Phenomenology of iQCD

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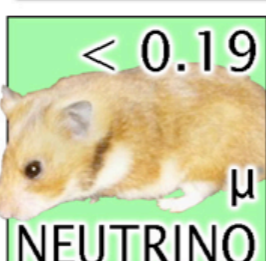
Collaborators: Kingman Cheung and Wai-Yee Keung

Seminar at 中原大學, Dec. 2 (2008)

References

- Bjorken, SLAC-PUB-2372 (1979)

- Okun, JETP Lett. 31, 144 (1980); Nucl. Phys. B173, 1 (1980)

- Gupta and Quinn, PRD 25, 838 (1982)

- Kang and Luty, arXiv:0805.4642

- Kang, Luty and Nasri, JHEP 09, 086 (2008)

- Burdman, Chacko, Goh, Harnik and Krenke, arXiv:0805.4667

- Cheung, Keung and Yuan, arXiv:0810.1524, to appear in Nucl.Phys. B

- Harnik and Wizansky, arXiv:0810.3948

Introduction

The Standard Model fundamental particle zoo
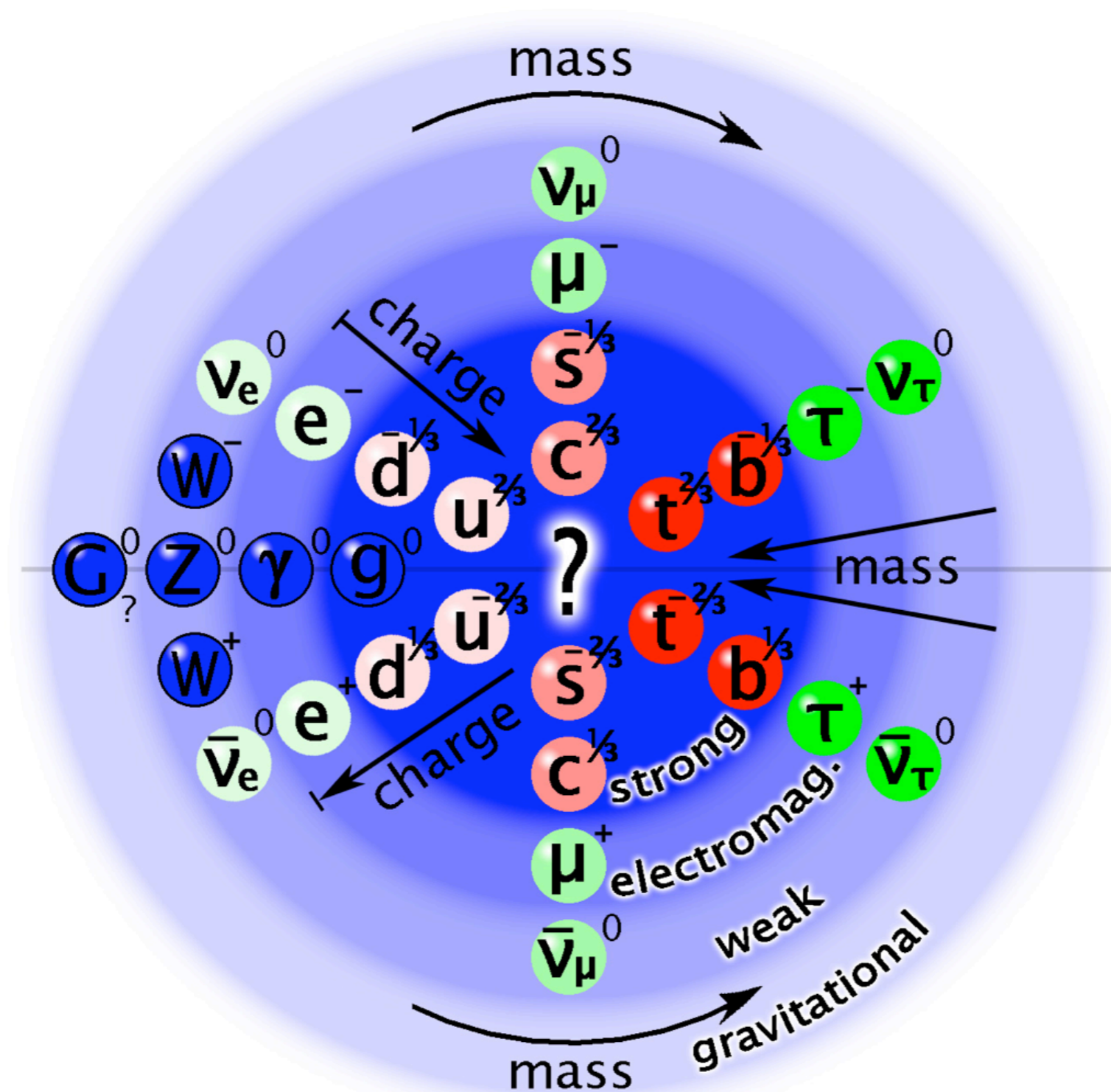
$SU_{\mathrm{color}}(3) \times SU_L(2) \times U_Y(1)$ **The Standard Model**

Spontaneous Symmetry Breaking in Magnet

High Temperature
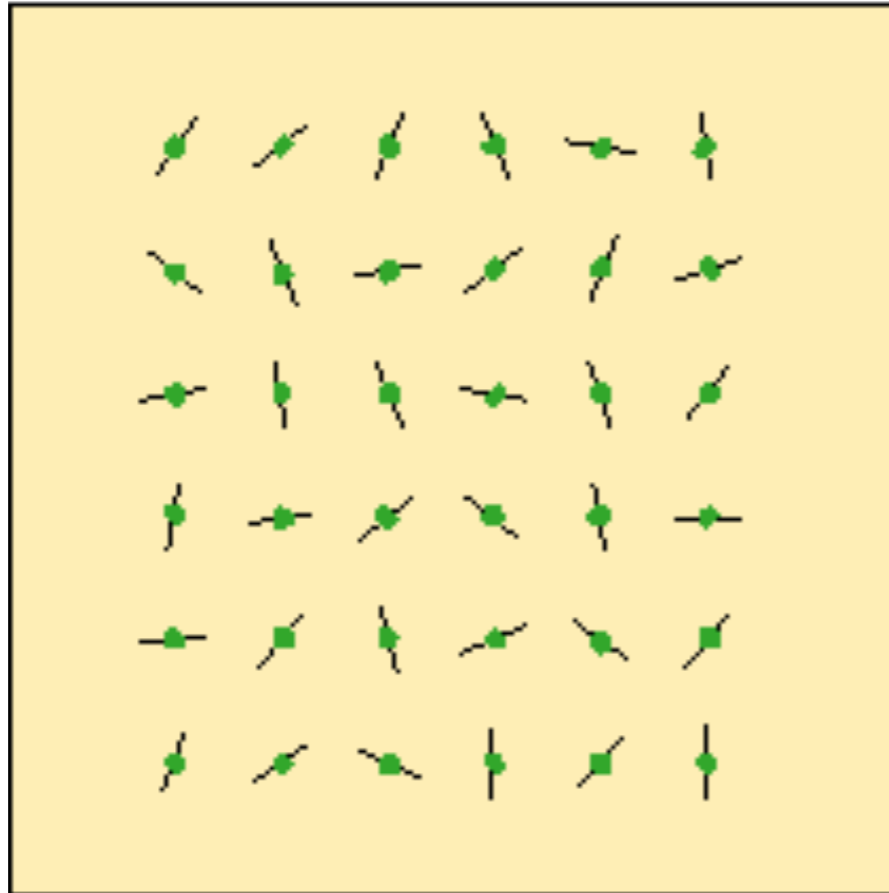
Low Temperature
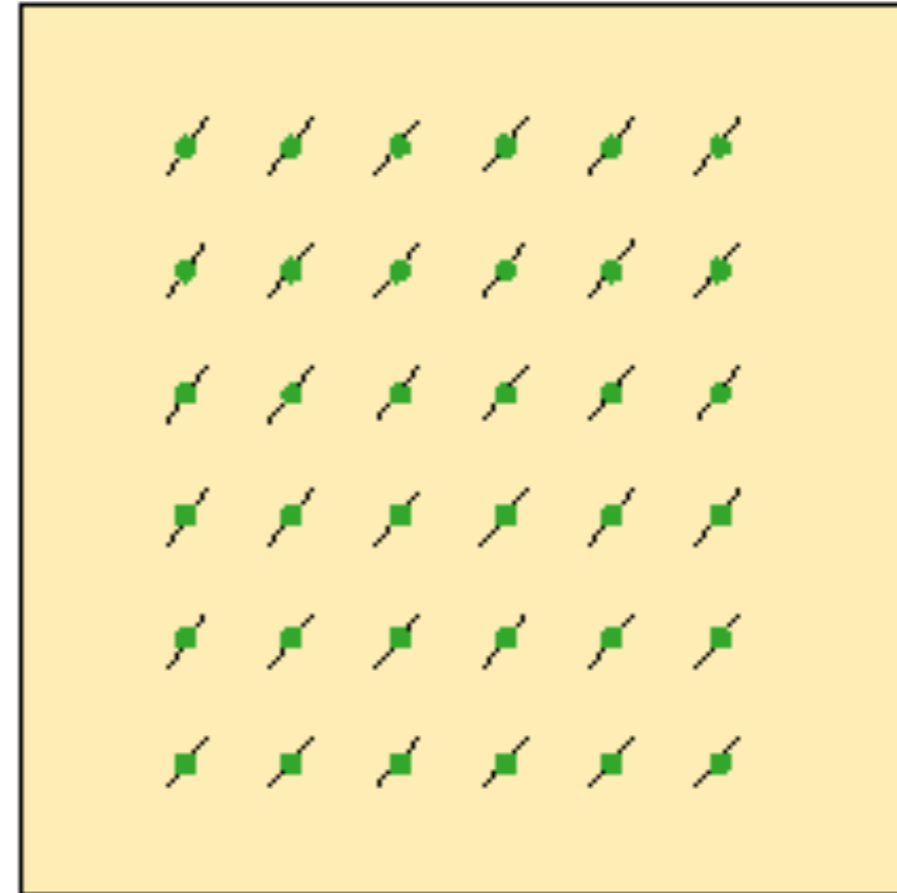
Rotational Inv.

Degenerate ground states!

Massless Excitation
(Nambu-Goldstone Mode)

Light/massless particles are natural only if protected by global or local symmetry.

2008 1/2 Nobel Prize Winner: Nambu
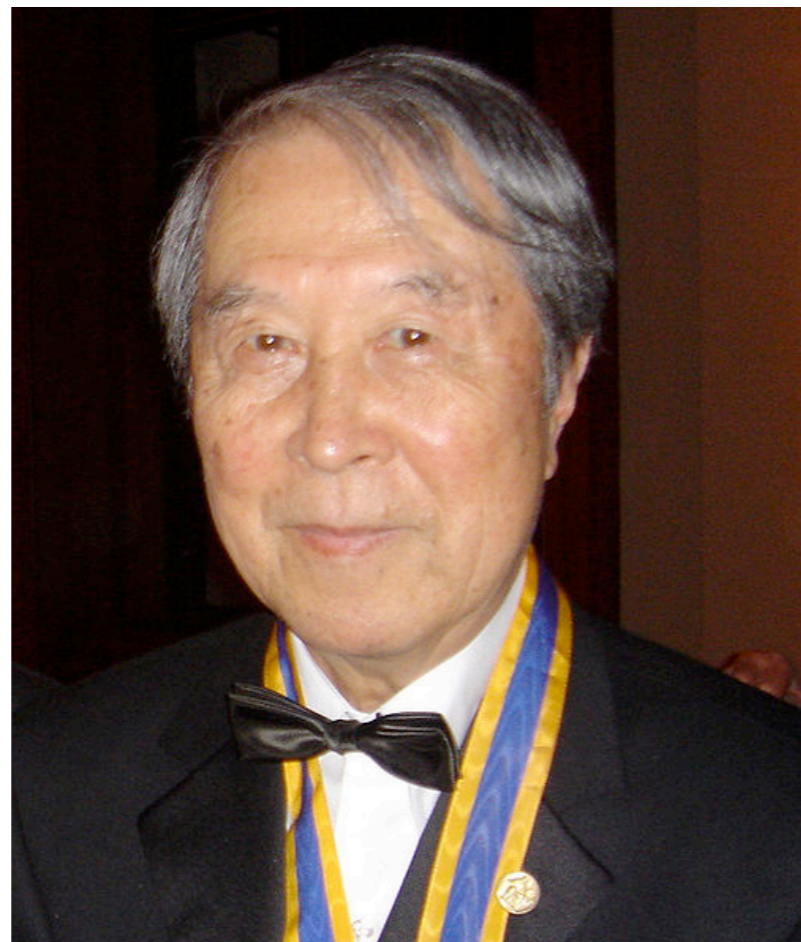
An Exception:
Mass Generation

Spontaneous Symmetry Breaking of Gauge Symmetry and Higgs Mechanism

$$V(\phi) = \lambda(\phi^2 - \mu^2)^2 \,, \quad \mu^2 > 0$$
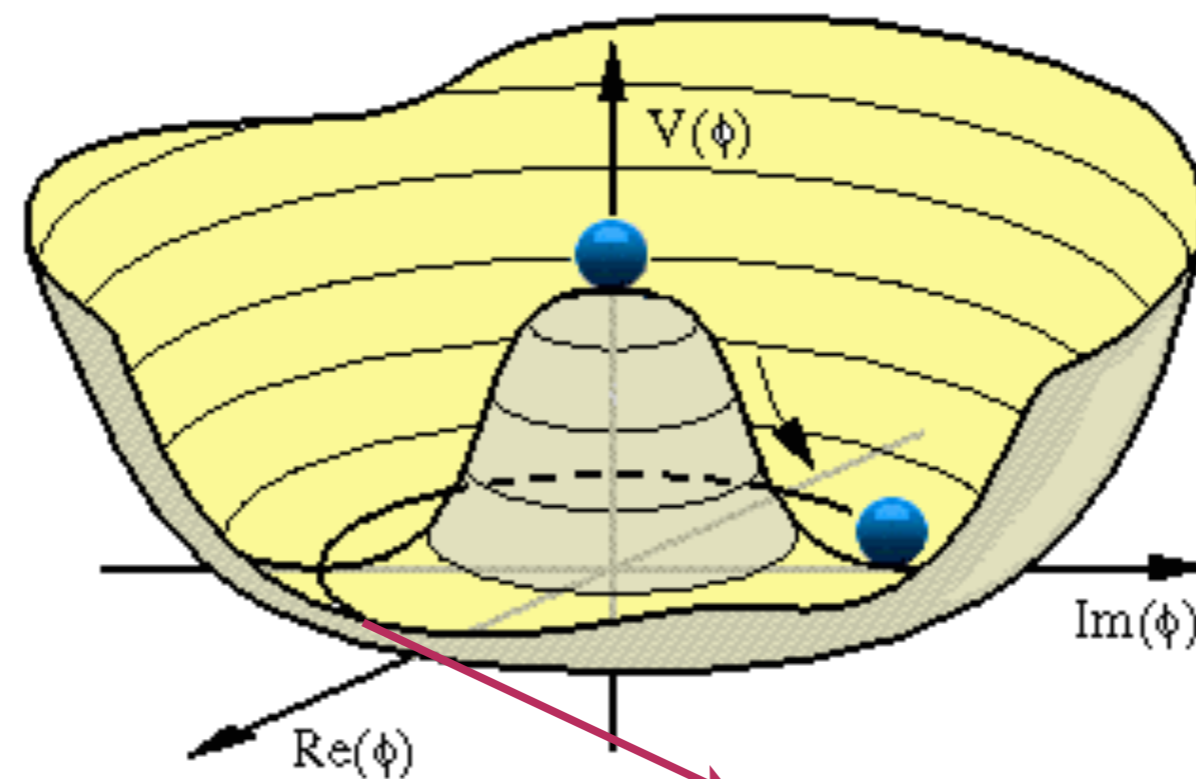
W_L, Z_L Would be Nambu-Goldstone modes eaten by gauge particles becomes their longitudinal modes

Higg field ϕ is still missing!

Higgs Search Limits
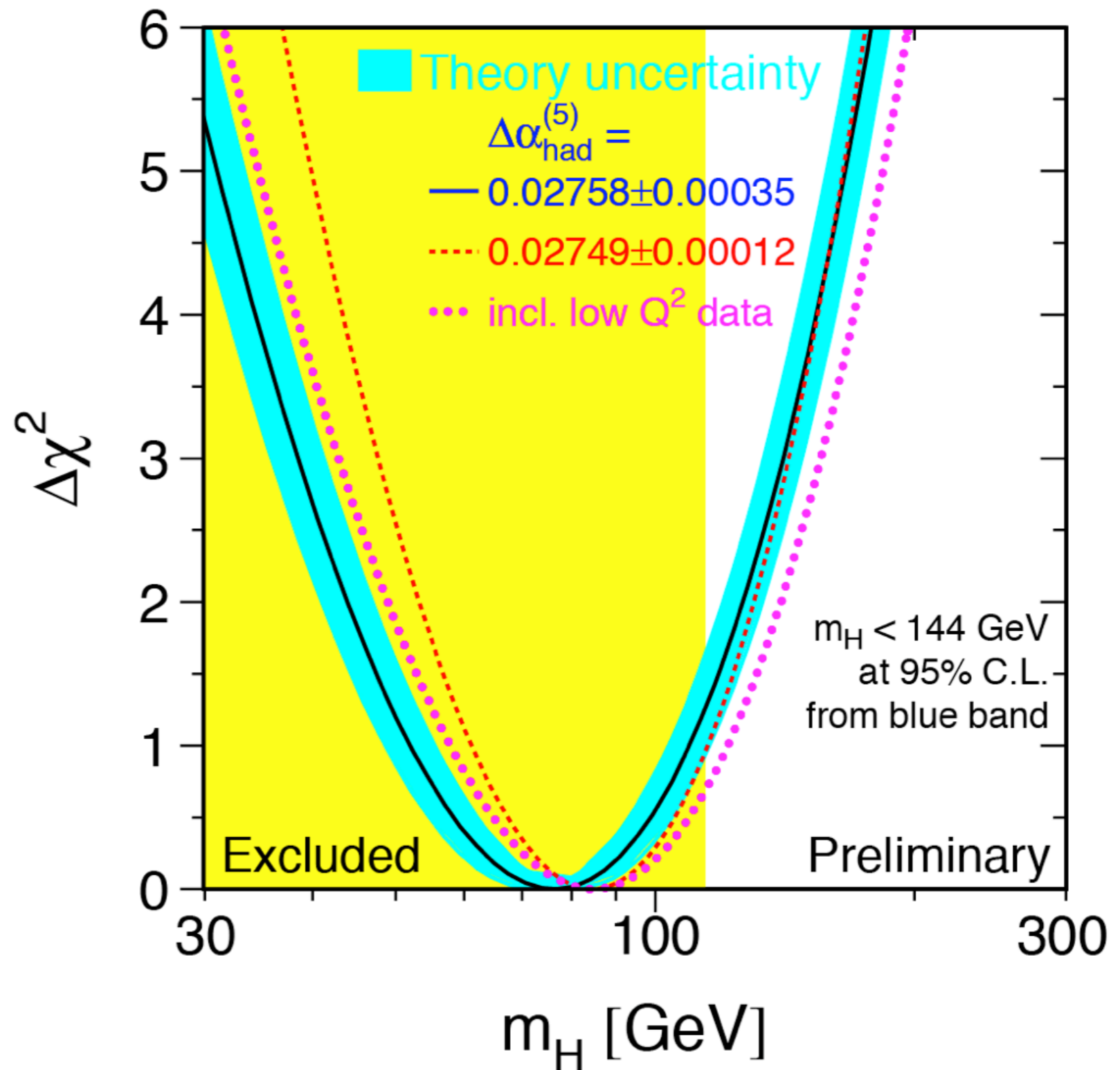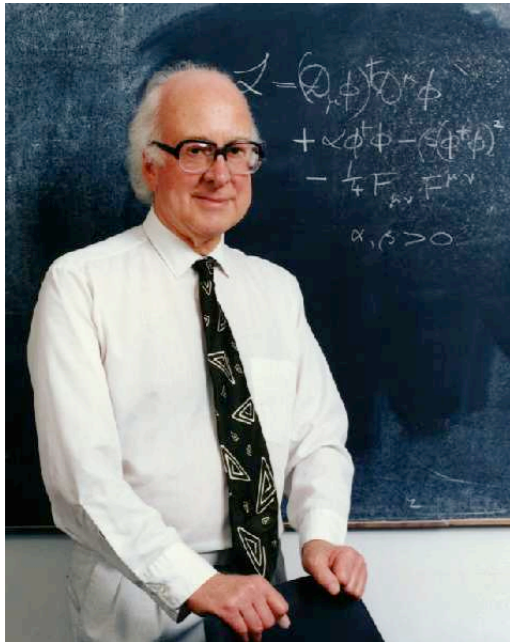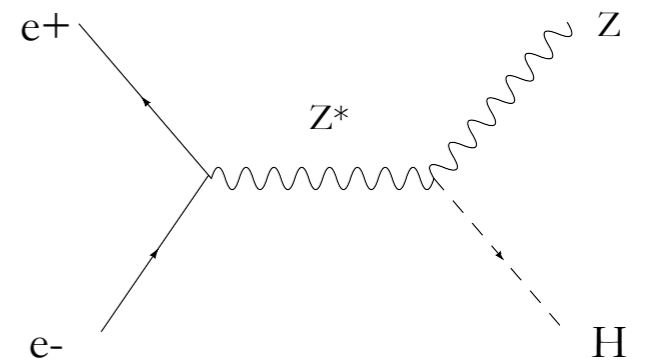
Large Hadron Collider (LHC) outside Geneva
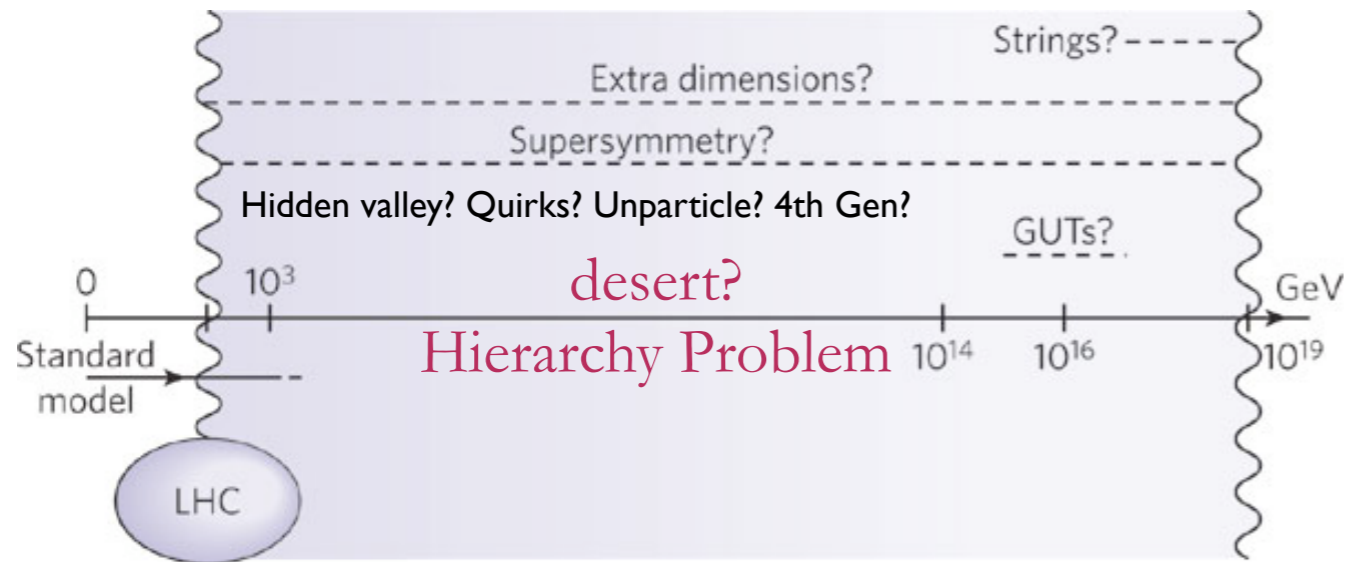
Probe EW symmetry breaking

$\sqrt{s} = 14$ TeV
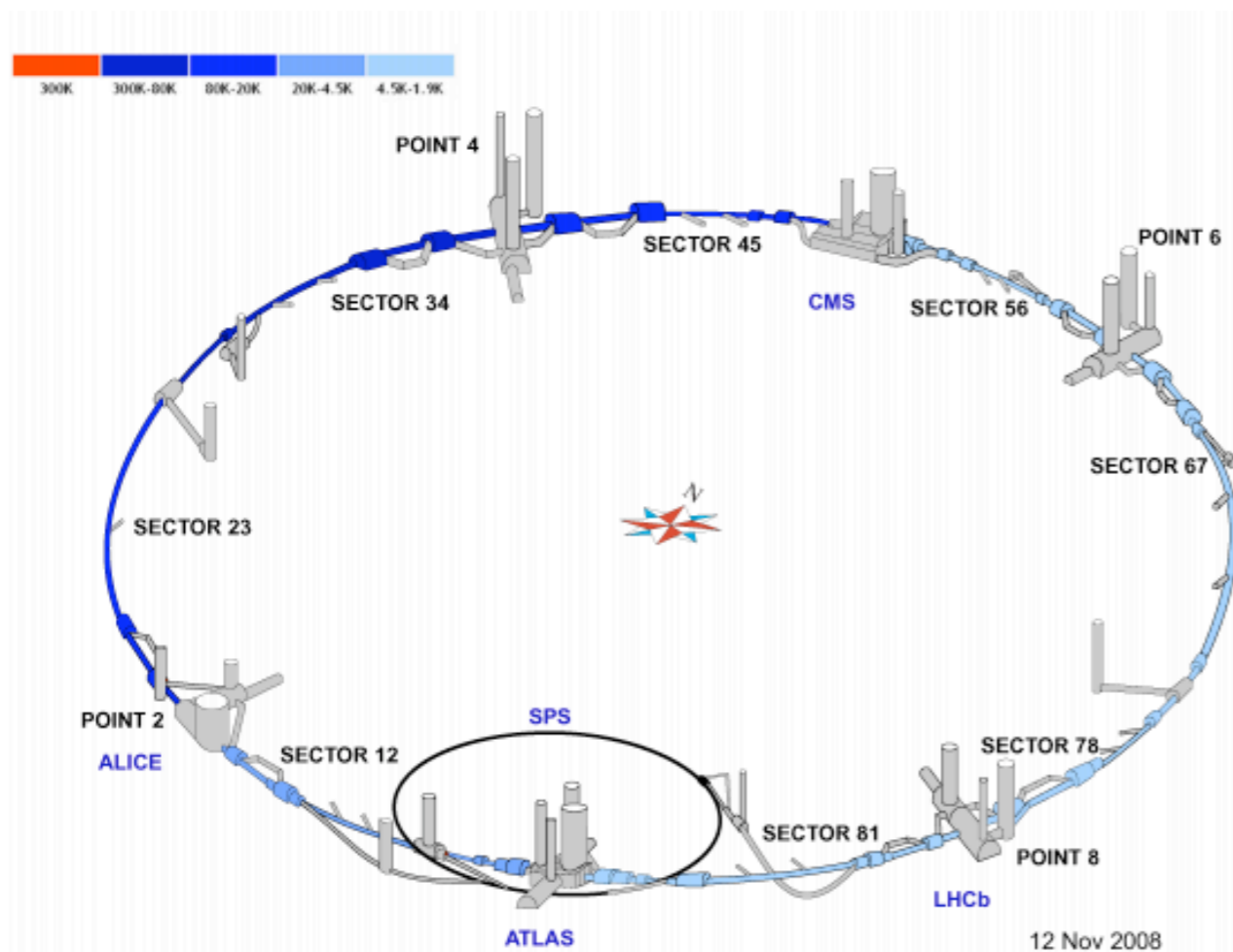
Hidden Strongly Interacting Sector ?
(New Physics NOT related to EW symmetry breaking)

- Familiar Example: Extra Z boson models

- Hidden Valley Models (Strassler)

- Unparticle (Georgi)

- Quirks and infracolor QCD (Luty)

THETA PARTICLES

L.B. OKUN

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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 $\qquad \Lambda' \ll \text{TeV}$

In particular $\qquad\qquad\qquad\qquad \Lambda' \ll M_Q$

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.

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, long range force
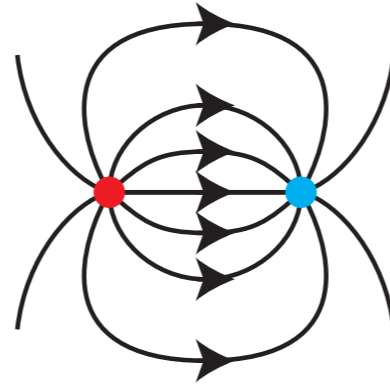
Confined breakable string => Independent fragementation

light quark pair creation
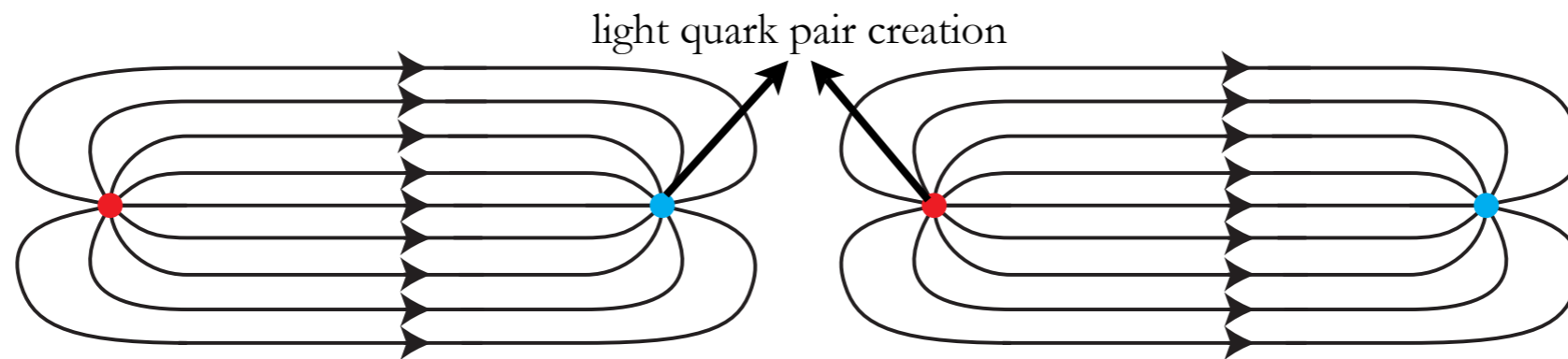
Confined unbreakable string

confinement radius

$\sim \Lambda'^{-1}$

$$\text{Tension} \approx \Lambda'^2$$
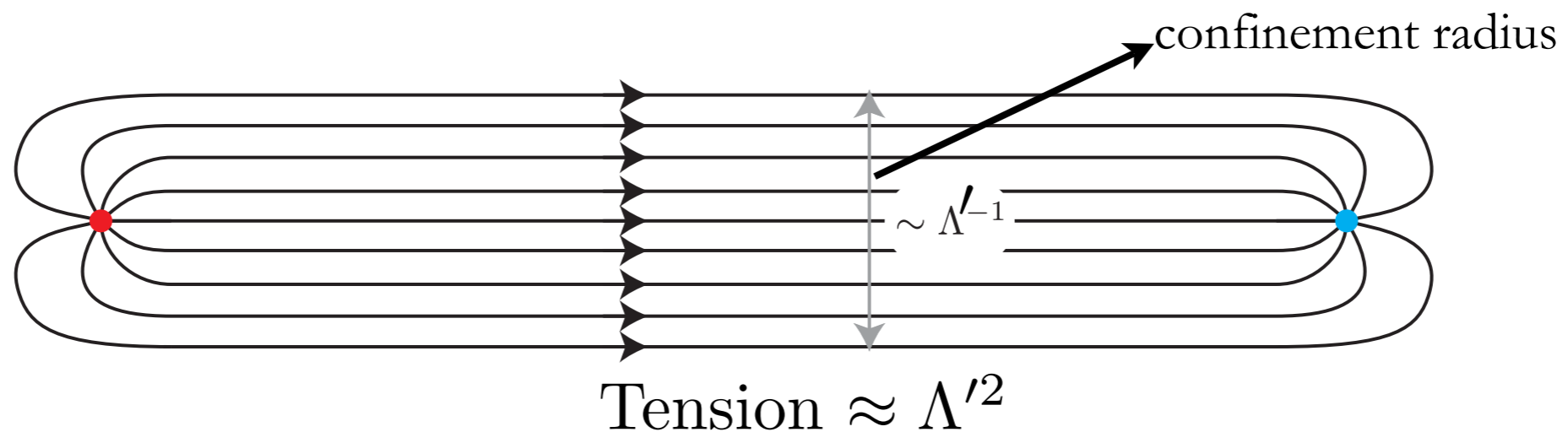
Suppression of soft hadronization

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

QCD
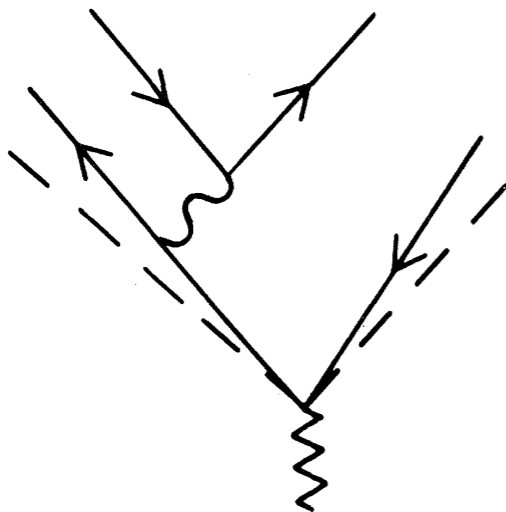
FIG. 1. A diagram for color neutralization by quark-antiquark pair production. The diagram also indicates space-time evolution in the center-of-mass frame. The dashed line indicates the light cone.
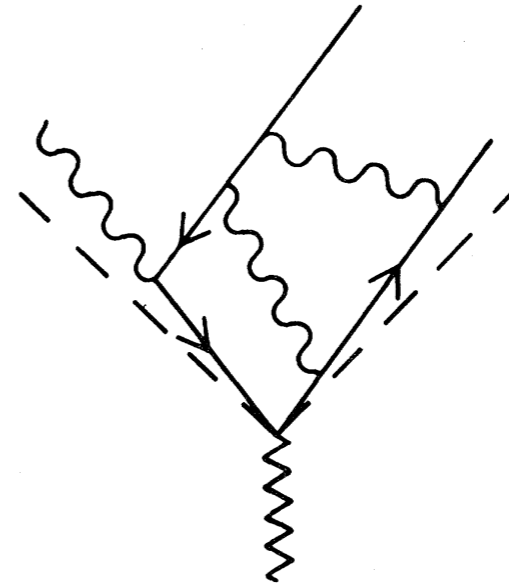
FIG. 2. Diagram for color neutralization by turning around the quark by gluon emission. The diagram also indicates space-time evolution.

iQCD

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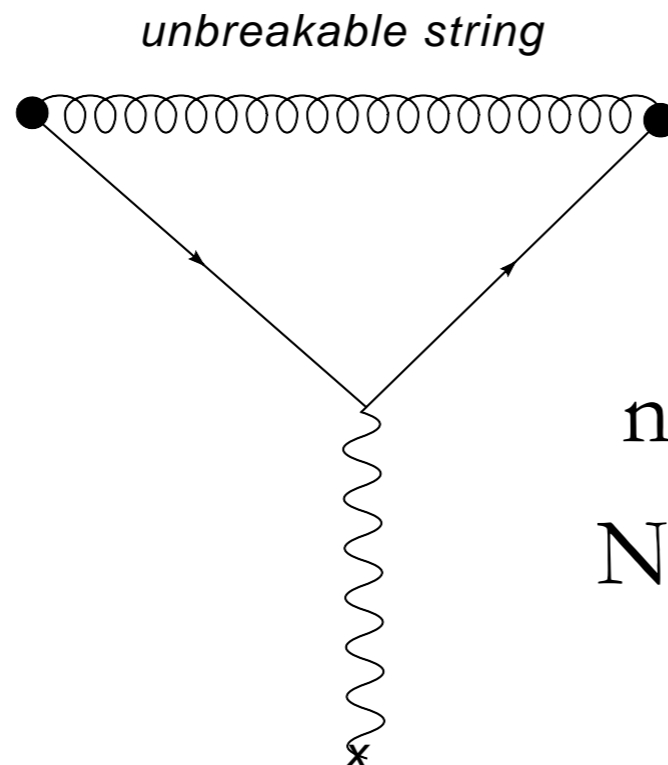
NP stringy effect is important, not suppressed at high Q squared

NP effect may modify PQCD 2-jet prediction

Trendy names suggested

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

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

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

$$\text{etc}$$

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

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

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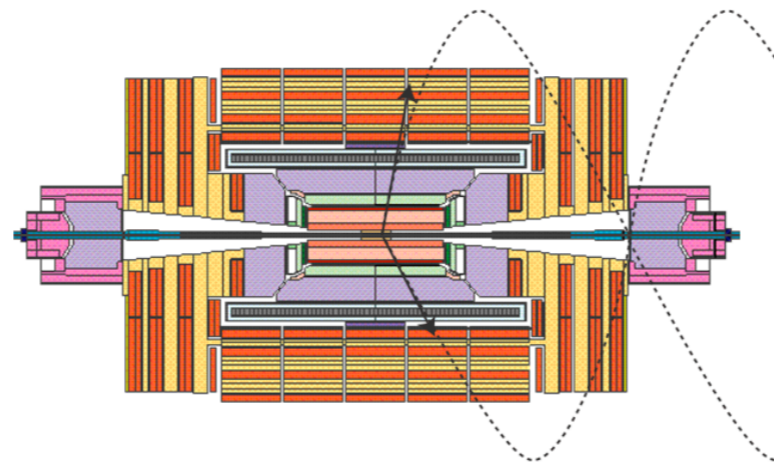
quirky tracks

(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 decoherence

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

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

iQuarks are confined into bound states

Salient features:

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

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

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

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

$R \sim \Lambda^{-1}$ or Λ'^{-1}

Geometric cross section

Wave function overlapp (WKB)

π

(i)glueballs

hadronic fireball

photons

Energy loss

hard SM stuff

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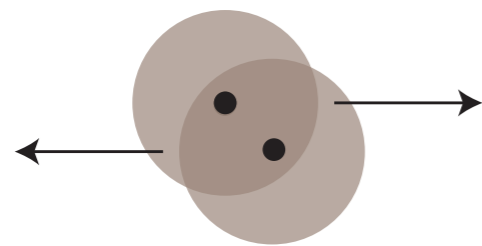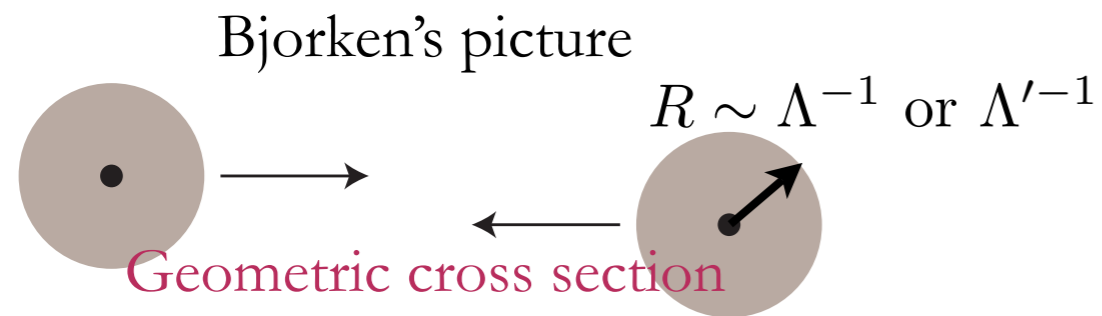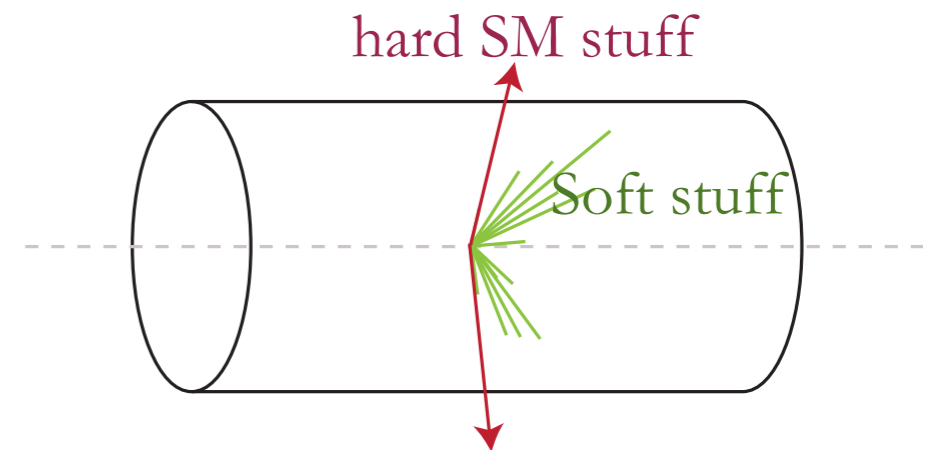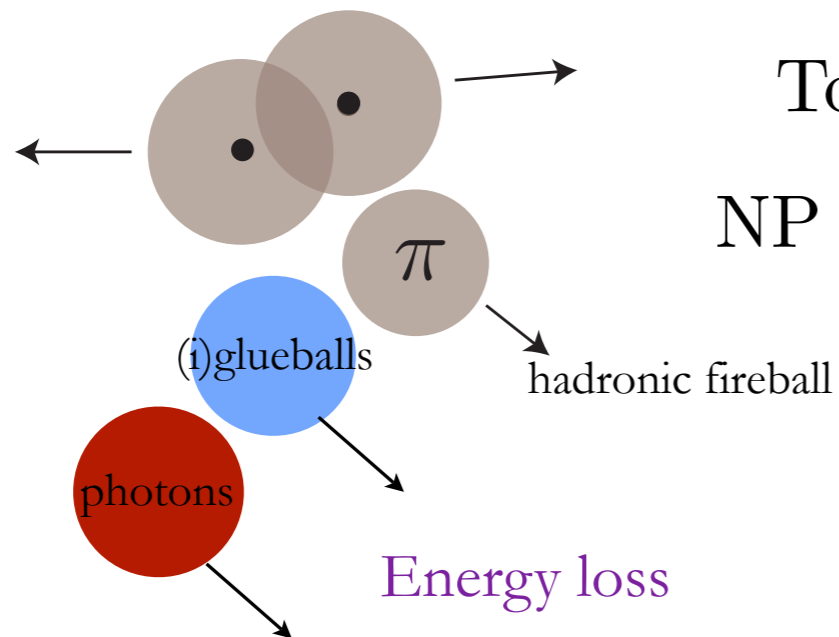
Fig. 9. Schematic depiction of hadronic fireball and hard annihilation into muons. Note that the the asymmetry of the muons and the fireball are in the same direction.

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

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

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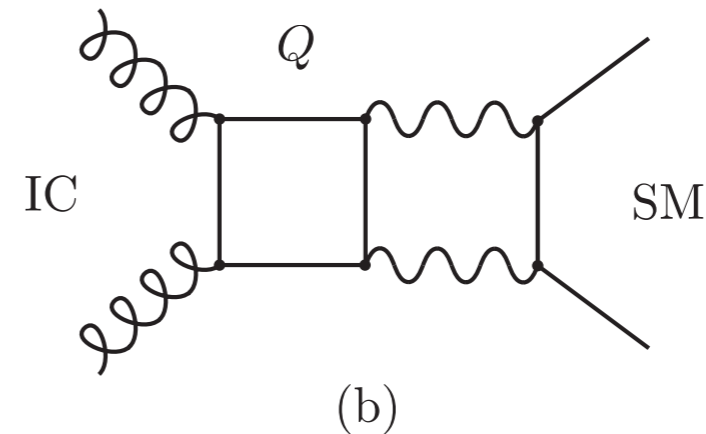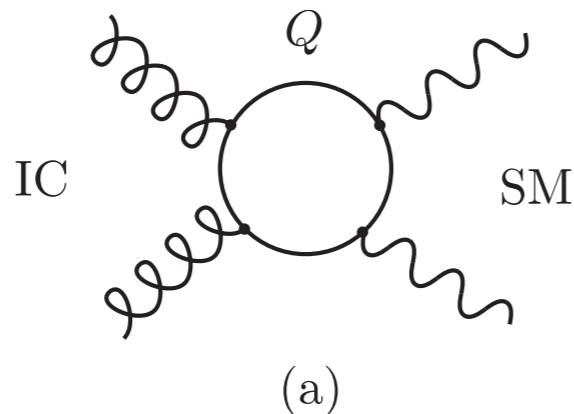
$$\mathcal{L}_{\text{eff}} \sim \frac{g^2 g'^2}{16\pi^2 m_Q^4} F_{\mu\nu}^2 F_{\rho\sigma}'^2.$$

Needs 2 loop to couple
to SM fermions

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

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

$\Lambda' \geq 50$ 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)**
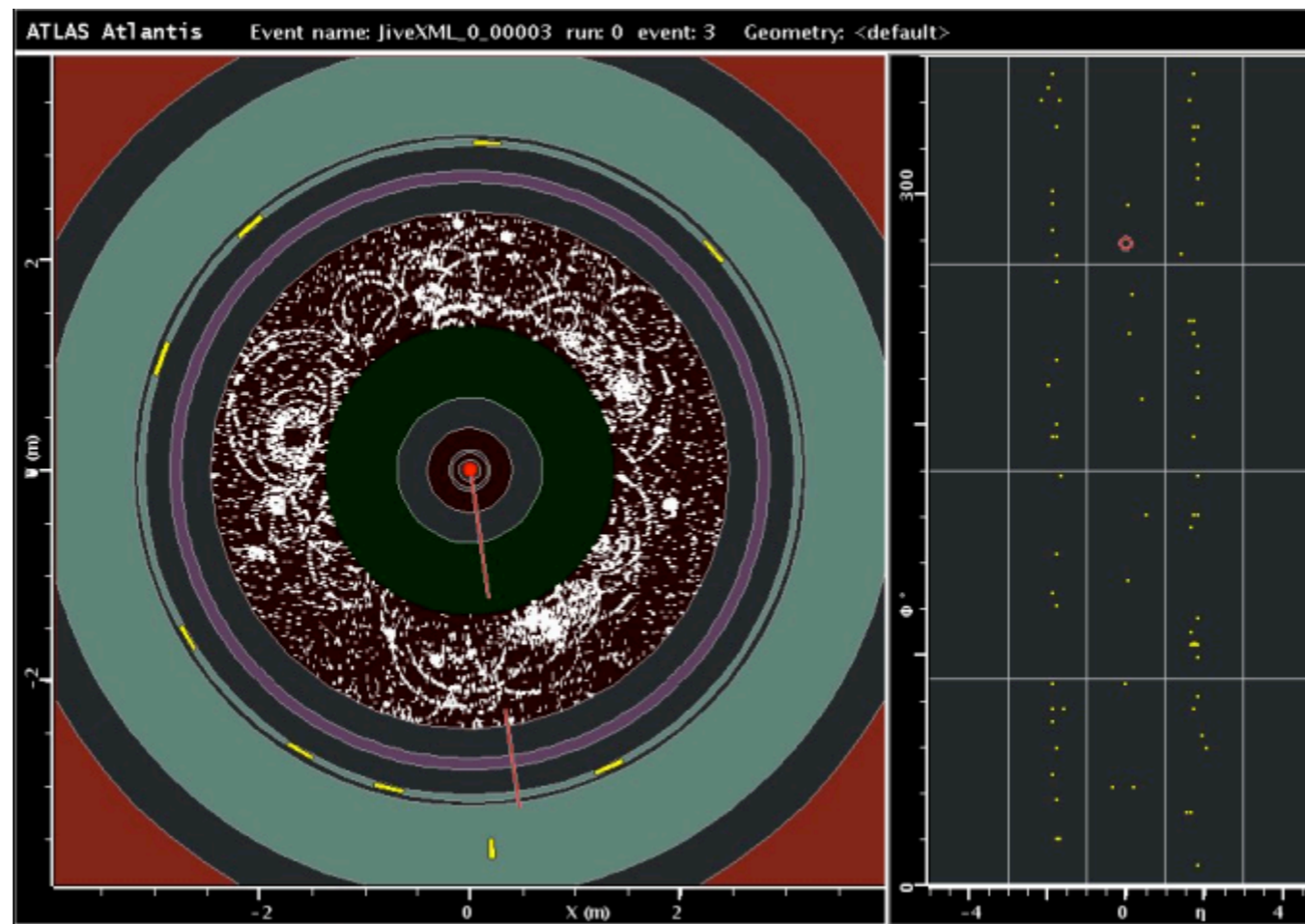
Taken from Chacko's talk

`Antenna Pattern'
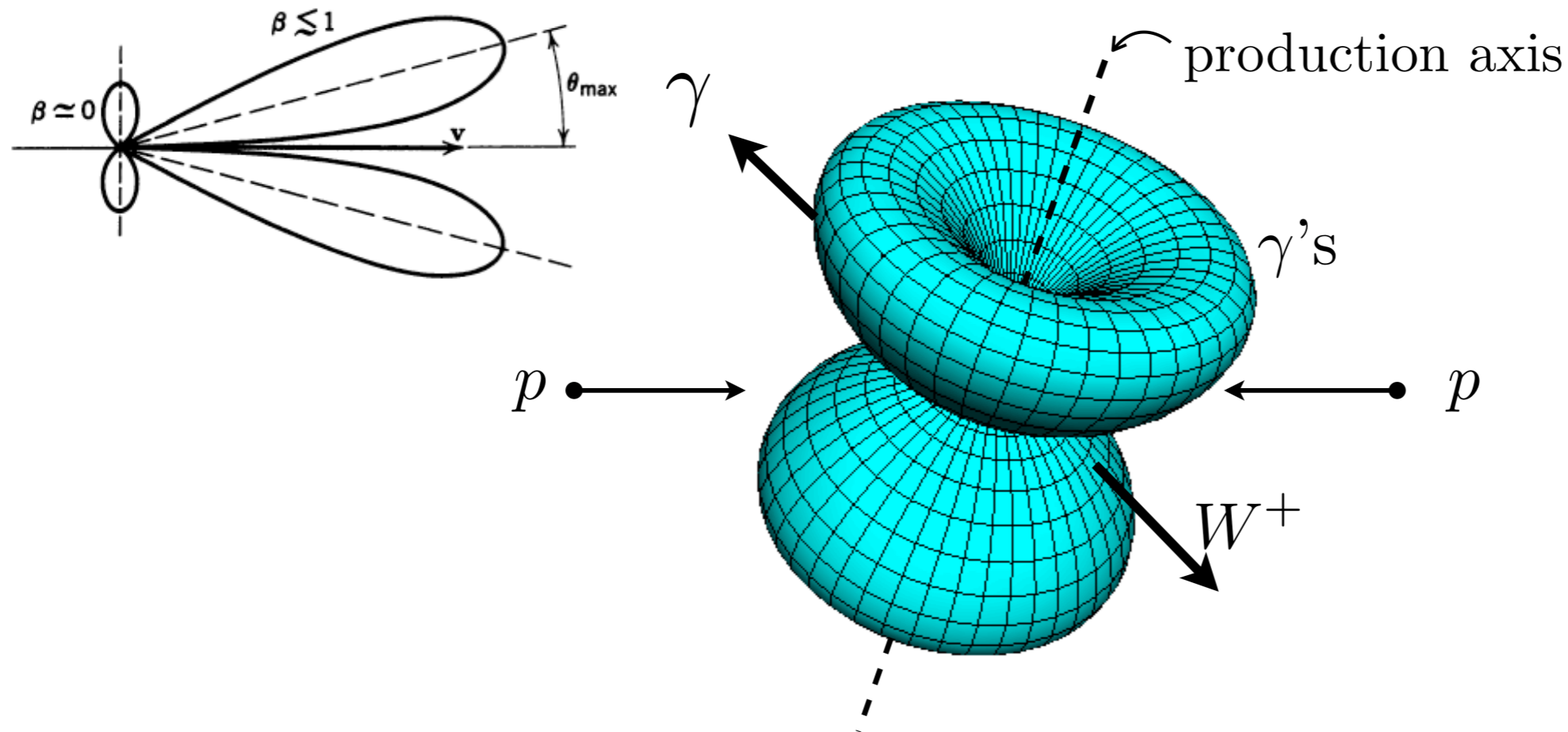
Figure 1: A schematic cartoon of the initial and final states of an LHC event with squirk production via an s-channel $W^{\pm}$. The two protons are incoming along the horizontal axis. The squirks are produced and oscillate along the dashed axis. The final state includes an antenna pattern of soft photons (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.

a) 100 % energy loss to photons

b) 10 % energy loss to photons
90 % to invisible

c) SM background

CMB-like analysis

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.

iQuarks are interesting stuff!

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

Vectorial
$$\mathcal{Q}_{L,R} = \begin{pmatrix} \mathcal{U} \\ \mathcal{D} \end{pmatrix}_{L,R} \sim \left(N_{\text{IC}}, 1, 2, \frac{1}{3} \right) \qquad \text{Assume MeV} \leq \Lambda' \ll M_Q$$

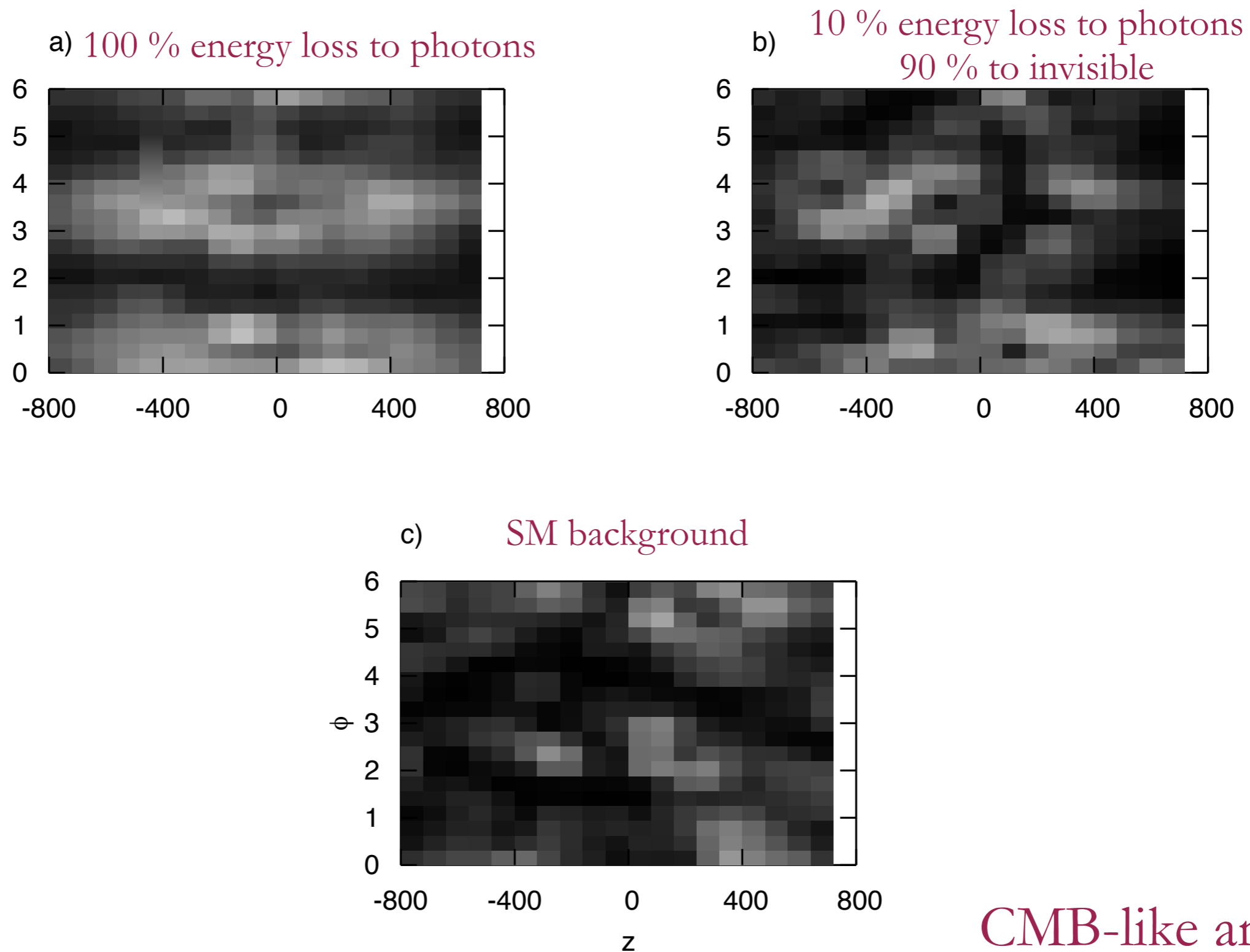(Microscopic string scenario)

$$\mathcal{L}_{\text{gauge}} = - \; g'_s G'^a_\mu \overline{\mathcal{Q}} \gamma^\mu T^a \mathcal{Q} - eA^\mu \left(e_{\mathcal{U}} \overline{\mathcal{U}} \gamma^\mu \mathcal{U} + e_{\mathcal{D}} \overline{\mathcal{D}} \gamma^\mu \mathcal{D} \right)$$
$$- \; \frac{g}{\cos\theta_W} Z_\mu \left(v_{\mathcal{U}} \overline{\mathcal{U}} \gamma^\mu \mathcal{U} + v_{\mathcal{D}} \overline{\mathcal{D}} \gamma^\mu \mathcal{D} \right) - \frac{g}{\sqrt{2}} \left(W^+_\mu \overline{\mathcal{U}} \gamma^\mu \mathcal{D} + W^-_\mu \overline{\mathcal{D}} \gamma^\mu \mathcal{U} \right)$$

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

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

Embedded into GUT

Vector iQuarks can arise in complete SU(5)

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

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)]

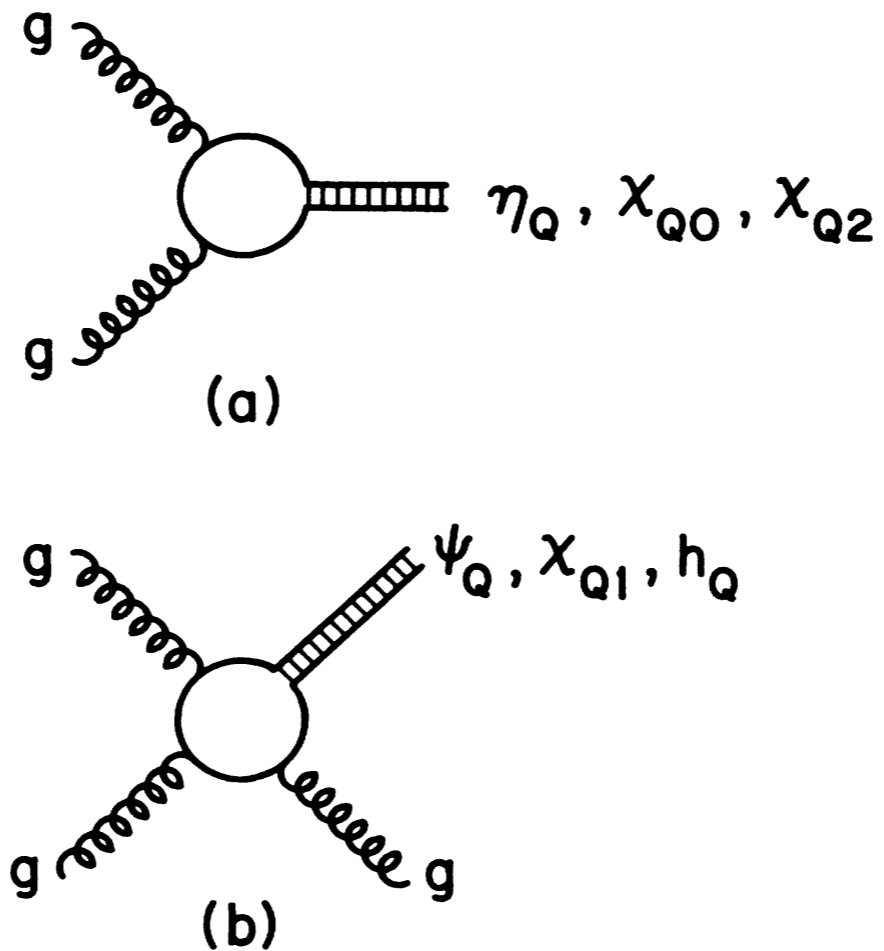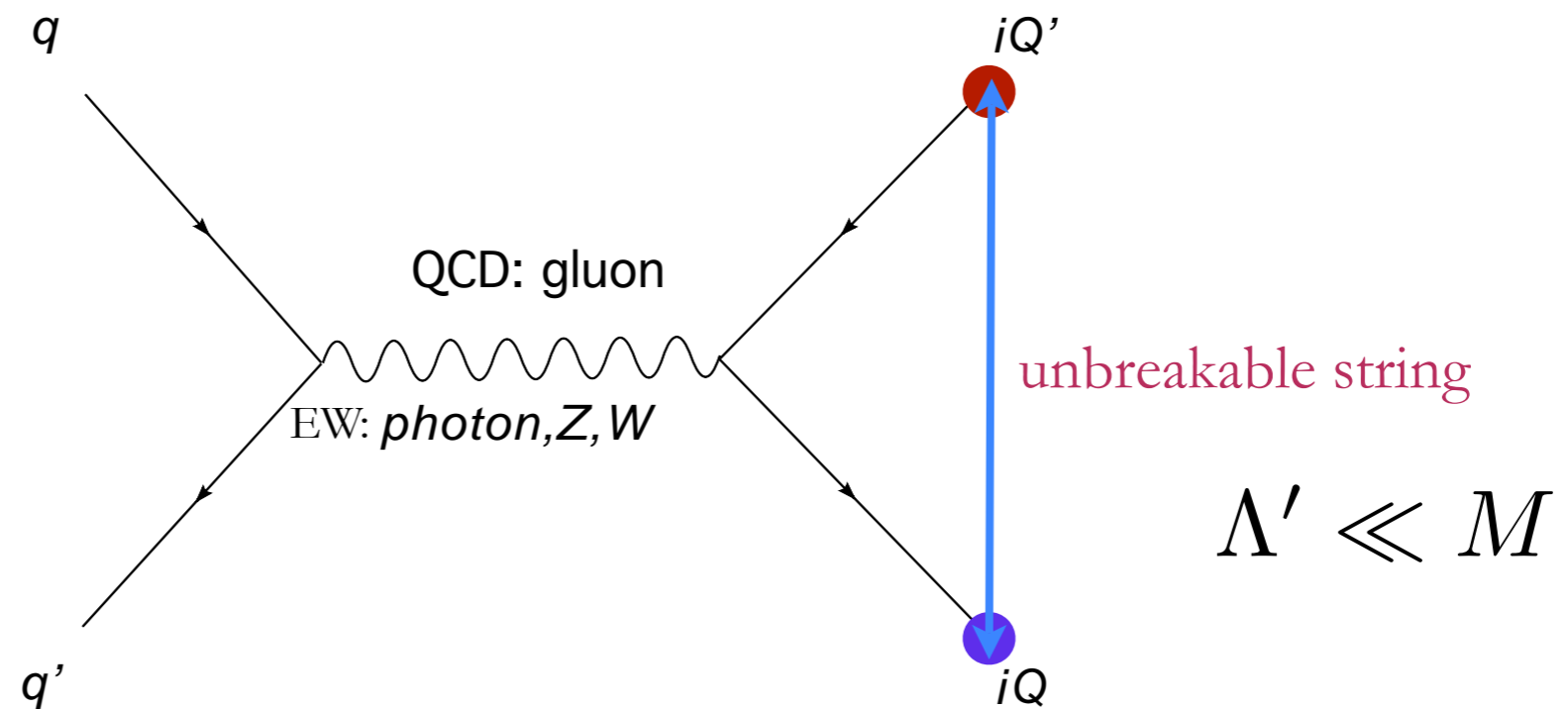# *iQuark Production at LHC*

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

q

iQ'

QCD: gluon

EW: *photon,Z,W*

unbreakable string

$$\Lambda' \ll M$$

q'

iQ

Open production cross section for iQuarks at LHC

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 $N_{\text{IC}} = 3$.

Open squirk (siquark) production in folded SUSY
(Burdman, Chacko, Goh, Harnik and Krenke, arXiv:0805.4667)

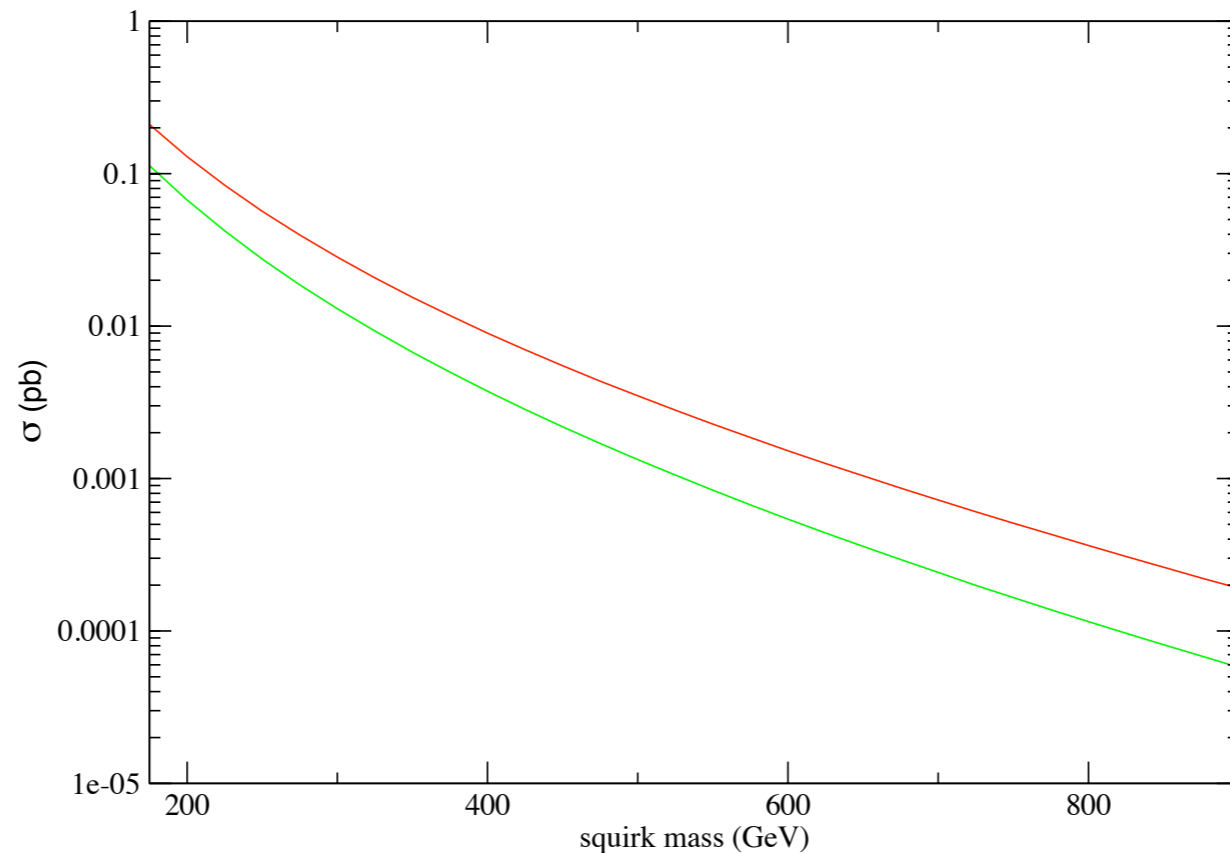FIG. 1: The total cross-section for production of first generation squirk anti-squirk pairs via an s-channel W^+ (top curve) and W^- (bottom curve) at the LHC as a function of the squirk mass. The up and down squirks have been taken to be degenerate.

## iQuark has larger production rate than scalar iQuark!

Prompt Annihilation (After Energy Loss)

[Cheung, Keung and TCY, 0810.1524]

iQuark Annihilations/iQuarkonium Decays

Lightest iQuark is stable. No weak beta decay.

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

wave function
at origin

Hard kernel

Projection op

(a)

W
(b)

(c)

(d)

(e)
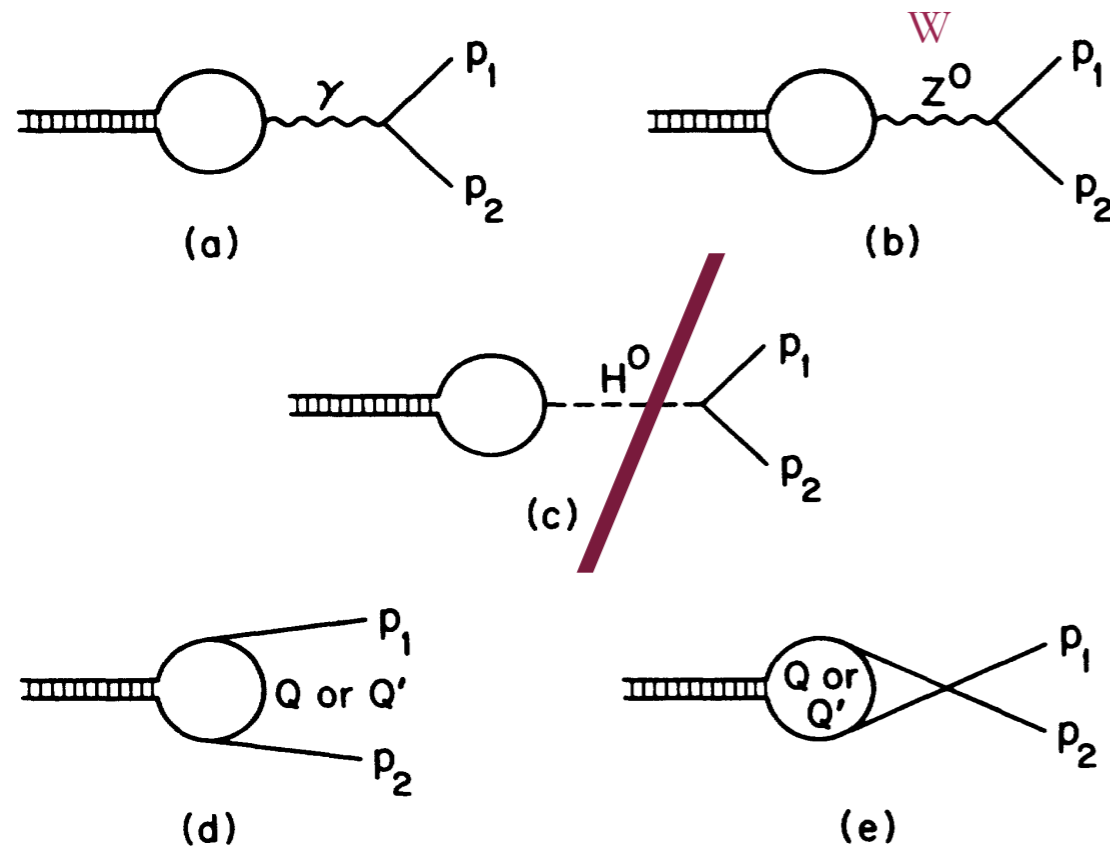
Generic diagrams for 2-body decays

$$A(\eta) = \left[\frac{3}{16\pi M_\eta}\right]^{1/2} R_S(0)\mathrm{Tr}[\mathscr{O}_F\gamma_5(-\mathbf{Q}+M_\eta)] \ ,$$

$$A(\psi) = -\left[\frac{3}{16\pi M_\psi}\right]^{1/2} R_S(O)\mathrm{Tr}[\mathscr{O}_F\slashed{\epsilon}(-\mathbf{Q}+M_\psi)] \ ,$$

$$A(\chi_0) = i\left[\frac{3}{4\pi M_\chi}\right]^{1/2} R'_P(0)\mathrm{Tr}\left[\mathscr{O}_F^\alpha\left[\gamma_\alpha+\frac{Q_\alpha}{M_\chi}\right]\left[\frac{-\mathbf{Q}+M_\chi}{2}\right]+3\mathscr{O}_F\right]$$

Annihilation Amplitudes

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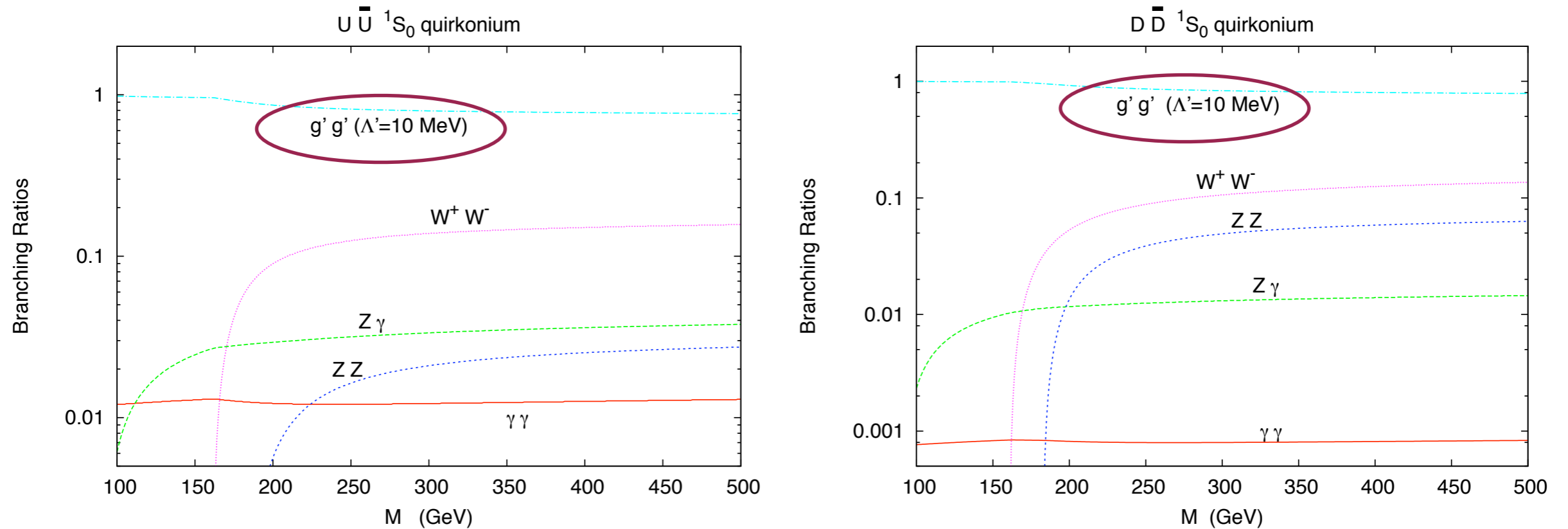
FIG. 2: Branching fractions of the quirkonium of (a) $^1S_0(\mathcal{U}\overline{\mathcal{U}})$ and (b) $^1S_0(\mathcal{D}\overline{\mathcal{D}})$ versus the quirkonium mass M. We have chosen $n_Q = 1$ and $\Lambda' = 10$ MeV in the running α'_s.

Dominant Decay Mode: Invisible $g'g'$ mode
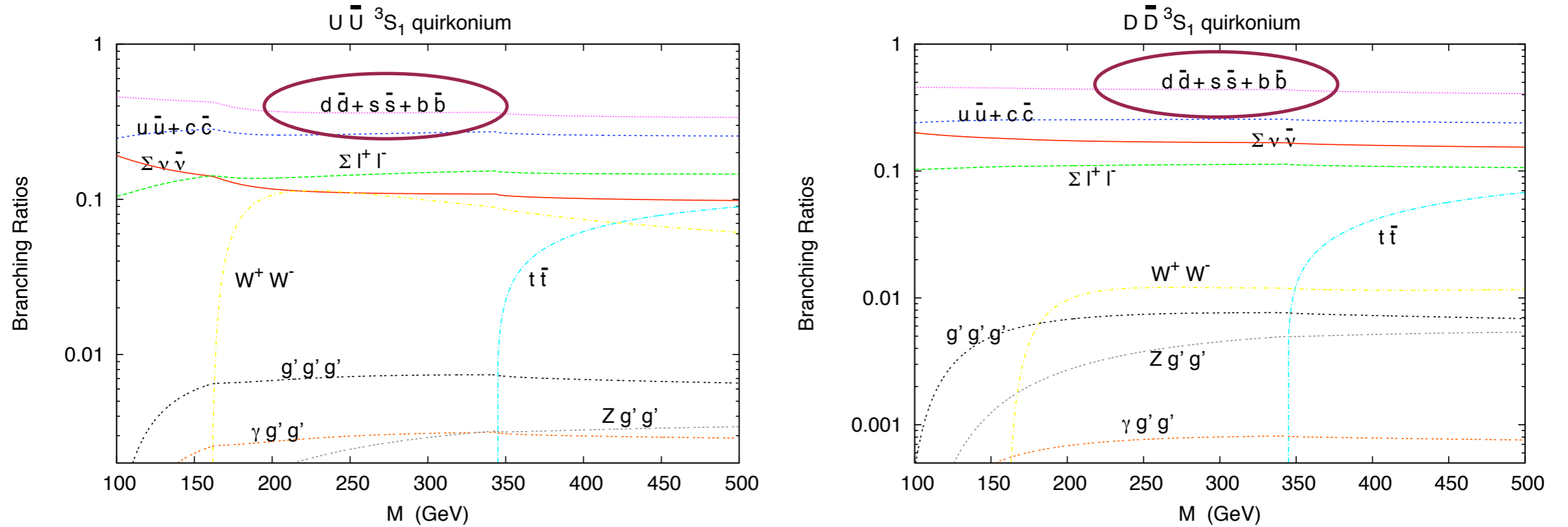
$^3S_1$ neutral iquarkonium

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 quirko-nium mass M. We have chosen $n_Q = 1$ and $\Lambda' = 10$ MeV in the running α'_s.

Dominant decay mode: 2-jet

WW mode has large cancellation among amplitudes for vector iQuarks

Comparison with superheavy Quarkonium
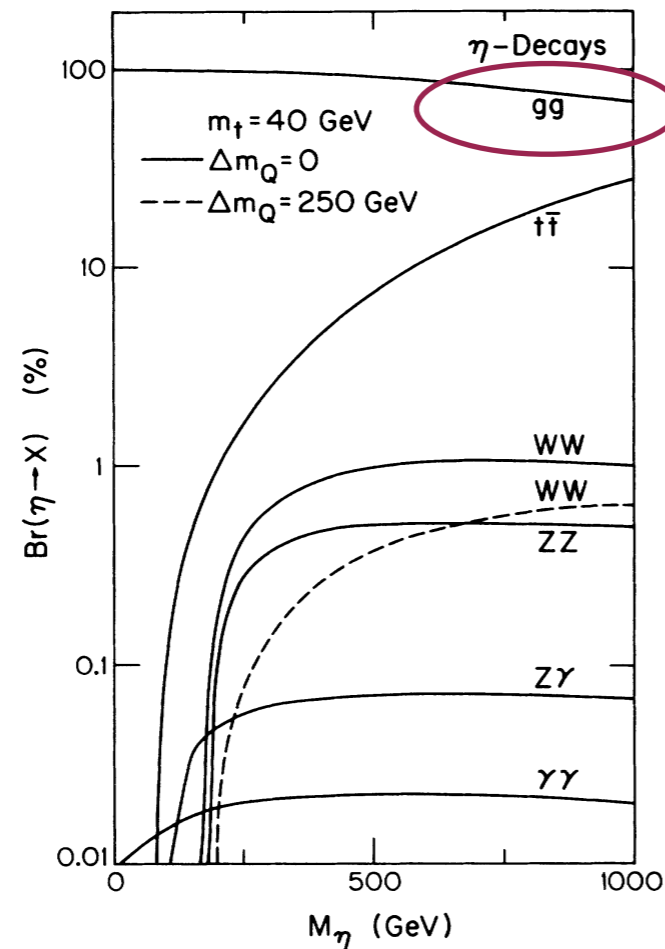## (Barger et al PRD 35, 3366 (1987))

V. BARGER *et al.*

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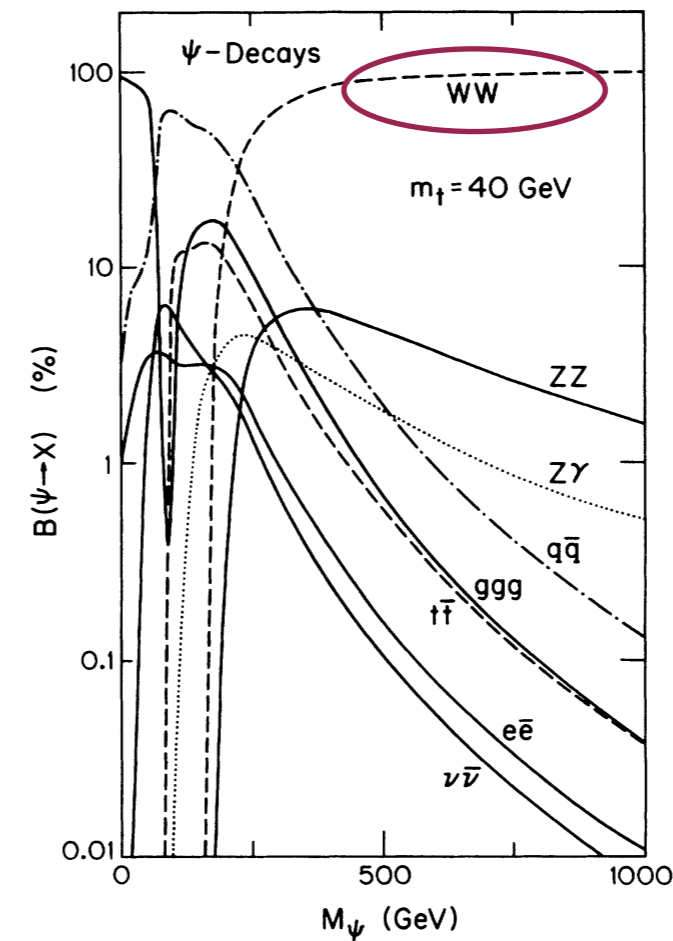
FIG. 10. The branching fractions for the decays of ψ_Q. We have fixed $m_{Q'}=m_Q+250$ GeV.

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

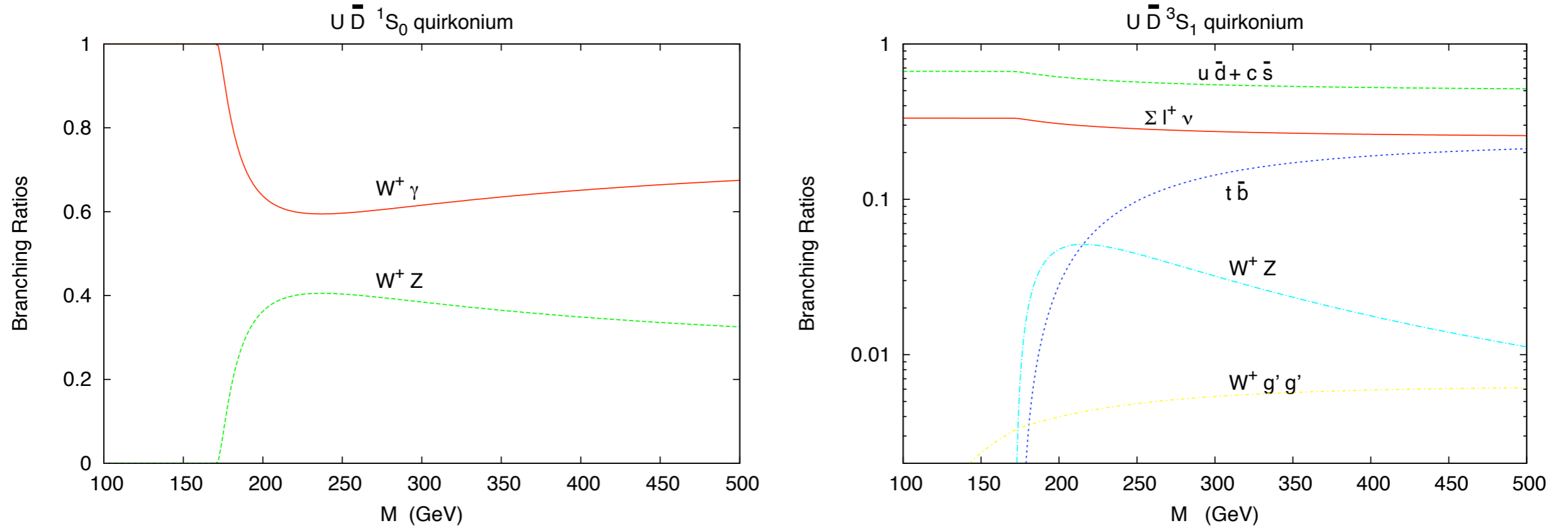2-jet

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) iQuarks production
(2) Soft energy loss
(3) Hard Annihilation

iQuarks linked by macroscopic string may or may not lead to observable tracks. Detailed analysis is missing but interesting classical 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.

Backup Slides

Comparison with folded supersymmetry
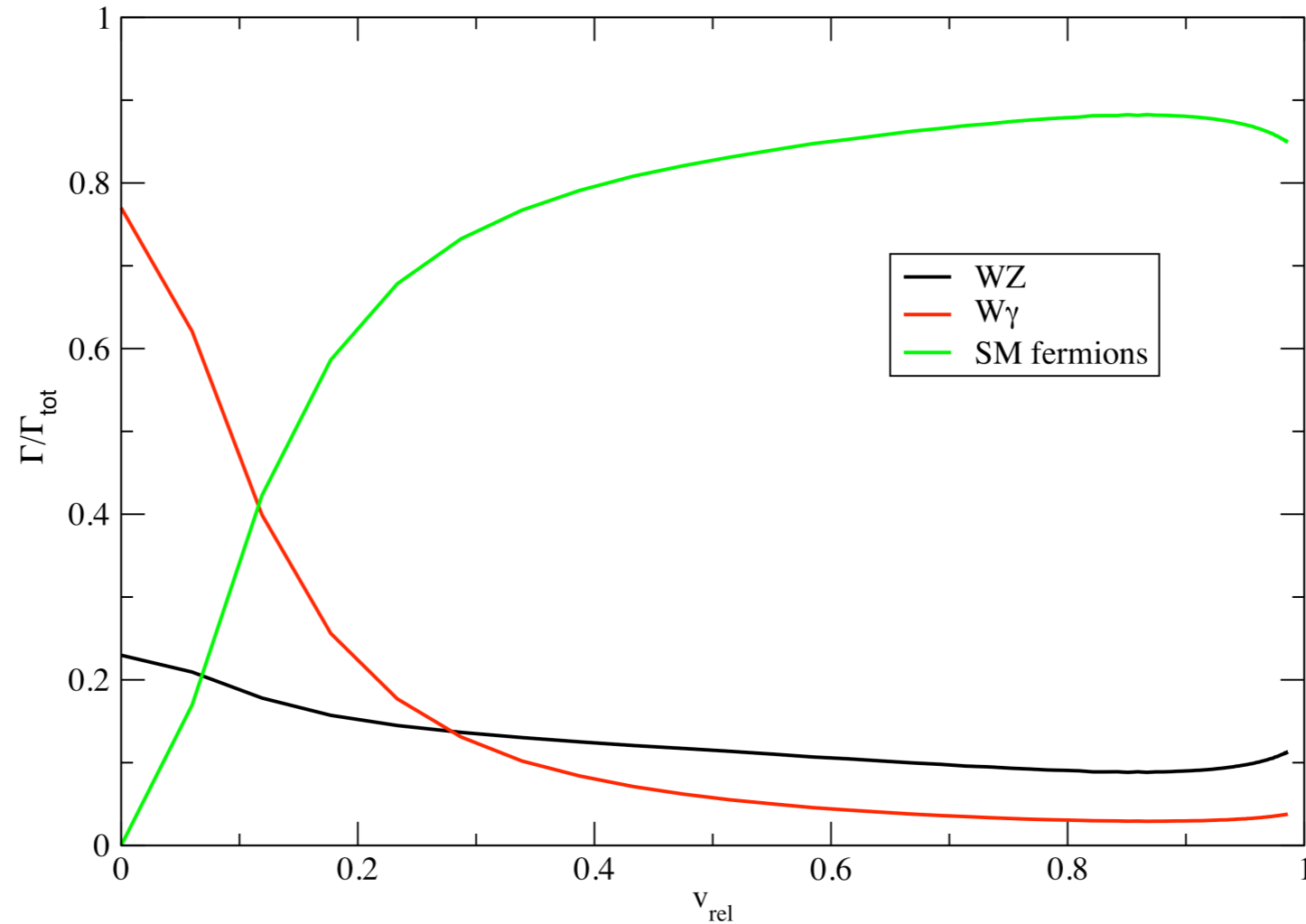## (Burdman, Chacko, Goh, Harnik and Krenke, arXiv:0805.4667)

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!