The multiquark states in the b-quark sector - II/II

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Dubna 2013

Exotica

Belle & others [Zupanc et al. 09] , [Bondar et al., PRL 12] , [Liu et al., 13] , [Ablikim et al., 13]

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes	Also observed by	date
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$	BaBar*, BESII	2006
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi, D\bar{D}^*$	$B \to KX(3872), p\bar{p}$	BaBar CDF, D0	2003
$Z(3900)$	3899 ± 6	46 ± 22	1^+	$\pi^\pm J/\psi$	$Z(4260) \to Z(3900)\pi$	BESIII*	2013
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$		2009
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$		2009
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$		2005
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	$B \to KY(3940)$	BaBar	2005
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)		2005
$Z(4020)$	4022 ± 3	6 ± 4	1^+	$\pi^\pm J/\psi$	$Z(4260) \to Z(4020)\pi$	BESIII* (*only*)	2013
$Z(4025)$	4026 ± 5	25 ± 10	1^+	$\pi^\pm J/\psi$	$Z(4260) \to Z(4025)\pi$	BESIII* (*only*)	2013
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$		2008
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	BaBar*, CLEO	2005
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)	BaBar*	2007
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^- (ISR)		2008
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)		2007
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4050)$		2008
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4250)$		2008
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$		2007
$Z_b(10610)$	$10,607 \pm 2$	18.4 ± 2.4	1^+	$\pi^\pm h_b(1,2P), \pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10610)\pi$		2011
$Z_b(10650)$	$10,652 \pm 2$	11.5 ± 2.2	1^+	$\pi^\pm h_b(1,2P), \pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10650)\pi$		2011
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$		2008

Light states [PDG] :

$a_0(980)$ in 1965, $\sigma(600)^{\text{now } 500}$ in 1972, $f_0(980)$ in 1979, $\kappa(980)$ in 1997
discussion reopened: ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB 08]

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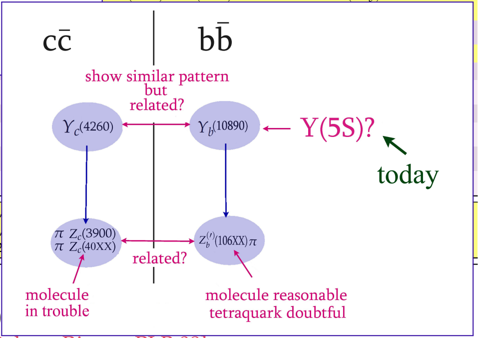
focus here:
$Z_c(3900, 4020, 4025)$
$Y_c(4260)$
$Z_b(106XX)$
$Y_b(10890)$



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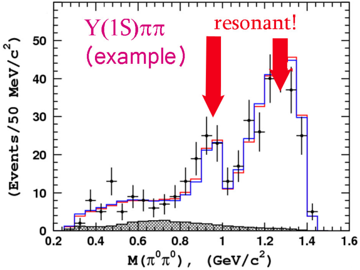
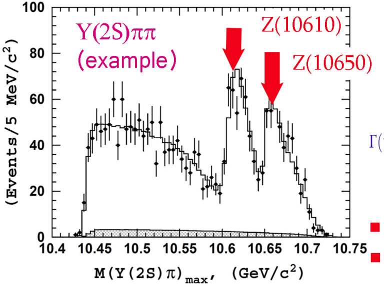
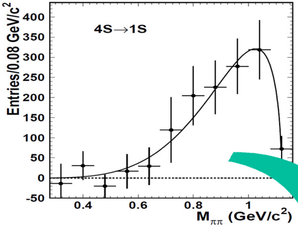
Why is the data @$\Upsilon(5S)$ anomalous?

[Belle Collaboration (2012)]

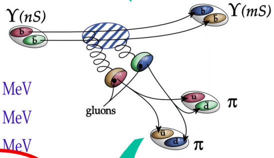






theory works well (multipole exp.) [Brown, Cahn PRL 75] [Voloshin, JETP 75]

Process:



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$\Gamma(\Upsilon(3S) \to \Upsilon(1S)\pi\pi) \approx 0.0009$ MeV

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$\Gamma(\text{“}\Upsilon(5S)\text{“} \to \Upsilon(1S)\pi^+\pi^-) \approx 0.59$ MeV

- distinct resonant structure ↯
- differs by two orders of Magnitude! ↯

- NO resonant structure
- Zweig forbidden

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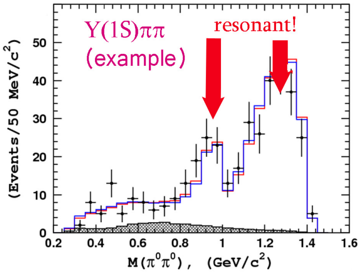

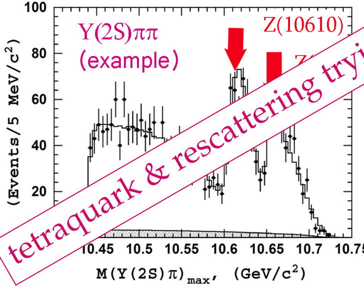

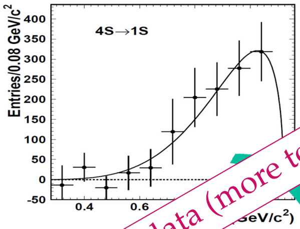

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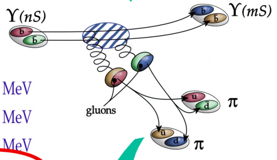
[Brown, Cahn PRL 75]
[Vo..., JETP 75]
...cess.



tetraquark & rescattering trying to explain data (more today)

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Tetraquark vs. Rescattering

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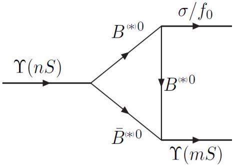

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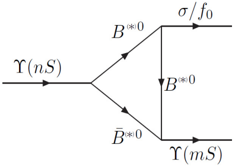
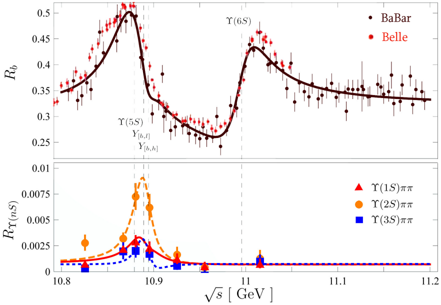


Rough estimate in Rescattering [Meng, Chao, PRD 08] :

$$\Gamma_{\Upsilon(6S)\to\Upsilon(1,2,3S)\pi\pi} \gtrsim \Gamma_{\Upsilon(5S)\to\Upsilon(1,2,3S)\pi\pi}$$

(Problem of approach:
introduced ad hoc form factor to suppress phase space enhancement)



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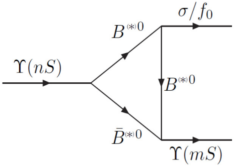

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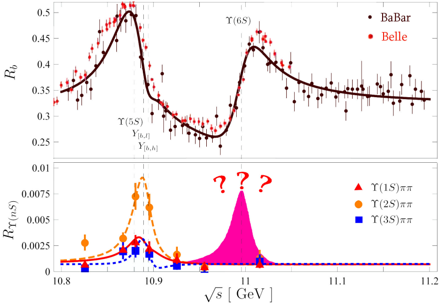


Establishing exoticness of Υ_b: Plan A

(isospin)

Plan A

- [Ali, CH, Aslam, PRL 10] [Ali, CH, Mishima, PRL 11] : model dependent assumption: point-like diquarks → isospin effects in e^+e^- production
- isodoublet structure $[bu][\bar{b}\bar{u}]$ and $[bd][\bar{b}\bar{d}]$ seen in different final states?

Experiment

channel	Z_b contribution
$\Upsilon(1S)\pi\pi$	negligible
$\Upsilon(2S)\pi\pi$	large
$\Upsilon(3S)\pi\pi$	large
$h_b(1P)\pi\pi$	dominant
$h_b(2P)\pi\pi$	dominant
$BB^*\pi$	dominant?
$B^*B^*\pi$	dominant?

Coupling Y_b & Z_b complicated
→ use „unpolluted" $\Upsilon(1S)PP'$
final states for Y_b analysis

theory

$e^+e^- \to Y_b \to \Upsilon(1S)PP'$

$PP' = \pi^+\pi^-, K^+K^-, \eta\pi^0$

fit data

$\Upsilon(1S)\,\pi^+\pi^-$

predict

$\Upsilon(1S)K^+K^-$

$\Upsilon(1S)\eta\pi^0$

Mixing of flavor states

- $Y_b^{(1)}$ mass eigenstates:

$$
\begin{aligned}
Y_{[b,l]} &= \cos\theta\, Y_{[bu]} + \sin\theta\, Y_{[bd]} \\
Y_{[b,h]} &= -\sin\theta\, Y_{[bu]} + \cos\theta\, Y_{[bd]}
\end{aligned}
$$

- mass breaking:

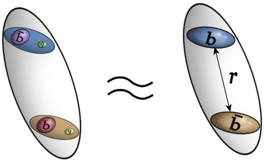
$$M(Y_{[b,h]}) - M(Y_{[b,l]}) = (7 \pm 3)\ \cos(2\theta)\ \mathrm{MeV}$$

- effective diquark charge:

$$
\begin{aligned}
Q_{Y_{[b,l]}} &= \frac{1}{3}\cos\theta - \frac{2}{3}\sin\theta \\
Q_{Y_{[b,h]}} &= -\frac{1}{3}\sin\theta - \frac{2}{3}\cos\theta
\end{aligned}
$$

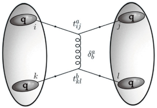
- $\theta = -45^\circ$ $\rightarrow$ Isospin eigenstates

Model assumptions



- One gluon exchange model

  ↪ Color factor determines binding:
  Negative sign → Attractive



- Quarks in diquark transform as:

$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \cancel{\mathbf{6}}$$

- qq bound state color factor:

$$t^a_{ij} t^a_{kl} = -\frac{2}{3} \underbrace{(\delta_{ij}\delta_{kl} - \delta_{il}\delta_{kj})/2}_{\text{antisymmetric: projects } \bar{\mathbf{3}}} + \frac{1}{3} \underbrace{(\delta_{ij}\delta_{kl} + \delta_{il}\delta_{kj})/2}_{\text{symmetric: projects } \mathbf{6}}$$

- diquarks small $SU(3)_C$ triplets

  ↪ model from *bb*-onia

- wave function described by Coulomb + linear potential

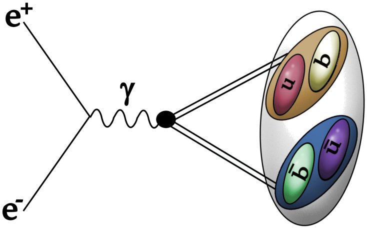
$$V(r) = -a\,\frac{1}{r} + b\,r$$

Y_b Production

- Van Royen-Weisskopf formula
  $\Rightarrow \Gamma(1^{--} \to e^+e^-)$

Assumption: Point-like diquarks

[Ali, CH, Mishima, PRL (2010)]



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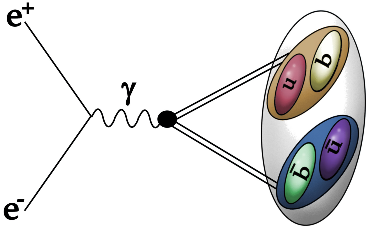

$$\Gamma_{ee}(Y_{[b,l/h]}) = \frac{24\alpha^2 Q^2_{[b,l/h]}}{M^4_{Y_{[b,l/h]}}} \kappa^2 \left|R^{(1)}_{11}(0)\right|^2$$

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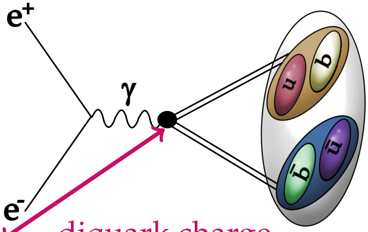

diquark charge

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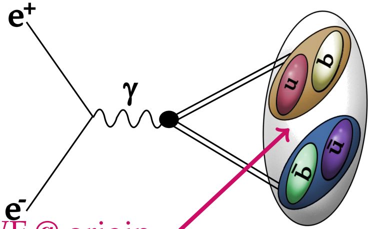

radial tetraquark WF @ origin

$$\Gamma_{ee}(\Upsilon_{[b,l/h]}) = \frac{24\alpha^2 Q^2_{[b,l/h]}}{M^4_{\Upsilon_{[b,l/h]}}} \kappa^2 \left| R^{(1)}_{11}(0) \right|^2$$

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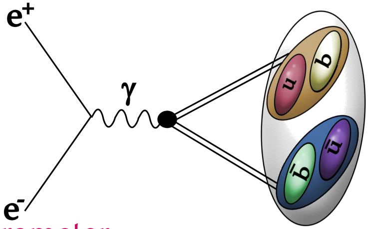

hadronic size parameter

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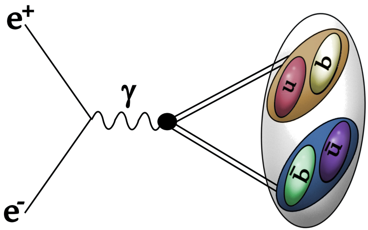

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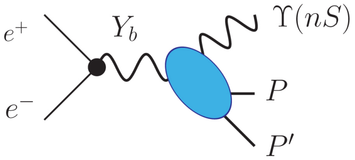
- Suppressed $\mathcal{O}(10)$ vs $\Upsilon(5S)$
- Production ratio: $\Gamma_{Y_{[b,l]}} / \Gamma_{Y_{[b,h]}} = \left(\frac{1-2\tan\theta}{2+\tan\theta}\right)^2$
- Isospin breaking through production

  e.g. $\frac{\sigma_{\Upsilon(1S)K^+K^-}}{\sigma_{\Upsilon(1S)K^0\bar{K}^0}} = \frac{Q^2_{[bu]}}{Q^2_{[bd]}} = \frac{1}{4}$

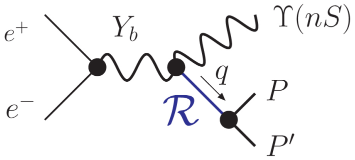
Y_b decay

Continuum



$+$

Resonance



- Breit-Wigner shape for resonance:

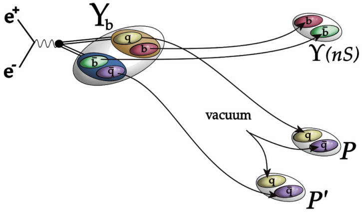
$$\frac{1}{(q^2 - M^2) + iM\Gamma}$$

$q^2 \equiv M^2_{PP'}$ → Resonances show in $M_{PP'}$ spectrum

Not in $M_{\Upsilon P}$ spectrum since Z_b negligible

Continuum Contribution

- Zweig allowed tetraquark continuum [Brown, Cahn, PRL (1975)] :



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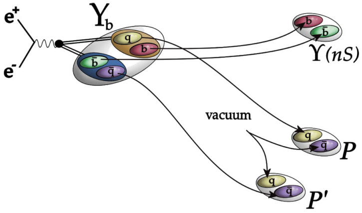
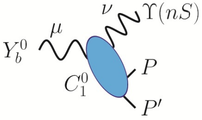
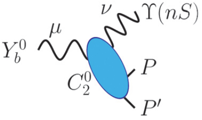
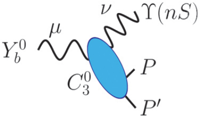


- Possible structures:



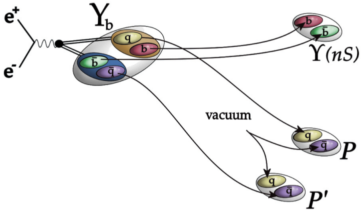




$\propto$ $g_{\mu\nu}$ $\qquad$ $\propto$ $g_{\mu\nu}(\cos^2\theta - \frac{1}{3})$ $\qquad$ $\propto$ $(k_{1\mu}k_{2\nu} + k_{2\mu}k_{1\nu})$

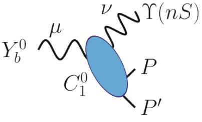
Continuum Contribution

- Zweig allowed tetraquark continuum [Brown, Cahn, PRL (1975)] :

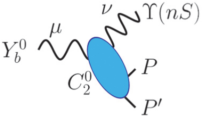


HQ spin interaction $\propto 1/m_b$

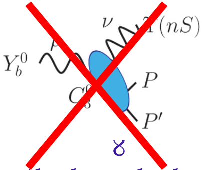
- Possible structures:



$\propto g_{\mu\nu}$



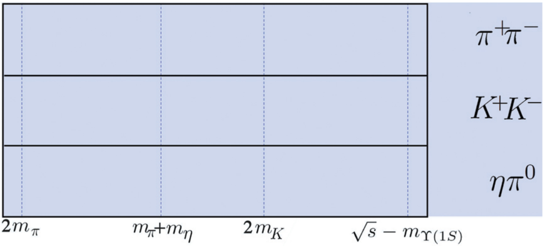
$\propto g_{\mu\nu}(\cos^2\theta - \frac{1}{3})$

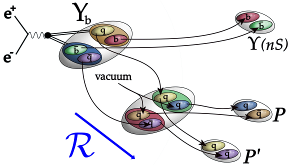


$\propto (k_{1\mu}k_{2\nu} + k_{2\mu}k_{1\nu})$

Resonances in $M_{PP'}$ Spectrum

- Resonance $\mathcal{R}$ contributions for each channel:





Resonances in $M_{PP'}$ Spectrum

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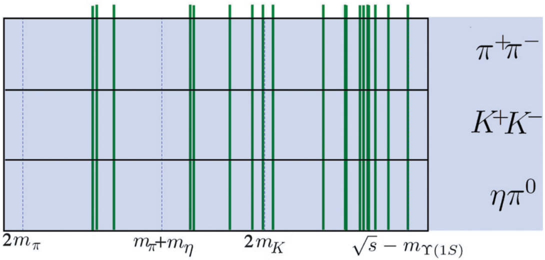

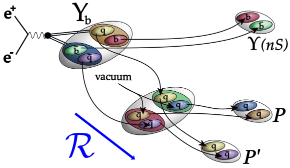

Resonances in $M_{PP'}$ Spectrum

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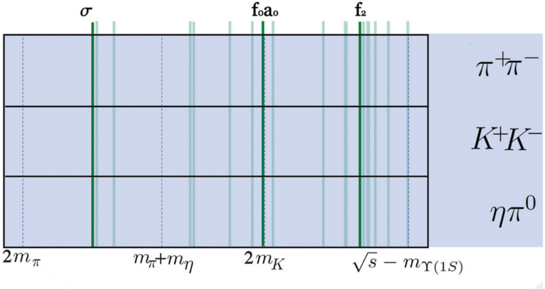
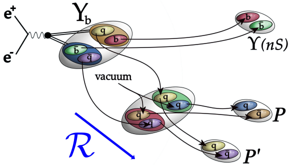
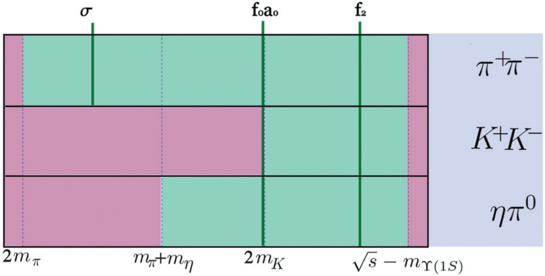


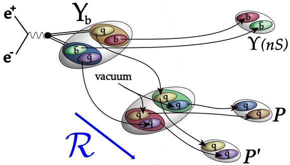


- Only 0^{++} and 2^{++} allowed

Resonances in $M_{PP'}$ Spectrum

- Resonance $\mathcal{R}$ contributions for each channel:





  - Only 0^{++} and 2^{++} allowed
  - Kinematical constraints

Resonances in $M_{PP'}$ Spectrum

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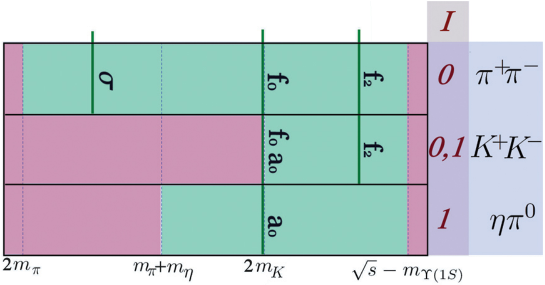

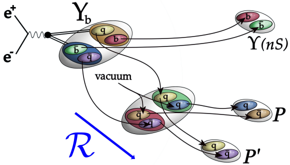

  - Only 0^{++} and 2^{++} allowed
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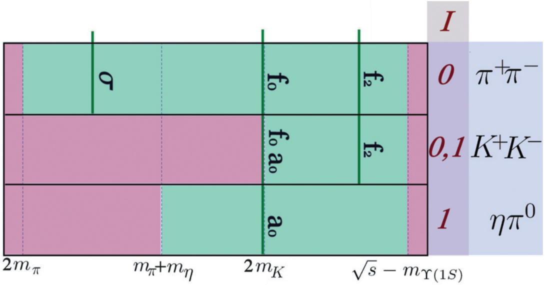
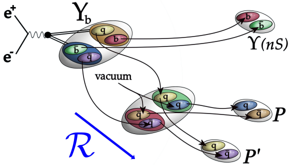
  - Final state isospin

Resonances in $M_{PP'}$ Spectrum

- Resonance $\mathcal{R}$ contributions for each channel:

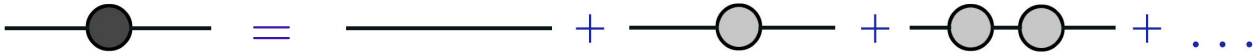




- Only 0^{++} and 2^{++} allowed
- Kinematical constraints
- Final state isospin
- Threshold effects for f_0, a_0, σ → Flatté formalism [Flatte, PLB (1976)]

Unstable (scalar) particles on thresholds

1 PI insertions:



$$= \frac{i}{p^2 - m_0^2} + \frac{i}{p^2 - m_0^2}(-iM^2)\frac{i}{p^2 - m_0^2} + \ldots$$

$$= \frac{i}{p^2 - m_0^2 - M^2(p^2)}$$

unstable → $M^2(p^2)$ imaginary, set $m^2 - m_0^2 - \mathrm{Re}M^2(p^2) = 0$

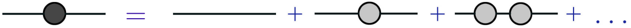
$$= \frac{iZ}{p^2 - m^2(p^2) - iZ\,\mathrm{Im}[\mathrm{M}^2(\mathrm{p}^2)]}$$

optical theorem:

$$Z\,\mathrm{Im}[M^2(p^2)] = -\mathrm{Im}[\mathcal{M}(a \to a)] = \frac{1}{2}\sum_f \int d\prod_f |\mathcal{M}(a \to f)| = -m\Gamma$$

Unstable (scalar) particles on thresholds

1 PI insertions:



$$= \frac{i}{p^2 - m_0^2} + \frac{i}{p^2 - m_0^2}(-iM^2)\frac{i}{p^2 - m_0^2} + \ldots$$

$$= \frac{i}{p^2 - m_0^2 - M^2(p^2)}$$

unstable → $M^2(p^2)$ imaginary, set $m^2 - m_0^2 - \mathrm{Re}M^2(p^2) = 0$

iZ

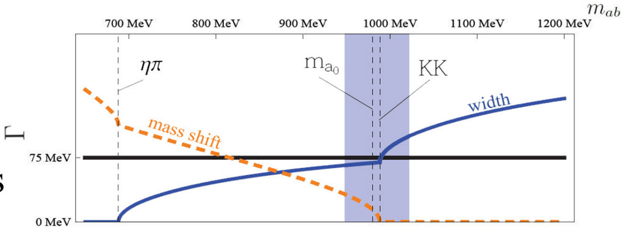
$\boxed{\text{Flatté: } m_0\tilde{\Gamma}(p^2) \equiv M^2(p^2),\ \tilde{\Gamma} \text{ complex}}$

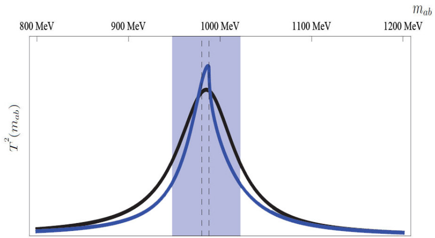
optical theorem:

$$Z\,\mathrm{Im}[M^2(p^2)] = -\mathrm{Im}[\mathcal{M}(a \to a)] = \frac{1}{2}\sum_f \int d\prod_f |\mathcal{M}(a \to f)| = -m\Gamma$$

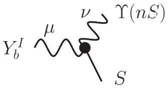
Unstable (scalar) particles on thresholds

shape changes
&
mass shifts,
depending on
couplings

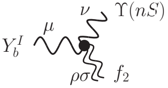




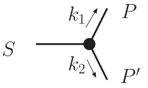
Effective Lagrangian



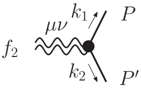
$i g_{Y_b \Upsilon S} g_{\mu\nu}$



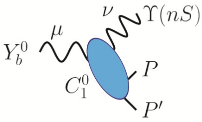
$i g_{Y_b \Upsilon f_2} g_{\mu\rho} g_{\nu\sigma}$



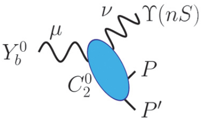
$-i g_{SPP'} k_1 . k_2$



$i g_{f_2 PP'} \frac{1}{2} \times$
$(k_1 - k_2)_\mu (k_1 - k_2)_\nu$



$g_{\mu\nu} ((\mathcal{M}_1^C)^2)$



$g_{\mu\nu} ((\mathcal{M}_2^C)^2) \left(\cos^2\theta - \frac{1}{3}\right)$

unknown transitions encoded in effective couplings $g, \mathcal{M}$

Υ_b Analysis

Different interfering contributions:

$\pi^+\pi^-$:

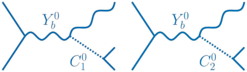
K^+K^-:

$\eta\pi^0$:

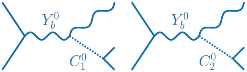
Y_b Analysis

Different interfering contributions:

$\pi^+\pi^-$:



K^+K^-

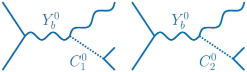


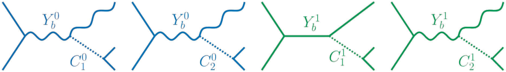
$\eta\pi^0$:

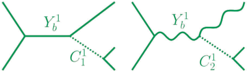
- $I = 0$ continuum

Y_b Analysis

Different interfering contributions:

$\pi^+\pi^-$: 

K^+K^- 

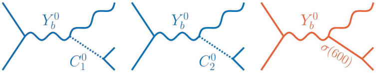
$\eta\pi^0$ 

● $I = 0$ continuum ● $I = 1$ continuum

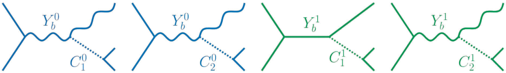
Y_b Analysis

Different interfering contributions:

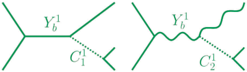
$\pi^+\pi^-$:



K^+K^-



$\eta\pi^0$



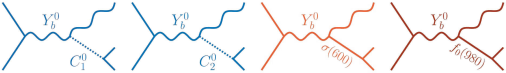
$I = 0$ continuum $I = 1$ continuum

$\sigma(600)$

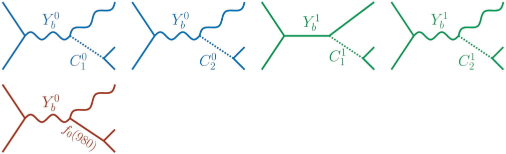
Y_b Analysis

Different interfering contributions:

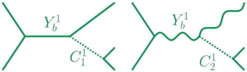
$\pi^+\pi^-$:



K^+K^-



$\eta\pi^0$

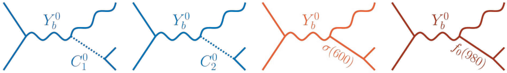


- $I = 0$ continuum
- $I = 1$ continuum
- $\sigma(600)$
- $f_0(980)$

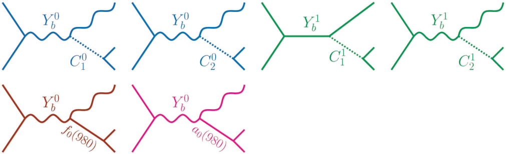
Y_b Analysis

Different interfering contributions:

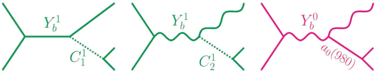
$\pi^+\pi^-$:



K^+K^-



$\eta\pi^0$



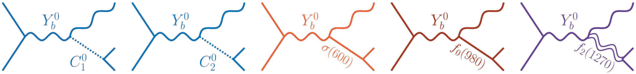
● $I = 0$ continuum ● $I = 1$ continuum

● $\sigma(600)$ ● $f_0(980)$ ● $a_0^0(980)$

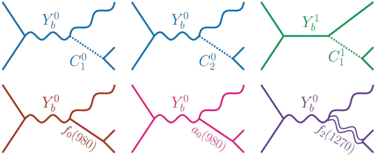
Y_b Analysis

Different interfering contributions:

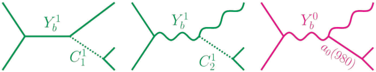
$\pi^+\pi^-$:



K^+K^-



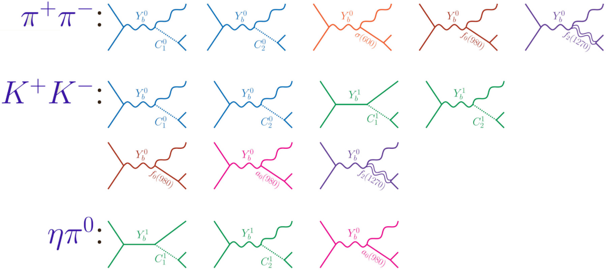
$\eta\pi^0$



$I = 0$ continuum　　$I = 1$ continuum

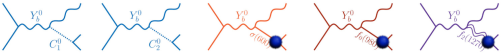
$\sigma(600)$　$f_0(980)$　$a_0^0(980)$　$f_2(1270)$

Couplings: Overview

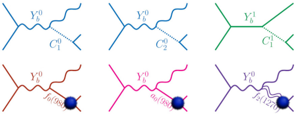


Couplings: Overview

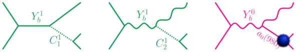
$\pi^+\pi^-$:



K^+K^-:



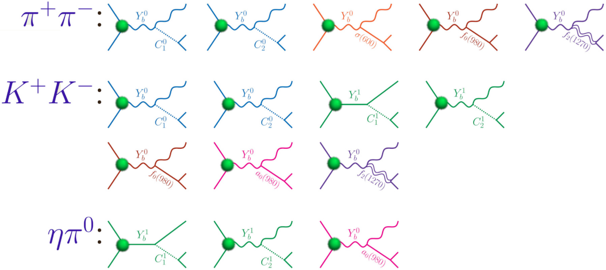
$\eta\pi^0$:



BES, CB, KLOE

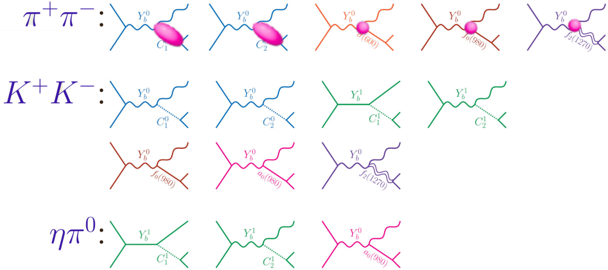
- known: Experimental input

Couplings: Overview



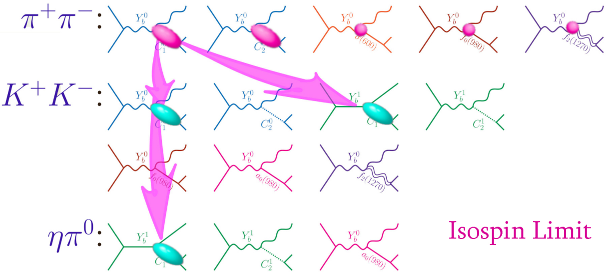
- known: Experimental input
- known: Our Van Royen-Weisskopf formula

Couplings: Overview



- known: Experimental input
- known: Our Van Royen-Weisskopf formula
- unknown: Fit parameters

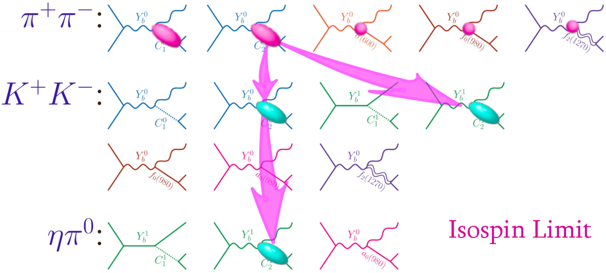
Couplings: Overview



- known: Experimental input
- known: Our Van Royen-Weisskopf formula
- unknown: Fit parameters → • predicted:

A', B', $g'_{Y_b^0\Upsilon(1S)\sigma}(= g'_{Y_b^0\Upsilon(1S)f_0})$, $g'_{Y_b^0\Upsilon(1S)f_2}$, φ_σ, φ_{f_0}, φ_{f_2}

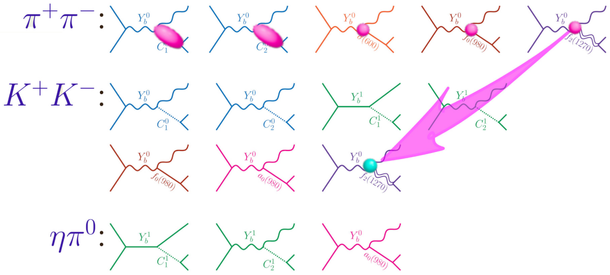
Couplings: Overview



- known: Experimental input
- known: Our Van Royen-Weisskopf formula
- unknown: Fit parameters → predicted:

$$A',\ B',\ g'_{\Upsilon_b^0\Upsilon(1S)\sigma}(=g'_{\Upsilon_b^0\Upsilon(1S)f_0}),\ g'_{\Upsilon_b^0\Upsilon(1S)f_2},\ \varphi_\sigma,\ \varphi_{f_0},\ \varphi_{f_2}$$

Couplings: Overview



- known: Experimental input
- known: Our Van Royen-Weisskopf formula
- unknown: Fit parameters → predicted:

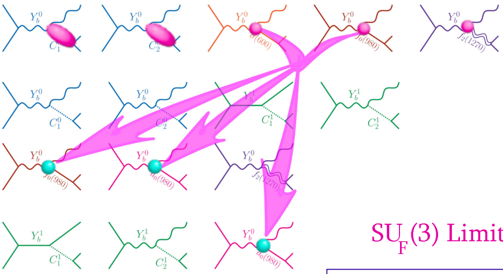
A', B', $g'_{\Upsilon_b^0\Upsilon(1S)\sigma}(=g'_{\Upsilon_b^0\Upsilon(1S)f_0})$, $g'_{\Upsilon_b^0\Upsilon(1S)f_2}$, φ_σ, φ_{f_0}, φ_{f_2}

Couplings: Overview

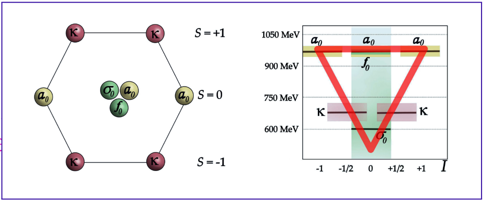
$\pi^+\pi^-$:

K^+K^-:

$\eta\pi^0$:



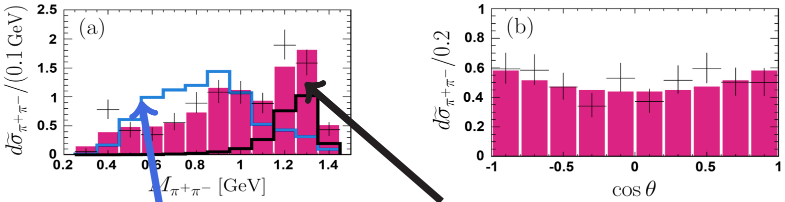
SU$_F$(3) Limit



- known: Experimental input
- known: Our Van Royen-Weisskopf
- unknown: Fit parameters → pre

$A', B', g'_{Y_b^0 \Upsilon(1S)\sigma} (= g'_{Y_b^0 \Upsilon(1S) f_0}), g'_{Y_b^0 \Upsilon(1S) f_2}, \varphi_\sigma, \varphi_{f_0}, \varphi_{f_2}$

Fit to $\sigma(e^+e^- \to Y_b \to \Upsilon(1S)\pi^+\pi^-)$



2^{++} meson $f_2(1270)$

0^{++} tetraquarks $\sigma(500)\ +\ f_0(980)$

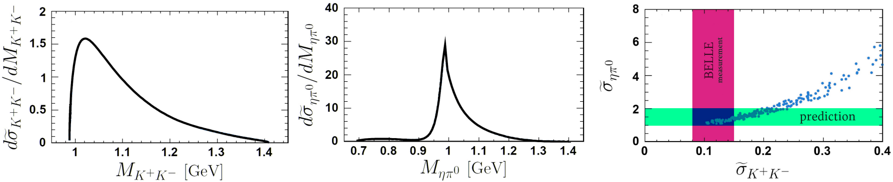
- Fit results, data from [Belle, PRL 08]
- $\chi^2/\mathrm{d.o.f.} = 21.5/15$ → Good agreement with data
- Clear resonance dominance!

($\tilde{\sigma}$: normalized to measurement)

Predictions for $\Upsilon(1S)(K^+K^-, \eta\pi^0)$

Fit determines couplings (assume $SU(3)$ flavor symmetry for couplings $(\sigma(500), f_0(980), a_0(980)) \rightarrow PP'$, ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB 08])

➥ predictions for spectra:



- Agreement with $\tilde{\sigma}_{K^+K^-} = 0.11^{+0.04}_{-0.03}$ (BELLE)
  - ➥ $1.0 \lesssim \tilde{\sigma}_{\eta\pi^0} \lesssim 2.0$ predicted
- Resonance dominance
  - ➥ Characteristic shape
    - ➥ **Excellent tests (relying on Y_b has 2 flavor states)**

Establishing exoticness of Y_b: Plan B

(hadroproduction)

Spectroscopy above Threshold

channel	spectrum	integrated	Z_b contribution
$\Upsilon(1S)\pi\pi$	✓	✓	negligible
$\Upsilon(2S)\pi\pi$	✓	✓	large
$\Upsilon(3S)\pi\pi$	✓	✓	large
$\Upsilon(1S)KK$	soon?	✓	
$\Upsilon(2S)KK$	not yet	not yet	
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$h_b(1P)\pi\pi$	✓	✓	dominant
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$\Upsilon(1S)\eta\pi^0$	not yet	not yet	
$\eta_b\rho\pi$	not yet	not yet	
$BB^*\pi$	✓	✓	dominant?
$B^*B^*\pi$	✓	✓	dominant?
@$\Upsilon(6S)$	BELLE II	BELLE II	

our prediction

important to confirm exotic state

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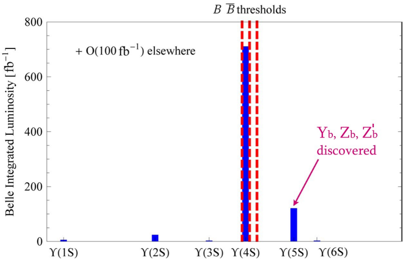

- multiquark states typically above hadronic thresholds
- few data for $b\bar{b}$ ($c\bar{c}$ advantage ISR & B decays)
- blank area likely full of surprises
- important to understand $b\bar{b}$ & $c\bar{c}$ simultaneously

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maybe sooner?

our prediction

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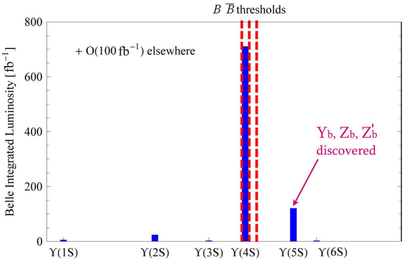

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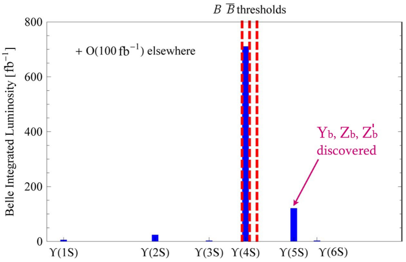

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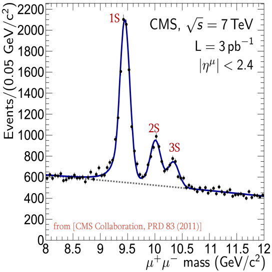
LHCb promising to map uncharted $b\bar{b}$ region including more than $J^{PC} = 1^{--}$

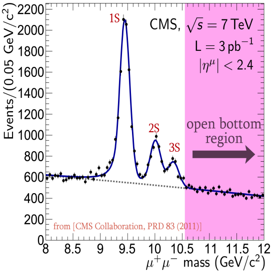
caveat: hadroproduction more complicated than electroproduction

Hadroproduction of Bottomonia



- $\mu^+\mu^-$ channel: Common particle detection for bottomonia

Hadroproduction of Bottomonia



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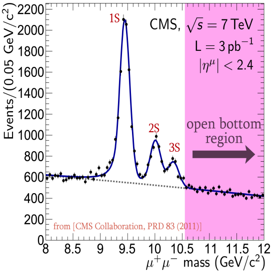

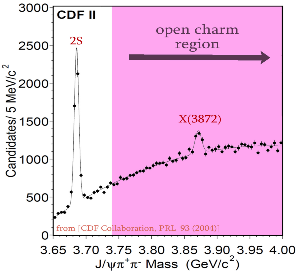

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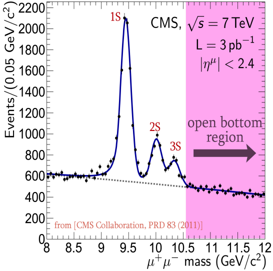

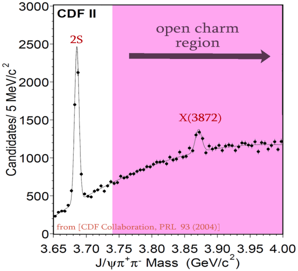

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[Ali, CH, Wang,13] :

Acquire knowledge of bottomonia above hadronic thresholds (NRQCD, pNRQCD [Brambilla, Pineda, Soto, Vairo, NP 00])

clarify nature of observed states

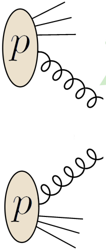
NRQCD details [see lecture Brambilla [sadly she can't come :-( ]]

$\sigma_N(p\bar{p}(p) \to \Upsilon + X)$

NRQCD details [see lecture Brambilla [sadly she can't come :-( ]]

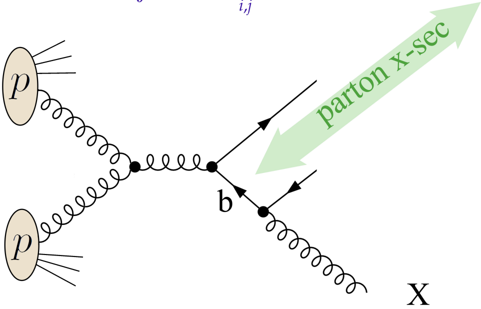
$$\sigma_N(p\bar{p}(p) \to \Upsilon + X) \quad = \quad \int dx_1 dx_2 \sum_{i,j} f_i(x_1) f_j(x_2)$$

convolute with PDFs



NRQCD details [see lecture Brambilla [sadly she can't come :-( ]]

$$\sigma_N(p\bar{p}(p) \to \Upsilon + X) \quad = \quad \int dx_1 dx_2 \sum_{i,j} f_i(x_1) f_j(x_2) \times \hat{\sigma}(ij \to \ \bar{b}b \quad + X)$$



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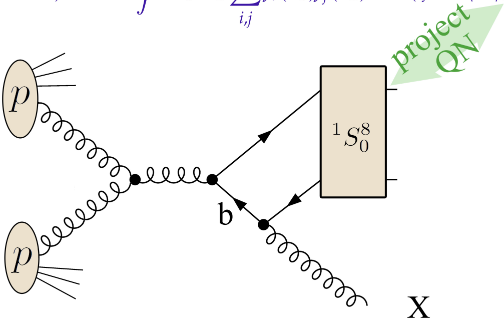

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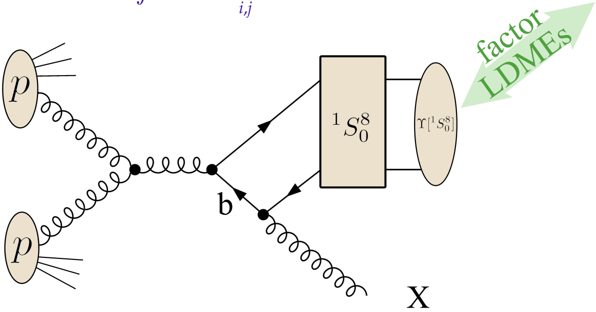

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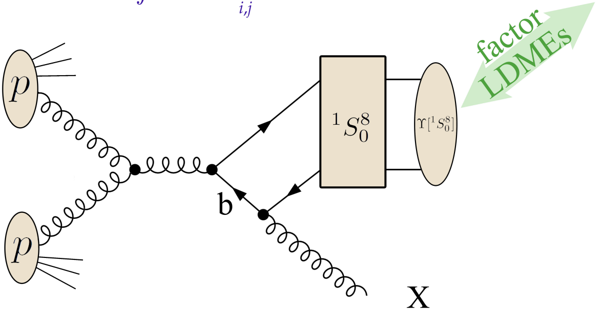


- partonic channels (include NLO for CS):
  $gg \to \Upsilon[^3S_1^1] + g,$ $\quad gg \to \Upsilon[^1S_0^8,\ ^3S_1^8] + g$
  $gq \to \Upsilon[^1S_0^8,\ ^3S_1^8] + q,$ $\quad q\bar{q} \to \Upsilon[^1S_0^8,\ ^3S_1^8] + g$
- calculate p_t distribution - take $p_t > 3$ GeV ➡ avoid soft gluon resummation
  $p_\Upsilon = \left(\sqrt{M_\Upsilon^2 + p_t^2}\cosh(y), p_t, 0, \sqrt{M_\Upsilon^2 + p_t^2}\sinh(y)\right)$

Collecting parts

- CS LDMEs from potential models via VRW (well-known)
- currently CO LDEMEs not known → large uncertainties if contribution sizable
- model dependence enters via $\mathcal{B}(\Upsilon(6S) \to \Upsilon(nS)\pi\pi)$ estimate

CS LDMEs:

at NLO

$$|R(0)|^2_{\Upsilon(5S)} = 2.37 \ \mathrm{GeV}^3$$

$$|R(0)|^2_{\Upsilon(6S)} = 1.02 \ \mathrm{GeV}^3$$

$$< O^H \ {}^3S_1^1 >= 3|R(0)|^2/(4\pi)$$

CO LDMEs $[10^{-2}\mathrm{GeV}^3]$:

H	$< O^H \ {}^1S_0^8 >$	$< O^H \ {}^3S_1^8 >$
$\Upsilon(1S)$	11.15 ± 0.43	-0.41 ± 0.24
$\Upsilon(2S)$	3.55 ± 2.12	0.30 ± 0.78
$\Upsilon(3S)$	-1.07 ± 1.07	2.71 ± 0.13

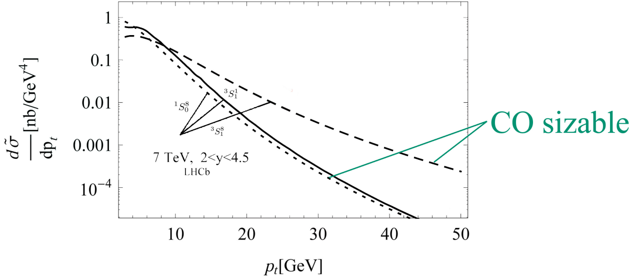
error estimate

[Gong, Wan,Wang, Zhang, 13]

Branching Ratios:

$\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-)$	$(0.53 \pm 0.06)\%$	@Υ(5S)
$\mathcal{B}(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)$	$(0.78 \pm 0.13)\%$	
$\mathcal{B}(\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-)$	$(0.48 \pm 0.18)\%$	
$\mathcal{B}(\Upsilon(6S) \to \Upsilon(1S)\pi^+\pi^-)$	$\approx 0.4\%$	rescattering model
$\mathcal{B}(\Upsilon(6S) \to \Upsilon(2S)\pi^+\pi^-)$	$(0.4 - 1.2)\%$	
$\mathcal{B}(\Upsilon(6S) \to \Upsilon(3S)\pi^+\pi^-)$	$(1.2 - 2.5)\%$	
$\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$	$(2.48 \pm 0.05)\%$	data
$\mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-)$	$(1.93 \pm 0.17)\%$	
$\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-)$	$(2.18 \pm 0.21)\%$	

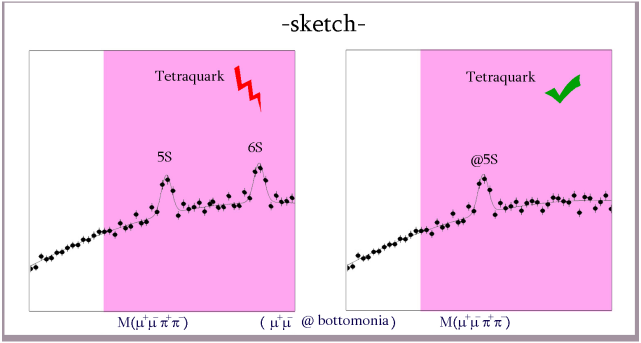
$p\bar{p}(p) \to \Upsilon(5S,6S) \to (\Upsilon(nS) \to \mu^+\mu^-)\pi^+\pi^-$ in pb



	$\Upsilon(5S)$			$\Upsilon(6S)$		
	$n=1$	$n=2$	$n=3$	$n=1$	$n=2$	$n=3$
Tevatron	2 ± 1	2 ± 1	1.2 ± 0.8	1.4 ± 1.0	2 ± 1	4 ± 3
LHC 7	9 ± 6	10 ± 7	7 ± 5	6 ± 4	9 ± 7	23 ± 17
LHCb 7	3 ± 2	3 ± 2	2 ± 1	2 ± 1	3 ± 2	7 ± 5
LHC 8	10 ± 7	12 ± 8	8 ± 5	7 ± 5	11 ± 8	27 ± 20
LHCb 8	3 ± 2	3 ± 2	2.4 ± 1.6	2.7 ± 2.0	3 ± 2	8 ± 6
LHC 14	19 ± 13	22 ± 15	15 ± 11	13 ± 10	20 ± 15	51 ± 39
LHCb 14	6 ± 4	7 ± 5	5 ± 3	4 ± 3	7 ± 5	17 ± 12

$\mathcal{O}$(pb) sufficient to be observed!

Expectations



Tetraquark refuted:

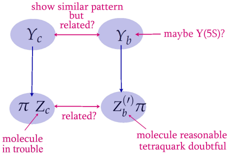
- $\pi^+\pi^-\mu^+\mu^-$ channel opens new possibilities for NRQCD and quarkonia production due to large *Br*

Tetraquark confirmed:

- important exotic state in $b\bar{b}$ confirmed
- HQ pattern established

Conclusions

- Mass estimates strongly model dependent - market is messy
- Important puzzle remains:



- Tetraquarks provide a credible explanation for BELLE anomaly @$Y(5S)$
- Predicted spectra for $Y_b(10980)$ provide crucial tests - final proof needed urgently!
- Hadrobroduction able to decide disputed nature of $Y_b(10980)$

Outlook

- Dedicated lattice studies are important
- Radiative decays may be theoretically treatable in QCDSR - need sufficient statistics
- Hadroproduction of bottomonia & tetraquarks very interesting in the near future!

  heaps of new states expected!


Exotica:
* nobody knows, whats going on
* good ideas more important, than extensive calculations
thank you!