Doubly Heavy SUSY Mesons

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Based on the works with J.K. Chen, J.Y. Cui, J.-M. Yang, X.G. Wu (EPJC 50: 969 (2007); Commun. Theor. Phys. 39:197 (2002)

- **Introduction**
- **General Feature**

1. Spectroscopy
2. Decay and lifetime
3. Fragmentation function

- **Production at Tevatron & LHC**

Introduction

- Heavy flavors:

  Light Quarks: u, d, s, (m < χ ∧)

  Heavy Quarks: c, b, (t) (m > χ ∧)

  The Lightest S-quark $\tilde{t}_1 : (\tilde{t}_L, \tilde{t}_R)$ or $\tilde{b}_1 : (\tilde{b}_L, \tilde{b}_R)$

- SUSY-hadrons:

  If the lightest s-quark e.g. $\tilde{t}_1$ has

  $m_{\tilde{t}_1} \sim m_t$ **(even** $m_{\tilde{t}_1} \leq m_t$**) and** $\tau_{\tilde{t}_1} \geq \frac{1}{\Lambda_{QCD}}$ **(not ruled out yet):**

$$
\begin{aligned}
&(\tilde{t}_1\bar{c}) : \widetilde{H}_{\tilde{t}_1\bar{c}}, \widetilde{H'}_{\tilde{t}_1\bar{c}}, \cdots \\
&(\tilde{t}_1\bar{b}) : \widetilde{H}_{\tilde{t}_1\bar{b}}, \widetilde{H'}_{\tilde{t}_1\bar{b}}, \cdots \\
&(\tilde{t}_1\bar{\tilde{t}}_1) : \widetilde{H}_{\tilde{t}_1\bar{\tilde{t}}_1}, \widetilde{H'}_{\tilde{t}_1\bar{\tilde{t}}_1}, \cdots \\
&\cdots\cdots
\end{aligned}
$$

doubly heavy SUSY mesons

$$
\begin{aligned}
&(\tilde{t}_1 cq) : \widetilde{\Xi}_{\tilde{t}_1 cq}, \widetilde{\Xi}'_{\tilde{t}_1 cq}, \cdots \\
&(\tilde{t}_1 bq) : \widetilde{\Xi}_{\tilde{t}_1 bq}, \widetilde{\Xi}'_{\tilde{t}_1 bq}, \cdots \\
&(\tilde{t}_1\tilde{t}_1 q) : \widetilde{\Xi}_{\tilde{t}_1\tilde{t}_1 q}, \widetilde{\Xi}'_{\tilde{t}_1\tilde{t}_1 q}, \cdots \\
&\cdots\cdots
\end{aligned}
$$

doubly heavy SUSY baryons

Introduction

Here we focus on the doubly heavy SUSY mesons only and consider $\tilde{t}_1$ as an example.

- The interests:
  - QCD binding systems but an elementary 0-spin component (as a new platform for potential model, lattice QCD, NRQCD etc)

    non-relativistic nature (potential model, NRQCD etc)

    spectroscopy & transitions
  - S-quark ($\tilde{t}_1$) search & weak decay studies
  - Heavy flavor physics (c, b decays; CKM matrix elements Vcb, Vcs, Vub, Vcd, etc)
  - Production mechanism studies (hadro-production)
  - etc.

Introduction

- **Why 'doubly heavy SUSY mesons'?**

A two-body binding system of doubly heavy components by QCD interaction (in non-relativistic nature and with a 0-spin component instead of a 1/2-spin one to compare with doubly heavy mesons)

thus

potential model, lattice QCD for spectroscopy,

NRQCD can be applied to production and decays

theoretical predictions can be more reliable etc.

in comparison

' heavy-light SUSY mesons' such as $(\tilde{\bar{t}}_1, q), (q = u, d, s)$

a light quark is involved (relativistic nature)

more non-perturbative effects due to the light quark etc

theoretical predictions for production cannot be very reliable

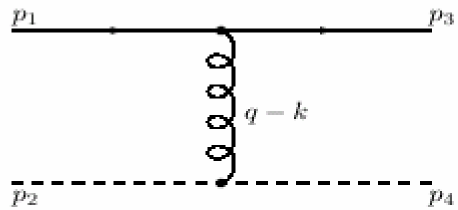
General Feature

1. Spectroscopy
(here QCD inspired potential model)

Potential:

$$G(P,q,k) = G_{short}(P,q,k) + G_{long}(P,q,k)$$

'short distance' G_{short}



$$P = p_1 + p_2 = p_3 + p_4, \quad q = \lambda_2 p_1 - \lambda_1 p_2, \quad k = \lambda_2 p_3 - \lambda_1 p_4$$
$$\lambda_i = \frac{m_i}{m_1 + m_2}$$

$$G_{short}(P,q,k) = \frac{4}{3}(4\pi\alpha_s)\frac{\not{p}_2 + \not{p}_4}{(p_2 - p_4)^2 - \alpha^2} \qquad \alpha_s = \frac{12\pi}{27}\frac{1}{ln(a + \frac{(q-k)^2}{\Lambda^2_{QCD}})}$$

General Feature

'long distance' G_{long}

$$G_{long}(P,q,k) = (2\pi)^3(2m_2)\{\frac{\lambda}{\alpha}\delta^3(\mathbf{q}-\mathbf{k}) - \frac{\lambda}{\pi^2}\frac{1}{((\mathbf{q}-\mathbf{k})^2+\alpha^2)^2}\}$$

G_{long} corresponds to

$$\frac{\lambda}{\alpha}(1-e^{-\alpha r})$$

Parameters:

Λ_{QCD}, a, α fixed by fitting the spectrum of the heavy quarkonia $(Q\bar{Q})$:

	Calculated	Observed[9]
$1\ ^1S_0(c\bar{c})$	2.960	2.9788± 0.0019
$1\ ^3S_1(c\bar{c})$	3.100	3.09688± 0.00004
$2\ ^1S_0(c\bar{c})$	3.616	
$2\ ^3S_1(c\bar{c})$	3.666	3.6800± 0.00010
$1\ ^1S_0(b\bar{b})$	9.421	
$1\ ^3S_1(b\bar{b})$	9.463	9.46037± 0.00021
$2\ ^1S_0(b\bar{b})$	9.980	
$2\ ^3S_1(b\bar{b})$	9.996	10.02330± 0.00031
$3\ ^1S_0(b\bar{b})$	10.331	
$3\ ^3S_1(b\bar{b})$	10.340	10.3553±0.0005
$4\ ^1S_0(b\bar{b})$	10.601	
$4\ ^3S_1(b\bar{b})$	10.609	10.5800±0.0035

with

$$\Lambda_{QCD} = 0.162\text{GeV}, a = 2.713,$$

$$\lambda = 0.23(GeV)^2, \alpha = 0.06\text{GeV}$$

and

$$m_b = 4.83\text{GeV}, m_c = 1.55\text{GeV}$$

General Feature

The spectrum:

The mass of the $(c\bar{\tilde{Q}}_1)$ bound states (GeV) with different $m_{\tilde{Q}_1}$ (GeV).

		$n(\frac{1}{2})^+$	$n(\frac{3}{2})^-$
$m_{\tilde{Q}_1}$=10.0	n=1	11.509	11.884
	n=2	12.035	12.257
	n=3	12.375	12.537
$m_{\tilde{Q}_1}$=20.0	n=1	21.500	21.867
	n=2	22.016	22.231
	n=3	22.346	22.503
$m_{\tilde{Q}_1}$=40.0	n=1	41.494	41.857
	n=2	42.005	42.216
	n=3	42.330	42.483
$m_{\tilde{Q}_1}$=60.0	n=1	61.490	61.854
	n=2	62.003	62.211
	n=3	62.325	62.476
$m_{\tilde{Q}_1}=\cdots$	n=1	$\cdots$	$\cdots$
	n=2	$\cdots$	$\cdots$
	n=3	$\cdots$	$\cdots$

The mass of the $(b\bar{\tilde{Q}}_1)$ bound states (GeV) with different $m_{\tilde{Q}_1}$ (GeV).

		$n(\frac{1}{2})^+$	$n(\frac{3}{2})^-$
$m_{\tilde{Q}_1}$=10.0	n=1	14.557	14.946
	n=2	15.090	15.307
	n=3	15.424	15.583
$m_{\tilde{Q}_1}$=20.0	n=1	24.519	24.902
	n=2	25.045	25.255
	n=3	25.371	25.523
$m_{\tilde{Q}_1}$=40.0	n=1	44.497	44.878
	n=2	45.020	45.230
	n=3	45.339	45.496
$m_{\tilde{Q}_1}$=60.0	n=1	64.492	64.869
	n=2	65.015	65.219
	n=3	65.336	65.484
$m_{\tilde{Q}_1}=\cdots$	n=1	$\cdots$	$\cdots$
	n=2	$\cdots$	$\cdots$
	n=3	$\cdots$	$\cdots$

The wave functions are obtained too.

General Feature

2. Decay and lifetime

$(Q\bar{\tilde{t}}_1)$ decay: Q -decay ($\tilde{t}_1$ as a spectator)

$\tilde{t}_1$ -decay (Q as a spectator)

$(Q\bar{\tilde{t}}_1)$ -annihilation (SUSY model)

The decay products from the 'spectator' may be used to reject background in 'search for' SUSY experiments.

(Generally $\tilde{t}_1$ decays into a quark and a virtual or a real chargino or neutrolino in SUSY models)

General Feature

$(Q\tilde{\bar{t}}_1)$ lifetime:

$$\tau_{(Q\tilde{\bar{t}}_1)} = \frac{1}{\Gamma_{(Q\tilde{\bar{t}}_1)}} = \frac{1}{\Gamma_Q + \Gamma_{\tilde{t}_1} + \Gamma_{ann}}$$

and $\Gamma_Q \sim \Gamma_{(Q\bar{q})}$

Therefore (generally & roughly)

If $\Gamma_Q \geq \Gamma_{\tilde{\bar{t}}_1}$, then the lifetime $\tau_{(Q\tilde{\bar{t}}_1)} \simeq \tau_Q$,

If $\Gamma_Q \leq \Gamma_{\tilde{\bar{t}}_1}$, then the lifetime $\tau_{(Q\tilde{\bar{t}}_1)} \simeq \tau_{\tilde{t}_1}$.

(Note: in general, $\Gamma_a nn(Q + \tilde{\bar{t}}_1 \to \cdots)$ cannot be larger than Γ_Q or $\Gamma_{\tilde{t}_1}$ for most SUSY models)

General Feature

3. Fragmentation function

DEGLAP equation

$$\frac{dD_{i\to\tilde{H}}(z,Q^2)}{d\tau} = \sum_j \frac{\alpha_s(Q^2)}{2\pi} \int_z^1 \frac{dy}{y} P_{i\to j}(z/y)\, D_{j\to\tilde{H}}(y,Q^2)$$

and

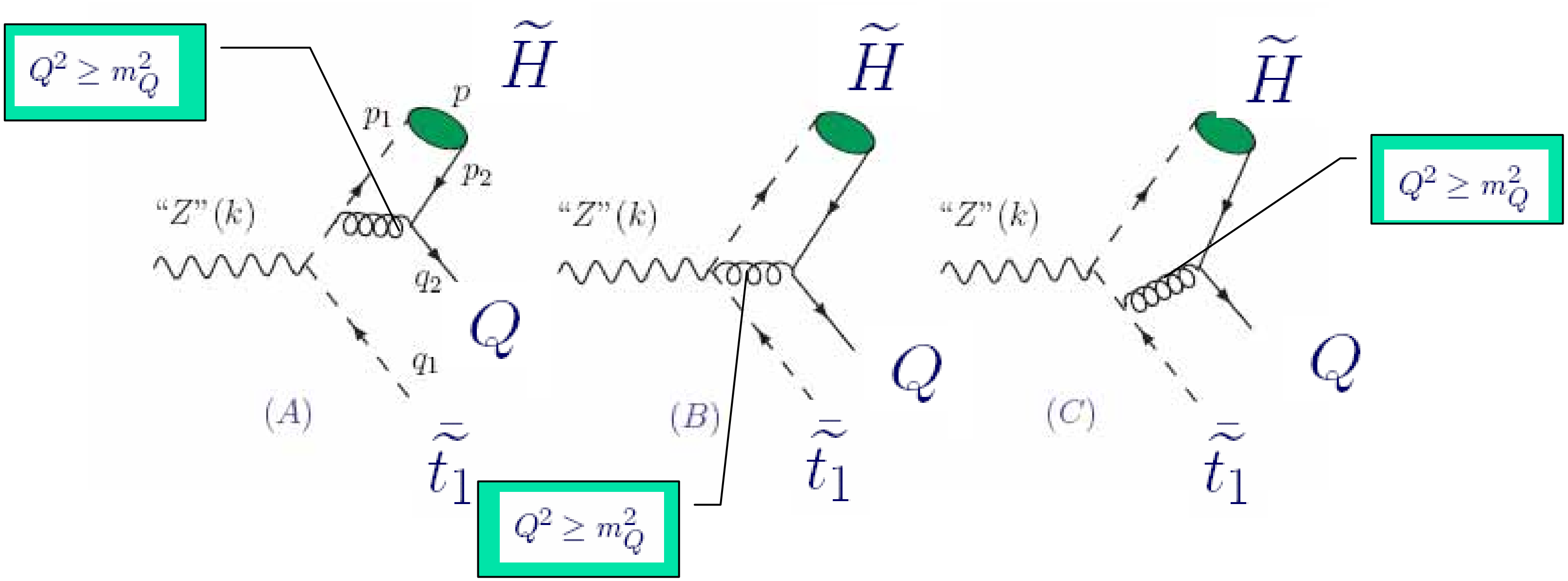
$$P_{\tilde{t}_1\to\tilde{t}_1 g}(x) = \frac{4}{3}\left[\frac{1+x^2}{(1-x)_+} - (1-x) + \delta(1-x)\right]$$

$$\tau = \log(Q^2/\Lambda^2_{QCD})$$

the 'initiate condition': $D_{i\to\tilde{H}}(z,Q_0^2) = ?$

General Feature

To calculate the ‘initial condition’:



Only when a heavy quark Q pair is produced, the gluon is hard

$D_{\tilde{t}_1 \to \tilde{H}}(z, m_Q^2)$ can be calculated reliable by NRQCD.

General Feature

Fragmentation function $D_{\tilde{t}_1 \to \tilde{H}}(z, m_Q^2)$ **:**

$$D_{\tilde{t}_1 \to \tilde{H}}(z) = F_{\tilde{t}_1} \cdot f_{\tilde{t}_1}(z)$$

$$F_{\tilde{t}_1} = \frac{16\alpha_s(4m_Q^2)|\psi(0)|^2}{27\pi m_Q^2 m_{\tilde{t}_1}},$$

$$f_{\tilde{t}_1}(z) = \frac{1}{6}\frac{(1-z)^2 z^2}{(1-\alpha_1 z)^6} \cdot \left[2\alpha_1^2(z-4)z + \alpha_1^3(3\alpha_1 z - 2z + 2)z + 3\alpha_1^2 - 6\alpha_1 + 6\right]$$

To compare with the case of heavy quark anti-b quark into B_c

$$D_{\bar{b}}(z) = F_{\bar{b}} \cdot f_{\bar{b}}(z)$$

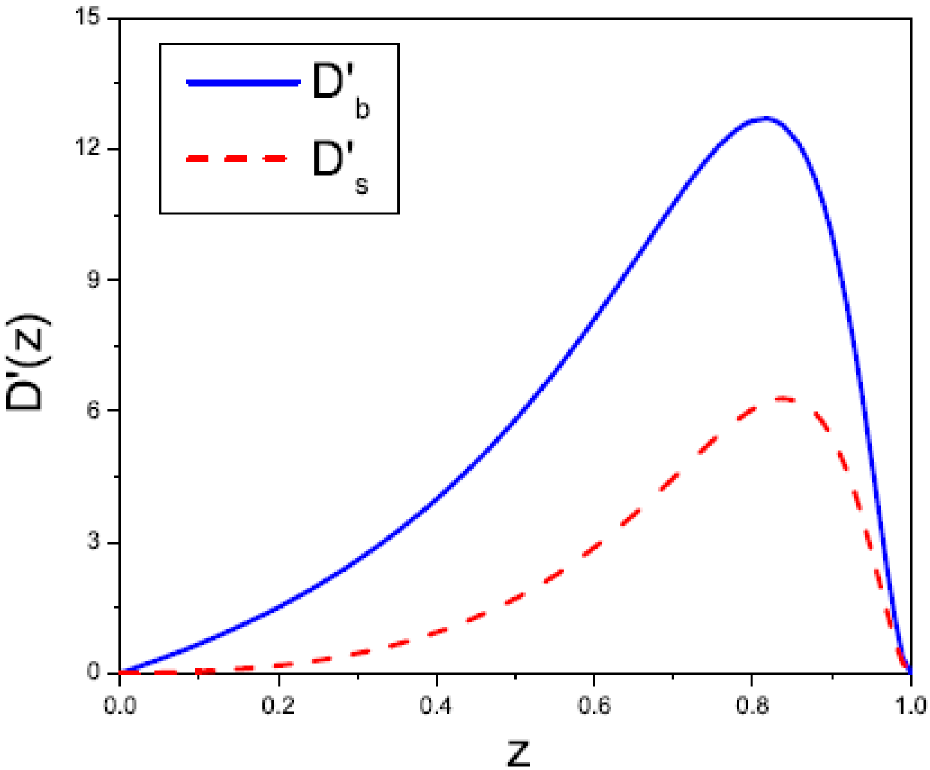
$$F_{\bar{b}} = \frac{8\alpha_s^2|\psi_0(0)|^2}{27 M m_c^2}$$

$$f_{\bar{b}}(z) = \frac{z(1-z)^2}{(1-\lambda_1 z)^6}\Big\{[12\lambda_2 z - 3(\lambda_1 - \lambda_2)(1-\lambda_1 z)(2-z)](1-\lambda_1 z)z + 6(1+\lambda_2 z)^2(1-\lambda_1 z)^2 - 8\lambda_1\lambda_2 z^2(1-z)\Big\},$$

$\lambda_1 = \frac{m_b}{M}$, $\lambda_2 = \frac{m_c}{M}$ and $M = m_b + m_c$.

General Feature

Due to spin-0 of s-quark, the asymptotic behavior is different



$D'_b(z) \equiv f_{\bar{b}}(z)$
$D'_s(z) \equiv f_{\tilde{t}_1}(z).$
If $m_{\tilde{t}_1} = m_b = 5.18$ GeV
$m_c = 1.84$ GeV

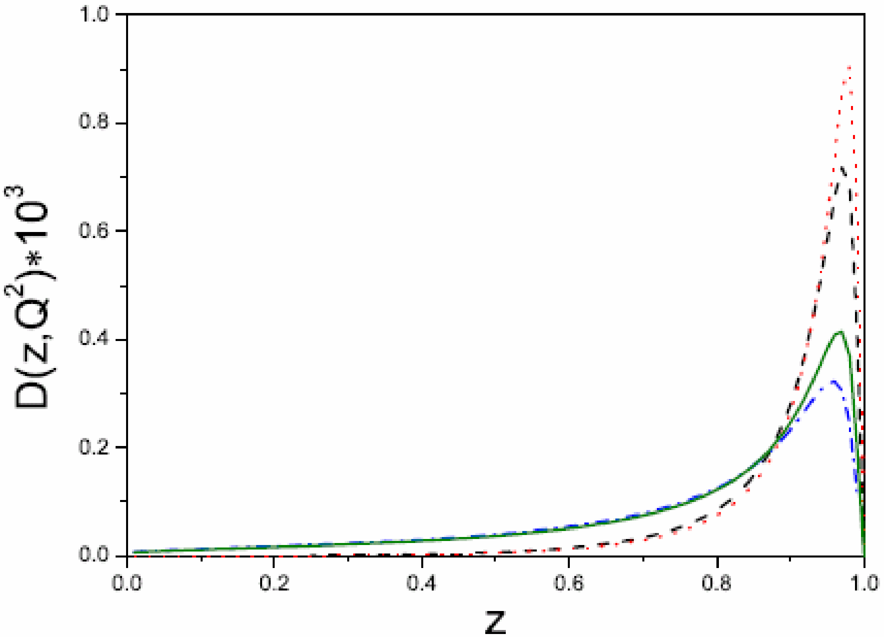
Asymptotic behavior

When $z \longrightarrow 0$
$D'_b(z) \rightarrow\sim z$
$D'_s(z) \rightarrow\sim z^2.$

When $z \longrightarrow 1$
$D'_b(z) \rightarrow\sim (1-z)^2$
$D'_s(z) \rightarrow\sim (1-z)^2.$

General Feature

Approximate solution of DGLAP equation ($Q^2 \gg m^2_{\tilde{t}_1}$) with Field's method:



$D_{\tilde{t}_1 \to \tilde{H}}(z, Q^2 = 4TeV^2)$ (S-wave $\widetilde{H}$):
solid line with $m_{\tilde{t}_1} = 150$ GeV
dash-dot line $m_{\tilde{t}_1} = 120$ GeV:
$D_{\tilde{t}_1 \to \tilde{H}}(z, 4m^2_Q)$:
dotted line with $m_{\tilde{t}_1} = 150$ GeV
dashed lines with $m_{\tilde{t}_1} = 120$ GeV

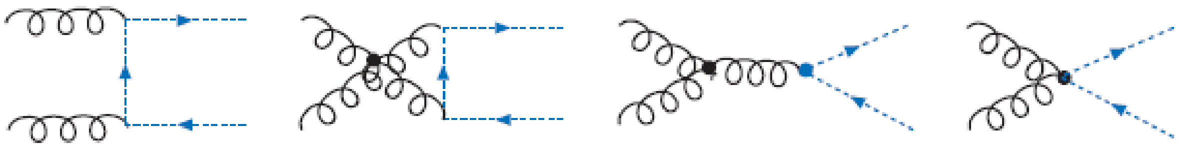
$m_{\tilde{t}_1}$		120 GeV	150 GeV
$\psi(0)_{(\tilde{t}_1\bar{b})}$	$(GeV)^{3/2}$	2.502	2.530
$\psi(0)_{(\tilde{t}_1\bar{c})}$	$(GeV)^{3/2}$	0.693	0.695

Production at Tevatron & LHC

Factorization:

$$d\sigma_{H_1H_2\to\widetilde{H}X} = \sum_{ijk}\int dx_1 \int dx_2 \int dz f_{i/H_1}(x_1,\mu_f) f_{j/H_2}(x_2,\mu_f) \cdot d\hat{\sigma}_{ij\to kX}(x_1,x_2,z;\mu_f,\mu_R)\cdot D_{k\to\widetilde{H}}(z,\mu_f),$$

Gluon-gluon fusion $g+g\to\tilde{t}_1+\bar{\tilde{t}}_1$ **:**



(A) (B) (C) (D)

$$d\hat{\sigma}(gg\to\tilde{t}_1\bar{\tilde{t}}_1) = \frac{3\pi^2\alpha_s^2}{16\pi\hat{s}^2}\left[1-2A-\frac{1}{9}\right]\left[1-2\frac{m_{\tilde{t}_1}^2}{A\hat{s}}(1-\frac{m_{\tilde{t}_1}^2}{A\hat{s}})\right]d\hat{t}$$

Quark-antiquark annihilation $q+\bar{q}\to\tilde{t}_1+\bar{\tilde{t}}_1$ **(similar):**

Production at Tevatron & LHC

$$d\hat{\sigma}(q\bar{q} \to \tilde{t}_1\bar{\tilde{t}}_1) = \frac{\pi\alpha_s^2[\hat{s}^2 - 4\hat{s}m_{\tilde{t}_1}^2 - (\hat{t}-\hat{u})^2]}{9\hat{s}^4}d\hat{t}$$

The hadronic cross sections (in unit: fb) for the superhadrons $(\tilde{t}_1\bar{c})$ and $(\tilde{t}_1\bar{b})$ with $J^P = (\frac{1}{2})^-$.

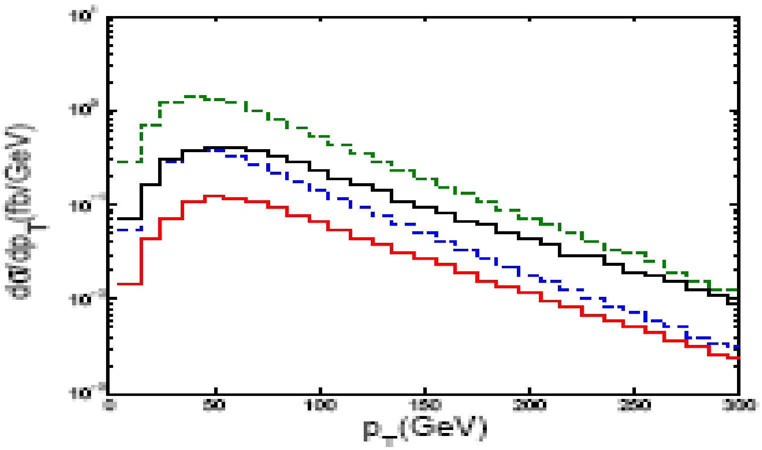
		LHC ($\sqrt{S}$=14. TeV)		TEVATRON ($\sqrt{S}$ = 1.96 TeV)	
Constituents		subprocess gg	subprocess $q\bar{q}$	subprocess gg	subprocess $q\bar{q}$
$m_{\tilde{t}_1} = 120$ GeV	$(\tilde{t}_1\bar{c})$	114.51	0.36469	0.26975	1.2E-3
	$(\tilde{t}_1\bar{b})$	30.489	0.10374	0.0696	3.E-4
$m_{\tilde{t}_1} = 150$ GeV	$(\tilde{t}_1\bar{c})$	42.176	0.14591	0.0537	2.E-4
	$(\tilde{t}_1\bar{b})$	11.812	0.0431	0.0142	7.E-5

The contribution from gluon-gluon fusion is greater than that from quark-antiquark annihilation

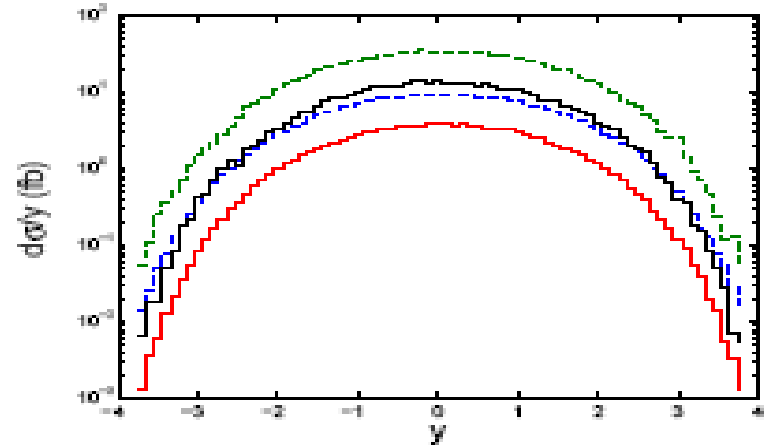
General features (SUSY hadrons)

At LHC

P_T-distributions with $|y| < 1.5$ via gluon-gluon fusion



Rapidity(y)-distribution via gluon-gluon fusion



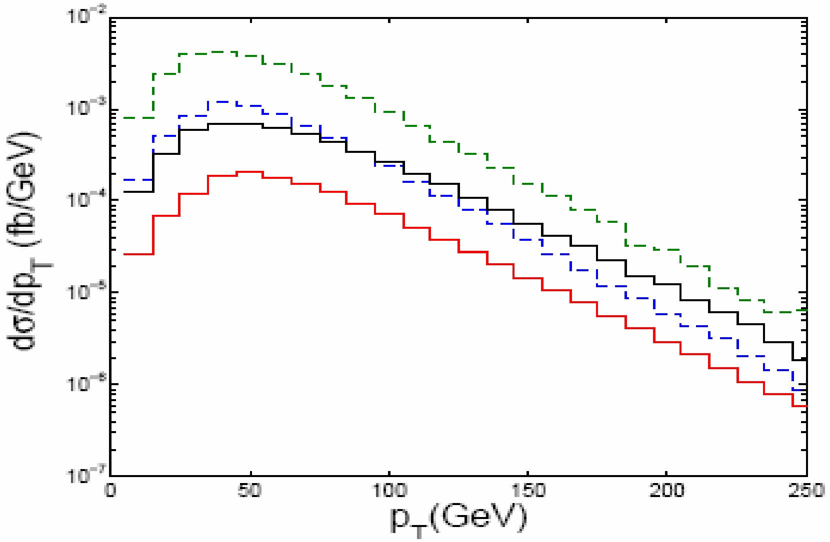
The dashed lines (with $m_{\tilde{t}_1} = 120$ GeV): the upper for $(\tilde{t}_1 \bar{c})$, the lower for $(\tilde{t}_1 \bar{b})$

The solid lines (with $m_{\tilde{t}_1} = 150$ GeV): the upper for $(\tilde{t}_1 \bar{c})$, the lower for $(\tilde{t}_1 \bar{b})$

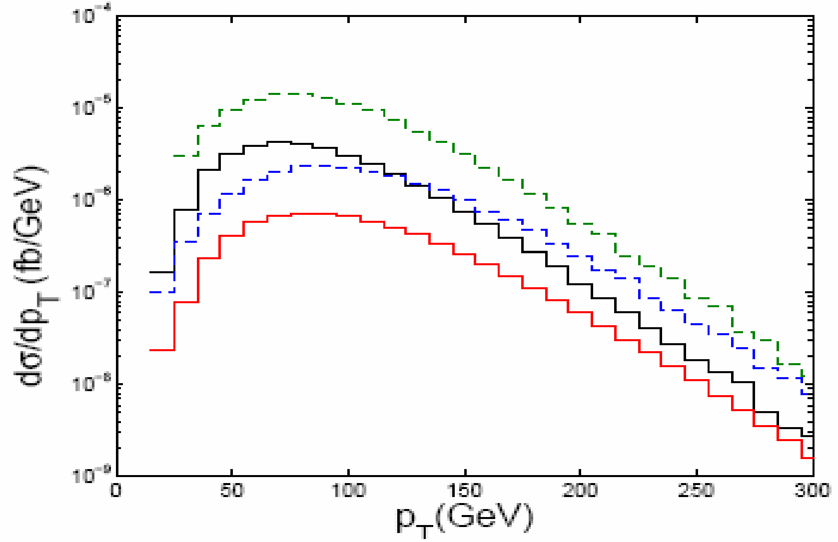
Production at Tevatron & LHC

At Tevatron

P_T-distributions with $|y| < 0.6$ via gluon-gluon fusion



Rapidity(y)-distribution via gluon-gluon fusion



The dashed lines (with $m_{\tilde{t}_1} = 120$ GeV): the upper for $(\tilde{t}_1\bar{c})$, the lower for $(\tilde{t}_1\bar{b})$

The solid lines (with $m_{\tilde{t}_1} = 150$ GeV): the upper for $(\tilde{t}_1\bar{c})$, the lower for $(\tilde{t}_1\bar{b})$

Production at Tevatron & LHC

Conclusion: to observe such doubly heavy SUSY hadrons at LHC & Tevatron (for Tevatron it also depends on the s-quark mass) is accessible, if there exists such a ‘long life’ s-quark indeed in realistic SUSY model !

Whereas

According to the experience on the ratio for production of B-meson to Bc-meson, one can expect that the cross section for heavy-light SUSY mesons (the top-squark with a light quark) can be greater than that of doubly heavy one presented here by

a factor ~10^(2—3).

Thus there are more chances to observe the heavy-light SUSY mesons not only at LHC but also at Tevatron, if the experience really can be applied to the case for SUSY mesons, in addition to that there exists a ‘long life’ s-quark in realistic SUSY model.

Thank you !