Exotic Quarks in Twin Higgs Models

Yuhsin Tsai

In collaboration with Hsin-Chia Cheng, Sunghoon Jung and Ennio Salvioni

Brookhaven Forum 2015, Oct 7 2015

Twin Higgs serves as a good example of Neutral Naturalness, which sets an important challenge for the experimental searches

(also see D. Curtin's talk)

On the other hand, a UV-completion is necessary for a calculable model

In this talk, we are going to

Study the Twin-Higgs UV-completion
at colliders

Twin Higgs as solution to little hierarchy

Chacko, Goh, Harnik 05'

$$H \xrightarrow{\text{spontaneously}} \langle H \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

fundamental under global SU(4)

break into SU(3), produce 7 NGB

explicitly

$$(H_A, H_B) \xrightarrow{Z_2 \text{ symmetry}} \Lambda^2 (H_A^\dagger H_A + H_B^\dagger H_B)$$

gauge into SU(2)sm x SU(2)twin
1 uneaten GSB, SM Higgs

SU(4) symmetric, no quadratic divergence in Higgs mass

UV-sensitivity in the Higgs potential

Z2 invariant, but breaks the SU(4)

$$\sim \frac{3y_t^4}{16\pi^2} \log\left(\frac{\Lambda^2}{y_t^2 |H_{A,B}|^2}\right) \left(|H_A|^4 + |H_B|^4\right)$$

Need a UV-completion to make things calculable!

Focusing on top, one possible extension (Chacko, Goh, Harnik 05')

Enlarge the global symmetry of top Yukawa to SU(6) x SU(4) x U(1), and gauge (SU(3)$_C$ x SU(2) x U(1))$_{A,B}$

Requires new fermions charged under BOTH the SM & twin gauge group

Exotic-quarks

The extended Yukawa coupling: $\quad y_t \begin{pmatrix} H_A^\dagger & H_B^\dagger \end{pmatrix} Q \begin{pmatrix} t_A \\ t_B \end{pmatrix}$

$$Q =$$

	SM SU(3)c	twin SU(3)c
SM SU(2)	q_A	$\tilde{q}_B$
twin SU(2)	$\tilde{q}_A$	q_B

Appear in all the non-SUSY UV-completion models so far

Exotic-quarks

The extended Yukawa coupling: $\quad y_t \begin{pmatrix} H_A^\dagger & H_B^\dagger \end{pmatrix} Q \begin{pmatrix} t_A \\ t_B \end{pmatrix}$

$$Q =$$

	SM SU(3)c	twin SU(3)c
SM SU(2)	q_A	$\tilde{q}_B$
twin SU(2)	$\tilde{q}_A$	q_B

Can be produced at hadron colliders. Our focus in this talk.

Upper bound on the exo-quark mass

The log-divergent is regulated by the exo-quark mass

$$\sim \frac{3y_t^4}{16\pi^2} \log\left(\frac{M_{\tilde{q}}^2}{y_t^2 |H_{A,B}|^2}\right) \left(|H_A|^4 + |H_B|^4\right)$$

The Higgs quartic coupling is sensitive to $M_{\hat{q}}$

To obtain the right Higgs mass and positive quartic coupling up to the cutoff scale (no other deeper vacuum exists)

$$M_{\tilde{q}_{A,B}} \sim 5 - 10\,\text{TeV}$$

Look for them at future collider experiments!

In this talk, we assume
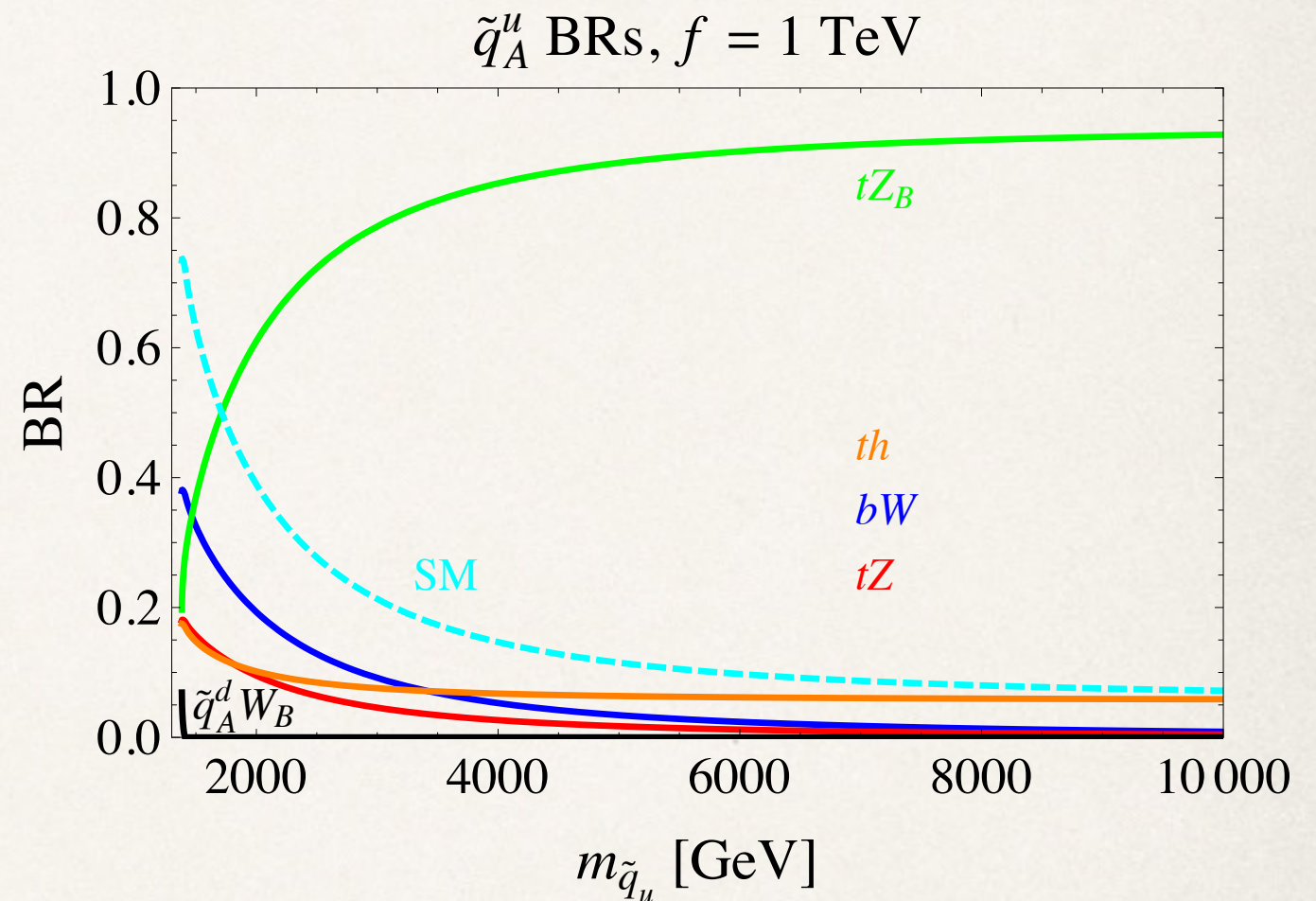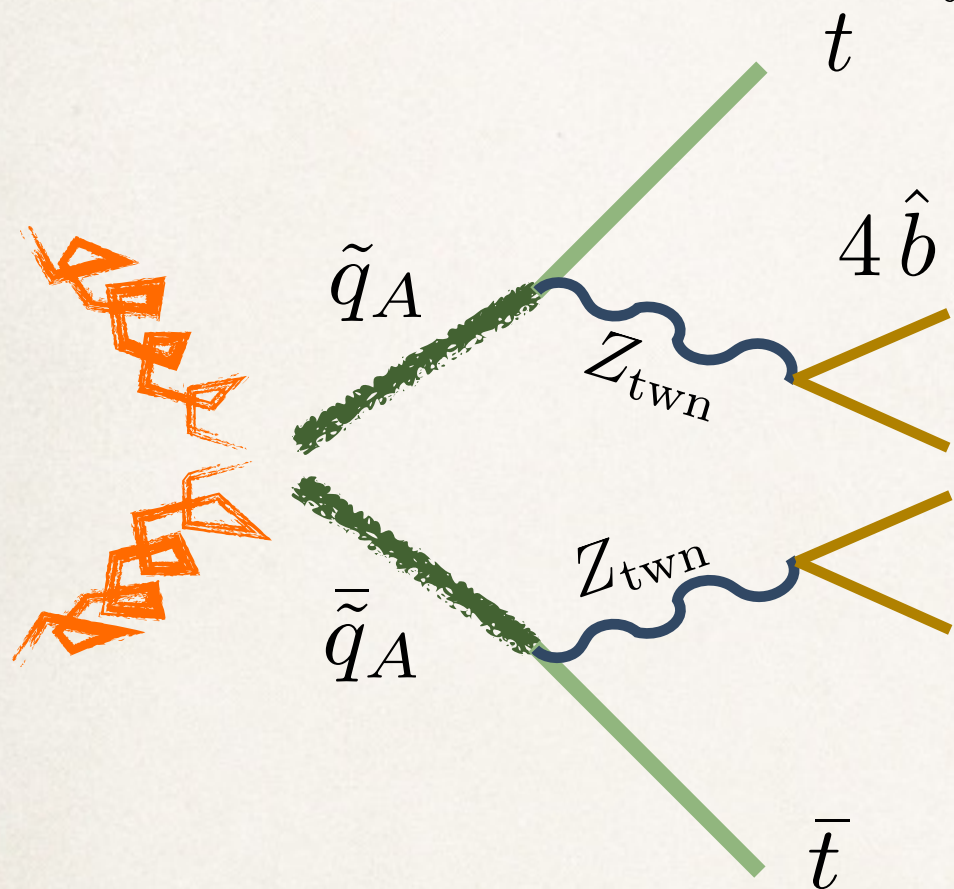
Fraternal Twin-Higgs model
— third generation only
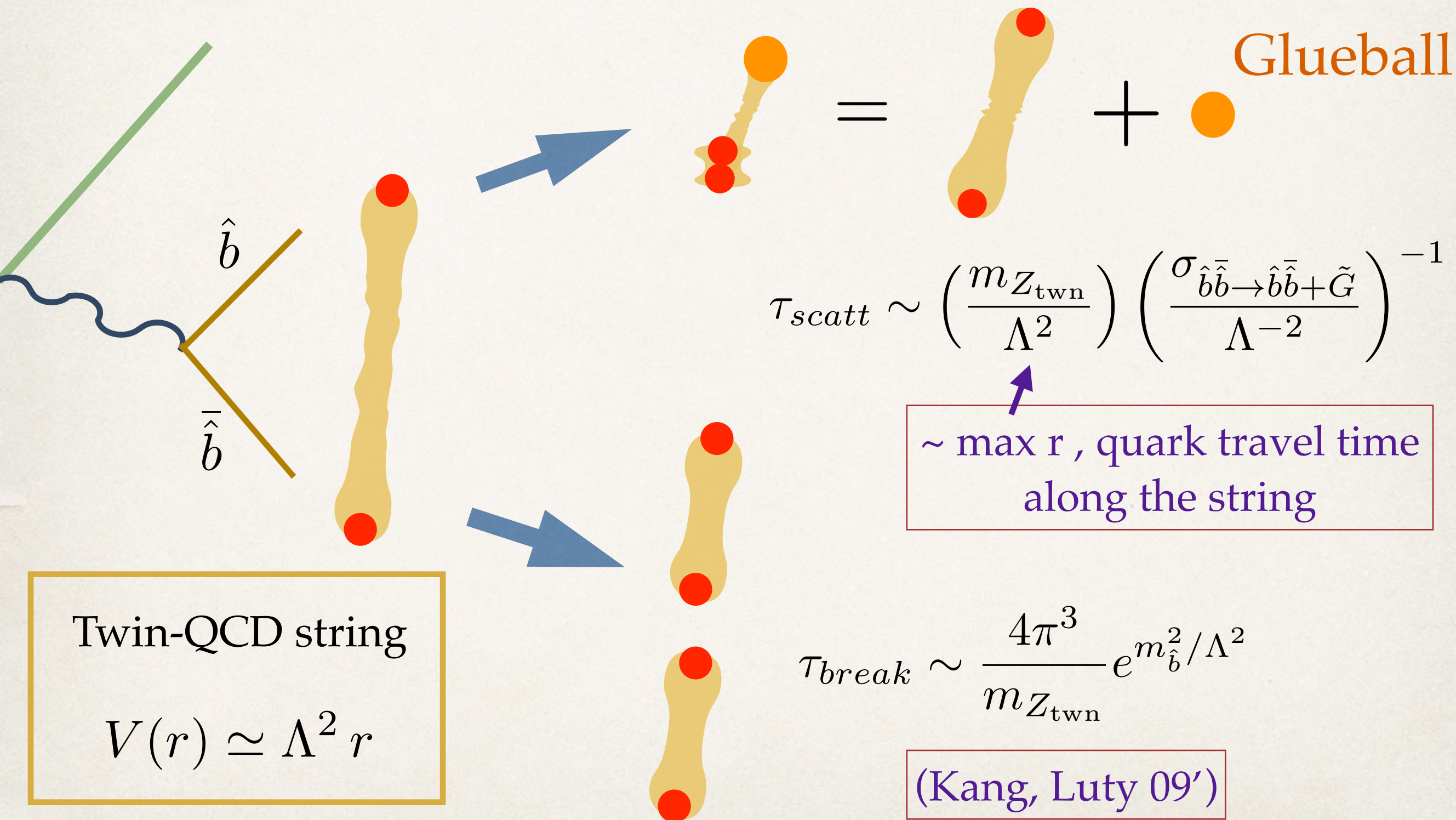
Heavy Twin-leptons
0++ bound states decay into SM

Exo-quark productin & decay

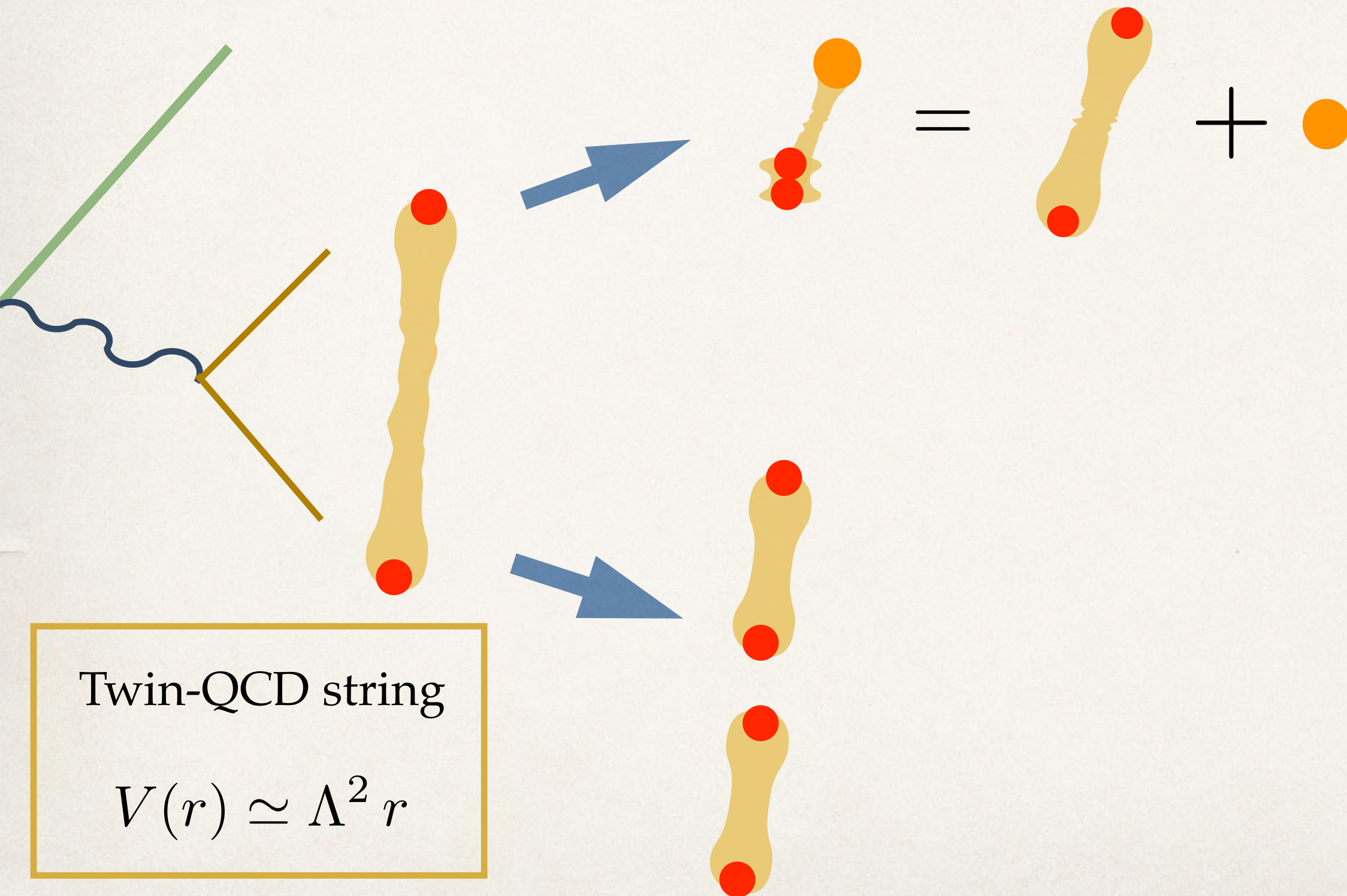$$y_t \, \bar{\tilde{q}}_A \, t_R^A \, \boxed{H_B} \supset Z_{\text{twn}}, W_{\text{twn}}, \frac{v}{f} h$$

$\tilde{q}_A$

$\bar{\tilde{q}}_A$

Z_{twn}

Z_{twn}

t

$\bar{t}$

$4\,\hat{b}$

$\tilde{q}_A^u$ BRs, $f = 1$ TeV

BR

$m_{\tilde{q}_u}$ [GeV]

tZ_B

th

bW

tZ

SM

$\tilde{q}_A^d W_B$

The $t\bar{t}$ can help to trigger the signal, making the displaced searches background free!

Twin-quark dynamics

Glueball

$$= \quad + \quad$$

$\hat{b}$

$\bar{\hat{b}}$

$$\tau_{scatt} \sim \left(\frac{m_{Z_{\mathrm{twn}}}}{\Lambda^2} \right) \left(\frac{\sigma_{\hat{b}\bar{\hat{b}} \to \hat{b}\bar{\hat{b}} + \tilde{G}}}{\Lambda^{-2}} \right)^{-1}$$

~ max r , quark travel time
along the string

Twin-QCD string

$$V(r) \simeq \Lambda^2 \, r$$

$$\tau_{break} \sim \frac{4\pi^3}{m_{Z_{\mathrm{twn}}}} e^{m_{\hat{b}}^2/\Lambda^2}$$

(Kang, Luty 09')

For $f = 1\,\mathrm{TeV},\quad \Lambda = 5\,\mathrm{GeV}$

Twin-QCD string

$V(r) \simeq \Lambda^2\, r$

Glueball-dominated signals

Twin-QCD string
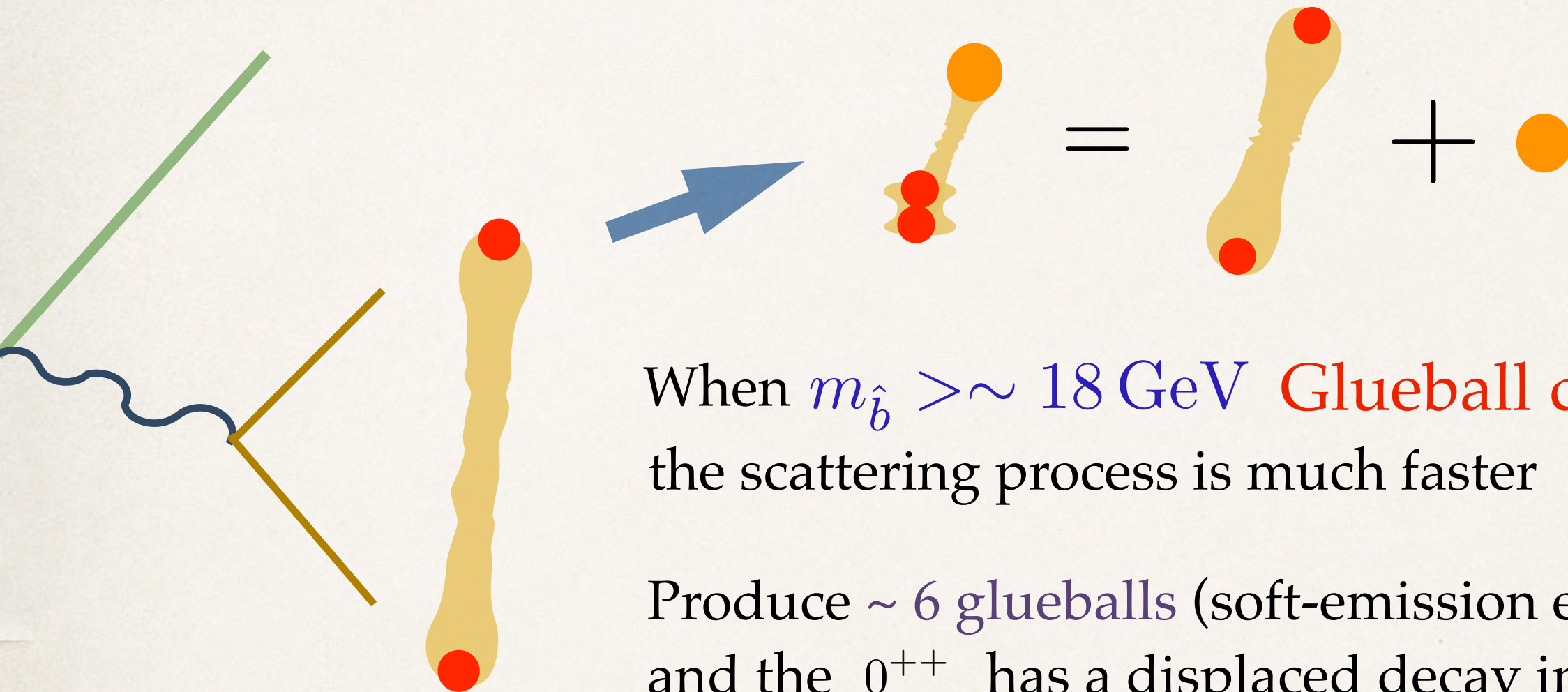
$$V(r) \simeq \Lambda^2\, r$$

When $m_{\hat{b}} > \sim 18\,\mathrm{GeV}$ Glueball dominates the scattering process is much faster

Produce ~ 6 glueballs (soft-emission estimation), and the 0^{++} has a displaced decay into SM $b\bar{b}$ through the Higgs mixing

$$c\tau_{0^{++}} \simeq 1\mathrm{cm} \left(\frac{5\,\mathrm{GeV}}{\Lambda} \right)^{7} \left(\frac{f}{1\,\mathrm{TeV}} \right)^{4}$$

Bottomonium-dominated signals

When $m_{\hat{b}} < 9\,\mathrm{GeV}$ B-onium dominates
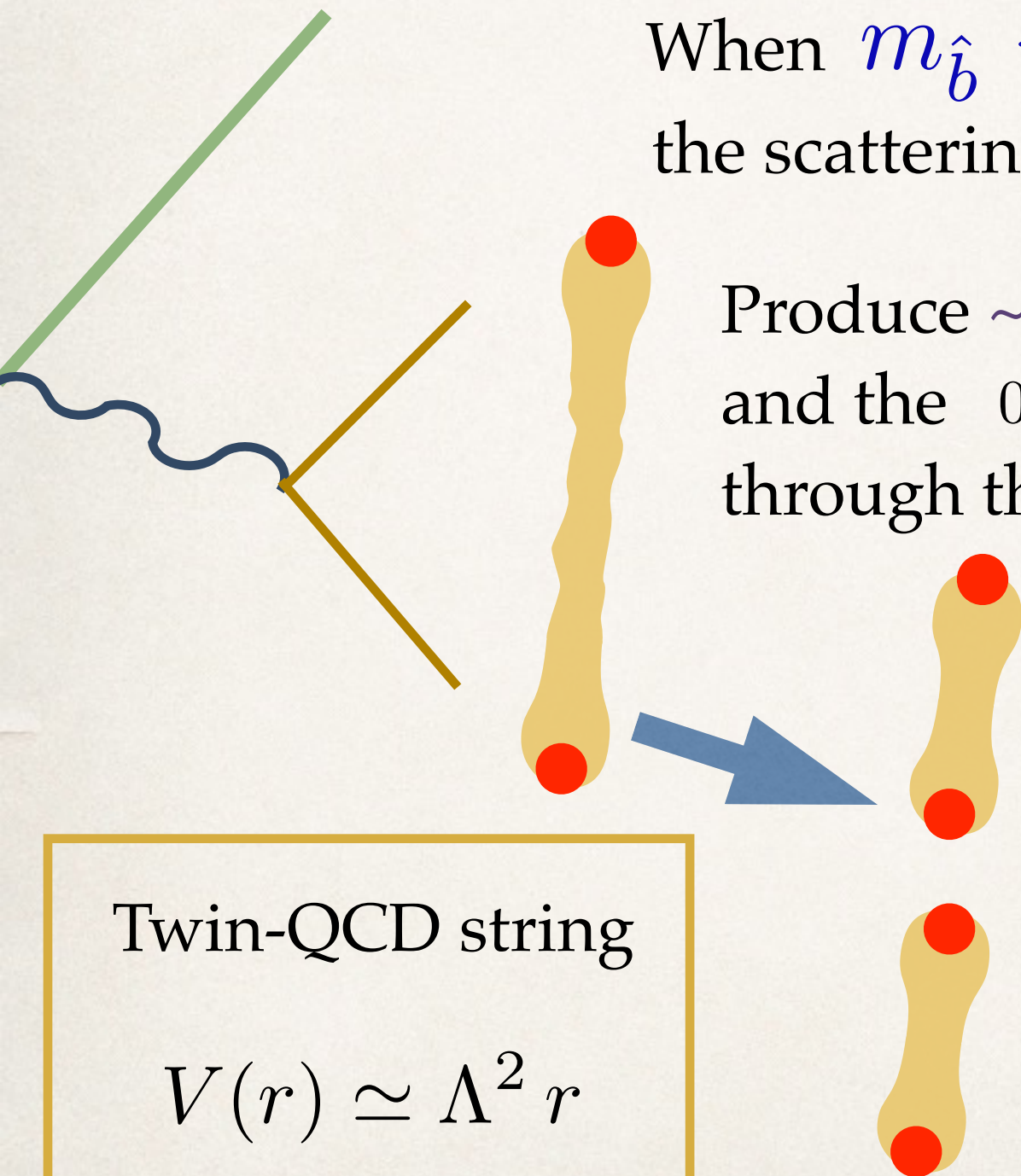the scattering process is much faster

Produce ~ 8 mesons (simple string breaking model)
and the 0^{++} has a displaced decay into SM
through the Higgs mixing

$$c\tau_{0^{++}} \simeq 4.4\mathrm{cm} \left(\frac{m_b}{m_{\hat{b}}}\right)^5 \left(\frac{f}{1\mathrm{TeV}}\right)^4 \left(\frac{5\mathrm{GeV}}{\Lambda}\right)^2$$

Twin-QCD string

$$V(r) \simeq \Lambda^2\, r$$

More energetic mesons than non-relativistic
description. The same derivation gives a
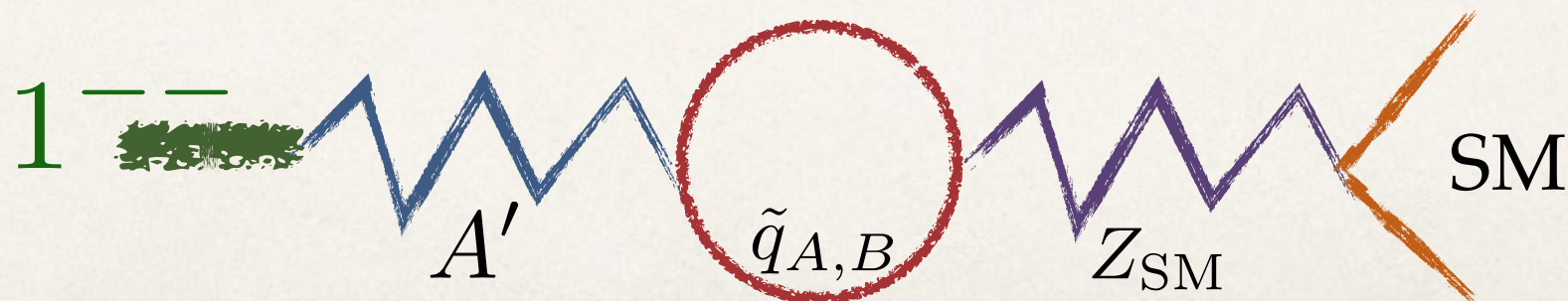good approximation of the $\psi(4415)$ width

A cosmological connection to the collider search

For the three lightest B-onium $\quad 0^{-+},\ 1^{--},\ 0^{++}$

0^{++} decay through Higgs mixing

1^{--} decay through a loop-induced kinetic mixing

$$c\tau_{1^{--}} \simeq 1\,\text{cm} \left(\frac{m_{A'}}{100\,\text{GeV}}\right)^4 \left(\frac{5\text{GeV}}{\Lambda}\right)^2 \left(\frac{5\text{GeV}}{m_{\hat{b}}}\right)^3 \left(\frac{10^{-3}}{\epsilon}\right)^2$$

1^{--} A' $\tilde{q}_{A,B}$ Z_{SM} SM

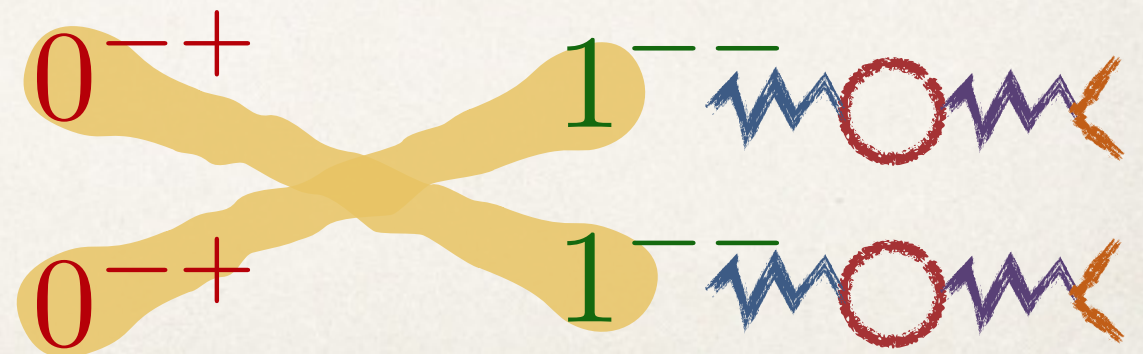# A cosmological connection to the collider search

For the three lightest B-onium $\quad 0^{-+}, 1^{--}, 0^{++}$

0^{-+} No direction mediation, can decay through anomaly with two off-shell dark photons

The life time is long (> BBN time), and can cause cosmological problems

Want to have the 1^{--} life time to be short enough, so the 0^{-+} can deplete its density before BBN
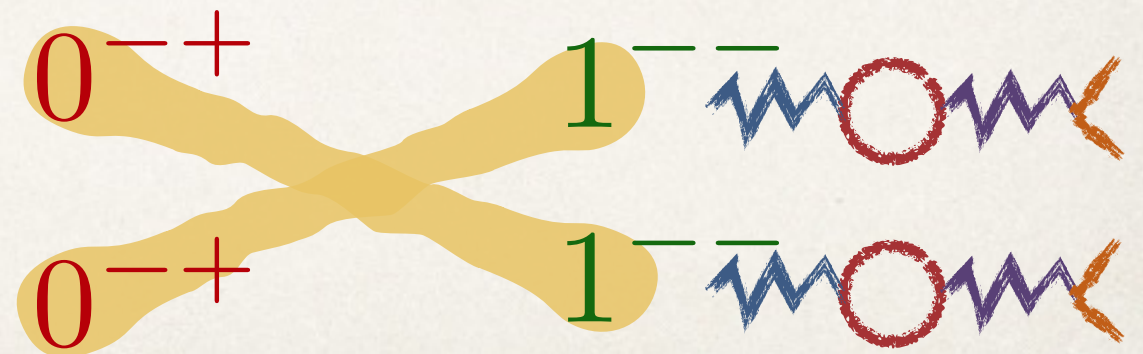
$$0^{-+} \qquad 1^{--}$$
$$0^{-+} \qquad 1^{--}$$

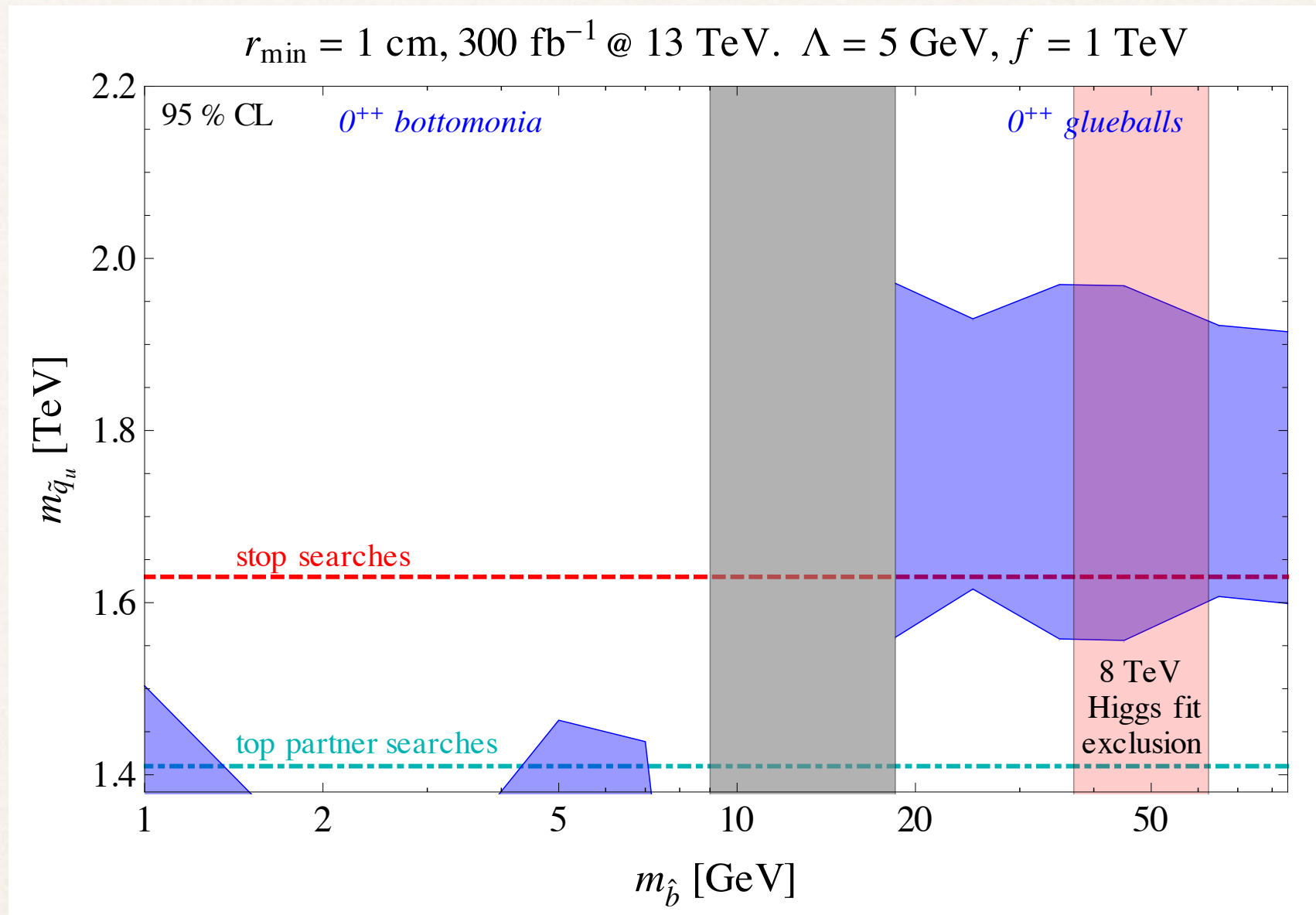# A cosmological connection to the collider search

For the three lightest B-onium $\quad 0^{-+}, 1^{--}, 0^{++}$

> To reduce the 0^{-+} density for not disturbing BBN, we need $\tau_{1^{--}} < 10^{-9}\,\mathrm{sec}$, so the decay should happen ``inside'' the detector

Want to have the 1^{--} life time to be short enough, so the 0^{-+} can deplete its density before BBN
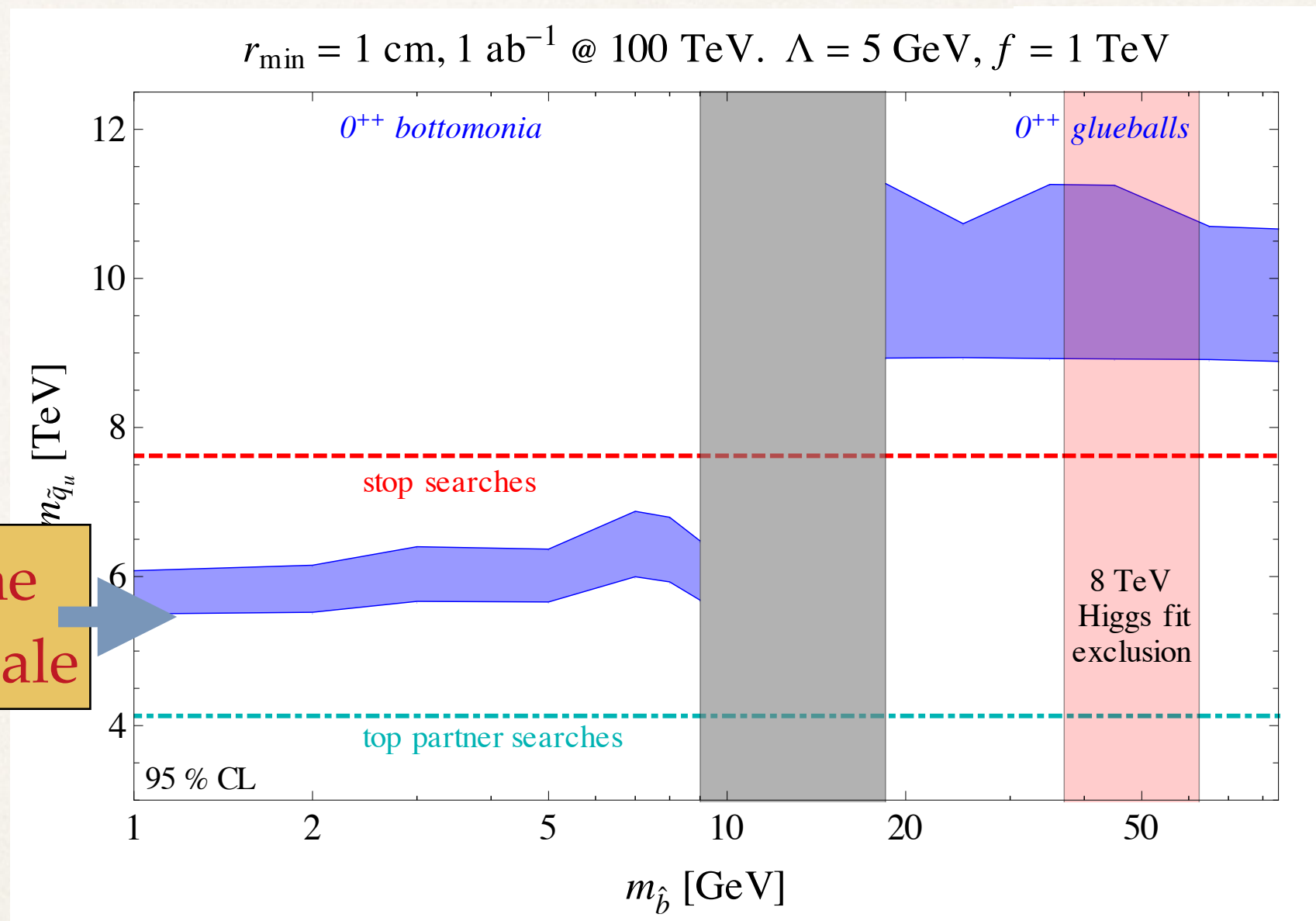
$$0^{-+} \qquad 1^{--}$$
$$0^{-+} \qquad 1^{--}$$

The reach @ 13 TeV LHC

$r_{\min} = 1$ cm, 300 fb^{-1} @ 13 TeV. $\Lambda = 5$ GeV, $f = 1$ TeV

95 % CL 0^{++} *bottomonia* 0^{++} *glueballs*

$m_{\tilde{q}_{lu}}$ [TeV]

stop searches

top partner searches

8 TeV Higgs fit exclusion

$m_{\hat{b}}$ [GeV]

Glueball: (upper) at least one 0++ is produced, (lower) equally distributed d.o.f. among all the three-lightest glueballs. B-onium: (upper) equally distributed d.o.f. among $0 \le \ell \le 1$ states, (lower) among $0 \le \ell \le 2$. H-fit exclusion: bound from the invisible H-decay. stop/top-partner search: PDF rescaling
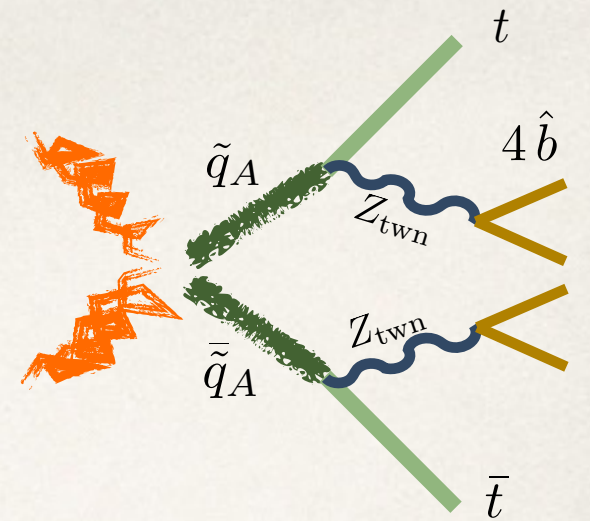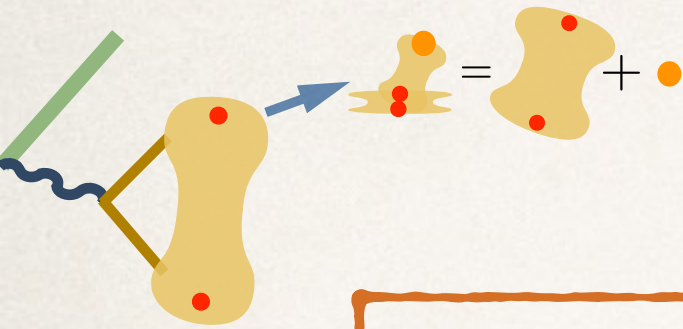
The reach @ 100 TeV collider

$r_{\mathrm{min}} = 1$ cm, 1 ab^{-1} @ 100 TeV. $\Lambda = 5$ GeV, $f = 1$ TeV

can reach the exo-quark scale

0^{++} bottomonia

0^{++} glueballs

stop searches

8 TeV Higgs fit exclusion

top partner searches

95 % CL

$m_{\tilde{q}_u}$ [TeV]

$m_{\hat{b}}$ [GeV]

Glueball: (upper) at least one 0++ is produced, (lower) equally distributed d.o.f. among all the three-lightest glueballs. B-onium: (upper) equally distributed d.o.f. among $0 \le \ell \le 1$ states, (lower) among $0 \le \ell \le 2$. H-fit exclusion: bound from the invisible H-decay. stop/top-partner search: PDF rescaling

Conclusion

Exotic-quark gives distinct signatures for various Twin-Higgs UV-completions

Signals: displaced decays $+ t\bar{t}$, plus stop-like signals, can reach the expected mass range at 100 TeV collider

Twin-strong dynamics: may be described by the string models

Cosmology constraints: can provide complimentary bounds to collider searches