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Improved discovery of nearly degenerate model: MUED using M_{T2} at the LHC

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Based on the collaboration with H. Murayama and M. Nojiri

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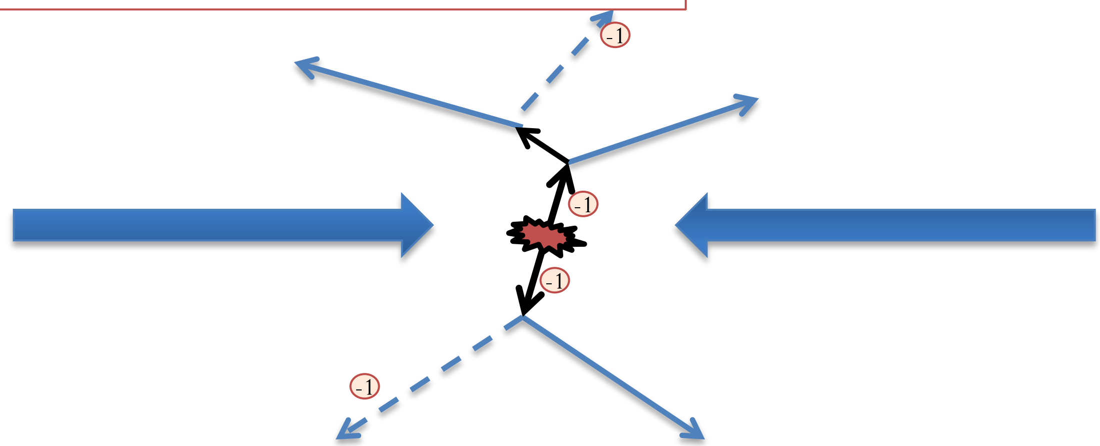
1. Introduction

LHC is searching for new physics models,
and invisible particles are expected for the dark matter.

Models with a conserved discrete symmetry e.g.) MSUGRA with R parity

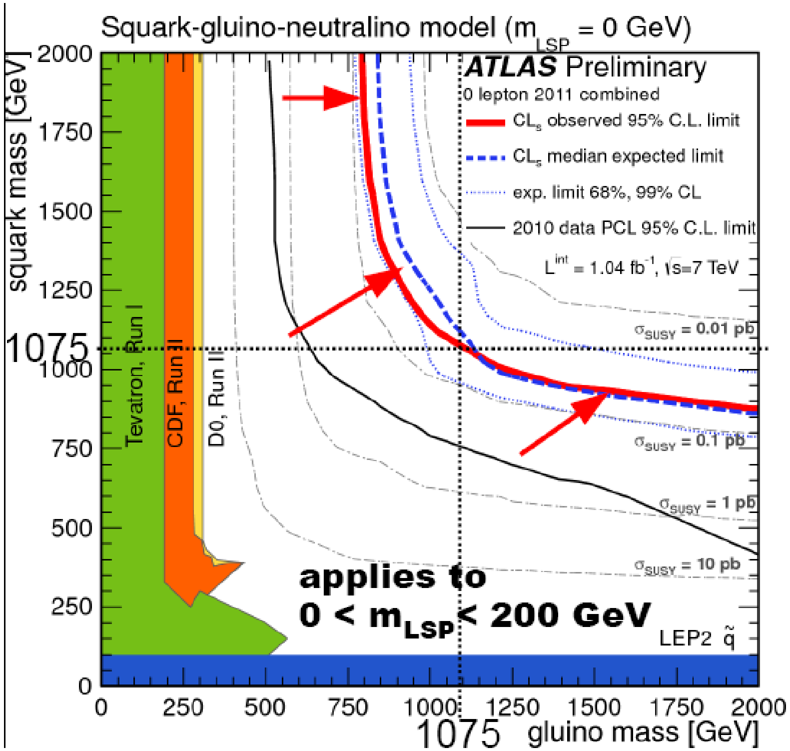
New colored particles pair-production
⇒ SM (visible) particles and invisible particles

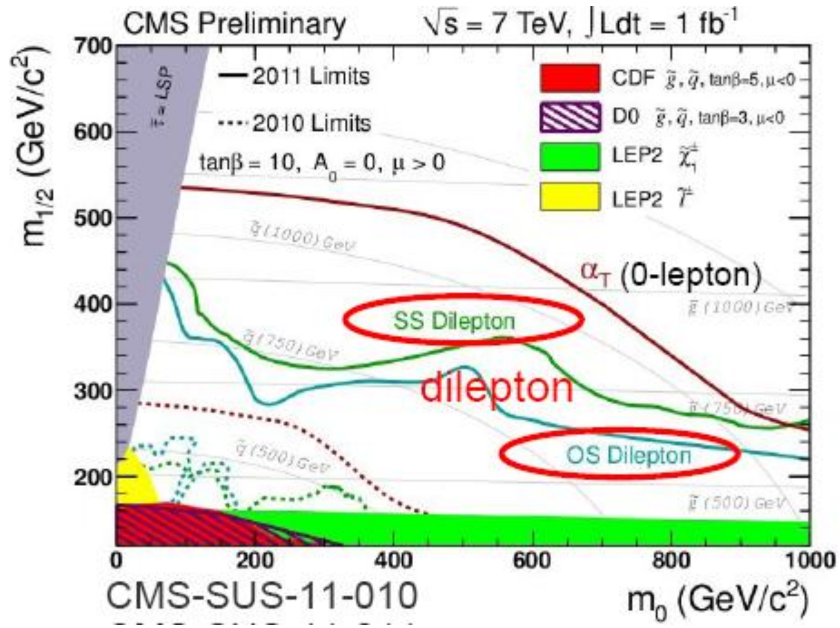


The typical signature …
Large missing energy (E_T^{miss}) & Multiple hard jets (and/or leptons)

1. Introduction

BSM Results from LHC, Lepton-Photon 2011 (22-27 August 2011)





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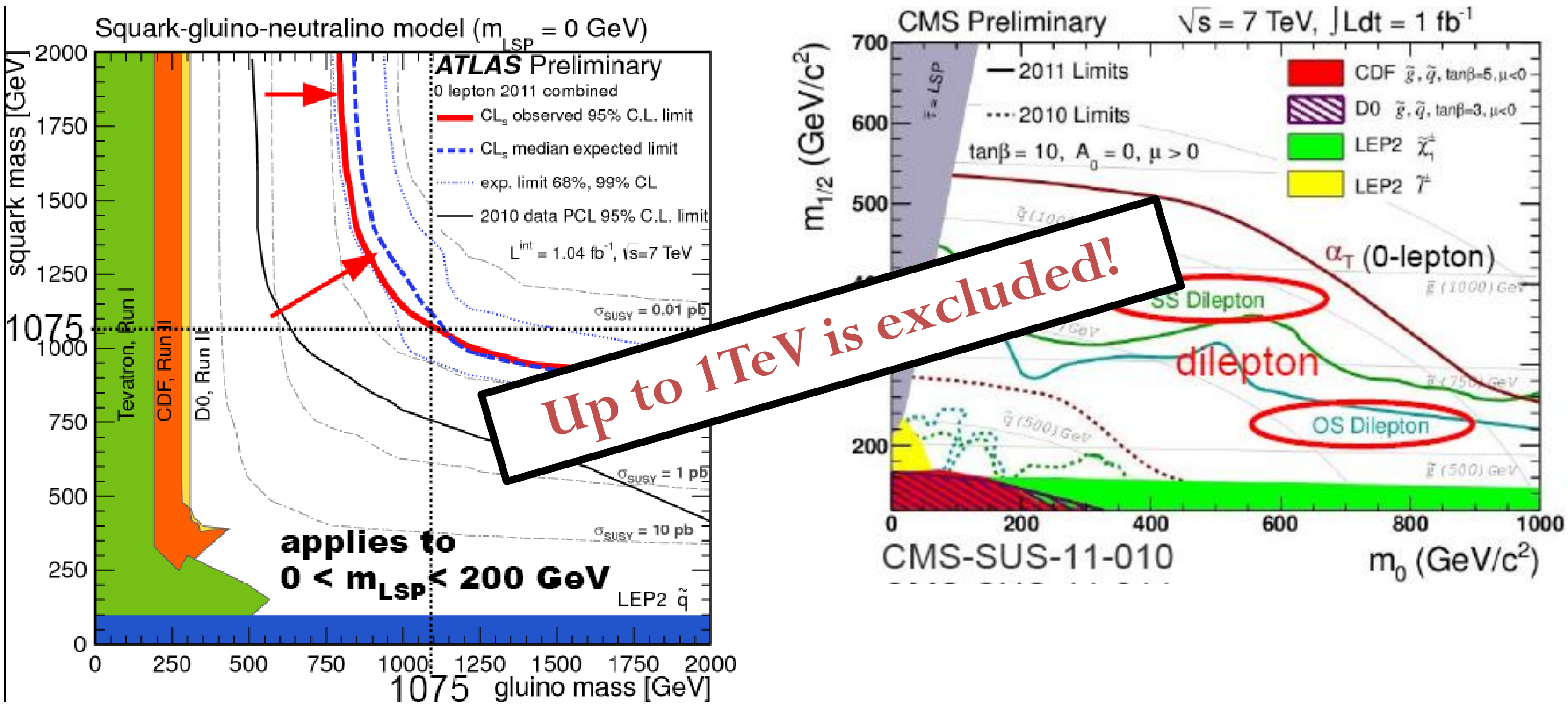


- SUSY in its most hoped for incarnation is starting to be in trouble
  - → Of course we will continue looking and increasing our reach
- What if SUSY were hiding? (e.g. no Missing E_T)
  - → “Split”, “low-MET”, “squashed”, “mashed?”
  - → Even if very soft cascade at tree level, Initial State Radiation still creates MET, but this needs to be studied further

1. Introduction

Motivation

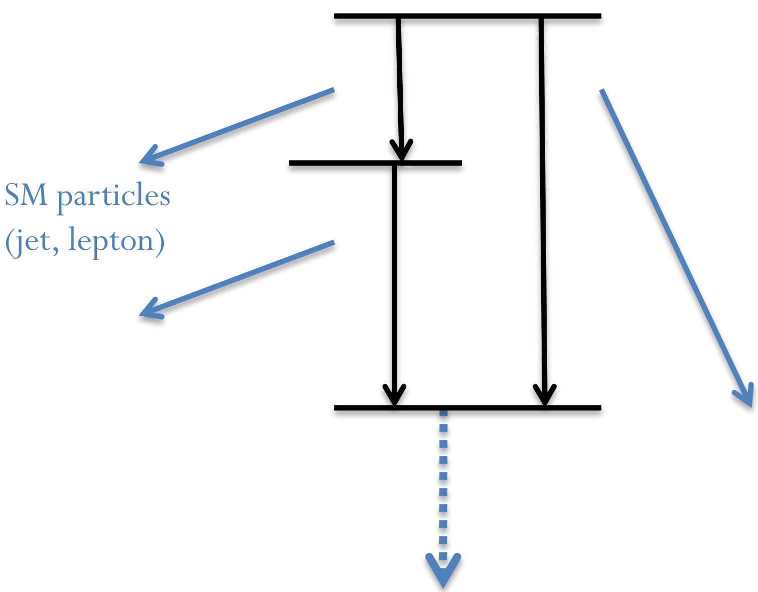
A weak point of LHC: **degeneracy**

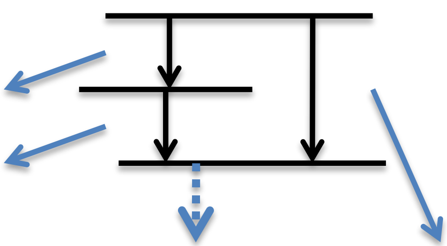
The spectrum of a new physics model is can be degenerate.

Most energy is carried away by invisible particles (but its momentum is small)

The signature of most events is…

Small missing energy (E_T^{miss}) & soft jets (and/or leptons)





In the analysis expecting multiple hard jets and missing, it is difficult to discover such a degenerate new physics model from the SM backgorund (ttbar, W/Z+jets).

1. Introduction

The previous studies for the degenerate new physics model

- Specific analysis by model

  e.g.) 4leptons + E_T^{miss} for the MUED

- Initial state radiations (ISR) + E_T^{miss} [Alwall, Le, Lisani, Wacker (2008,2009)]

  Hard ISR accompanies with heavy particle productions

  Cuts on traditional variables (E_T^{miss}, H_T) are optimized

MY POINT

The M_{T2} cut is effective in the search for the degenerate model

KEY: Invisible particle mass (test mass) is set to zero

•Correct for the SM (neutrino)→ $M_{T2}^{SM} \lesssim m_{top}$.

•Wrong for new physics model → M_{T2} can be large depending on the boost

Signal excess in the high M_{T2} region

- M_{T2} combinatric effect enhances the signal excess

1. Introduction

Minimal Universal Extra Dimension model (MUED)

is taken as an example of the degenerate model

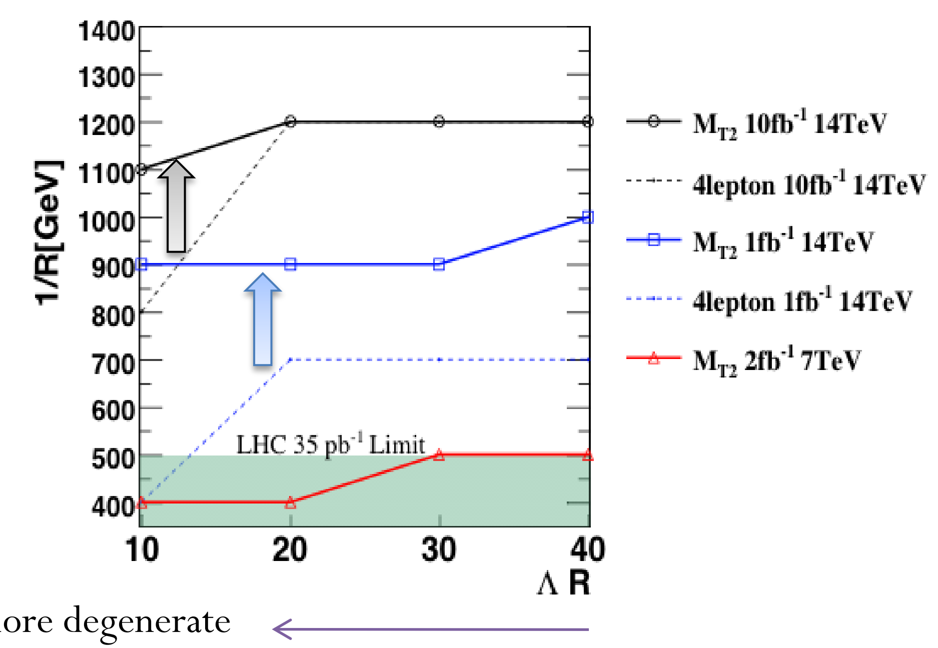
Previous study: 4leptons + E_T^{miss} … *extremely low background but low statistics*

[Cheng, Matchev, Schmaltz (2002)]

We improve the discovery potential of the MUED using the M_{T2} cut in multijet + lepton mode

The improvement is significant for the most degenerate parameter we consider

Bottom line



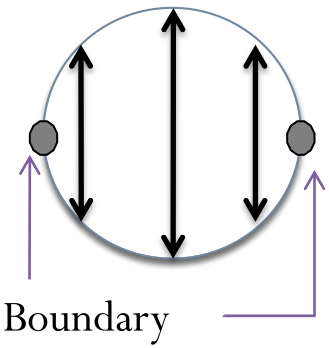
The contents of this talk

✓ 1. Introduction
2. Typical degenerate model: MUED
3. Ideas of the M_{T2} cut
4. Improvement of the MUED discovery potential
5. Summary and Future work

2. Typical degenerate model: MUED

Minimal Universal Extra Dimension model (MUED) in 5D

…gives a good DM candidate



Universal Extra Dimension (UED) [Appelquist, Cheng, Dobrescu (2001)]

- All the SM fields universally propagate in the flat extra dimension
- Orbifold compactification S^1/Z_2 to obtain the SM chiral fermions

⇓

- Fields → Kaluza-Klein modes in 4D / Zero mode corresponds to the SM particle
- The orbifolding violates the 5th dim. momentum (KK number n) conservation, but KK parity $(-1)^n$ remains unbroken
- The lightest KK odd particle (LKP), $\gamma^{(1)}$, is stable and a DM candidate

MUED

- No additional boundary terms
- 3 parameters: the 5th dim. radius R, a cutoff Λ, and the Higgs mass m_h
- MUED scale $1/R$ is about 1 TeV for the LKP relic abundance

2. Typical degenerate model: MUED

Why is the MUED degenerate?

At tree level, the nth KK mode mass is highly degenerate. ($n \geq 1$)

$$m_n = \sqrt{m_{\rm SM}^2 + \frac{n^2}{R^2}} \sim \frac{n}{R}$$

Radiative corrections relax the degeneracy

[Cheng, Matchev, Schmaltz (2002)]

$$m_n = \sqrt{m_{\rm SM}^2 + \frac{n^2}{R^2}} + \delta m_n \qquad \delta m_n \propto \frac{n}{R} \ln \Lambda R$$

δm_n is proportional to ln ΛR, but Λ cannot be very large.

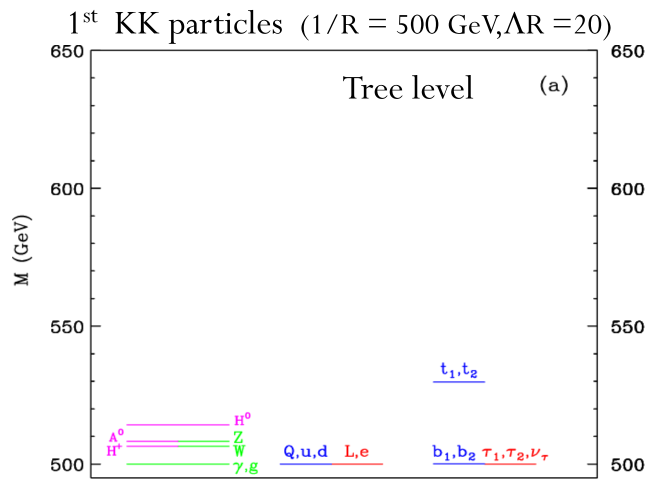
•E>1/R, many KK particles appear

the running of gauge coupling becomes power law

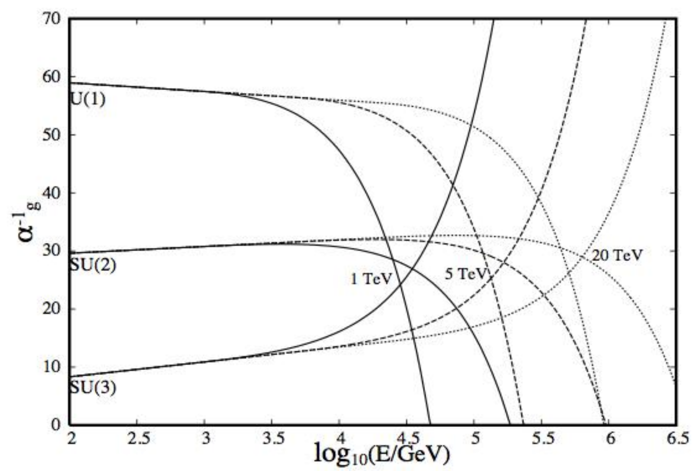
$$\beta^{SM} \to \beta^{SM} + (ER-1)\beta^{KK}, \quad 1/R < E < \Lambda$$

U(1) gauge coupling blows up immediately at $\Lambda \sim 40/R$

Appropriate cutoff scale: $\Lambda R = O(10)$



[Bhattacharyya, Datta, Majee, Raychaudhuri (2007)]



The mass spectrum is still nearly degenerate

2. Typical degenerate model: MUED

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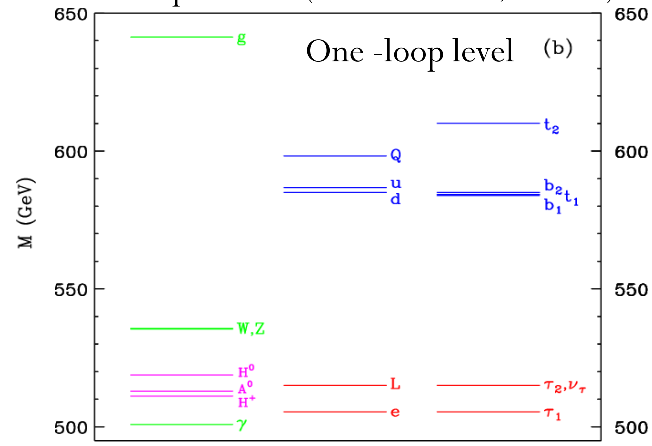
Appropriate cutoff scale: $\Lambda R = O(10)$

1st KK particles (1/R = 500 GeV, ΛR =20)



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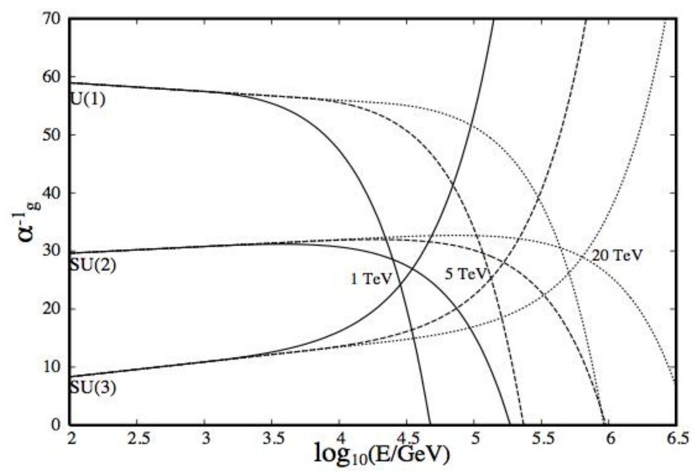


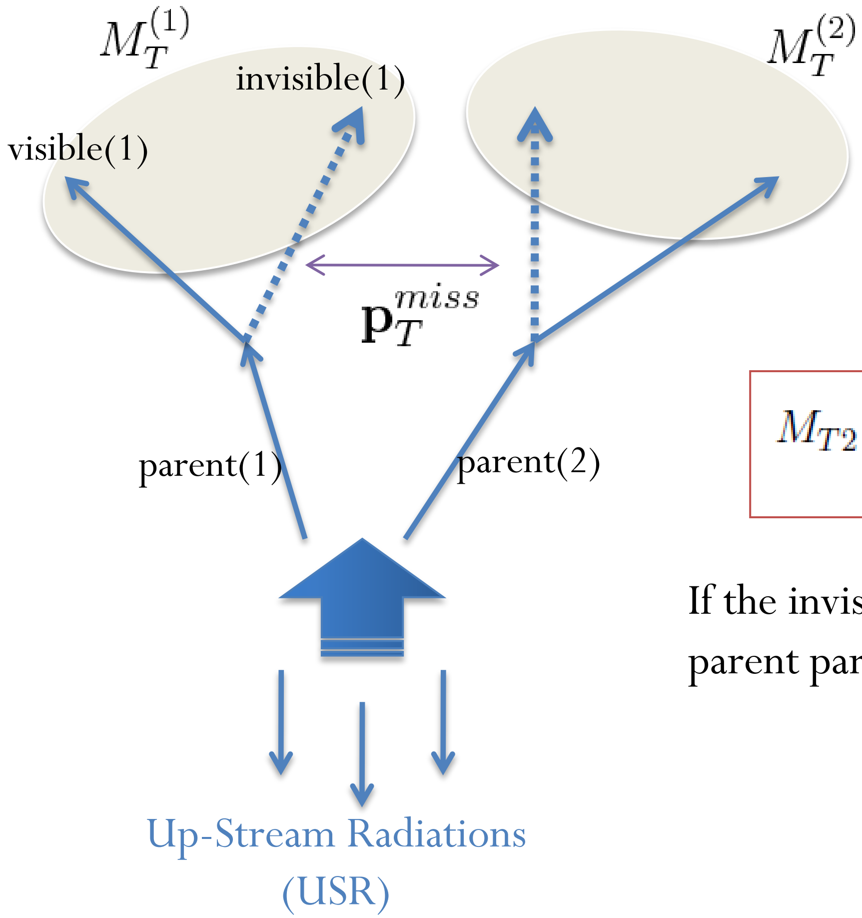
<u>The mass spectrum is still nearly degenerate</u>

3. Ideas of the M_{T2} cut

M_{T2}, an extension of transverse mass M_T [Lester, Summers (1999)]

Topology: 2 visible particles and 2 invisible particles from pair produced particles

(ttbar, new physics with discrete symmetry)



$$M_T^{(i)} = \sqrt{m_{vis(i)}^2 + m_{inv(i)}^2 + 2\left(E_T^{vis(i)} E_T^{inv(i)} - \mathbf{p}_T^{vis(i)} \cdot \mathbf{p}_T^{inv(i)}\right)}$$

$$E_T \equiv \sqrt{m^2 + |\mathbf{p}_T|^2}.$$

$$M_{T2} \equiv \min_{\mathbf{p}_T^{inv(1)} + \mathbf{p}_T^{inv(2)} = \mathbf{p}_T^{miss}} \left[\max\left\{M_T^{(1)},\ M_T^{(2)}\right\}\right]$$

If the invisible particle mass is given, MT2 is bounded by the parent particle mass

$$M_{T2} \leq m_{\text{parent}}$$ (M_{T2}^{max} = invariant mass)

3. Ideas of the M_{T2} cut

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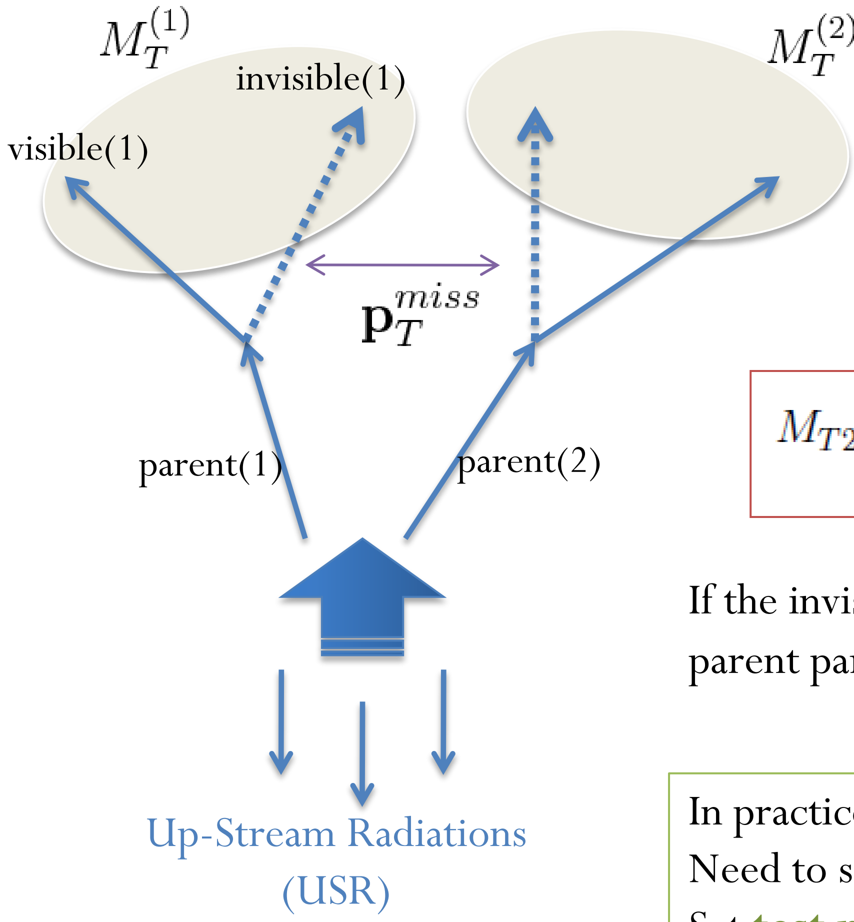

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If the invisible particle mass is given, MT2 is bounded by the parent particle mass

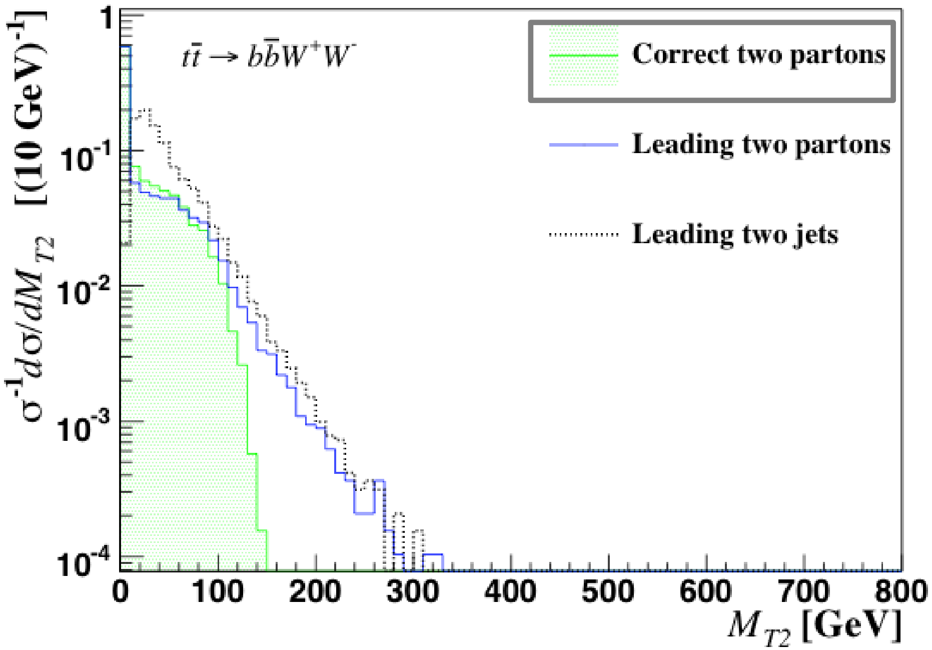
$$M_{T2} \leq m_{\text{parent}}$$ (M_{T2}^{max} = invariant mass)

In practice, invisible particles are unknown
Need to set "**test mass**" to the invisible particle mass!
Set **test mass** **(m_{inv})= 0**

3. Ideas of the M_{T2} cut

The M_{T2} cut for the SM background

the dominant background is $t\bar{t}$



$$M_{T2} \leq m_{\text{parent}} \leq m_{top}$$

Other good properties of the M_{T2} cut
[Barr, Gwenlan (2009)]
(assuming visible particle mass ~ 0)

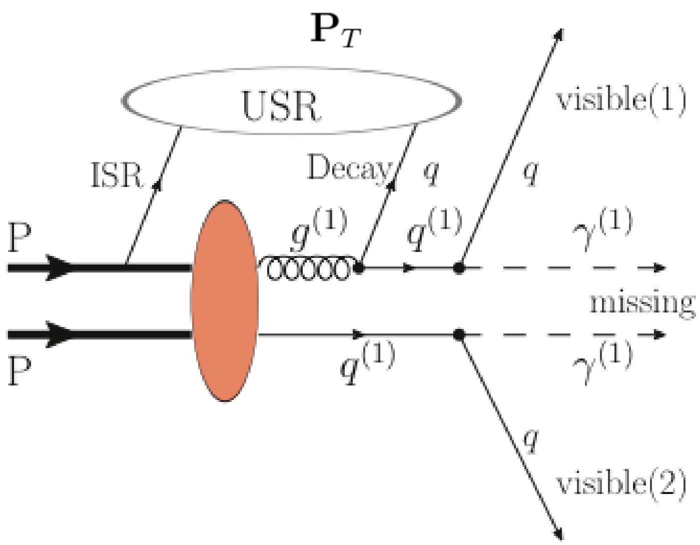
- Event without missing energy, $M_{T2} \to 0$
- Event with fake missing energy ($\mathbf{p}_T^{miss} \propto \mathbf{p}_T^{vis}$), $M_{T2} \to 0$

A significant excess in the high M_{T2} region above m_{top} should be a signature of new physics

3. Ideas of the M_{T2} cut

Up-Stream Radiations (USR)

<ISR + decay products>



USR gives the recoil momentum of the subsystem of parent particles

p_T of USR: $\mathbf{P}_T \equiv -\mathbf{p}_T^{vis(1)} - \mathbf{p}_T^{vis(2)} - \mathbf{p}_T^{miss}$

M_{T2} endpoint (M_{T2}^{max}) has different behaviors depending on whether the test mass is correct.

We set the test mass to zero and construct M_{T2} with two jets

True → Neutrinos (SM backgrounds)

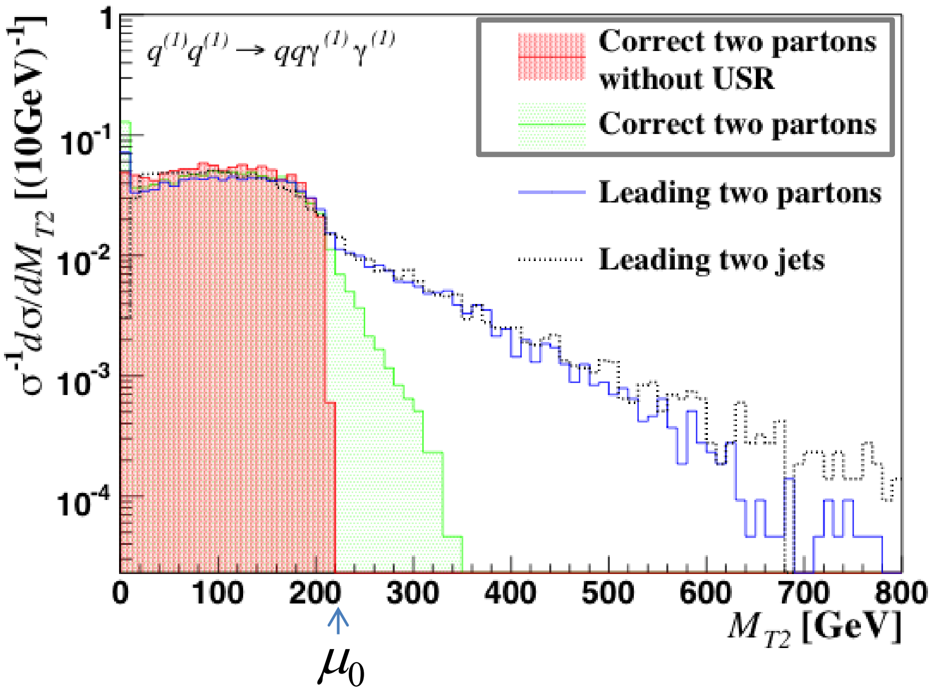
M_{T2}^{max} is independent of USR
$M_{T2} \leq m_{\text{parent}}$

False → Massive invisible particles(new physics)

M_{T2}^{max} depends on USR and is not bounded the parent particle mass anymore

3. Ideas of the M_{T2} cut

The M_{T2} cut for the new physics signal



1/R =900 GeV, ΛR=20

$q^{(1)}$: 912 GeV, $\gamma^{(1)}$: 800 GeV, μ_0: 211 GeV

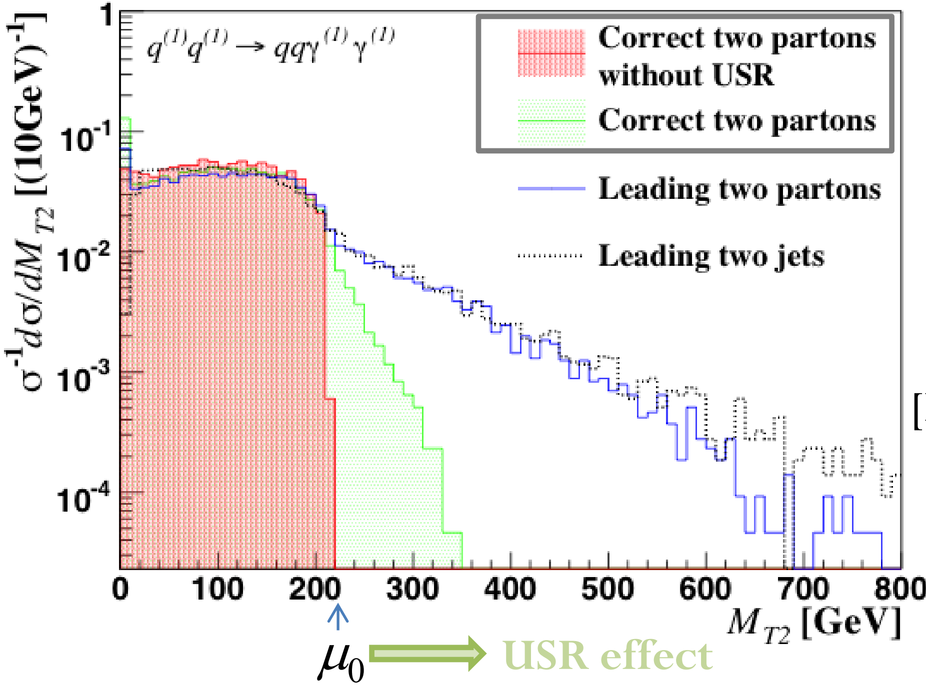
[Events without USR] M_{T2}^{max} is a mass combination,

$$M_{T2}^{max} = \frac{m_{parent}^2 - m_{inv}^2}{m_{parent}} \equiv \mu_0$$

It is difficult to discover the signal excess for the degenerate spectrum (e.g. $\mu_0 < m_{top}$)

3. Ideas of the M_{T2} cut

The M_{T2} cut for the new physics signal



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[Events with USR] M_{T2}^{max} increases as,

$$M_{T2}^{max} = \sqrt{\mu(P_T)^2 + P_T\mu(P_T)} \geq \mu_0$$

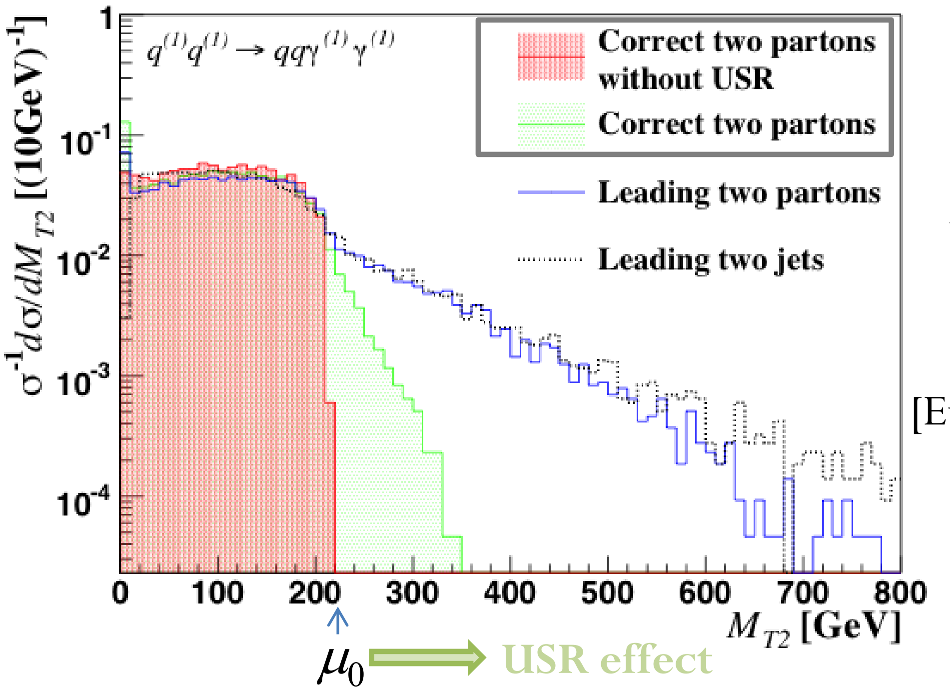
where P_T is a magnitude of USR's p_T

$$\mu(P_T) \equiv \mu_0 \left(\sqrt{1+\left(\frac{P_T}{2m_{parent}}\right)^2} - \frac{P_T}{2m_{parent}}\right)$$

$$\to \mu_0 \left(\frac{m_{parent}}{P_T}\right) \qquad \text{for } P_T \gg m_{parent}$$

3. Ideas of the M_{T2} cut

The M_{T2} cut for the new physics signal



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$$\to \mu_0 \left(\frac{m_{parent}}{P_T} \right) \quad \text{for } P_T \gg m_{parent}$$

The heavy particle productions often come along with hard ISR
⇒ Rich source of USR

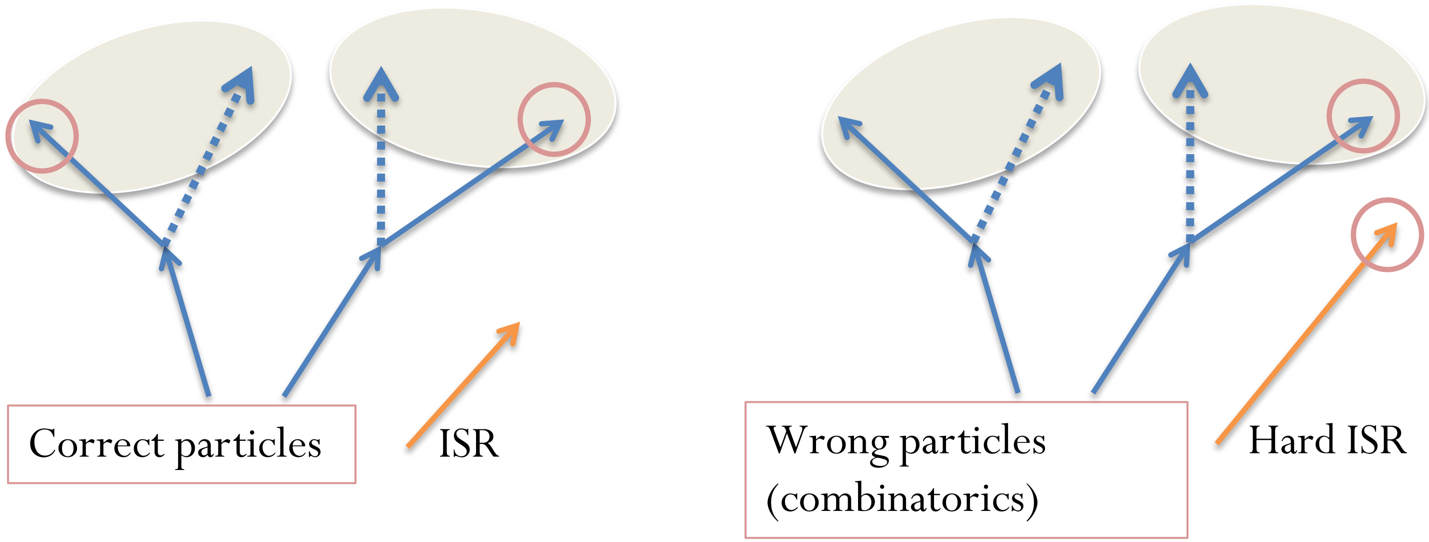
M_{T2} can be large depending on USR

3. Ideas of the M_{T2} cut

Combinatoric effect

Use leading visible particles in pT to define M_{T2}

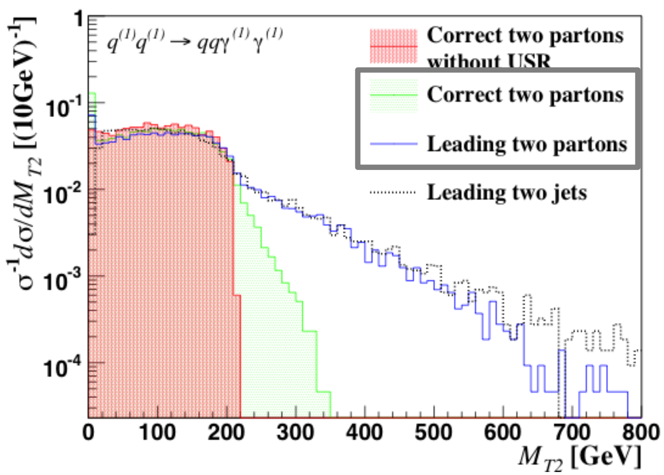
⇒leading particles do not always correspond to particles we want

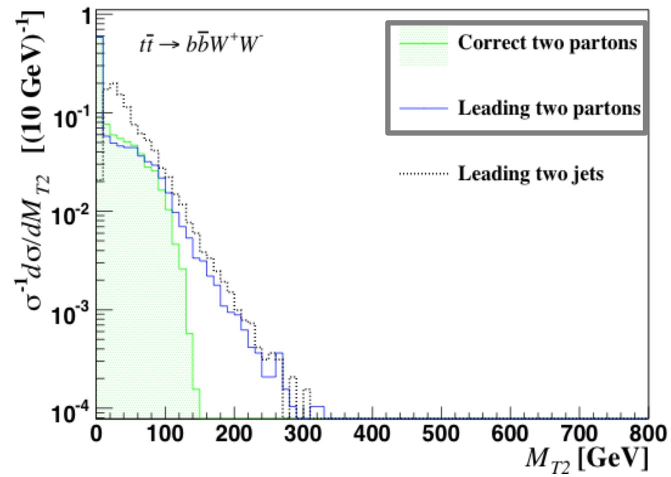


3. Ideas of the M_{T2} cut

Combinatoric effect

- Combinatorics smears the M_{T2} distribution & the smearing is significant for high M_{T2}
- The SM background in the high M_{T2} region is due to the combinatorics





- In most events, leading particles = correct particles
- The smearing effect is different in each process

Parton level	$q^{(1)}q^{(1)} \to qq\gamma^{(1)}\gamma^{(1)} + 0, 1$ jet	$t\bar{t} \to b\bar{b}W^+W^- + 0, 1$ jet
$M_{T2}^{leading} = M_{T2}^{correct}$	61.6%	49.1%
$M_{T2}^{leading} > M_{T2}^{correct}$	30.3%	22.4%
$M_{T2}^{leading} < M_{T2}^{correct}$	8.1%	28.5%

3. Ideas of the M_{T2} cut

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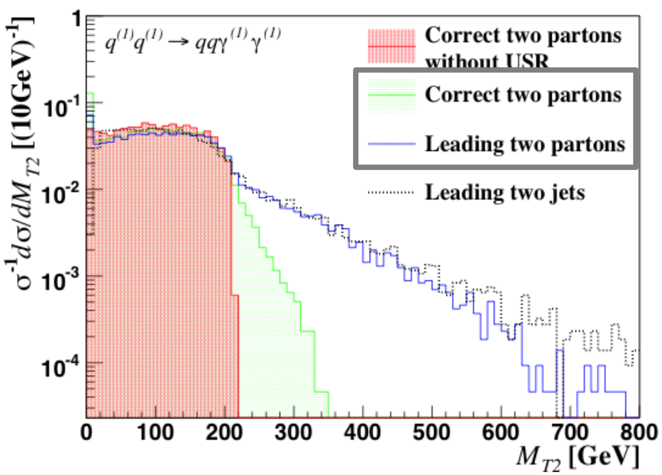

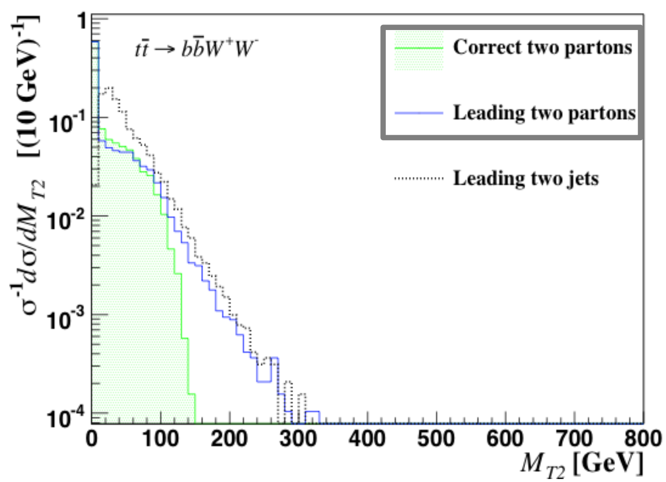

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<u>Combinatorics assists to enhance the signal to background ration for high M_{T2}</u>

4. Improvement of the MUED discovery potential

Study the discovery potential of MUED using M_{T2} in the multijet + lepton mode and compare it with the previous study, 4leptons + E_T^{miss} analysis.

Dominant production processes at LHC

- KK quark ($Q^{(1)}/q^{(1)}$)+ KK gluon ($g^{(1)}$)
- KK quark + KK quark

- $Z^{(1)}/W^{(1)}$ decay only leptonically

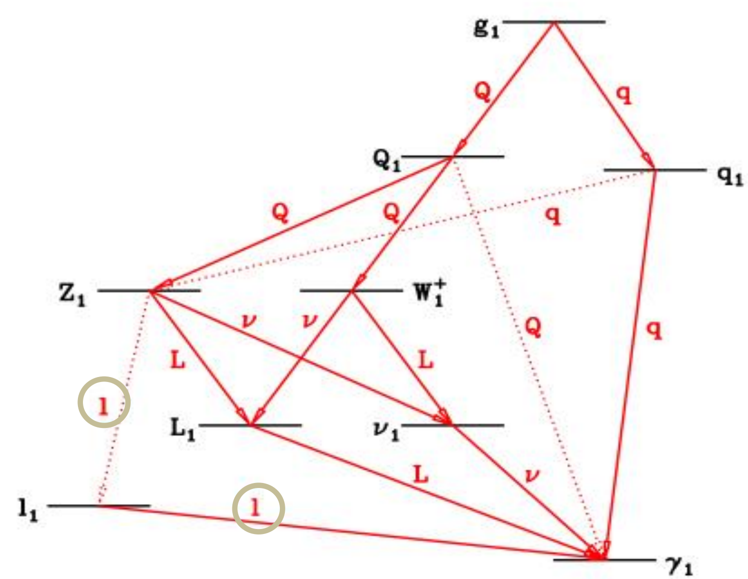
4leptons

$$Q^{(1)} \to Q + (Z^{(1)} \to l^{(1)} l \to ll\gamma^{(1)}) \quad \times 2$$

~ 1% of the total production

Multijet (≥2jet) + lepton

~ 65% of the total production



4. Improvement of the MUED discovery potential

Monte Carlo simulation

SM backgrounds: $t\bar{t}$, W/Z+jets, Diboson, W/Z+ $t\bar{t}/b\bar{b}$
+ Off-shell Z^*/γ^* processes
Generated by Madgraph/Madevent 4.4
Matrix Element corrections up to 2 jets + MLM matching
$t\bar{t}$, W/Z+jets were normalized to the NLO cross section

MUED signal: KK gluon+KK gluon, KK gluon+KK quark,
KK quark+KK quark, KK quark+KK antiquark
Generated by Pythia 6.4
No Matrix Element correction & No NLO correction
→ Conservative estimation
(For a benchmark point, Pythia and MG/ME +MLM matching were compared)

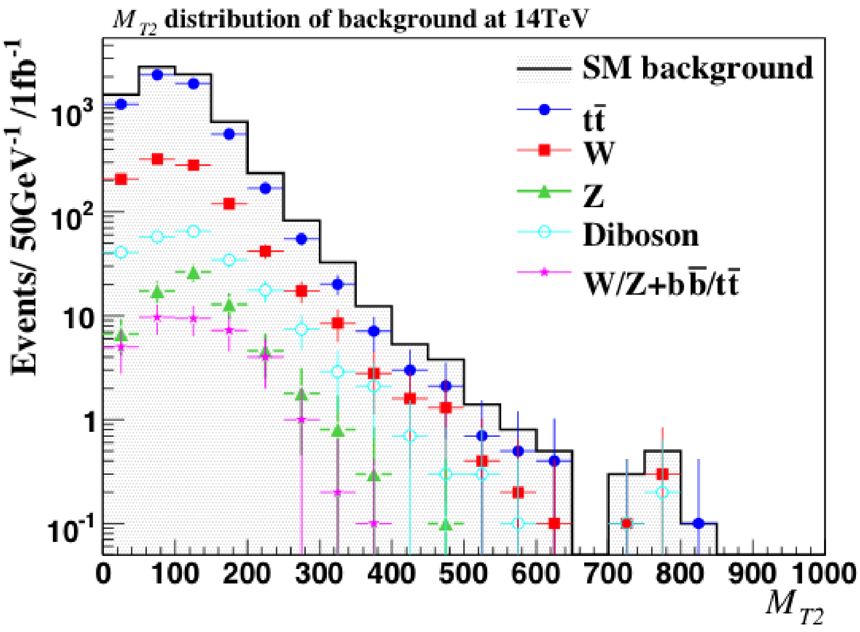
PGS 4 detector simulation
Luminosities: 2 fb^{-1} at 7 TeV & 10 fb^{-1} at 14 TeV

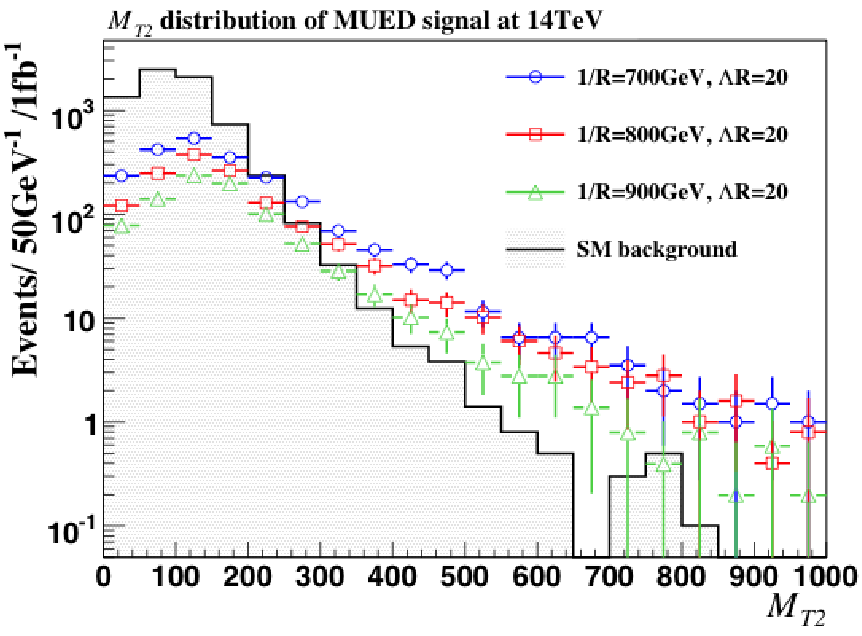
4. Improvement of the MUED discovery potential

Event selection

(lepton isolation was imposed)

- CUT1: $p_T^{jet} > \{100, 20 \text{ GeV}\}$
- CUT2: $E_T^{miss} > 100$ GeV
- CUT3: At least one lepton with $p_T^{lep} > 20$ GeV
- CUT4: If the number of lepton is one, $M_T^{lep,miss} > 100$ GeV





4. Improvement of the MUED discovery potential

Process		CUT1	CUT2	CUT3	CUT4	CUT5 (Optimal)
$g^{(1)} + g^{(1)}$	MG/ME	1,028	832	119	62	25
	PYTHIA	937	757	108	63	22
$g^{(1)} + q^{(1)}/Q^{(1)}$	MG/ME	9,196	7,218	1,234	675	241
	PYTHIA	8,569	6,694	1,344	731	223
$q^{(1)}/Q^{(1)}$ $+q^{(1)}/Q^{(1)}$	MG/ME	5,315	4,035	863	508	148
	PYTHIA	4,497	3,276	690	436	84
$q^{(1)}/Q^{(1)}$ $+\bar{q}^{(1)}/\bar{Q}^{(1)}$	MG/ME	1,444	1,075	206	115	27
	PYTHIA	1,301	955	163	112	20
Total MUED	MG/ME	16,983	13,160	2,422	1,360	441
	PYTHIA	15,304	11,682	2,305	1,342	349
$t\bar{t}$		426,074	57,533	23,239	5,620	243
W		400,527	97,907	35,386	1,031	85
Z		142,368	53,801	916	107	12
$W/Z + t\bar{t}/b\bar{b}$		1,121	304	103	49	10
Diboson		29,141	4,482	1,335	252	40
Total Standard Model		999,231	214,027	60,979	7,059	390
Total MUED Z_B	MG/ME	0.05	0.17	0.06	0.78	4.10
	PYTHIA	0.05	0.14	0.05	0.77	3.37 (7.57)

4. Improvement of the MUED discovery potential

Discovery potential

following the ATLAS MC study [hep-ex/0901.0512]

Discovery: significance $Z_B > 5$ & $Ns > 10$

(Z_B is a convolution of Poisson and Gaussian terms to account for the background systematic uncertainty. Estimation of the systematic uncertainty: ±20%)

Our MT2 analysis : find the optimal M_{T2} cut> 200 GeV to maximize Z_B

Previous 4lepton analysis

- CUT1: $p_T^{lep} > \{30, 25, 15, 10 \text{ GeV}\}$
- CUT2: $E_T^{miss} > 50$ GeV
- CUT3: $|M_{ll} - m_Z| > 10$ GeV

for all same flavor opposite sign pairs

[Cheng, Matchev, Shmaltz (2002)]

4. Improvement of the MUED discovery potential

Discovery potential

following the ATLAS MC study [hep-ex/0901.0512]

Discovery: significance $Z_B > 5$ & $Ns > 10$

(Z_B is a convolution of Poisson and Gaussian terms to account for the background systematic uncertainty. Estimation of the systematic uncertainty: ±20%)

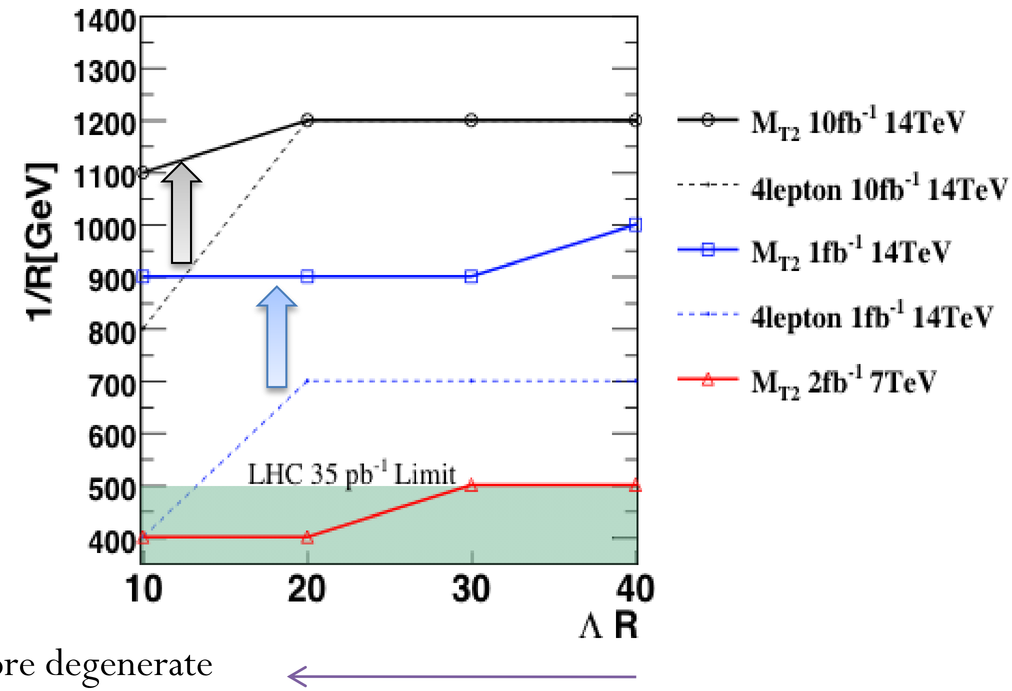
Our MT2 analysis : find the optimal M_{T2} cut> 200 GeV to maximize Z_B

Previous 4lepton analysis

- CUT1: $p_T^{lep} > \{30, 25, 15, 10 \text{ GeV}\}$
- CUT2: $E_T^{miss} > 50$ GeV
- CUT3: $|M_{ll} - m_Z| > 10$ GeV

for all same flavor opposite sign pairs

[Cheng, Matchev, Shmaltz (2002)]



More degenerate

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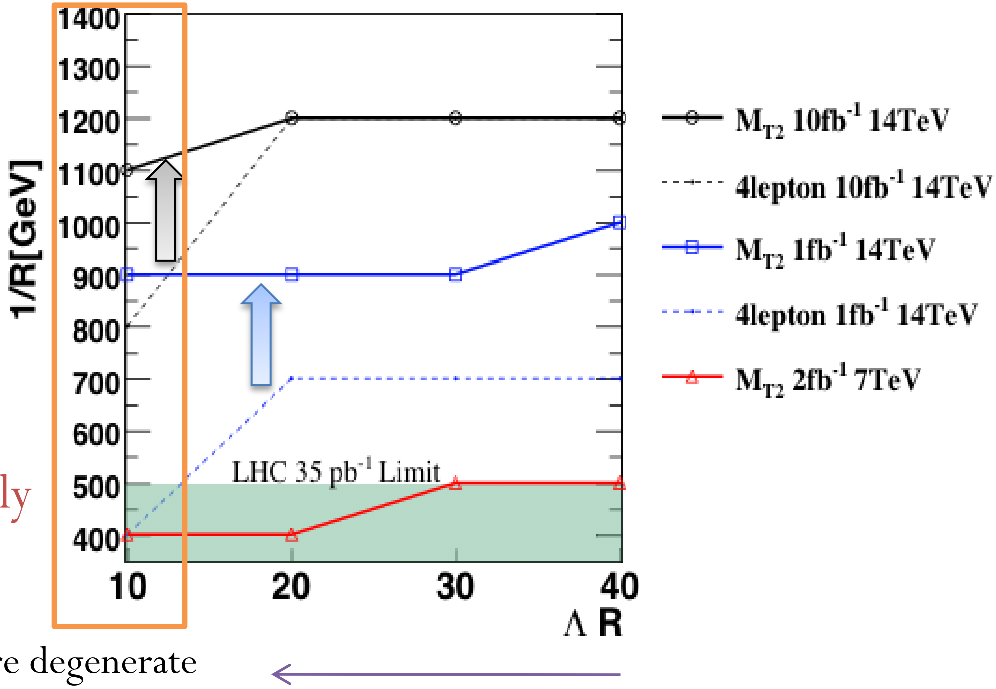


Significantly Improved!

More degenerate

5. Summary and Future work

Summary

- The test mass is correct for the SM background, $M_{T2} \leq m_{\text{parent}} \leq m_{top}$
- The wrong test mass for the signal leads the M_{T2} dependence on USR
  & heavy colored particles will have hard ISR ($\longrightarrow$ USR)

Signal excess in the high M_{T2} region

- Combinatoric effect enhances the signal excess
- MUED discovery potential is improved,
  and the improvement is significant for the most degenerate parameter

Future work

- Further improvement by other cuts or in the other channels

  e.g.) b-jet veto, or multiple jets channel
- How about the other models like SUSY?

Thank you for your attention

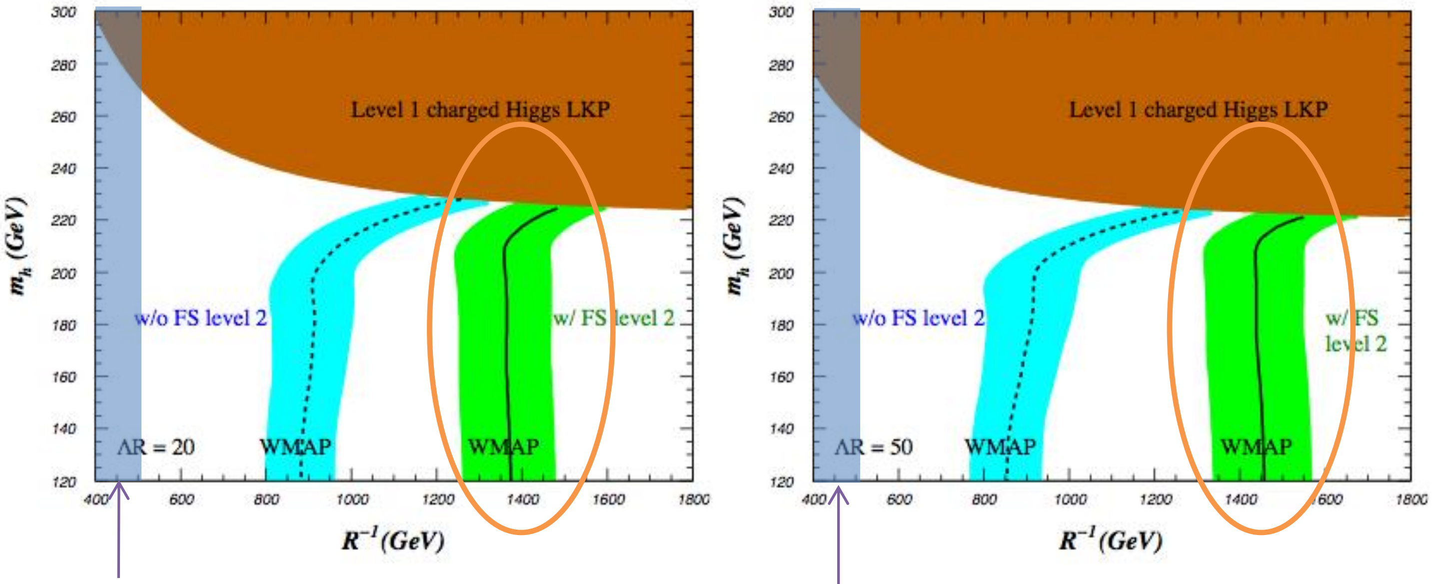
ありがとうございました

Backup slides

The LKP DM scenario   [Servant, Tait (2003) etc.]

Estimation of the LKP relic abundance

- Co-annihilation effect is important
- Second KK particles enters in the computation (at one-loop level)



Electroweak precision test & Br(b→sγ)

[Belanger, Kakizaki, Pukhov (2011)]

<u>$1/R \sim 1.5$ TeV is favored by the LKP DM scenario</u>

The search at LHC is possible but challenging due to the high mass scale & degeneracy

Backup slides

Monte Carlo simulation

Process
$t\bar{t} + 0, 1, 2$ jets
$(W \to l\nu) + 1, 2$ jets†
$(Z \to l^+l^-, \nu\bar{\nu}) + 1, 2$ jets†
$W^+W^- + 0, 1, 2$ jets
$WZ + 0, 1, 2$ jets
ZZ +0, 1, 2 jets
$Z^*/\gamma^* Z^*/\gamma^* \to 2l^+2l^-$
$Z + b\bar{b}$
$W + b\bar{b}$
$(Z/\gamma^* \to l^+l^-, \nu\bar{\nu}) + t\bar{t}$
$(W \to l\nu) + t\bar{t}$

Process		flavor
KK gluon + KK gluon	$g + g \to g^{(1)} + g^{(1)}$	
KK quark + KK gluon	$g + q \to g^{(1)} + Q^{(1)};\ g^{(1)} + q^{(1)}$	
KK quark + KK quark	$q_i + q_j \to Q_i^{(1)} + Q_j^{(1)};\ q_i^{(1)} + q_j^{(1)}$	all i, j
	$q_i + q_j \to Q_i^{(1)} + q_j^{(1)}$	all i, j
KK quark + KK antiquark	$g + g \to Q^{(1)} + \bar{Q}^{(1)};\ q^{(1)} + \bar{q}^{(1)}$	
	$q + \bar{q} \to Q^{(1)} + \bar{Q}^{(1)};\ q^{(1)} + \bar{q}^{(1)}$	
	$q_i + \bar{q}_j \to Q_i^{(1)} + \bar{q}_j^{(1)}$	$i \neq j$
	$q_i + \bar{q}_j \to Q_i^{(1)} + \bar{Q}_j^{(1)};\ q_i^{(1)} + \bar{q}_j^{(1)}$	$i \neq j$
	$q_i + \bar{q}_i \to Q_j^{(1)} + \bar{Q}_j^{(1)}$	$i \neq j$

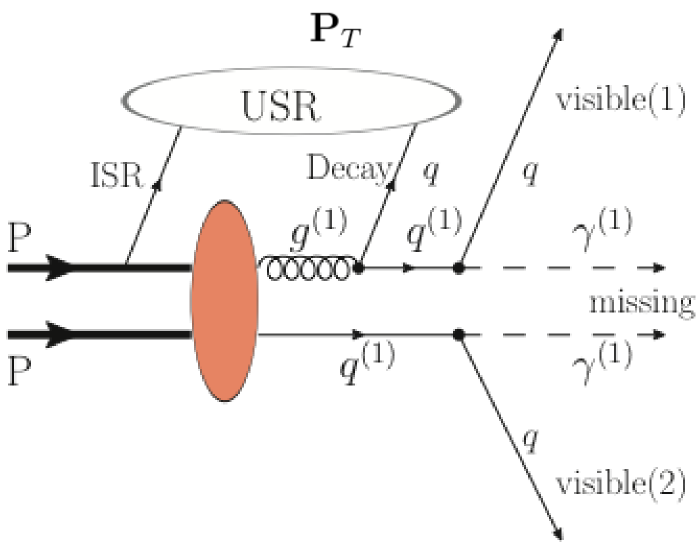
5.1 Object selection

The object selection is that an electron and a muon are required to have $p_T > 10$ GeV and $|\eta| < 2.5$ and a jet is required to have $p_T > 20$ GeV and $|\eta| < 2.5$. In order to avoid recognizing a shower from an electron as a jet, a jet within $\Delta R < 0.2$ ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$) from any electron is removed. Charged leptons from hadronic activity also should be removed. If an electron and a jet are found within $0.2 < \Delta R < 0.4$, the jet is kept and the electron is rejected Similarly, if a muon and a jet are found within $\Delta R < 0.4$, the muon is rejected.

Backup slides

Up-Stream Radiations (USR)

<ISR + decay products>



USR gives the recoil momentum of the subsystem of parent particles

p_T of USR: $\mathbf{P}_T \equiv -\mathbf{p}_T^{vis(1)} - \mathbf{p}_T^{vis(2)} - \mathbf{p}_T^{miss}$

M_{T2} endpoint (M_{T2}^{max}) has different behaviors depending on whether the test mass is correct.

We set the test mass to zero and construct M_{T2} with two jets

True → Neutrinos (SM backgrounds)

M_{T2}^{max} is independent of USR
$M_{T2} \leq m_{\text{parent}}$

False → Massive invisible particles(new physics)

M_{T2}^{max} depends on USR and is not bounded the parent particle mass anymore