Tree Level Gauge Mediation Phenomenology in the LHC era

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based on

MM, Nardecchia, Romanino, Ziegler **JHEP 1110 (2011) 022**

MM, Pierini, Romanino, Spinrath (to appear soon)

Plan of the Talk

- SUSY and SUSY breaking
  - Hints on SUSY, SUSY breaking, mediation of SUSY breaking
  - Gauge mediation: ordinary and tree level one
- Tree Level Gauge Mediation: an SO(10) model
  - Construction, field content, superpotential
  - Results: sfermion masses, gaugino masses, low energy spectrum
  - Phenomenological analysis through Razor variable
- Tree Level Gauge Mediation Extended: an E_6 model
  - Construction, field content, superpotential
  - Results: sfermion masses, gaugino masses
- Conclusions

SUSY and SUSY breaking

- Supersymmetry is one of the most attractive possibilities beyond SM
  - Stabilizes the EW scale
  - Provides candidates for Dark Matter
  - Predicts gauge coupling unification
  - Provides a scenario for radiative EWSB

- It predicts new particles with different statistic with respect to SM

These particles should have the same mass of SM ones

Partners of SM particles never observed

SUSY must be broken in the vacuum state chosen by Nature

SUSY breaking 2

- The situation is even more involved
- The correct statement on masses of the particles is in Str formula

$$Str\mathcal{M}^2 \equiv 3tr\mathcal{M}_1^2 - 2tr\mathcal{M}_{\frac{1}{2}}\mathcal{M}_{\frac{1}{2}}^\dagger + tr\mathcal{M}_0^2 = -2g\langle D^a\rangle trT^a$$

It holds in spontaneously broken SUSY theories & @ tree level for renormalizable theories

- Some of the MSSM squarks and sleptons would be unacceptably light

- Many hints that a separate sector for SUSY breaking is needed

SUSY breaking takes place

Gravity
Gauge
ED/Anomaly

MSSM fields

Gauge mediation 1

The hidden sector provides SUSY breaking.

[Giudice, Rattazzi (1998) and refs. therein]

In a minimal model a chiral superfield takes both a scalar and an F-term VEV

$$\langle X \rangle = M + \theta^2 F$$

The messenger sector is made of chiral superfields:

- Interact with observable sector through gauge interactions
- Interact with hidden sector through superpotential interactions

$$W = \lambda_{ij} \overline{\Phi}_i X \Phi_j$$

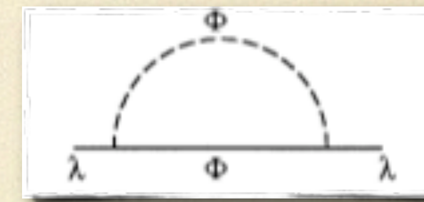
The spectrum of the messenger fields is not SUSY anymore

- fermions $\longrightarrow$ $m_\psi = \lambda M$
- scalars $\longrightarrow$ $m_\phi^2 = (\lambda M)^2 \pm \lambda F$

Gauge mediation 2

Gaugino masses

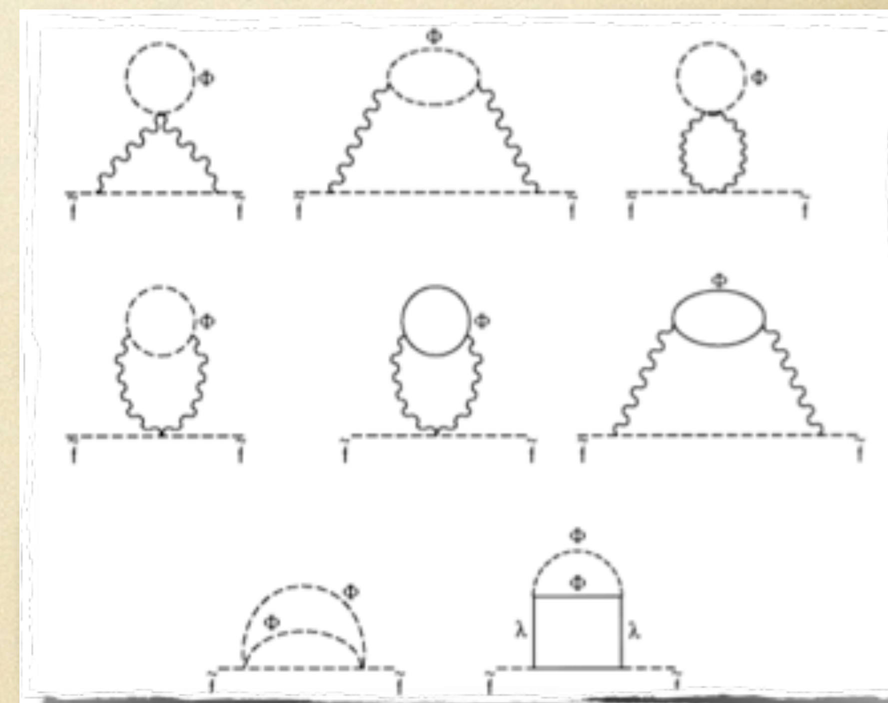
[Giudice, Rattazzi (1998)]



Arises from 1-loop graph

$$M_{\lambda_r}(t) = k_r \frac{\alpha_r(t)}{4\pi} \Lambda_G$$

Sfermion masses



Arises from 2-loop graphs

$$m^2_{\widetilde{f}}(t) = 2 \sum_{r=1}^{3} C_r^{\widetilde{f}} k_r \frac{\alpha_r^2(0)}{(4\pi)^2} \left(\Lambda_S^2 + h_r \Lambda_G^2 \right)$$

$$\Lambda_G = N \frac{F}{M} \qquad N = \sum_{1}^{N_f} n_i$$

$$\Lambda_S = N \frac{F^2}{M^2} \qquad h_r = \frac{k_r}{b_r} \left(1 - \frac{\alpha_r^2(t)}{\alpha_r^2(0)} \right)$$

- The messengers can be gauge fields (gauge messengers)

[Giudice, Rattazzi (1997)]

Tree Level Gauge Mediation

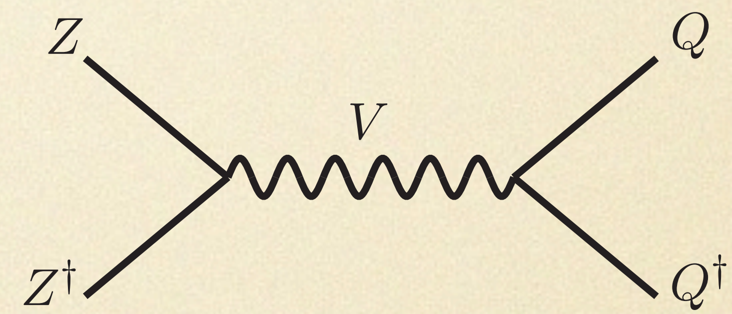
- Which operator generates sfermion masses?

$$\int d^4\theta \frac{ZZ^\dagger QQ^\dagger}{M^2}$$

Z Q

V

$Z^\dagger$ $Q^\dagger$



- Problems? Why usually loop-gauge mediation is used?

$$Str\mathcal{M}^2 \equiv 3tr\mathcal{M}_1^2 - 2tr\mathcal{M}_{\frac{1}{2}}\mathcal{M}_{\frac{1}{2}}^\dagger + tr\mathcal{M}_0^2 = -2g\langle D^a\rangle trT^a$$

Valid at tree level for renormalizable theories with spontaneous SUSY breaking

Solution is to extend the gauge group: consider at least an extra U(1)

sfermion masses @ tree level

→ possible tension

gaugino masses @ 1 loop

An SO(10) model of TGM 1

[Nardecchia, Romanino, Ziegler (2009)]

- G = SO(10) (rank = 5) for simplicity suppose SM = SU(5)

- SUSY breaking mediated by the SU(5)-invariant generator X

$16 = 10 + \overline{5} + 1$ $\qquad$ $10 = \overline{5} + 5$

$1 \quad -3 \quad 5$ ⟵ X charges ⟶ $2 \quad -2$

- Matter contained in three 16_i and three 10_i (see next slide)

- GUT breaking (SO(10) $\longrightarrow$ SU(5)) by 16 and $\overline{16}$: the singlets get VEV

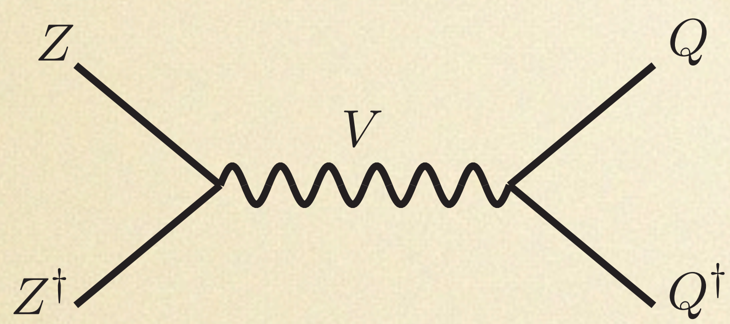
$$\langle 1^{16} \rangle = \langle 1^{\overline{16}} \rangle = M$$

- SUSY breaking by $16'$ and $\overline{16}'$

$$\langle 1^{16'} \rangle = \theta^2 F \qquad \langle 1^{\overline{16}'} \rangle = 0$$

An SO(10) model of TGM 2 (sfermion masses)

- Why do we consider matter both in 16 and 10 ?



generate sfermion masses of the form

$$\widetilde{m}^2_Q = \frac{X_Q}{2X_Z}\frac{F^2}{M^2}$$

X_Q and X_Z must have the same sign to get positive sfermion masses

$$16 = \underset{1}{10} + \underset{-3}{\overline{5}} + \underset{5}{1} \qquad 10 = \underset{2}{\overline{5}} + \underset{-2}{5}$$

can be light fields, the other must be made heavy ⟶ next slide we see how we do that

- Impossible to do the usual embedding of one family in a single 16
- Peculiar prediction for ratio of sfermion masses (@ GUT scale)

$$\widetilde{m}^2_{q,u^c,e^c} = \frac{1}{2}\widetilde{m}^2_{l,d^c}$$

- Solve the SUSY flavour problem (masses are flavour universal)

An SO(10) model of TGM 3 (superpotential)

- What is left?
  - Make the extra fields in $16_i + 10_i$ heavy
  - Compute gaugino masses
- Write a superpotential W to take these into account

$$W = \frac{y_{ij}}{2} 16_i 16_j 10 + h_{ij} 16_i 10_j 16 + h'_{ij} 16_i 10_j 16'$$

- What happens?

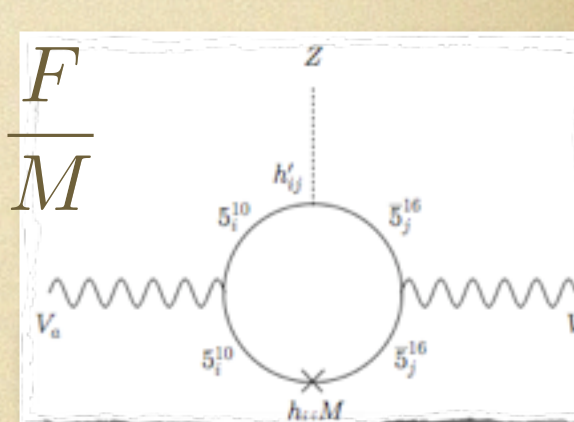
These fields get a SUSY mass M

$$16 = 10 + \overline{5} + 1 \qquad 10 = \overline{5} + 5$$

$$\;\;1 \quad -3 \quad 5 \qquad\qquad 2 \quad -2$$

- Gaugino are massless at tree level, not at 1-loop level

The heavy fields run in the loop. One gets $M_g = \frac{\alpha}{4\pi} Tr(h' h^{-1}) \frac{F}{M}$



For the sfermion masses we got $\widetilde{m}_t = \frac{F}{\sqrt{10} M}$

Thus the ratio is $\frac{M_2}{\widetilde{m}_t} = \frac{3\sqrt{10}}{(4\pi)^2} \lambda$

Numerical factor helps in keeping the hierarchy small (~O(10))

$\lambda = g^2 \frac{Tr(h' h^{-1})}{3}$

An SO(10) model of TGM 4 (low energy spectrum)

- One can evolve the parameters to check what low energy spectrum can be obtained. An example is given below

Higgs:	m_{h^0}	114
	m_{H^0}	1543
	m_A	1543
	$m_{H^\pm}$	1545
Gluinos:	$M_{\tilde{g}}$	448
Neutralinos:	$m_{\chi_1^0}$	62
	$m_{\chi_2^0}$	124
	$m_{\chi_3^0}$	1414
	$m_{\chi_4^0}$	1415
Charginos:	$m_{\chi_1^\pm}$	124
	$m_{\chi_2^\pm}$	1416
Squarks:	$m_{\tilde{u}_L}$	1092
	$m_{\tilde{u}_R}$	1027
	$m_{\tilde{d}_L}$	1095
	$m_{\tilde{d}_R}$	1494
	$m_{\tilde{t}_1}$	1007
	$m_{\tilde{t}_2}$	1038
	$m_{\tilde{b}_1}$	1069
	$m_{\tilde{b}_2}$	1435
Sleptons:	$m_{\tilde{e}_L}$	1420
	$m_{\tilde{e}_R}$	1091
	$m_{\tilde{\tau}_1}$	992
	$m_{\tilde{\tau}_2}$	1387
	$m_{\tilde{\nu}_e}$	1418
	$m_{\tilde{\nu}_\tau}$	1382

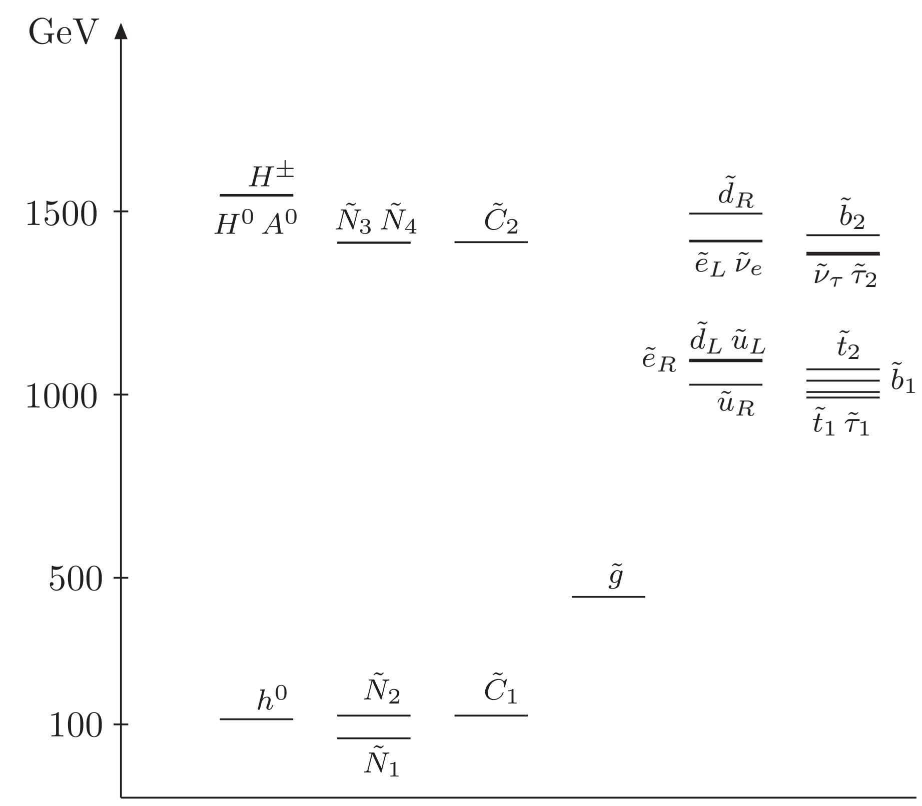


Figure 2: An example of spectrum, corresponding to $m = 3.2\,\text{TeV}$, $M_{1/2} = 150\,\text{GeV}$, $\theta_d = \pi/6$, $\tan\beta = 30$ and $\text{sign}(\mu) = +$, $A = 0$, $\eta = 1$. All the masses are in GeV, the first two families have an approximately equal mass.

This spectrum is constructed without considering the presence of intermediate scales and consider SM as a SU(5) theory

An improved version is what follows

TGM at Colliders

[MM, Pierini, Romanino, Spinrath (in prep)]

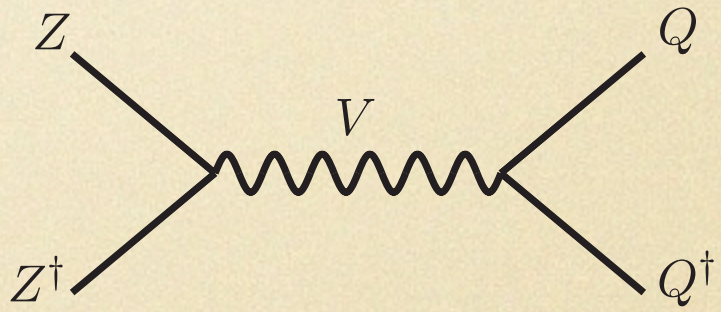
- What's next?
  - Introduce the effects of intermediate scales
  - Consider a non SU(5)-invariant theory
  - Phenomenological analysis of the possible outcomes

$$W = \frac{y_{ij}}{2} 16_i 16_j 10 + h_{ij} 16_i 10_j 16 + h'_{ij} 16_i 10_j 16'$$

$$\langle 1^{16} \rangle = M$$

$$W \supset h^D_{ij} M D^c_i \overline{D^c}_j + h^L_{ij} M L_i \overline{L}_j + h^{D'}_{ij} Z D^c_i \overline{D^c}_j + h^{L'}_{ij} Z L_i \overline{L}_j$$

Then SUSY gets broken $\langle Z \rangle = \theta^2 F$



The sfermions? $\widetilde{m}^2_{q,u^c,e^c} = \frac{1}{2} \widetilde{m}^2_{l,d^c}$

And the higgses?

$$\widetilde{m}^2_{h_d} = (2cos^2\theta_d - 3sin^2\theta_d)\widetilde{m}^2_q \qquad \widetilde{m}^2_{h_u} = (-2cos^2\theta_u + 3sin^2\theta_u)\widetilde{m}^2_q$$

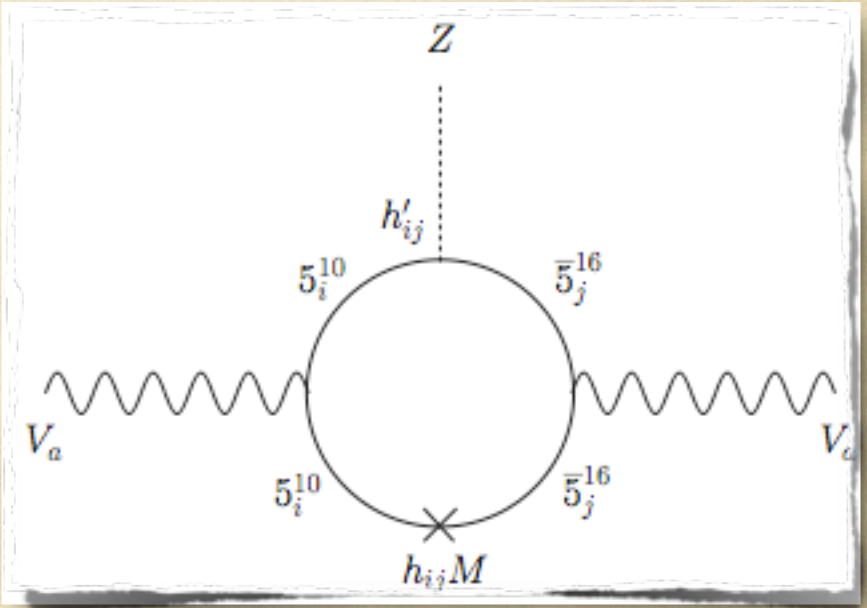
TGM at Colliders (gaugino masses)

For gaugino masses?

at any scale $h_i^{D,L} M$ we integrate out a contribution $M_a^{D,L} = \frac{\alpha_a}{4\pi} b_a^{D,L} \gamma_i^{D,L} \frac{F}{M}$

where $b^L = (3/5, 1, 1)\,,\; b^D = (2/5, 1, 1)$ $\gamma_i^D = \left(\frac{h_i^{D'}}{h_i^D} \right)\,,\; \gamma_i^L = \left(\frac{h_i^{L'}}{h_i^L} \right)$

Non universal gaugino masses



A sum rule @ GUT scale

$$r = \frac{M_2}{M_3}$$

$$M_1 = \frac{3}{5} M_2 + \frac{2}{5} M_3$$

TGM at Colliders (summing up)

The relevant parameters are

$$\widetilde{m}_{10}$$

$$M_{1/2} = \frac{M_2 + M_3}{2}$$

$$r = \frac{M_2}{M_3}$$

$$\theta_u \quad \theta_d$$

$$\tan\beta$$

$$\text{sign}\mu$$

→ **What do we obtain?**

TGM at Colliders (General features: Higgs mass)

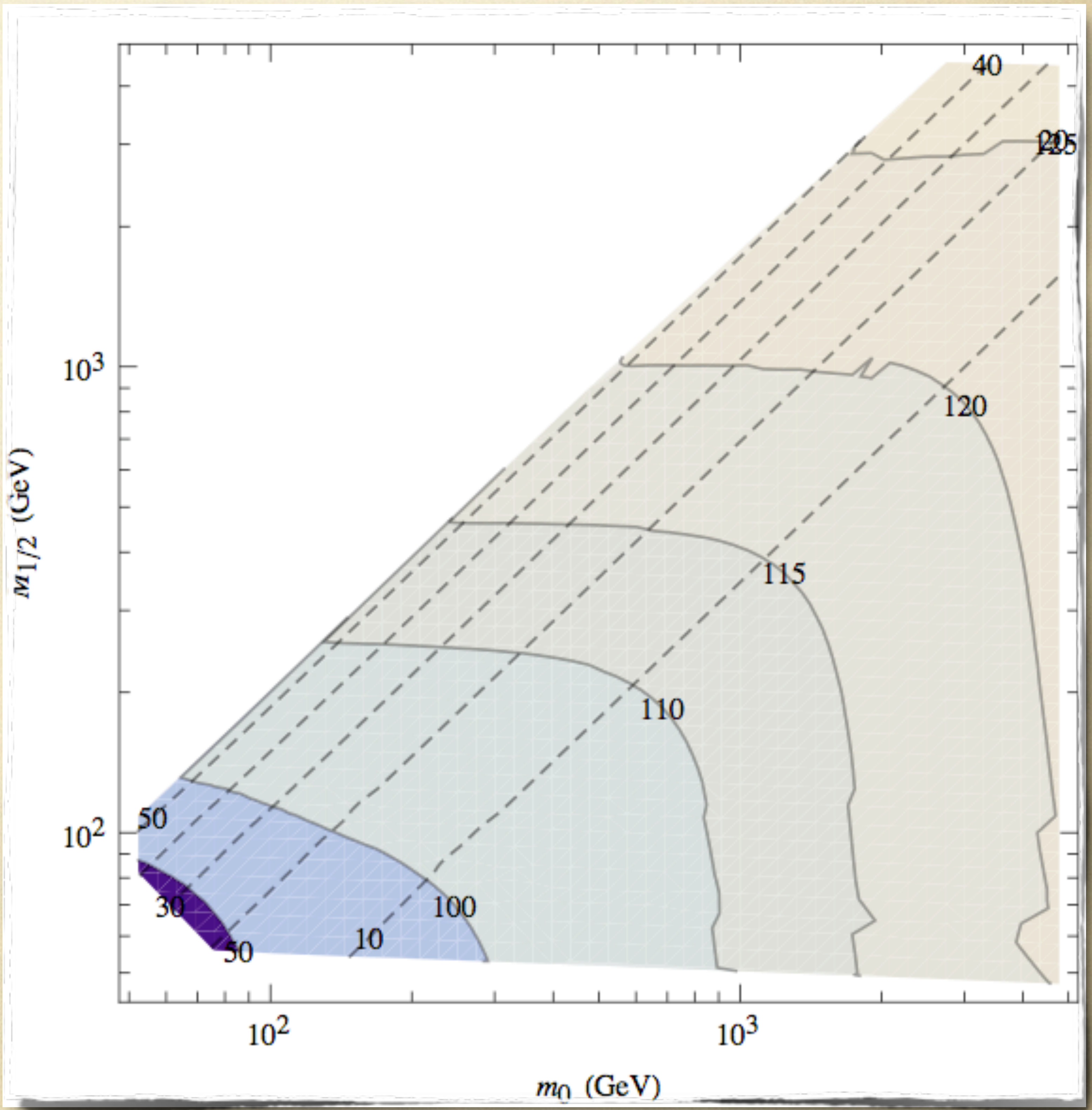
Parameters

$cos^2\theta_u, cos^2\theta_d = 0.8$

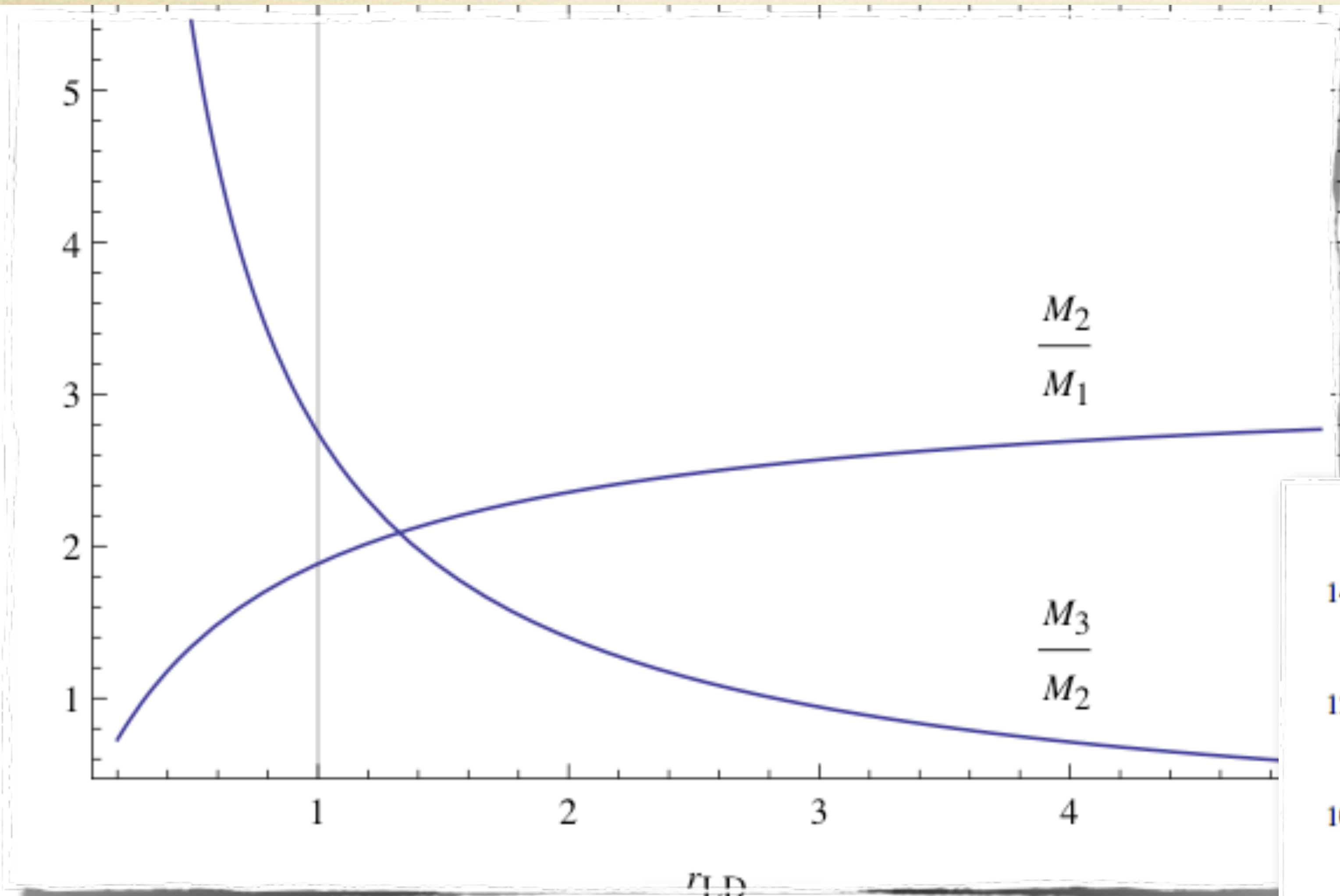
$r = 1\,,\ \tan\beta = 10$

The road to 125 GeV?

- Enlarge sfermion masses
- NMSSM



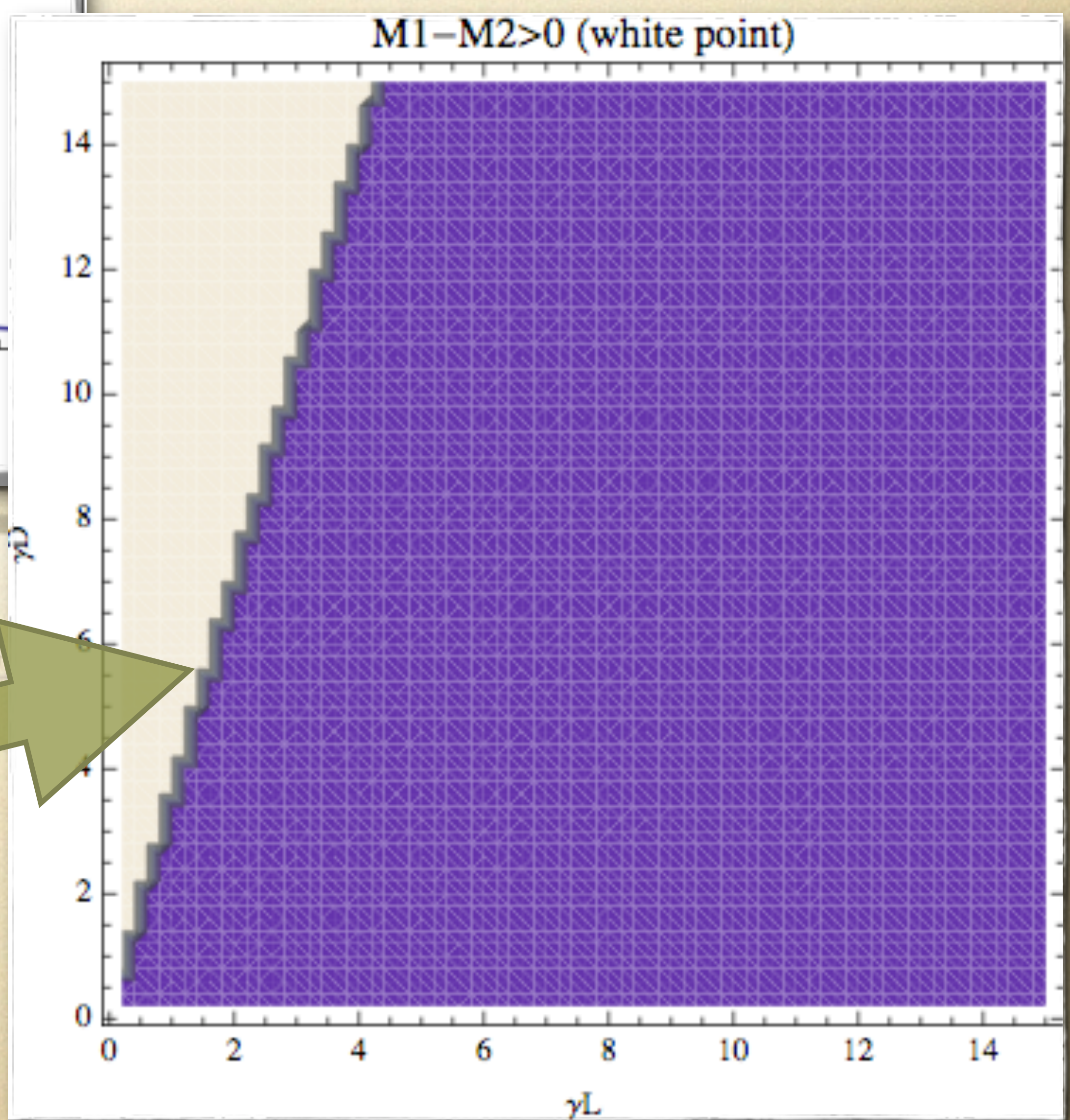
TGM at Colliders (General features: Gauginos)



Parameters

$$m_0 = 1\text{TeV}\ ,\ \tan\beta = 10$$

$$cos^2\theta_u, cos^2\theta_d = 0.8$$



For r < 0.3
Wino < Bino

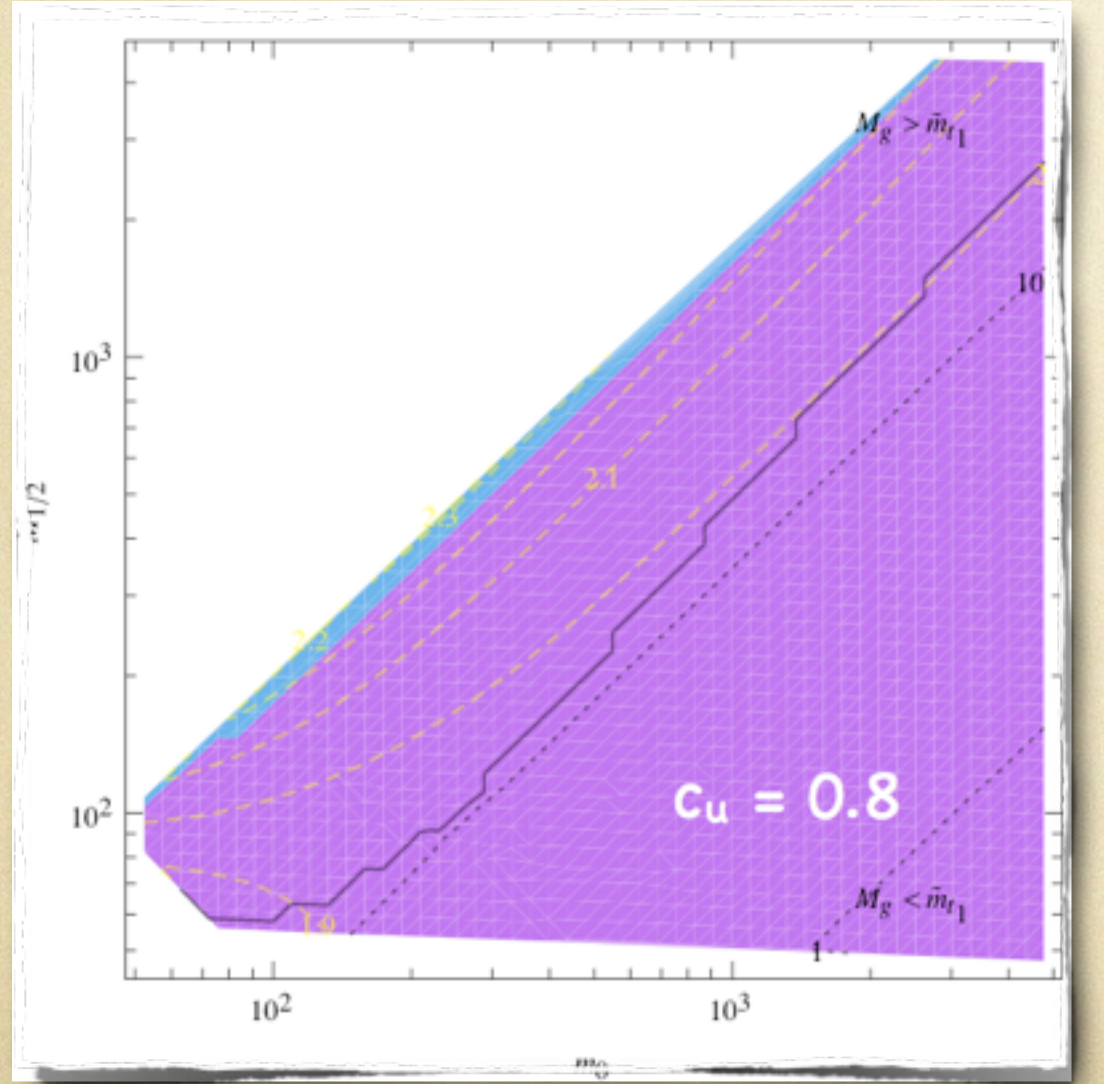
TGM at Colliders (NLSP)

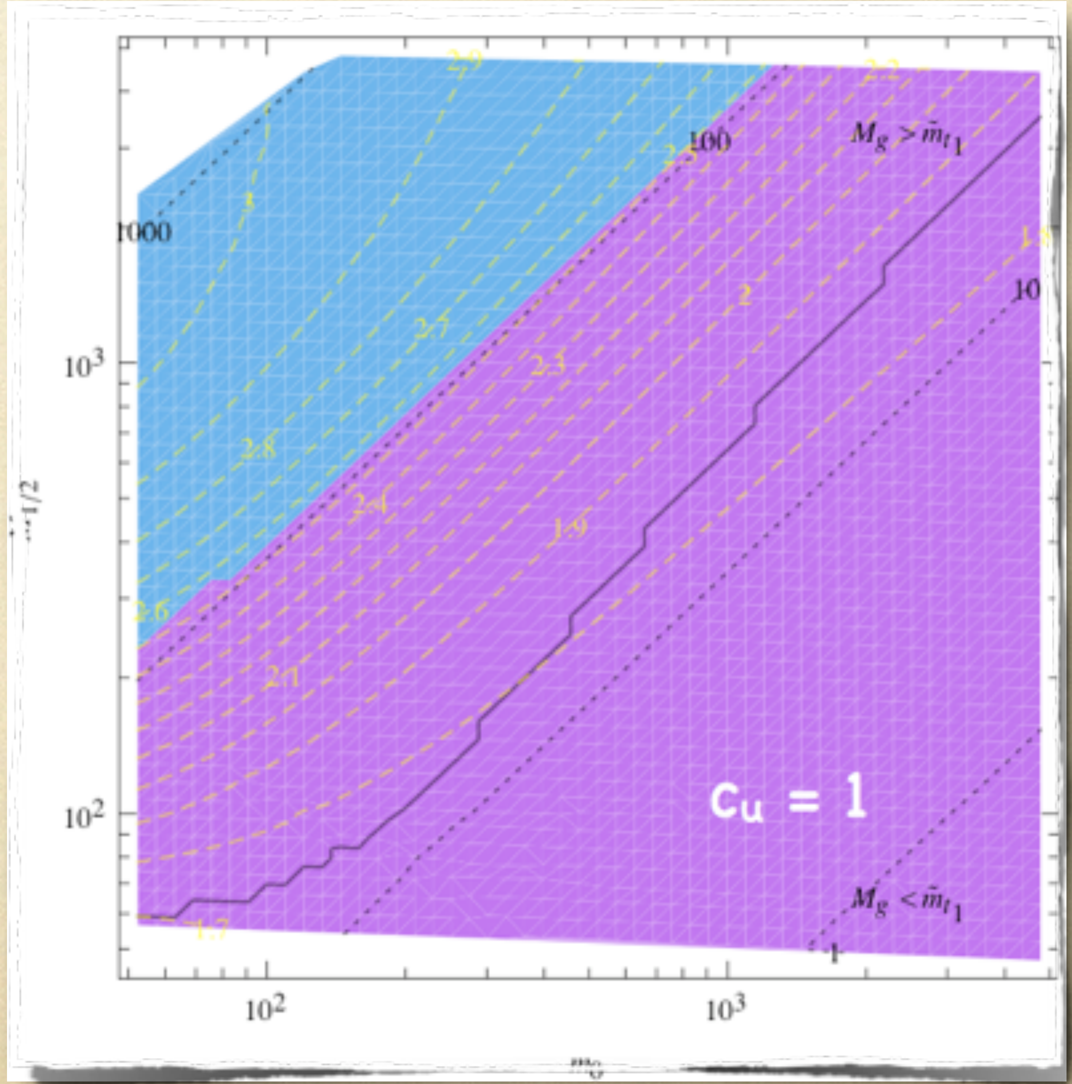
Parameters $cos^2\theta_d = 0.8 \quad r = 1\,,\, \tan\beta = 10$

NLSP?

- For r < 0.3 is the Wino
- Otherwise....

blue = Stau, purple = Bino





Razor Analysis

[Rogan (2011)]

- A new tool for inclusive searches
  - Perfect recipe for events like $pp \to \widetilde{q}\widetilde{q} \to 2j + \text{MET}$
- Let us consider $pp \to G_1 G_2 \to Q_1 \chi_1 + Q_2 \chi_2$

massive, unseen

massless, seen

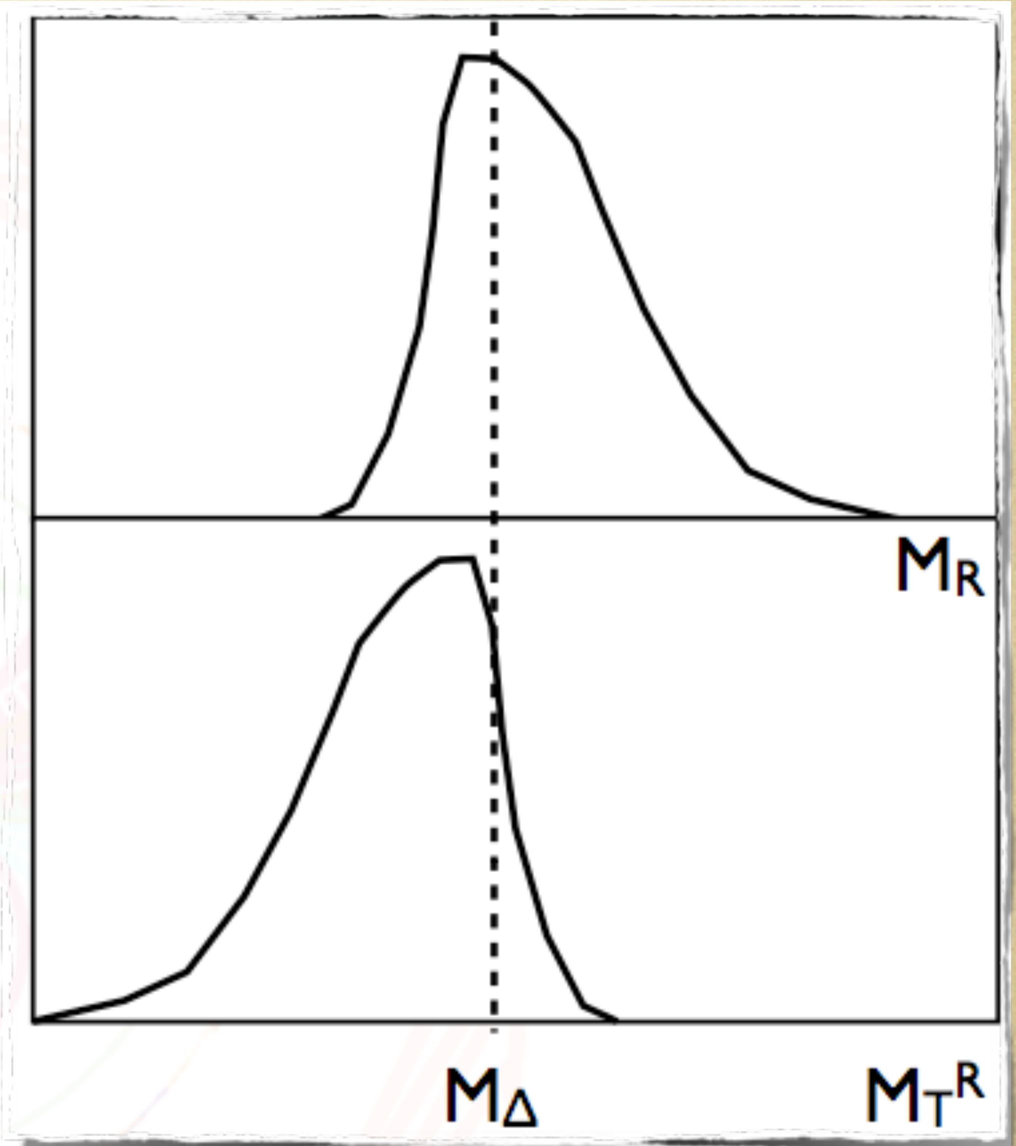
$$M_\Delta = \frac{M_G^2 - M_\chi^2}{M_G}$$

- We can construct the variables

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_1})^2}$$

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \overrightarrow{E}_T^{miss}(\overrightarrow{p}_T^{j_1} + \overrightarrow{p}_T^{j_2})}{2}}$$

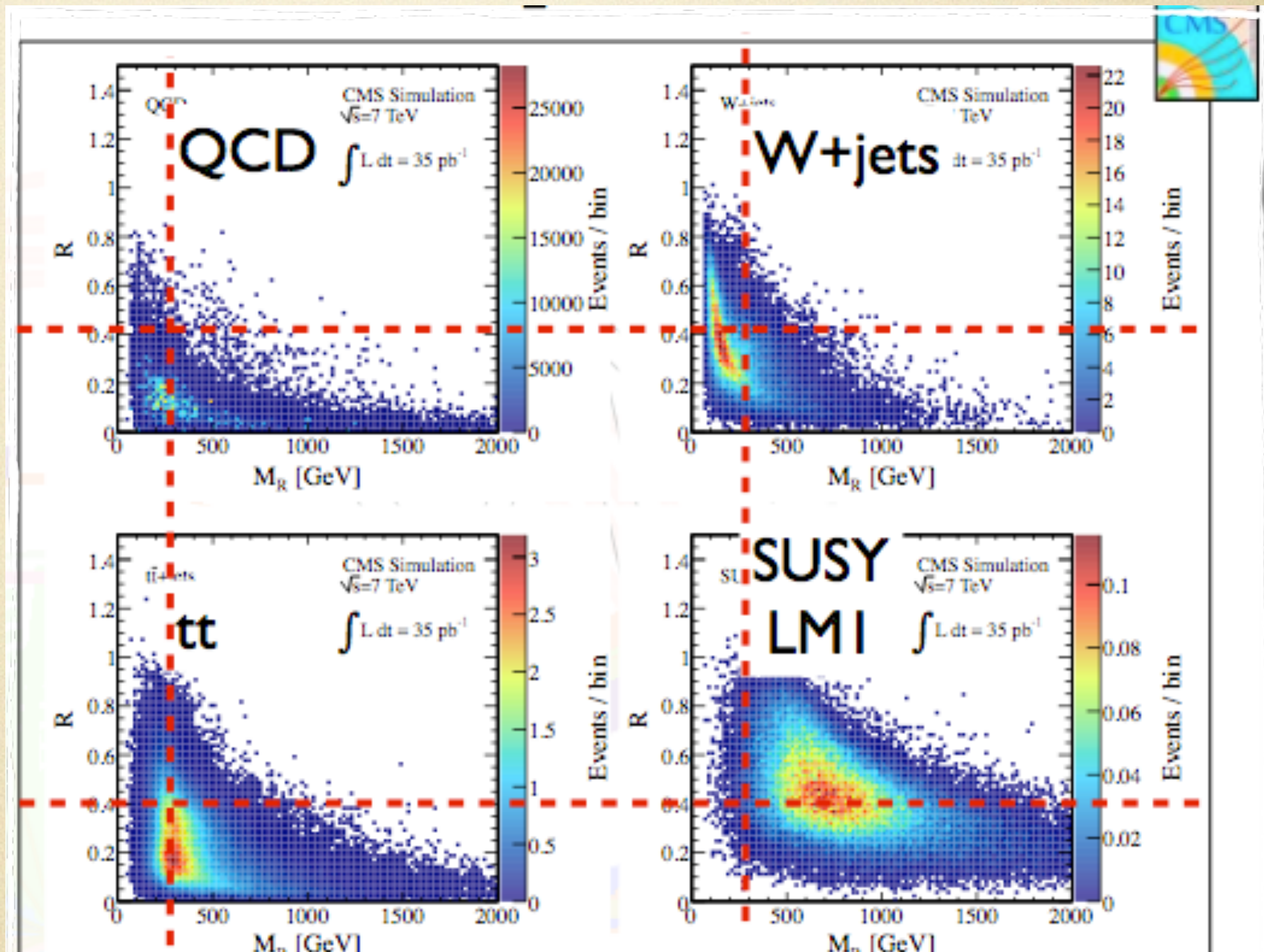
$$R \equiv \frac{M_T^R}{M_R}$$



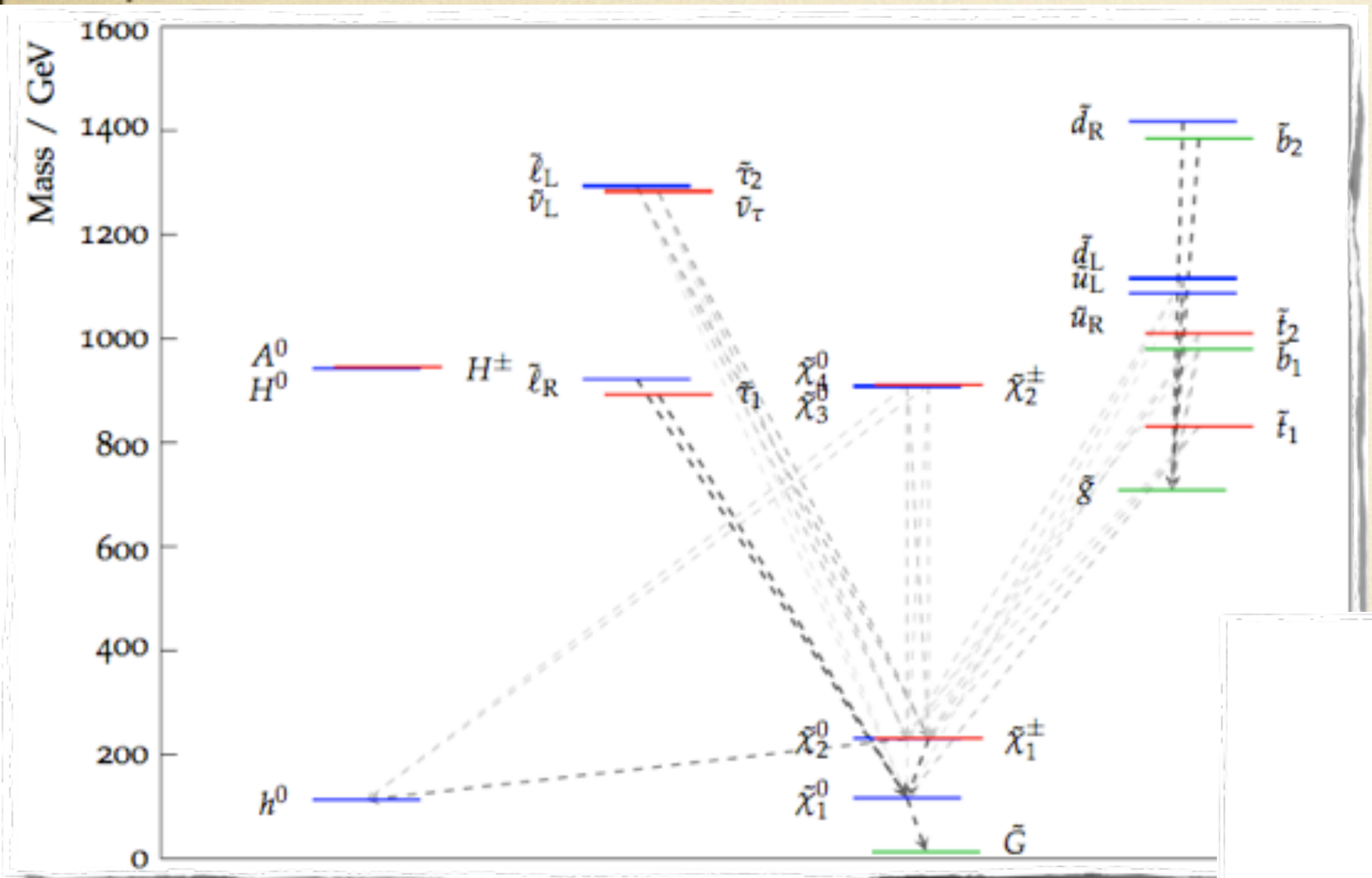
Razor Analysis

- **Very useful for discriminating events!!!**

- **For signal events**
  - M_R peaks at M_Δ
  - M_R^T has edge at M_Δ
  - R peaks at 0.5



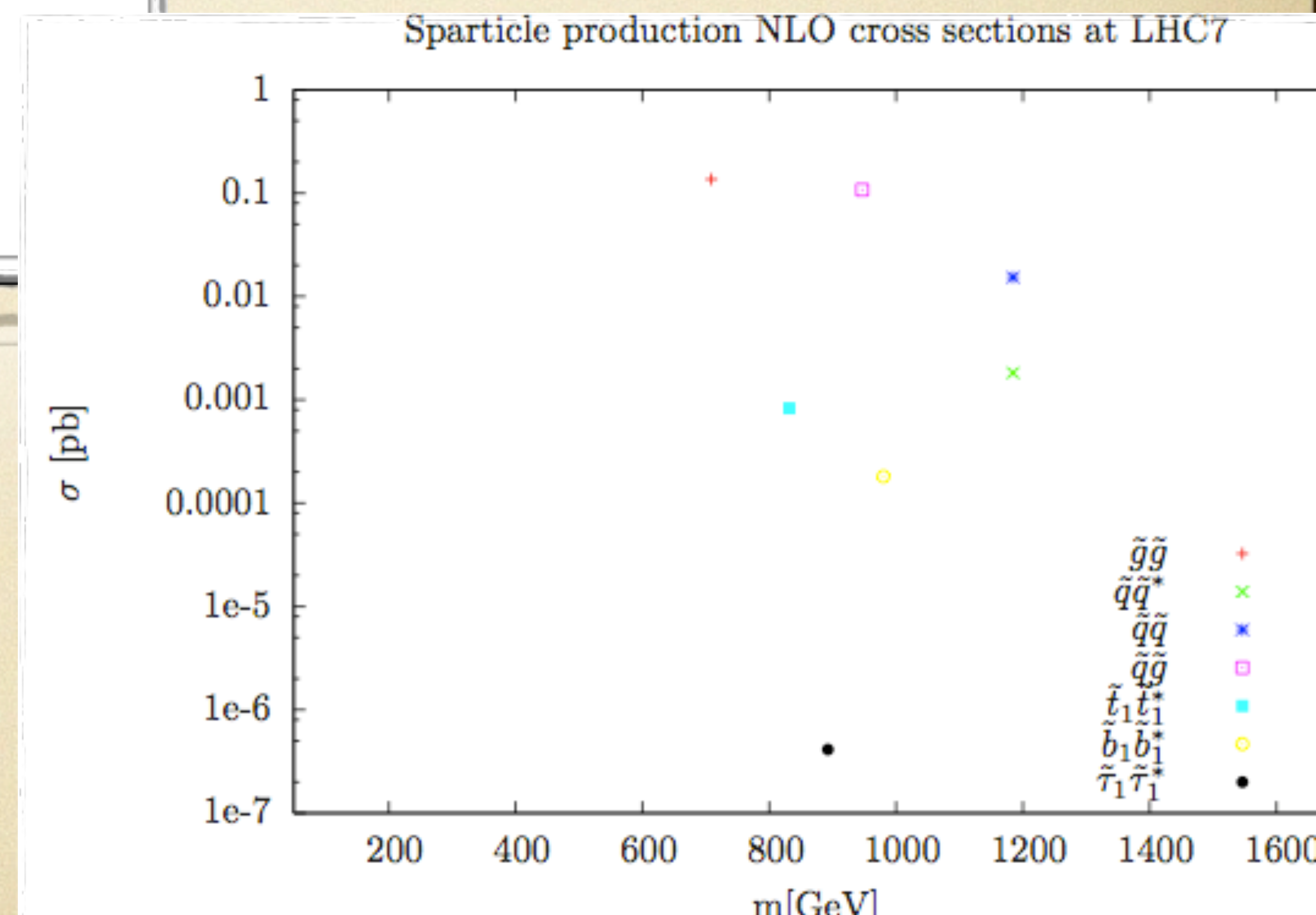
Benchmark point 1: Bino



$$m_0 = 900\text{GeV}, M_{1/2} = 315\text{GeV}$$

$$\tan\beta = 10, r = 1$$

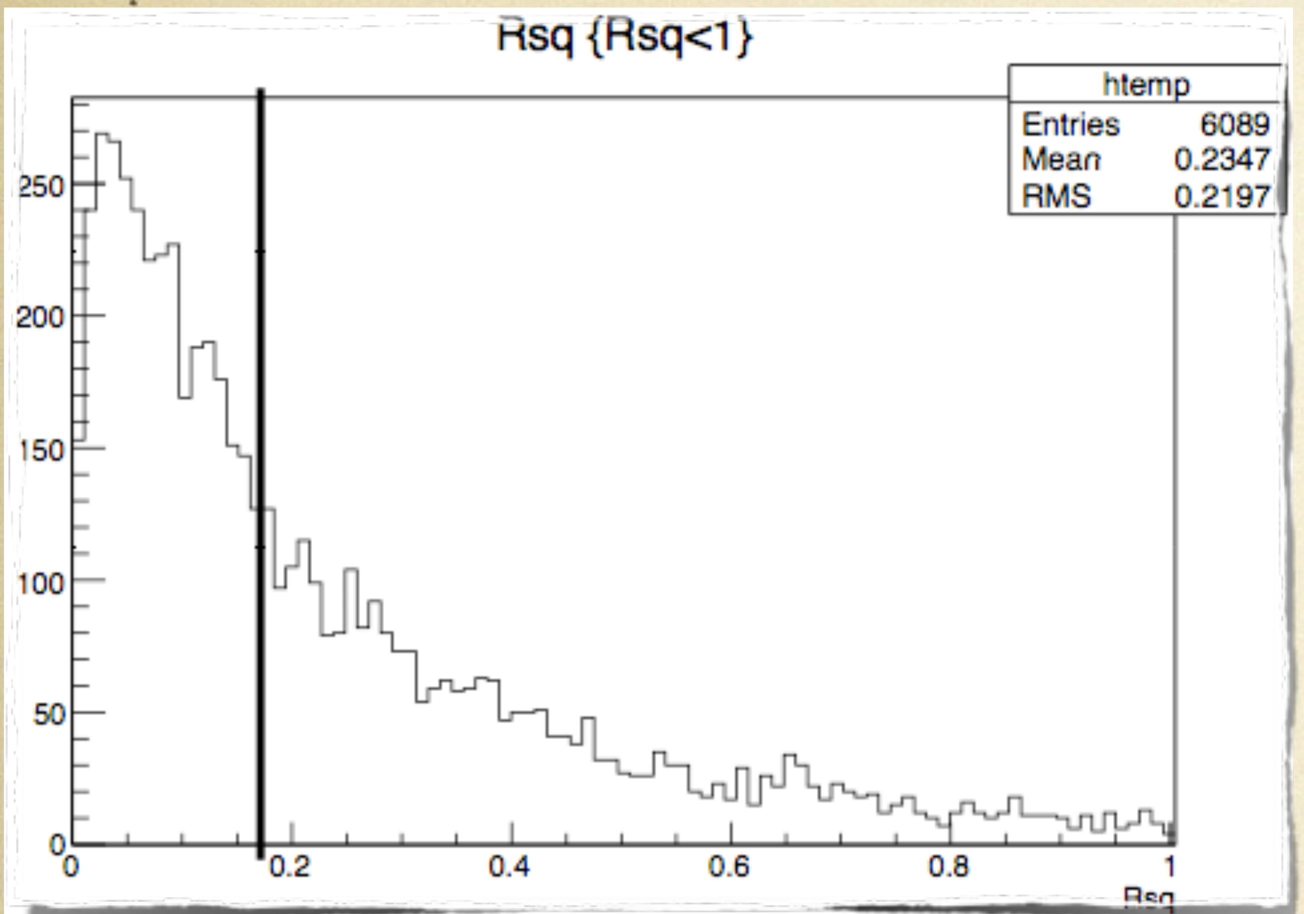
$$cos^2\theta_u = cos^2\theta_d = 0.8$$

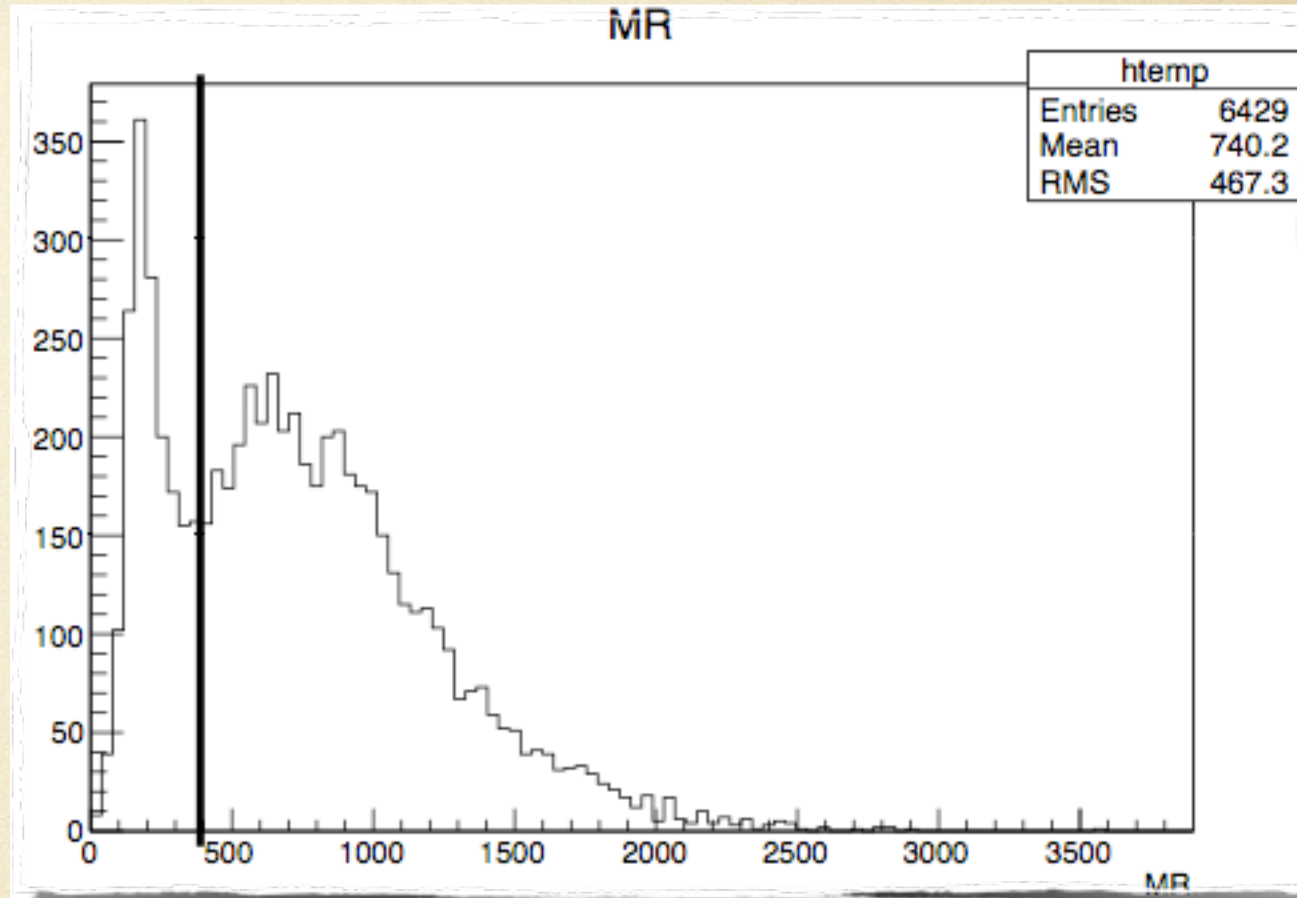


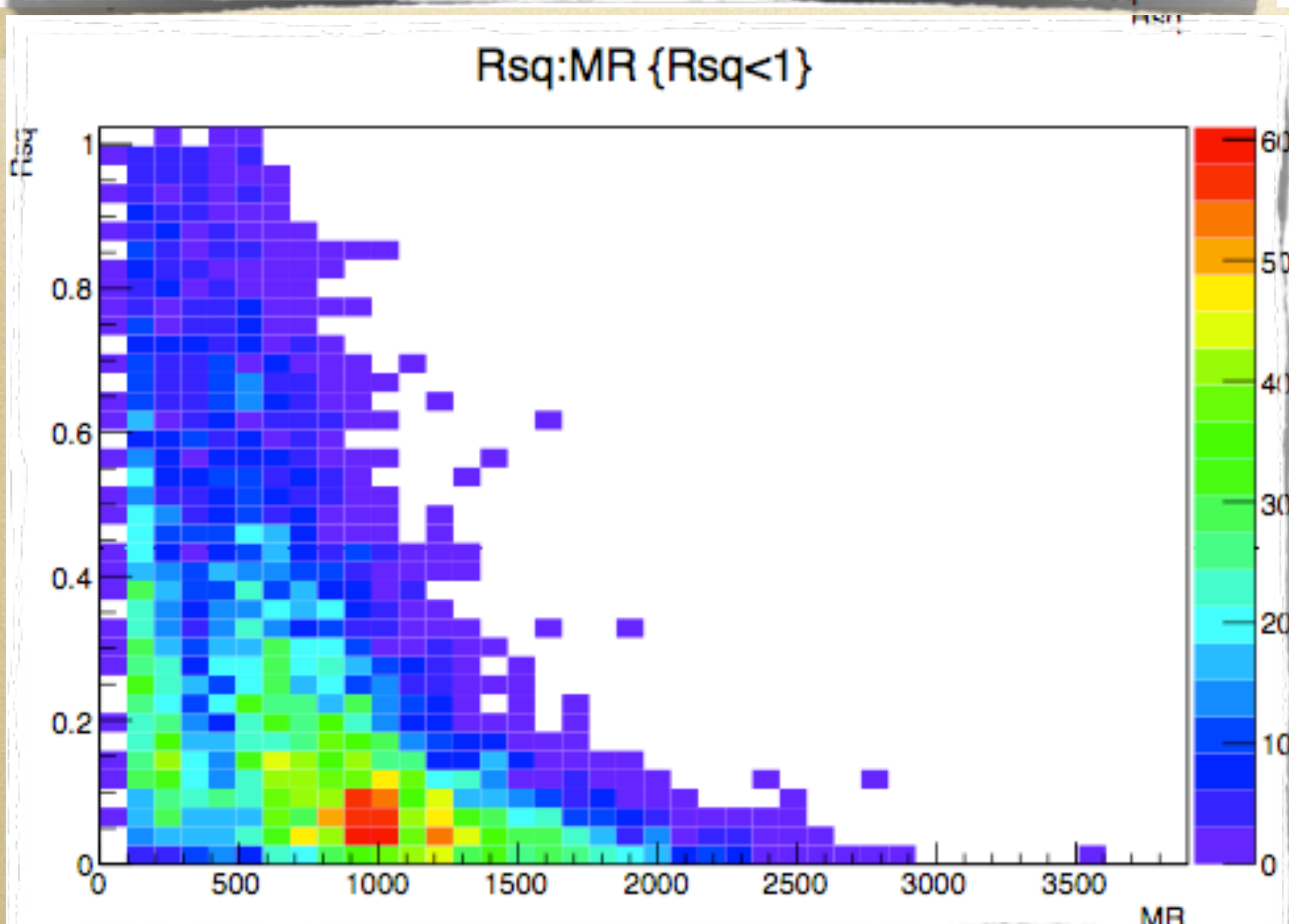
Comments...

- Higgs in χ_2^0 cascade decays (80/90%)
- Large MET (χ_1^0)
- Multijet b-enriched final states through EW decays

Benchmark point 1: Bino



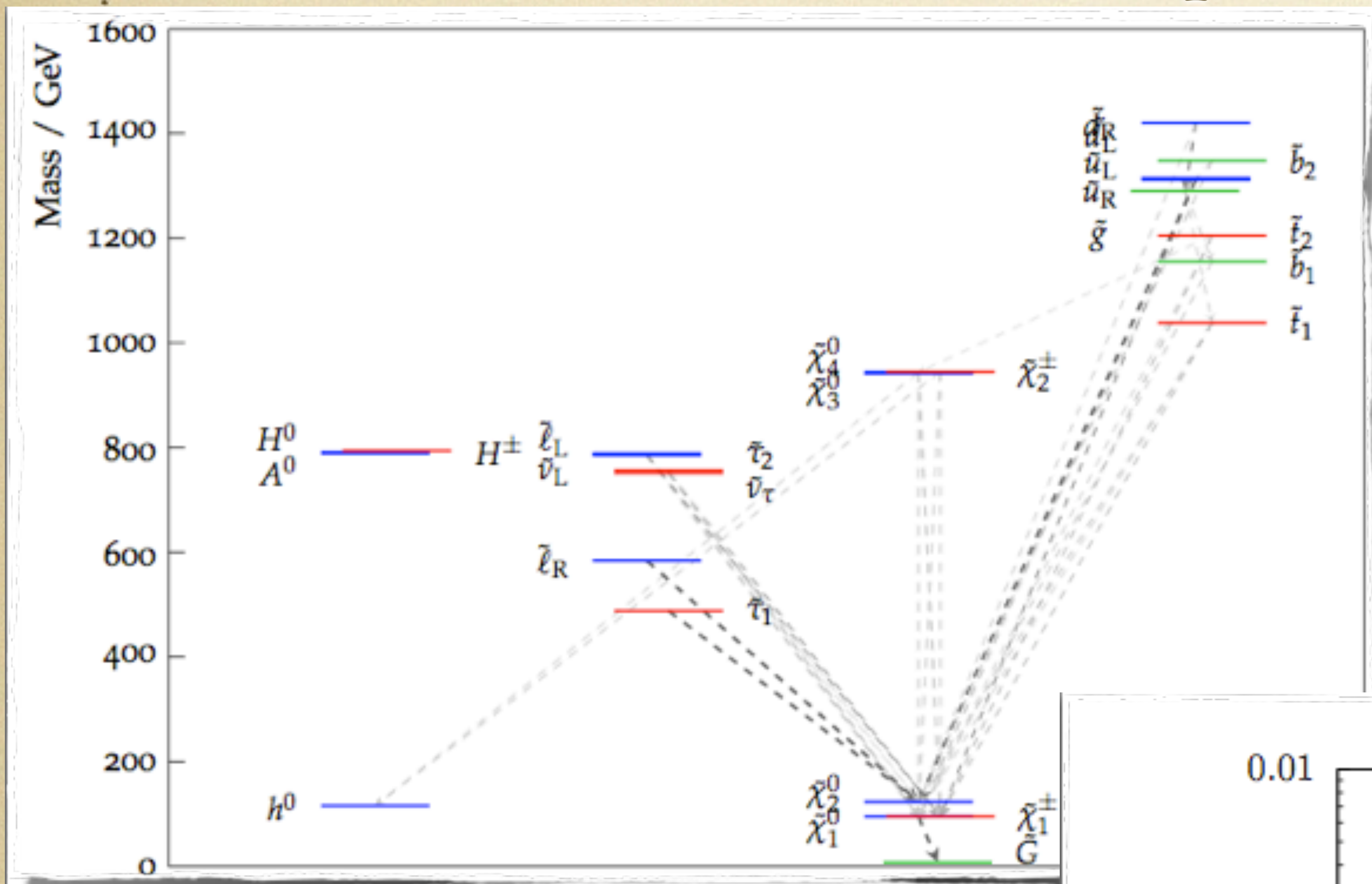




Comments...

- Can be seen from Razor analysis...
- ...but better to be seen from exclusive searches
- DISCLAIMER: multijet b-enriched final state still not very considered

Benchmark point 2: Wino



$$m_0 = 550\text{GeV}, M_{1/2} = 390\text{GeV}$$

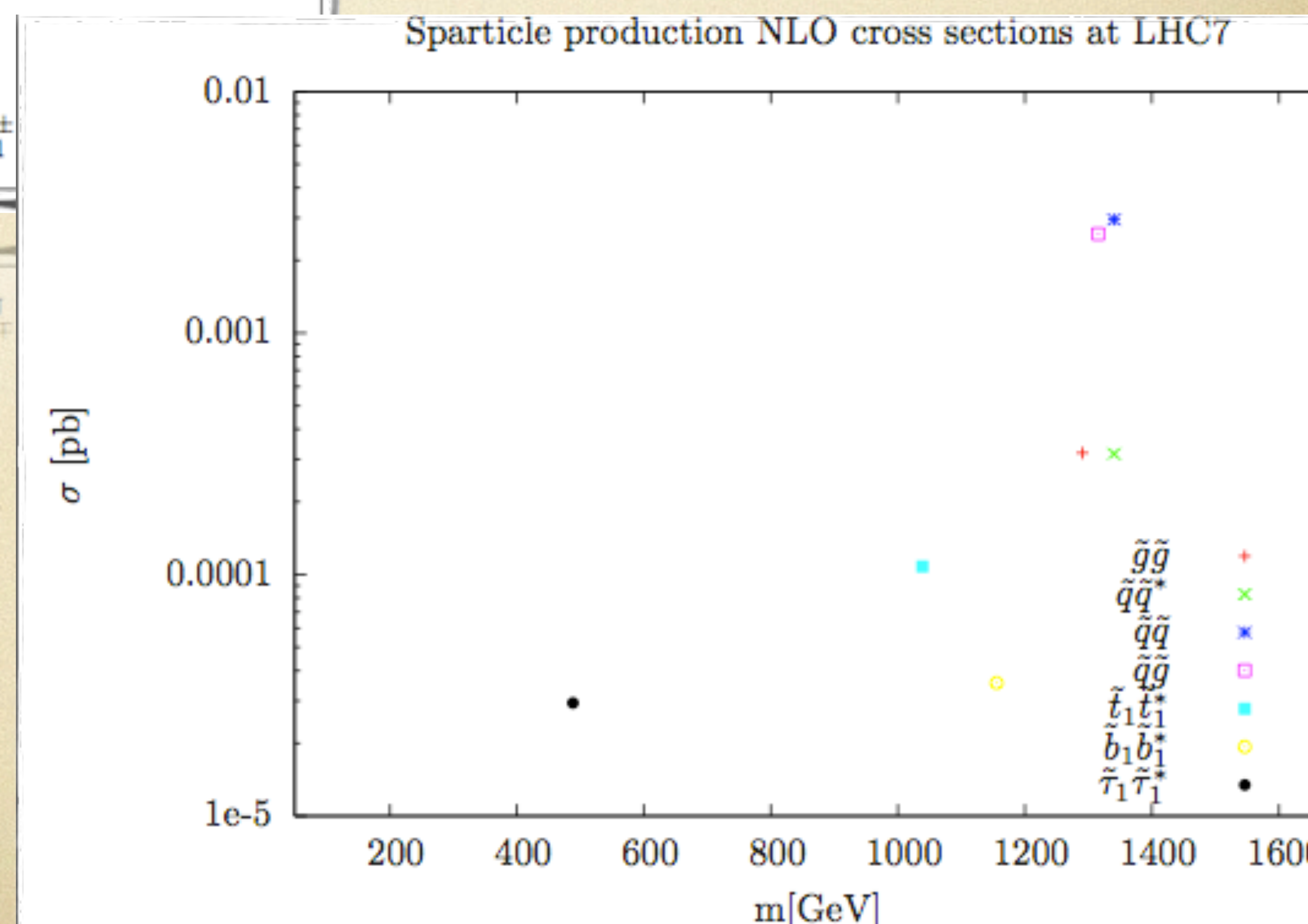
$$\tan\beta = 10, r = 0.2$$

$$cos^2\theta_u = cos^2\theta_d = 0.8$$

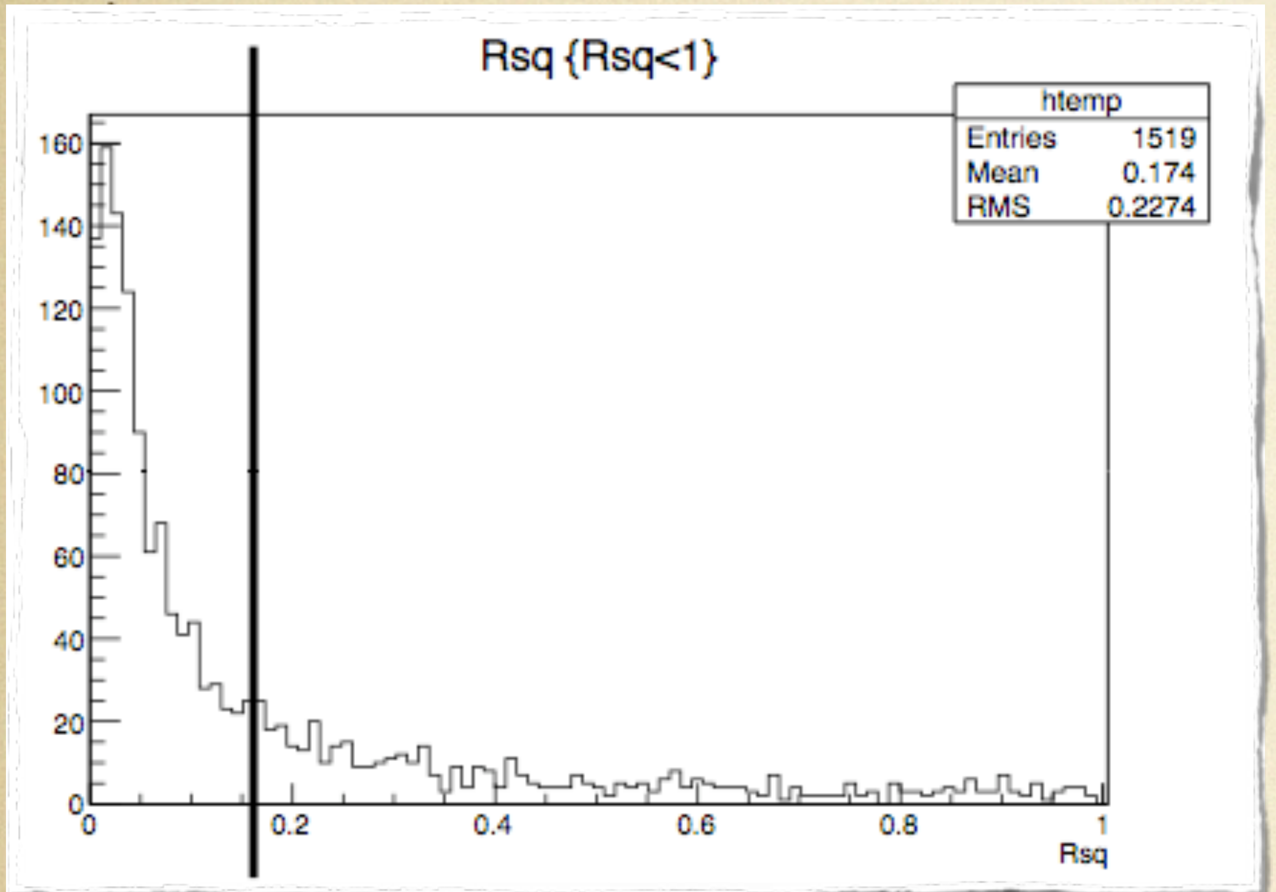
Comments...

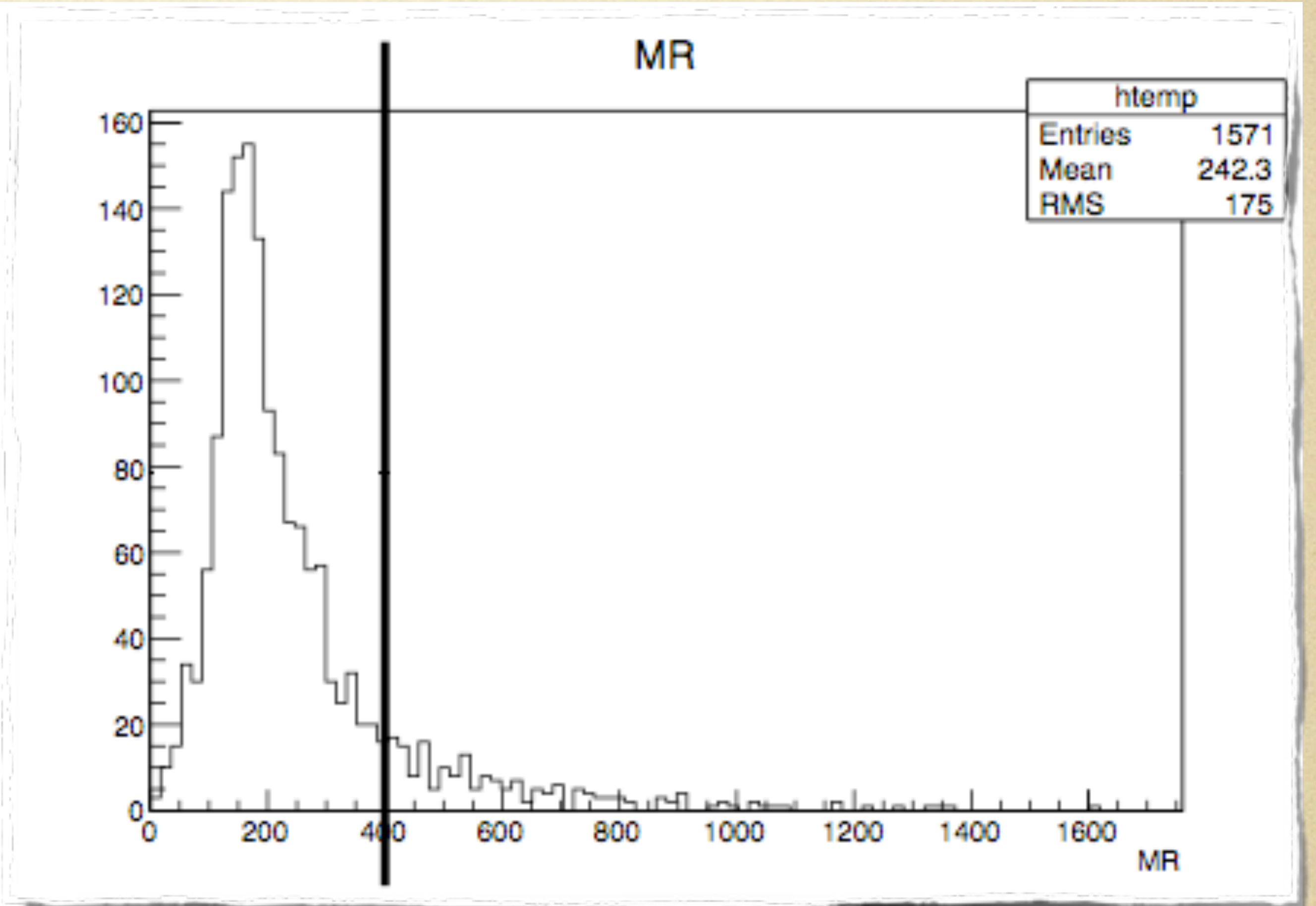
- Largish spectrum and very small X-sections, whole 2012 run probably necessary for getting relevant results
- Quite standard analysis:

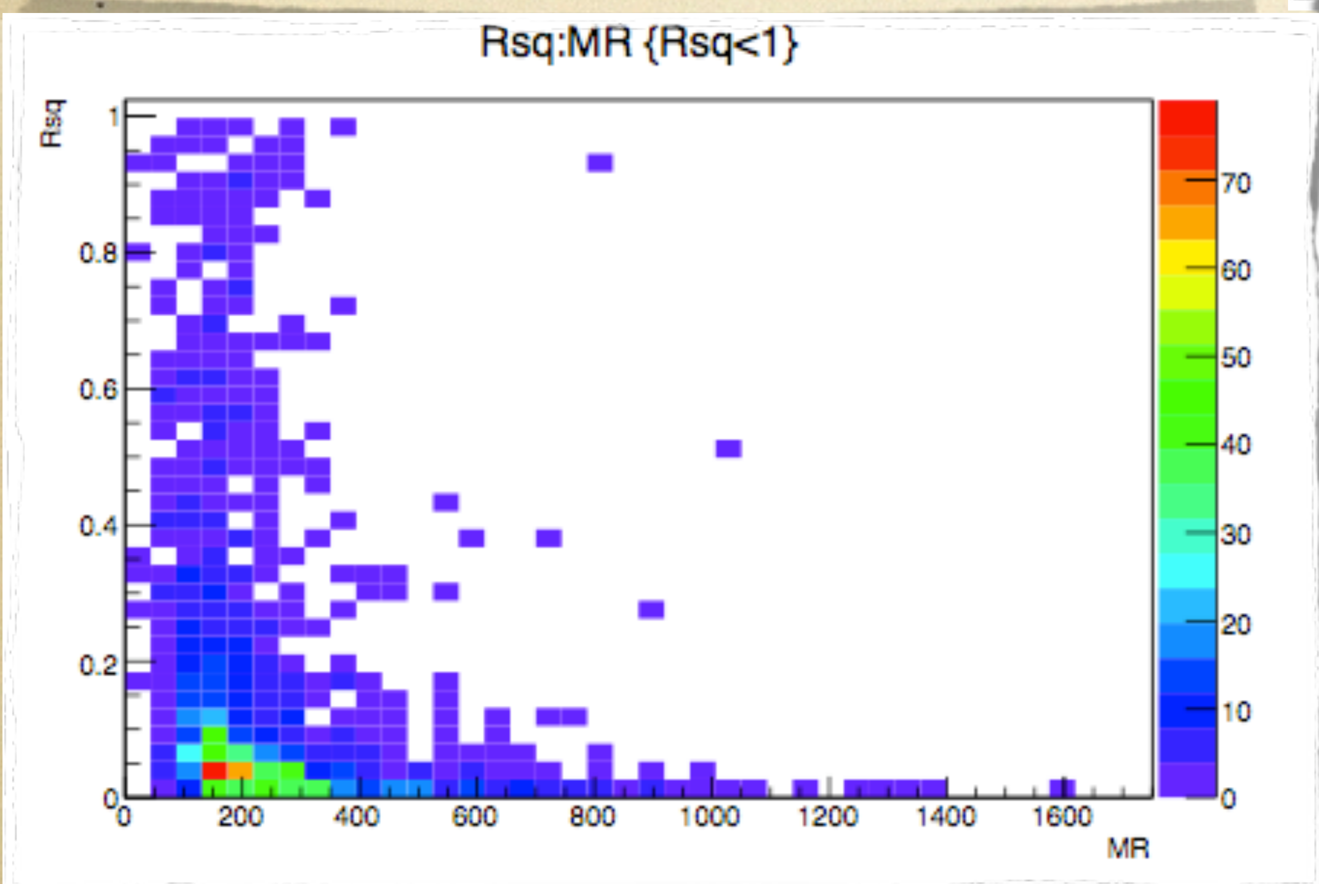
$$\widetilde{q}\widetilde{q} \rightarrow 2j + \text{MET}$$



Benchmark point 2: Wino







Comments...

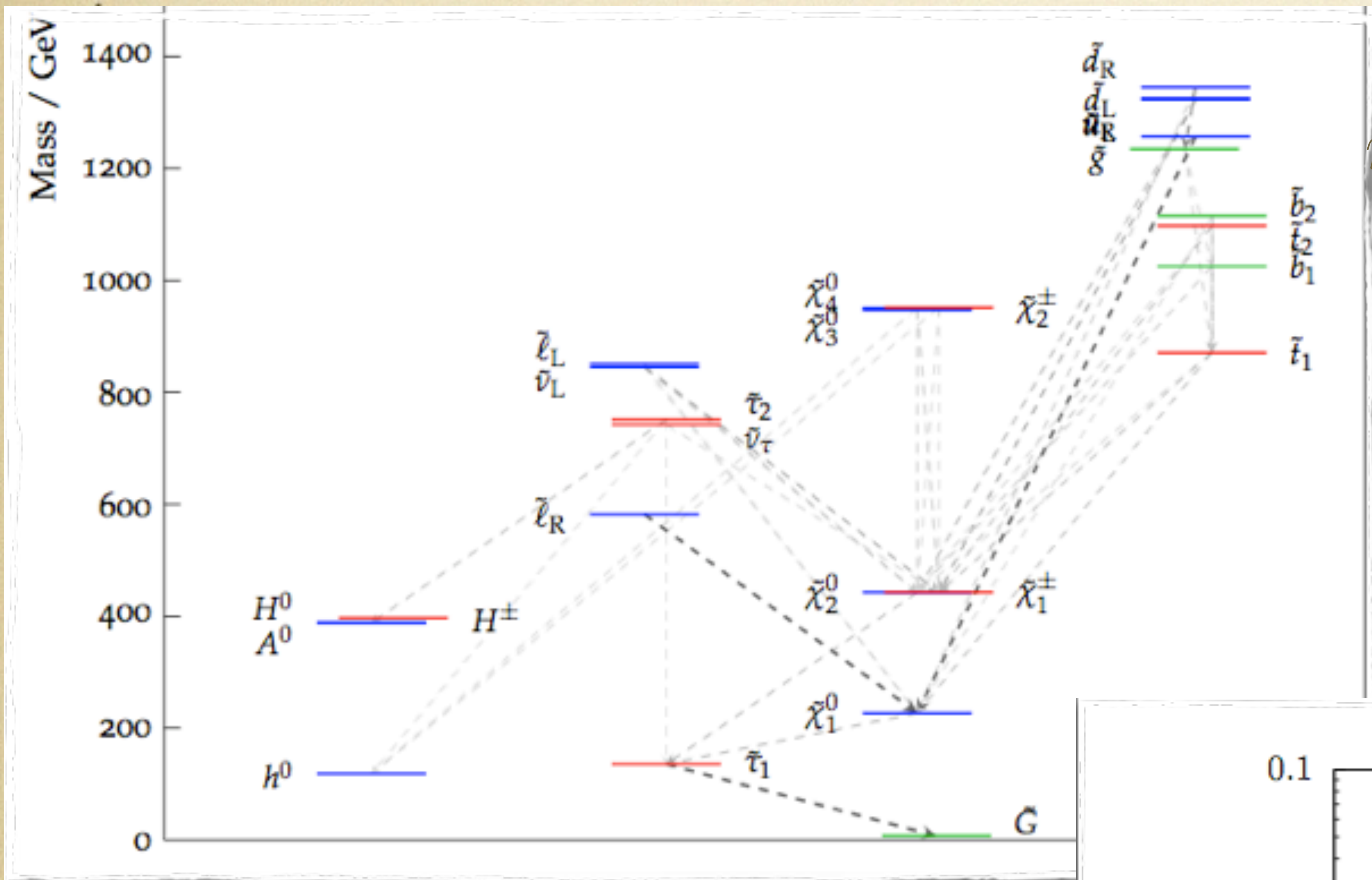
☺

- Perfect for Razor analysis

  $\widetilde{q}\widetilde{q} \rightarrow 2j + \text{MET}$

- Fairly heavy spectrum, need more data (even whole 2012 could be not enough)

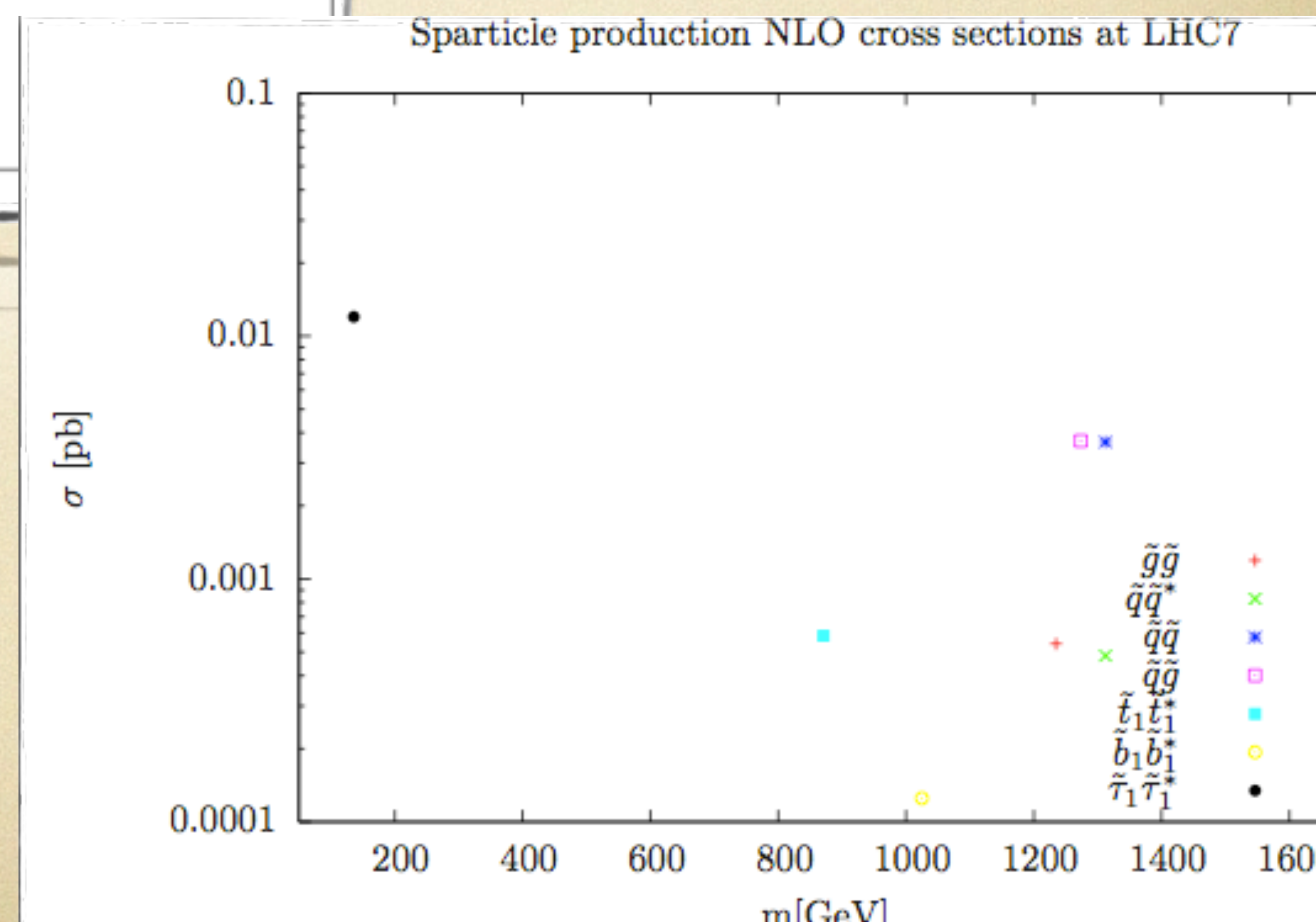
Benchmark point 3: Stau



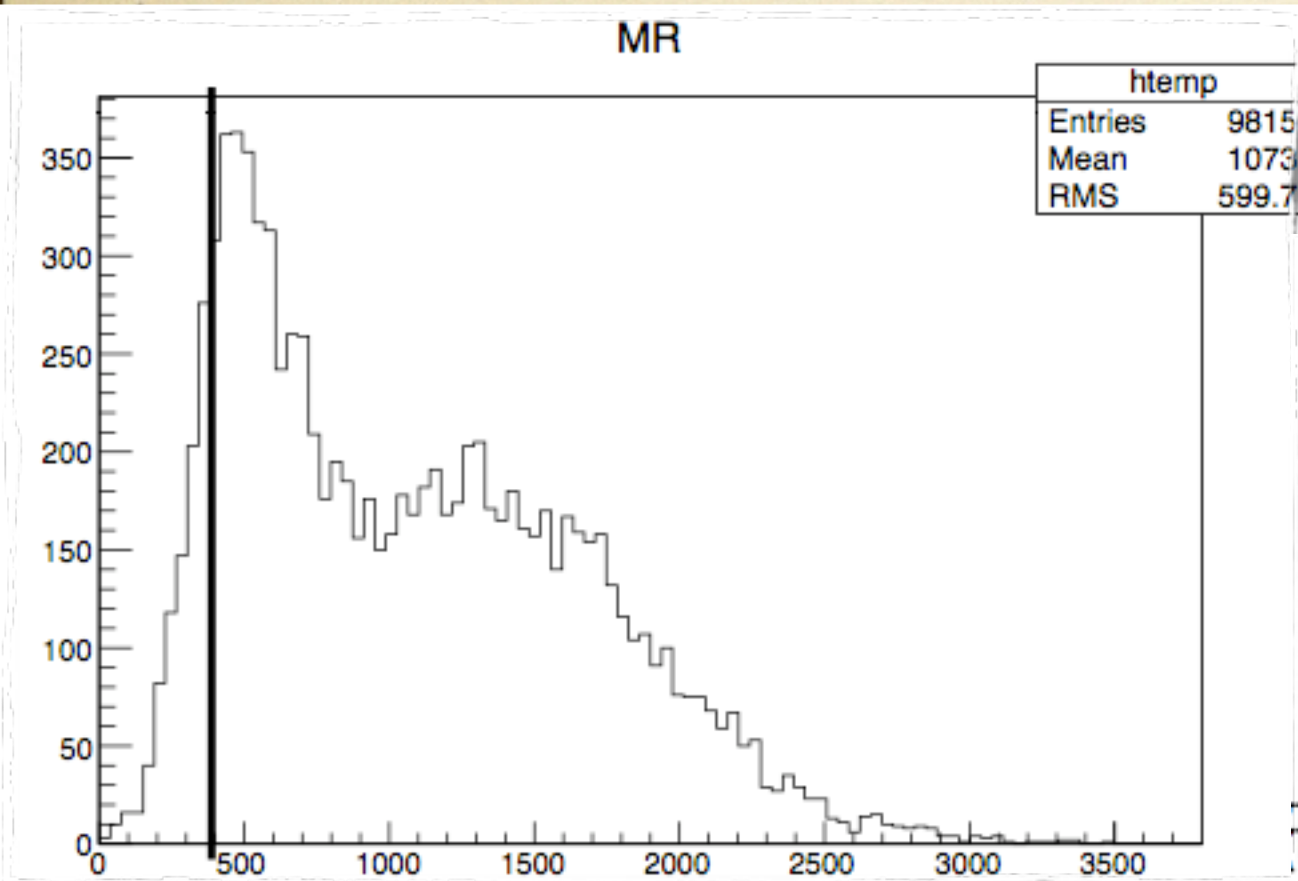
$$m_0 = 500\text{GeV}, M_{1/2} = 610\text{GeV}$$

$$\tan\beta = 35, r = 1$$

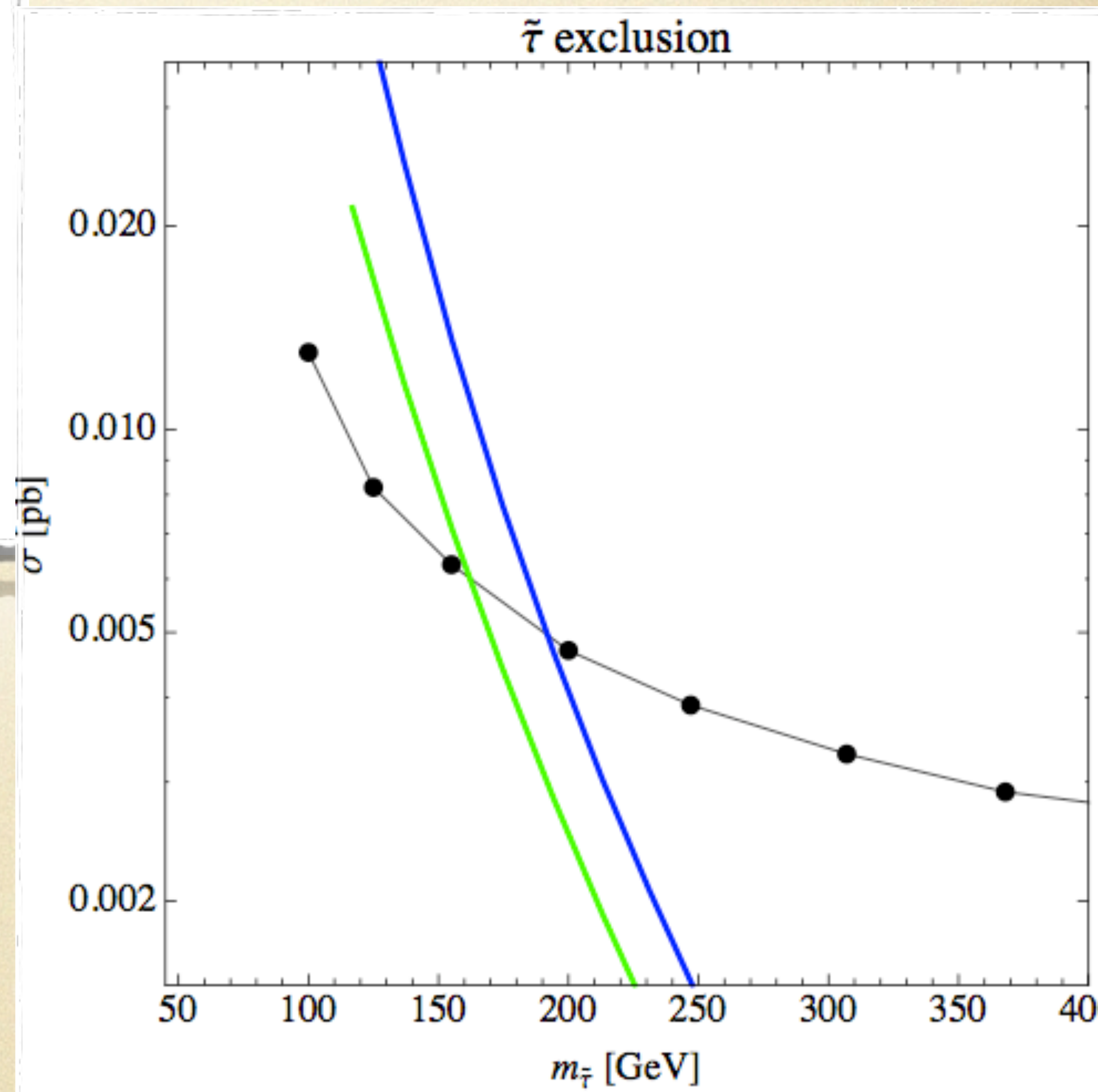
$$cos^2\theta_u = cos^2\theta_d = 0.8$$



Benchmark point 3: Stau



[Lindert, Steffen, Trenkel (2011)]



Comments...

- Limit on stau mass > 180 GeV from EXOTICA analyses

Some early conclusions before going on...

- TGM is a simple and testable scenario at the LHC...

  ....with nice predictions!!!

  - In SO(10) realization has a peculiar relation for the ratio of soft masses
  - Can have very different phenomenologies depending on the NLSP
  - Can be tested through inclusive (Razor) or exclusive analyses...

    ...need for multi-b oriented searches (still not on the market)

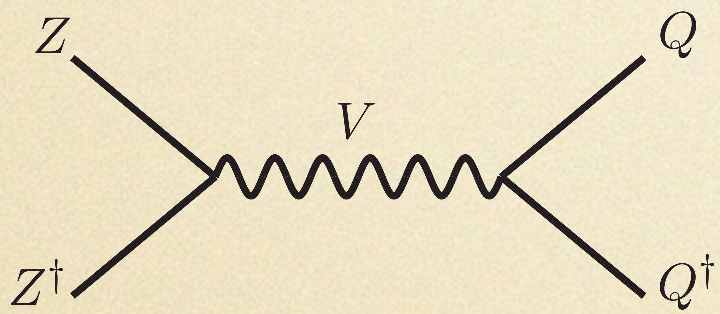
TGM beyond SO(10): an E_6 model

[MM, Nardecchia, Romanino, Ziegler (2011)]

- The essential idea is to extend the previous model. Why?
  - Extend the model
    - SO(10) is the minimal situation, E6 represents the next-to-minimal one. Greater freedom.
    - It happens that the fundamental representation of E6 is the 27 containing both a 10 and a 16 of SO(10). This would allow to have all the MSSM fermions in a single GUT representation.
  - In TGM theory arises a particular operator that can generate Dirac neutrino masses.
  - Connection to string theory

TGM strikes back

- In general TGM theory we have a breaking $G \to H$
  - Generators of G/H are heavy, $(M^2_{V_0})_{ab} = g^2 \phi_0^\dagger \{T^h_a, T^h_b\} \phi_0 = M^2_{V_a} \delta_{ab}$
- Sfermion masses are given by the graph below



$$\tilde{m}^2_{ij} = 2g^2 (T^h_a)_{ij} \frac{F_0^\dagger T^h_a F_0}{M^2_{V_a}}$$

- F-term vevs induce D-term for the heavy vector superfields

$$\langle D^h_a \rangle = -2g \frac{F_0^\dagger T^h_a F_0}{M^2_{V_a}} \longrightarrow \tilde{m}^2_{ij} = -g (T^h_a)_{ij} \langle D^h_a \rangle$$

- In SO(10) just one induced D-term.
- In E_6? $\longrightarrow$ ***UP TO 4 SM SINGLET GENERATORS***

Some E$_6$ group stuff

- E$_6$ is a rank 6 group. I study the following two subgroups

$$SM \times U(1)_5 \times U(1)_{10} \longleftarrow E_6 \longrightarrow SM \times SU(2)' \times U(1)'$$

From the breaking chain

$$E_6 \to SO(10) \times U(1)_{10} \to SU(5) \times U(1)_5 \times U(1)_{10}$$

the fundamental representation breaks as $27 \to 16_1 + 10_{-2} + 1_4$

$$16_1 \to \overline{5}_{-3,1} + 10_{1,1} + 1_{5,1} \qquad 10_{-2} \to \overline{5}_{2,-2} + 5_{-2,-2} \qquad 1_4 \to 1_{0,4}$$

the adjoint representation breaks as $78 \to 45_0 + 16_{-3} + \overline{16}_3 + 1_0$

$$45_0 \to 24_{0,0} + 10_{-4,0} + \overline{10}_{4,0} + 1_{0,0} \qquad 1_0 \to 1'_{0,0}$$

$$16_{-3} \to \overline{5}_{-3,-3} + 10_{1,-3} + 1_{5,-3} \qquad \overline{16}_3 \to 5_{3,3} + \overline{10}_{-1,3} + 1_{-5,3},$$

- Induced D-terms from SM singlets of 78 representation
- SM fields embedded in 27 representation

One messenger case

- Consider the case in which $E_6 \to SM \times G$

- Only one SM singlet generator in G

- Only one induced D-term

$$m_X^2$$

$$\hat{t}_X = sin\theta_X\, \hat{t}_5 + cos\theta_X\, \hat{t}_{10}$$

$$m^2(\overline{5}_{2,-2}) = 2(\hat{s}_X - \hat{c}_X)m_X^2$$
$$m^2(10_{1,1}) = (\hat{s}_X + \hat{c}_X)m_X^2$$
$$m^2(\overline{5}_{-3,1}) = (-3\hat{s}_X + \hat{c}_X)m_X^2$$

- Mass sum rule

$$m^2(\overline{5}_{-3,1}) + m^2(\overline{5}_{2,-2}) + m^2(10_{1,1}) = 0$$

Two different embeddings

One messenger case

- What we obtained before? $\hat{t}_X = sin\theta_X \, \hat{t}_5 + cos\theta_X \, \hat{t}_{10}$

$$m^2(\overline{5}_{2,-2}) = 2(\hat{s}_X - \hat{c}_X)m_X^2$$
$$m^2(10_{1,1}) = (\hat{s}_X + \hat{c}_X)m_X^2$$
$$m^2(\overline{5}_{-3,1}) = (-3\hat{s}_X + \hat{c}_X)m_X^2$$

- Case 1: standard SO(10) TGM prediction

$$cos\theta_X = 0 \qquad m_{\overline{5}}^2 = 2m_{10}^2$$

- Case 2: SO(10) invariant sfermion masses

$$sin\theta_X = 0 \qquad m_{\overline{5}}^2 = m_{10}^2$$

SUGRA (CMSSM) prediction!!!

Two and Four messengers cases

- In general with rank 6 groups

$$E_6$$

$$SM \times U(1)_5 \times U(1)_{10} \qquad SM \times SU(2)' \times U(1)'$$

Two different induced D-terms — Two different soft masses

Any ratio m_5/m_{10} can be obtained

Less predictive... but **Still SU(5) invariant prediction!!!**

- And higgs soft masses?

They heavily depend on the specific embedding...

- And gaugino masses?

There are no new relevant features, they just depend on yukawa ratios...

Summary

- TGM is a simple and testable scenario at the LHC...

  ....with nice predictions!!!

  - In SO(10) realization has a peculiar relation for the ratio of soft masses
  - Can have very different phenomenologies depending on the NLSP
  - Can be tested through inclusive (Razor) or exclusive analyses...

    ...need for multi-b oriented searches (still not on the market)

- TGM 2.0
  - Any ratio of soft masses can be obtained
  - Predictions of TGM are SU(5) invariant