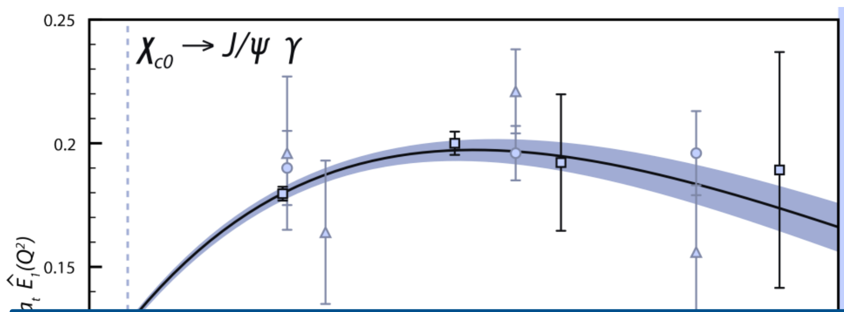


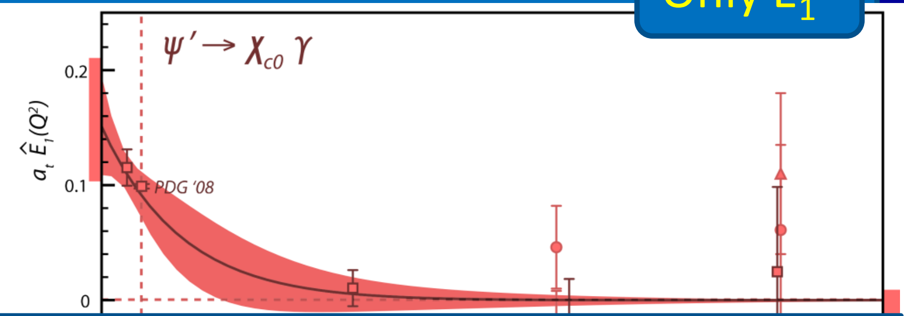




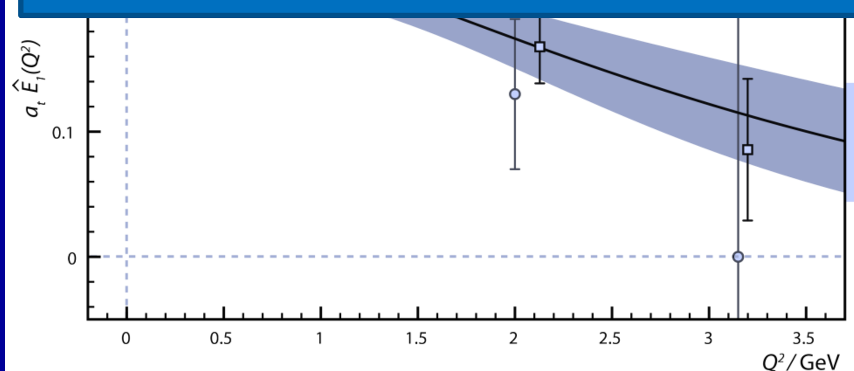
Scalar 0^{++} – Vector 1^{--}

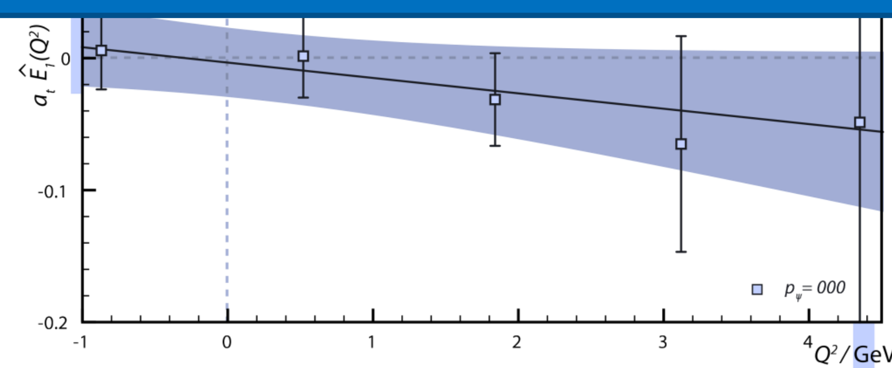
Only E_1





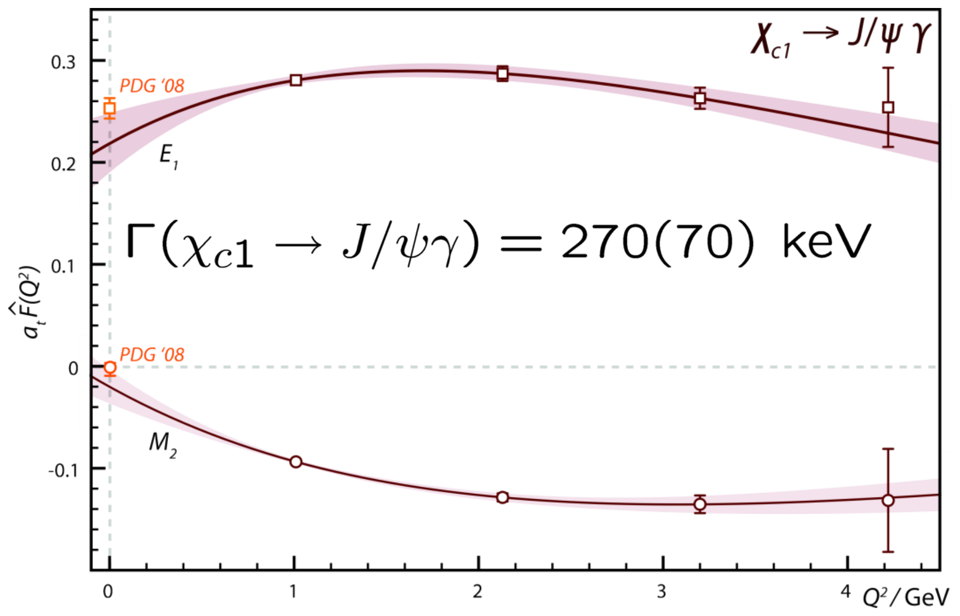
Γ / keV	Lattice	Exp. (PDG08)	Barnes, Godfrey, Swanson 'NR'	'GI'	Eichten et. al.
$\chi_{c0} \to J/\psi(1^3S_1)\gamma$	199(6)	131(14)	152	114	120, 105
$\psi'(2^3S_1) \to \chi_{c0}\gamma$	26(11)	30(2)	63	26	46, 38
$\psi''(1^3D_1) \to \chi_{c0}\gamma$	265(66)	199(26)	403	213	287
$\psi''(3^3S_1) \to \chi_{c0}\gamma$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

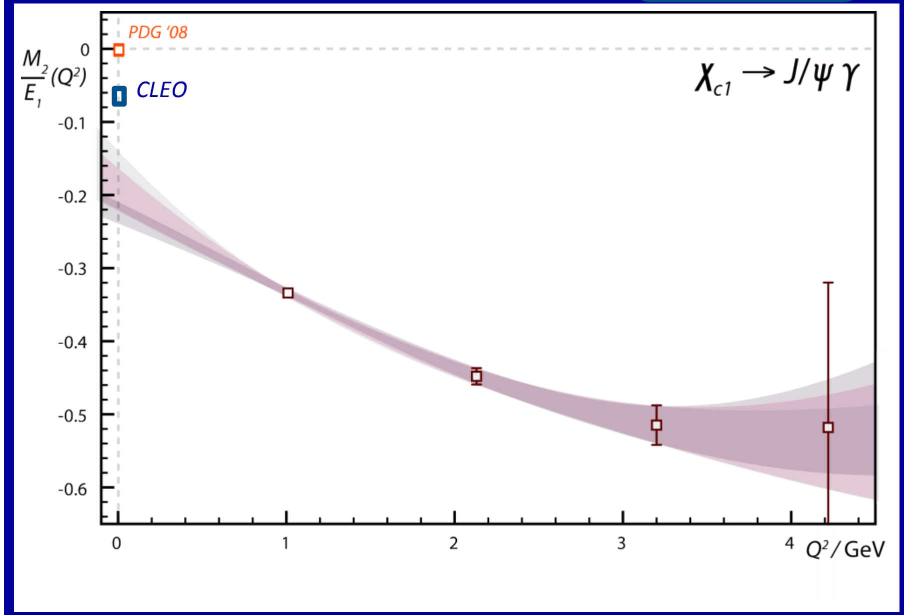




Axial 1^{++} – Vector 1^{--}

E_1, M_2





c.f. PDG08: 320(25) keV

c.f. quark models (1^3P_1) ~ 215 – 314 keV

Expected hierarchy: $|E_1(0)| > |M_2(0)|$

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

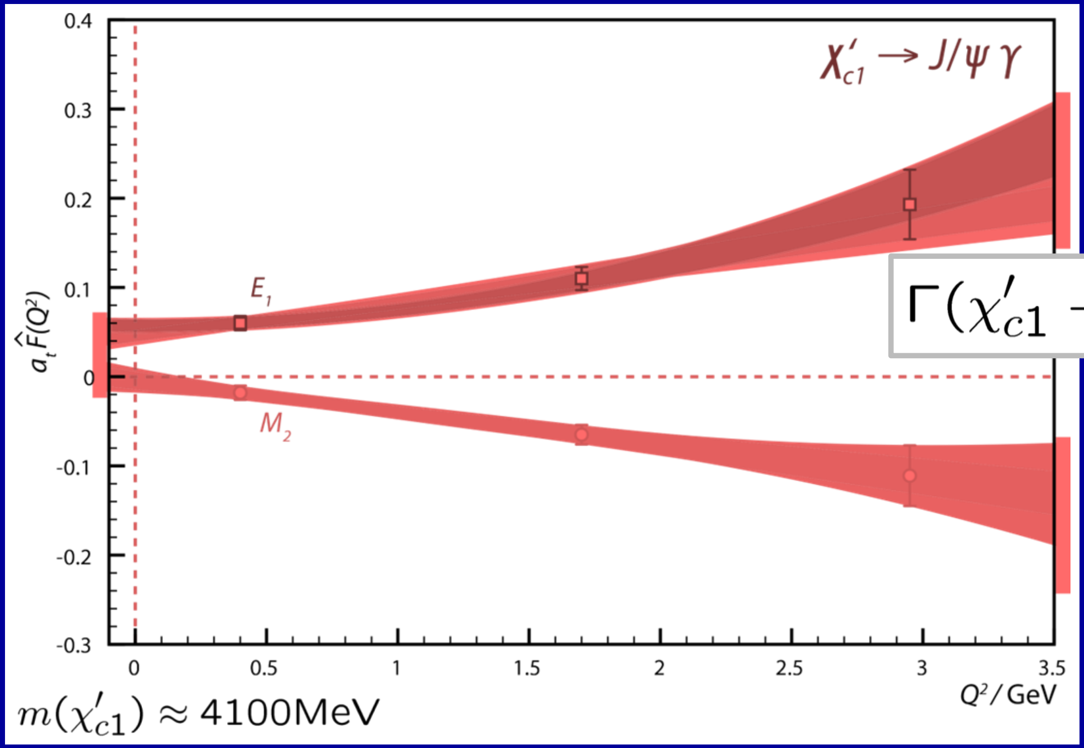
PDG08: $-0.002^{+0.008}_{-0.017}$

CLEO: -0.063(7)

[CLEO PRD80 112003 (2009)]

Axial 1^{++} – Vector 1^{--}

E_1, M_2



$$\Gamma(\chi'_{c1} \to J/\psi\gamma) = 21(12)\ \text{keV}$$

c.f. quark models (2^3P_1) ~ 14 – 71 keV