Collider phenomenology of Split-UED

Michihisa Takeuchi
(Heidelberg University)

In collaboration with
Chuan-Ren Chen, Mihoko M.Nojiri, SeongChan Park, Jing Shu
at IPMU

JHEP 0909:078,2009.
arxiv: 0903.1971[hep-th]

Models beyond the SM

The SM describes interaction between particles well, but still has two problems.
Fine tuning problem and existence of DM.

	Fine tuning prob.	Z_2 Parity	Dark matter	Additional mass parameters
MSSM	Supersymmetry (boson-fermion)	R-parity	$\tilde{\chi}_1^0, \tilde{G}$	μ, R-parity conserving soft mass parameters
mUED	5D translation sym 5D Planck mass	KK-parity	B_1	$1/R$

Symmetry → Partner particles for SM particles.

Parity structure → Stable DM

Always produced in pairs at colliders.

Each decay into DM (Missing momentum)

Models beyond the SM

The SM describes interaction between particles well, but still has two problems.
Fine tuning problem and existence of DM.

	Fine tuning prob.	Z_2 Parity	Dark matter	Additional mass parameters
MSSM	Supersymmetry (boson-fermion)	R-parity	$\tilde{\chi}_1^0$, $\tilde{G}$	μ, R-parity conserving soft mass parameters
split-UED	5D translation sym 5D Planck mass	KK-parity	B_1	$1/R$ + KK-parity conserving mass parameters

Symmetry ➡ Partner particles for SM particles.

Parity structure ➡ Stable DM

Always produced in pairs at colliders.

Each decay into DM (Missing momentum)

mUED model

T. Appelquist, H-C. Cheng, B. A. Dobrescu

All SM fields live in 5D $x^M = (x^0 = t, x^1, x^2, x^3, x^5) = (x^\mu, y)$

S^1 compactified: $-\pi R < y < \pi R$ R^{-1}:compactification scale

$$\Phi(x,y) = \frac{1}{\sqrt{2\pi R}}\phi^{(0)}(x) + \frac{1}{\sqrt{\pi R}}\sum_{n=1}^{\infty}\left[\phi^{(+n)}(x)\cos\frac{ny}{R} + \phi^{(-n)}(x)\sin\frac{ny}{R}\right].$$

Zero modes as SM fields

To obtain chiral fermions,

S^1/Z_2 **orbifording** $\Psi'(x') = \eta_P \gamma^5 \Psi(x)$ under $x^M = (x^\mu, y) \to x'^M = (x^\mu, -y)$.

$\eta_P = -1$ (L-handed): Q, L

$\eta_P = +1$ (R-handed): U, D, E, N

$$\Psi_L(x^\mu, y) = \frac{1}{\sqrt{2\pi R}}\Psi_L^{(0)}(x^\mu) + \sum_{n=1}^{\infty}\frac{1}{\sqrt{\pi R}}\Psi_{L+}^{(n)}(x^\mu)\cos\frac{ny}{R}$$

$$\Psi_R(x^\mu, y) = \sum_{n=1}^{\infty}\frac{1}{\sqrt{\pi R}}\Psi_{R-}^{(n)}(x^\mu)\sin\frac{ny}{R}.$$

KK-mass and KK-parity

4D eff. Lagrangian obtained by y-integration (0<y<πR).

$$\mathcal{L} = \bar{\Psi} i \Gamma^M \partial_M \Psi = \bar{\Psi}_L i\gamma^\mu \partial_\mu \Psi_L + \bar{\Psi}_R i\gamma^\mu \partial_\mu \Psi_R + \boxed{\bar{\Psi}_L \partial_y \Psi_R - \bar{\Psi}_R \partial_y \Psi_L}$$

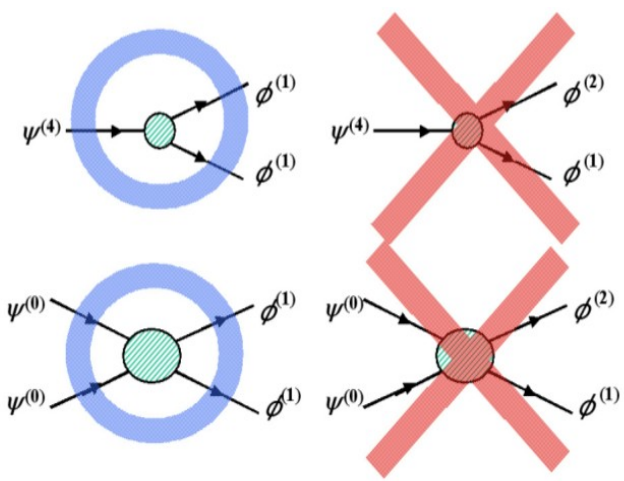
y-integration

KK-mass term $\boxed{\frac{n}{R}(\bar{\Psi}_L^{(n)} \Psi_R^{(n)} + \bar{\Psi}_R^{(n)} \Psi_L^{(n)})}$

→ Degenerate mass spectrum

KK-parity $\Psi^{(2n)}$: even

$\Psi^{(2n+1)}$: odd



$$\Psi_L^{(n)} \cos\frac{ny}{R} + \Psi_R^{(n)} \sin\frac{ny}{R}$$

Reflection about πR/2

$$\cos\begin{cases} n : \text{even} \rightarrow \text{even} \\ n : \text{odd} \rightarrow \text{odd} \end{cases} \qquad \sin\begin{cases} n : \text{even} \rightarrow \text{odd} \\ n : \text{odd} \rightarrow \text{even} \end{cases}$$

Only even terms under the reflection survive

$$\partial_y : \text{odd} \leftrightarrow \text{even}$$

mUED: KK parity is conserved → LKPDM is stable

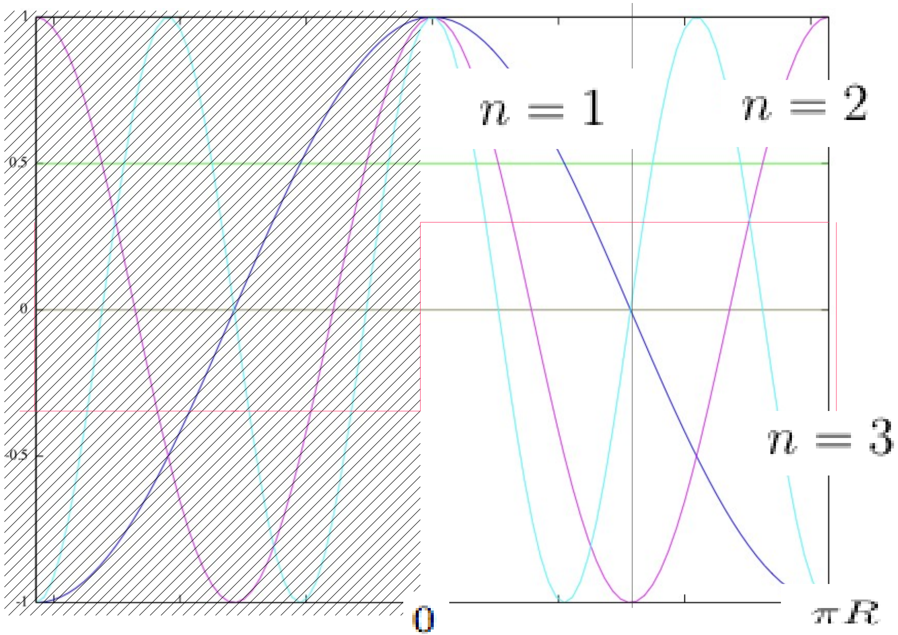
Bulk mass term

If we introduce simple vector-like mass term $\mu(\bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L)$

$$S_{\mathrm{split-UED}} = \int d^4x \int_0^{\pi R} dy \left[\mathcal{L}_{\mathrm{mUED}} - \mu \bar{\Psi}_q(x,y) \Psi_q(x,y) \right]$$

The term gives mixing between KK parity odd and even states,

for example, $m(\bar{\Psi}_L^{(0)} \Psi_R^{(1)} + \bar{\Psi}_R^{(1)} \Psi_L^{(0)})$ (cf. ∂_y : odd $\leftrightarrow$ even)



With simple mass term
KK parity is no longer conserved

→ DM cannot be stable

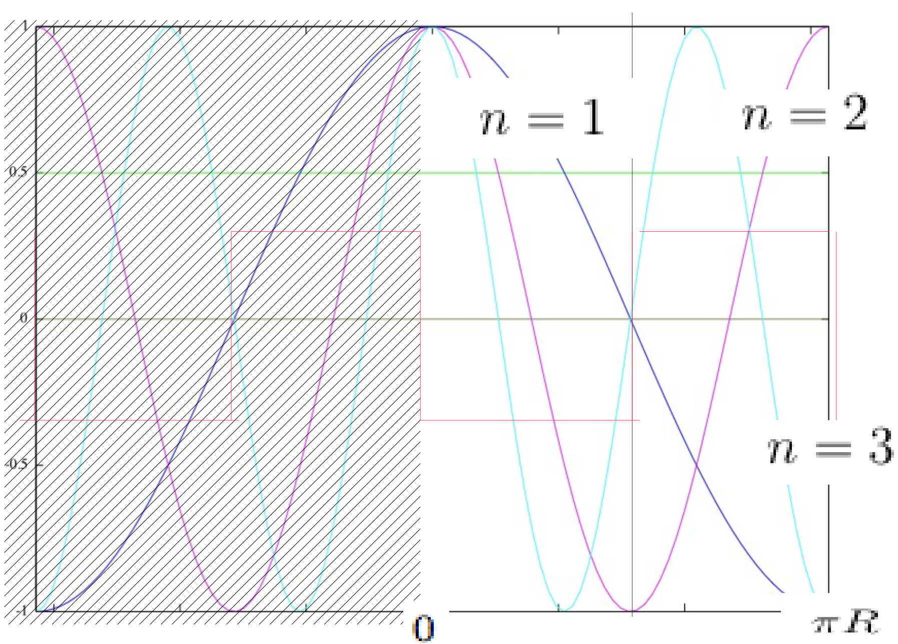
Split-UED model

S.C. Park, J. Shu

Instead, we introduce $\mu\epsilon(y)(\bar{\Psi}_L\Psi_R + \bar{\Psi}_R\Psi_L)$ $\epsilon(y) = \begin{cases} -1 & (0 < y < \frac{\pi R}{2}) \\ +1 & (\frac{\pi R}{2} < y < \pi R) \end{cases}$

$$S_{\text{split}-\text{UED}} = \int d^4x \int_0^{\pi R} dy \left[\mathcal{L}_{\text{mUED}} - \mu\epsilon(y)\bar{\Psi}_q(x,y)\Psi_q(x,y)\right]$$

After y-integration, the term gives $m(\bar{\Psi}_L^{(0)}\Psi_R^{(2)} + \bar{\Psi}_R^{(2)}\Psi_L^{(0)})$ etc.



Mixing among $\Psi_L^{(0)}, \Psi^{(2)}, \Psi^{(4)}, \ldots$

$\Psi^{(1)}, \Psi^{(3)}, \ldots$

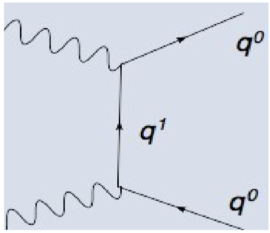
KK parity is still conserved ➡ DM is stable

Mass Spectrum

In this way, mass terms for any fields can be added like MSSM.

MSSM like mass spectrum can be obtained. Better for spin analysis.

Simple model: Mass term only for quark fields.
(Leptonic DM annihilation by PAMELA)



$$S_{\text{split-UED}} = \int d^4x \int_0^{\pi R} dy \left[\mathcal{L}_{\text{mUED}} - \mu \epsilon(y) \bar{\Psi}_q(x,y) \Psi_q(x,y) \right]$$

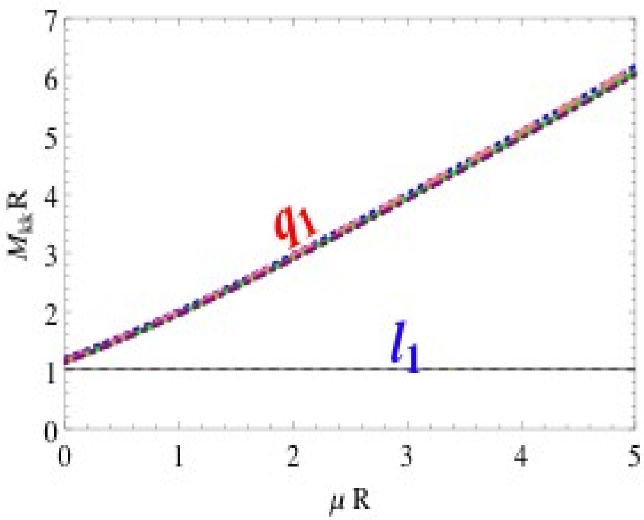
Only 2 parameters, 1/R and μ

$$m_{q_n}^{\text{tree}} = \sqrt{\mu^2 + k_n^2},$$

$$m_{l_n}^{\text{tree}} = n/R\,,$$

$$k_{n^-} = -|\mu| \tan k_n L,$$

$$k_{n^+} = n/R\,.$$



Split-UED :

$$M_{q_1} - M_{l_1} \sim \mu$$

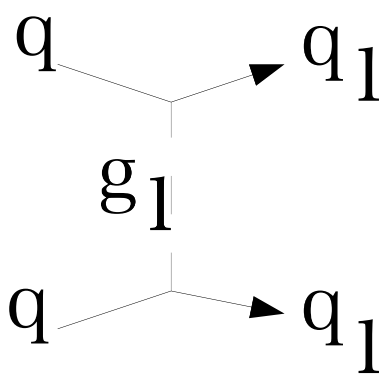
mUED : $M_{q_1} - M_{l_1} \sim 0$

(With radiative correction $\sim 0.1\, R^{-1}$)

Collider signatures at LHC

$q_1\, q_1$ signal

- Large production cross section $\sigma(q_1 q_1) = 10 \sim 100\sigma(\tilde{q}\tilde{q})$

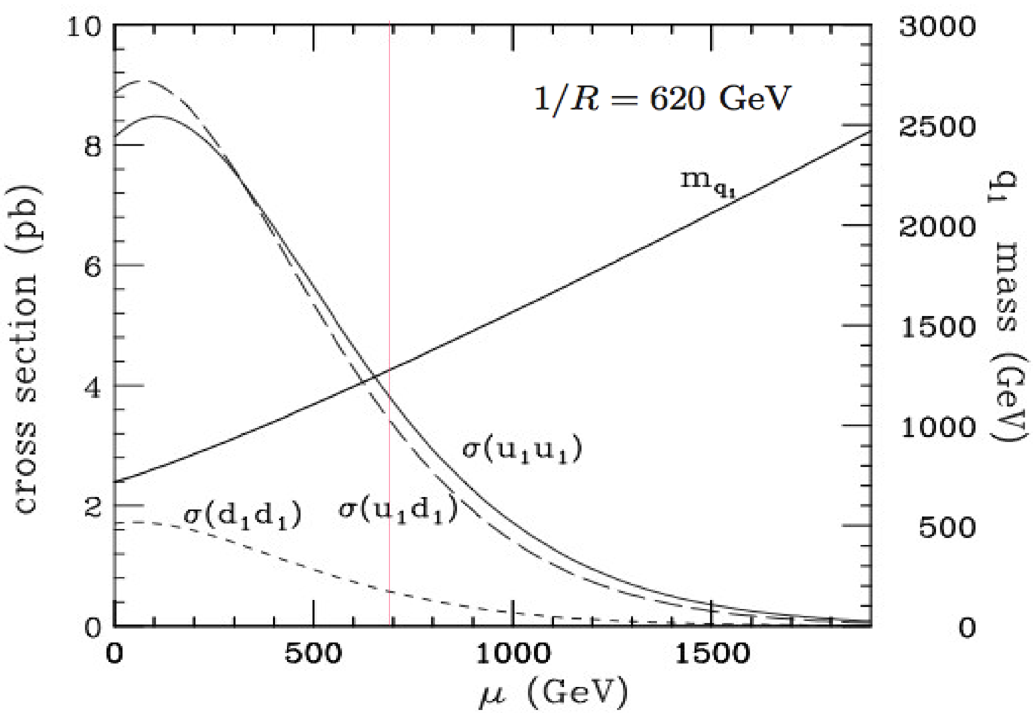


Fermionic quark partner $\mathcal{M} \sim \frac{1}{t}\bar{u}_4\gamma^\mu u_2 \bar{u}_3 \gamma_\mu u_1$

Unlike SUSY (scalar) $\mathcal{M} \sim \frac{1}{t}\bar{v}_2(\not{p}_3 - \not{p}_1 + m_{\tilde{g}})u_1$

M.M. Nojiri, M.T. PRD76:015009,2007

No p-wave suppression, threshold behavior $\sim \beta^3 \rightarrow \beta$



$1/R = 620$ GeV $\quad \mu = 700$ GeV

$\sigma(\tilde{q}\tilde{q}) = 0.13\text{pb}$

60 times larger

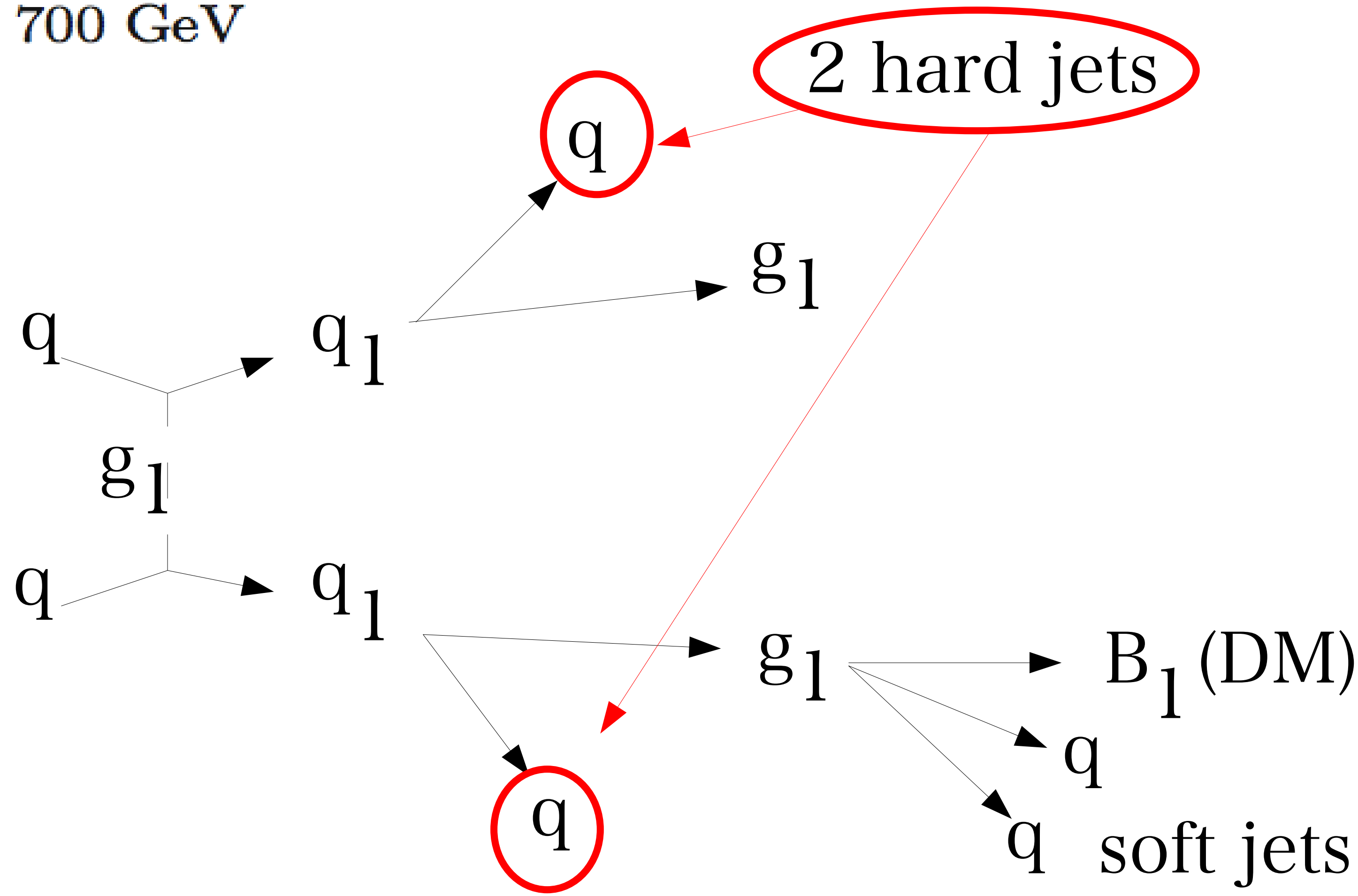
$\sigma(q_1 q_1) = 7.6\text{pb}$

$q_1\, q_1$ signal

- Large mass splitting ➡ Simple Kinematics

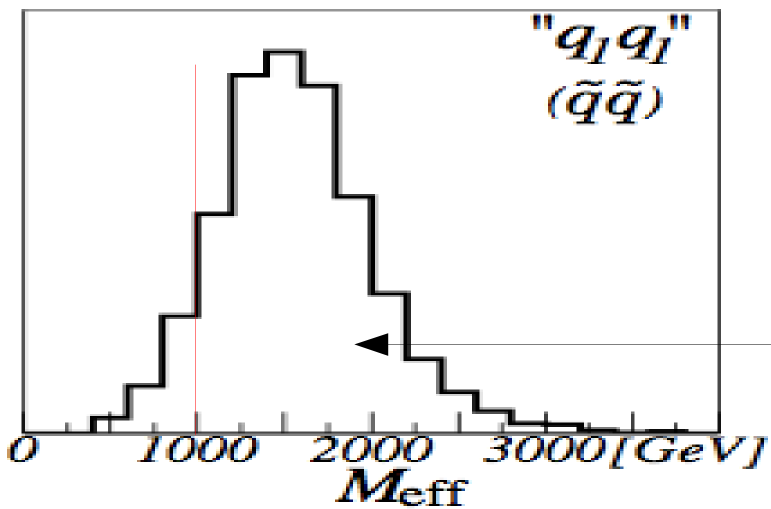
$1/R = 620$ GeV $\quad \mu = 700$ GeV

split-UED	mass
q_{L1}	1347 GeV
u_{R1}	1322 GeV
d_{R1}	1318 GeV
g_1	794 GeV
B_1	621 GeV



Signal : Two hard jets + missing momentum.

Meff distribution and SMBG

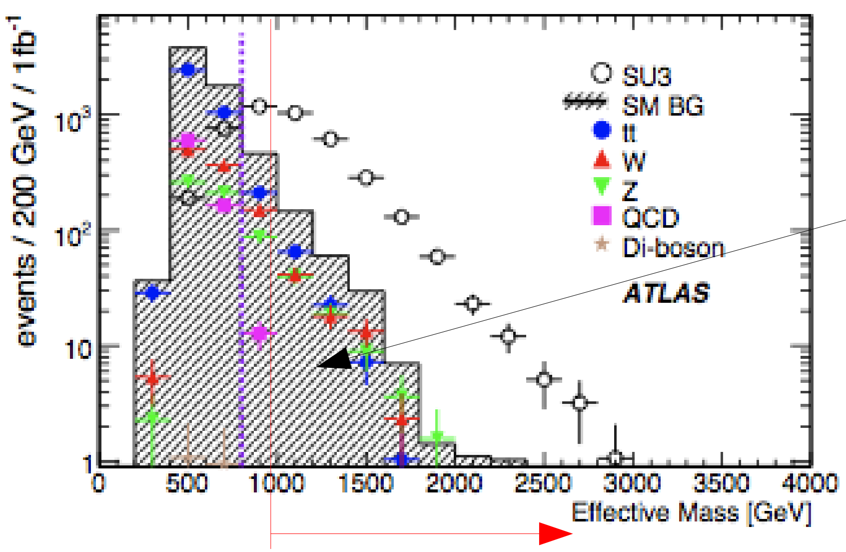


$$M_{eff} \equiv \sum_{i=1}^{4} p_T^{jet,i} + \sum_{i=1} p_T^{lep,i} + E_T^{miss}$$

$$M_{eff} > 1\text{TeV}$$

Signal > 1000/fb^{-1}

From ATLAS CSC note (0-lepton mode) [2008 Dec]



SMBG < 300/fb^{-1}

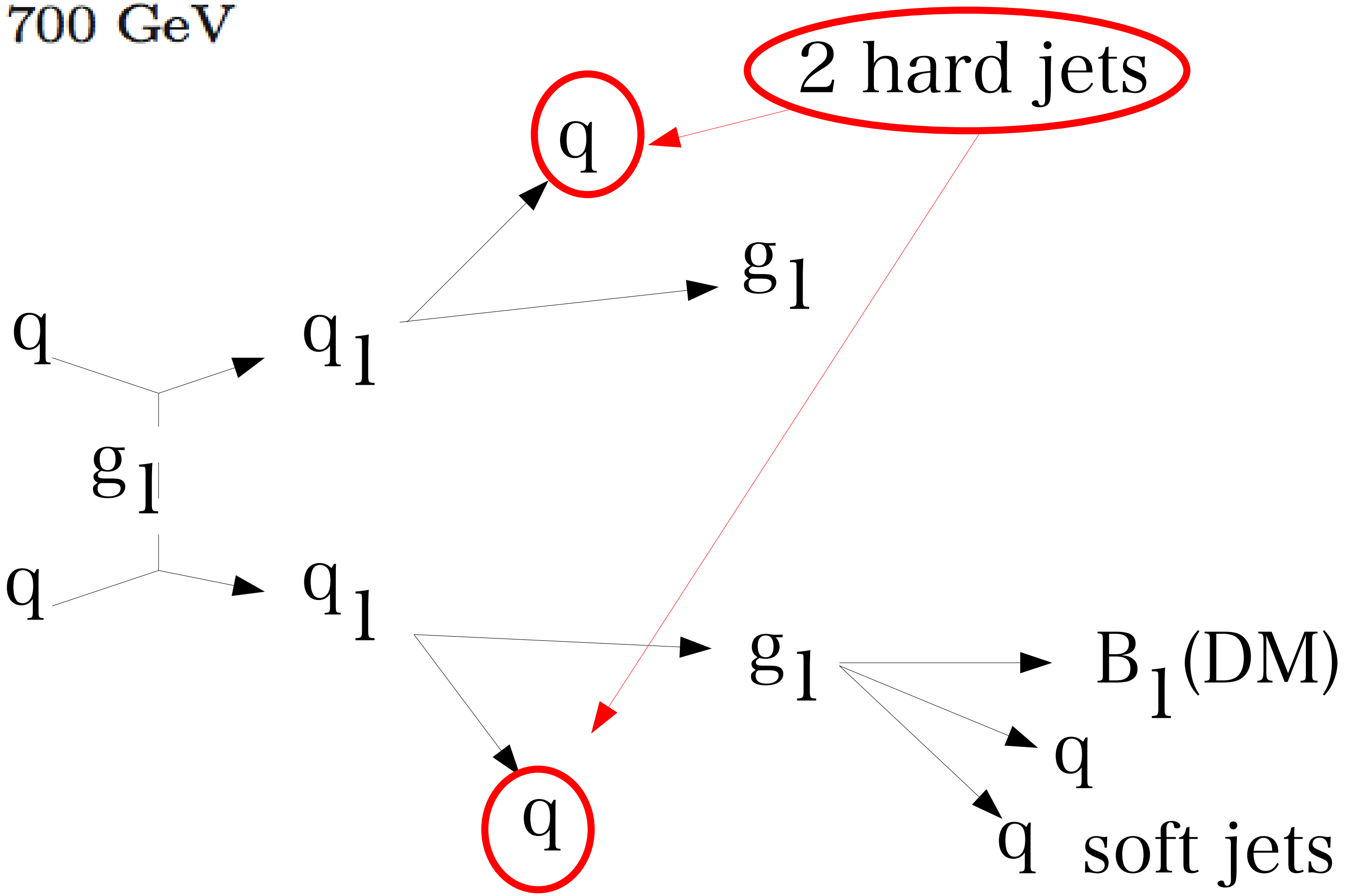
Discovery is easy!

$q_1\, q_1$ signal

- Large mass splitting ➡ Simple Kinematics

$1/R = 620$ GeV $\mu = 700$ GeV

split-UED	mass
q_{L1}	1347 GeV
u_{R1}	1322 GeV
d_{R1}	1318 GeV
g_1	794 GeV
B_1	621 GeV



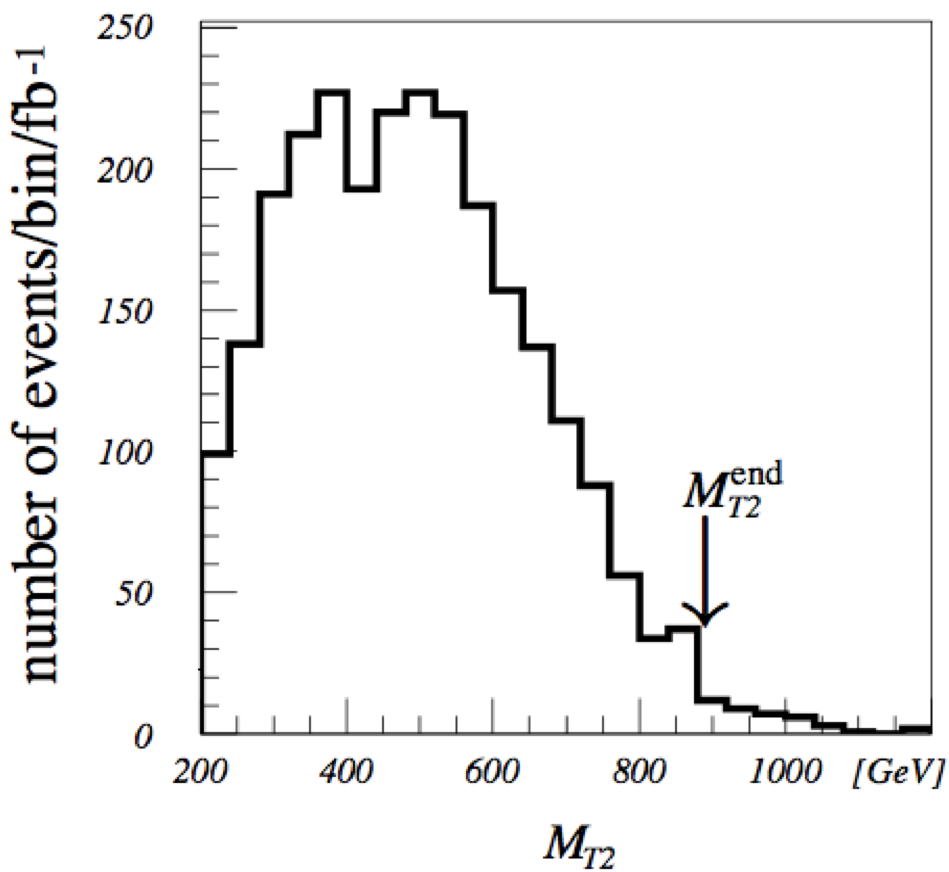
The same Kinematics as $\tilde{q}_R\, \tilde{q}_R$ pair production ➡ M_{T2}

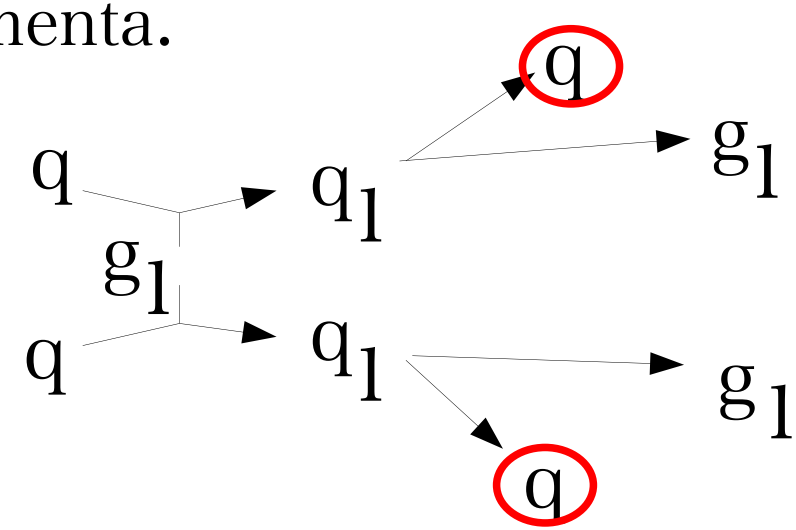
M_{T2} distribution

A. Barr, C. Lester, P. Stephens

$$M_{T2}(\mathbf{p}_1, \mathbf{p}_2, \not{E}_T) = \min_{\not{\mathbf{p}}_1 + \not{\mathbf{p}}_2 = \not{E}_T} \left[\max\{M_T(\mathbf{p}_1, \not{\mathbf{p}}_1), M_T(\mathbf{p}_2, \not{\mathbf{p}}_2)\}\right]$$

Two highest pt jets for visible momenta.





M_{T2} endpoint is given by

$$M_{T2}^{\mathrm{end}} = m_A - \frac{m_X^2}{m_A},$$

which should be

$$m_{q_1} - \frac{m_{g_1}^2}{m_{q_1}} \simeq 880 \text{ GeV}.$$

Summary

Split-UED is generalization of mUED (mUED + mass term).

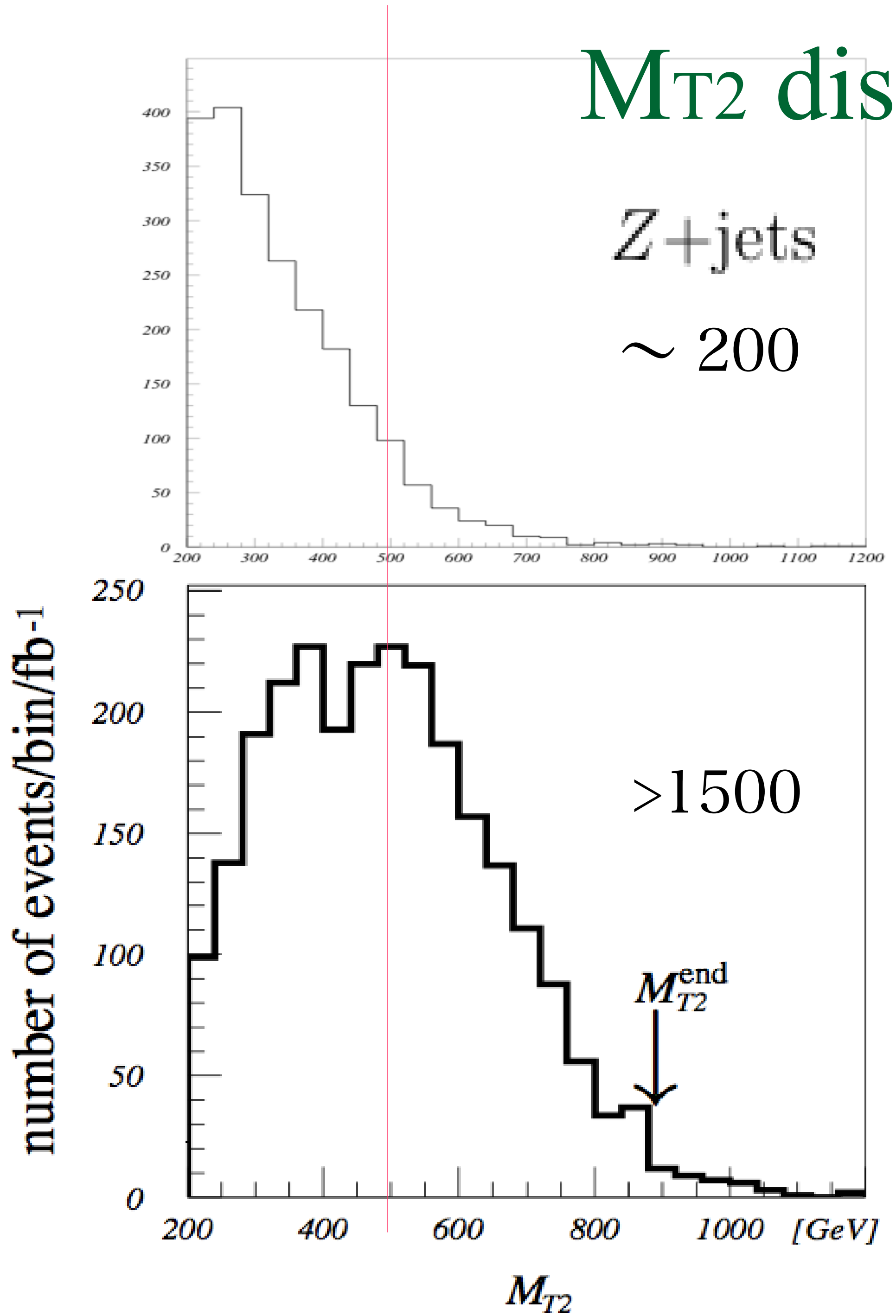
Mass term is well defined in 5D like soft mass in MSSM.

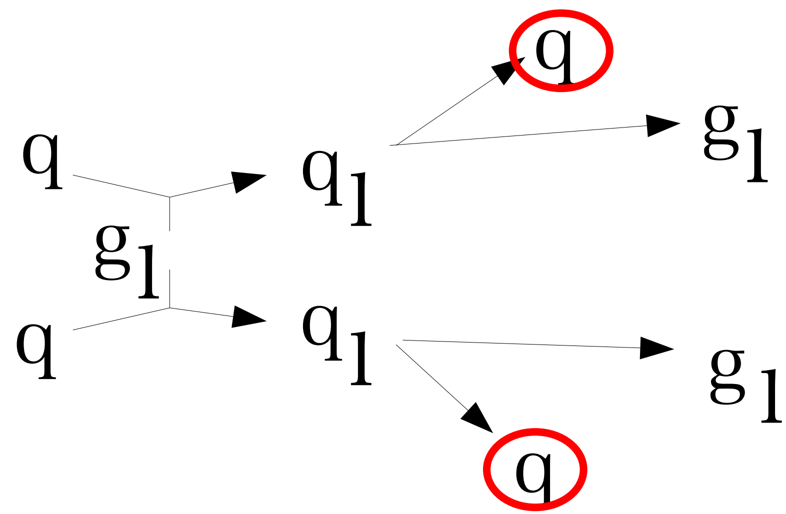
Better for spin analysis between UED and MSSM.

Collider phenomenology with heavy quark partner is demon-strated, inspired from leptonic DM annihilation (PAMERA)

- Easy to detect (large cross section, simple Kinematics)
- q_1 mass measurement using M_{T2}

M_{T2} distribution





M_{T2} endpoint is given by

$$M_{T2}^{\rm end} = m_A - \frac{m_X^2}{m_A},$$

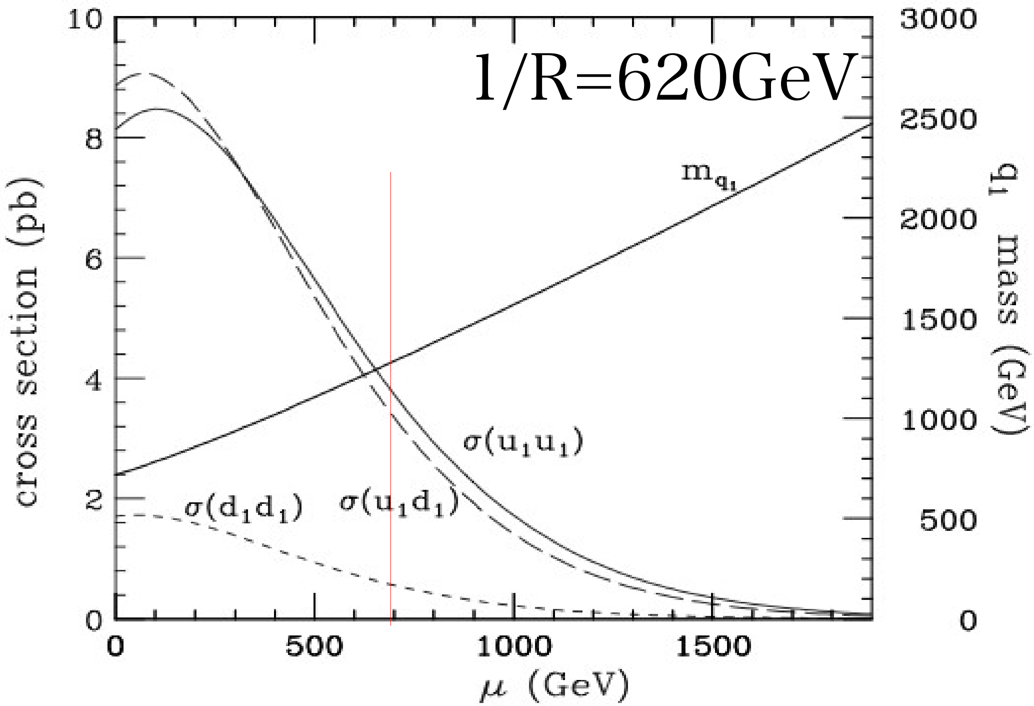
which is

$$m_{q_1} - \frac{m_{g_1}^2}{m_{q_1}} \simeq 880 \text{ GeV}.$$

SM back ground:

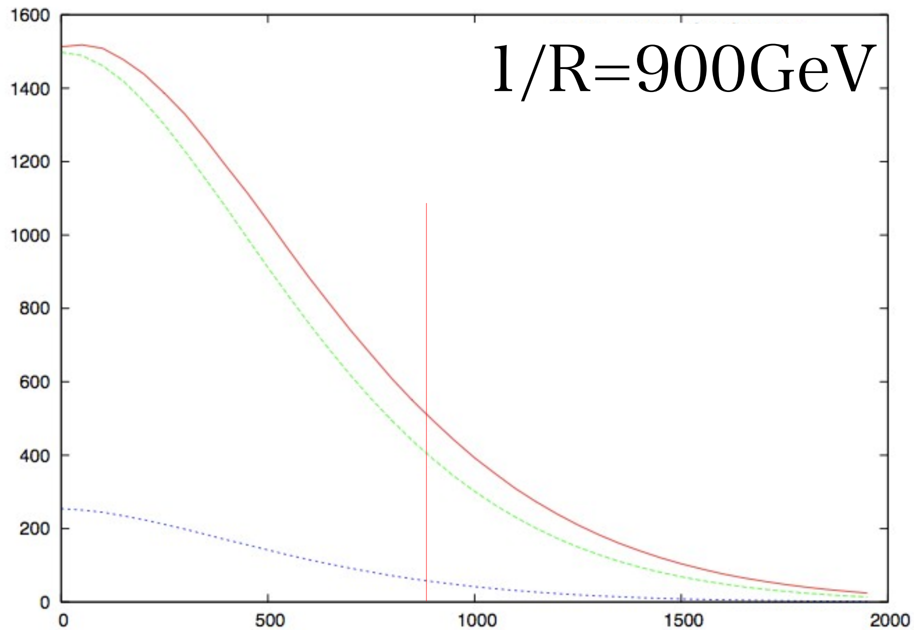
Z+jets events give smaller M_{T2}

Effects by increasing masses



SMBG < 300/1 fb^{-1}

Signal > 1000/1 fb^{-1}



Cross section becomes ～1/10 for μ=900 GeV (mass ～2 TeV)

Signal ～100/1 fb^{-1}

Even detectable and MT2 endpoint will be measurable.

S^1/Z_2 Orbifolding

Consider the parity transformation in y: $x^M = (x^\mu, y) \to x'^M = (x^\mu, -y)$.

The parity transformation for the fermion fields is defined as

$\Psi'(x') = \eta_P \gamma^5 \Psi(x)$ (We can choose η_P for each field.)

If we choose $\eta_P = +1$

We obtain zero mode only for R field.

$$
\begin{aligned}
\Psi(x^\mu, y) &= \Psi_L(x^\mu, y) + \Psi_R(x^\mu, y) \\
&= \left\{ \frac{1}{\sqrt{2\pi R}} \Psi_L^{(0)}(x^\mu) \right. \\
&\quad \left. + \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi R}} \Psi_{L+}^{(n)}(x^\mu) \cos\frac{ny}{R} + \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi R}} \Psi_{L-}^{(n)}(x^\mu) \sin\frac{ny}{R} \right\} \\
&+ \left\{ \frac{1}{\sqrt{2\pi R}} \Psi_R^{(0)}(x^\mu) \right. \\
&\quad \left. + \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi R}} \Psi_{R+}^{(n)}(x^\mu) \cos\frac{ny}{R} + \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi R}} \Psi_{R-}^{(n)}(x^\mu) \sin\frac{ny}{R} \right\}
\end{aligned}
$$

S^1/Z_2 Orbifolding

Consider the parity transformation in y: $x^M = (x^\mu, y) \to x'^M = (x^\mu, -y)$.

For the fermion fields, the parity transformation is

$\Psi'(x') = \eta_P \gamma^5 \Psi(x)$ (We can choose η_{P} for each field.)

If we choose η_{P}=+1

We obtain zero mode only for R field.

$$\Psi(x^\mu, y) = \Psi_L(x^\mu, y) + \Psi_R(x^\mu, y)$$
$$= \left\{ \frac{1}{\sqrt{2\pi R}} \Psi_L^{(0)}(x^\mu) + \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi R}} \Psi_{L+}^{(n)}(x^\mu) \cos\frac{ny}{R} + \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi R}} \Psi_{L-}^{(n)}(x^\mu) \sin\frac{ny}{R} \right\}$$
$$+ \left\{ \frac{1}{\sqrt{2\pi R}} \Psi_R^{(0)}(x^\mu) + \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi R}} \Psi_{R+}^{(n)}(x^\mu) \cos\frac{ny}{R} + \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi R}} \Psi_{R-}^{(n)}(x^\mu) \sin\frac{ny}{R} \right\}$$

With η_{P}=-1 ,we obtain zero mode only for L field.

For the SM, we choose:

η_{P}=+1 for U, D, E, N

η_{P}=-1 for Q, L

LHC Physics

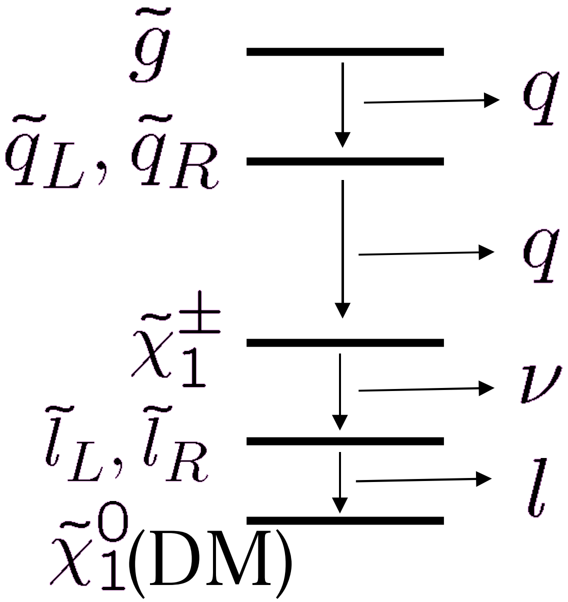
LHC: proton – proton collider (√s=14TeV)

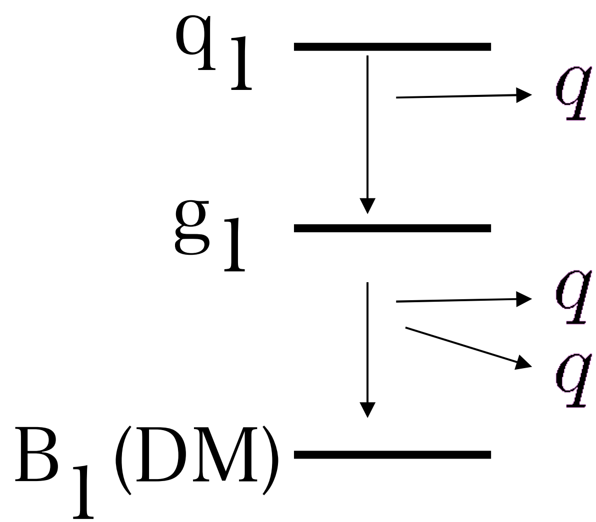
Proton: mixture of u, d, g, and sea quarks

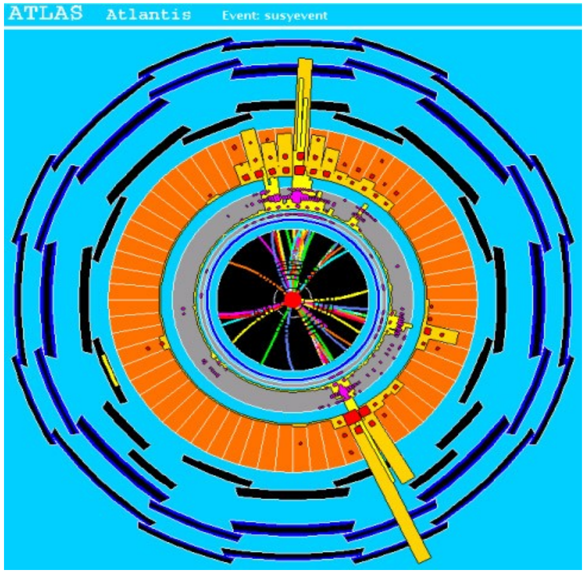
➡ Colored particles are copiously produced. (SM events also are)

Z2 parity odd particles are produced in pair.

Each decays in cascade







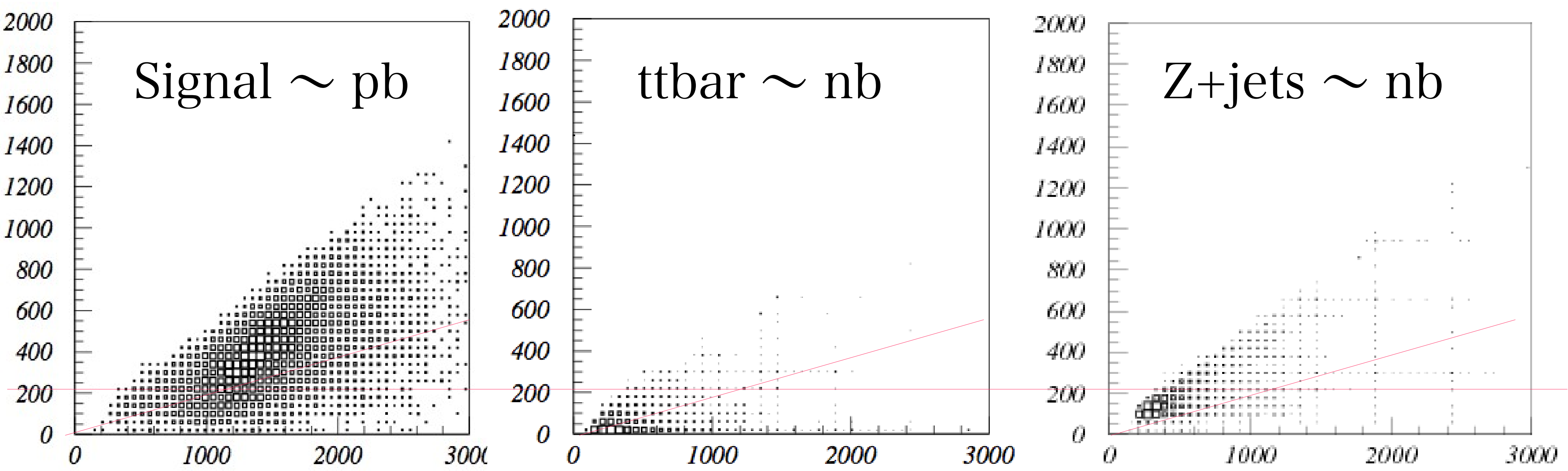
Large missing momentum $\not{E}_T \equiv |\sum_{visible} \mathbf{p}_T|$

Many hard jets, hard leptons ➡ **Large** $M_{\rm eff} = \not{E}_T + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4}.$

SM background

Using missing momentum and effective mass,

We separate Signal from SM background (ttbar, W,Z+jets, QCD)



Emiss>max(200,0.2Meff) is commonly used cut to reduce SM events.

Large missing momentum $\not{E}_T \equiv |\sum_{visible} \mathbf{p}_T|$

Many hard jets, hard leptons ➡ **Large** $M_{\text{eff}} = \not{E}_T + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4}.$

Event simulation and selection cuts

split-UED	mass	SUSY	mass
q_{L1}	1347 GeV	$\tilde{u}_L$,$\tilde{d}_L$	1355, 1358 GeV
u_{R1}	1322 GeV	$\tilde{u}_R$	1304 GeV
d_{R1}	1318 GeV	$\tilde{d}_R$	1263 GeV
g_1	794 GeV	$\tilde{g}$	799 GeV
B_1	621 GeV	$\tilde{\chi}_1^0$	622 GeV

Mimic Split-UED using MSSM point and generate events using HERWIG.
(Kinematics is almost the same)

- Selection cuts are from ATLAS EP note (0-lepton mode)

1. At least four jets with $p_T > 50$ GeV at least one of which must have $p_T > 100$ GeV; and $E_T^{\text{miss}} >$ 100 GeV.
2. $E_T^{\text{miss}} > 0.2 M_{\text{eff}}$.
3. Transverse sphericity, $S_T > 0.2$.
4. $\Delta\phi(\text{jet}_1 - E_T^{\text{miss}}) > 0.2$, $\Delta\phi(\text{jet}_2 - E_T^{\text{miss}}) > 0.2$, $\Delta\phi(\text{jet}_3 - E_T^{\text{miss}}) > 0.2$.
5. Reject events with an e or a μ.