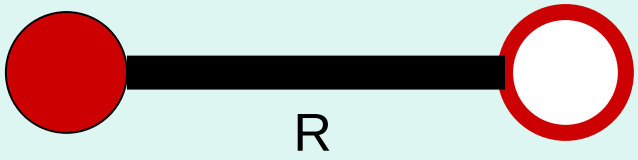
Looking for gluonic hybrid charmonium in e+e- at BaBar and Belle

And the accidental discovery of a new spectroscopy?

Work by FC with Clark Downum; Chris Thomas and Tim Burns

gluonic degrees-of-freedom

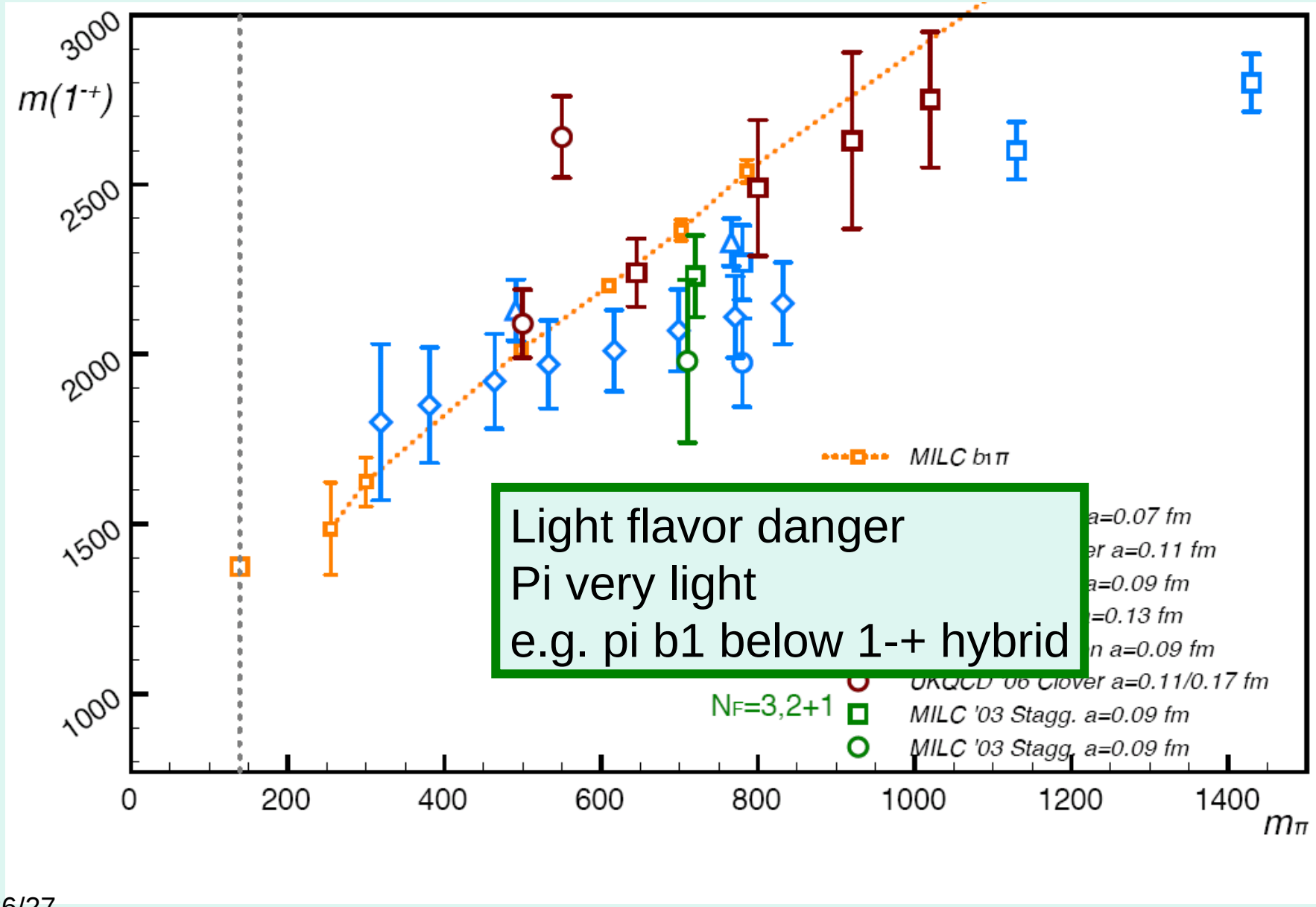


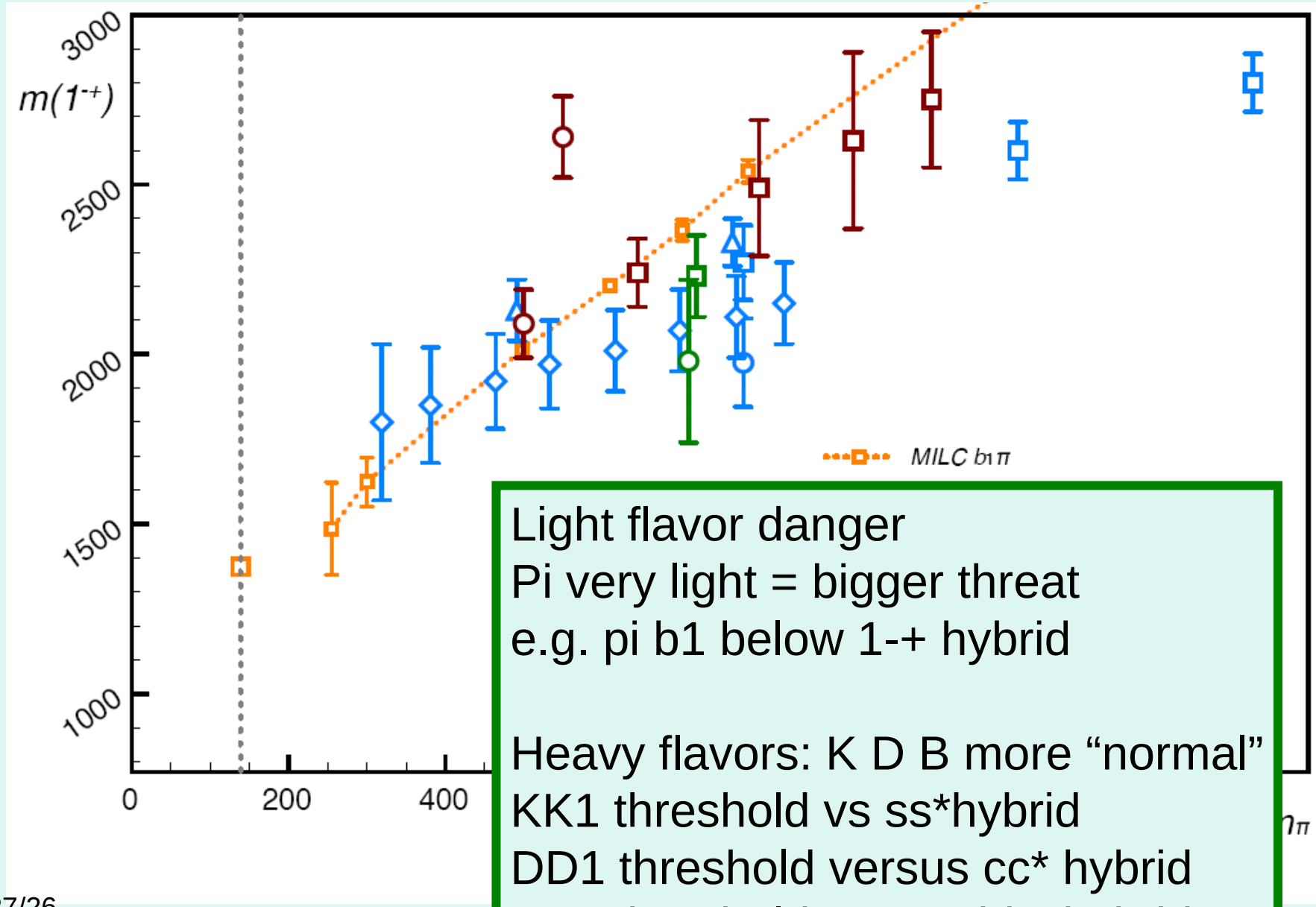
Costs about 1 to 1.5GeV energy to excite phonon "pi/R"
Hybrid qq* @ 2GeV; Hybrid cc* @ 4-4.5GeV

Barnes FC Swanson 93

TABLE I. Predicted 1^{-+} Hybrid Masses.

state	mass (GeV)	model
$H_{u,d}$	1.3-1.8	bag model
	1.8-2.0	flux tube model
–	\sim 2.2 GeV ss* quarks LGT \sim 2 GeV ud flavours….. ……..but beware……	UKQCD…
–		


m(1⁻⁺)
3000
2500
2000
1500
1000
0
200
400
600
800
1000
1200
1400
mπ
MILC b1π
Light flavor danger
Pi very light
e.g. pi b1 below 1-+ hybrid
NF=3,2+1
a=0.07 fm
er a=0.11 fm
a=0.09 fm
=0.13 fm
n a=0.09 fm
UKQCD '06 Clover a=0.11/0.17 fm
MILC '03 Stagg. a=0.09 fm
MILC '03 Stagg. a=0.09 fm



Light flavor danger
Pi very light = bigger threat
e.g. pi b1 below 1-+ hybrid

Heavy flavors: K D B more “normal”
KK1 threshold vs ss*hybrid
DD1 threshold versus cc* hybrid
BB1 threshold versus bb* hybrid

Predicted 1-+ Hybrid masses (with spin splittings)

H_c	≈ 3.9	adiabatic bag model
	4.2-4.5	flux tube model
	4.1-5.3	QCD sum rules (most after 1984)
	4.19(3) $\pm$ sys.	HQLGT

charmonium

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H_c	≈ 3.9	adiabatic bag model
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	4.1-5.3	QCD sum rules (most after 1984)
	4.19(3) $\pm$ sys.	HQLGT

charmonium

Near D(L=0)+D(L=1) thresholds: **DD0; DD1; D*D0;D*D1**
and strongly coupled to these channels

Predicted 1-+ Hybrid masses (with spin splittings)

H_c	≈ 3.9	adiabatic bag model
	4.2-4.5	flux tube model
	4.1-5.3	QCD sum rules (most after 1984)
	4.19(3) $\pm$ sys.	HQLGT

e+e- feebly coupled

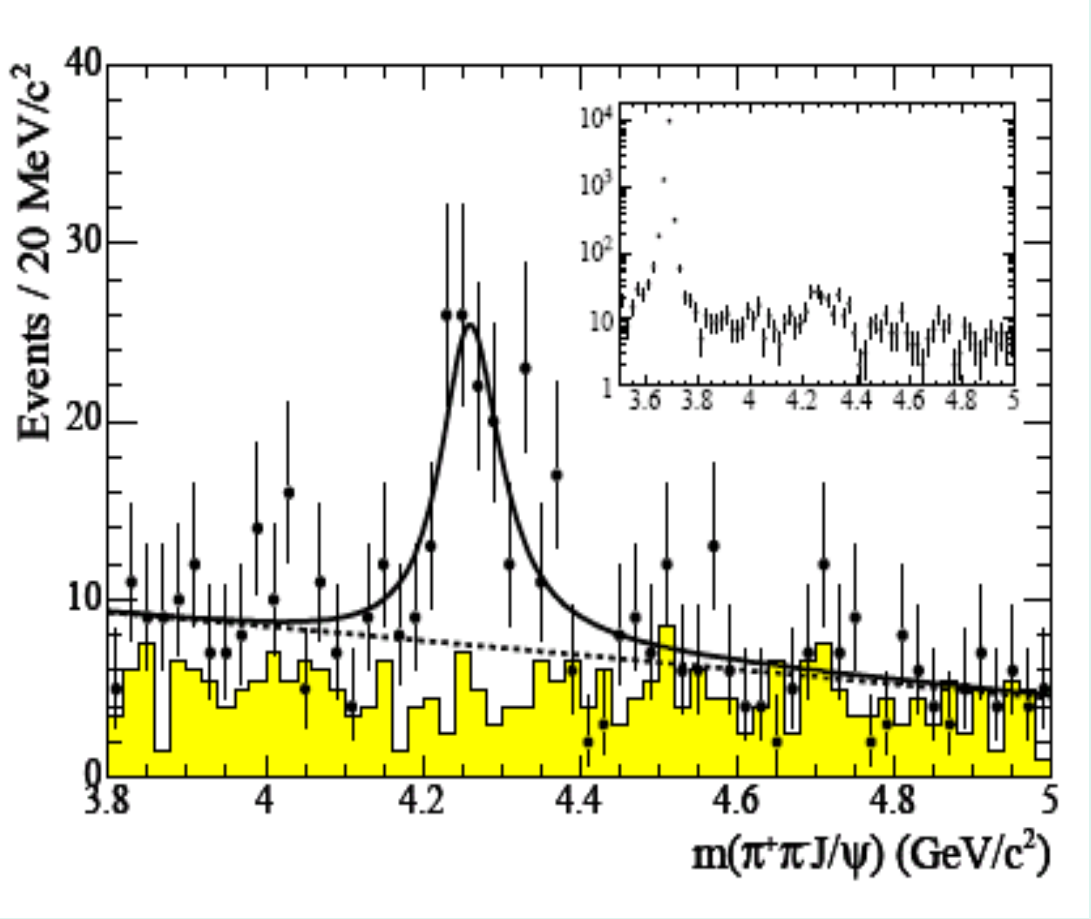
e+e- \to \psi + X?

Spin hyperfine splittings

Barnes FC 82
Chanowitz Sharpe

1- - (4.25) Y(4260?)
1- + (4.1) HQLGT
0- + (3.95) X(3940?)

e+e- \to psi pi pi BaBar sees unusual vector cc*



Y(4260)

No sign of established
3S/2D(4040/4160)
4S(4400)
in the psi pipi data

Y(4260) thus seems anomalous

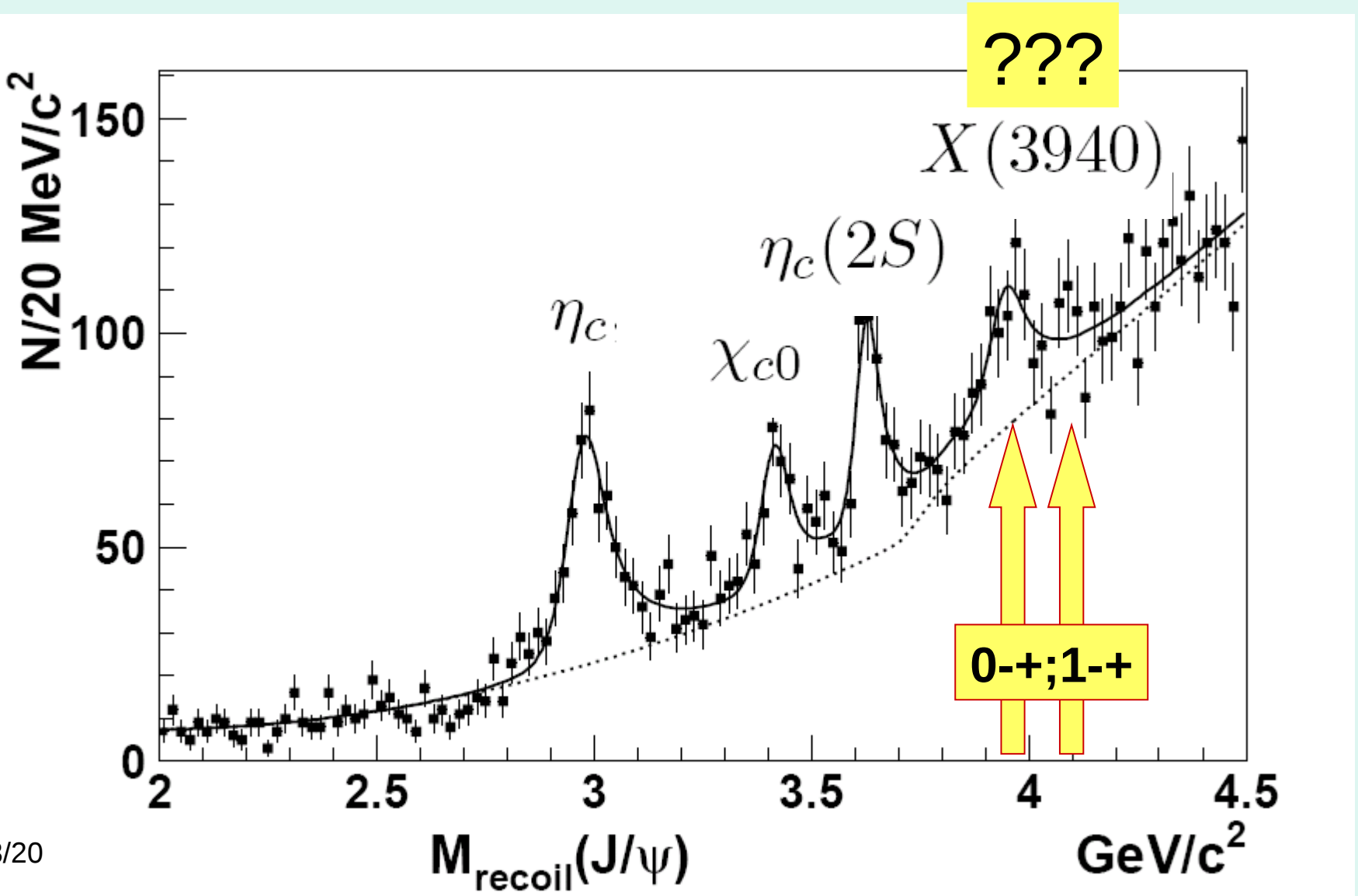
Also no place
for extra cc* state

\Gamma(ee) 5-80eV
Compare \sim 1 keV !!

But width 90MeV dominantly psi pipi !

Belle

e+e- to ψ + X



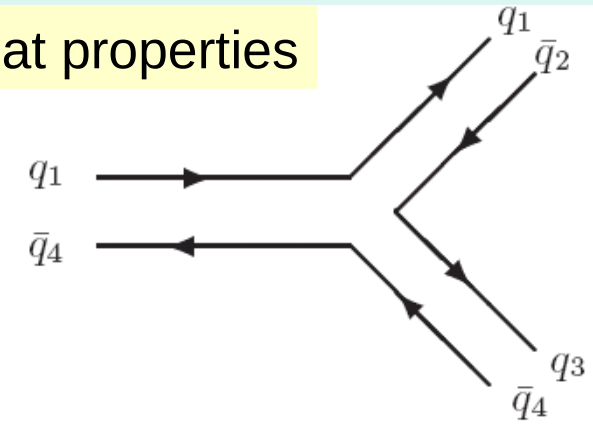
Beyond Spectroscopy

To do more need dynamics:
Production; decays; selection rules

What can lattice say?

Lattice decay and FT compare
Factorisation of OZI
Application to hybrids

What properties

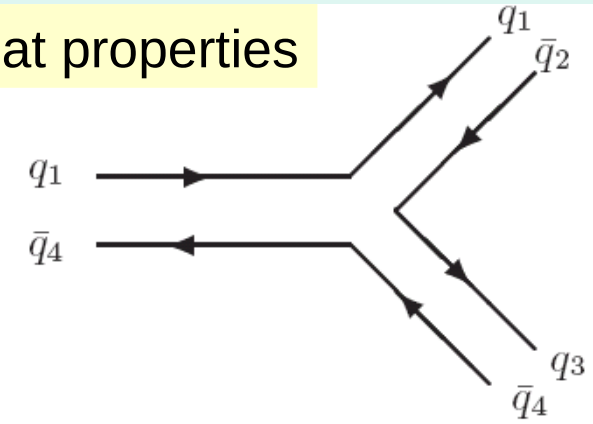


PHYSICAL REVIEW D **77,** 034008 (2008)

Dynamics of hadron strong production and decay

T. J. Burns,* F. E. Close,† and C. E. Thomas‡

What properties



PHYSICAL REVIEW D **77,** 034008 (2008)

Dynamics of hadron strong production and decay

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Lattice S-wave decays now calculated Michael McNeile

confirms Flux Tube for hybrid:conventional

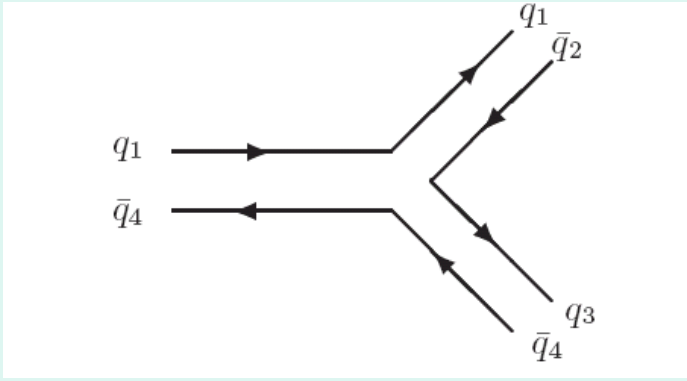
	$\pi_1 \to b_1(^1P_1)\pi$	$\pi_1 \to f_1(^3P_1)\pi$
Lattice	2.9 ± 0.4	1.5 ± 0.4
Flux tube	2.9	1.4

Michael McNeile 06

FC Burns 06

Exactly **WHAT** is Lattice revealing about dynamics:
What aspect(s) of Flux Tube model are being confirmed?

$$^1P_1\pi : ^3\!\acute{P}_1\pi$$



qq* create in S=1

$$\left\{\begin{matrix}0&1&1\\0&0&0\\0&1&1\end{matrix}\right\}\left\{\begin{matrix}0&1&1\\0&1&1\end{matrix}\right\}\left\{\begin{matrix}0&1&1\\1&1&1\end{matrix}\right\}\left\{\begin{matrix}\frac{1}{2}&\frac{1}{2}&0\\\frac{1}{2}&\frac{1}{2}&0\\1&1&0\end{matrix}\right\}$$

$$\left\{\begin{matrix}1&1&1\\0&0&0\\1&1&1\end{matrix}\right\}\left\{\begin{matrix}1&1&1\\0&1&1\end{matrix}\right\}\left\{\begin{matrix}1&1&1\\1&1&1\end{matrix}\right\}\left\{\begin{matrix}\frac{1}{2}&\frac{1}{2}&1\\\frac{1}{2}&\frac{1}{2}&0\\1&1&1\end{matrix}\right\}$$

→ **2**

qq* create in S=0

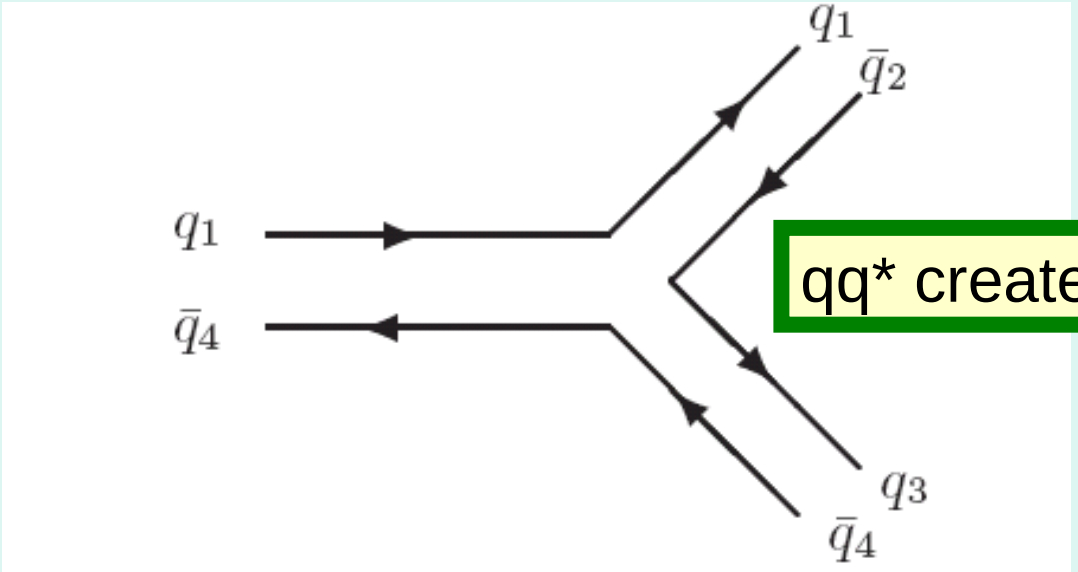
$$\left\{\begin{matrix}\frac{1}{2}&\frac{1}{2}&0\\\frac{1}{2}&\frac{1}{2}&0\\0&1&0\end{matrix}\right\}:\left\{\begin{matrix}\frac{1}{2}&\frac{1}{2}&0\\\frac{1}{2}&\frac{1}{2}&0\\0&1&1\end{matrix}\right\}$$

→ **0**

	$\pi_1 \to b_1(^1P_1)\pi$	$\pi_1 \to f_1(^3P_1)\pi$
Lattice	2.9 ± 0.4	1.5 ± 0.4
Flux tube	2.9	1.4

J – S = “L”

Factorisation of S and L



qq* created in S=1

Factorisation and S=1 creation is powerful result if generally true.

S=0 cannot decay to S=0 + S=0 “spin singlet selection rule”

Determine nature of Y(4260) by DD_1 pattern

SL Factorisation and S=1 selection rules for psi*(cc*) \to DD_1

PHYSICAL REVIEW D 77, 034008 (2008)

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T. J. Burns,* F. E. Close,† and C. E. Thomas‡

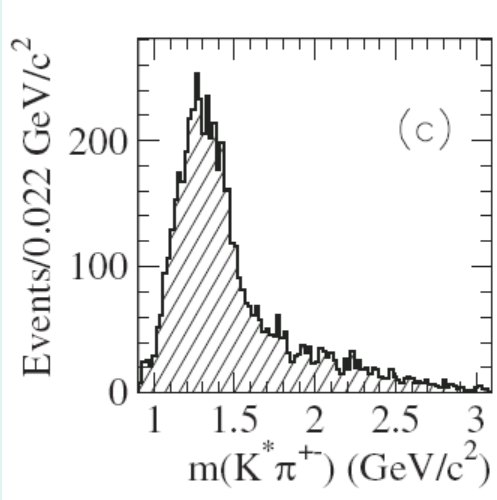
$$\Gamma(^3\mathrm{S}_1 \to D_{1H} D) = 0$$
$$\Gamma(^3\mathrm{D}_1 \to D_{1L} D) = 0$$
$$\Gamma(^1\Pi\mathrm{P}_1(\mathrm{hybrid}) \to D_1(^1\mathrm{P}_1) D) = 0$$

Also applies to KK_1 decays of ss* vectors e.g. ISR around 2.2 GeV

PHYSICAL REVIEW D 71, 052001 (2005)

$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, and $K^+K^-K^+K^-$ cross sections at center-of-mass energies 0.5–4.5 GeV measured with initial-state radiation

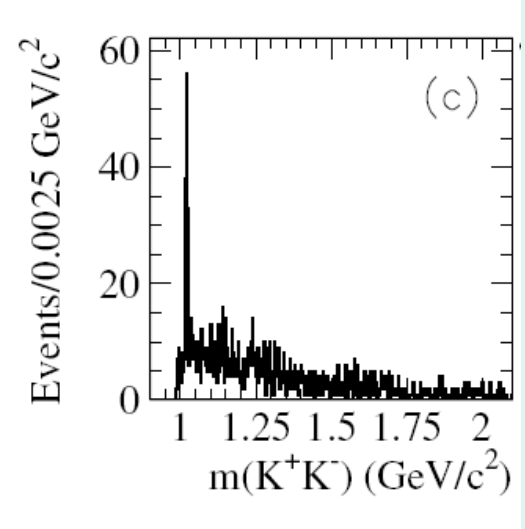
e+e- ⇒ KK_1

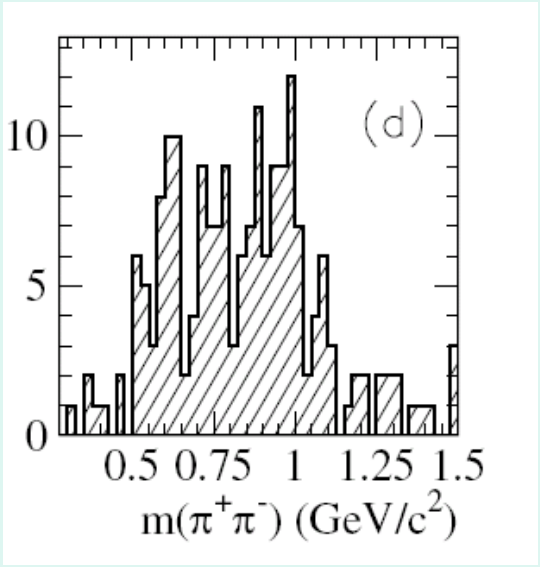


Intriguing resonant signal at 2175
= phi(hybrid)??

2175 – m(phi) = 4265 – m(psi) !!??

⇒ phi pi pi





Jlab look in diffractive

SL Factorisation and S=1 selection rules for psi*(cc*) \to DD_1

PHYSICAL REVIEW D 77, 034008 (2008)

Dynamics of hadron strong production and decay

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$$\Gamma(^3\mathrm{S}_1 \to D_{1H} D) = 0$$
$$\Gamma(^3\mathrm{D}_1 \to D_{1L} D) = 0$$
$$\Gamma(^1\Pi\mathrm{P}_1(\mathrm{hybrid}) \to D_1(^1\mathrm{P}_1) D) = 0$$

Problem is – it can fail **BIG**

Factorisation implies a **small** scalar

$$\sigma(e^+e^- \to {}^3\mathrm{S}_1 + {}^3\mathrm{P}_1) > \sigma(e^+e^- \to {}^3\mathrm{S}_1 + {}^3\mathrm{P}_0)$$

$^3\mathrm{S}_1$

$$\sigma(\psi\chi_2) \to 0$$

$$\sigma(\psi\chi_0) = \frac{3}{4}\sigma(\psi\chi_1).$$

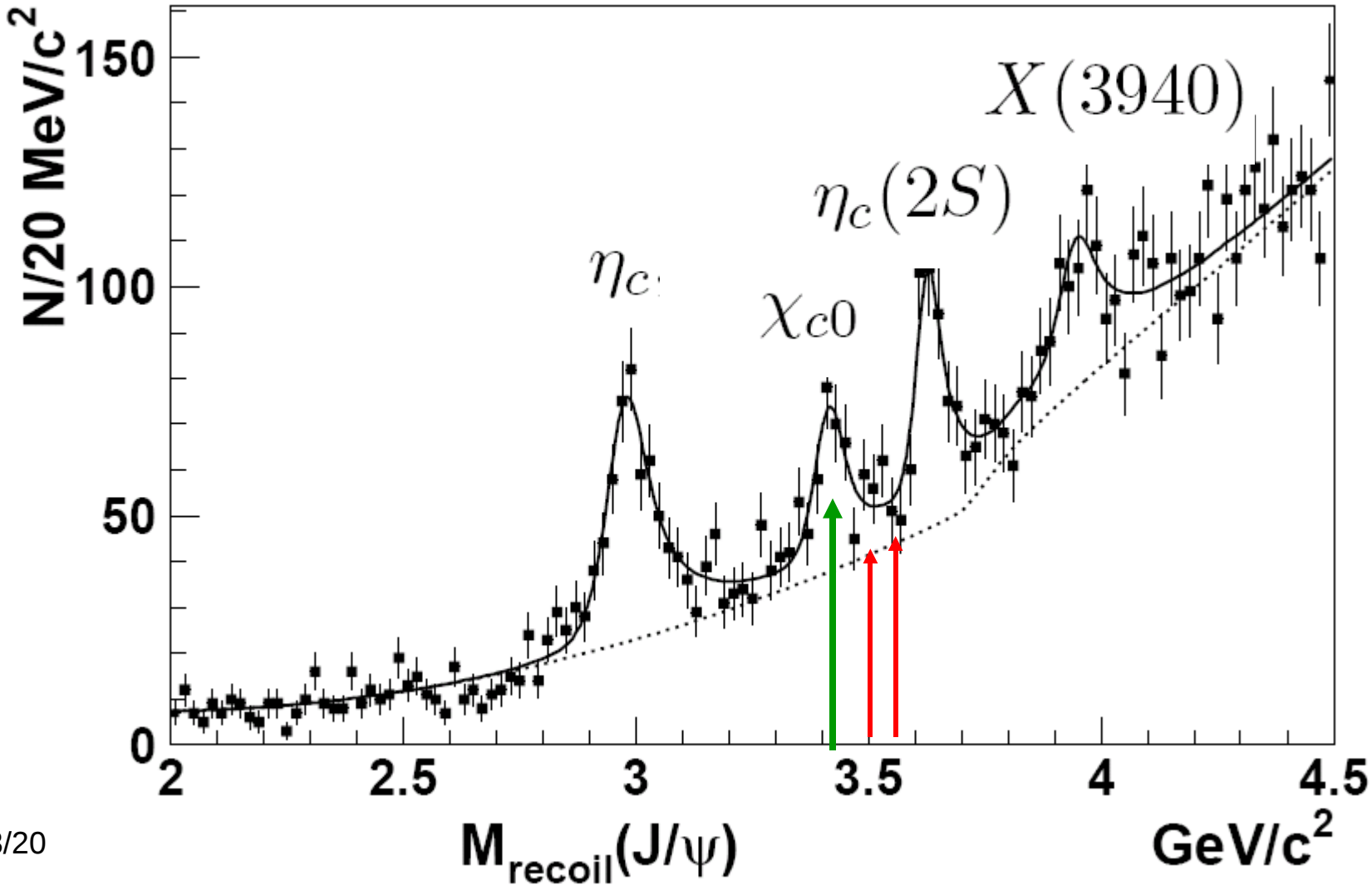
$^3\mathrm{D}_1$

$$\sigma(\psi\chi_0) \to 0$$

$$\sigma(\psi\chi_1) = \frac{5}{3}\sigma(\psi\chi_2)$$

Belle

e+e- to ψ + X



Factorisation implies a small scalar

$$\sigma(e^+e^- \to {}^3\mathrm{S}_1 + {}^3\mathrm{P}_1) > \sigma(e^+e^- \to {}^3\mathrm{S}_1 + {}^3\mathrm{P}_0)$$

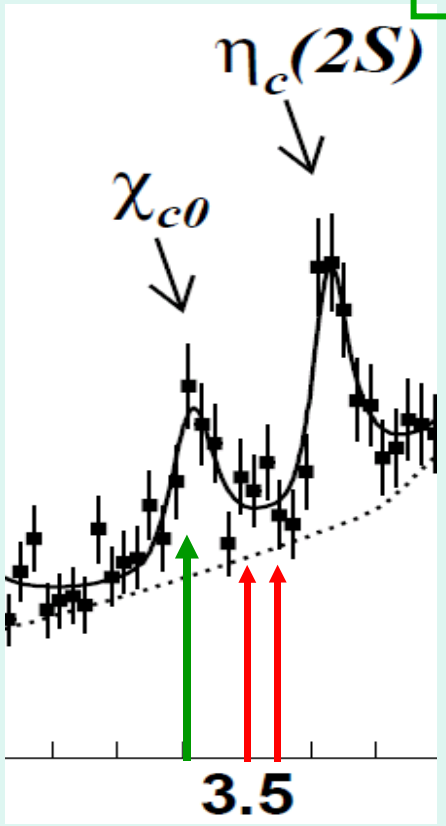
OgE implies a LARGE scalar

$$\sigma(\psi\chi_2 : \psi\chi_1 : \psi\chi_0) \sim 5 : 3 : 121.$$

Charmonium production in $e^+e^- \to \psi + X(c\bar{c})$ and $e^+e^- \to D^*D_J$

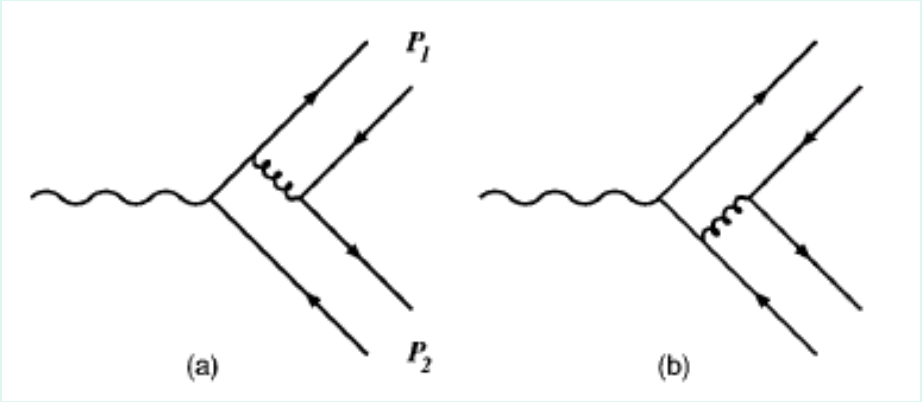
Frank Close*
Rudolf Peierls Centre for Theoretical Physics, University of Oxford , 1 Keble Road, Oxford, OX1 3NP

Clark Downum†
Clarendon Laboratory, University of Oxford, Parks Road, Oxford, OX1 3PU



Data = Large (only?) scalar

Charm meson production: V+(SAT)

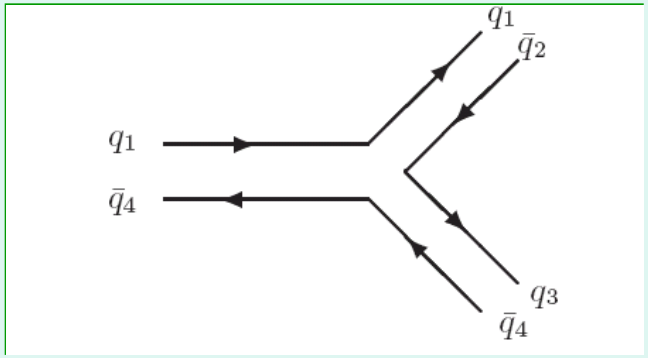


ONLY D* D0; not D*D1 or D*D2

Test factorisation rule:

e+e- \to D*(-)D2(++) = 0

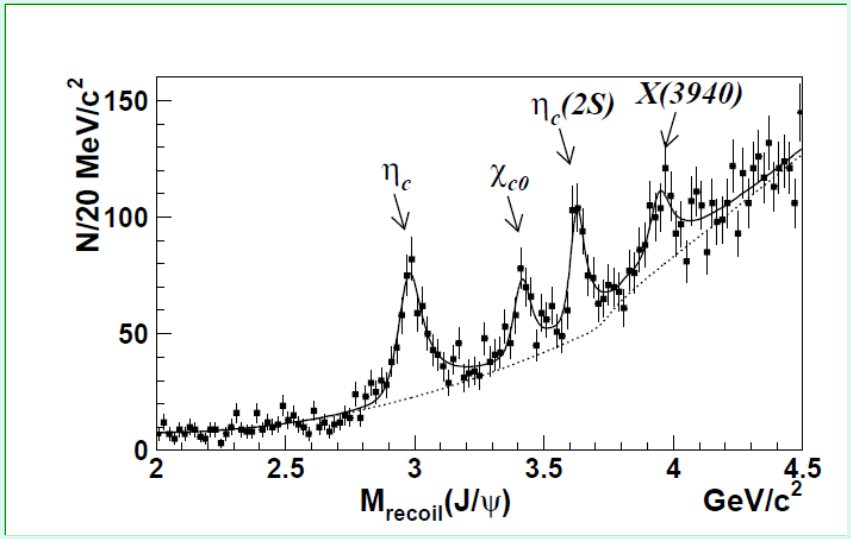
Summary



Factorisation of J and S (L)

Dynamics driven by Clebsches

Selection rules: V(-)T(++)=0



Large scalar = OgE

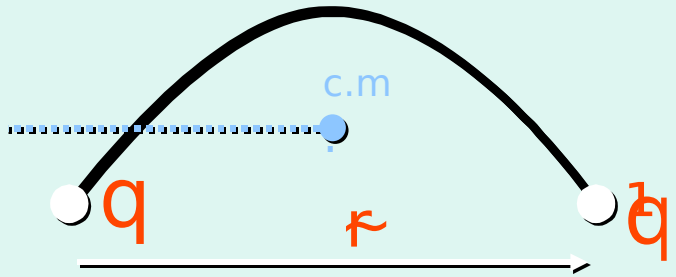
Violates selection rules:V(-)T(++) large

4260 decays….

…using strong selection rules to distinguish candidates…

Conventional charmonium
Hybrid charmonium
Tetraquark csc*s*;
Charm molecule D*D1

flux-tube breaking and hybrid decays



Isgur Paton 92 light exotics

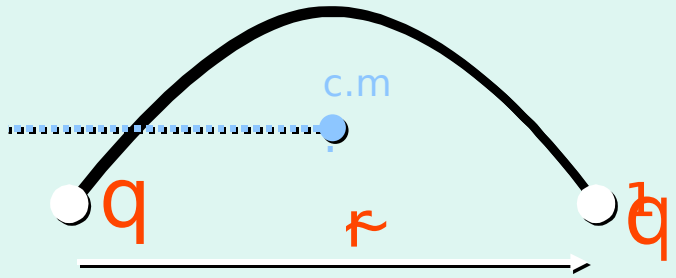
FC Page 95 all

Break tube: S+P states yes; S+S suppressed

flux-tube breaking and hybrid decays

Isgur Paton 92 light exotics

FC Page 95 all



Break tube: S+P states yes; S+S suppressed

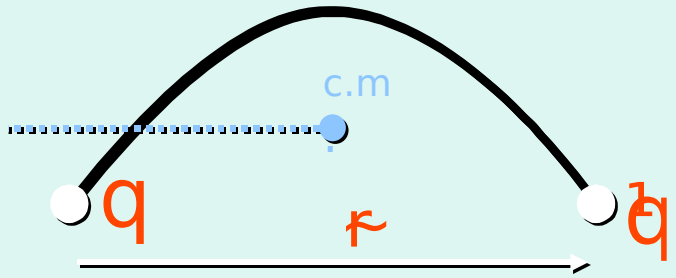
Look for DD_1 and D*D_0 near threshold

Look for psi pipi and h1c eta

flux-tube breaking and hybrid decays

Isgur Paton 92 light exotics

FC Page 95 all



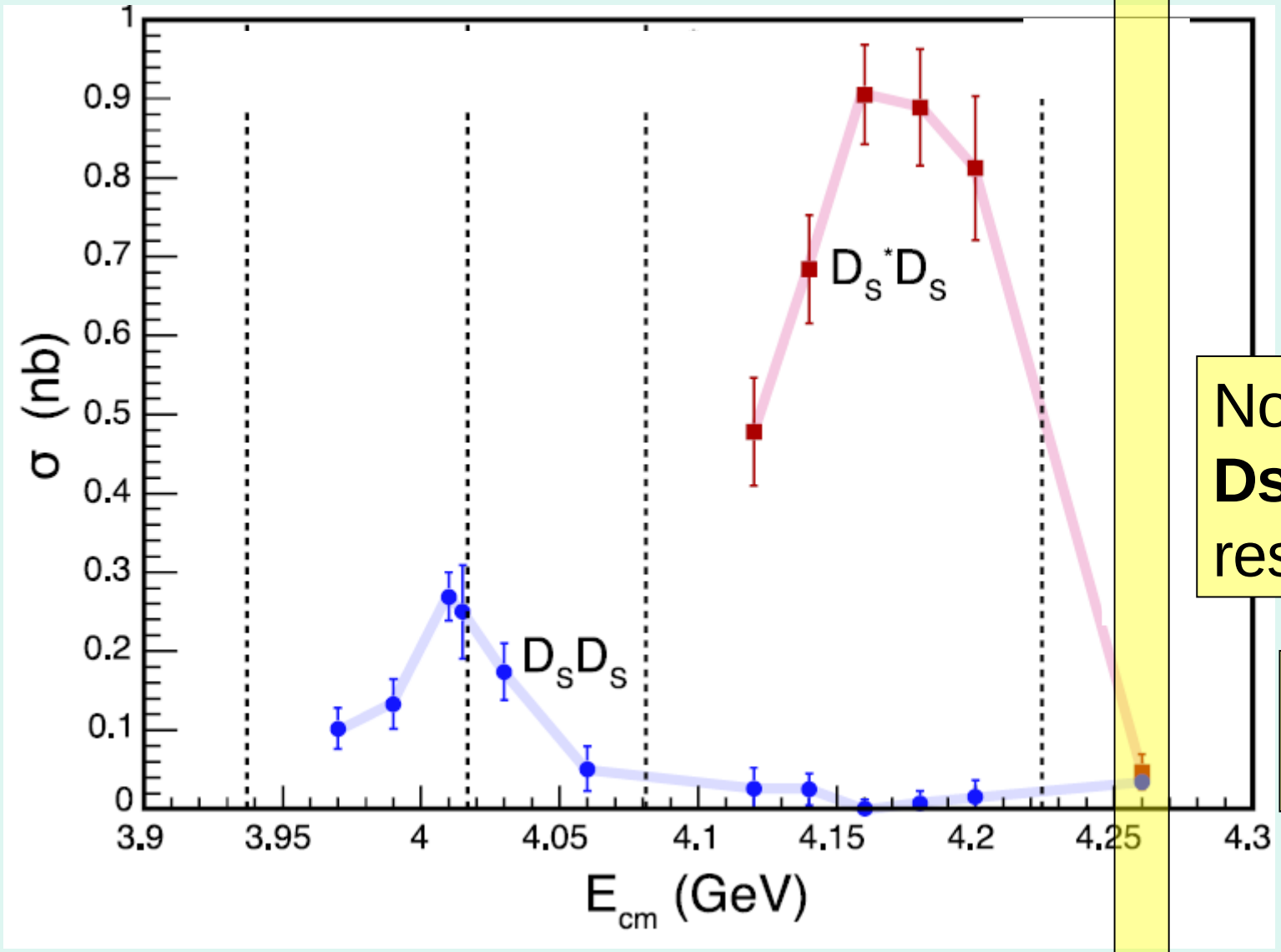
Break tube: S+P states yes; S+S suppressed

Look for DD_1 and D*D_0 near threshold

Look for psi pipi and h1c eta

Absence of DD; DD*; DsDs …

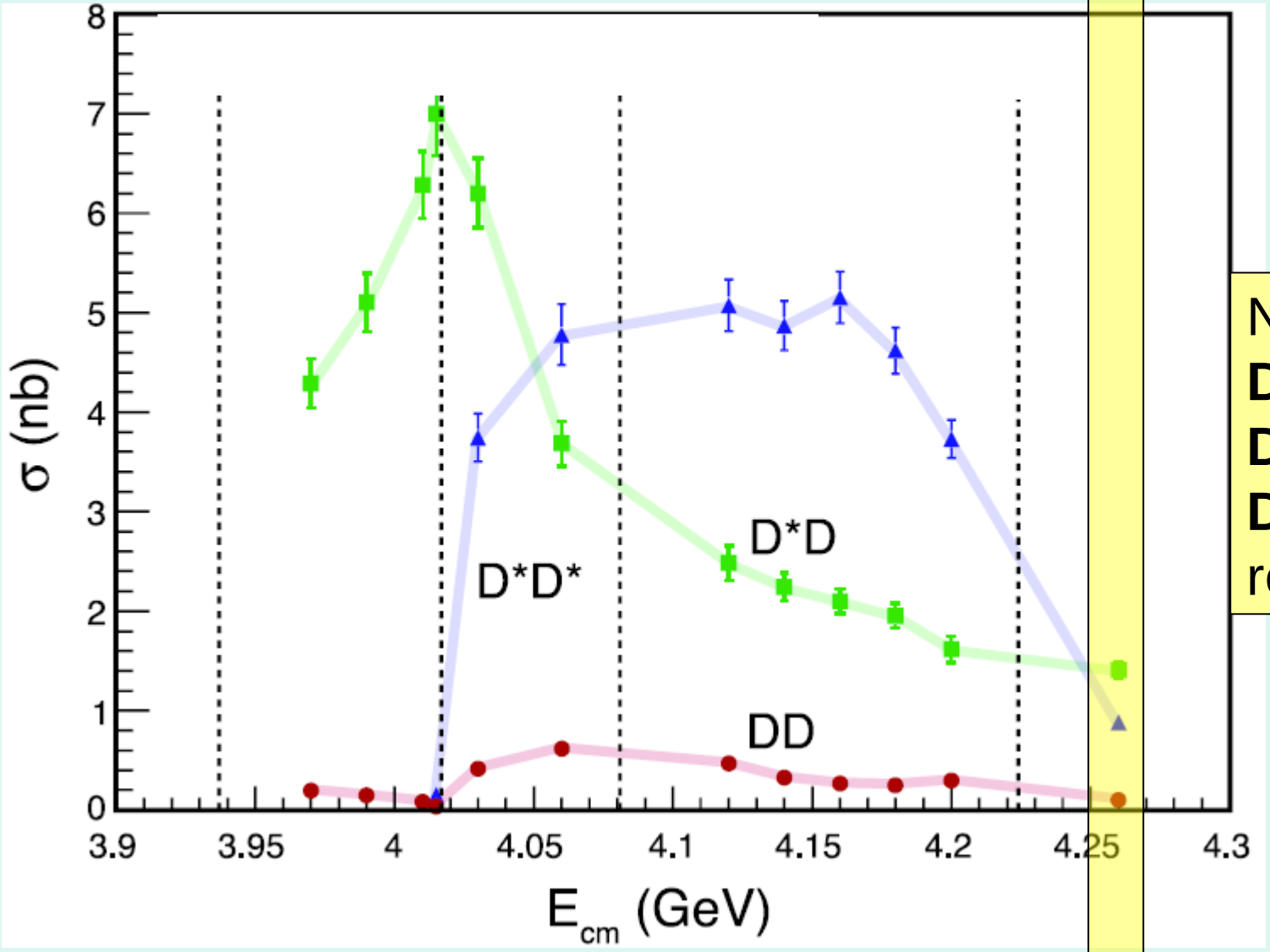
Y(4260): D_s and D_s* channels



No **DsDs** resonance

eliminates tetraquark csc*s*

Y(4260): D and D* channels



No
DD
DD* or
D*D*
resonance

All consistent with **predictions** for hybrid charmonium
FC+Page 1995

The mass coincides with the $D_1(2420)D$ *threshold:*

The decay modes $\psi\sigma/\eta$, $\psi f_0(980)/a_0(980)$ *appear to dominate:*

$\Gamma(Y(4260) \to e^+e^-)$ *is much smaller than all other* 1^{--} *charmonia:*

$$5.5\ eV \leq \Gamma(Y(4260) \to e^+e^-) \lesssim 62\ eV,$$

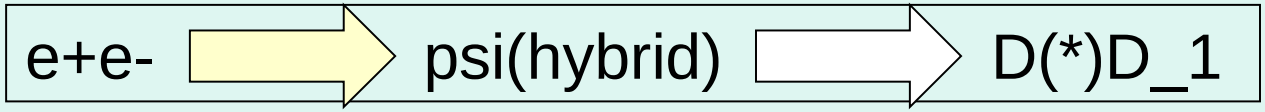
$\Gamma(Y(4260) \to \psi\pi^+\pi^-)$ *is much larger than all* 1^{--} *charmonia:*

$$\Gamma(Y(4260) \to \psi\pi^+\pi^-) \gtrsim 7.8\ MeV.$$

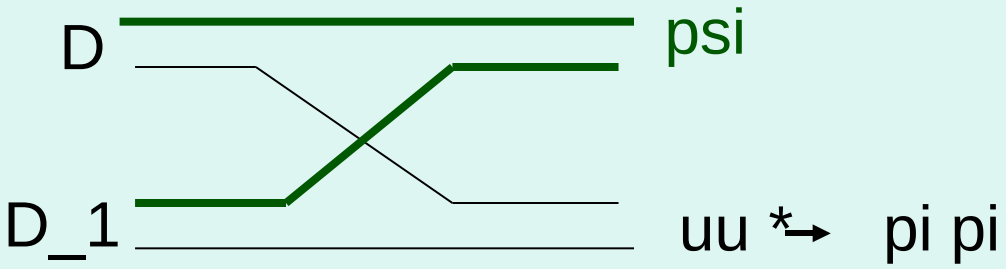
Search DD_1 and D*D_0 in DD\pi\pi

If NOT hybrid cc* then why not/where is it ?!

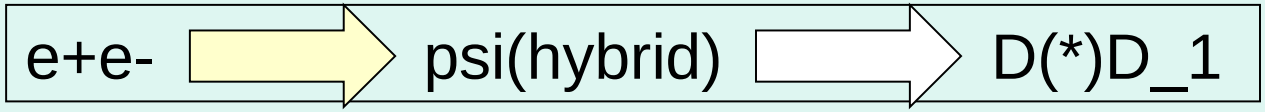
The large psi +pi pi = hint of large D(*)D1



S-wave, relative mom \sim 0;
DD_1 interchange constituents to make psi pipi “strongly”



The large psi +pi pi = hint of large D(*)D1



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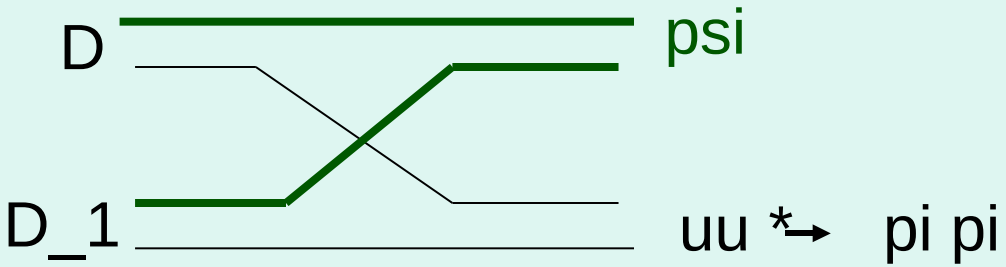
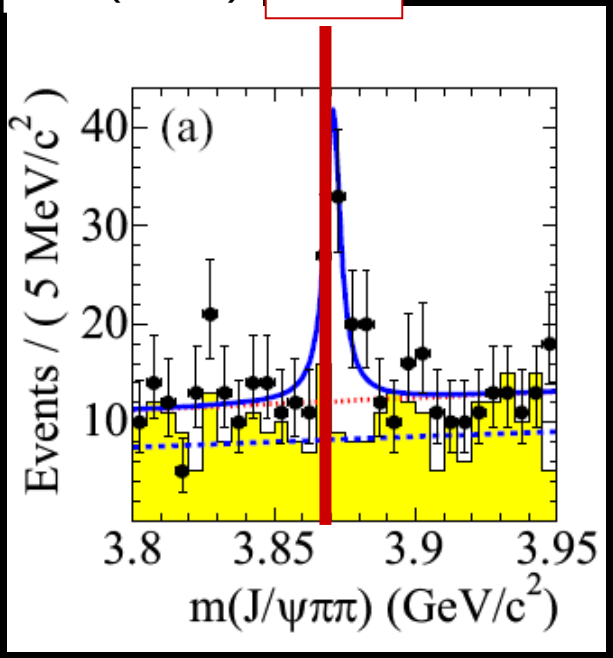


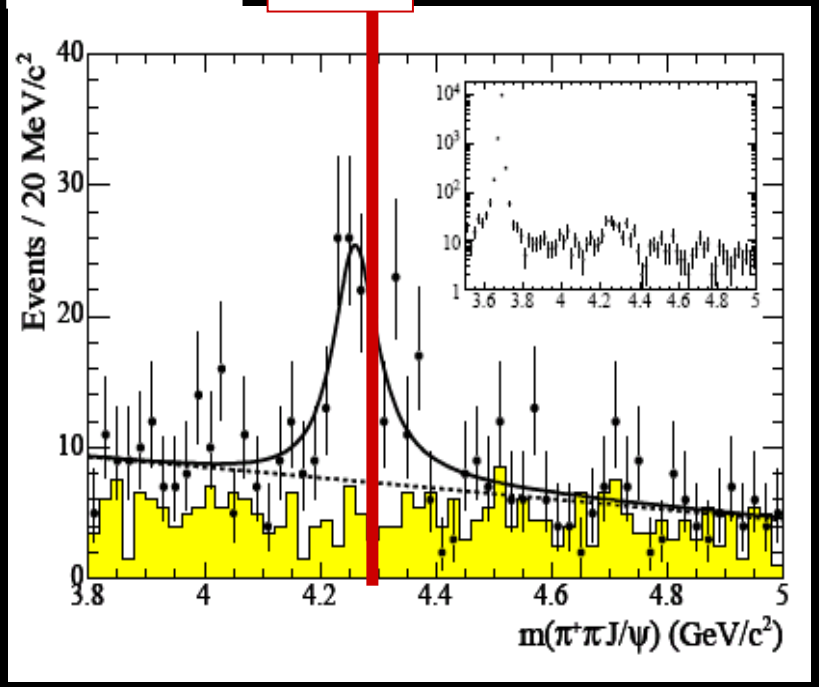
Problem: Heavy cc* preserve their spin.
Psi has cc* with S=1
Hybrid has cc* with S=0

Problem: and other states: 4360;4430…

1++(3872) DD*



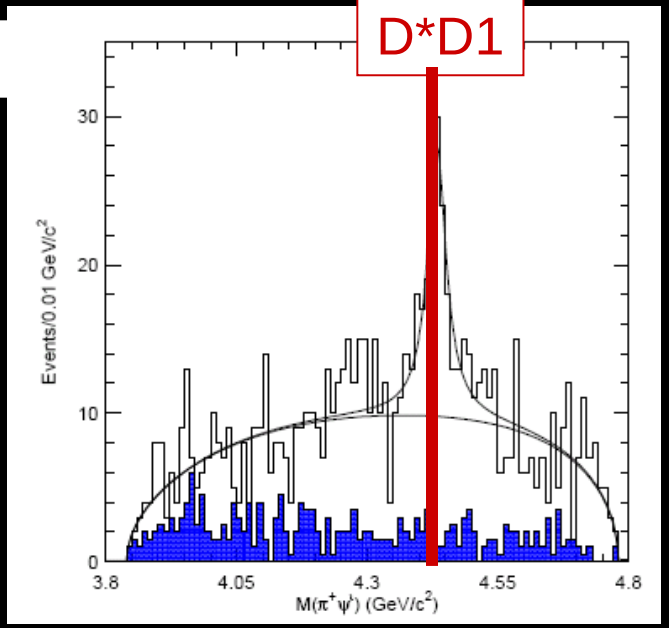
1--(4260) DD1



JPC?(4430)

I=1 !?

D*D1



Pi psi*
What about
Pi psi??

Hybrid affected by thresholds

Attractive force from pi exchange:

4260 a result of D1D* (!!) threshold:
look for e+e- \to DDbar + 3pi

And what about 4360 in psiprime pipi
and 4430 in psiprime pi .....????

The Answer: A new spectroscopy

- At least…..something unexpected!
- 1++(3872) DD* via \pi exchange in p-wave

- 1– (4260 etc) D1D* via \pi exchange

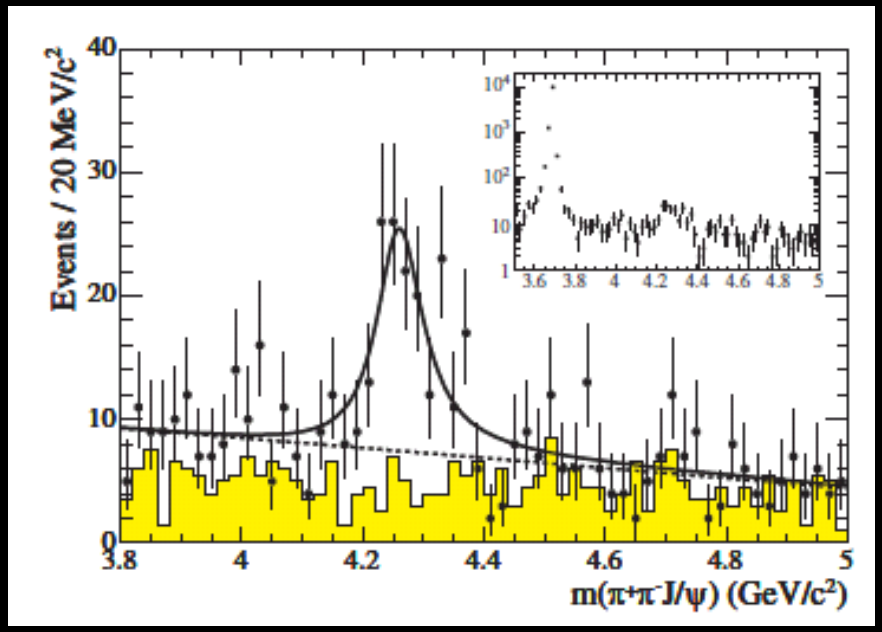
……..

The Answer: A new spectroscopy

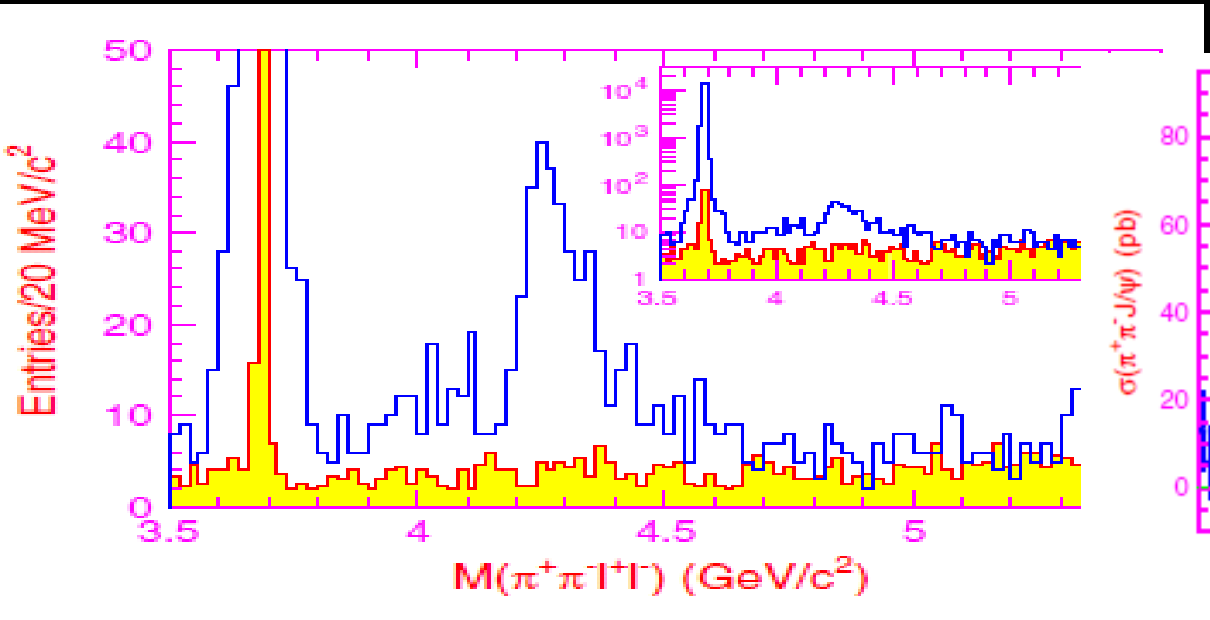
- At least…..something unexpected!
- 1++(3872) DD* via \pi exchange in p-wave

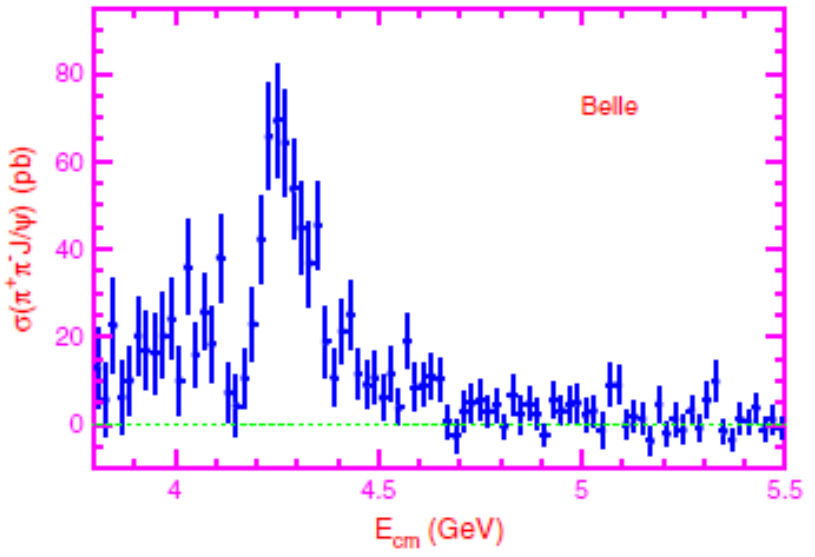
- 1– (4260 etc) D1D* via \pi exchange

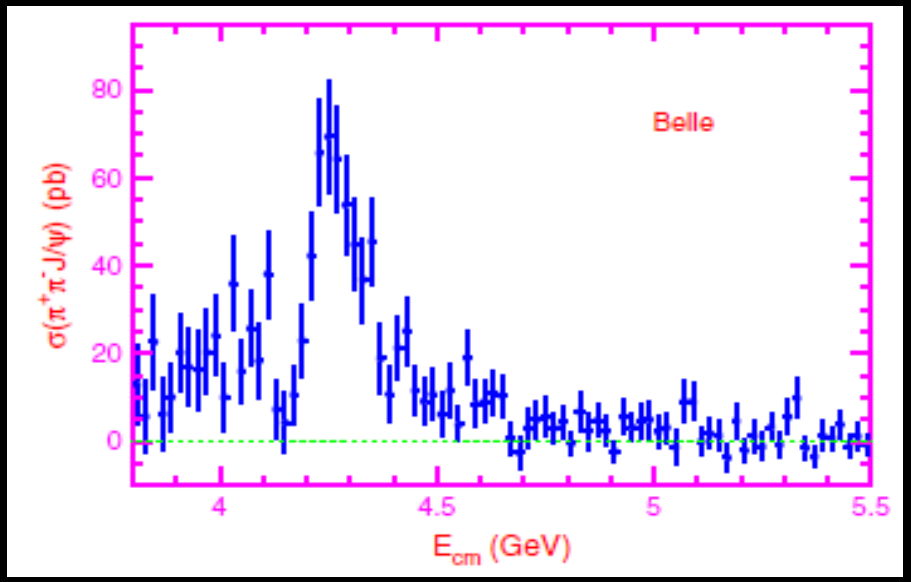
in s-wave!



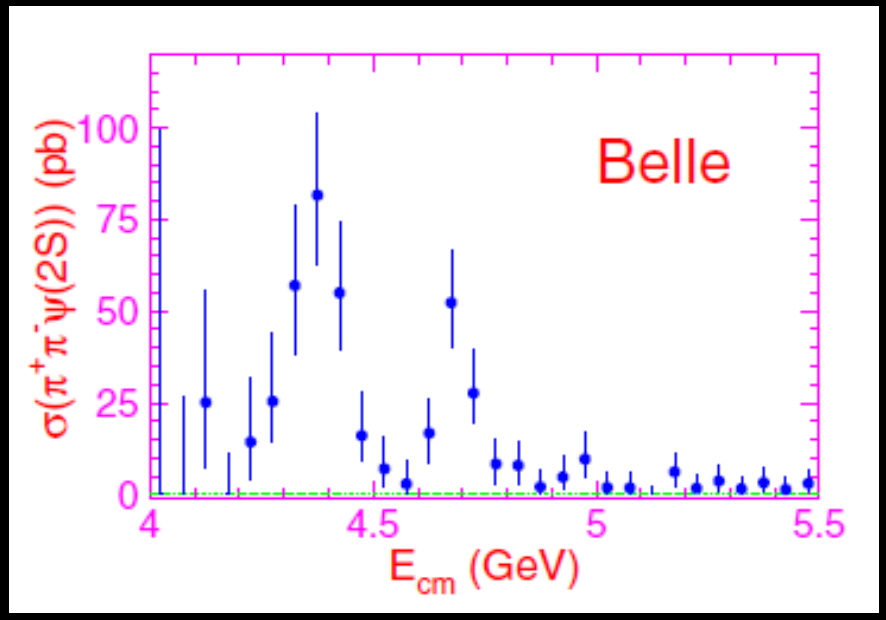
Psi pipi (4260)







Psi(1S)pipi (4260)



Psi(2S)pipi (4360) and (?) 4600

On the possibility of Deeply Bound Hadronic Molecules from single Pion Exchange

Frank Close*
Rudolf Peierls Centre for Theoretical Physics, University of Oxford,
1 Keble Road, Oxford, OX1 3NP

Clark Downum†
Clarendon Laboratory, University of Oxford,
Parks Road, Oxford, OX1 3PU

$$V_P(\boldsymbol{q}) = -\frac{g^2}{f_\pi^2}\frac{(\boldsymbol{\sigma}_i \cdot \boldsymbol{q})(\boldsymbol{\sigma}_j \cdot \boldsymbol{q})}{|\boldsymbol{q}|^2 + \mu^2}(\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j)$$

N N pi: deuteron; **O(1 MeV)**

D* to D pi (**P** wave) **O(q^2)**
DD* to D*D binding **O(1 MeV)**
X(3872)

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DD* to D*D binding **O(1 MeV)**
X(3872)

$$V_S(\boldsymbol{q}) = -\frac{h^2}{2f_\pi^2}\frac{(m_A-m_B)^2}{|\boldsymbol{q}|^2+\mu^2}$$

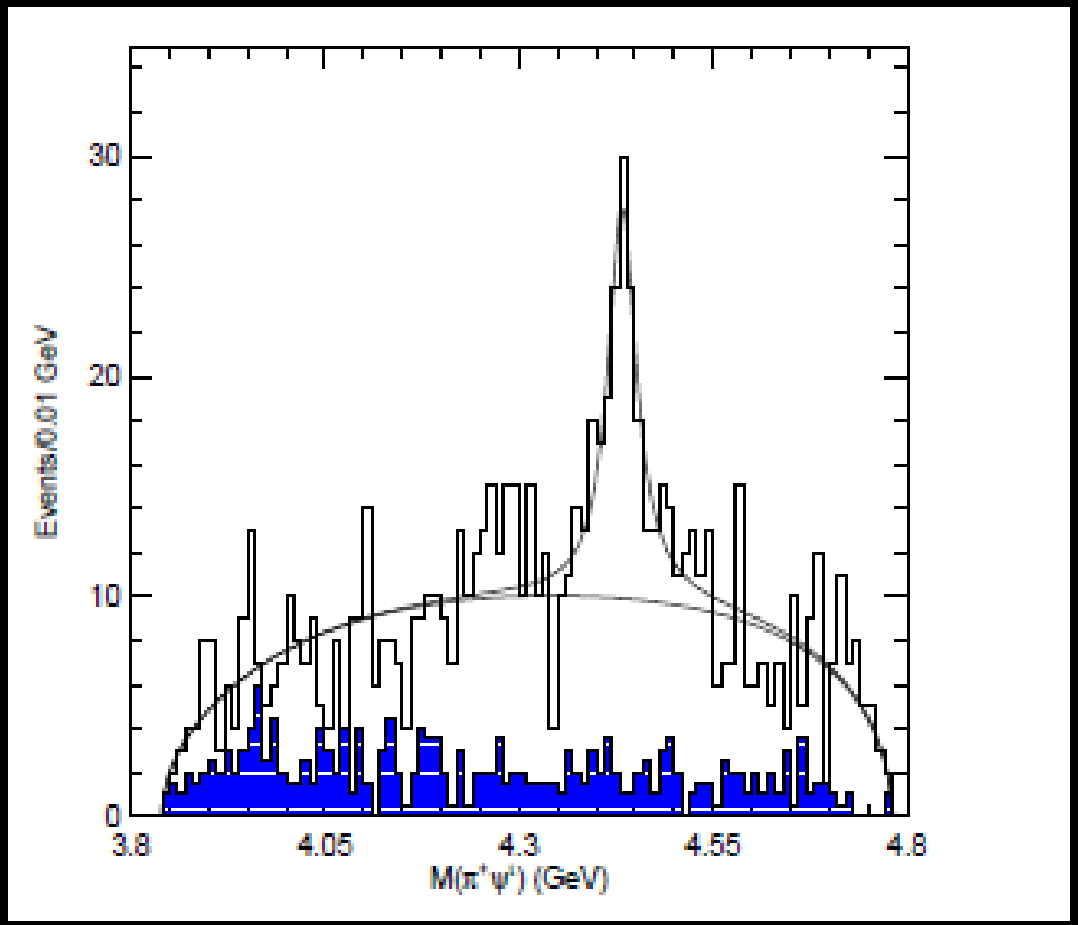
D1 to D* pi (**S** wave) **O(mA-mB)^2**
D1 D* binding **O(100 MeV)**

M = D*D1(4440) - **O(100MeV**) **4260; 4360** ??

PHYSICAL REVIEW D 77, 034003 (2008)

Is $Z^+(4430)$ a loosely bound molecular state?

Xiang Liu,[1,*] Yan-Rui Liu,[2,†] Wei-Zhen Deng,[1,‡] and Shi-Lin Zhu[1,§]



Look at I=1 D1D* 1^{--}
S wave pi exchange
Find it does NOT bind

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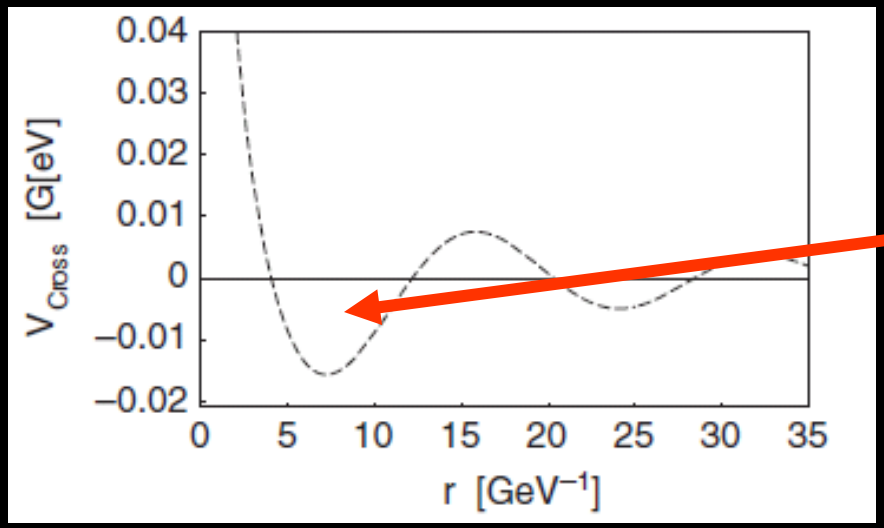
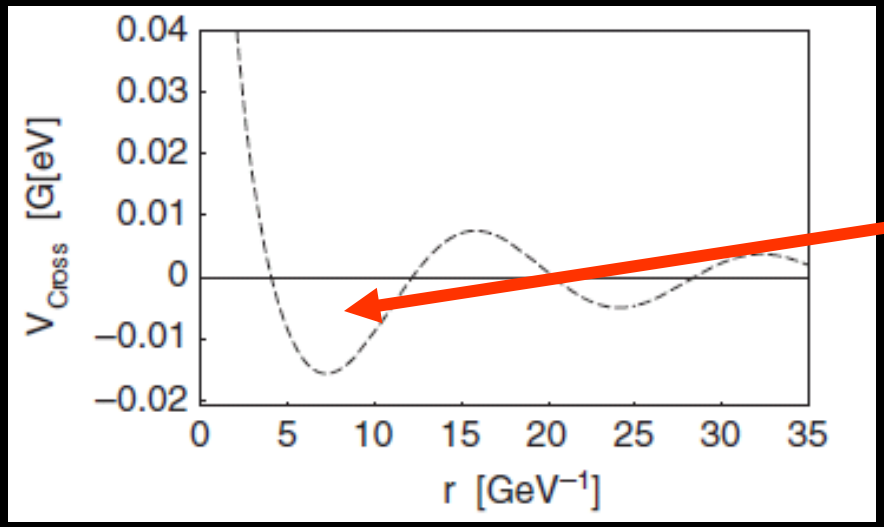
$$V_S(r) = \frac{h^2(m_A - m_B)^2}{8\pi f_\pi^2}\frac{\cos(\mu r)}{r}$$

$$V_S(q) = -\frac{h^2}{2f_\pi^2}\frac{(m_A - m_B)^2}{|q|^2 + \mu^2}$$



I=1 feeble binding if any Z(4430)
Liu et al PRD77 034003



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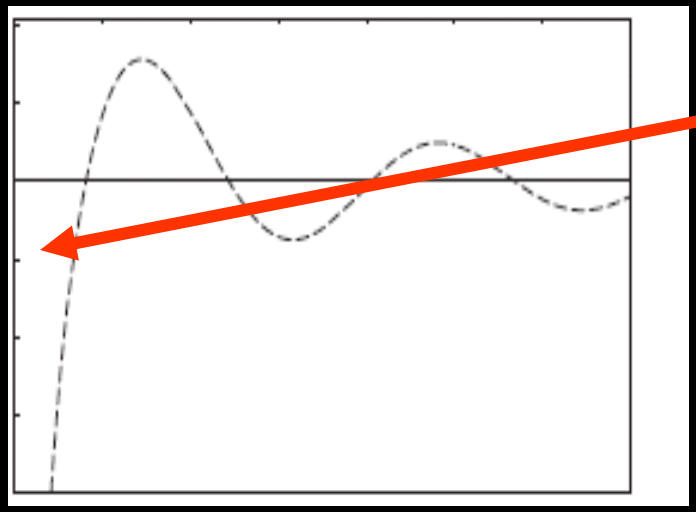
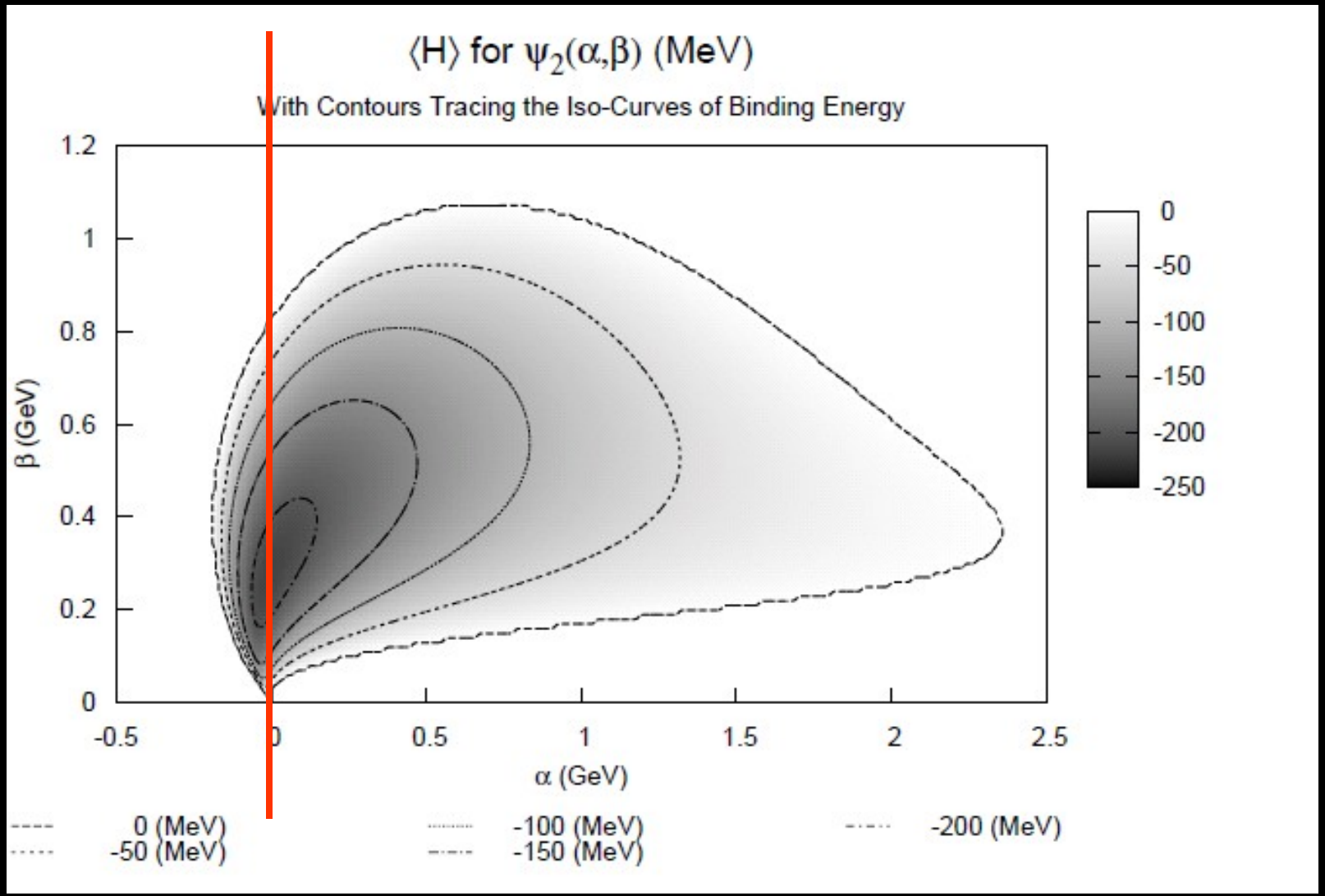


I=0 strong binding

Binding Energy: variational wfns

$$\psi(r) = (1 + \alpha r^2)e^{-\beta r^2}$$



Ground state B.E can be 100-200 MeV !!

Radial excitation bound also??

Vector D*D1 spectroscopy

D*D1 threshold

4430 I=1

2S 4360 → Psi(2S) pi pi

1S 4260 → Psi(1S) pi pi

Also 0- 1- 2- with C=- or +

On the new exotic charmonium states

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Vector D*D1 spectroscopy

D*D1 threshold

4430 I=1

2S 4360

gamma

4300

?? 1P

1S 4260

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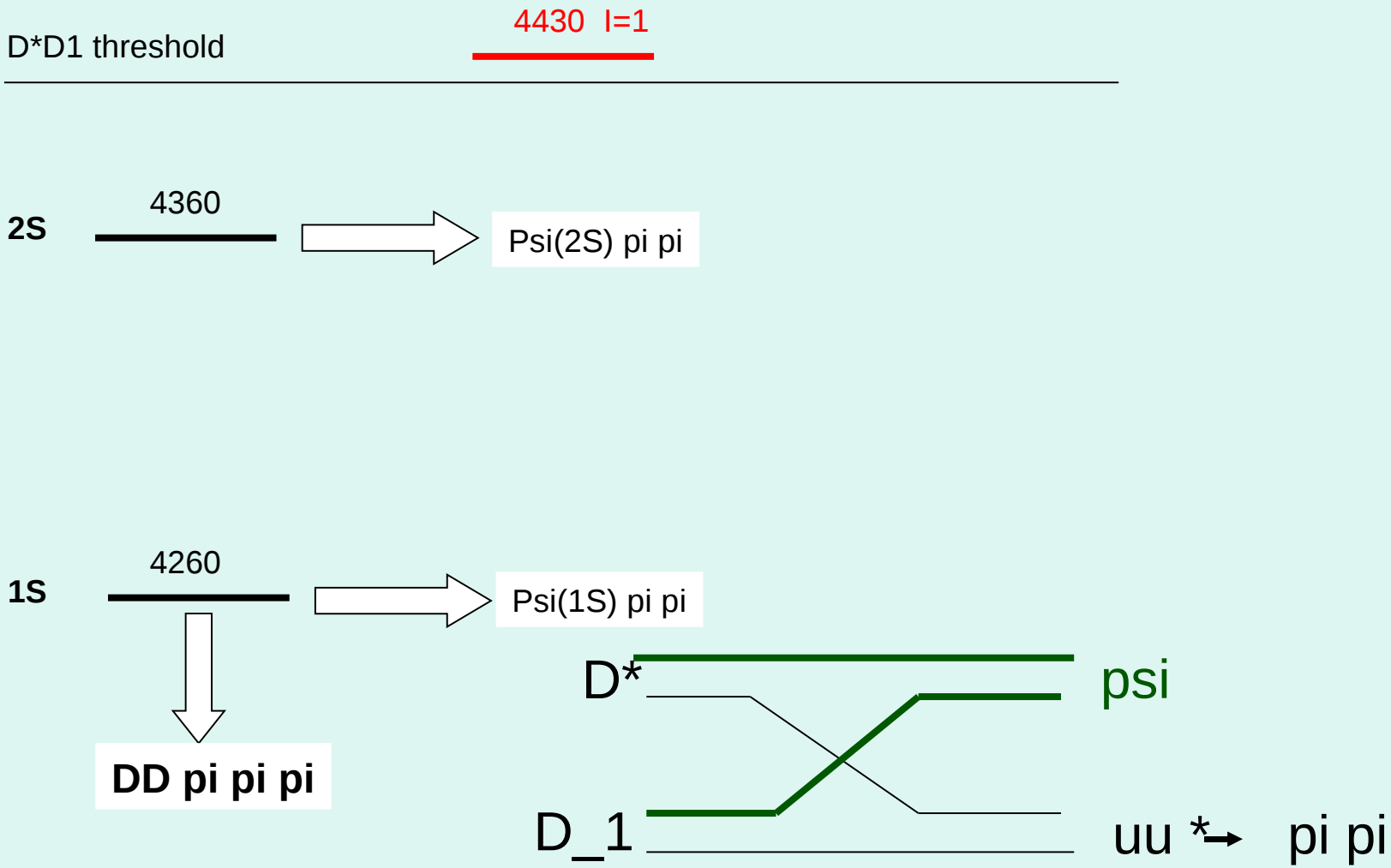
And Possible transitions to exotic 1-+

Vector D*D1 spectroscopy



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Phys Rev Letters (in press)

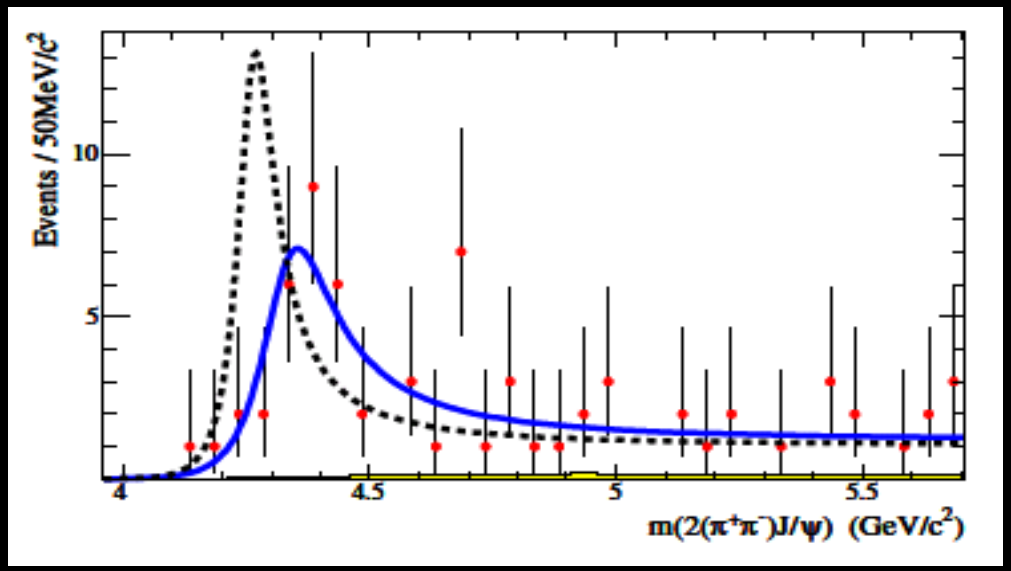
The immediate test is 4260 decay to

$$D\bar{D}3\pi$$

Then look for other exotica. Also in Bottomonium and strangeonium

Compare DD1 selection rules in DD 2pi for conventional or hybrid cc*


ANTIMATTER
FRANK CLOSE



Psiprime pipi (4360)

And (??) (4600)