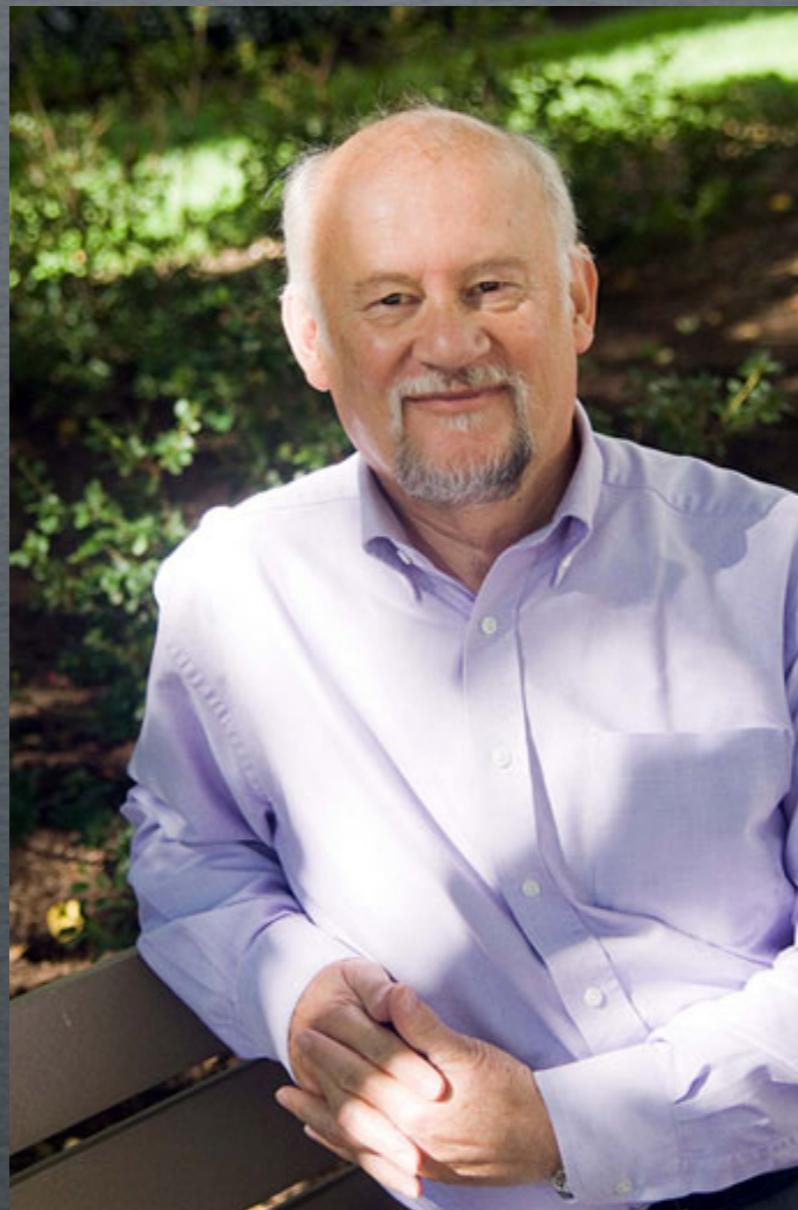
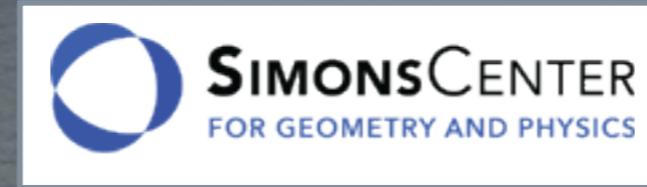


Michael R. Pennington

1946 -2018



[239-137]



May, 2018

Exotic Hadrons and Flavor Physics

HYBRID MESONS AND THEIR DECAYS

Eric Swanson



Past ideas for hybrid mesons

VOLUME 37, NUMBER 18

PHYSICAL REVIEW LETTERS

1 NOVEMBER 1976

ψ Spectroscopy of a Charm String*

R. C. Giles and S.-H. H. Tye

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 13 August 1976)

PHYSICAL REVIEW D

VOLUME 17, NUMBER 3

1 FEBRUARY 1978

Model of mesons with constituent gluons*

D. Horn[†]

California Institute of Technology, Pasadena, California 91125

J. Mandula[‡]

Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 28 January 1977)

COLOURED QUARK AND GLUON CONSTITUENTS IN THE MIT BAG MODEL: A MODEL OF MESONS

Ted Barnes

Department of Physics, University of Southampton, Southampton SO9 5NH, England

Volume 124B, number 3,4

PHYSICS LETTERS

Received 24 October 1977

(Revised 7 May 1979)

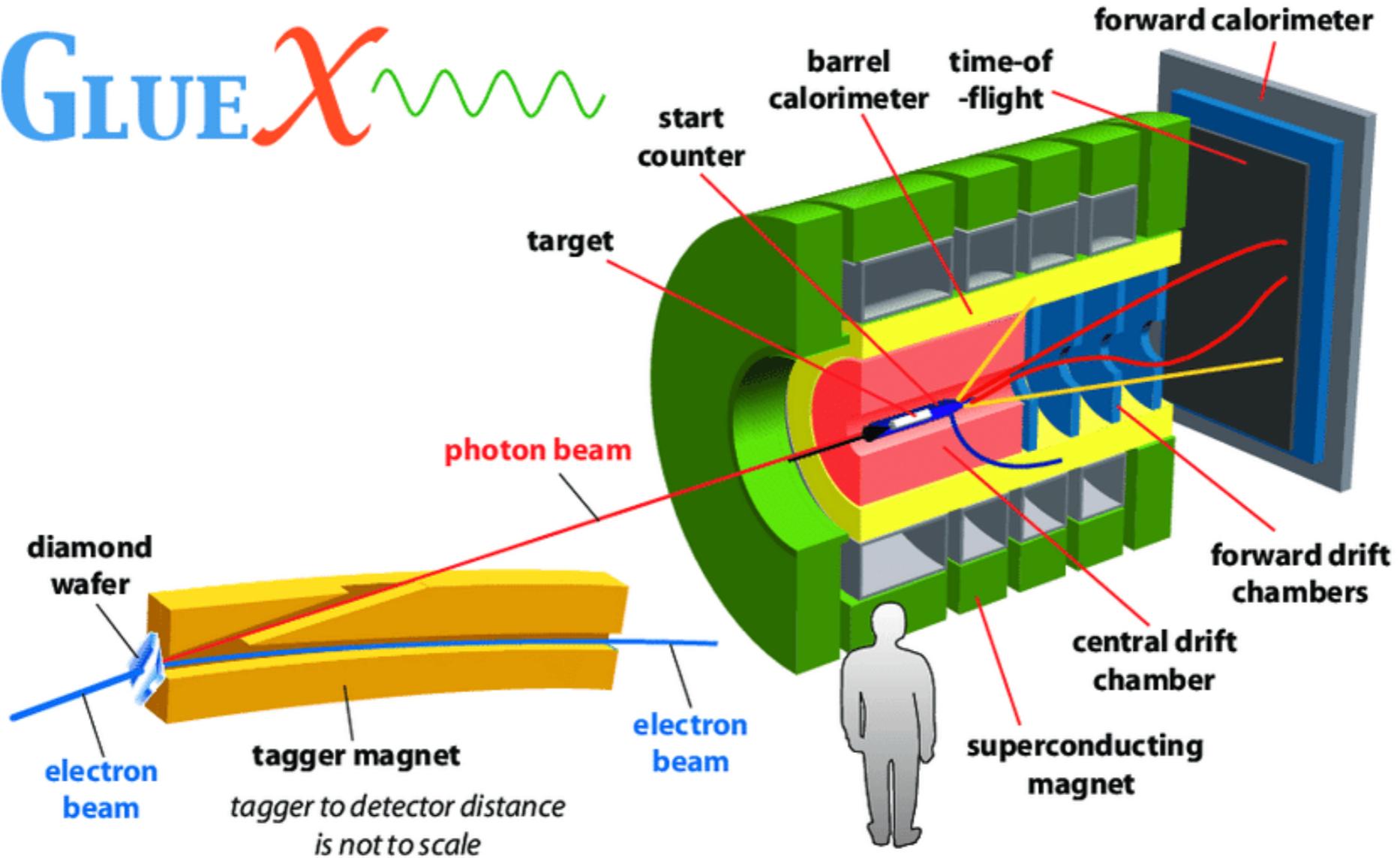
A FLUX TUBE MODEL FOR HADRONS

Nathan ISGUR^{1,2} and Jack PATON

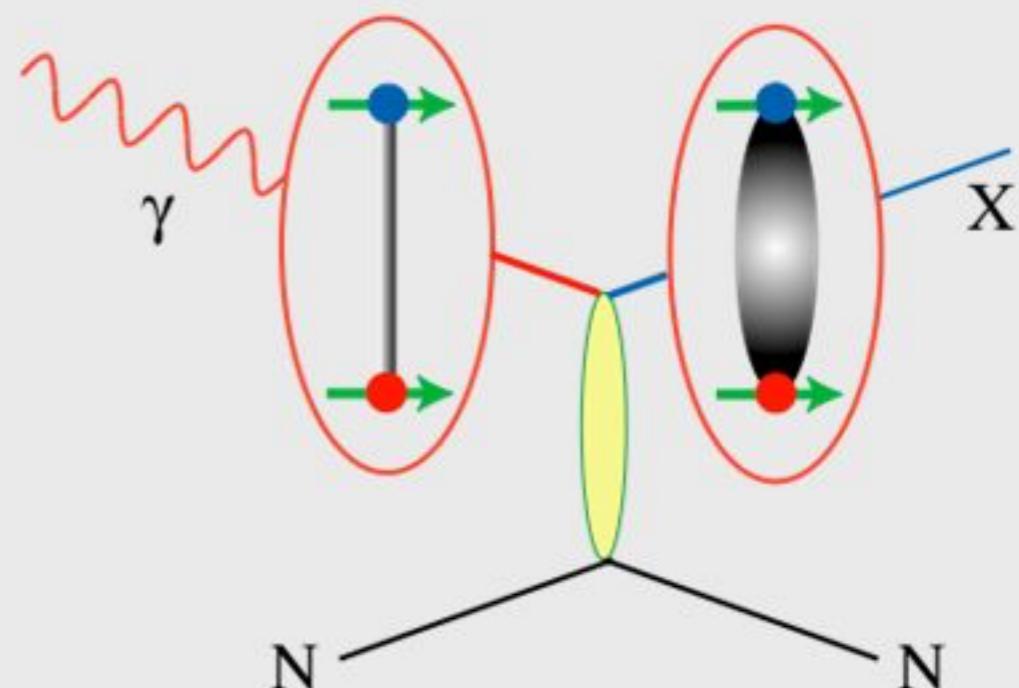
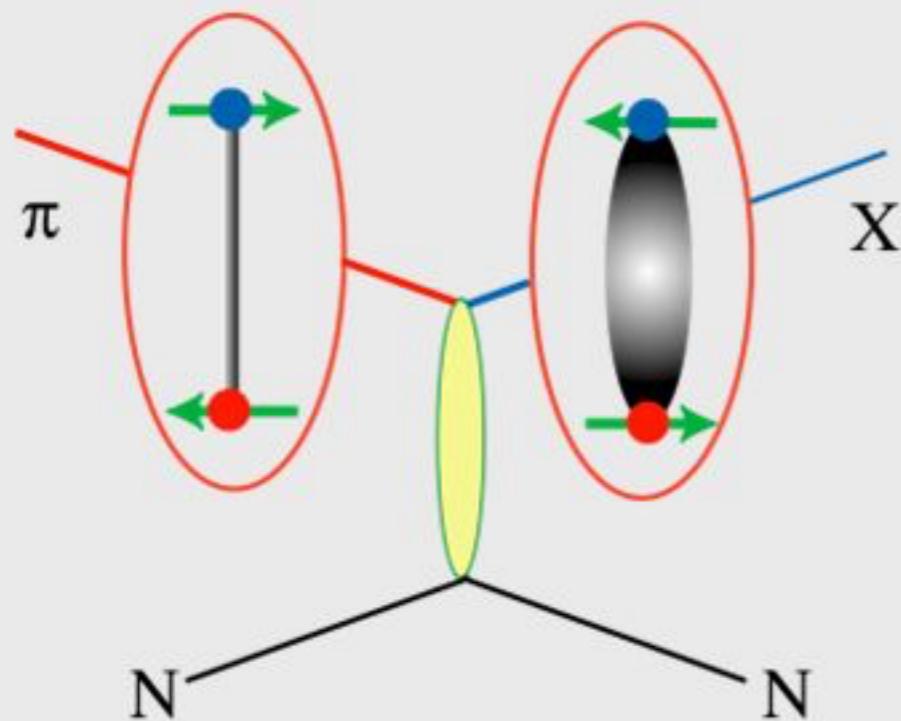
Department of Theoretical Physics, University of Oxford, 1 Keble Road, Oxford, OX1, 3NP, England

Received 20 December 1982

GLUE χ



Photoproduction



More likely to find exotic hybrid mesons
using beams of photons



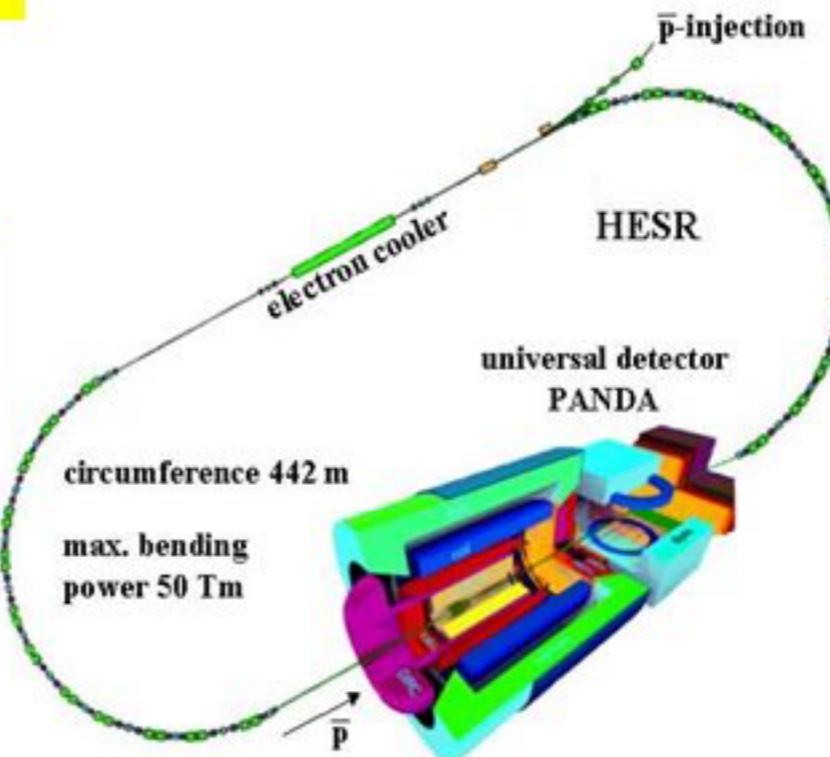
Physics with Panda

J/ ψ spectroscopy
confinement

Glueballs (ggg)
Hybrids ($\bar{c}cg$)

Charmed hadrons
in the nuclear
medium

Proton
Formfactor in
the Timelike
region



inverted deeply virtual
Compton scattering

CP-violation
(D/ Λ - sector)

What has happened in the mean time?

Lattice Hybrid Computations

Volume 129B, number 5

PHYSICS LETTERS

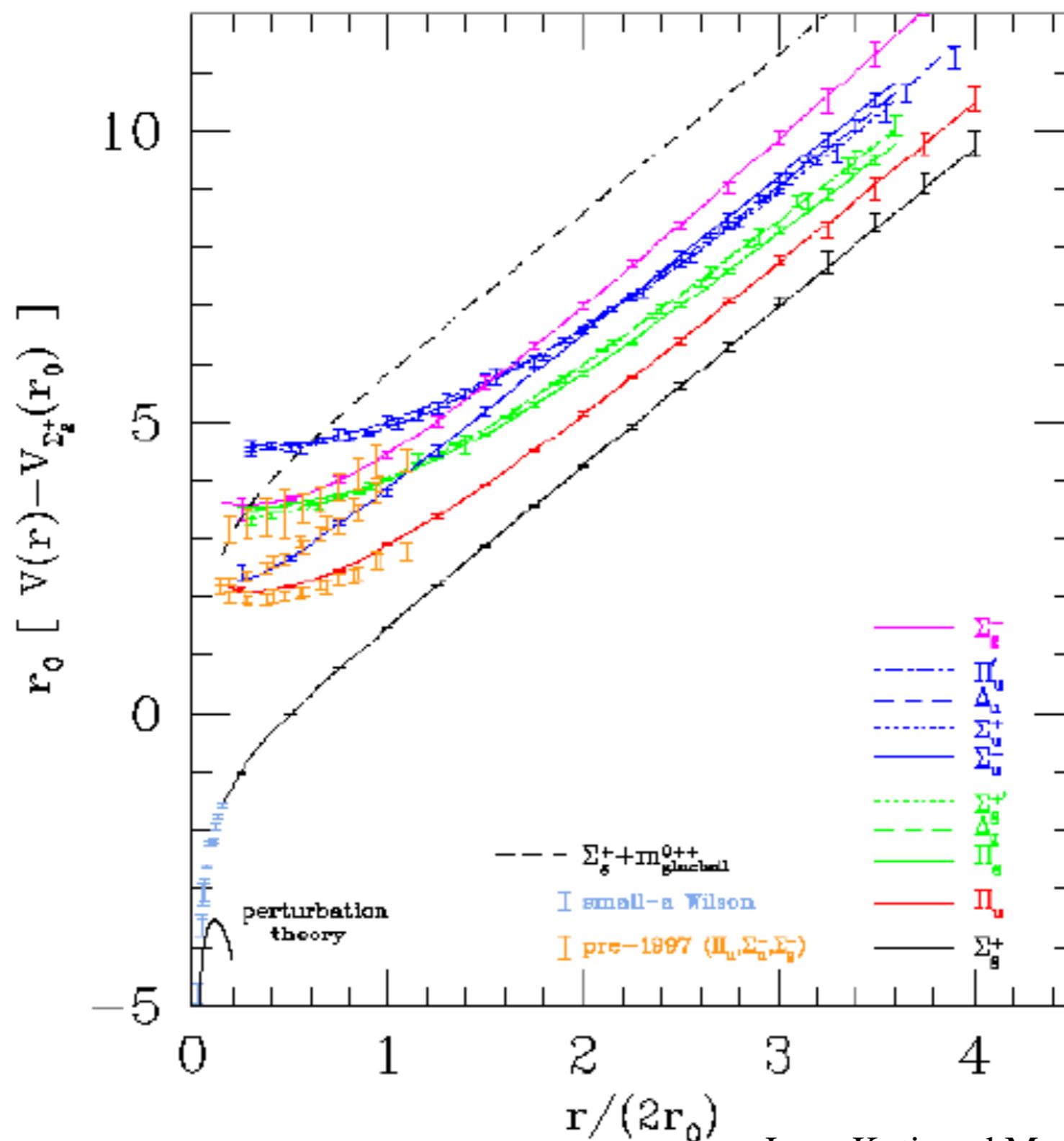
29 September 1983

MESONS WITH EXCITED GLUE

L.A. GRIFFITHS, C. MICHAEL and P.E.L. RAKOW

Department of Applied Mathematics and Theoretical Physics, University of Liverpool, P.O. Box 147, Liverpool L69 3BX, UK

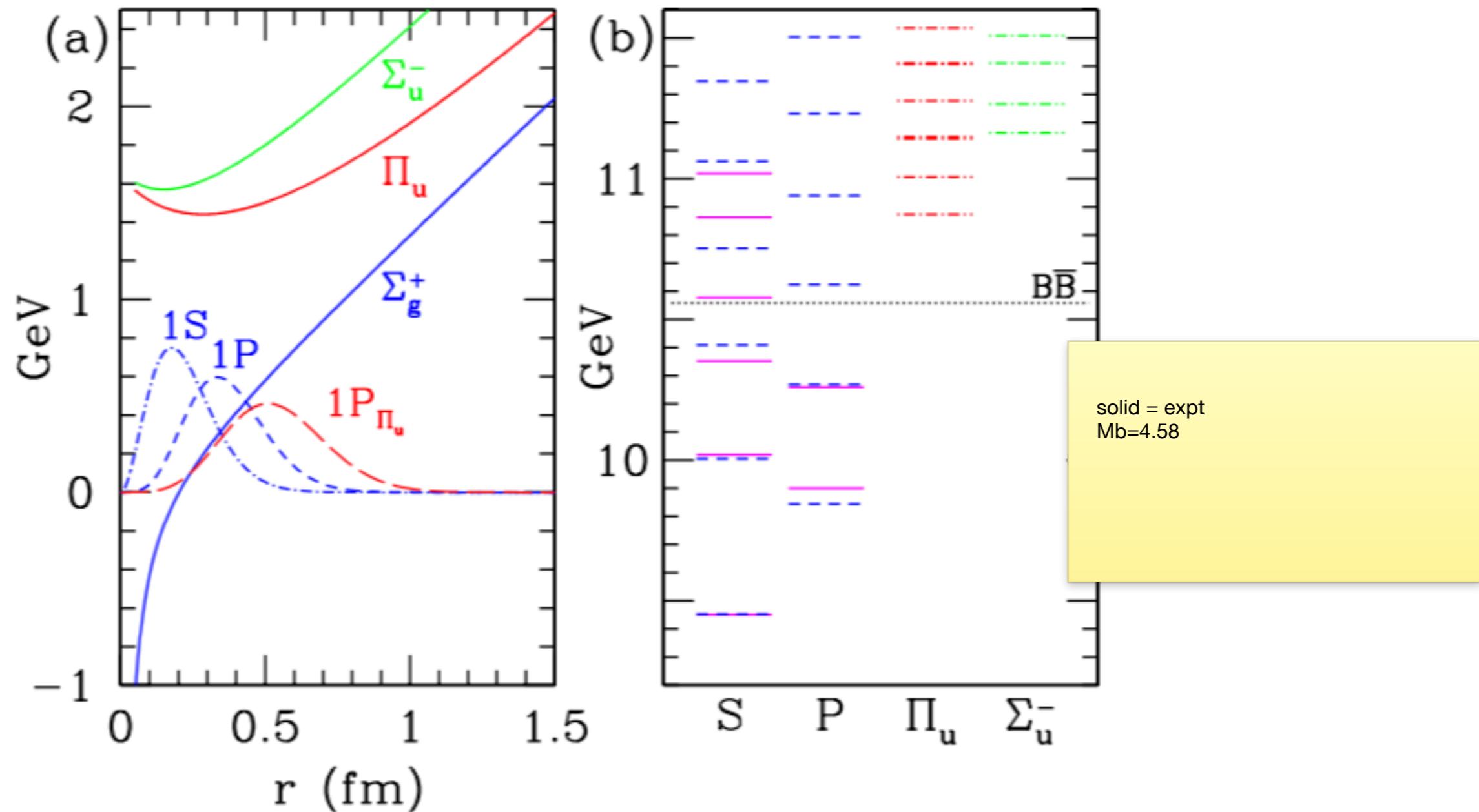
Lattice Hybrid Computations



$+/- \Rightarrow$ reflection in plane containing the QQ axis

u/g = reflection in plane bisecting the QQ (+ C)

Lattice Hybrid Computations



Lattice Hybrid Computations

The ‘gluelump’ spectrum (static octet source + glue)

J^{PC}	mass (GeV)
1^{+-}	0.87(15)
1^{--}	1.25(16)
2^{--}	1.45(17)
2^{+-}	1.86(19)
3^{+-}	1.86(18)
0^{++}	1.98(18)
4^{--}	2.13(18)
1^{-+}	2.15(20)

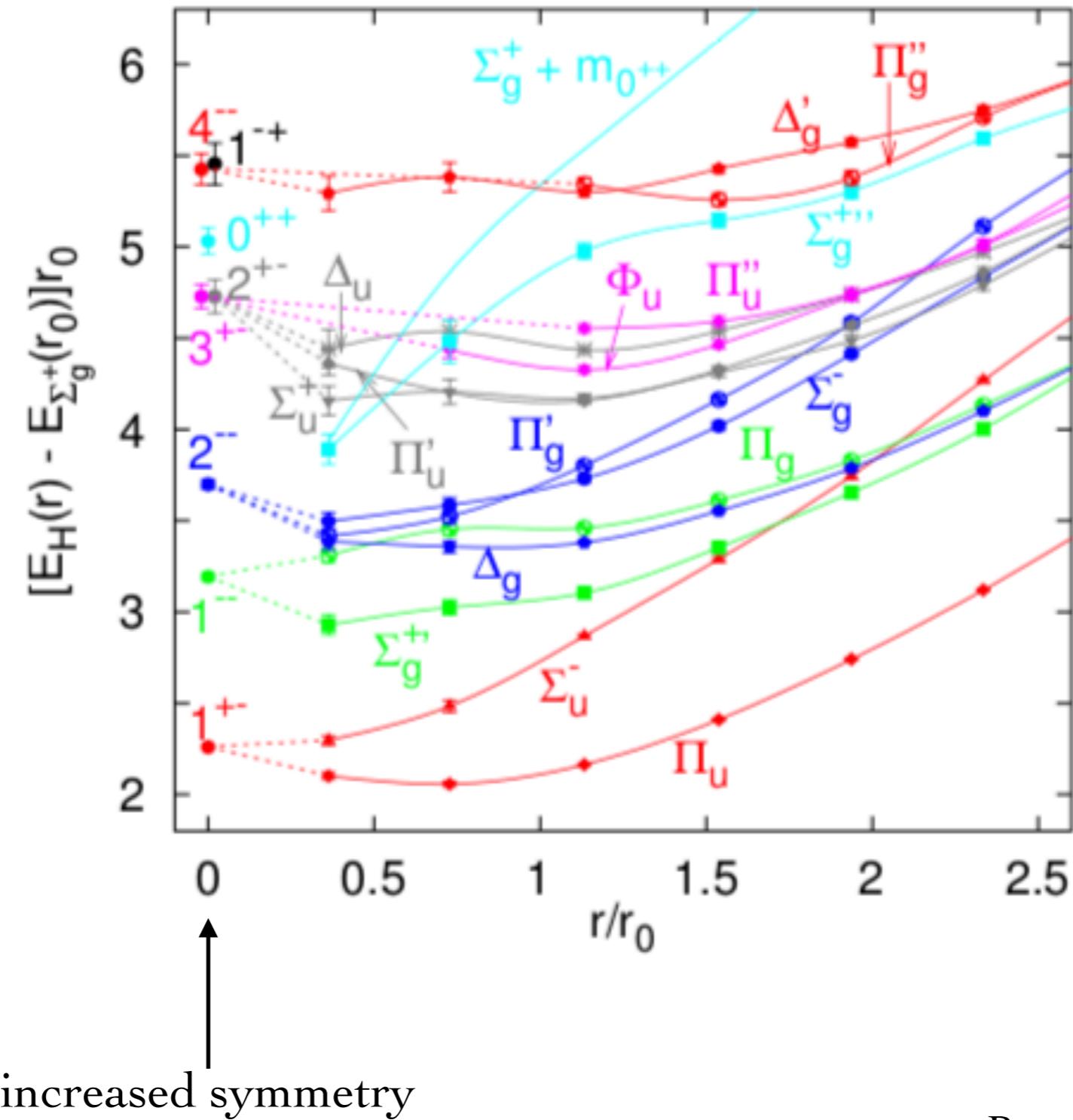
[only mass differences are well-defined]

M. Foster and C. Michael [UKQCD Collaboration], Phys. Rev. D 59, 094509 (1999).

G. S. Bali and A. Pineda, Phys. Rev. D 69, 094001 (2004)

K. Marsh and R. Lewis, Phys. Rev. D 89, 014502 (2014)

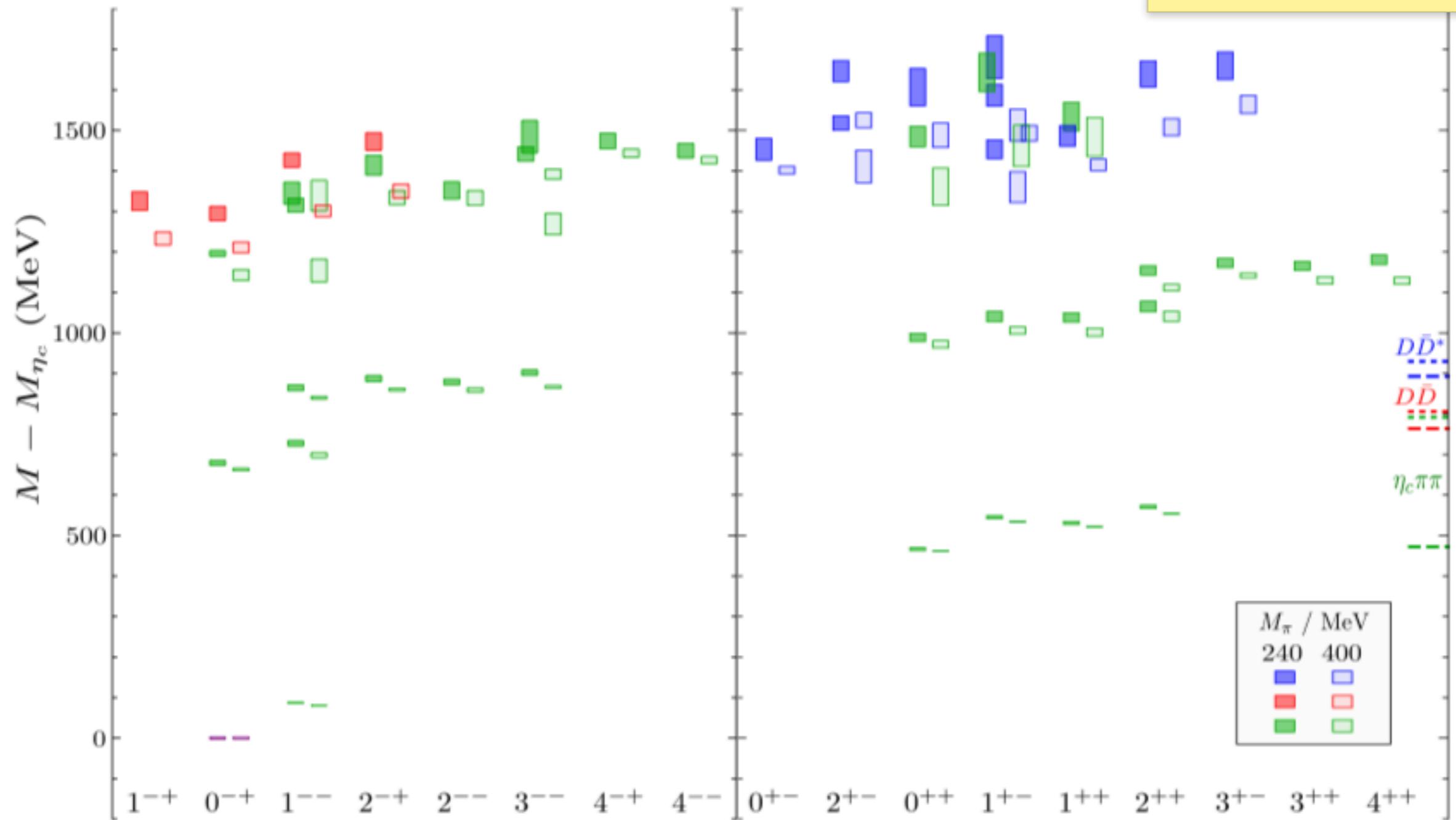
Lattice Hybrid Computations



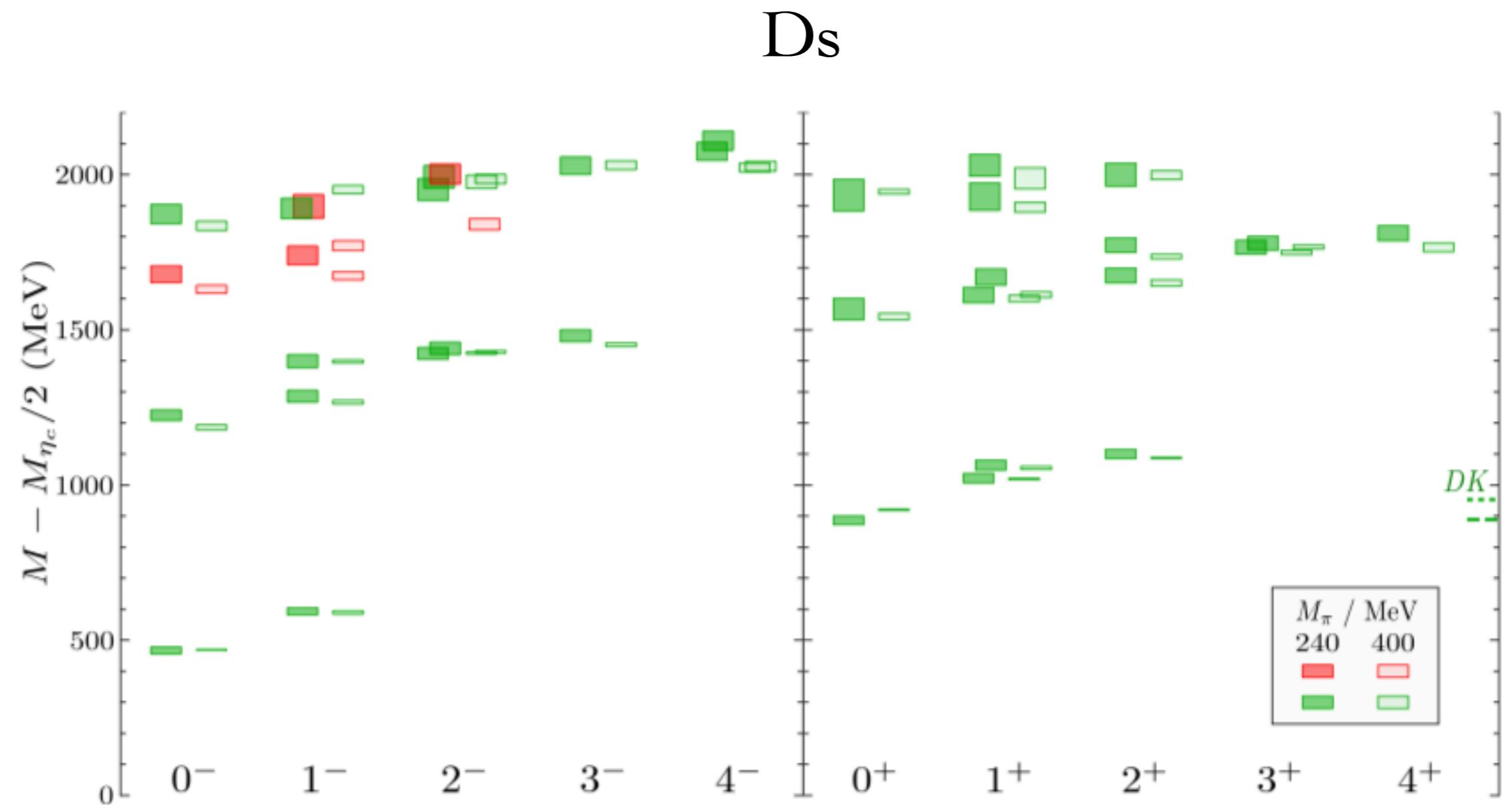
Lattice Hybrid Computations

mspi(400) = 3063
mspi(240)=3070
mspi(expt) = 3097

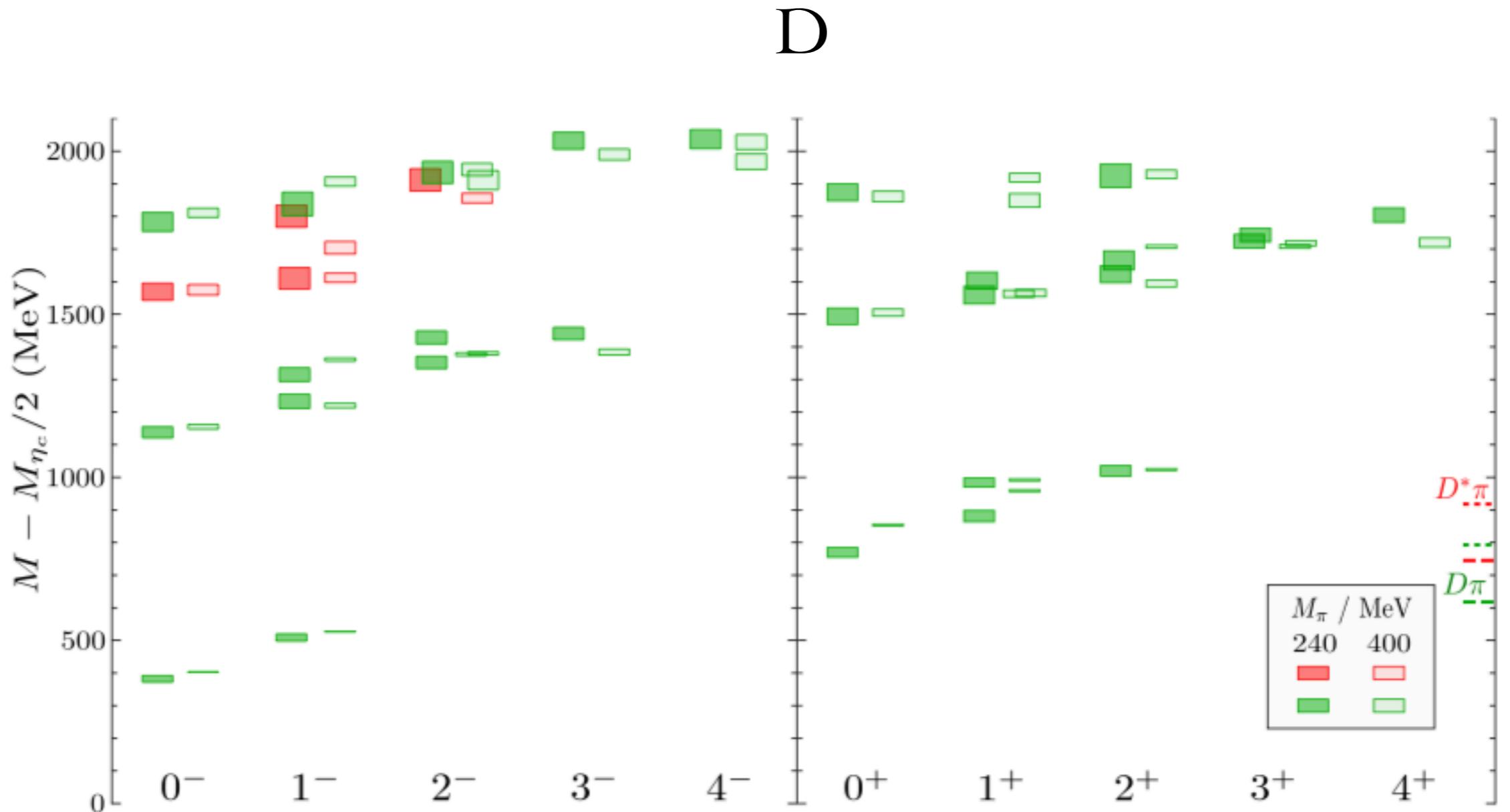
CC



Lattice Hybrid Computations



Lattice Hybrid Computations



Effective Field Theory

Obtain Schrödinger-type equations for heavy quark hybrids with pNRQCD.

$$\mathcal{L} = \text{tr} \left(H^{i\dagger} (\delta_{ij} i\partial_0 - h_{Hij}) H_j \right)$$

$$h_{Hij} = \left(-\frac{\nabla^2}{m_Q} + V_{\Sigma_u^-}(r) \right) \delta_{ij} + (\delta_{ij} - \hat{r}_i \hat{r}_j) \left[V_{\Pi_u}(r) - V_{\Sigma_u^-}(r) \right]$$

$$\left[-\frac{1}{mr^2} \partial_r r^2 \partial_r + \frac{1}{mr^2} \begin{pmatrix} l(l+1) + 2 & 2\sqrt{l(l+1)} \\ 2\sqrt{l(l+1)} & l(l+1) \end{pmatrix} + \begin{pmatrix} E_\Sigma^{(0)} & 0 \\ 0 & E_\Pi^{(0)} \end{pmatrix} \right] \begin{pmatrix} \psi_\Sigma^{(N)} \\ \psi_{-\Pi}^{(N)} \end{pmatrix} = \mathcal{E}_N \begin{pmatrix} \psi_\Sigma^{(N)} \\ \psi_{-\Pi}^{(N)} \end{pmatrix}$$

$$\left[-\frac{1}{mr^2} \partial_r r^2 \partial_r + \frac{l(l+1)}{mr^2} + E_\Pi^{(0)} \right] \psi_{+\Pi}^{(N)} = \mathcal{E}_N \psi_{+\Pi}^{(N)}$$

$r = r_{QQ}$, gluons are integrated out

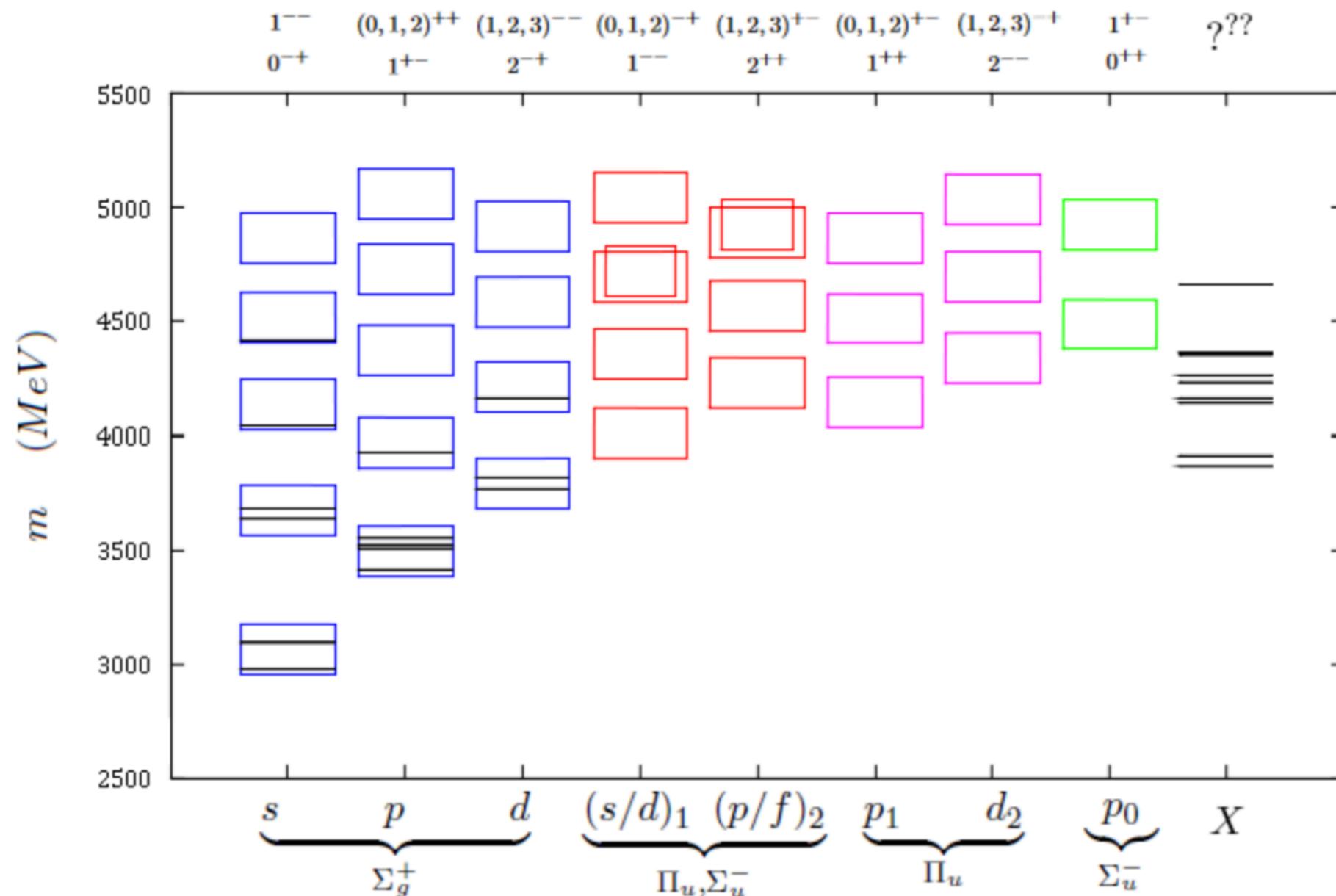
curious angular mom due to
projectons of nabla along or perp
 r_{QQ} . Called lambda-doubling in old
molecule literature

M. Berwein, N. Brambilla, J. Castella, A. Vairo, arXiv:1510.04299

R. Oncala and J. Soto, arXiv: 1702.03900

N. Brambilla, W.-K. Lai, J. Segovia, J. Castella, A. Vairo, arXiv:1805.07713

Effective Field Theory



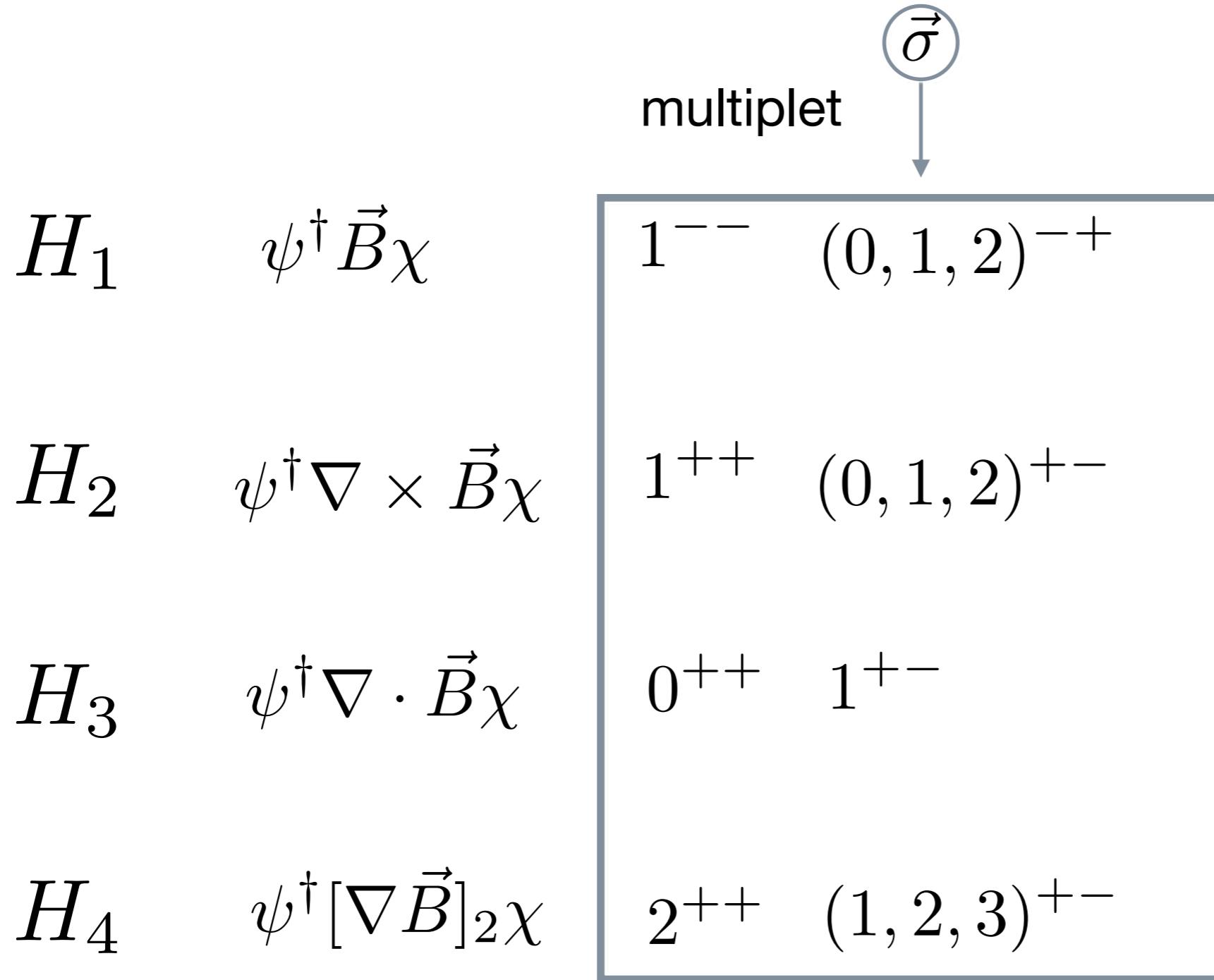
Born-Oppenheimer Approximation

		$\vec{\sigma}$		
		multiplet		
H_1	$\psi^\dagger \vec{B} \chi$	1^{--}	$(0, 1, 2)^{-+}$	
H_2	$\psi^\dagger \nabla \times \vec{B} \chi$	1^{++}	$(0, 1, 2)^{+-}$	
H_3	$\psi^\dagger \nabla \cdot \vec{B} \chi$	0^{++}	1^{+-}	
H_4	$\psi^\dagger [\nabla \vec{B}]_2 \chi$	2^{++}	$(1, 2, 3)^{+-}$	

Born-Oppenheimer Approximation

$\vec{\sigma}$			
multiplet			
H_1	$\psi^\dagger \vec{B} \chi$	1^{--}	$(0, 1, 2)^{-+}$
H_2	$\psi^\dagger \nabla \times \vec{B} \chi$	1^{++}	$(0, 1, 2)^{+-}$
H_3	$\psi^\dagger \nabla \cdot \vec{B} \chi$	0^{++}	1^{+-}
H_4	$\psi^\dagger [\nabla \vec{B}]_2 \chi$	2^{++}	$(1, 2, 3)^{+-}$
flux tube model multiplet			

Born-Oppenheimer Approximation



bag models with TE modes

Born-Oppenheimer Approximation

$$H_1 \quad \psi^\dagger \vec{B} \chi \quad 1^{--} \quad (0, 1, 2)^{-+}$$

multiplet

$\vec{\sigma}$

$$H_2 \quad \psi^\dagger \nabla \times \vec{B} \chi \quad 1^{++} \quad (0, \boxed{1}, 2)^{+-}$$
$$H_3 \quad \psi^\dagger \nabla \cdot \vec{B} \chi \quad 0^{++} \quad 1^{+-}$$
$$H_4 \quad \psi^\dagger [\nabla \vec{B}]_2 \chi \quad 2^{++} \quad (1, 2, 3)^{+-}$$

vector constituent gluon

Born-Oppenheimer Approximation

		multiplet
H_1	$\psi^\dagger \vec{B} \chi$	
H_2	$\psi^\dagger \nabla \times \vec{B} \chi$	
H_3	$\psi^\dagger \nabla \cdot \vec{B} \chi$	
H_4	$\psi^\dagger [\nabla \vec{B}]_2 \chi$	

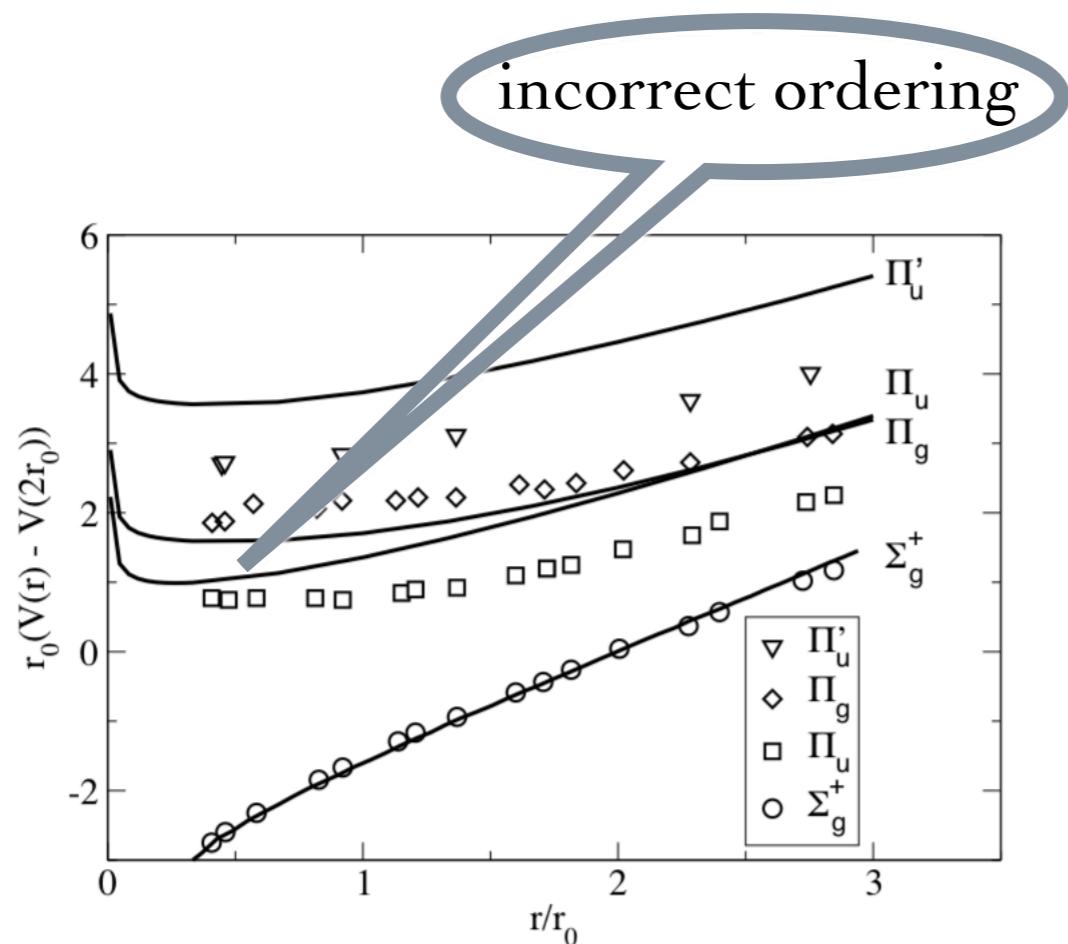
constituent gluon with $(J^{PC})_g = 1^{+-}$

Back to Modelling

- ➊ follow the BO or EFT approach and use the adiabatic surfaces
- ➋ introduce explicit gluonic degrees of freedom
 - permits mixing, decay calculations
 - should reproduce
 - gluelump spectrum
 - adiabatic surfaces
 - BO multiplets
 - lattice hybrid spectrum

Back to Modelling

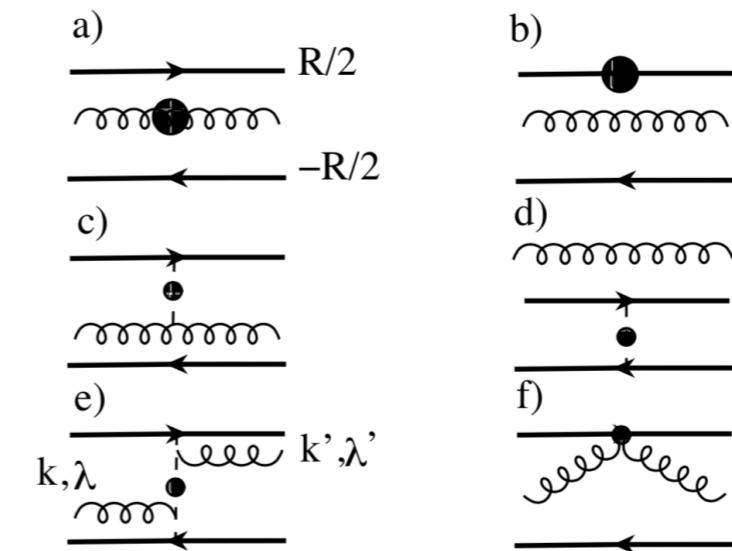
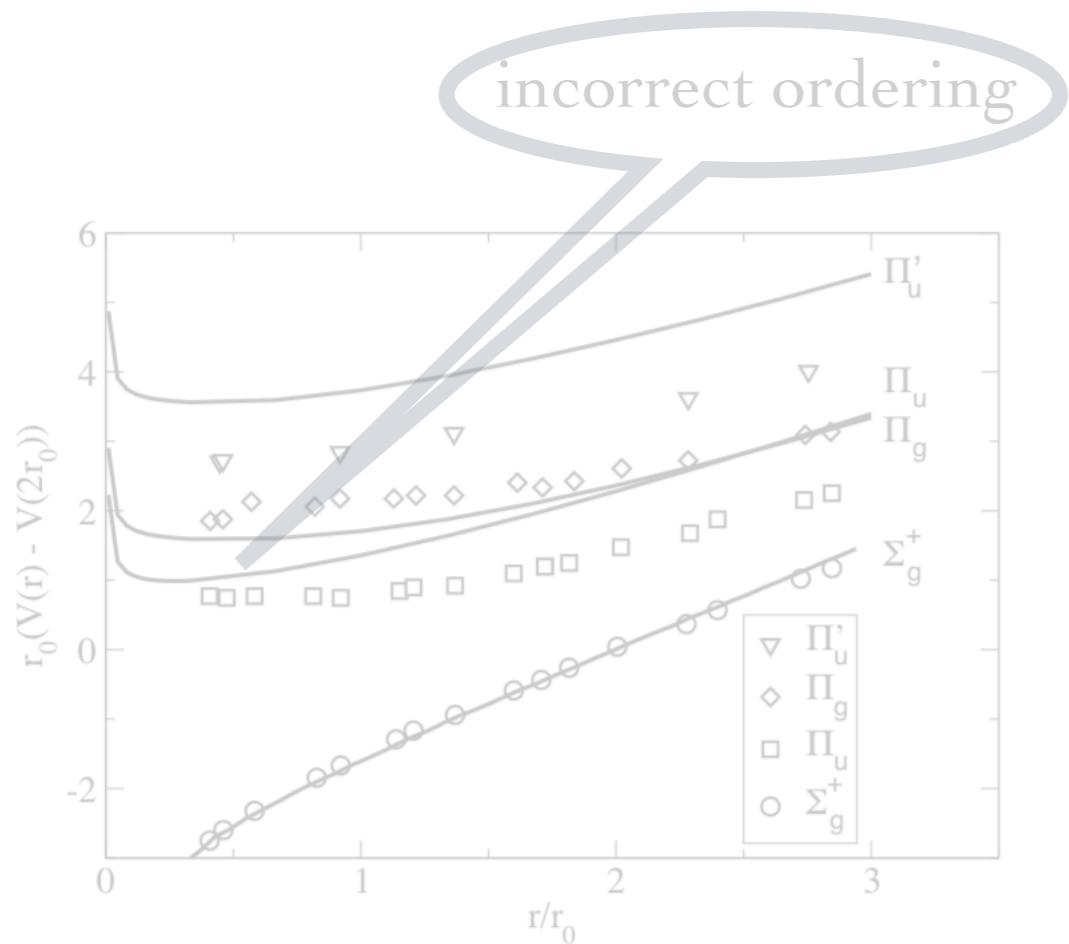
Attempt a model with Coulomb gauge QCD as a guide.



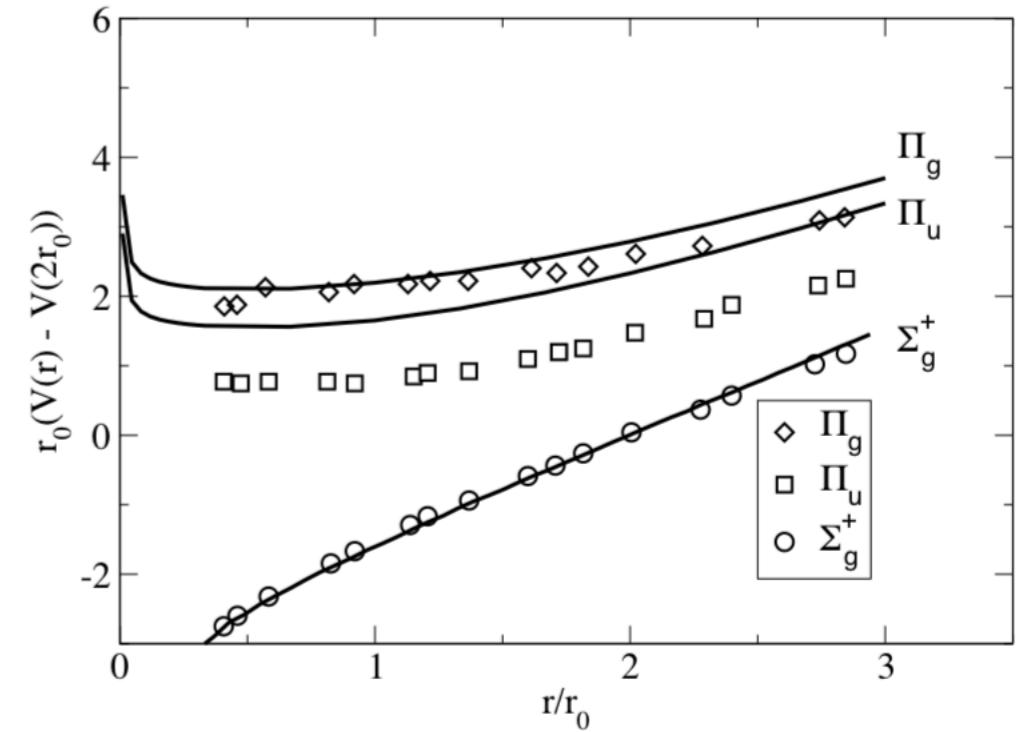
Swanson and Szczepaniak, Phys. Rev. D 59, 014035 (1998).

Back to Modelling

Attempt a model with Coulomb gauge



three-body interactions



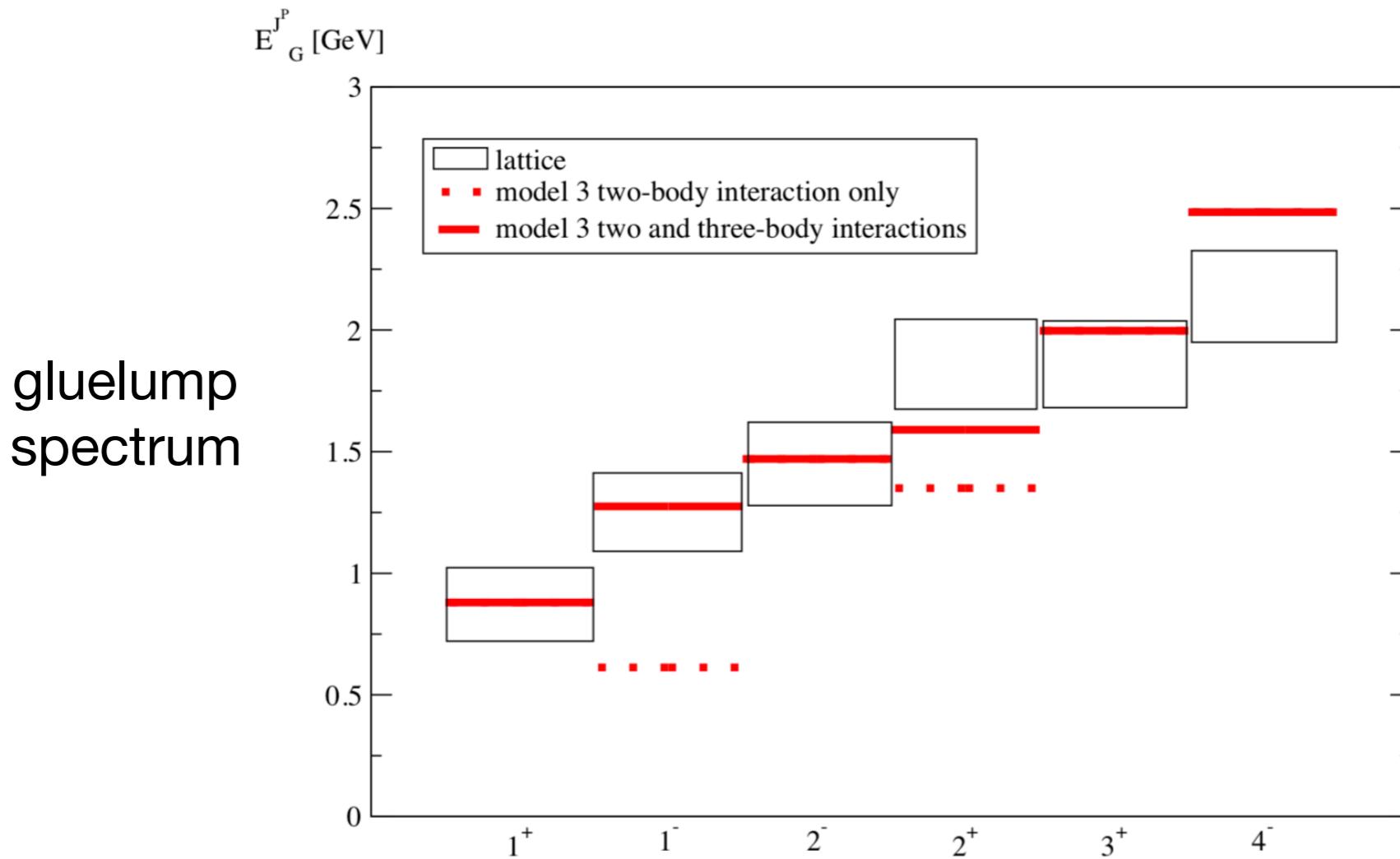
Swanson and Szczepaniak, Phys. Rev. D 59, 014035 (1998).

A. Szczepaniak and P. Krupinski , Phys. Rev. D 73, 116002 (2006).

Back to Modelling

two-body $Jp=1-$ is S-wave $Jp=1+$ is p-wave

three-body interaction is 0 for $1+$ and repulsive for $1-$... saves the day



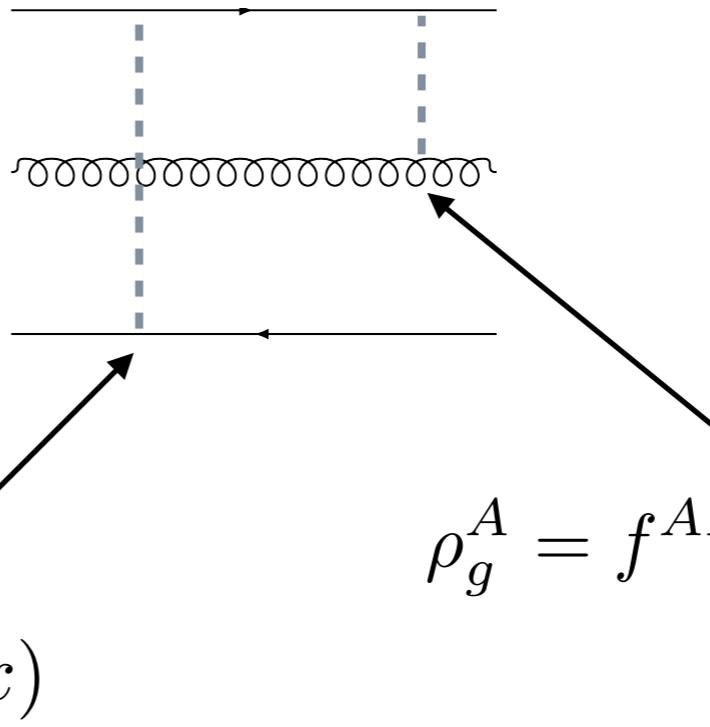
Back to Modelling

Construct hybrids with transverse constituent TE gluons

$$\begin{aligned} |JM[LS\ell j_g\xi]\rangle &= \frac{1}{2}T_{ij}^A \sum \int \frac{d^3k}{(2\pi)^3} \frac{d^3q}{(2\pi)^3} \phi_{j_g}(\vec{k}) \phi_\ell(\vec{q}) \left\langle \frac{1}{2}m \frac{1}{2}\bar{m} |SM_S\rangle \langle \ell m_\ell j_g m_g |LM_L\right\rangle \cdot \\ &\cdot \langle SM_S LM_L | JM \rangle \sqrt{\frac{2j_g + 1}{4\pi}} D_{m_g \lambda'}^{j_g*}(\hat{k}) \chi_{\lambda' \lambda}^\xi \cdot b_{\vec{q}-\vec{k}/2 mi}^\dagger d_{-\vec{q}-\vec{k}/2 \bar{m} i}^\dagger a_{\vec{q} \lambda A}^\dagger |0\rangle \end{aligned}$$

Back to Modelling

Model spectrum



$$V_{1\!\! 1} = -\frac{4}{3} \left(\frac{\alpha}{R} - \frac{3}{4} R \right)$$

$$V_8 = +\frac{1}{6} \left(\frac{\alpha}{R} - \frac{3}{4} R \right)$$

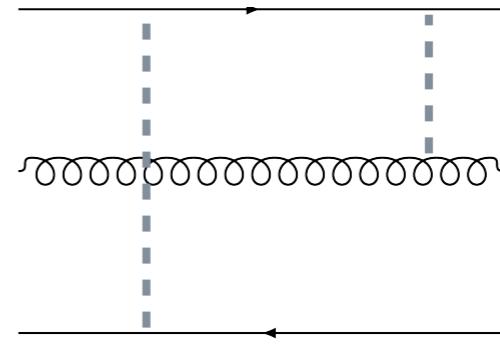
$$V_{qg} = -\frac{3}{2} \left(\frac{\alpha}{R} - \frac{3}{4} R \right)$$

[no need for three-body if focussing on lowest multiplets]

$$\left[\quad \mathcal{J}^{-1/2} \rho_q^A \mathcal{J}^{1/2} = \rho_q^A \quad \quad \quad \mathcal{J}^{-1/2} \rho_g^C \mathcal{J}^{1/2} = \rho_{\text{eff}}^C(\vec{A}) \quad \right]$$

Back to Modelling

adiabatic surfaces

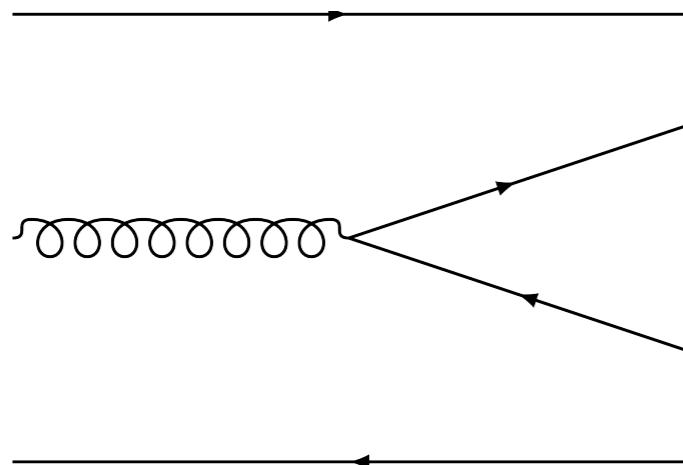


$$V(R) \sim V_{Q\bar{Q}}(R) + \int d^3r \exp(-\beta^2 r^2) \left(b|r - R/2| + b|r + R/2| + \frac{\alpha}{|r - R/2|} + \frac{\alpha}{|r + R/2|} \right)$$

$$V(R) \sim \frac{1}{6} \frac{\alpha}{R} - \frac{1}{8} bR + \frac{9}{8} bR + \text{blob}(R)$$

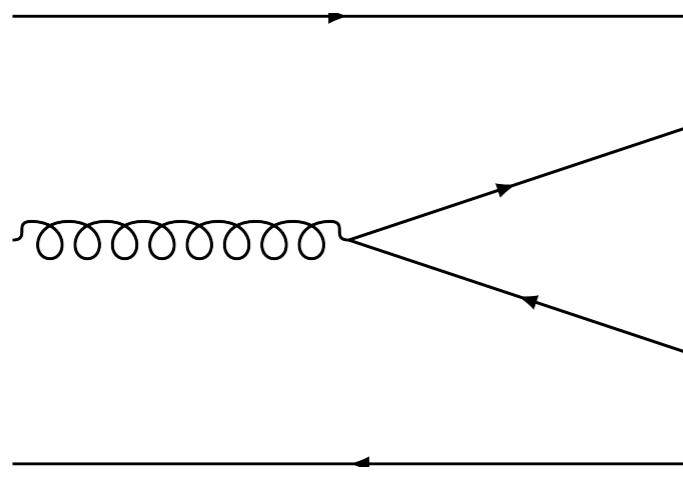
[agrees reasonably well with Π_u surface]

Modelling Decays



M. Tanimoto, Phys. Lett. B 116, 198 (1982)
F. Iddir, S. Safir, O. Pene, Phys. Lett. B 433, 125 (1998)

Modelling Decays



Q: what should the coupling be?

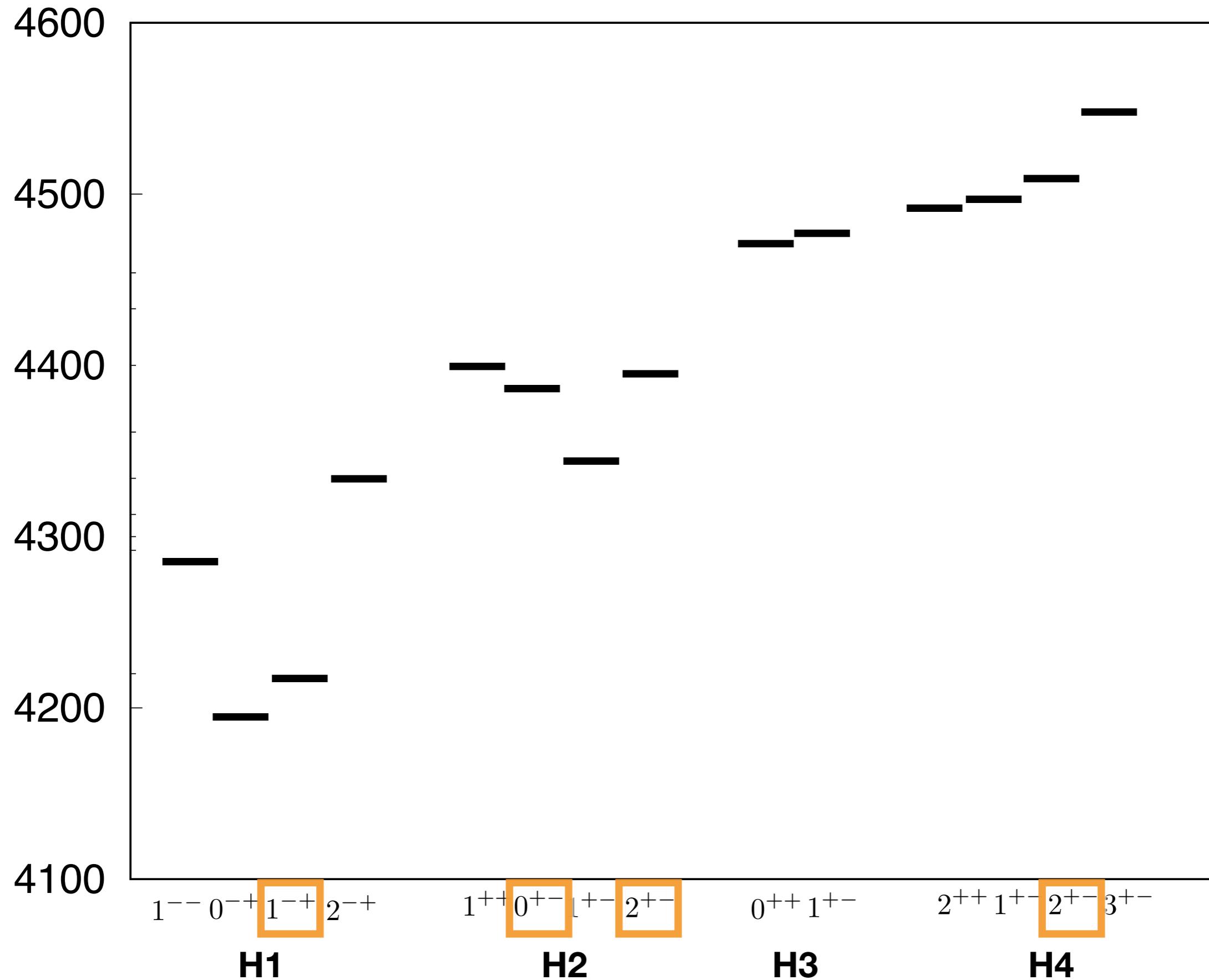
$$\alpha_S(c\bar{c}) \approx 0.5$$

$$\alpha_S(\text{string}) \approx \frac{\pi}{12}$$

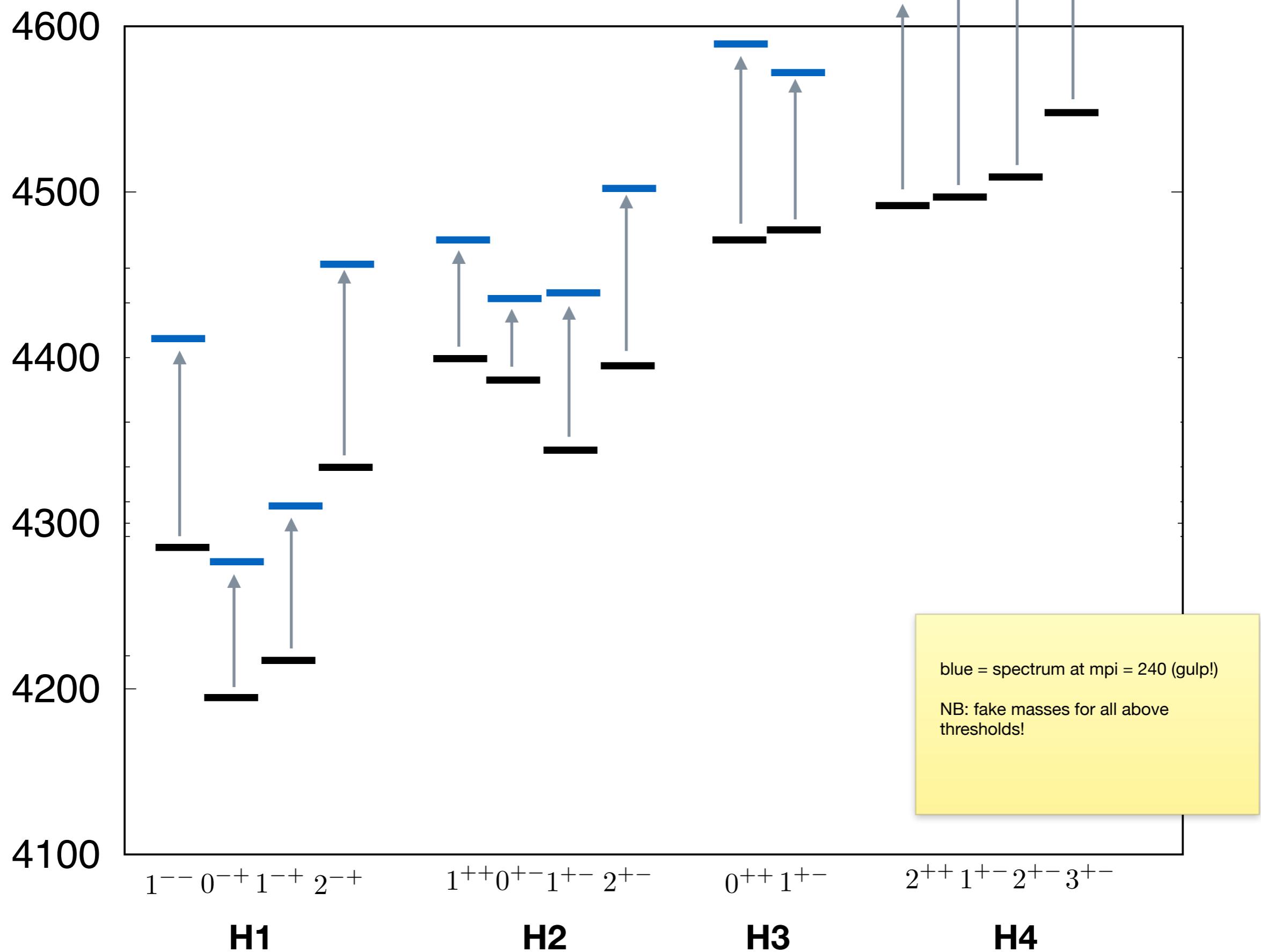
$$\alpha_S(\text{eff}) = ?$$

[obtain ‘usual’ selection rules]

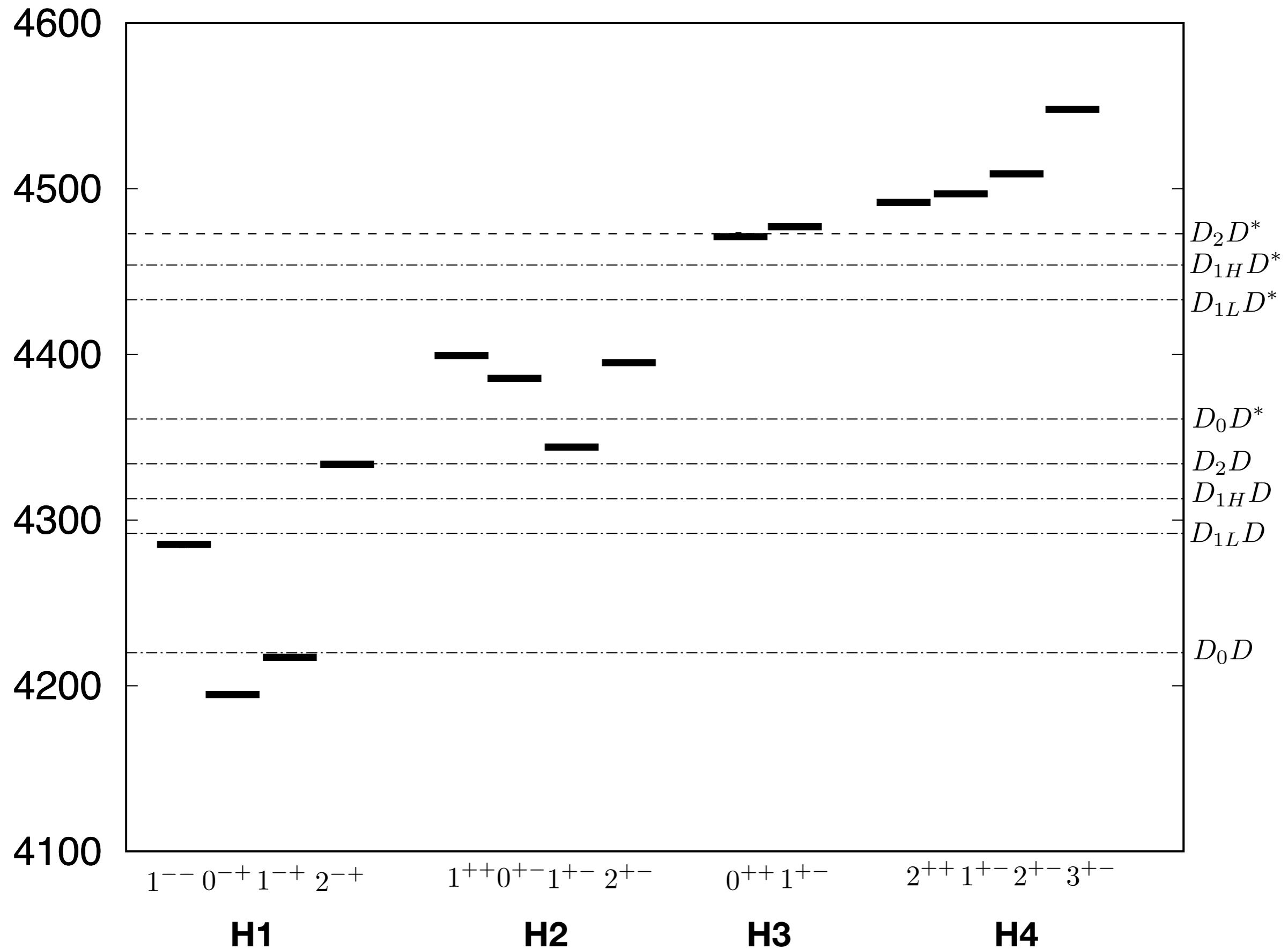
Decay Results



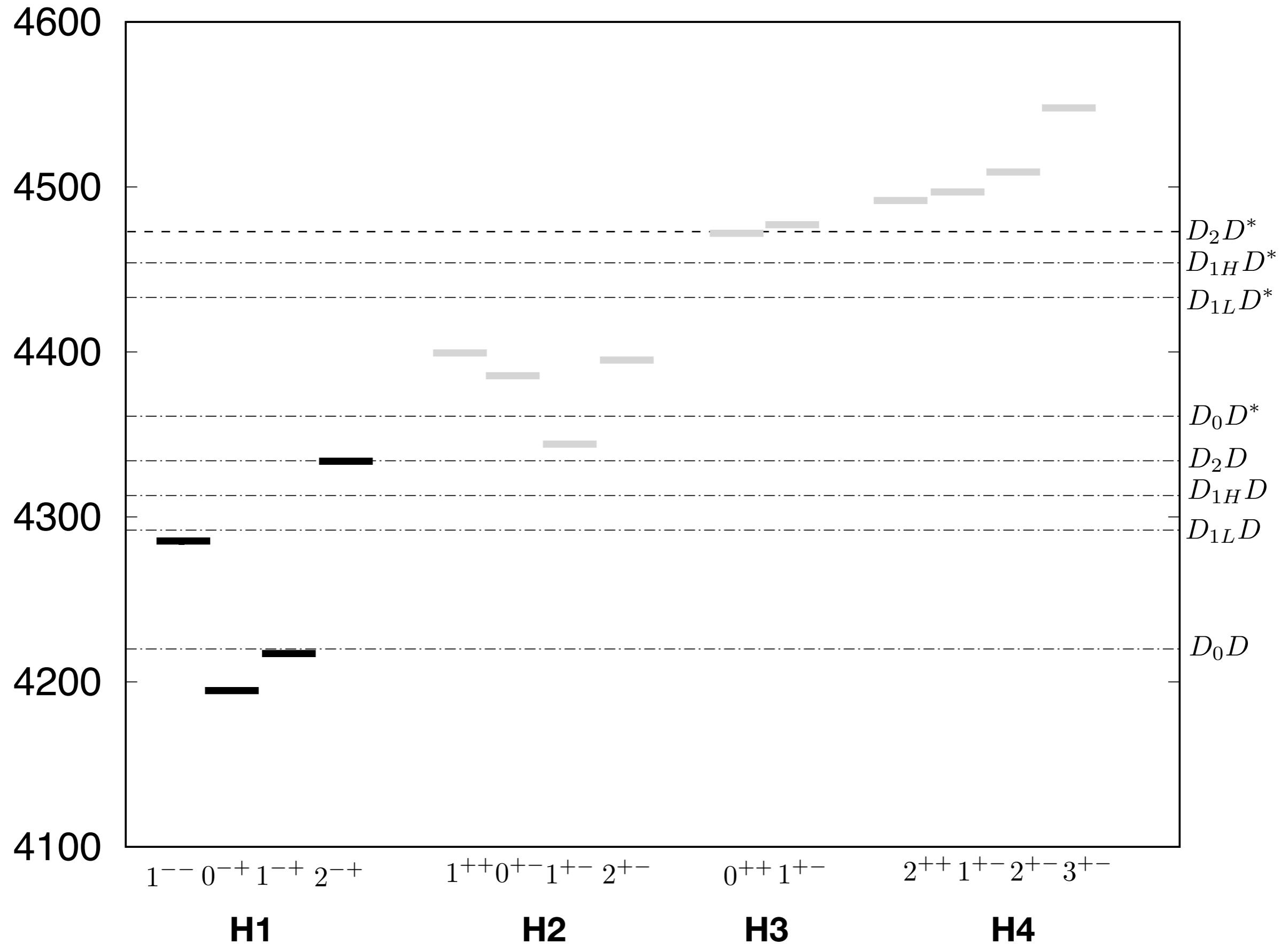
Decay Results



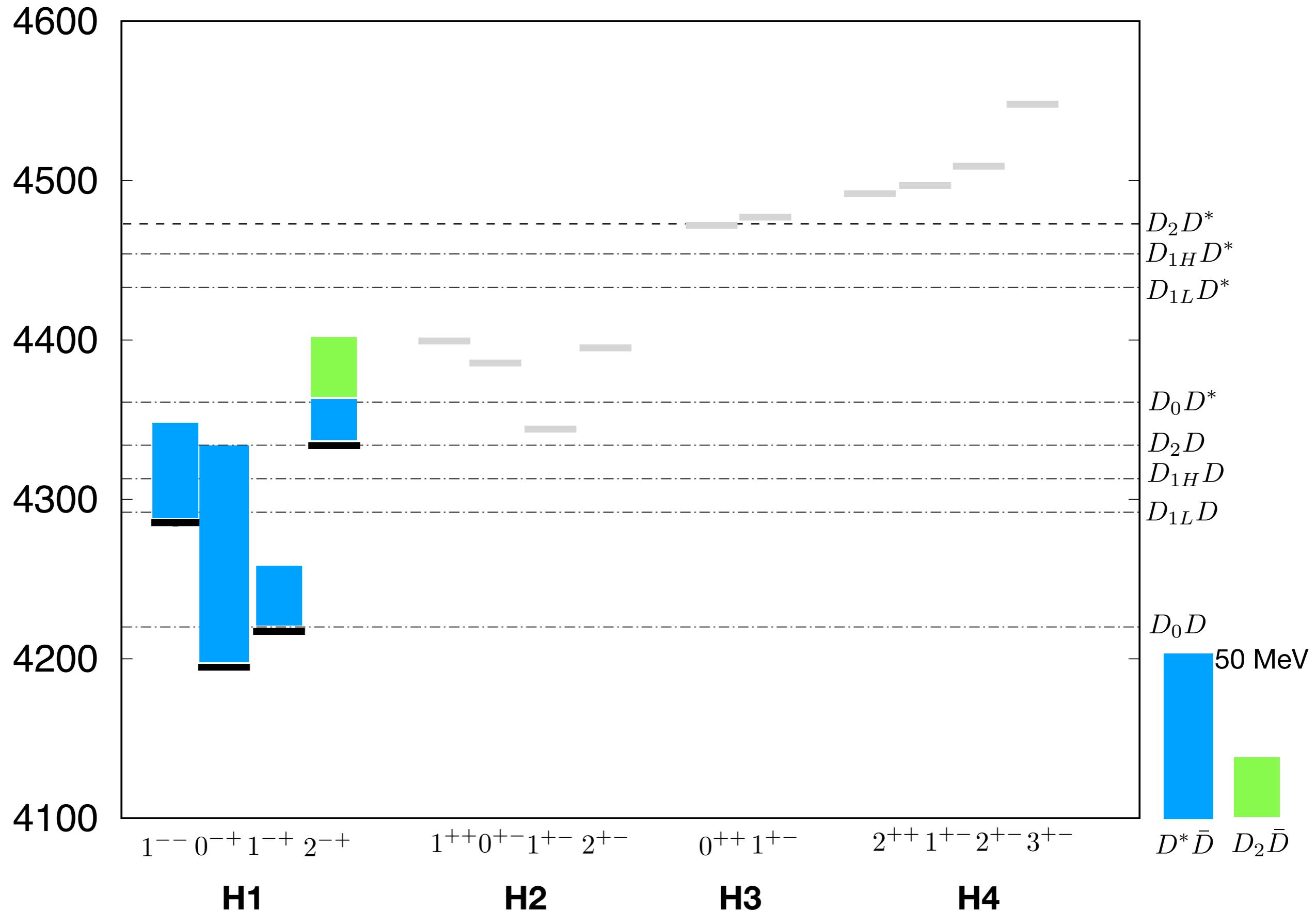
Decay Results



Decay Results



Decay Results



Comparison to Lattice

- $\Gamma(\pi_1 \rightarrow b_1\pi) = 400 \pm 120 \text{ MeV}$ $\Gamma(\pi_1 \rightarrow f_1\pi) = 90 \pm 60 \text{ MeV}.$

π_1 mass is estimated to be $2.2(2)$ GeV. π is around 600 MeV

[near zero relative momentum]

C. McNeile and C. Michael [UKQCD Collaboration], Phys. Rev. D 73, 074506 (2006).

- Burns and Close, use the flux tube model adjust for phase space and estimate

$$\Gamma(\pi_1 \rightarrow b_1\pi) \approx 80 \text{ MeV} \text{ and } \Gamma(\pi_1 \rightarrow f_1\pi) \approx 25 \text{ MeV}.$$

The lattice results also suggest that the light quark creation vertex has spin triplet quantum numbers.

T. Burns and F. Close, arXiv:hep-ph/0604161

- [model gives a large width]

Comparison to Lattice

$$\langle Q\bar{Q}| - cg \frac{\sigma \cdot B}{2M} |Q\bar{Q}g\rangle$$

$$|\langle \Upsilon |Q\bar{Q}g(1^{--})\rangle|^2 \approx 0.4\%,$$

$$|\langle J/\psi |Q\bar{Q}g(1^{--})\rangle|^2 \approx 2.3\%,$$

$$|\langle \eta_b |Q\bar{Q}g(0^{-+})\rangle|^2 \approx 1\%,$$

$$|\langle \eta_c |Q\bar{Q}g(0^{-+})\rangle|^2 \approx 6\%.$$

T. Burch and D. Toussaint [MILC Collaboration], Phy. Rev. D68, 094504 (2003).

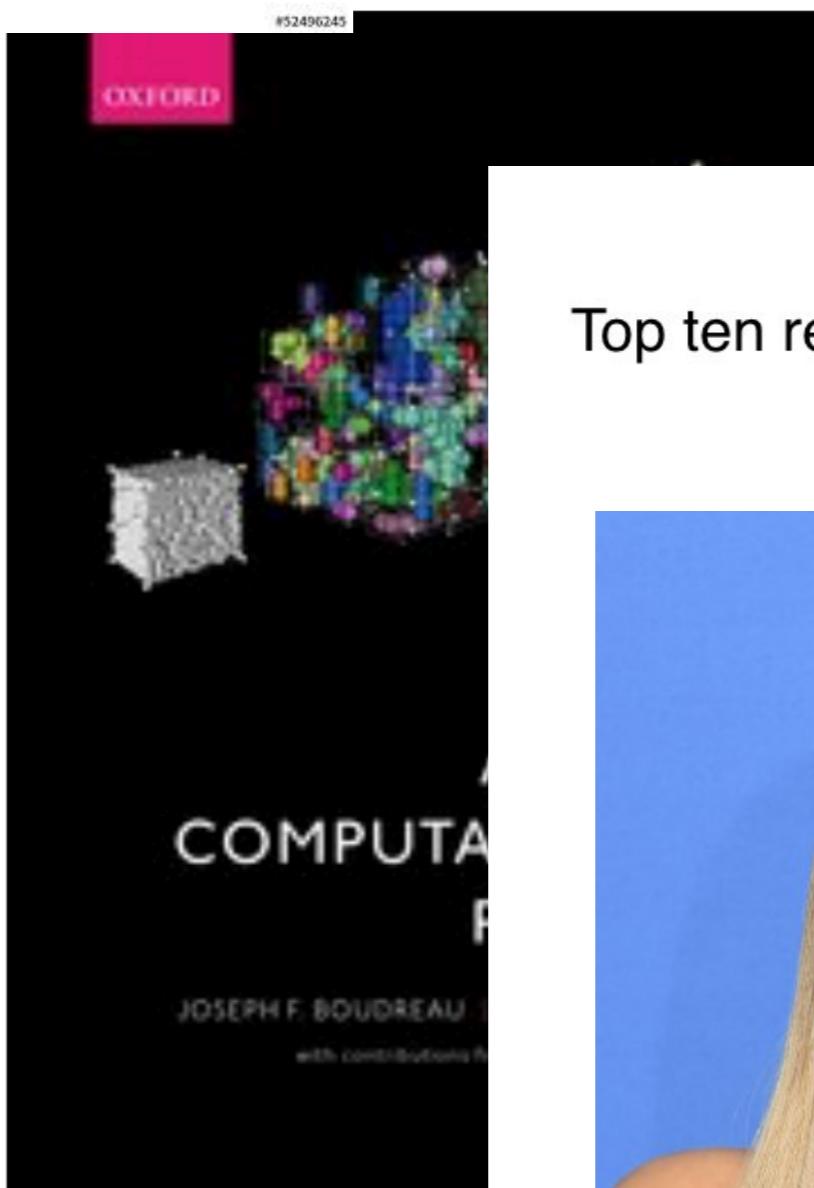
Comparison to Lattice

transition	Γ_{lattice} (keV)	Γ_{expt} (keV)
$\chi_{c0} \rightarrow J/\psi \gamma$	199(6)	131(14)
$\psi' \rightarrow \chi_{c0} \gamma$	26(11)	30(2)
$\psi'' \rightarrow \chi_{c0} \gamma$	265(66)	199(26)
$c\bar{c}g(1^{--}) \rightarrow \chi_{c0} \gamma$	< 20	
<hr/>		
$J/\psi \rightarrow \eta_c \gamma$	2.51(8)	1.85(29)
$\psi' \rightarrow \eta_c \gamma$	0.4(8)	0.95 – 1.37
$\psi'' \rightarrow \eta_c \gamma$	10(11)	
$c\bar{c}g(1^{--}) \rightarrow \eta_c \gamma$	42(18)	
<hr/>		
$c\bar{c}g(1^{-+}) \rightarrow J/\psi \gamma$	115(16)	

Conclusions

- its time to build new dynamical models of hybrids
- refine spectrum (spin splittings!)
- decays characteristics are largely unknown

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