Mon 25th July, Lattice 2016

Hindered M1 Radiative Decay of $\Upsilon(2S)$ and $\eta_b(2S)$ from Lattice NRQCD

arXiv:1508.01694

C. Hughes, R. Dowdall, C. Davies,

R. Horgan, G. Von Hippel, M. Wingate

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- M1 $\bar{b}b$ Radiative Decay $\Longrightarrow$ Requires Spin Flip

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- Allowed M1 : $n'\,{}^3S_1 \to n\,{}^1S_0\gamma, \quad n' = n$
- Hindered M1 : $n'\,{}^3S_1 \to n\,{}^1S_0\gamma, \quad n' \neq n$

Inspirational Motivation!!

- Full Understanding of Low-Lying States/Decays

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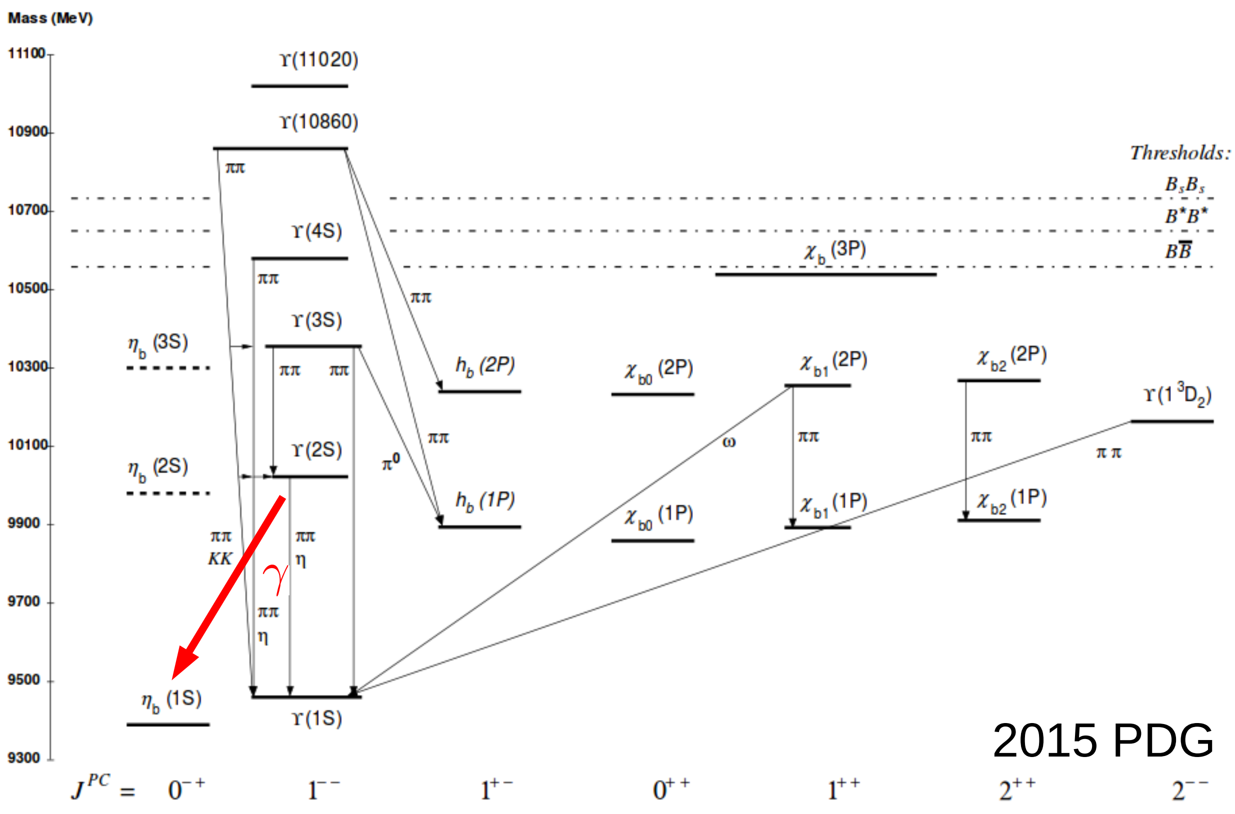

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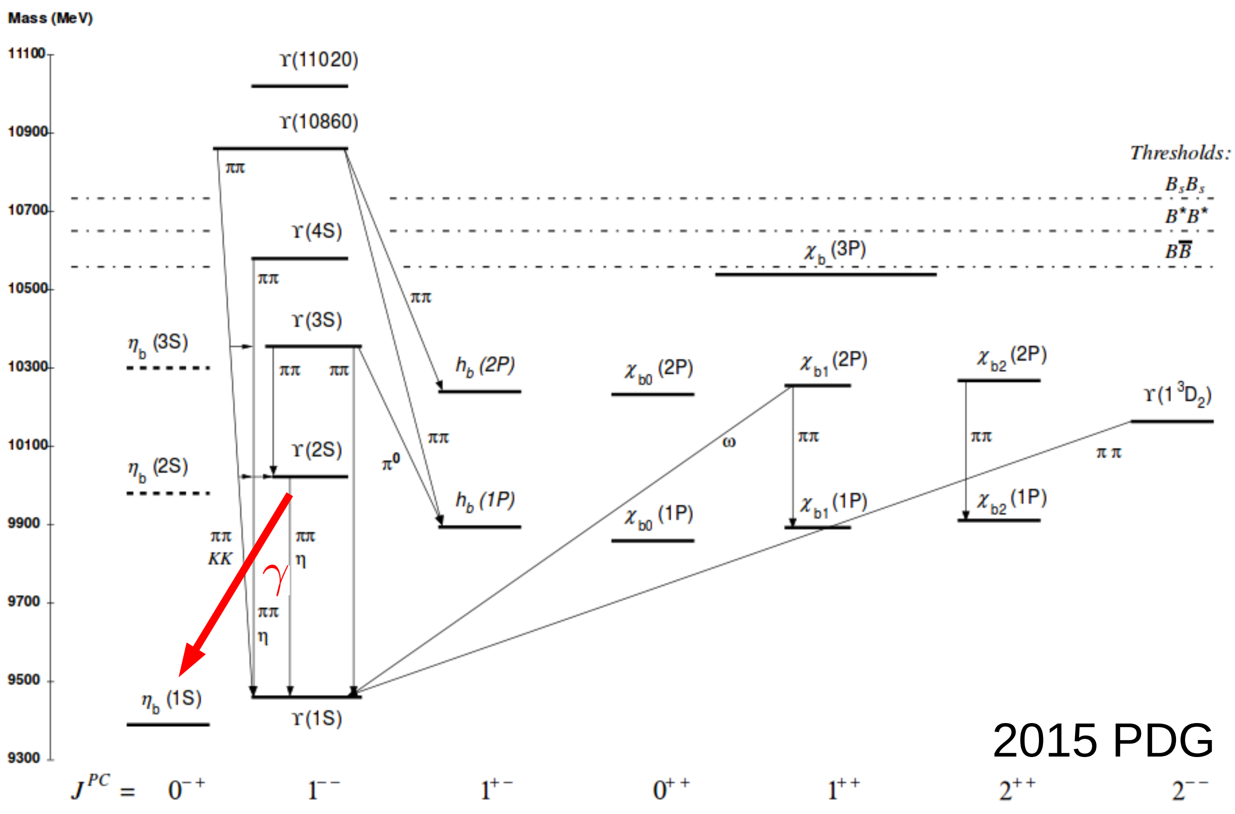

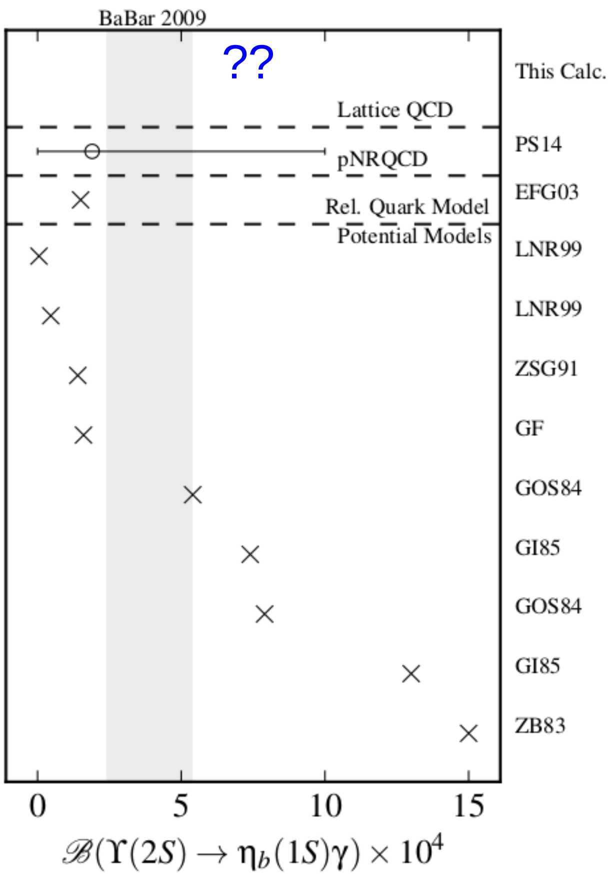

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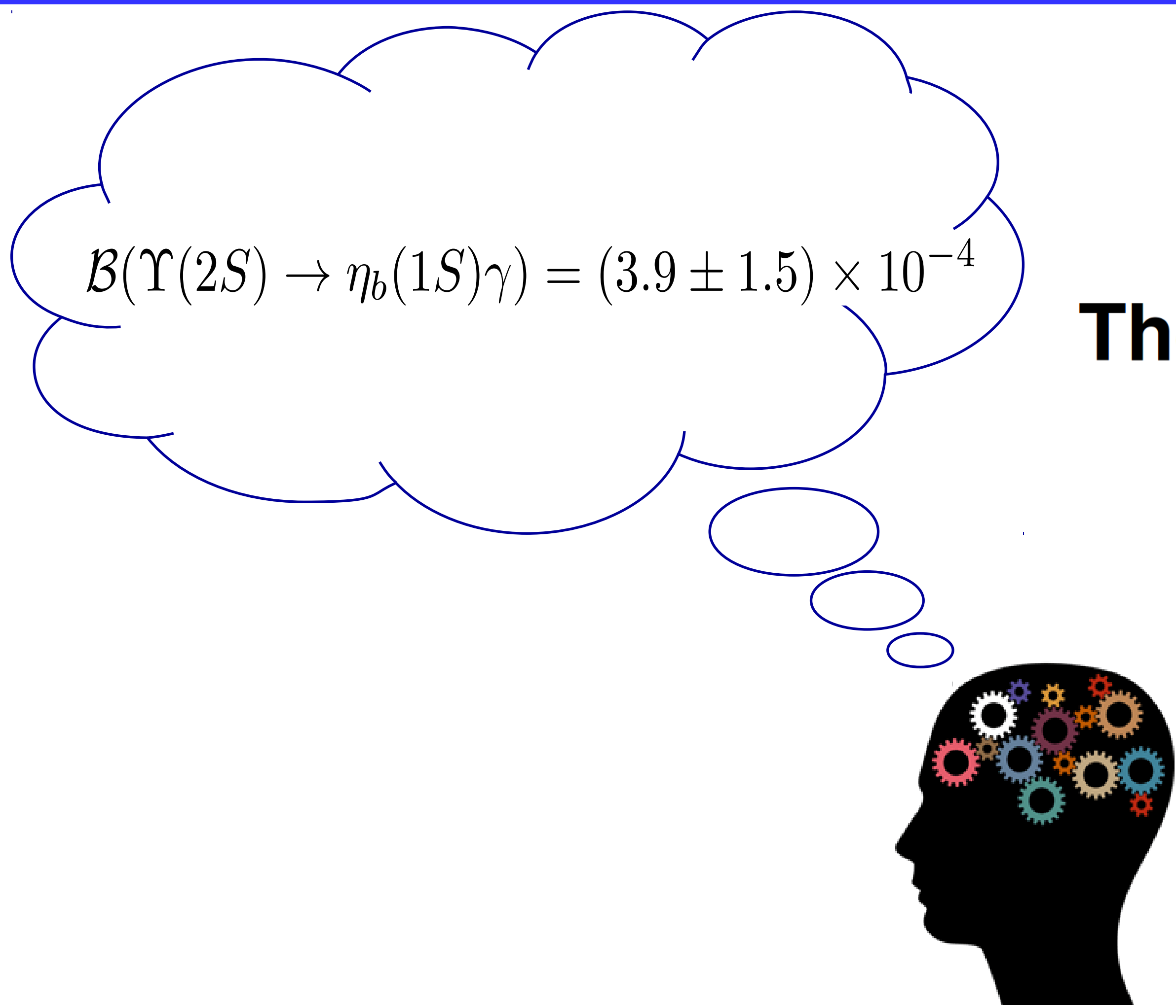
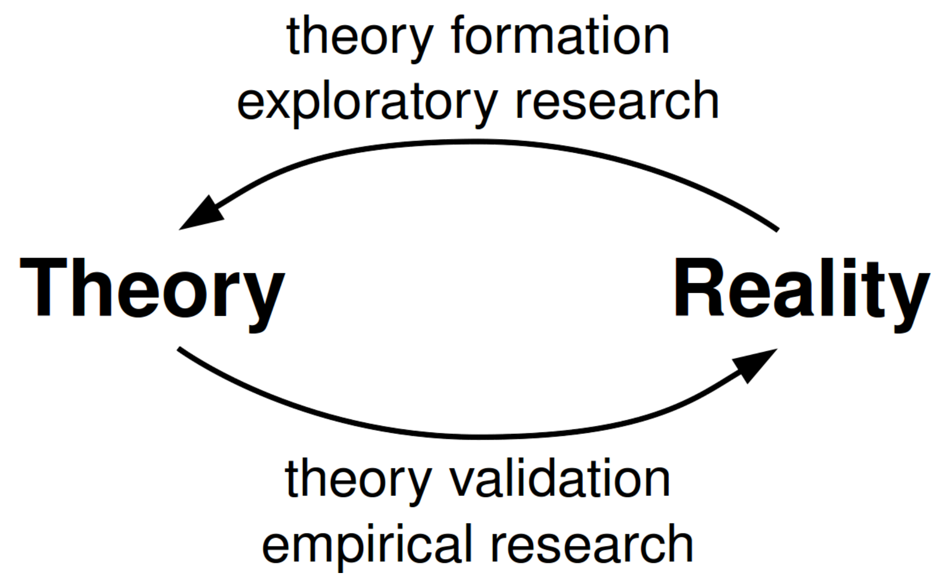
- Full Understanding of Low-Lying States/Decays
- Production of Spin Singlets: η_b
- Exclusion of parity odd Higgs
- Laboratory to test relativistic effects: NRQCD =? Experiment

Decay Rate: $\Upsilon(2S) \to \eta_b(1S)\gamma$





Decay Rate: $\Upsilon(2S) \to \eta_b(1S)\gamma$

$$\langle \eta_{b(mS)}(p_i)|J^\mu(0)|\Upsilon_{(nS)}(p_f, s_\Upsilon)\rangle = \frac{2\mathbf{V_{21}^{\Upsilon\eta_b}(q^2)}}{M_\Upsilon + M_{\eta_b}} \varepsilon^{\mu\alpha\beta\tau} p_{i,\alpha} p_{f,\beta} \epsilon_\tau(p_f, s_\Upsilon)$$

$$\Gamma_{\Upsilon\to\eta_b\gamma} = \alpha_{QED} e_q^2 \frac{16}{3} \frac{|\mathbf{q}|^3}{(M_\Upsilon + M_{\eta_b})^2} \left|\mathbf{V_{21}^{\Upsilon\eta_b}(q^2 = 0)}|_{\text{lat.}}\right|^2$$

NRQCD Evolution: $v^2 \sim 0.1$

$$
\begin{aligned}
aH &= aH_0 + a\delta H_{v^4} + a\delta H_{v^6} \\
aH_0 &= -\frac{\Delta^{(2)}}{2am_b}, \\
a\delta H_{v^4} &= -c_1 \frac{(\Delta^{(2)})^2}{8(am_b)^3} + c_2 \frac{i}{8(am_b)^2} \left(\nabla \cdot \tilde{\mathbf{E}} - \tilde{\mathbf{E}} \cdot \nabla\right) \\
&\quad -c_3 \frac{1}{8(am_b)^2} \sigma \cdot \left(\tilde{\nabla} \times \tilde{\mathbf{E}} - \tilde{\mathbf{E}} \times \tilde{\nabla}\right) \\
&\quad -c_4 \frac{1}{2am_b} \sigma \cdot \tilde{\mathbf{B}} + c_5 \frac{\Delta^{(4)}}{24am_b} - c_6 \frac{(\Delta^{(2)})^2}{16n(am_b)^2}, \\
a\delta H_{v^6} &= -c_7 \frac{1}{8(am_b)^3} \left\{\Delta^{(2)}, \sigma \cdot \tilde{\mathbf{B}}\right\} \\
&\quad -c_8 \frac{3i}{64(am_b)^4} \left\{\Delta^{(2)}, \sigma \cdot \left(\tilde{\nabla} \times \tilde{\mathbf{E}} - \tilde{\mathbf{E}} \times \tilde{\nabla}\right)\right\} \\
&\quad +c_9 \frac{1}{8(am_b)^3} \sigma \cdot \tilde{\mathbf{E}} \times \tilde{\mathbf{E}}
\end{aligned}
$$

Currents and Power Counting from NRQCD + NRQED

$$|\mathbf{q}_\gamma| \sim 0.6\mathrm{GeV} \sim mv^2,\ v^2 \sim 0.1$$

$$\mathcal{O}_F : \quad \omega_F \frac{ee_b}{2m_b}\psi_b^\dagger \sigma \cdot \mathbf{B}^{\mathbf{QED}} \psi_b \sim v^4$$

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$$O_{W1} : \omega_{W1} \frac{ee_b}{8m_b^3} \psi_b^\dagger \{\mathbf{D}^2, \sigma \cdot \mathbf{B}^{\mathbf{QED}}\} \psi_b \sim v^6$$

$$\mathcal{O}_S : \quad \omega_S \frac{iee_b}{8m_b^2} \psi_b^\dagger \sigma \cdot [\mathbf{D}\times, \mathbf{E}^{\mathbf{QED}}] \psi_b \sim v^5$$

$$\mathcal{O}_{S2} : \omega_{S2} \frac{3iee_b}{64m_b^4} \psi_b^\dagger \sigma \cdot \{\mathbf{D}^2, [\mathbf{D}\times, \mathbf{E}^{\mathbf{QED}}]\} \psi_b \sim v^7$$

Currents and Power Counting from NRQCD + NRQED

Need matching coefficient of L.O. Current Operator:

$$\mathcal{O}_F : \quad \omega_F \frac{e e_b}{2m_b} \psi_b^\dagger \sigma \cdot \mathbf{B}^{\mathbf{QED}} \psi_b \sim v^4$$

with $\omega_F = 1 + \omega_F^{(1)} \alpha_s + \mathcal{O}(\alpha_s^2)$,

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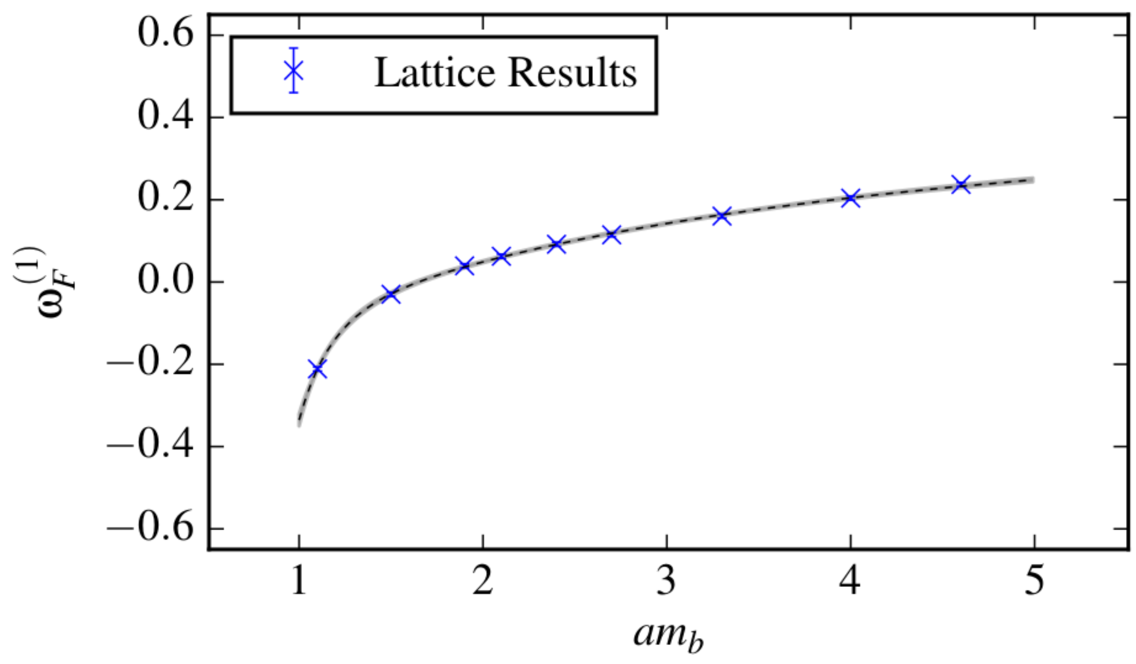

Lattice Methodology

Lattice Methodology on one slide

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2. Compute the 2pt functions: $C_{2pt}(n_{src}, n_{skn}; T) = \langle \mathcal{O}(n_{snk}, T + t_0) \mathcal{O}^\dagger(n_{src}, t_0) \rangle$

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$$C_{3pt}(n_{src}, n_{skn}; T, t) = \langle \mathcal{O}(n_{snk}, T + t_0)\mathcal{O}_C(t + t_0)\mathcal{O}^\dagger(n_{src}, t_0)\rangle$$

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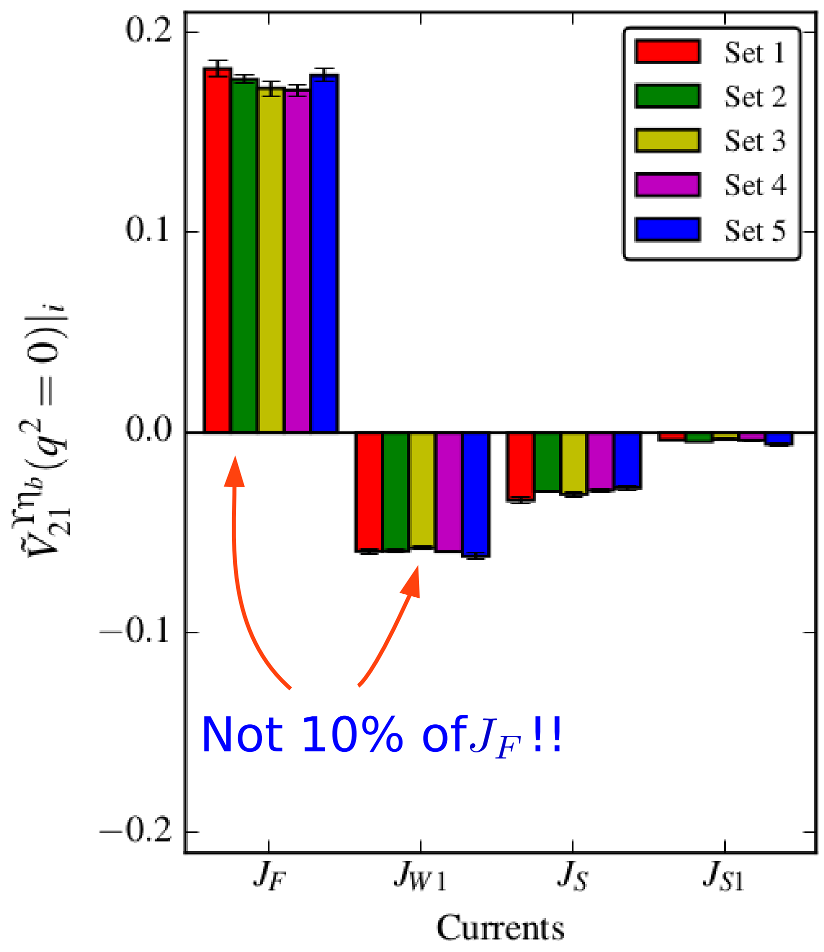
4. Fit the data in your favourite way!

Lattice Methodology on one slide

NB: Details swept under the rug, ask if interested!

For this talk, only necessary to know that it is possible to accurately extract energies and matrix elements from lattice QCD

Results for Form Factors



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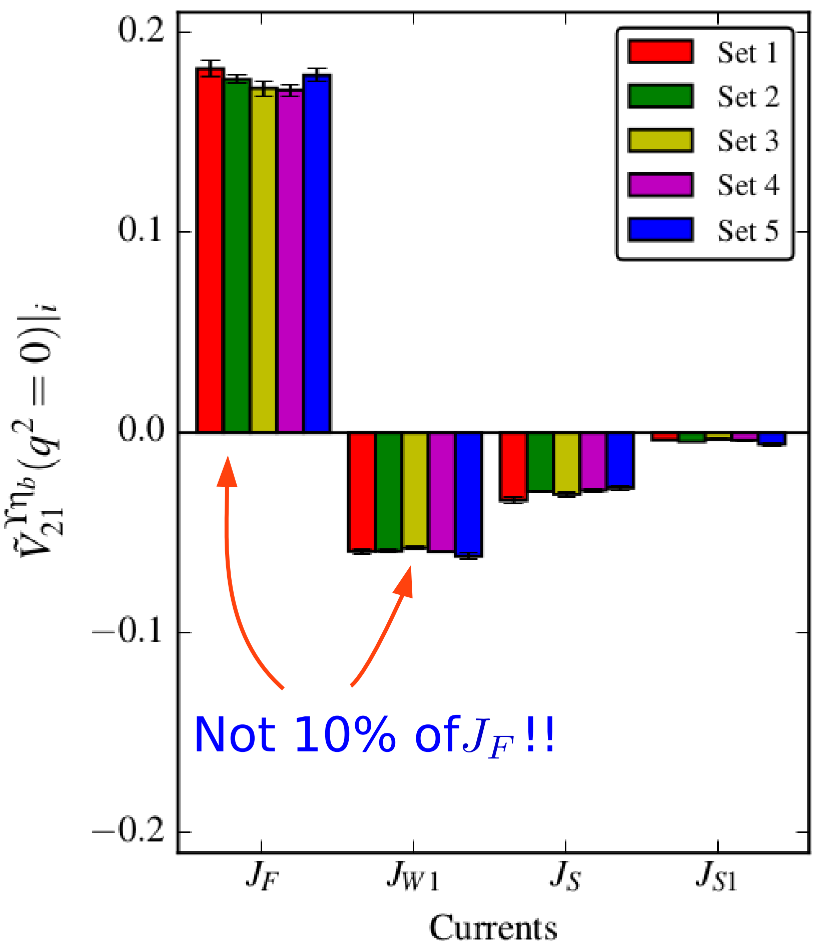

$$\langle \eta_b(mS)|J_F|\Upsilon(nS)\rangle = \mathcal{S}_{fi}\int_0^\infty dr\; r^2 R^*_{m,\eta_b}(r) j_0\left(\frac{|q|r}{2}\right) R_{n,\Upsilon}(r)$$

$$\int_0^\infty dr\; r^2 R^*_{m,\eta_b}(r) j_0\left(\frac{|q|r}{2}\right) R_{n,\Upsilon}(r) =$$

$$\delta_{nm} + a_2 \underbrace{|q_\gamma|^2 r_0^2}_{v^2} + a_4 |q_\gamma|^4 r_0^4 + \cdots$$

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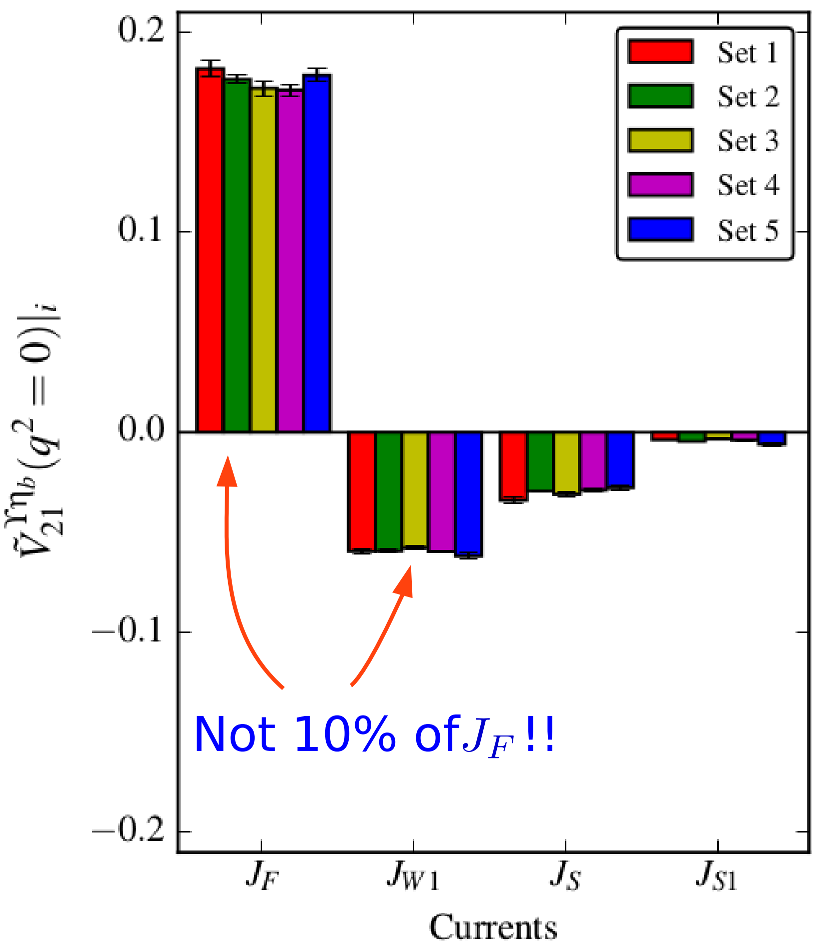

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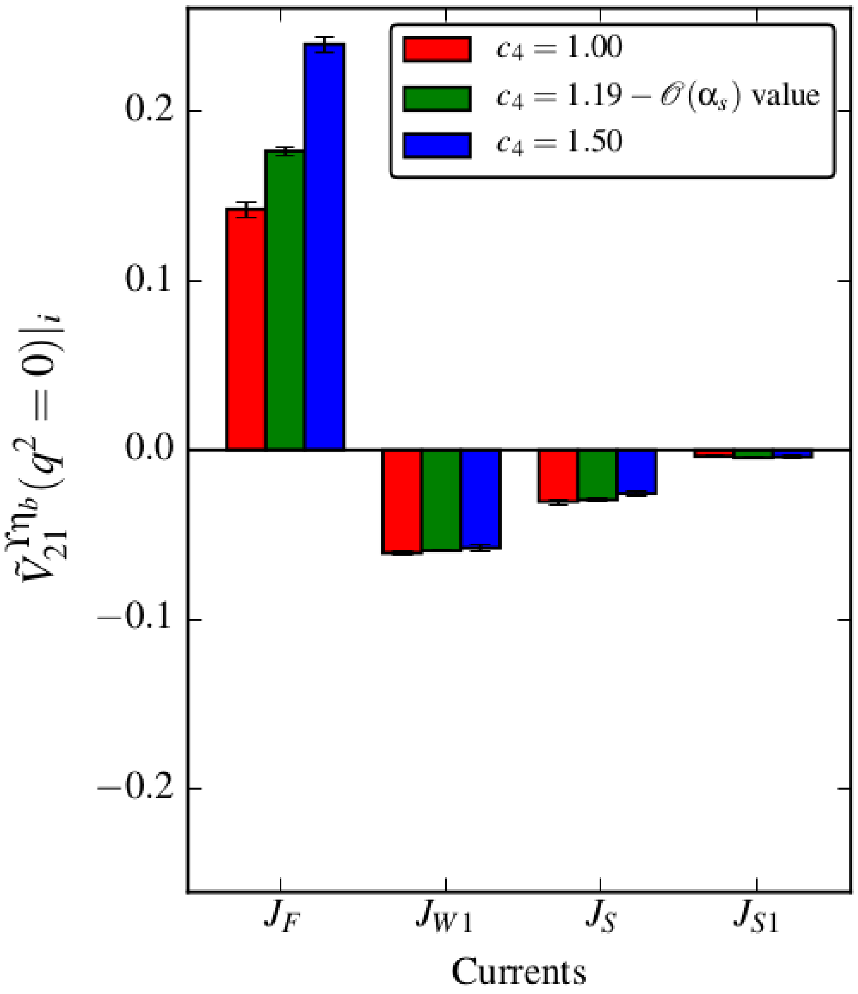
N.B., In hindered decays ($n \neq m$) the leading order matrix element is suppressed, making sub-leading currents appreciable

N.B., Destructive Interference occurs in the $\Upsilon(2S) \to \eta_b(1S)\gamma$ decay

Results for Form Factors



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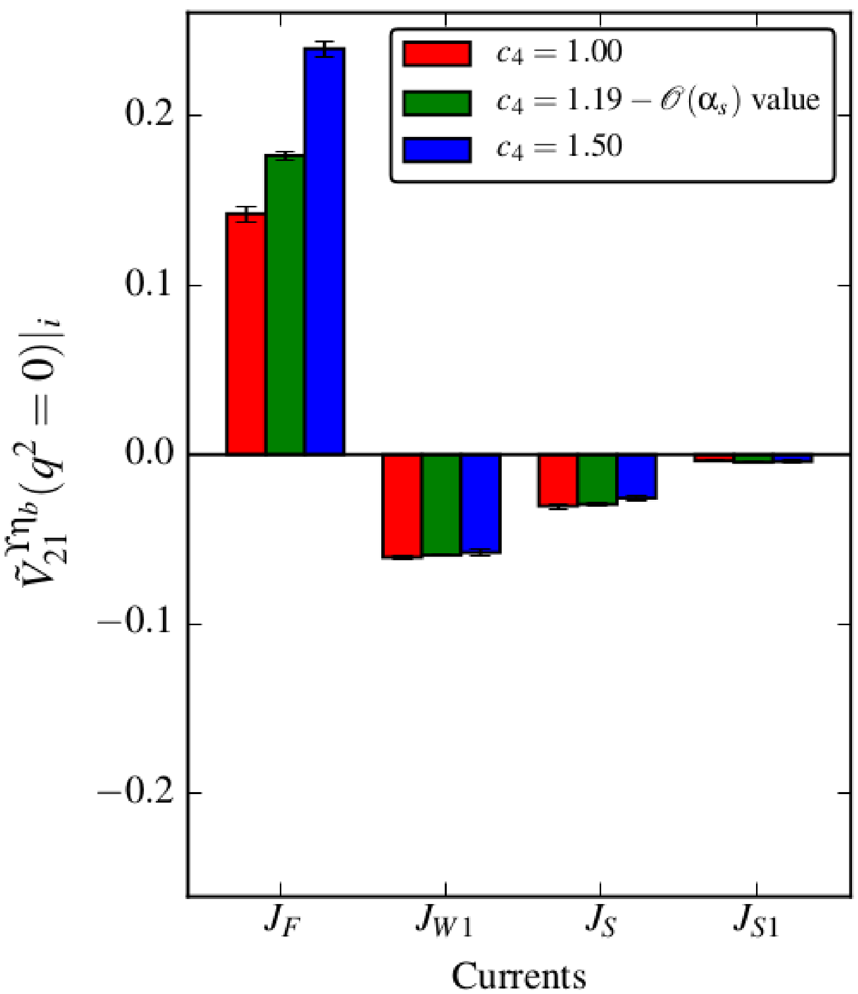

$$|\eta_b(1S)\rangle^{(1)} = |\eta_b(1S)\rangle^{(0)} - \sum_{m\neq 1} |\eta_b(mS)\rangle^{(0)} \frac{V_{m1}^{\eta_b}}{E_{m1}^{\eta_b}}$$

$$|\Upsilon(2S)\rangle^{(1)} = |\Upsilon(2S)\rangle^{(0)} - \sum_{n\neq 2} |\Upsilon(nS)\rangle^{(0)} \frac{V_{n2}^{\Upsilon}}{E_{n2}^{\Upsilon}} .$$

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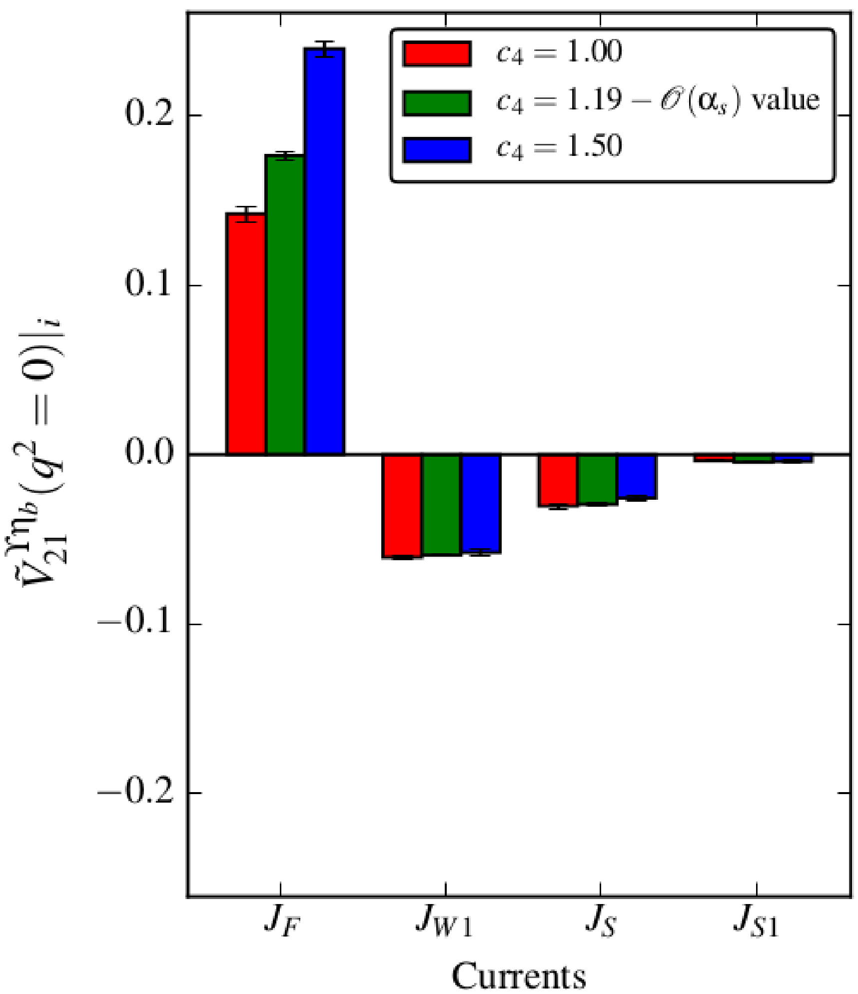

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Overlap Suppressed

$$^{(1)}\langle\eta_b(1S)|J_i|\Upsilon(2S)\rangle^{(1)} \approx$$

$$^{(0)}\langle\eta_b(1S)|J_i|\Upsilon(2S)\rangle^{(0)} \quad \rightarrow \checkmark$$

$$- \frac{V_{21}^{\eta_b *}}{E_{21}^{\eta_b}} \, ^{(0)}\langle\eta_b(2S)|J_i|\Upsilon(2S)\rangle^{(0)} \quad \rightarrow ✗$$

$$- \frac{V_{12}^{\Upsilon}}{E_{12}^{\Upsilon}} \, ^{(0)}\langle\eta_b(1S)|J_i|\Upsilon(1S)\rangle^{(0)} \quad \rightarrow ✗$$

N.B.

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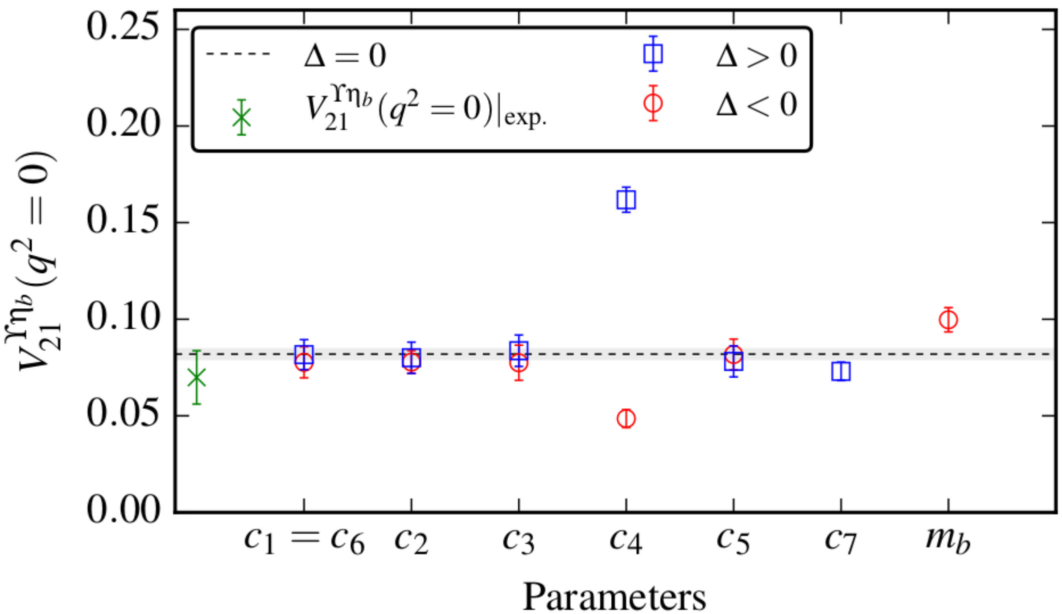

Parameter	p^{test} for $\Delta < 0$	$p^{\mathcal{O}(\alpha_s)}$ for $\Delta = 0$	p^{test} for $\Delta > 0$
$c_1 = c_6$	1.00	1.31	1.50
c_2	0.75	1.02	1.25
c_3	0.75	1.00	1.25
c_4	1.00	1.19	1.50
c_5	1.00	1.16	1.50
c_7	———	1.00	1.50
m_b	2.5935	2.73	———

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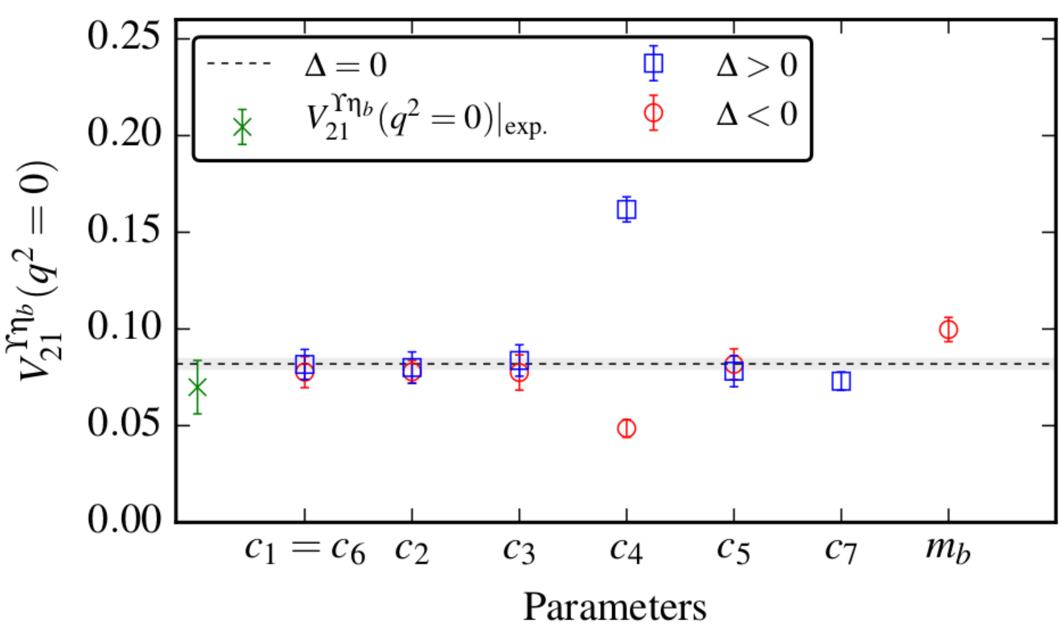

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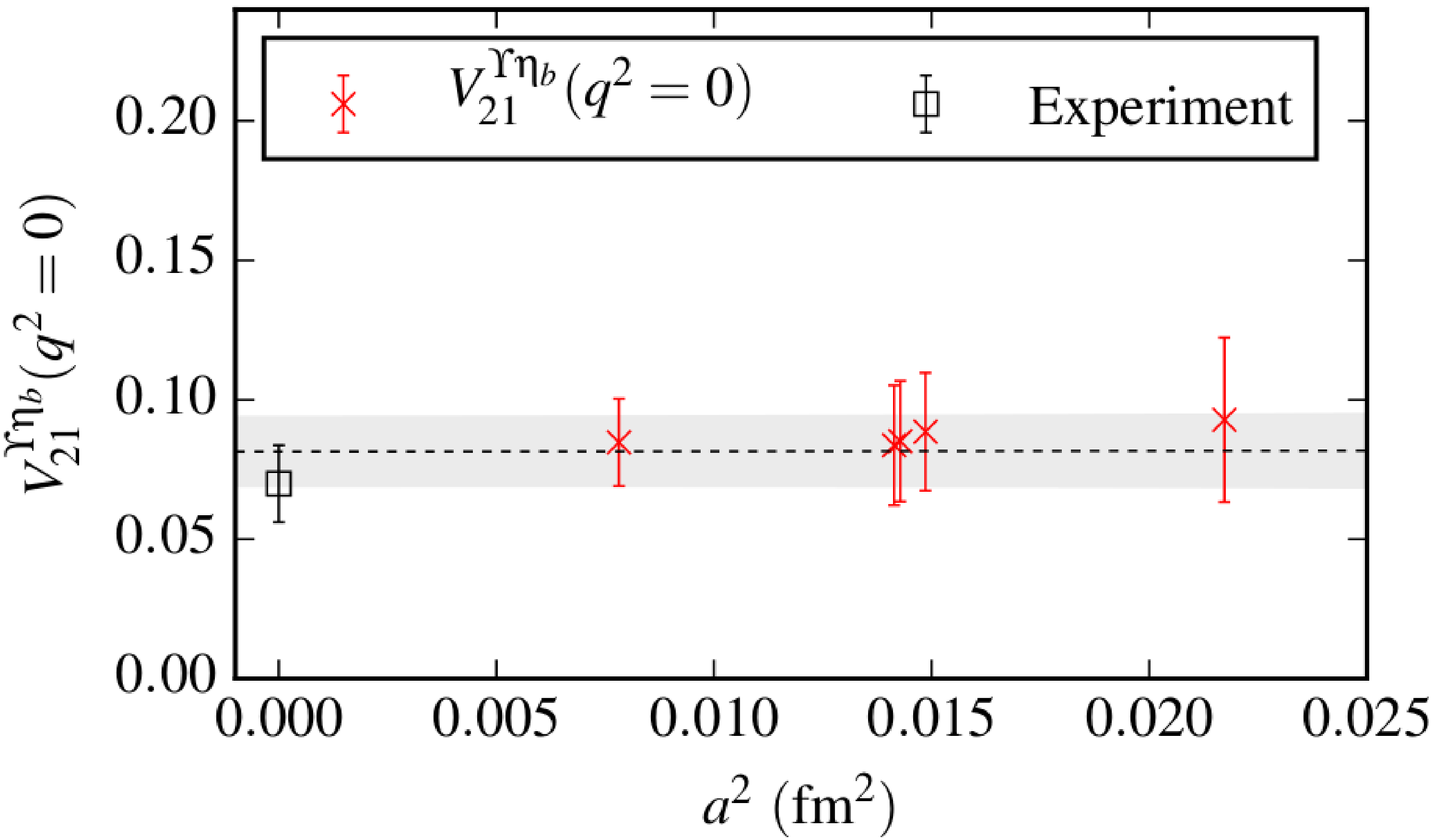
N.B., In hindered decays the leading order matrix element is suppressed, making particular relativistic corrections due to perturbative potentials (arising from terms in the Hamiltonian) appreciable

Extrapolation

$$V_{21}^{\Upsilon\eta_b}(q^2) = \sum_{i}^{currents} V_{21}^{\Upsilon\eta_b}(q^2)|_i$$



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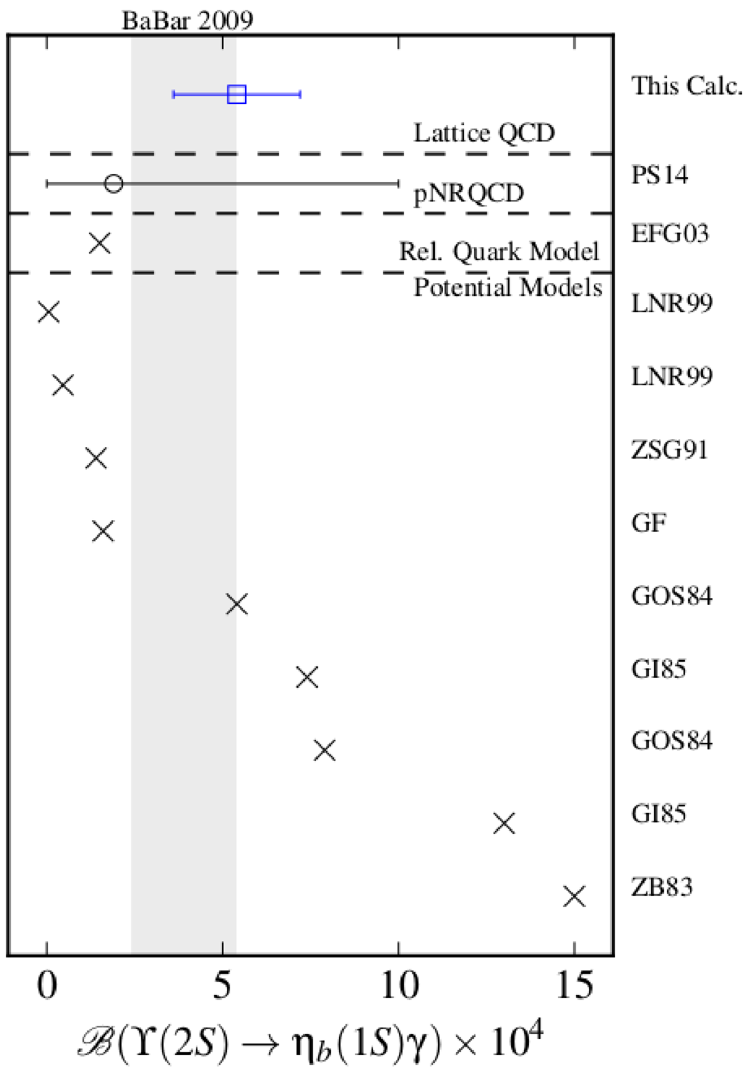

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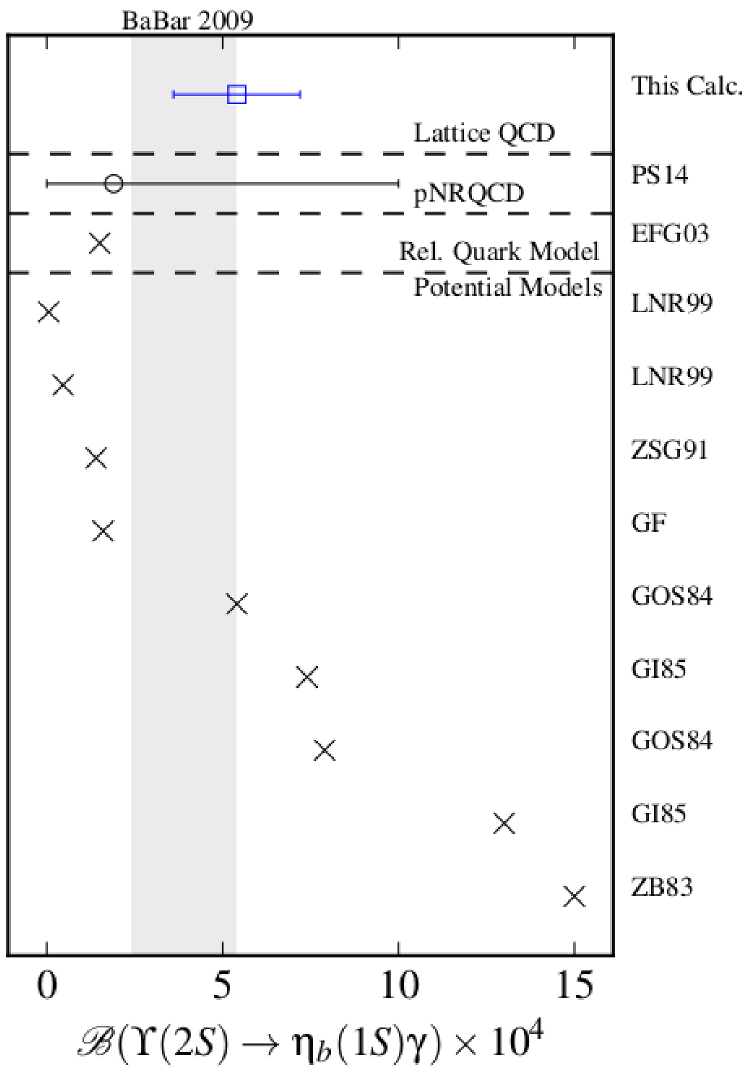

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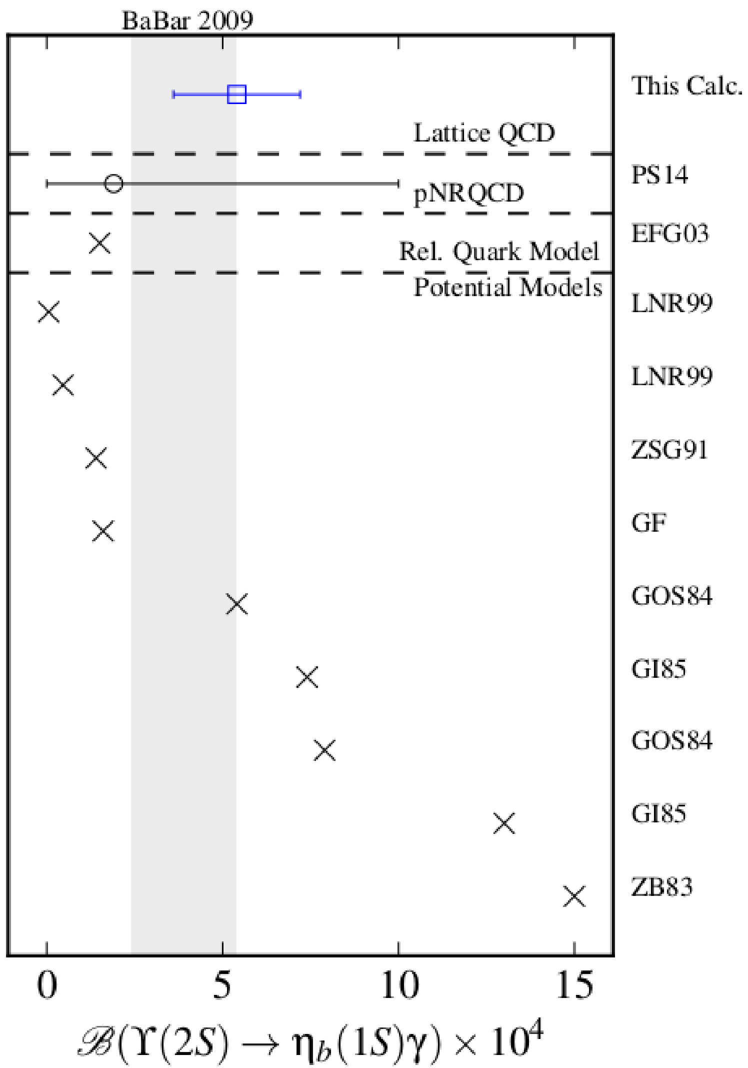

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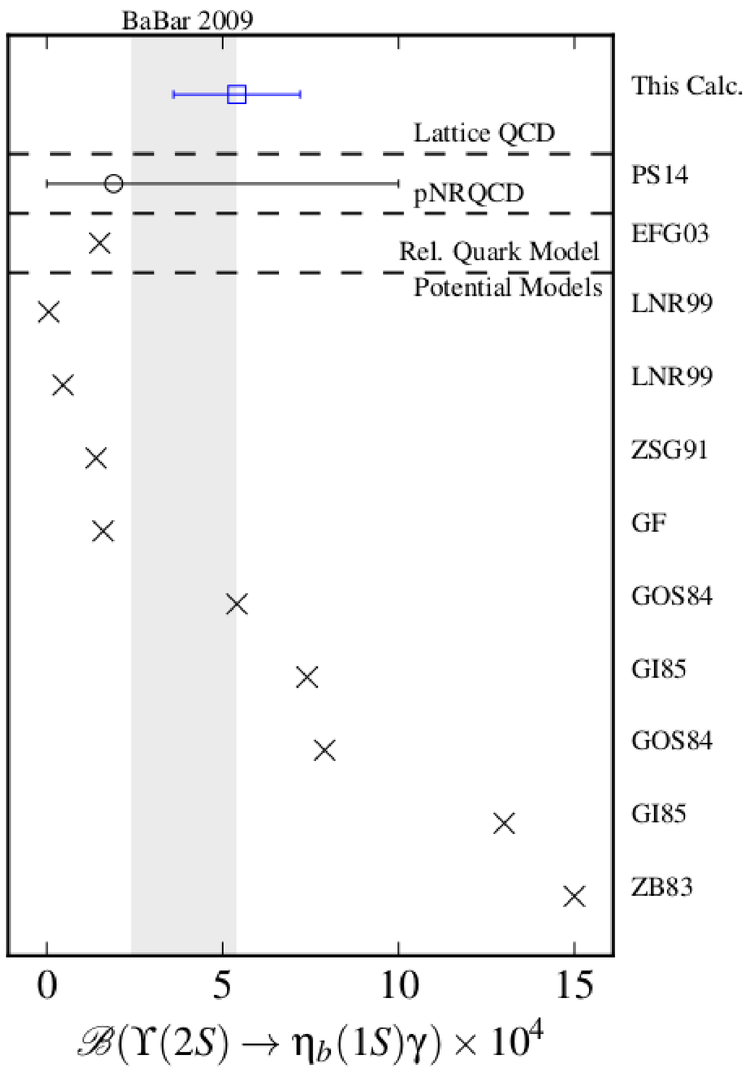

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- Radiative corrections in action (Need precise matching coefficients)

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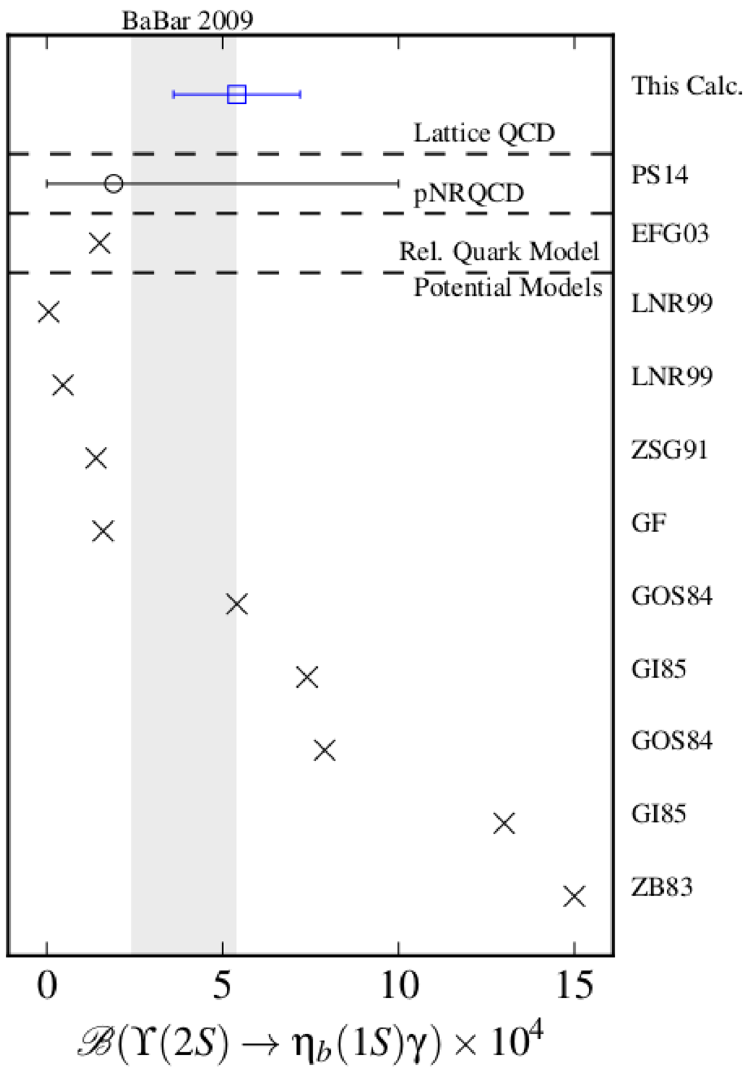

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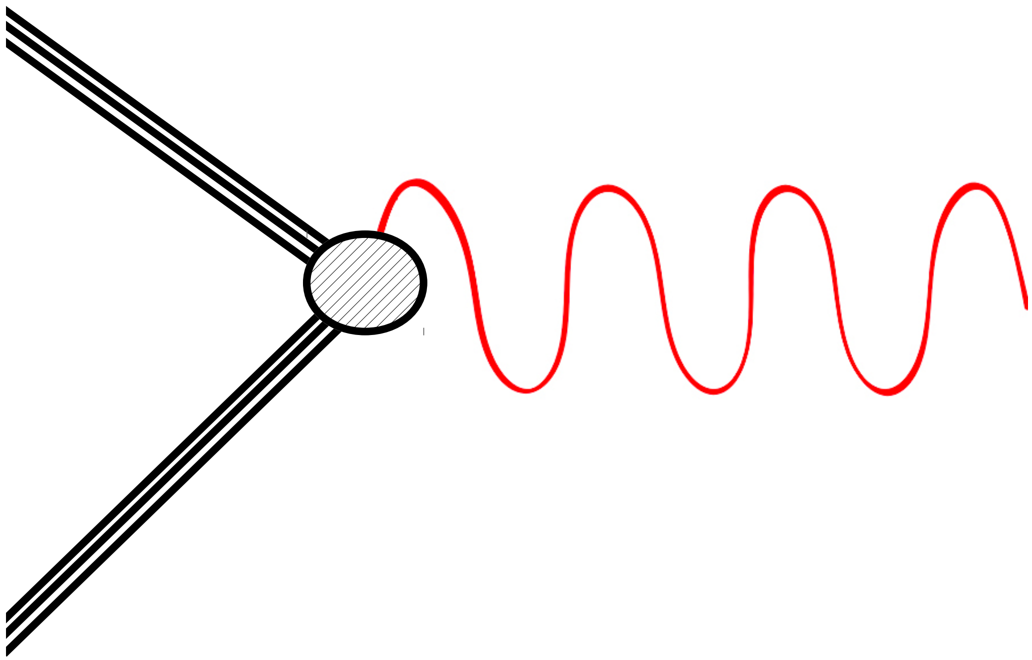
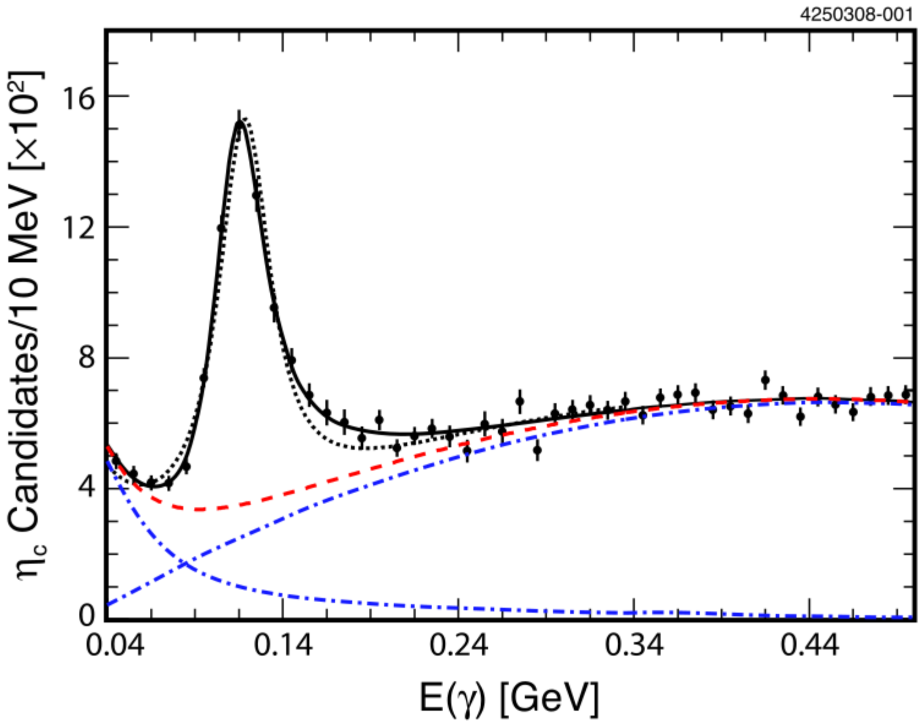
We (HPQCD) Have Done THIS!!!

Radiative Decays

What do experimentalists see?!



Line Shape from $J/\psi \to \eta_c\gamma$



CLEO:ArXiv:0805.0252

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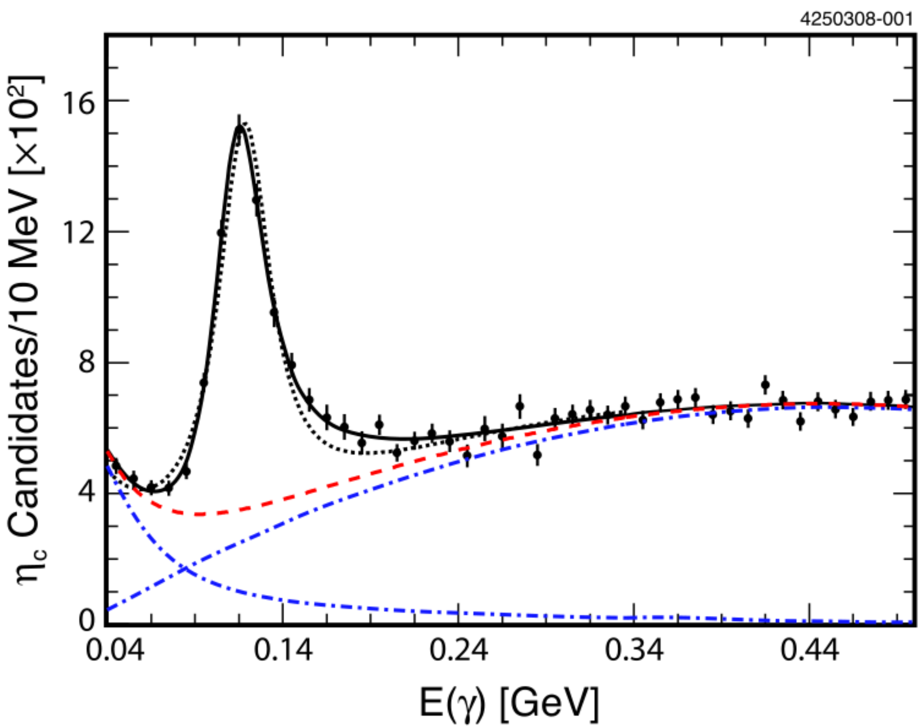


CLEO:ArXiv:0805.0252

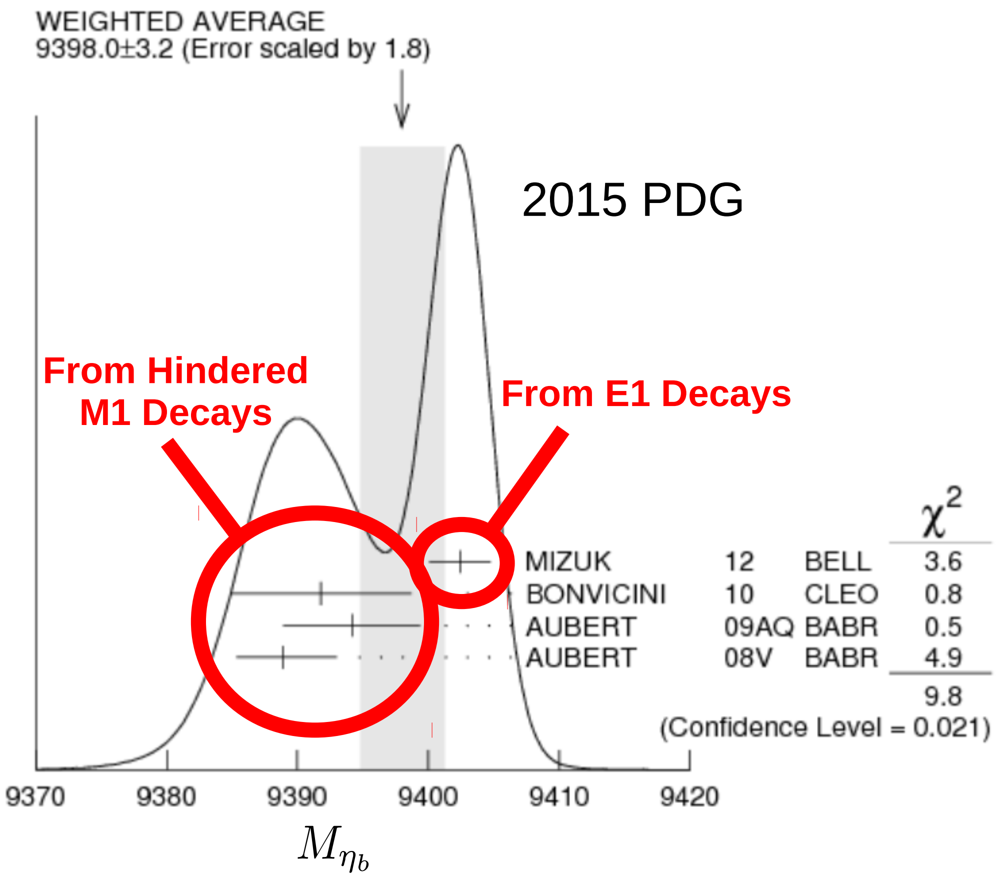
KEDR:ArXiv:1002.2071

$$\frac{dN_\gamma}{d\omega} = N_\psi \mathcal{B} \int_0^{M_\psi/2} d\omega' \frac{d\Gamma(\omega')}{d\omega'} \frac{\epsilon(\omega') g(\omega,\omega')}{\Gamma_{\eta_c\gamma}}$$

$$\frac{d\Gamma(\omega)}{d\omega} = \frac{4}{3}\alpha \frac{e_c^2}{m_c^2} \omega^3 |M|^2 BW(\omega)$$

N.B., Need Energy Dependence of matrix element ("damping" function) to fit line shape correctly.

Mass of the η_b



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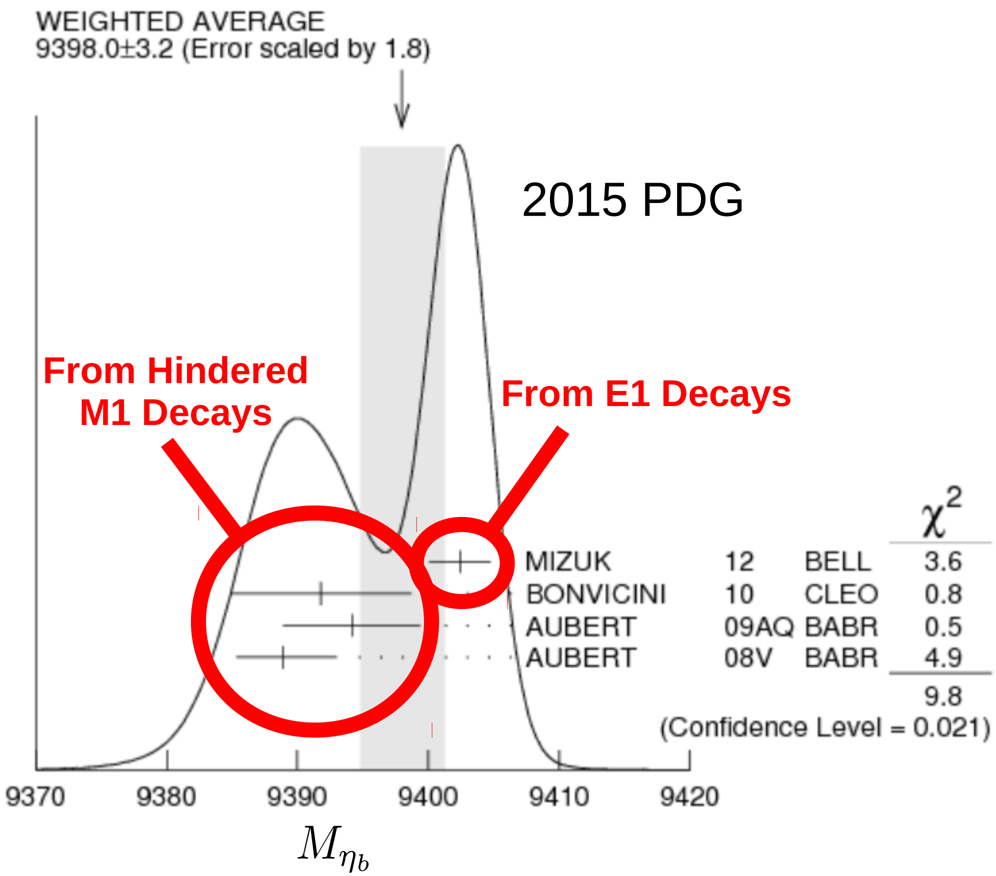

Reason for tension here:

Correct damping function (matrix element including suppression effects) needs to be used when fitting line shape from hindered M1 decays???

The Hindered M1 $\eta_b(2S) \to \Upsilon(1S)\gamma$ Decay

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- Hindered M1 decays are difficult to predict as the L.O. matrix element is suppressed
- This produces sensitivity to relativistic and radiative corrections
- Yet, it is possible to accurately and reliably calculate from first principles (using LQCD)
- A damping function (including suppression effects) might be needed when fitting the experimental line-shape from hindered M1 decays

Future/Questions

- Get $h_b(1P)$ width from $h_b(1P) \to \eta_b(1S)\gamma$

- $B_s^* \to B_s\gamma$ needed for new-physics search in $B_s^* \to \ell\ell$ (arXiv:1509.05049)

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Questions!?! (ch558@cam.ac.uk)

Back Up Slides

Two Point Calculation

1. Build interpolating operators $\mathcal{O}(n, t_0)$, which overlap with states having specific quantum numbers J^{PC}, e.g.,Υ, η_b
2. Calculate $C_{2pt}(n_{src}, n_{skn}; T) = \langle \mathcal{O}(n_{snk}, T + t_0)\mathcal{O}^\dagger(n_{src}, t_0)\rangle$ numerically on the lattice

Three Point Calculation

1. Build current operators which we are interested in: $\mathcal{O}_C(t+t_0)$
2. Calculate $C_{3pt}(n_{src}, n_{skn}; T, t) = \langle \mathcal{O}(n_{snk}, T+t_0)\mathcal{O}_C(t+t_0)\mathcal{O}^\dagger(n_{src}, t_0)\rangle$ numerically with the same twist as in the two point calculation

Bayesian Fitting

- Simultaneously fit two point correlator for Υ, η_b data to

$$C_{2pt}(n_{src}, n_{snk}) = \sum_{i}^{m} a_i(n_{src}) a_i(n_{snk}) \exp(-E_i t)$$

and three point correlator data in order to

$$C_{3pt}(n_{src}, n_{snk}) = \sum_{i,f}^{m} a_i(n_{src}) V_{i,f} b_f(n_{snk}) \exp(-E_i t) \exp(-E_f (T - t))$$

and extract what we need: $V_{i,f}$

Coulomb Gauge Fixed Ensembles

MILC Configurations ($n_f = 2 + 1 + 1$ HISQ)

Set	β	a_Υ (fm)	am_l	am_s	am_c	$N_s \times N_T$	n_{cfg}
1	5.8	0.1474(15)	0.013	0.065	0.838	16×48	1020
2	6.0	0.1219(9)	0.0102	0.0509	0.635	24×64	1052
3	6.0	0.1195(10)	0.00507	0.0507	0.628	32×64	1000
4	6.0	0.1189(9)	0.00184	0.0507	0.628	48×64	1000
5	6.3	0.0884(6)	0.0074	0.037	0.440	32×96	1008

Fitting

$$V(a^2, am_b) = V_{\text{phys}} \times \left[1 + \sum_{j=1,2} k_j (a\Lambda)^{2j} (1 + k_{jb}\delta x_m + k_{jbb}(\delta x_m)^2)\right]. \quad (4)$$

The lattice spacing dependence is set by a scale $\Lambda = 500$ MeV, and $\delta x_m = (am_b - 2.7)/1.5$ allows for mild dependence on the effective theory cutoff am_b. We take priors of 0(1) on all the coefficients except k_1 which is 0.0(3) since the action includes radiatively improved a^2 lattice spacing corrections. We have tested that our results are not sensitive to the fit form or the priors.

Potential Model for L.O. Matrix Element

$$\Gamma_{\Upsilon \to \eta_b \gamma} = \alpha_{QED} e_q^2 \frac{4}{3m_b^2} |\mathbf{q}_\gamma|^3 \left| \int r^2 dr R^*_{\eta_b}(1S) j_0(\frac{|\mathbf{q}_\gamma| r}{2}) R_\Upsilon(2S) \right|^2$$

$$V(q^2)_{nm} \propto \int r^2 dr R^*_{\eta_b}(mS) j_0(\frac{|\mathbf{q}_\gamma| r}{2}) R_\Upsilon(nS)$$

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- $V(q^2)^{\text{Hyd}}_{21} \propto \underbrace{\frac{a_0^2|\mathbf{q}|^2}{16}}_{\sim v^2}\left(1 + \frac{a_0^2|\mathbf{q}|^2}{16}\right)^{-3} \quad \xrightarrow{|\mathbf{q}|\to 0} 0$

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$\Longrightarrow$ Suppressed. Difficult to predict.

L.O. Matrix Element dependence on spin-spin potential

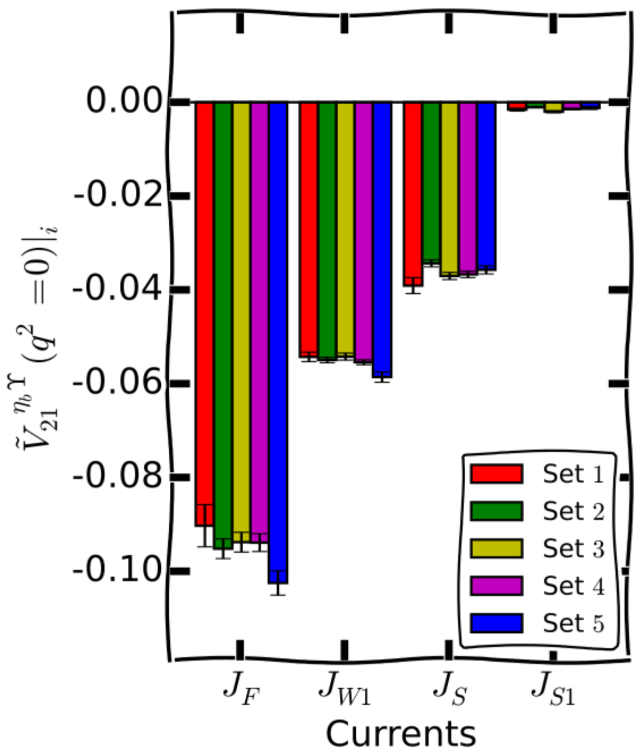
ArXiv:1302.3528

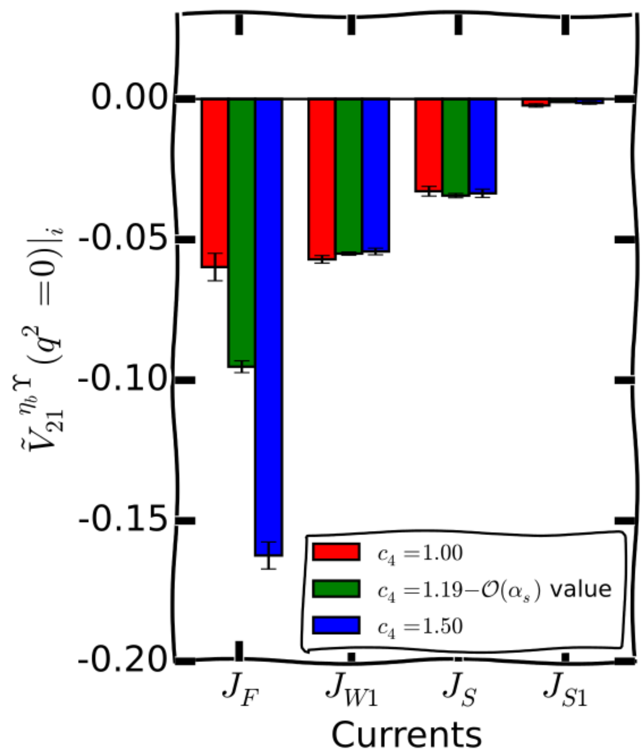
$$\Gamma(\psi(2S) \to \eta_c \gamma) = \frac{16\alpha}{27 m_c^2} \tilde{q}_\gamma^3 \left[\frac{\tilde{q}_\gamma^2}{24} {}_{\eta_c}\langle r^2 \rangle_{\psi(2S)} + \frac{5}{6} \frac{{}_{\eta_c}\langle p^2 \rangle_{\psi(2S)}}{m_c^2} - \frac{2}{m_c^2} \frac{{}_{\eta_c}\langle V_{S^2}(\vec{r}) \rangle_{\psi(2S)}}{E_{\psi(2S)} - E_{\eta_c}} \right]^2$$

$$\Gamma(\eta_c(2S) \to J/\psi \gamma) = \frac{16\alpha}{9 m_c^2} q_\gamma^3 \left[\frac{q_\gamma^2}{24} {}_{J/\psi}\langle r^2 \rangle_{\eta_c(2S)} + \frac{5}{6} \frac{{}_{J/\psi}\langle p^2 \rangle_{\eta_c(2S)}}{m_c^2} + \frac{2}{m_c^2} \frac{{}_{J/\psi}\langle V_{S^2}(\vec{r}) \rangle_{\eta_c(2S)}}{E_{\eta_c(2S)} - E_{J/\psi}} \right]^2$$

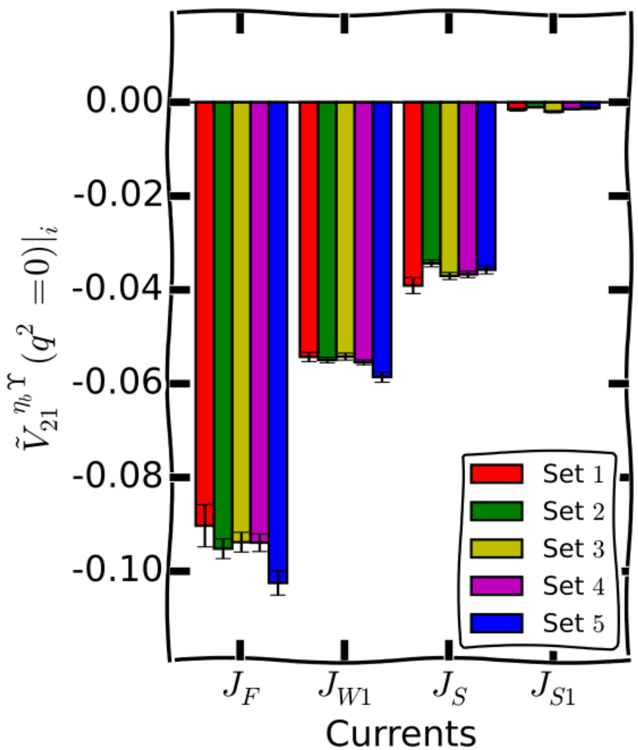
The Hindered M1 $\eta_b(2S) \to \Upsilon(1S)\gamma$ Decay

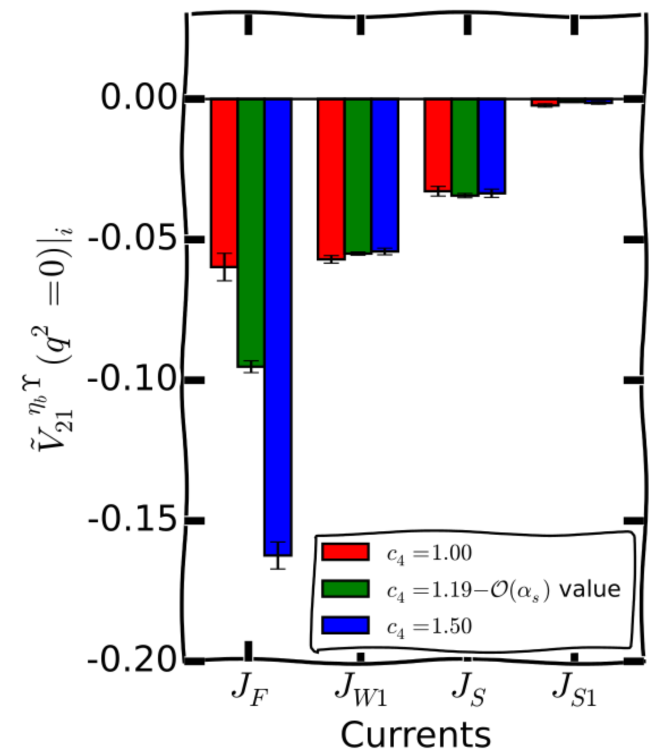
The Hindered M1 $\eta_b(2S) \to \Upsilon(1S)\gamma$ Decay





The Hindered M1 $\eta_b(2S) \to \Upsilon(1S)\gamma$ Decay





- N.B., Matrix element dependence on spin-spin potential has opposite sign in this decay relative to $\Upsilon(2S) \to \eta_b(1S)\gamma$ (backup slides)
- N.B., spin-spin potential contribution dominates and L.O. matrix element becomes negative

The Hindered M1 $\eta_b(2S) \to \Upsilon(1S)\gamma$ Decay