Heavy Flavor, Quarkonium Production and Decay

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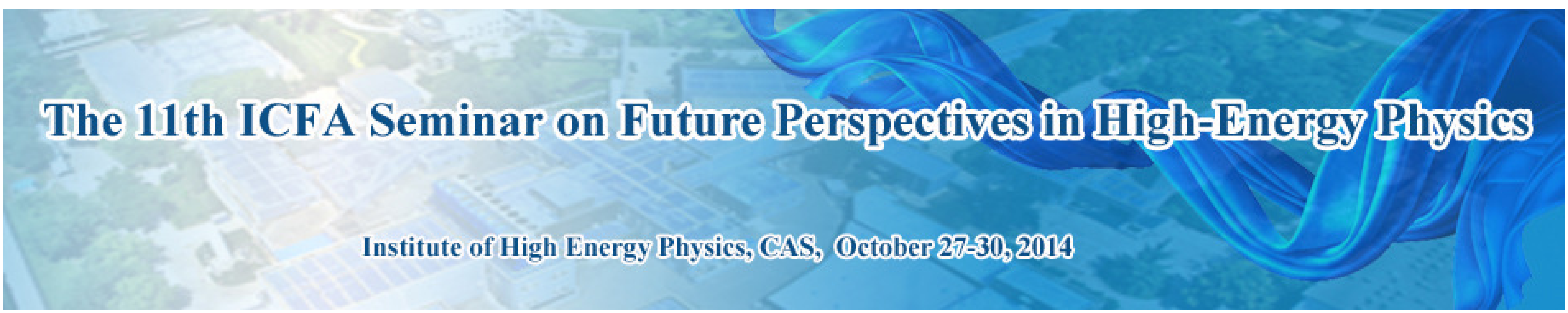
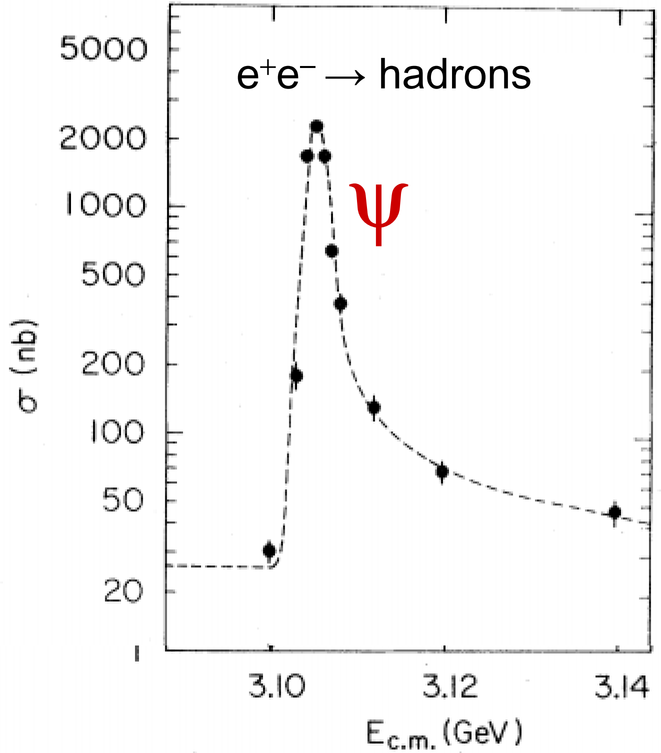
Syracuse University

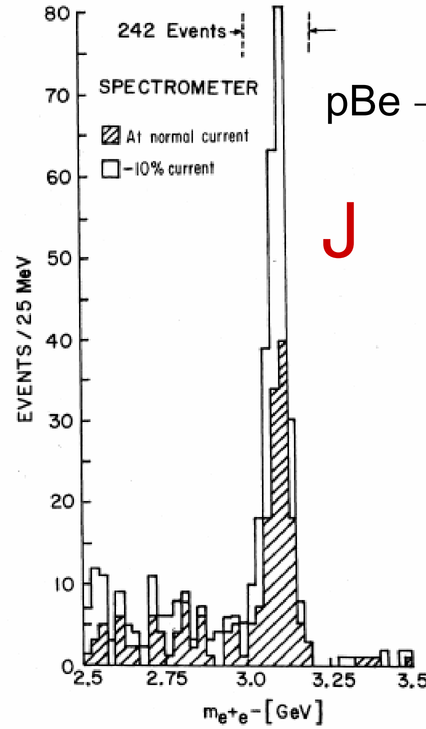
(weak decays of heavy flavors: see Tom Browder's talk)



Birth of heavy flavor: November revolution 1974

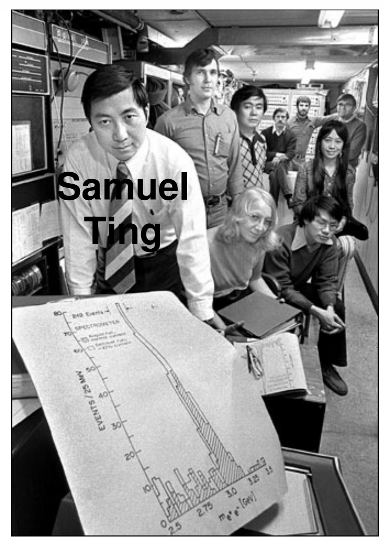
Log-scale!





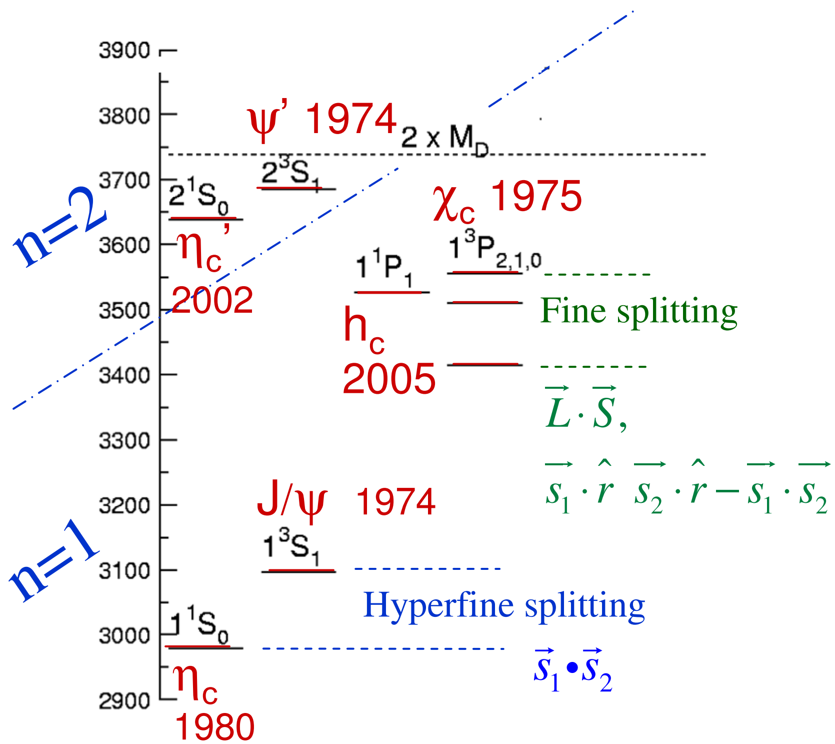
$pBe \to e^+e^- X$

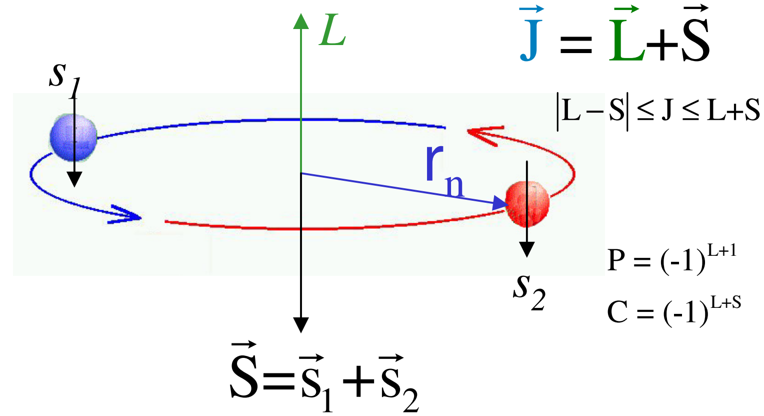
Nobel Prize, 1976



Charmonium – narrow (i.e. long-lived) states

$n\,^{2S+1}L_J$ $\quad c\bar{c}$



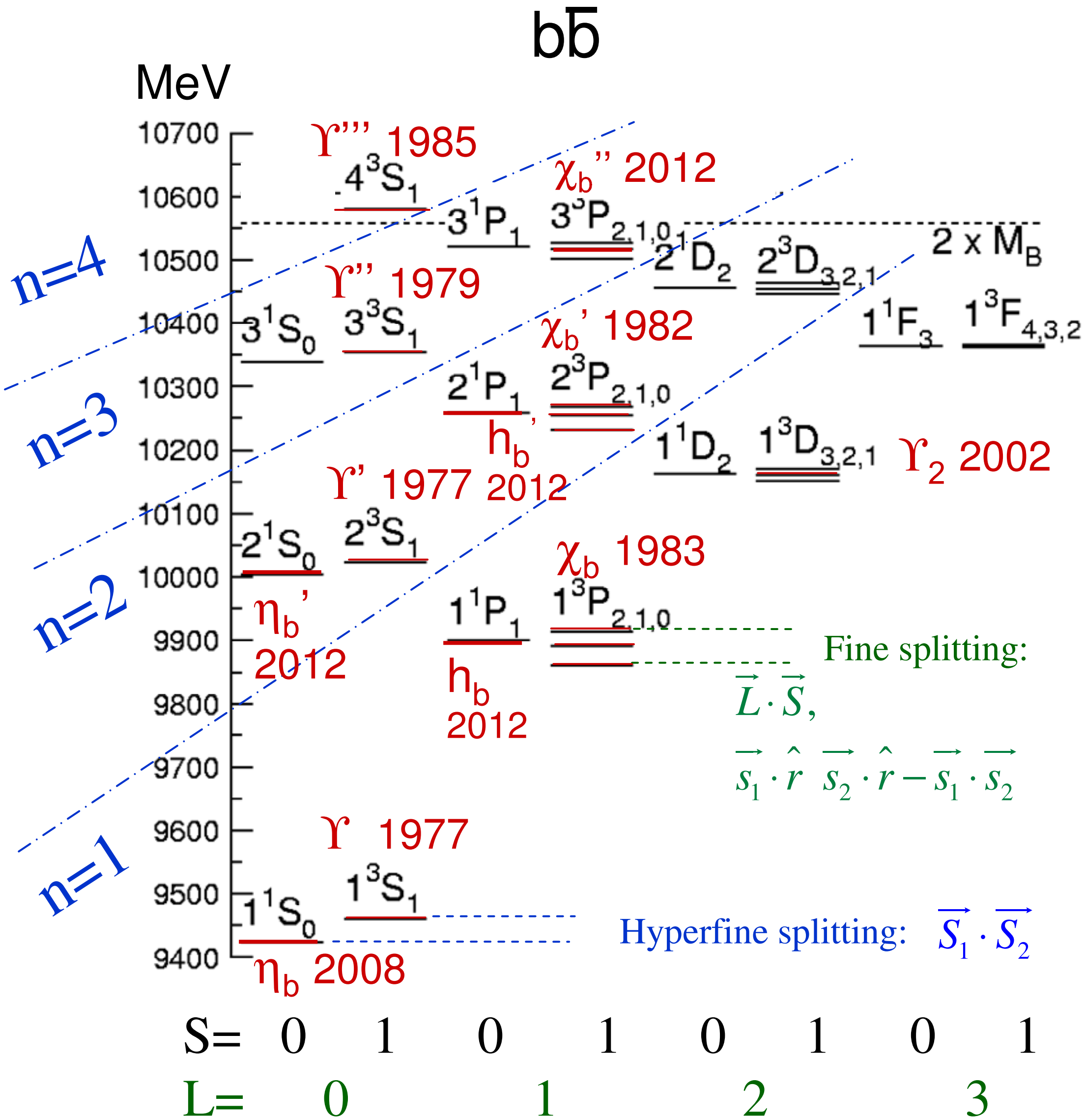


- Simple positronium-like level structure:
  - Relative importance of fine and hyperfine splitting magnified by $(\alpha_s/\alpha)^2 \sim 10^3$
  - Non-degenerate 2S,1P energies (not a Coulomb potential)
- Masses precisely reproducible with simple phenomenological potentials
- Gluon annihilation widths roughly predictable via perturbative QCD

1974 November revolution:

- Quark Model and $q\bar{q}$ hypothesis for mesons firmly established!

Bottomonium – narrow states



- More long-lived states
- The spin-averaged mass splitting of lowest excitations are as expected from charmonium and flavor independence of strong interactions
- Decreased magnitude of fine and hyperfine splitting reflects decrease of magnetic effects due to the slower quark speeds
- Major photon transition rates predictable without relativistic corrections

Heavy flavors and theory

- Semiclassical approach with purely phenomenological potential models in early years
- **Effective Field Theories** in recent years:

Separation of scales leads to factorization:

$$m_Q \gg \Lambda_{QCD}$$

Perturbative QCD at heavy parton level

expansion in α_s

Nonperturbative low-energy terms (extracted from the **data, phenomenological models** or **lattice QCD**)

$Q\bar{q}$

Heavy Quark Symmetry (HQS):

Properties of bound states independent of Q flavor and its spin orientation

$m_Q \to \infty$

HQET

$1/m_Q$ *corrections*

$Q\bar{Q}$

$$m_Q \gg m_Q \upsilon (> m_Q \upsilon^2) >, \sim \Lambda_{QCD}$$

Momentum transfer between partons

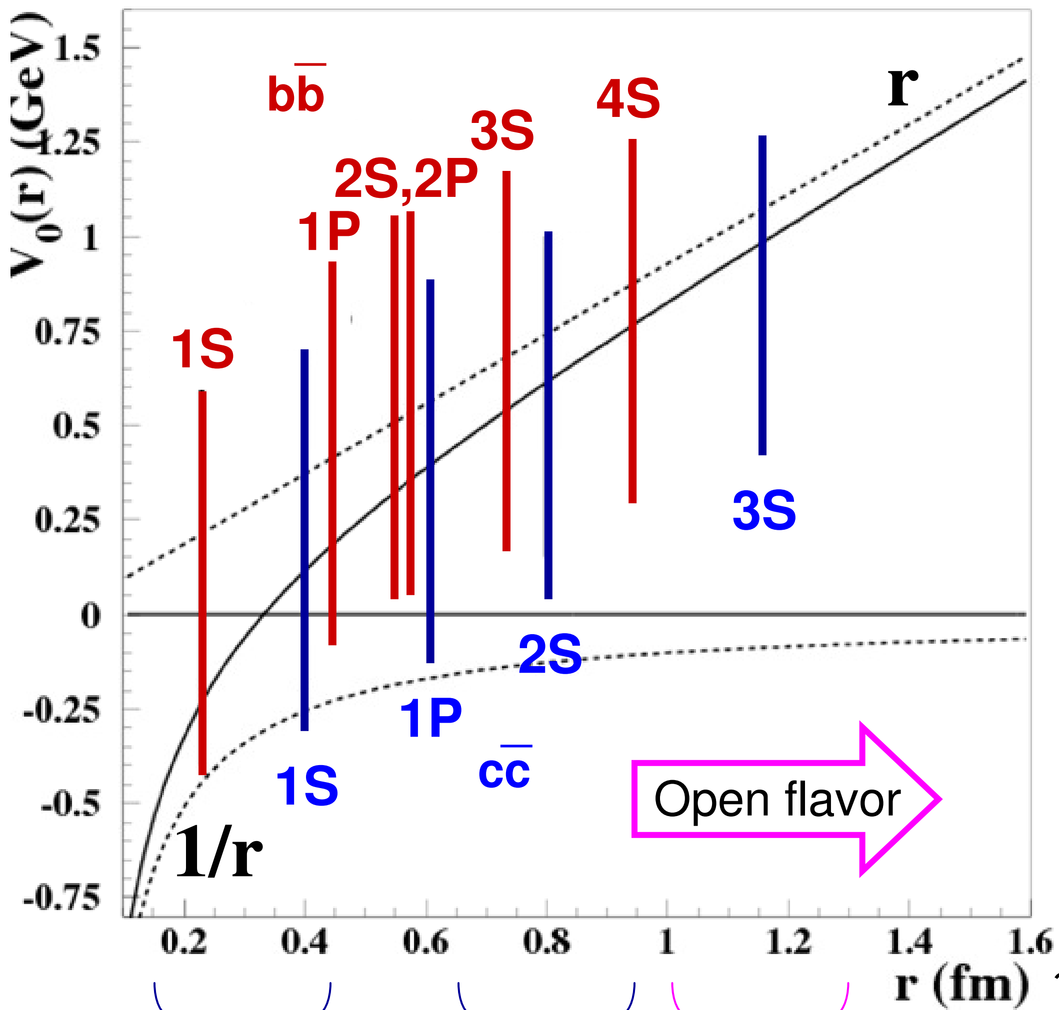
Kinetic and potential (i.e. binding) energy

$1/m_Q, 1/\upsilon$ *corrections*

NRQCD **(Potential NRQCD)**

- In recent years also **full lattice calculations** for charm quarks without the factorization approach (bottom too heavy for present sizes of lattice spacing).

$Q\overline{Q}$ states and their energy scales



$\sim 1/m_Q v$

non-perturbative corrections

small large

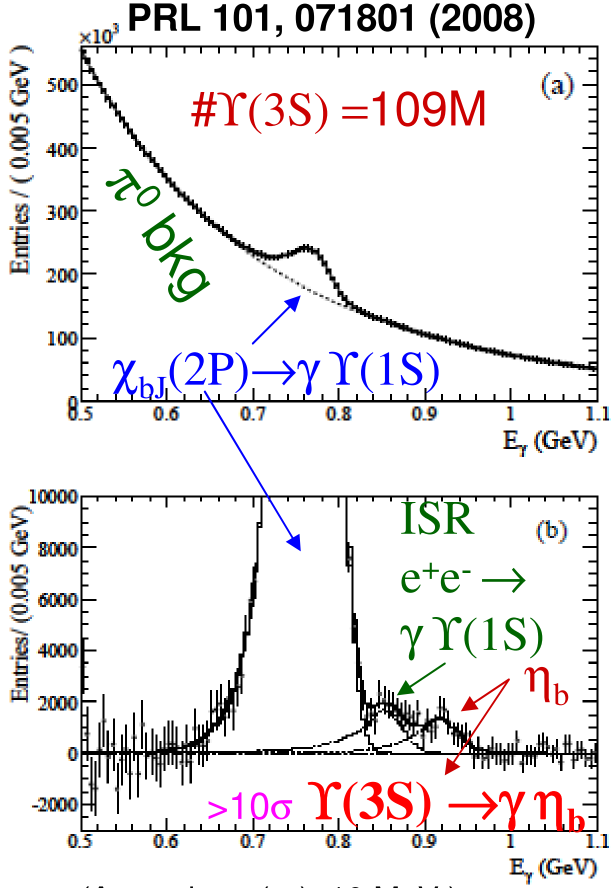
Breakdown of NRQCD due to couplings to new degrees of freedom (open flavor decays, molecules, possibly tertraquarks, hybrids etc.)

WAY BELOW OPEN FLAVOR THRESHOLD STATES

(α_s,m_Q determinations
→Kronfeld's talk)

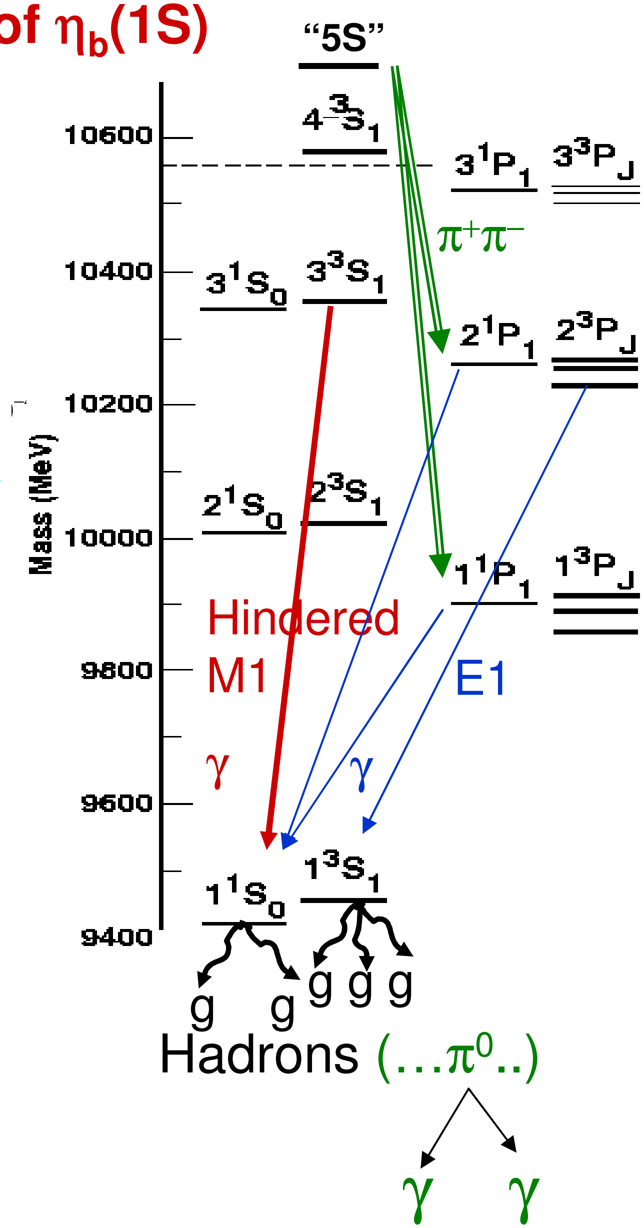
Mass of $\eta_b(1S)$

BaBar
PRL 101, 071801 (2008)

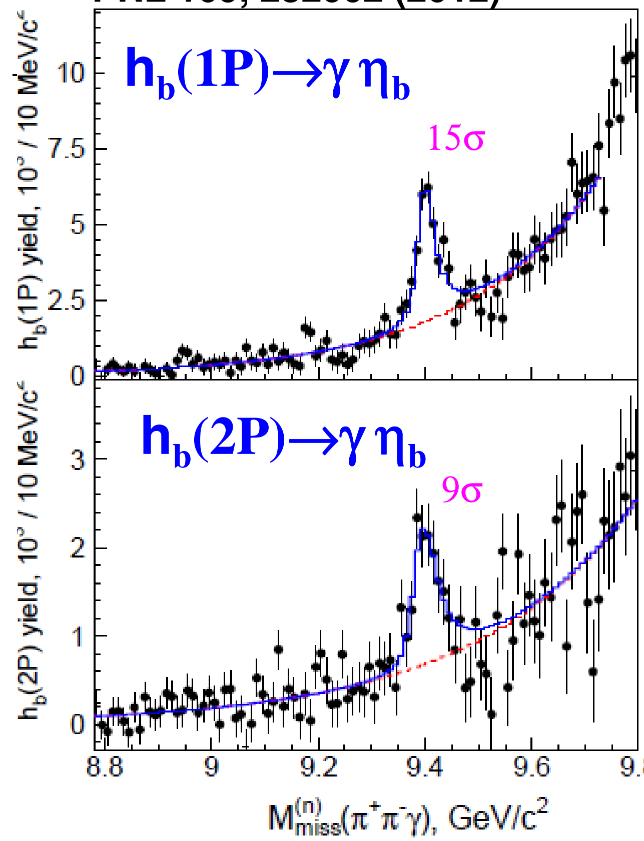


(Assuming $\Gamma(\eta_b)$=10 MeV)

$$B(\Upsilon(3S)\to\gamma\eta_b) = (4.8\pm0.5\pm0.6)\times10^{-4}$$



Belle
PRL 109, 232002 (2012)

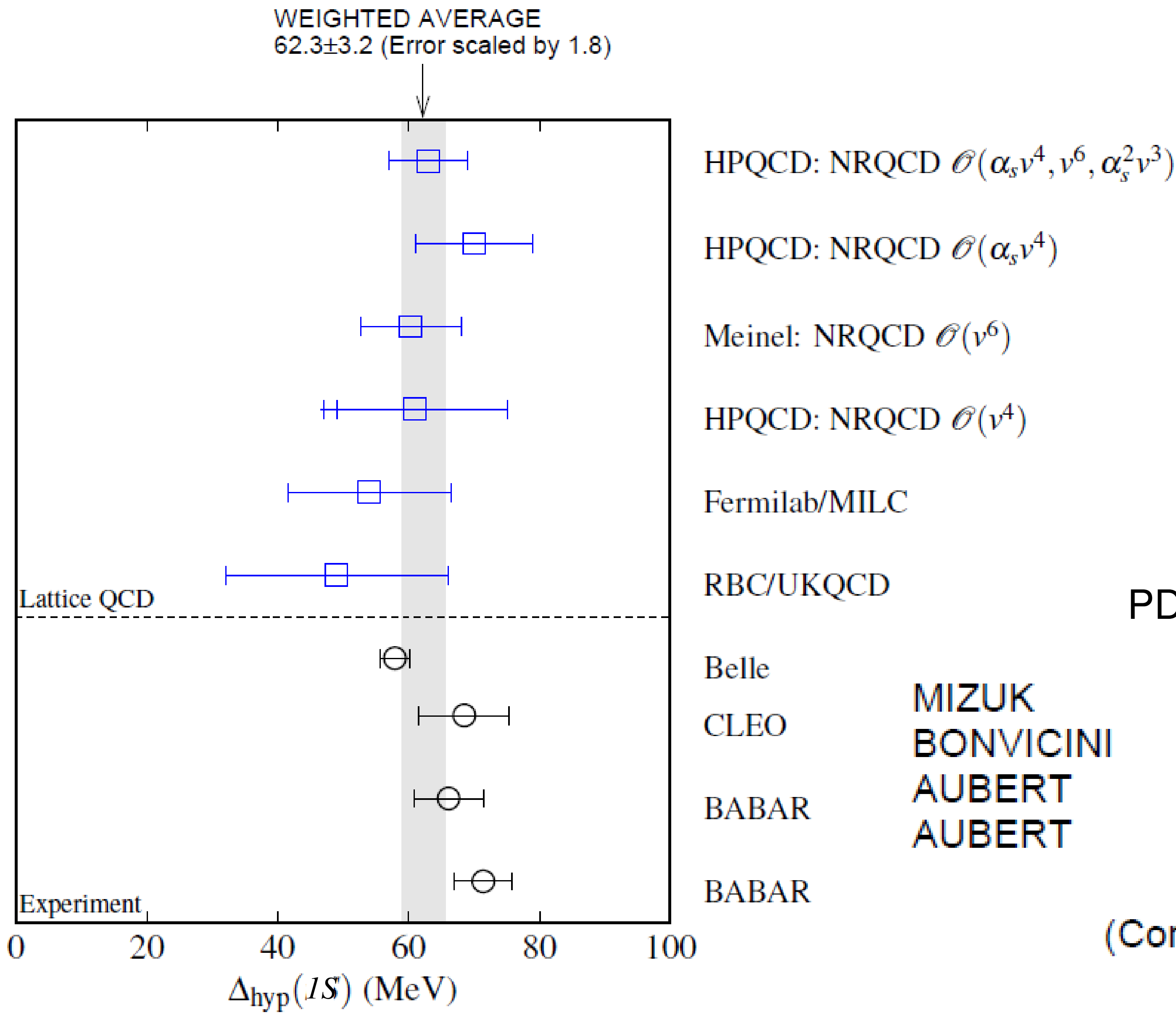


$\Gamma[\eta_b(1S)] = 10.8^{+4.0+4.5}_{-3.7-2.0}$ MeV

$$B(h_b(1P)\to\gamma\eta_b) = (4.92\pm0.57\pm0.56)\times10^{-1}$$

$9388.9^{+3.1}_{-2.3}\pm2.7$ MeV	**2.9σ disagreement**	$9402.4\pm1.5\pm1.8$ MeV

Hyperfine splitting of $b\bar{b}(1S)$



R. J. Dowdall et al.
PRD89, 031502 (2014)

n_f=2+1+1
non-pert. 4q inter.

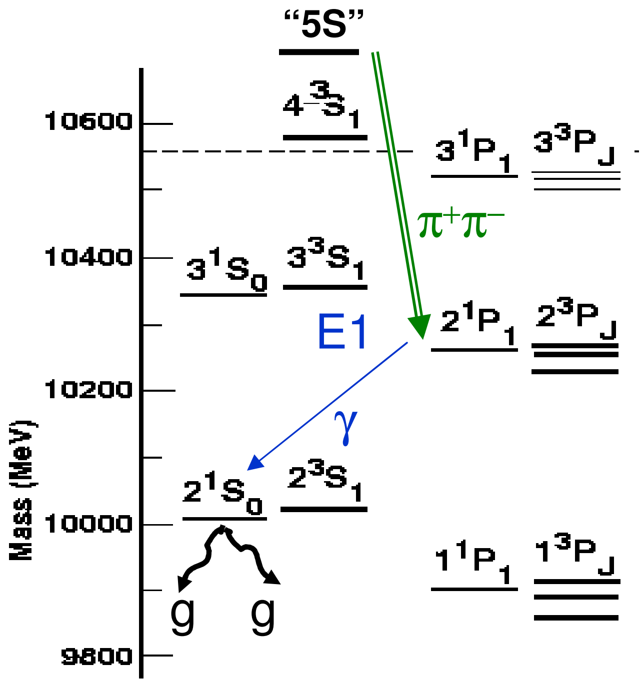
PDG 2014

			χ^2
MIZUK	12	BELL	3.5
BONVICINI	10	CLEO	0.8
AUBERT	09AQ	BABR	0.5
AUBERT	08V	BABR	4.9
			9.8

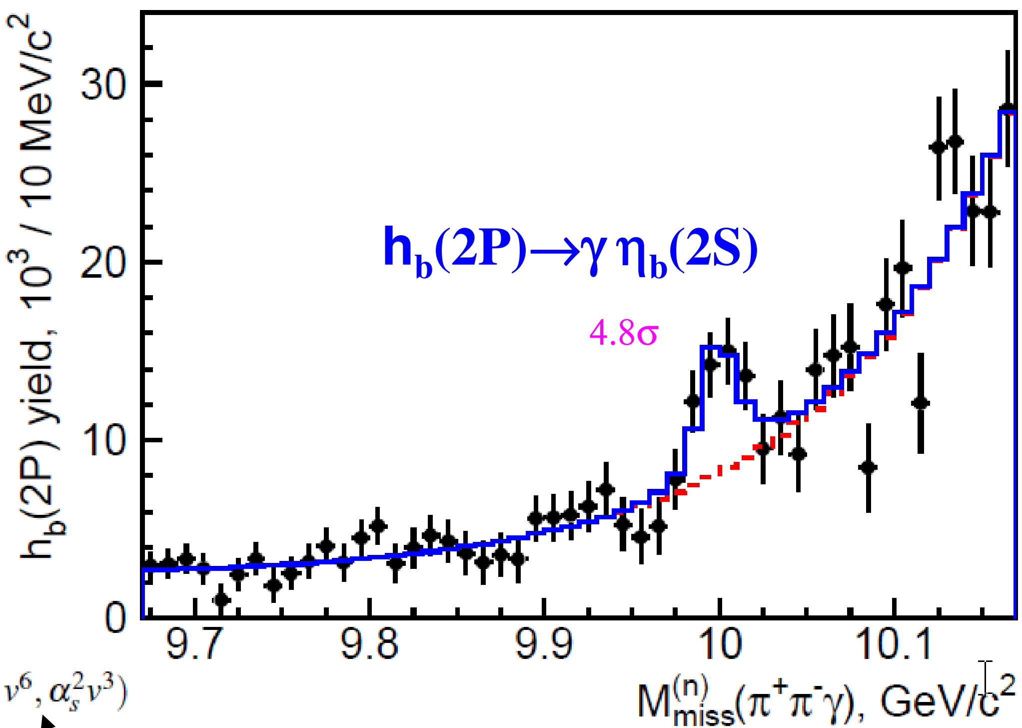
(Confidence Level = 0.021)

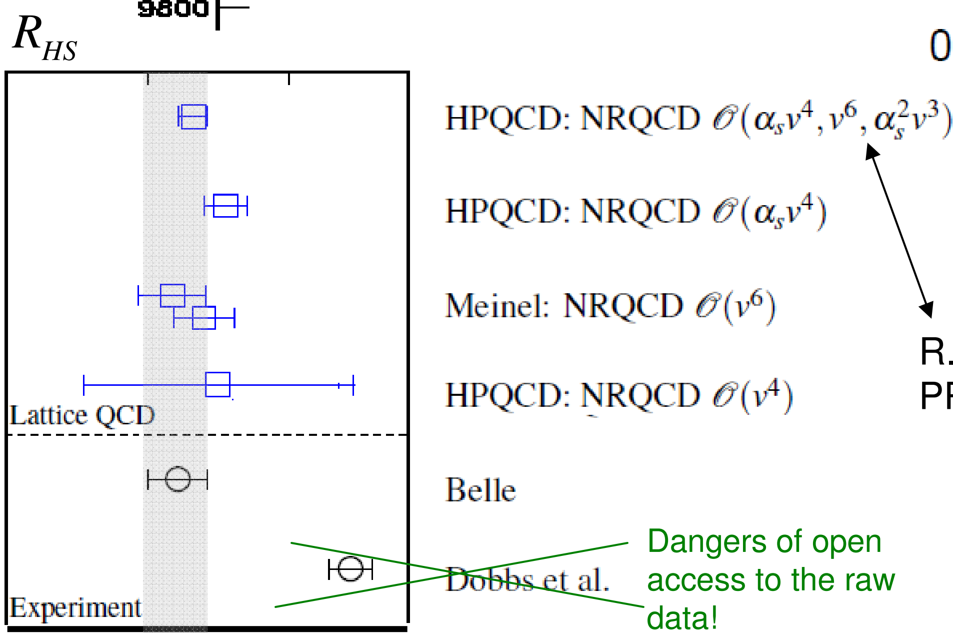
Now good agreement with the predictions. Theory error larger than the experimental.

Hyperfine splitting of $b\bar{b}(2S)$



Belle
PRL 109, 232002 (2012)





Dangers of open access to the raw data!

$$R_{HS} = \frac{M_{\Upsilon(2S)} - M_{\eta_b(2S)}}{M_{\Upsilon(1S)} - M_{\eta_b(1S)}} = 0.39 \pm 0.08$$

R. J. Dowdall et al. (HPQCD) PRD89, 031502 (2014) 0.425 ± 0.025

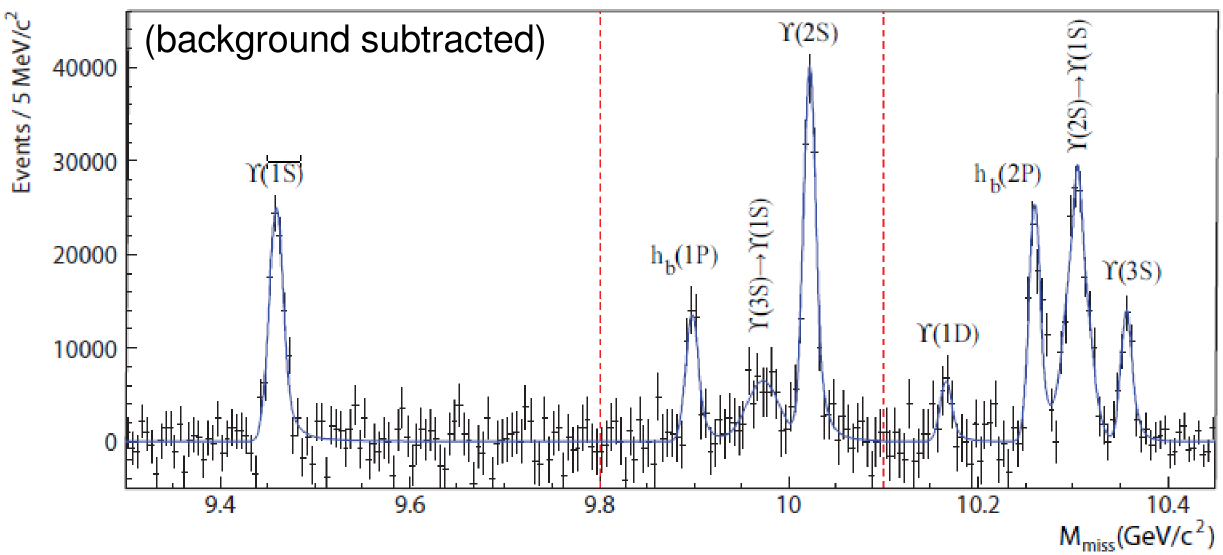
Good agreement with the theory.
Experimental error is large compared to theoretical one.

BELOW OPEN FLAVOR THRESHOLD STATES

Singlet $b\bar{b}$(1,2P) states

- Studies of $\pi^+\pi^-$ transitions at "Υ(5S)" led also to the first observations of $h_b(1^1P_1)$,$h_b(2^1P_1)$ states

Belle
PRL 108, 032001 (2012)

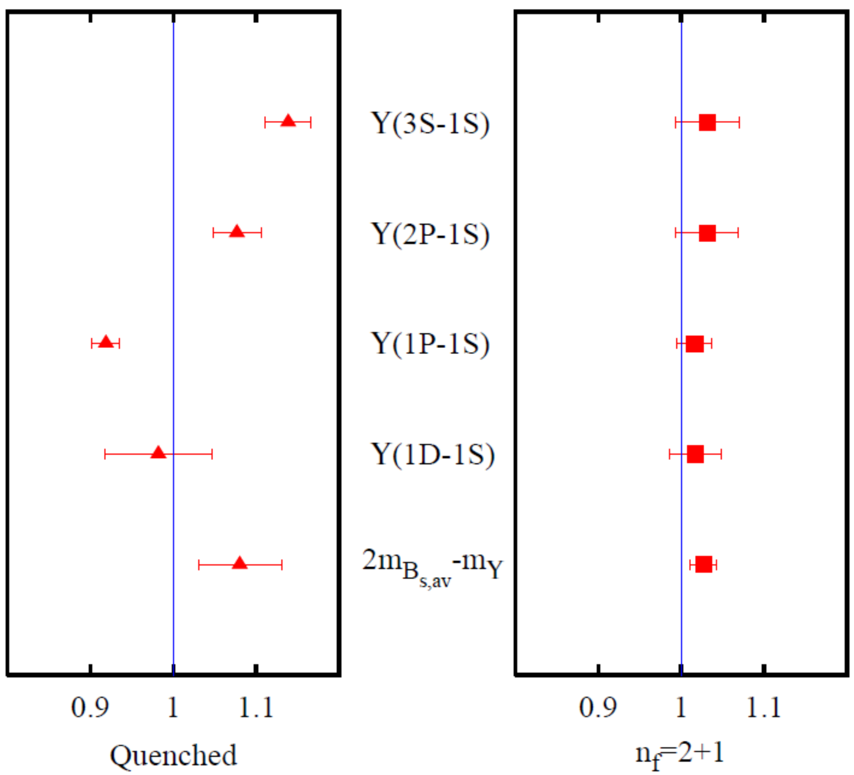


$M_{recoil}(\pi^+\pi^-)$

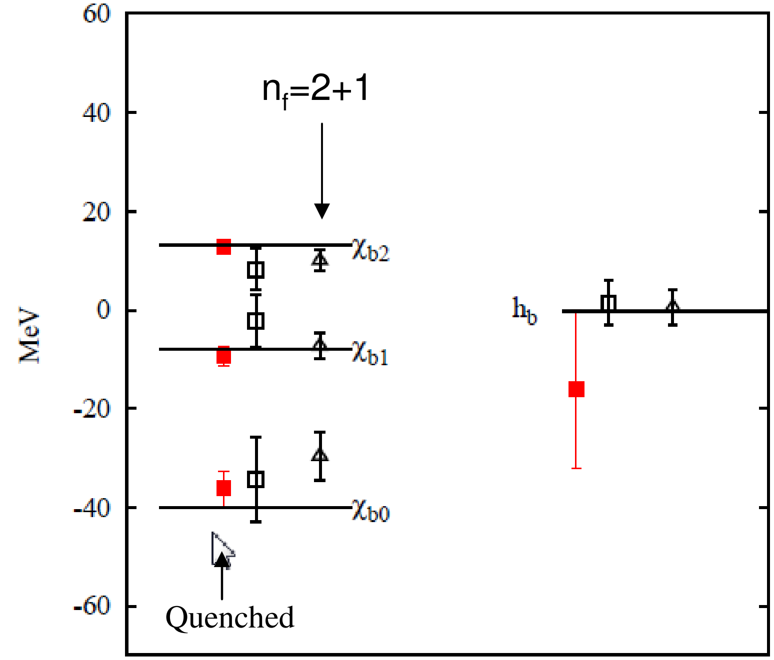
Masses of bottomonium states from Lattice NRQCD

A. Gray, I. Allison, C.T.H. Davies, Emel Dalgic, G.P. Lepage, J. Shigemitsu, M. Wingate
(HPQCD and UKQCD collaborations) **PRD,72, 094507 (2005)**

Radial and orbital excitations



Fine structure

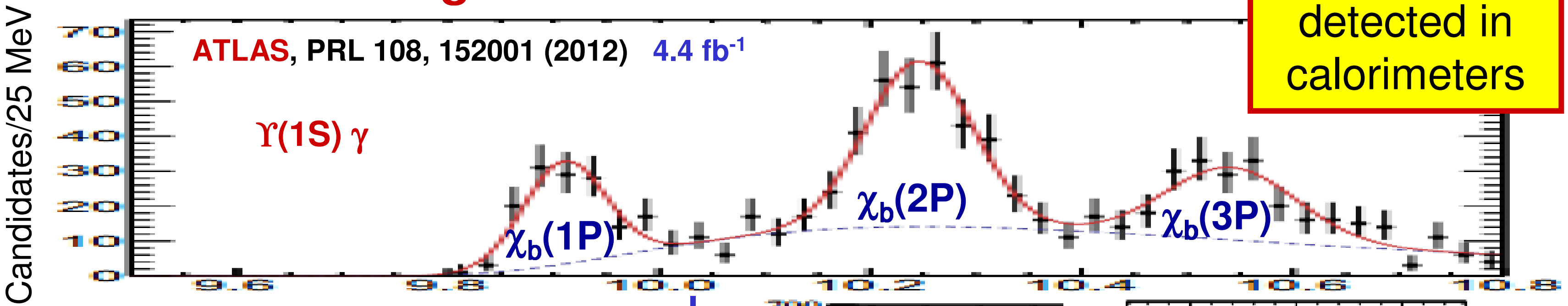


(hyperfine splitting in states other than S-states is consistent with zero both experimentally and theoretically)

NEAR OPEN FLAVOR THRESHOLD STATES

Recent results on long-lived $b\bar{b}$ states: 3P

Photons detected in calorimeters



Confirmed by D0 with larger errors

D0, PRD86, 031103 (2012)

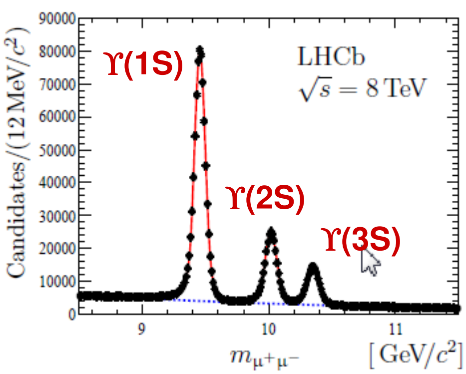
new

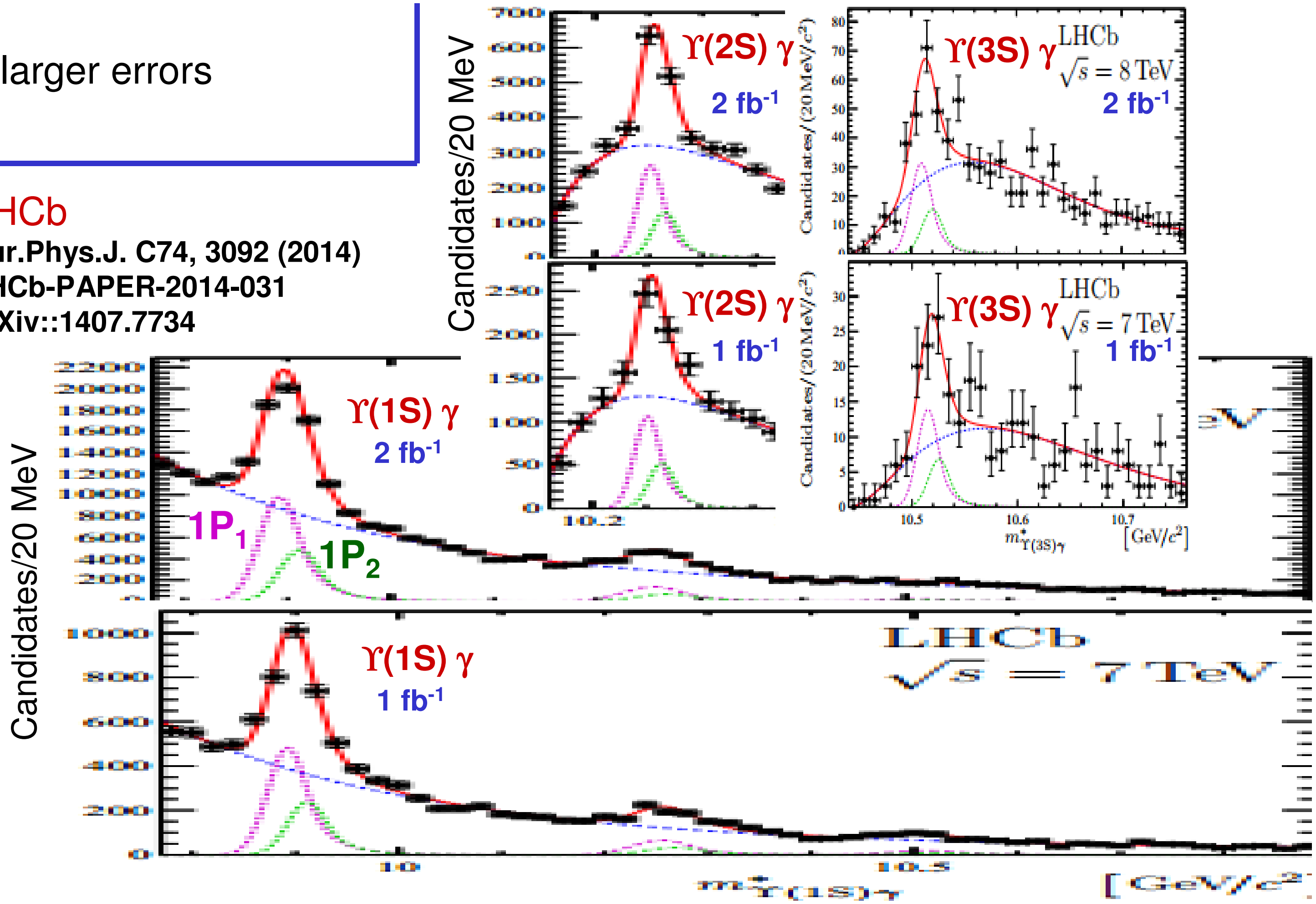
LHCb

Eur.Phys.J. C74, 3092 (2014)

LHCb-PAPER-2014-031

arXiv::1407.7734

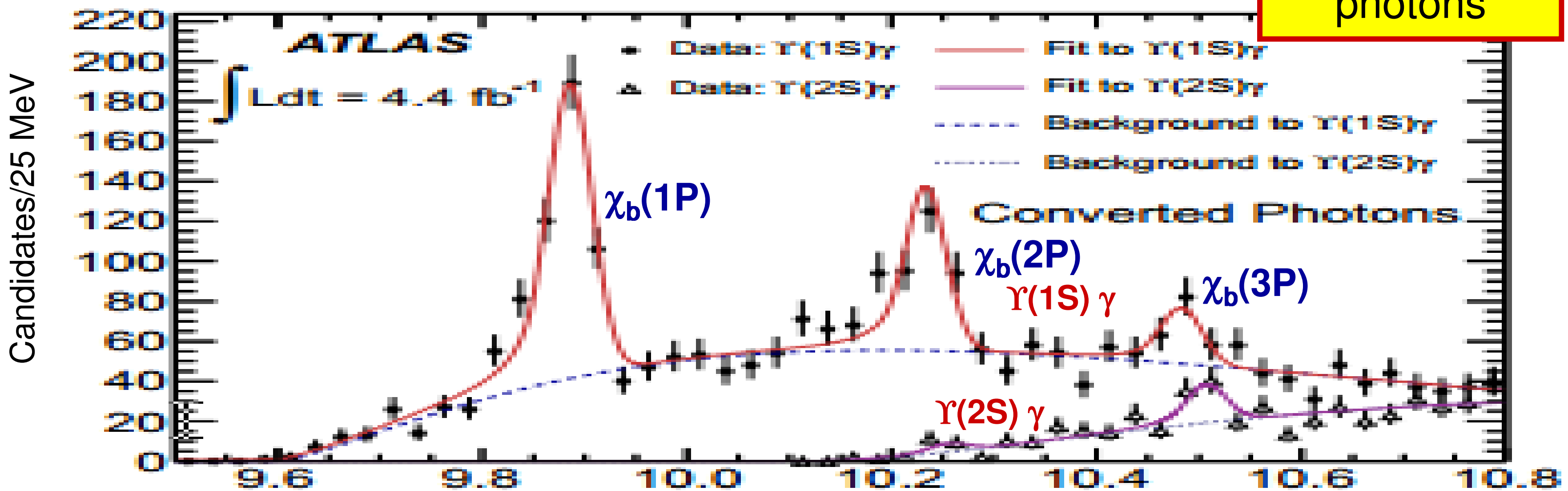




Better statistics and resolution.
Fit J=1,2 lines instead of a single Gaussian.

Recently measured long-lived $b\bar{b}$ state: 3P

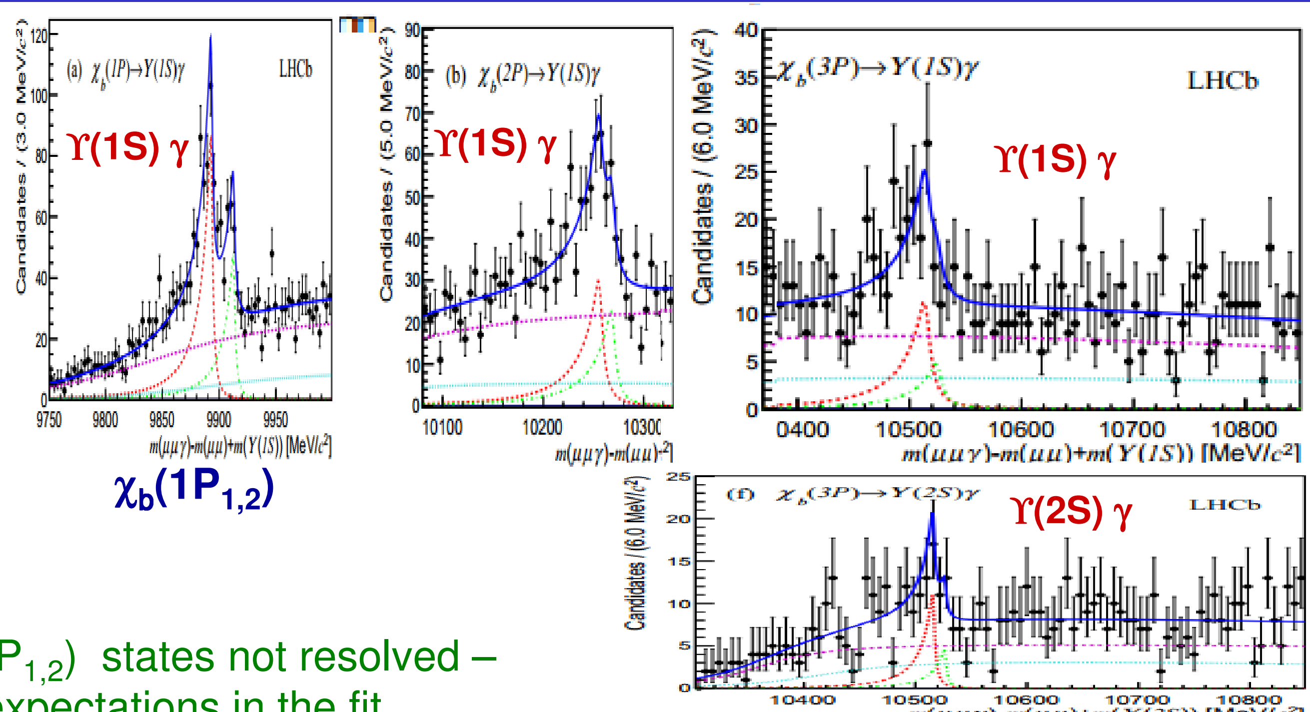
Converted photons



new

LHCb

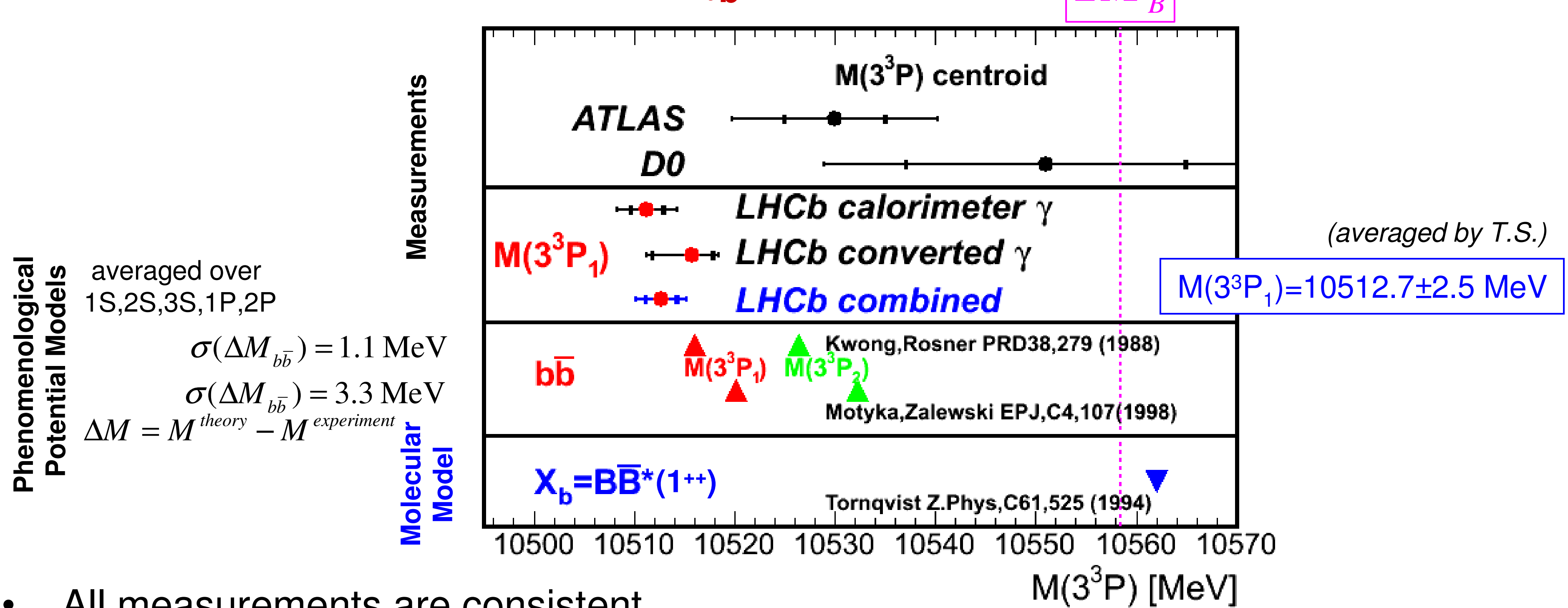
JHEP 1410, 88 (2014)
LHCb-PAPER-2014-040
arXiv::1409.1408



Better statistics and resolution.
Fit J=1,2 lines instead of a single Gaussian.

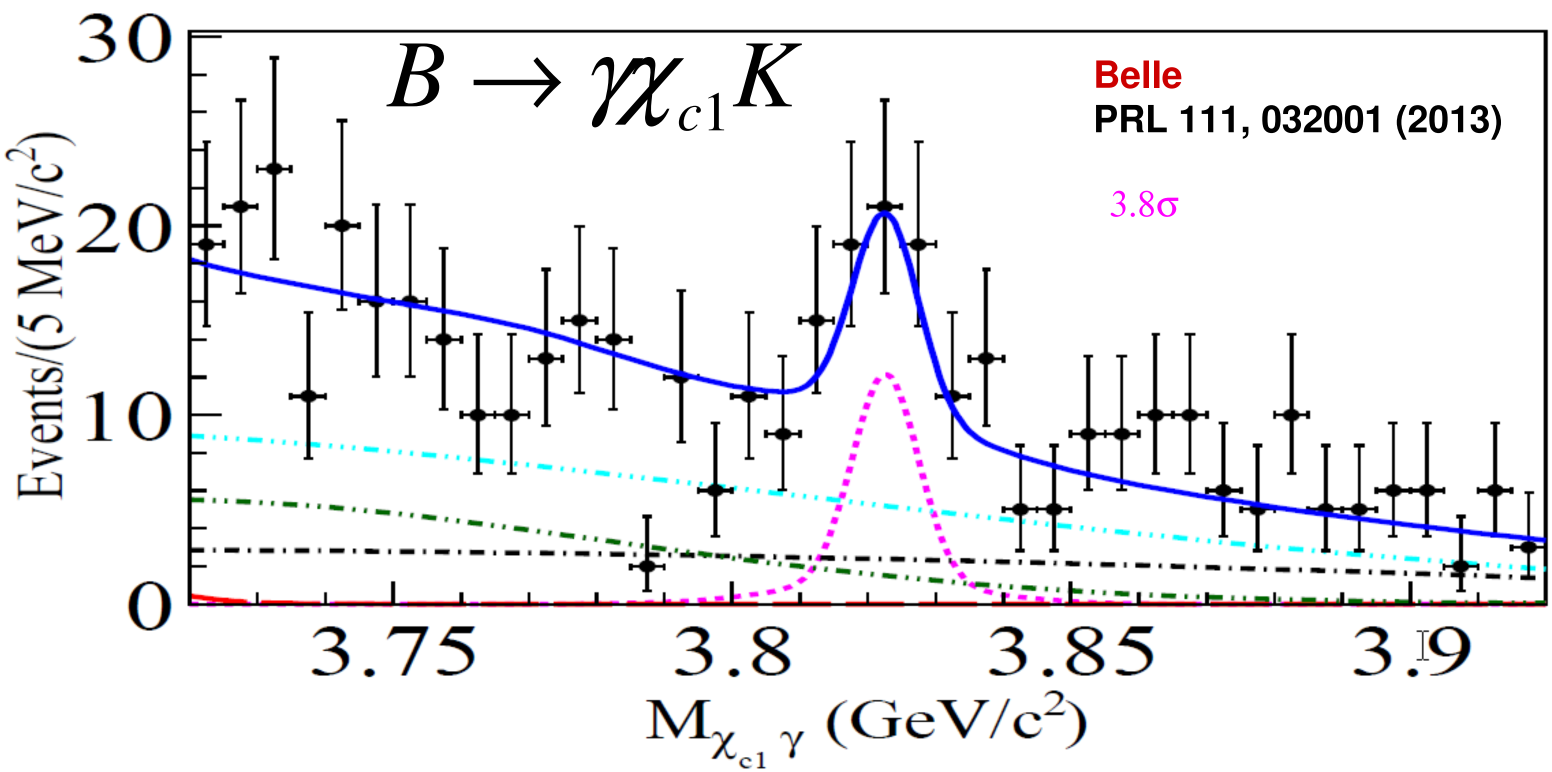
Fine structure of $\chi_b(3^3P_{1,2})$ states not resolved – constrained from the expectations in the fit.

Masses of $\chi_b(3P)$ states



- All measurements are consistent
- The new LHCb measurements have much improved errors
- The measured mass of the $\chi_b(3^3P_1)$ state is within a few MeV of the potential model predictions which are up to 26 years old !
  - Some theoretical models predict large mass shifts from couplings to virtual $B^{(*)}\overline{B^{(*)}}$ pairs due to the proximity of the open flavor threshold (e.g. Ferretti, Galata, arXiv:1401.4431)
  - It appears that such corrections are either small or well absorbed into an effective potential adjusted to the experimental data on the other $b\bar{b}$ states
  - Karliner, Rosner arXiv:1410.7729 (posted today!) think that $\chi_b(3^3P_1)$ could have a substantial X_b $I=0$ (analog of X(3872)) component, which may affect its decays. High statistics studies on 3P states needed to clarify this.

Recently discovered long-lived $c\bar{c}$ state: $\psi_2(1D)$



$$M_{\psi(1^3D_2)} = 3823.1 \pm 1.8 \pm 0.7 \text{ MeV}$$

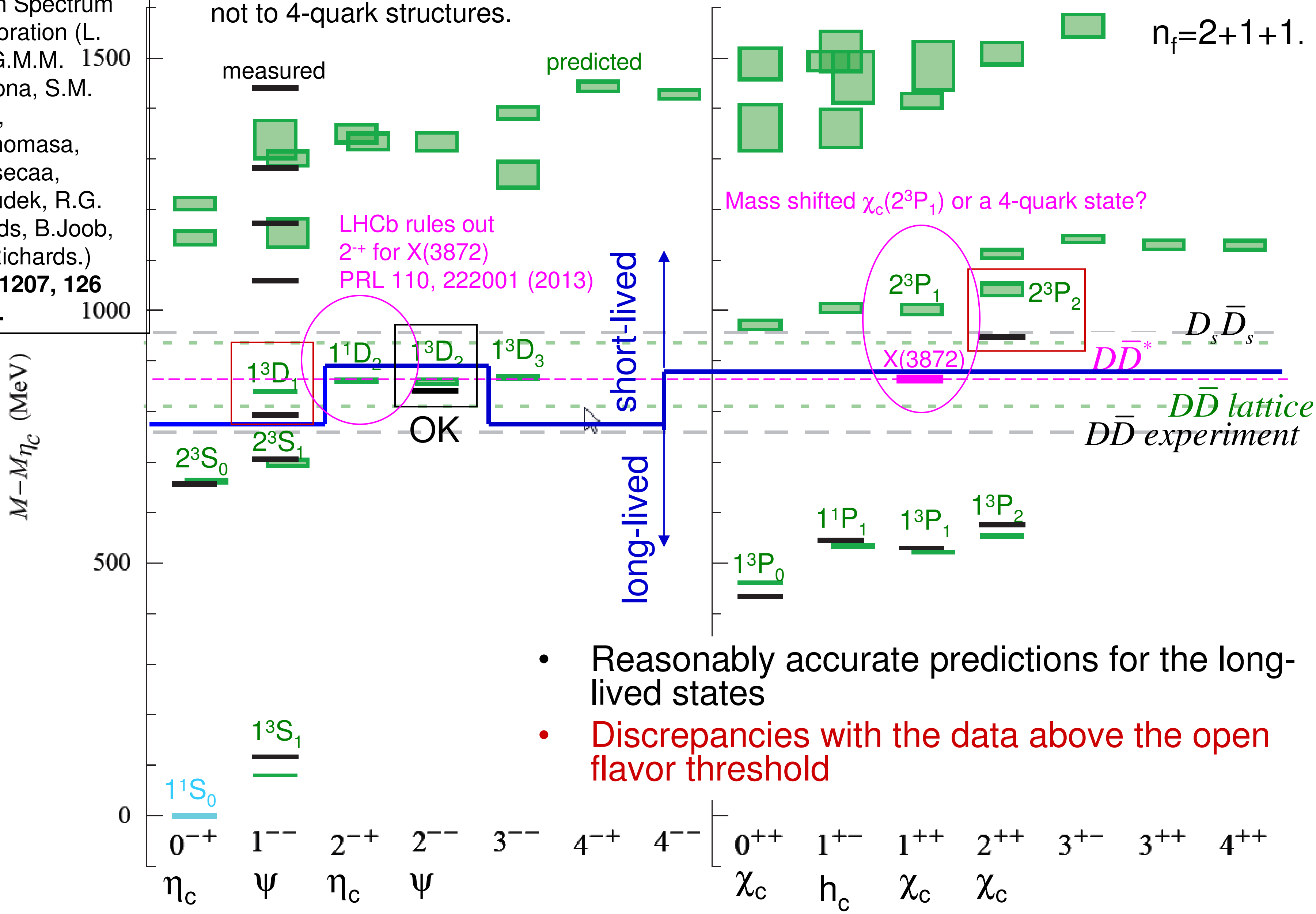
Visible peak width is consistent with the detector resolution.

- The mass is above the $D\bar{D}$ threshold, but below $D\bar{D}^*$. This state is expected to be narrow since $J^{PC}=2^{--}$ cannot decay to $D\bar{D}$

Masses of charmonium states from lattice QCD

Unquenched with dynamical charm quarks. Sensitive to hybrid ($q\bar{q}g$) contributions but not to 4-quark structures.

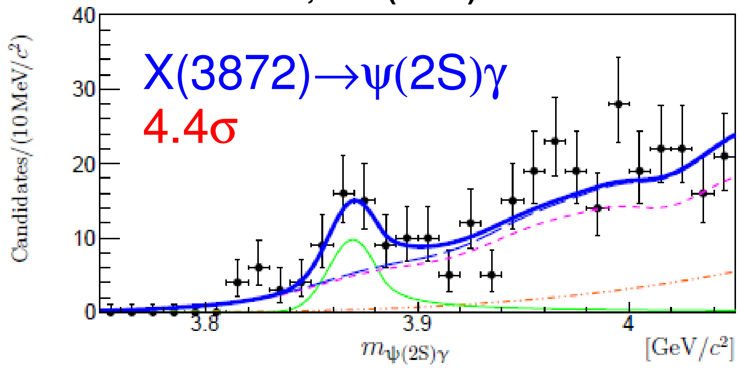
Hadron Spectrum Collaboration (L. Liua, G.M.M. Peardona, S.M. Ryana, C.E.Thomasa, P.Vilasecaa, J.J. Dudek, R.G. Edwards, B.Joob, D.G. Richards.) **JHEP 1207, 126 (2012).**



- Reasonably accurate predictions for the long-lived states
- Discrepancies with the data above the open flavor threshold

Radiative decays of X(3872) in LHCb

LHCb **NP B886, 665 (2014)** arXiv:1404.0275



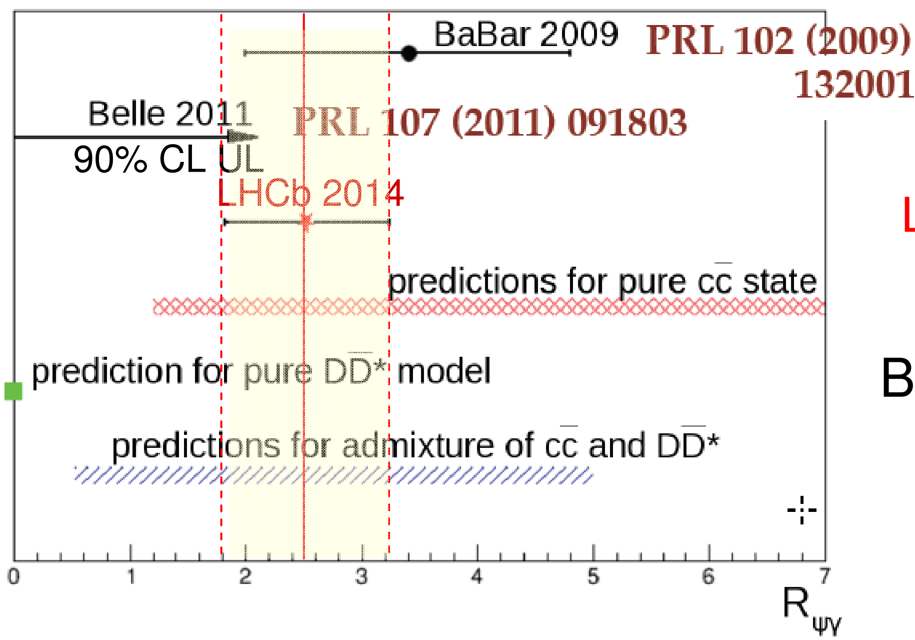
new

Measurement of

$R_{\psi\gamma}$=BR(X(3872)→ψ(2S)γ)/BR(X(3872)→J/ψγ)

a good probe for internal structure of X(3872)

	Signal events: B⁺→X(3872)K⁺, X(3872)→ψ(2S)γ, J/ψγ	Signal significance: ψ(2S)γ, J/ψγ
	$25.4 \pm 7.3,\ 23.0 \pm 6.4$	3.6σ, 3.5σ
	$5.0^{+11.9}_{-11.0},\ 30.0^{+8.2}_{-7.4}$	0.4σ, 4.9σ
LHCb	$36.4 \pm 9.0,\ 591.0 \pm 48.0$	4.4σ, 12σ



BR(X(3872)→ψ(2S)γ)/BR(X(3872)→J/ψγ)

= 2.48±0.64±0.29

- The LHCb results are consistent with, but more precise than, the BaBar and Belle results
- The results are not consistent with the expectations for pure molecular X(3872)

Status of X(3872)

- Not a (pure) $c\bar{c}$ state:
  - Mass coincides with the $M(D^0)+M(D^{0*})$
  - $BR(X(3872)\to\rho^0 J/\psi)$ ~ $BR(X(3872)\to\omega J/\psi)$
    - extreme case of isospin violation
  - Mass too low?
- Not a (pure) $D^0\bar{D}^{*0}$ molecule:
  - Sizeable prompt production at Tevatron & LHC
  - $BR(X(3872)\to\gamma\psi(2S))$ ~ $BR(X(3872)\to\gamma J/\psi)$
- X(3872) is likely a mixture of a $\chi_{c1}(2^3P_{1++})$ charmonium state and of D^0D^{*0} molecule or cusp (phenomenological model of such mixing have been constructed)
- Recently at least one lattice QCD calculation [S. Prelovsek L. Leskovec, **PRL 111, 192001 (2013)**] found evidence for X(3872) in $I=0$ state when both $c\bar{c}$ and dimeson operators are included in the simulations:
  - More work is needed to clarify if tertra-quark (tight $Q\bar{Q}q\bar{q}$ bound state) operators should be included as well

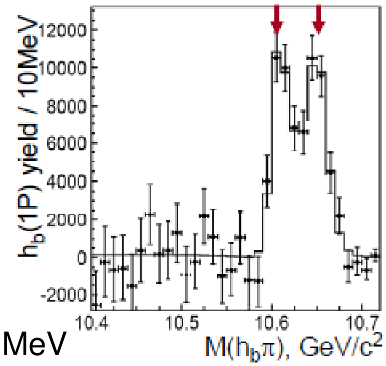
More mass peaks near the open flavor thresholds

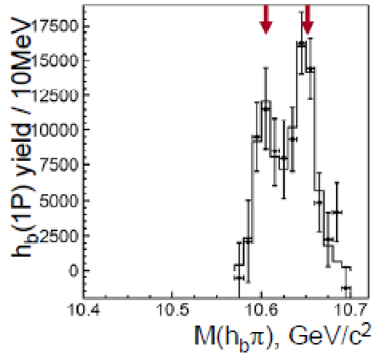
$e^+e^- \to "\Upsilon(5S)" \to \pi^{\pm}(\pi^{\mp} h_b(\to \gamma\eta_b))$ $\quad$ $e^+e^- \to Y(4260) \to \pi^{\pm}(\pi^{\mp} J/\psi)$

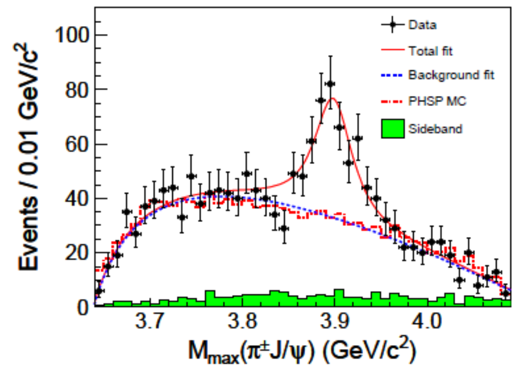
Belle
PRL 108, 122001 (2012)

$Z_b(10610)^+$
$Z_b(10650)^+$

$2^*M_{B^*} = 10650$
$M_B + M_{B^*} = 10604$ MeV







BESIII
PRL 110, 252001 (2013)

$Z_c(3900)^+$

$M_{D0} + M_{D+^*} = 3865$ MeV

TABLE 10: Quarkonium-like states at the open flavor thresholds. For charged states, the C-parity is given for the neutral members of the corresponding isotriplets.

From N. Brambilla et al.
arXiv:1404.3723

Can't be $Q\bar{Q}$!

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [810, 1030] (>10), BaBar [1031] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi) \ldots$	CDF [1032, 1033] (11.6), D0 [1034] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi) \ldots$	LHCb [1035, 1036] (np)	2012	Ok
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle [1037] (4.3), BaBar [1038] (4.0)	2005	Ok
				$B \to K(\gamma J/\psi)$	Belle [1039] (5.5), BaBar [1040] (3.5) LHCb [1041] (> 10)	2005	Ok
				$B \to K(\gamma\, \psi(2S))$	BaBar [1040] (3.6), Belle [1039] (0.2) LHCb [1041] (4.4)	2008	NC!
				$B \to K(D\bar{D}^*)$	Belle [1042] (6.4), BaBar [1043] (4.9)	2006	Ok
$Z_c(3885)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III [1044] (np)	2013	NC!
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III [1045] (8), Belle [1046] (5.2) T. Xiao *et al.* [CLEO data] [1047] (>5)	2013	Ok
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BES III [1048] (8.9)	2013	NC!
$Z_c(4025)^+$	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III [1049] (10)	2013	NC!
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(10860) \to \pi(\pi\Upsilon(1S, 2S, 3S))$	Belle [1050–1052] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1051] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B\bar{B}^*)^+$	Belle [1053] (8)	2012	NC!
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [1050, 1051] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1051] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle [1053] (6.8)	2012	NC!

WAY ABOVE OPEN FLAVOR THRESHOLD STATES

First-discovered charged four-quark candidate: $Z_c(4430)^+$

Belle 2008 **PRL 100, 142001**

$M(Z) = 4433 \pm 4 \pm 2$ MeV

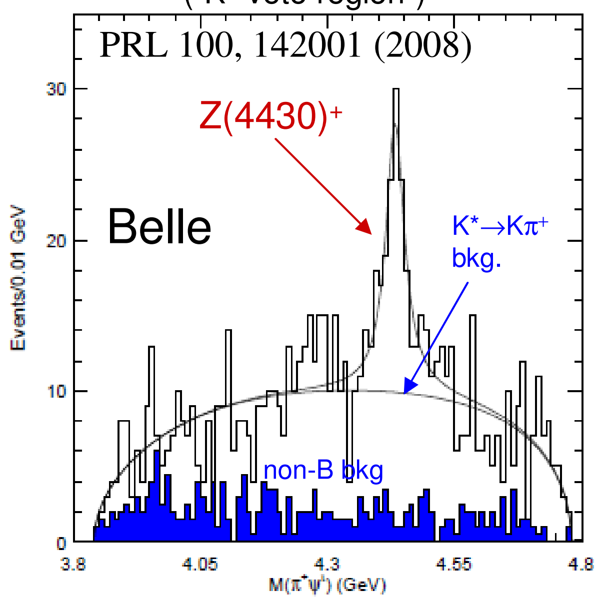
$\Gamma(Z) = 45^{+18}_{-13}\,{}^{+30}_{-13}$ MeV

significance 6.5σ

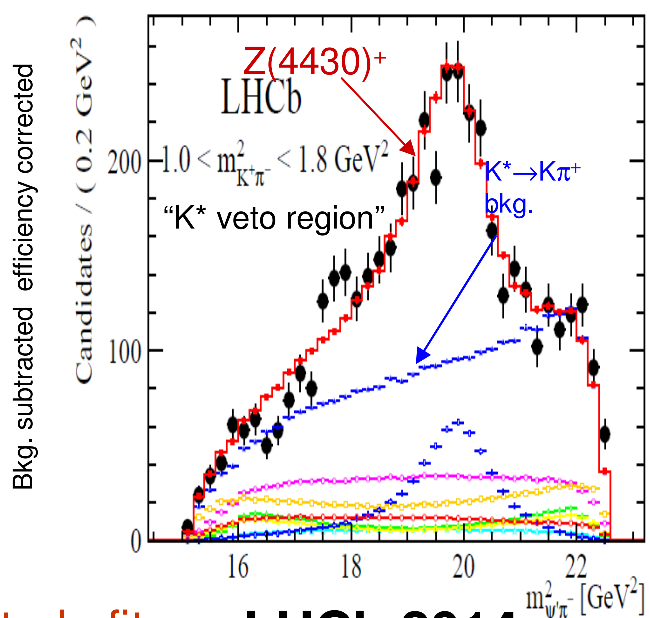
Z+ K*

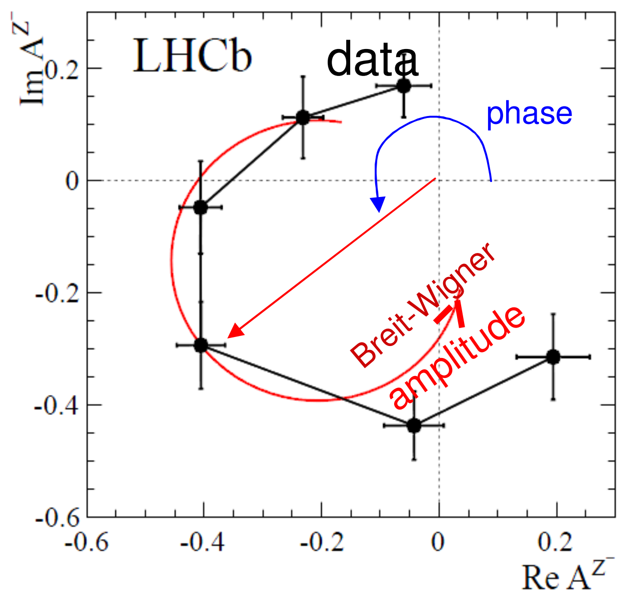
$B \to \psi' \pi^+ K$

1D M(ψ'π⁻) mass fit
("K* veto region")



LHCb
PRL 112, 222002 (2014) new





Belle 2013 4D amplitude fits **LHCb 2014**

Argand diagram

PRD88, 074026

$M(Z) = 4485^{+22}_{-22}\,{}^{+28}_{-11}$ MeV

$\Gamma(Z) = 200^{+41}_{-46}\,{}^{+26}_{-35}$ MeV

5.6σ with sys.

$J^P=1^+$ preferred by $>3.4\sigma$

$M(Z) = 4475 \pm 7^{+15}_{-25}$ MeV

$\Gamma(Z) = 172 \pm 13^{+37}_{-34}$ MeV

13.9σ

$J^P=1^+$ preferred by $>9.7\sigma$

Consistent with a resonant amplitude

$Z_c(4430)^+$ companion : $Z_c(4200)^+$

Belle
arXiv:1408.6457 new

Updated Oct.16!

Z^+ K^{*0}

$B \to J/\psi \pi^+ K^-$

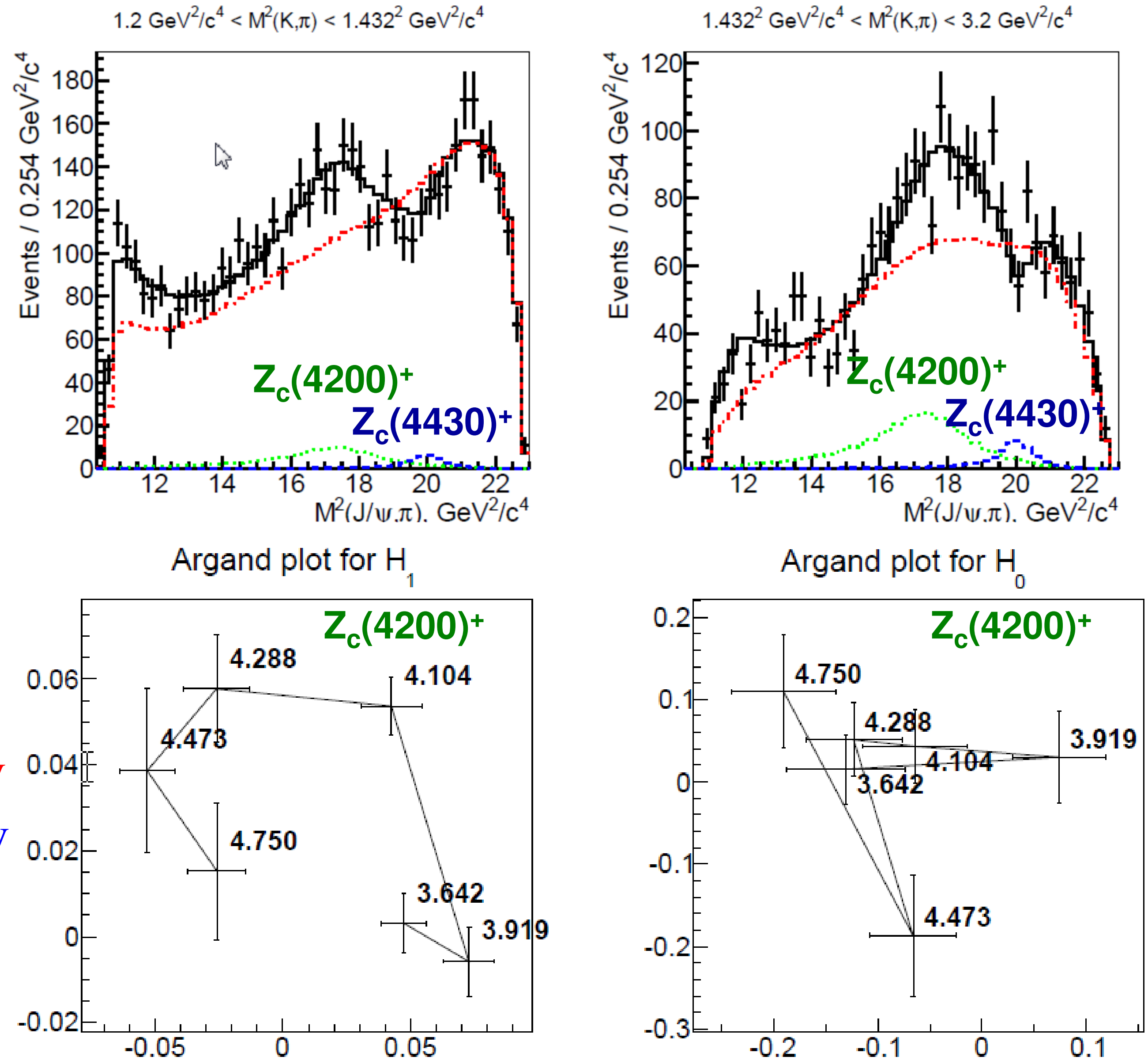
$Z_c(4430)^+$ $(0.5^{+0.4}_{-0.1})\%$ 5.1σ

$Z_c(4200)^+$ $(1.9^{+0.7}_{-0.5})\%$ 8.2σ

$J^P(4200)=1^+$ preferred by >8.6σ

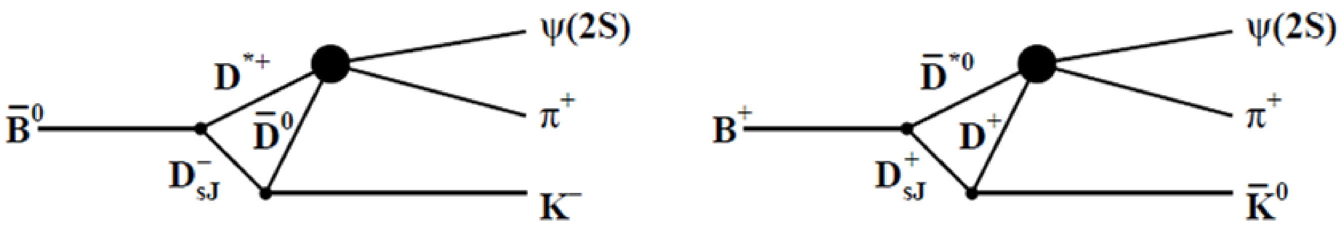
$M(4200) = 4196^{+31}_{-29}\ ^{+17}_{-13}$ MeV

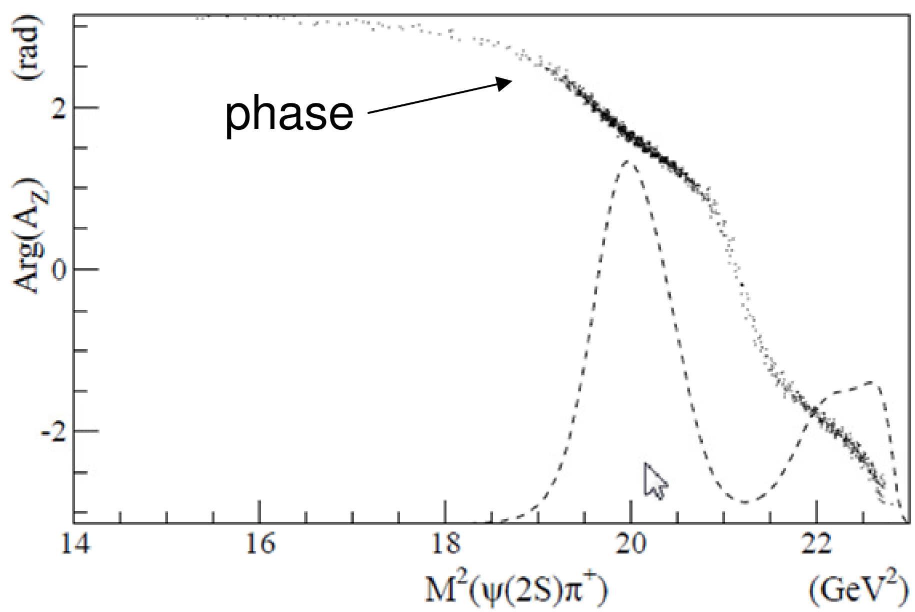
$\Gamma(4200) = 370^{+70}_{-70}\ ^{+70}_{-132}$ MeV



$Z_c^+(4430)$ as rescattering effect?

P. Paklov, T. Uglov
arXiv:1408.5295 (2014)





Phase running in opposite way to Breit-Wigner.

The same rescattering mechanism can be used to generate 1^+ structure at lower masses ($\rightarrow Z_c^+(4200)$)

- Such models should be put into amplitude fits by experimentalists, to see if can be discriminated against resonant interpretation

More mass peaks well above the open flavor thresholds

TABLE 12: Quarkonium-like states above the corresponding open flavor thresholds. For charged states, the C-parity is given for the neutral members of the corresponding isotriplets.

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$Y(3915)$	3918.4 ± 1.9	20 ± 5	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [1088] (8), BaBar [1038, 1089] (19)	2004	Ok
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [1090] (7.7), BaBar [1091] (7.6)	2009	Ok
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [1092] (5.3), BaBar [1093] (5.8)	2005	Ok
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [1086, 1087] (6)	2005	NC!
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [1046, 1094] (7.4)	2007	NC!
$\psi(4040)$	4039 ± 1	80 ± 10	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)}(\pi))$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.0)	2013	NC!
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (5.0), Belle [1099] (1.9),	2009	NC!
					LHCb [1100] (1.4), CMS [1101] (>5)		
					D0 [1102] (3.1)		
$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)})$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.5)	2013	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [1087] (5.5)	2007	NC!
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$B^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (7.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (2.0)	2008	NC!
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar [1104, 1105] (8), CLEO [1106, 1107] (11)	2005	Ok
					Belle [1046, 1094] (15), BES III [1045] (np)		
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [1105] (np), Belle [1046] (np)	2012	Ok
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
				$e^+e^- \to (\gamma\,X(3872))$	BES III [1108] (5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (3.1), LHCb [1100] (1.0),	2011	NC!
					CMS [1101] (>3), D0 [1102] (np)		
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [1109] (3.2)	2009	NC!
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (8), BaBar [1111] (np)	2007	Ok
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [1112, 1113] (6.4), BaBar [1114] (2.4)	2007	Ok
					LHCb [1115] (13.9)		
				$B^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (4.0)	2014	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle [1116] (8.2)	2007	NC!
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (5.8), BaBar [1111] (5)	2007	Ok
$\Upsilon(10860)$	10876 ± 11	55 ± 28	1^{--}	$e^+e^- \to (B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi))$	PDG [1]	1985	Ok
				$e^+e^- \to (\pi\pi\Upsilon(1S, 2S, 3S))$	Belle [1051, 1052, 1117] (>10)	2007	Ok
				$e^+e^- \to (f_0(980)\Upsilon(1S))$	Belle [1051, 1052] (>5)	2011	Ok
				$e^+e^- \to (\pi Z_b(10610, 10650))$	Belle [1051, 1052] (>10)	2011	Ok
				$e^+e^- \to (\eta\Upsilon(1S, 2S))$	Belle [986] (10)	2012	Ok
				$e^+e^- \to (\pi^+\pi^-\Upsilon(1D))$	Belle [986] (9)	2012	Ok
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [1118] (2.3)	2008	NC!

From N. Brambilla et al.
arXiv:1404.3723

Plethora of mass states near or above the open flavor thresholds!

Many need confirmation.

Many of them can't be QQ states (charged!)

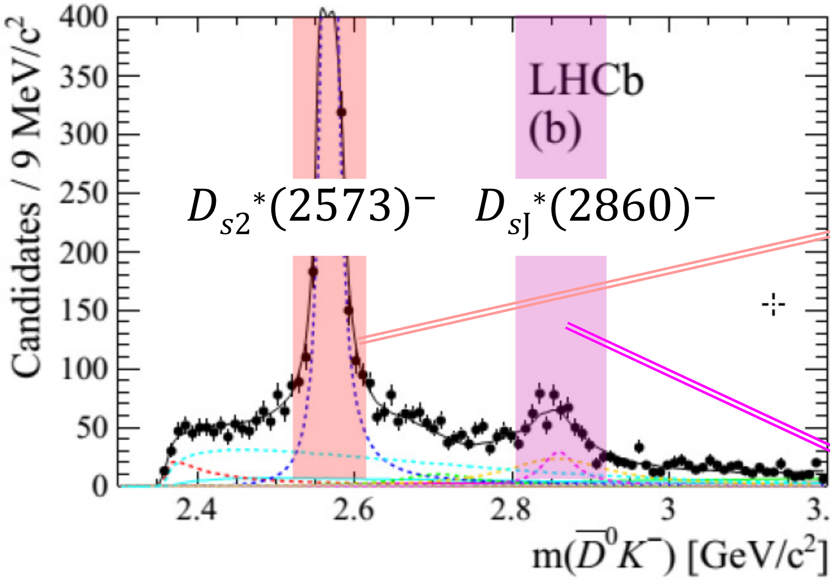
They require survey of their decay channels and, broad ones, high statistics phase studies to clarify if they originate from dimeson rescattring or 4-quark (molecular or tetraquark) bound-states.Hybrids may be present too.

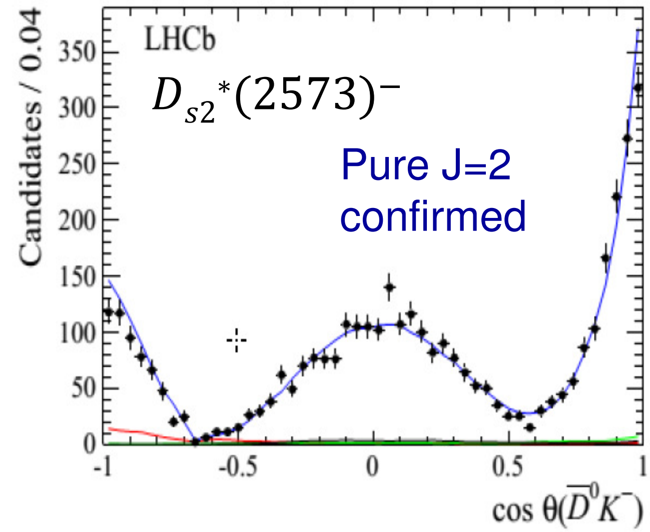
Need improvements in theoretical framework as well.

See also S. Olsen talk!

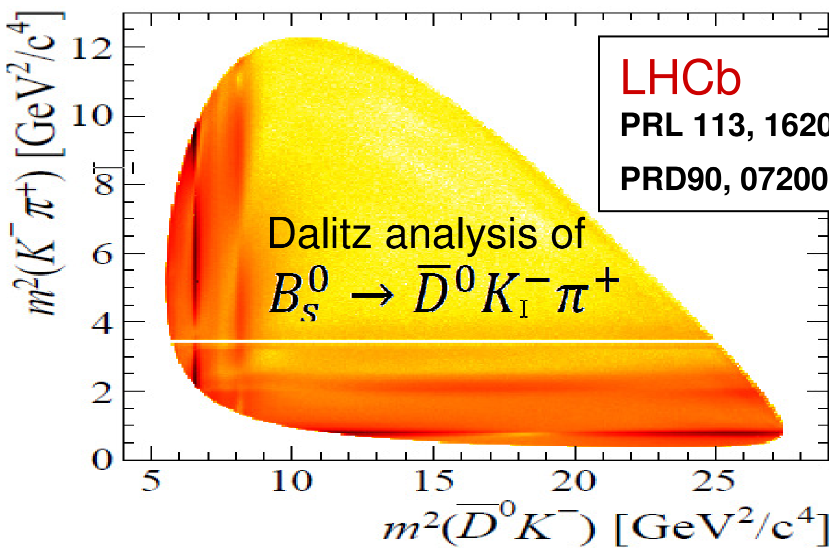
News in heavy-light sector

Good experimental and theoretical understanding of $Q\bar{q}$ states is necessary for sorting out XYZ states



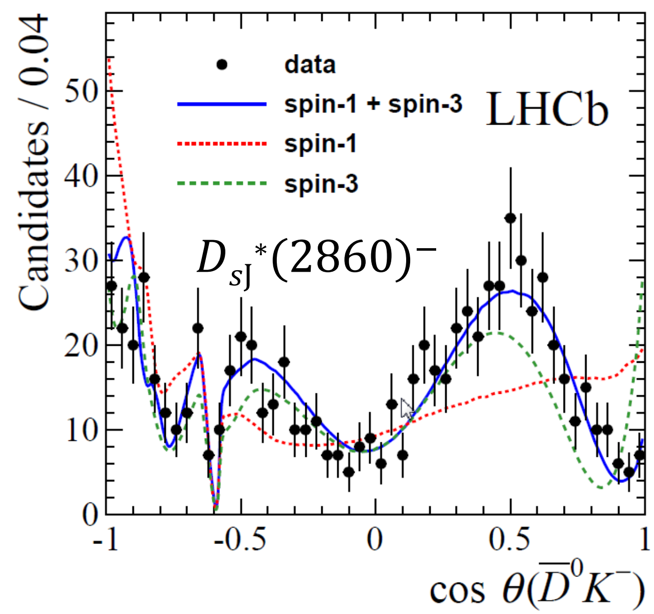


$1P_2$ state



new

LHCb
PRL 113, 162001 (2014)
PRD90, 072003 (2014)



$1D_{1,3}$ states

The 2860 peak resolved into J=1 and 3 resonances (first J=3 state observed in B decays)

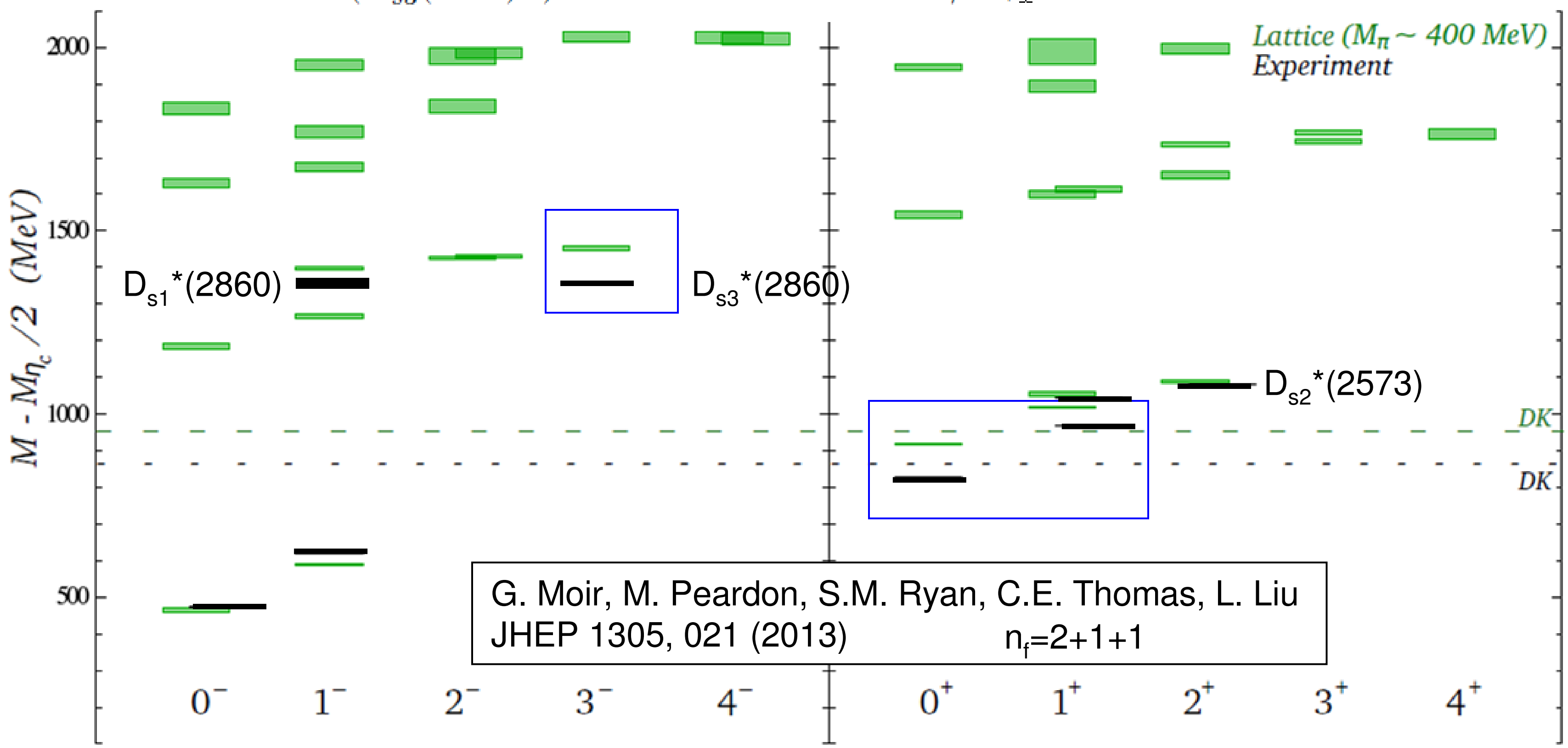
Lattice simulations of D_s states

LHCb

PRL 113, 162001 (2014)

PRD90, 072003 (2014)

$$m(D_{s2}^*(2573)^-) = 2568.39 \pm 0.29 \pm 0.19 \pm 0.18\,\mathrm{MeV}/c^2\,,$$
$$\Gamma(D_{s2}^*(2573)^-) = 16.9 \pm 0.5 \pm 0.4 \pm 0.4\,\mathrm{MeV}/c^2\,,$$
$$m(D_{s1}^*(2860)^-) = 2859 \pm 12 \pm 6 \pm 23\,\mathrm{MeV}/c^2\,,$$
$$\Gamma(D_{s1}^*(2860)^-) = 159 \pm 23 \pm 27 \pm 72\,\mathrm{MeV}/c^2\,,$$
$$m(D_{s3}^*(2860)^-) = 2860.5 \pm 2.6 \pm 2.5 \pm 6.0\,\mathrm{MeV}/c^2\,,$$
$$\Gamma(D_{s3}^*(2860)^-) = 53 \pm 7 \pm 4 \pm 6\,\mathrm{MeV}/c^2\,,$$



- Improvements in lattice calculations are needed (couplings to 4-quarks missing)

Excited B_c^+ state ($c\bar{b}$)

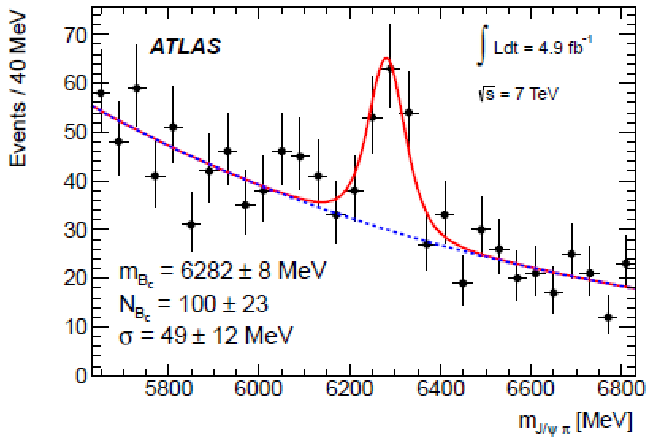
ATLAS

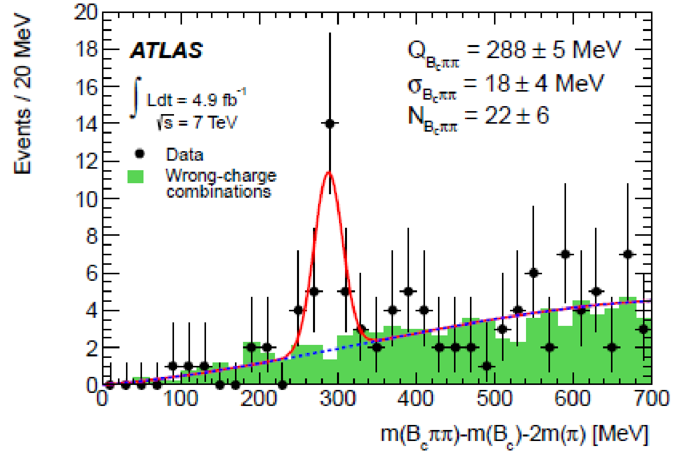
new

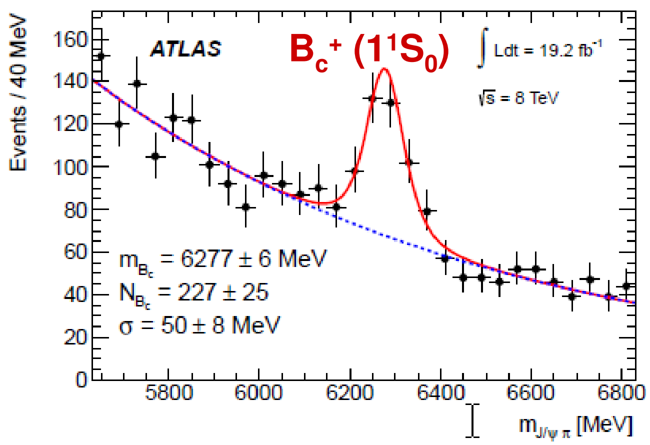
arXiv::1407.1032

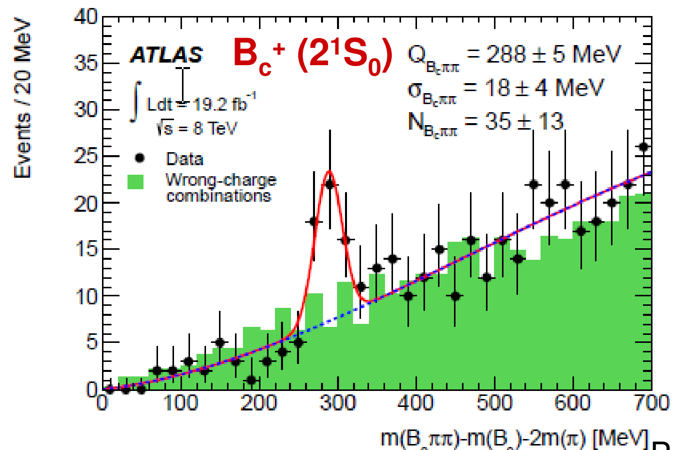
5.2σ

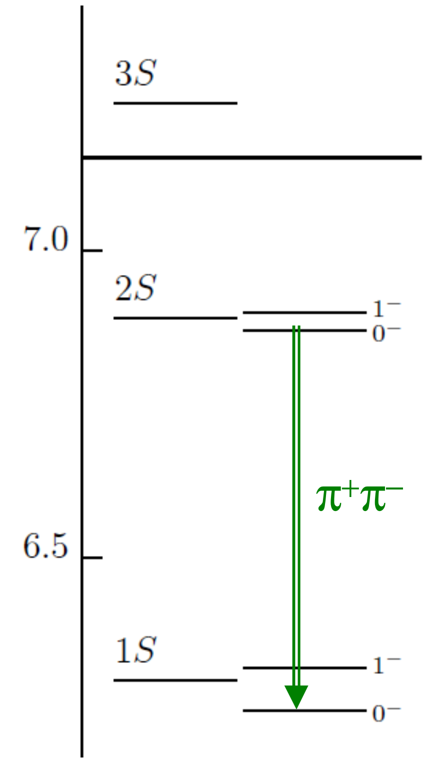
Quarkonium like spectrum except no annihilation corrections











6275.6 ± 1.1 MeV

6842 ± 4 ± 5 MeV

Splitting $b\bar{c}$: 566 ± 6 MeV

($c\bar{c}$ 655.8 ± 1.5 MeV $b\bar{b}$ 601 ± 6 MeV)

Potential model by:
D. Ebert, R. N. Faustov, V. O. Galkin
Phys.Rev.D67:014027 (2003)

$c\bar{c}$ 609 $b\bar{b}$ 593 $b\bar{c}$ 565 MeV

Need lattice QCD calculations!

Production of quarkonium states

- **Assume** NRQCD factorization applies
  - Additional energy scale in the considerations: p_t

$$\sigma^H(p_T, m_Q) = \sum_n \sigma_n(p_T, m_Q, \Lambda)\langle 0|\mathcal{O}_n^H(\Lambda)|0\rangle$$

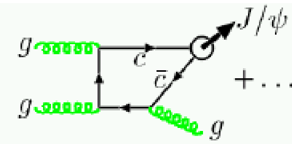
Process dependent short-distance partonic cross-sections

(theory)

Universal (?) long-distance probabilities ("LDMEs") of evolving from partons to given bound state

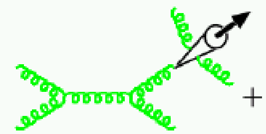
(data,models,…)

leading-order colour-singlet: $g+g \to c\bar{c}[^3S_1^{(1)}] + g$



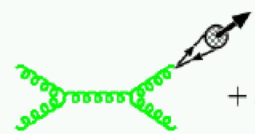
$+\ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^4}{p_t^8}$

colour-singlet fragmentation: $g+g \to [c\bar{c}[^3S_1^{(1)}] + gg] + g$



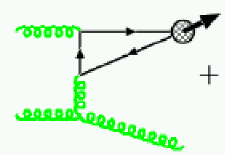
$+\ldots \qquad \sim \alpha_s^5 \frac{1}{p_t^4}$

colour-octet fragmentation: $g+g \to c\bar{c}[^3S_1^{(8)}] + g$



$+\ldots \qquad \sim \alpha_s^3 \frac{1}{p_t^4} v^4$

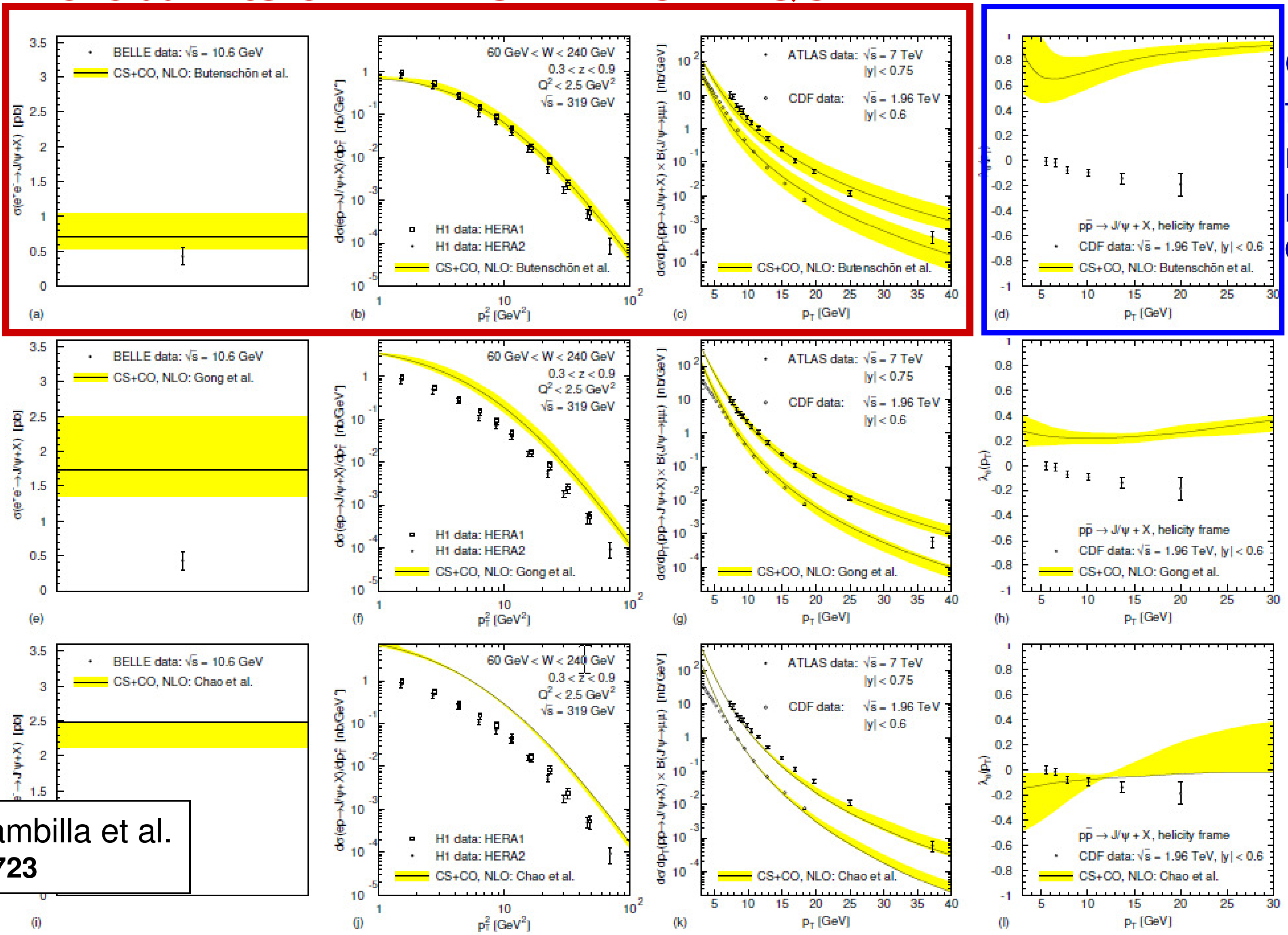
colour-octet fusion: $g+g \to c\bar{c}[^1S_0^{(8)}, {}^3P_J^{(8)}] + g$



$+\ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^6} v^4$

Global fits of LDMEs in NLO NRQCD

Great Success in describing measured cross-sections with Universal LDMEs

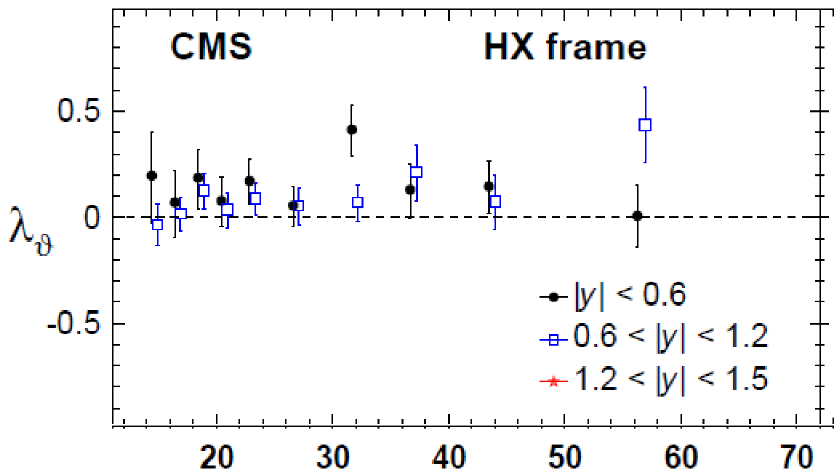


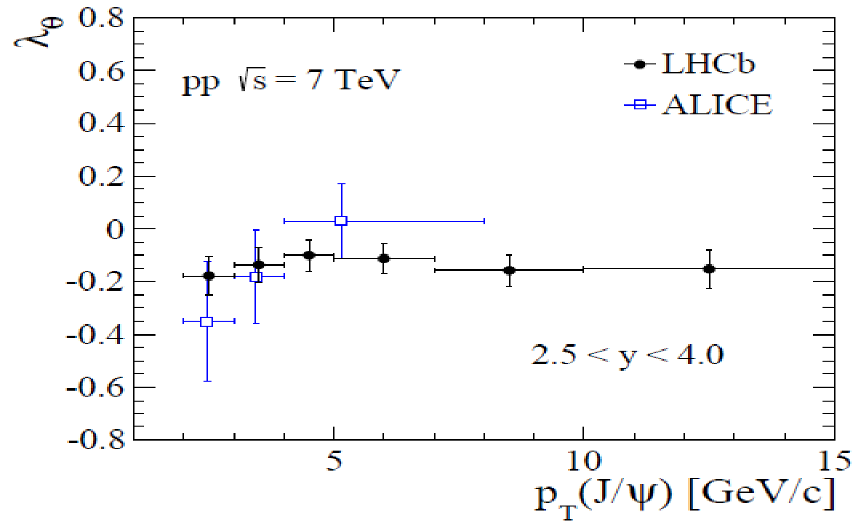
Great failure in reproducing polarization data

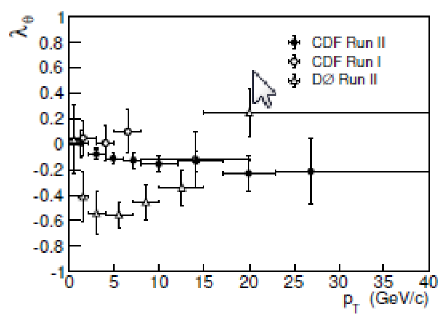
From N. Brambilla et al.
arXiv:1404.3723

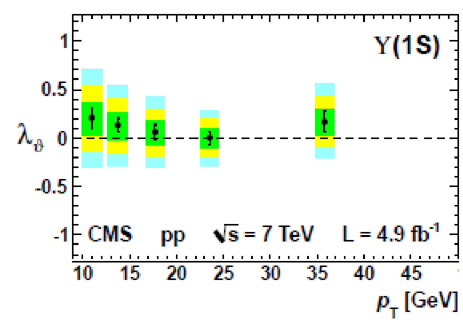
FIG. 33: The predictions of the J/ψ total e^+e^- cross section measured by Belle [1175], the transverse momentum distributions in photoproduction measured by H1 at HERA [1172, 1186], and in hadroproduction measured by CDF [1142] and ATLAS [1143], and the polarization parameter λ_θ measured by CDF in Tevatron run II [1160]. The predictions are plotted using the values of the CO LDMEs given in [771], [1182] and [1184] and listed in Table 13. The error bars of graphs a–g refer to scale variations, of graph d also fit errors, errors of graph h according to [1182]. As for graphs i–l, the central lines are evaluated with the default set, and the error bars evaluated with the alternative sets of the CO LDMEs used in [1184] and listed in Table 13. From [1187].

Polarization and other measurements from LHC









- Many other new production measurements from the LHC experiments: J/ψ, $\psi(2S)$, $\chi_{cJ}(1P)$, X(3872), Υ(1,2,3S), χ_{bJ}(1,2,3S), B_c, doublecharm…
- The data should help to deal with cross-feed between various excitations and to improve the theory

Summary

Light hadrons
1950-

1964

3x3=
8+1

$q\bar{q}$,
qqq,
…

Long-lived
charm & beauty onia
1974-

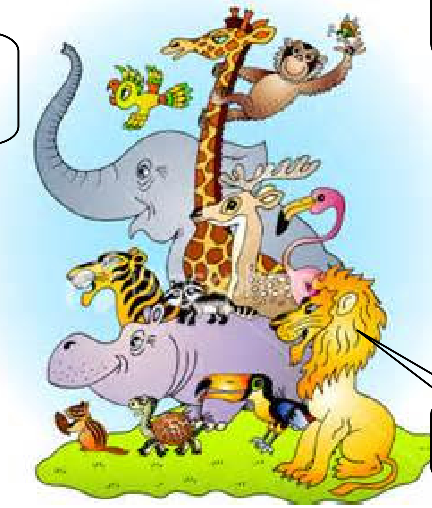
$q\bar{q}$!

Precision
spectroscopy from
the fundamental
theory:
lattice (NR)QCD

…,
$qqqq\bar{q}$?

Pentaquarks

XYZ states
2003-



…,
$q\bar{q}q\bar{q}$

$q\bar{q}g$?

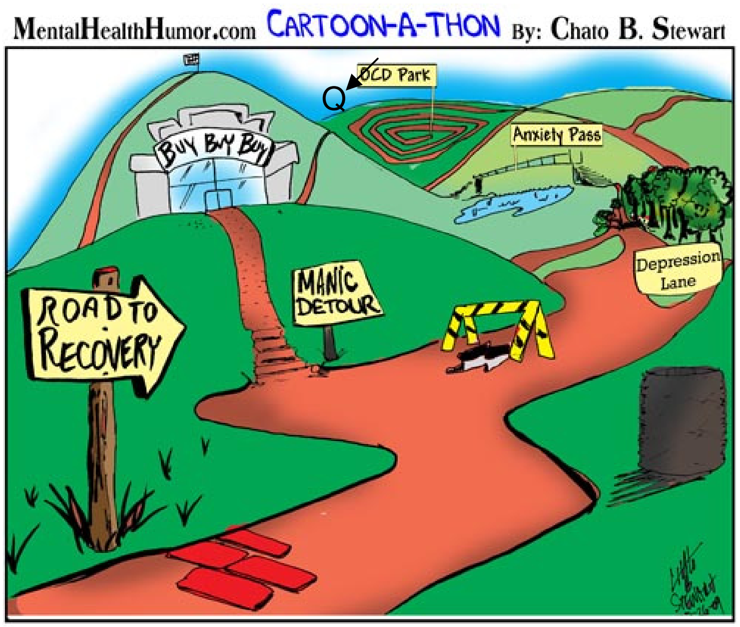
Back to the ZOO:
we still have to face
all the consequences
of the Quark Model
and strongly coupled
QCD

Heavy flavor hadrons
($Q\bar{Q}$,$Q\bar{Q}q\bar{q}$,$Q\bar{Q}g$) offer the best
playground to face this
challenge

Future

- Roadmap out of the new ZOO:
  - Experiments:
    - clean-up and survey of new states
    - precision phase evolution studies (amplitude fits) as improvement over peakology (though there are also dangers of fitology…)
    - pursue heavy-light spectroscopy since it impacts heavy-heavy states above the open flavor threshold
    - B_c^+ spectroscopy vs heavy onia spectroscopy will expose role of annihilation corrections in the latter
    - The past record shows that all existing and new facilities will contribute (higher luminosity charm and beauty e^+e^-, upgraded LHCb,…)
  - Theory:
    - phenomenological models are helpful, especially if they have predictive rather than postdictive power, but…
    - need serious effort to move lattice QCD with dynamical charm quarks way above the open flavor threshold
    - overcoming NRQCD limitations in failure to account for onia polarization measurements in inclusive production

(OCD – Obsessive Compulsive Disorder)



Road To Recovery