Collider phenomenology of Split-UED

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In collaboration with
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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.

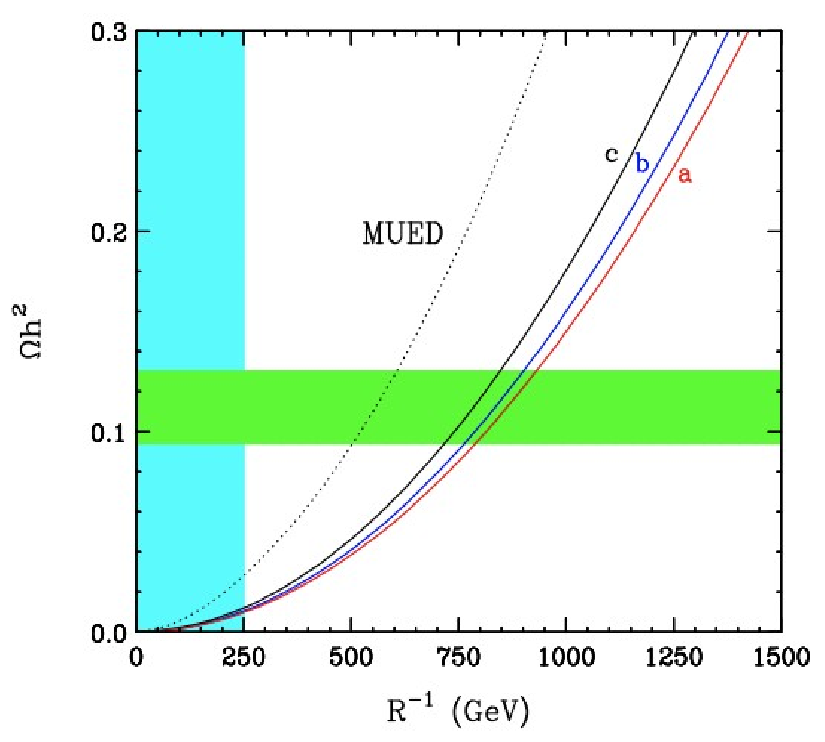
Parity structure → always produced in pairs at colliders.

Couplings are given by SM couplings (predictive).

mUED

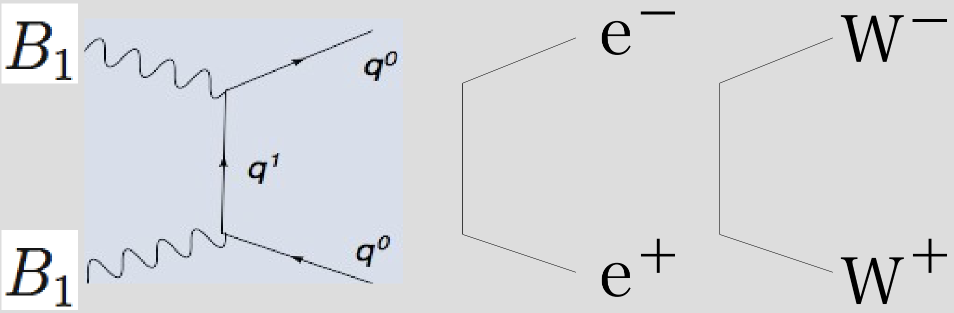
T. Appelquist, H-C. Cheng, B. A. Dobrescu

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



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

600 ～ 900 GeV LKP DM gives correct DM abundance



e^- W^-

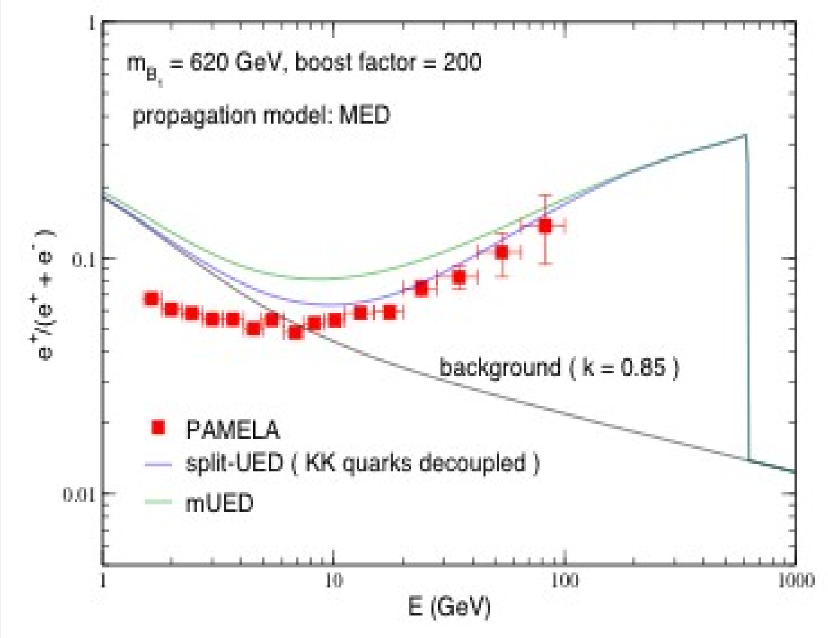
e^+ W^+

Possible cosmic ray sources

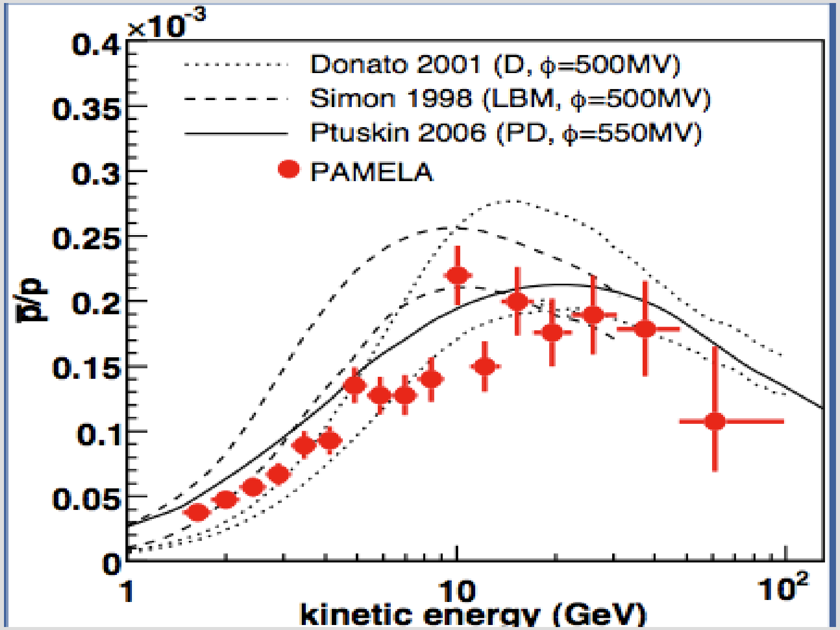
PAMELA

PAMELA Collaboration (Oscar Adriani et al.)

e+/(e- + e+) flux



anti-p / p flux



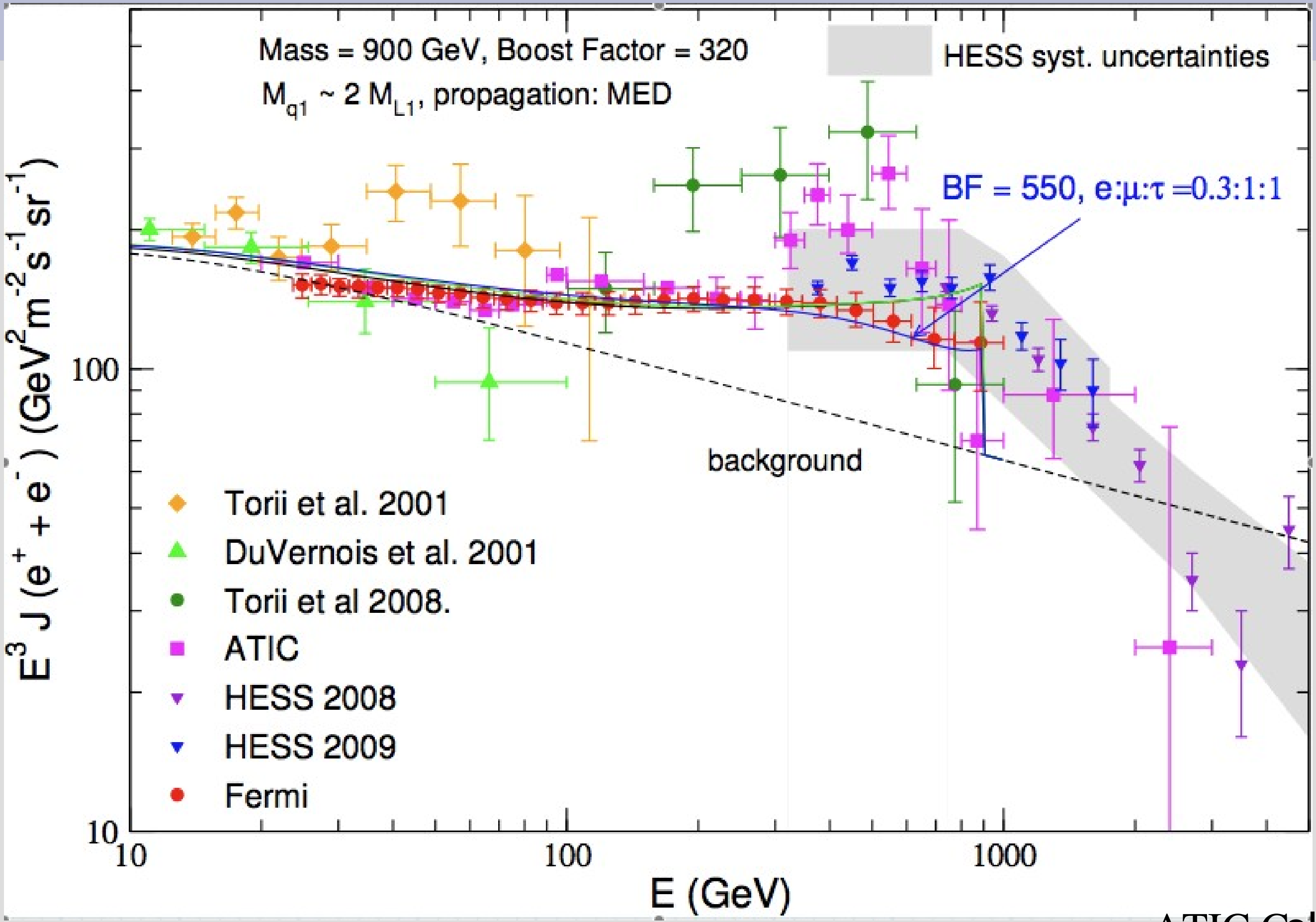
Existence of e+ sources

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 = source of e^+ flux excess (PAMELA)

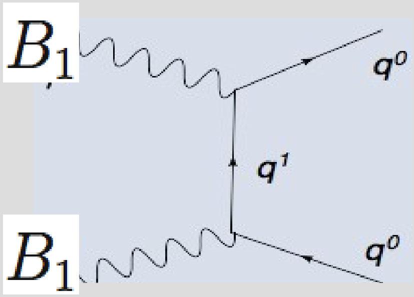
and

ATIC peak with 620 GeV DM

Fermi excess with 900 GeV DM

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

Increase the mass of q_1 → suppress



Need model with heavy quark partner.

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

$\Psi'(x') = \eta_P \gamma^5 \Psi(x)$ $\quad x^M = (x^\mu, y) \to x'^M = (x^\mu, -y).$

Physical domain becomes $0<y<\pi R$.

For the SM, we choose:

η_P=-1 for Q, L

η_P=+1 for 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 parity

4D eff. Lagrangian obtained by y-integration.

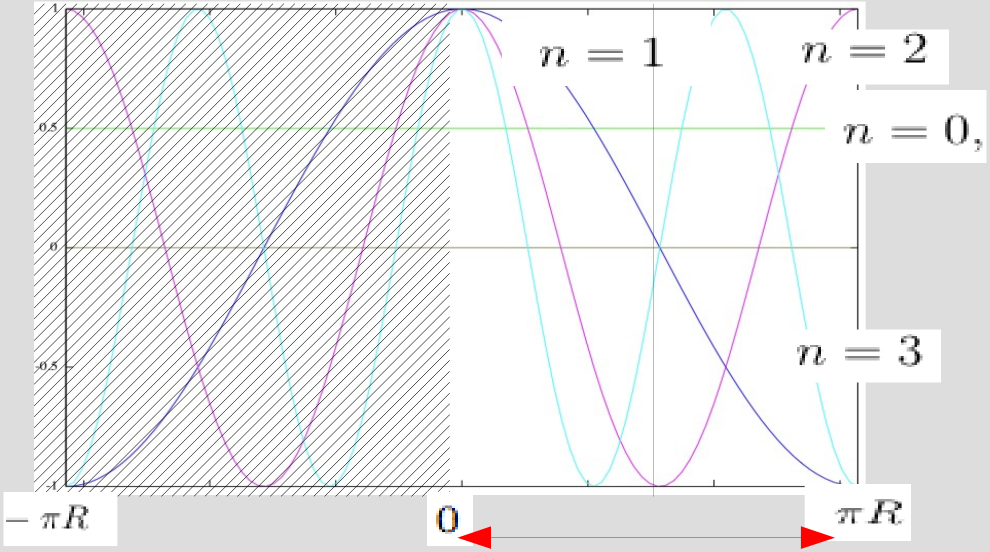
Only terms even under the reflection symmetry survive.

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

$$\big\downarrow$$

$$\boxed{\frac{n}{R}\left(\bar{\Psi}_L^{(n)} \Psi_R^{(n)} + \bar{\Psi}_R^{(n)} \Psi_L^{(n)}\right)}$$

Vector like mass term



Physical domain

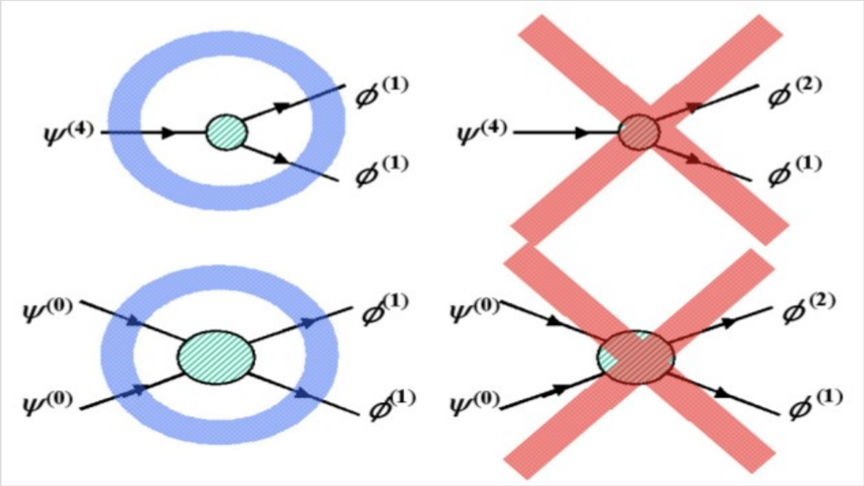
$$\Psi_L(x^\mu, y) = \frac{1}{\sqrt{2\pi R}} \Psi_L^{(0)}(x^\mu) + \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi R}} \Psi_{L+}^{(n)}(x^\mu) \cos\frac{ny}{R}$$

Symmetry as KK-parity of fields.

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

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

Each vertex conserves KK-parity.

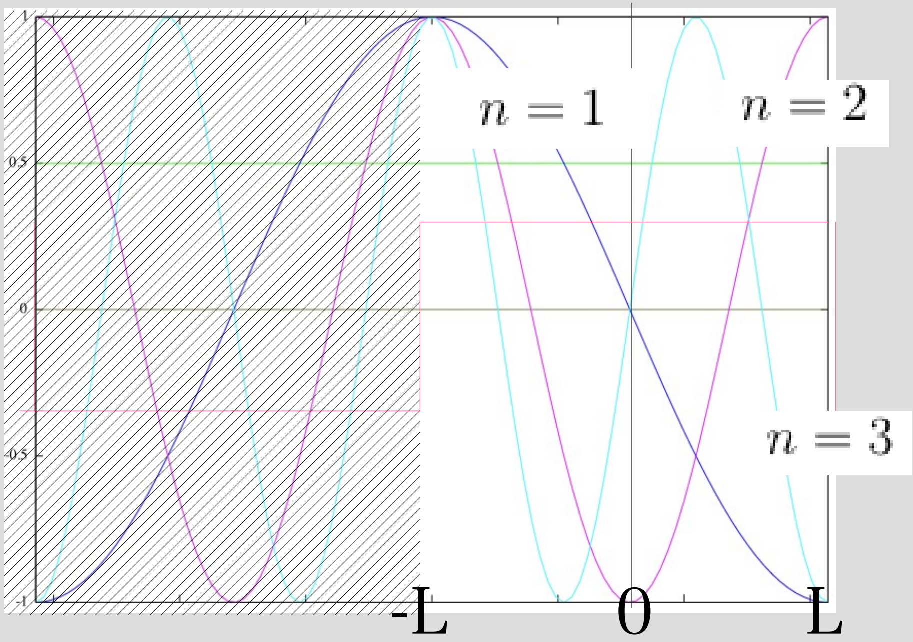


Bulk mass term

To obtain heavy quark partners,

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

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



After y-integration,
The term gives KK parity violating terms,

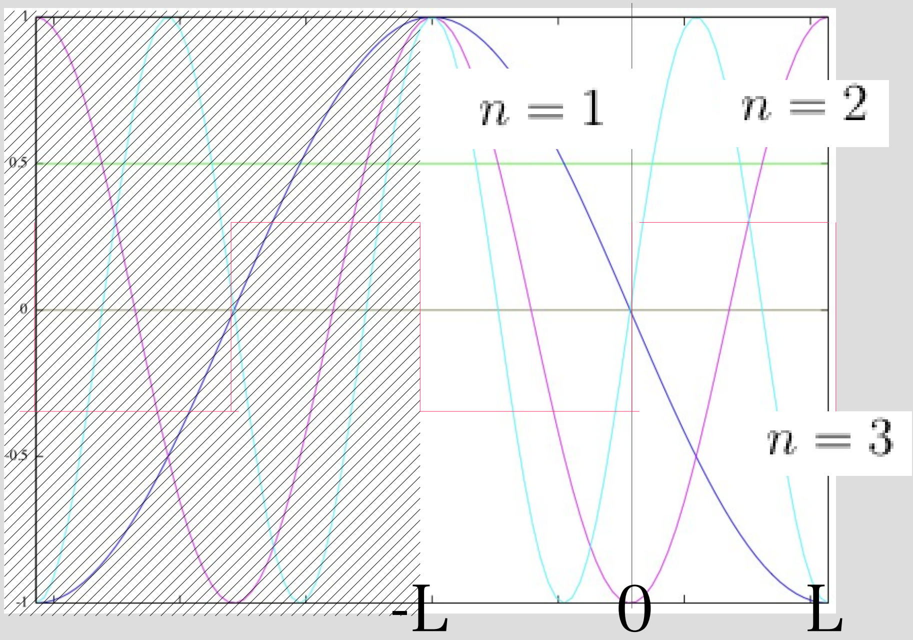
$$m(\bar{\Psi}_L^{(0)}\Psi_R^{(1)} + \bar{\Psi}_R^{(1)}\Psi_L^{(0)})$$

Split-UED model

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

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

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



After y-integration, terms like

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

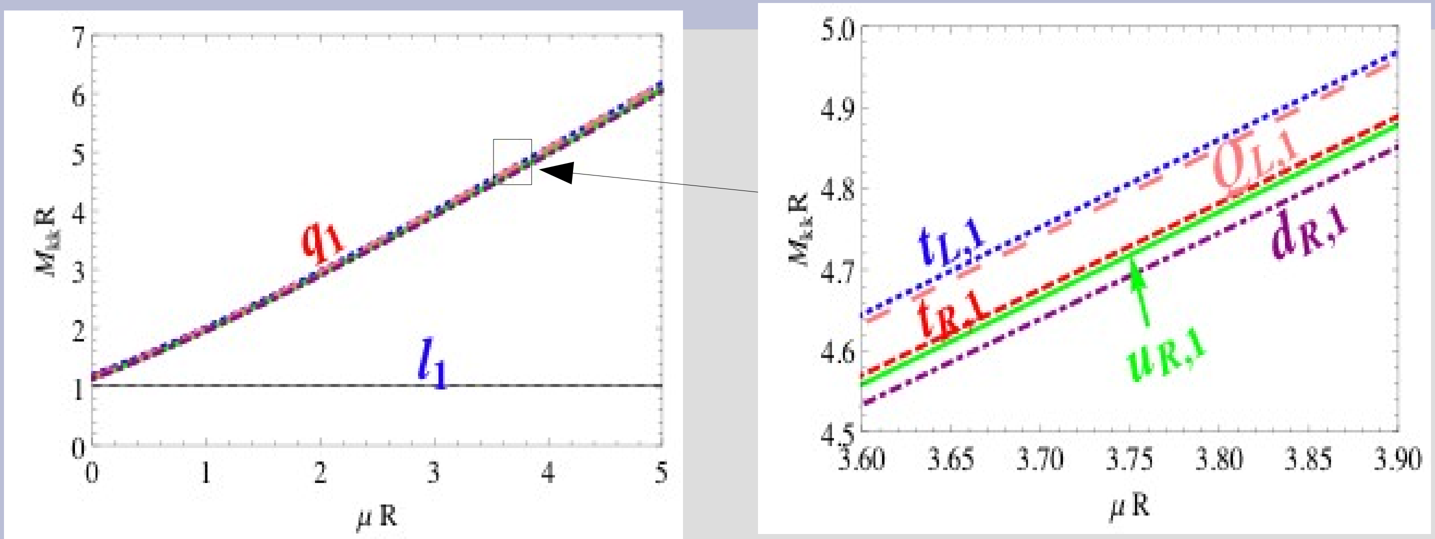
These terms give mixing among

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

KK parity conserving

Spectrum

Split-UED

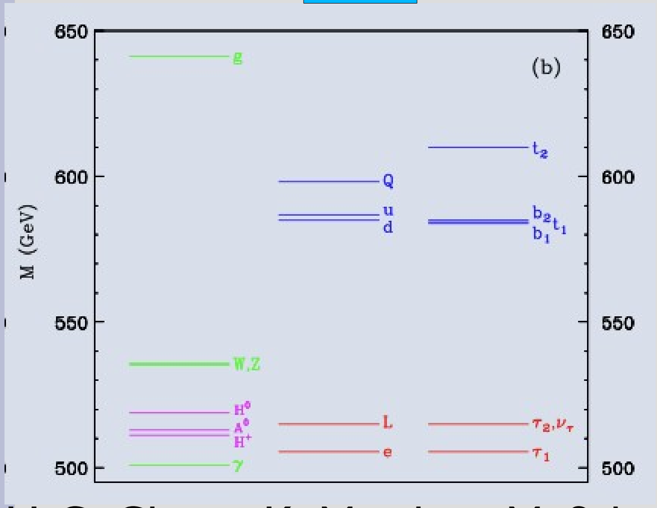


$$m_{q_n}^{\text{tree}} = \sqrt{\mu^2 + k_n^2},$$

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

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

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



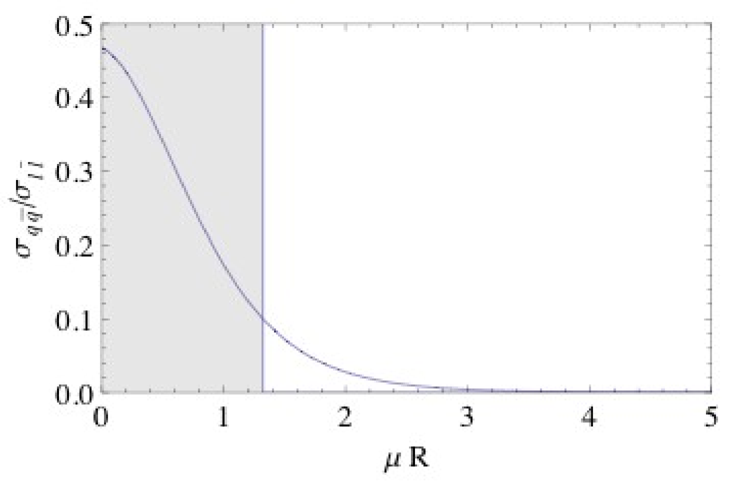
H-C. Cheng, K. Matchev, M. Schmaltz

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

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

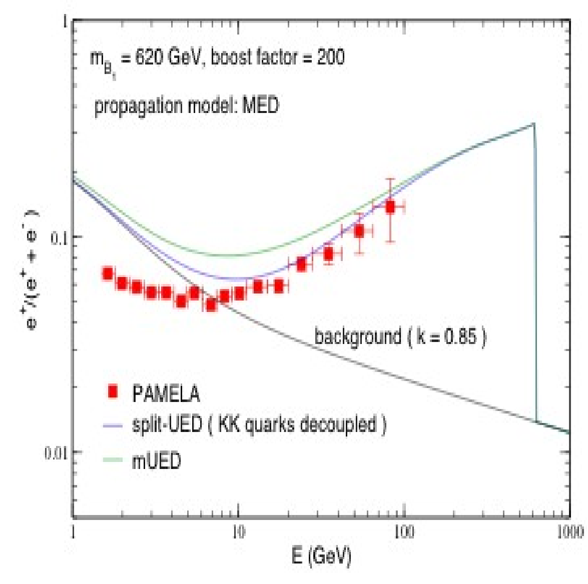
Fit data

With split-UED, we can reproduce data

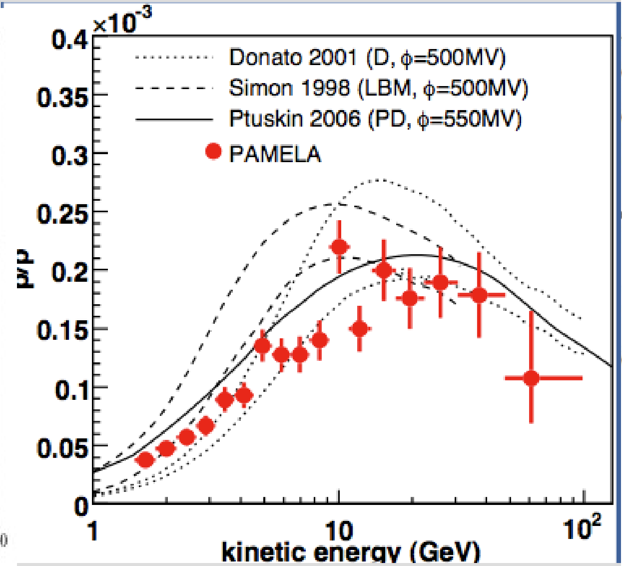


$$\mu \gtrsim \frac{1}{R}$$ for p mode suppression

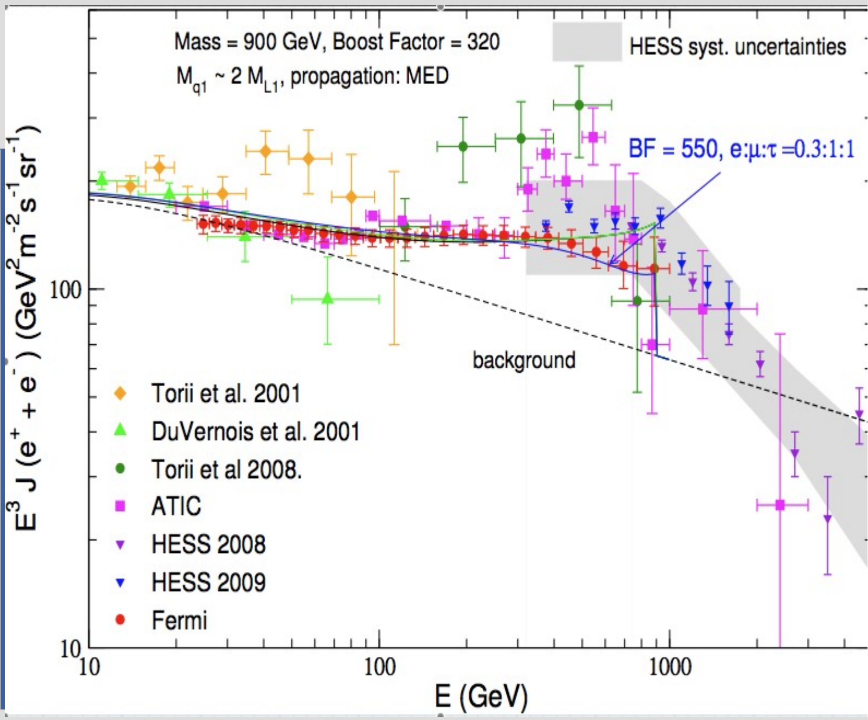
e+/(e- + e+) flux



anti-p / p flux



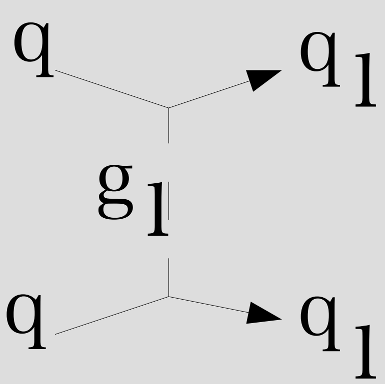
e+ & e- flux



Collider signatures

q_1 q_1 signal

- Large production cross section



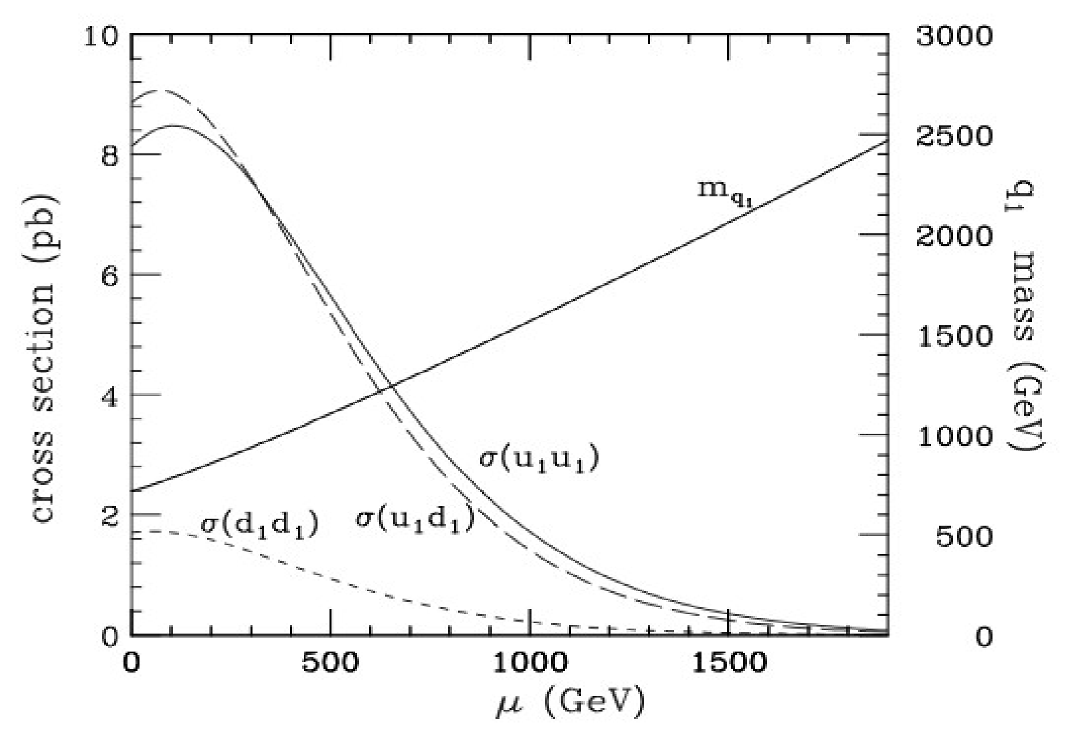
Fermionic quark partner

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

Unlike SUSY (scalar)

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

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



No p-wave suppression

Threshold behavior $\sim \beta^3$ → β

→ $10 \sim 100$ times larger for the same masses

$q_1 q_1$ 7.64 pb

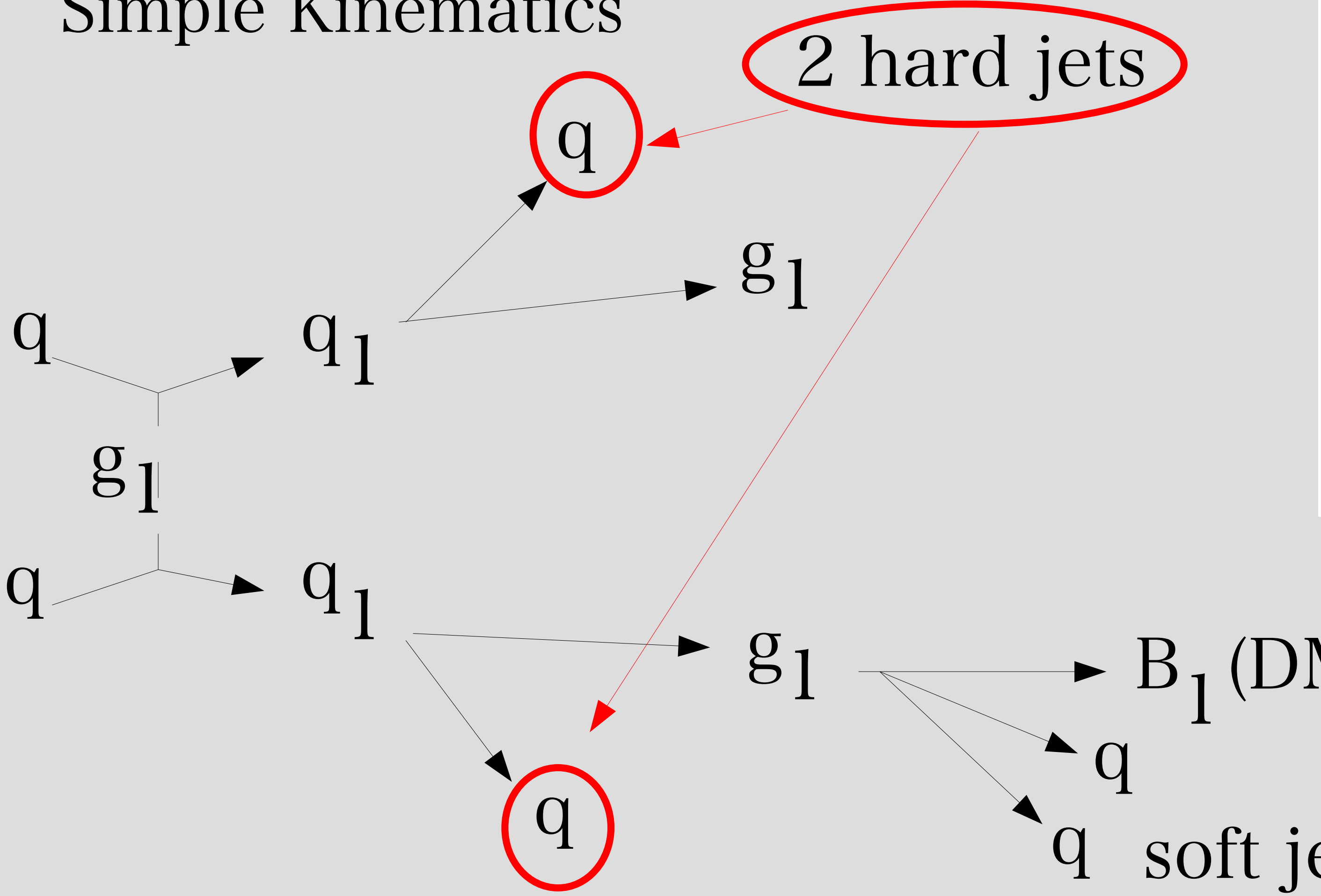
$\tilde{q}\tilde{q}$ 125 fb

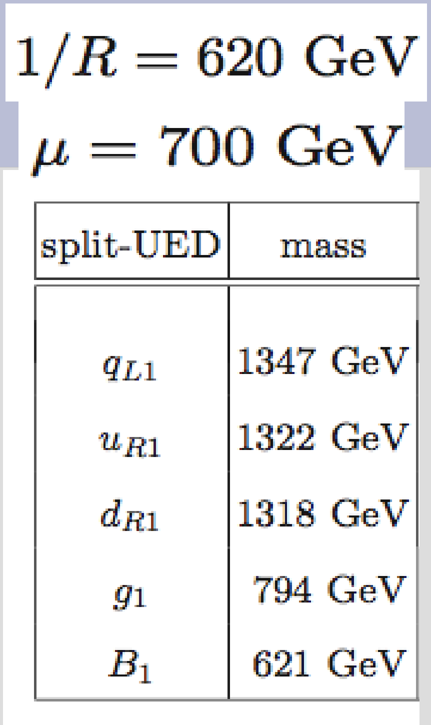
60 times larger

q_1 q_1 signal

- Large mass splitting

Simple Kinematics




$1/R = 620$ GeV

$\mu = 700$ GeV

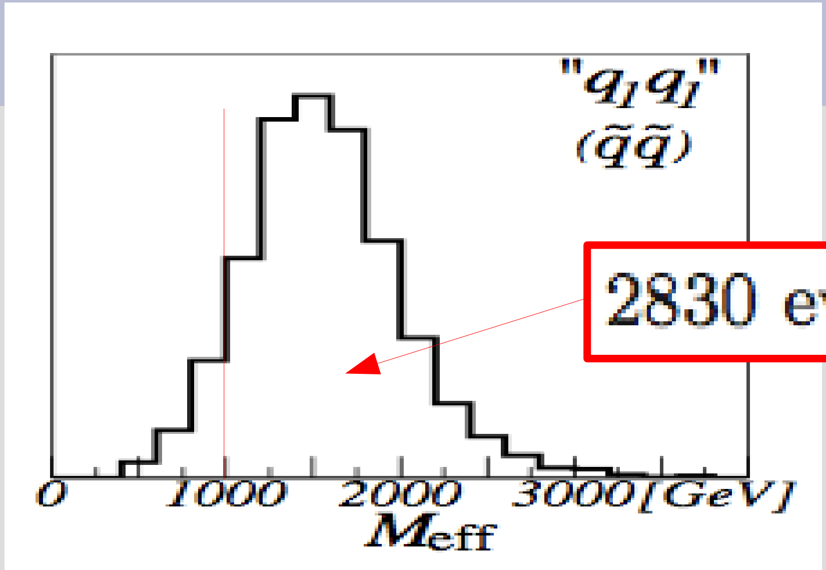
split-UED	mass
q_{L1}	1347 GeV
u_{R1}	1322 GeV
d_{R1}	1318 GeV
g_1	794 GeV
B_1	621 GeV

Signal is Two hard jets + missing momentum.

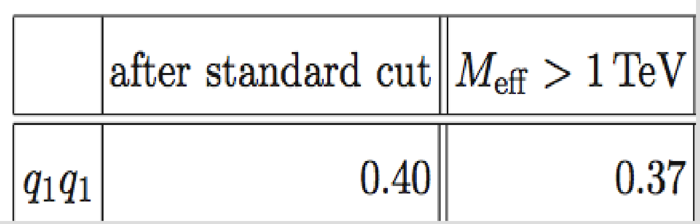
Meff distribution and SMBG

For $1\mathrm{fb}^{-1}$

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



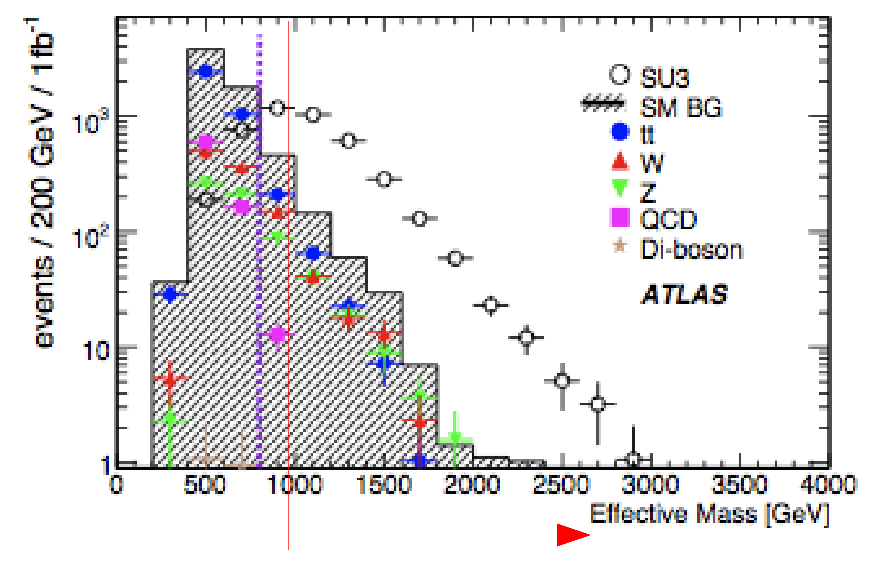
2830 events



	after standard cut	$M_{\mathrm{eff}} > 1\,\mathrm{TeV}$
q_1q_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

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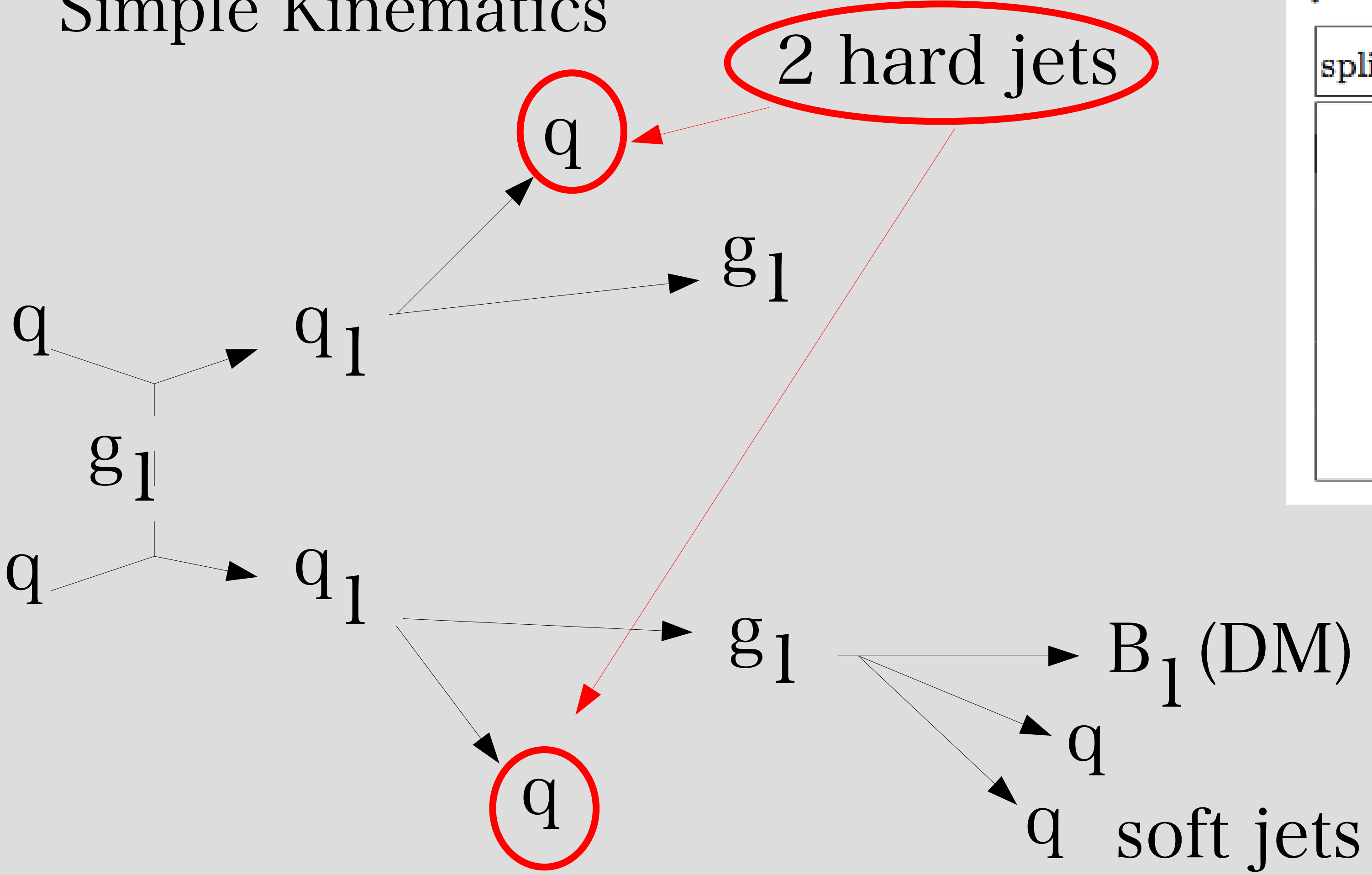


The same Kinematics as $\tilde{q}_R\ \tilde{q}_R$ pair production → M_{T2}

M_{T2}

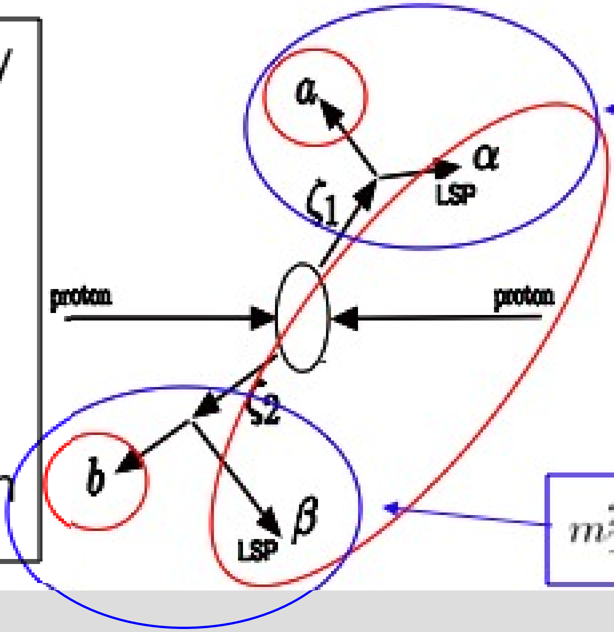
A. Barr, C. Lester, P. Stephens

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



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

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

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

Defined with two momenta and Missing transverse momentum

The endpoint gives mother particle mass

M_{T2}

A. Barr, C. Lester, P. Stephens

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

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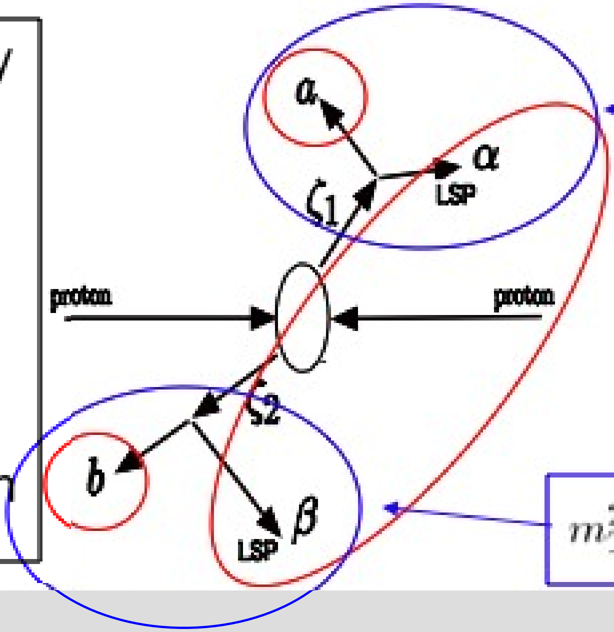

$$m_T^2(\mathbf{p}_T^a, \not{p}_T^{\alpha}; m_{\tilde\chi_1^0}) \le m_\zeta^2.$$

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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

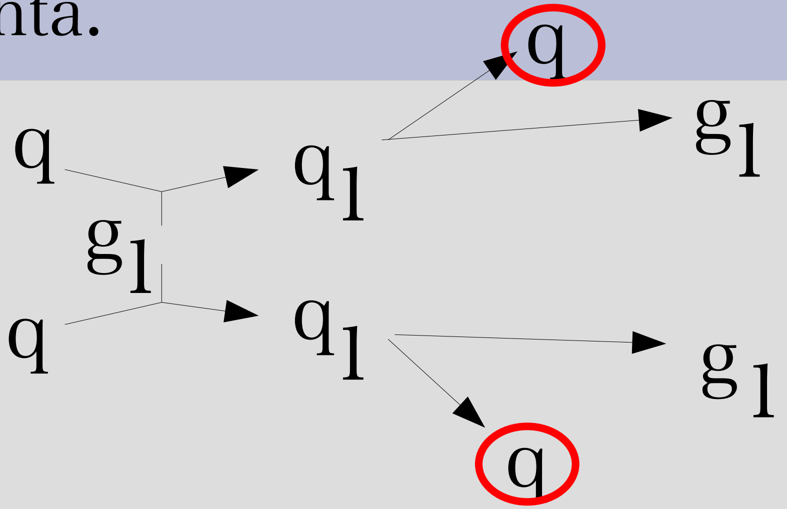
$$M_{T2}^{\rm end} = m_A - \frac{m_X^2}{m_A},$$

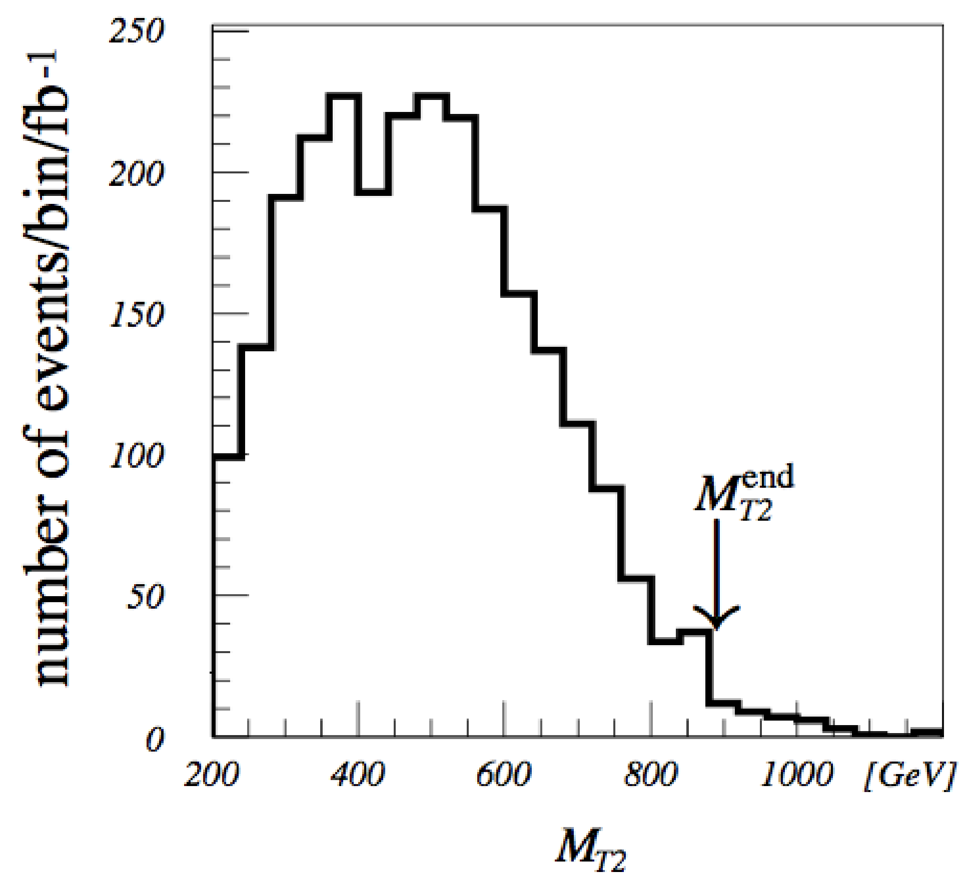
(No ISR limit)

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

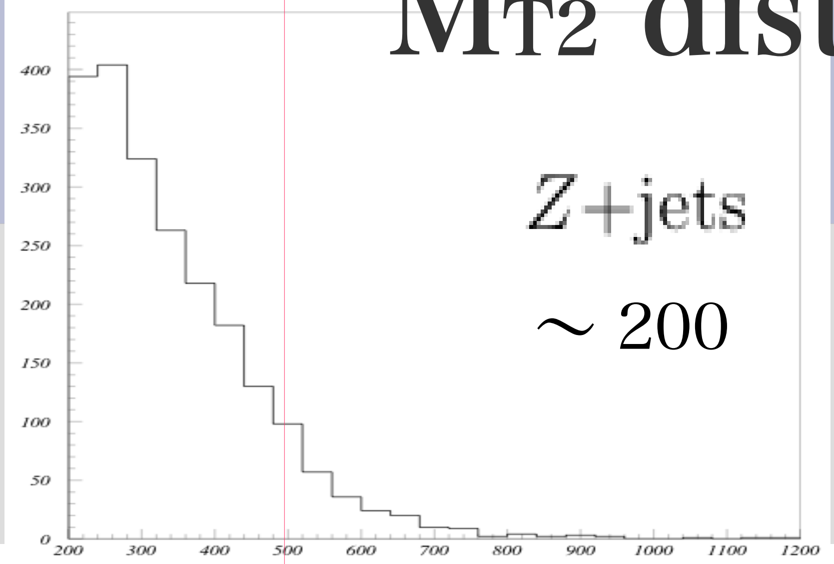
$$m_{q_1} - \frac{m_{g_1}^2}{m_{q_1}} \simeq 880\ \text{GeV}.$$

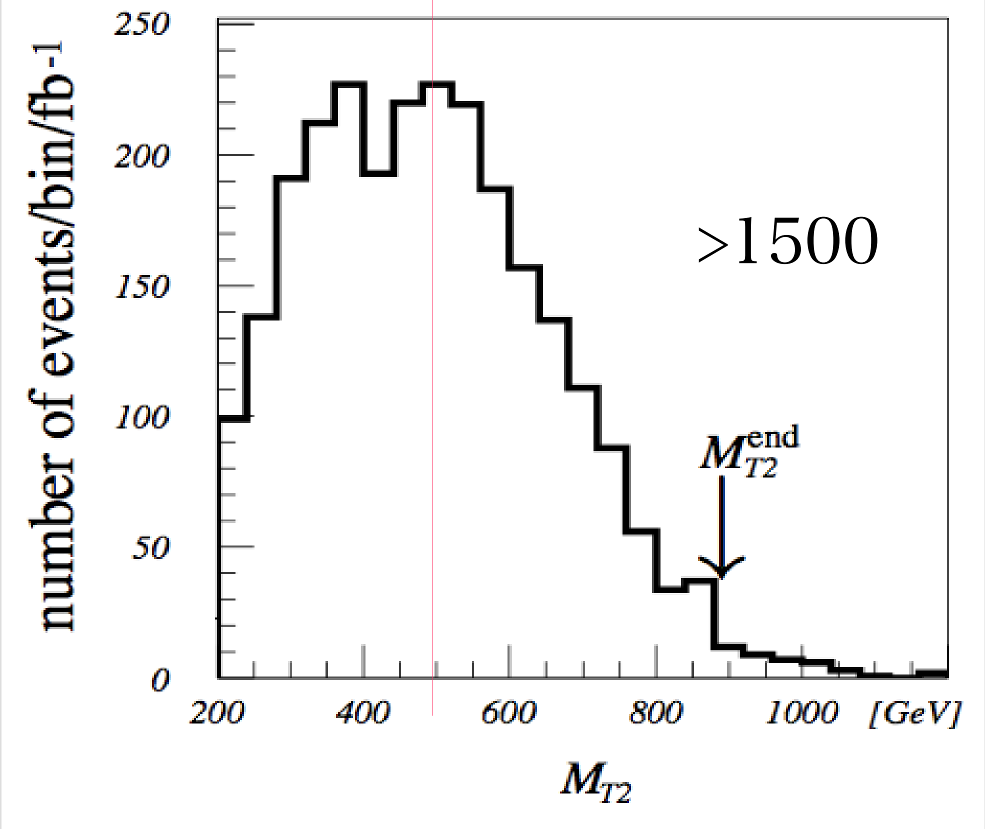
Summary

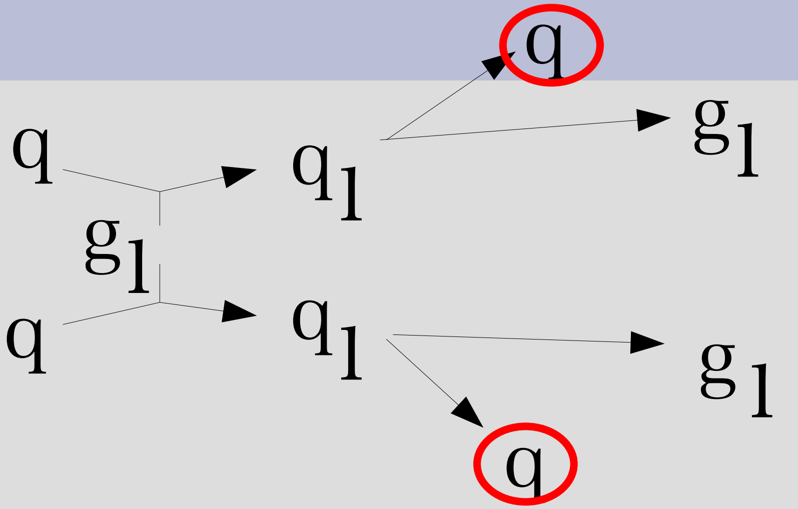
- e+ e- flux observations
  - ⇨ DM annihilation dominated by leptonic modes
  - ⇨ Split-UED with heavy quark partner

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

MT2 distribution







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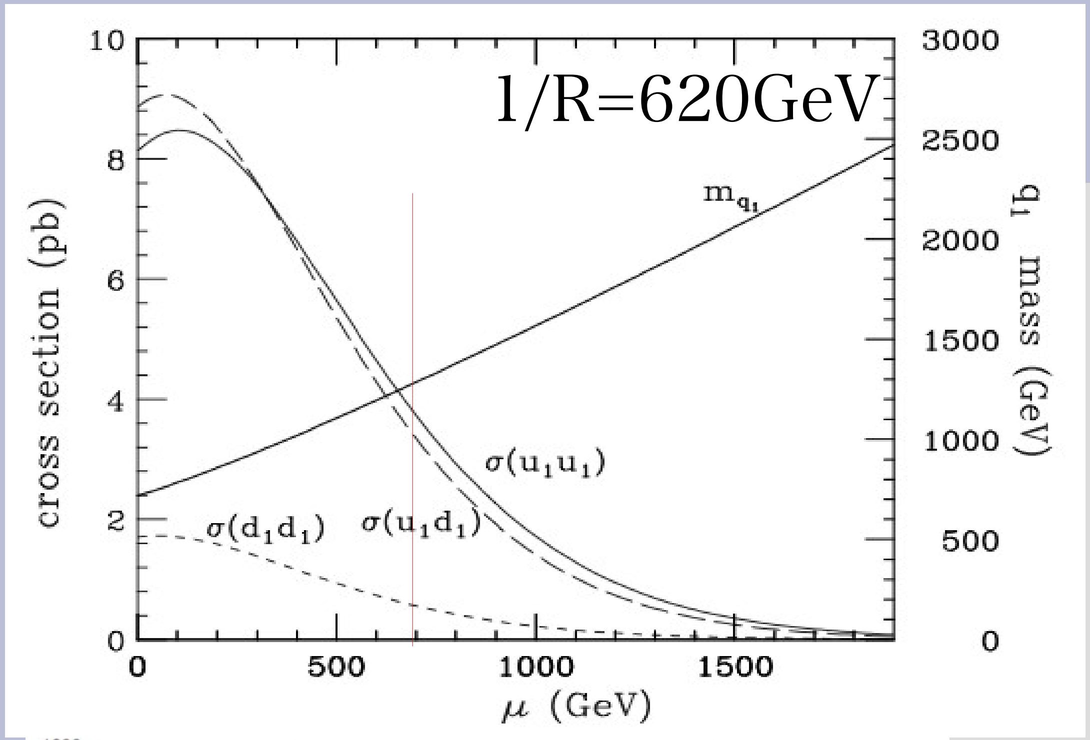
SM back ground:

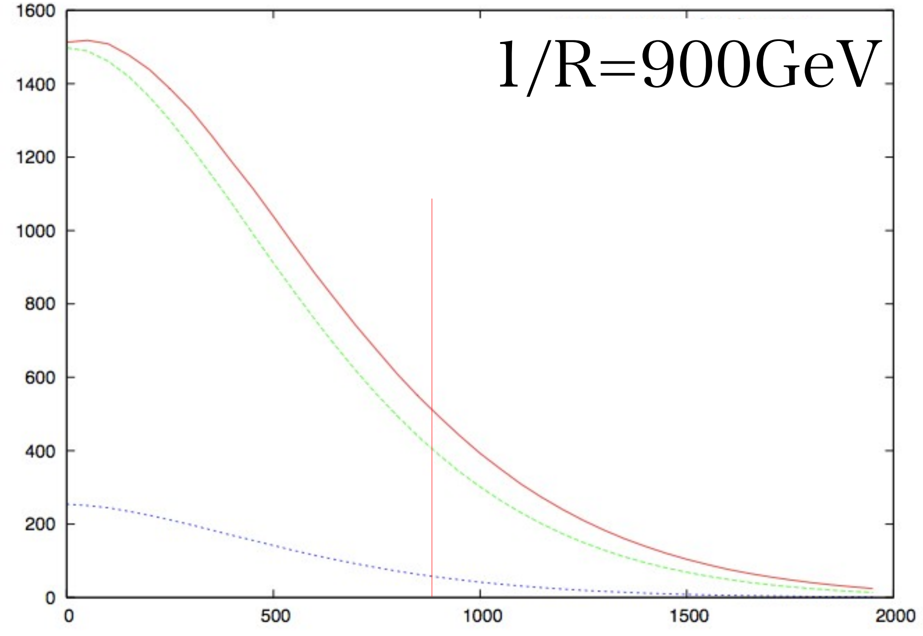
Z+jets events give smaller MT2

Effects by increasing masses



$\text{SMBG} < 300/1\ \text{fb}^{-1}$

$\text{Signal} > 1000/1\ \text{fb}^{-1}$



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

$\text{Signal} \sim 100/1\ \text{fb}^{-1}$

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.

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

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

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

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If we choose η_P=+1

→ We obtain zero mode only for R field.

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

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

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

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

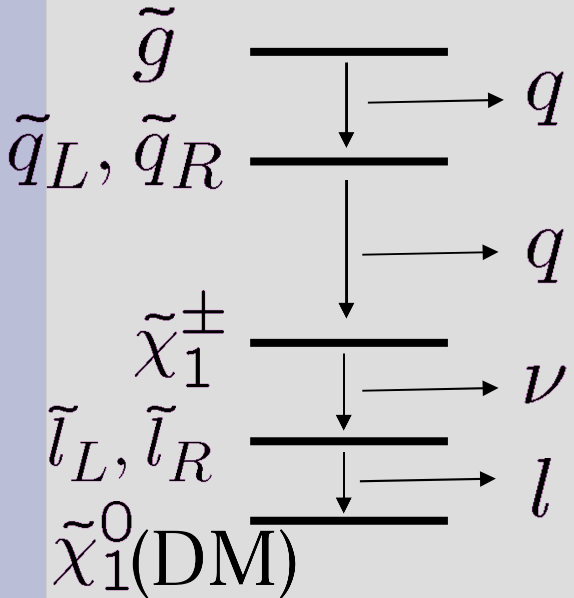
LHC: proton – proton collider ($\sqrt{s}$=14TeV)

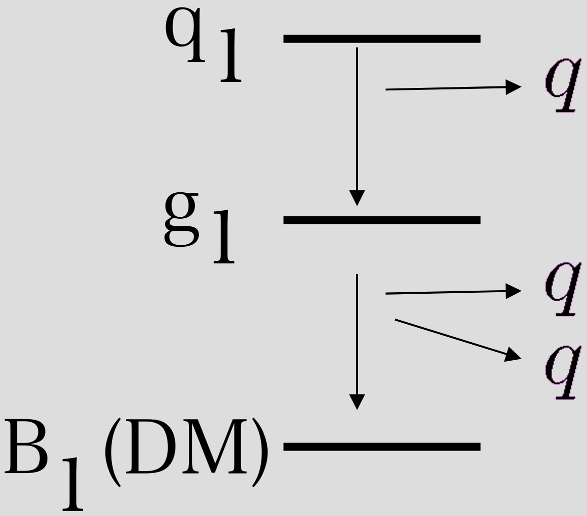
Proton: mixture of u, d, g, and sea quarks

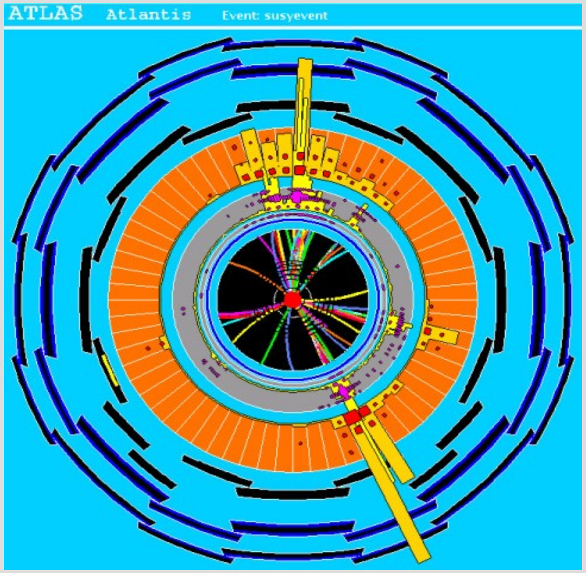
➡ Colored particles are copiously produced. (SM events also are)

Z2 parity odd particles are produced in pair.

Each decays in cascade







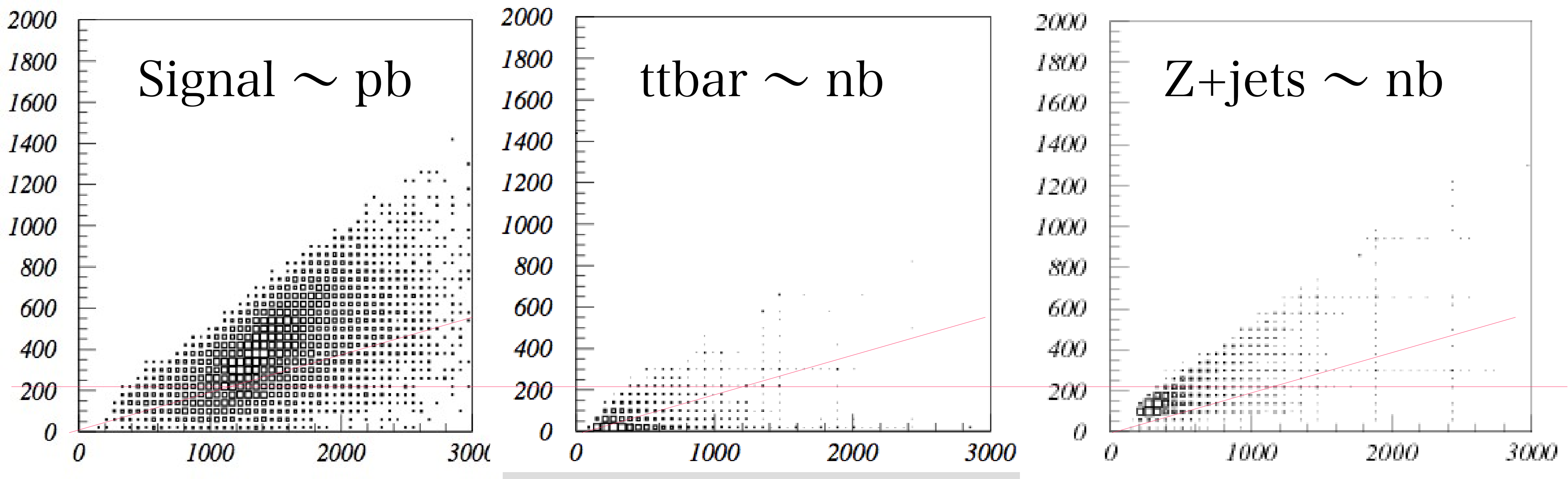
Large missing momentum $\not{E}_T \equiv |\sum_{visible} \mathrm{p}_T|$

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

SM background

Using missing momentum and effective mass,

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

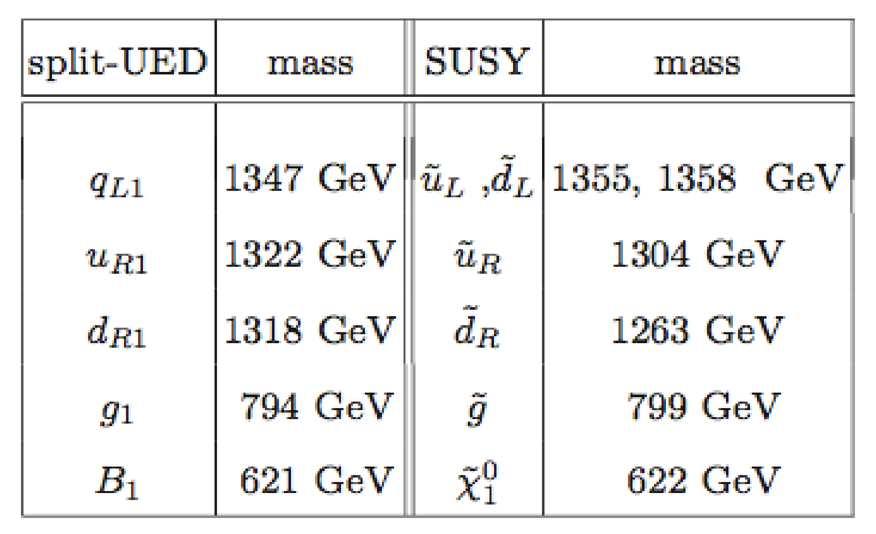


Emiss>max(200,0.2Meff) is commonly used cut to reduce SM events.

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

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

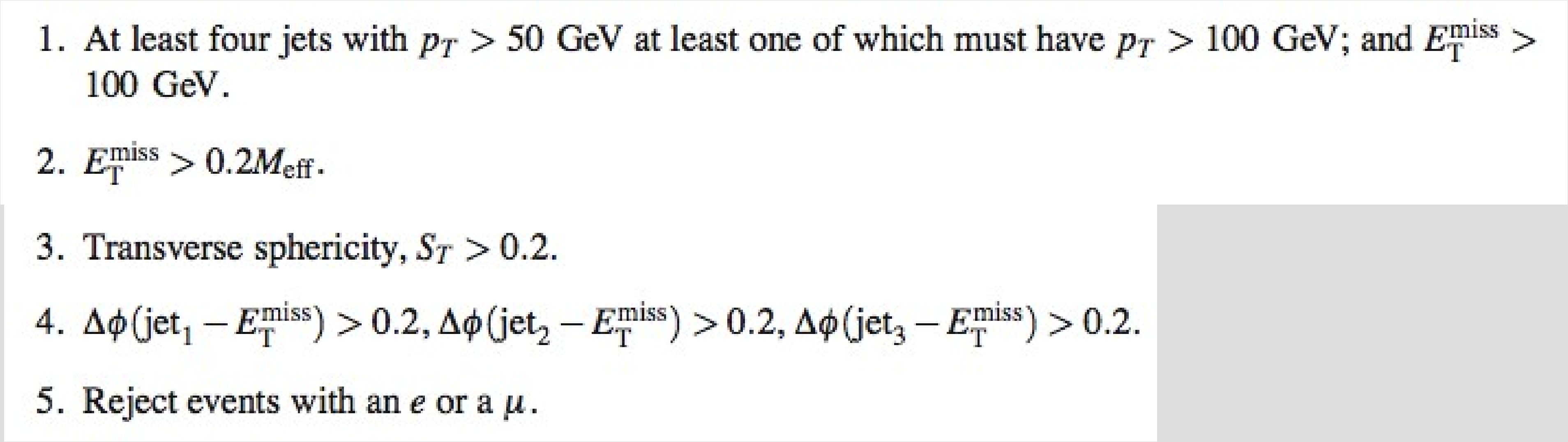
Event simulation and selection cuts



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. $E_{\mathrm{T}}^{\mathrm{miss}} > 0.2 M_{\mathrm{eff}}$.
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.