SAPIENZA UNIVERSITÀ DI ROMA and INFN Istituto Nazionale di Fisica Nucleare

THE NEW MESONS: DIRECT & INDIRECT SEARCH

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Work done mainly with
AD Polosa and F Piccinini

SuperB Meeting - Elba May 30, 2011

Outline

- Standard Charmonium/Bottomonium and Charmonium/Bottomonium-like resonances (XYZ mesons).
- Exotic mesons: molecules, tetraquarks, hybrids, hadrocharmonium.
- Direct searches.
- Indirect searches.
  Inclusive production of J/ψ in B decays: state of the art and update.
  - Two body modes (color singlet).
  - Non resonant multi body modes (color octet) NRQCD.
  - Contribution from XYZ mesons.

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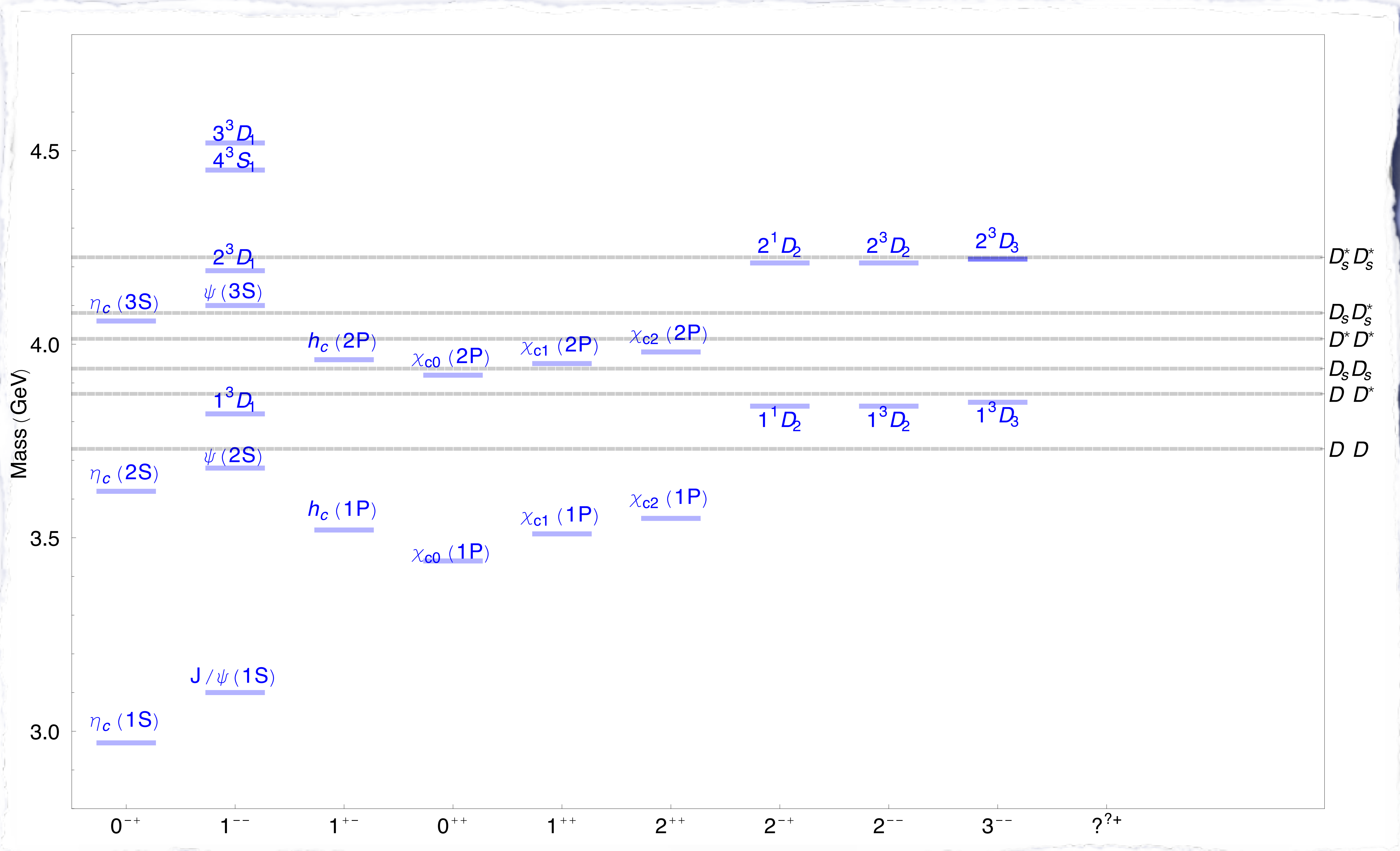
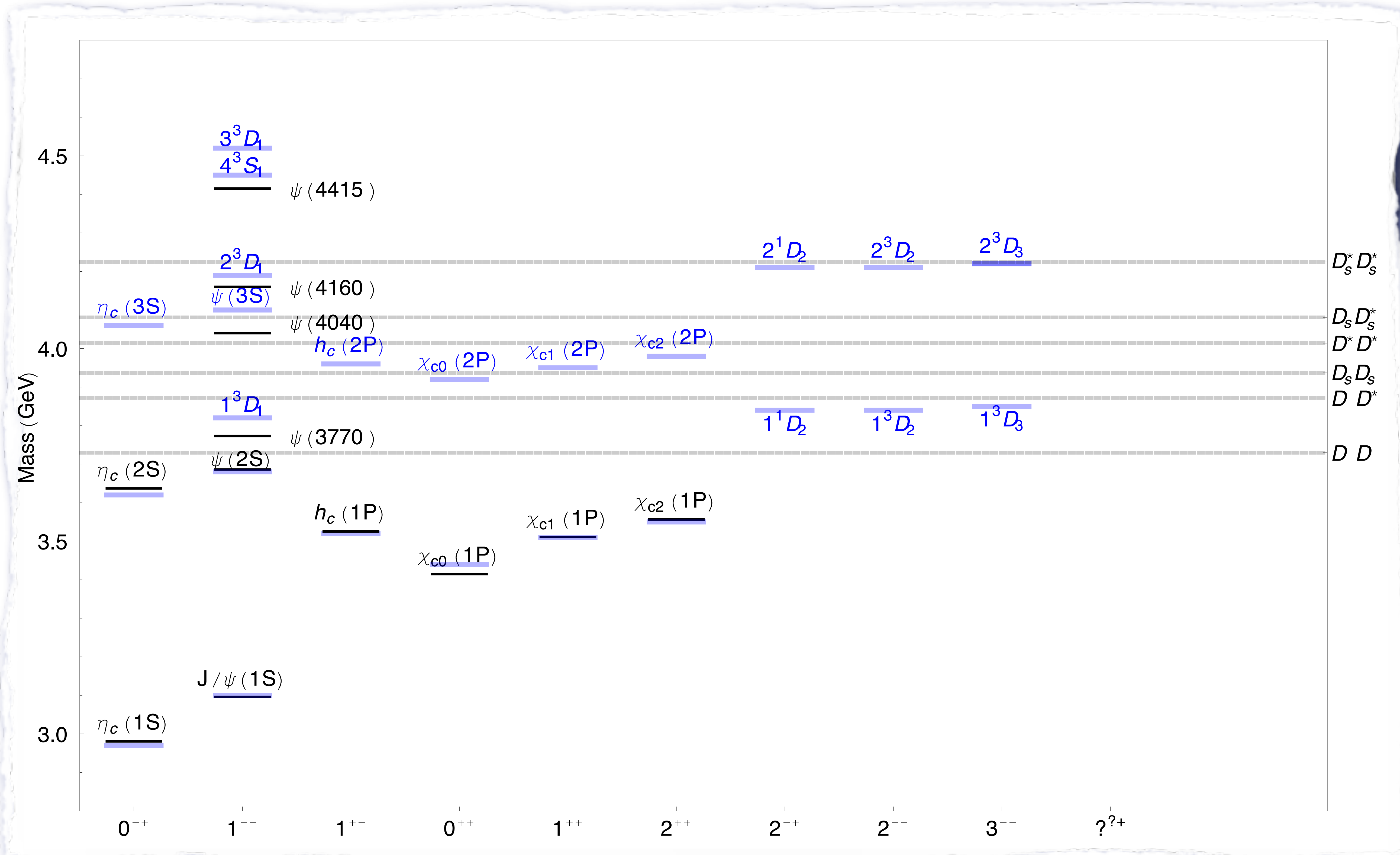
SUPER FLAVOUR FACTORIES CAN SOLVE MANY PUZZLES: HIGHER STATISTICS IS NEEDED.

Predictions for cc* states

:: Godfrey, Isgur, Phys. Rev. D 32, 189–231 (1985) ::

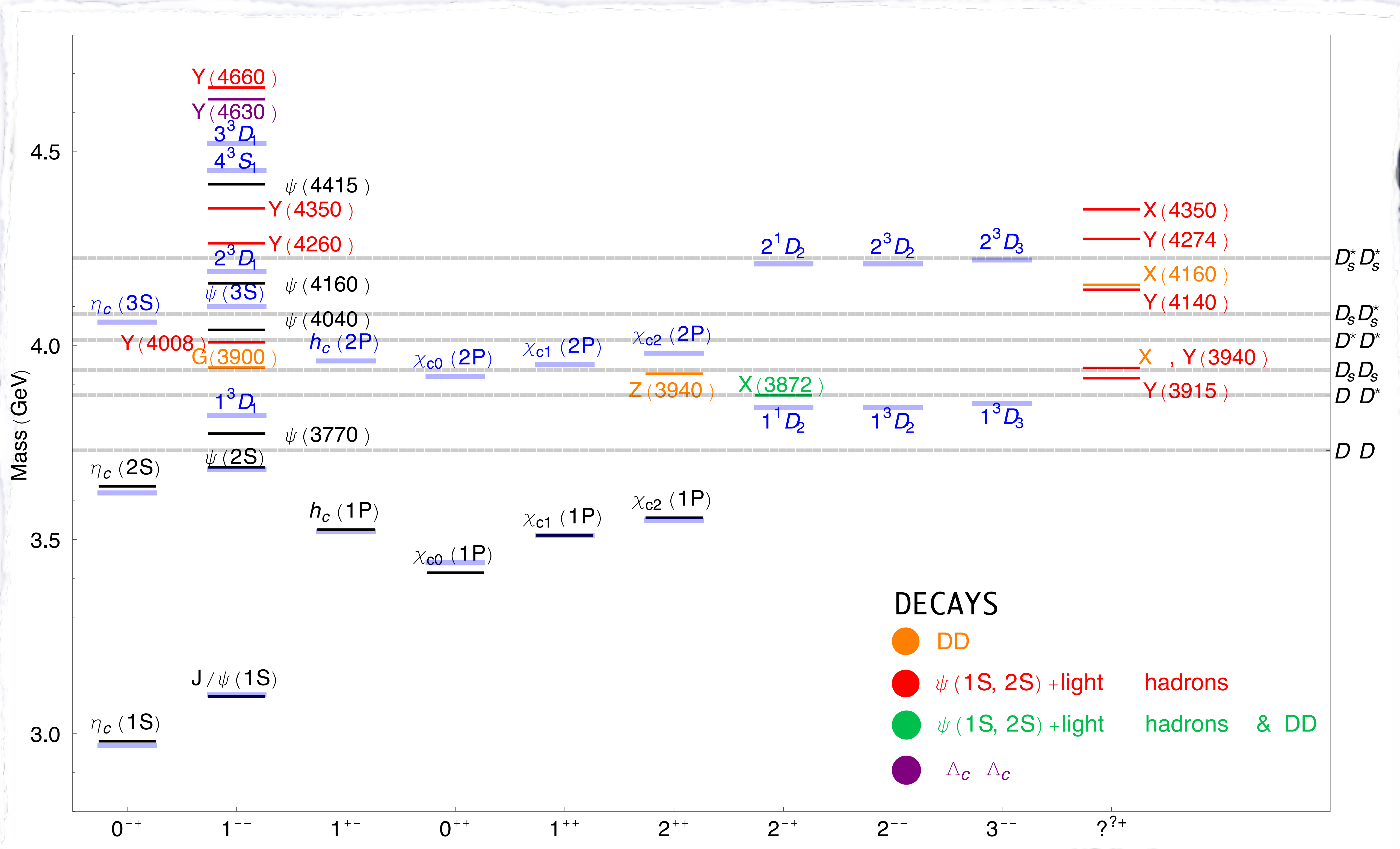


Data for cc* states



Unexpected (1)

:: Heavy Quarkonium Working Group, Eur.Phys.J. C71 (2011) 1534 ::



Unexpected (2)

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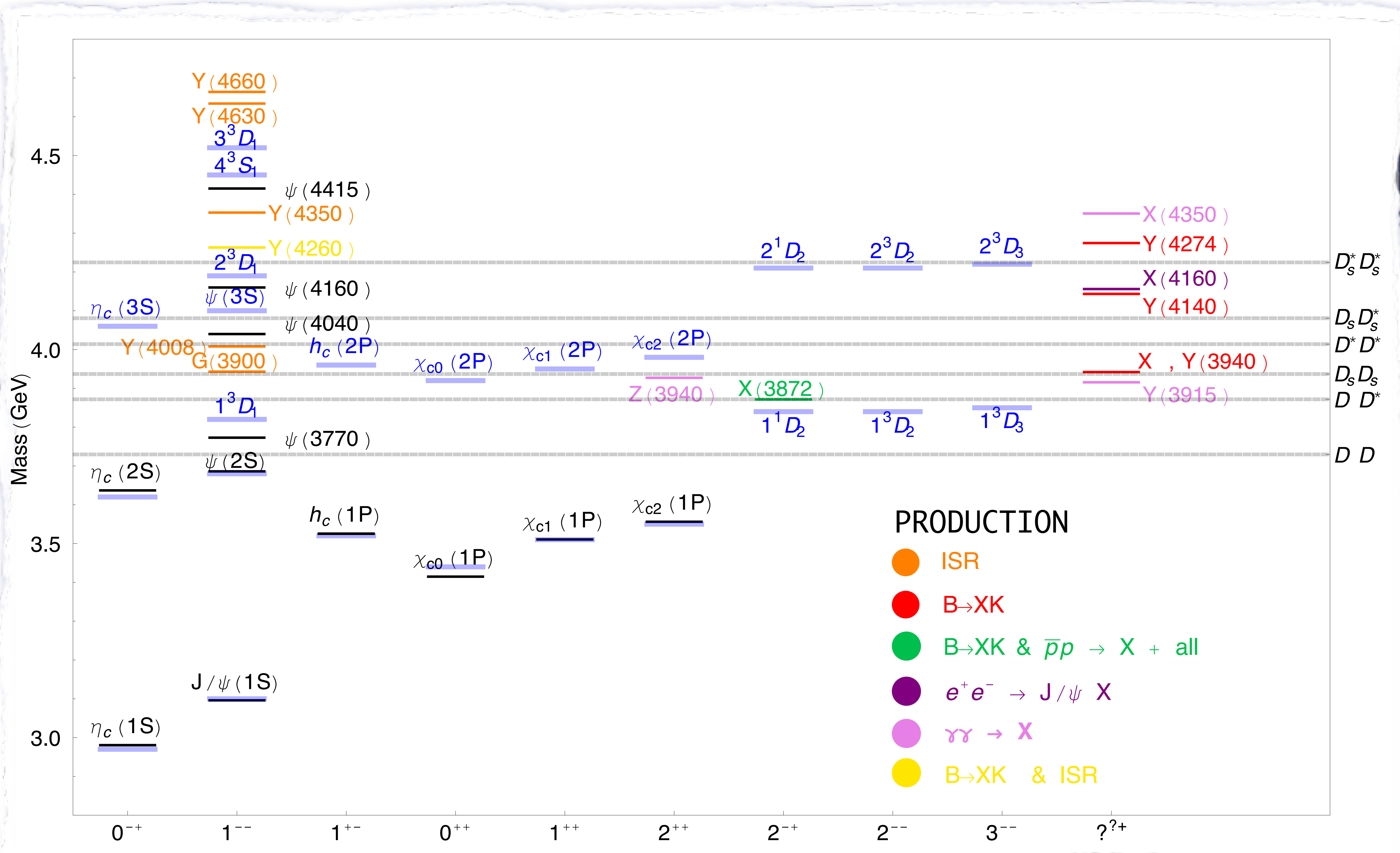
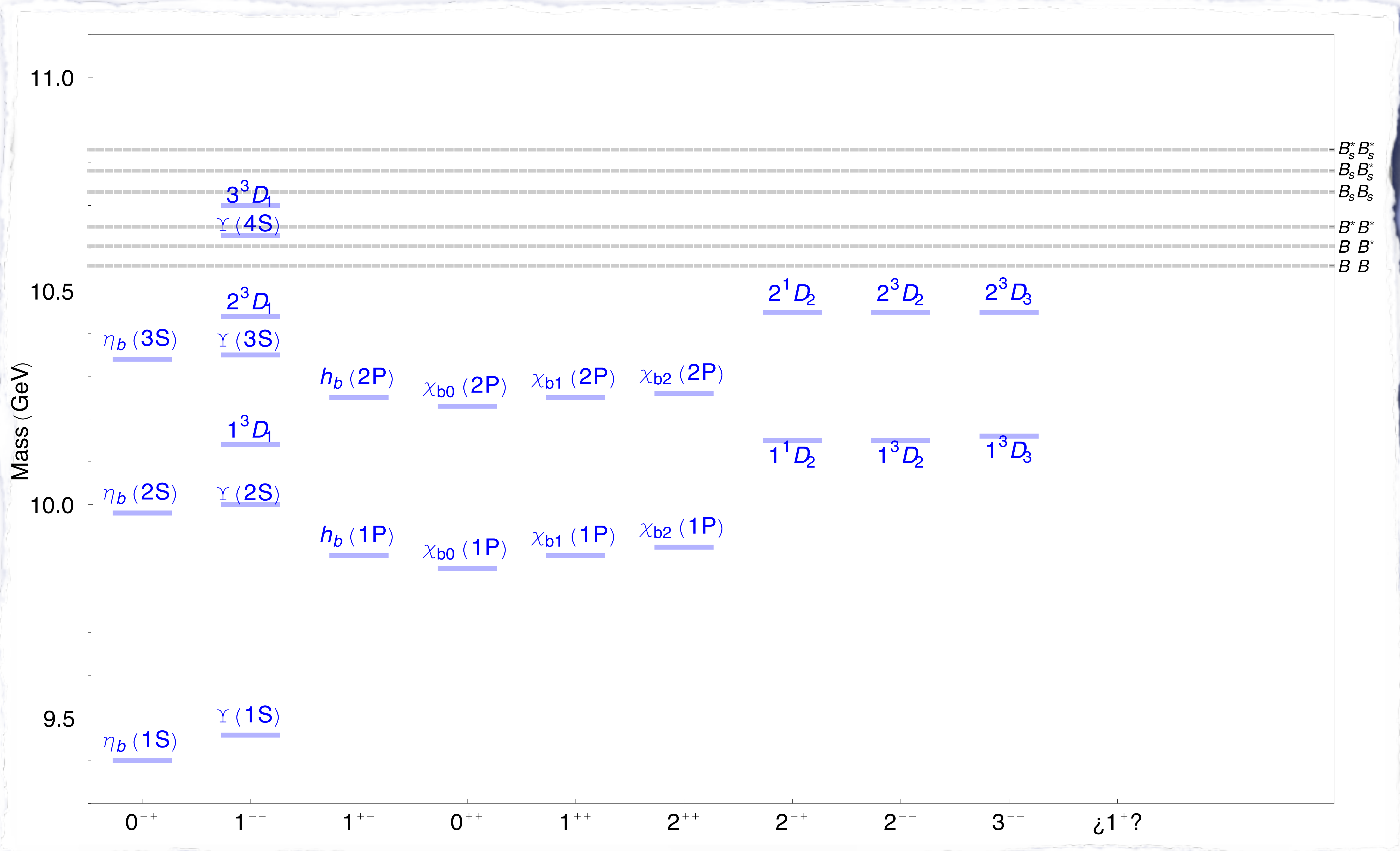
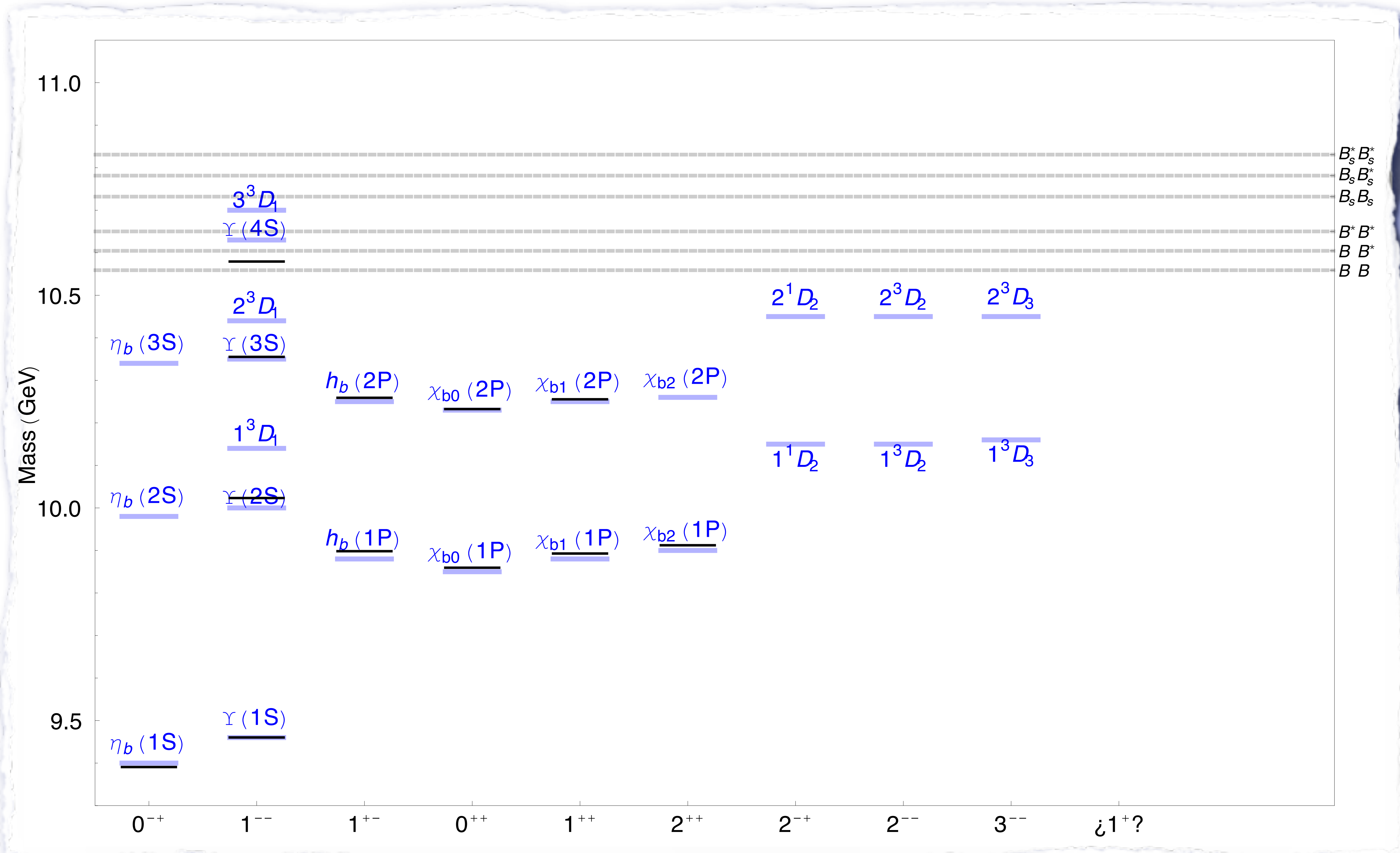


Predictions for bb* states

:: Godfrey, Isgur, Phys. Rev. D 32, 189–231 (1985) ::

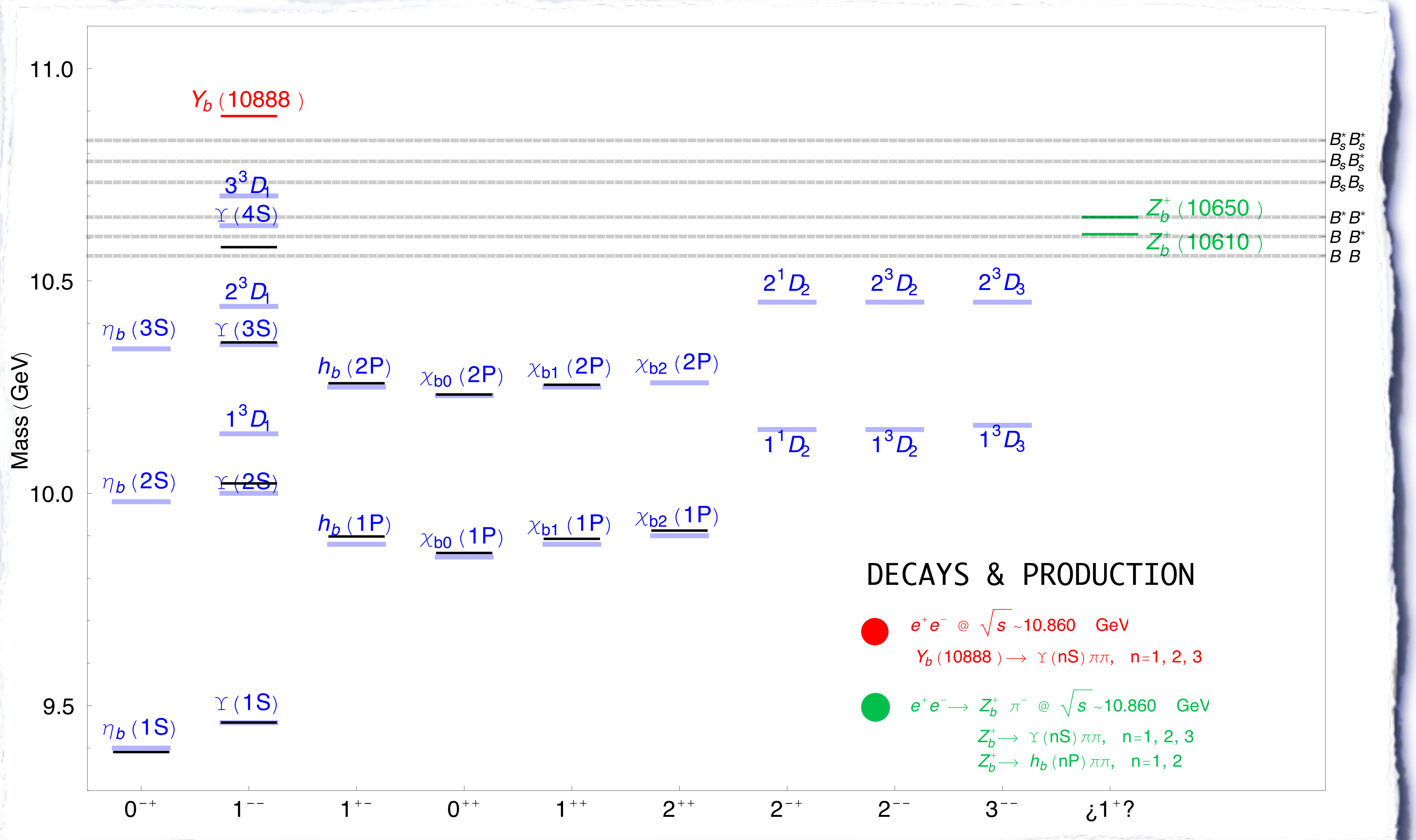


Data for bb* states



Unexpected

:: Belle, Phys.Rev.Lett. 100 (2008) 1120014 ::
:: Belle, arXiv:1105.4583 ::



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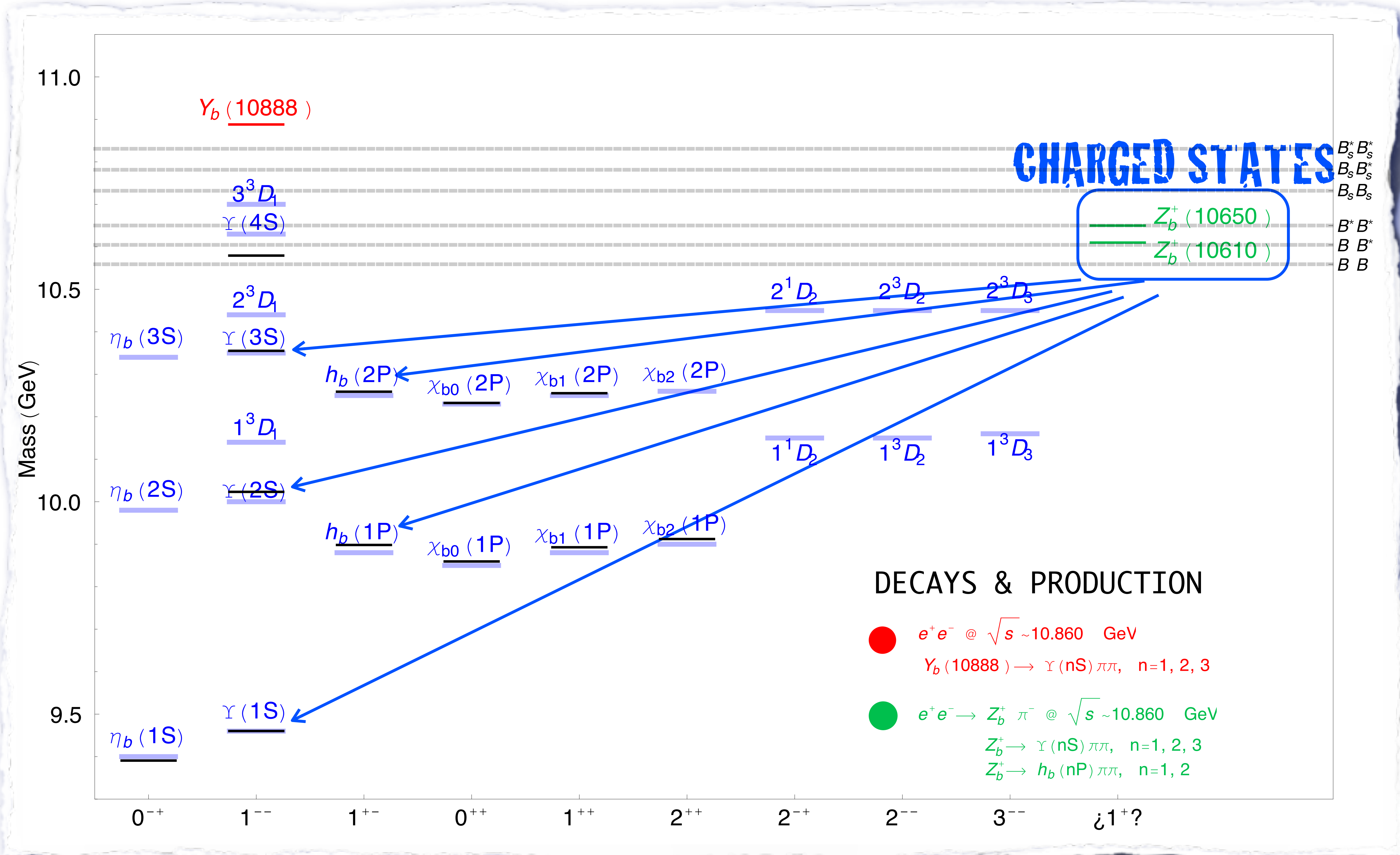
:: Belle, arXiv:1105.4583 ::



The road to $Z^+_b(10610)$ & $Z^+_b(10650)$: $\Upsilon(5S)$

Belle, Phys. Rev. Lett. 100, 112001 (2008)

- Anomalous production of $\Upsilon(nS)\ \pi^+\pi^-$ (n=1,2,3) @ the $\Upsilon(5S)$ resonance (e^+e^- collisions at $\sqrt{s} \approx 10.87$ GeV).

TABLE II. The total width Γ_{total}, and the partial width $\Gamma_{e^+e^-}$, $\Gamma_{\Upsilon(1S)\pi^+\pi^-}$. Most values are from Refs. [3,4,11].

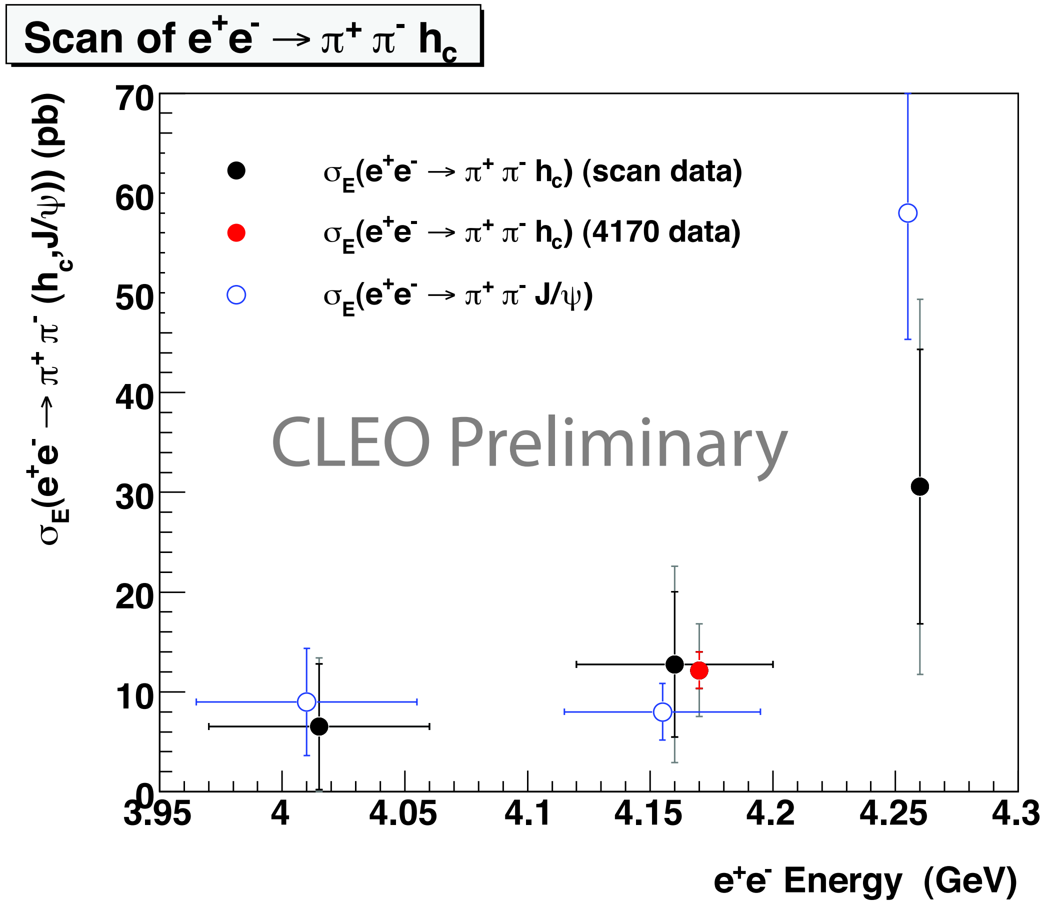
Process	Γ_{total}	$\Gamma_{e^+e^-}$	$\Gamma_{\Upsilon(1S)\pi^+\pi^-}$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.032 MeV	0.612 keV	0.0060 MeV
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.020 MeV	0.443 keV	0.0009 MeV
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	20.5 MeV	0.272 keV	0.0019 MeV
$\Upsilon(10\,860) \to \Upsilon(1S)\pi^+\pi^-$	110 MeV	0.31 keV	0.59 MeV

- Interpretations:
  - Exotic - tetraquark state Y_b =[cq][c*q*]
    A. Ali, C. Hambrock, and M. Aslam, Phys.Rev.Lett. 104, 162001 (2010)
  - Standard - rescattering $\Upsilon(5S) \to BB\pi\pi \to \Upsilon(nS)\pi\pi$
    Simonov JETP Lett 87,147(2008)

The road to $Z^+_b(10610)$ & $Z^+_b(10650)$: h_c

R. E. Mitchell (2011), 1102.3424.

- Similar in all respects to the Υ(4260) resonance in the charm sector.
- The (S=0, L=1) charmonium state h_c has been discovered by CLEO-c in a scan around $\sqrt{s} \approx 4.26$ GeV.



- This is the motivation for the Belle search of h_b at the Υ(5S) peak.

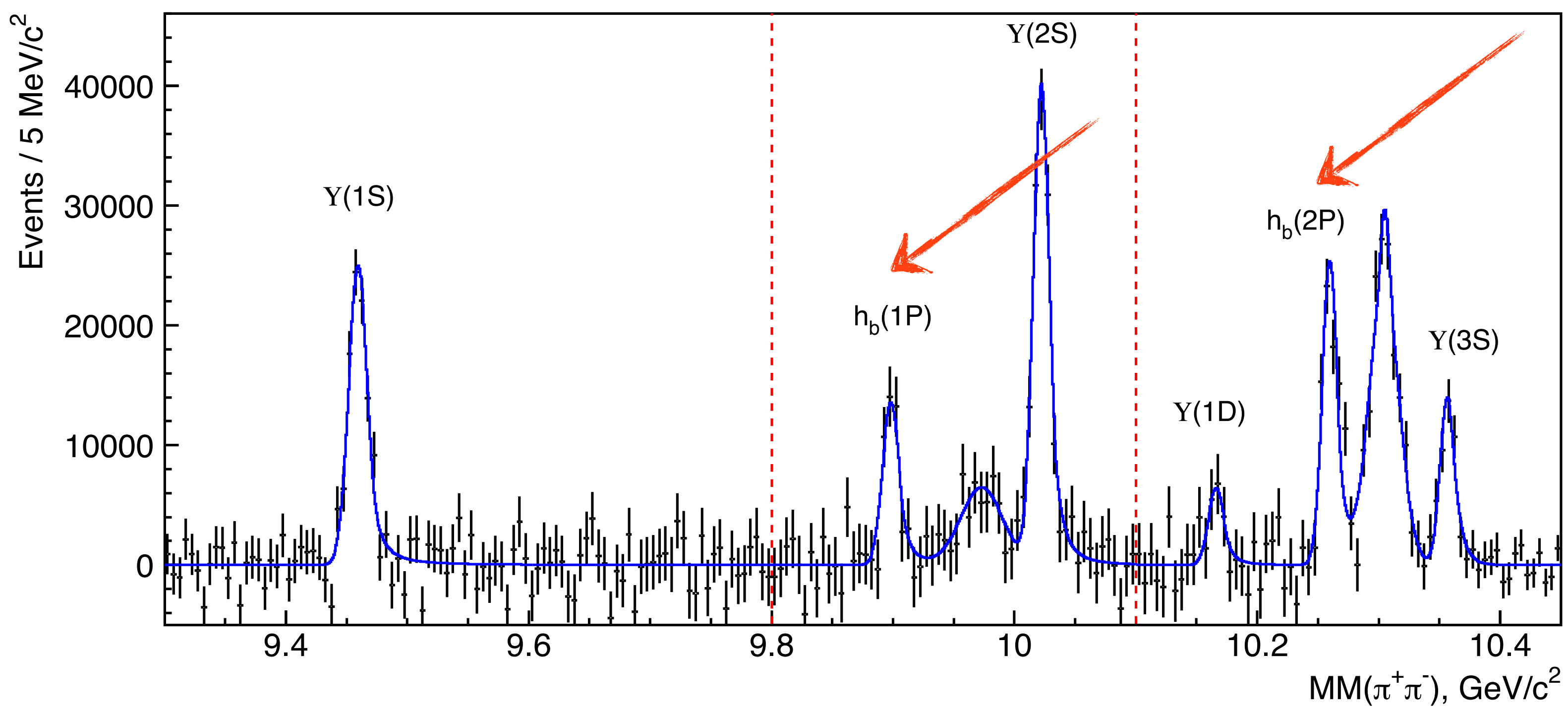
The road to $Z^+_b(10610)$ & $Z^+_b(10650)$: h_b

Belle, arXiv:1103.3419

- hb is the n^1P_1 bb* state. Missing dipion mass: $M_{\pi^+\pi^-} = \sqrt{(E_{\rm cm} - E^\star_{\pi^+\pi^-})^2 - p^{\star\,2}_{\pi^+\pi^-}}$

M(hb(1P)) = $(9898.25 \pm 1.06^{+1.03}_{-1.07})$ MeV
M(hb(2P)) = $(10259.76 \pm 0.64^{+1.43}_{-1.03})$ MeV

Both values are compatible with the heavy-quarkonia expectation: $< M(n^3P_J) > = M(n^1P_1)$



$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-]} = \begin{cases} 0.407 \pm 0.079^{+0.043}_{-0.076} & \text{for } h_b(1P) \\ 0.78 \pm 0.09^{+0.22}_{-0.10} & \text{for } h_b(2P) \end{cases}$$

$S(h_b) = 0 \Rightarrow$ spin-flip
no spin-flip

[From A. Bondar FPCP2011]

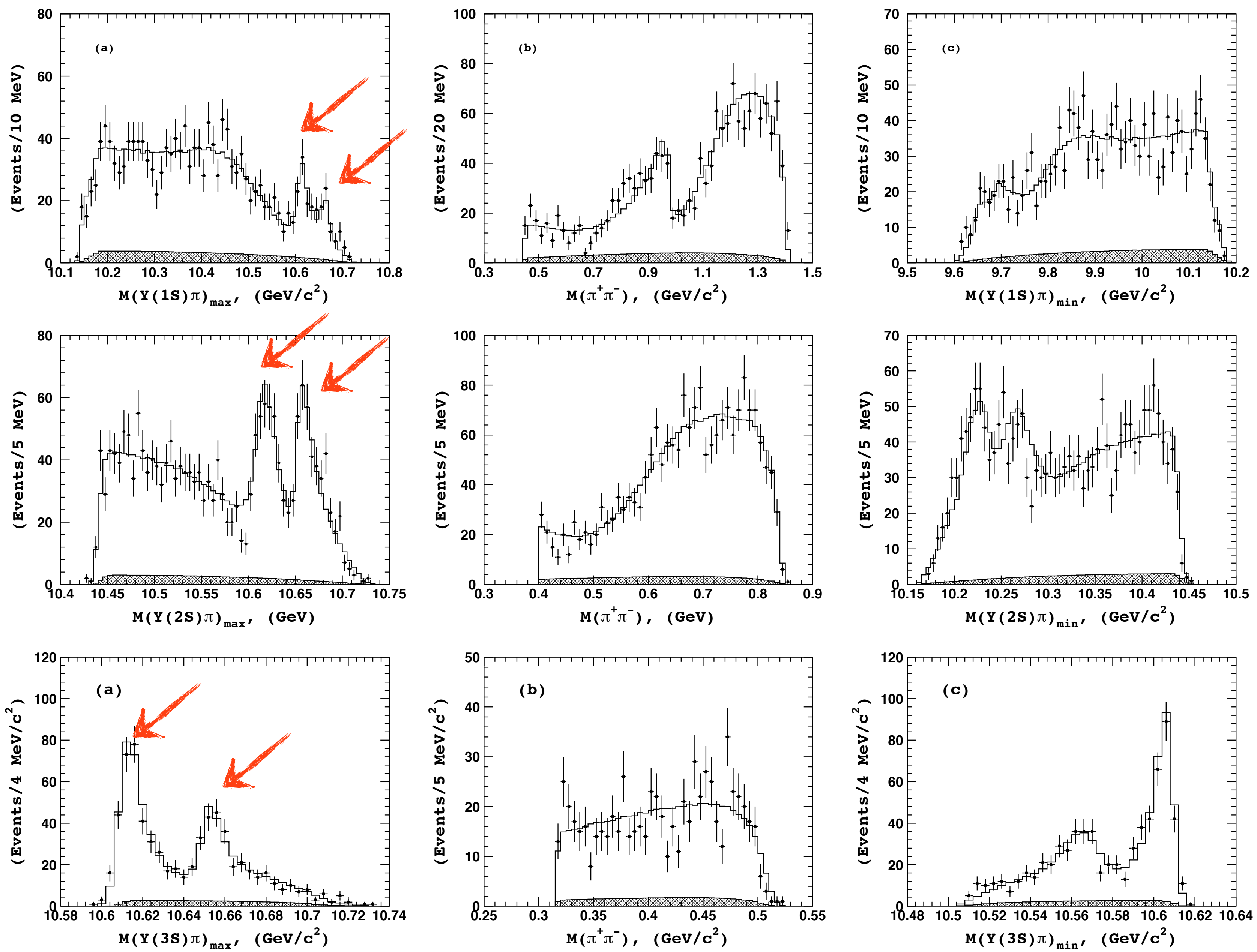
⇒ Mechanism of $\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-$ decay is exotic!
This motivates us to study resonant substructure of this process

$Z^+_b(10610)$ & $Z^+_b(10650)$

:: Belle, Phys.Rev.Lett. 100 (2008) 1120014 ::
:: Belle, arXiv:1105.4583 ::

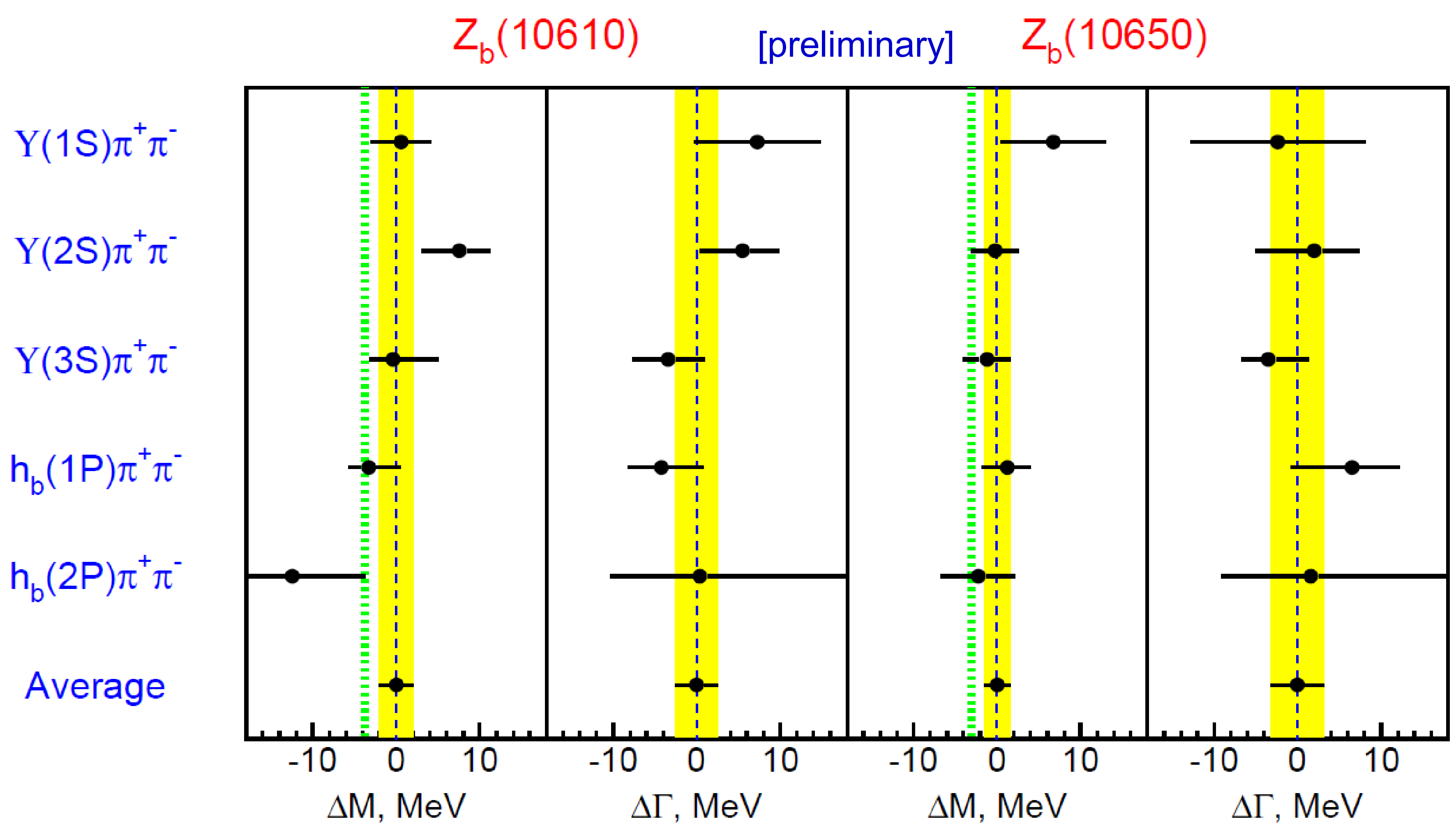
- $e^+e^- \to \Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-$, n=1,2,3
- $e^+e^- \to \Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-$, n=1,2

@ $\sqrt{s} \approx 10.87$ GeV, $\mathcal{L} = 121.4\ \text{fb}^{-1}$



$Z^+_b(10610)$ & $Z^+_b(10650)$

[From A. Bondar FPCP2011]



$Z_b(10610)$

M=10608.4±2.0 MeV

Γ=15.6±2.5 MeV

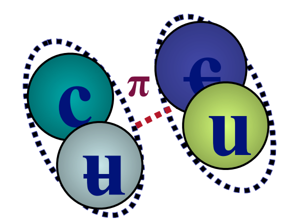
$Z_b(10650)$

M=10653.2±1.5 MeV

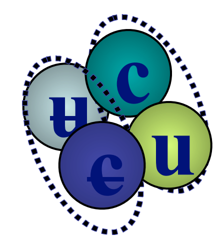
Γ=14.4±3.2 MeV

Are they exotic hadrons?

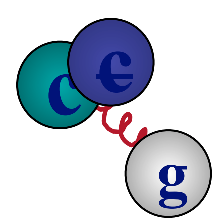
- Many exotic candidates have been identified among the so-called XYZ particles.
- Exotic means non qq^* or qqq structures ... what else?
  - Strongly interacting clusters of hadrons: molecules [Voloshin; Tornqvist; Close; Braaten; Swanson...]



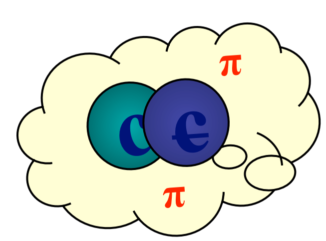
  - Tetraquark mesons, Pentaquarks, ... [Maiani,Piccinini,Polosa,Riquer ...]



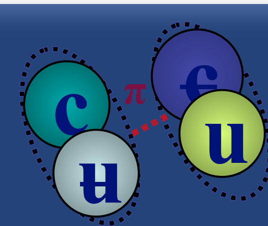
  - Hybrids [Close, Kou&Pene, ...]



  - Hadrocharmonium [Voloshin]



Hadronic Molecules



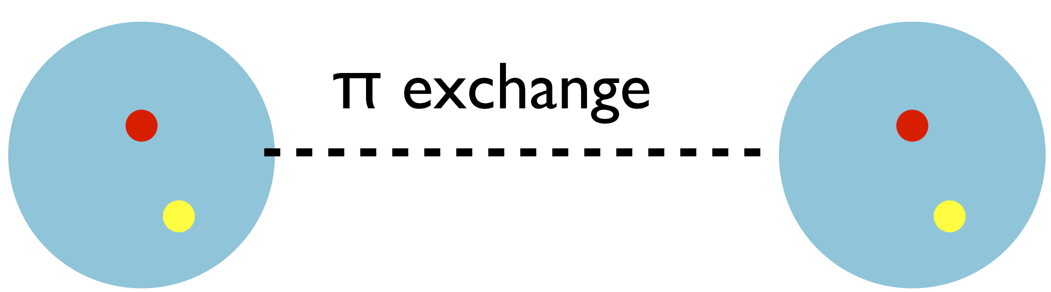
- Bound states of mesons or baryons.

  We will focus on meson-meson molecules. Main features:

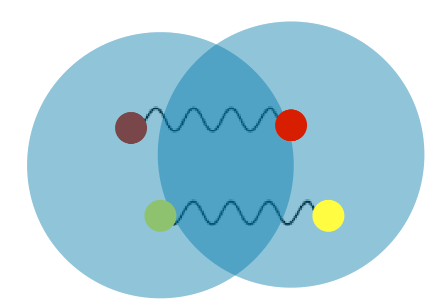
  - short range interactions between mesons → L=0 states
  - typical binding energy 50 MeV for light mesons resonances, 10 MeV for heavy mesons resonances (R~1 fm and $E=1/(2\mu R^2)$)
  - large branching fractions to final states containing the constituent mesons

- How do we model the interaction?

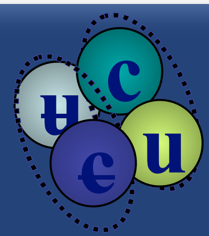
Long distance



Short distance



Tetraquark



- Tetraquark:
  a diquark-antidiquark bound state

- Diquark: bound state of two quarks
  ⇒ not neutral in color, needs to be bound to an antidiquark

$$\begin{cases} [qq'] \in 3_C \otimes 3_C = \bar{3}_C \oplus 6_C \\ [\bar{q}\bar{q}'] \in \bar{3}_C \otimes \bar{3}_C = 3_C \oplus 6_C \end{cases}$$

$$3_C \otimes \bar{3}_C = 1_C \oplus 8_C$$

- Tetraquarks can be classified with:
  - **S** total spin of the diquark-antidiquark system $S=S_1 \oplus S_2=(0,1)\oplus(0,1) = 0,1,2$
  - **L** orbital excitation between the diquark and the antidiquark

$$\mathbf{J} = \mathbf{L} \oplus \mathbf{S}, \quad \mathbf{P} = (-1)^{\mathbf{L}}, \quad \mathbf{C} = (-1)^{\mathbf{L}+\mathbf{S}}$$

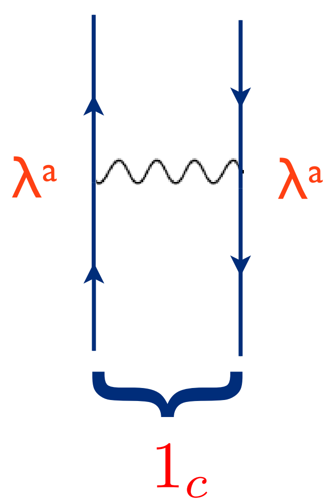
Diquarks

- Why a diquark should be bound? One Gluon Exchange:

$$Q_C \propto \sum_a T^a_A T^a_B = \frac{1}{2}\sum_a \left(T^{a2}_{A\otimes B} - T^{a2}_A - T^{a2}_B\right) \Longrightarrow Q_c \propto \frac{1}{2}\Big(C(A\otimes B) - C(A) - C(B)\Big)$$

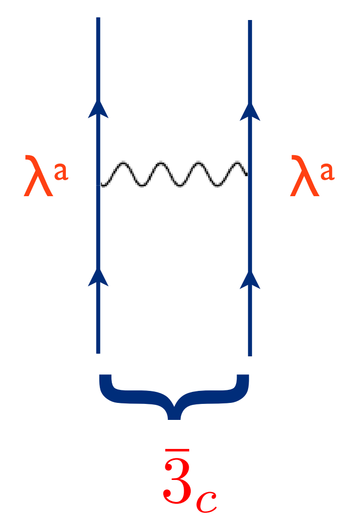
R	1_c	$\bar{3}_c$	6_c	8_c
$C(R)$	0	$4/3$	$10/3$	3

Ordinary Meson



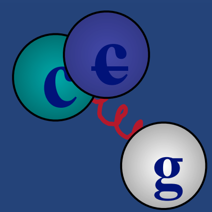
$$\begin{cases} A = 3_c, \quad B = \bar{3}_c \\ A\otimes B = 1_c \Rightarrow Q_c \propto -4/3 \end{cases}$$

Diquark



$$\begin{cases} A = 3_c, \quad B = 3_c \\ A\otimes B = \bar{3}_c \Rightarrow Q_c \propto -2/3 \\ A\otimes B = 6_c \Rightarrow Q_c \propto +1/3 \end{cases}$$

Hybrids

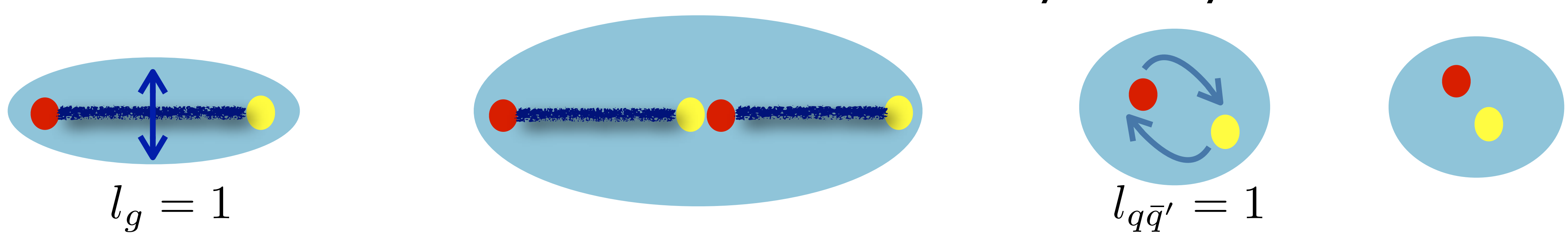


- One can obtain a color singlet combining q̄ q g

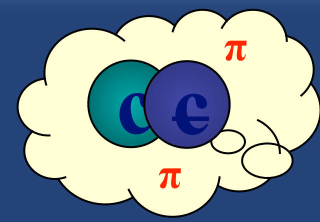
Ordinary Meson Hybrid meson

- In a constituent gluons model the gluon has a fixed orbital angular momentum with respect to the qq* pair. The hybrid state is characterized by l_g $l_{q\bar{q}}$ $s_{q\bar{q}}$

- In a flux tube model instead one can describe the decay of an hybrid meson



Hadrocharmonium (1)



Slides by Mikhail Voloshin - QWG 2010

https://indico.fnal.gov/getFile.py/access?contribId=51&sessionId=16&resId=0&materialId=slides&confId=3347

$Y(4.26)$, $Y(4.32-4.36)$, $Y(4.66)$

- $Y(4260)$: Confirmed by Belle, CLEO, CLEO-c. Also seen in $B \to \pi^+\pi^- J/\psi K$.

$Y(4260) \to \pi^+\pi^- J/\psi$: $M = 4264^{+10}_{-12}\,\text{MeV}$, $\Gamma = 83^{+20}_{-17}\,\text{MeV}$

Other decay modes seen: $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$. $\frac{\Gamma(Y\to K^+K^- J/\psi)}{\Gamma(Y\to\pi^+\pi^- J/\psi)} \approx 0.15$

No decays with $D\bar{D}$ in the final state were seen. In particular:

$\frac{\Gamma(Y\to D\bar{D})}{\Gamma(Y\to\pi^+\pi^- J/\psi)} \lesssim 1.0$, $\quad \frac{\Gamma(Y\to D\bar{D}+pions)}{\Gamma(Y\to\pi^+\pi^- J/\psi)} \lesssim 1.0$

Impossible to explain if $Y(4260)$ is a pure charmonium state!

Compare e.g. with $\Gamma(\psi(3770) \to D\bar{D})/\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) \approx 400$

- $Y(4.32-4.36)$:

"Broad structure" in (ISR) $e^+e^- \to \pi^+\pi^-\psi'$ (not J/ψ!)

BaBar: $M = 4324 \pm 24\,\text{MeV}$, $\Gamma = 172 \pm 33\,\text{MeV}$ Belle: $M = 4361 \pm 9 \pm 9\,\text{MeV}$, $\Gamma = 74 \pm 15 \pm 10\,\text{MeV}$ and additionally:

- $Y(4.66)$

Peak in $\pi^+\pi^-\psi'$ at $M = 4664 \pm 11 \pm 5\,\text{MeV}$, $\Gamma = 48 \pm 15 \pm 3\,\text{MeV}$.

Hadrocharmonium (2)

Slides by Mikhail Voloshin - QWG 2010

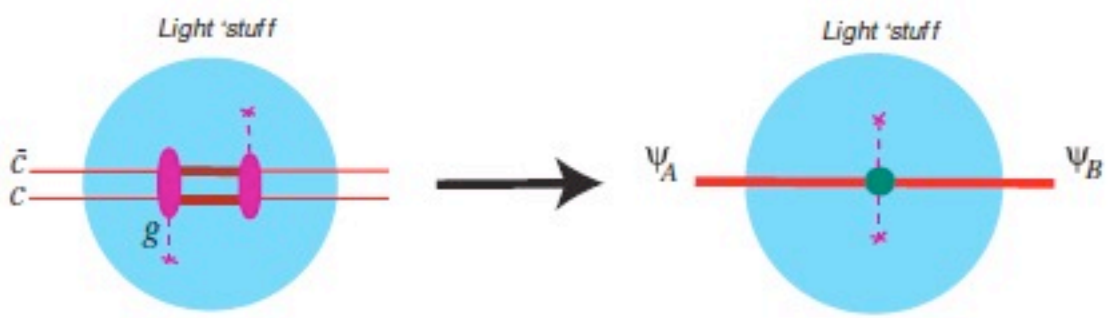
https://indico.fnal.gov/getFile.py/access?contribId=51&sessionId=16&resId=0&materialId=slides&confId=3347

- If you ask me...

To me $Y(4260)$, $Y(4.32-4.36)$, $Y(4.66)$, $Z(4430)$ all look like 'a charmonium stuck in a light hadron'. At least this can explain why dominantly a specific charmonium state e.g. J/ψ or ψ' appears in the decay.

Here's what I mean:

Van der Waals interaction of charmonium with light hadronic matter



$$\langle B|H_{eff}|A\rangle = -\frac{1}{2}\alpha_{AB}\,\vec{E}^a \cdot \vec{E}^a$$

Chromo-polarizability: α_{AB}. Chromo-electric field $\vec{E}^a$.

$|\alpha_{\psi' J/\psi}| \approx 2\,GeV^{-3}$ is known from $\psi' \to \pi\pi\, J/\psi$.

Schwartz inequality: $\alpha_{J/\psi}\alpha_{\psi'} \geq \alpha^2_{\psi' J/\psi}$, so that either $\alpha_{J/\psi}$ or $\alpha_{\psi'}$ or both should be bigger than $2\,GeV^{-3}$.

Direct Searches

:: Drenska et al., Riv.Nuovo Cim. 033 (2010) 633-712 ::

- Many final states have not been even searched for: one should: look in existing data from B-factories

B decays	JPC	J/ψππ	J/ψω	J/ψγ	J/ψφ	J/ψη	ψ(2S)ππ	ψ(2S)ω	ψ(2S)γ	$\chi_c\gamma$	pp	ΛΛ	ΛcΛc	DD	DD*	D*D*	Ds(*)Ds(*)	γγ
X(3872)	1++ [2-+]	S	S*	S	N/A	N/S	N/A	N/A	S	N/S	M/F	M/F	N/A	N/A	S	N/A	N/A	N/S
X,Y (3940)	0-+	M/F	S	N/S	N/A	N/A	N/A	N/A	M/F	N/A	M/F	M/F	N/A	M/F	N/S	N/A	N	N
Z(3940)	2++	M/F	S?^	N/S	N/A	N/A	N/A	N/A	M/F	N/A	M/F	M/F	N/A	M/F	M/F	N/A	N	N
Y(4140)	JP+	M/F	M/F	N	S	N/A	N	N/A	N	N/A	M/F	M/F	N/A	M/F	N	N	N	N
X(4160)	0P+	M/F	M/F^	N	M/F	N/A	N	N/A	N	N/A	M/F	M/F	N/A	M/F	N	N	N	N
Y(4260)	1--	S	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	N/A	N	N	N	N	N/A
X(4350)	JP+	M/F	M/F^	N	M/F	N/A	N	N	N	N/A	M/F	M/F	N/A	N	N	N	N	N
Y(4350)	1--	M/F	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	N/A	N	N	N	N	N/A
Y(4660)	1--	N	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	M/F^^	N	N	N	N	N/A

ISR	JPC	J/ψππ	ψ(2S)ππ	J/ψη	$\chi_c\gamma$	pp	ΛΛ	ΛcΛc	DD	DD*	D*D*	Ds(*)Ds(*)
Y(4260)	1--	S	N/S	N/S	N/S	N/S	M/F	N/A	N/S	N/S	N/S	N
Y(4350)	1--	N/S	S	M/F	M/F	M/F	M/F	N/A	M/F	M/F	M/F	N
Y(4660)	1--	N/S	S	M/F	M/F	M/F	M/F	S	M/F	M/F	M/F	N

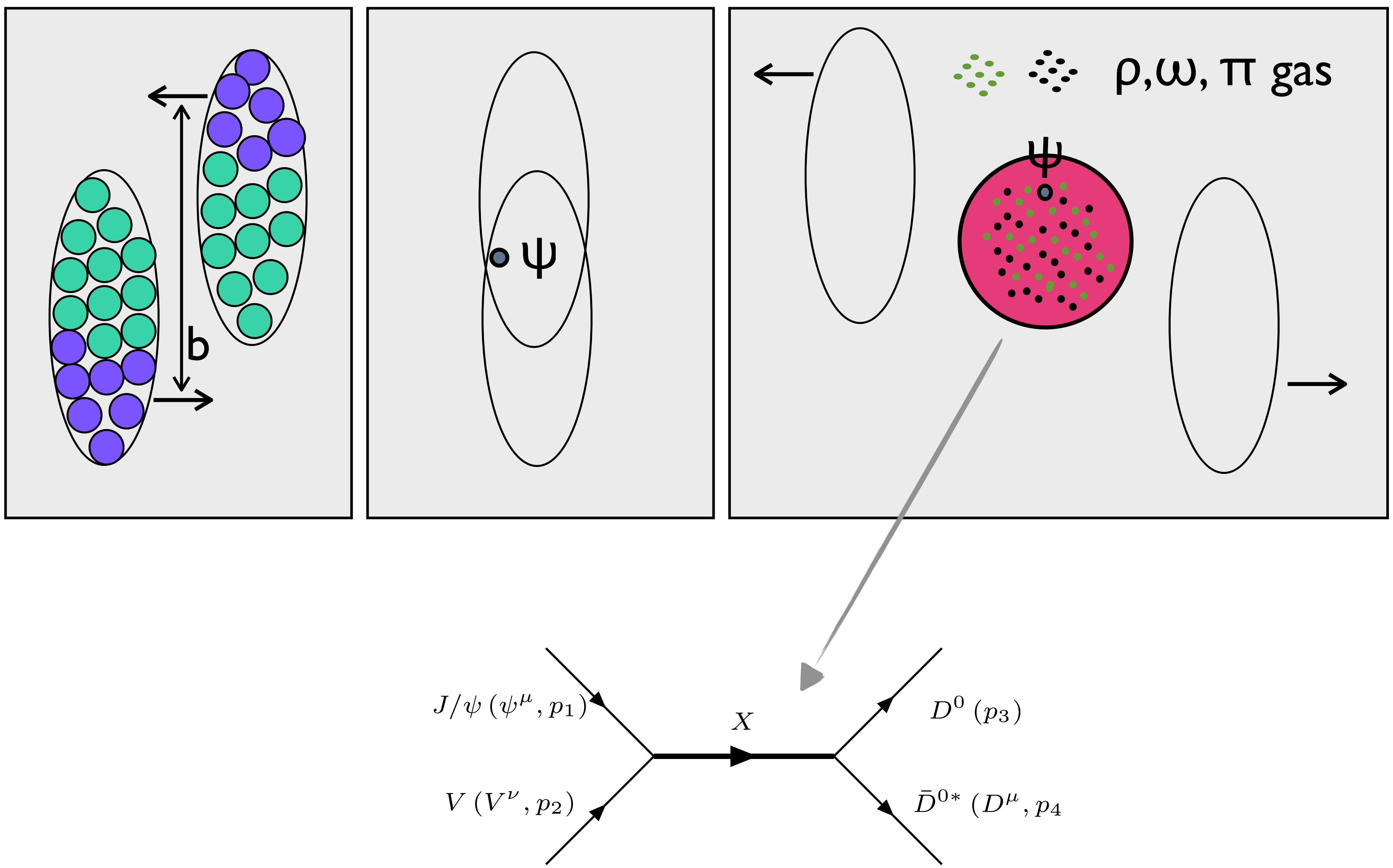
legenda
- S: seen
- M/F: missing fit
- N/S: not seen
- N: not searched
- N/A: not applicable
- N/F: not feasible

- "Nonetheless in the present generation of experiments statistics is extremely low and ***we will not be able to have a convincing picture until the results of ultra-high intensity machines, LHC and the Super Flavour Factories will be available***".

Indirect Searches (I)

Brazzi, Grinstein, Piccinini, Polosa, Sabelli, arxiv: 1103.3155

- Exotic mesons can be intermediate states in a number of processes.
  - Can they explain ψ suppression in Heavy Ions Collisions ?



Indirect Searches (2)

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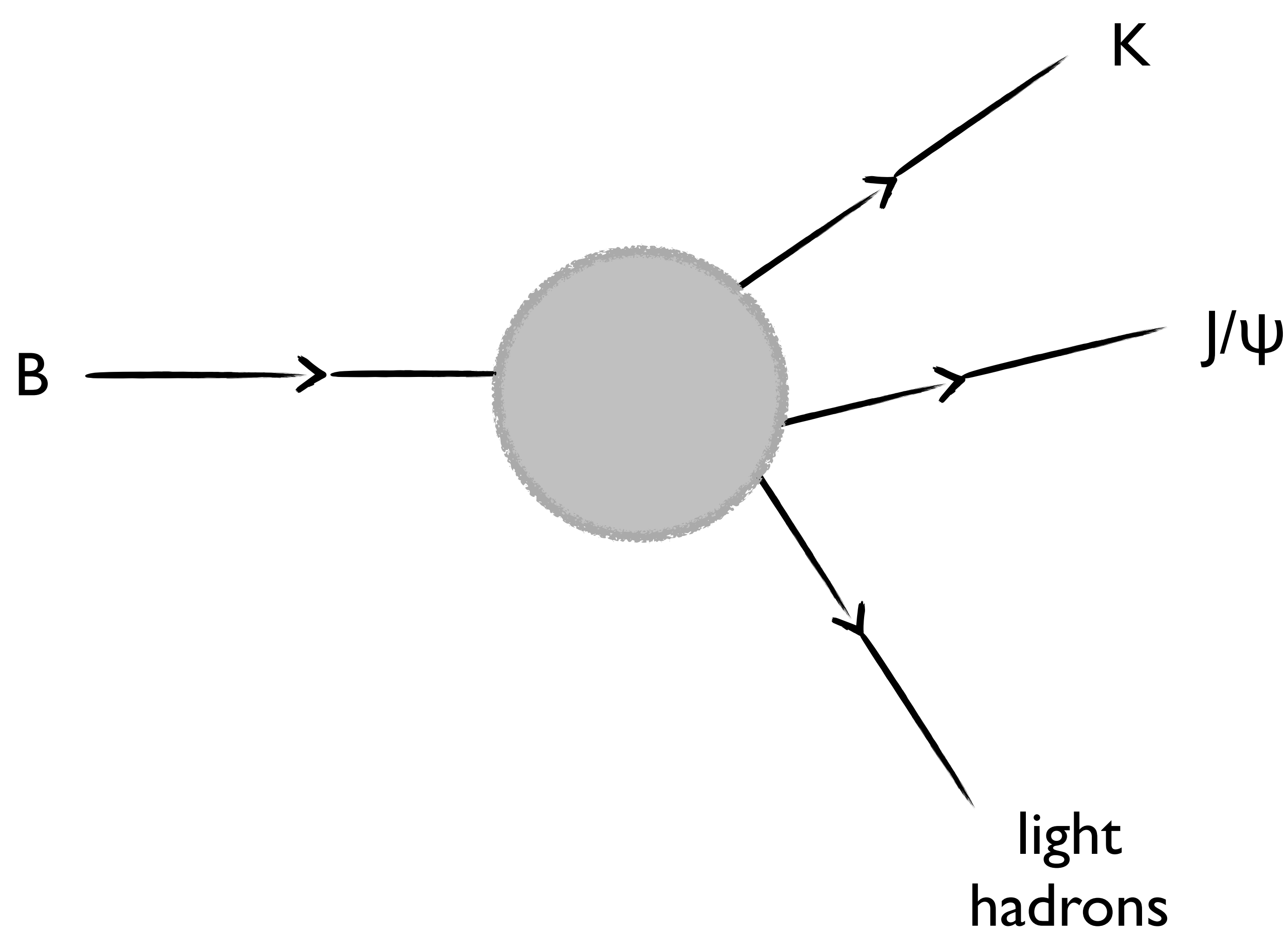

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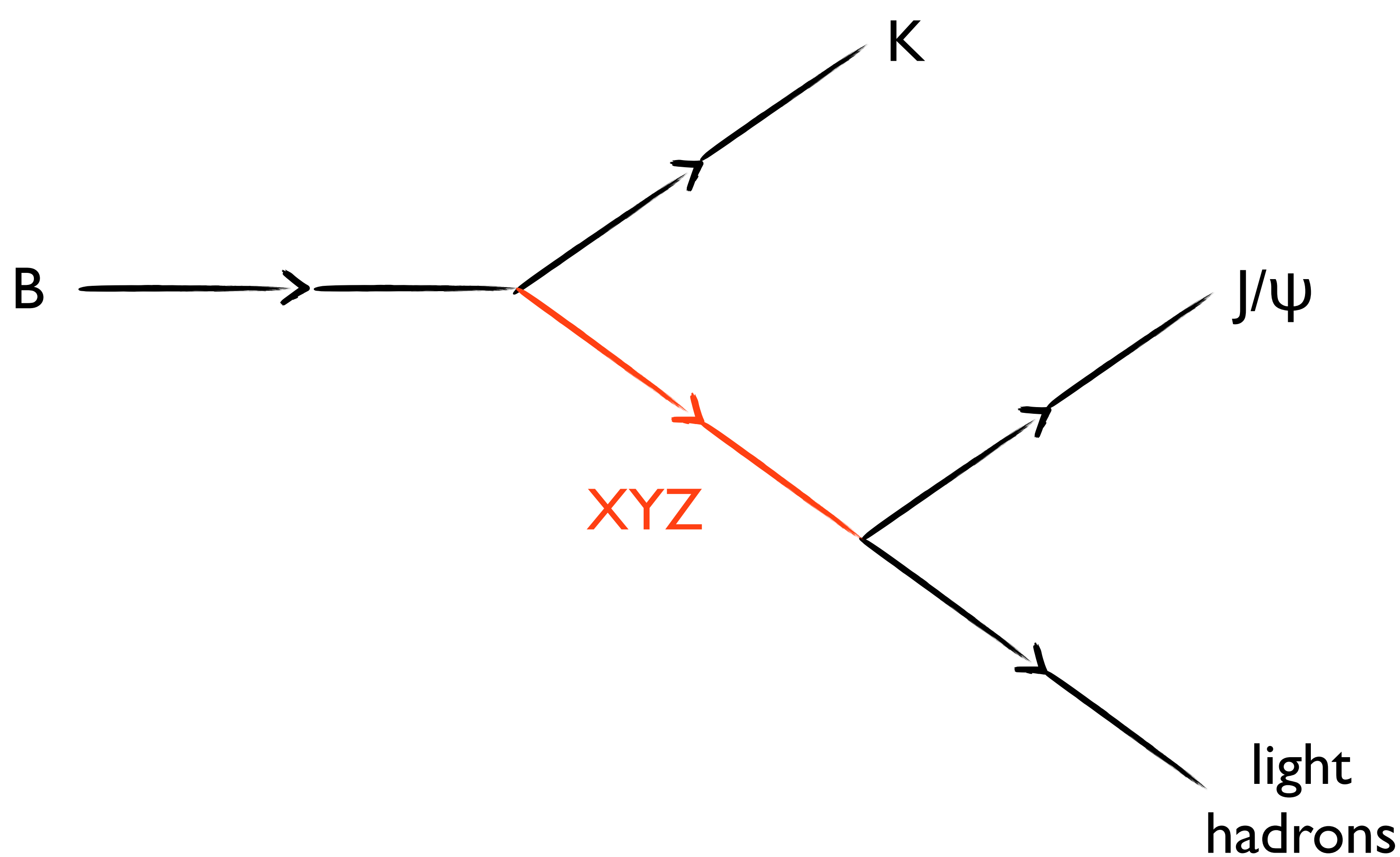
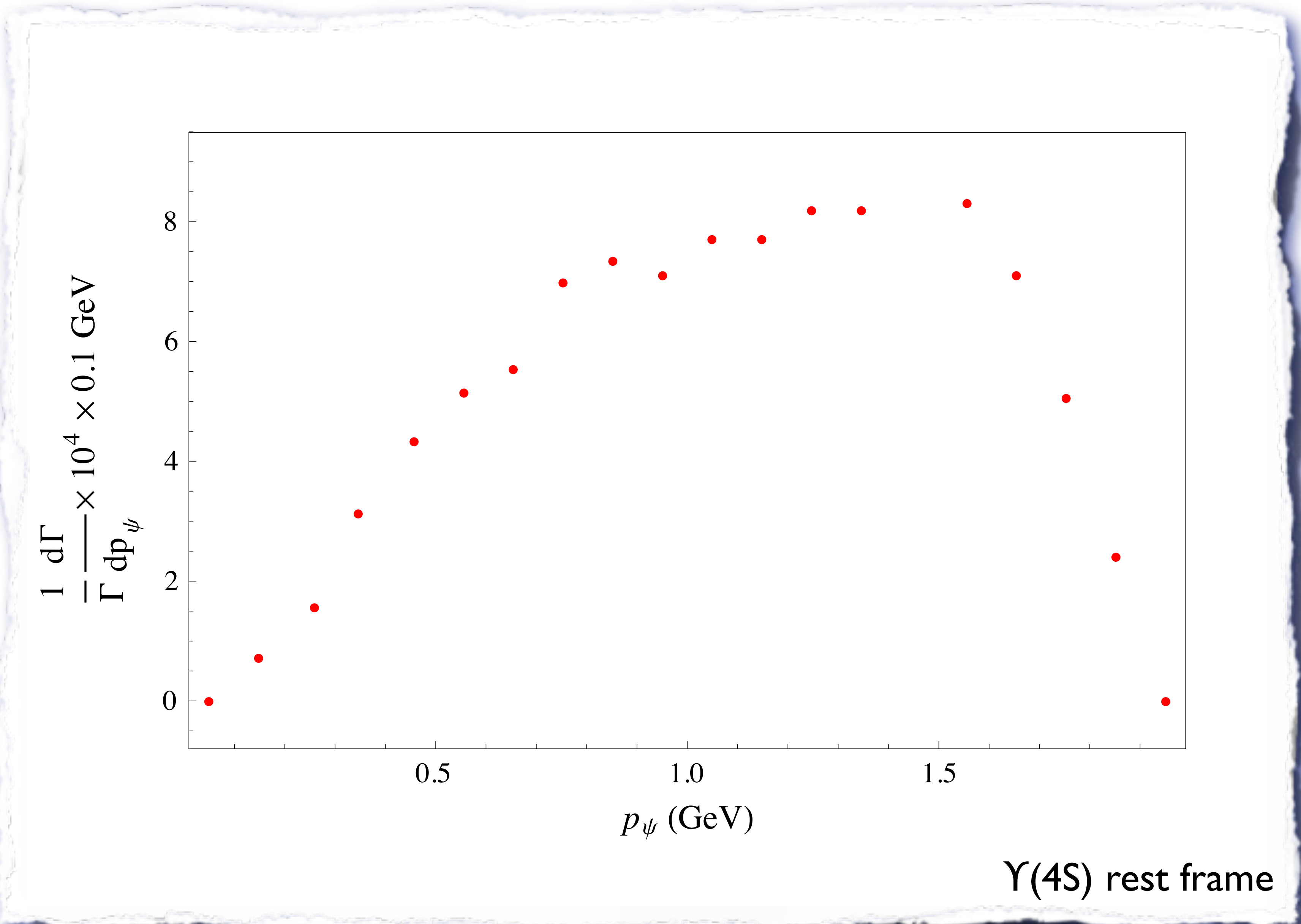


$B \to J/\psi + \mathrm{All}$

:: BaBar, Phys. Rev. D67,032002 ::

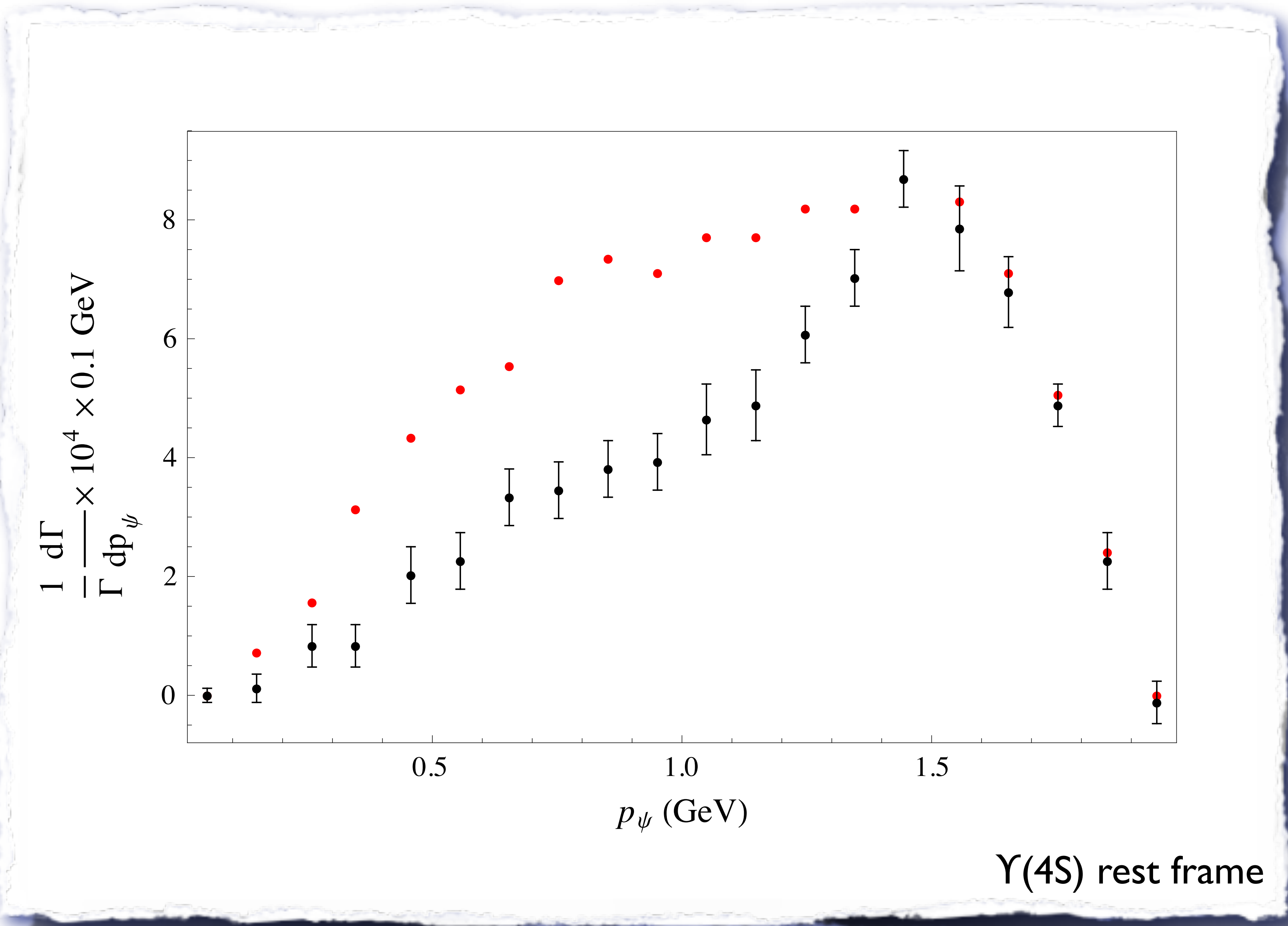
- In e^+e^- collisions at $\sqrt{s} \sim m_{\Upsilon(4S)}$ with 20.3 fb^{-1} they measure: $B \to J/\psi + \mathrm{All}$.
- In $B \to J/\psi + \mathrm{All}$ there is a feed-down from $\chi_{c1,2} \to J/\psi\, \gamma$ and $\psi(2S) \to J/\psi\, \pi^+\pi^-$.



B → J/ψ + All : direct

:: BaBar, Phys. Rev. D67,032002 ::

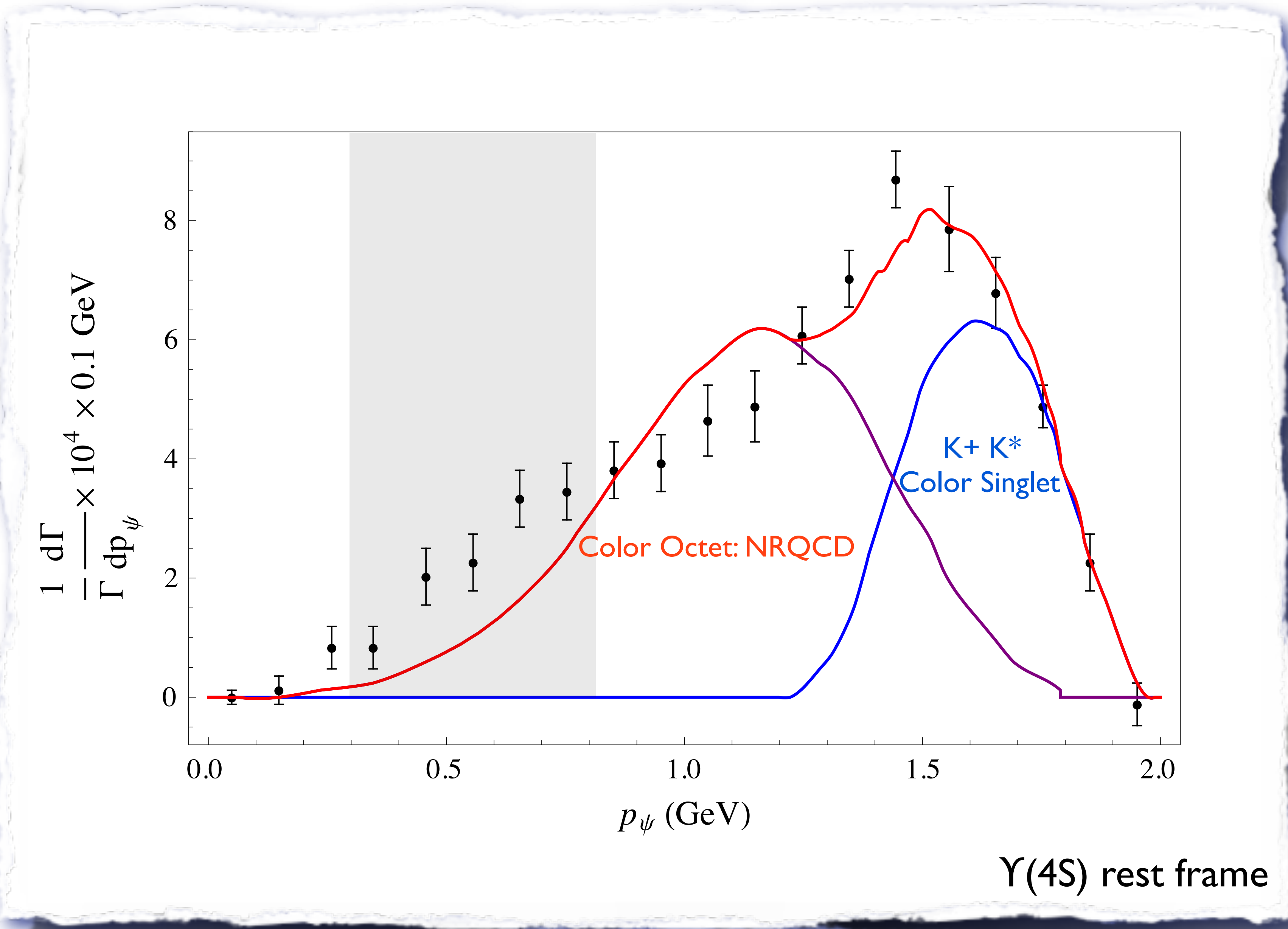
- Subtracting the feed-down from $\chi_{c1,2}$ → J/ψ γ and ψ(2S) → J/ψ $\pi^+ \pi^-$, they obtain the p^* decay distribution of J/ψ produced directly in B decays.



B → J/ψ + All : direct

:: BaBar, Phys. Rev. D67,032002 ::

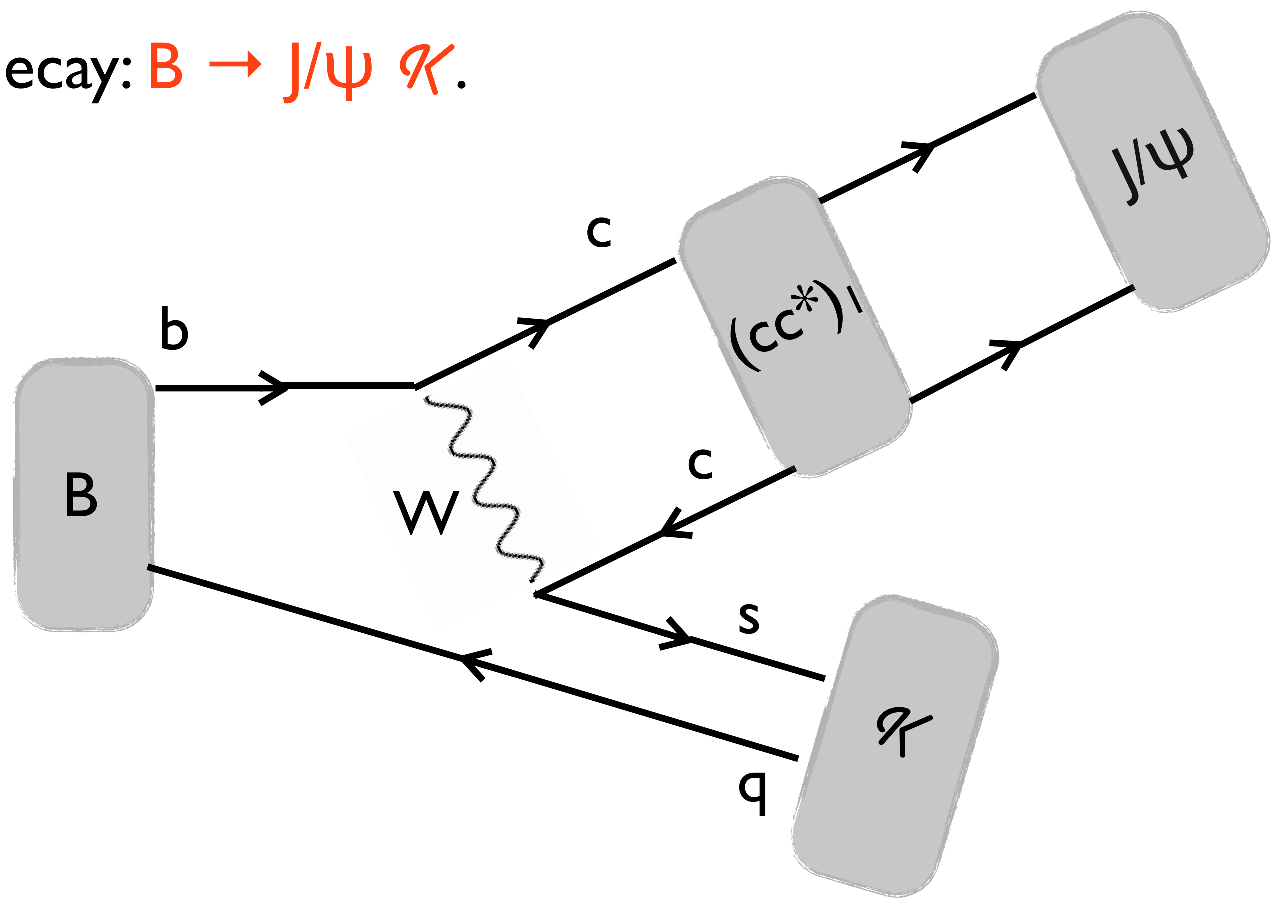
- Subtracting the feed-down from $\chi_{c1,2} \to J/\psi\ \gamma$ and $\psi(2S) \to J/\psi\ \pi^+ \pi^-$, they obtain the p^* decay distribution of J/ψ produced directly in B decays.
- Theoretical predictions reveal an excess at low p_ψ .



B → J/ψ + $\mathcal{K}$

:: K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010) ::

- If the cc* pair is produced in color singlet configuration one has a two body decay: B → J/ψ $\mathcal{K}$.



B^+ DECAY MODES	Fraction (Γ_i/Γ)
Charmonium modes	
$J/\psi(1S)K^+$	$(1.007 \pm 0.035) \times 10^{-3}$
$J/\psi(1S)K^*(892)^+$	$(1.43 \pm 0.08) \times 10^{-3}$
$J/\psi(1S)K(1270)^+$	$(1.8 \pm 0.5) \times 10^{-3}$

B → J/ψ + $\mathcal{K}$

:: Belle, Phys. Rev. D83,032005 ::

PHYSICAL REVIEW D 83, 032005 (2011)

Study of the $K^+\pi^+\pi^-$ final state in $B^+ \to J/\psi K^+\pi^+\pi^-$ and $B^+ \to \psi' K^+\pi^+\pi^-$

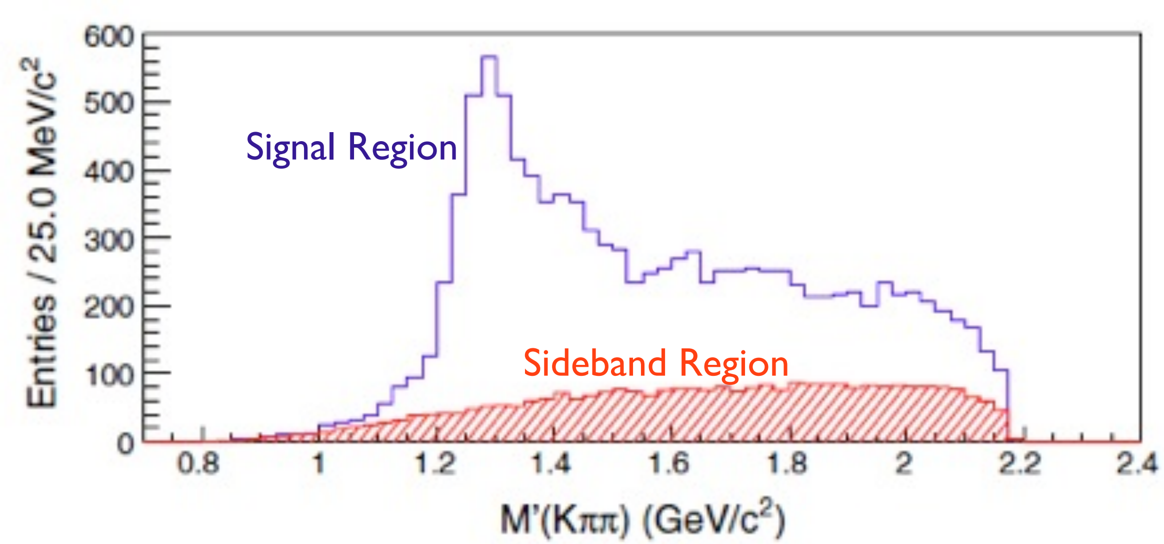
(The Belle Collaboration)

J_1	Submode	Decay fraction
	Nonresonant $K^+\pi^+\pi^-$	$0.152 \pm 0.013 \pm 0.028$
1^+	$K_1(1270) \to K^*(892)\pi$	$0.232 \pm 0.017 \pm 0.058$
	$K_1(1270) \to K\rho$	$0.383 \pm 0.016 \pm 0.036$
	$K_1(1270) \to K\omega$	$0.0045 \pm 0.0017 \pm 0.0014$
	$K_1(1270) \to K_0^*(1430)\pi$	$0.0157 \pm 0.0052 \pm 0.0049$
	$K_1(1400) \to K^*(892)\pi$	$0.223 \pm 0.026 \pm 0.036$
1^-	$K^*(1410) \to K^*(892)\pi$	$0.047 \pm 0.016 \pm 0.015$
2^+	$K_2^*(1430) \to K^*(892)\pi$	$0.088 \pm 0.011 \pm 0.011$
	$K_2^*(1430) \to K\rho$	0.0233 (fixed)
	$K_2^*(1430) \to K\omega$	0.00036 (fixed)
	$K_2^*(1980) \to K^*(892)\pi$	$0.0739 \pm 0.0073 \pm 0.0095$
	$K_2^*(1980) \to K\rho$	$0.0613 \pm 0.0058 \pm 0.0059$
2^-	$K(1600) \to K^*(892)\pi$	$0.0187 \pm 0.0058 \pm 0.0050$
	$K(1600) \to K\rho$	$0.0424 \pm 0.0062 \pm 0.0110$
	$K_2(1770) \to K^*(892)\pi$	$0.0164 \pm 0.0055 \pm 0.0061$
	$K_2(1770) \to K_2^*(1430)\pi$	$0.0100 \pm 0.0028 \pm 0.0020$
	$K_2(1770) \to Kf_2(1270)$	$0.0124 \pm 0.0033 \pm 0.0022$
	$K_2(1770) \to Kf_0(980)$	$0.0034 \pm 0.0017 \pm 0.0011$

TABLE V. Fitted parameters of the signal function for $B^+ \to J/\psi K^+\pi^+\pi^-$, along with the corresponding decay fractions.

$$B^+ \to \mathcal{K}_j J/\psi \to \mathcal{R}_i J/\psi \to J/\psi\, K^+\pi^+\pi^-$$

$$\mathcal{B}(B^+ \to \mathcal{K}_j J/\psi \to \mathcal{R}_i J/\psi \to J/\psi\, K^+\pi^+\pi^-) = \mathcal{B}_{\text{tot}} \mathrm{f}_{\mathrm{i}}^{\mathrm{j}}$$



B → J/ψ + $\mathcal{K}$

:: Burns, Piccinini, Polosa, Prosperi, Sabelli, arXiv:1104.1781::

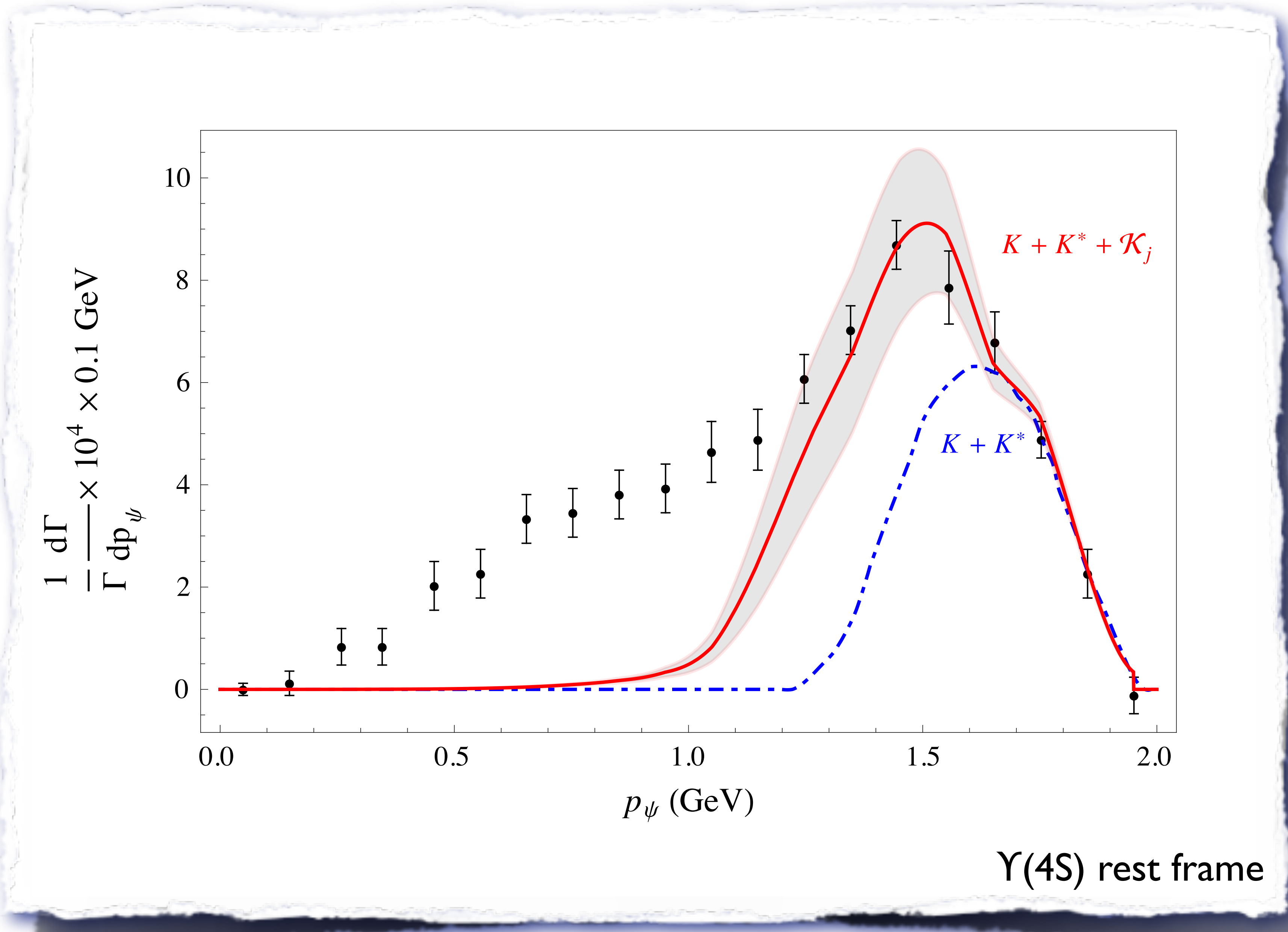
- From the fractions we compute the two body branching ratios

$\mathcal{K}_j$	$m_{\mathcal{K}_j}$ (GeV)	$\Gamma_{\mathcal{K}_j}$ (GeV)	$\mathcal{B}(B^+ \to \mathcal{K}_j J/\psi) \times 10^5$	
K	0.494	–	95.0 ± 3.6	*
K^*	0.892	0.050	137.0 ± 7.8	*
$K_1(1270)$	1.270	0.090	144.0 ± 29.3	
$K_1(1400)$	1.403	0.174	25.1 ± 5.7	
$K^*(1410)$	1.414	0.232	$> 5.1 \pm 2.4$ and $< 11.8 \pm 5.7$	
$K_2^*(1430)$	1.430	0.100	40.2 ± 24.0	
$K_2(1600)$	1.605	0.115	$> 8.4 \pm 2.9$	
$K_2(1770)$	1.773	0.186	$> 4.4 \pm 1.5$	
$K_2(1980)$	1.973	0.373	$> 15.2 \pm 2.5$	

* http://hfag.phys.ntu.edu.tw/b2charm/index.html

B → J/ψ + $\mathcal{K}$

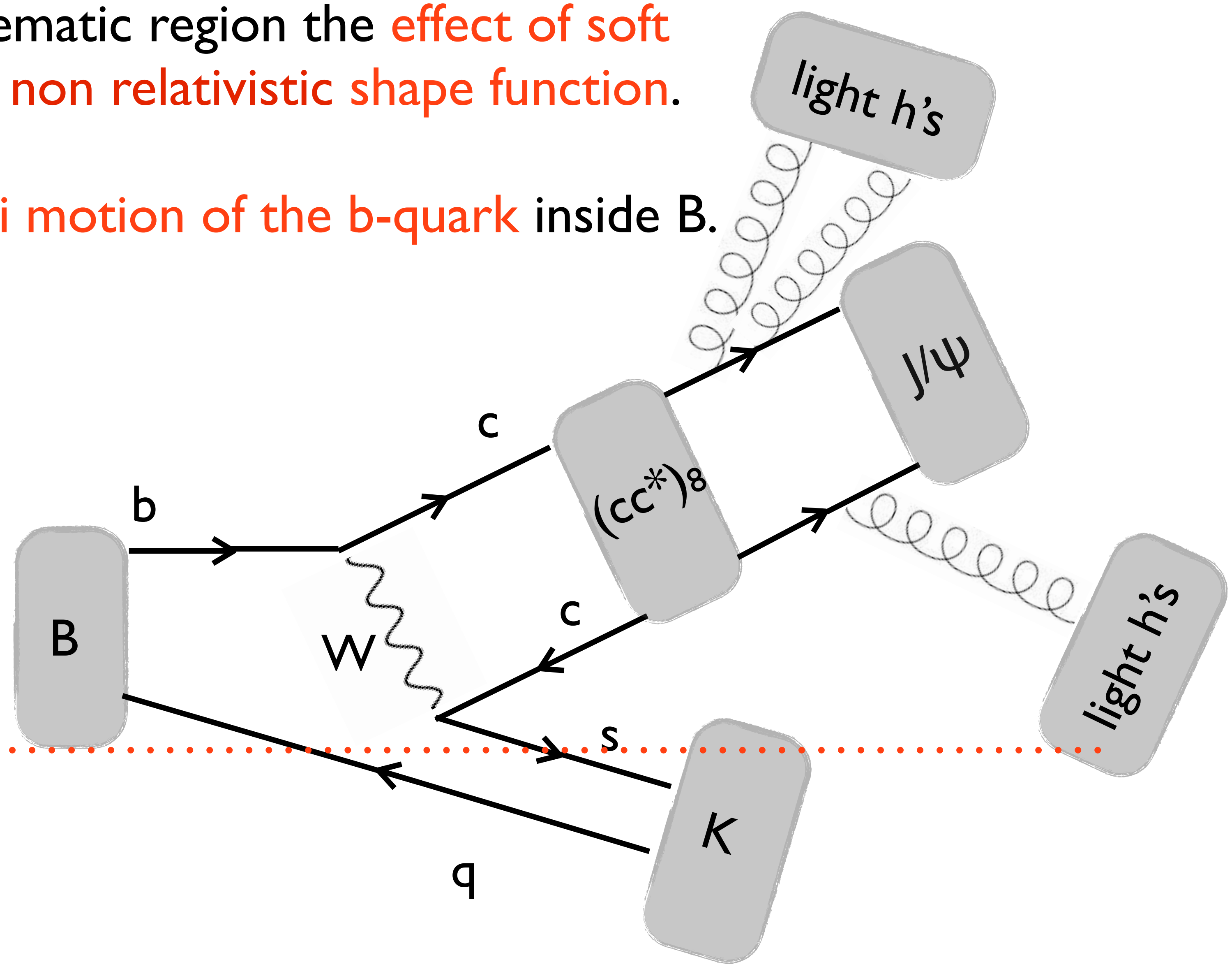
- Two body contributions accounts for the high p_ψ region: we found good agreement for p_ψ > 1.2 GeV.



Color Octet Contribution

:: Beneke, Schuler, Wolf, Phys.Rev. D62 (2000) 034004 ::

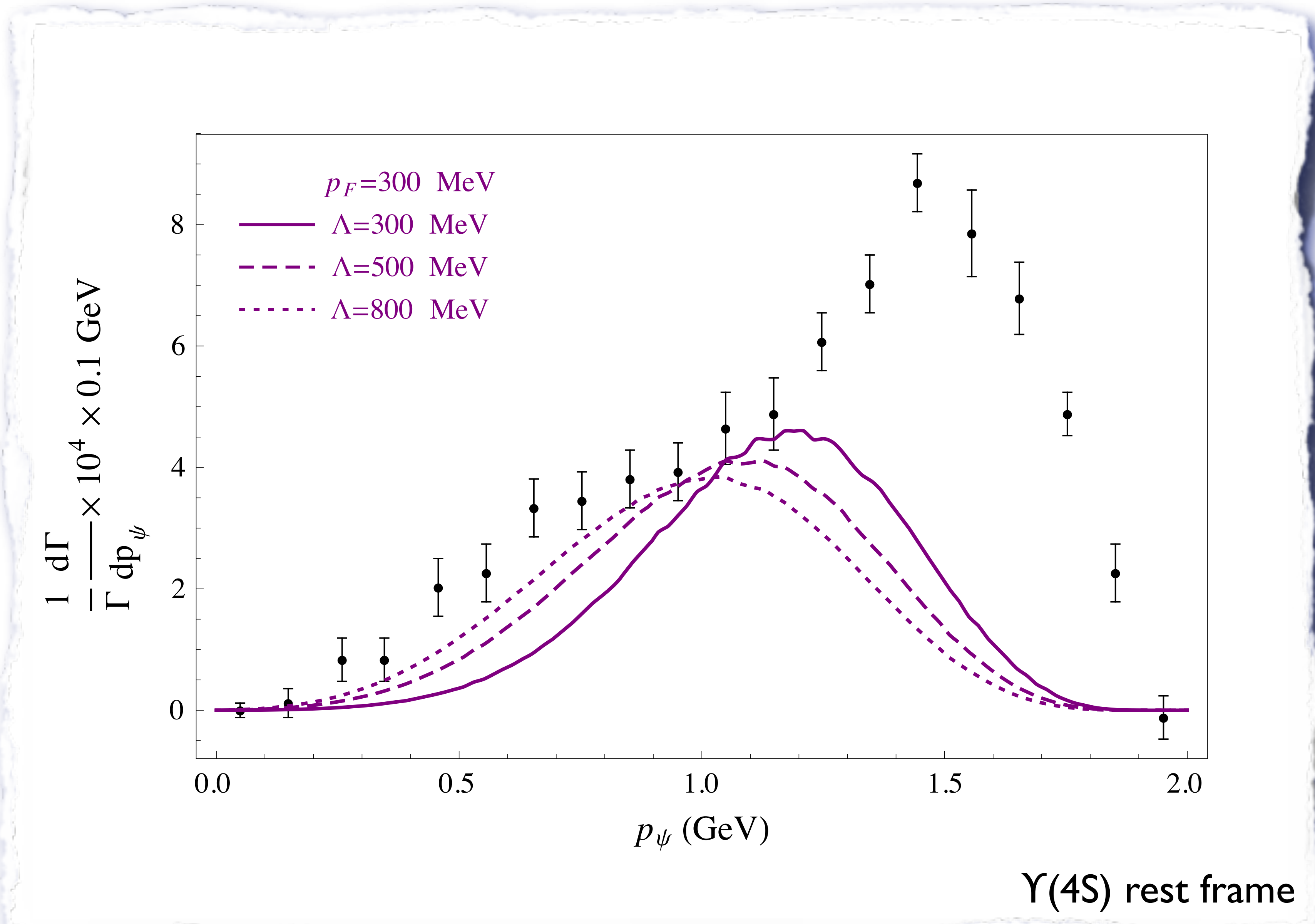
- If the $c\bar{c}^*$ pair is produced in color octet configuration one has a multi body decay.
- NRQCD matrix elements describe the fragmentation $(c\bar{c}^*)_8 \rightarrow J/\psi$.
- Near the extreme endpoint of the kinematic region the effect of soft gluon emission can be modelled with a non relativistic shape function.
- ACCMM model accounts for the Fermi motion of the b-quark inside B.



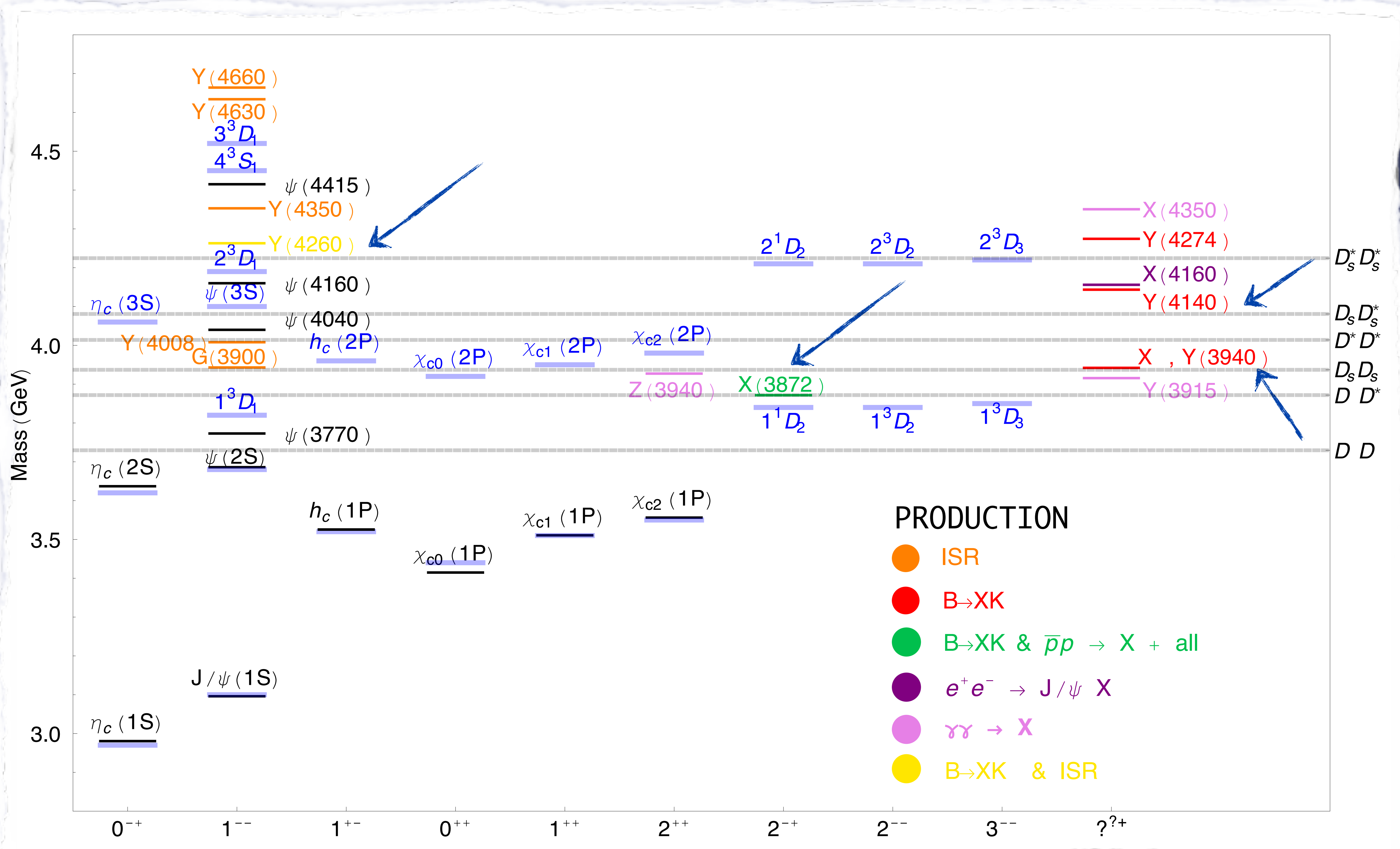
Hypothesis:
no interaction between the hard part and soft part of the process.

Color Octet Contribution

- Two main parameters to model the color octet contribution:
  $\Lambda_{QCD} \in [200,450]$MeV :the characteristic energy-momentum scale of the soft gluons;
  $p_F \in [300,450]$MeV : Fermi momentum of the b-quark inside the B-meson.



Which XYZ contribute to B → J/ψ + All ?



B → $\mathcal{K}\,\mathcal{X}$ → $\mathcal{K}$ J/ψ + light hadrons

- B → K(500) $\mathcal{X}$ → K(500) J/ψ + light hadrons branching ratios are known:

$\mathcal{X}_j$	$m_{\mathcal{X}_j}$ (GeV)	$\Gamma_{\mathcal{X}_j}$ (GeV)	Final State	$\mathcal{B}(B \to K\mathcal{X}_j \to K J/\psi + \text{light hadrons}) \times 10^5$
$X(3872)$	3.872	0.003	$J/\psi\,\rho \to J/\psi\,\pi^+\pi^-$	0.72 ± 0.22 [A]
			$J/\psi\,\omega$	0.6 ± 0.3 [B]
$Y(3940)$	3.940	0.087	$J/\psi\,\omega$	3.70 ± 1.14 [C]
$Y(4140)$	4.140	0.012	$J/\psi\,\phi$	0.9 ± 0.4 [D]
$Y(4260)$	4.260	0.095	$J/\psi\,f_0 \to J/\psi\,\pi^+\pi^-$	2.00 ± 0.73 [C]

[A] B. Aubert et al. (BABAR), Phys. Rev. **D77**, 111101 (2008), 0803.2838.
[B] P. del Amo Sanchez et al. (BABAR), Phys. Rev. **D82**, 011101 (2010), 1005.5190.
[C] `http://hfag.phys.ntu.edu.tw/b2charm/index.html`.
[D] K. Yi and f. t. C. collaboration, PoS EPS-HEP **2009**, 2009:085,2009 (2009), 0910.3163.

- For heavy kaons $\mathcal{K}$ we deduce the coupling B-$\mathcal{K}\,\mathcal{X}$ from the B-K(500)$\mathcal{X}$ one:

<u>Spin 0 $\mathcal{K}$</u> $\langle \mathcal{X}(\epsilon,p)\mathcal{K}(q)|B(P)\rangle = g\,\epsilon\cdot q$

<u>Spin 1 $\mathcal{K}$</u> $\langle \mathcal{X}(\epsilon,p)\mathcal{K}(\eta,q)|B(P)\rangle = g'\,\epsilon\cdot\eta$

$$g' = \Lambda\, g$$

Λ some mass scale

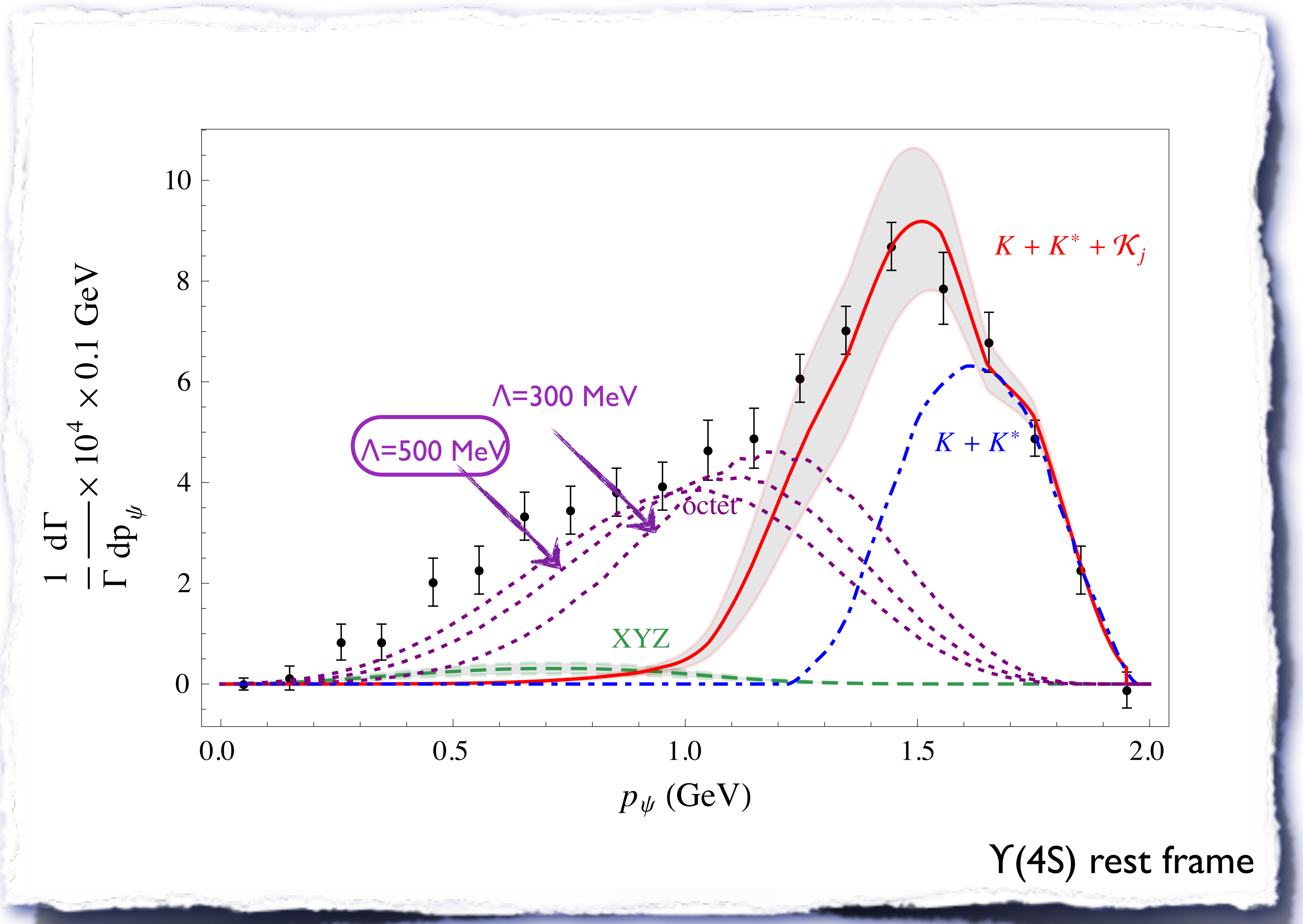
We assume

Λ = $m_{K(J=1)}$

taking all $\mathcal{X}$ to be Spin 1 states.

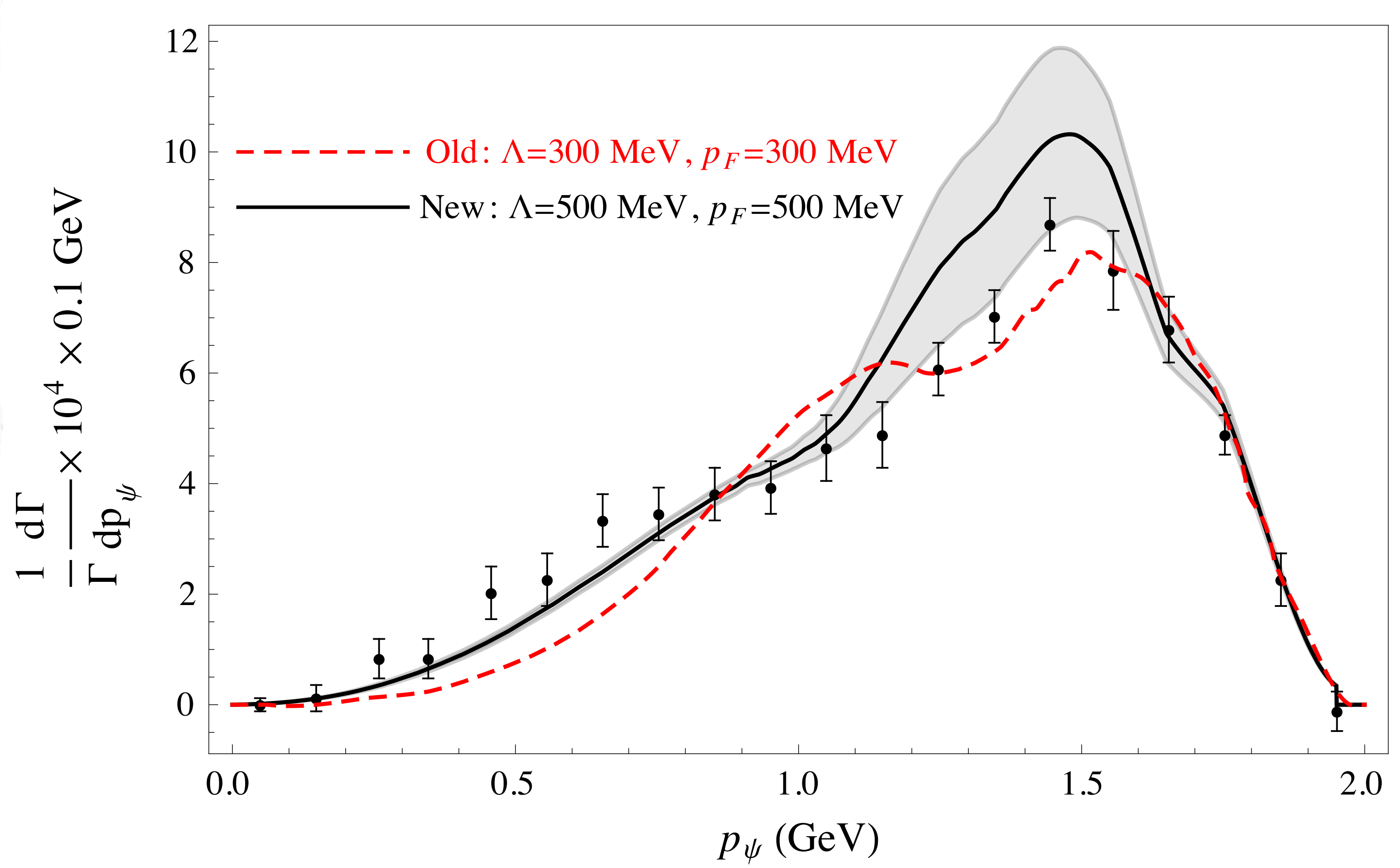
Results (I)

- We simulate the decay B → $\mathcal{K}$X → $\mathcal{K}$ J/ψ + light hadrons taking into account the partial decay wave.
- We fit the sum of all the contributions to data using as a free parameter the overall normalization of the color octet component.



Results (2)

- The best fit in the allowed region for the two parameters (Λ_{QCD}, p_F) is obtained choosing: Λ_{QCD} = 500 MeV and p_F = 500 MeV .

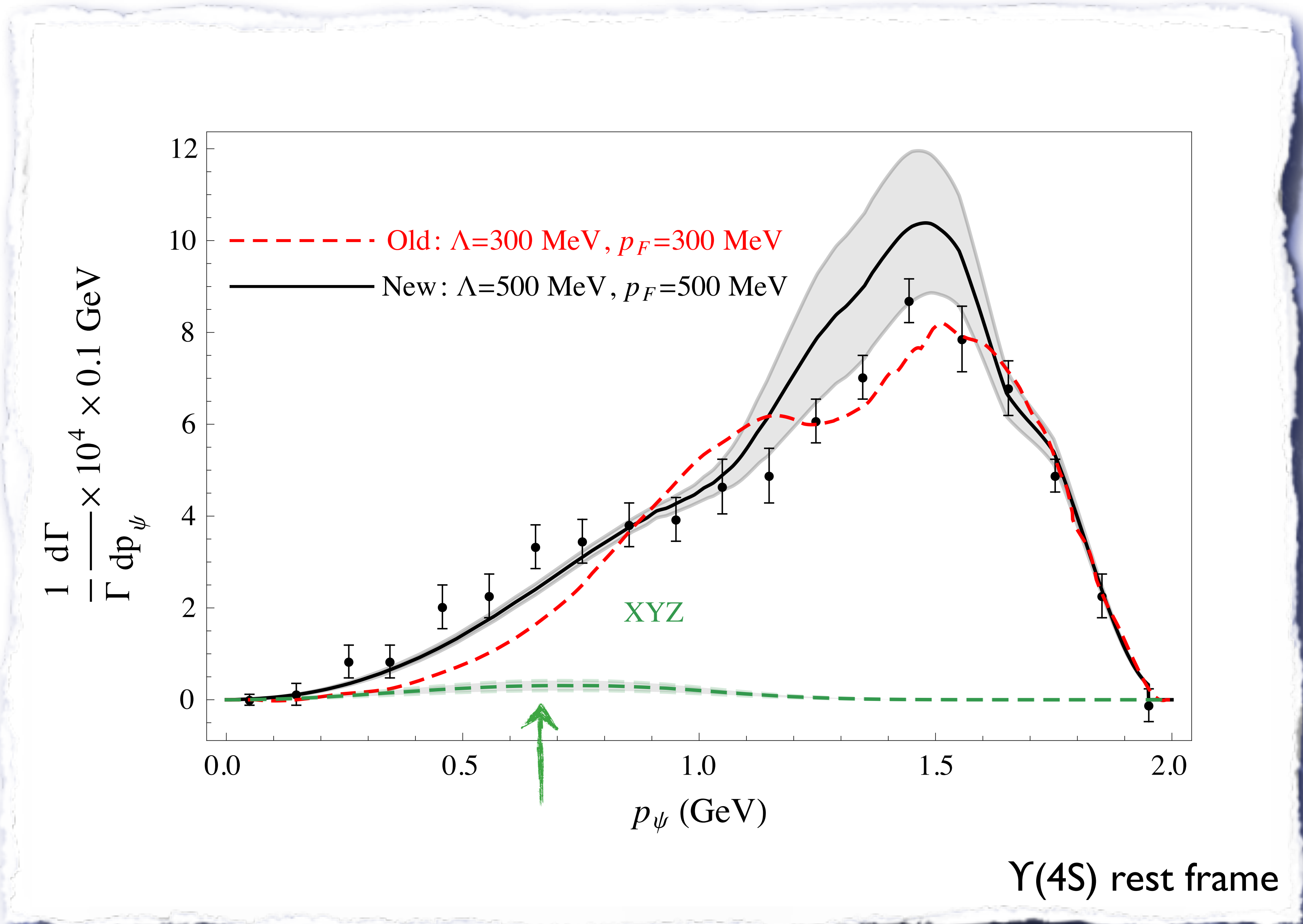


Υ(4S) rest frame

Old: χ^2=60/19
New: χ^2=22/19

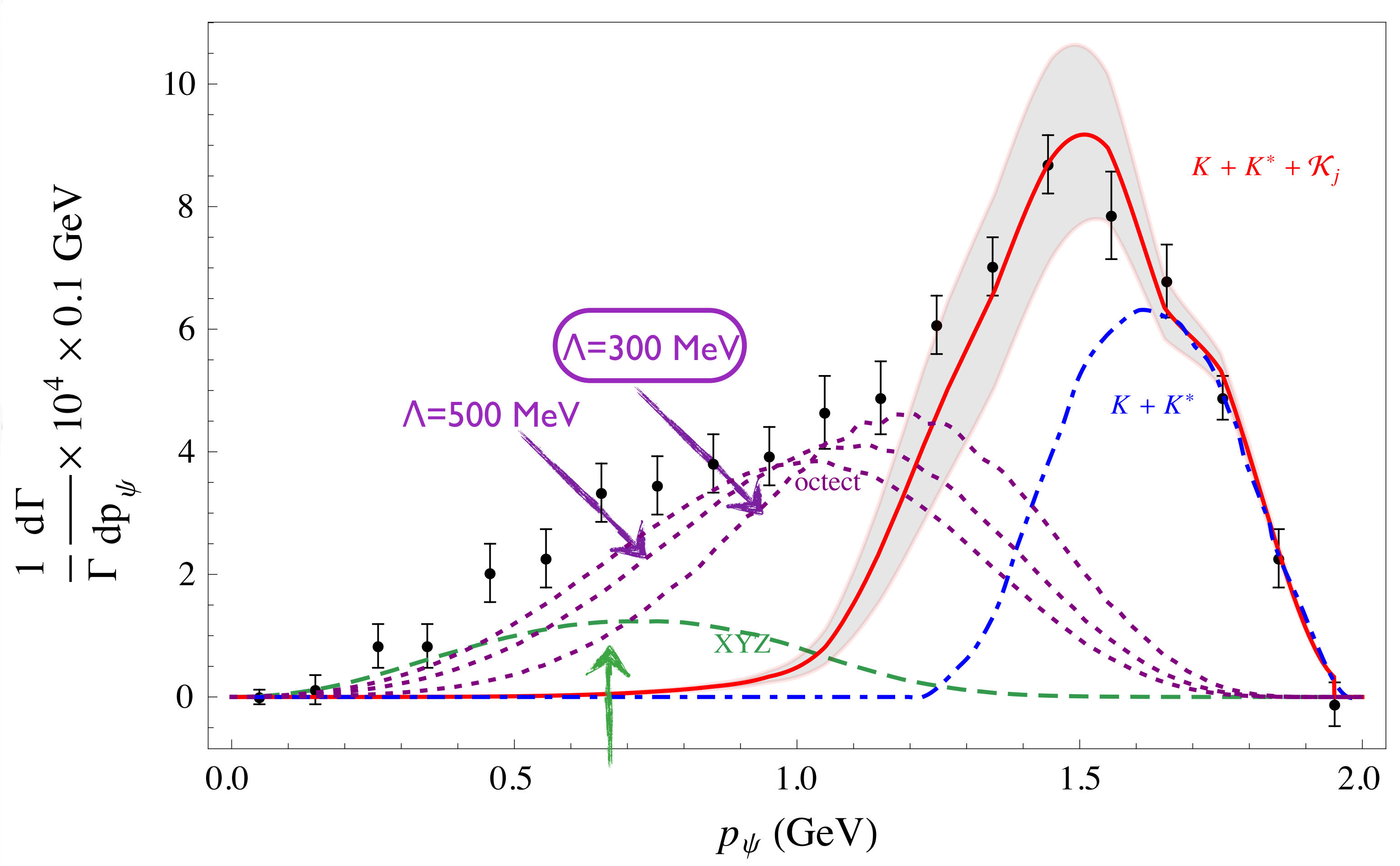
Results (2)

- The best fit in the allowed region for the two parameters (Λ_{QCD} , p_F) is obtained choosing: Λ_{QCD} = 500 MeV and p_F = 500 MeV .



Results (3)

- If the branching ratio due to XYZ turns out to be larger than the one measured (more XYZ states!) the best fit could be obtained with more reasonable parameters for the color octet component.



Υ(4S) rest frame

Conclusions

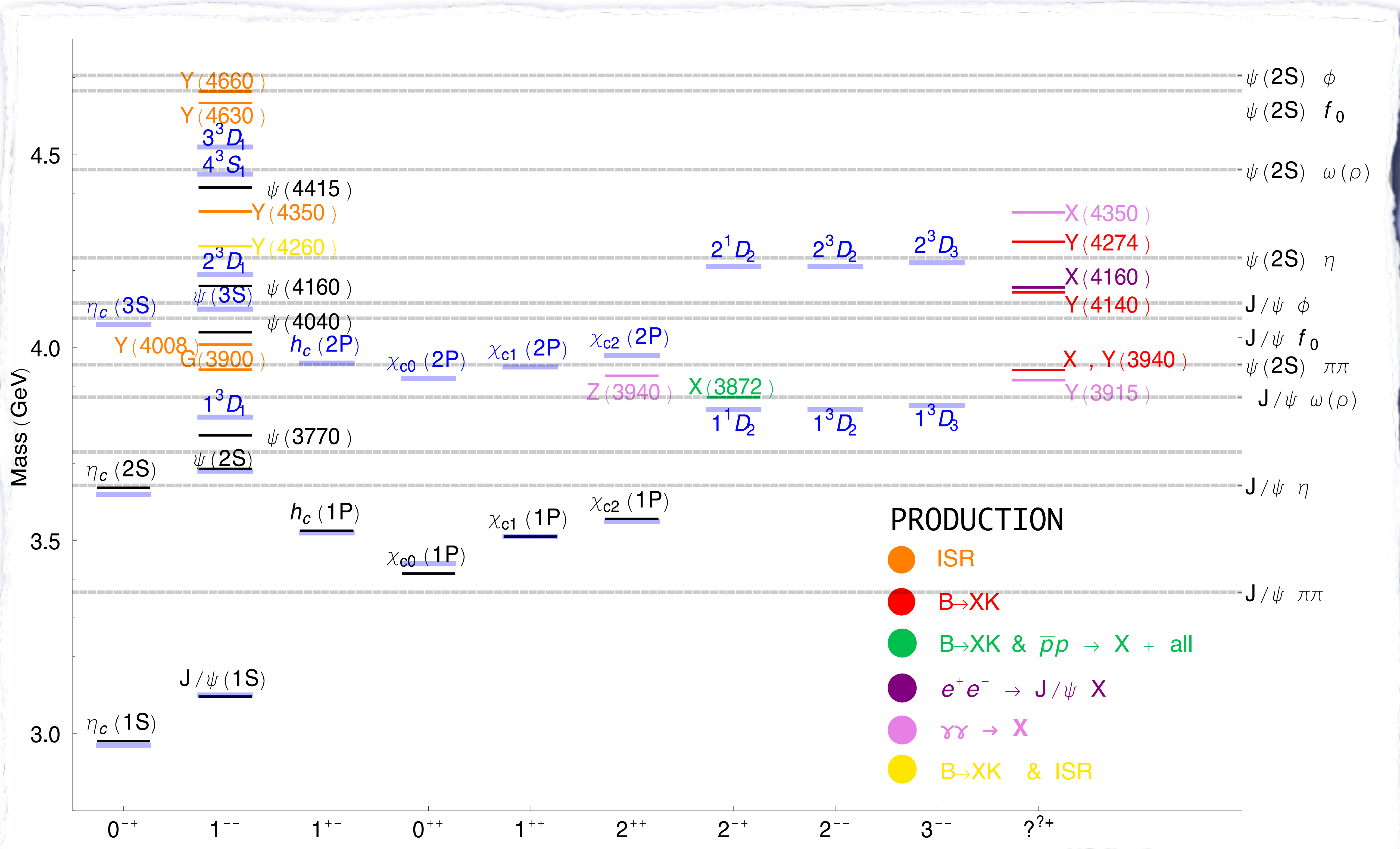
- Almost ten years of studies have uncovered a completely new spectroscopy .
- A unifying picture is still lacking :
  - Data
    - a strong interplay between theory and experiments is needed
    - higher statistics is needed
  - Theory
    - the appearance of exotic states both at threshold and far away from thresholds may suggest that a mechanism relating thresholds to multiquark states does exist.
- Indirect searches may represent a complementary strategy.

SUPER B OFFERS US THIS POSSIBILITY

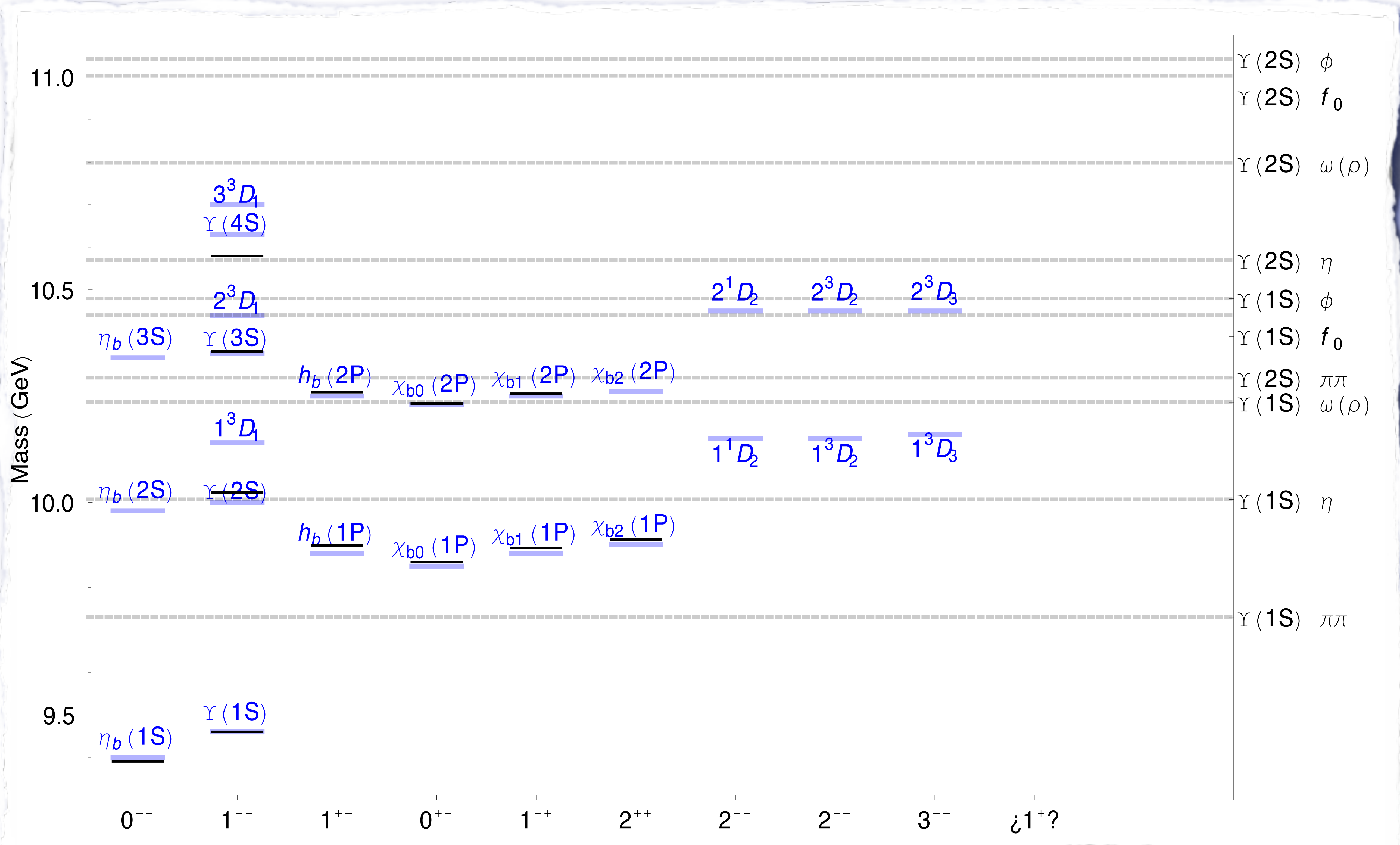
Back Up

Unexpected (2)

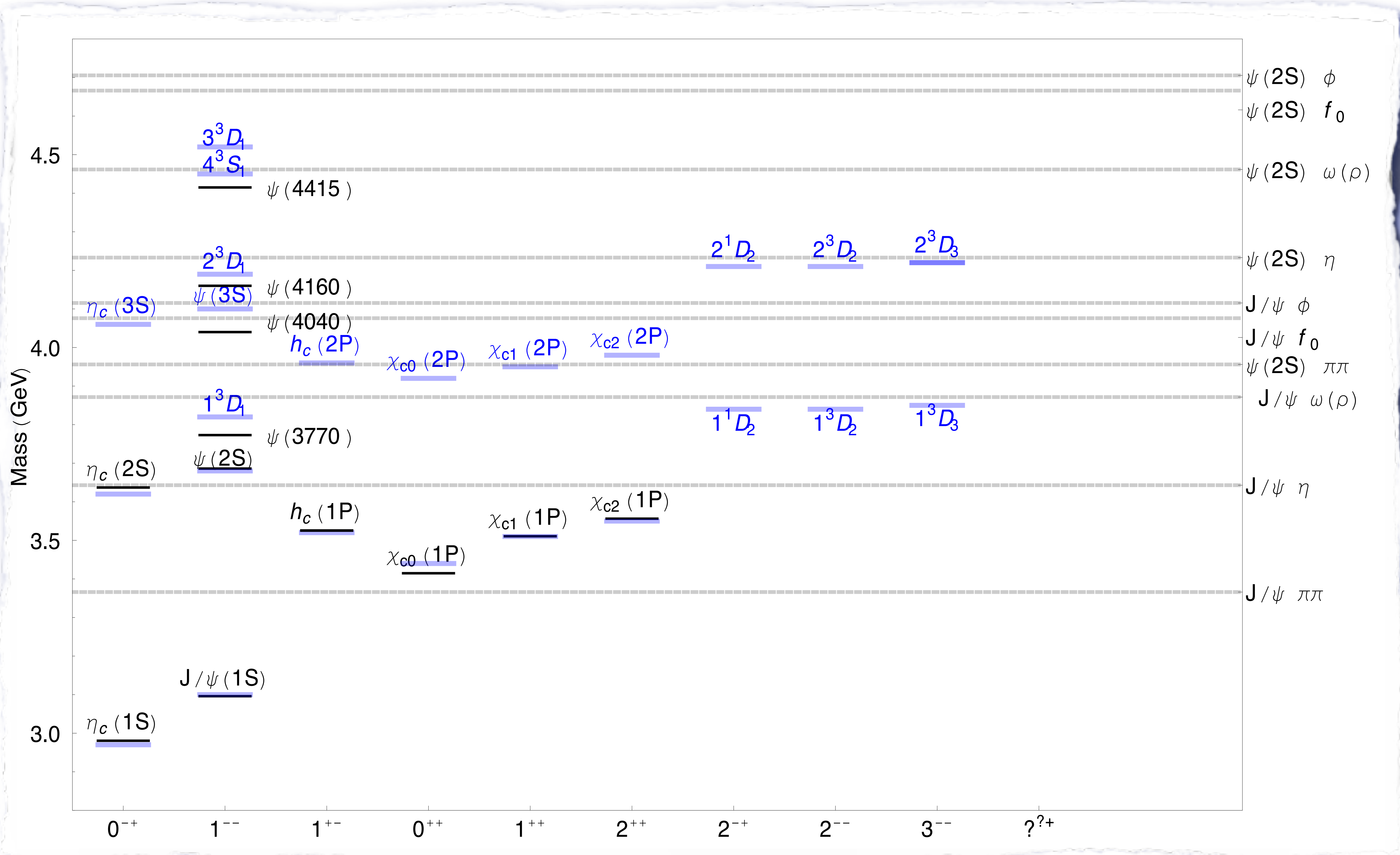
:: Heavy Quarkonium Working Group, Eur.Phys.J. C71 (2011) 1534 ::



Data for bb* states

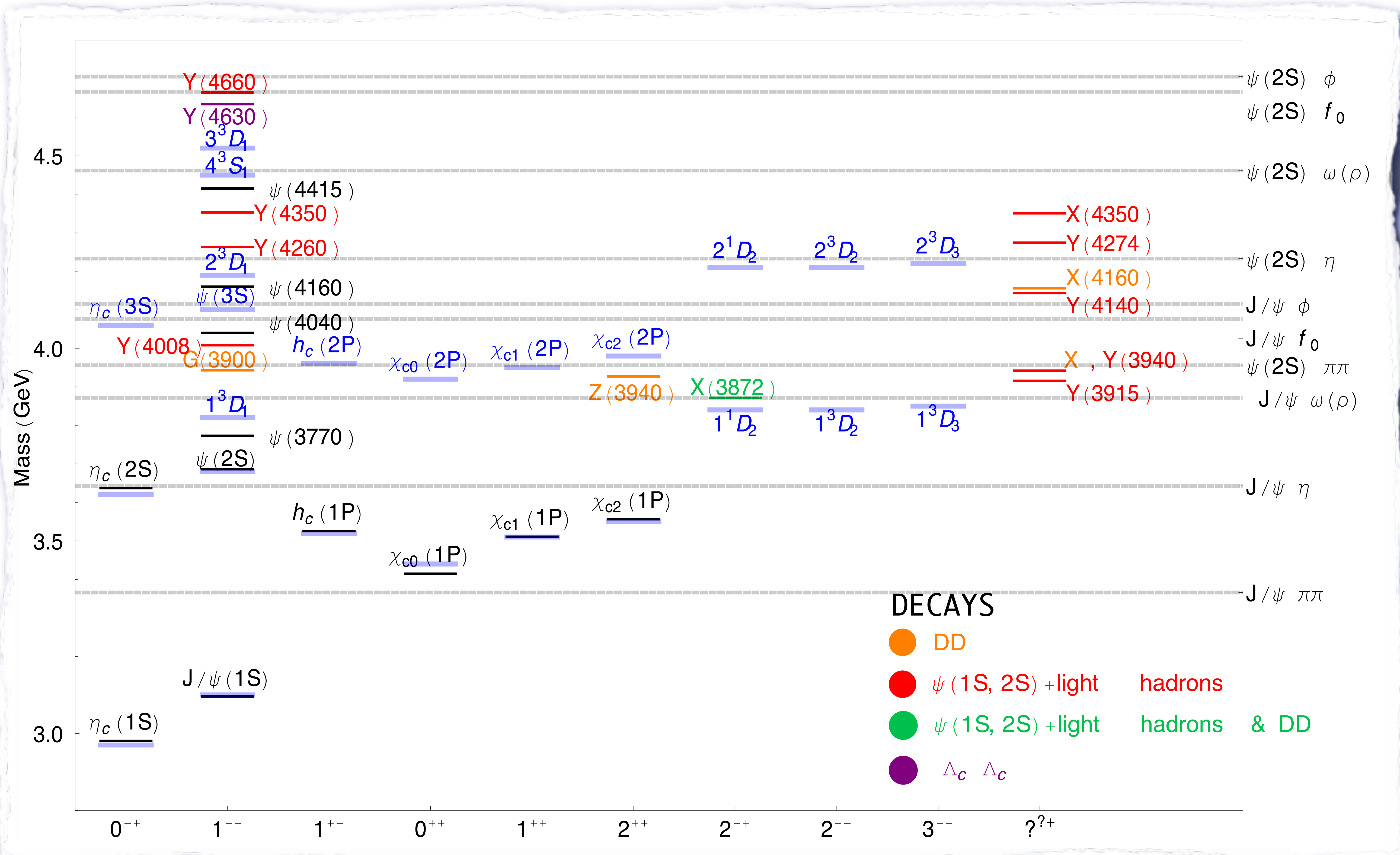


Data for cc* states



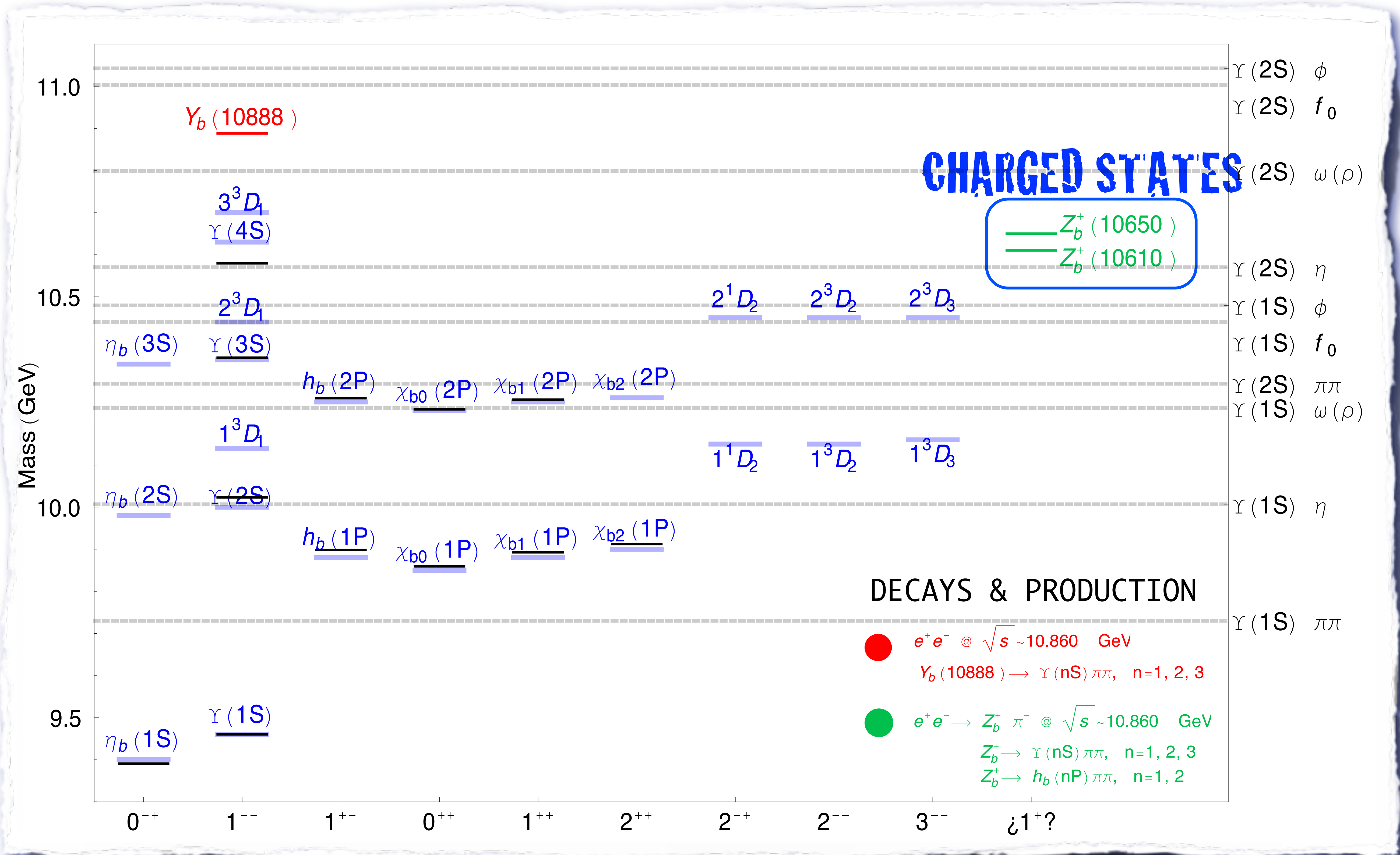
Unexpected (I)

:: Heavy Quarkonium Working Group, Eur.Phys.J. C71 (2011) 1534 ::



Unexpected

:: Belle, Phys.Rev.Lett. 100 (2008) 1120014 ::
:: Belle, arXiv:1105.4583 ::



$B \to J/\psi$ + All

:: BaBar, Phys. Rev. D67,032002 ::

- In e^+e^- collisions at $\sqrt{s} \sim m_{\Upsilon(4S)}$ with 20.3 fb^{-1} they measure:
  $B \to J/\psi$ + All, $B \to \psi(2S)$ + All, $B \to \chi_{c1,2}$ + All.

- $J/\psi \to e^+e^-$, $\mu^+\mu^-$
  $\psi(2S) \to e^+e^-$, $\mu^+\mu^-$ and $J/\psi\, \pi^+\pi^-$
  $\chi_{c1,2} \to J/\psi\, \gamma$

- $\mathcal{B}(J/\psi \to e^+e^-)$=5.94%
  $\mathcal{B}(J/\psi \to \mu^+\mu^-)$=5.93%

- $\mathcal{B}(\psi(2S) \to e^+e^-)$=0.765%
  $\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$=0.760%
  $\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)$=33.1%

- $\mathcal{B}(\chi_{c1} \to J/\psi\, \gamma)$=34.1%
  $\mathcal{B}(\chi_{c2} \to J/\psi\, \gamma)$=19.4%

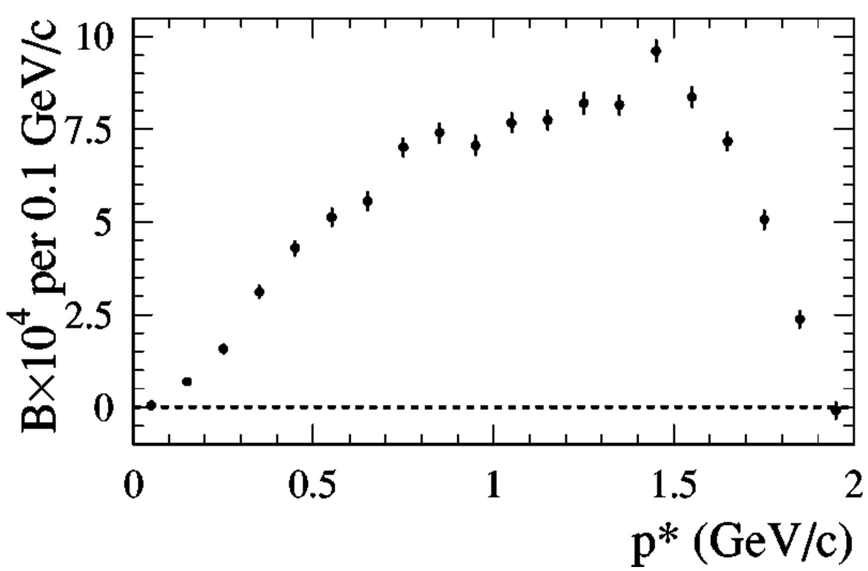
TABLE II. Summary of B branching fractions (percent) to charmonium mesons with statistical and systematic uncertainties. The direct branching fraction is also listed, where appropriate. The last column contains the world average values [15].

Meson	*Value*	*Stat*	*Sys*	*World Average*
J/ψ	1.057	$\pm$0.012	$\pm$0.040	1.15$\pm$0.06
J/ψ direct	0.740	$\pm$0.023	$\pm$0.043	0.80$\pm$0.08
χ_{c1}	0.367	$\pm$0.035	$\pm$0.044	0.36$\pm$0.05
χ_{c1} direct	0.341	$\pm$0.035	$\pm$0.042	0.33$\pm$0.05
χ_{c2}	0.210	$\pm$0.045	$\pm$0.031	0.07$\pm$0.04
χ_{c2} direct	0.190	$\pm$0.045	$\pm$0.029	-
$\psi(2S)$	0.297	$\pm$0.020	$\pm$0.020	0.35$\pm$0.05

B → J/ψ + All

:: BaBar, Phys. Rev. D67,032002 ::

Total contribution



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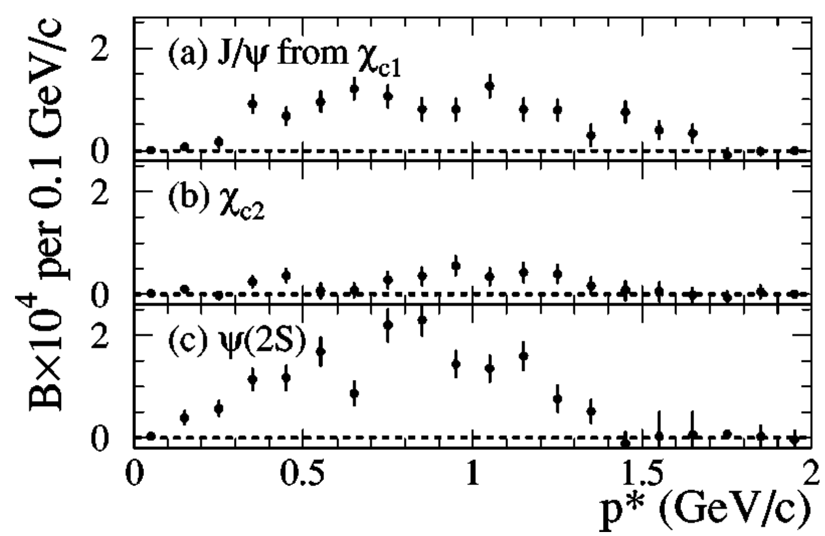
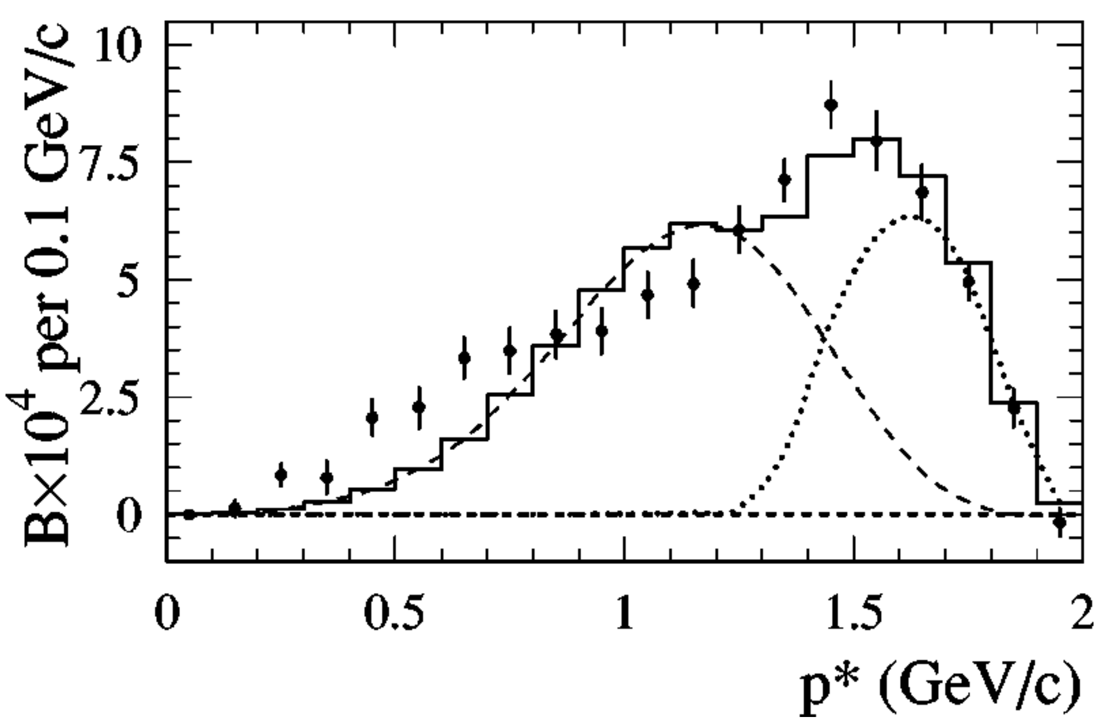
Feed-down contribution



Direct contribution



$B \to J/\psi + \mathcal{K}$

:: Belle, Phys. Rev. D83,032005 ::

- 535×10^6 $B\bar{B}^*$ events ($492\ fb^{-1}$) from e^+e^- collisions at $\sqrt{s} \sim m_{\Upsilon(4S)}$
- $\Delta E = E^*(B) - E_{beam}$ and $M_{bc} = \sqrt{(E^2_{beam} - P^{*2}(B))}$
  Signal region: $-3\sigma_{\Delta E} < \Delta E - \mu_{\Delta E} < 3\sigma_{\Delta E}$
  Sideband region: -0.13 GeV $< \Delta E - \mu_{\Delta E} < -0.05$ GeV
  & $+0.05$ GeV $< \Delta E - \mu_{\Delta E} < +0.13$ GeV
- $\mathcal{B}(B \to J/\psi K^+\pi^+\pi^-) = (7.16 \pm 0.10 \pm 0.60) \times 10^{-4}$
  $\mathcal{B}(B \to \psi(2S) K^+\pi^+\pi^-) = (4.31 \pm 0.20 \pm 0.50) \times 10^{-4}$
- The PDF is p(<u>x</u>,<u>a</u>), with <u>x</u>=$M^2(K\pi\pi)$,$M^2(K\pi)$,$M^2(\pi\pi)$ and <u>a</u>=fit parameters

$$p(\vec{x};\vec{a}) = \boxed{n_B \frac{p_B(\vec{x})}{\int p_B(\vec{x})d^3x}} + \boxed{n_S \frac{p_S(\vec{x};\vec{a})}{\int p_S(\vec{x};\vec{a})d^3x}}$$

Background modelled from sideband region

Signal

$$p_S(\vec{x};\vec{a}) = \varepsilon(\vec{x})\phi(\vec{x})s(\vec{x};\vec{a})$$

$$s(\vec{x};\vec{a}) \equiv s(\vec{x};a_k)$$

$$= |a_{nr}A_{nr}(\vec{x})|^2 + \sum_{J_1}\left|\sum_{J_2} a_{J_1J_2}A_{J_1J_2}(\vec{x})\right|^2$$

B → J/ψ + $\mathcal{K}$

:: Belle, Phys. Rev. D83,032005 ::

- The $K^+\pi^+\pi^-$ final state is modelled as a non resonant signal plus a superposition of initial state resonances R_1.
  The latter are assumed to decay through intermediate state resonances R_2

$$R_1 \to a\, R_2 \quad \text{and} \quad R_2 \to bc$$

Signal

$$p_S(\vec{x};\vec{a}) = \varepsilon(\vec{x})\phi(\vec{x})s(\vec{x};\vec{a})$$

$$s(\vec{x};\vec{a}) \equiv s(\vec{x};a_k)$$

$$= |a_{nr}A_{nr}(\vec{x})|^2 + \sum_{J_1}\left|\sum_{J_2} a_{J_1J_2}A_{J_1J_2}(\vec{x})\right|^2$$

complex coefficients

- Since the components of the signal function are not individually normalized, a decay fraction is calculated as

$$f_k = \frac{\int \phi(\vec{x})|a_kA_k(\vec{x})|^2 d^3x}{\int \phi(\vec{x})s(\vec{x};\vec{a})d^3x}$$

B → J/ψ + $\mathcal{K}$

:: Burns, Piccinini, Polosa, Prosperi, Sabelli, arXiv:1104.1781::

- Belle measures

$$\mathcal{B}(B^+ \to \mathcal{K}_j J/\psi \to R_i J/\psi \to J/\psi\, K^+\pi^+\pi^-) = \mathcal{B}_{\rm tot} f_i^j$$

where the intermediate resonant states are

$$\mathcal{R}_i = K\rho,\ \ K\omega,\ \ K^*\pi,\ \ K_0^*(1430)\pi,\ \ K_2^*(1430)\pi\ \text{ and }\ K f_{0,2}$$

- To extract two body branching ratios one needs to take into account isospin multiplicity

$$\mathcal{B}(B^+ \to \mathcal{K}_j J/\psi \to R_i J/\psi \to J/\psi\, K^+\pi^+\pi^-) = \mathcal{I}_i \times \mathcal{B}(B^+ \to \mathcal{K}_j J/\psi) \times \mathcal{B}(\mathcal{K}_j \to R_i) \times \mathcal{B}(R_i \to K\pi\pi)$$

where the isospin factors are

$$\mathcal{I}(K\rho) = 1/3,\ \ \mathcal{I}(K^*\pi) = \mathcal{I}(K_0^*(1430)\pi) = 4/9,\ \ \mathcal{I}(K\omega) = 1,\ \ \mathcal{I}(K f_0) = \mathcal{I}(K f_2) = 2/3$$

so that

$$\mathcal{B}(B^+ \to \mathcal{K}_j J/\psi) = \frac{\mathcal{B}(B^+ \to \mathcal{K}_j J/\psi \to R_i J/\psi \to J/\psi\, K^+\pi^+\pi^-)}{\mathcal{I}_i \times \mathcal{B}(\mathcal{K}_j \to R_i) \times \mathcal{B}(R_i \to K\pi\pi)} = \frac{\mathcal{B}_{\rm tot} f_i^j}{\mathcal{I}_i \times \mathcal{B}(\mathcal{K}_j \to R_i) \times \mathcal{B}(R_i \to K\pi\pi)}$$

B → J/ψ + $\mathcal{K}$

:: Burns, Piccinini, Polosa, Prosperi, Sabelli, arXiv:1104.1781::

- Interference effects among different heavy kaons $\mathcal{K}_j$ have been neglected, so that one needs to rescale the two body branching ratios by some factor.

$$\mathcal{B}(B^+ \to \mathcal{K}_j J/\psi \to \mathcal{R}_i J/\psi \to J/\psi\ K^+\pi^+\pi^-) = \mathcal{B}_{\rm tot}\,\tilde{f}_i^j$$

$$\tilde{f}_i^j = C \times \left(1 - \frac{\Gamma_j}{m_j}\right) f_i^j \qquad \mathcal{B}_{\rm tot} = (71.6 \pm 1 \pm 6) \times 10^{-5}$$

$\mathcal{K}_j$	$m_{\mathcal{K}_j}$ (GeV)	$\Gamma_{\mathcal{K}_j}$ (GeV)	$\mathcal{B}(B^+ \to \mathcal{K}_j J/\psi) \times 10^5$	
K	0.494	–	95.0 ± 3.6	*
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$K_1(1270)$	1.270	0.090	144.0 ± 29.3	
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* http://hfag.phys.ntu.edu.tw/b2charm/index.html

B → $\mathcal{K}\,\mathcal{X}$ → $\mathcal{K}$ J/ψ + light hadrons

- B → K(500) $\mathcal{X}$ → K(500) J/ψ + light hadrons branching ratios are known:

$\mathcal{X}_j$	$m_{\mathcal{X}_j}$ (GeV)	$\Gamma_{\mathcal{X}_j}$ (GeV)	Final State	$\mathcal{B}(B \to K\mathcal{X}_j \to KJ/\psi + \text{light hadrons}) \times 10^5$
$X(3872)$	3.872	0.003	$J/\psi\,\rho \to J/\psi\,\pi^+\pi^-$	0.72 ± 0.22 [A]
			$J/\psi\,\omega$	0.6 ± 0.3 [B]
$Y(3940)$	3.940	0.087	$J/\psi\,\omega$	3.70 ± 1.14 [C]
$Y(4140)$	4.140	0.012	$J/\psi\,\phi$	0.9 ± 0.4 [D]
$Y(4260)$	4.260	0.095	$J/\psi\,f_0 \to J/\psi\,\pi^+\pi^-$	2.00 ± 0.73 [C]

[A] B. Aubert et al. (BABAR), Phys. Rev. **D77**, 111101 (2008), 0803.2838.
[B] P. del Amo Sanchez et al. (BABAR), Phys. Rev. **D82**, 011101 (2010), 1005.5190.
[C] `http://hfag.phys.ntu.edu.tw/b2charm/index.html`.
[D] K. Yi and f. t. C. collaboration, PoS EPS-HEP **2009**, 2009:085,2009 (2009), 0910.3163.

- For heavy kaons $\mathcal{K}$ we deduce the coupling B-$\mathcal{K}\,\mathcal{X}$ from the B-K(500)$\mathcal{X}$ one:

<u>Spin 0</u> $\mathcal{K}$ $\quad \langle \mathcal{X}(\epsilon, p)\mathcal{K}(q)|B(P)\rangle = g\,\epsilon \cdot q$

<u>Spin 1</u> $\mathcal{K}$ $\quad \langle \mathcal{X}(\epsilon, p)\mathcal{K}(\eta, q)|B(P)\rangle = g'\,\epsilon \cdot \eta$

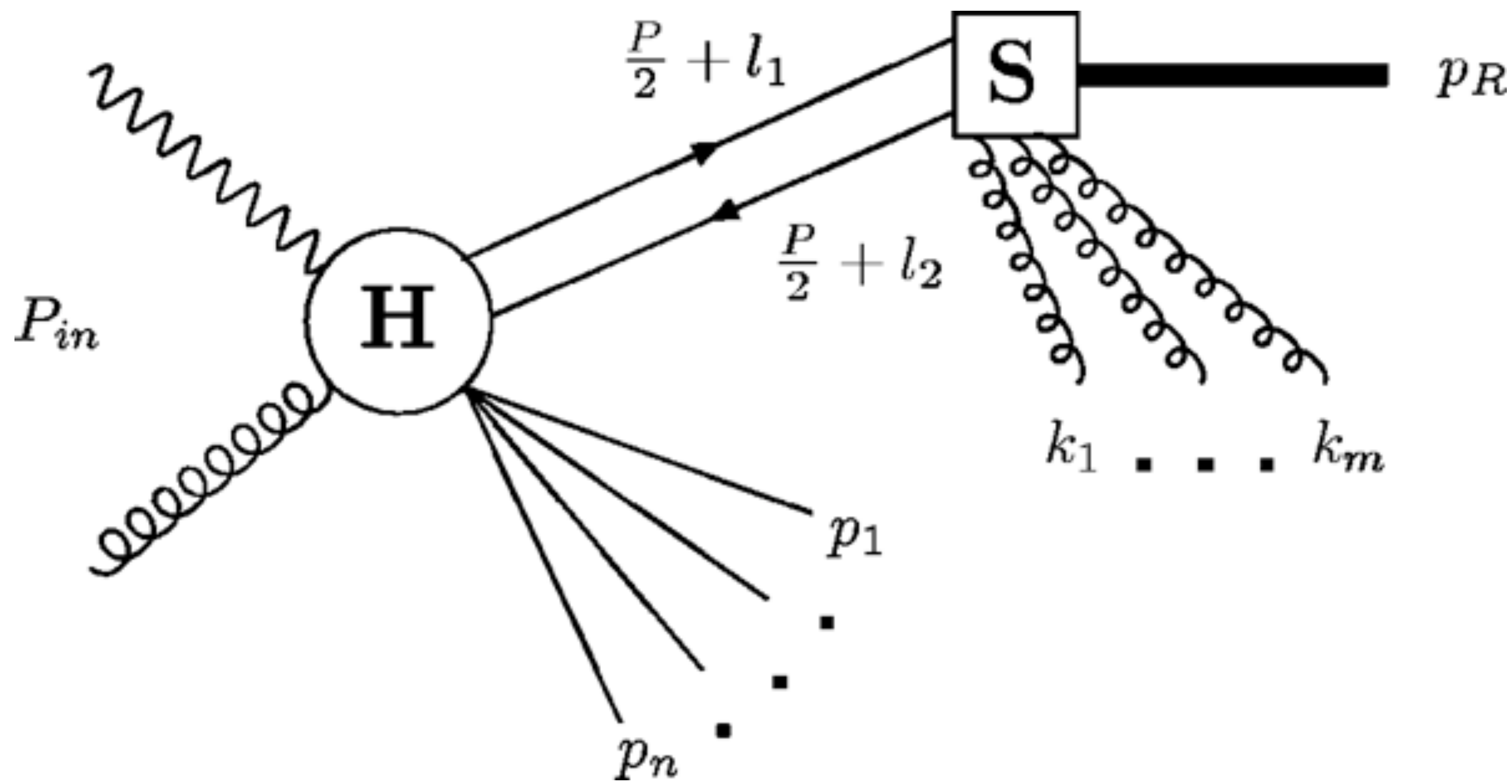
$$g' = \Lambda\, g$$

Λ some mass scale

From $\mathcal{B}(B \to K^* X(3872)) \times \mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-) < 0.34 \times 10^{-5}$
we deduce Λ > 600 MeV ≈ m_{K^*} and thus we assume Λ = m_{K1},
taking all $\mathcal{X}$ to be Spin 1 states.

Color Octet Contribution

:: Beneke, Schuler, Wolf, Phys.Rev. D62 (2000) 034004 ::



- At leading order in the non-relativistic expansion the cc* pair has to be produced in a color singlet $^3S_1$ state.
- At relative order $v^4 \approx 1/15$ in the non-relativistic expansion, J/ψ can also be produced through cc* in $^1S_0^{(8)}$, $^3P_J^{(8)}$, $^3S_1^{(8)}$ color octet states
- The short-distance structure of the ΔB=1 weak effective Hamiltonian favors the production of color octet cc* pairs in the b→cc*q transition

Factorization

:: Beneke, Schuler, Wolf, Phys.Rev. D62 (2000) 034004 ::

- The hard and soft part of the process can be factorized

$$(2\pi)^3 2p_R^0 \frac{d\sigma}{d^3p_R} = \sum_n \int \frac{d^4 l}{(2\pi)^4} \hat{\sigma}(c\bar{c}[n])(l) F_n(l)$$

$$F_n(l) = \int \frac{dk^2}{2\pi} \frac{d^3 \boldsymbol{k}}{(2\pi)^3 2k^0} (2\pi)^4 \times \delta(p_R + k - P - l) \Phi_n(k; p_R, P)$$

shape function

$$\mathrm{flux} \times \int d\mathrm{PS}[p_i] (2\pi)^4 \delta\left(P + l + \sum_i p_i - P_{in}\right) \times H_n(P_{in}, P, l, p_i)$$

hard process cross section

- The distribution can be written as an integral over the energy and invariant mass of the soft radiated system:

$$(2\pi)^3 2p_R^0 \frac{d\sigma}{d^3p_R} = \sum_n \int_0^{\alpha\beta} \frac{dk^2}{2\pi} \int_{(\alpha^2+k^2)/(2\alpha)}^{(\beta^2+k^2)/(2\beta)} dk_0 \times \mathrm{flux} \times \bar{H}_n(P_{in}, P, l, p_X) \frac{1}{4\pi(\beta-\alpha)} \Phi_n(k; p_R, P)$$

Shape Function

:: Beneke, Schuler, Wolf, Phys.Rev. D62 (2000) 034004 ::

- The color octet configurations which contribute to B→J/ψ + All are

$$n = {}^1S_0^{(8)}, {}^3P_0^{(8)}, {}^3S_1^{(8)}$$

- The shape function is related to the NRQCD matrix elements as

$$\int \frac{d^4 l}{(2\pi)^4} F_n(l) = \frac{1}{(2\pi)^3} \int_0^\infty dk^2 \int_{\sqrt{k^2}}^\infty dk_0 \times \sqrt{k_0^2 - k^2}\, \Phi_n(k; p_R, P) = \langle \mathcal{O}_n^{J/\psi} \rangle,$$

- An ansatz for the shape function is

$$\Phi_n(k; p_R, P) = a_n |k|^{b_n} \exp(-k_0^2/\Lambda_n^2) k^2 \exp(-k^2/\Lambda_n^2)$$

which is exact in the Coulombic limit. The exponential cutoff reflects the expectations that the typical energy and invariant mass of the radiated system is of order $\Lambda_n \approx m_c v^2$

Shape Function

:: Beneke, Schuler, Wolf, Phys.Rev. D62 (2000) 034004 ::

- The decay distribution in the rest frame of the cc* pair is

$$\frac{d\hat{\Gamma}}{d\hat{E}_R} = \frac{|\hat{p}_R|}{4\pi^2} \sum_n \int_0^{\alpha\beta} \frac{dk^2}{2\pi} \int_{(\alpha^2+k^2)/(2\alpha)}^{(\beta^2+k^2)/(2\beta)} dk_0$$

$$\times \frac{1}{2m_b} H_n(m_b, M_{c\bar{c}}(k)) \frac{M_R}{8\pi m_b |\hat{p}_R|} \Phi_n(k)$$

where

$$M_{c\bar{c}}^2(k) = (p+l)^2 = (p_R+k)^2 = M_R^2 + 2M_R k_0 + k^2$$

- To normalize the shape function one uses

$$\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle = (0.5\text{–}1.0)\times 10^{-2}\ \text{GeV}^3$$

$$M_k^{J/\psi}(^1S_0^{(8)}, {}^3P_0^{(8)}) = \langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle + \frac{k}{m_c^2}\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle \qquad M_{3.1}^{J/\psi}(^1S_0^{(8)}, {}^3P_0^{(8)}) = (1.0\text{–}2.0)\times 10^{-2}\ \text{GeV}^3$$

Fermi Motion

:: Beneke, Schuler, Wolf, Phys.Rev. D62 (2000) 034004 ::

- The b quark is moving inside the B meson at rest with a momentum p according to some distribution with a width of few hundred MeV. The cloud of gluons and light quarks is treated as spectator.

$$\Phi_{\mathrm{ACM}}(p) = \frac{4}{\sqrt{\pi} p_F^3} \exp(-p^2/p_F^2)$$

- One needs thus to consider a floating b-mass

$$m_b^2(p) = M_B^2 + m_{sp}^2 - 2M_B\sqrt{m_{sp}^2 + p^2}$$

- To obtain the distribution in the B rest frame

$$\frac{d\Gamma}{dE_R} = \int_{\max\{0, p_-\}}^{p_+} dp\, p^2 \Phi_{\mathrm{ACM}}(p) \frac{m_b^2(p)}{2pE_b(p)} \times \int_{\hat{E}_R^{\min}(p)}^{\hat{E}_R^{\max}(p)} \frac{d\hat{E}_R}{\hat{E}_R} \frac{d\hat{\Gamma}}{d\hat{E}_R}.$$