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Distinguishing spins at the LHC using bound state signals

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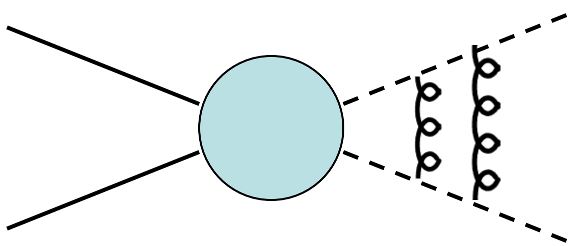
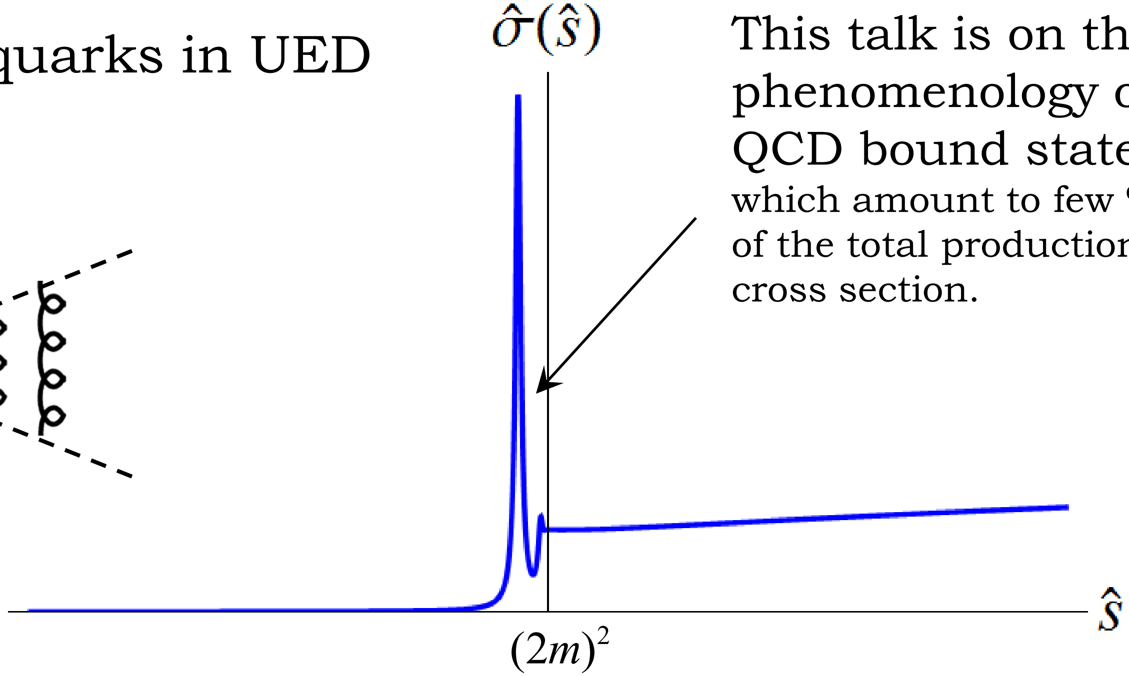
Based on work with Dilani Kahawala, arXiv:1103.3503

Pair-produced colored particles:

- Gluinos, squarks in MSSM
- KK gluons, KK quarks in UED

or anything else.

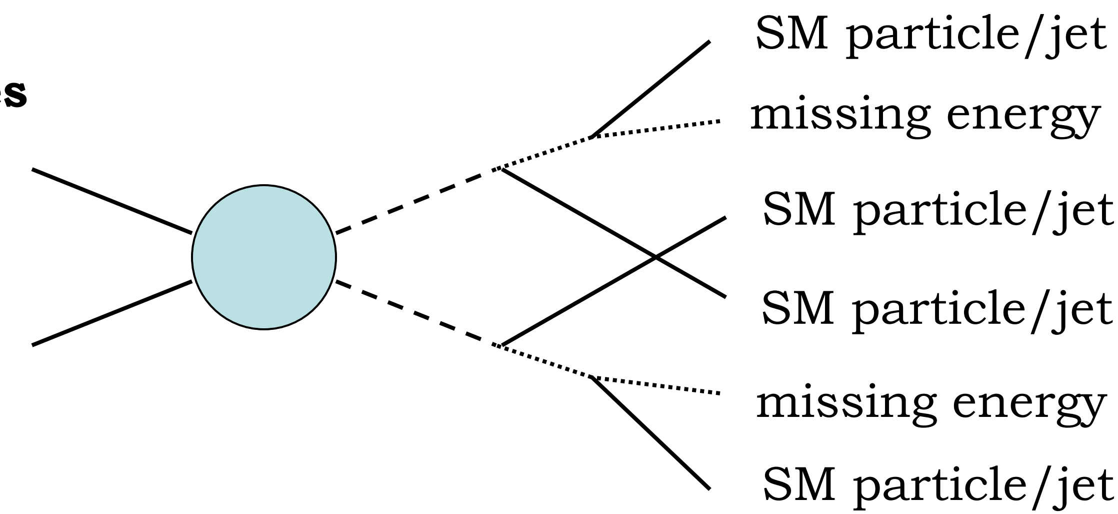




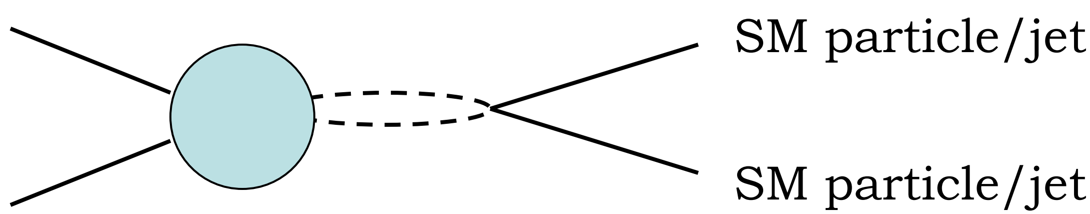
This talk is on the phenomenology of QCD bound states which amount to few % of the total production cross section.

Collider signals

Usual signature of a pair of MSSM or UED particles



Bound state formation and annihilation

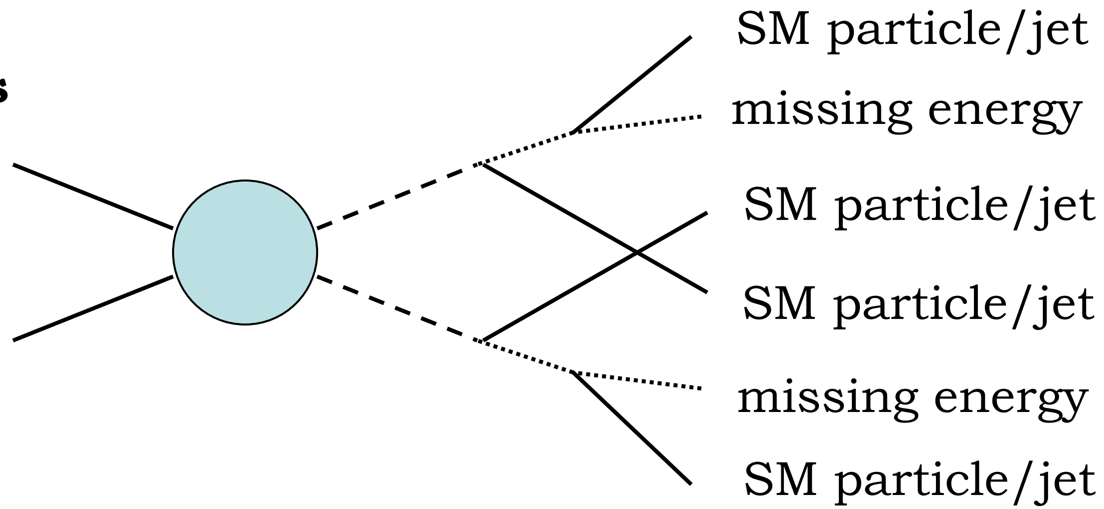


Small resonances at $M \approx 2m$ in channels such as $t\bar{t}$, $b\bar{b}$, $\gamma\gamma$, l^+l^-.

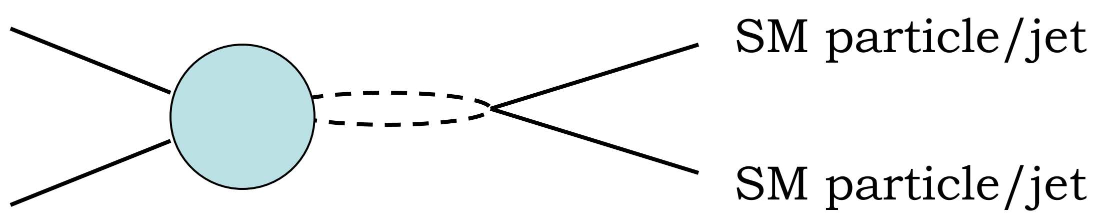
An *independent* and *more direct* way for studying the properties of the new particles.

Collider signals

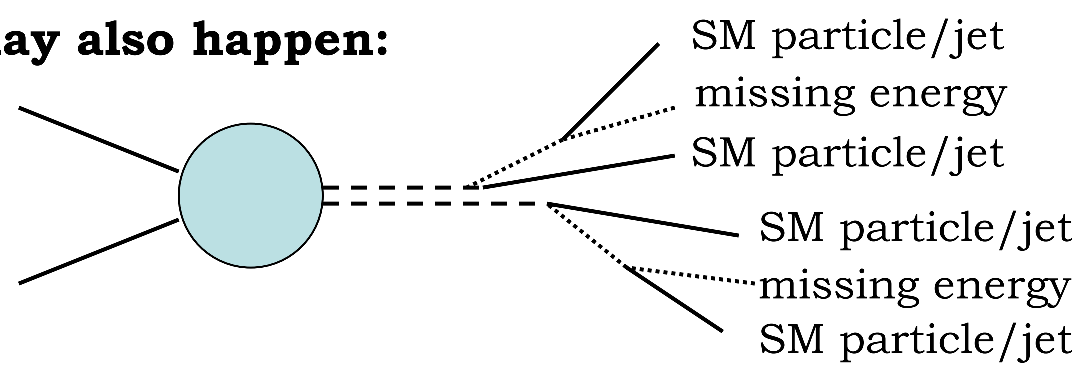
Usual signature of a pair of MSSM or UED particles



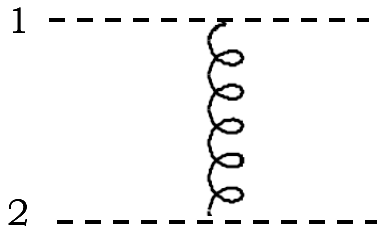
Bound state formation and annihilation



However, the following may also happen:



How to compute bound states



$$V(r) = -C\frac{\overline{\alpha}_s}{r} \qquad C = \frac{1}{2}\left(C_1 + C_2 - C_{(12)}\right)$$

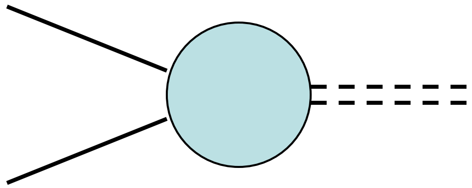
quadratic Casimirs

$$\overline{\alpha}_s \equiv \alpha_s(1/a_0)$$

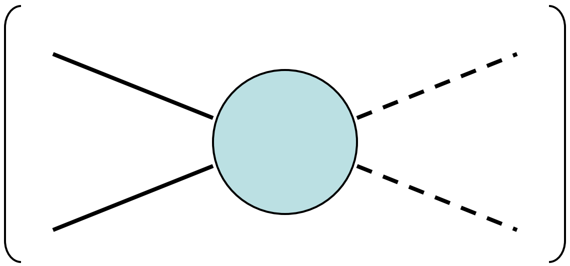
Binding energy $E_b = \frac{C^2\overline{\alpha}_s^2 m}{4}$

Wave function $|\psi(\mathbf{0})|^2 = \frac{1}{\pi a_0^3} = \frac{C^3\overline{\alpha}_s^3 m^3}{8\pi}$

Matrix element for bound state production or annihilation:



$$= \frac{\psi(\mathbf{0})}{\sqrt{m}}$$



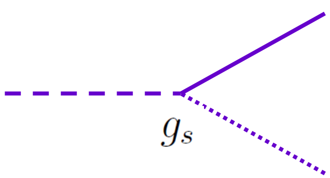
Comes from $$\int \frac{d^3\mathbf{p}_{12}}{(2\pi)^3}\,\tilde{\psi}(\mathbf{p}_{12})\,\mathcal{M}(\overline{\mathbf{p}},\mathbf{p}_{12}) \simeq \mathcal{M}(\overline{\mathbf{p}},0)\,\psi(\mathbf{0})$$

When does annihilation dominate?

Bound state annihilation rate:

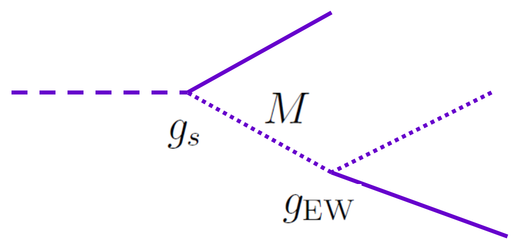
$$\Gamma_{\text{ann}} \sim \frac{\alpha_s^2}{m^2} |\psi(\mathbf{0})|^2 \sim \alpha_s^2 \overline{\alpha}_s^3 m$$

Single-particle two-body decay (example)



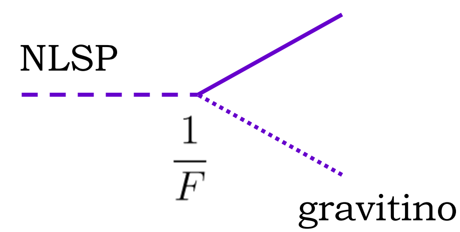
$$\Gamma_{\text{decay}} \sim \alpha_s m$$

Single-particle three-body decay (example)



$$\Gamma_{\text{decay}} \sim \alpha_s \alpha\, m \left(\frac{m}{M}\right)^4 \sim \alpha_s^3 m \left(\frac{m}{M}\right)^4$$

Single-particle decay with a suppressed coupling (example)



$$\Gamma_{\text{decay}} \sim \frac{m^5}{F^2}$$

Single decays will dominate

Annihilation can easily dominate

MSSM vs UED

Superpartners or level-1 KK modes?

- Same gauge interactions
- Mass spectrum is unknown
  (freedom in the soft parameters in MSSM,
  boundary terms in UED)
- Different spins!

  But not straightforward to measure from the cascade decays.

Bound states in UED and MSSM

KK gluonium (UED)

Gluinonium (MSSM)

	color	J^{PC}	can couple to
$(g^\star g^\star)$	$\mathbf{1}, \mathbf{8_S}$	0^{++}	$G^{\rho\sigma}G_{\rho\sigma},\ \bar{t}t$
	$\mathbf{8_A}$	1^{+-}	$\epsilon^{\mu\nu\rho\sigma} i\bar{t}\left[\gamma_\rho, \gamma_\sigma\right] t$
	$\mathbf{1}, \mathbf{8_S}$	2^{++}	$G^{\rho\mu}G_{\rho\nu},\ G^{\rho\sigma}D_\mu D_\nu G_{\rho\sigma},\ i\overline{q}\gamma^\mu D_\nu q$
$(\tilde{g}\tilde{g})$	$\mathbf{1}, \mathbf{8_S}$	0^{-+}	$G^{\rho\sigma}\tilde{G}_{\rho\sigma},\ i\bar{t}\gamma^5 t$
	$\mathbf{8_A}$	1^{--}	$\overline{q}\gamma^\mu q,\ i\bar{t}\left[\gamma^\mu, \gamma^\nu\right] t$

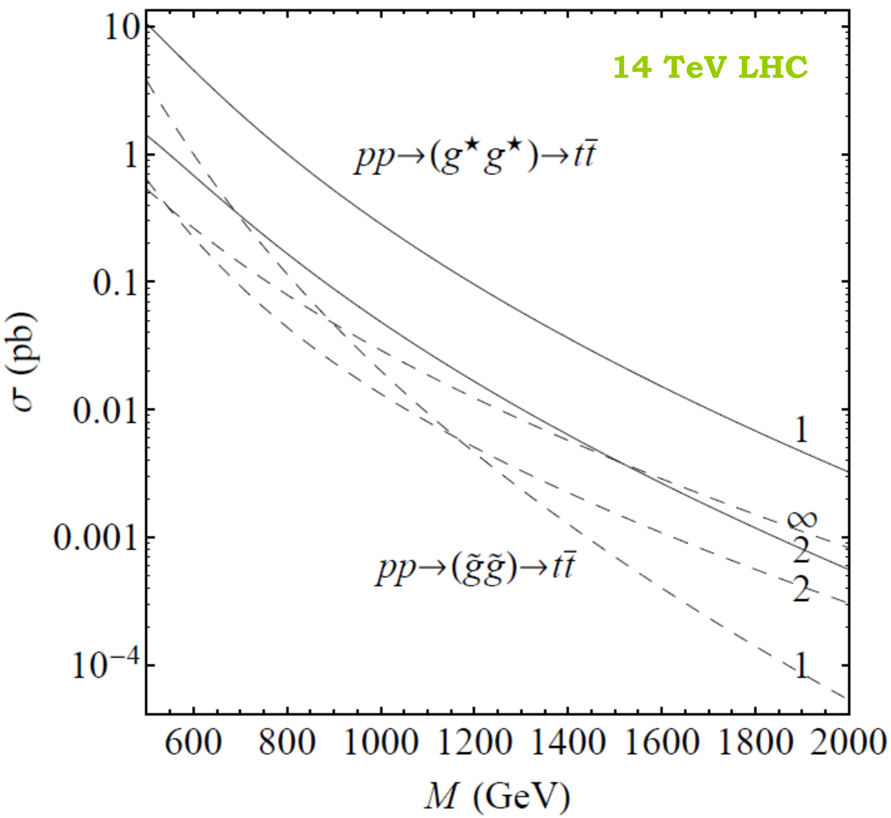
KK quarkonium (UED)

Squarkonium (MSSM)

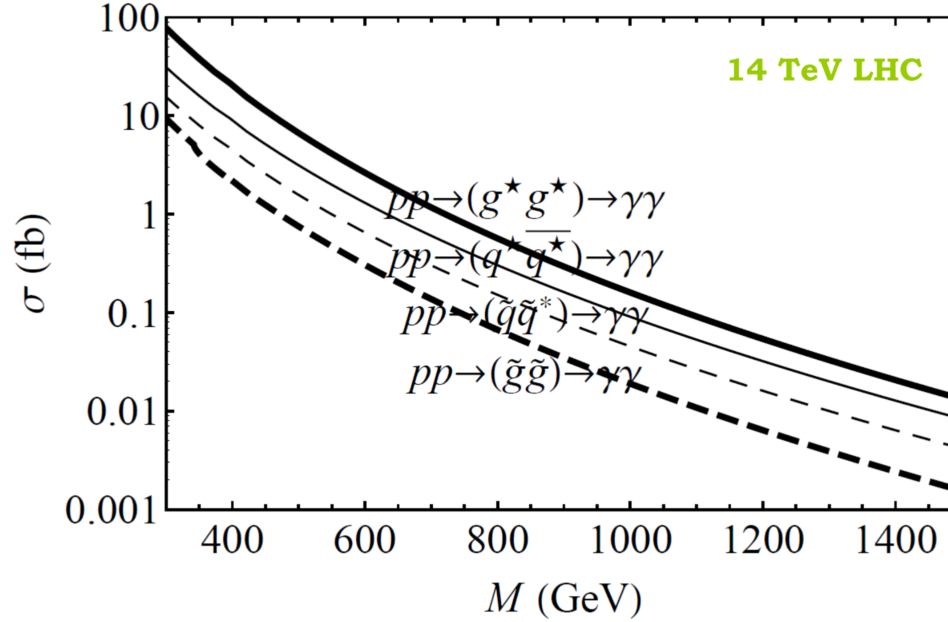
	color	J^{PC}	can couple to
$(q_R^\star \overline{q_R^\star}) + (q_L^\star \overline{q_L^\star})$	$\mathbf{1}$	0^{-+}	$G^{\rho\sigma}\tilde{G}_{\rho\sigma},\ i\bar{t}\gamma^5 t$
$(q_R^\star \overline{q_R^\star}) - (q_L^\star \overline{q_L^\star})$	$\mathbf{1}$	0^{+-}	—
$(q_L^\star \overline{q_R^\star})$	$\mathbf{1}$	0^{-+}	$i\overline{q}P_R q,\ i\bar{t}\gamma^5 t$
$(q_R^\star \overline{q_R^\star}) + (q_L^\star \overline{q_L^\star})$	$\mathbf{1}$	1^{--}	$\overline{q}\gamma^\mu q,\ i\bar{t}\left[\gamma^\mu, \gamma^\nu\right] t,\ \bar{\ell}\gamma^\mu \ell,\ \bar{\ell}\gamma^\mu\gamma^5 \ell$
$(q_R^\star \overline{q_R^\star}) - (q_L^\star \overline{q_L^\star})$	$\mathbf{1}$	1^{++}	$\overline{q}\gamma^\mu\gamma^5 q,\ \bar{\ell}\gamma^\mu \ell,\ \bar{\ell}\gamma^\mu\gamma^5 \ell$
$(q_L^\star \overline{q_R^\star})$	$\mathbf{1}$	1^{--}	$i\overline{q}\left[\gamma^\mu, \gamma^\nu\right] P_R q,\ \bar{t}\gamma^\mu t$
$(\tilde{q}_R \tilde{q}_R^*) + (\tilde{q}_L \tilde{q}_L^*)$	$\mathbf{1}$	0^{++}	$G^{\rho\sigma}G_{\rho\sigma},\ \bar{t}t$
$(\tilde{q}_R \tilde{q}_R^*) - (\tilde{q}_L \tilde{q}_L^*)$	$\mathbf{1}$	0^{--}	—
$(\tilde{q}_L \tilde{q}_R^*)$	$\mathbf{1}$	0^{++}	$\overline{q}P_R q,\ \bar{t}t$

UED/MSSM discrimination
using the size of the annihilation signals (examples)

$t\bar{t}$ channel



Diphoton channel



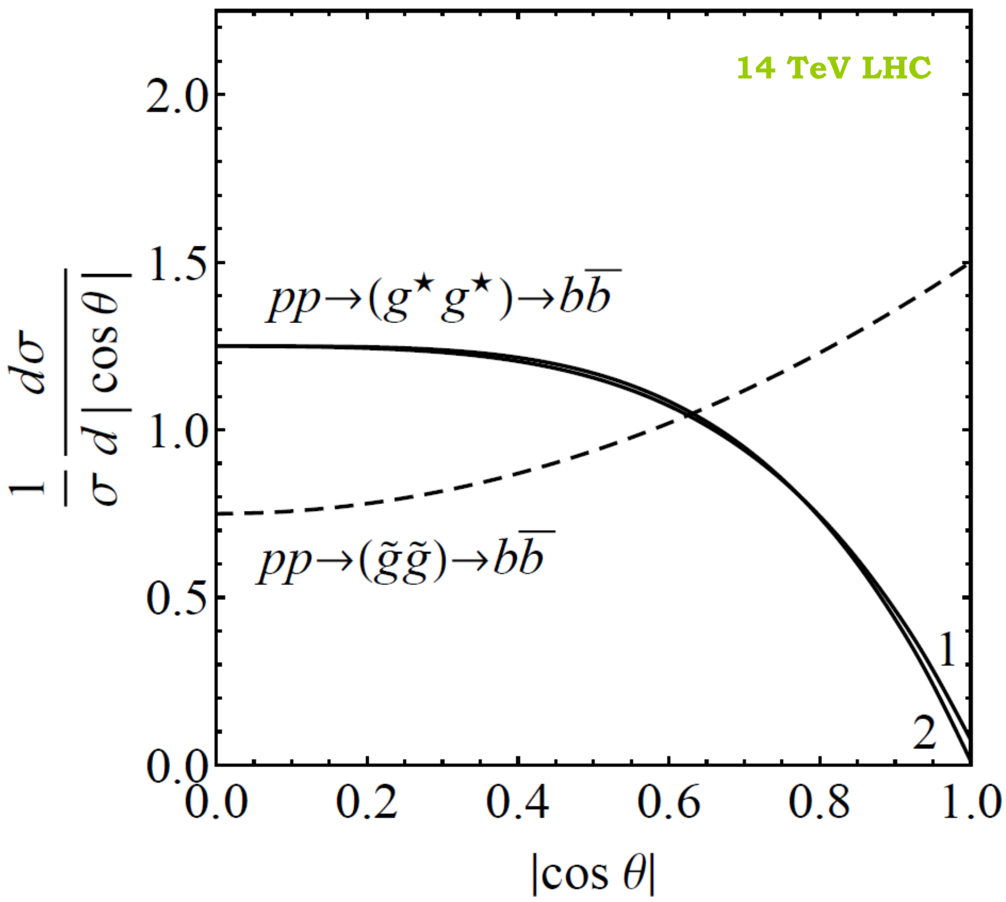
Dilepton channel

Singal exists for (mostly first-generation) KK quarkonia but not for squarkonia.

UED/MSSM discrimination

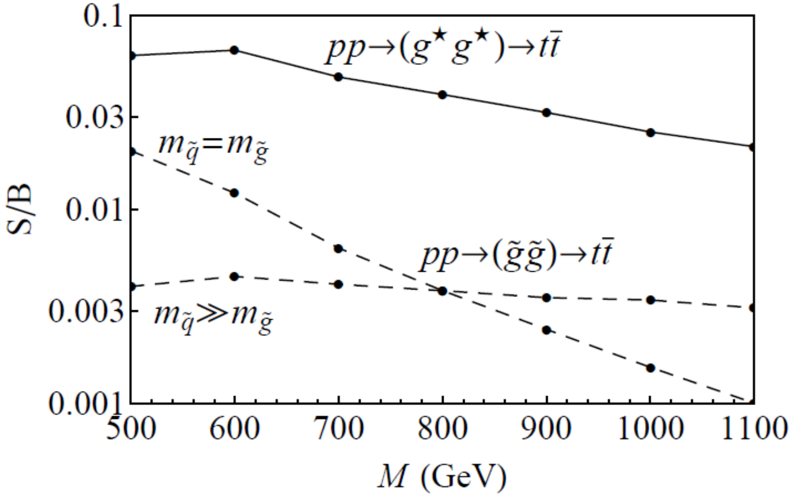
using the angular distributions of the annihilation products (example)

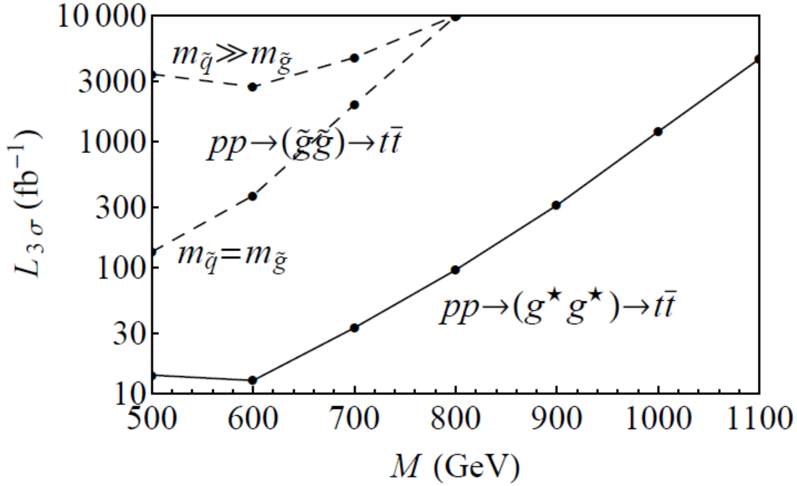
$b\bar{b}$ channel



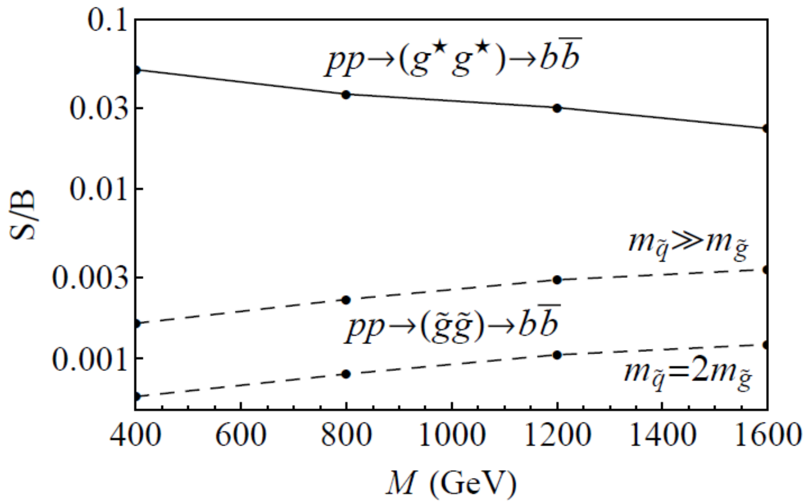
Detection prospects (14 TeV LHC)

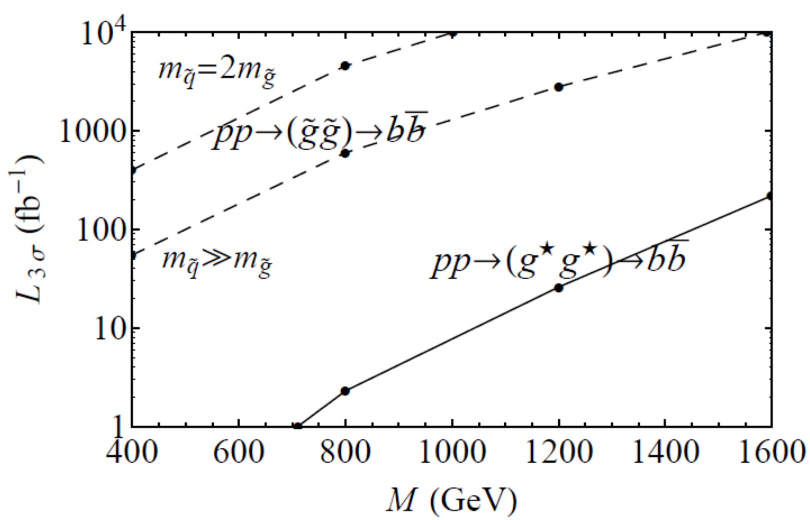
$t\bar{t}$ channel (semileptonic)





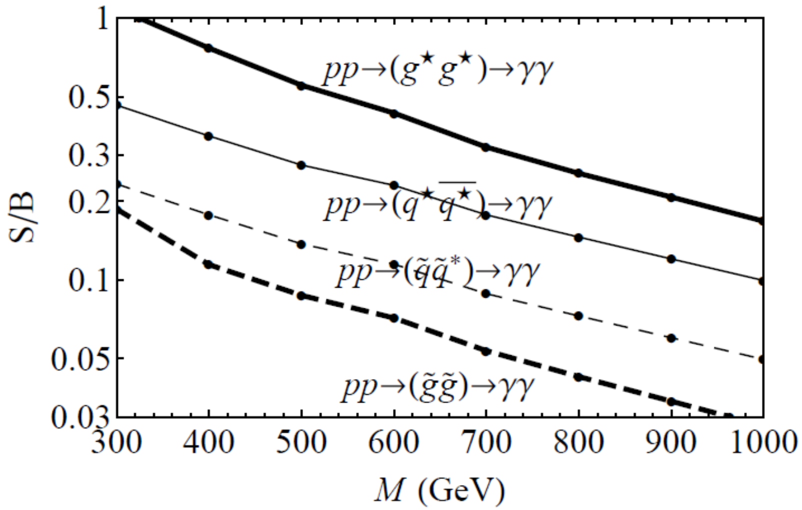
$b\bar{b}$ channel (assumes 60% tagging efficiency, probably too optimistic for the higher masses)

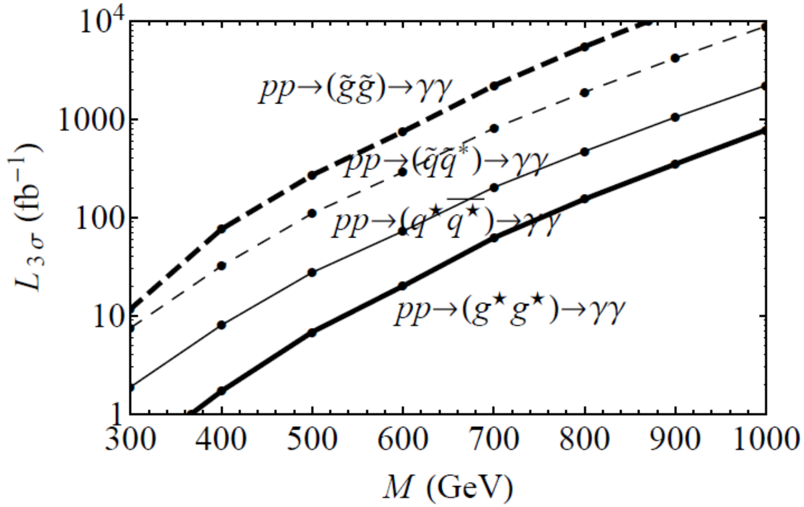




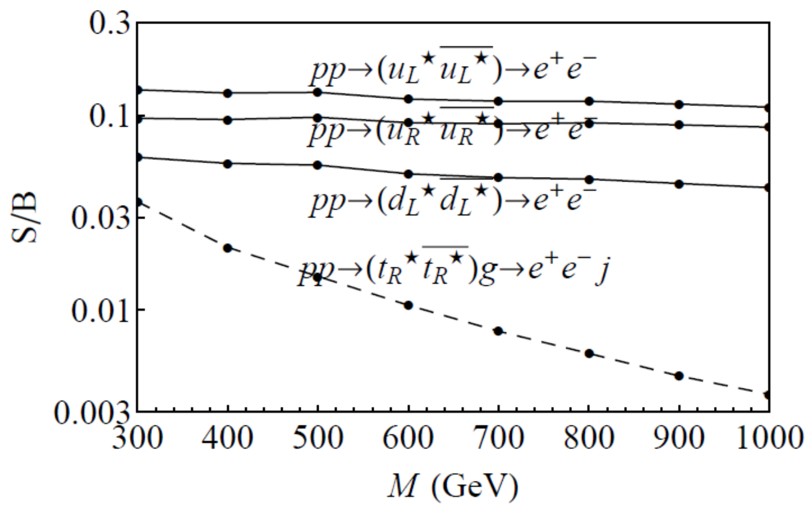
Detection prospects (14 TeV LHC)

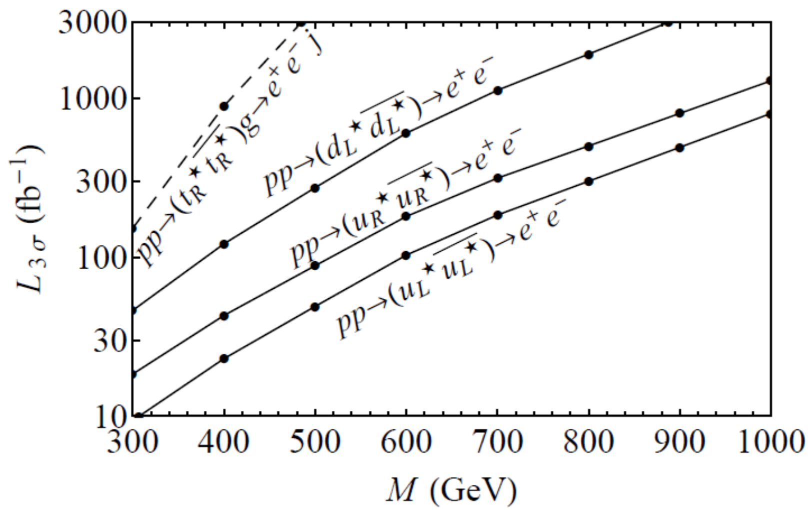
Diphoton channel





Dilepton channel





Summary

- *Any* pair-produced colored particles form near-threshold QCD bound states (few % of the cross section)

- If the particles decay via a heavier mediator (or a suppressed coupling) the bound states are likely to annihilate

- Annihilation signals (small resonances in $t\bar{t}$, $b\bar{b}$, $\gamma\gamma$, l^+l^- channels) provide an *independent* and *simple* way for determining the properties of the new particles (mass, spin, etc.)

- Annihilation signals will be observable at the LHC if the particles are sufficiently light (masses up to ~500 GeV, i.e., 1 TeV resonance).

- Important questions for future work:
  - (theory) Higher-order QCD corrections (K-factors of ~2)
  - (experiment) Reliable isolation of small bumps
  - (experiment) Search for resonances also in the $b\bar{b}$ channel
  - (theory/experiment) Methods for b-tagging at high p_{T}