(1) Z' to ZZ / *(2)* iQuarkonium

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(1) with Ian Low and Jing Shu
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(2) with Kingman Cheung and T.C. Yuan
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Table 17–2

Rotation matrices for spin one

Three states: $|+\rangle$, $m = +1$
$|0\rangle$, $m = 0$
$|-\rangle$, $m = -1$

$R_z(\phi)$	$\vert +\rangle$	$\vert 0\rangle$	$\vert -\rangle$
$\langle + \vert$	$e^{+i\phi}$	0	0
$\langle 0 \vert$	0	1	0
$\langle - \vert$	0	0	$e^{-i\phi}$

$R_y(\theta)$	$\vert +\rangle$	$\vert 0\rangle$	$\vert -\rangle$
$\langle + \vert$	$\frac{1}{2}(1 + \cos\theta)$	$+\frac{1}{\sqrt{2}}\sin\theta$	$\frac{1}{2}(1 - \cos\theta)$
$\langle 0 \vert$	$-\frac{1}{\sqrt{2}}\sin\theta$	$\cos\theta$	$+\frac{1}{\sqrt{2}}\sin\theta$
$\langle - \vert$	$\frac{1}{2}(1 - \cos\theta)$	$-\frac{1}{\sqrt{2}}\sin\theta$	$\frac{1}{2}(1 + \cos\theta)$

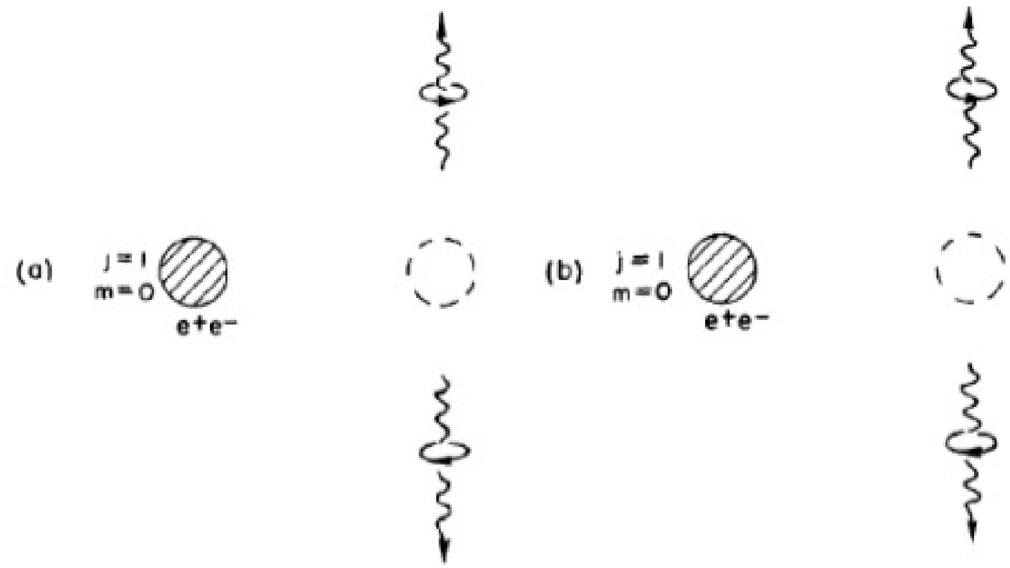

Fig. 18–7. For the $j = 1$ state of positronium, the process (a) and its 180° rotation about y (b) are exactly the same.

Feynman's Lecture III

Now we want to show that two-photon annihilation is not possible at all from the spin-one state. You might think that if we took the $j = 1$, $m = 0$ state—which has zero angular momentum about the z-axis—it should be like the spin-zero state, and could disintegrate into two RHC photons. Certainly, the disintegration sketched in Fig. 18–7(a) conserves angular momentum about the z-axis. But now look what happens if we rotate this system around the y-axis by 180°; we get the picture shown in Fig. 18–7(b). It is exactly the same as in part (a) of the figure. All we have done is interchange the two photons. Now photons are Bose particles; if we interchange them, the amplitude has the same sign, so the amplitude for the disintegration in part (b) must be the same as in part (a). But we have assumed that the initial object is spin one. And when we rotate a spin-one object in a state with $m = 0$ by 180° about the y-axis, its amplitudes change sign (see Table 17–2 for $\theta = \pi$). So the amplitudes for (a) and (b) in Fig. 18–7 should have opposite signs; the spin-one state *cannot disintegrate into two photons.*

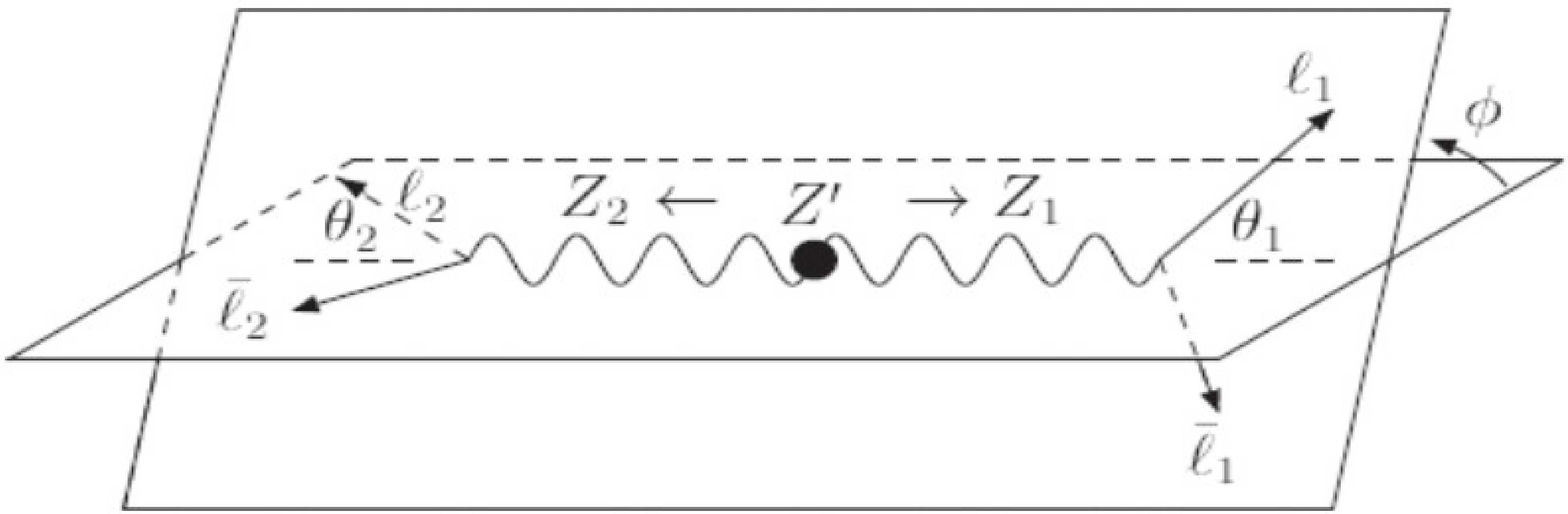

FIG. 1: *Two decay planes of $Z_1 \to \ell_1\bar{\ell}_1$ and $Z_2 \to \ell_2\bar{\ell}_2$ define the azimuthal angle $\phi \in [0, 2\pi]$ which rotates ℓ_2 to ℓ_1 in the transverse view. The polar angles θ_1 and θ_2 shown are defined in the rest frame of Z_1 and Z_2, respectively.*

$$O_{CPV} = f_4 Z'_\mu (\partial_\nu Z^\mu) Z^\nu, O_A = f_5 \epsilon^{\mu\nu\rho\sigma} Z'_\mu Z_\nu (\partial_\rho Z_\sigma)$$

Amplitudes

$$Z'(q_1+q_2,\mu) \to Z(q_1,\alpha)Z(q_2,\beta)$$

$$\Gamma^{\mu\alpha\beta}_{Z'\to Z_1 Z_2} = if_4(q_2^\alpha g^{\mu\beta} + q_1^\beta g^{\mu\alpha}) + if_5\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho.$$

$$\beta^2 = 1 - 4m_Z^2/m_{Z'}^2$$

$$\begin{aligned}\mathcal{M}_{+,+0} &= -\mathcal{M}_{-,0+} = R(-f_5\beta + if_4)\\ \mathcal{M}_{+,0-} &= -\mathcal{M}_{-,-0} = R(-f_5\beta - if_4)\end{aligned}$$

$$R = \frac{\beta m_{Z'}^2}{2m_Z}$$

$$\sum_{\kappa,h_1,h_2}\left|\sum_{\lambda_1,\lambda_2}\mathcal{M}_{\kappa,\lambda_1\lambda_2}\, g_{h_1} f^{h_1}_{\lambda_1}(\theta_1,\phi)\, g_{h_2} f^{h_2}_{\lambda_2}(\theta_2,0)\right|^2$$

$$f^h_m(\bar\theta,\bar\phi) = (1+mh\cos\bar\theta)\frac{e^{im\bar\phi}}{2},\ f^h_0(\bar\theta,\bar\phi) = \frac{h}{\sqrt{2}}\sin\bar\theta.$$

Amp. Squared sum

$$\mathcal{M}[+\to(+,0)\text{ or }(0,-)]_{RR} = +g_R^2[(1+\cos\theta)e^{i\phi}\sin\theta' + (1-\cos\theta')\sin\theta]$$

$$\mathcal{M}[+\to(+,0)\text{ or }(0,-)]_{LL} = -g_L^2[(1-\cos\theta)e^{i\phi}\sin\theta' + (1+\cos\theta')\sin\theta]$$

$$\mathcal{M}[-\to(-,0)\text{ or }(0,+)]_{RR} = +g_R^2[(1-\cos\theta)e^{-i\phi}\sin\theta' + (1+\cos\theta')\sin\theta]$$

$$\mathcal{M}[-\to(-,0)\text{ or }(0,+)]_{LL} = -g_L^2[(1+\cos\theta)e^{-i\phi}\sin\theta' + (1-\cos\theta')\sin\theta]$$

$$\mathcal{M}[+\to(+,0)\text{ or }(0,-)]_{RL} = -g_R g_L[(1+\cos\theta)e^{i\phi}\sin\theta' - \sin\theta(1+\cos\theta')]$$

$$\mathcal{M}[+\to(+,0)\text{ or }(0,-)]_{LR} = +g_L g_R[(1-\cos\theta)e^{i\phi}\sin\theta' - \sin\theta(1-\cos\theta')]$$

$$\mathcal{M}[-\to(-,0)\text{ or }(0,+)]_{RL} = -g_R g_L[(1-\cos\theta)e^{-i\phi}\sin\theta' - \sin\theta(1-\cos\theta')]$$

$$\mathcal{M}[-\to(-,0)\text{ or }(0,+)]_{LR} = +g_L g_R[(1+\cos\theta)e^{-i\phi}\sin\theta' - \sin\theta(1+\cos\theta')]$$

$$4(g_L^2+g_R^2)^2[1-\cos^2\theta\cos^2\theta' - \cos\theta\cos\theta'\sin\theta'\sin\theta\cos\phi] + 4(g_L^2-g_R^2)^2\sin\theta\sin\theta'\cos\phi$$

Universal Angular dependence

$$\frac{8\pi dN}{N\,d\cos\theta_1 d\cos\theta_2 d\phi} = \frac{9}{8}\left[1 - \cos^2\theta_1\cos^2\theta_2\right.$$

$$- \cos\theta_1\cos\theta_2\sin\theta_2\sin\theta_1\cos(\phi + 2\delta)$$

$$\left. + \frac{(g_L^2 - g_R^2)^2}{(g_L^2 + g_R^2)^2}\sin\theta_1\sin\theta_2\cos(\phi + 2\delta)\right]$$

Ang. Integrated Oscillation

$$\frac{2\pi dN_\pm}{N d\phi} = \frac{1}{2}\left[1 \mp \frac{1}{8}\cos(\phi + 2\delta) + \frac{9\pi^2}{128}\frac{(g_L^2 - g_R^2)^2}{(g_L^2 + g_R^2)^2}\cos(\phi + 2\delta)\right]$$

SM ZZ background 79 fb

For 100 fb^{-1} luminosity at the LHC, if we require the

ratio of the signal S to the statistical error in the background $\sqrt{B}$ to be 5

we need a signal (Z' to ZZ) about 70 fb for a 240 GeV Z'. To resolve the angular dependence, that requires 900 fb.

In the Littlest Higgs Model with T-parity, the predicted 1300 fb iQuarkonium

With Kingman Cheung and T.C. Yuan

THETA PARTICLES

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The hypothesis is considered, according to which there exist elementary particles of a new type, theta particles, their gauge interaction being characterized by a macroscopic radius of confinement. The quanta of the corresponding gauge field, thetons, are massless vector particles, analogous to gluons. The bound systems of two or three thetons have macroscopic dimensions. The existence of such objects is not excluded by experiment, as the interaction of thetons with ordinary particles must be very weak. However, the production of heavy theta leptons and theta quarks at accelerators would open the way to intensive creation of thetons and theta strings.

Infracolor QCD of Kang and Luty

New confining strong interaction with $\Lambda' \ll \text{TeV}$

In particular $\Lambda' \ll M_Q$

In infracolor QCD, quarks becomes quirks, gluons becomes infracolor gluons.

Quirks carries both SM quantum numbers and infracolor

In infracolor QCD, there are no light quirks.

Trendy names suggested

$$\begin{aligned} \text{quirk} &\quad\leftrightarrow\quad \text{iquark} \\ \text{infracolor gluon} &\quad\leftrightarrow\quad \text{igluon} \\ \text{infracolor glueball} &\quad\leftrightarrow\quad \text{iglueball} \end{aligned}$$

etc

$^1S_0$ neutral iquarkonium

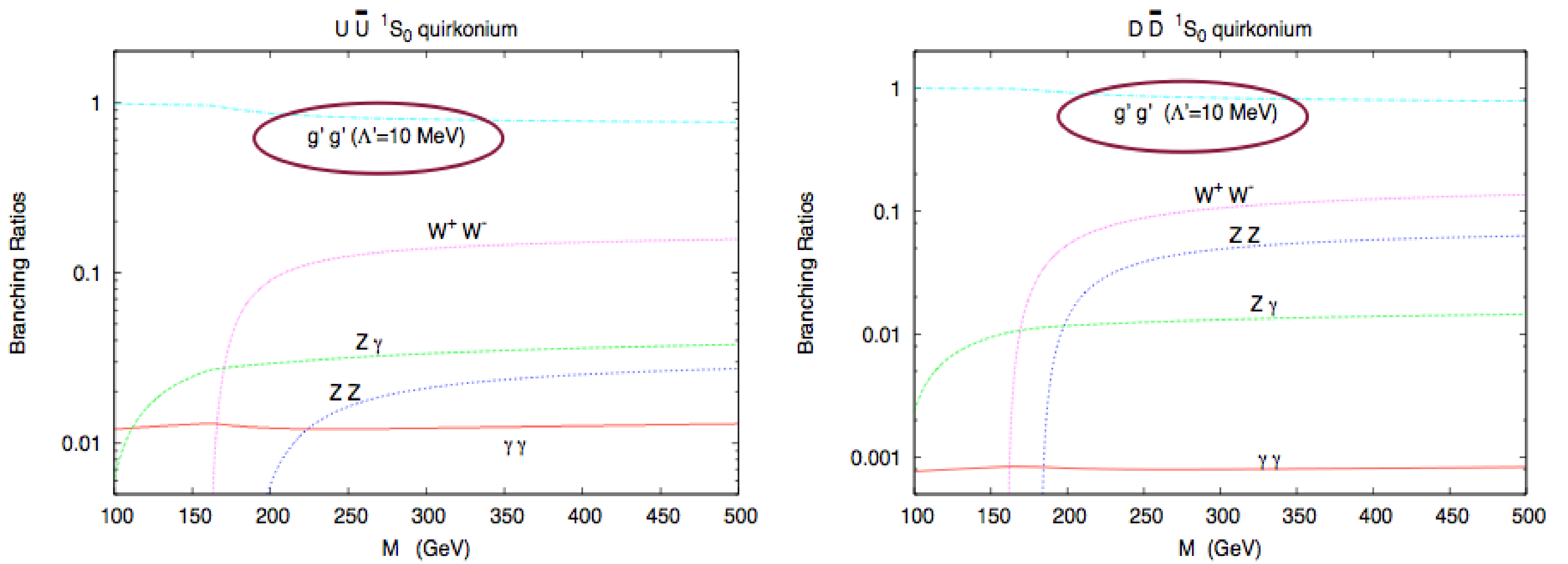

FIG. 2: Branching fractions of the quirkonium of (a) $^1S_0(\mathcal{U}\overline{\mathcal{U}})$ and (b) $^1S_0(\mathcal{D}\overline{\mathcal{D}})$ versus the quirkonium mass M. We have chosen $n_Q = 1$ and $\Lambda' = 10$ MeV in the running α'_s.

$^3S_1$ neutral iquarkonium

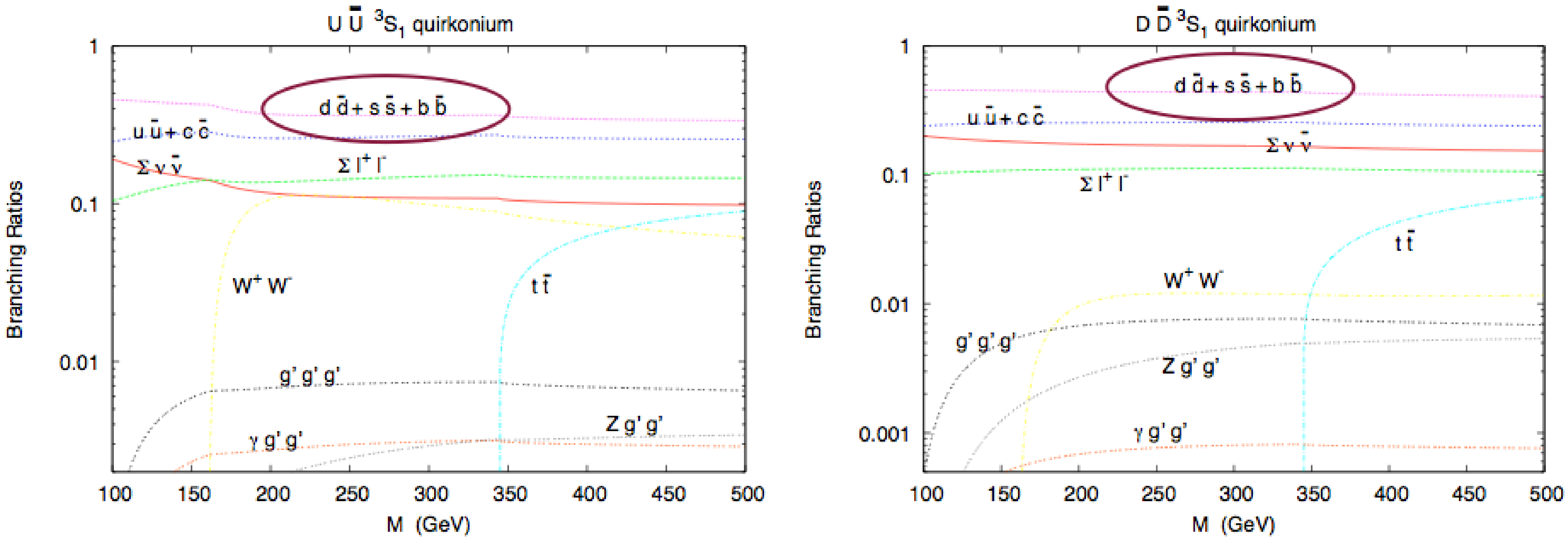

FIG. 3: Branching fractions of the quirkonium of (a) $^3S_1(\mathcal{U}\overline{\mathcal{U}})$ and (b) $^3S_1(\mathcal{D}\overline{\mathcal{D}})$ versus the quirkonium mass M. We have chosen $n_Q = 1$ and $\Lambda' = 10$ MeV in the running α'_s.

Major decay mode: 2-jet

WW mode has large cancellation among amplitudes for vector iQuarks