Collider phenomenology of Split-UED

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(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

To solve both the fine tuning problem and existence of DM, there are several popular models which give the SM as effective theory.

	Fine tuning problem	Z_2 Parity	Dark matter candidate
SUSY	boson-fermion sym.	R-parity	$\tilde{\chi}_1^0, \ \tilde{G}$
Little Higgs with T-parity	Global sym.	T-parity (Anomalies; Hill&Hill)	A_H
mUED	Lorentz sym in 5dim Low Planck scale	KK-parity	B_1

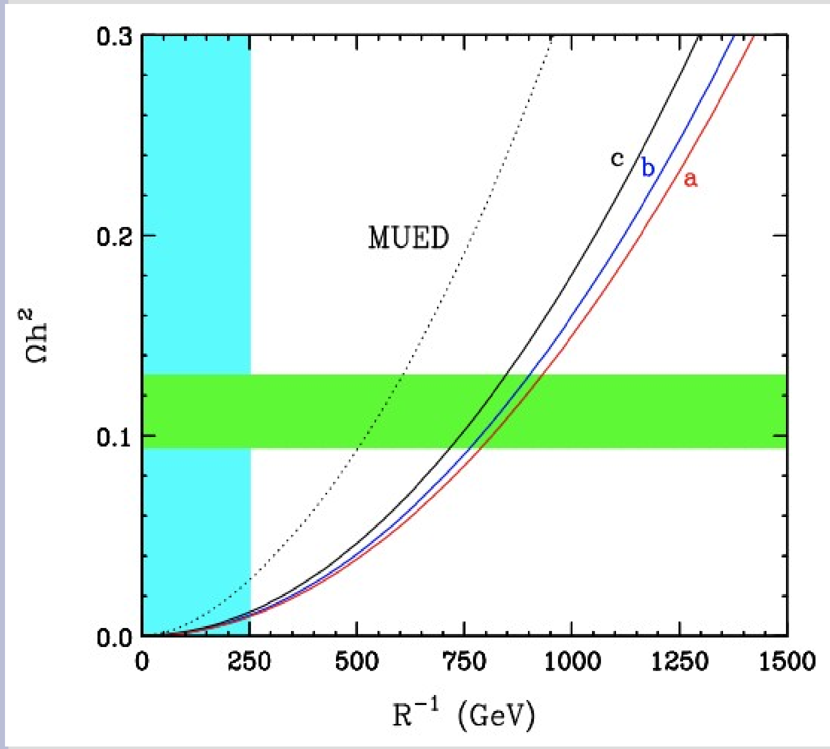
Partners for SM particles.

Parity structure → always produced in pairs at colliders.

Couplings are given by SM couplings (predictive).

mUED

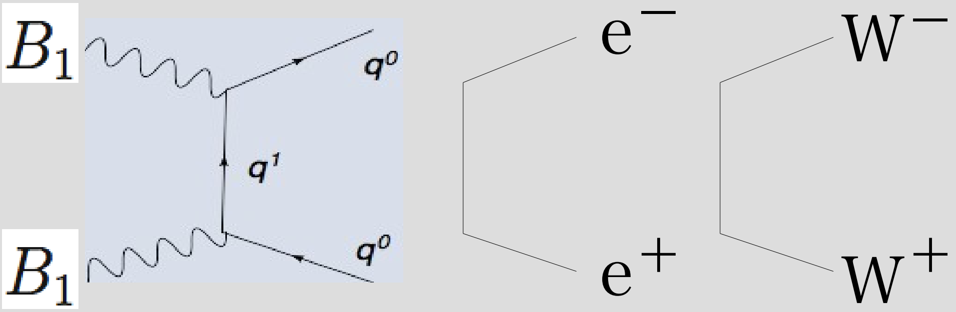
T. Appelquist, H-C. Cheng, B. A. Dobrescu



K. Kong, K. Matchev, JHEP 0601:038, (2006)

In mUED, LKP (heavy photon) is DM candidate. G.Servant, T.M.P. Tait

600 ∼ 900 GeV LKP DM gives correct DM abundance

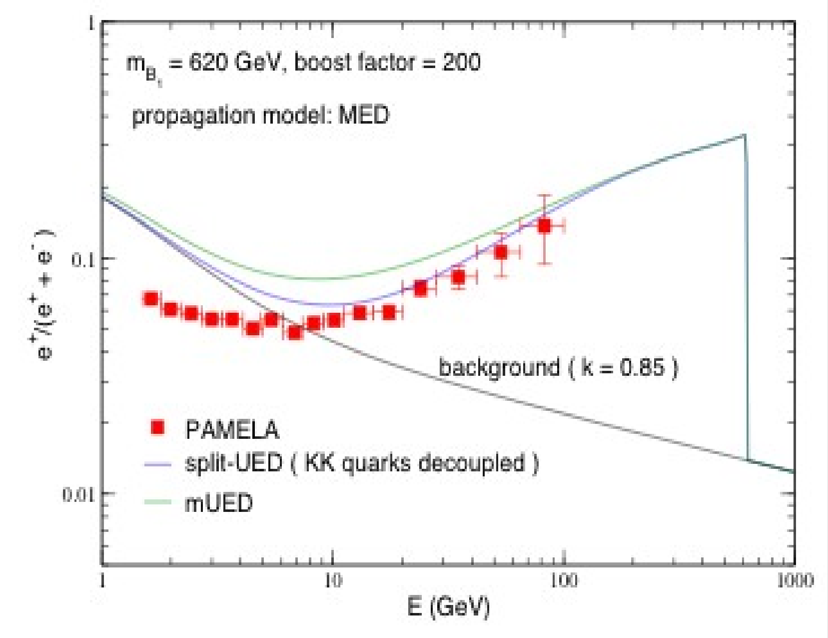


Possible cosmic ray sources

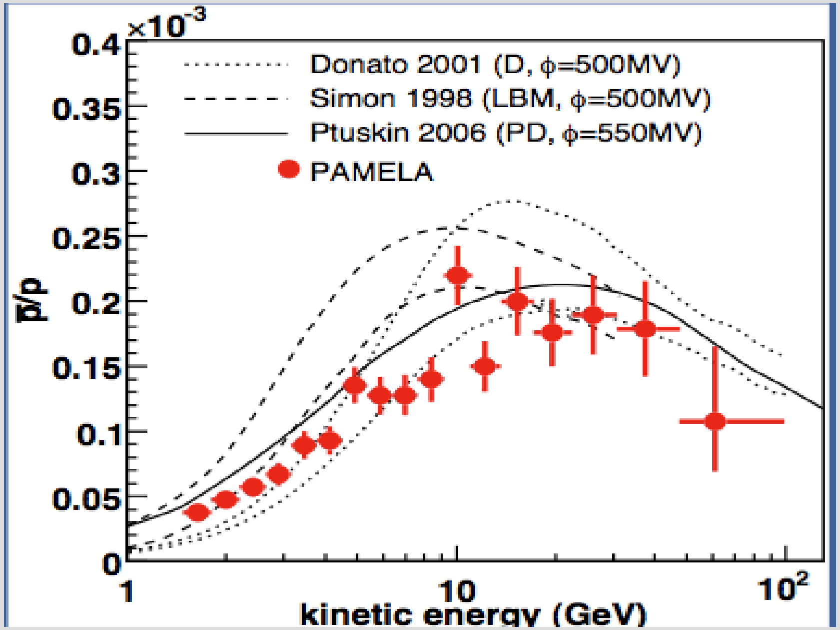
PAMELA

PAMELA Collaboration (Oscar Adriani et al.)

e+/(e- + e+) flux



anti-p / p flux



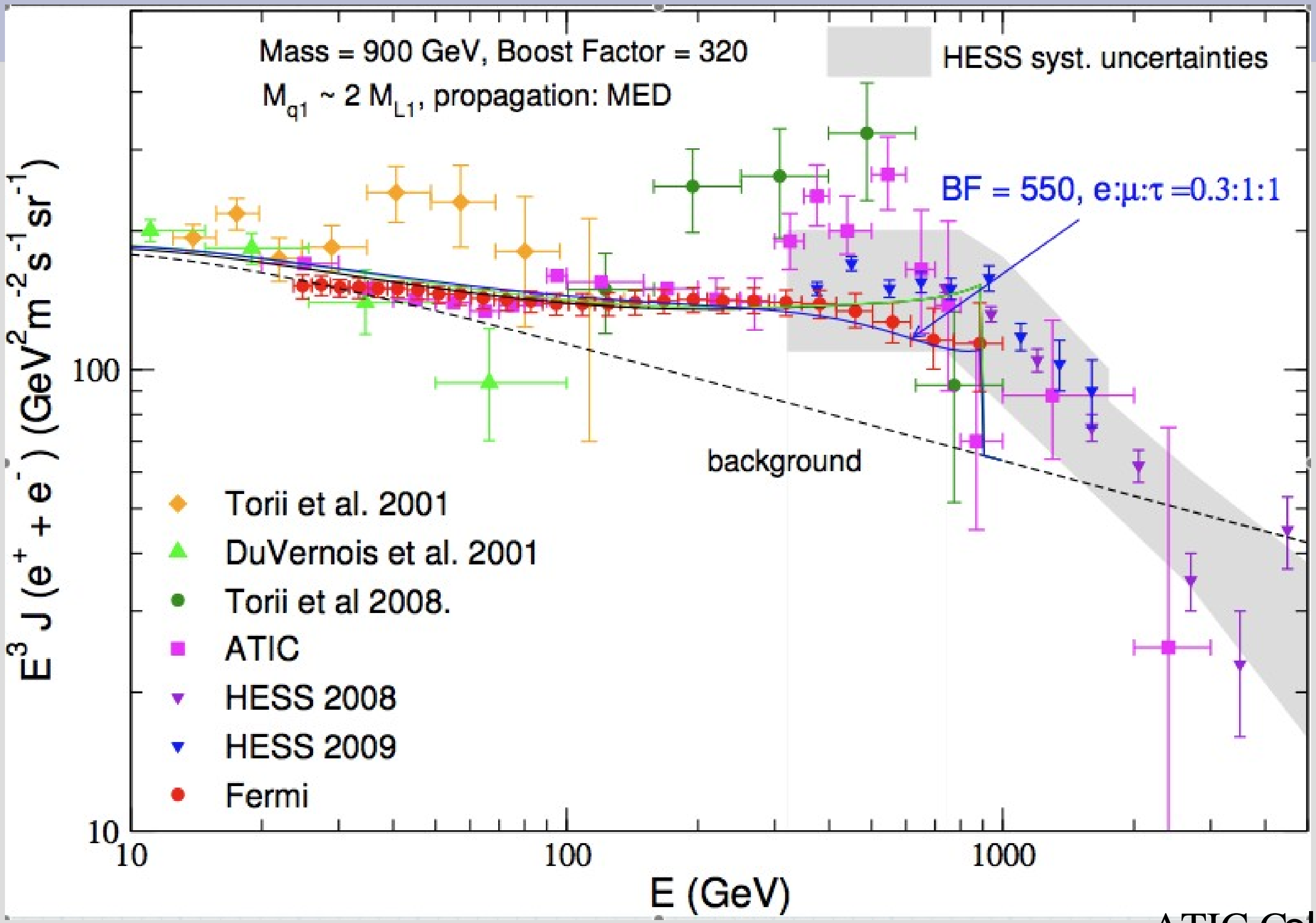
Existence of e+ sources

with > 100GeV

(Pulsar ? V. Barger, Y. Gao, Wai Yee Keung, D. Marfatia, G. Shaughnessy)

No Excess

$e^+ + e^-$ flux (FERMI,ATIC)



FERMI Fermi LAT Collaboration (Aous A. Abdo et al.)

Excess on ～900 GeV data ?

ATIC ATIC Collaboration J. Chang *et al*.

Peak around 600 GeV

(Ruled out by Fermi)

Motivation of Split-UED

DM annihilation $\stackrel{?}{=}$ source of e^+ flux excess (PAMELA)

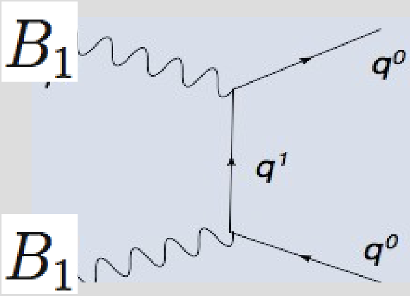
and

ATIC peak with 620 GeV DM (Original motivation)

Fermi excess with 900 GeV DM

On the other hand, hadron modes contribute little. (PAMELA)

Increase the mass of q_1 ➡ suppress



Need mechanism to increase only quark partner mass.

Plan

- Introduction & Motivation
- Model

Split-UED $=$ mUED + 5D Bulk mass μ

  - Fermionic partners for SM fermions
  - Almost degenerate mass spectrum
  - Heavy quark partner (q_1)

- Collider signatures

mUED model

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

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

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

Zero modes as SM fields

To obtain chiral fermions,

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

For the SM, we choose:

η_P=-1 for Q, L

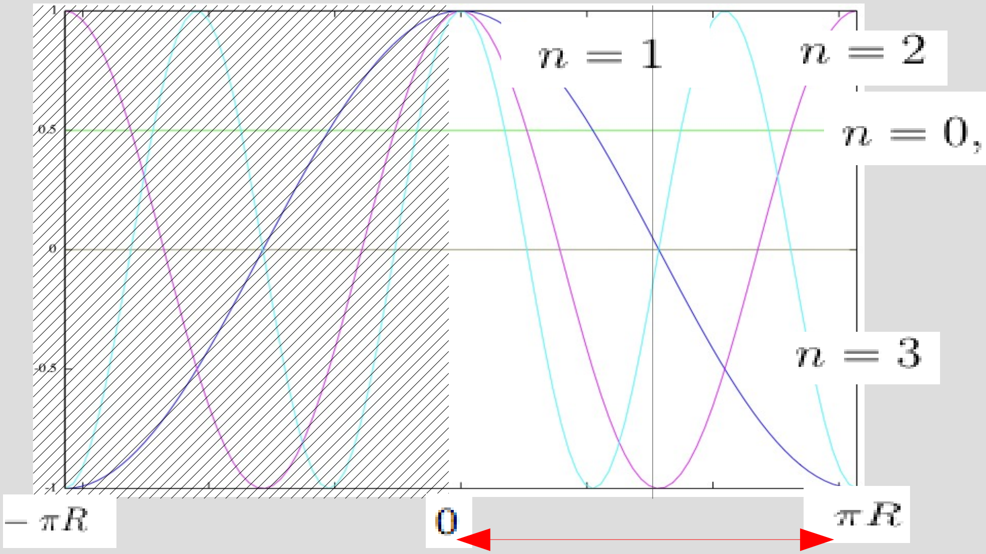
$$\Psi_L(x^\mu, y) = \frac{1}{\sqrt{2\pi R}}\Psi_L^{(0)}(x^\mu) + \sum_{n=1}^{\infty}\frac{1}{\sqrt{\pi R}}\Psi_{L+}^{(n)}(x^\mu)\cos\frac{ny}{R}$$

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

η_P=+1 for U, D, E, N

KK parity

Physical domain is 0<y<πR. 4D eff. Lagrangian obtained by y-integration.
Only terms even under the reflection symmetry survive.



Physical domain

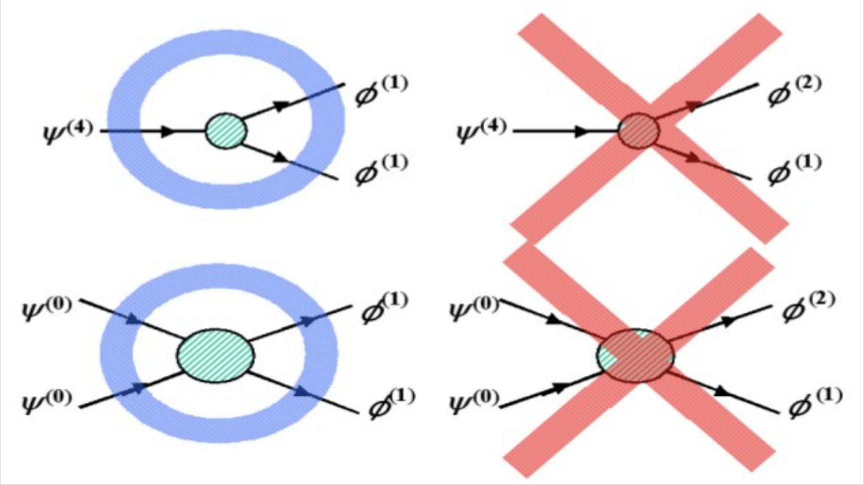
$$\Psi_L(x^\mu,y) = \frac{1}{\sqrt{2\pi R}}\Psi_L^{(0)}(x^\mu) + \sum_{n=1}^{\infty}\frac{1}{\sqrt{\pi R}}\Psi_{L+}^{(n)}(x^\mu)\,\cos\frac{ny}{R}$$

Symmetry as KK-parity of fields.

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

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

Each vertex conserves KK-parity.



Split-UED model

- mUED + bulk mass μ

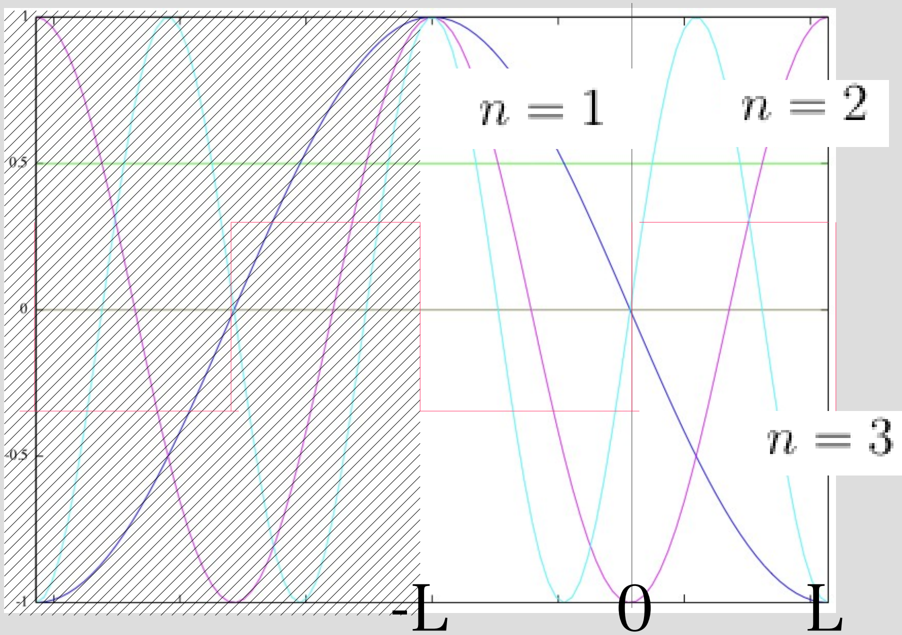
If we introduce normal vector-like mass term $M(\bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L)$

after y-integration, it gives KK parity violating terms, $m(\bar{\Psi}_L^{(0)} \Psi_R^{(1)} + \bar{\Psi}_R^{(1)} \Psi_L^{(0)})$

Instead, we introduce mass term $M\epsilon(y)(\bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L)$ S.C. Park, J. Shu

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

$$\epsilon(y) = \begin{cases} +1 & (0 < y < L) \\ -1 & (-L < y < 0) \end{cases}$$



After y-integration, terms like

$m(\bar{\Psi}_L^{(0)} \Psi_R^{(2)} + \bar{\Psi}_R^{(2)} \Psi_L^{(0)})$ remain.

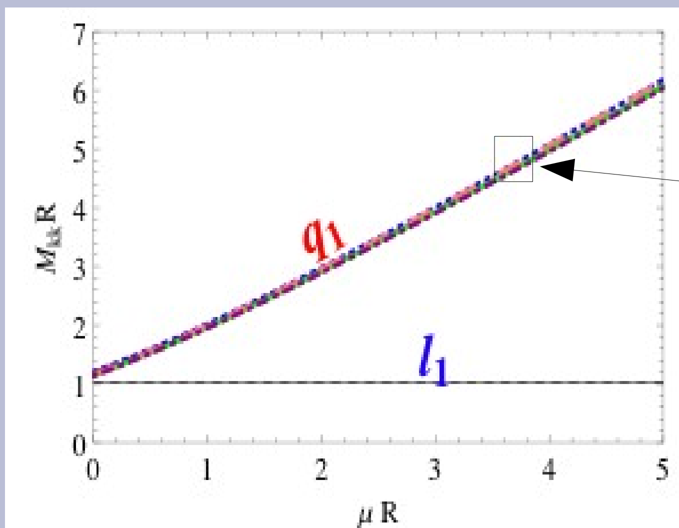
These terms give mixing among

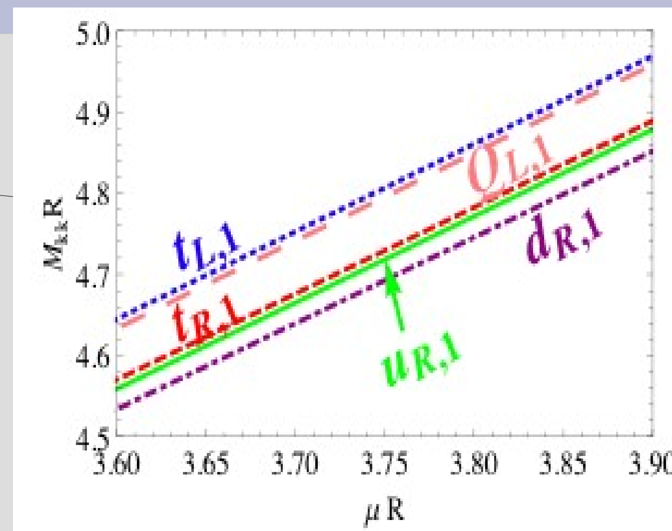
$\Psi_L^{(0)}, \Psi^{(2)}, \Psi^{(4)}, \ldots$ and $\Psi^{(1)}, \Psi^{(3)}, \ldots$

KK parity conserving

Spectrum

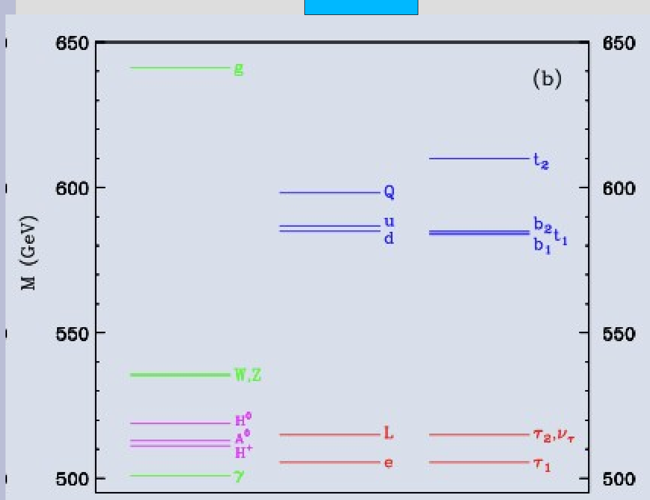
Split-UED REF





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

$$k_{n-} = -|\mu| \tan k_n L,$$
$$k_{n+} = n/R\,.$$



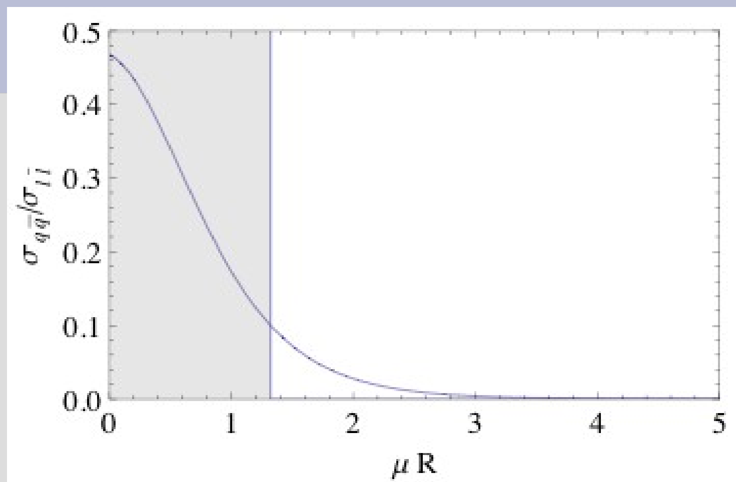
H-C. Cheng, K. Matchev, M. Schmaltz

mUED : All masses of the first excited states are degenerate within ~ 100 GeV

Mass differences between quark partners and others becomes $\sim \mu$

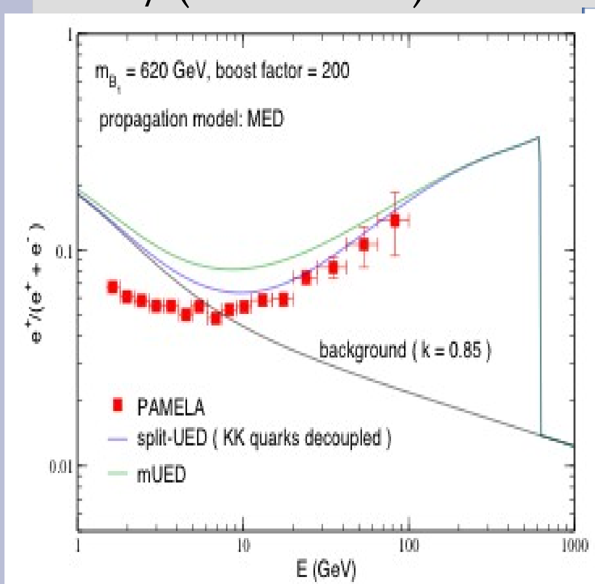
Fit data

With split-UED, we can reproduce data

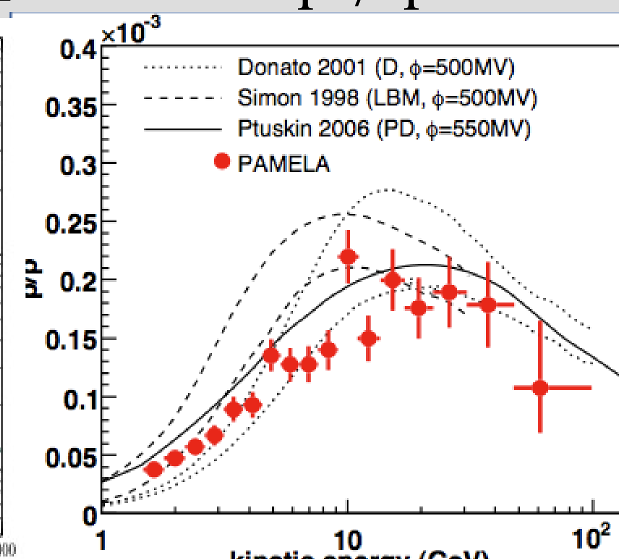


$$\mu \gtrsim \frac{1}{R} \quad \text{for p mode suppression}$$

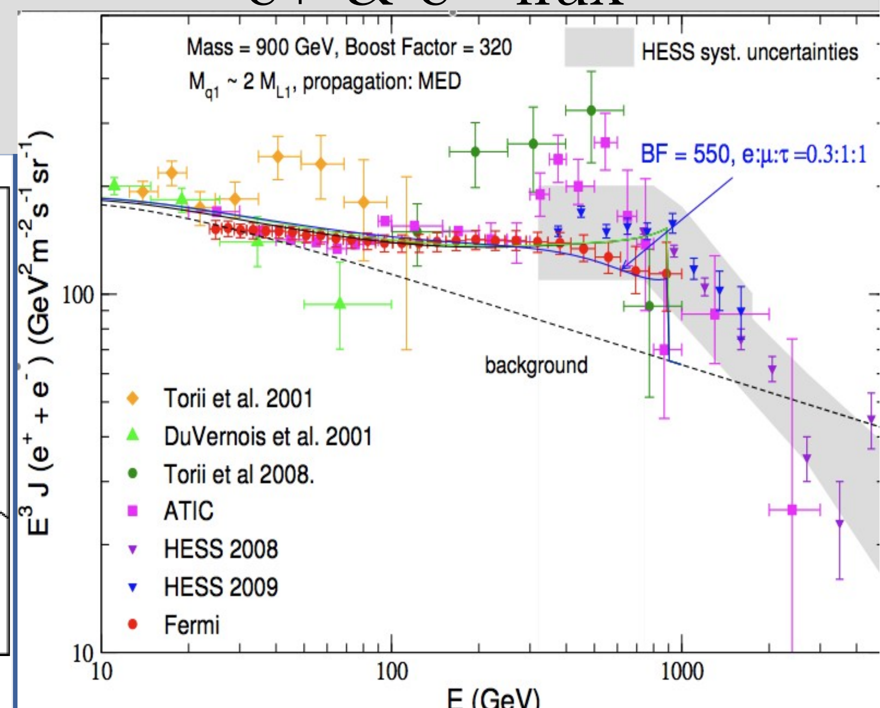
e+/(e- + e+) flux



anti-p / p flux



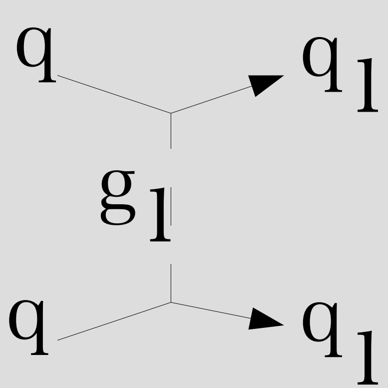
e+ & e- flux



Collider signatures

q_1 q_1 signal

- Large production cross section



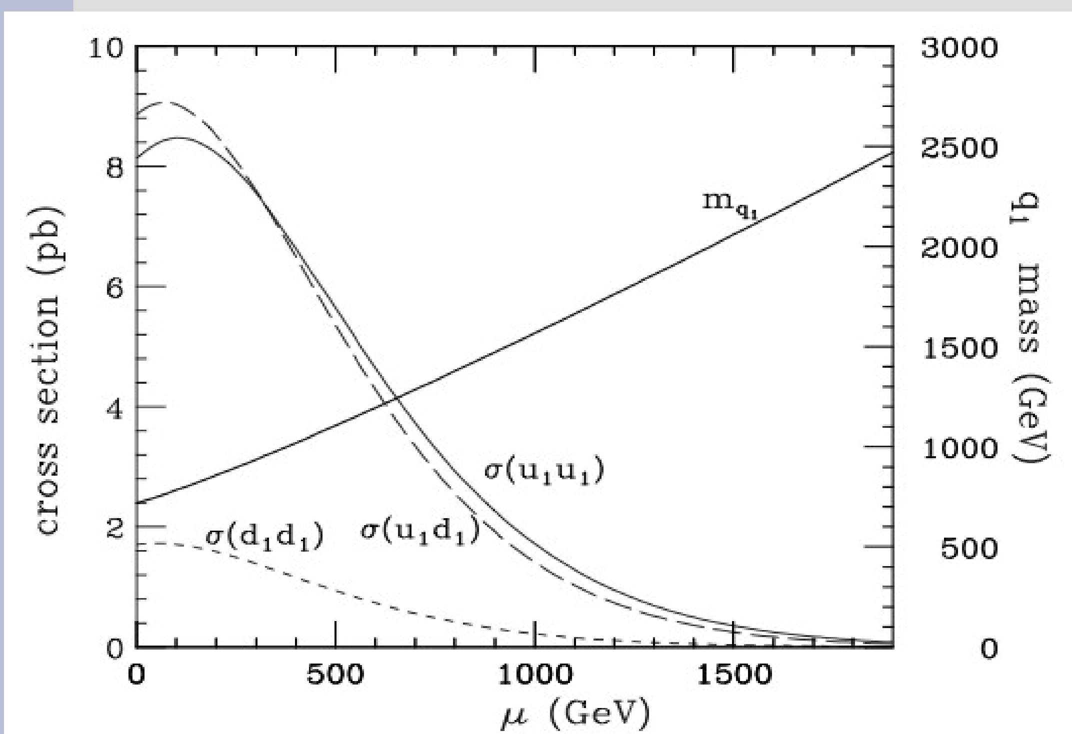
Fermionic quark partner

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

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 $\sim \beta^3$ → β

→ 10 ～ 100 times larger for the same masses

$q_1 q_1$ 7.64 pb

$\tilde{q}\tilde{q}$ 125 fb

60 times larger

q_1 q_1 signal

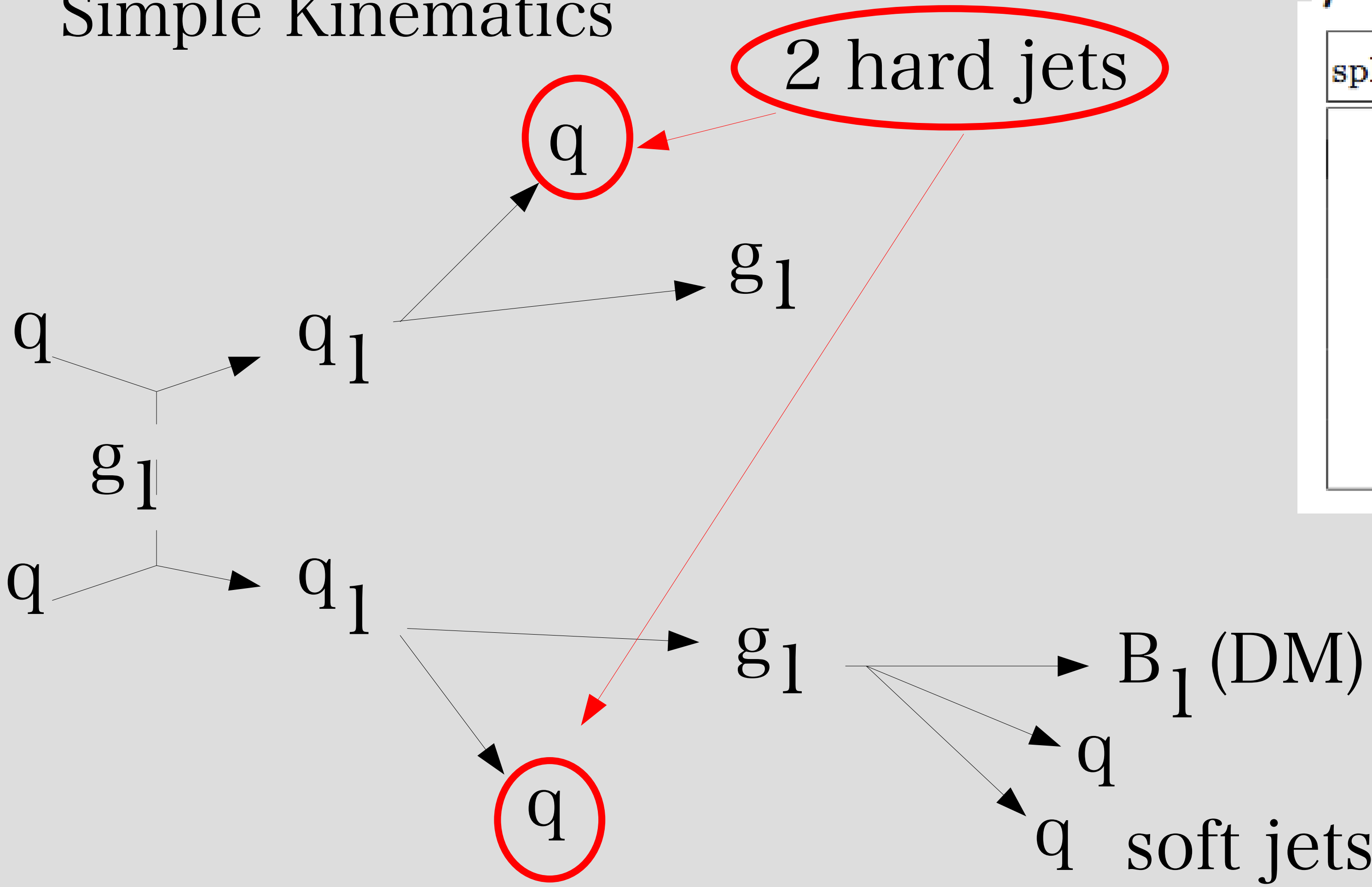
- Large mass splitting

Simple Kinematics

$$1/R = 620 \text{ GeV}$$

$$\mu = 700 \text{ GeV}$$

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

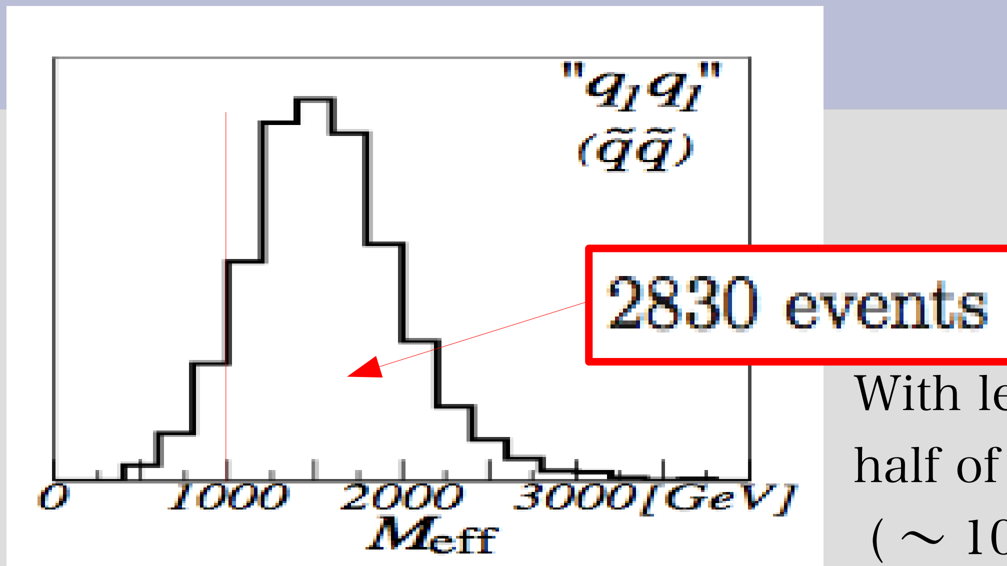


Signal is Two hard jets + missing momentum.

Meff distribution and SMBG

For $1 fb^{-1}$

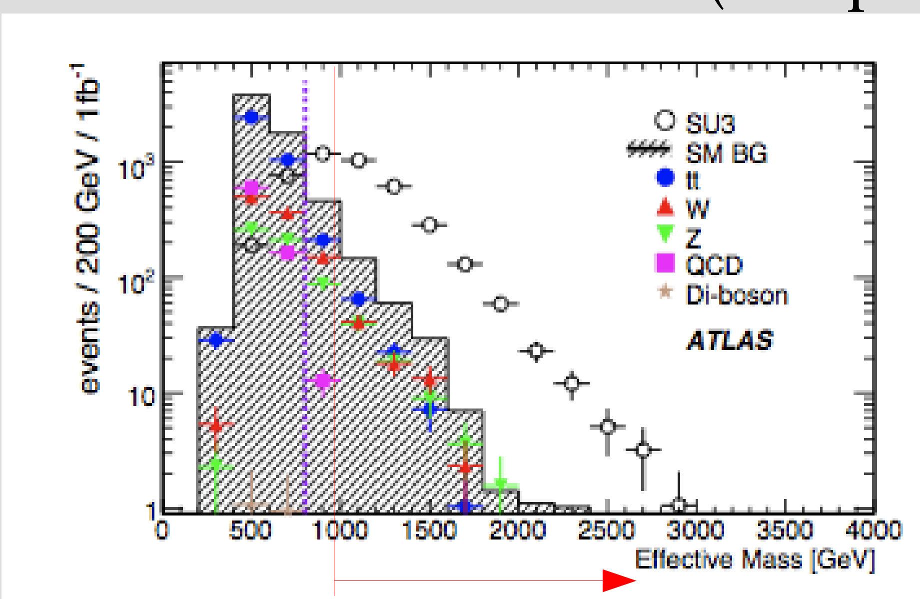
$$M_{\rm eff} \equiv \sum_{i=1}^{4} p_T^{{\rm jet},i} + \sum_{i=1} p_T^{{\rm lep},i} + E_{\rm T}^{\rm miss}$$



	after standard cut	$M_{\rm eff} > 1$ TeV
$q_1 q_1$	0.40	0.37

With lepton veto cuts,
half of events will remains
(∼ 1000 events)

- From ATLAS EP note (0-lepton mode)



SMBG < $300/1 fb^{-1}$
Signal > $1000/1 fb^{-1}$

Discovery is easy!

q_1 q_1 signal

- Large mass splitting

Simple Kinematics

$1/R = 620$ GeV

$\mu = 700$ GeV

split-UED	mass
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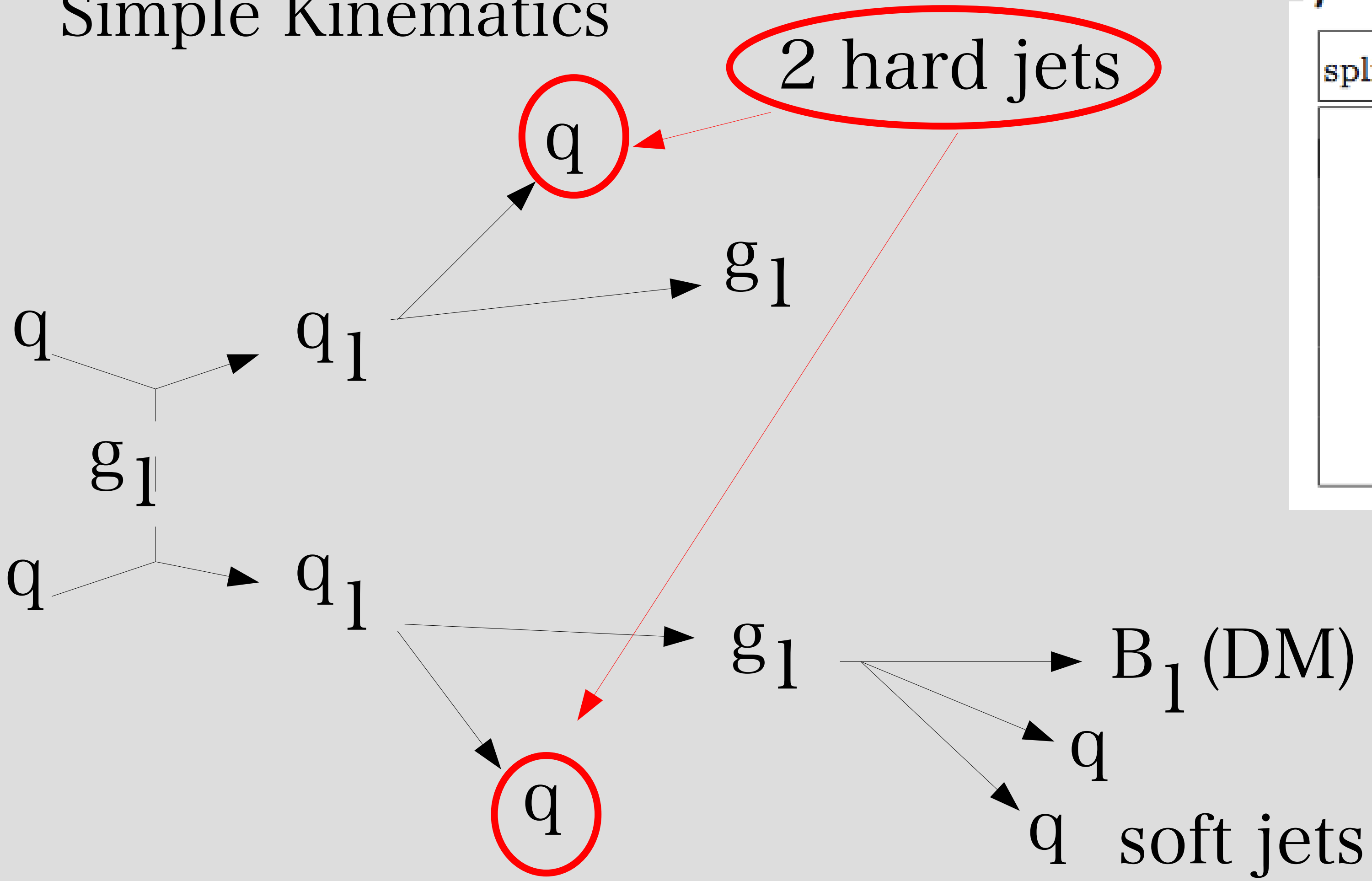


The same Kinematics as $\tilde{q}_R\,\tilde{q}_R$ pair production ⇨ M_{T2}

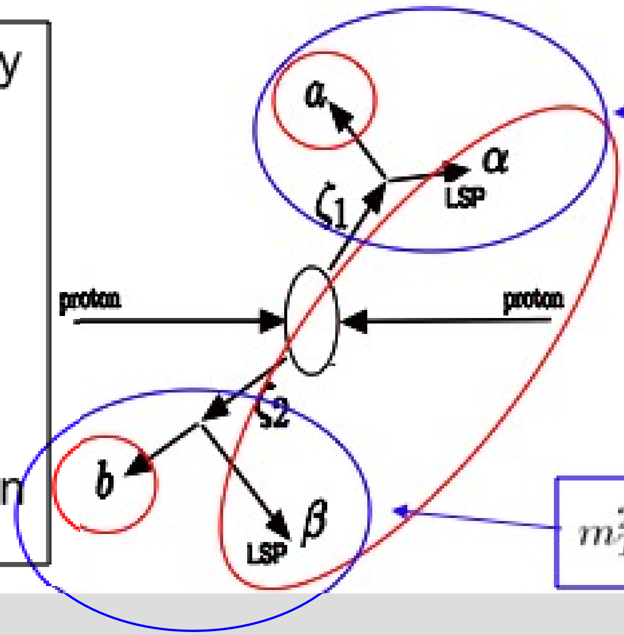
M_{T2} A. Barr, C. Lester, P. Stephens

1. Consider all possible way of separation

$$\not{E}_T = \not{p}_T^{\alpha} + \not{p}_T^{\beta}$$

2. Calculate two m_T and take larger one

3. Minimize in the separation



$$m_T^2(\mathbf{p}_T^a, \not{\mathbf{p}}_T^{\alpha}; m_{\tilde{\chi}_1^0}) \leq m_\zeta^2.$$

$$m_T^2(\mathbf{p}_T^b, \not{\mathbf{p}}_T^{\beta}; m_{\tilde{\chi}_1^0}) \leq m_\zeta^2.$$

$$m_{T2}^2(\mathbf{p}_T^a, \mathbf{p}_T^b, \not{\mathbf{p}}_T; m_{\tilde{\chi}_1^0}) \equiv \min_{\not{\mathbf{p}}_T^{\alpha}+\not{\mathbf{p}}_T^{\beta}=\not{\mathbf{p}}_T} \left[\max\left\{m_T^2(\mathbf{p}_T^a, \not{\mathbf{p}}_T^{\alpha}; m_{\tilde{\chi}_1^0}), m_T^2(\mathbf{p}_T^b, \not{\mathbf{p}}_T^{\beta}; m_{\tilde{\chi}_1^0})\right\}\right] \leq m_\zeta^2$$

Defined with two momenta and Missing transverse momentum

The endpoint gives mother particle mass

M_{T2}

A. Barr, C. Lester, P. Stephens

1. Consider all possible way of separation

$$\not{E}_T = \not{p}_T^\alpha + \not{p}_T^\beta$$

2. Calculate two m_T and take larger one

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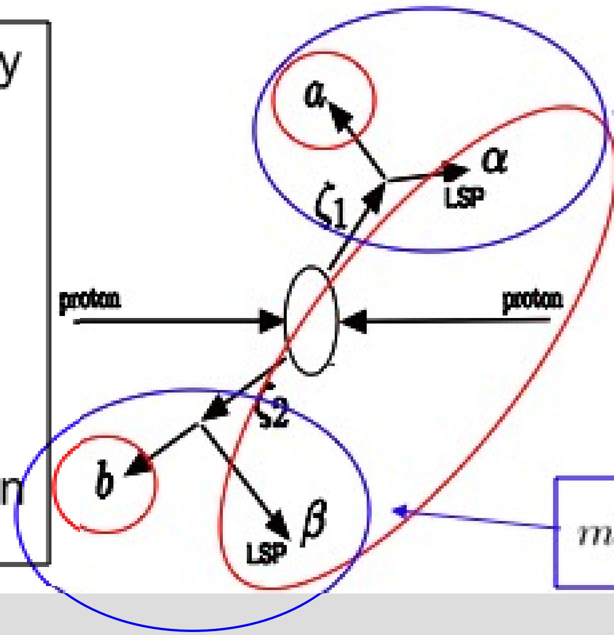


$$m_T^2(\mathbf{p}_T^a, \not{p}_T^\alpha; m_{\tilde{\chi}_1^0}) \leq m_\zeta^2.$$

$$m_T^2(\mathbf{p}_T^b, \not{p}_T^\beta; m_{\tilde{\chi}_1^0}) \leq m_\zeta^2.$$

$$m_{T2}^2(\mathbf{p}_T^a, \mathbf{p}_T^b, \not{p}_T; m_{\tilde{\chi}_1^0}) \equiv \min_{\not{p}_T^\alpha + \not{p}_T^\beta = \not{p}_T} \left[\max\left\{ m_T^2(\mathbf{p}_T^a, \not{p}_T^\alpha; m_{\tilde{\chi}_1^0}), m_T^2(\mathbf{p}_T^b, \not{p}_T^\beta; m_{\tilde{\chi}_1^0}) \right\} \right] \leq m_\zeta^2$$

Defined with two momenta and Missing transverse momentum

The endpoint gives mother particle mass

In case DM mass is unknown
Set test mass to be 0 gives

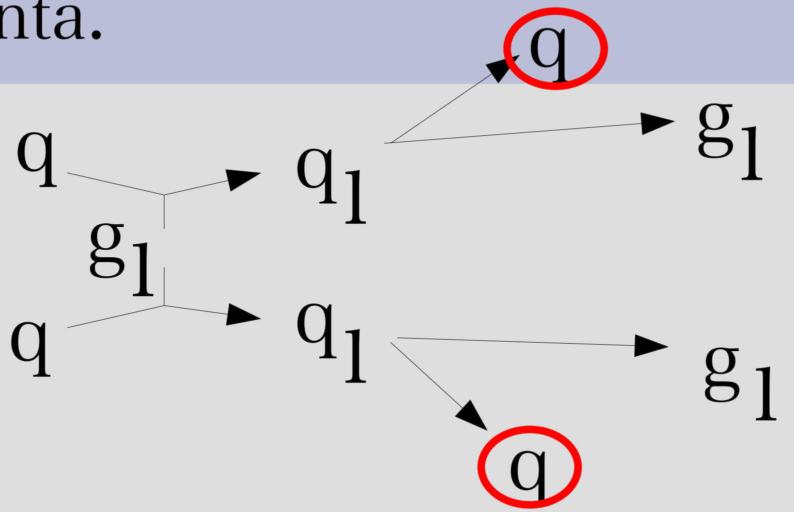
$$M_{T2}^{\text{end}} = m_A - \frac{m_X^2}{m_A},$$

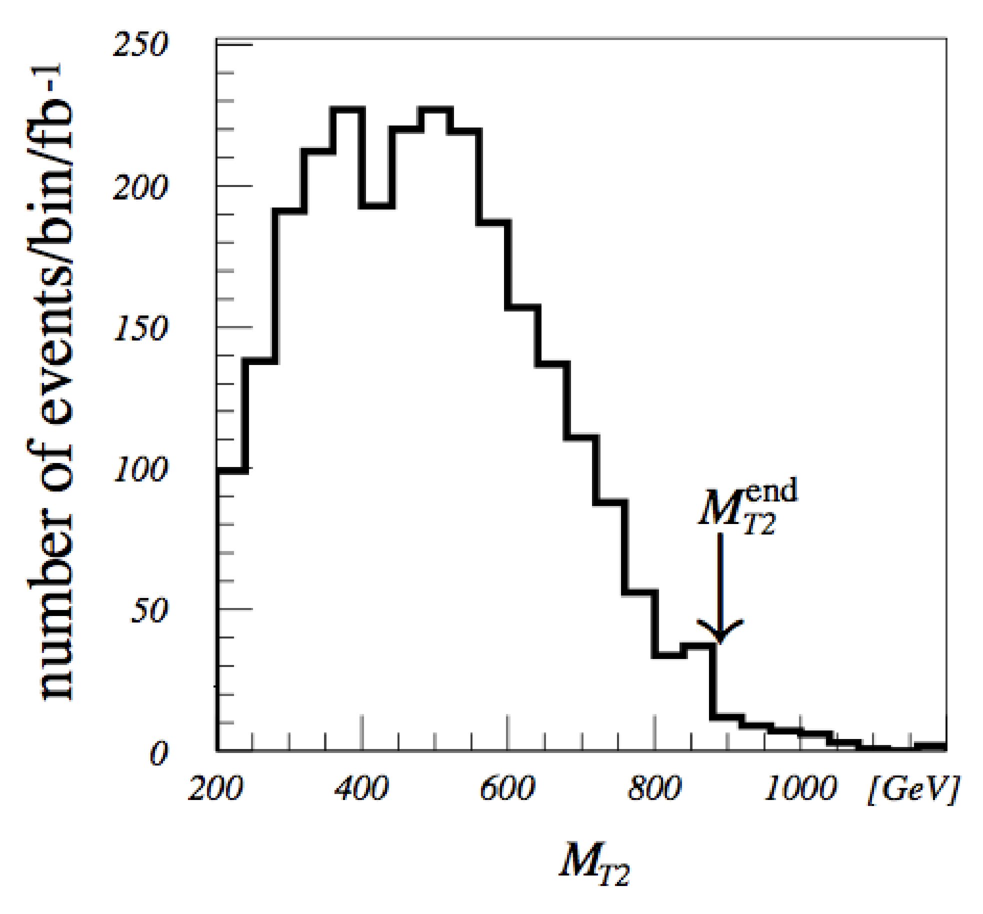
(No ISR limit)

M_{T2} distribution

Two highest pt jets for visible momenta.

$$p_{T\text{miss}} = -p_{Tj_1} - p_{Tj_2}$$





M_{T2} endpoint is given by

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

which is

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

Summary

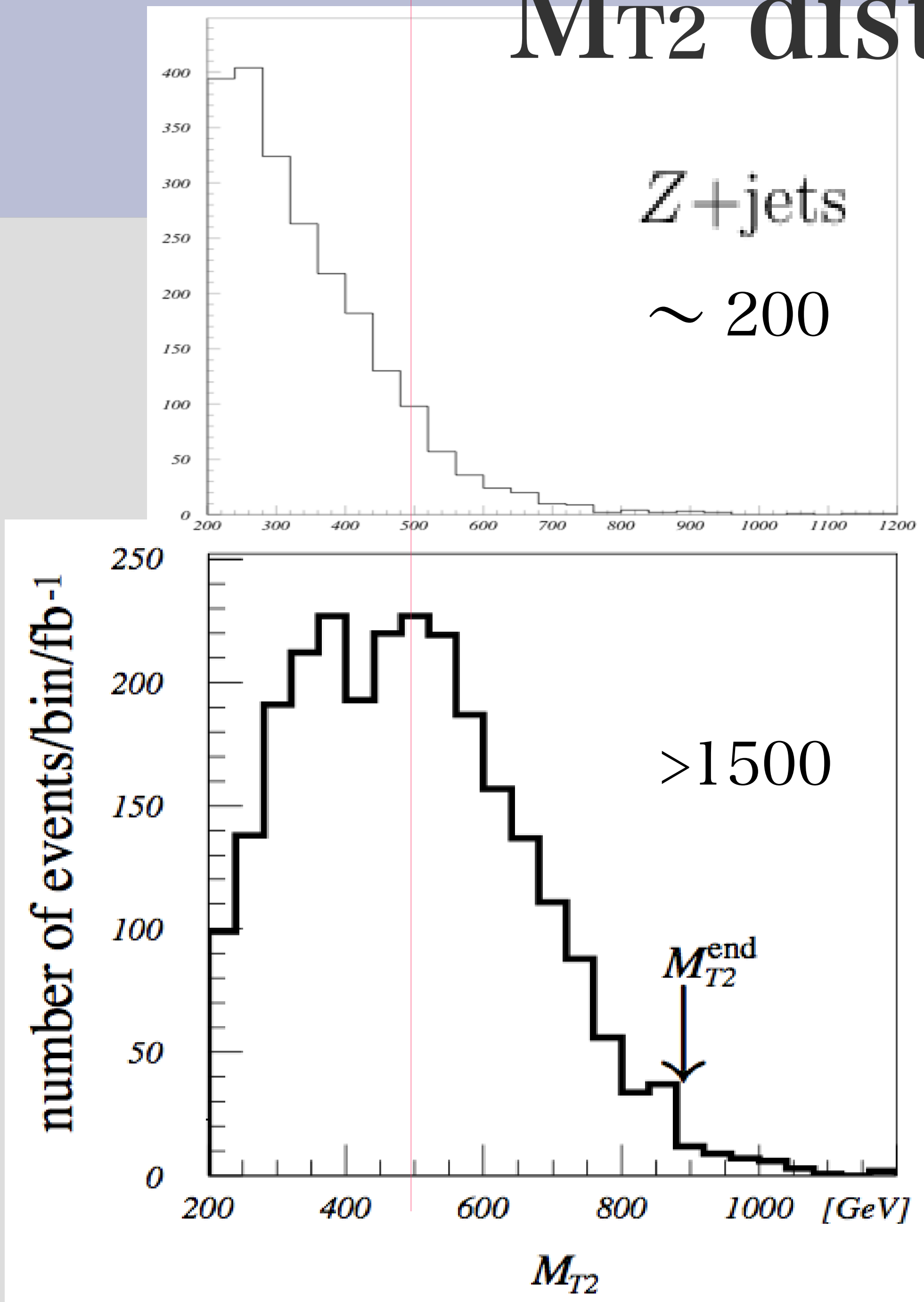
- e+ e- flux observations

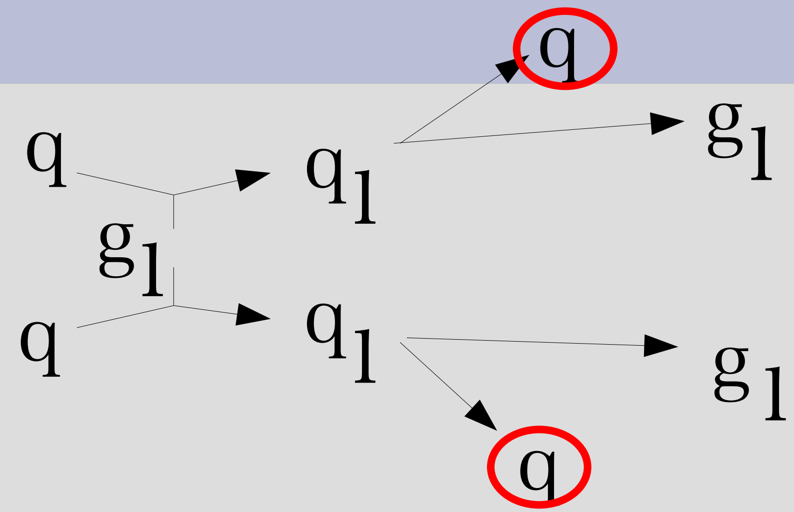
  ⇨ DM annihilation dominated by leptonic modes

  ⇨ Split-UED with heavy quark partner

- Large cross section (fermion partner)
- Easy to detect because of simple decay kinematics
- q_1 mass measurement using M_{T2}

M_{T2} distribution





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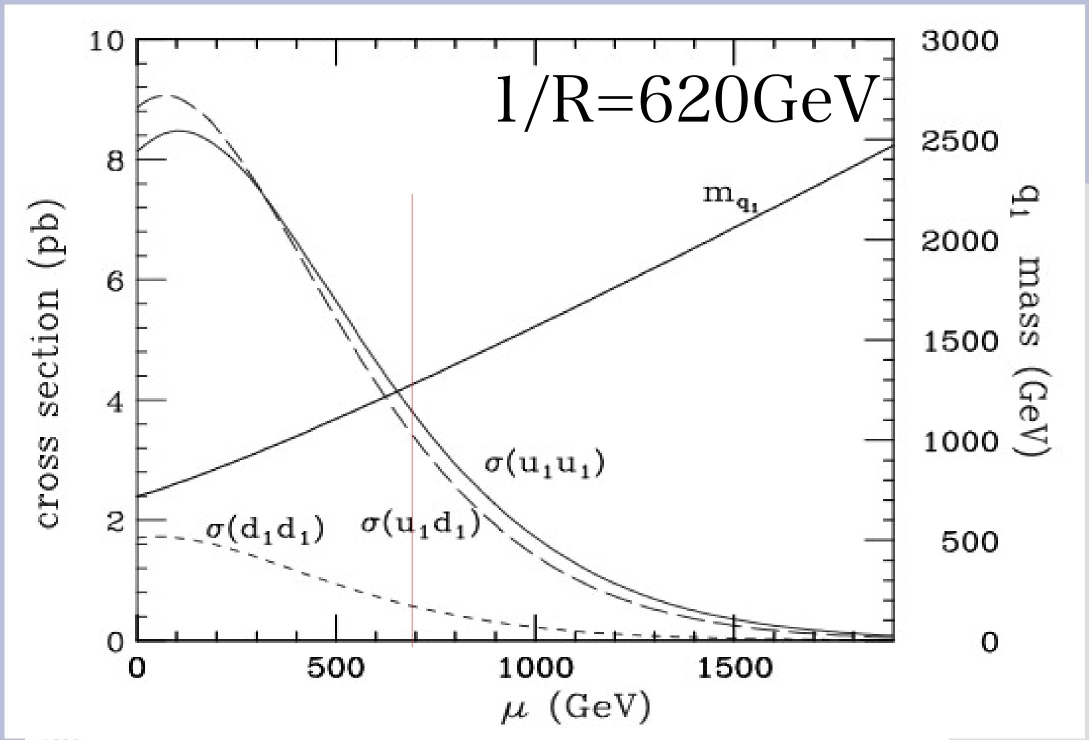
which is

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

SM back ground:

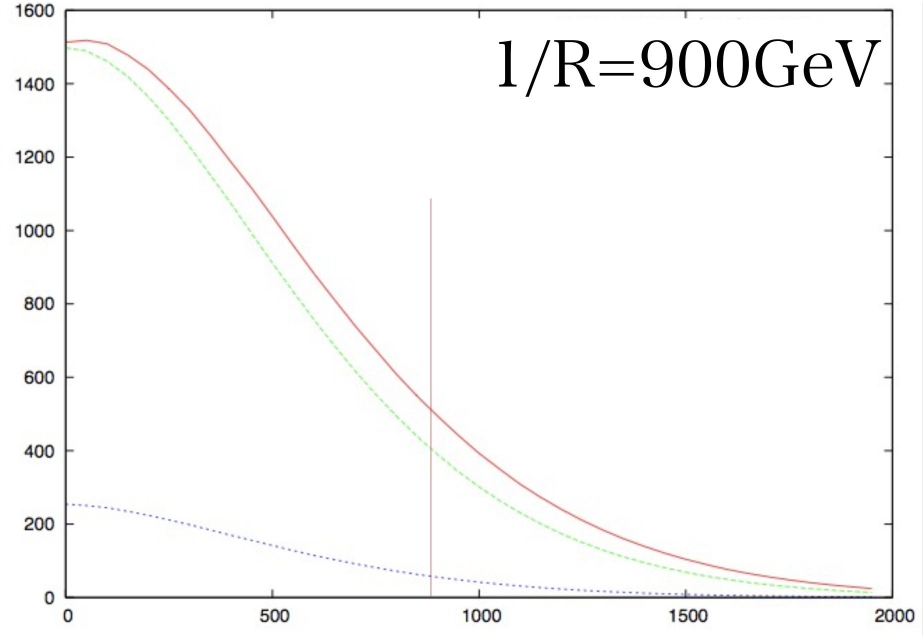
Z+jets events give smaller M_{T2}

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.

$$\Psi(x^\mu, y) = \Psi_L(x^\mu, y) + \Psi_R(x^\mu, y)$$

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

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

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

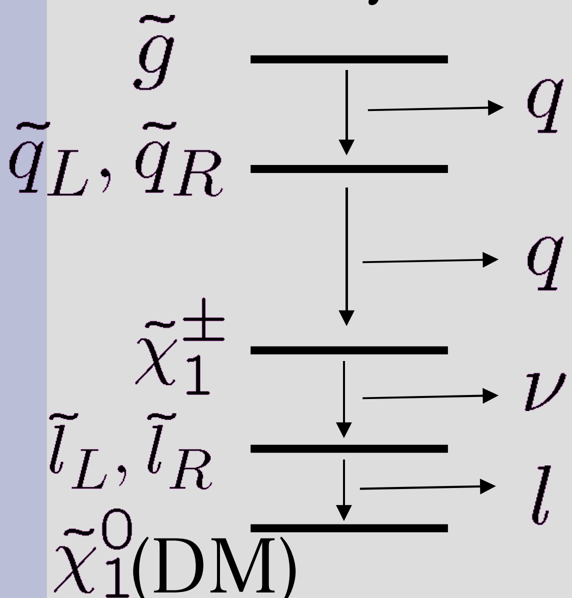
LHC: proton – proton collider ($\sqrt{s}$=14TeV)

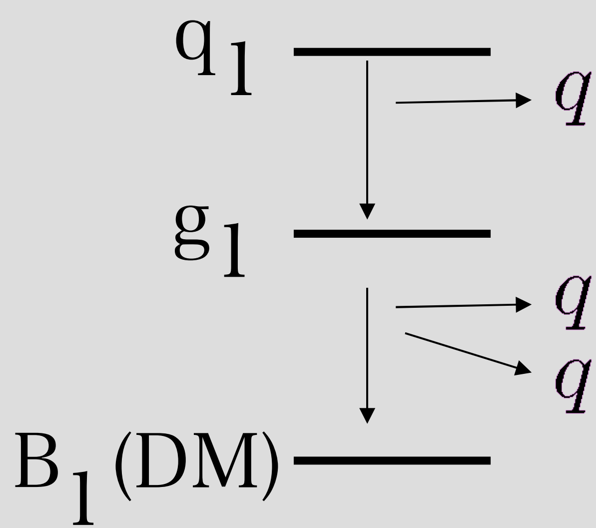
Proton: mixture of u, d, g, and sea quarks

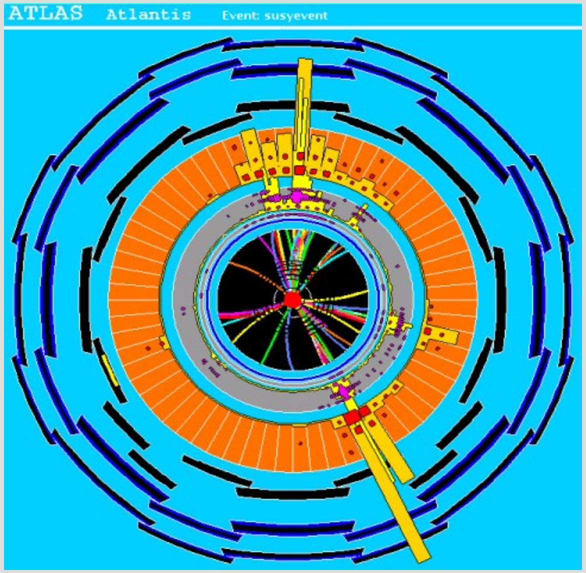
➡ Colored particles are copiously produced. (SM events also are)

Z_2 parity odd particles are produced in pair.

Each decays in cascade







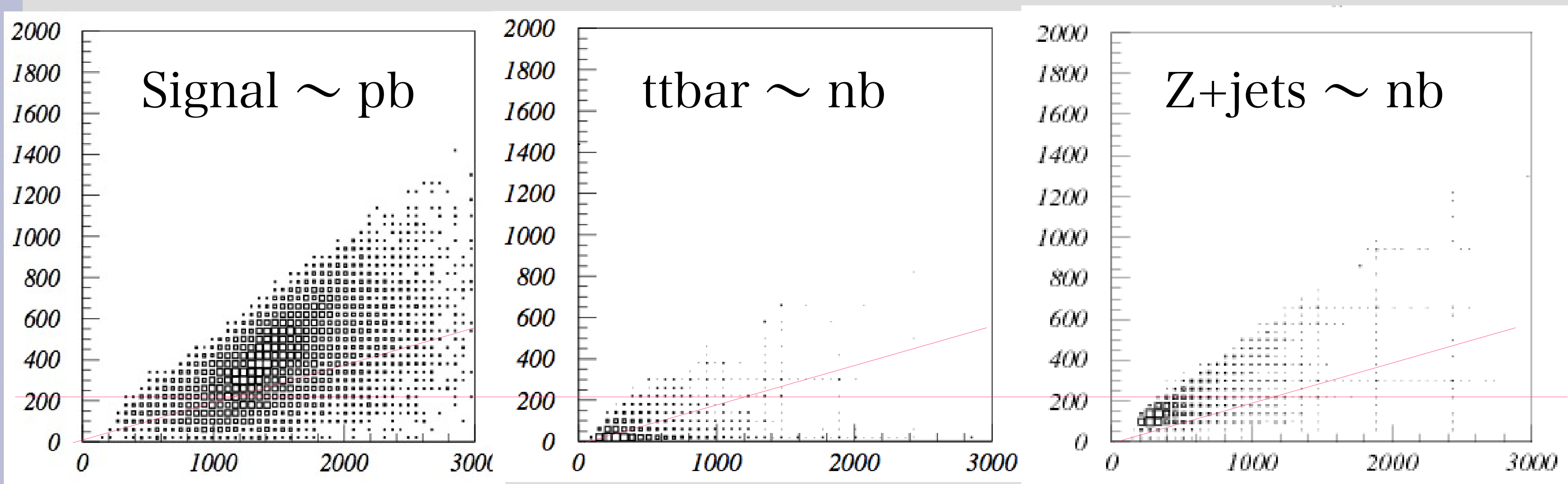
Large missing momentum $\not{E}_T \equiv |\sum_{visible} \mathbf{p}_T|$

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 $M_{\rm eff} = \not{E}_T + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4}.$

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 $E_{\mathrm{T}}^{\mathrm{miss}} >$ 100 GeV.
2. $E_{\mathrm{T}}^{\mathrm{miss}} > 0.2M_{\mathrm{eff}}$.
3. Transverse sphericity, $S_T > 0.2$.
4. $\Delta\phi(\mathrm{jet}_1 - E_{\mathrm{T}}^{\mathrm{miss}}) > 0.2$, $\Delta\phi(\mathrm{jet}_2 - E_{\mathrm{T}}^{\mathrm{miss}}) > 0.2$, $\Delta\phi(\mathrm{jet}_3 - E_{\mathrm{T}}^{\mathrm{miss}}) > 0.2$.
5. Reject events with an e or a μ.