Complementarity of the beauty and charm hadron physics

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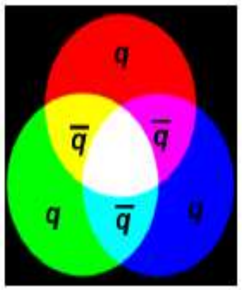
(Novosibirsk, May 21, 2018)

QCD

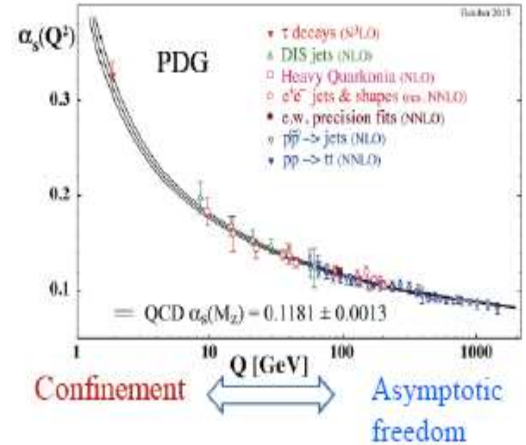
$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b,t} \bar{q}\,(i\gamma_\mu D^\mu - m_q)\,q \quad - \frac{1}{4}\mathcal{F}^{\mu\nu}\mathcal{F}_{\mu\nu}$$



$SU(3)_{color}$

Gluons with color-anticolor charge

1973



Hadrons = Non-perturbative QCD

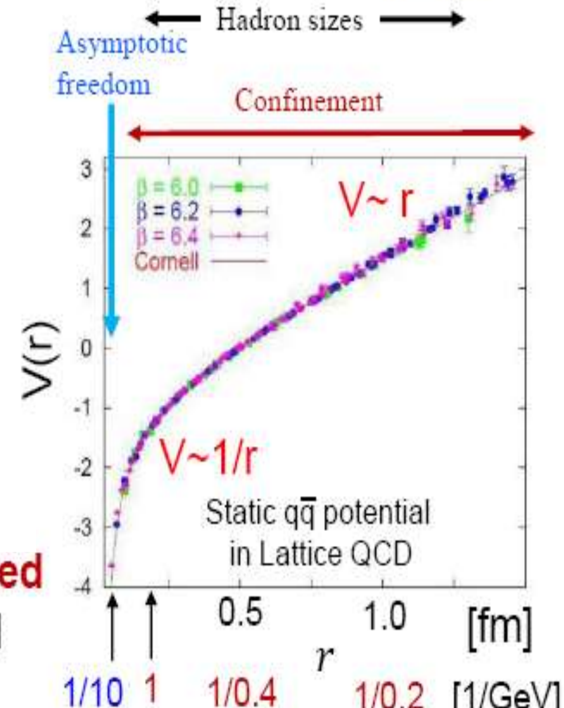
Lattice QCD works well for lowest-excitations of $(q\bar{q}), (qqq)$.

Only approximate lattice simulations for **unstable** higher excitations.

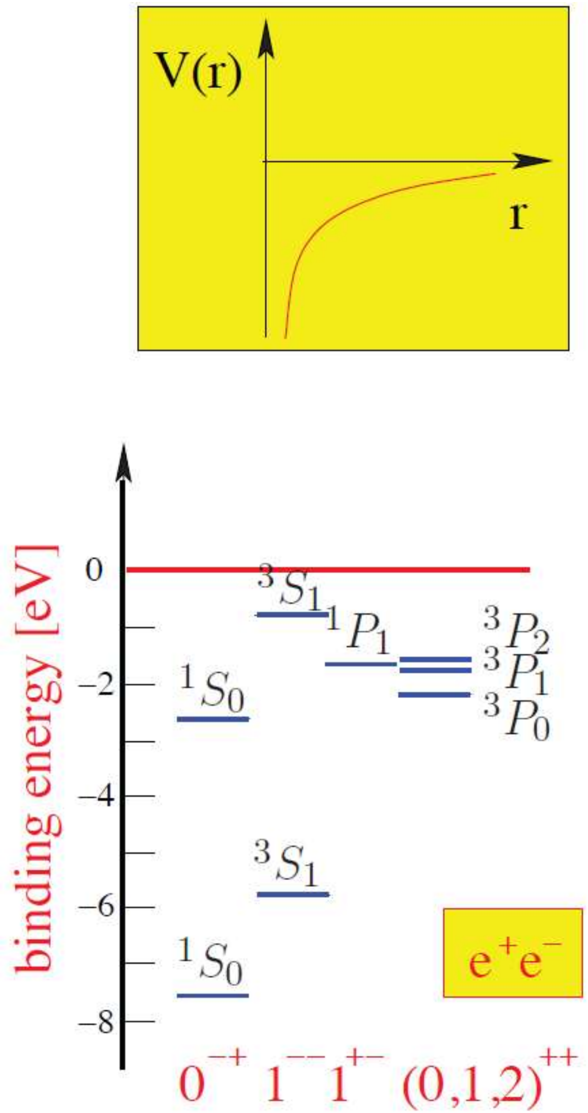
Expect hadrons with gluons as constituents:

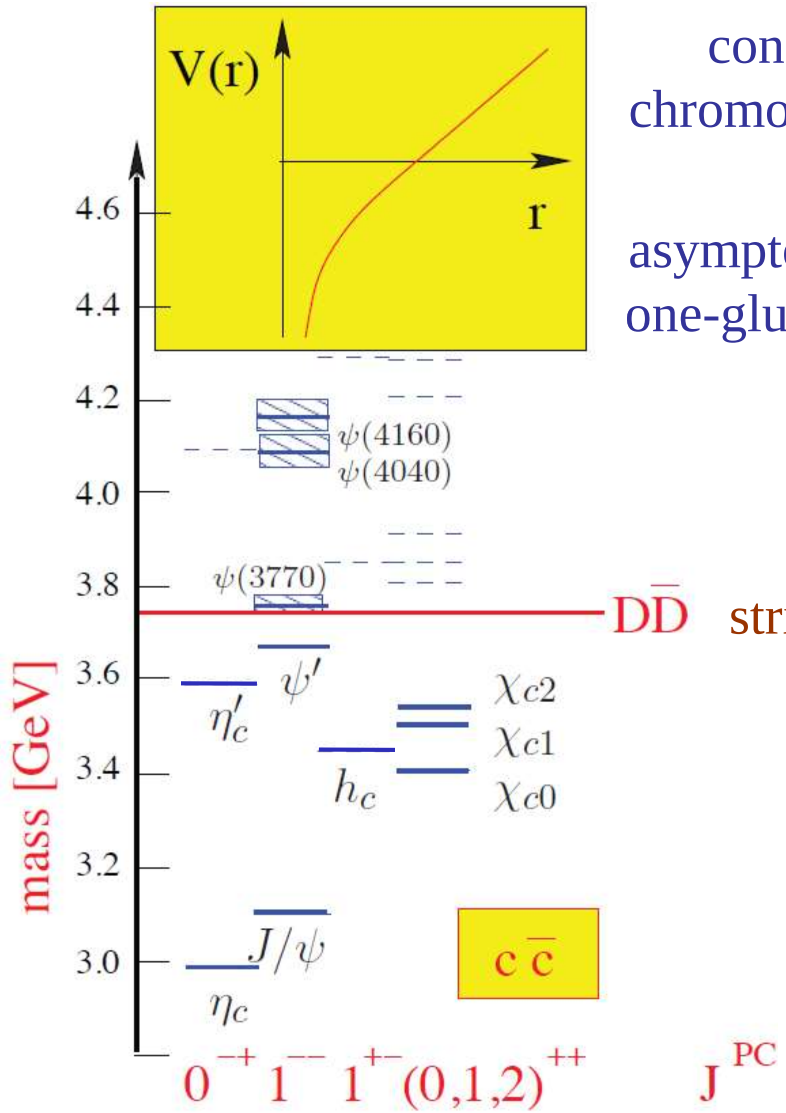
- **Hybrids:** $(q\bar{q}g), (qqqg), \ldots$
- **Glueballs:** $(gg), \ldots$

We have to **rely on data and QCD-motivated phenomenology** when trying to understand more complex hadronic structures.



Classification of $c\bar{c}$ and $b\bar{b}$ levels is the same as in positronium: L, S, n_r :



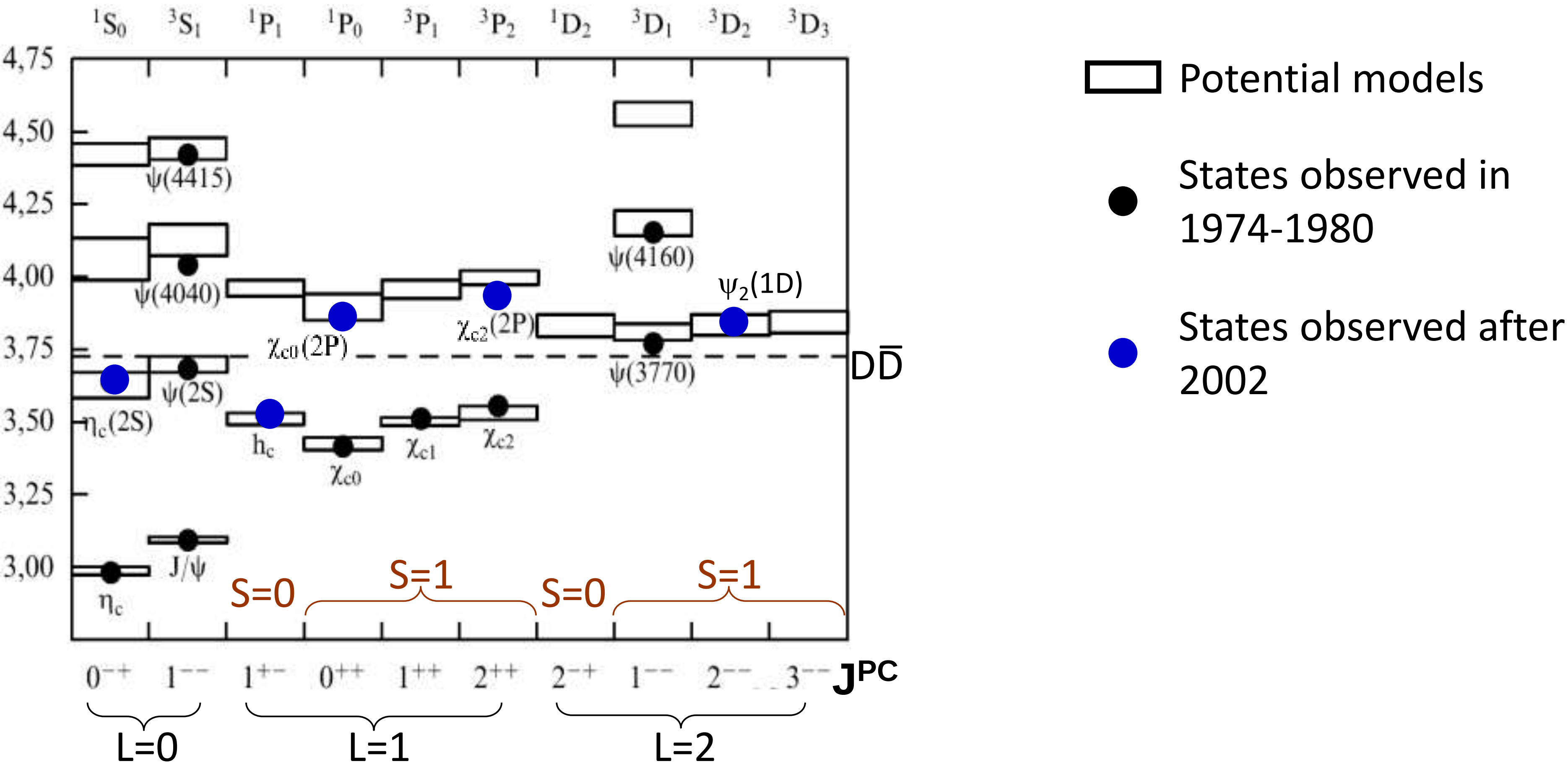


confinement
chromoelectric tube

asymptotic freedom
one-gluon exchange

string breaking

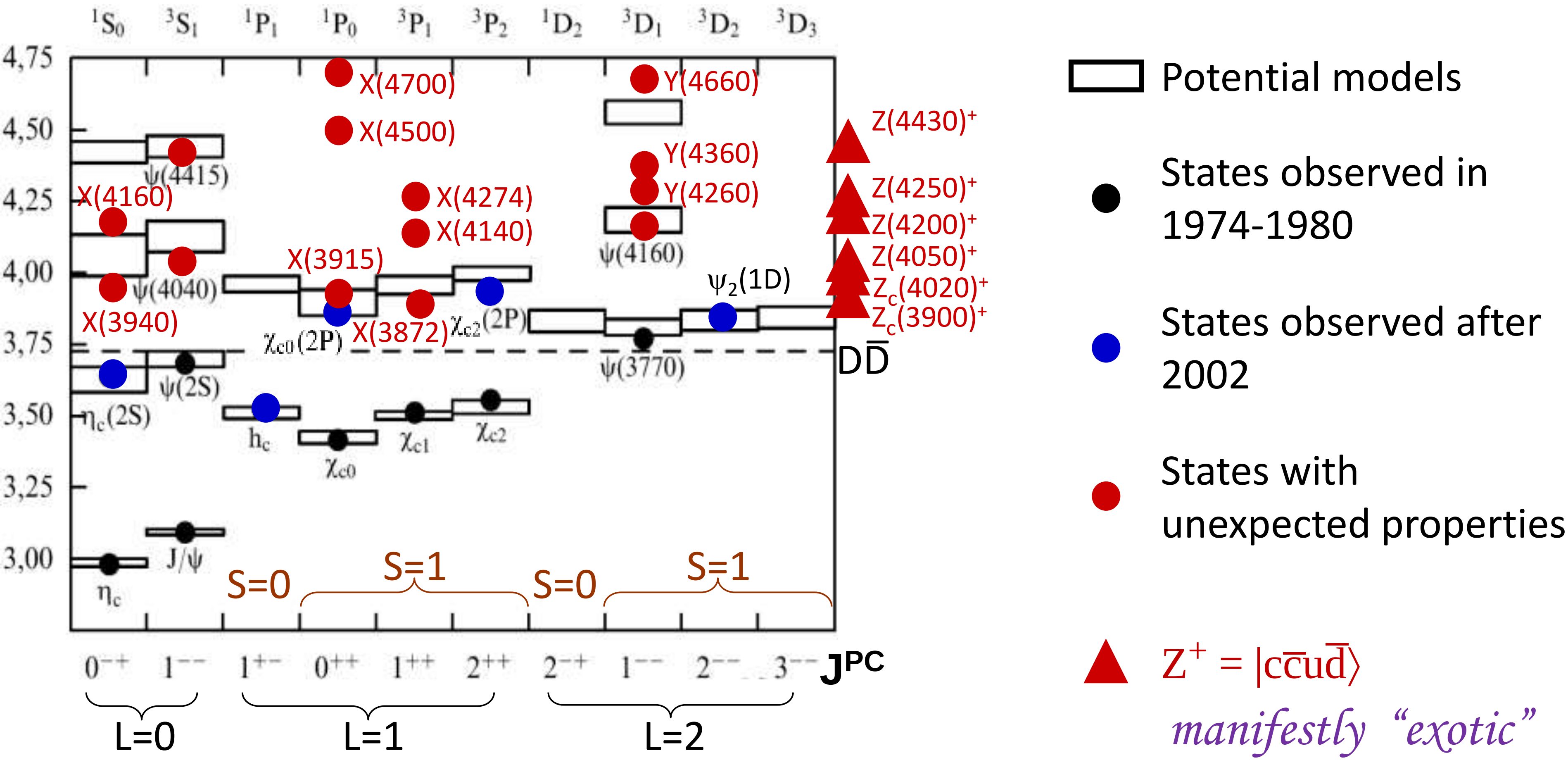
Charmonium table



States below DD̄ threshold are narrow (annihilation or → other charmonia)

States above DD̄ threshold are broad (→ DD̄, DD̄*, ...)

Charmonium table



States below DD̄ threshold are narrow (annihilation or → other charmonia)

States above DD̄ threshold are broad (→ DD̄, DD̄*, ...)

Multiquark states conceived already at the birth of the Quark Model

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

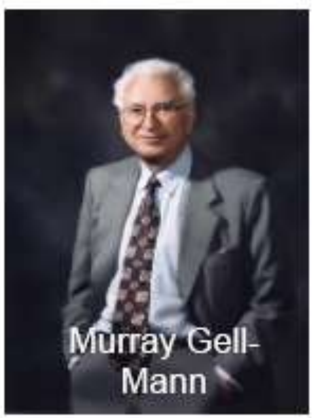
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

. . .

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while



8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

G. Zweig
CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

. . .

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

Conventional and "exotic" hadrons

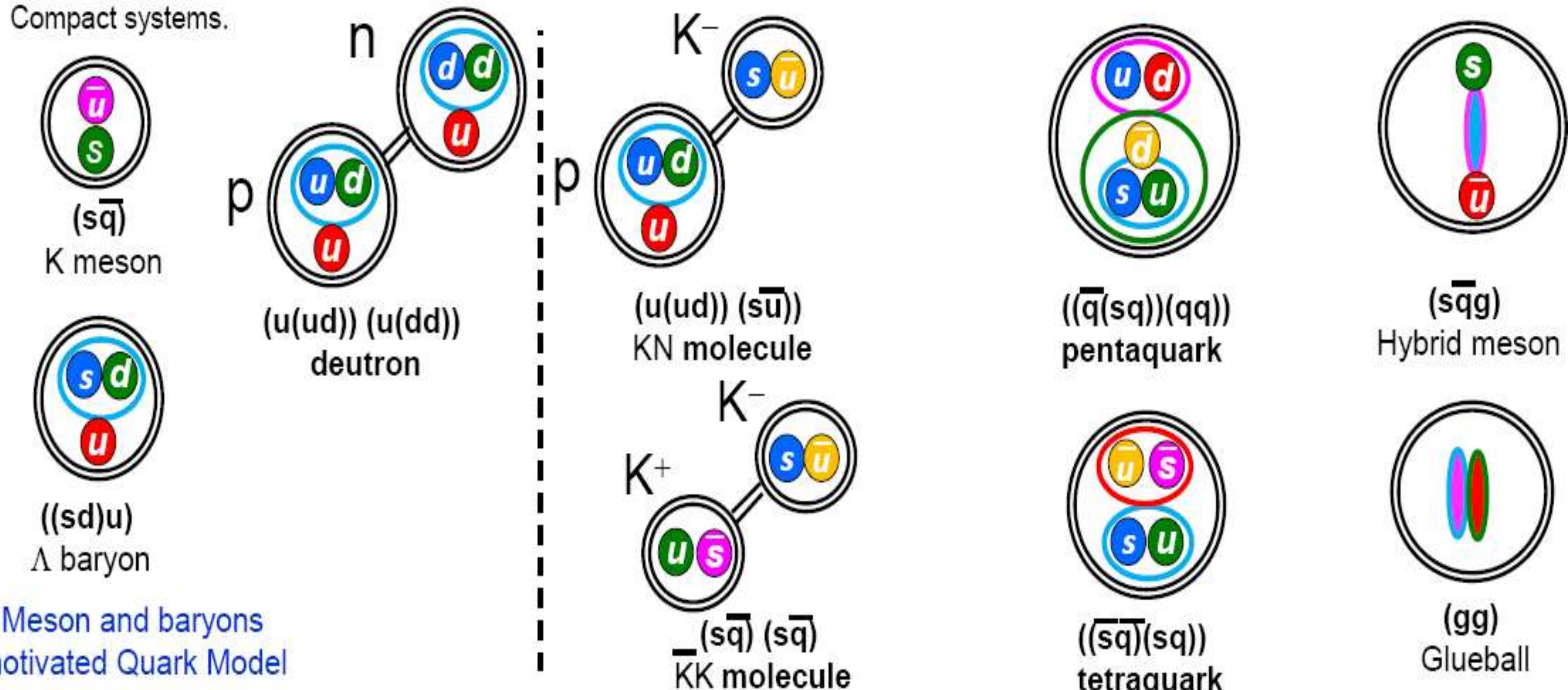
Conventional

Strong binding. Compact systems.

Weak binding. Large systems.

"Exotic"

Strong binding. Compact systems.



Meson and baryons motivated Quark Model and QCD

Baryonic molecules exist

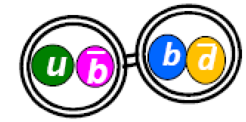
Are molecular forces in such systems strong enough to create bound states, or pronounced effects?

QCD predicts attractive forces in some of such configurations. Do they live long enough to produce observable states/effects ?

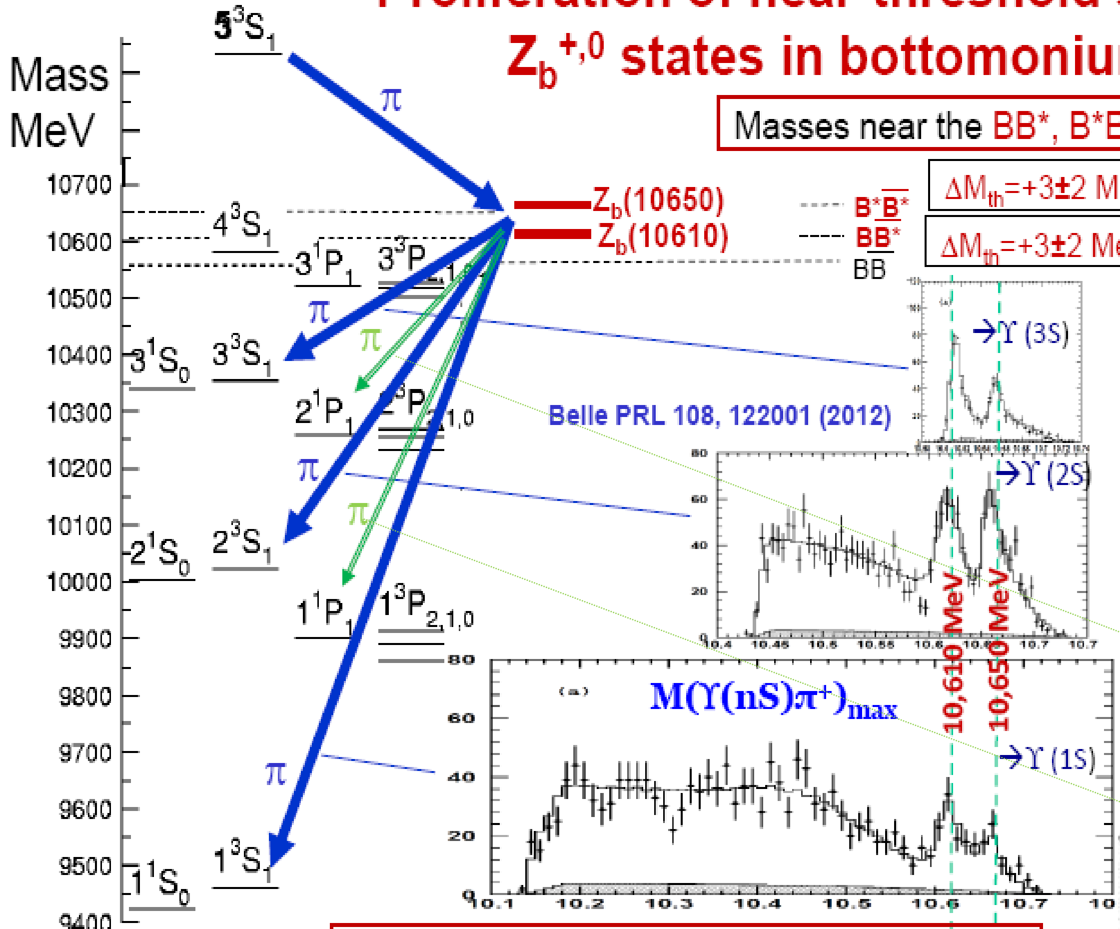
Firmly expected in QCD

Charged and neutral

$I^G = 1^+$



Proliferation of near-threshold states: $Z_b^{+,0}$ states in bottomonium



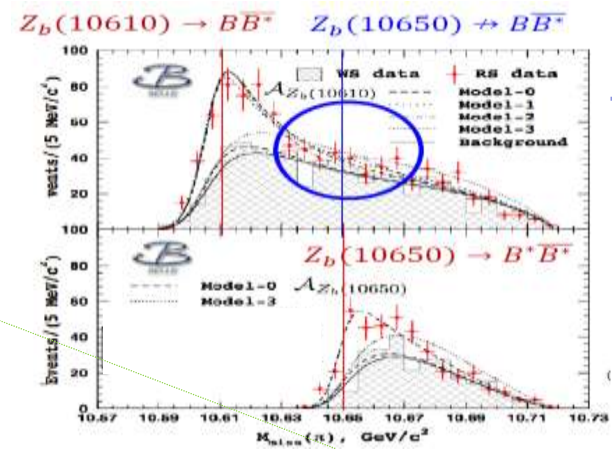
Masses near the BB*, B*B* thresholds ✓

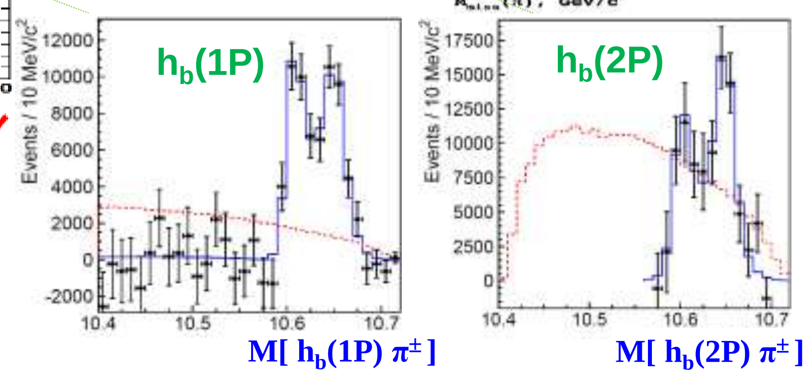
ΔM_{th}=+3±2 MeV

ΔM_{th}=+3±2 MeV

Γ 11.5 ± 2.2, 18.4 ± 2.4 MeV ✓

Both $J^{P(C)}=1^{+(-)}$ ✓





Large rate to fall-apart modes observed ✓

- Likely molecular states of $B\bar{B}^*$, $B^*\bar{B}^*$
- Tightly bound diquark tetraquarks

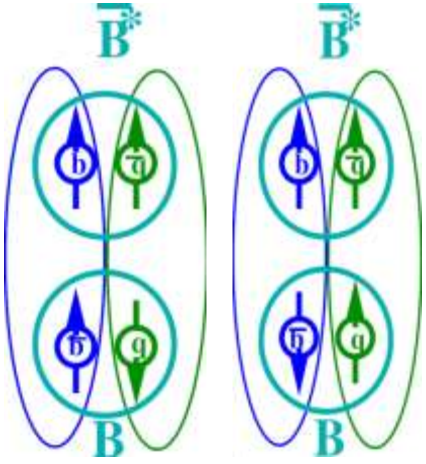
Heavy quark structure in Z_b

A.B.,A.Garmash,A.Milstein,R.Mizuk,M.Voloshin PRD84 054010 (arXiv:1105.4473)

Wave func. at large distance – B(*)B*

$$|Z_b'\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} - \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$

$$|Z_b\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} + \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$



Explains

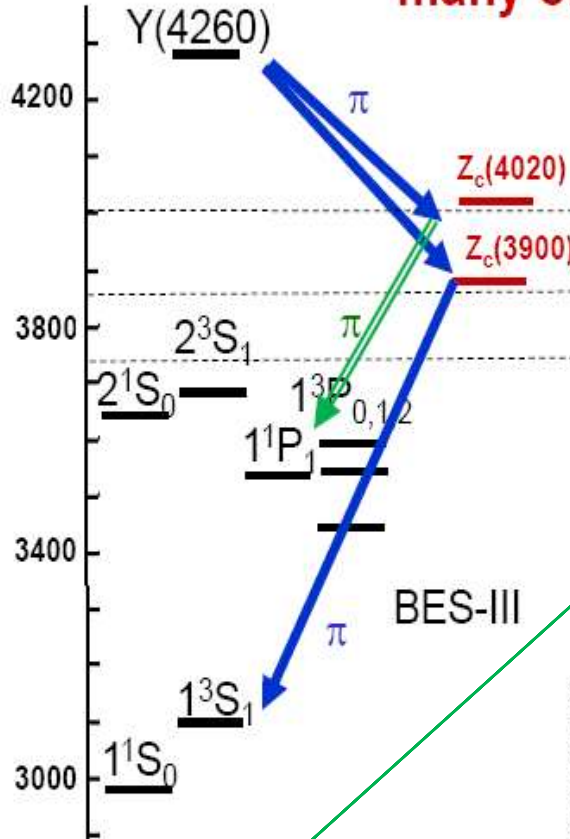
- Why $h_b\pi\pi$ is unsuppressed relative to $\Upsilon\pi\pi$
- Relative phase ~0 for Υ and ~180^0 for h_b
- Production rates of $Z_b(10610)$ and $Z_b(10650)$ are similar
- Dominant decays to B(*)B*
- Similar structures in $\Psi\pi$ and $h_c\pi$

Other Possible Explanations

- Coupled channel resonances (I.V.Danilkin et al, arXiv:1106.1552)
- Cusp (D.Bugg Europhys.Lett.96 (2011),arXiv:1105.5492)
- Tetraquark (M.Karliner, H.Lipkin, arXiv:0802.0649)

More near-threshold states: many of $Z_c^{+,0}$ charmonium states

- Expected from Z_b states and Heavy Quark Symmetry



Masses a few MeV above the $D\bar{D}^*$, $D^*\bar{D}^*$ thresholds ✓

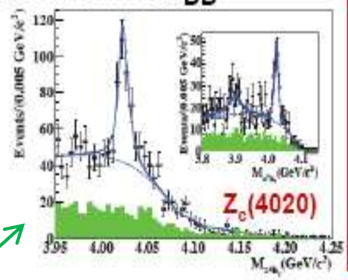
ΔM_{th}=+7±2 MeV

ΔM_{th}=+11±3 MeV

Γ	13 ± 5	MeV
	28.1 ± 2.6	

✓

$J^{P(C)}=1^{+(-)}$ (established only for $Z_c(3900)$) ✓

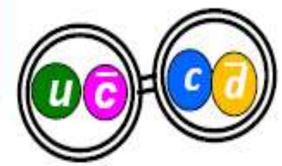


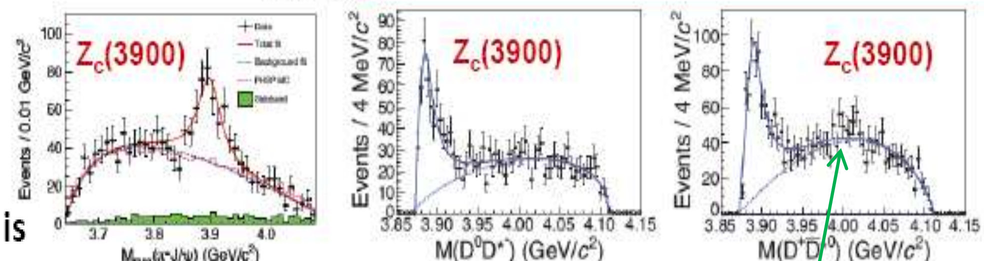
Large rate to fall-apart modes

$$\frac{\Gamma[Z_c(4025)\to D^*D^*]}{\Gamma[Z_c(4020)\to\pi h_c]} \sim 9.$$

$$\frac{\Gamma[Z_c(3900)\to DD^*]}{\Gamma[Z_c(3900)\to\pi J/\psi]} = 6.2 \pm 1.1_{\rm stat} \pm 2.7_{\rm sys}$$

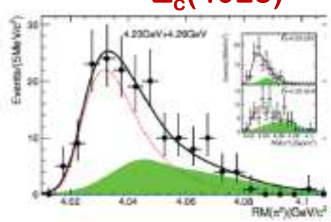
✓





Charged and neutral versions detected / $I^G=1^+$

$Z_c(4025)$



Large non $Z_c\pi$ component is observed in the $Y(4260)\to h_c\pi^+\pi^-$ amplitude.

(also seen by Belle)

Molecular states of $D\bar{D}^*$, $D^*\bar{D}^*$?

Diquark tetraquarks ?

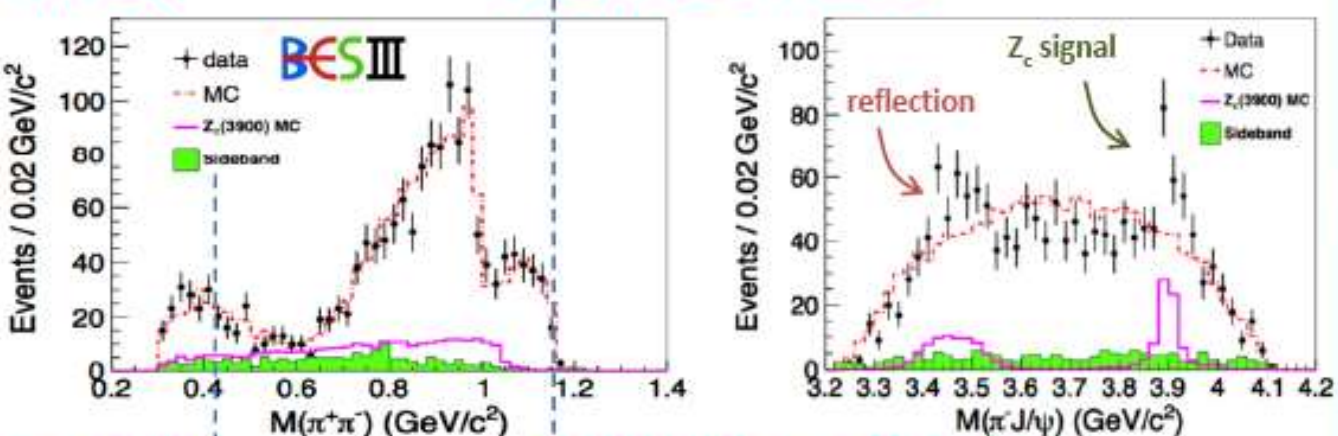
No sign of Zc(4025) decay in DD*

Charm vs Beauty: I

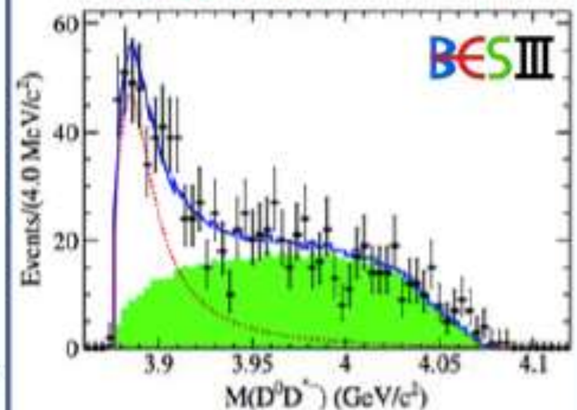
What is in common?

- $\Upsilon(10860)/Y(4260)$ demonstrates anomalously large coupling to $\Upsilon\pi^+\pi^-/\psi\pi^+\pi^-$ and $h_b\pi^+\pi^-/h_c\pi^+\pi^-$ final states. **$J^P = 1^+$ for both, PRL119 (2017), 072001**

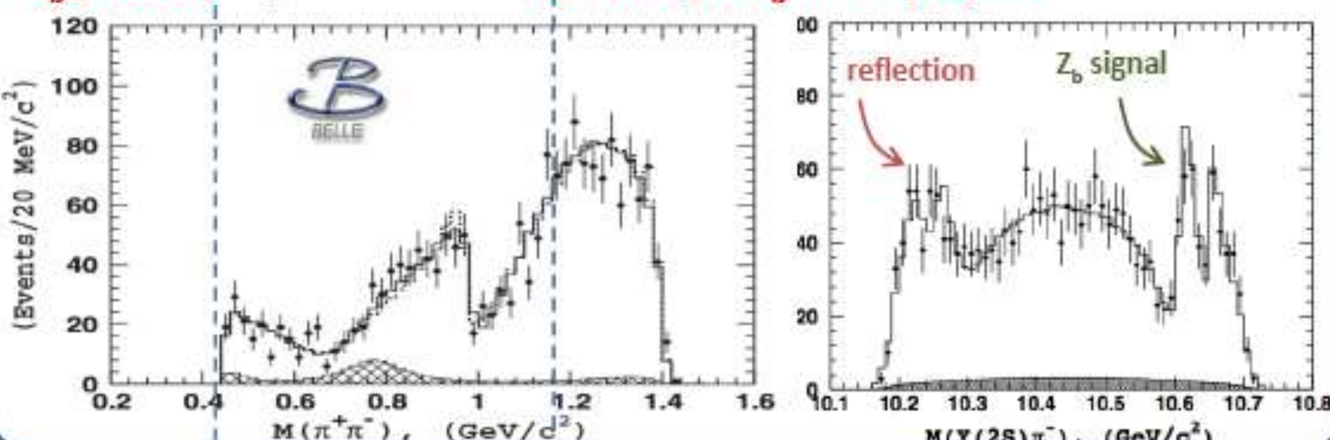
$Z_c(3900)$ is produced in $Y(4260)\to Z_c\pi\to \psi\pi^+\pi^-$



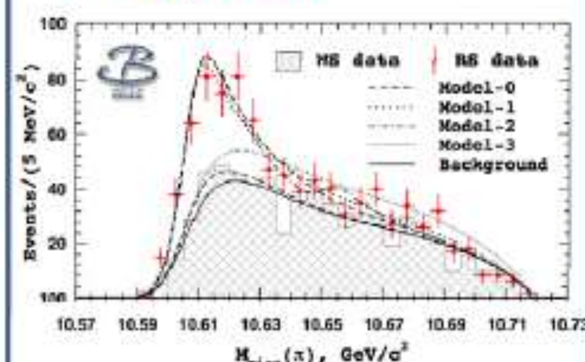
$\to Z_c\pi\to DD^*$



$Z_b(10610)$ is produced in $\Upsilon(10860)\to Z_b\pi\to \Upsilon(nS)\pi^+\pi^-$



$\to Z_b\pi\to BB^*$



Charm vs Beauty: II

What is different?

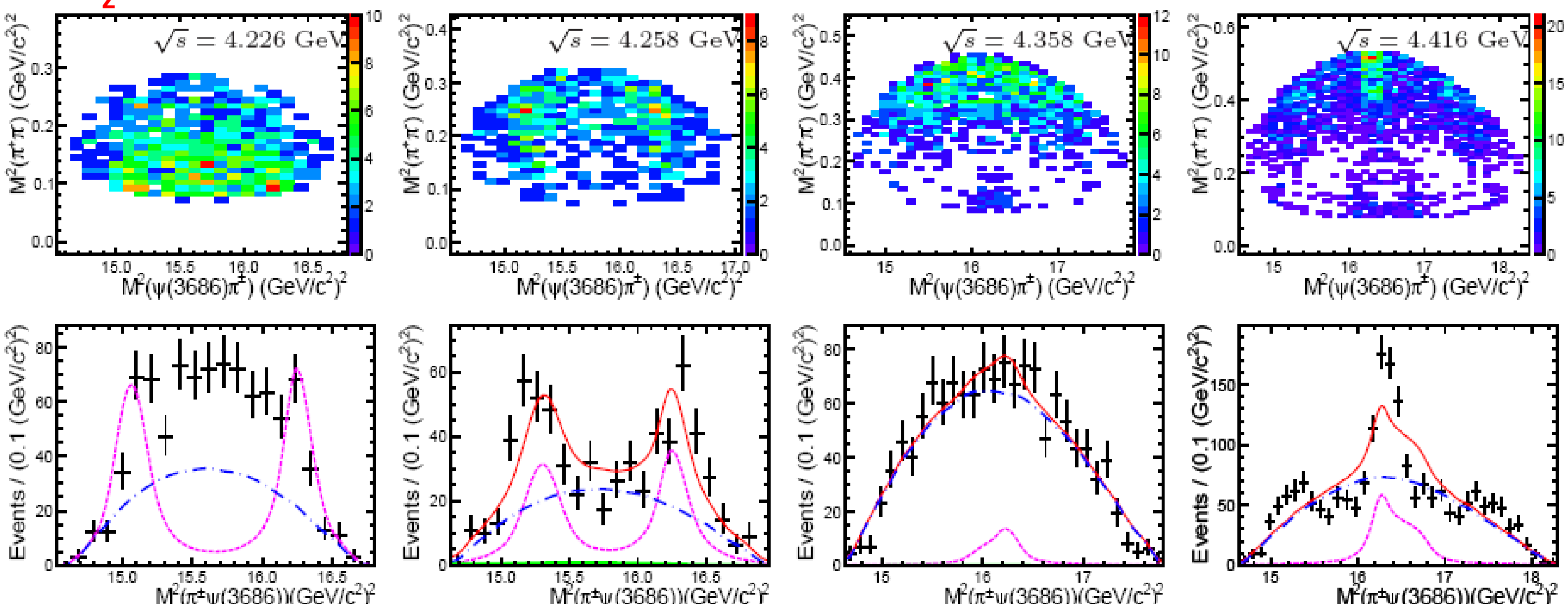
- Both $Z_b(10610)$ and $Z_b(10650)$ isotriplets are observed in the $\Upsilon(nS)\pi$, (n=1,2,3) and $h_b\pi$ final states.

- Only $Z_c(3900)$ is observed in the $J/\psi\pi$ while both $Z_c(3900)$ and $Z_c(4020)$ are observed in the $h_c\pi$ final state. None of them is observed in the $\psi(2S)\pi$ final state?

BESIII, PRD96 (2017),032004

$M_z = 4032.1 \pm 2.4$ MeV/c^2

$\Gamma_z = 26.1 \pm 5.3$ MeV

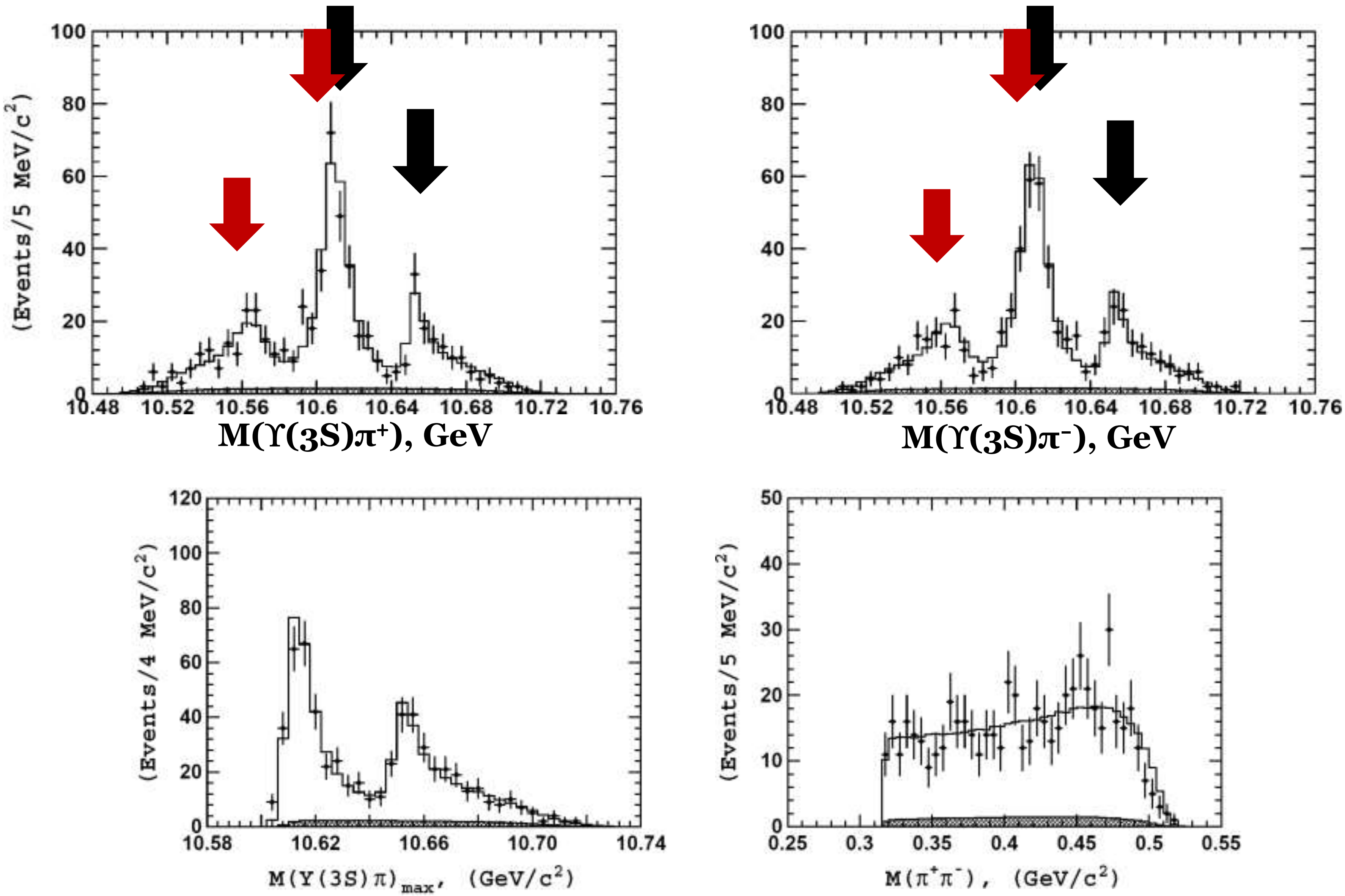


$Z_c(4020)$? $Z_c(4020)$?

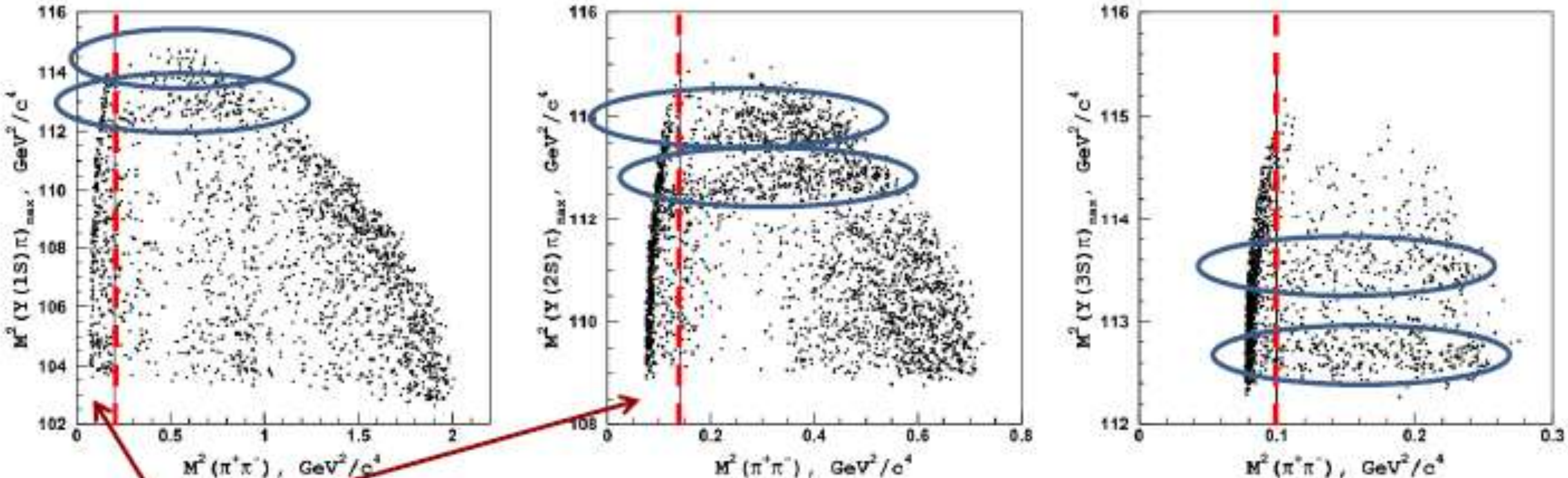
Mass, width not determined properly since did not allow for Z_c – NR bkg interference hinted by the Dalitz plot. This is likely $Z_c(4020) \to \psi(2S)\pi^+$ expected from $Z_b(10650) \to \Upsilon(2S)\pi^+$

AB

Results: $\Upsilon(3S)\pi^+\pi^-$



Amplitude Analysis of $\Upsilon(nS)\pi^+\pi^-$



Photon conversions

Flatte: $m = 950\ \mathrm{MeV}/c^2$; $g_{\pi\pi} = 0.23$; $g_{KK} = 0.73$
From the analysis of $B \to K\pi\pi$ by Belle

D-wave Breit-Wigner

$$S(s_1, s_2) = |A_{Z_{b1}} + A_{Z_{b2}} + A_{NR} + A_{f_0(980)} + A_{f_2(1275)}|^2$$

$$A_{Z_{bi}} = \frac{\sqrt{M_i\Gamma_i}}{M_i^2 - s_1 + iM_i\Gamma_i} + \frac{a_i e^{i\phi_i}\sqrt{M_i\Gamma_i}}{M_i^2 - s_2 + iM_i\Gamma_i}$$

$$s_i \equiv M^2_{\pi_i\Upsilon}$$

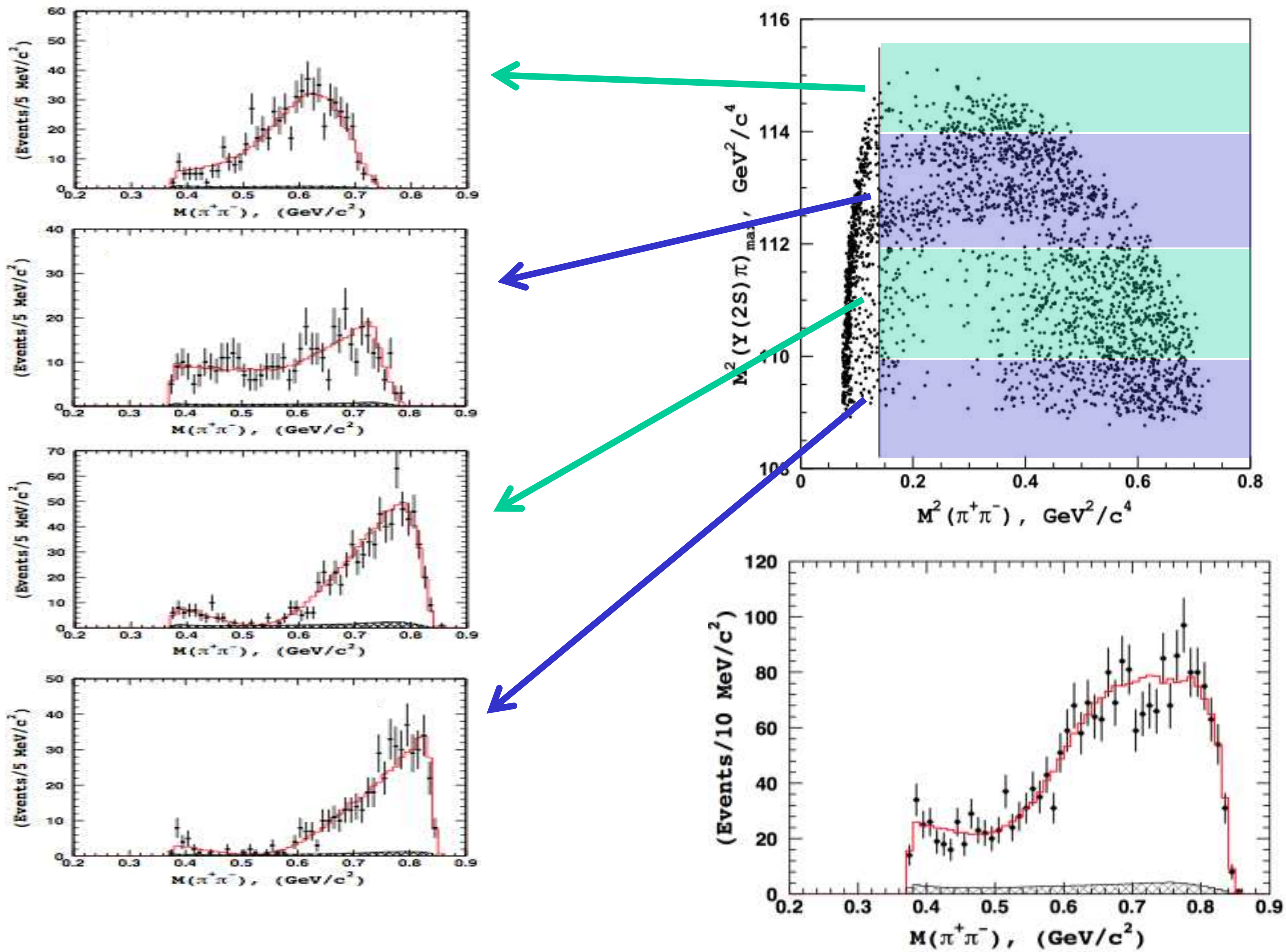
$$A_{NR} = c_1 + c_2 m^2_{\pi\pi}$$

M.B. Voloshin, Prog. Part. Nucl. Phys. 61:455, 2008.
M.B. Voloshin, Phys. Rev. D74:054022, 2006.

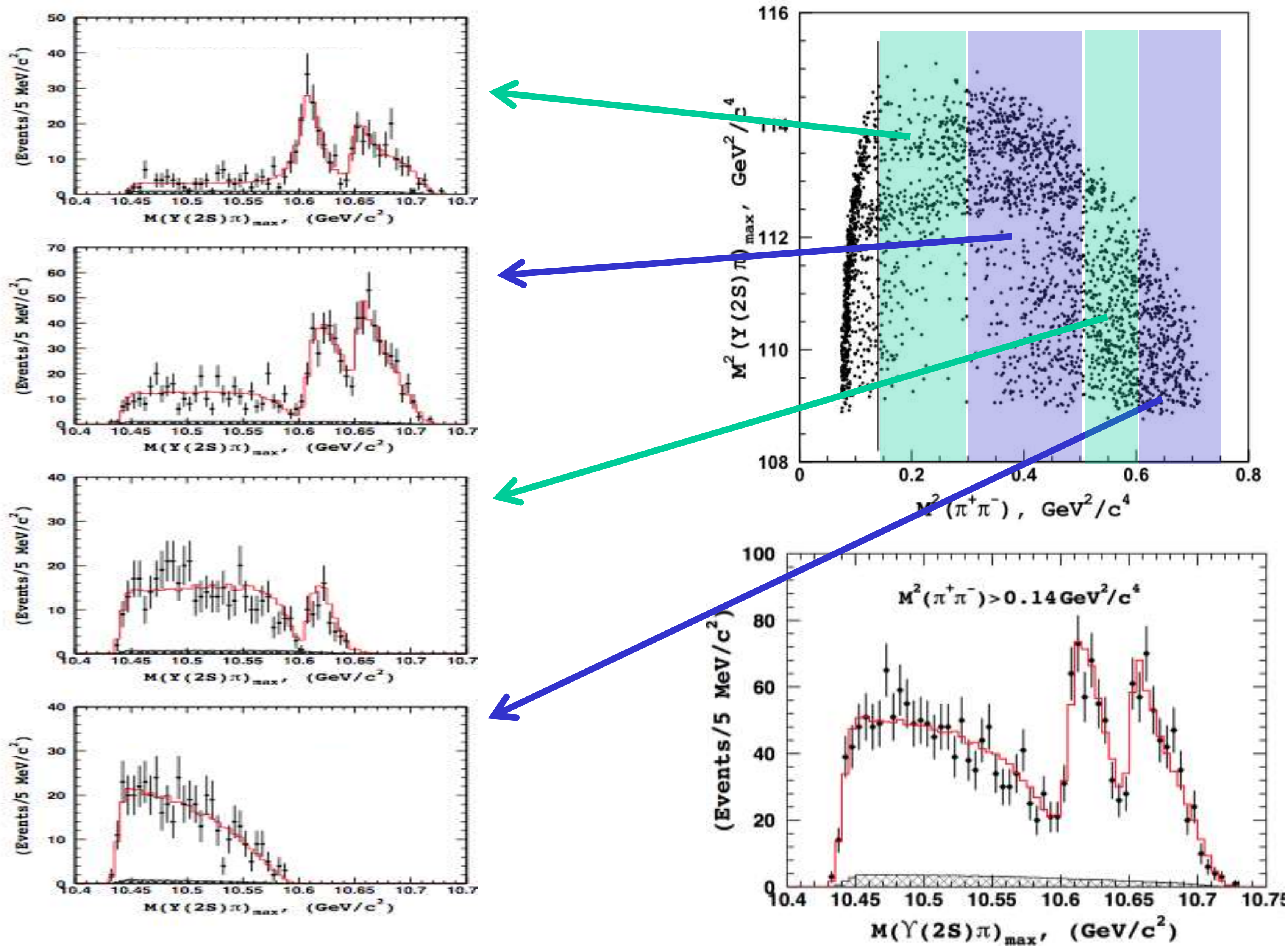
Combinatorial background is parameterized as a constant.

Unbinned ML fit to signal Dalitz plots

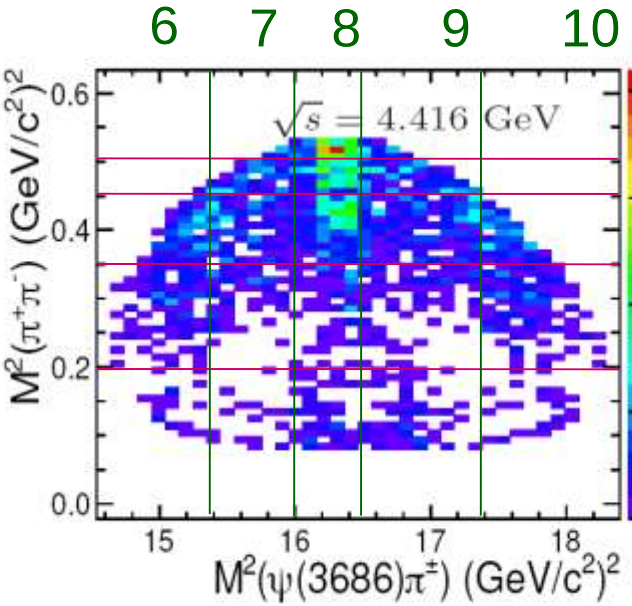
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ Results

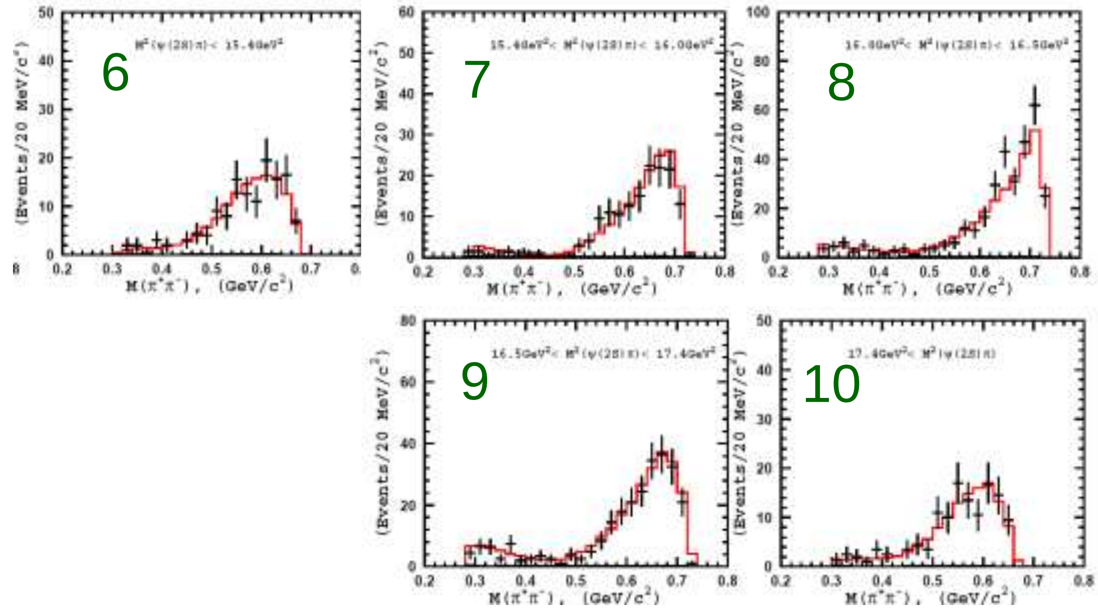


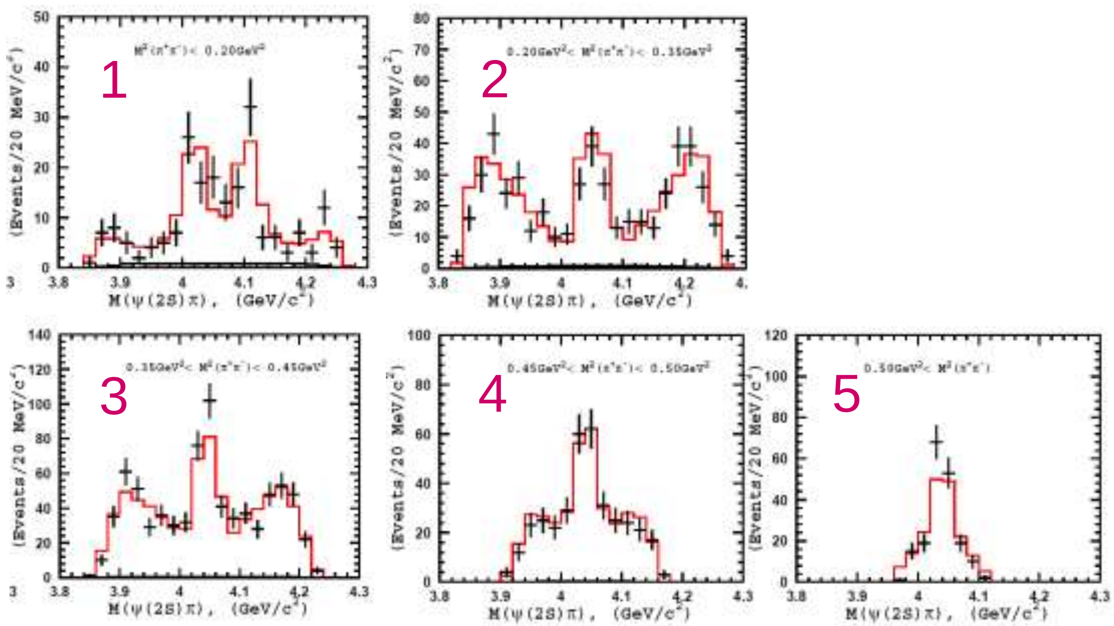
$\Upsilon(5S)\rightarrow\Upsilon(2S)\pi^+\pi^-$ Results



Toy Fit of BESIII data at 4.416 GeV







Toy Fit Results:

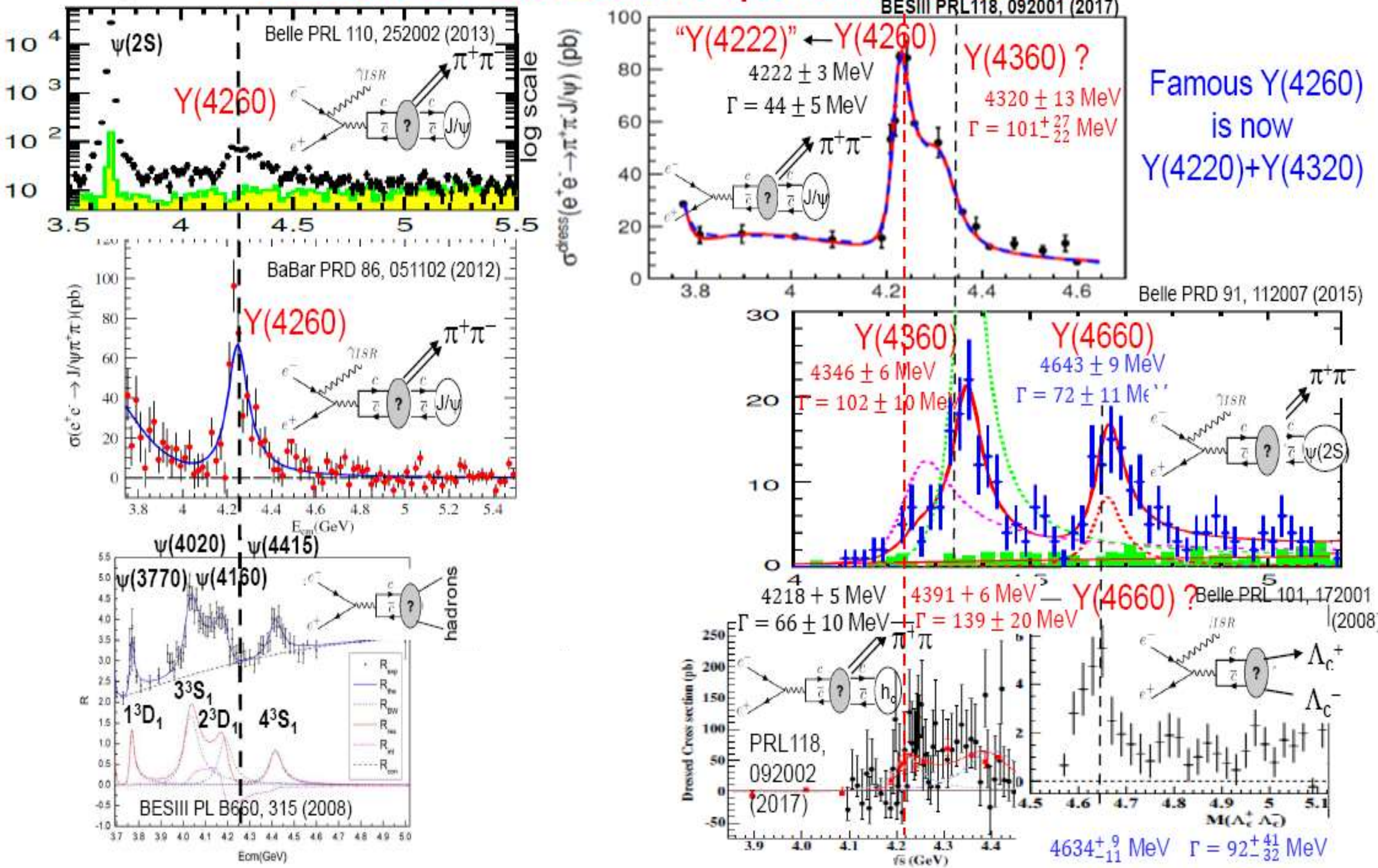
M_z = 4019 ± 1.9 MeV/c^2

Γ_z = 29 ± 4 MeV

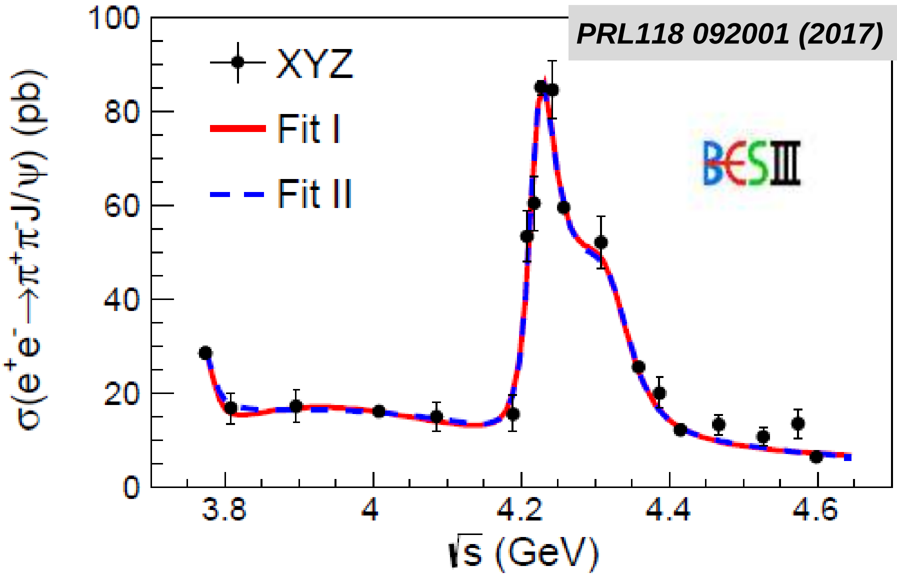
Fit Fraction 12 ± 3.7%

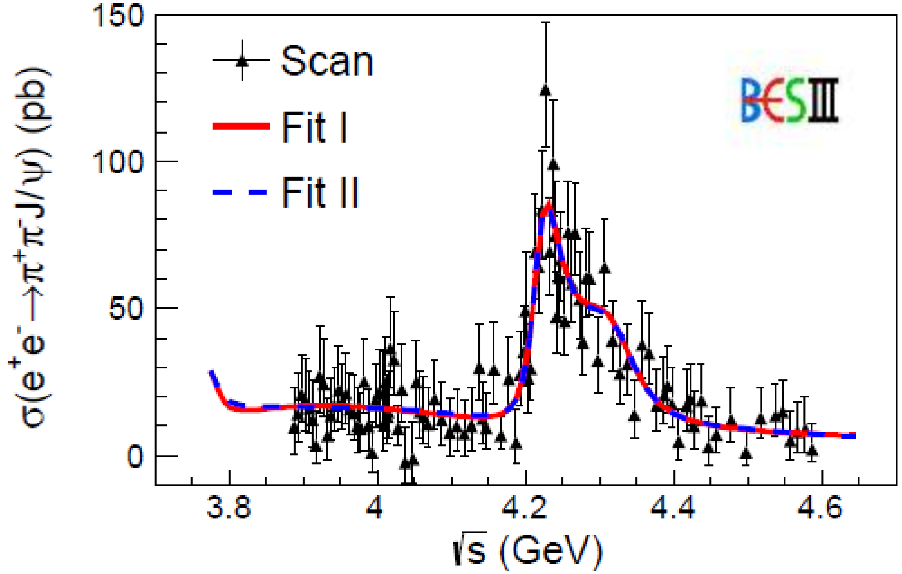
First observed by BaBar in 2005

Anomalous 1⁻⁻ states above open charm threshold



New precise measurements of $e^+e^- \to \pi^+\pi^- J/\psi$



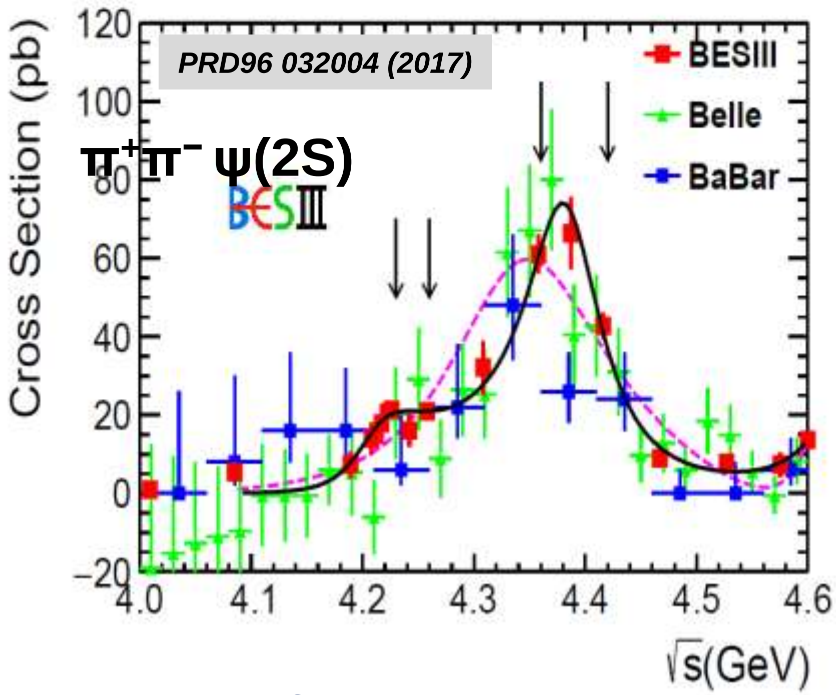


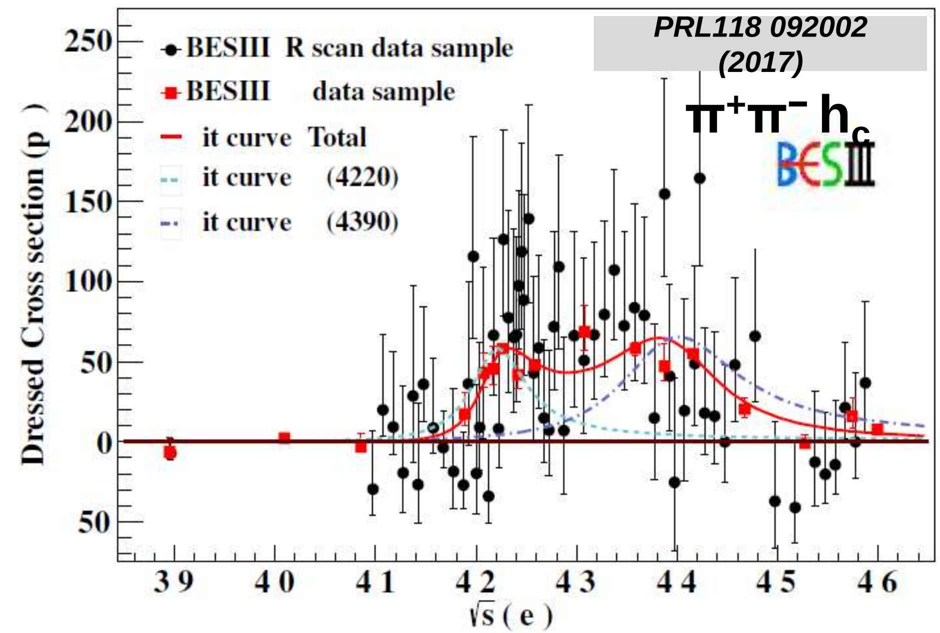
$e^+e^- \to \pi^+\pi^- J/\psi$ cross section is inconsistent with a single pick of Y(4260)

Two peaks are favored over one peak by 7.6 σ

	M, GeV/c^2	Γ, MeV	Decay mode
X(4260), PDG	**4230±8**	**55±19**	**$\pi^+\pi^- J/\psi$**
Y(4220), BESIII	**4222.0±3.1±1.4**	**44.1±4.3±2.0**	**$\pi^+\pi^- J/\psi$**
X(4360), PDG	**4341±8**	**102±9**	**$\pi^+\pi^- \psi(2S)$**
Y(4360), BESIII	**4320.0±10.4±7.0**	**$101.4^{+25.3}_{-19.7}$±10.2**	**$\pi^+\pi^- J/\psi$**

New precise measurements of $e^+e^- \to \pi^+\pi^- \psi(2S)$, $\pi^+\pi^- h_c$

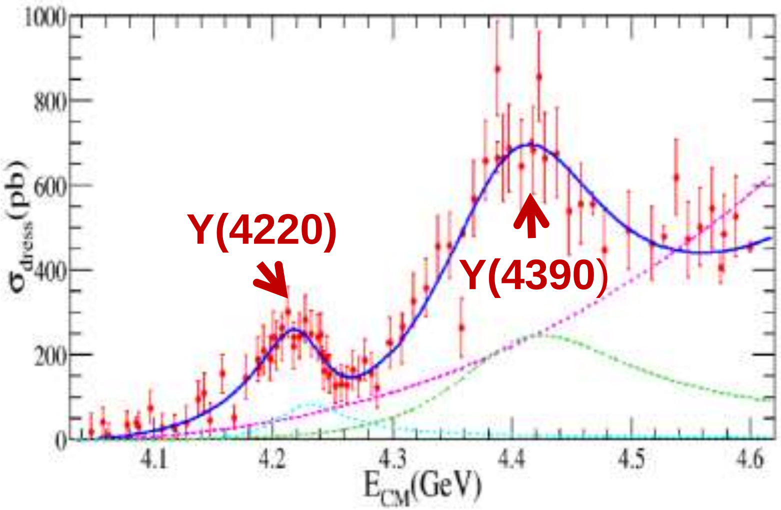




BESIII confirms line shape in $e^+e^- \to \pi^+\pi^- \psi(2S)$

	M, GeV/c2	Γ, MeV	Decay mode
Y(4220)	4209.5±7.4±1.4	80.1±24.6±2.9	$\pi^+\pi^- \psi(2S)$
Y(4220)	$4218.4^{+5.5}_{-4.5}\pm0.9$	$66.0^{+12.3}_{-8.3}\pm0.4$	$\pi^+\pi^- h_c$
Y(4390)	4383.8±4.2±0.8	84.2±12.5±2.1	$\pi^+\pi^- \psi(2S)$
Y(4390)	$4391.5^{+6.3}_{-6.8}\pm0.9$	$139.5^{+16.2}_{-20.6}\pm0.6$	$\pi^+\pi^- h_c$
X(4360), PDG	4341±8	102±9	$\pi^+\pi^- \psi(2S)$

BESIII: $e^+e^- \to D^0D^{*-}\pi^+$



Parameters	SolutionI	SolutionII	SolutionIII	SolutionIV
c (10^{-4})	5.5±0.6			
M_1 (MeV/c^2)	Y(4220) 4224.8±5.6			
Γ_1 (MeV)	72.3±9.1			
M_2 (MeV/c^2)	Y(4390) 4400.1±9.3			
Γ_2 (MeV)	181.7±16.9			
Γ_1^{el} (eV)	62.9±11.5	7.2±1.8	81.6±15.9	9.3±2.7
Γ_2^{el} (eV)	88.5±15.8	55.3±8.7	551.9±85.3	344.9±70.6
ϕ_1	-2.1±0.1	2.8±0.3	-0.9±0.1	-2.3±0.2
ϕ_2	1.9±0.3	2.3±0.2	2.3±0.1	-1.9±0.1

BESIII Preliminary

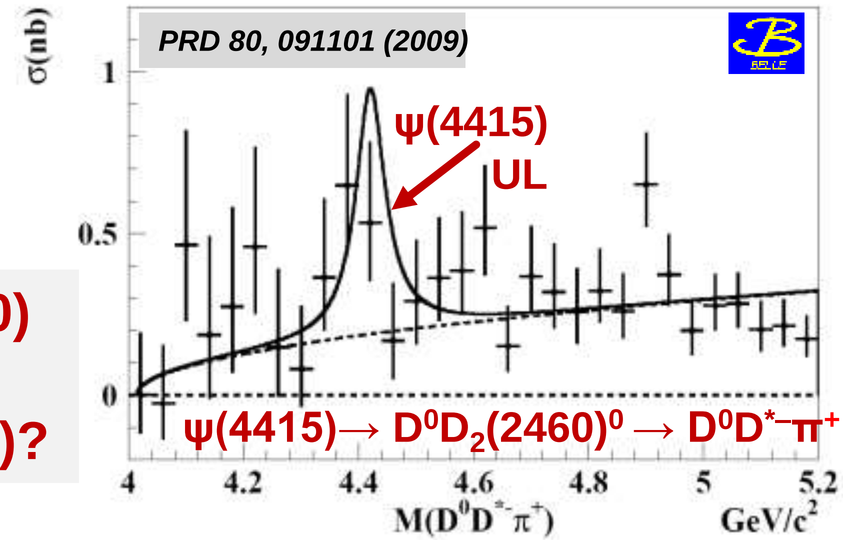
Y(4390) or ψ(4415)?

$\psi(4415) \to D^0D_2(2460)^0 \to D^0D^-\pi^+$

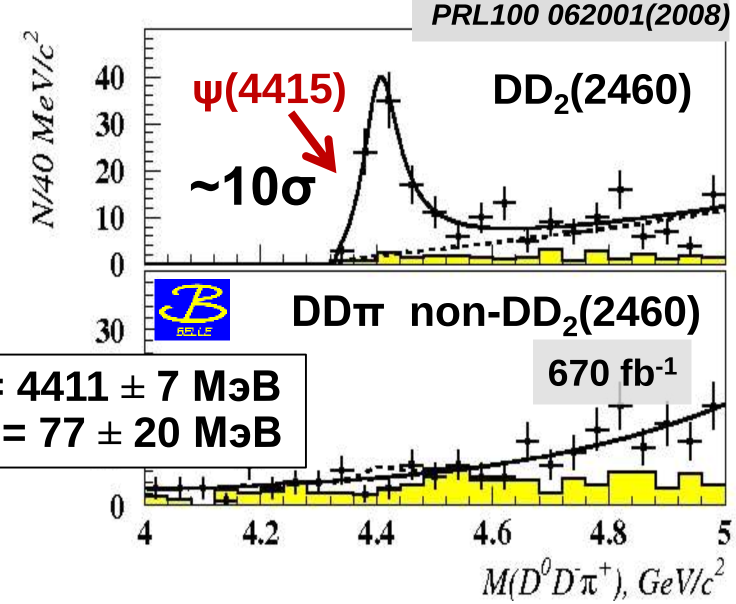
$\psi(4415) \to D^0D_2(2460)^0 \to D^0D^{*-}\pi^+$

UL due to limited statistics

Belle: $e^+e^- \to D^0D^{*-}\pi^+$



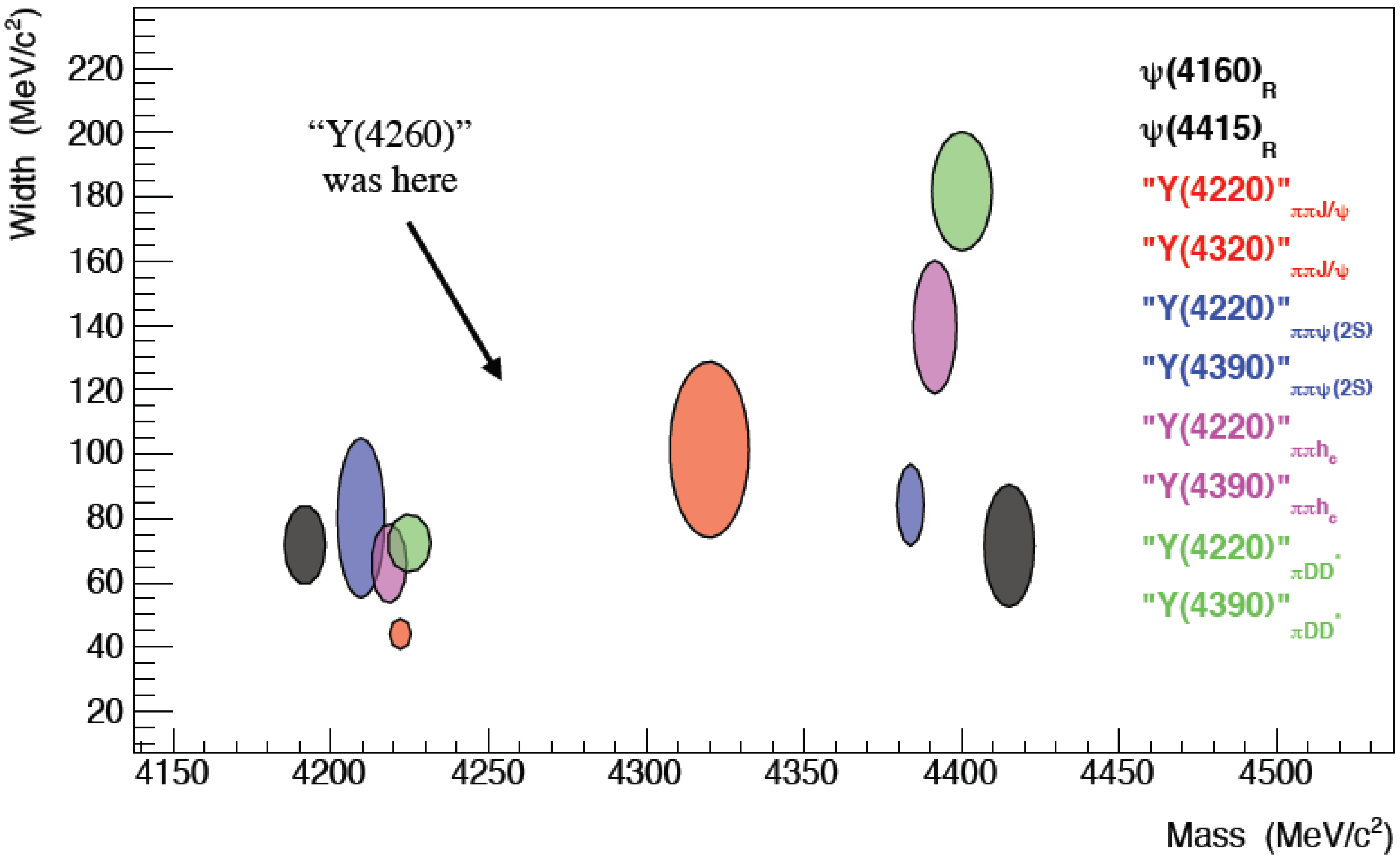
Belle: $e^+e^- \to D^0D^-\pi^+$



$M = 4411 \pm 7$ МэВ

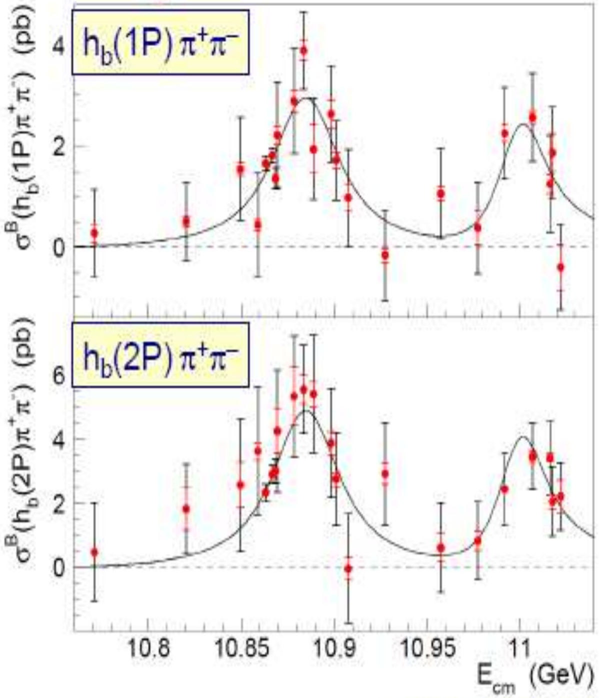
$\Gamma_{tot} = 77 \pm 20$ МэВ

Parameters of the Peaks in e^+e^- Cross Sections

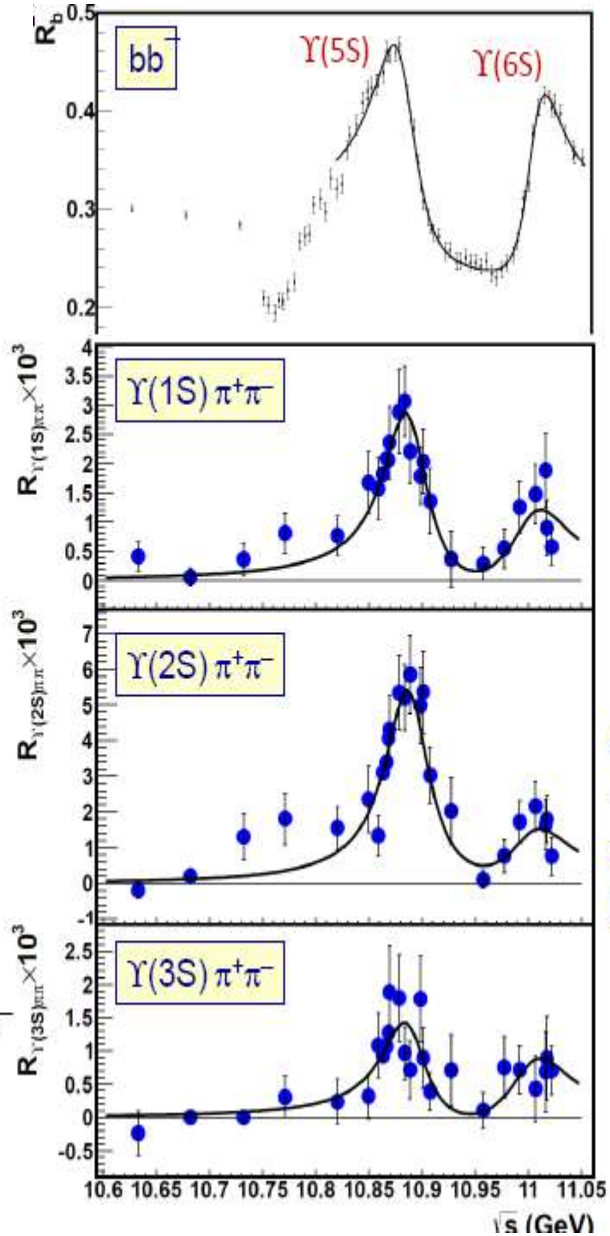


Ryan Mitchell (Indiana University), *Spectroscopy at the BESIII Experiment*, February 9, 2018

Anomalous behavior of 1^{--} states above open bottom threshold



PRL117,142001(2016)
PRD93,011101(2016)



However, $\Upsilon(5S)$, $\Upsilon(6S)$ $\rightarrow \Upsilon(1S,2S,3S)\,\pi^+\pi^-$ widths are 100 larger than $\Upsilon(3S)$, $\Upsilon(2S) \rightarrow \Upsilon(1S)\,\pi^+\pi^-$

OZI-rule violation

Also widths for $\Upsilon(5S)$, $\Upsilon(6S)$ $\rightarrow h_b(1P)$, $h_b(2P)\,\pi^+\pi^-$ are comparable, but require heavy quark spin flip

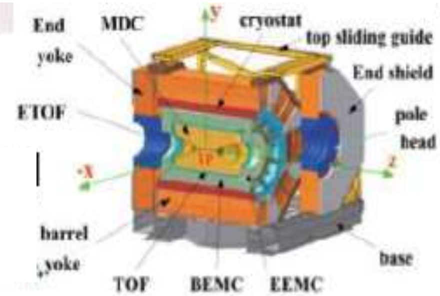
HQSS violation

Like in charmonium!

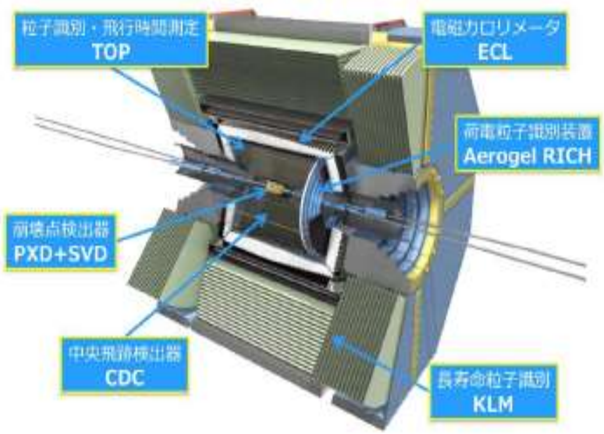
$e^+e^- \rightarrow \Upsilon(1S,2S,3S)\,\pi^+\pi^-$ and $h_b(1P,2P)\,\pi^+\pi^-$ proceed via $\Upsilon(5S)$, $\Upsilon(6S)$

Unlike in charmonium!

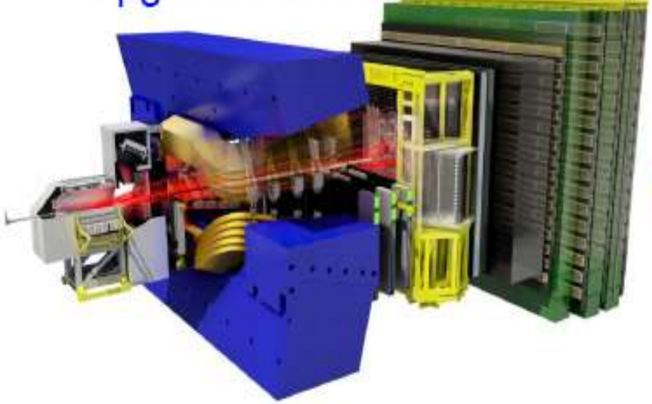
- Need more data to settle the phenomenological disputes
- More data are forthcoming!

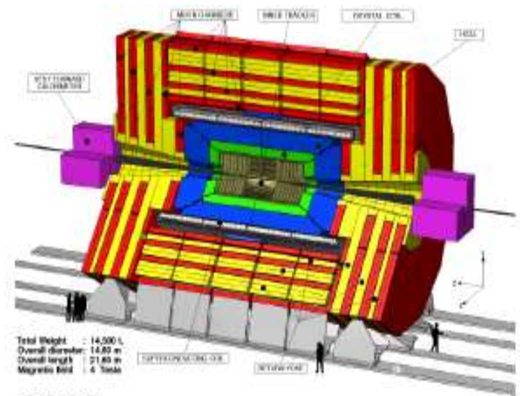


Belle II 測定器

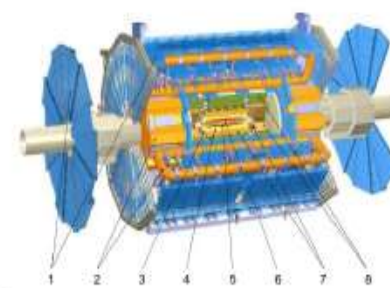


Upgraded LHCb

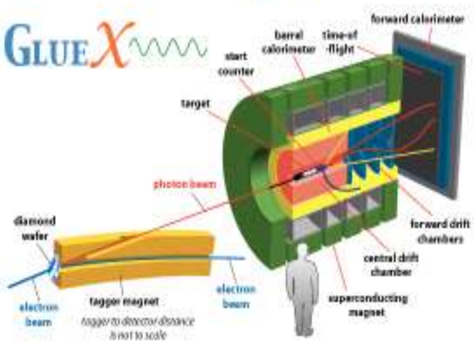


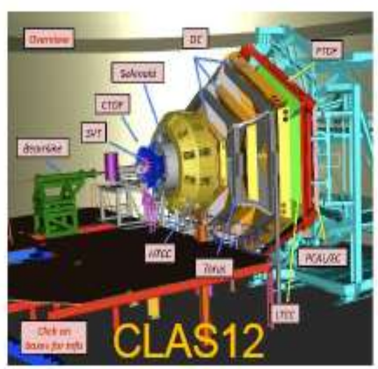


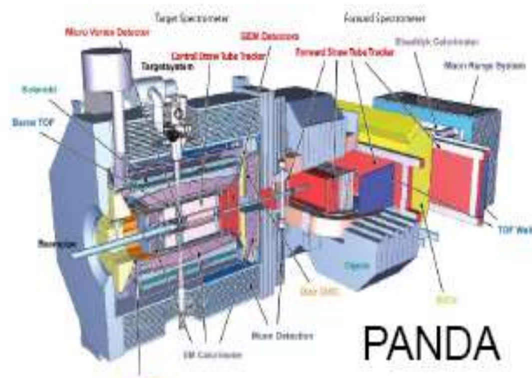
CMS



ATLAS







PANDA

and other…

Back up slides

Quarkonium Basics

c, b -quarks are heavy:

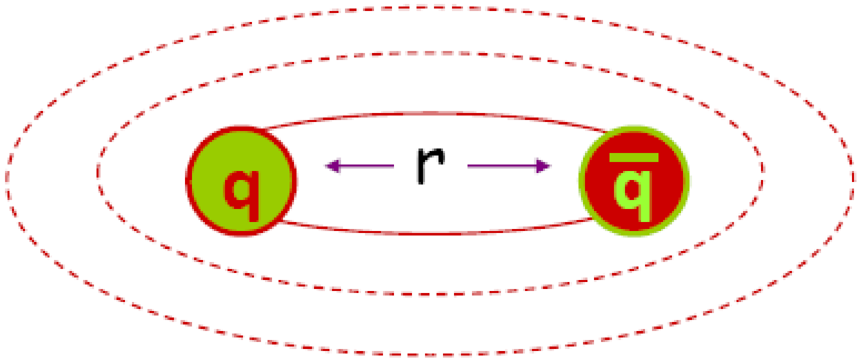
$m_c \sim 1.5$ GeV ~1.6 m_p ;

$m_b \sim 4.5$ GeV ~4.8 m_p ;

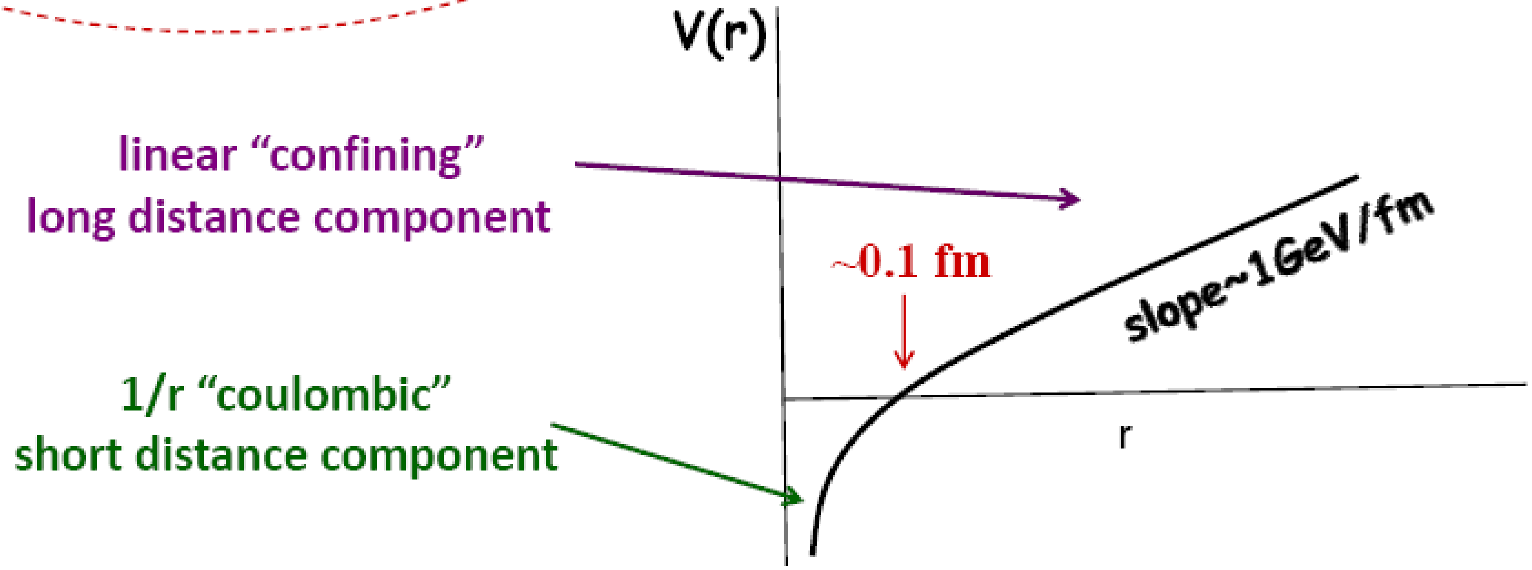
velocities are small:

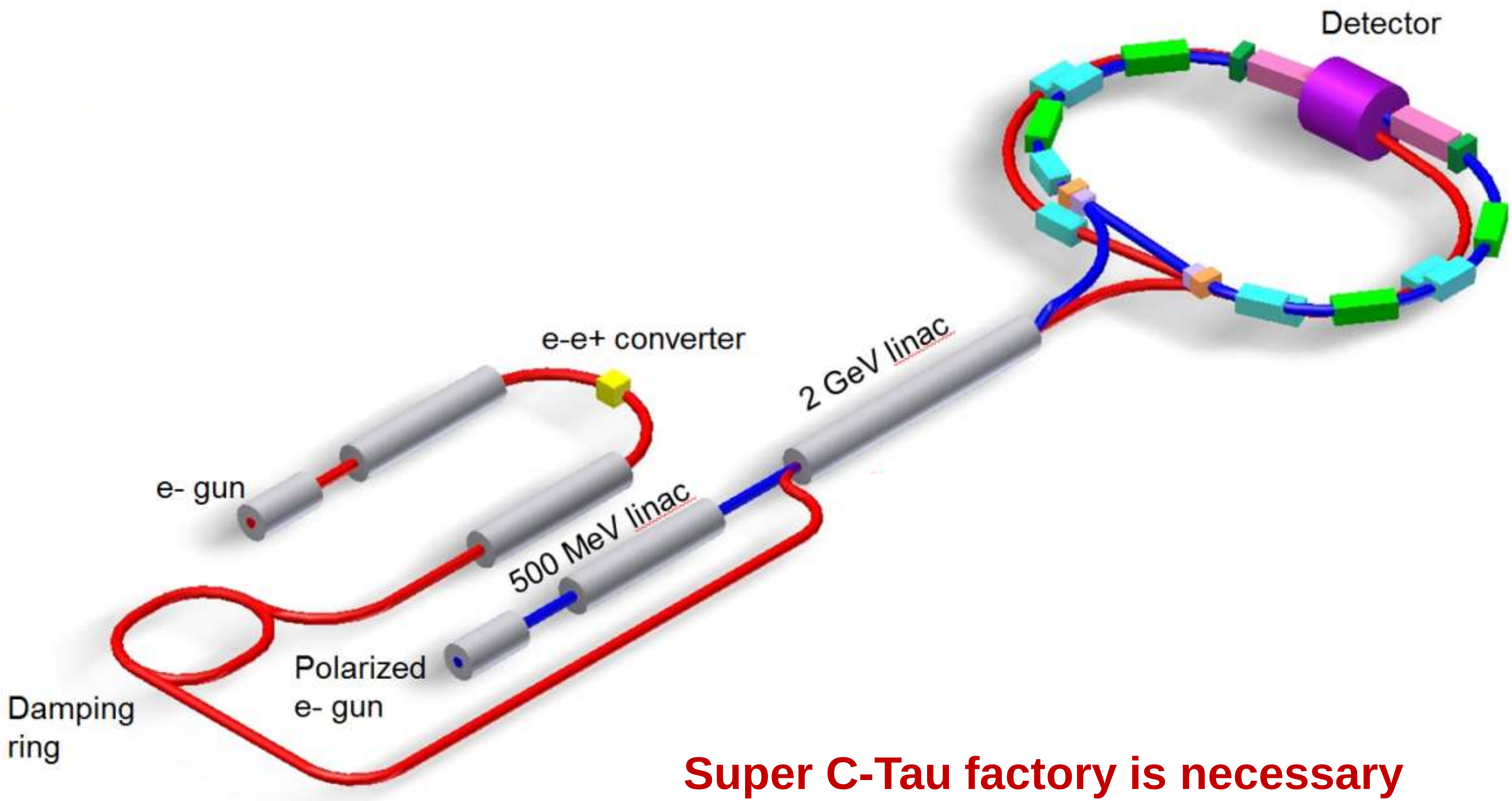
v/c~1/4 (for $b\bar{b}$, v/c~0.1)

non-relativistic QM applies



$$-\frac{\hbar^2}{2m_r}\nabla^2\Psi + V(r)\Psi = E\Psi$$



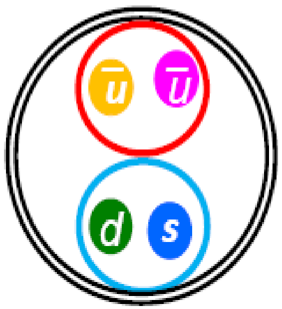


Super C-Tau factory is necessary instrument for future studies of the highly excited quarkonium

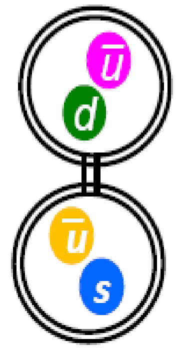
Tetraquarks vs meson-meson molecules

- The same quark content can, in principle, create a meson-meson molecule or a tetraquark
- However, mass spectrum from these two types of bindings are very different

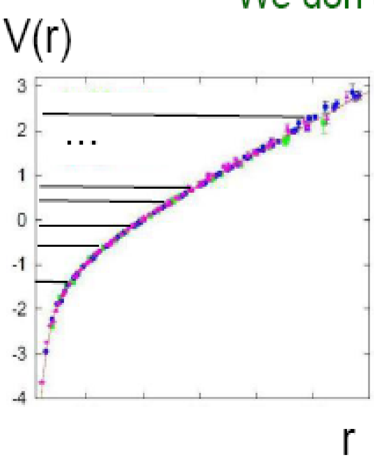
($(\bar{q}\bar{q})(qq)$)
tetraquark



$(q\bar{q})$-$(q\bar{q})$
meson-meson molecule

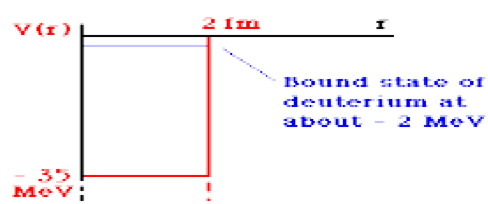


We don’t know if either one exist (“exotic hadron”)



Very rich mass spectrum expected!

However, states can be undetectable if extremely broad.



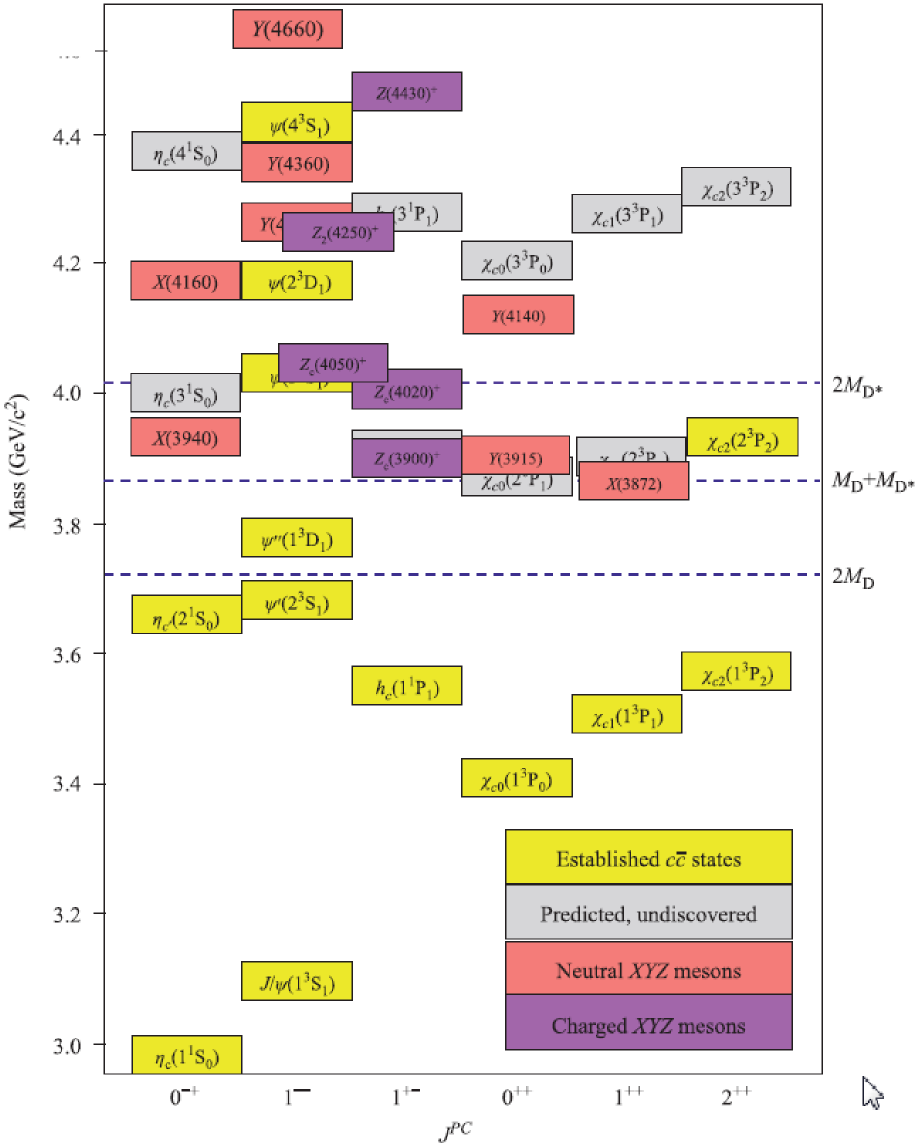
Typically expect only **one state** *n=1, L=0.*

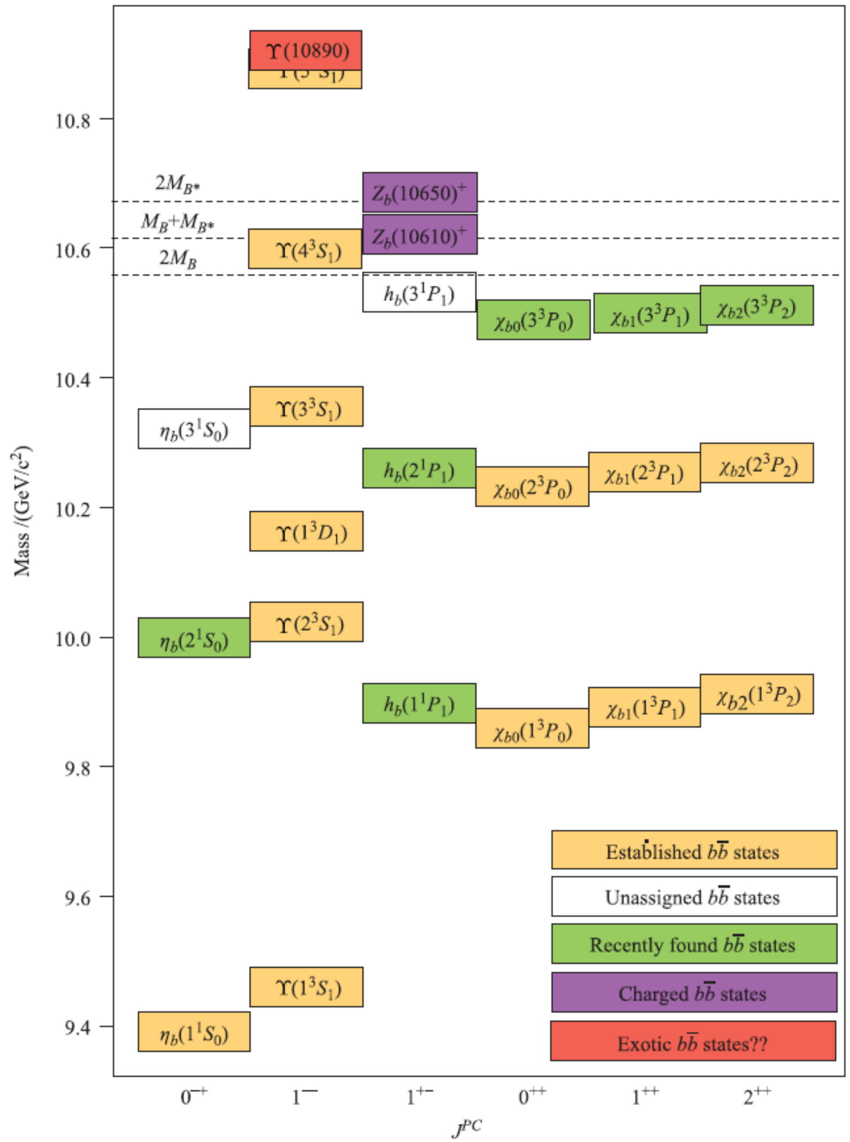
Fall apart prevented by spatial separation – long-lived states if below threshold.

Mass and J^P fairly constrained from the constituents.

Very reach experimental field

From S. Olsen, arXiv:1411.7738





Beginning of the XYZ saga

The X(3872) & other charmonium puzzles

Stephen Lars Olsen — Institute for Basic Science Daejeon, KOREA

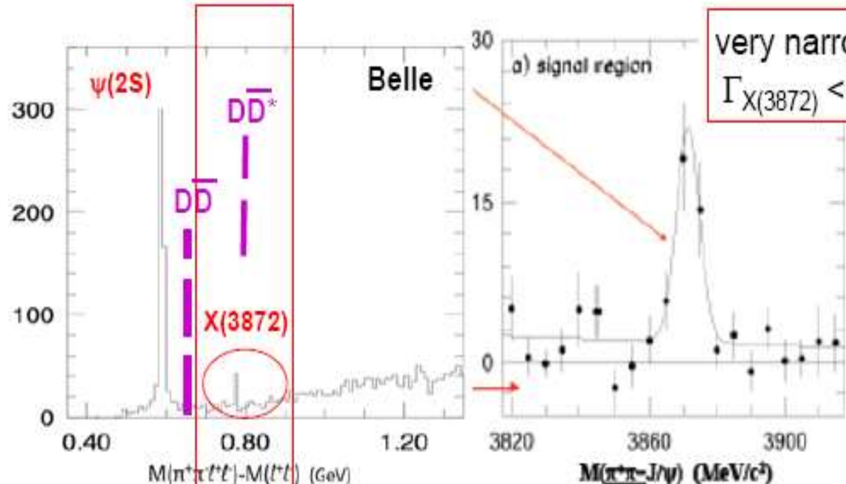
Workshop on Exotic Hadrons at 6th International Conference on New Frontiers in Physics, Kolymbari, Greece, Aug. 21-23, 2017

Phys.Rev.Lett. 91 (2003) 262001

The most cited Belle paper (1470 citations)

Observation of a narrow charmonium-like state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays

S.-K. Choi,[5] S. L. Olsen,[6] K. Abe,[7] T. Abe,[7] I. Adachi,[7] Byoung Sup Ahn,[14] H. Aihara,[43] K. Akai,[7] M. Akatsu,[20] M. Akemoto,[7] Y. Asano,[48] T. Aso,[47] V. Aulchenko,[1] …



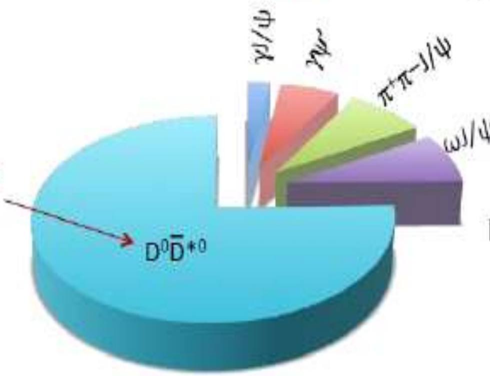
very narrow $\Gamma_{X(3872)} < 1.2$ MeV

Molecule?

Molecule?

$J^{PC}=1^{++}$

strong $D\bar{D}^*$ coupling



Preference for $\gamma\psi'$ over $\gamma J/\psi$ points to 2^3P_1 component

χ_{c1}' ?

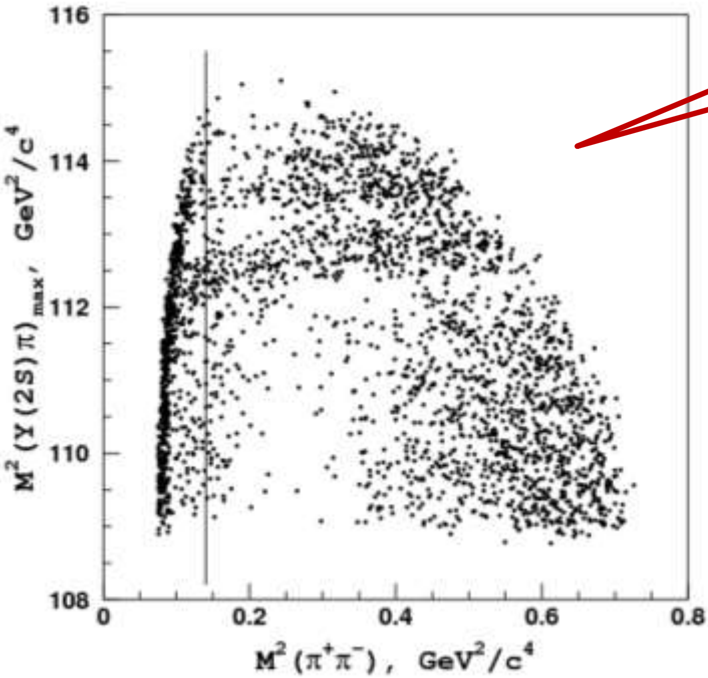
Large isospin violation in these decays, due to $m(D^0)-m(D^-)$?

Molecule?

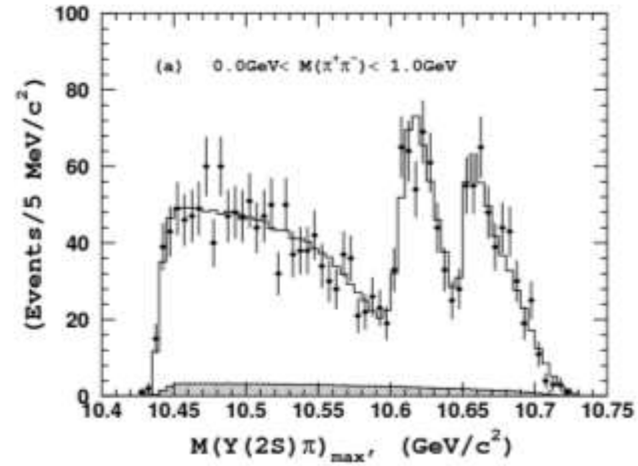
Huge fall-apart mode from the resonance tail above the $D^0\overline{D^{*0}}$ threshold

Molecule?

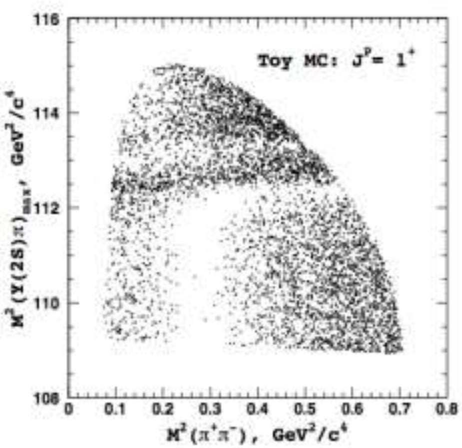
$\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-$: J^P Results



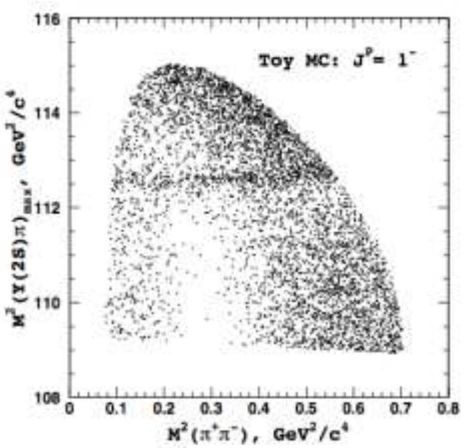
$\Upsilon(2S)\pi^+\pi$ Data



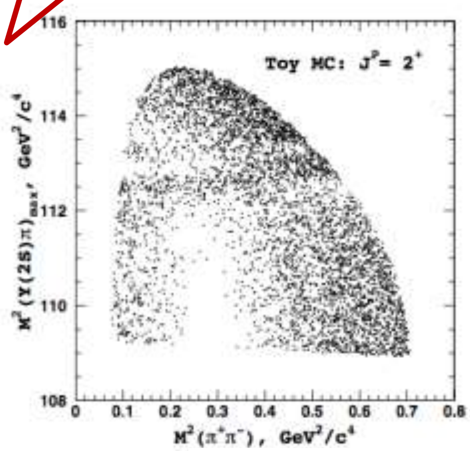
Toy MC with various J^P



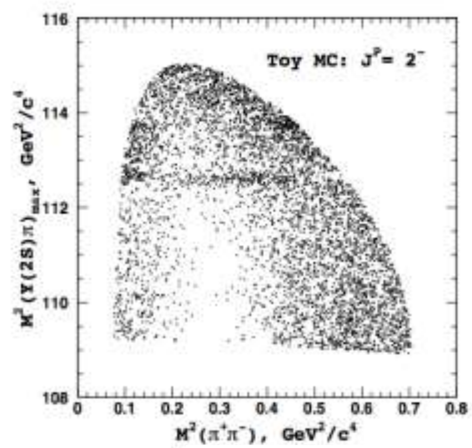
$J^P = 1^+$



$J^P = 1^-$

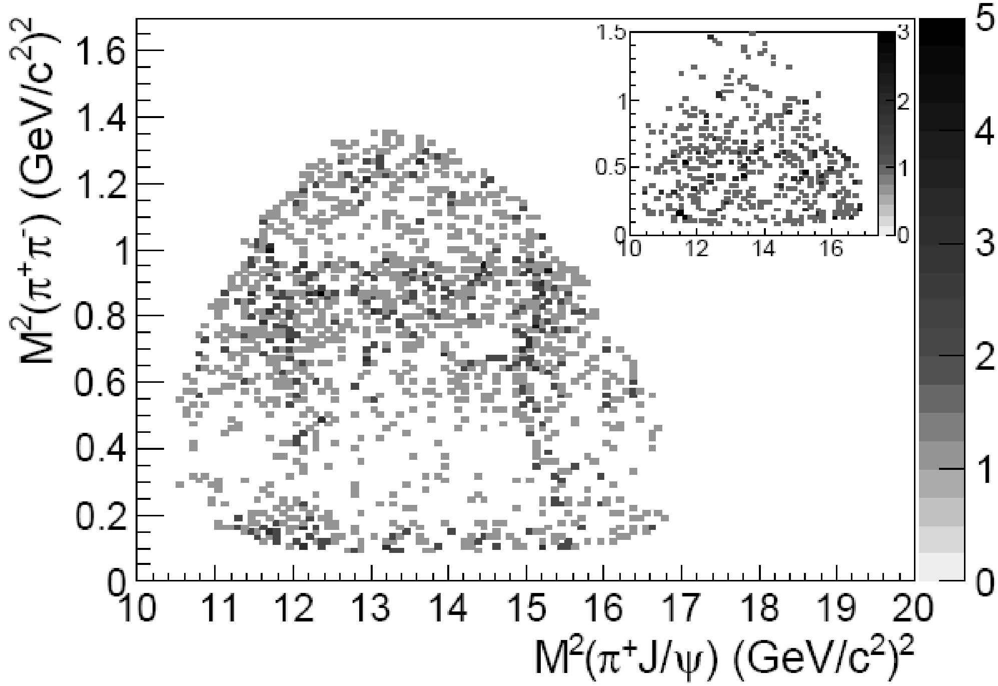


$J^P = 2^+$

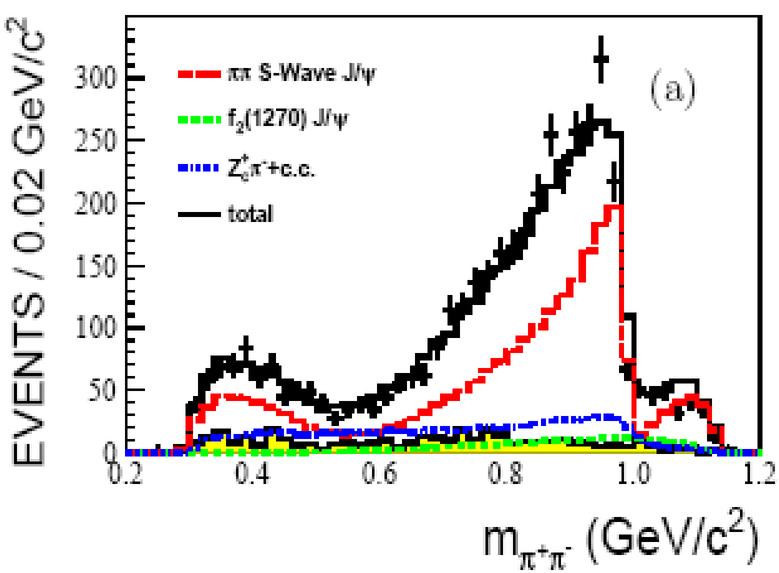


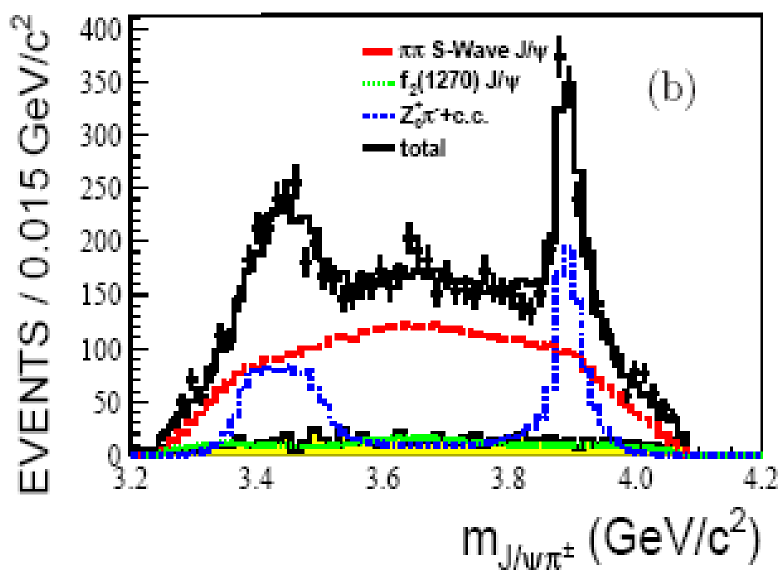
$J^P = 2^-$

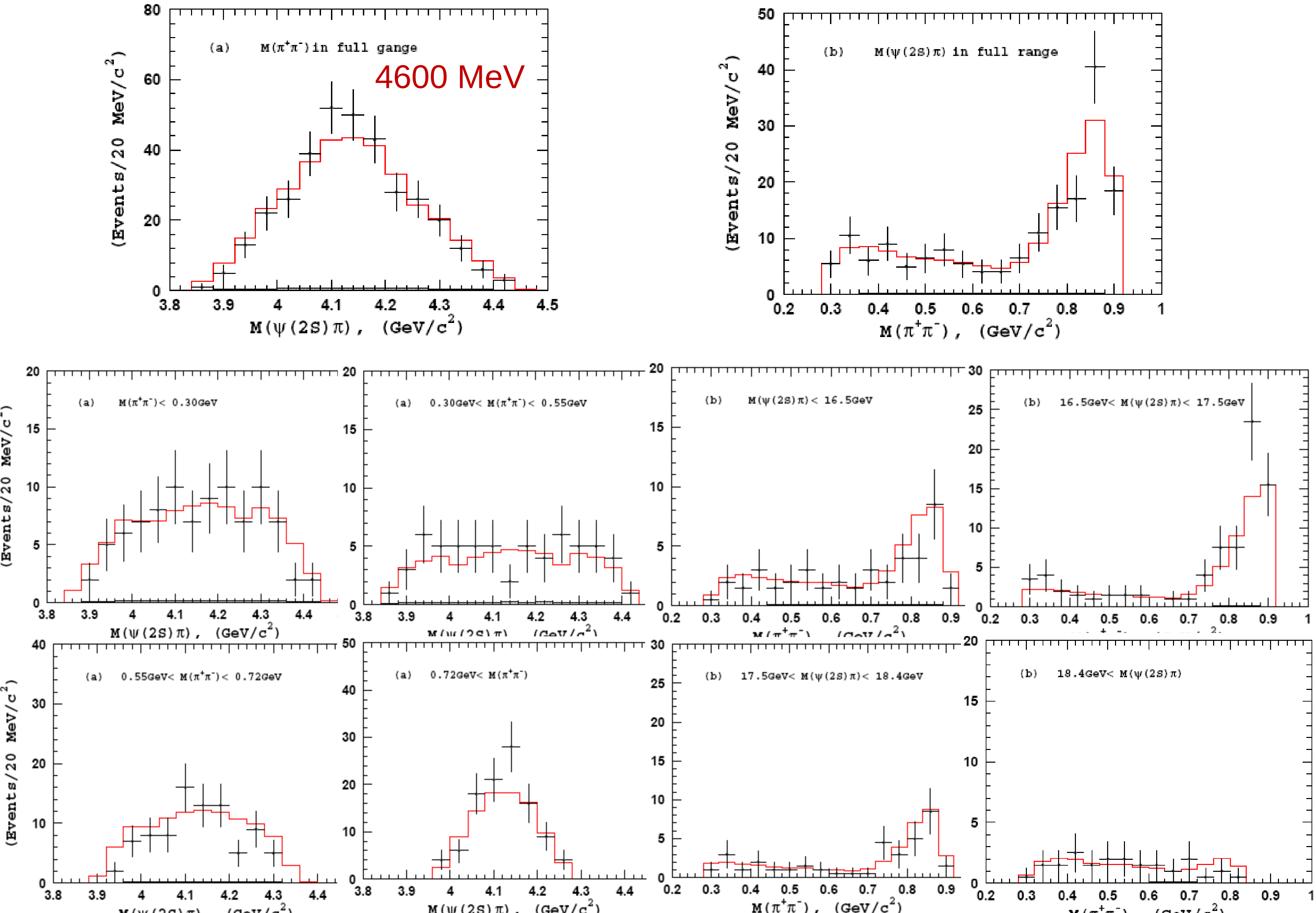
BESIII $e^+e^- \to \pi^+\pi^- J/\psi$ at 4260 MeV

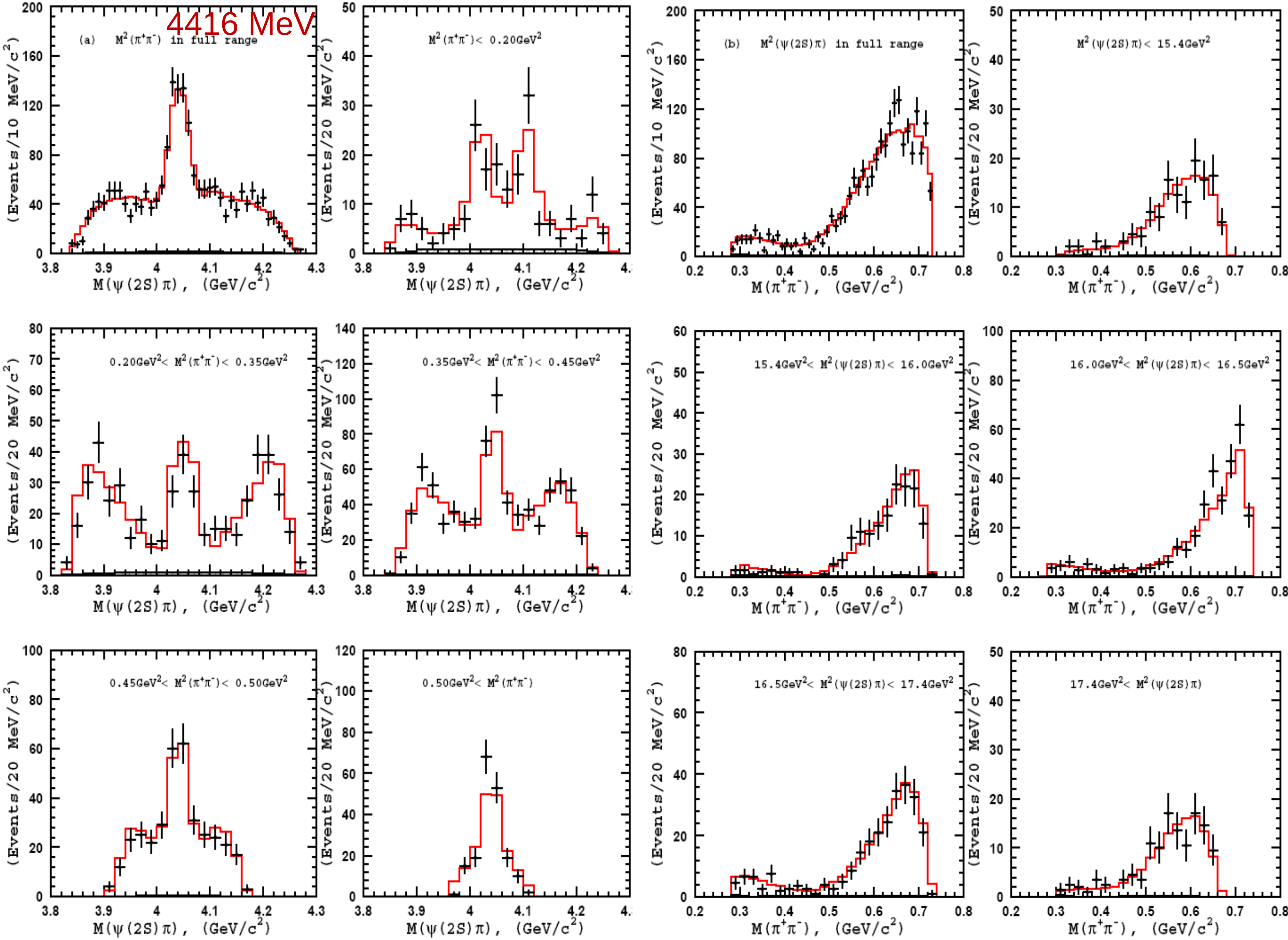


M_z = 3901.5 ± 2.7 ± 38.0 MeV/c²
Γ_z = 51.8 ± 4.6 ± 36.0 MeV
$J^P = 1^+$

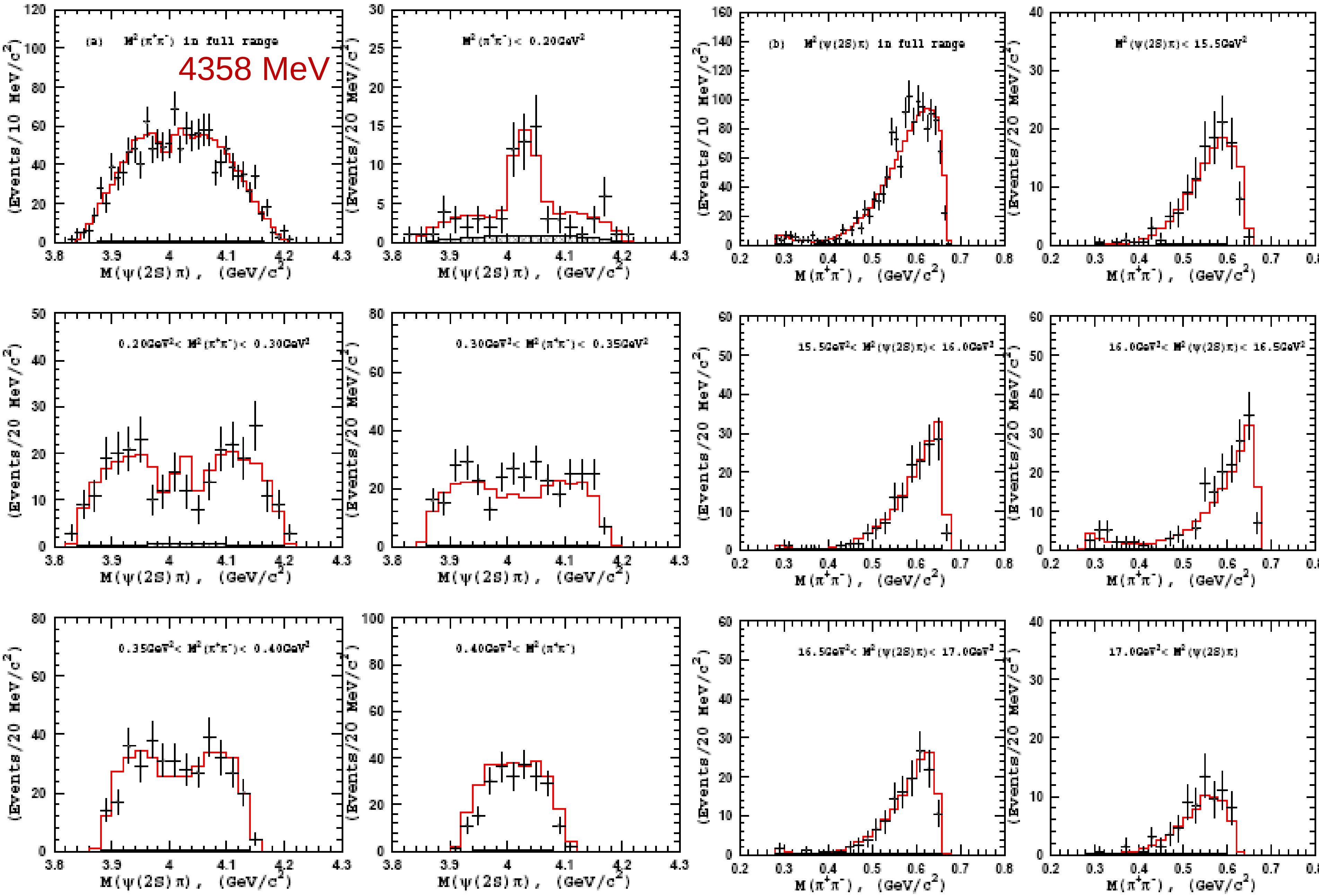




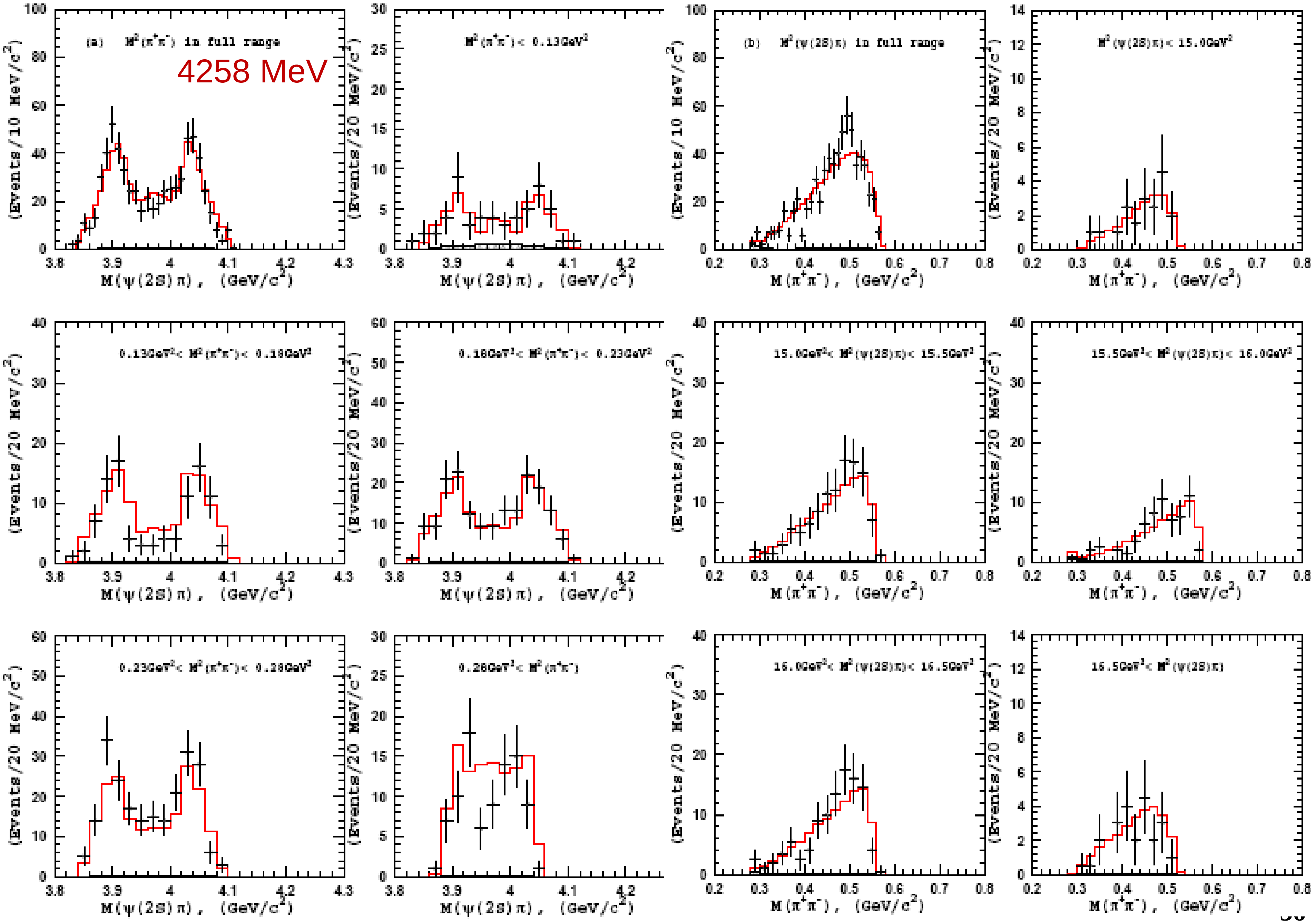

4600 MeV
(a) M(π⁺π⁻)in full gange
(b) M(ψ(2S)π) in full range
(Events/20 MeV/c²)
M(ψ(2S)π), (GeV/c²)
M(π⁺π⁻), (GeV/c²)
(a) M(π⁺π⁻)< 0.30GeV
(a) 0.30GeV< M(π⁺π⁻)< 0.55GeV
(b) M(ψ(2S)π)< 16.5GeV
(b) 16.5GeV< M(ψ(2S)π)< 17.5GeV
(a) 0.55GeV< M(π⁺π⁻)< 0.72GeV
(a) 0.72GeV< M(π⁺π⁻)
(b) 17.5GeV< M(ψ(2S)π)< 18.4GeV
(b) 18.4GeV< M(ψ(2S)π)

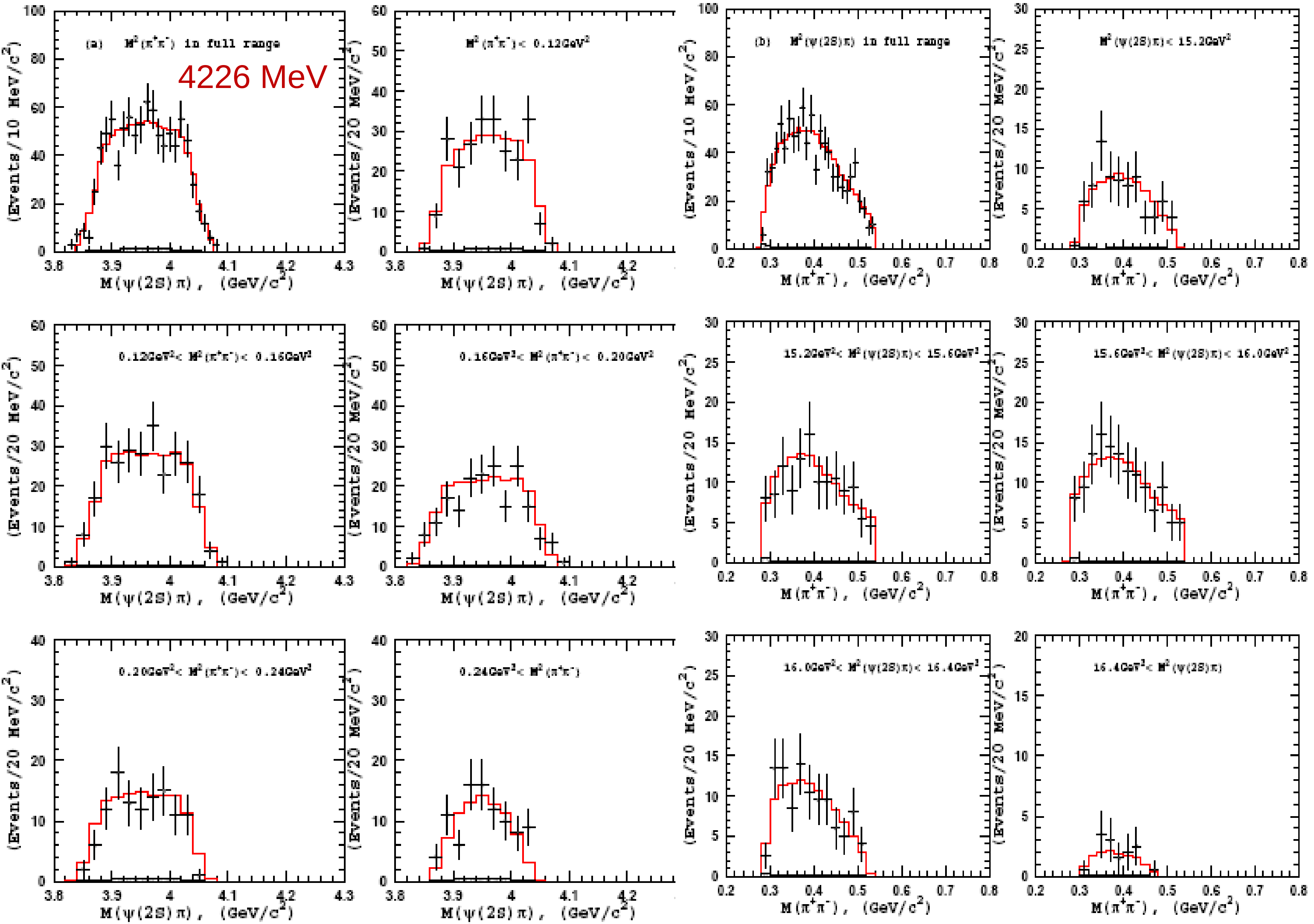


4416 MeV
(a) $M^2(\pi^+\pi^-)$ in full range
$M^2(\pi^+\pi^-) < 0.20GeV^2$
(b) $M^2(\psi(2S)\pi)$ in full range
$M^2(\psi(2S)\pi) < 15.4GeV^2$
$0.20GeV^2 < M^2(\pi^+\pi^-) < 0.35GeV^2$
$0.35GeV^2 < M^2(\pi^+\pi^-) < 0.45GeV^2$
$15.4GeV^2 < M^2(\psi(2S)\pi) < 16.0GeV^2$
$16.0GeV^2 < M^2(\psi(2S)\pi) < 16.5GeV^2$
$0.45GeV^2 < M^2(\pi^+\pi^-) < 0.50GeV^2$
$0.50GeV^2 < M^2(\pi^+\pi^-)$
$16.5GeV^2 < M^2(\psi(2S)\pi) < 17.4GeV^2$
$17.4GeV^2 < M^2(\psi(2S)\pi)$
(Events/10 MeV/c^2)
(Events/20 MeV/c^2)
$M(\psi(2S)\pi)$, (GeV/c^2)
$M(\pi^+\pi^-)$, (GeV/c^2)



(a) $M^2(\pi^+\pi^-)$ in full range
4358 MeV
$M^2(\pi^+\pi^-) < 0.20GeV^2$
(b) $M^2(\psi(2S)\pi)$ in full range
$M^2(\psi(2S)\pi) < 15.5GeV^2$
$0.20GeV^2 < M^2(\pi^+\pi^-) < 0.30GeV^2$
$0.30GeV^2 < M^2(\pi^+\pi^-) < 0.35GeV^2$
$15.5GeV^2 < M^2(\psi(2S)\pi) < 16.0GeV^2$
$16.0GeV^2 < M^2(\psi(2S)\pi) < 16.5GeV^2$
$0.35GeV^2 < M^2(\pi^+\pi^-) < 0.40GeV^2$
$0.40GeV^2 < M^2(\pi^+\pi^-)$
$16.5GeV^2 < M^2(\psi(2S)\pi) < 17.0GeV^2$
$17.0GeV^2 < M^2(\psi(2S)\pi)$
(Events/10 MeV/c^2)
(Events/20 MeV/c^2)
$M(\psi(2S)\pi)$, (GeV/c^2)
$M(\pi^+\pi^-)$, (GeV/c^2)


4258 MeV
(a) $M^2(\pi^+\pi^-)$ in full range
$M^2(\pi^+\pi^-) < 0.13 GeV^2$
(b) $M^2(\psi(2S)\pi)$ in full range
$M^2(\psi(2S)\pi) < 15.0 GeV^2$
$0.13 GeV^2 < M^2(\pi^+\pi^-) < 0.18 GeV^2$
$0.18 GeV^2 < M^2(\pi^+\pi^-) < 0.23 GeV^2$
$15.0 GeV^2 < M^2(\psi(2S)\pi) < 15.5 GeV^2$
$15.5 GeV^2 < M^2(\psi(2S)\pi) < 16.0 GeV^2$
$0.23 GeV^2 < M^2(\pi^+\pi^-) < 0.28 GeV^2$
$0.28 GeV^2 < M^2(\pi^+\pi^-)$
$16.0 GeV^2 < M^2(\psi(2S)\pi) < 16.5 GeV^2$
$16.5 GeV^2 < M^2(\psi(2S)\pi)$
(Events/10 MeV/c^2)
(Events/20 MeV/c^2)
$M(\psi(2S)\pi)$, (GeV/c^2)
$M(\pi^+\pi^-)$, (GeV/c^2)

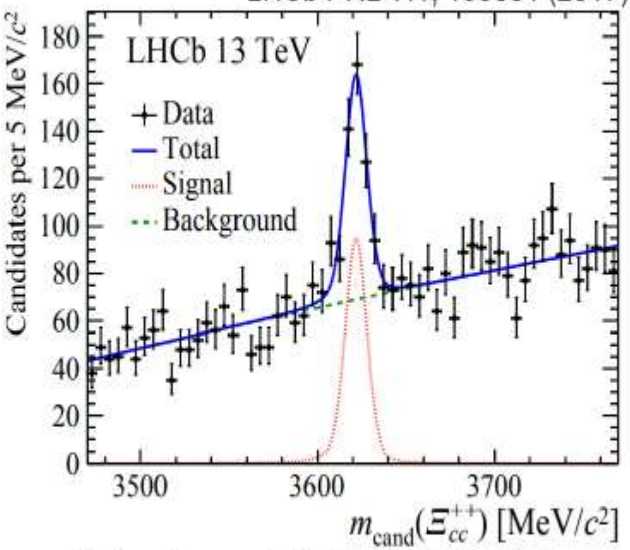


4226 MeV
(a) M²(π⁺π⁻) in full range
M²(π⁺π⁻) < 0.12GeV²
(b) M²(ψ(2S)π) in full range
M²(ψ(2S)π) < 15.2GeV²
0.12GeV² < M²(π⁺π⁻) < 0.16GeV²
0.16GeV² < M²(π⁺π⁻) < 0.20GeV²
15.2GeV² < M²(ψ(2S)π) < 15.6GeV²
15.6GeV² < M²(ψ(2S)π) < 16.0GeV²
0.20GeV² < M²(π⁺π⁻) < 0.24GeV²
0.24GeV² < M²(π⁺π⁻)
16.0GeV² < M²(ψ(2S)π) < 16.4GeV²
16.4GeV² < M²(ψ(2S)π)
M(ψ(2S)π), (GeV/c²)
M(π⁺π⁻), (GeV/c²)
(Events/10 MeV/c²)
(Events/20 MeV/c²)

Doubly heavy systems

baryon

LHCb PRL 111, 180001 (2017)



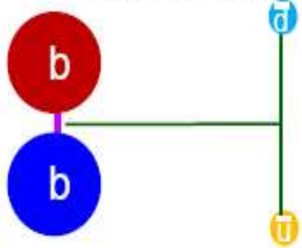
Karliner,Rosner PRD90,094007 (2014)

State	Quark content	$M(J=1/2)$	$M(J=3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ'_{bc}	$b(cq)$	6933 ± 12	$\cdots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

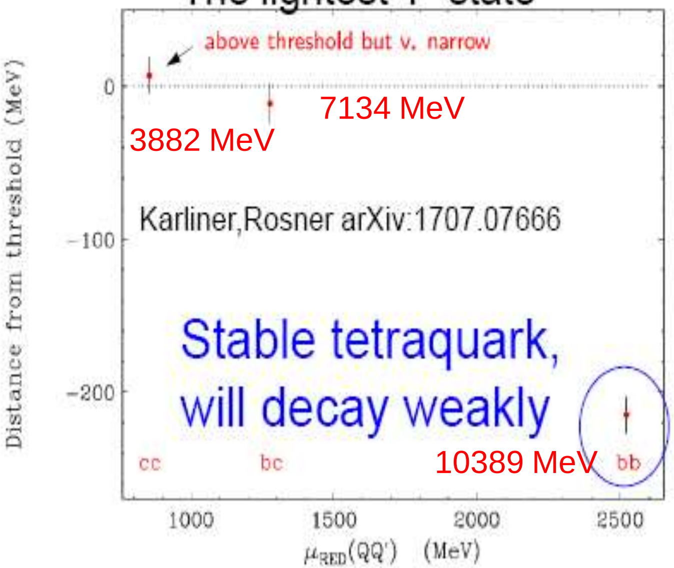
LHCb: 3621 ± 1 55

the same toolkit

tetraquark



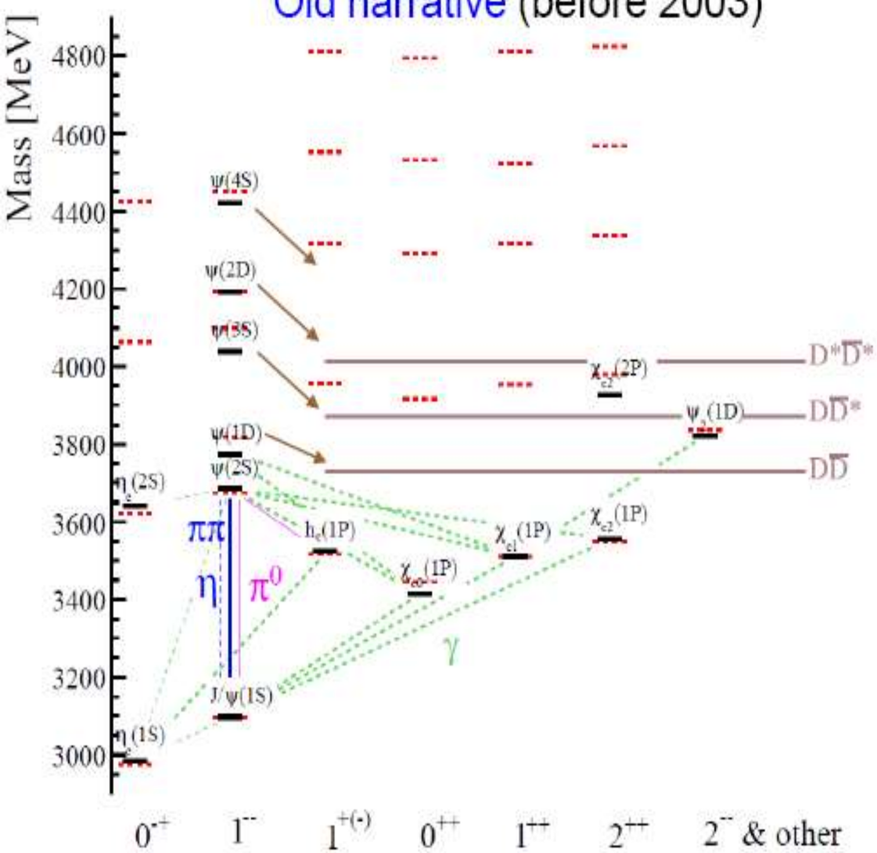
The lightest 1+ state



Consistent results predicted by LQCD: Francis,Hudspith,Lewis,Maltman PRL 1118,142001 (2017)

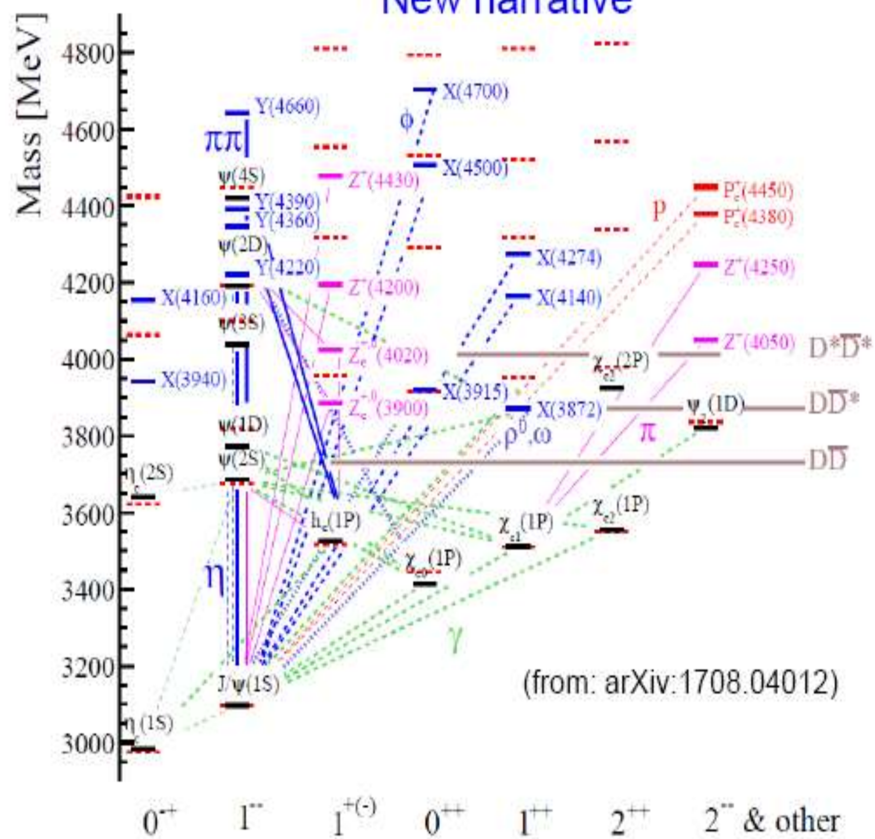
Summary I

Old narrative (before 2003)



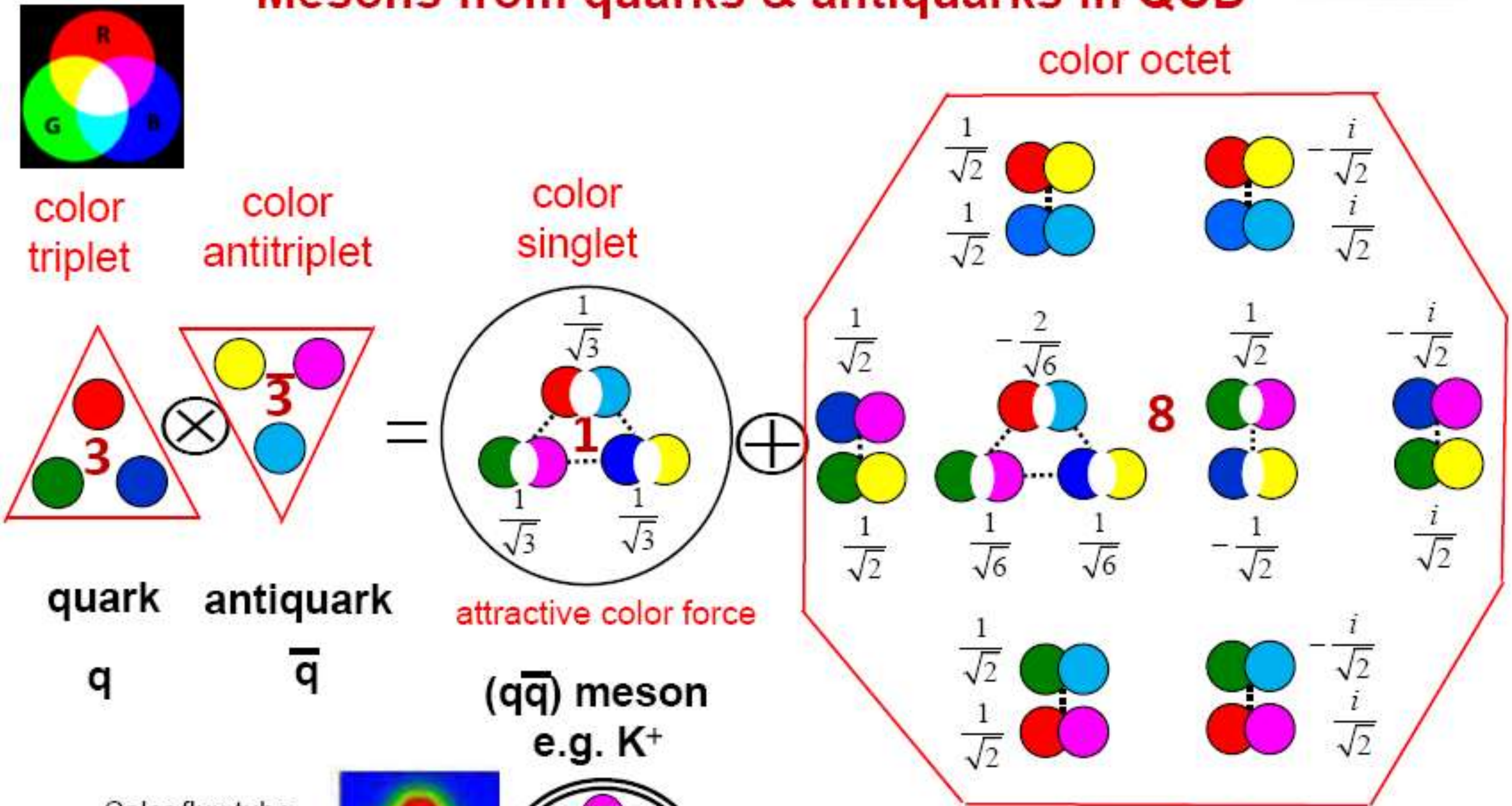
Mesons are $(q\bar{q})$ bound states.

New narrative

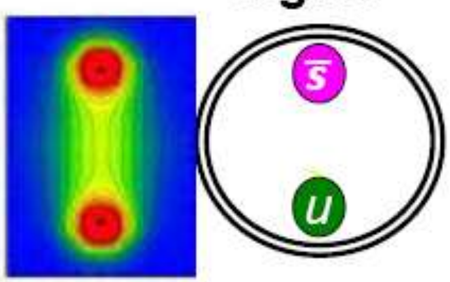


Mesons are **predominantly** $(q\bar{q})$ bound states below the open flavor threshold. They are more complex structures above it, and we have not yet understood them.

Mesons from quarks & antiquarks in QCD



Color flux tube stretched between quark and antiquark with attractive potential

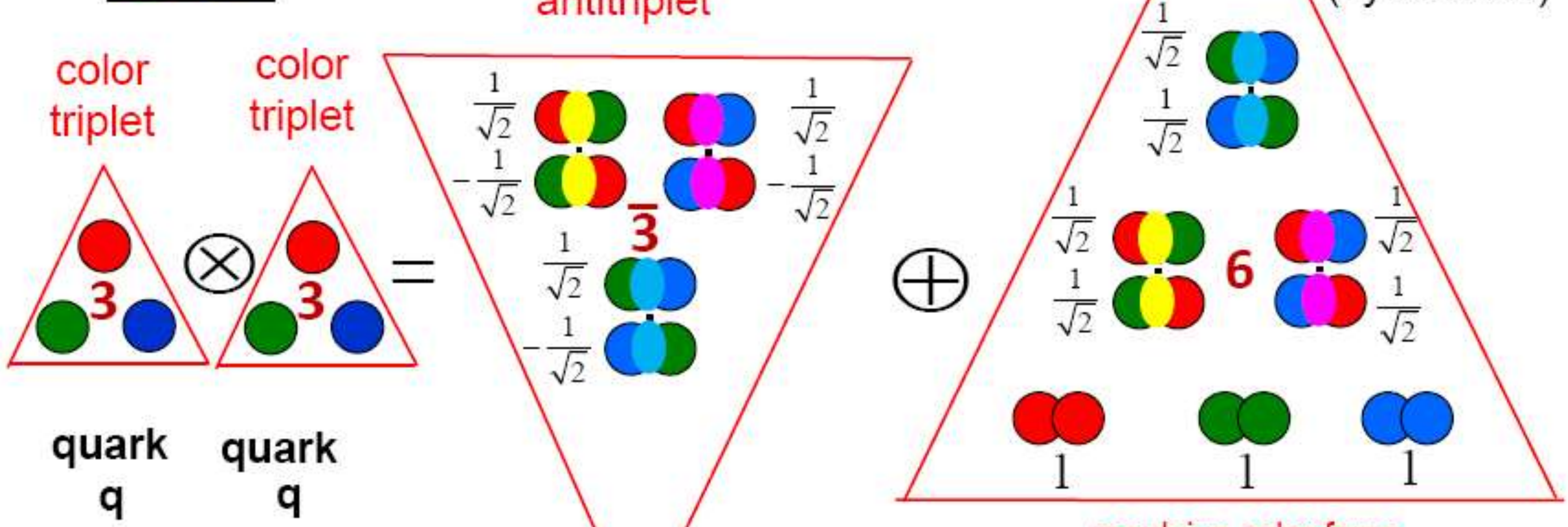


repulsive color force

quarks will pull apart in any octet configuration

gluons happen to belong to the color octet

(Colored) diquarks in QCD



attractive color force

(half as strong as in the meson)

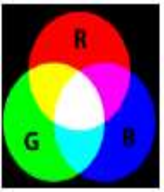
repulsive color force

quarks will pull apart in any sextet configuration

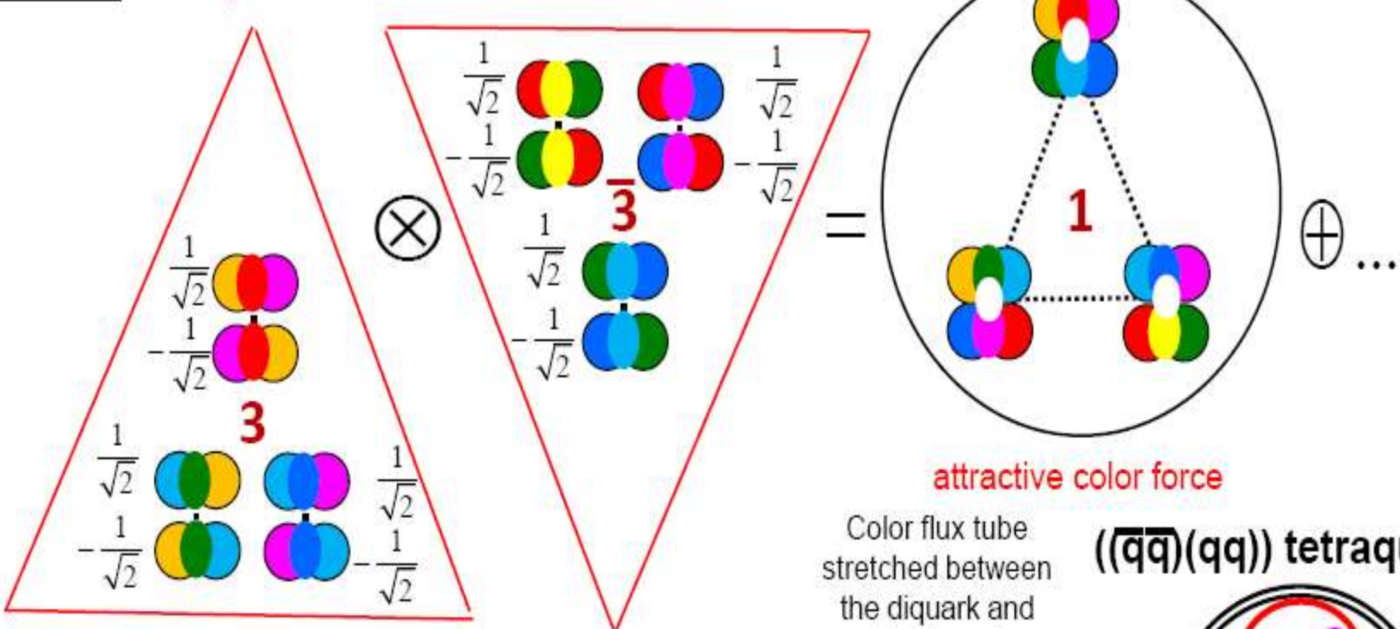
(qq) diquark

Color flux tube stretched between the quarks and extending to other color partners

Not a particle, just a building block in QCD



Diaquarks can make tetraquarks!



However, it is not clear if an efficient mechanisms to suppress the fall-apart mode to two mesons exists, especially when all quarks are light.

attractive color force

attractive color force

$(\bar{q}\bar{q})$ diantiquark

↑

q

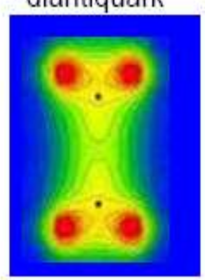
attractive color force

(qq) diquark

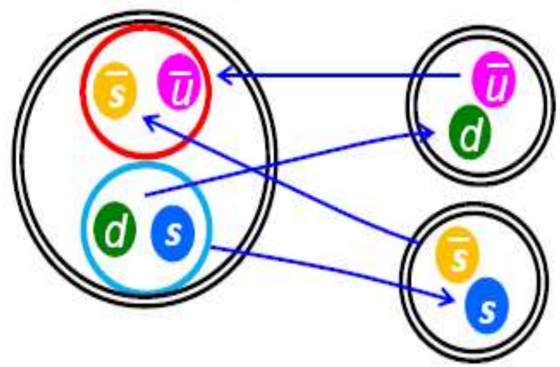
↑

$\bar{q}$

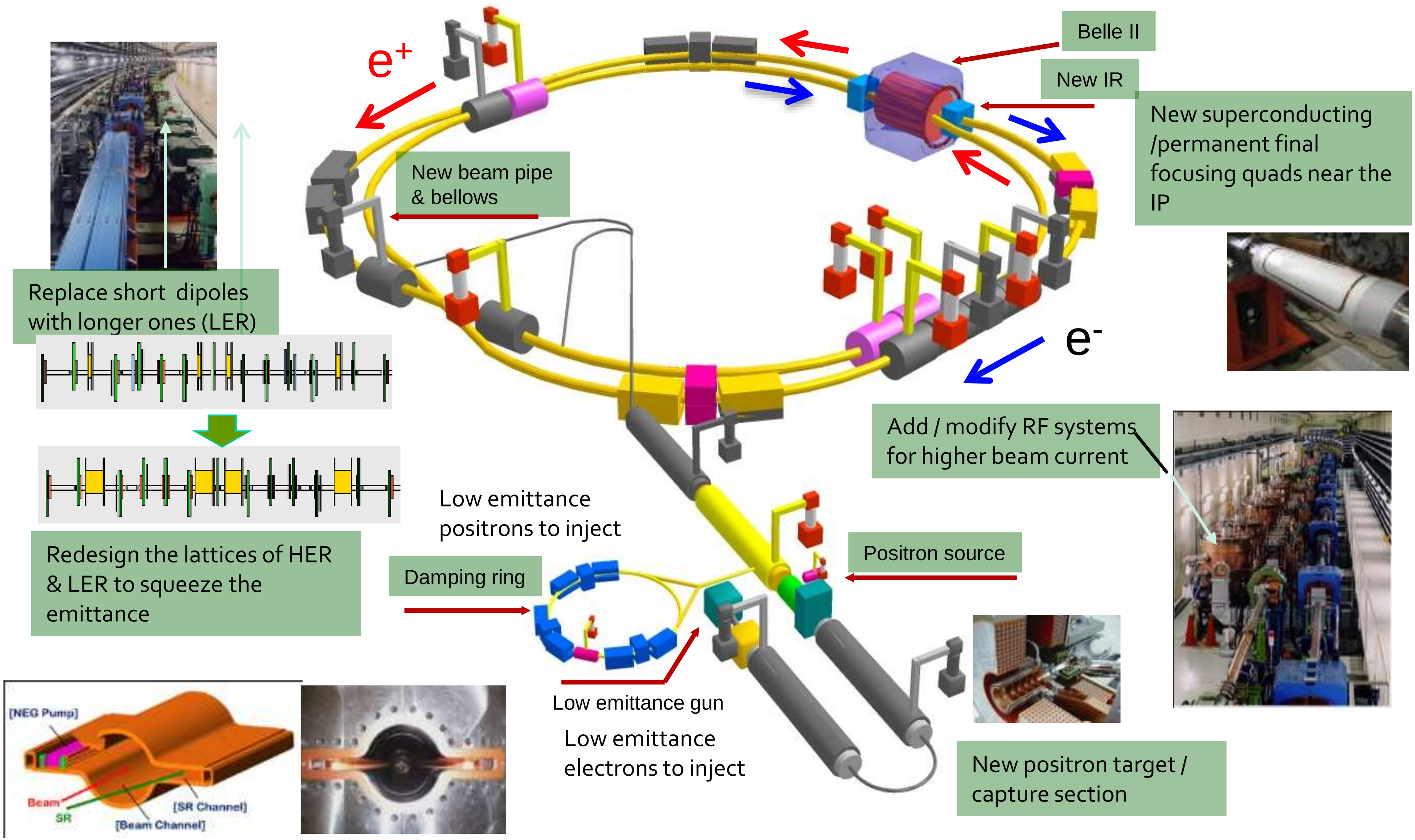
Color flux tube stretched between the diquark and diantiquark



$((\bar{q}\bar{q})(qq))$ tetraquark



SuperKEKB

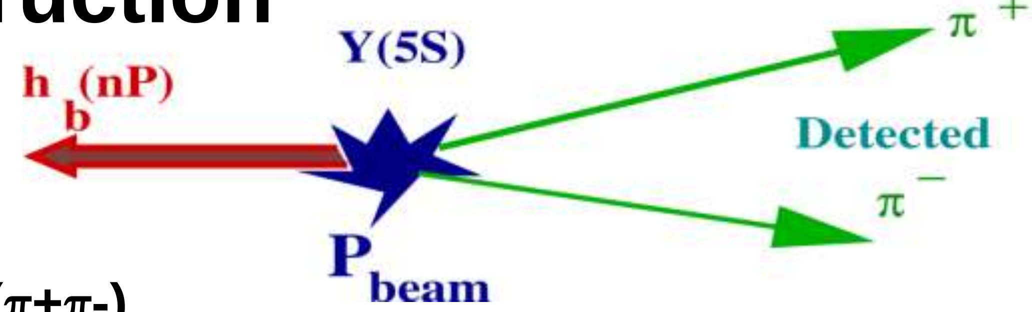


TiN-coated beam pipe with antechambers

To aim ×40 luminosity

h_b reconstruction

Missing mass to $\pi\pi$ system

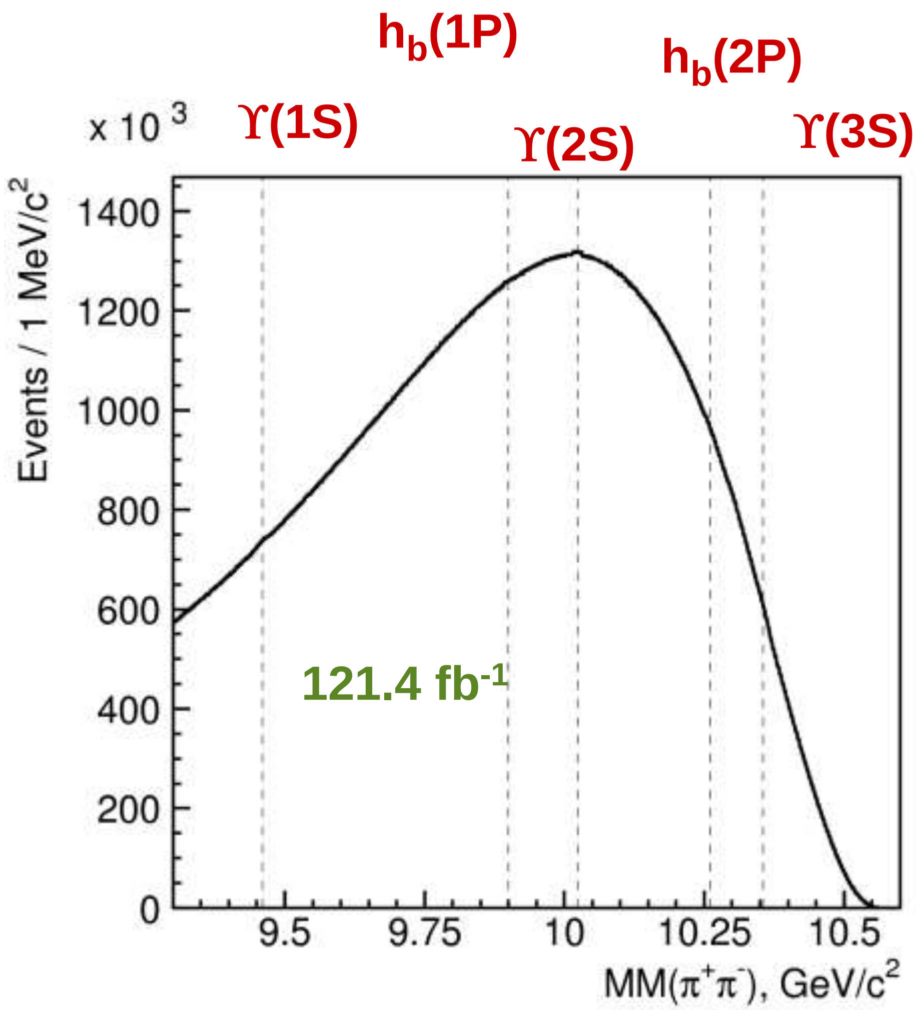


$$M_{hb(nP)} = \sqrt{(P_{\Upsilon(5S)} - P_{\pi+\pi-})^2} \equiv MM(\pi+\pi-)$$

Simple selection :

$\pi^+\pi^-$: good quality, positively identified

Suppression of continuum events
FW R2<0.3



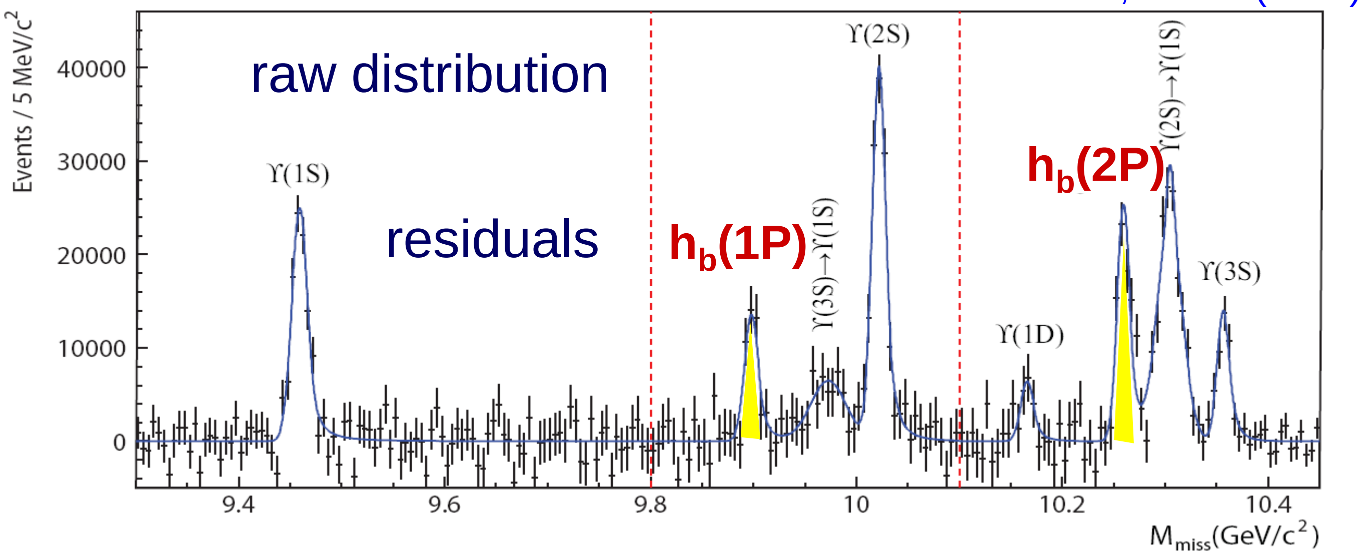
⇒ Search for $h_b(nP)$ peaks in $MM(\pi^+\pi^-)$ spectrum

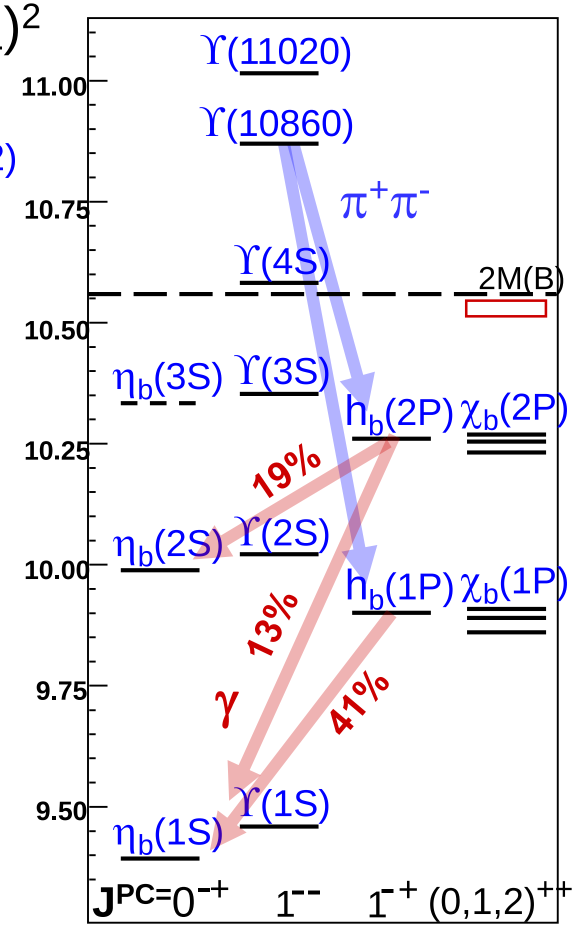
Observation of $h_b(1P,2P)$

$e^+e^- \to \Upsilon(5S) \to h_b(nP)\ \pi^+\pi^-$ ← reconstructed, use $\mathbf{M_{miss}(\pi^+\pi^-)}$

$\sqrt{(P_{e+e-} - P_{\pi+\pi-})^2}$

PRL108,032001(2012)





$\Delta M_{HF}(\mathbf{1P}) = +0.8 \pm 1.1$ MeV consistent with zero,

$\Delta M_{HF}(\mathbf{2P}) = +0.5 \pm 1.2$ MeV as expected

Large $h_b(1,2P)$ production rates

c.f. CLEO $e^+e^- \to \psi(4170) \to h_c\ \pi^+\pi^-$

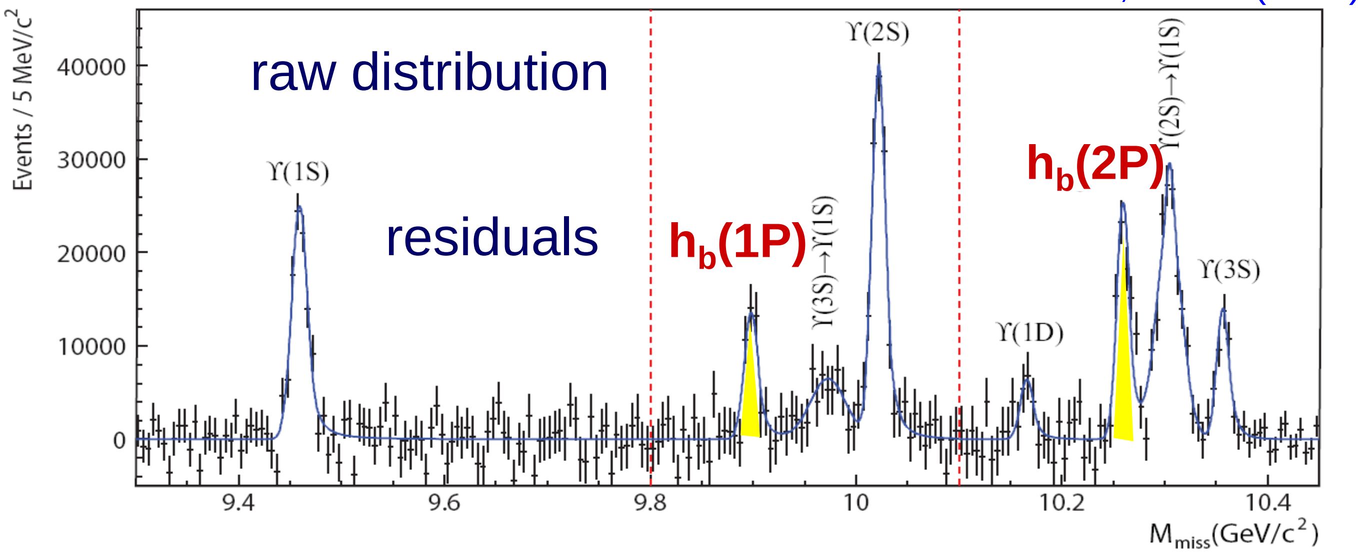
$h_b(nP)$ decays are a source of $\eta_b(mS)$

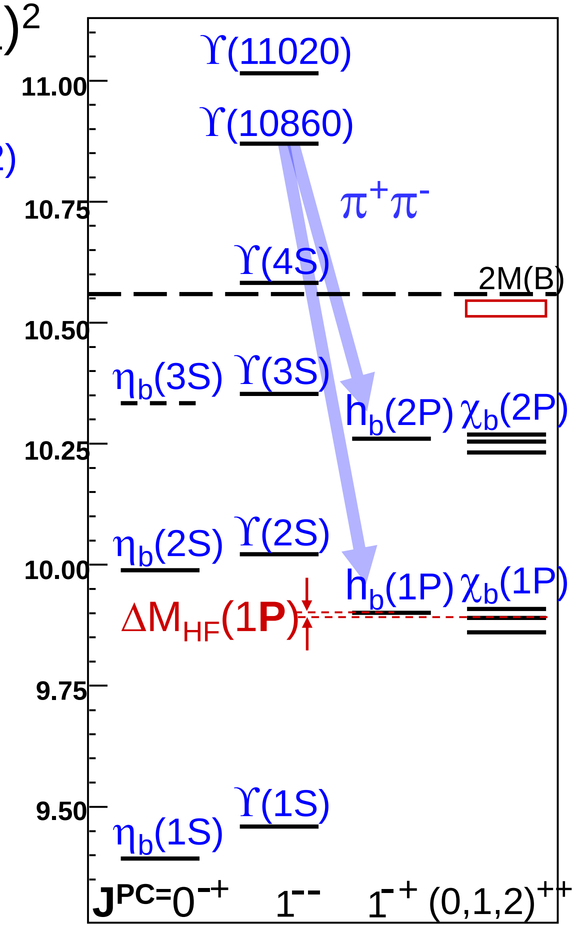
Observation of h_b(1P,2P)

$e^+e^- \to \Upsilon(5S) \to X\ \pi^+\pi^-$ ← reconstructed, use $M_{miss}(\pi^+\pi^-)$

$\sqrt{(P_{e+e-} - P_{\pi+\pi-})^2}$

PRL108,032001(2012)





ΔM_{HF}(**1P**) = +0.8 ± 1.1 MeV consistent with zero,

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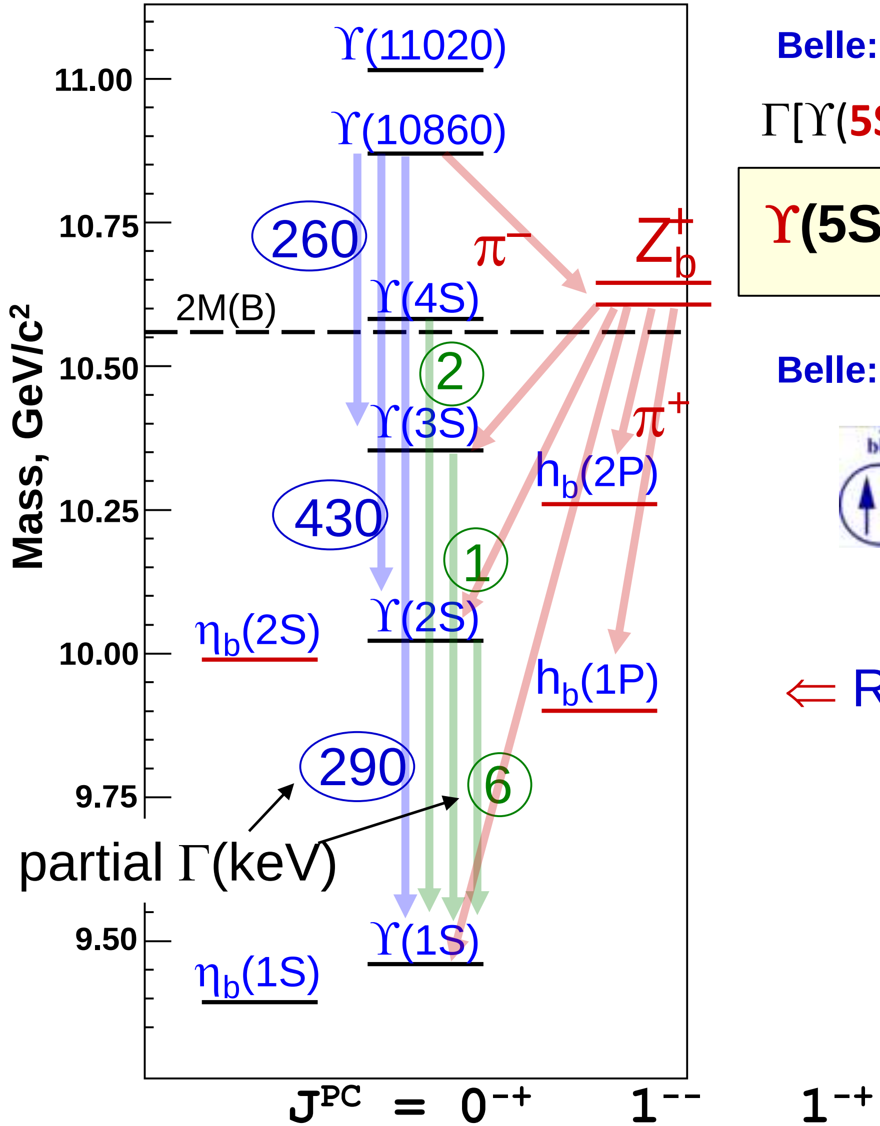
Large h_b(1,2P) production rates

c.f. CLEO $e^+e^- \to \psi(4170) \to h_c\ \pi^+\pi^-$

Anomalies in $\Upsilon(5S) \to (b\bar{b})\pi^+\pi^-$ transitions



Belle: PRL100, 112001 (2008)

$\Gamma[\Upsilon(5S) \to \Upsilon(1,2,3S)\,\pi^+\pi^-] \overset{\sim 100}{>>} \Gamma[\Upsilon(4,3,2S) \to \Upsilon(1S)\,\pi^+\pi^-]$

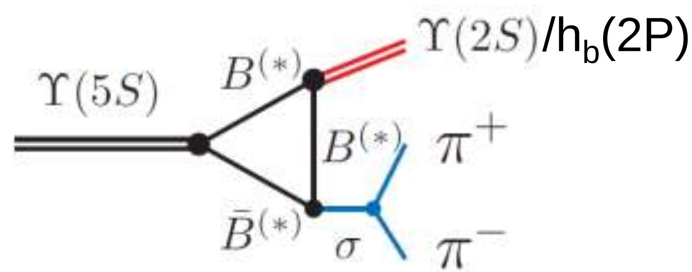
$\Upsilon(5S) \to h_b(1,2P)\,\pi^+\pi^-$ are not suppressed

Belle: PRL108, 032001 (2012)

expect suppression $\sim\Lambda_{QCD}/m_b$

~~Heavy Quark Symmetry~~

$\Leftarrow$ Rescattering of on-shell $B^{(*)}\bar{B}^{(*)}$?



h_b production mechanism? $\Upsilon(5S) \to h_b(1,2P)\,\pi^+\pi^-$ are not suppressed due to Z_b intermediate states! But it's not enough for $\Upsilon(nS)\,\pi^+\pi^-$.

Voloshin PRD D84 (2011) 031502,arXiv:1105.5829

$$|Z_b'\rangle = \frac{1}{\sqrt{2}} 0^-_{bb} \otimes 1^-_{Qq} - \frac{1}{\sqrt{2}} 1^-_{bb} \otimes 0^-_{Qq}$$

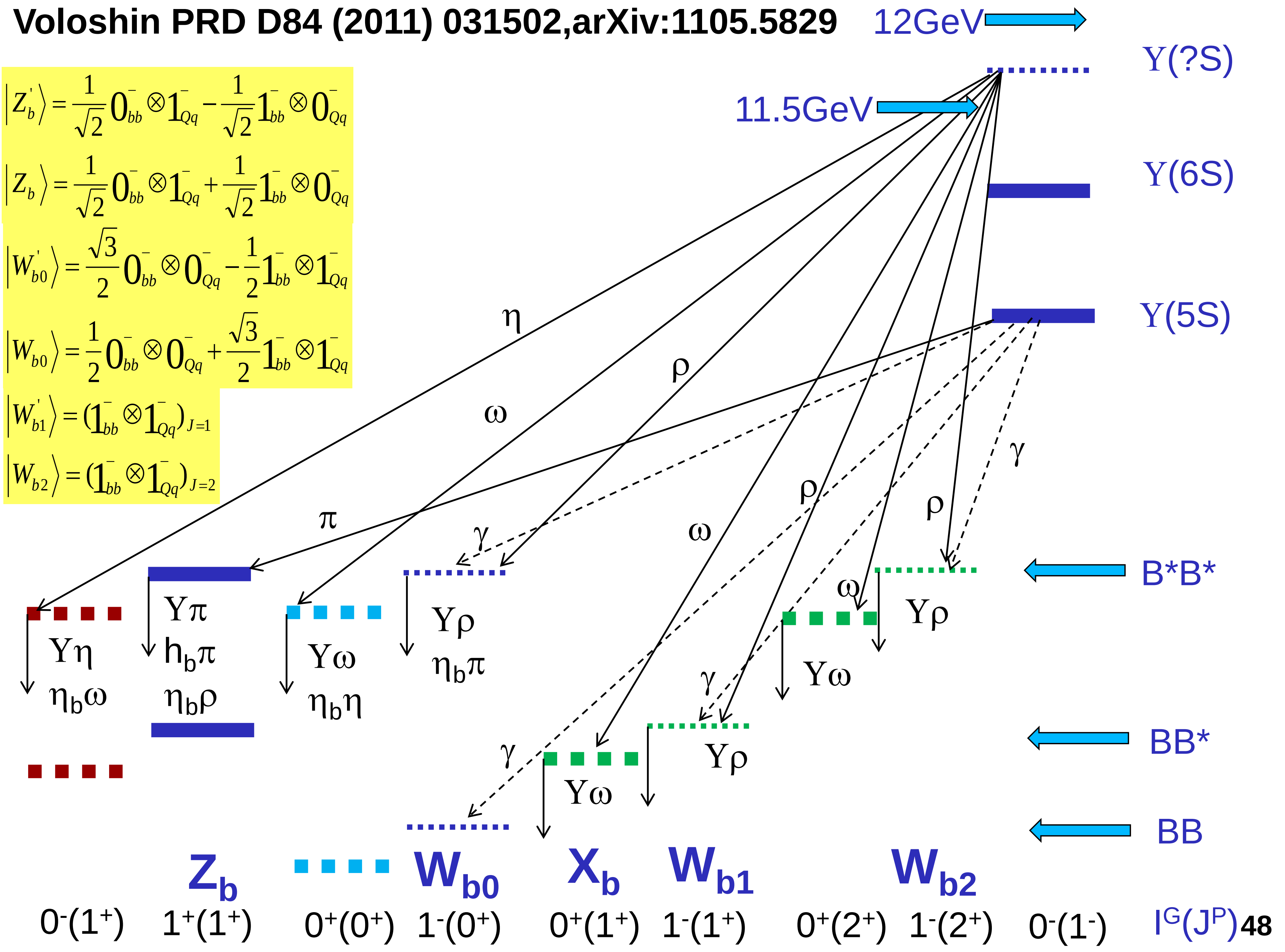
$$|Z_b\rangle = \frac{1}{\sqrt{2}} 0^-_{bb} \otimes 1^-_{Qq} + \frac{1}{\sqrt{2}} 1^-_{bb} \otimes 0^-_{Qq}$$

$$|W_{b0}'\rangle = \frac{\sqrt{3}}{2} 0^-_{bb} \otimes 0^-_{Qq} - \frac{1}{2} 1^-_{bb} \otimes 1^-_{Qq}$$

$$|W_{b0}\rangle = \frac{1}{2} 0^-_{bb} \otimes 0^-_{Qq} + \frac{\sqrt{3}}{2} 1^-_{bb} \otimes 1^-_{Qq}$$

$$|W_{b1}'\rangle = (1^-_{bb} \otimes 1^-_{Qq})_{J=1}$$

$$|W_{b2}\rangle = (1^-_{bb} \otimes 1^-_{Qq})_{J=2}$$



Tetraquark?

M ~ 10.2 – 10.3 GeV

Ying Cui, Xiao-lin Chen, Wei-Zhen Deng,
Shi-Lin Zhu, High Energy Phys.Nucl.Phys.31:7-13, 2007
(hep-ph/0607226)

M ~ 10.5 – 10.8 GeV

Tao Guo, Lu Cao, Ming-Zhen Zhou, Hong Chen, (1106.2284)

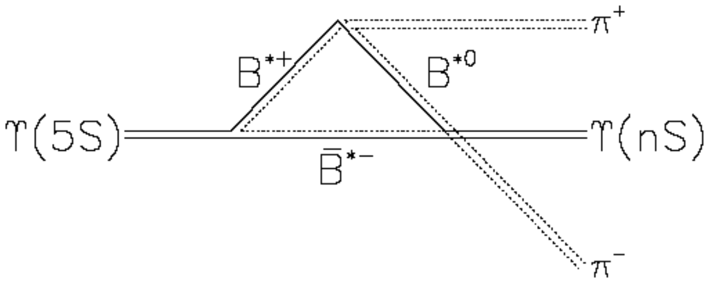
M ~ 9.4, 11 GeV

M.Karliner, H.Lipkin, (0802.0649)

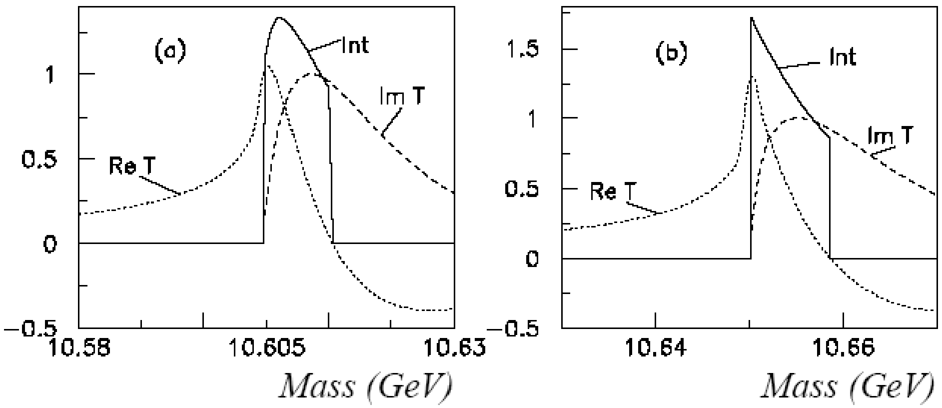
Cusp?

D.Bugg Europhys.Lett.96 (2011) (arXiv:1105.5492)

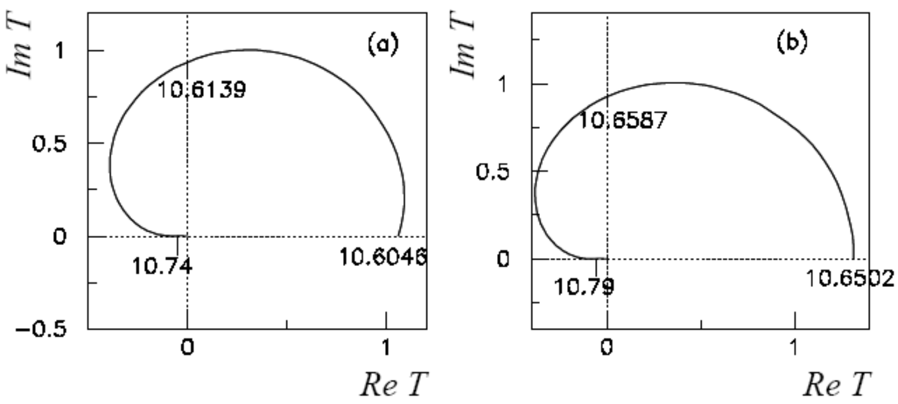
Amplitude



Line-shape



Not a resonance

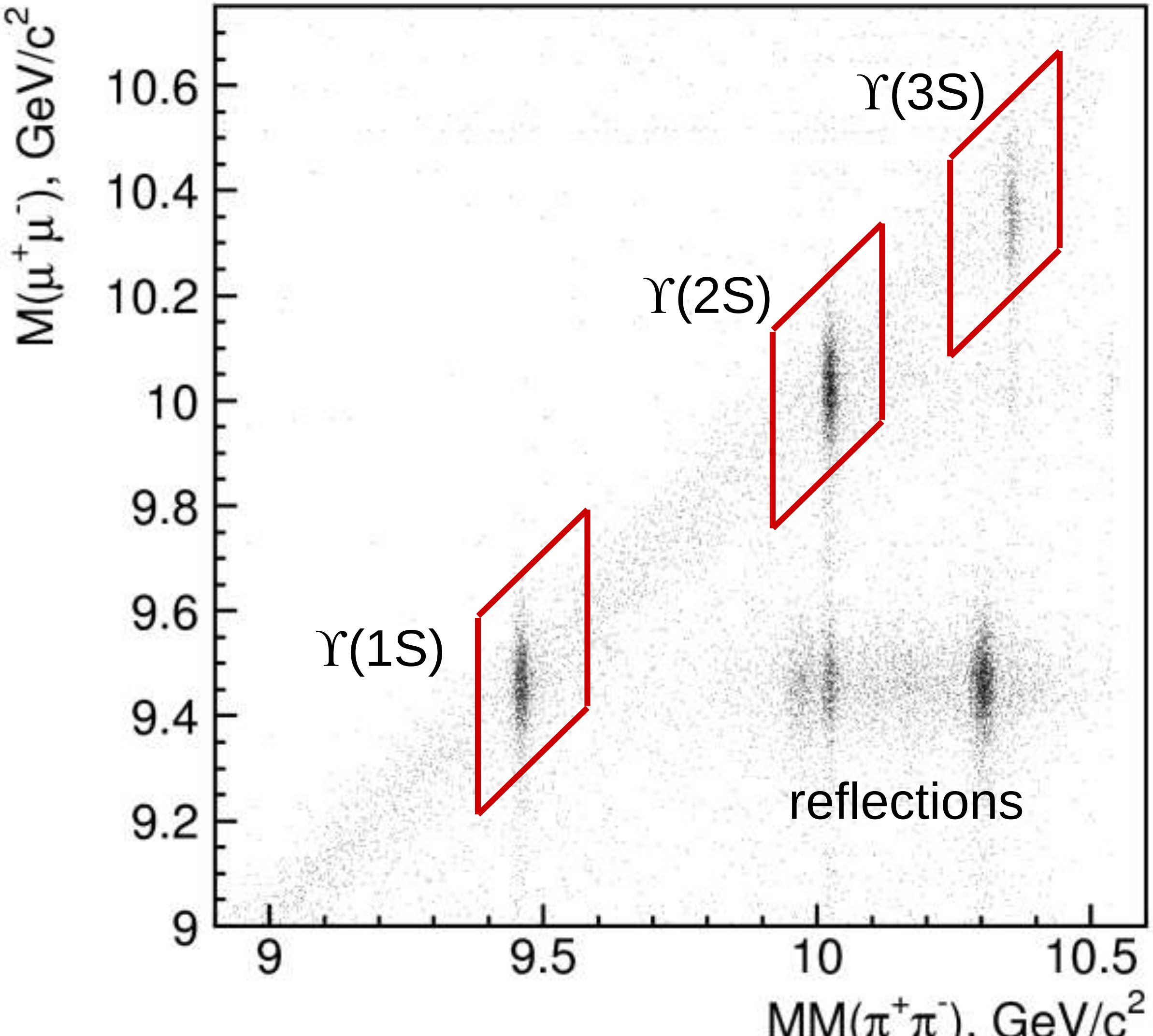


Exclusive $\Upsilon(5S) \to \Upsilon(nS)\ \pi^+\pi^-$

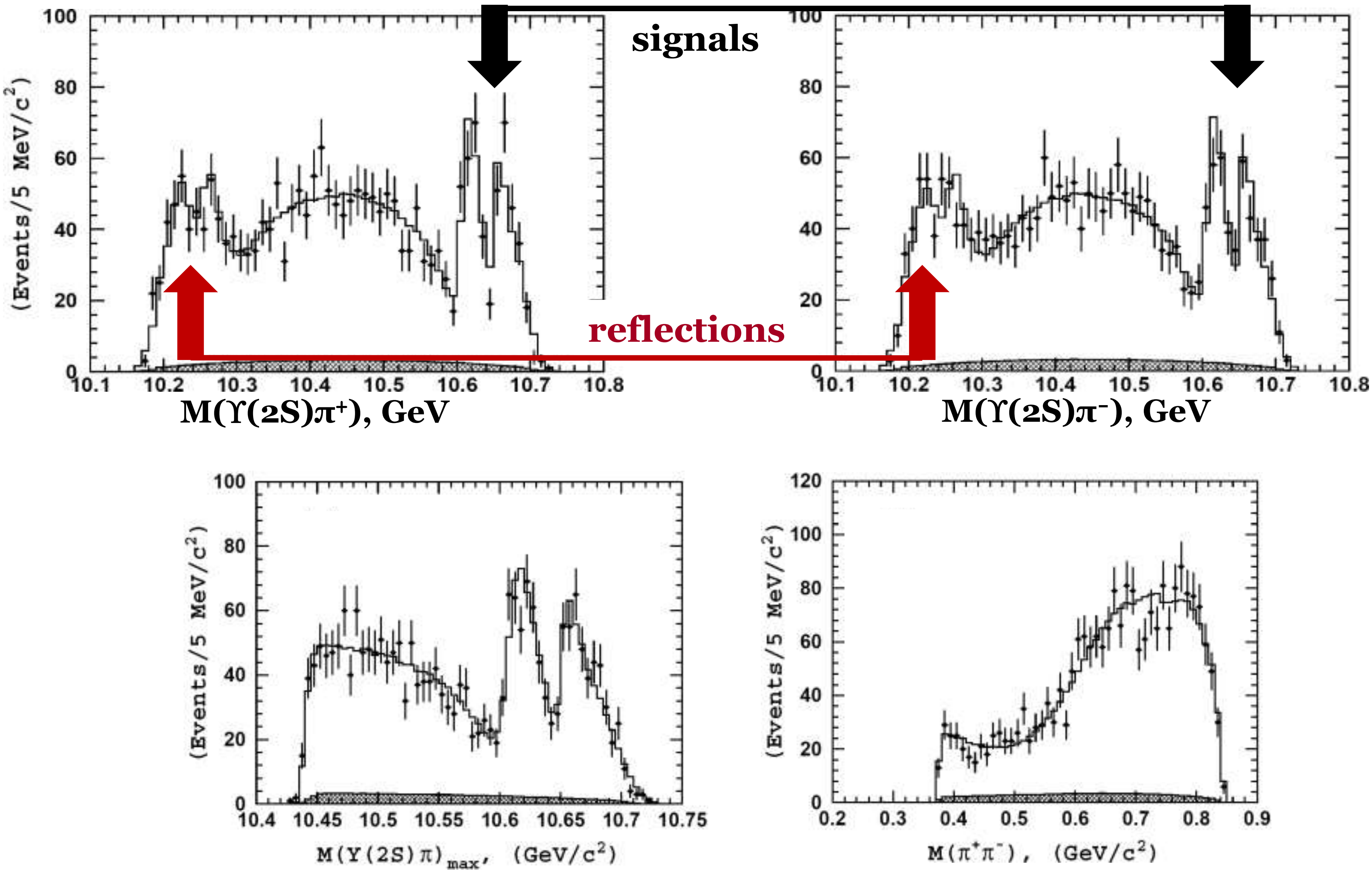
$\Upsilon(5S) \to \Upsilon(nS)\ \pi^+\pi^-$

$\Upsilon(nS) \to \mu^+\mu^-$

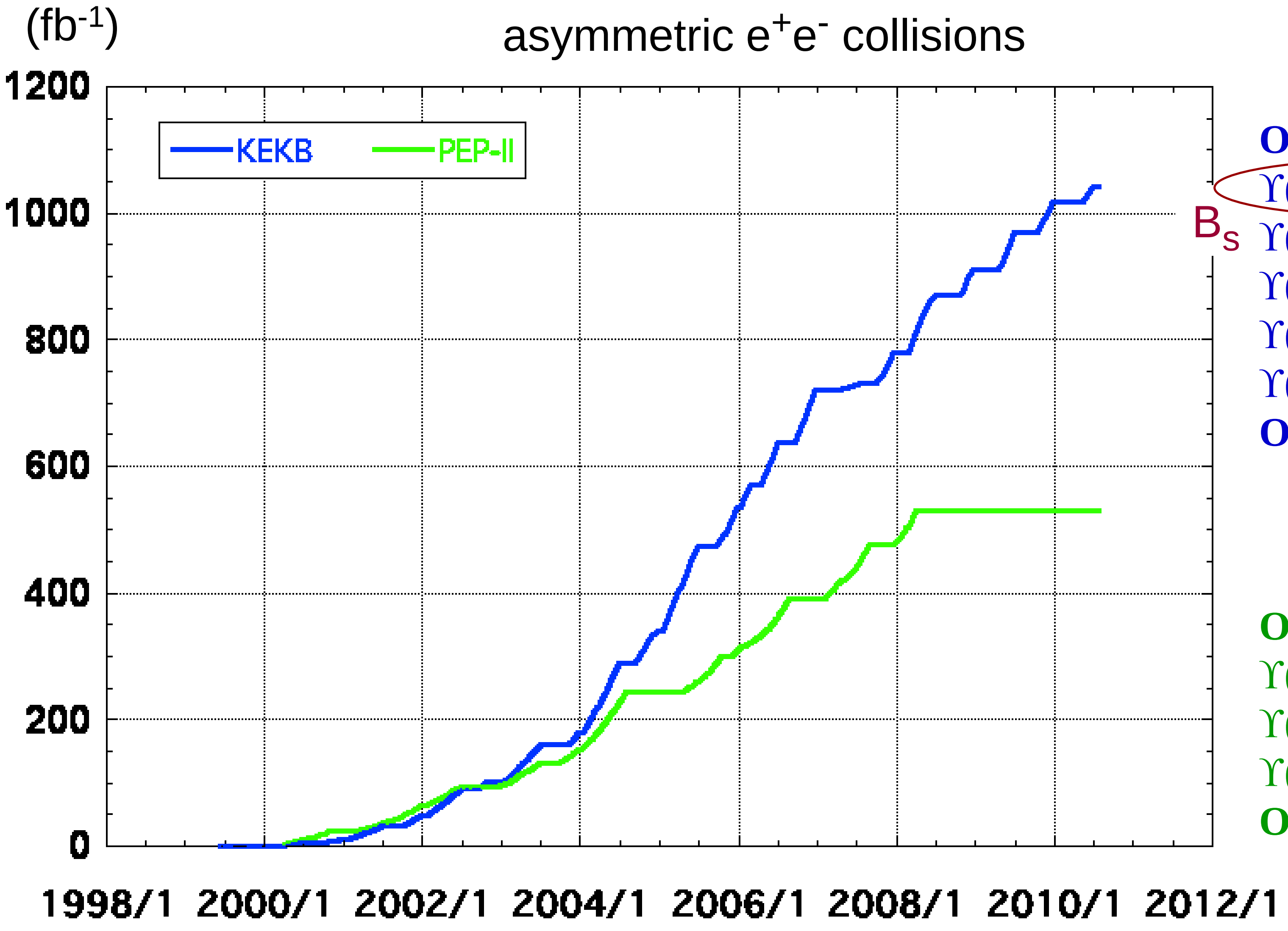
(n = 1,2,3)



Results: $\Upsilon(2S)\pi^+\pi^-$



Integrated Luminosity at B-factories



> 1 ab^{-1}

On resonance:

Υ(5S): 121 fb^{-1}

Υ(4S): 711 fb^{-1}

Υ(3S): 3 fb^{-1}

Υ(2S): 24 fb^{-1}

Υ(1S): 6 fb^{-1}

Off reson./scan :

~100 fb**-**1

530 fb^{-1}

On resonance:

Υ(4S): 433 fb^{-1}

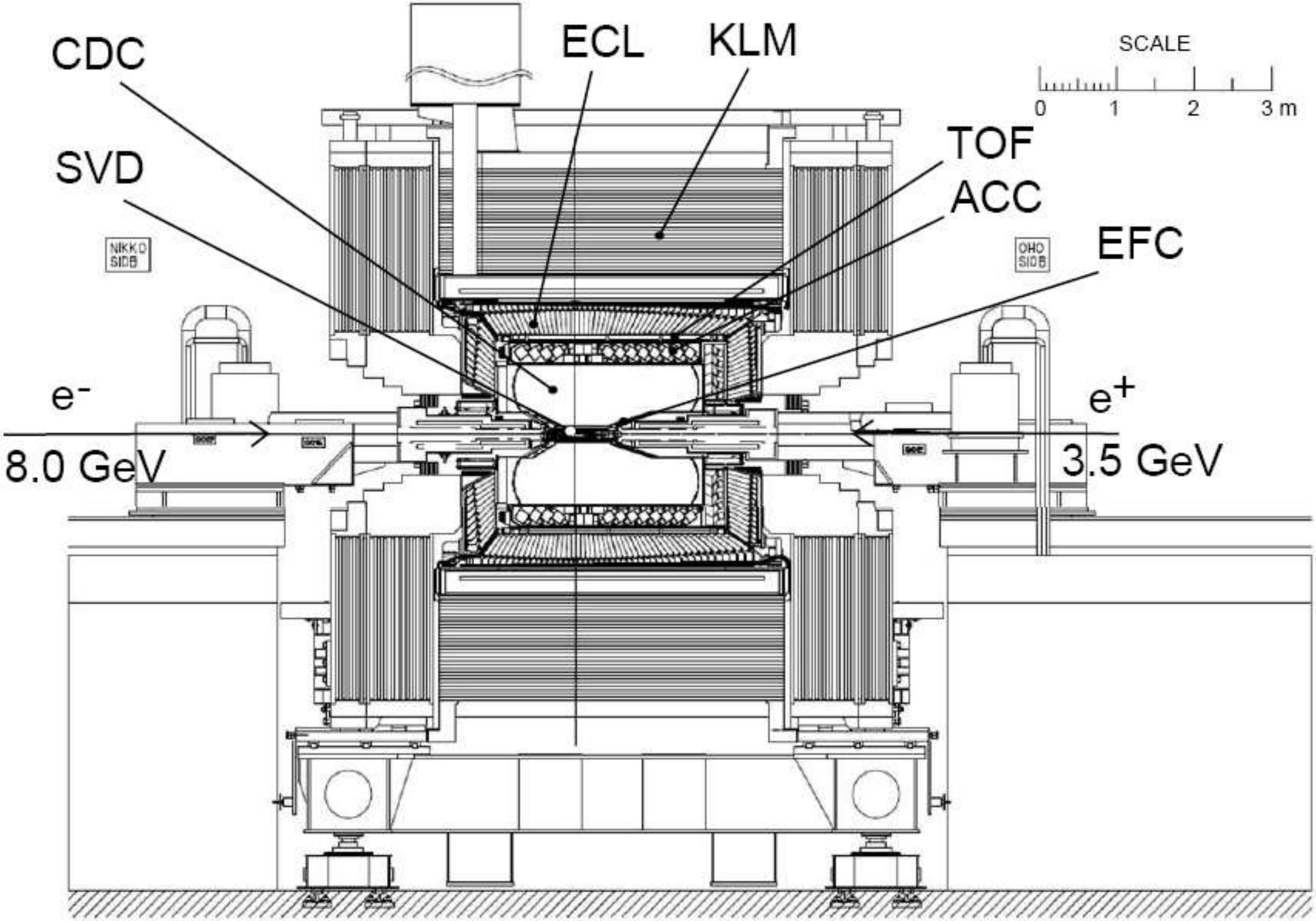
Υ(3S): 30 fb^{-1}

Υ(2S): 14 fb^{-1}

Off reson./scan :

~54 fb-1

Belle Detector



Heavy quarkonium – approximately a non-relativistic system.

System	Ground triplet state			$(v/c)^2$
	Name	Mass, MeV	Γ, MeV	
POSITRONIUM				
e^+e^-	Ortho-	1	$5\ 10^{-15}$	**~0.0001**
QUARKONIUM				
$u\bar{u}, d\bar{d}$	ρ	800	150	**~1.0**
$s\bar{s}$	φ	1000	4	**~0.8**
$c\bar{c}$	ψ	3100	0.09	**~0.25**
$b\bar{b}$	ϒ	9500	0.05	**~0.08**

Good approximation for heavy quarkonium – potential models.

Puzzles of Υ(5S) decays

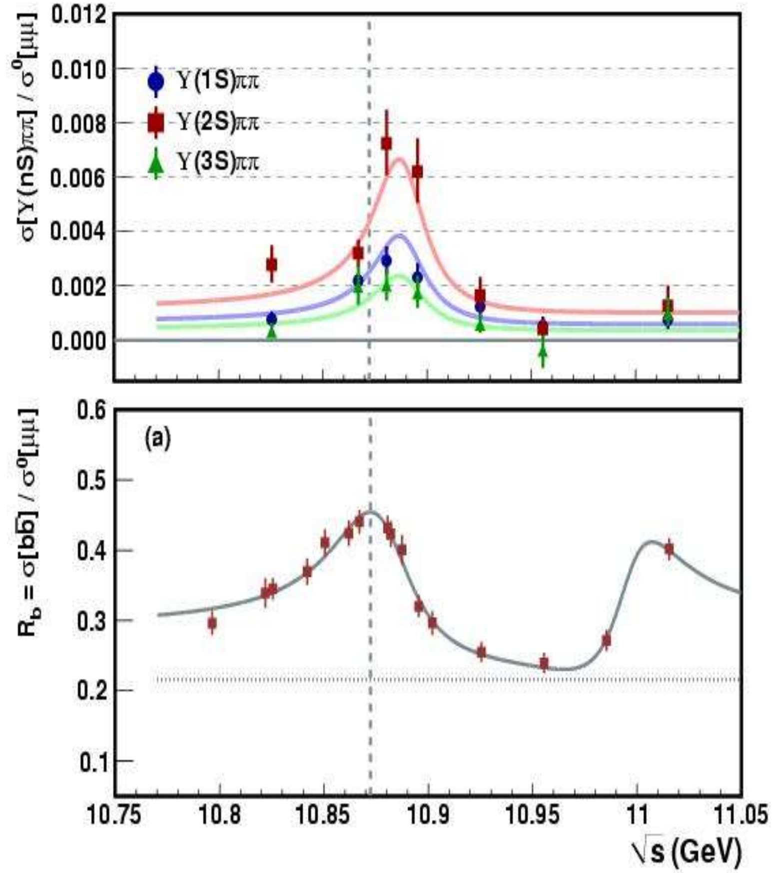
Anomalous production of Υ(nS) $\pi^+\pi^-$ with 21.7 fb^{-1}

PRL100,112001(2008)

	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

10^2

PRD82,091106R(2010)



Dedicated energy scan ⇒
shapes of R_b and σ(Υππ) different

Υ(5S) is very interesting and not yet understood
Finally Belle recorded 121.4fb^{-1} data set at Υ(5S)