[243] JLAB theory group May, 2020

Hybrids and Pentaquarks

Eric Swanson

Pentaquarks

LHCb Penta-peaks

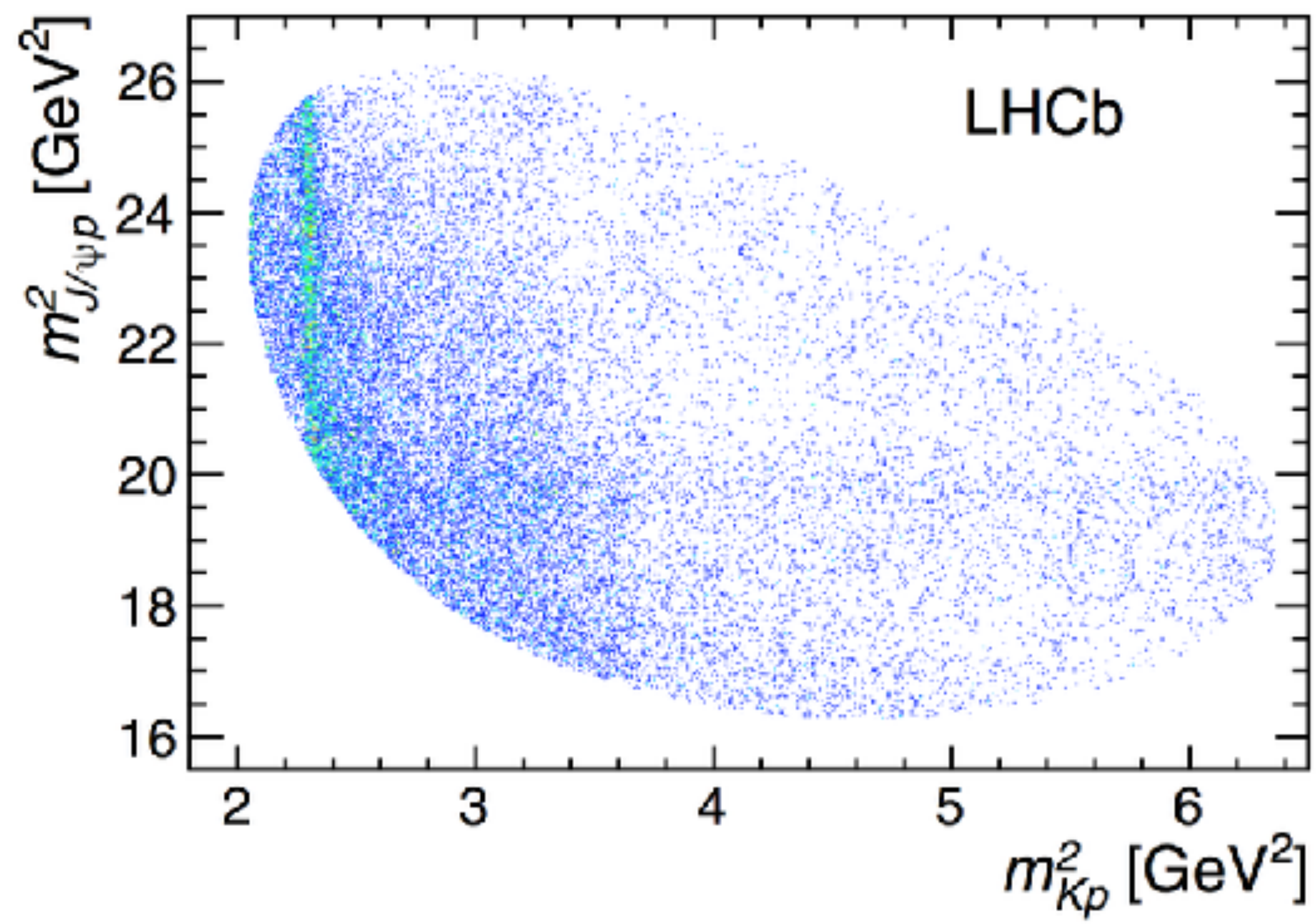
$P_c(4450) \qquad \Gamma = 39 \pm 5 \pm 19 \text{ MeV}$

$P_c(4380) \qquad \Gamma = 205 \pm 18 \pm 86 \text{ MeV}$

$$J^P = \frac{5}{2}^{\mp}$$

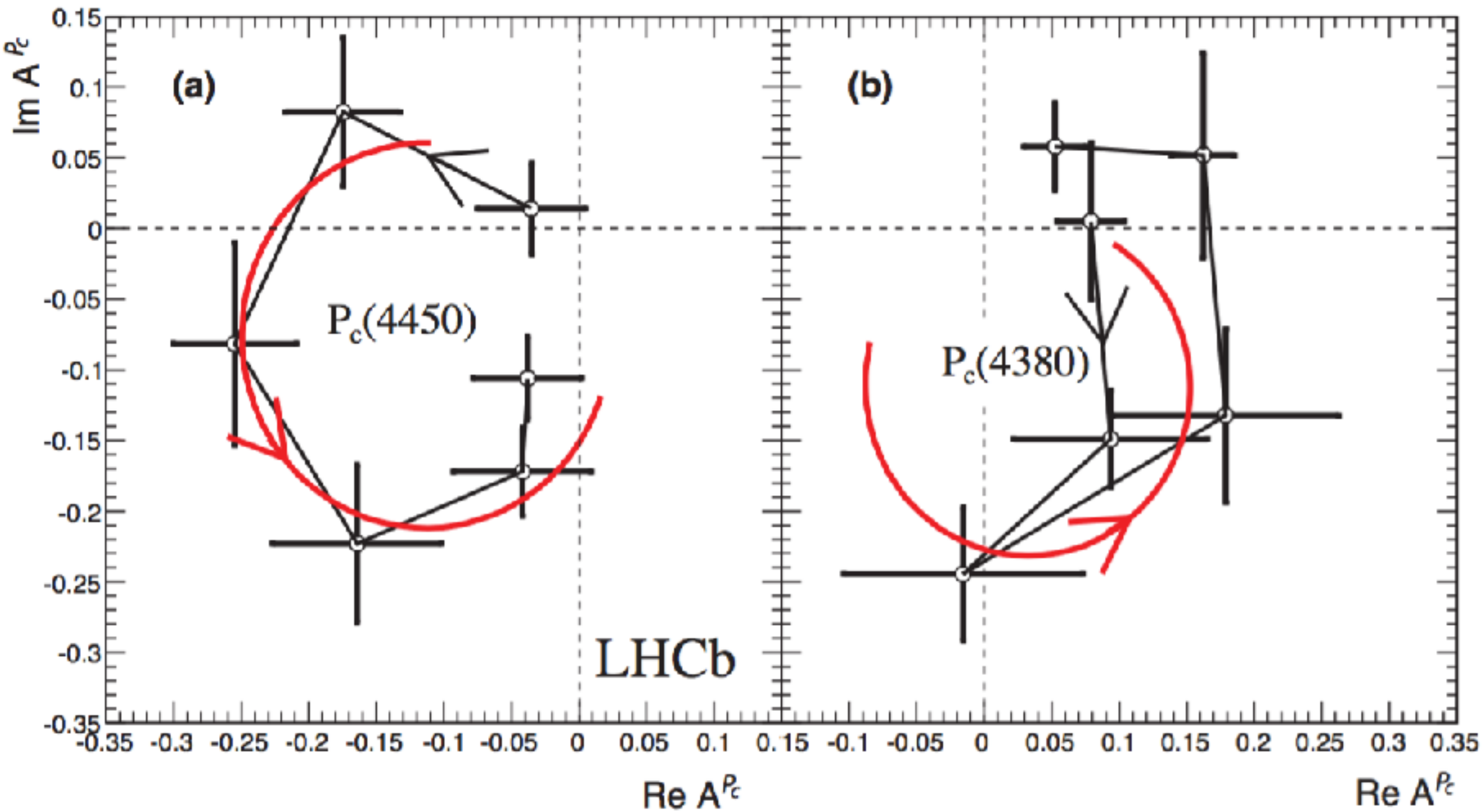
$$J^P = \frac{3}{2}^{\pm}$$

$\Lambda_b^0 \to J/\psi K^- p$

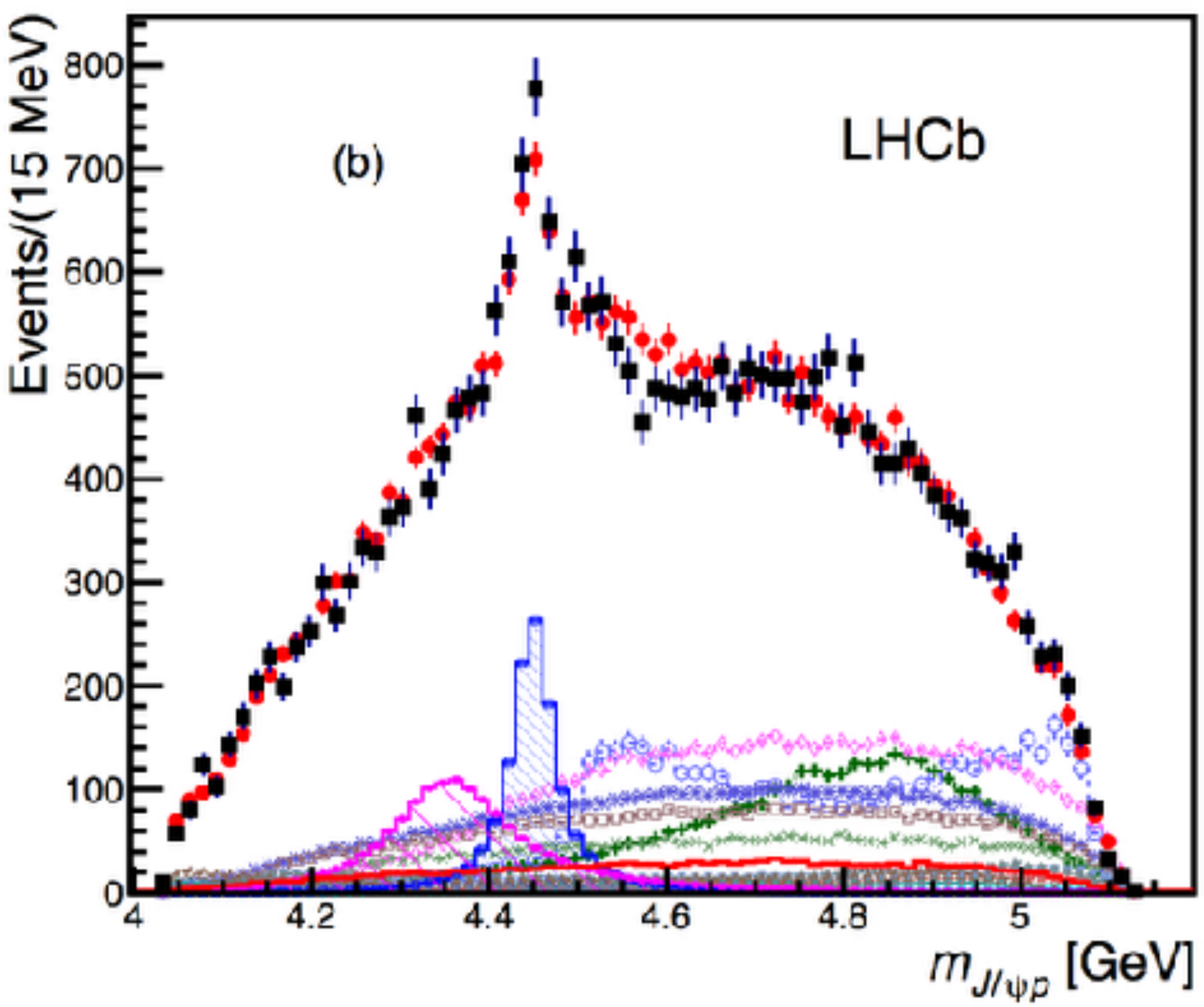


LHCb 1507.03414v2

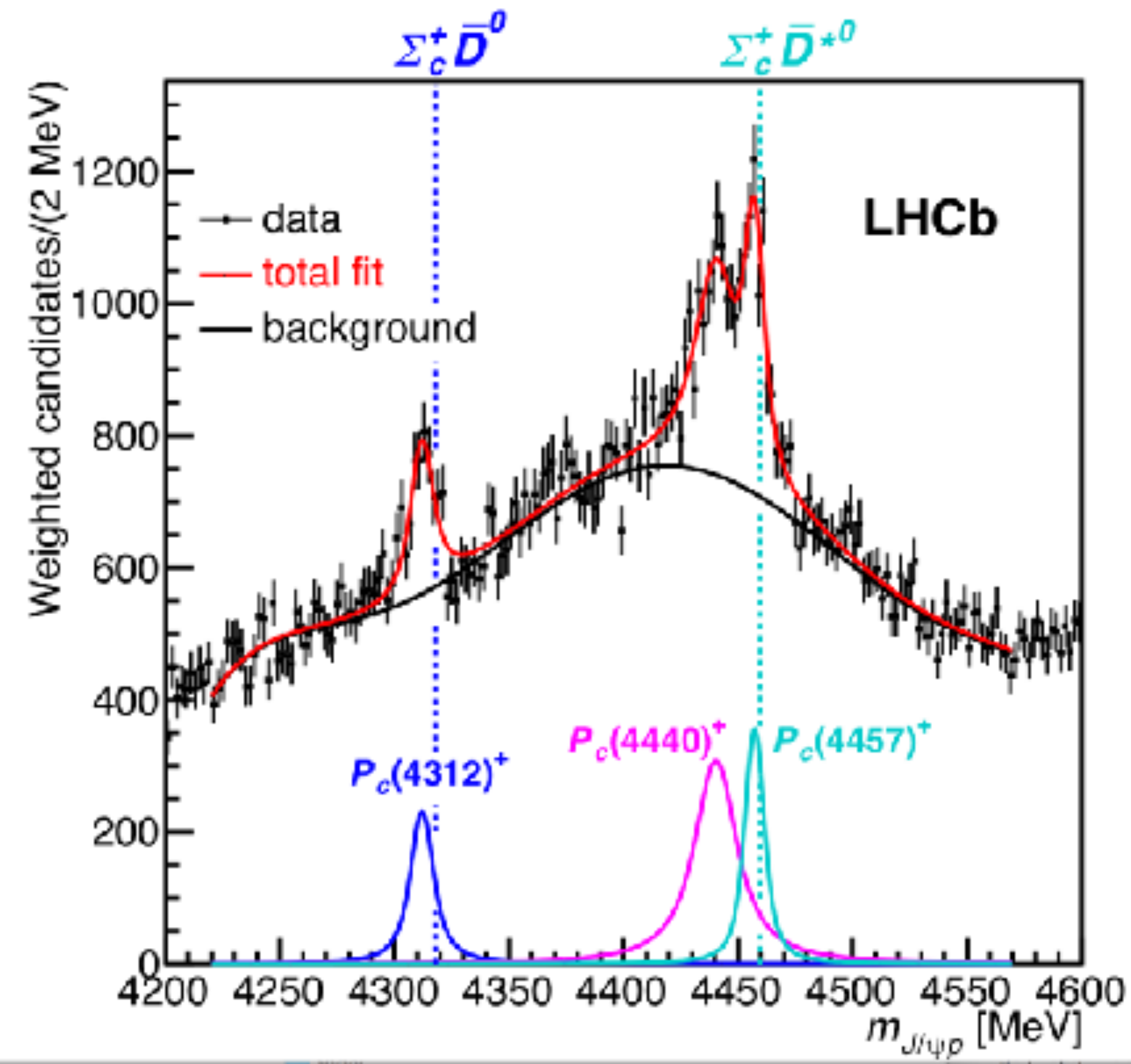
LHCb Penta-peaks



LHCb Penta-peaks



arXiv:1507.03414

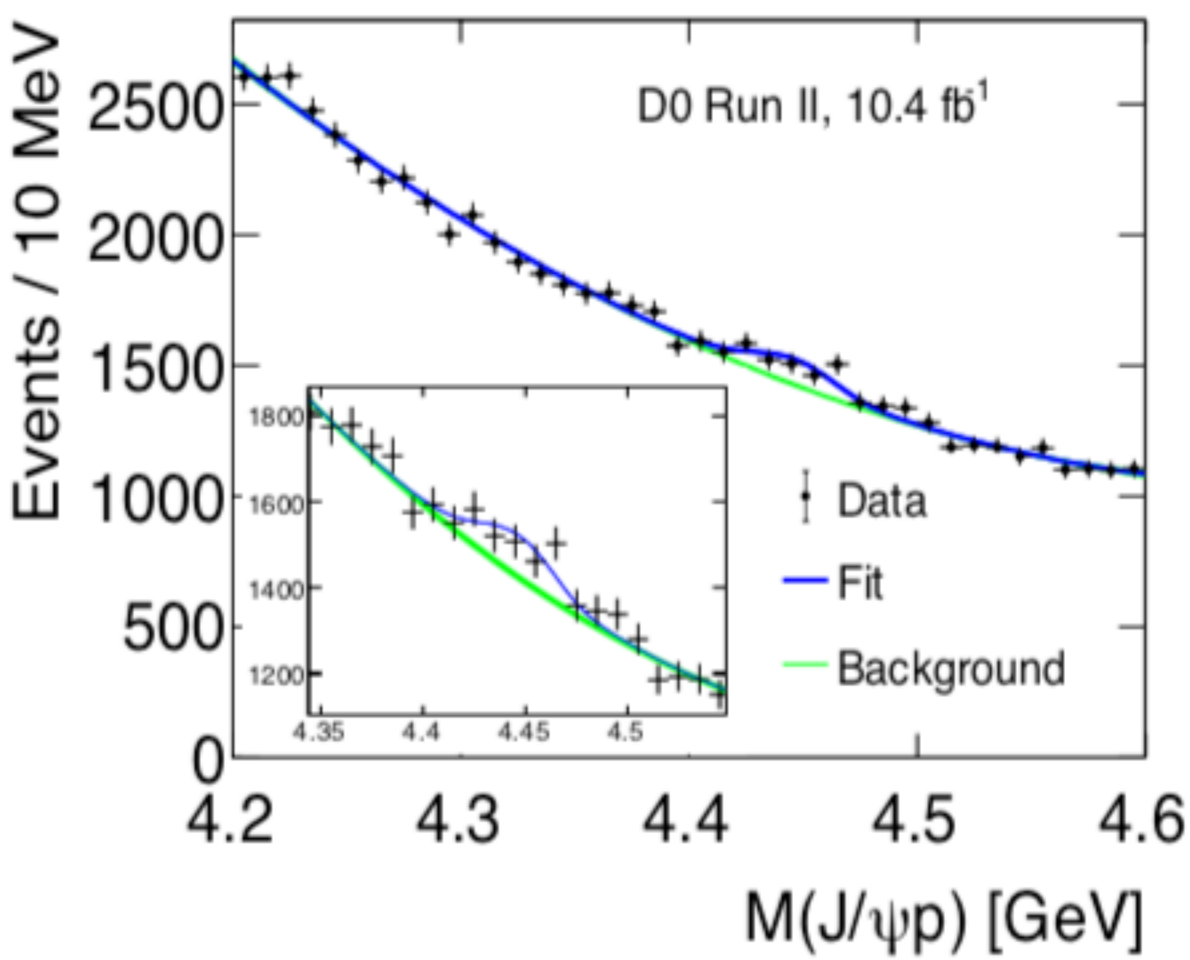


arXiv:1904.03947

LHCb Penta-peaks

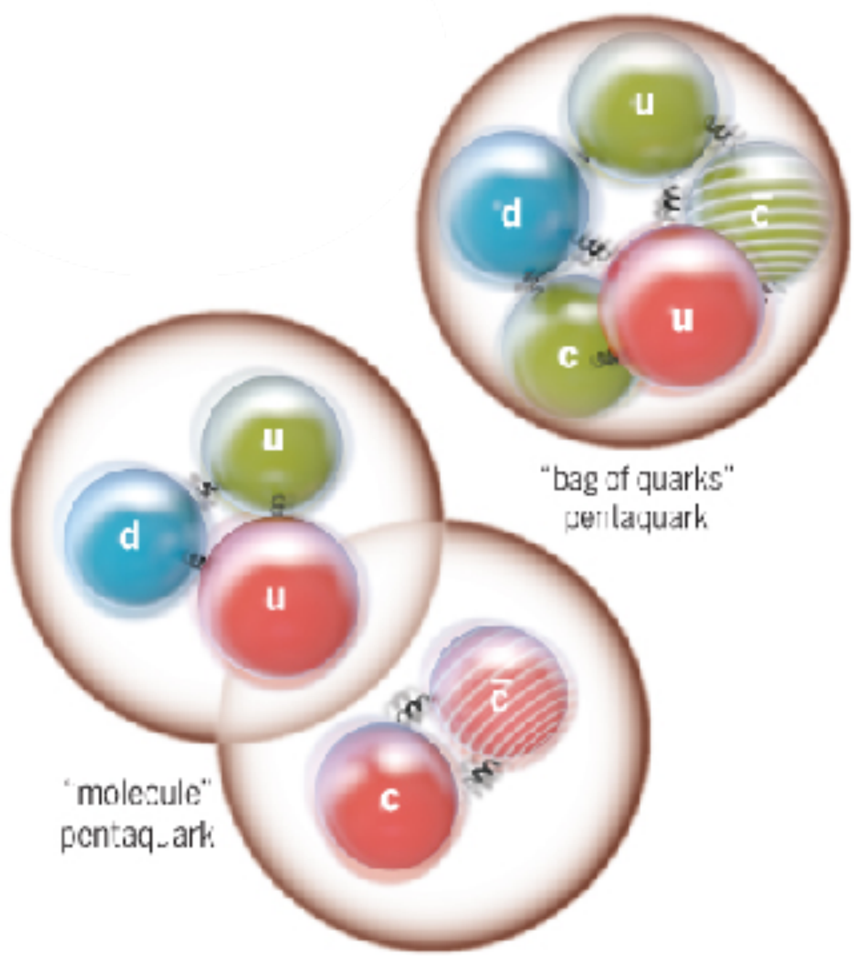
confirm Pc(4400) and Pc(4457) at Fermilab!

V.M. Abazov et al. [D0 Collaboration], arXiv:1910.11767



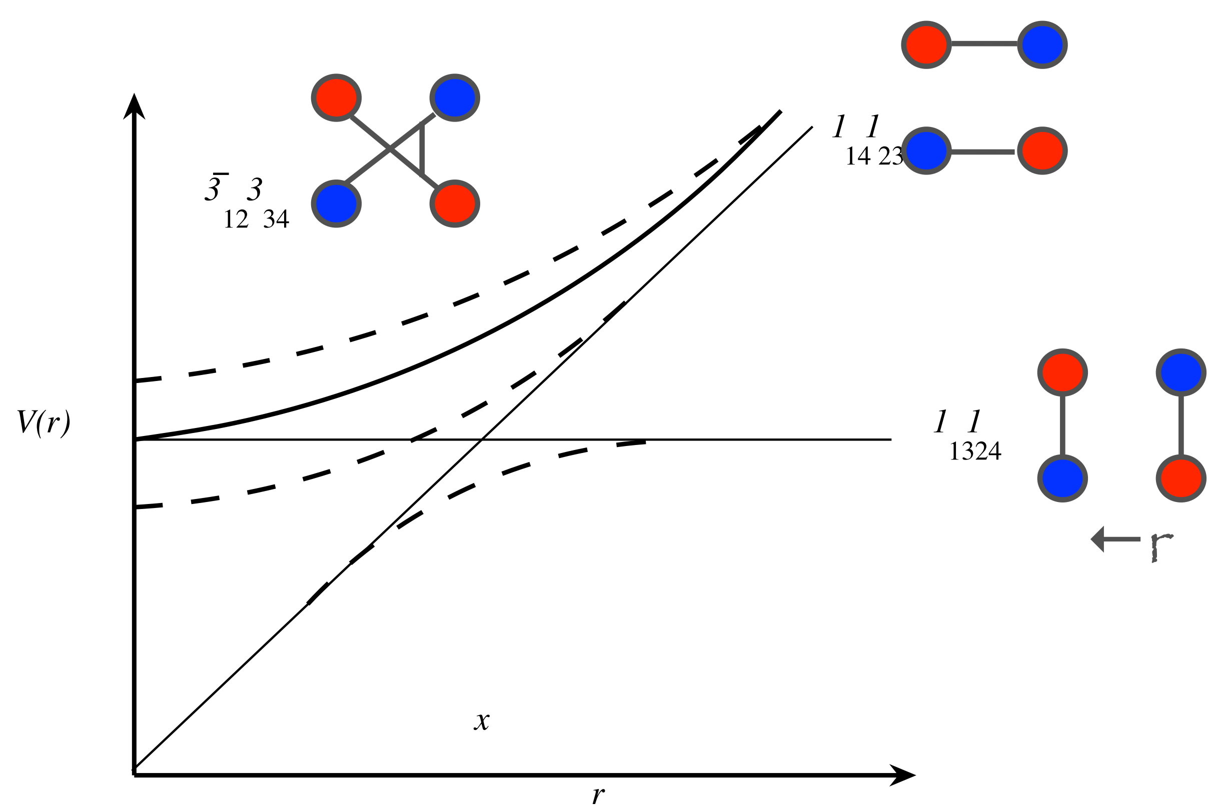
"incoherent sum of two Breit-Wigners with parameters set to the values reported in Ref [2]"

Penta-bags

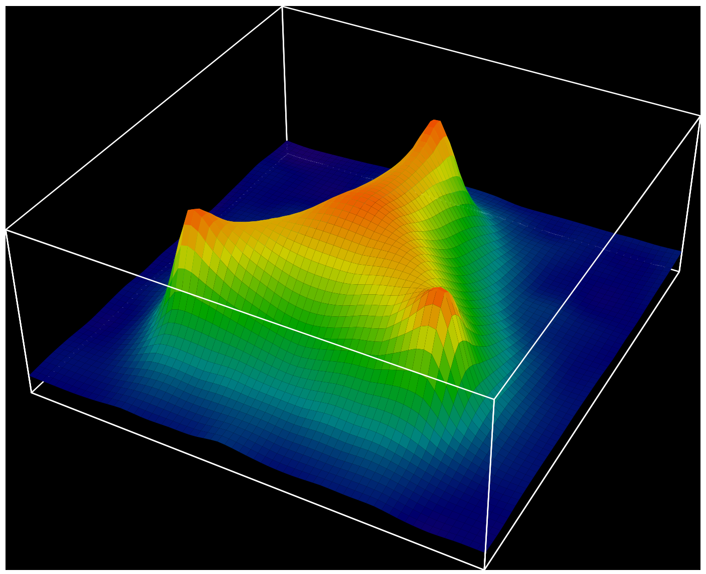


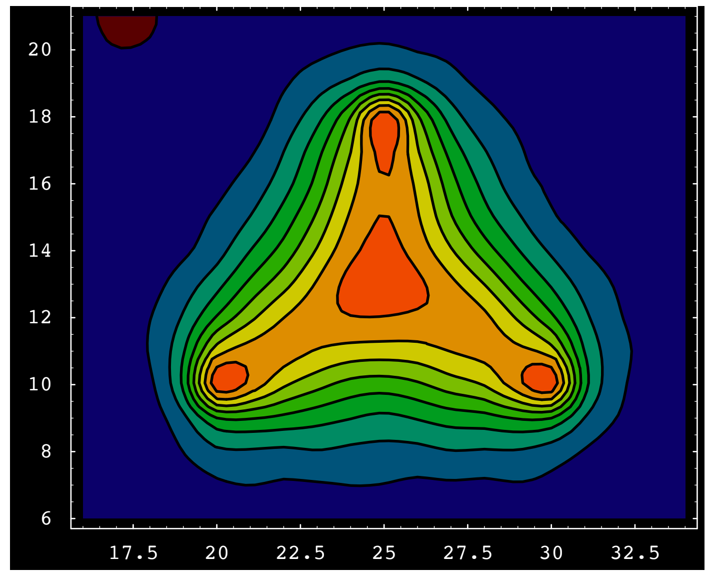
Penta-problems

colour dynamics becomes important beyond qqq!

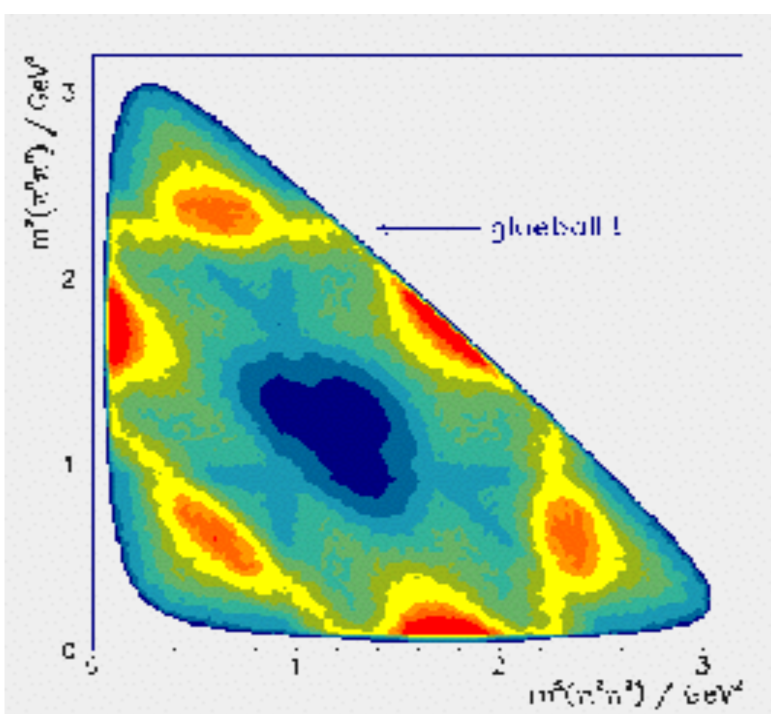


Penta-problems

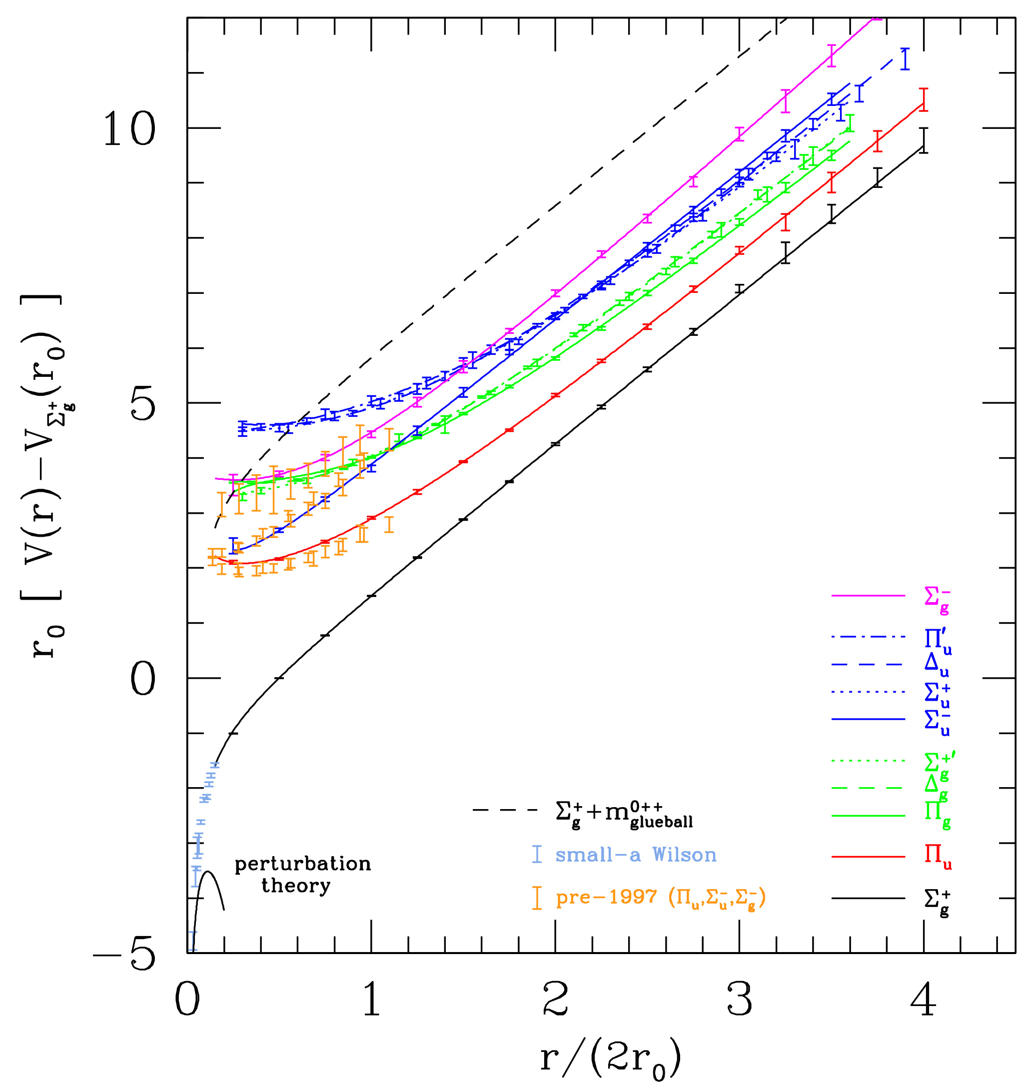




Ichie, Bornyakov, Schierholz, & Streuer, hep-lat/0212036



Juge, Kuti, & Morningstar.



Penta-problems

Multiquark physics has a dubious history which Isgur has dubbed the ‘multiquark fiasco’. The story is one of throwing caution to the winc
Modellers from four different camps were guilty.

(1) Bag Models. The bag model automatically confines all quarks which are placed into a bag. We have seen that the complicated dynamic
of confinement may be approximated by a confining volume for $q\bar{q}$ or qqq systems but that this is not true for multiquark systems. Nevertheless, some practitioners published detailed spectra of multiquarks confined to a single bag which they interpreted as having the same legitimacy as bag model predcitions for mesons.

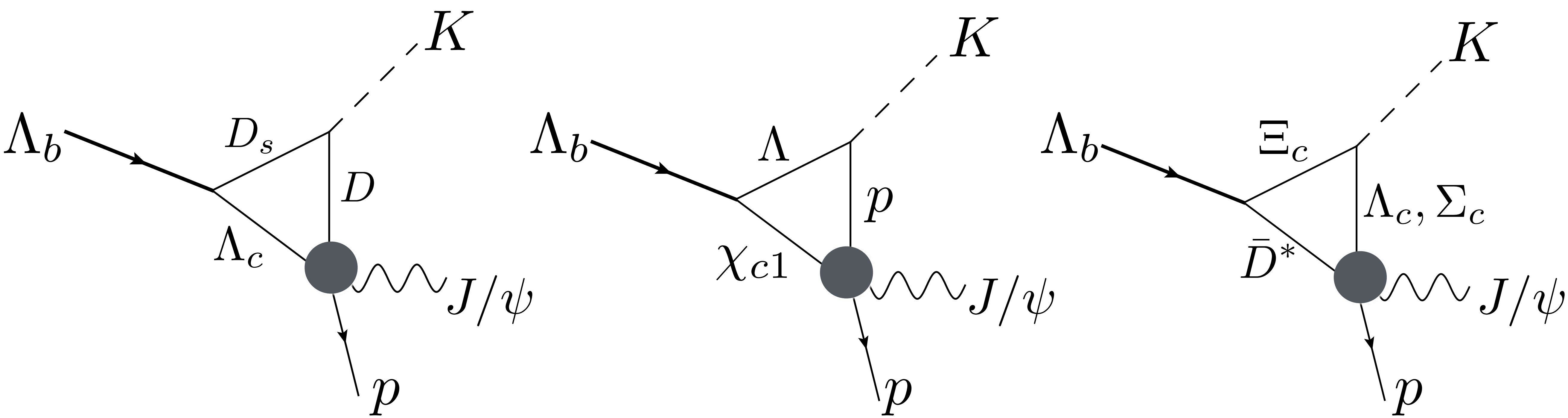
(2) Naive Potential Models. The analogue of the bag modellers error is to assume that multiquark systems confine in precisely the same w
that mesons and baryons do (essentially ignoring the colour factor in the potential). Of course this will also produce a rich spectrum of states.

(3) Colour Chemistry. A more sophisticated mistake was made by adherents to the ‘colour chemistry’ school. They recognized that multiquark systems could be connected by a variety of flux configurations and noted that some of them corresponded to a single unit of fo
quarks. This false analogy to mesons and baryons then permitted a rich spectrum of states. Of course the problem is that they neglected th
topological mixing which must be present.

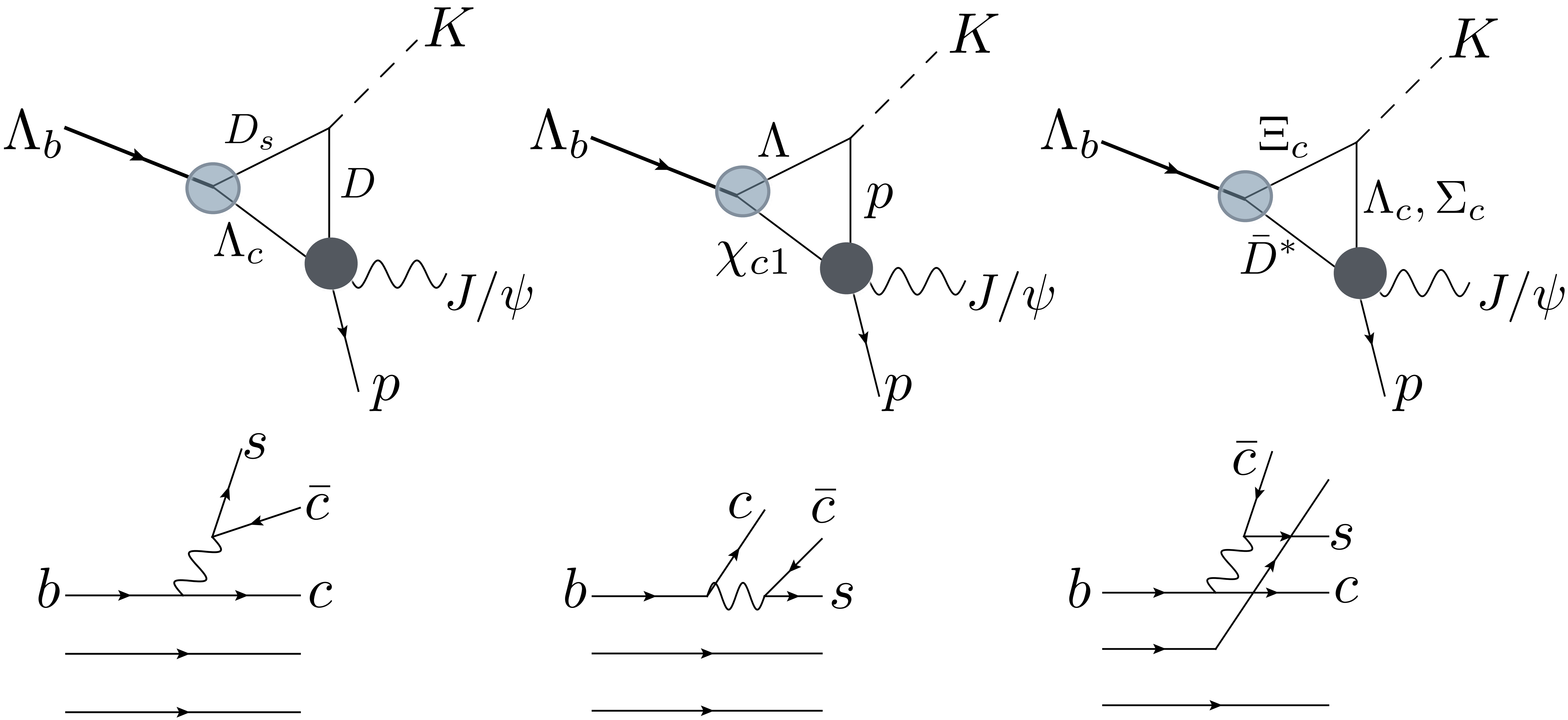
(4) $\vec{F}_i \cdot \vec{F}_j$ Potential Models. Finally there was a group who used a model with the correct characteristics but who, again, predicted a rich spectrum of states. The problem this time was the incorrect use of some approximations.

N. Isgur, Acta Phys. Aust. Suppl. XXVII, 177 (1985)

Penta-modelling



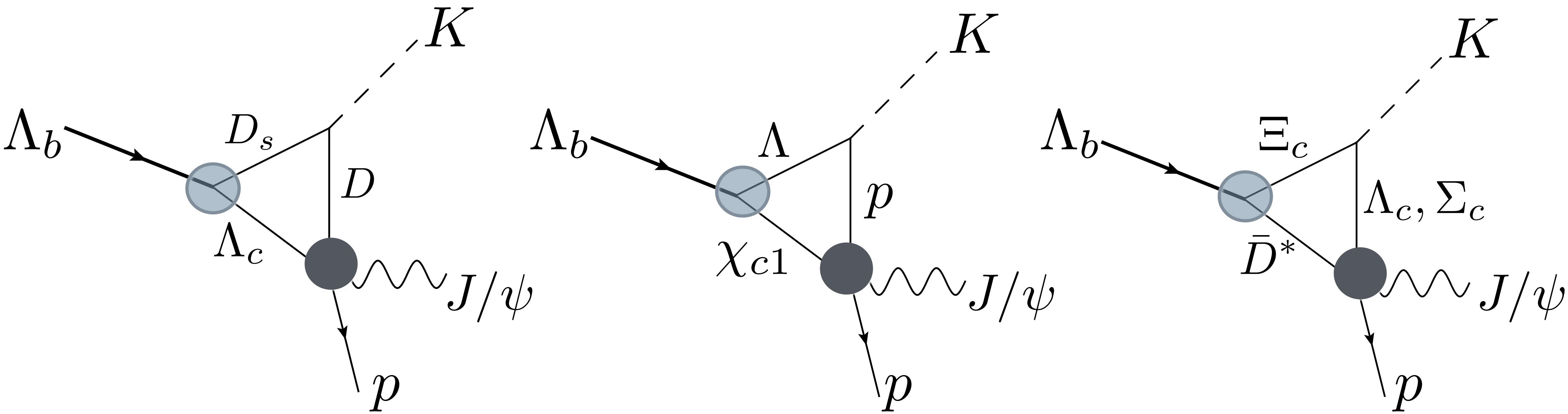
Penta-modelling

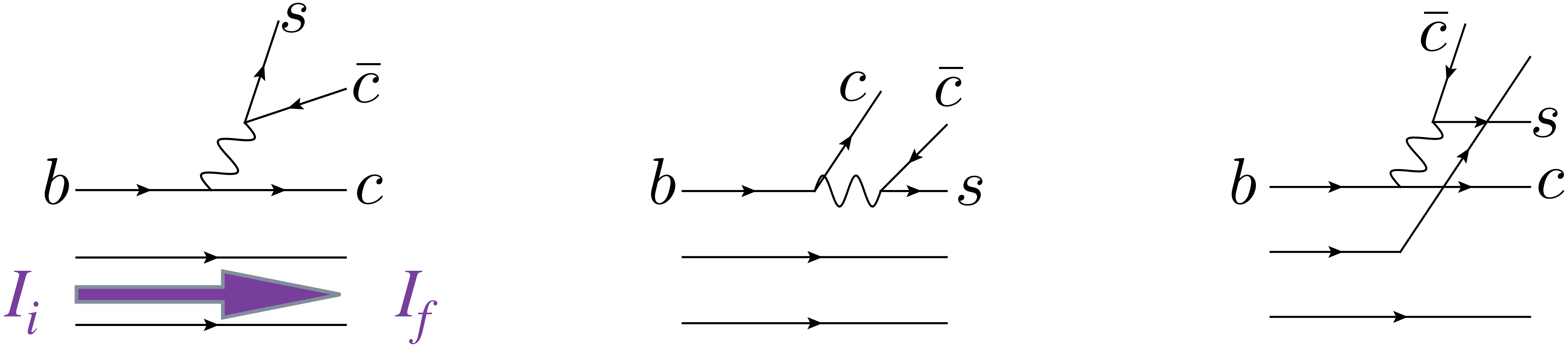


1/N

1/N

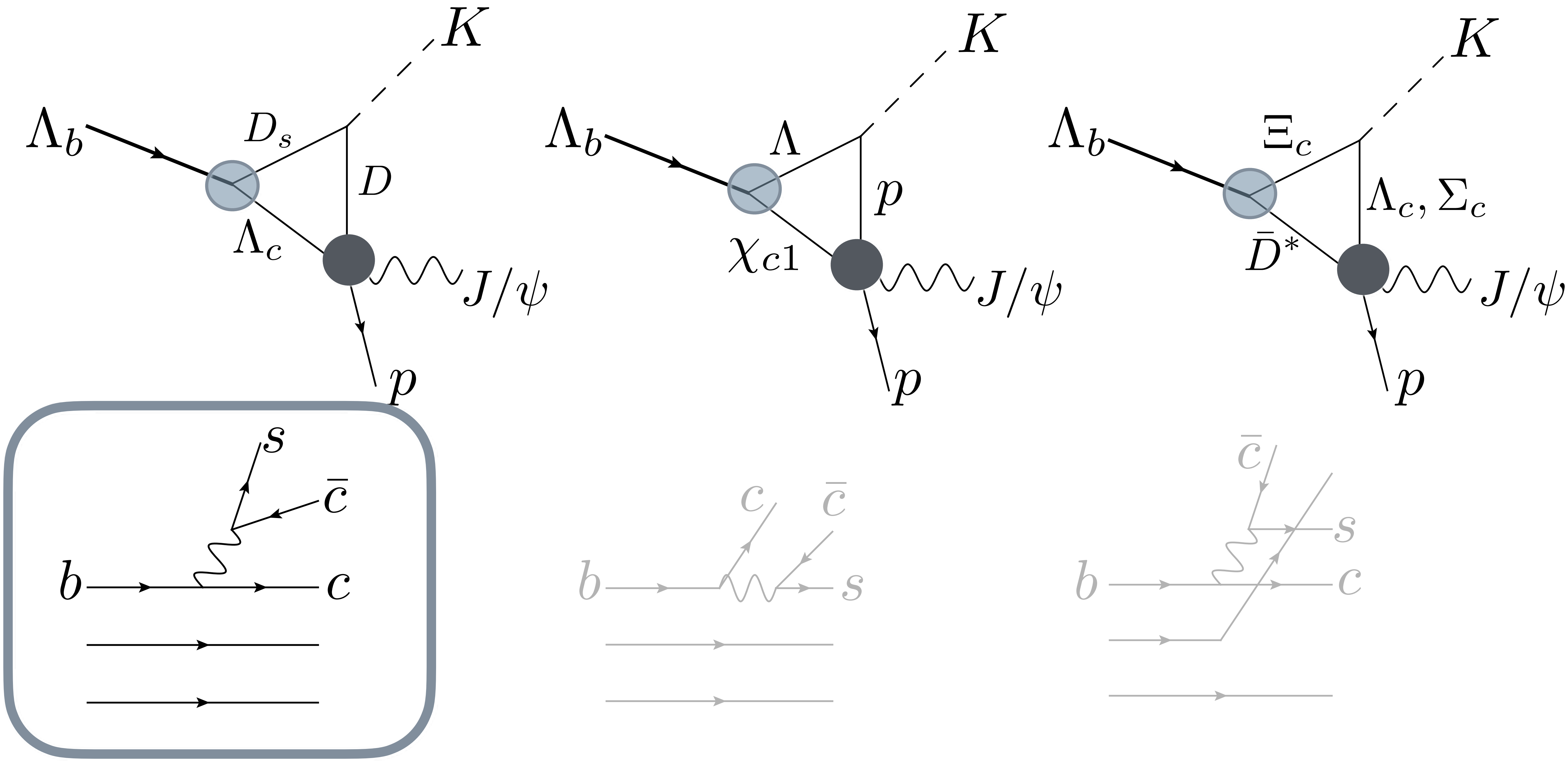
Penta-modelling





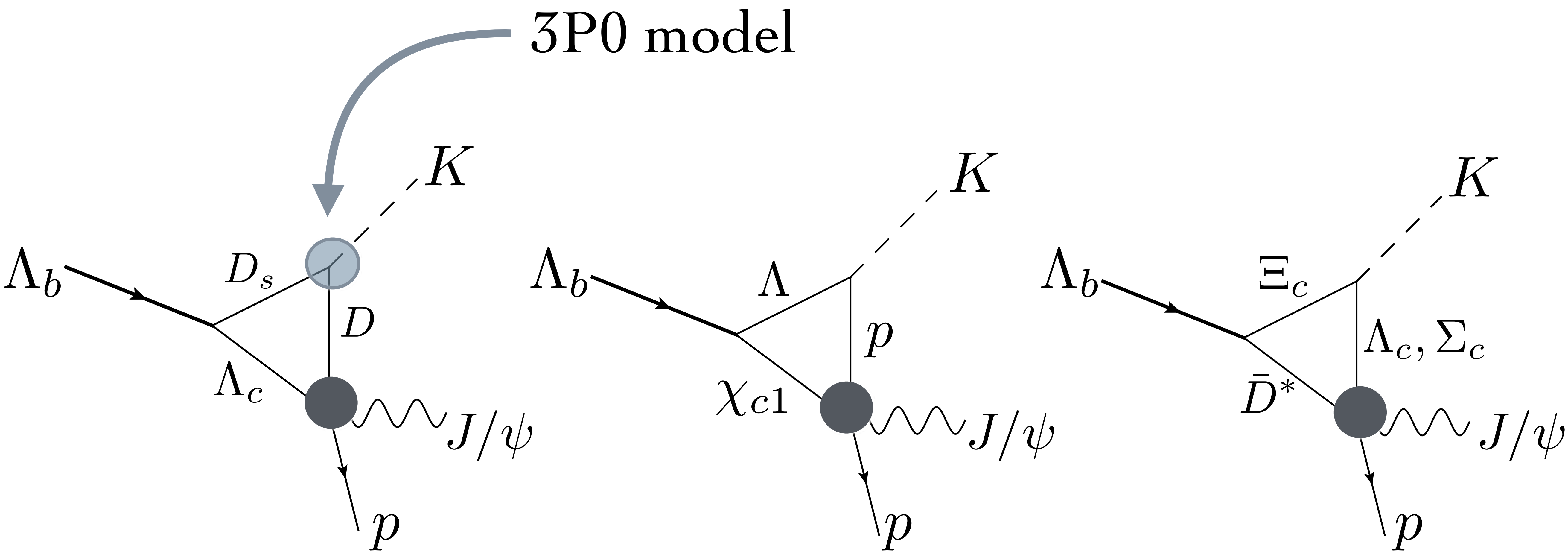
1/N 1/N

Penta-modelling



$$\langle \Lambda_c(1/2^+)\,|\, j^\mu \,|\, \Lambda_b(1/2^+)\rangle = \zeta(w)\,\bar{u}(v')[\gamma^\mu - \gamma^\mu\gamma_5]u(v)$$

Penta-modelling



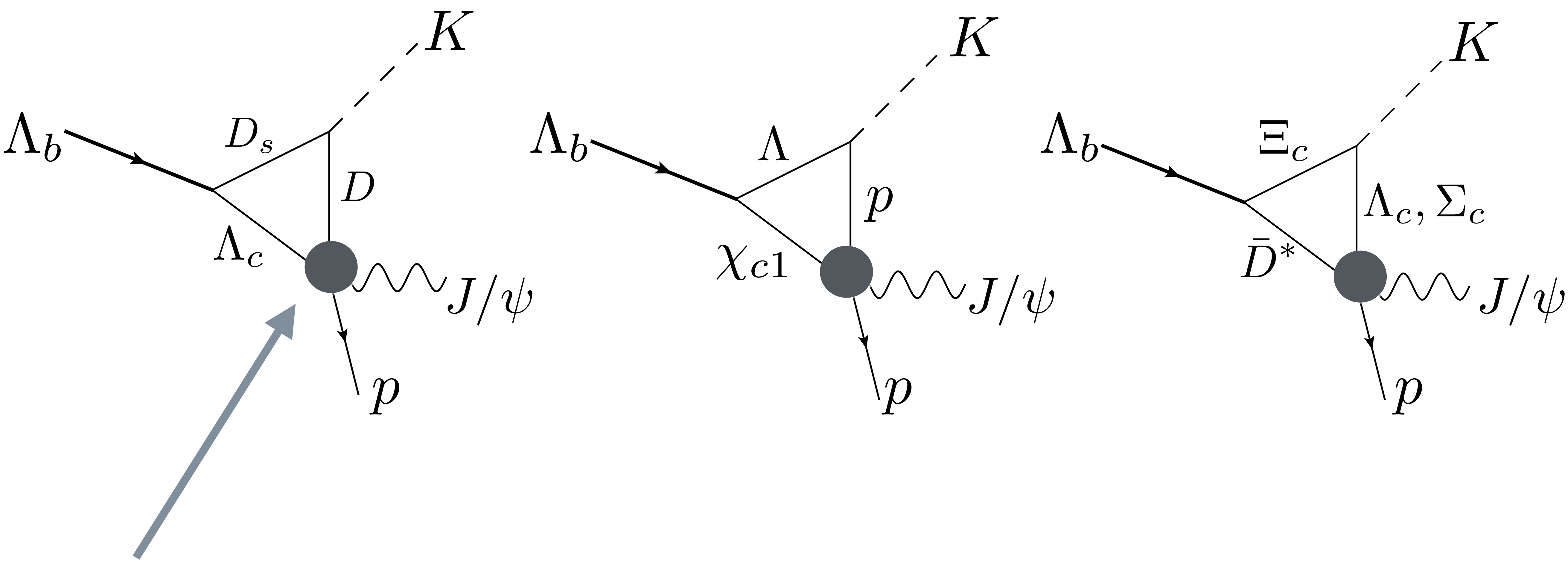
$D_s \to D^* K \qquad -\sqrt{3} f_P \phi$

$D_s^* \to D K \qquad f_P \phi$

$D_s^* \to D^* K \qquad -\sqrt{2} f_P \phi$

$$f_P(\mathrm{3P0}) = -\frac{\gamma}{\pi^{1/4}\sqrt{\beta}} \frac{2^5}{9} \frac{p}{\beta} \exp(-\frac{p^2}{12\beta^2})$$

Penta-modelling



final state interactions (ope?, short range?)

$$V_{\alpha\beta} = \lambda_{\alpha\beta}\, g(k) g(p) \qquad T_{\alpha\beta} = t_{\alpha\beta}\, g(k) g(p) \qquad t = (\mathbb{I} - \lambda \mathbb{G}(E))^{-1} \lambda$$

Penta-modelling

contact interactions from HQSS

$1/2^-$	$D_s^*\Lambda_c D$	$D_s^*\Lambda_c D^*$	$\Sigma_c D$	$\Sigma_c D^*$	$\Sigma_c^* D^*$	$J/\psi N$
$D_S^*\Lambda_c D$	A	0	0	$\sqrt{3}B$	$\sqrt{6}B$	$\frac{\sqrt{3}}{2}D$
$D_s^*\Lambda_c D^*$		A	$\sqrt{3}B$	$-2B$	$\sqrt{2}B$	$\frac{1}{2}D$
$\Sigma_c D$			C_a	$\frac{2}{\sqrt{3}}C_b$	$-\sqrt{2/3}C_b$	$-\frac{1}{2\sqrt{3}}E$
$\Sigma_c D^*$				$C_a - \frac{4}{3}C_b$	$-\frac{2}{3}C_b$	$\frac{5}{6}E$
$\Sigma_c^* D^*$					$C_a - \frac{5}{3}C_b$	$\frac{\sqrt{2}}{3}E$
$J/\psi N$						0

$3/2^-$	$D_s^*\Lambda_c D^*$	$\Sigma_c^* D$	$\Sigma_c D^*$	$\Sigma_c^* D^*$	$J/\psi N$
$D_s^*\Lambda_c D^*$	A	$-\sqrt{6}B$	B	$\sqrt{5}B$	D
$\Sigma_c^* D$		C_a	$\frac{C_b}{\sqrt{3}}$	$\sqrt{\frac{5}{3}}C_b$	$-\frac{E}{\sqrt{3}}$
$\Sigma_c D^*$			$C_a + \frac{2}{3}C_b$	$-\frac{\sqrt{5}}{3}C_b$	$\frac{E}{3}$
$\Sigma_c^* D^*$				$C_a - \frac{2}{3}C_b$	$\frac{\sqrt{5}}{3}E$
$J/\psi N$					0

Penta-modelling

contact interactions from HQSS

$1/2^-$	$D_s^*\Lambda_c D$	$D_s^*\Lambda_c D^*$	$\Sigma_c D$	$\Sigma_c D^*$	$\Sigma_c^* D^*$	$J/\psi N$
$D_S^*\Lambda_c D$	A	0	0	$\sqrt{3}B$	$\sqrt{6}B$	$\frac{\sqrt{3}}{2}D$
$D_s^*\Lambda_c D^*$		A	$\sqrt{3}B$	$-2B$	$\sqrt{2}B$	$\frac{1}{2}D$
$\Sigma_c D$			C_a	$\frac{2}{\sqrt{3}}C_b$	$-\sqrt{2/3}C_b$	$-\frac{1}{2\sqrt{3}}E$
$\Sigma_c D^*$				$C_a - \frac{4}{3}C_b$	$-\frac{2}{3}C_b$	$\frac{5}{6}E$
$\Sigma_c^* D^*$					$C_a - \frac{5}{3}C_b$	$\frac{\sqrt{2}}{3}E$
$J/\psi N$						0

$3/2^-$	$D_s^*\Lambda_c D^*$	$\Sigma_c^* D$	$\Sigma_c D^*$	$\Sigma_c^* D^*$	$J/\psi N$
$D_s^*\Lambda_c D^*$	A	$-\sqrt{6}B$	B	$\sqrt{5}B$	D
$\Sigma_c^* D$		C_a	$\frac{C_b}{\sqrt{3}}$	$\sqrt{\frac{5}{3}}C_b$	$-\frac{E}{\sqrt{3}}$
$\Sigma_c D^*$			$C_a + \frac{2}{3}C_b$	$-\frac{\sqrt{5}}{3}C_b$	$\frac{E}{3}$
$\Sigma_c^* D^*$				$C_a - \frac{2}{3}C_b$	$\frac{\sqrt{5}}{3}E$
$J/\psi N$					0

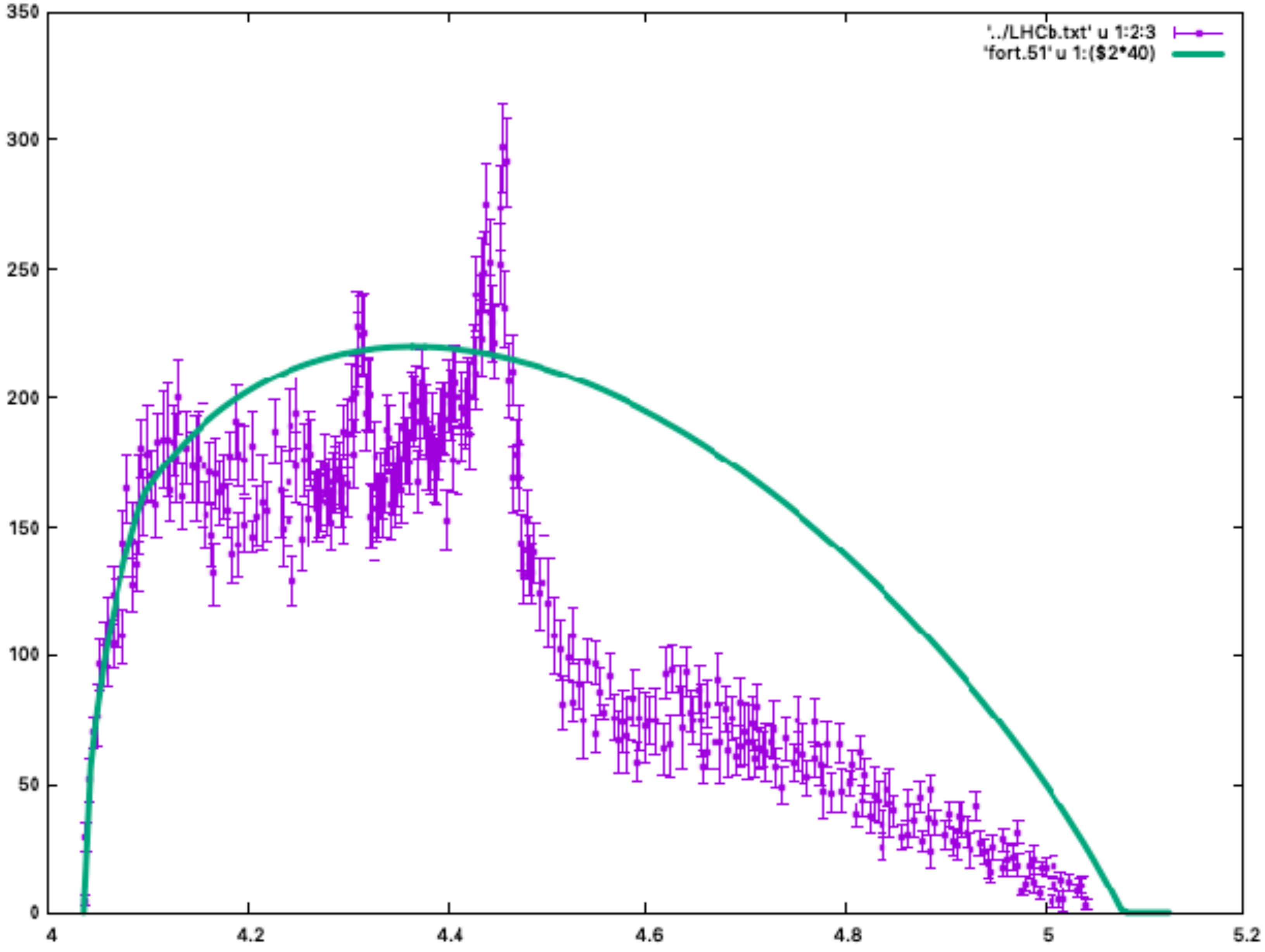
Penta-modelling

$$DPP = \int_{\Lambda^2_{KN}} ds_{12} \sum_{JP} \left| B(JP) + \sum_{d(JP)} \mathscr{A}_{d(JP)} \right|^2$$

$$\mathscr{A}_{d(JP)} = \sum_{\alpha(d)} \triangle_{d(\alpha)} \cdot T(\alpha : J/\psi N)$$

Penta-modelling

the constant background/phase space



Penta-modelling

1/2- FULL CASE channels (need 5 driving channels)

$$\Lambda D(2S); \Lambda D^*(2S); \Lambda D^*(4D); \Sigma D(2S); \Sigma D^*(2S); \Sigma D^*(4D); \Sigma^* D(4D); \Sigma^* D^*(2S); \Sigma^* D^*(4D); \Sigma^* D^*(6D); J/\psi N(S)$$

1/2- REDUCED CASE channels

$$D_s^* \Lambda D(2S); \cancel{D_s \Lambda D^*}(2S); D_s^* \Lambda D^*(2S) \,|\, \Sigma D(2S); \Sigma D^*(2S); \Sigma^* D^*(2S); J/\psi N(S)$$

[looks like we don't really need DsLD*…]

Penta-modelling

3/2- FULL CASE channels (need 7 driving channels)

$\Lambda D(2D); \Lambda D^*(4S); \Lambda D^*(2D); \Lambda D^*(4D) \quad \Sigma D(2D); \Sigma D^*(4S); \Sigma D^*(2D); \Sigma D^*(4D);$

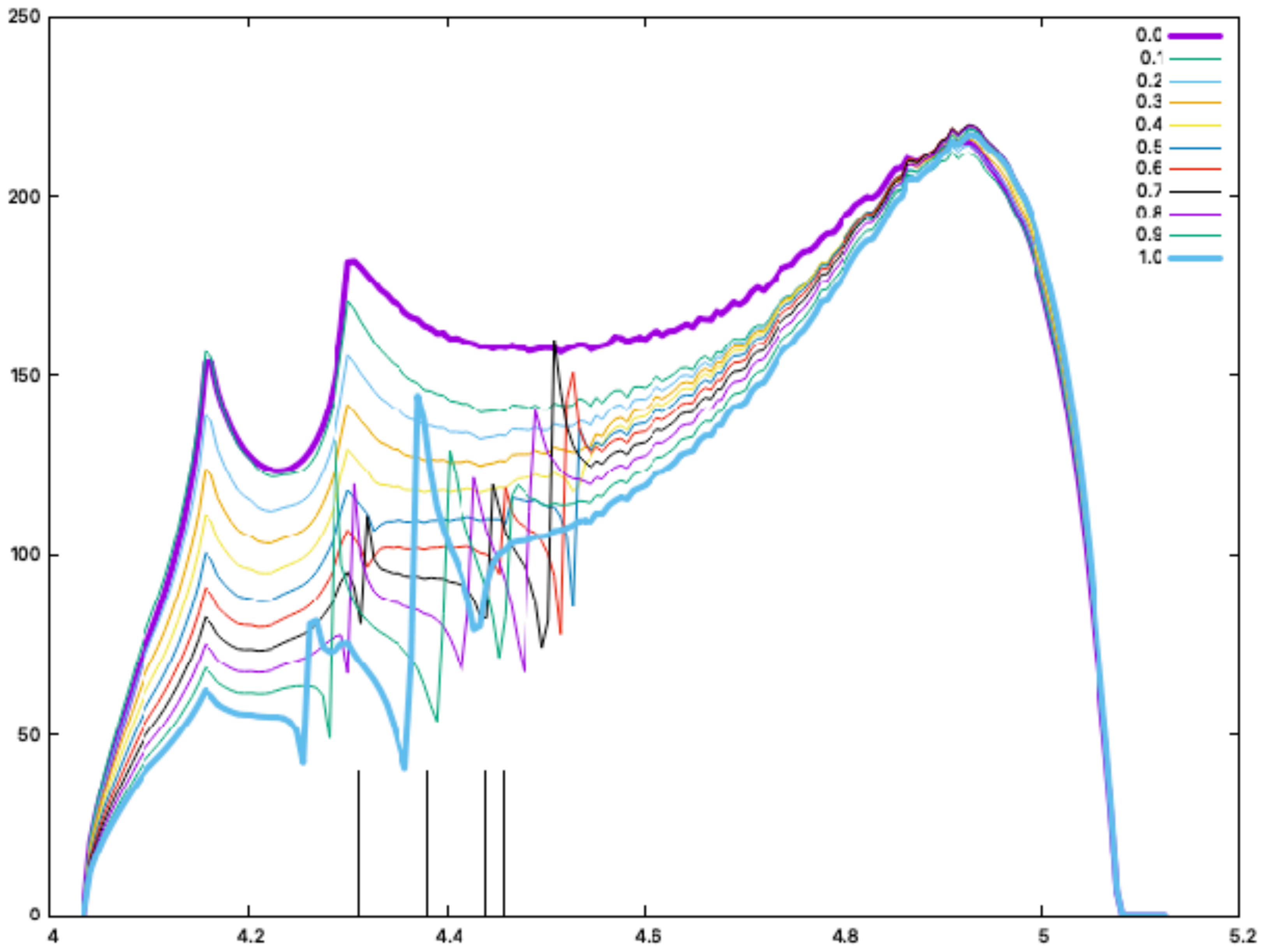
$\Sigma^* D(4S); \Sigma^* D(4D); \Sigma^* D^*(4S); \Sigma^* D^*(2D) \quad \Sigma^* D^*(4D); \Sigma^* D^*(6D); \Lambda' D(2P); J/\psi N(S)$

3/2- REDUCED CASE channels

$D_s^* \Lambda D^*(4S); D_s^* \Lambda \cancel{D}^*(2D); D_s^* \Lambda \cancel{D}^*(4D) \,|\, \Sigma D^*(4S); \Sigma^* D^*(4S); J/\psi N(S)$

Penta-modelling

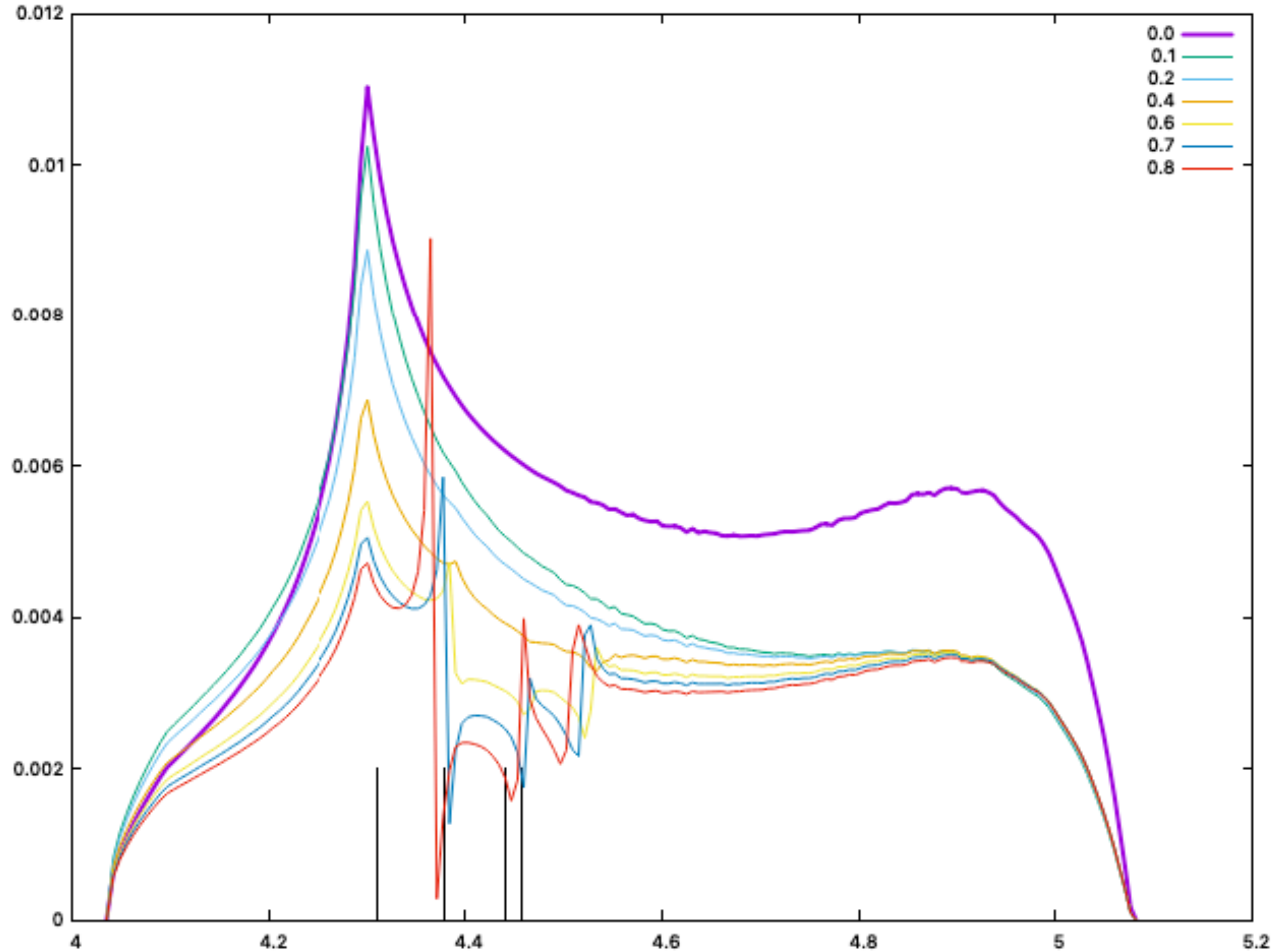
I=1/2 JP=1/2- FSIs reduced case



increasing FSI strength

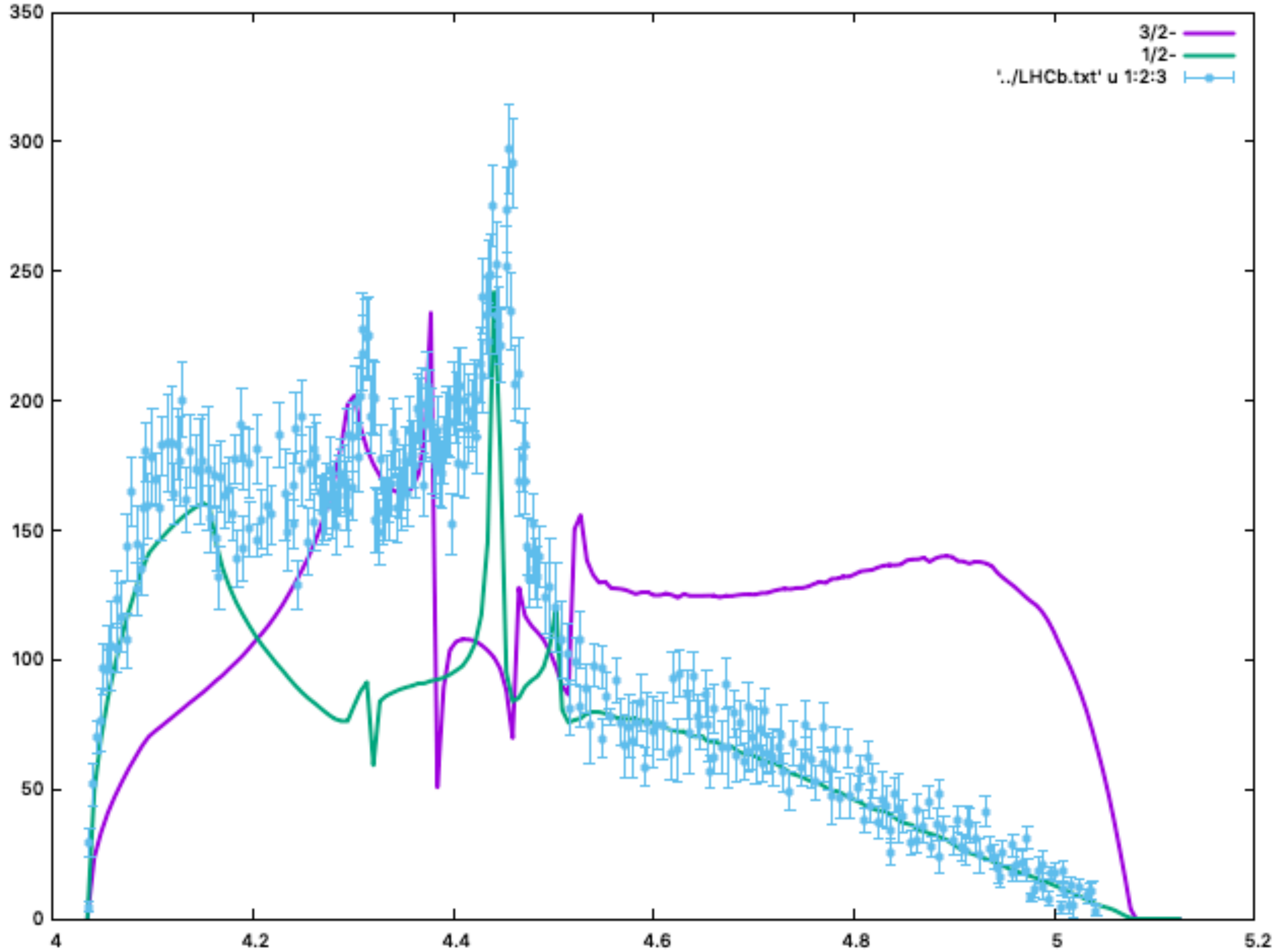
Penta-modelling

I=1/2 JP=3/2- FSIs reduced case



g1=1, bg=0,gee=various

Penta-modelling

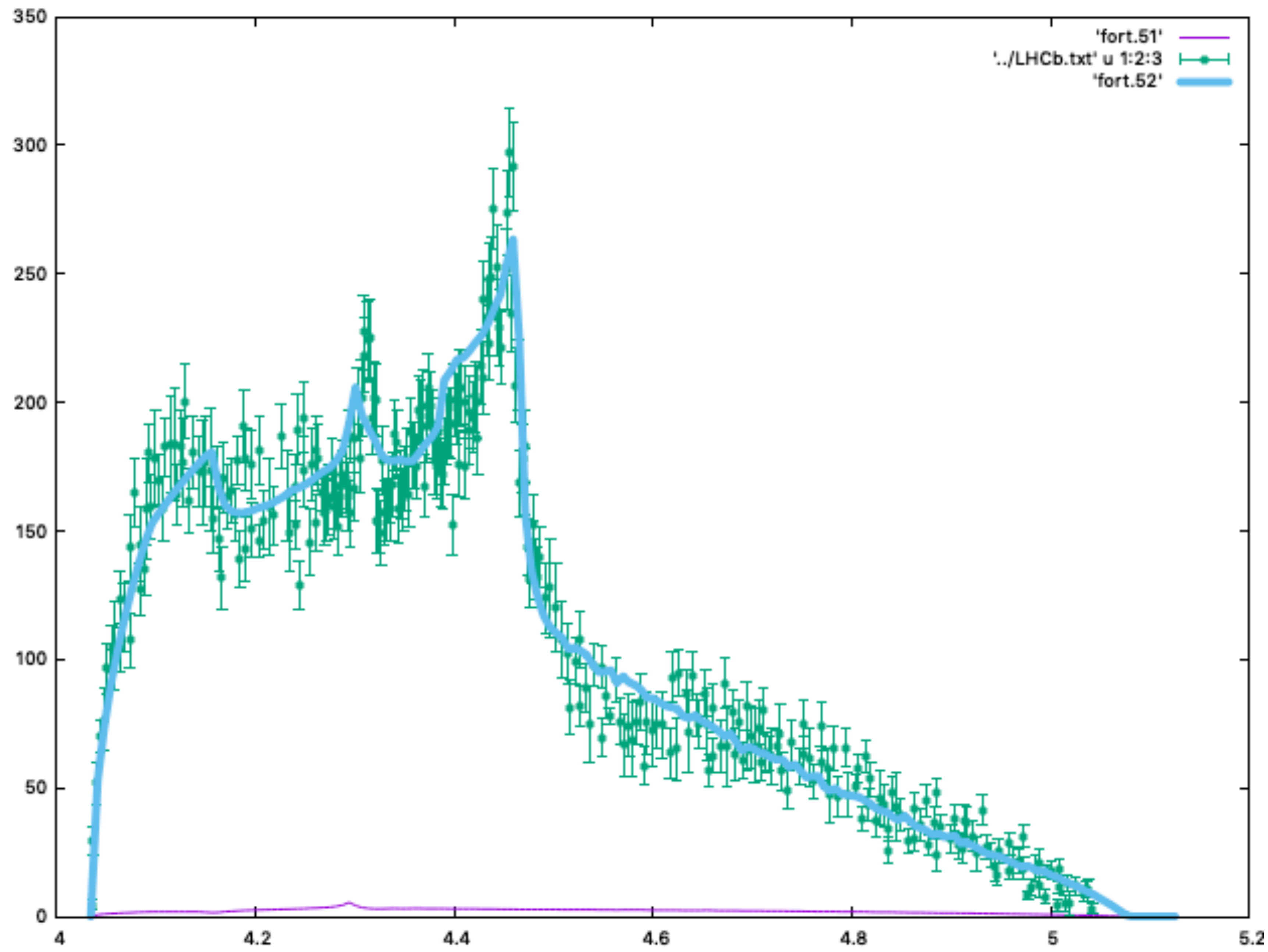


1/2-: gee=0.7, g1=1, g2=-1,bg=-0.1i

3/2-: gee=0.7,g1=1, bg=0

Penta-modelling

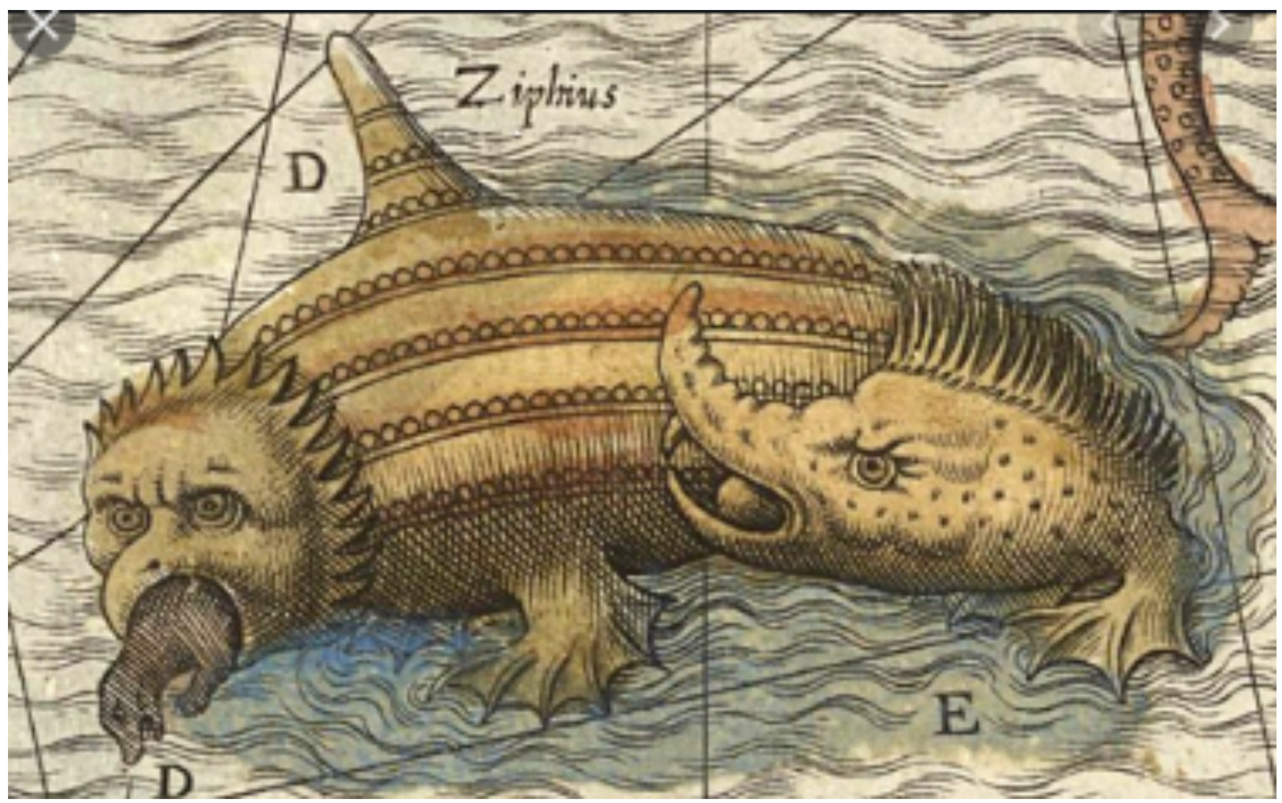
example fit with 3 JP channels



Penta-precis

- tempting to fit the peaks as Sigma_c(*) D(*) bound states
- triangle/loop cusps also contribute
- complicated final state interaction dynamics and range of scales bedevil the works
- but seems likely there is enough freedom to fit the data
- [& there is a lot of model ambiguity…]

Hybrids



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 02
(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

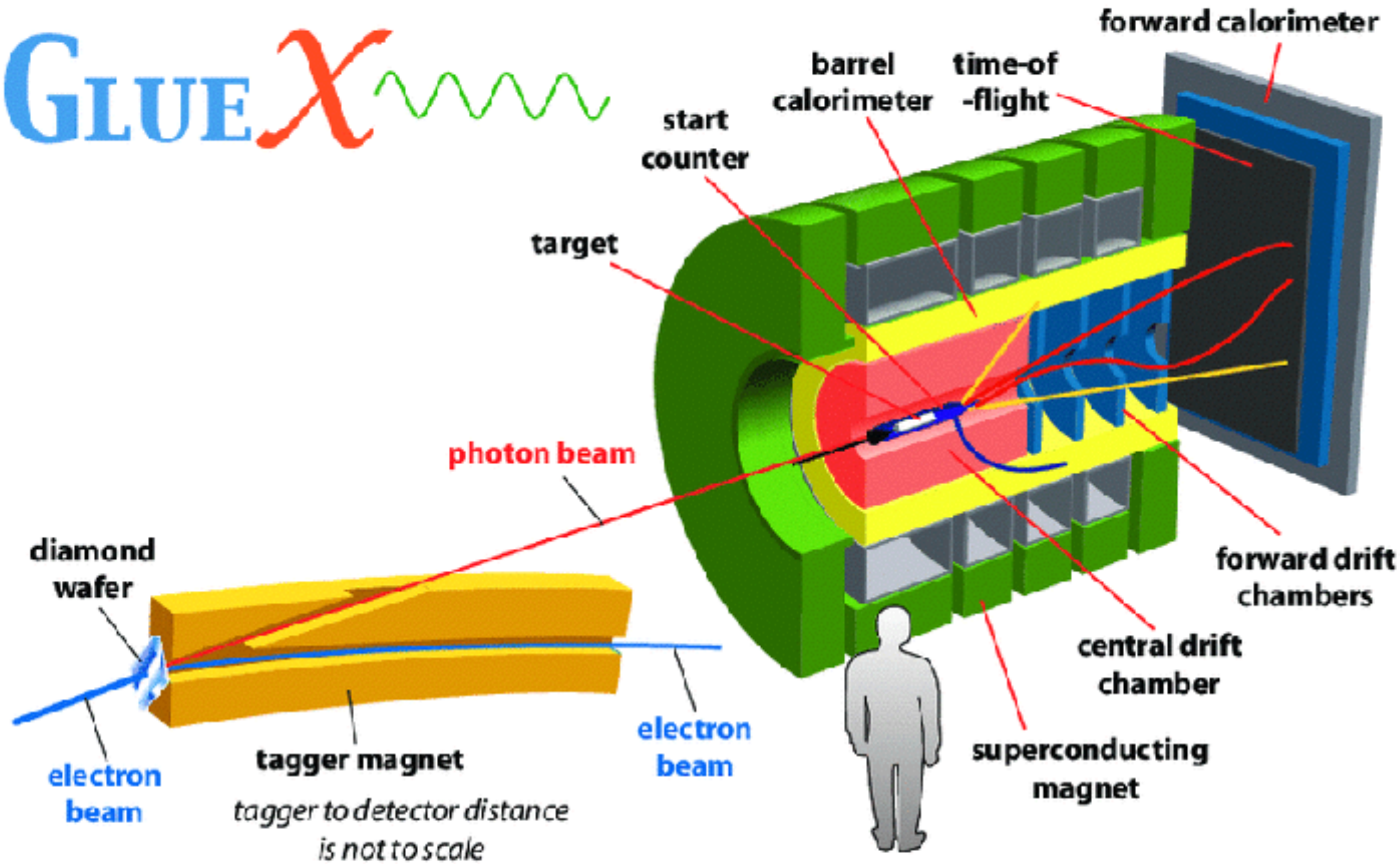
Received 24 October 1977
(Revised 7 May 1979)

Volume 124B, number 3,4 PHYSICS LETTERS

A FLUX TUBE MODEL FOR HADRONS

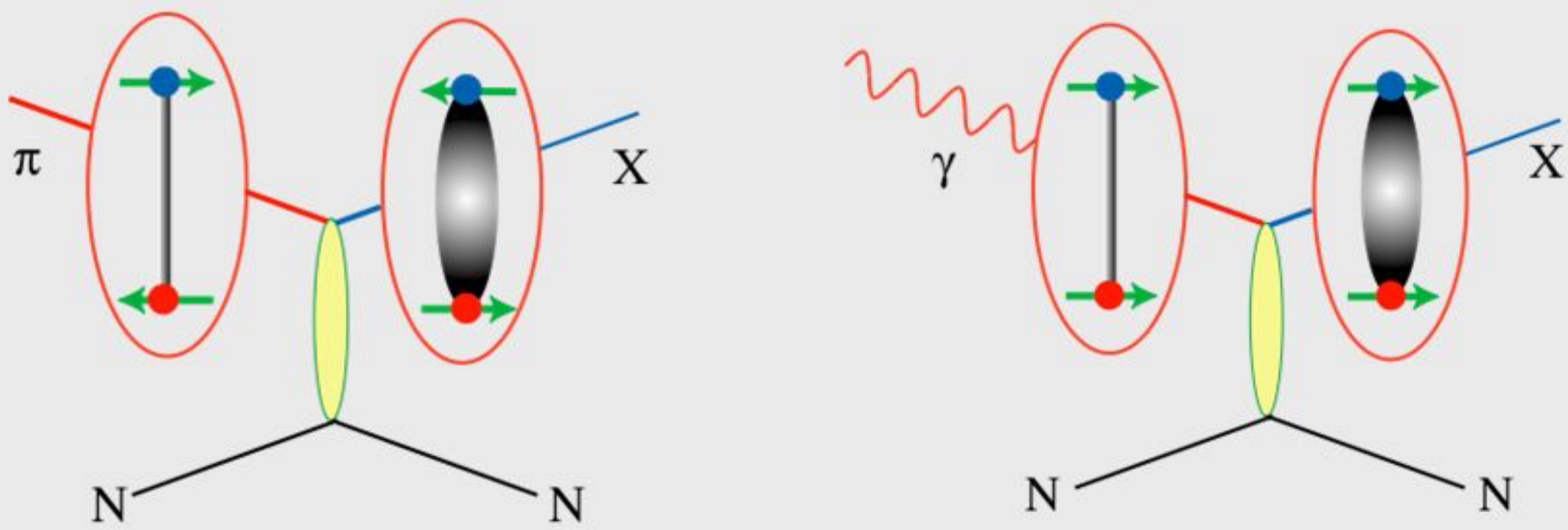
Nathan ISGUR [1,2] and Jack PATON
Department of Theoretical Physics, University of Oxford, 1 Keble Road, Oxford, OX1, 3NP, England

Received 20 December 1982



NCSU/JLab Workshop on Hybrids and Photoproduction Physics, Raleigh, NC, Nov, 1997.

Photoproduction



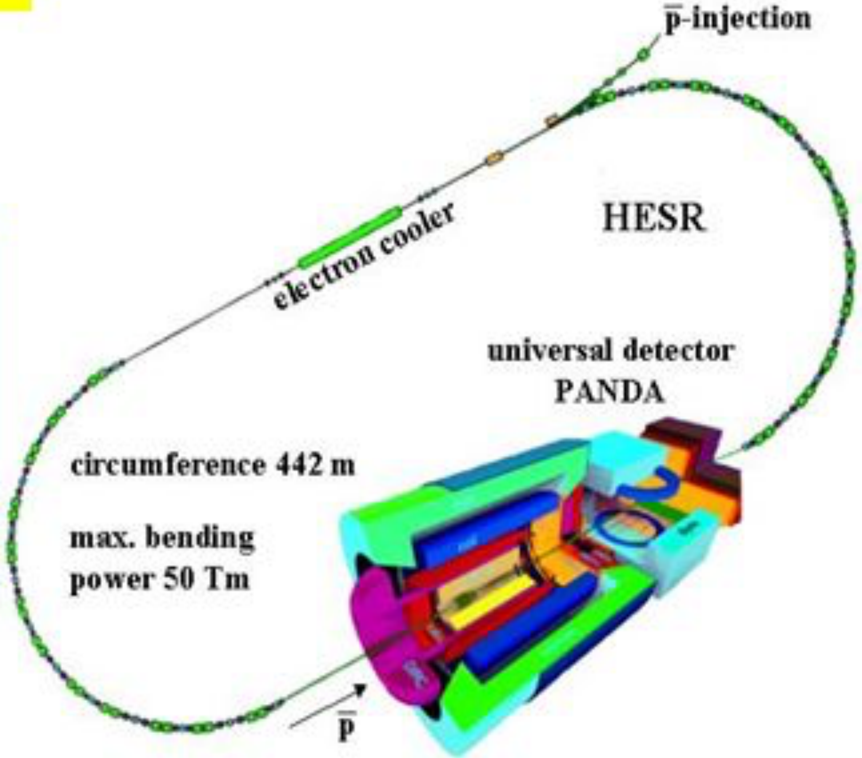
More likely to find exotic hybrid mesons
using beams of photons

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?

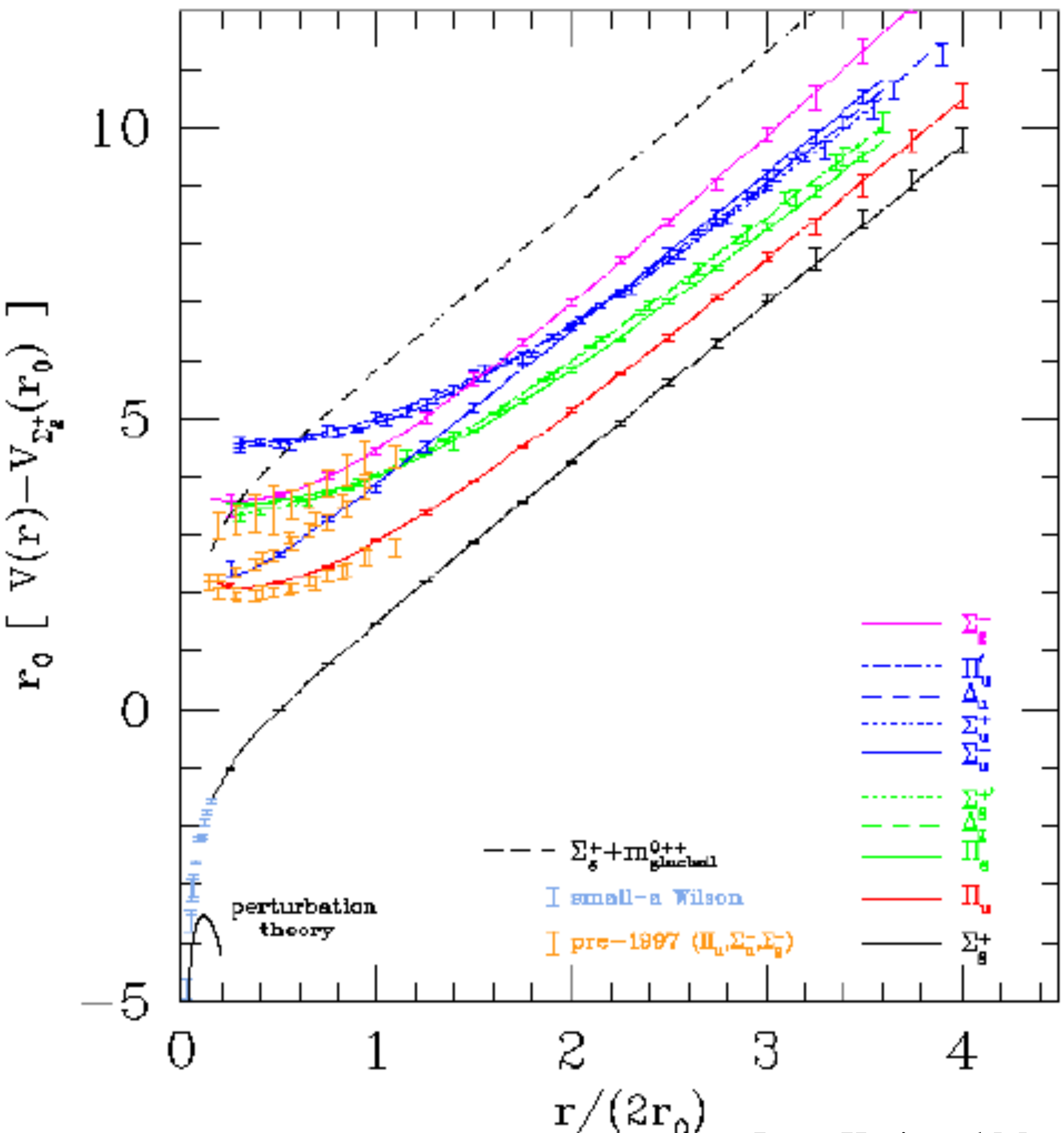
Lattice Hybrid Computations

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



Juge, Kuti, and Morningstar arXiv:hep-ph/9902336

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)

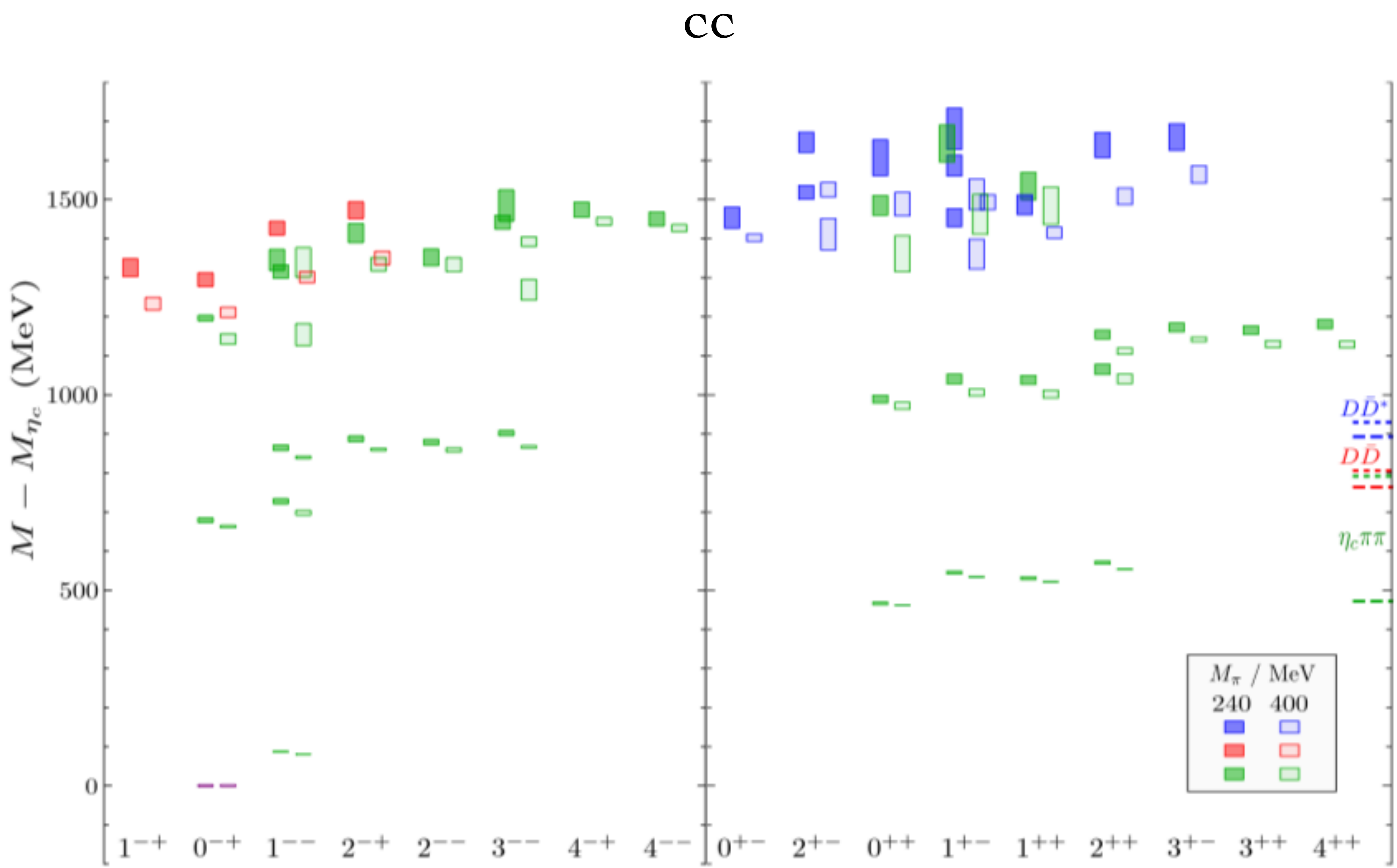
[only mass differences are well-defined]

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



Cheung et al. [HadSpec], JHEP 1612, 089 (2016).

Effective Field Theory

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

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

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

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

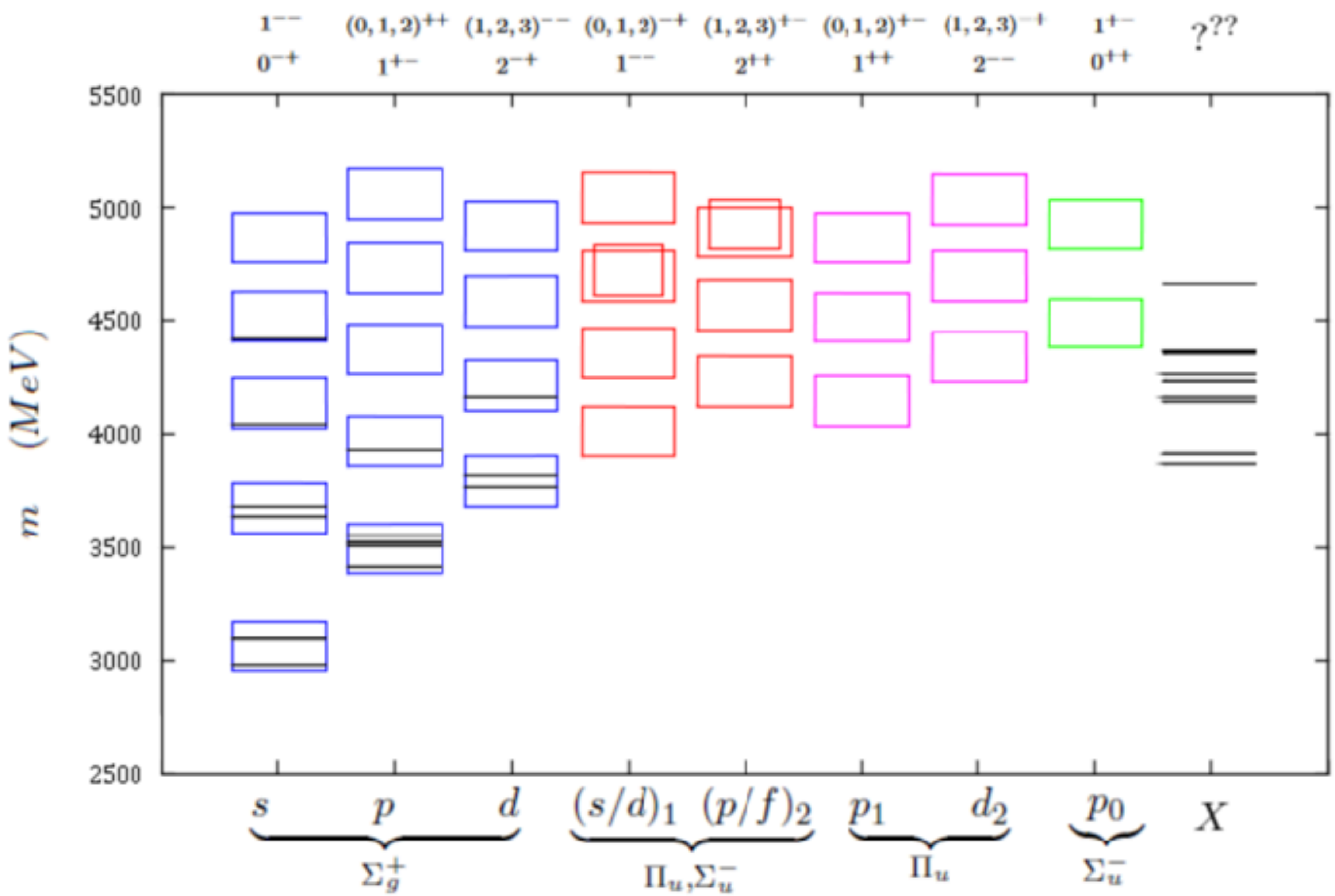
$$\left[-\frac{1}{mr^2}\partial_r r^2 \partial_r + \frac{l(l+1)}{mr^2} + E_\Pi^{(0)}\right]\psi_{+\Pi}^{(N)} = \mathcal{E}_N \psi_{+\Pi}^{(N)}$$

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

R. Oncala and J. Soto, arXix: 1702.03900

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

Effective Field Theory



R. Oncala and J. Soto, arXix: 1702.03900

Born-Oppenheimer Approximation

		multiplet	$\vec{\sigma}$
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^{++}	$(1,2,3)^{+-}$

Juge, Kuti, and Morningstar arXiv:hep-ph/9902336

Born-Oppenheimer Approximation

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

quantum number-exotic

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

$\vec{\sigma}$

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^{++}	$(1,2,3)^{+-}$

bag models with TE modes

Born-Oppenheimer Approximation

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

vector constituent gluon

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^{++}	$(1,2,3)^{+-}$

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

J. Dudek, arXiv:1106.5515

Back to Modelling

- follow the BO or EFT approach and use the adiabatic surfaces

- introduce explicit gluonic degrees of freedom

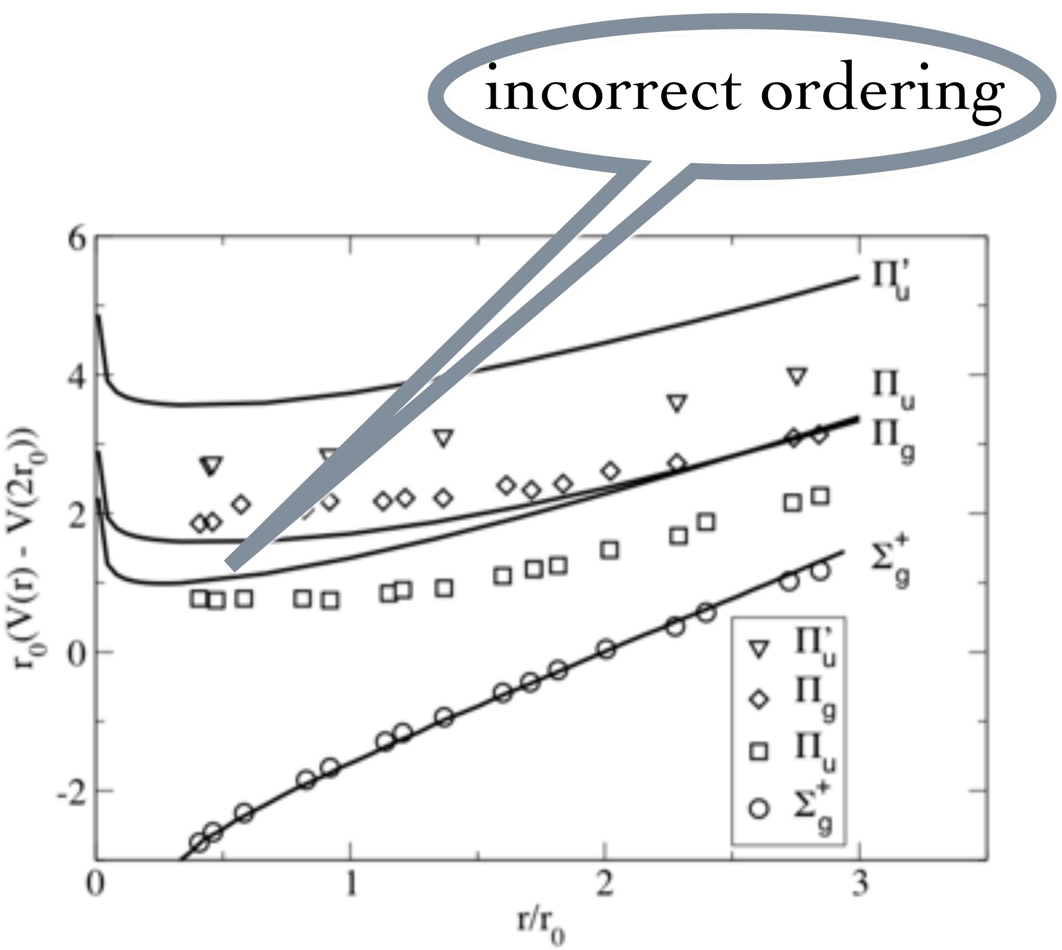
  permits mixing, decay calculations

  should reproduce

  - gluelump spectrum
  - adiabatic surfaces
  - BO multiplets
  - lattice hybrid spectrum

Back to Modelling

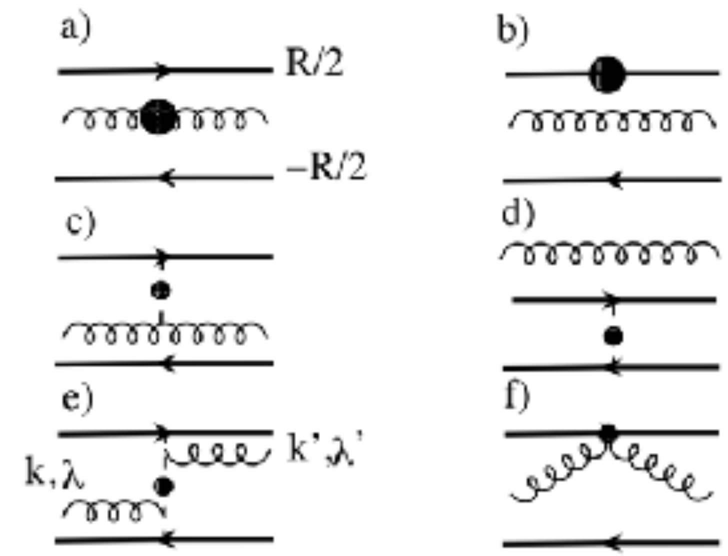
Attempt a model with Coulomb gauge QCD as a guide.



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

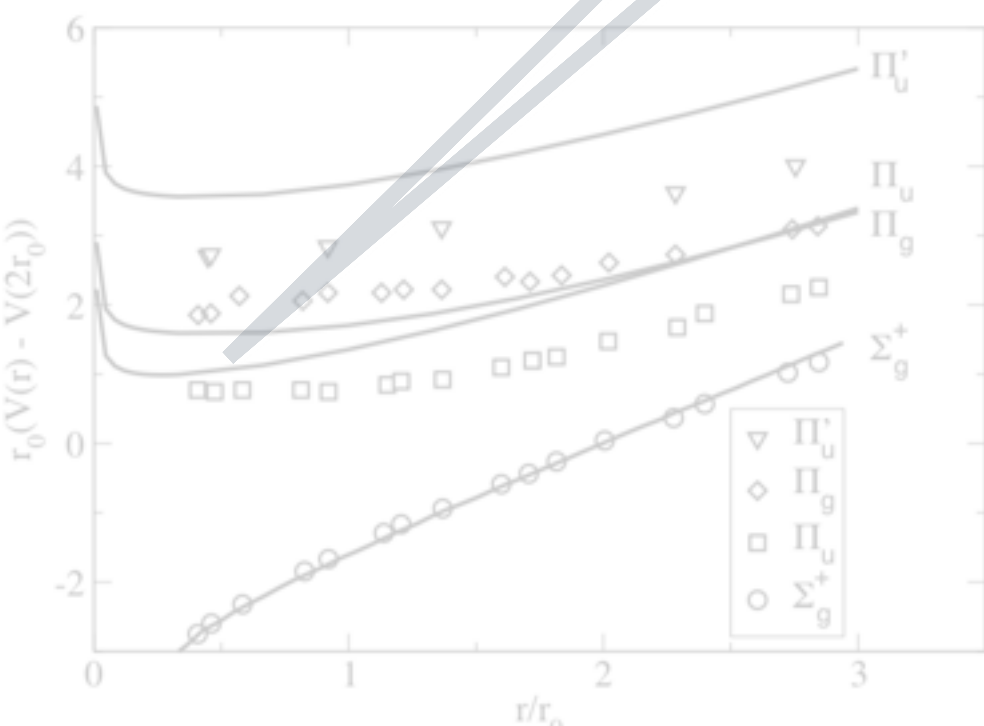
Back to Modelling

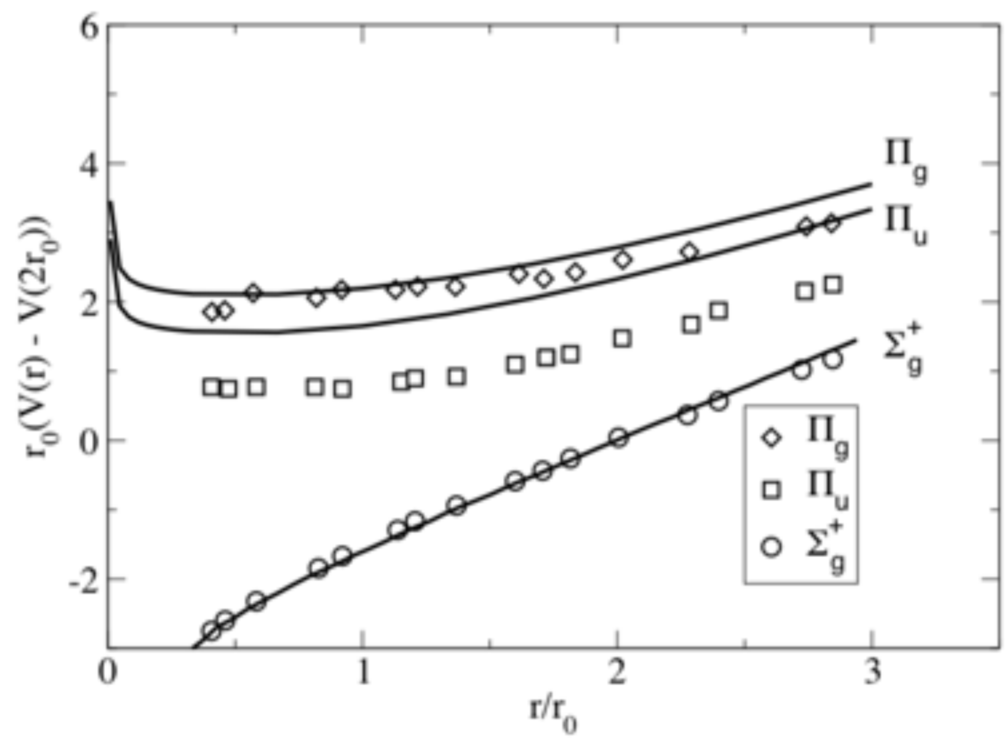
Attempt a model with Coulomb gaug



three-body interactions

incorrect ordering





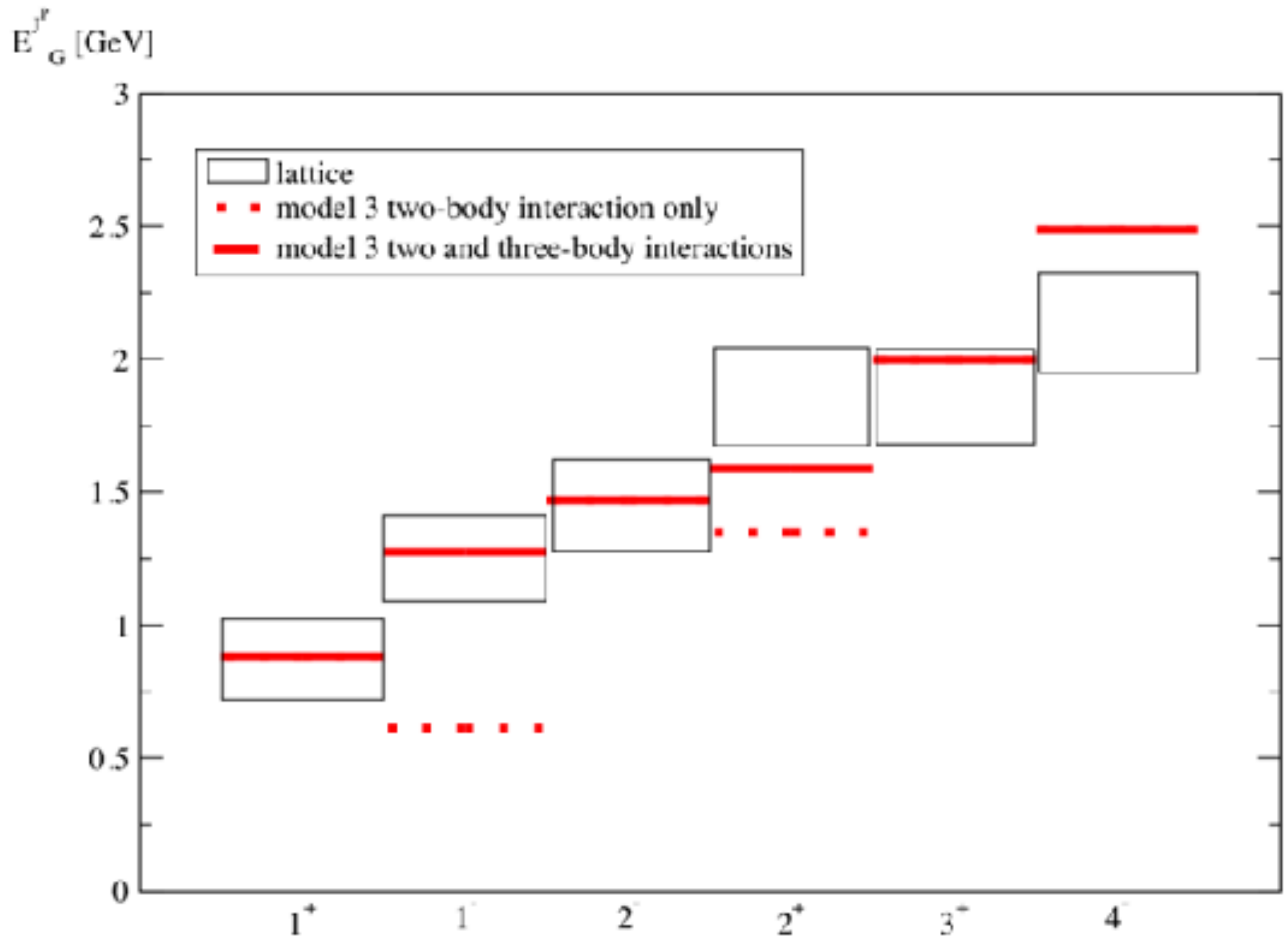
Swanson and Szczepaniak, Phys. Rev. D 59, 014035 (1998).

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

Back to Modelling

three-body interaction is null for 1+ and repulsive for 1- … saves the day

gluelump
spectrum



P. Guo, A. Szczepaniak, G. Galata, A. Vassallo, E. Santopinto, arXiv:0707.3156

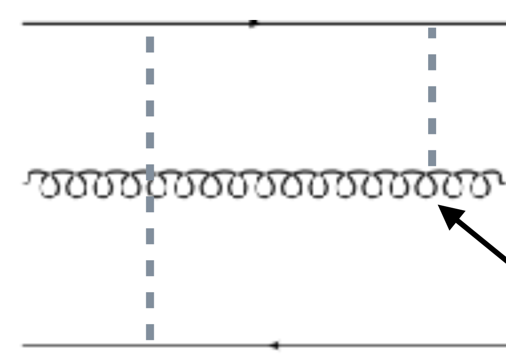
Back to Modelling

Construct hybrids with transverse constituent TE gluons

$$
\begin{aligned}
|JM[LS\ell j_g\xi]\rangle \quad = \quad & \frac{1}{2}T^A_{ij}\sum\int\frac{d^3k}{(2\pi)^3}\frac{d^3q}{(2\pi)^3}\,\phi_{j_g}(\vec{k})\,\phi_\ell(\vec{q})\,\langle\frac{1}{2}m\frac{1}{2}\bar{m}|SM_S\rangle\,\langle\ell m_\ell j_g m_g|LM_L\rangle\cdot \\
& Y_{\ell m_\ell}(\hat{q})\;\langle SM_S LM_L|JM\rangle\sqrt{\frac{2j_g+1}{4\pi}}D^{j_g *}_{m_g\lambda'}(\hat{k})\,\chi^{\xi}_{\lambda'\lambda}\cdot b^\dagger_{\vec{q}-\vec{k}/2\,mi}\,d^\dagger_{-\vec{q}-\vec{k}/2\,\bar{m}i}\,a^\dagger_{\vec{q}\lambda A}\,|0\rangle
\end{aligned}
$$

Back to Modelling

Model spectrum



$$\rho_g^A = f^{ABC}\vec{A}^B(x)\cdot\vec{\Pi}^C(x)$$

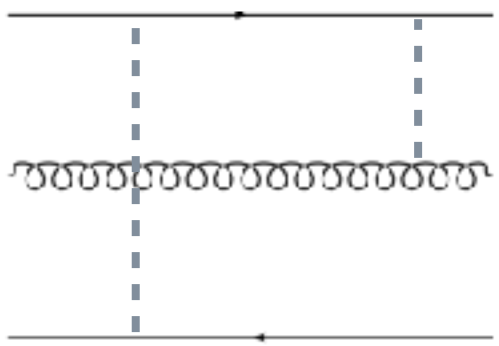
$$\rho_q^A = \psi^\dagger(x)T^A\psi(x)$$

$$V_1 = -\frac{4}{3}\left(\frac{\alpha}{R} - \frac{3}{4}bR\right) \qquad V_8 = +\frac{1}{6}\left(\frac{\alpha}{R} - \frac{3}{4}bR\right) \qquad V_{qg} = -\frac{3}{2}\left(\frac{\alpha}{R} - \frac{3}{4}bR\right)$$

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

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

Back to Modelling



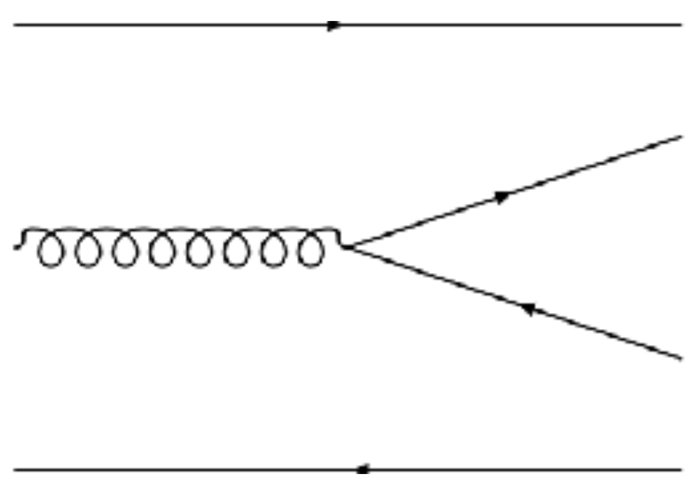
adiabatic surfaces

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

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

[agrees reasonably well with Π_u surface]

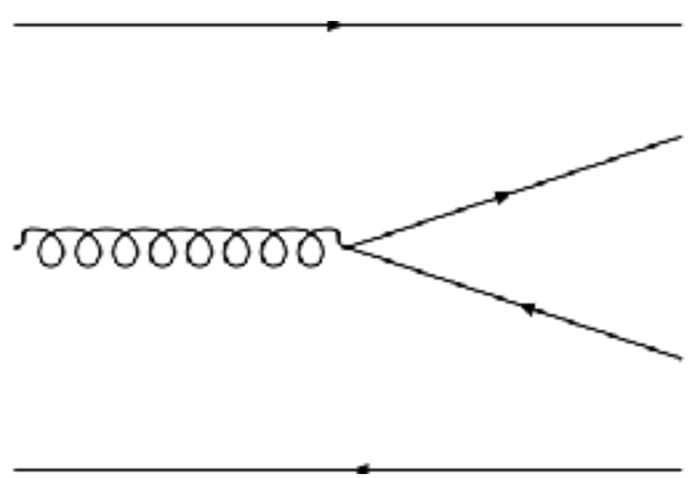
Modelling Decays



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?

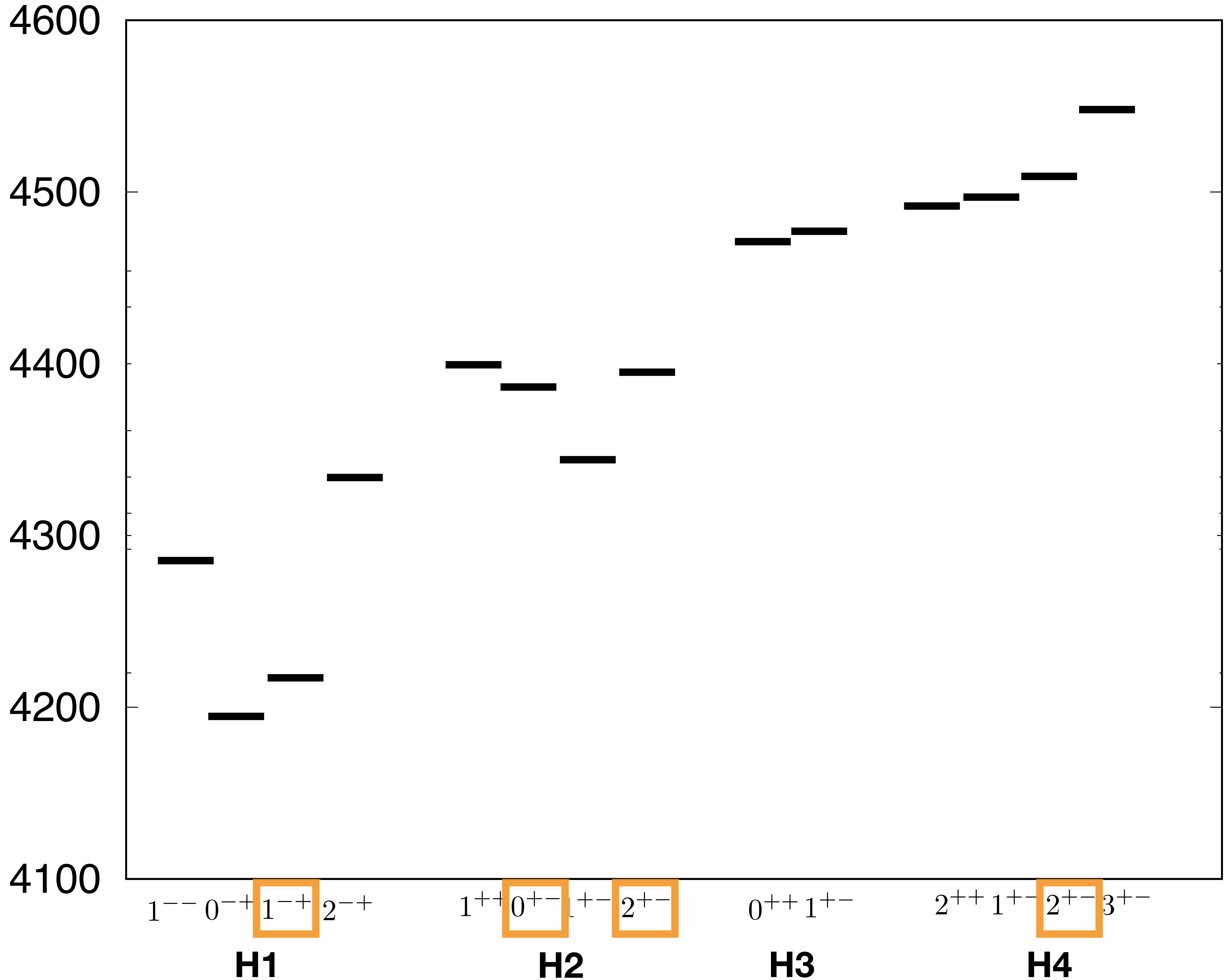
$$\alpha_S(c\bar{c}) \approx 0.5$$

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

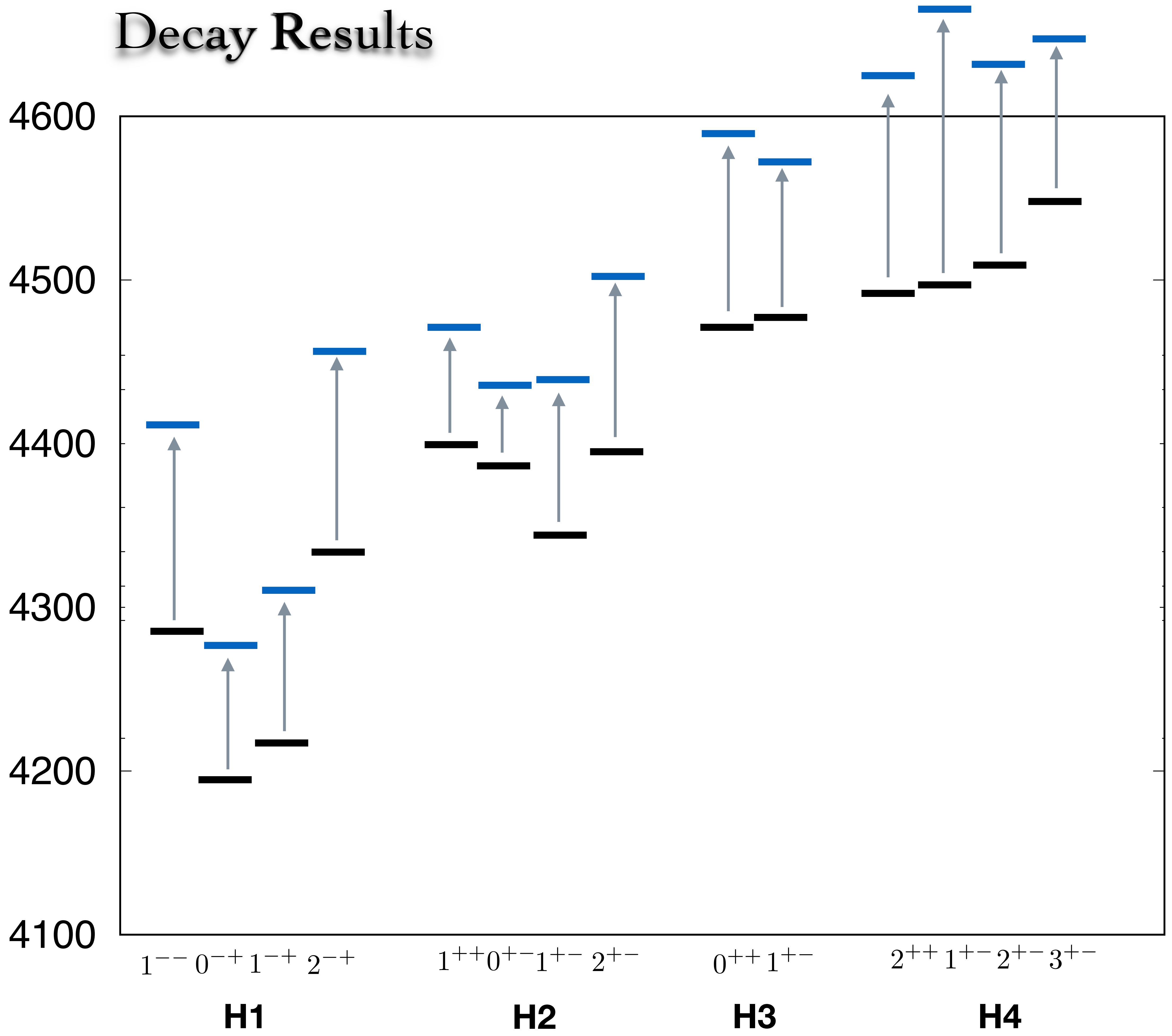
$$\alpha_S(\text{eff}) = ?$$

[obtain ‘usual’ selection rules]

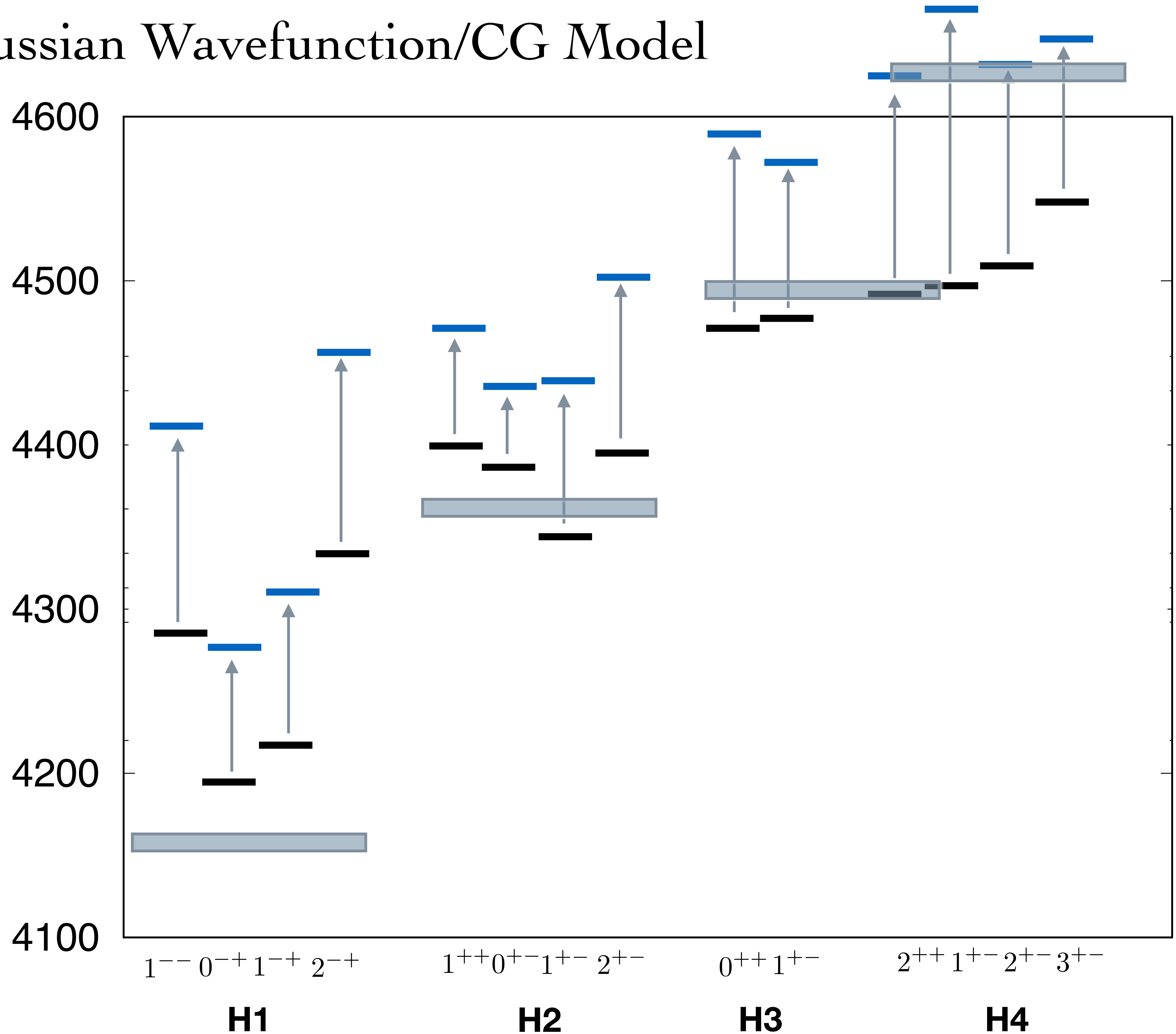
Decay Results



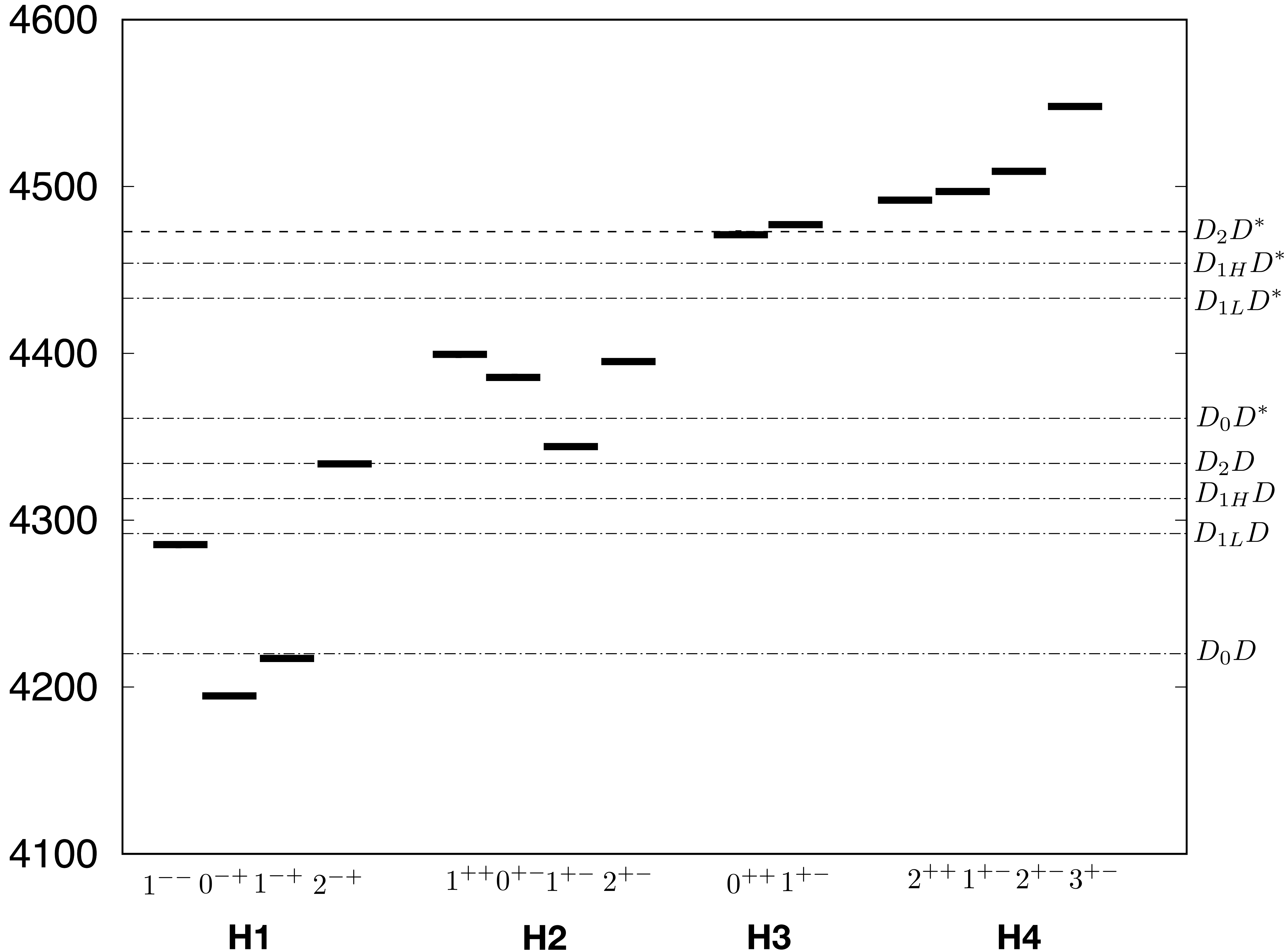
Decay Results



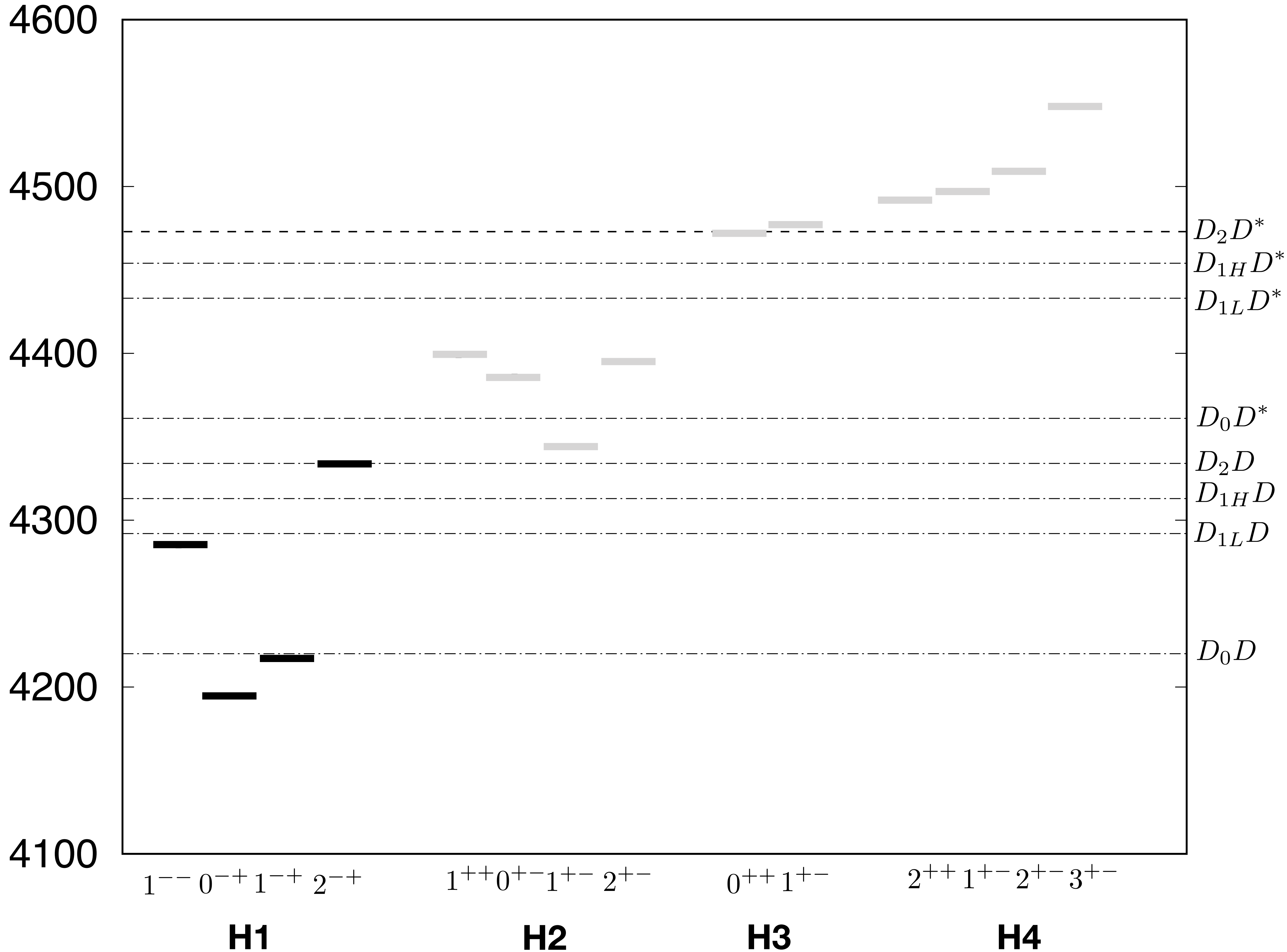
Gaussian Wavefunction/CG Model



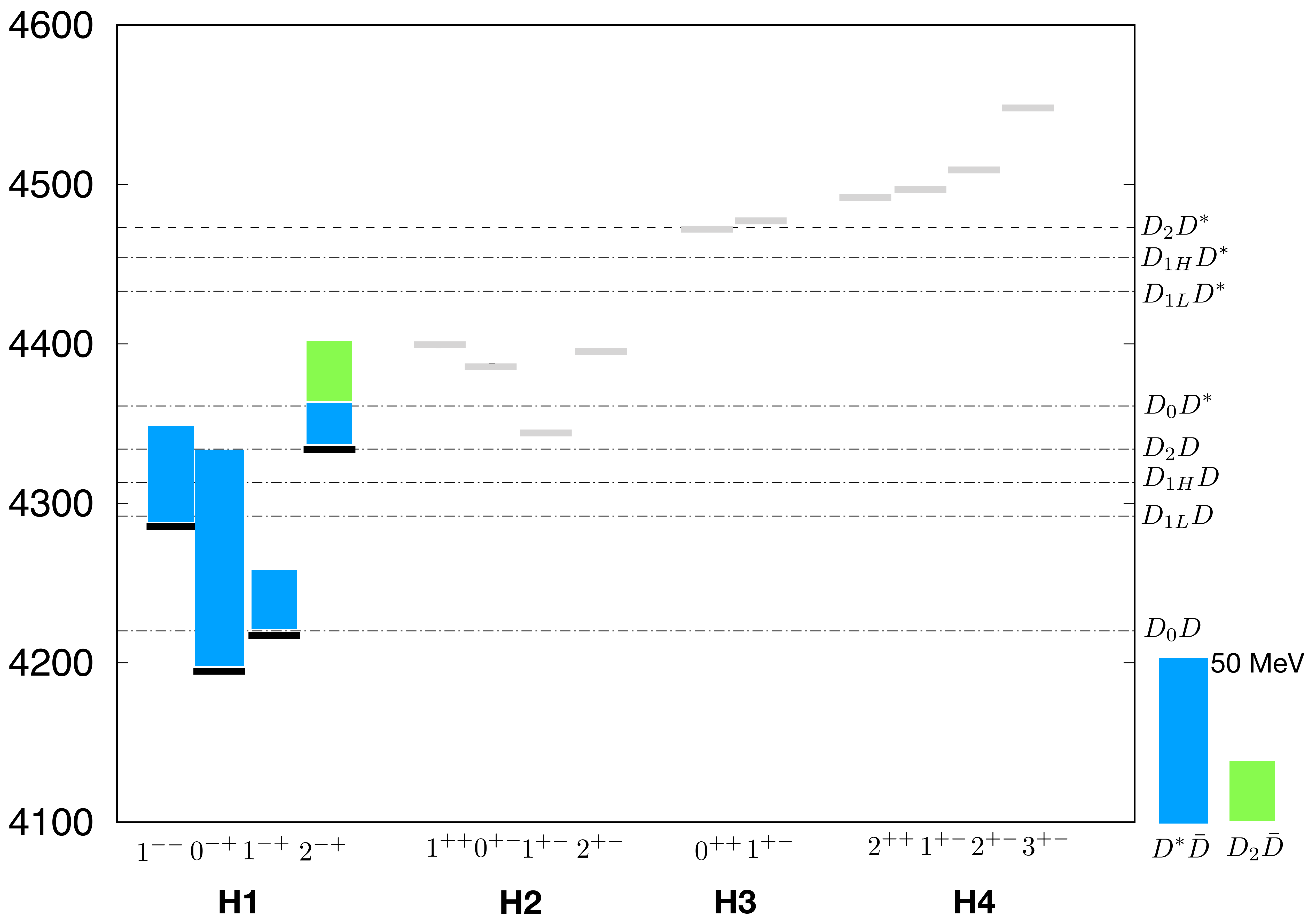
Decay Results



Decay Results



Decay Results



Comparison to Lattice

- $\Gamma(\pi_1 \to b_1\pi) = 400 \pm 120$ MeV $\Gamma(\pi_1 \to f_1\pi) = 90\pm60$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

  $\Gamma(\pi_1 \to b_1\pi) \approx 80$ MeV and $\Gamma(\pi_1 \to f_1\pi) \approx 25$ MeV.

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

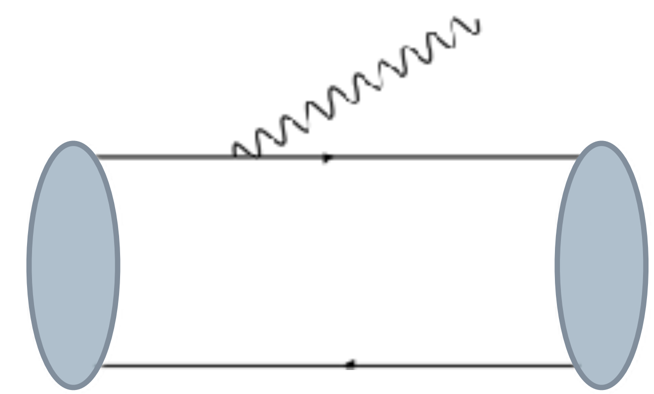
  T. Burns and F. Close, arXiv:hep-ph/0604161

- [model gives a large width]

Comments on Radiative Transitions

Comments on Radiative Transitions

Meson Reminder



no spin flip, parity flip (E1) ~ 100 keV

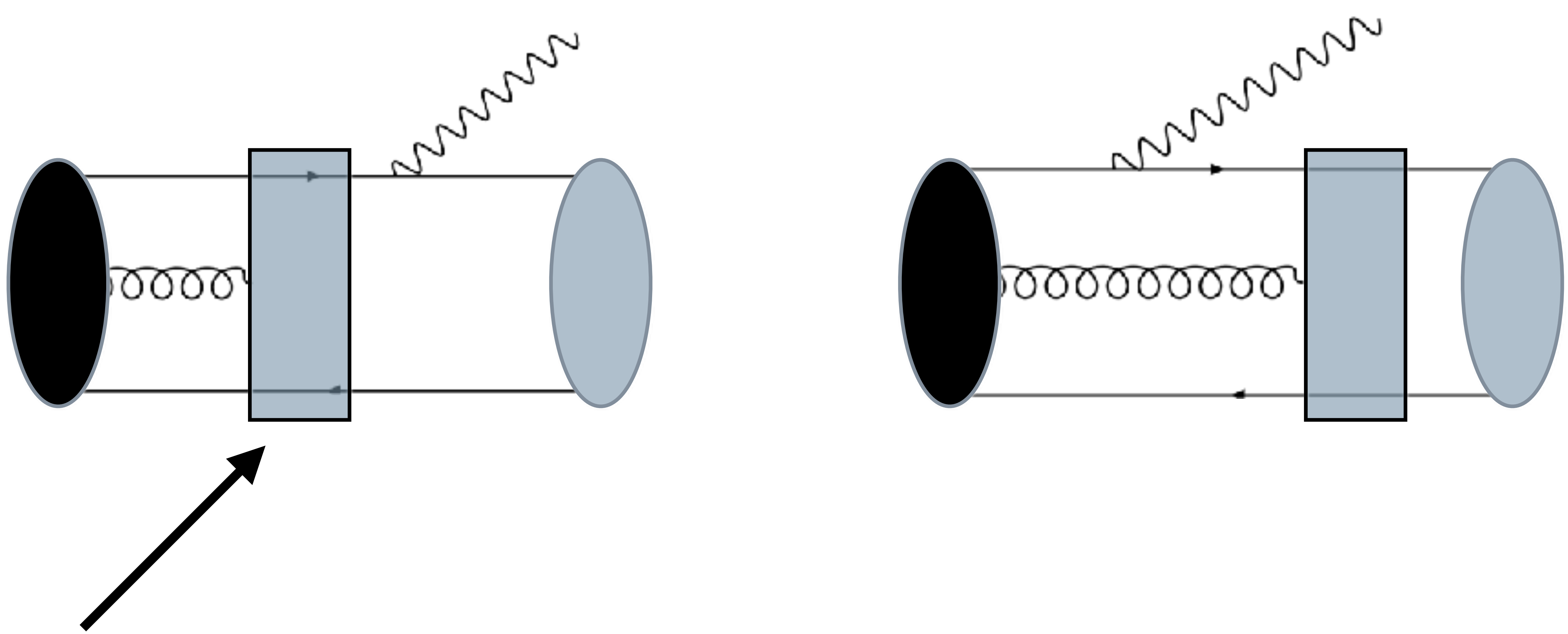
$\psi' \to \chi_{cJ}\gamma \qquad \chi_{cJ} \to J/\psi\gamma$

spin flip, no parity flip (M1) ~ 1 keV

$J/\psi \to \eta_c\gamma \qquad \psi' \to \eta_c\gamma$

Comments on Radiative Transitions

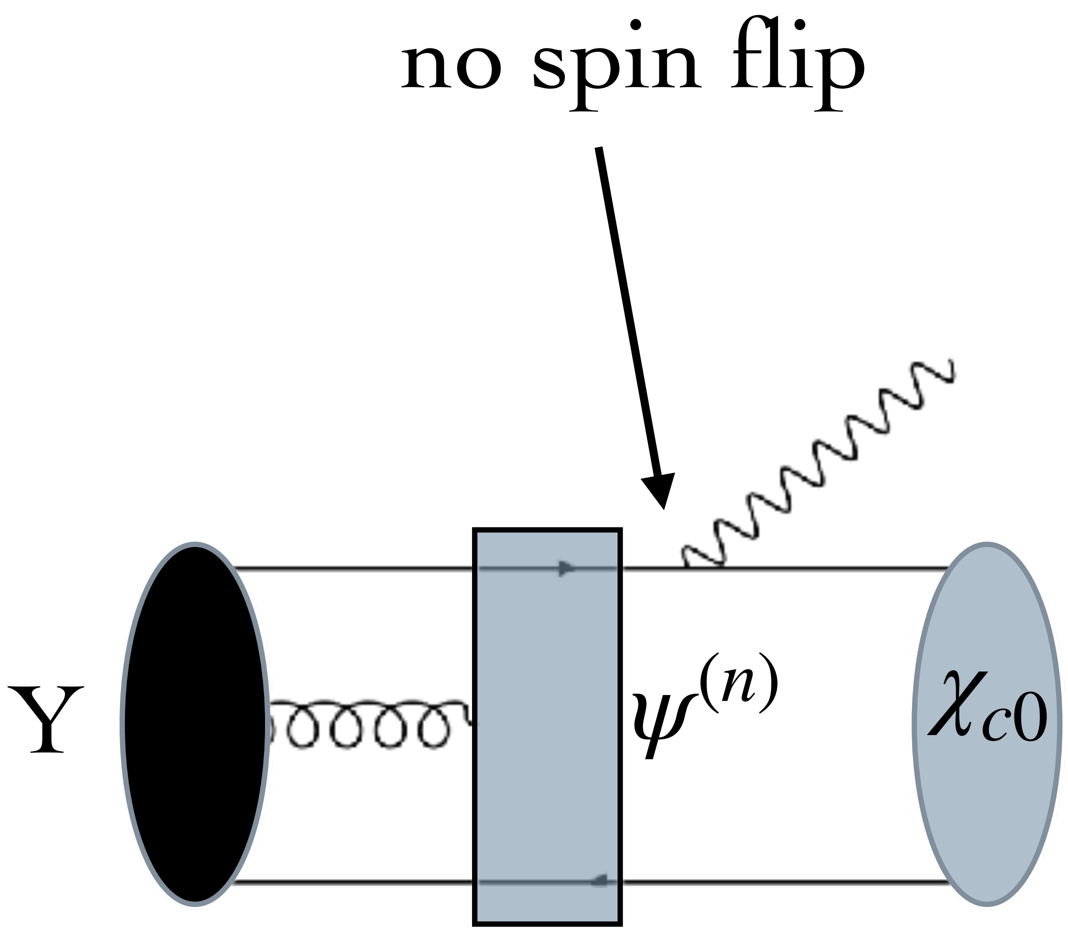
Peng & Szczepaniak

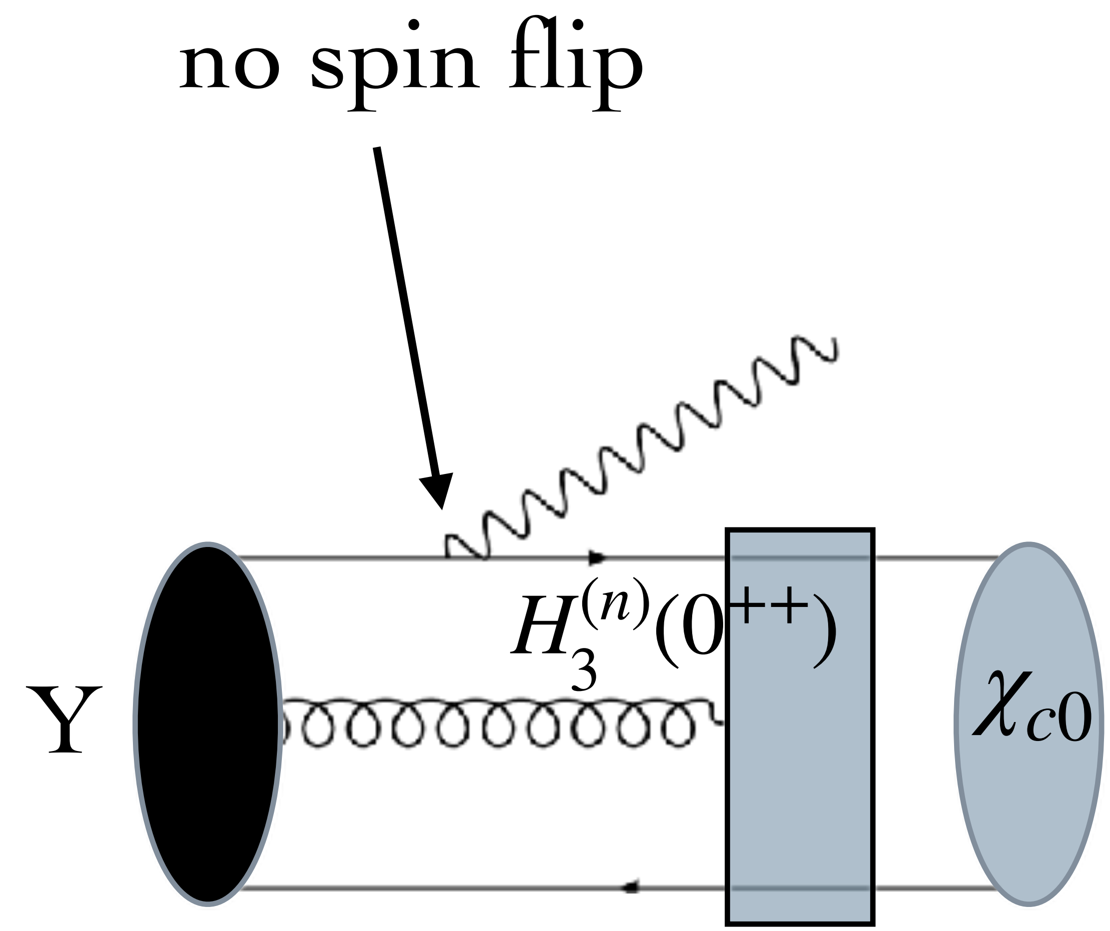


“flux tube de-excitation” [qqg or ggg; must contain a spin flip]

Comments on Radiative Transitions

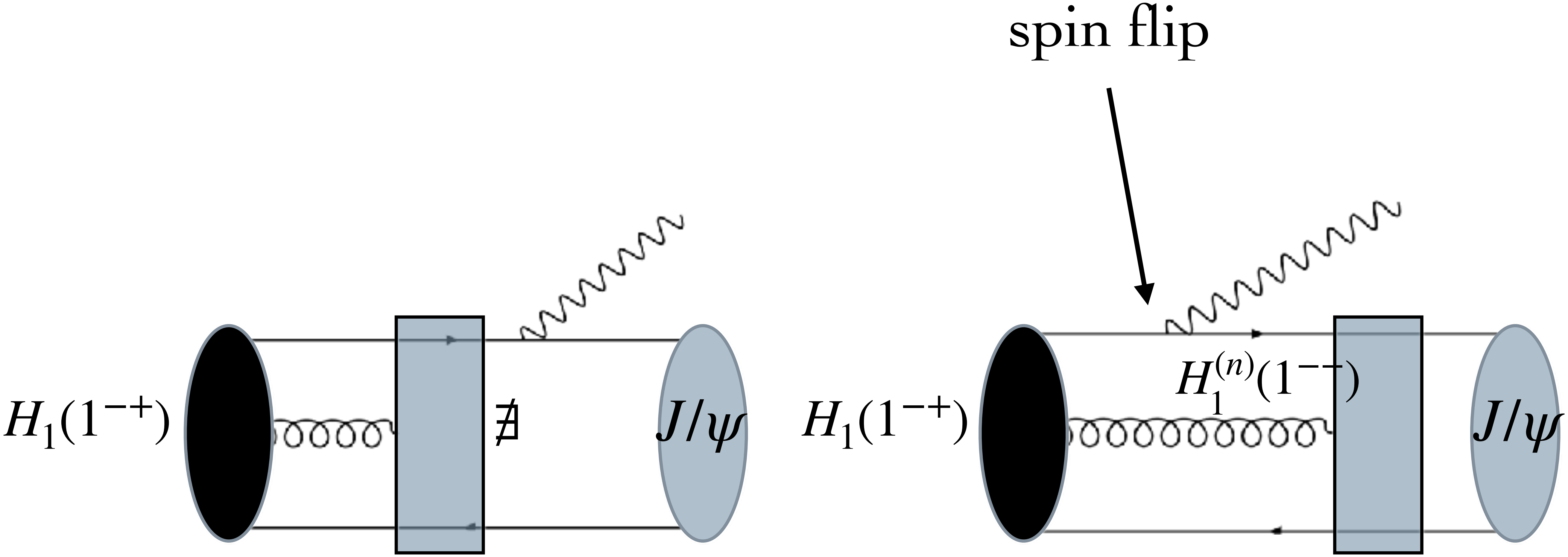
$$\Upsilon \to \chi_{c0}\gamma$$





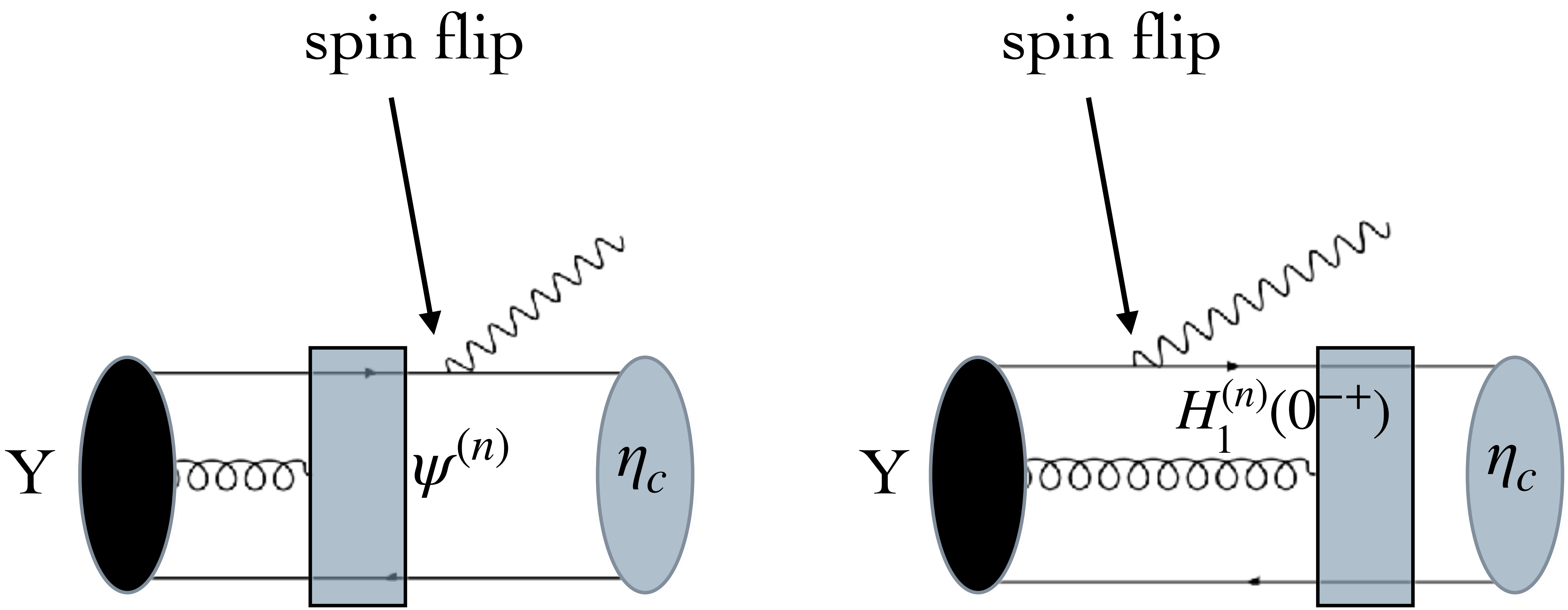
Comments on Radiative Transitions

$$H_1(1^{-+}) \to J/\psi\gamma$$



Comments on Radiative Transitions

$$Y \to \eta_c \gamma$$



Comments on Radiative Transitions

Conclusions:

$$Y \to \chi_{c0}\gamma \sim 100 \cdot [H_1(1^{-+}) \to J/\psi\gamma] \sim 25 \cdot [Y \to \eta_c\gamma]$$

Comparison to Lattice

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

J. J. Dudek, R. Edwards and C. E. Thomas, Phys. Rev. D 79, 094504 (2009).

Comments on Radiative Transitions

JLab HLGT:

$$Y \to \chi_{c0}\gamma \sim 100 \cdot [H_1(1^{-+}) \to J/\psi\gamma] \sim 25 \cdot [Y \to \eta_c\gamma]$$

< 20 keV   115(16) keV   42(18) keV

Comments on Radiative Transitions

JLab HLGT:

$$Y \to \chi_{c0}\gamma \sim 100 \cdot [H_1(1^{-+}) \to J/\psi\gamma] \sim 25 \cdot [Y \to \eta_c\gamma]$$

< 20 keV 115(16) keV 42(18) keV

New Conclusions:

I have no idea what I am talking about…

Complex Scaling Method

The idea:

Quantum mechanics remains well-defined under

$$U(\theta) r U^\dagger(\theta) = r \exp(i\ \theta)$$
$$U(\theta) p U^\dagger(\theta) = p \exp(-i\ \theta)$$

Doing so reveals poles of the Schrödinger equation

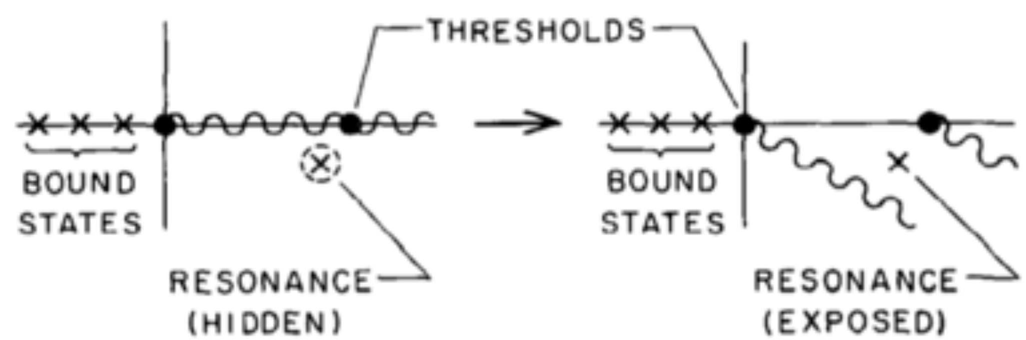
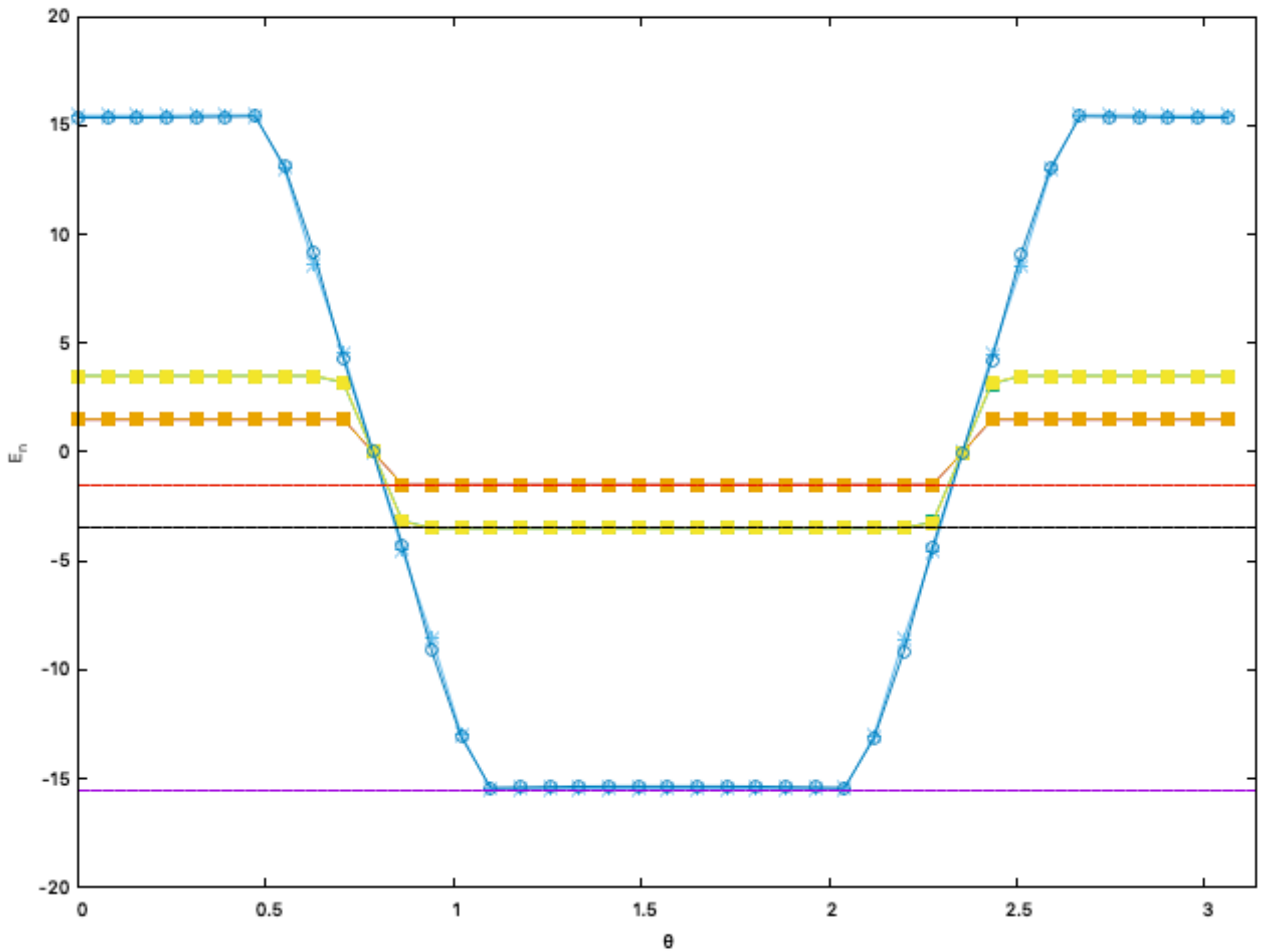


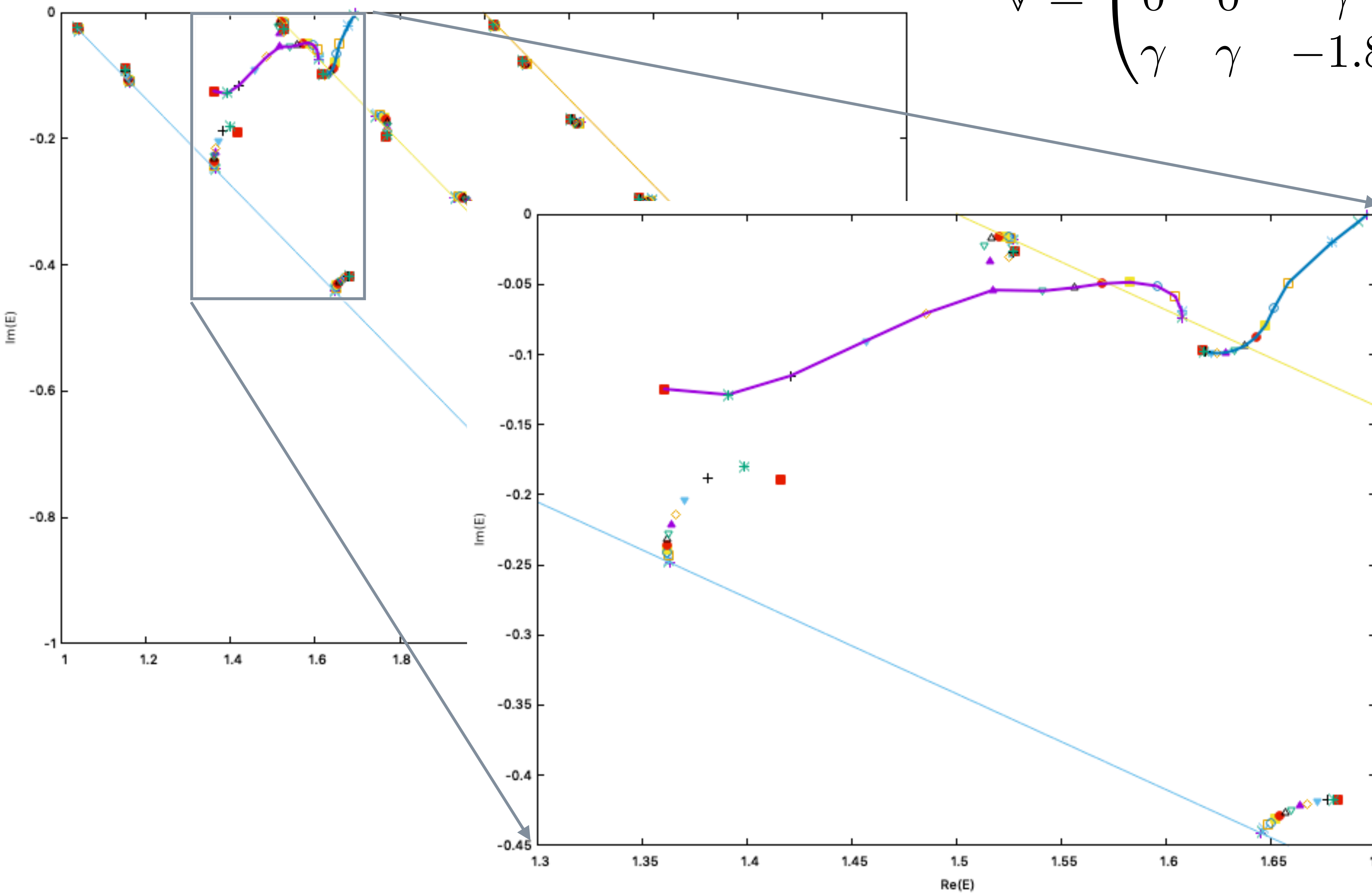
Figure 3 Effect of dilatation transformation on a many-body Hamiltonian. Again bound states and thresholds are invariant. However, as the continua rotate, complex resonance eigenvalues may be exposed. Such eigenvalues correspond to poles of the resolvent $R_\phi(z)$, but are "hidden" on a higher sheet if $\theta = 0$, and will be exposed if the cuts are appropriately moved.

Ex. SHO energy levels vs θ



Ex. Poles in a three-channel model

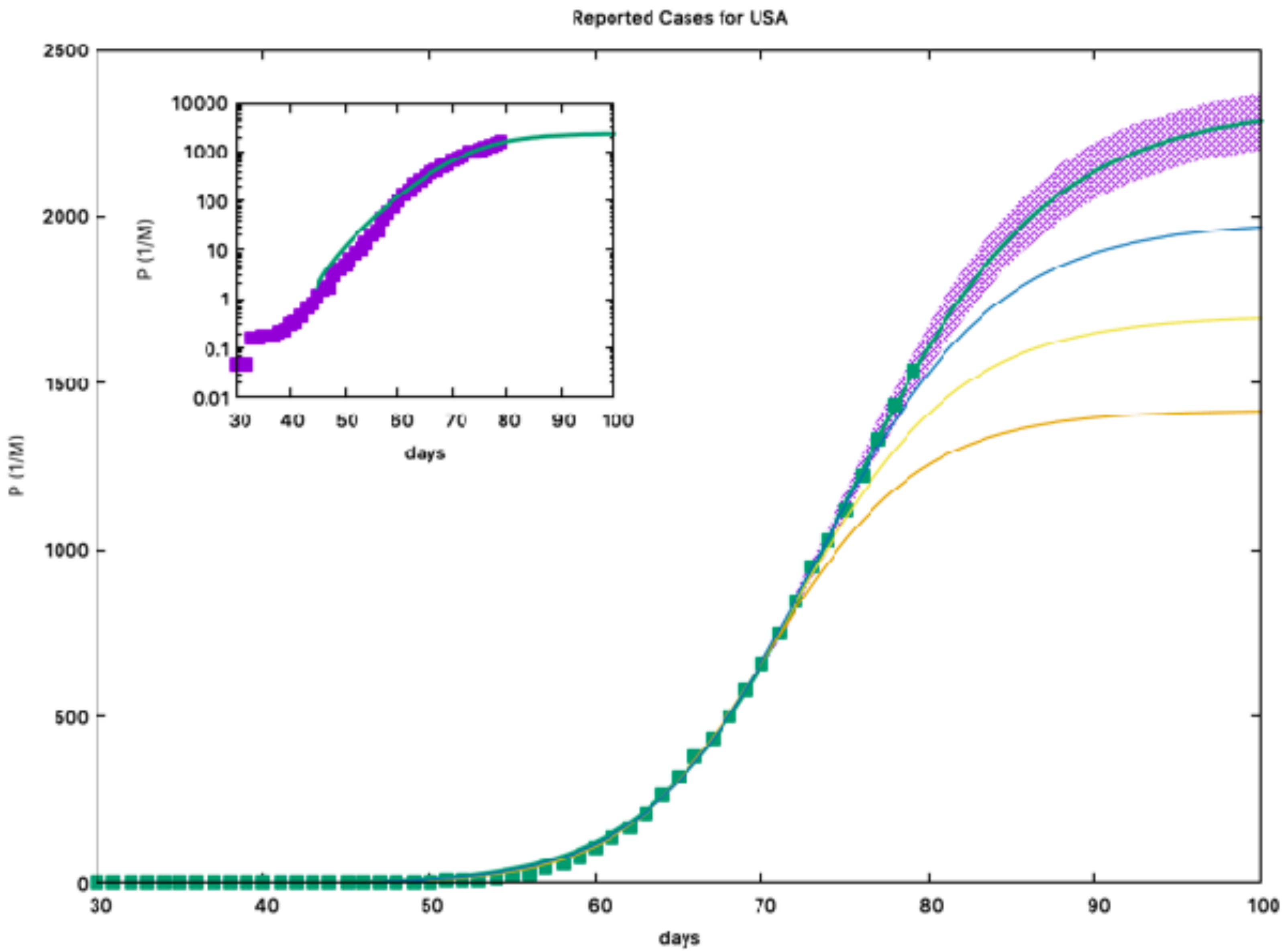
$$\mathbb{V} = \begin{pmatrix} 0 & 0 & \gamma \\ 0 & 0 & \gamma \\ \gamma & \gamma & -1.8 \end{pmatrix}$$



Coronavirus modelling

The 'Rona

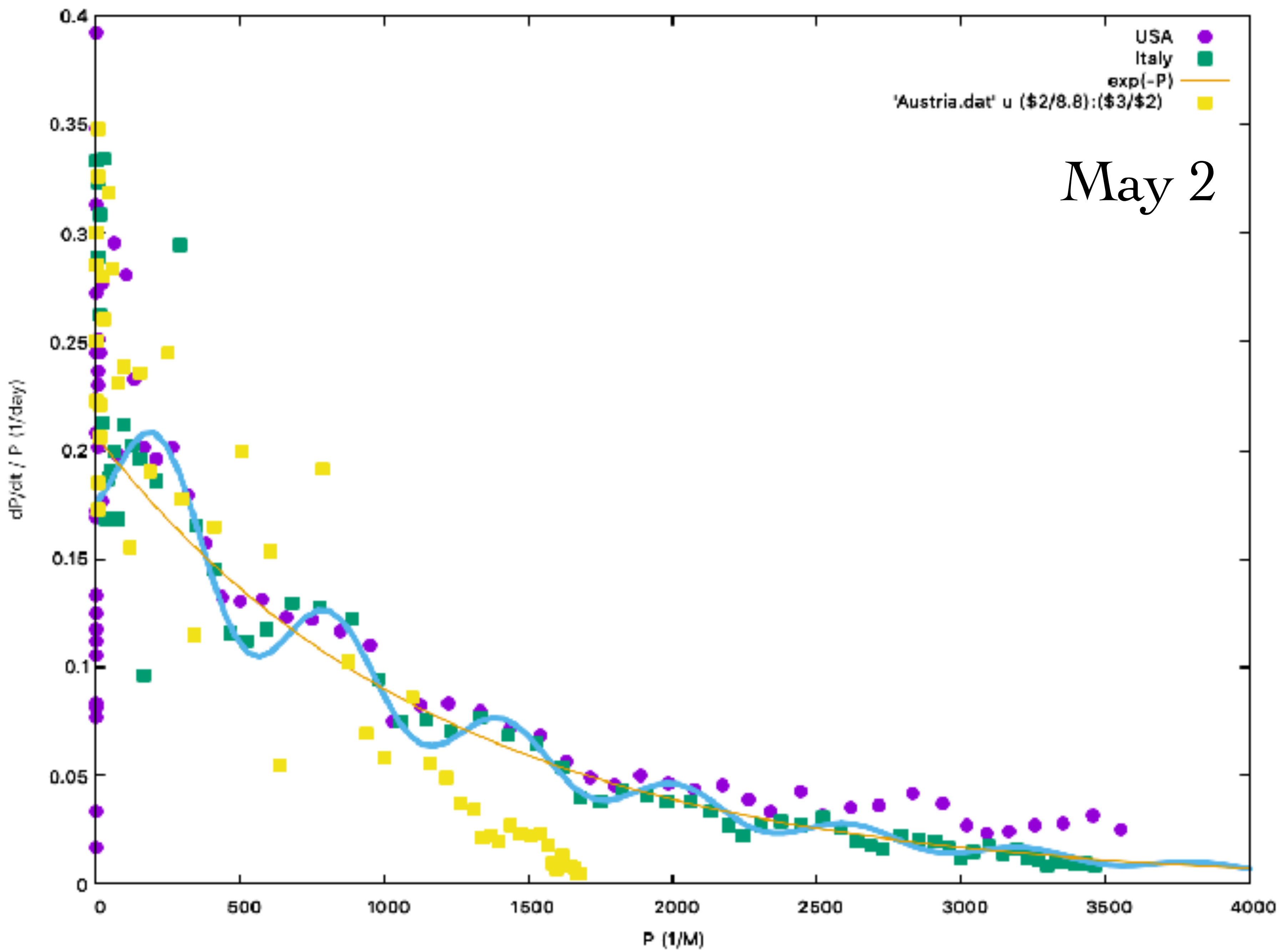
The dangers of a 'good fit'



US Apr 10

The 'Rona

USA tracks Italy with a two week delay. Austria does well!



The wiggles are real and have something to do with the disease progression.

The ‘Rona

A ‘better’ model

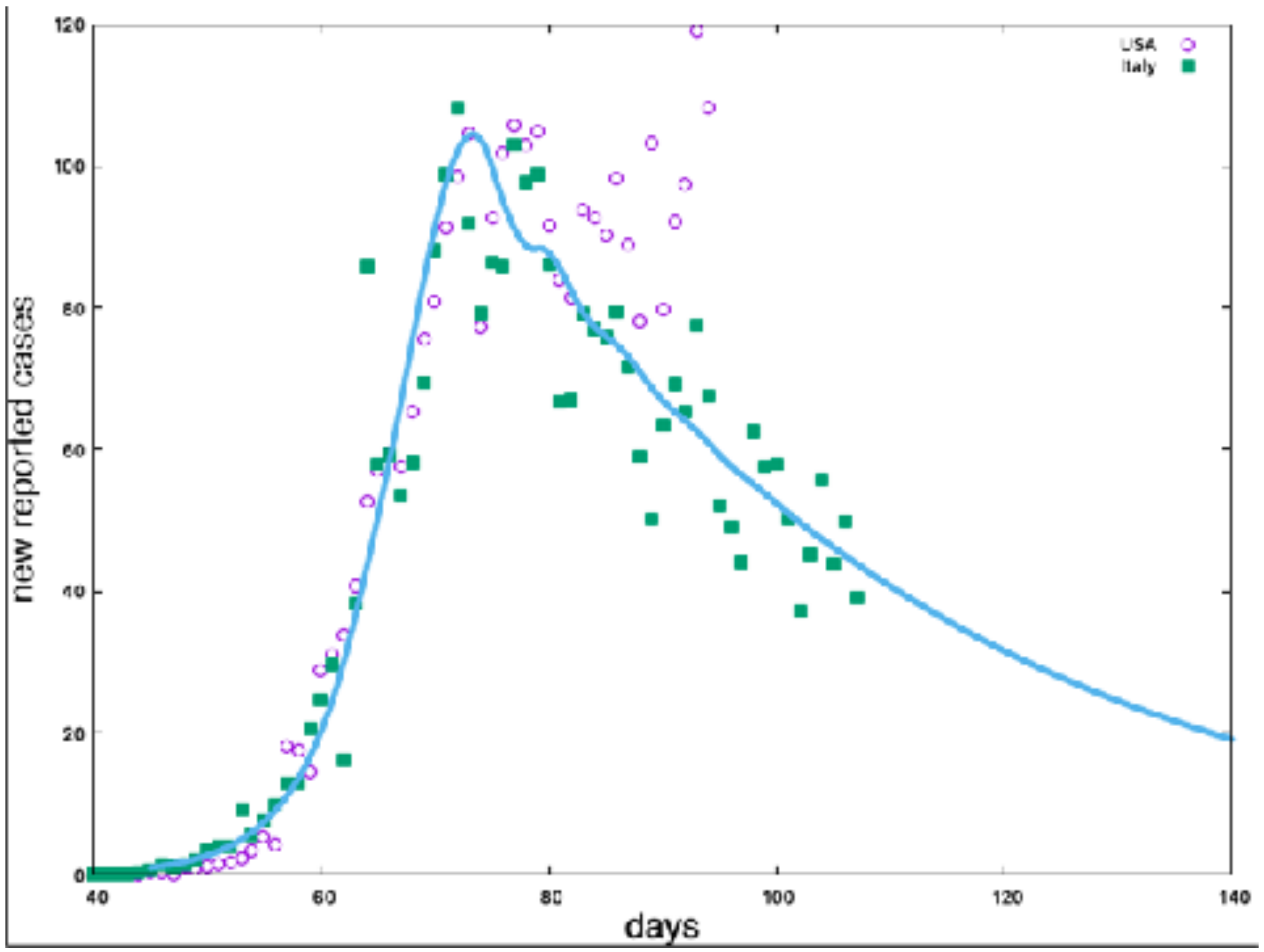
$$\rho(t) = S(t) \int_{-\infty}^{\infty} \beta(t-t')\,\rho(t-t')\,P(t')\,dt'$$

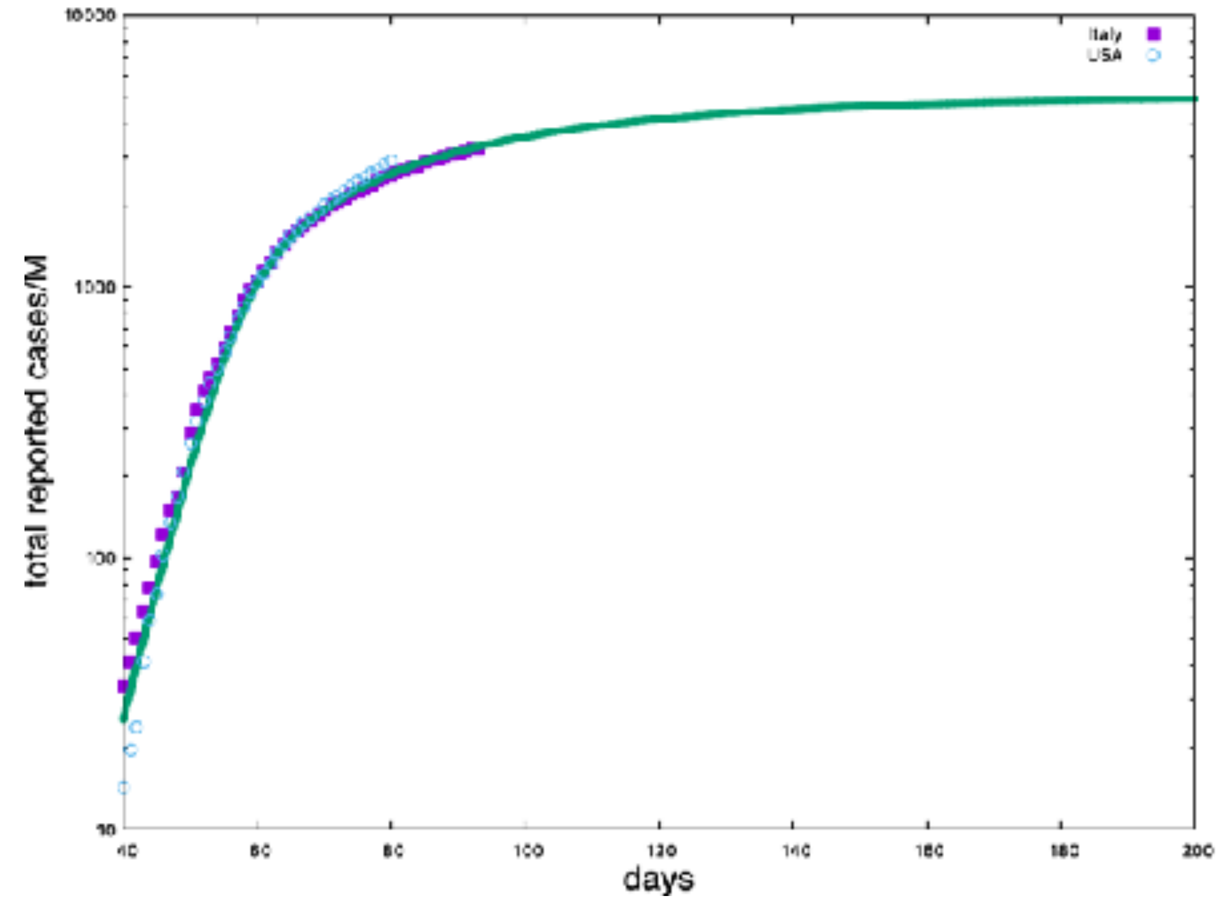
$$S(t) = 1 - \int_{-\infty}^{t} \rho(t')\,dt'$$

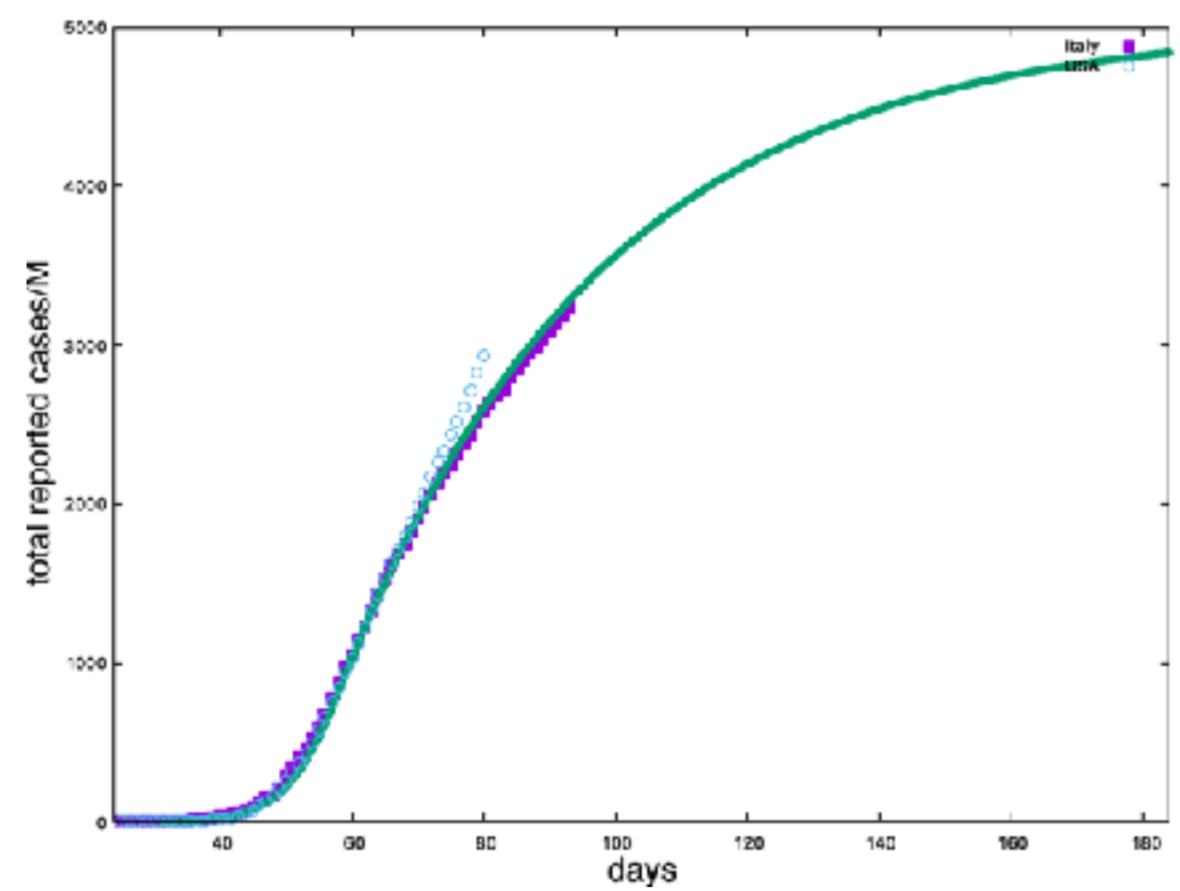
beta is time-dependent transmission

P represents probability of being infectious

The ‘Rona

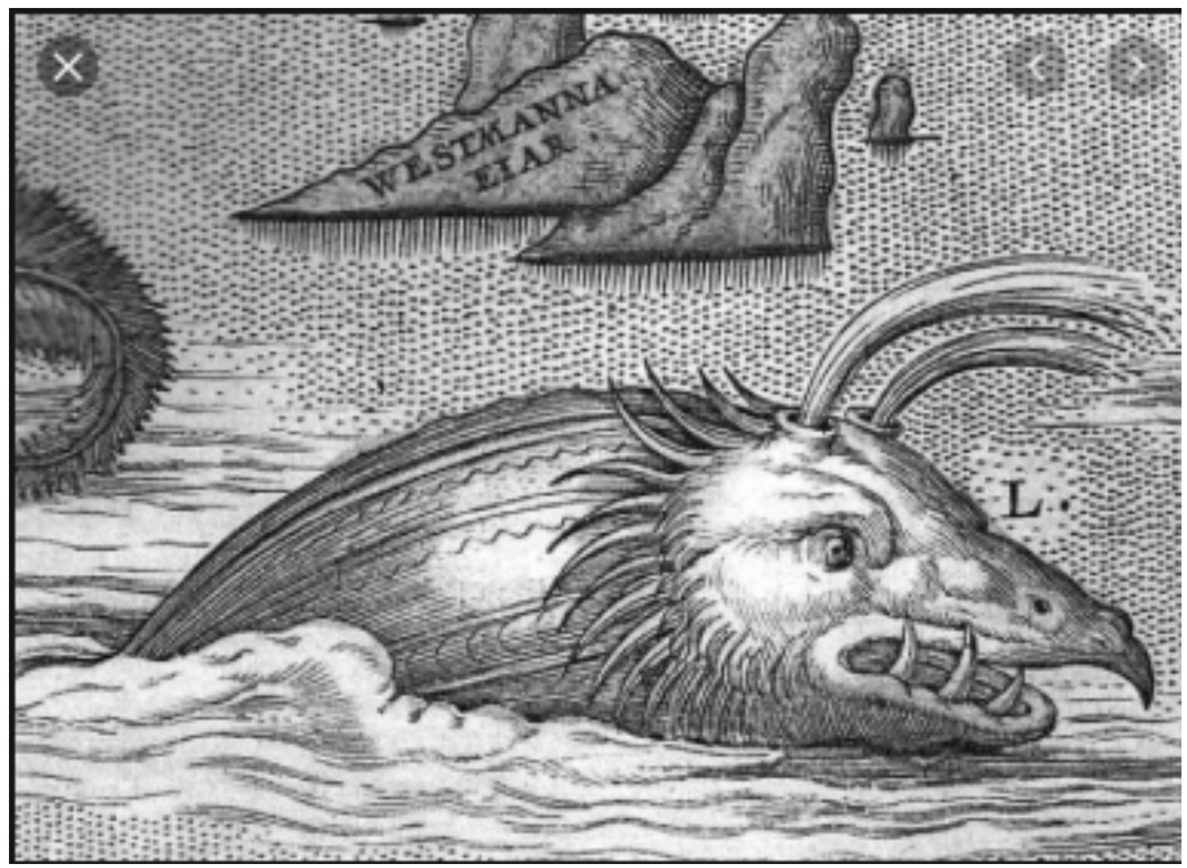






Apr 26, Italy & USA

Conclusions & Observations



Conclusions and Observations

- It appears likely that the LHCb Pqs are (i) real (ii) involve an intricate interplay of production and final state dynamics.
- I hope (!) that we are entering an era of experimental exploration of hybrid mesons, and that we may test the newer lattice/EFT/modelling paradigms.
- Good 'ol QCD will be surprising and challenging us for decades to come!

~fin~