Some Phenomenology of iQCD

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Outline

- Introduction
- iQuarks Production at LHC
- Prompt Annihilation (After Energy Loss)
- Summary

Quirky papers

- Kang and Luty, arXiv:0805.4642
- Jacoby and Nussinov, arXiv:0712.2681
- Kang, Luty and Nasri, JHEP 0809, 086 (2008) hep-ph/0611322
- Burdman, Chacko, Goh, Harnik and Krenke, PRD78:075028 (2008) [arXiv:0805.4667]
- Cheung, Keung and Yuan, Nucl.Phys. B in press [arXiv:0810.1524]
- Harnik and Wizansky, arXiv:0810.3948
- Cai, Cheng and Terning, arXiv:0812.0843

Older papers

- Bjorken, SLAC-PUB-2372 (1979)
- Okun, JETP Lett. 31, 144 (1980); Nucl. Phys. B173, 1 (1980)
- Gupta and Quinn, PRD 25, 838 (1982)

Introduction

Un-motivation

Hidden Strongly Interacting Sector ?
Or New Physics NOT (directly) related to EW symmetry breaking ?

- A Familiar Example: Extra Z boson models
- Hidden Valley Models (Strassler)
- Unparticle (Georgi)
- Quirks and infracolor QCD (Luty)

Nuclear Physics B173 (1980) 1–12

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.

1. Introduction: what we call θ-particles

In a recent letter [1] a hypothesis was put forward on the existence of a new type of particle, the interaction of which has a macroscopic confinement radius. This interaction is caused by non-abelian gauge fields, whose quanta (we denote them θ and call thetons) are massless neutral vector particles, analogous to gluons. At distances of the order of 1 GeV^{-1} (we use units, in which $\hbar = c = 1$), the interaction between thetons is characterized by a coupling constant of the order of α ($\alpha = \frac{1}{137}$).

2. Why a new local group $SU(N)_\theta$ is not implausible

As is well-known, the existing theory of electroweak [2] and strong [3,4] interactions is based on gauge groups $U(1) \times SU(2)_w \times SU(3)_c$, their quanta being γ, W, Z, g. Alongside these groups, a number of other groups is considered in literature: for instance, the so-called "technicolor" [5] $SU(N)_{tc}$ with its technigluons, and the so-called horizontal [6] group $SU(N)_h$. A vast literature exists on the so-called models of grand unification [7] $SU(5), SO(10), SO(14) \ldots$. In the highest of these groups there are dozens and even hundreds of gauge particles. In this atmosphere the hypothesis on existence of another three ($SU(2)_\theta$) or eight ($SU(3)_\theta$) gauge particles does not look very courageous. So we postulate that the entire local group has the form:

$$U(1) \times SU(2)_w \times SU(3)_c \times \ldots \times SU(N)_\theta .$$

It may turn out that the θ-group may help to solve some problems on the way to grand unification, but we will not pursue this possibility here.

3. Why the existence of a large radius of confinement is not implausible

The main difference between the group $SU(N)$ and other gauge groups, considered in the literature, is that the θ-group has a very large and maybe even macroscopic radius of confinement. Let us show by tracing the analogy with QCD, that this assumption also does not look fantastic. As is well-known, confinement for QCD is not yet proved; nevertheless, the excellent quantitative agreement of QCD with experiment, and the absence [8] of free quarks around us (see, however, ref. [9]) make us believe that $SU(3)_c$ confines. Furthermore, QCD phenomenology suggests that Λ_c is not far from 0.1 GeV, where $1/\Lambda_c$ is the confinement radius. It

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 infracolor and SM quantum numbers

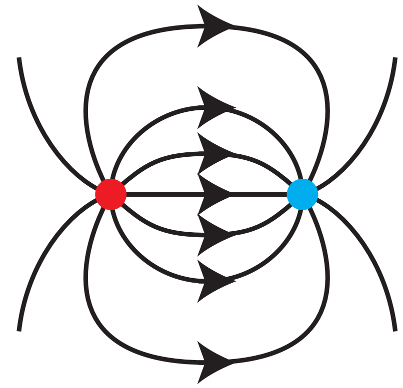
In infracolor QCD, there are no light quirks.

In QCD $\Lambda_{\text{QCD}} > m_\pi$, light quark-antiquark pairs can be easily created from the vacuum by string breaking

Heavy quirk-antiquirk pairs created from the vacuum by string breaking are exponentially suppressed.

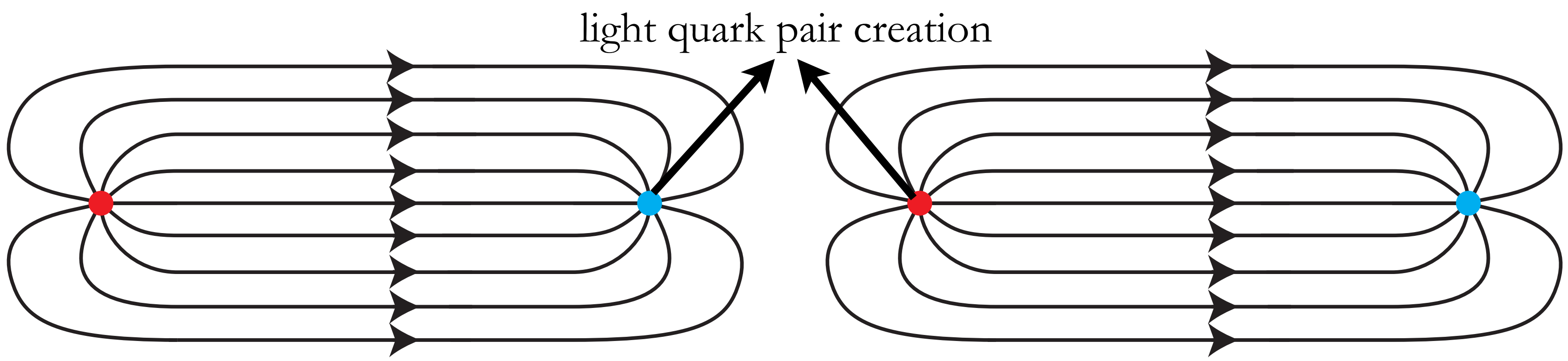
Unconfined

Couloumb potential dominates for small r

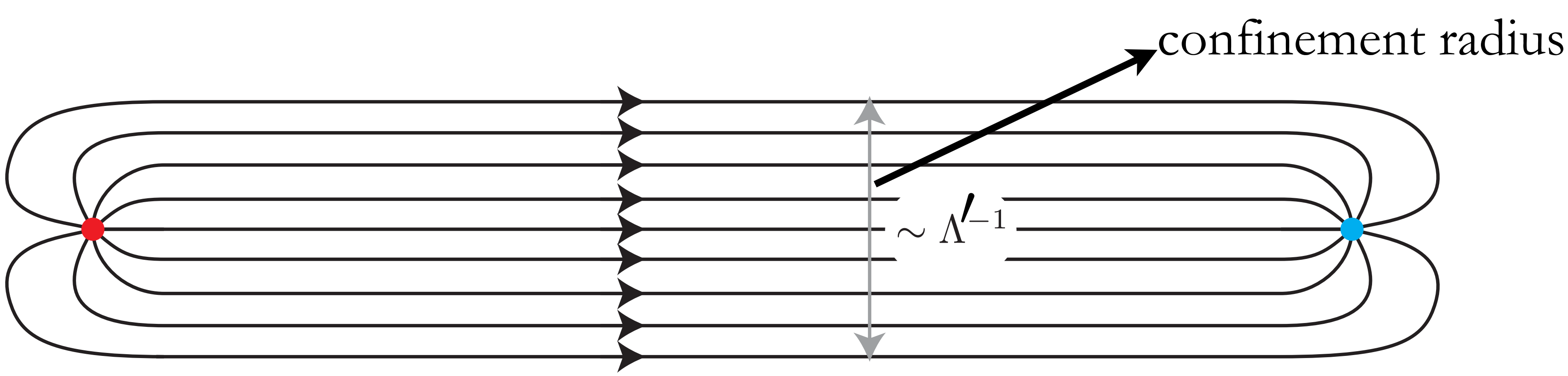


Confined breakable string => Independent fragmentation

$\Lambda \gg 2m_q$



Confined unbreakable string $(\Lambda' \ll 2m_Q)$



Tension $\approx \Lambda'^2$

Suppression of soft hadronization

[Bjorken (1979); Gupta and Quinn (1982)]

QCD

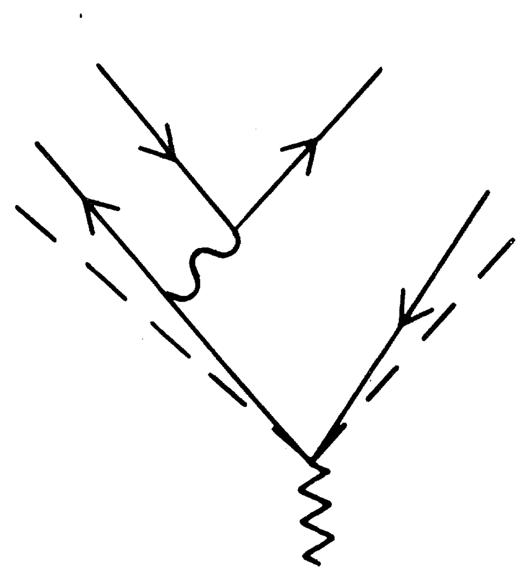
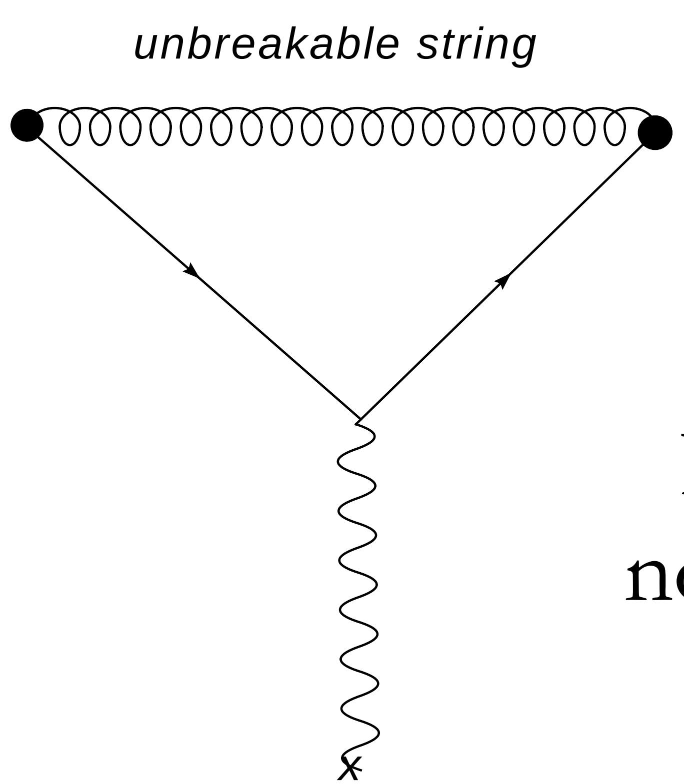


FIG. 1. A diagram for color neutralization by quark-antiquark pair production. The diagram also indicates space-time evolution in the center-of-mass frame. The dashed line indicates the light cone.

iQCD



NP stringy effect is important, not suppressed at high Q squared

Trendy names suggested

$$\text{quirk} \leftrightarrow \text{iquark}$$

$$\text{infracolor gluon} \leftrightarrow \text{igluon}$$

$$\text{infracolor glueball} \leftrightarrow \text{iglueball}$$

$$\text{etc}$$

$$\text{infracolor Object} \leftrightarrow \text{iObject}$$

(e.g. iMesons, iBaryons, etc)

Size of the string

Kinetic Energy of iQuark ~ String Potential Energy

$$\text{K.E.} = \sqrt{\hat{s}} - 2M_Q \sim M_Q$$

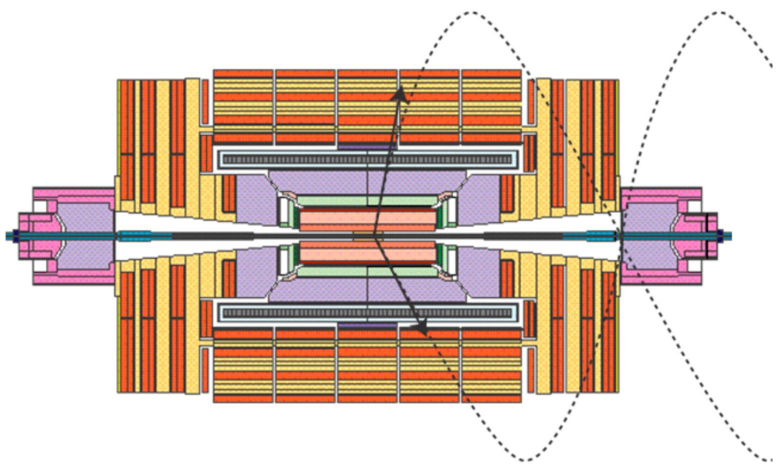
$$\text{String potential energy} \approx \Lambda'^2 L$$

$$L \approx \frac{M_Q}{\Lambda'^2} \approx 10\text{ m} \left(\frac{M_Q}{\text{TeV}}\right) \left(\frac{\Lambda'}{100\text{ eV}}\right)^{-2}$$

Phenomenology depends sensitively on size of string!

Macroscopic String

$$100\,\text{eV} \leq \Lambda' \leq 10\,\text{keV} <==> \text{mm} \leq L \leq 10\,\text{m}$$



quirky tracks

(Luty's Talk)

String tension causes the quirky tracks bent differently from those SM charged particles

Reconstruction algorithms fail to identify quirky tracks $\rightarrow$ Missing Energy

Energy loss mechanism: bremsstrahlung, ionization, etc.

Large lever arm =>Angular momentum de-coherence

=> iQuarks pair not easily meet to form bound states.
But one single quirky track event is sufficient for its discovery.

Mesoscopic String

$$10\ \text{keV} \leq \Lambda' \leq \text{MeV} \leftrightarrow \text{Å} \leq L \leq \text{mm}$$

- Too small to be resolved in detector but larger than atomic scale
- iQuark-anti-iQuark pair appears as single particle in the detector
- Matter interaction might be efficient to randomize angular momentum and prevent annihilation
- Otherwise, might lead to displaced vertex before annihilation

Microscopic String

$$\mathrm{MeV} \leq \Lambda' \leq \mathrm{GeV} \leftrightarrow 100\,\mathrm{fm} \leq L \leq 100\,\mathring{\mathrm{A}}$$

iQuarks are confined into bound states

Salient features:

$$K.E. \approx M_Q \leftrightarrow \text{highly excited}$$

$$L \gg \Lambda'^{-1} \leftrightarrow \text{classical string}$$

$$J \approx rp \approx M_Q^{-1} M_Q \approx 1 \quad \Rightarrow \quad \text{nearly spherical}$$

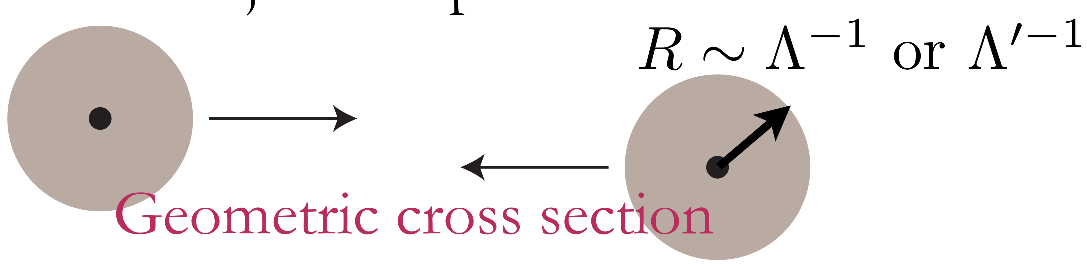
No large lever arm to randomize angular mom

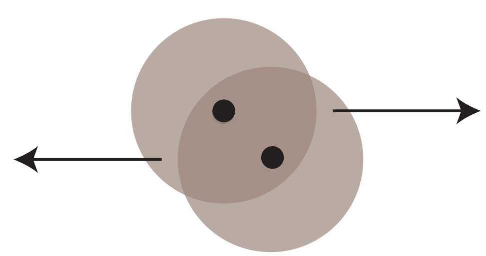
Prompt annihilation of these highly excited states?

Energy Loss when 2 iQuarks cross (Prevent Annihilation)

QCD/iQCD ``brown muck/imuck'' NP interactions ==> Energy Loss

Bjorken's picture





Wave function overlapp (WKB)

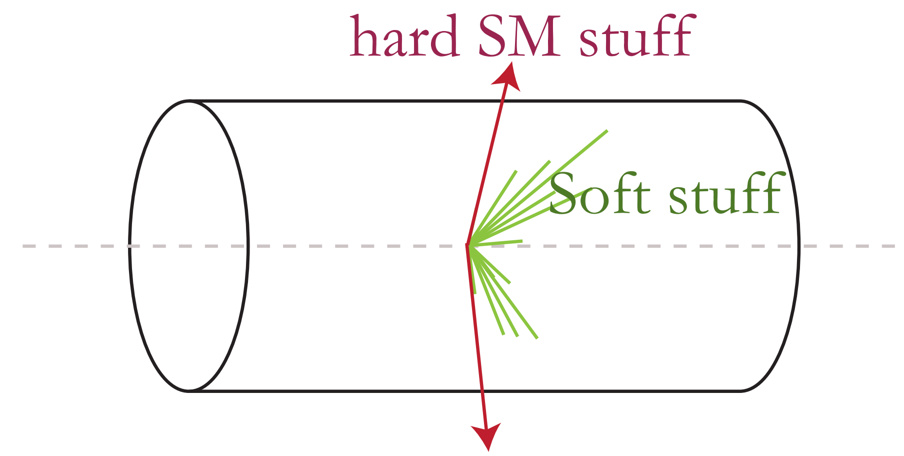
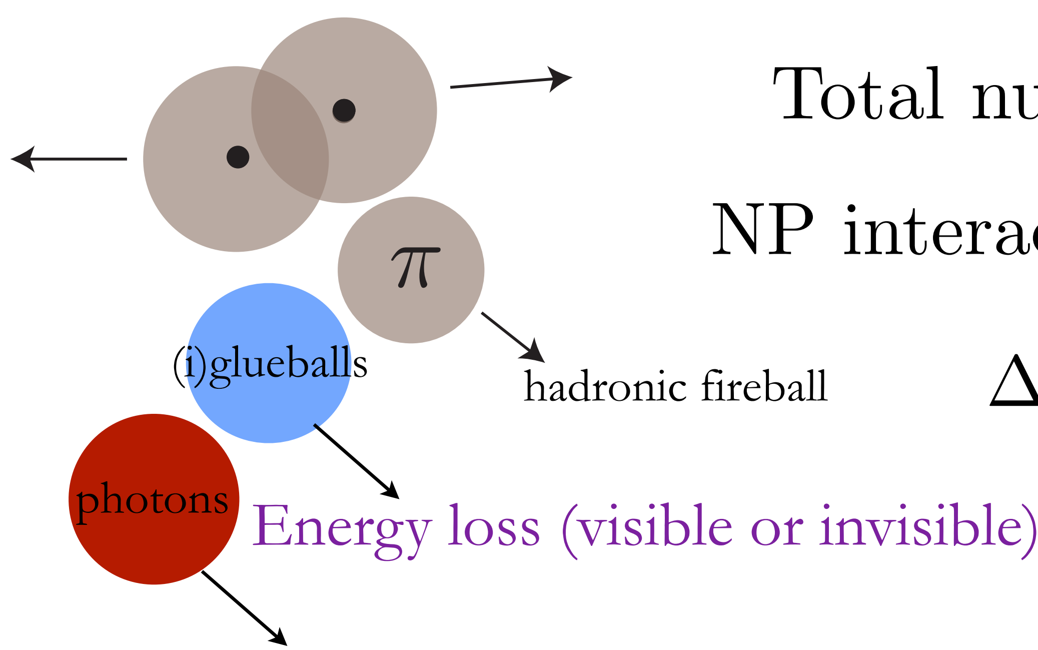


Fig. 9. Schematic depiction of hadronic fireball and hard annihilation into muons. Note that the the asymmetry of the muons and the fireball are in the same direction.



Total number of crossings $\sim M_Q/\Lambda \sim 10^3$

NP interaction effective up to $l_{max} \sim M_Q/\Lambda \sim 10^3$

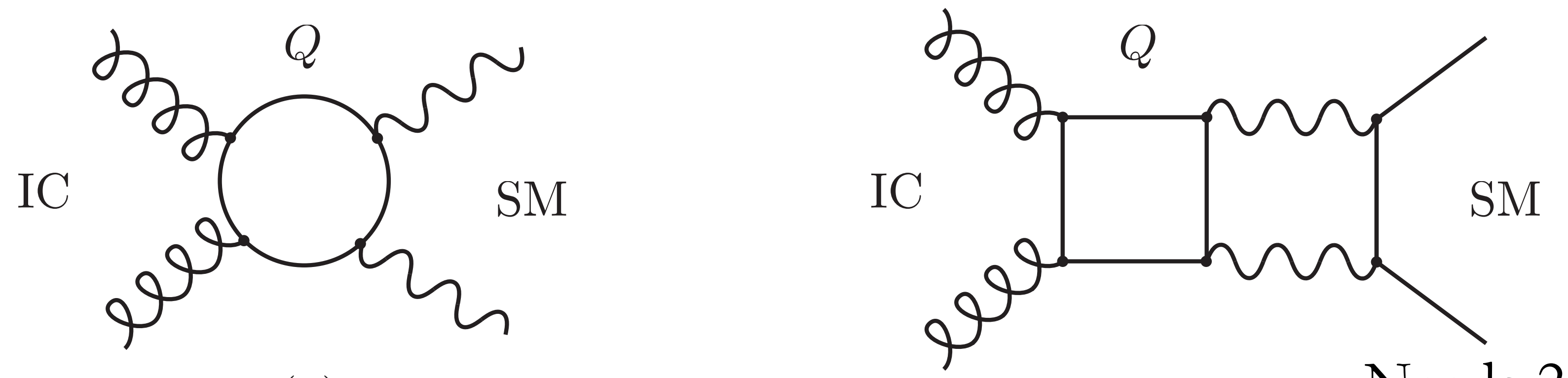
$\Delta E \sim$ GeV or Λ' per crossing

$\Delta L \sim 1$ each crossing

(Kang and Luty)

Can iGlueballs detectable?

iGluons do not carry SM charge ==> Loop Effects



(a) (b)

Needs 2 loop to couple to SM fermions

$$\mathcal{L}_{\text{eff}} \sim \frac{g^2 g'^2}{16\pi^2 m_Q^4} F_{\mu\nu}^2 F_{\rho\sigma}'^2 .$$

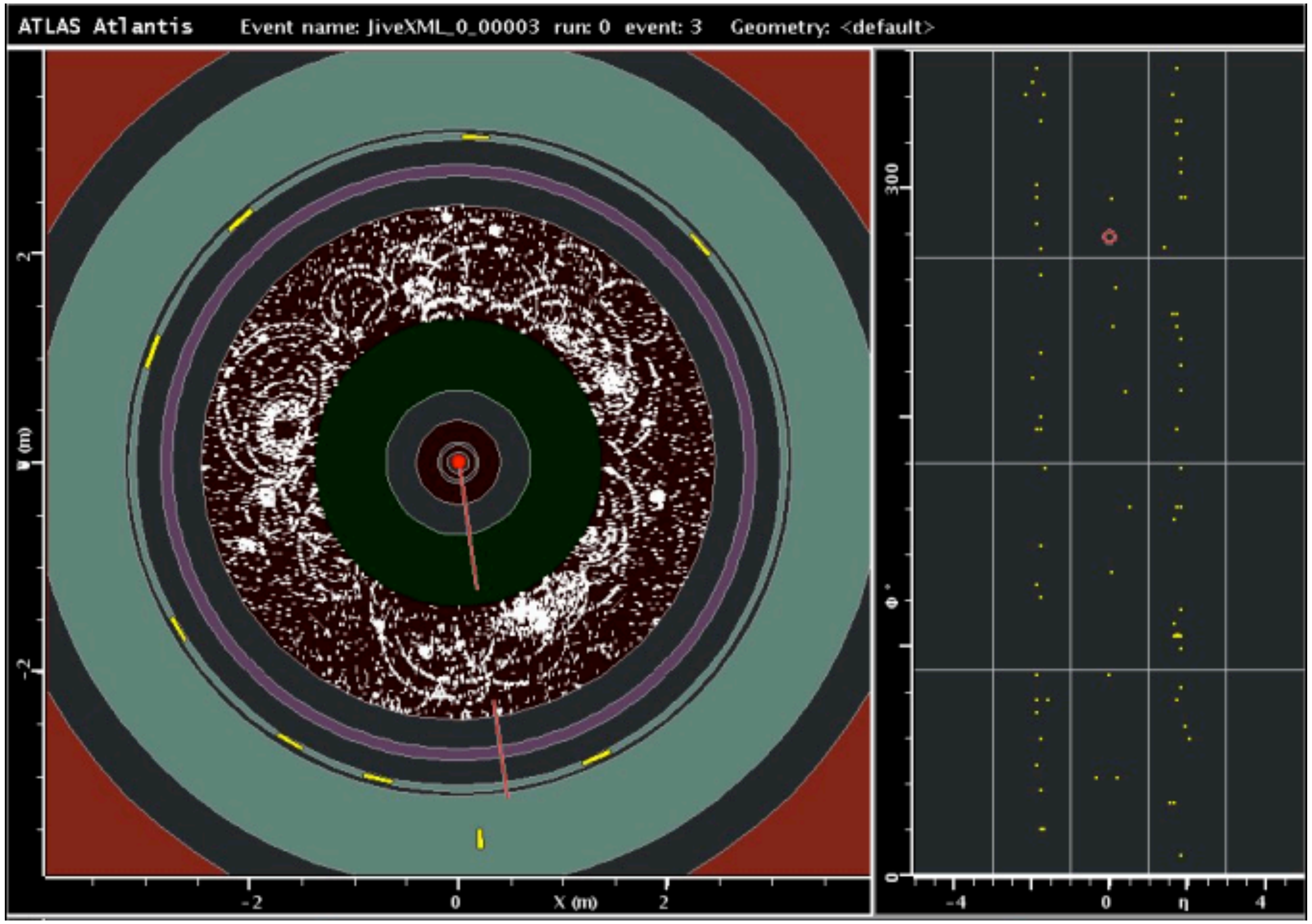
$$\Gamma \sim \frac{1}{8\pi} \left(\frac{g^2 g'^2}{16\pi^2 m_Q^4} \right)^2 \Lambda^9 .$$

$$c\tau \sim 10 \text{ m} \left(\frac{\Lambda}{50 \text{ GeV}} \right)^{-9} \left(\frac{m_Q}{\text{TeV}} \right)^{-8} .$$

$\Lambda' \geq 50$ GeV, iglueball decays inside detector

Electromagnetic Shower

Soft photons of this energy can be picked up by the tracking system, as seen in this picture from the ATLAS event display. (Cheu and Parnell-Lampen)



Taken from Chacko's talk

Harnik and Wizansky [arXiv:0810.3948]

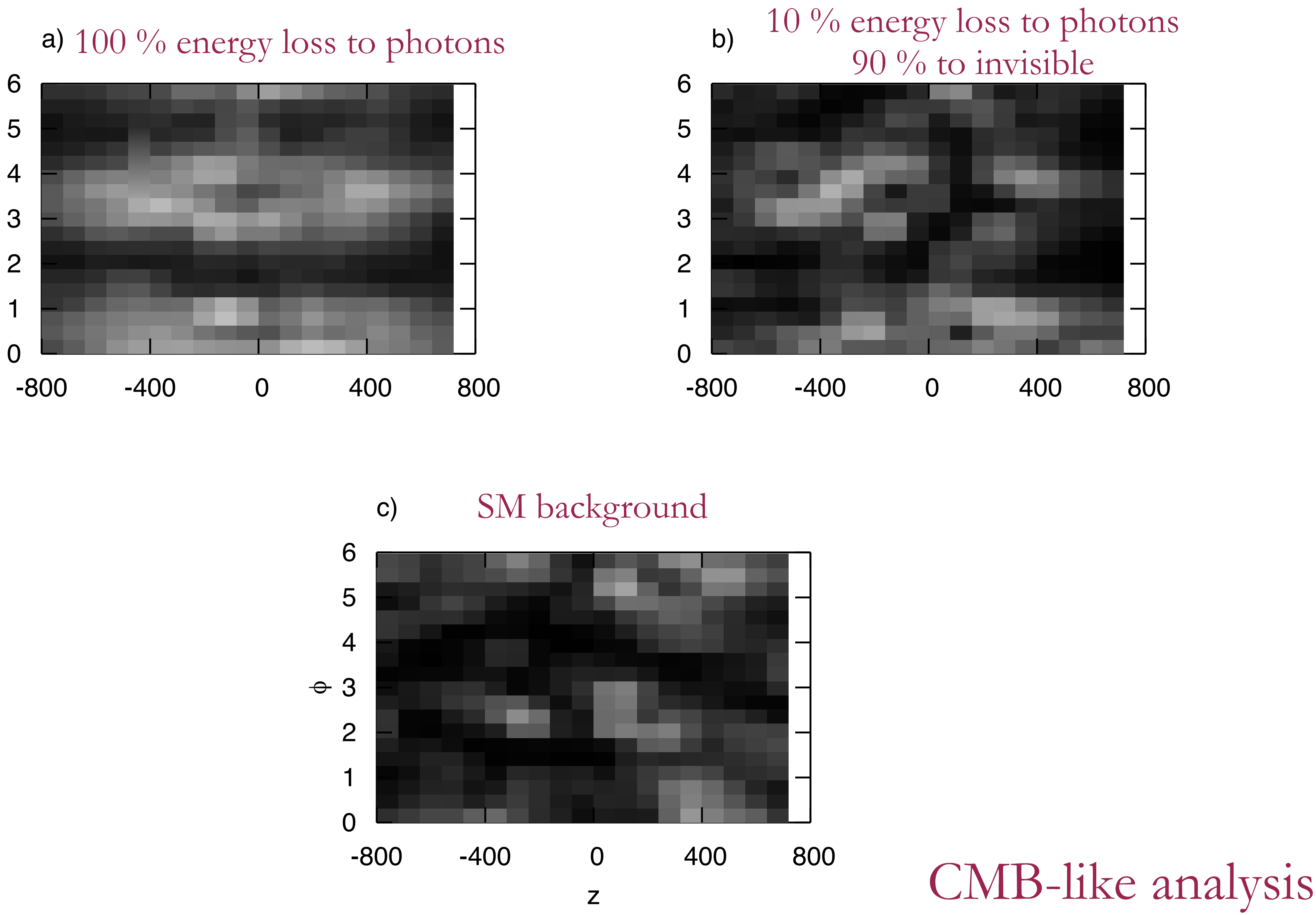
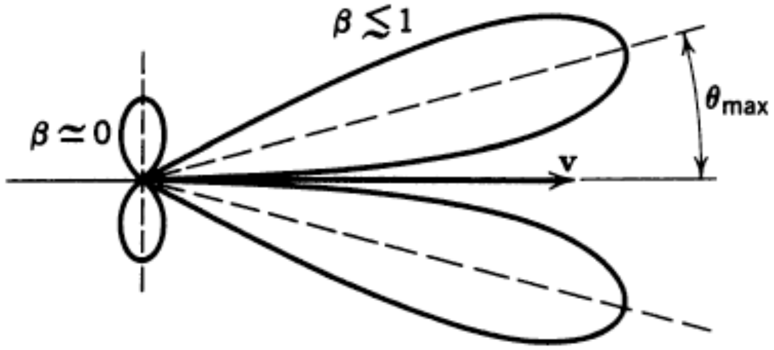


Figure 5: Calorimeter energy deposition in the toy detector simulation. The distribution is shown for (a) bound state radiation with 100% of the energy released in photons, (b) bound state radiation with 10% of the energy in photons and (c) a minimum bias event. Brighter squares indicate a higher energy deposition in the cell, however, the scale itself is arbitrary for each figure separately.

Cartoon from Harnik and Wizansky [arXiv:0810.3948]

`Antenna Pattern'



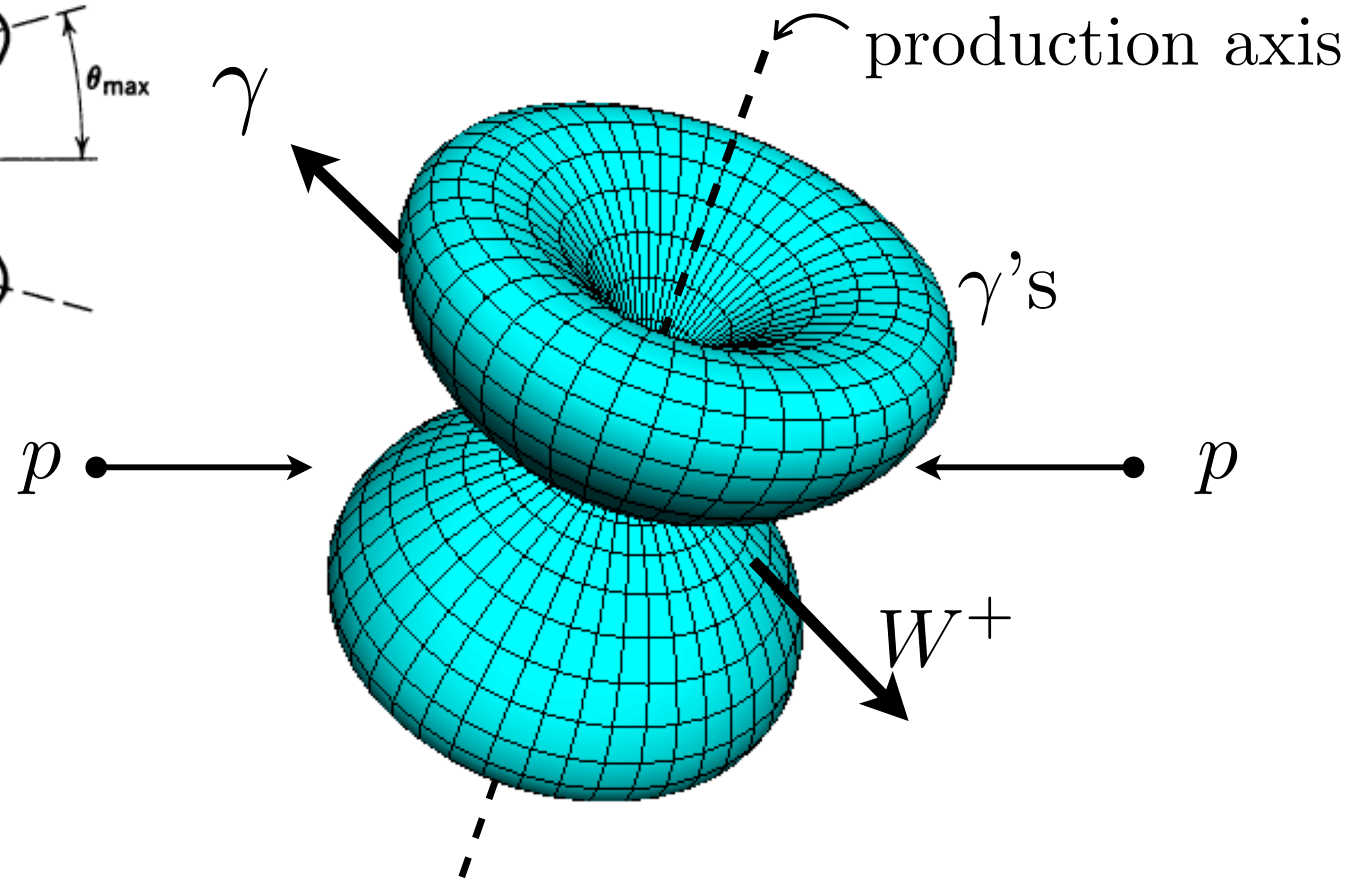


Figure 1: A schematic cartoon of the initial and final states of an LHC event with squirk production via an s-channel $W^{\pm}$. The two protons are incoming along the horizontal axis. The squirks are produced and oscillate along the dashed axis. The final state includes an antenna pattern of soft photons (two cone like shapes aligned with the squirk production axis) and a pair of hard annihilation products, $W\gamma$ in this case. The search strategy will first involve discovering a resonance in $W\gamma$ and then searching for signals of patterns of soft photons in the candidate signal events.

iQuark Production at LHC

A Simple Model $SU_{C'}(N_{\rm IC}) \times SU_C(3) \times SU_L(2) \times U_Y(1)$

[Cheung, Keung and TCY, 0810.1524]

Vectorial

$$\mathcal{Q}_{L,R} = \begin{pmatrix} \mathcal{U} \\ \mathcal{D} \end{pmatrix}_{L,R} \sim \left(N_{\rm IC}, 1, 2, \frac{1}{3}\right)$$

Assume MeV $\leq \Lambda' \ll M_Q$

(Microscopic string scenario)

$$\begin{aligned} \mathcal{L}_{\rm gauge} = & - g'_s G'^a_\mu \overline{\mathcal{Q}} \gamma^\mu T^a \mathcal{Q} - e A^\mu \left(e_\mathcal{U} \overline{\mathcal{U}} \gamma^\mu \mathcal{U} + e_\mathcal{D} \overline{\mathcal{D}} \gamma^\mu \mathcal{D} \right) \\ & - \frac{g}{\cos\theta_W} Z_\mu \left(v_\mathcal{U} \overline{\mathcal{U}} \gamma^\mu \mathcal{U} + v_\mathcal{D} \overline{\mathcal{D}} \gamma^\mu \mathcal{D} \right) - \frac{g}{\sqrt{2}} \left(W^+_\mu \overline{\mathcal{U}} \gamma^\mu \mathcal{D} + W^-_\mu \overline{\mathcal{D}} \gamma^\mu \mathcal{U} \right) \end{aligned}$$

$$v_Q = \frac{1}{2} \left(T_3(Q_L) + T_3(Q_R) \right) - e_Q \sin^2\theta_W$$

Fractional charged θ-leptons of Okun

Vectorial => Escape constraints from LEP EW precision data

No Yukawa coupling with SM Higgs

But a Dirac bare mass term is possible

Quarkonium Production

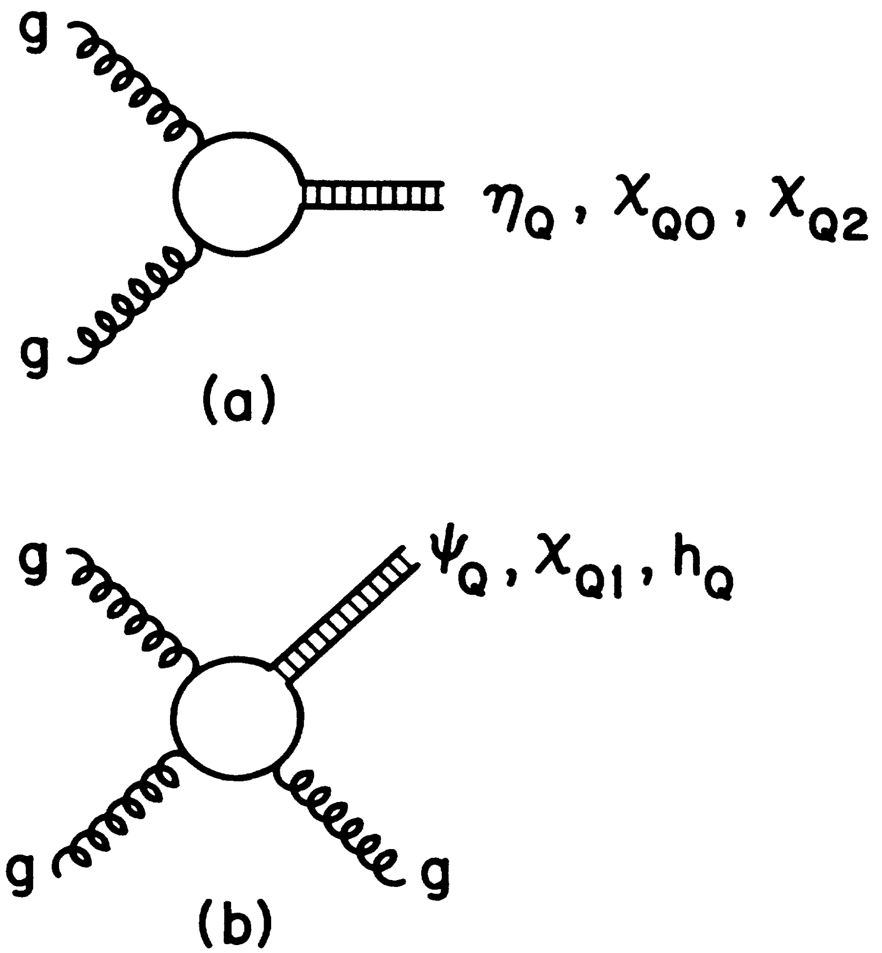
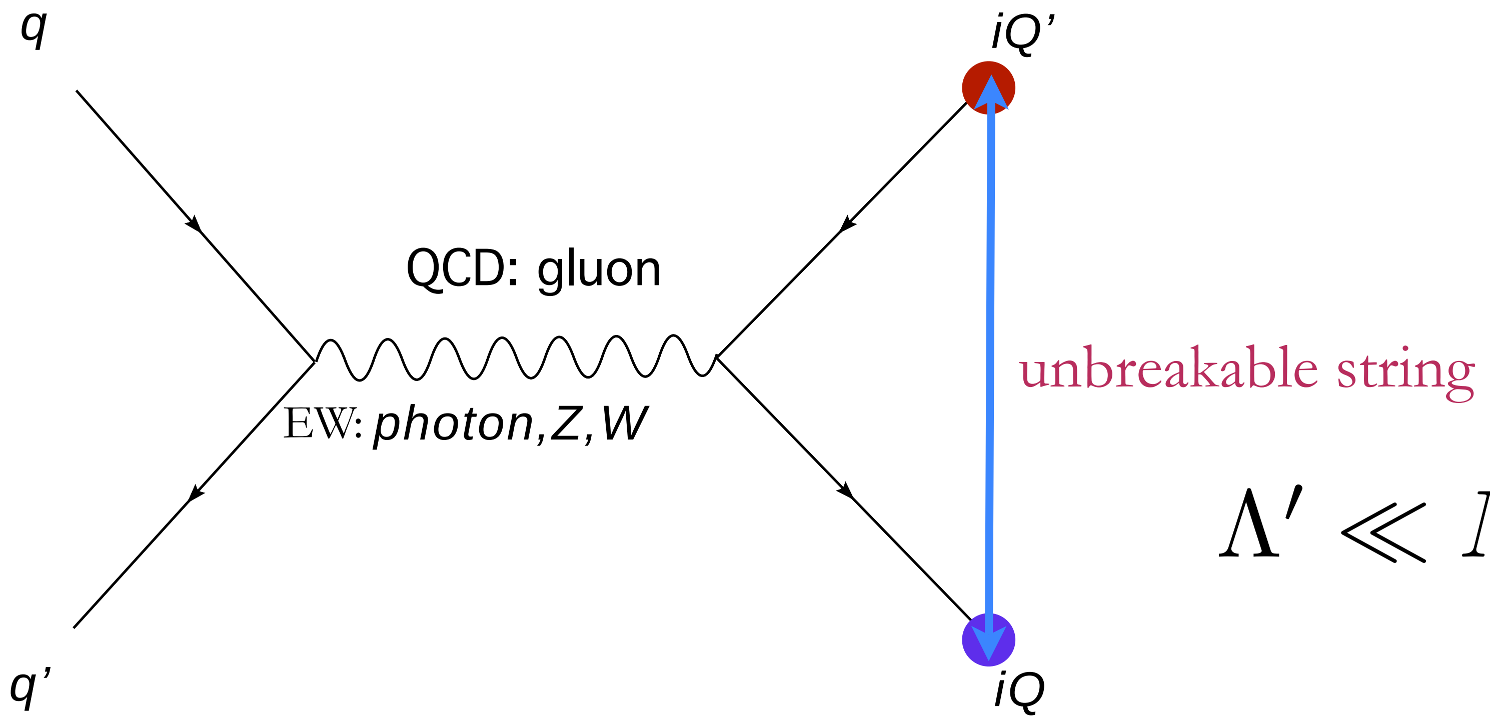


FIG. 5. Feynman diagrams for the production of the *S*- and *P*-wave quarkonium states by gluon collisions.

Plus fragmentation, color octet mechanism as well.

Colored/Uncolored iQuarks are produced via QCD/Electroweak hard processes



$$\Lambda' \ll M$$

Open production cross section for iQuarks at LHC

[Cheung, Keung and TCY, 0810.1524]

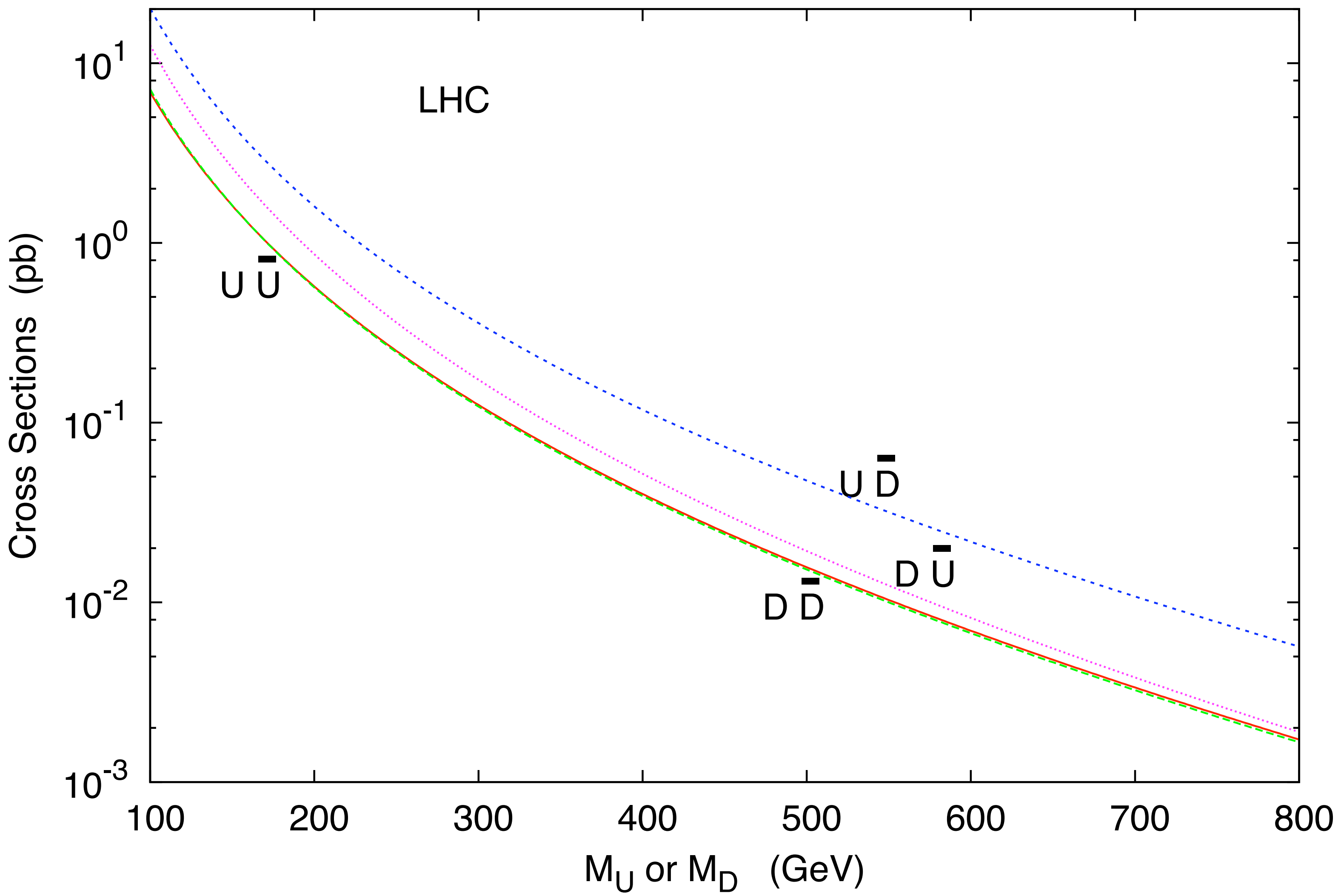


FIG. 1: Production cross sections for $pp \to \mathcal{U}\overline{\mathcal{U}}$, $\mathcal{D}\overline{\mathcal{D}}$, $\mathcal{U}\overline{\mathcal{D}}$ and $\mathcal{D}\overline{\mathcal{U}}$ at the LHC. The label $M_{\mathcal{U}}$ on the x-axis is for $\mathcal{U}\overline{\mathcal{U}}$, $\mathcal{U}\overline{\mathcal{D}}$ and $\mathcal{D}\overline{\mathcal{U}}$ production while $M_{\mathcal{D}}$ is for $\mathcal{D}\overline{\mathcal{D}}$ production. We assume $M_{\mathcal{U}} - M_{\mathcal{D}} = 10$ GeV and set $N_{\rm IC} = 3$.

Open squirk (siquark) production in folded SUSY

(Burdman, Chacko, Goh, Harnik and Krenke, arXiv:0805.4667)

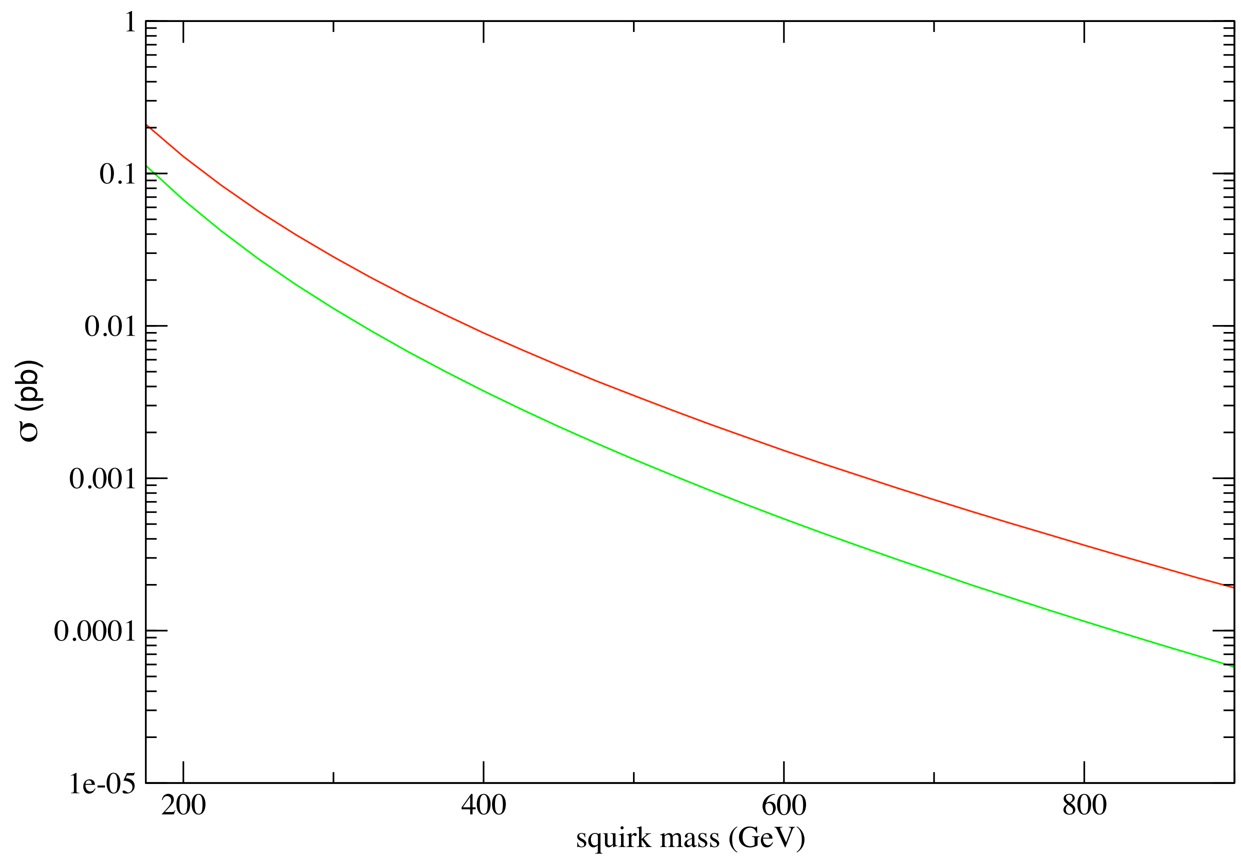


FIG. 1: The total cross-section for production of first generation squirk anti-squirk pairs via an s-channel W^+ (top curve) and W^- (bottom curve) at the LHC as a function of the squirk mass. The up and down squirks have been taken to be degenerate.

iQuark has larger production rate than scalar iQuark!

Open production of top quirk in Quirky Little Higgs Model (Cai, Cheng and Terning 0812.0843)

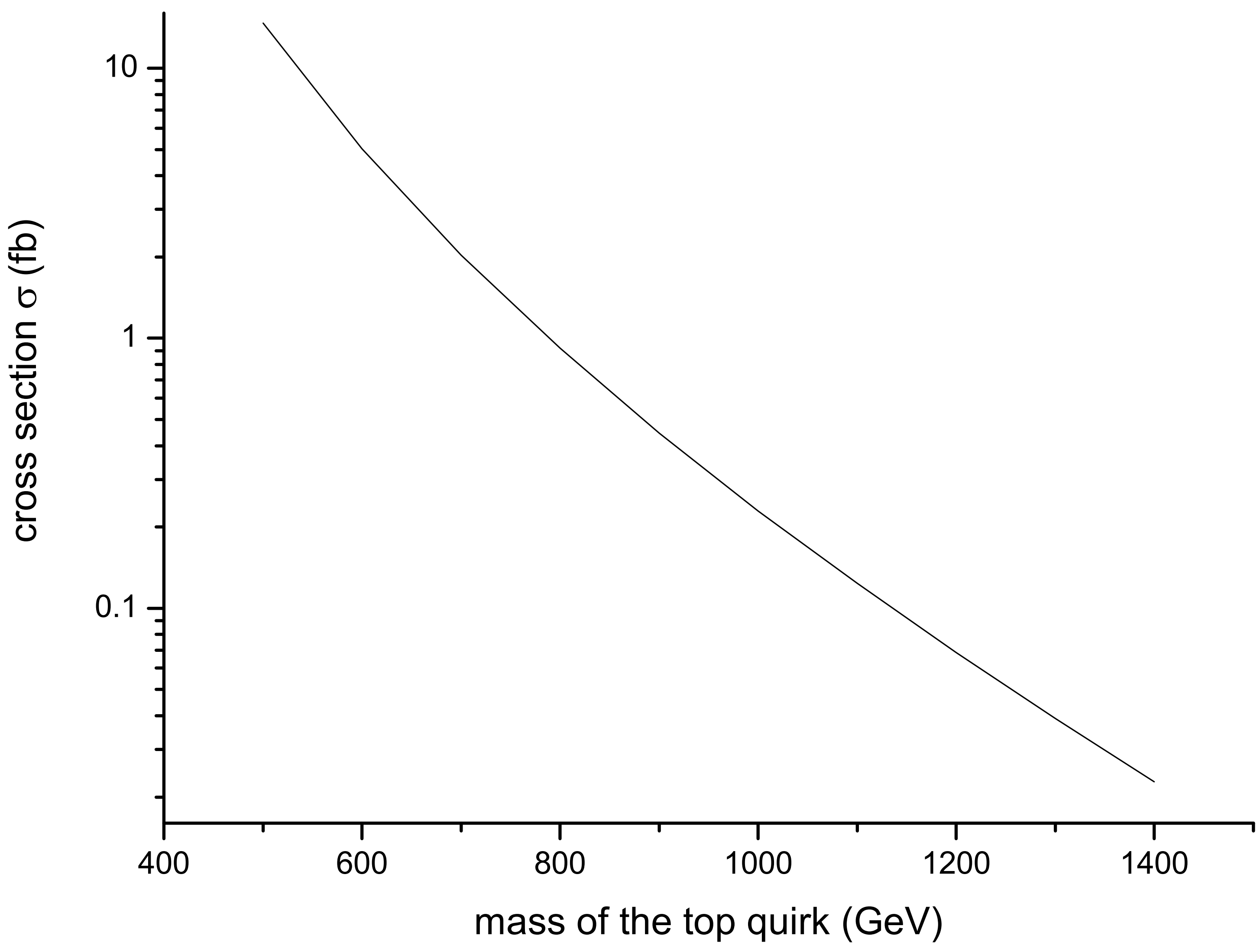


Figure 1: Total cross-sections vs. mass of top quirk

Prompt Annihilation (After Energy Loss)

$^1S_0$ neutral iquarkonium

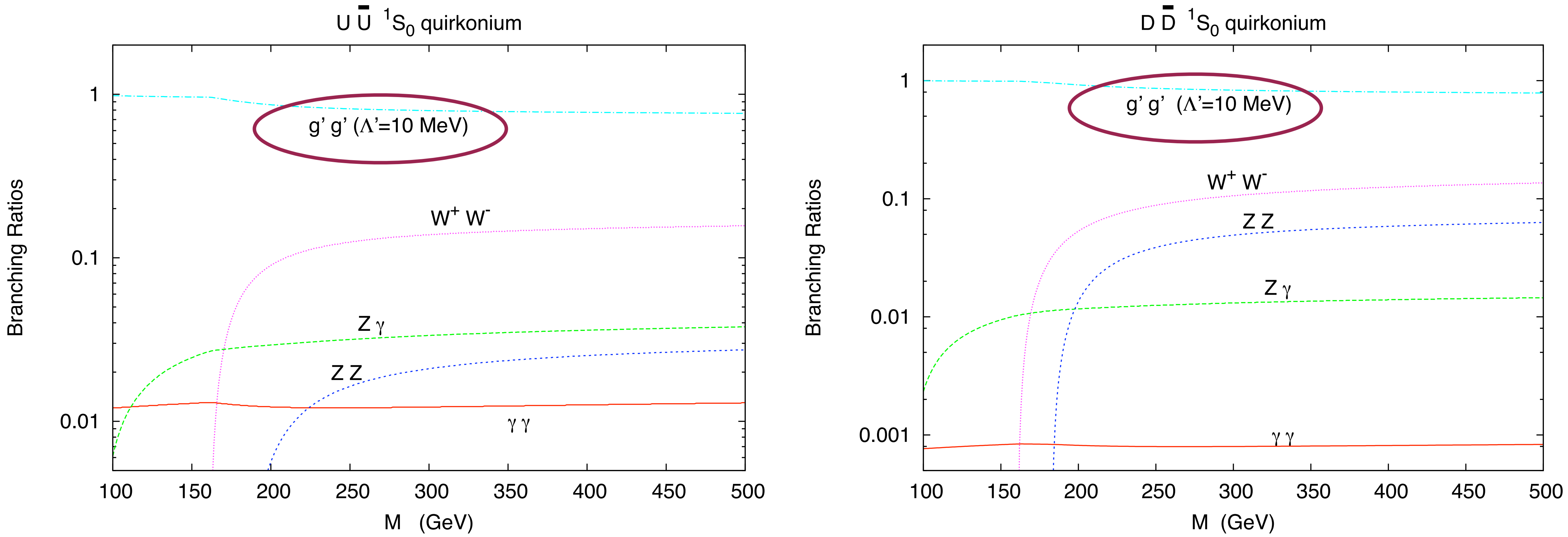


FIG. 2: Branching fractions of the quirkonium of (a) $^1S_0(\mathcal{U}\overline{\mathcal{U}})$ and (b) $^1S_0(\mathcal{D}\overline{\mathcal{D}})$ versus the quirkonium mass M. We have chosen $n_Q = 1$ and $\Lambda' = 10$ MeV in the running α'_s.

Dominant Decay Mode: Invisible $g'g'$ mode

$^3S_1$ neutral iquarkonium

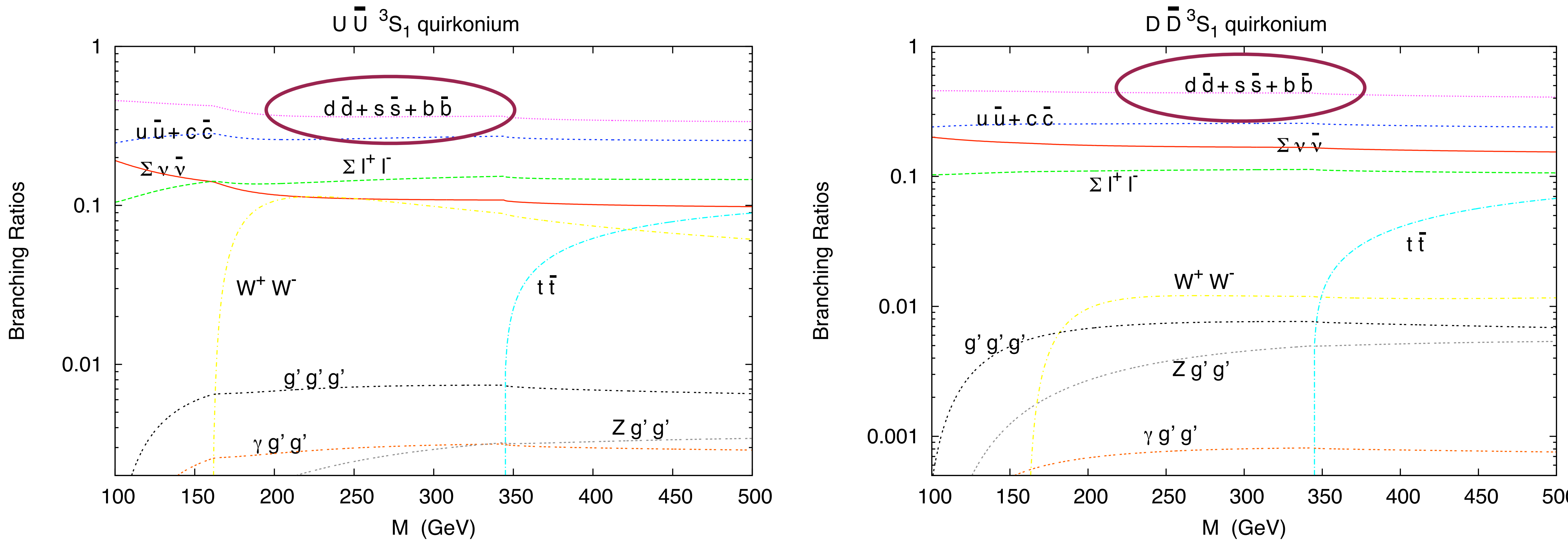


FIG. 3: Branching fractions of the quirkonium of (a) $^3S_1(\mathcal{U}\overline{\mathcal{U}})$ and (b) $^3S_1(\mathcal{D}\overline{\mathcal{D}})$ versus the quirkonium mass M. We have chosen $n_Q = 1$ and $\Lambda' = 10$ MeV in the running α'_s.

Dominant decay mode: 2-jet

No ZZ, $Z\gamma$ and $\gamma\gamma$ modes

WW mode has large cancellation among amplitudes for vector iQuarks

Comparison with superheavy Quarkonium

(Barger et al PRD 35, 3366 (1987))

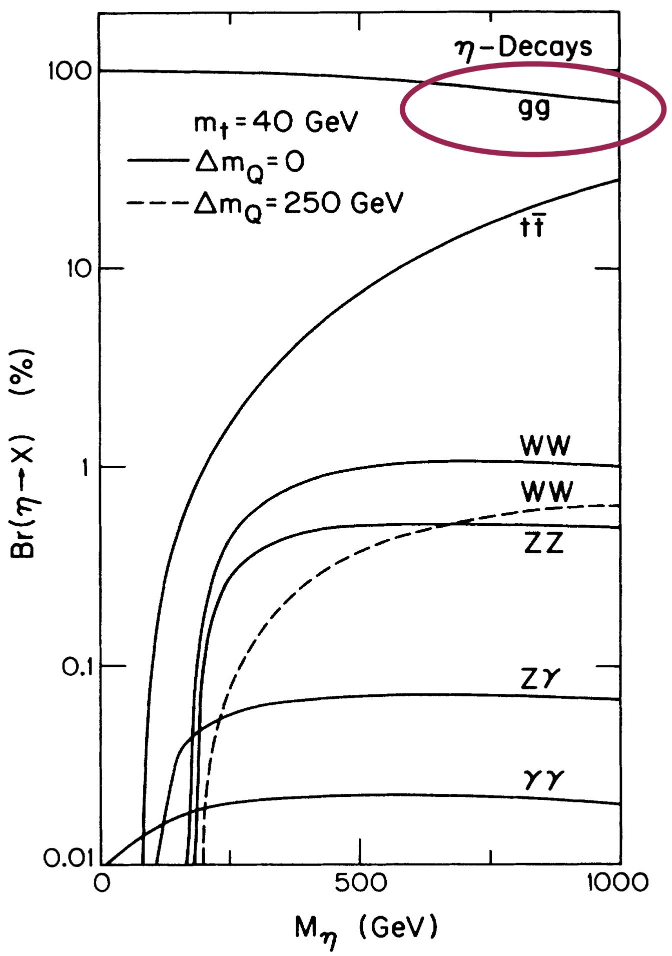


FIG. 9. The branching fraction for the decays of η_Q as a function of M_η. The W^+W^- branching fraction depends on the mass of Q' the SU(2) partner of Q and is shown for $m_{Q'}=m_Q$ (solid curve) and $m_{Q'}=m_Q+250$ GeV (dashed curve). Δm_Q in the figure denotes $m_{Q'}-m_Q$.

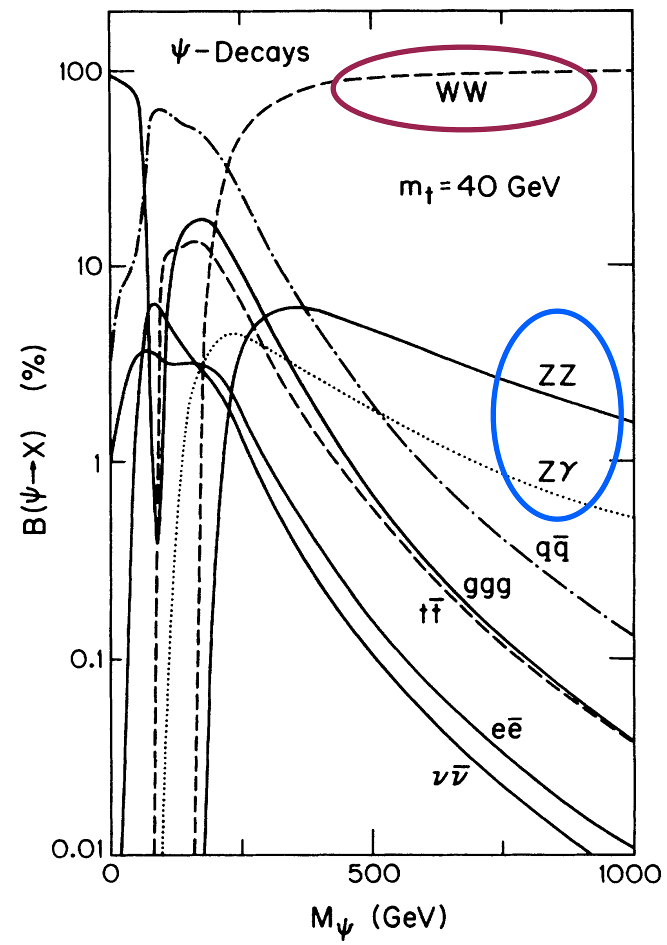


FIG. 10. The branching fractions for the decays of ψ_Q. We have fixed $m_{Q'}=m_Q+250$ GeV.

the wave functions given by the Wisconsin potential) in the branching ratio. Since the matrix elements and the

2-jet WW

S wave charged iquarkonium

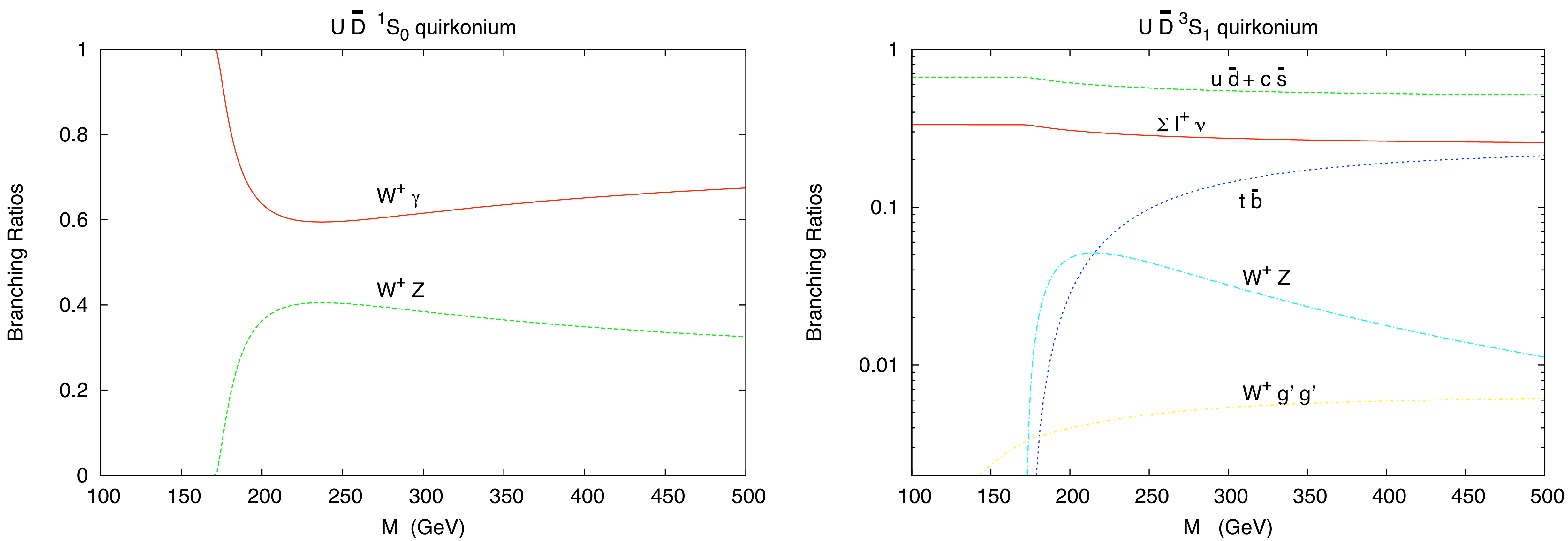


FIG. 4: Branching fractions of the charged quirkonium of (a) $^1S_0(\mathcal{U}\overline{\mathcal{D}})$ and (b) $^3S_1(\mathcal{U}\overline{\mathcal{D}})$ versus the quirkonium mass M. We have chosen $n_Q = 1$ and $\Lambda' = 10$ MeV in the running α'_s.

Similar to charged quarkonium

Summary

Phenomenology of iQuarkonium is quite different from quarkonium.

iQuarkonium collider signals involve 3 steps:

(1) iQuark pair production
(2) Soft energy loss (visible and invisible)
(3) Hard annihilation in SM particles

iQuarks linked by macroscopic string may lead to observable tracks. Detailed analysis is missing but interesting string dynamics.

iQuarks linked by microscopic string annihilates promptly into SM final states; distinguishable from superheavy quarkonium.

Energy loss via (i)glueballs and soft photon emission are important signals since the iQuarkonium was formed in highly excited state.

NP QCD effects for colored iQuarks can give rise to even more spectacular signals of hadronic fireball from energy loss.

iQuarks are not un-interesting stuff!

Backup Slides

Comparison with folded supersymmetry

(Burdman, Chacko, Goh, Harnik and Krenke, arXiv:0805.4667)

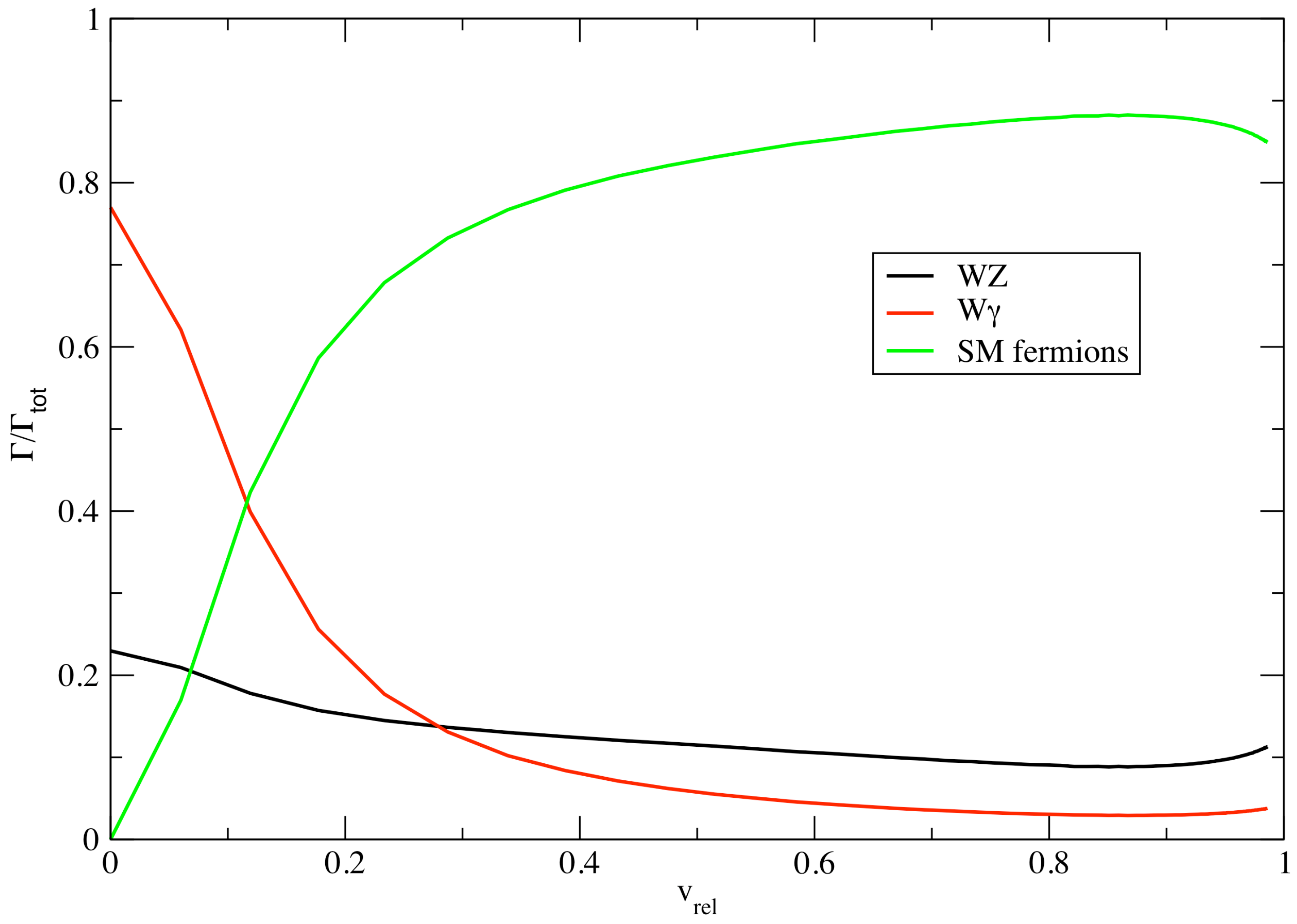


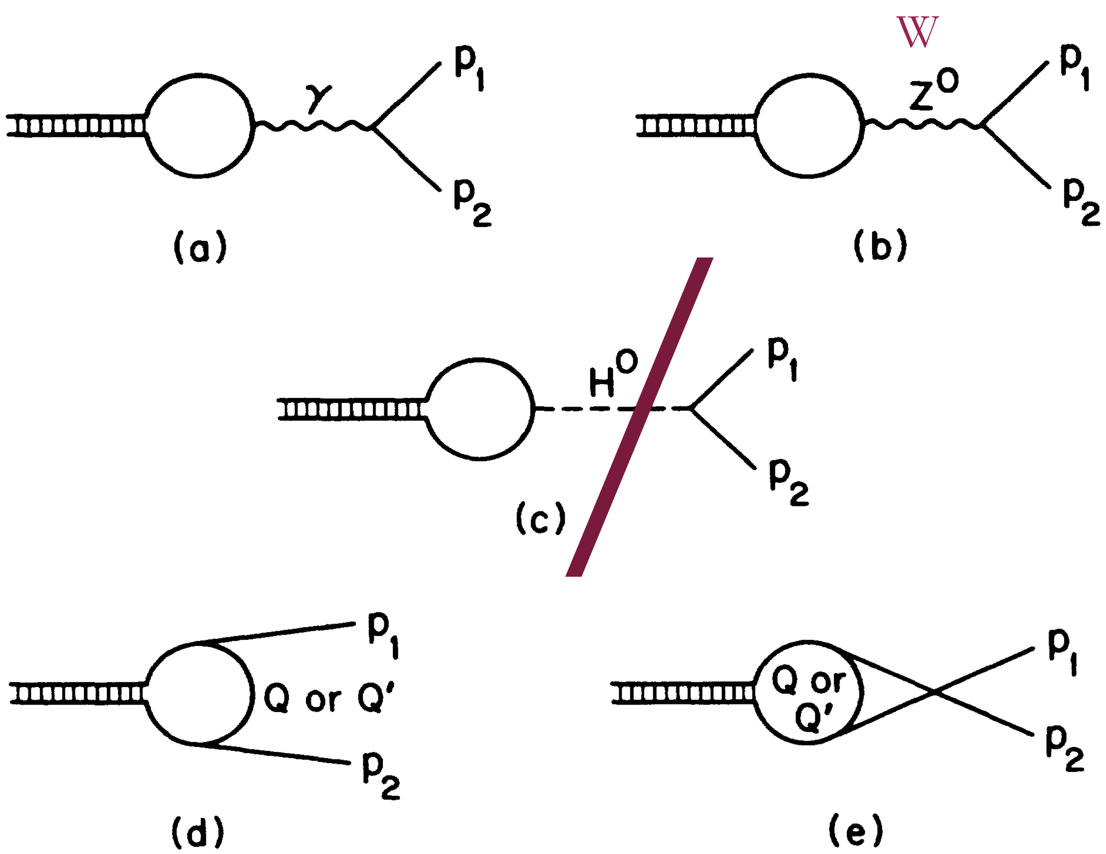
FIG. 2: Branching ratios for a charged squirk-antisquirk pair into various final states, as a function of the relative velovity of the pair.

Qualitative the same ?

iQuark Annihilations/iQuarkonium Decays

Lightest iQuark is stable. No weak beta decay.

iQuark-antiiQuark annihilation is a hard process -- calculable using perturbation theory + factorization



Generic diagrams for 2-body decays

wave function at origin

Hard kernel

Projection op

$$A(\eta)=\left[\frac{3}{16\pi M_\eta}\right]^{1/2} R_S(0)\mathrm{Tr}[\mathcal{O}_F\gamma_5(-\not{Q}+M_\eta)]\ ,$$

$$A(\psi)=-\left[\frac{3}{16\pi M_\psi}\right]^{1/2} R_S(O)\mathrm{Tr}[\mathcal{O}_F\not{\epsilon}(-\not{Q}+M_\psi)]\ ,$$

$$A(\chi_0)=i\left[\frac{3}{4\pi M_\chi}\right]^{1/2} R'_P(0)\mathrm{Tr}\left[\mathcal{O}_F^\alpha\left[\gamma_\alpha+\frac{Q_\alpha}{M_\chi}\right]\left[\frac{-\not{Q}+M_\chi}{2}\right]+3\mathcal{O}_F\right]$$

Annihilation Amplitudes

Embedded into GUT

Vector iQuarks can arise in complete SU(5)

$$5 \oplus \bar{5} \rightarrow (3,1)_{\frac{1}{3}} \oplus (\bar{3},1)_{-\frac{1}{3}} \oplus (1,2)_{\frac{1}{2}} \oplus (1,2)_{-\frac{1}{2}}$$

colored uncolored

For example, vector-like Higgs in SUSY GUT

In SUSY, any dynamics that generates the supersymmetric μ term will give mass to the vector iQuarks as well

Scalar quirks (siquarks) appear in models in folded supersymmetry
[Burdman et al, JHEP 0702, 009 (2007)]