# *Determining the masses of semi-invisibly decaying particles at the LHC*

Myeonghun Park

With: P. Konar(UF), KC.Kong(SLAC), Konstantin Matchev (UF)

# Difficulties

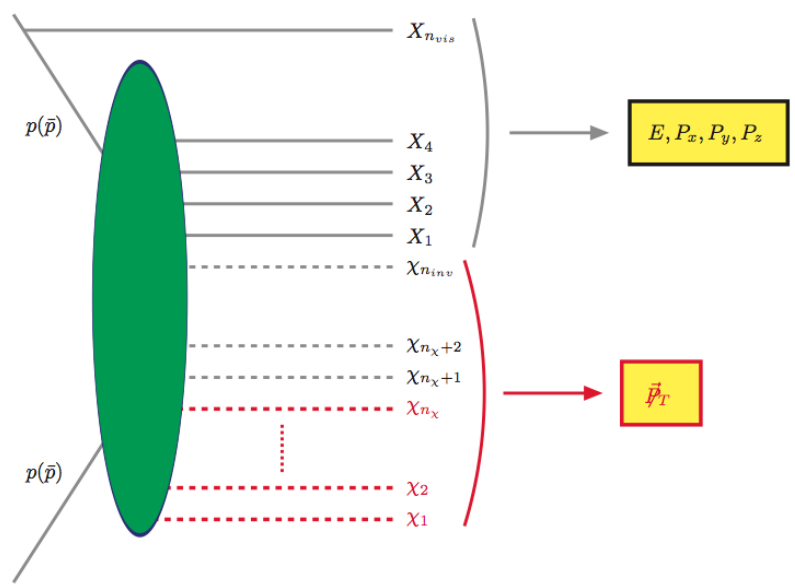
- O(100) parameters (MSSM) to determine the Model, compared to O(10) parameters in SM.
- Missing transverse energy signatures make it difficult to reconstruct events.
- Missing particles may come from BSM mixed with SM neutrino.
- We start with Hadron Collider:

  a) Uncertainty of CM energy and boost along the beam direction

  b) Jetty environment

# One way to go

- Starting from collider-related parameters:
  : (E, P ) ~ mass spectrum.
- Still hard to measure mass spectrum, requiring to design the proper techniques for LHC



# Contents

# Global variables

- The first variable to use with less assumptions.

  eg1) $M_{est} = \Sigma_i |p_{T(i)}| + E_T^{miss}$

  Proposed by Dan Tovey in hep-ph/0006276

  motivated by $p_T = \frac{1}{2}\left(M_p - \frac{M_c^2}{M_p^2}\right)$

  $M_{susy} = \frac{\sum_i \sigma_i m_i}{\sum_i \sigma_i}$ so that $M_{susy}^{eff} = \left(M_{susy} - \frac{M_\chi^2}{M_{susy}}\right)$

  called as $M_{eff}$ or $H_T$

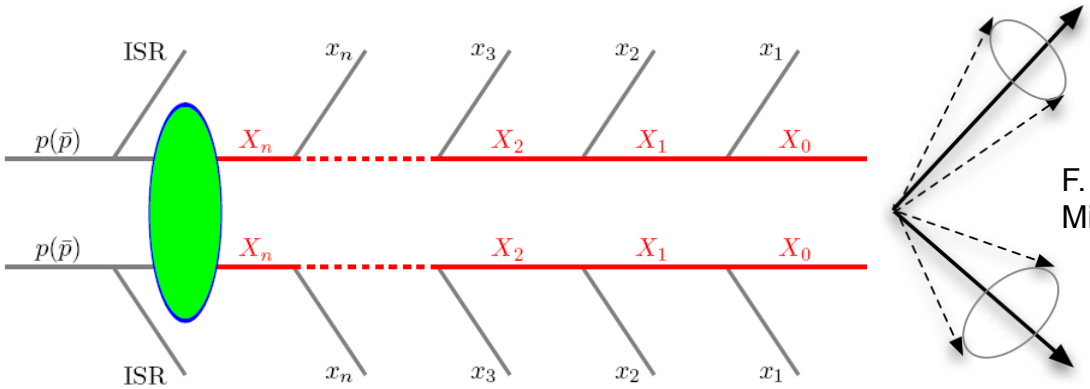
  eg2) $M_{TGen}$ motivated by $M_{T2}$ by C.G. Lest et.al

  JHEP 0712:102,2007

  eg3) $S_{min}$

# HT and MTgen

- Global variables under assumption:





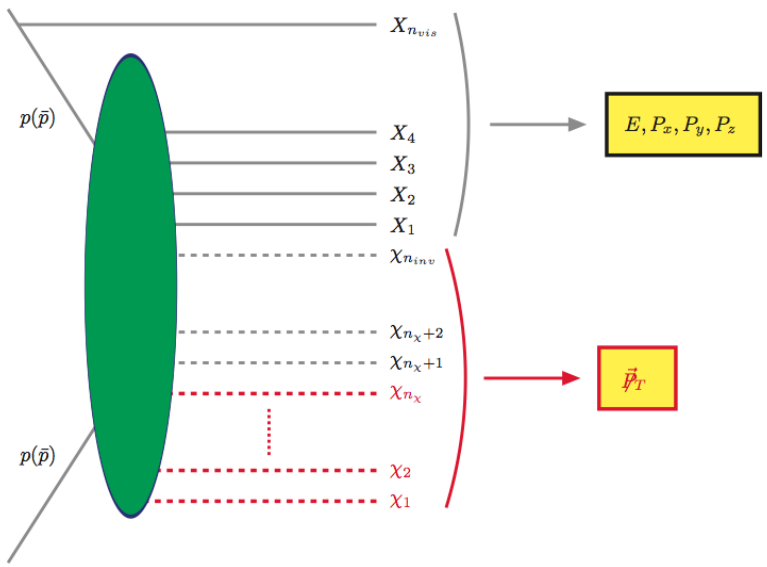

F. Moortgat and L. Pape, CMS Physics TDR, Vol. II
Mihoko M. Nojiri et.al arXiv:0802.2412

$$d(p_k, p_i^{\text{vis}}) = (E_i - |p_i^{\text{vis}}| \cos\theta_{ik}) \frac{E_i}{(E_i + E_k)^2}$$

- They need to make a partition with visible particles, for example using hemisphere method (HT) or taking smallest value out of all possible partitioning($M_{TGen}$)

# $S_{min}$

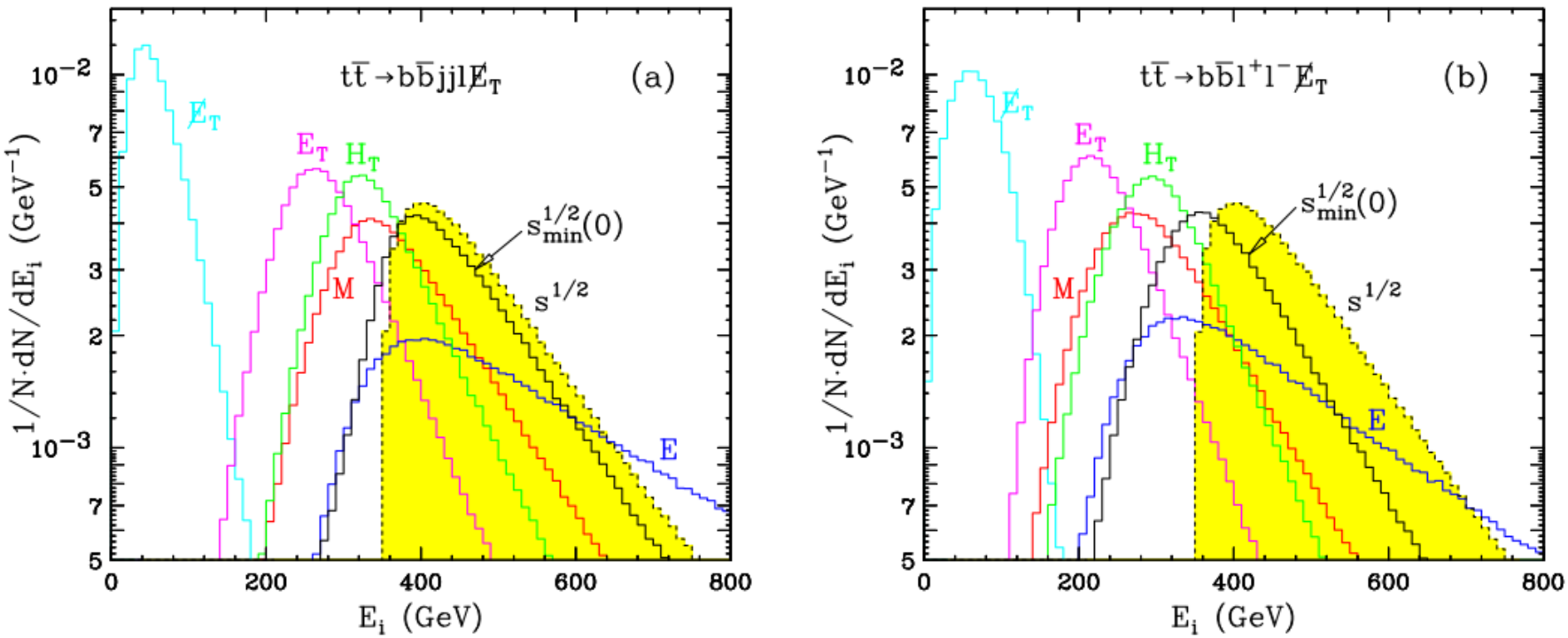
- Motivated to Mimic the true $\sqrt{\hat{S}}$




Minimize the parton-level CM energy with a constraint from MET: $\vec{P}_T + \vec{\not{P}}_T = 0$

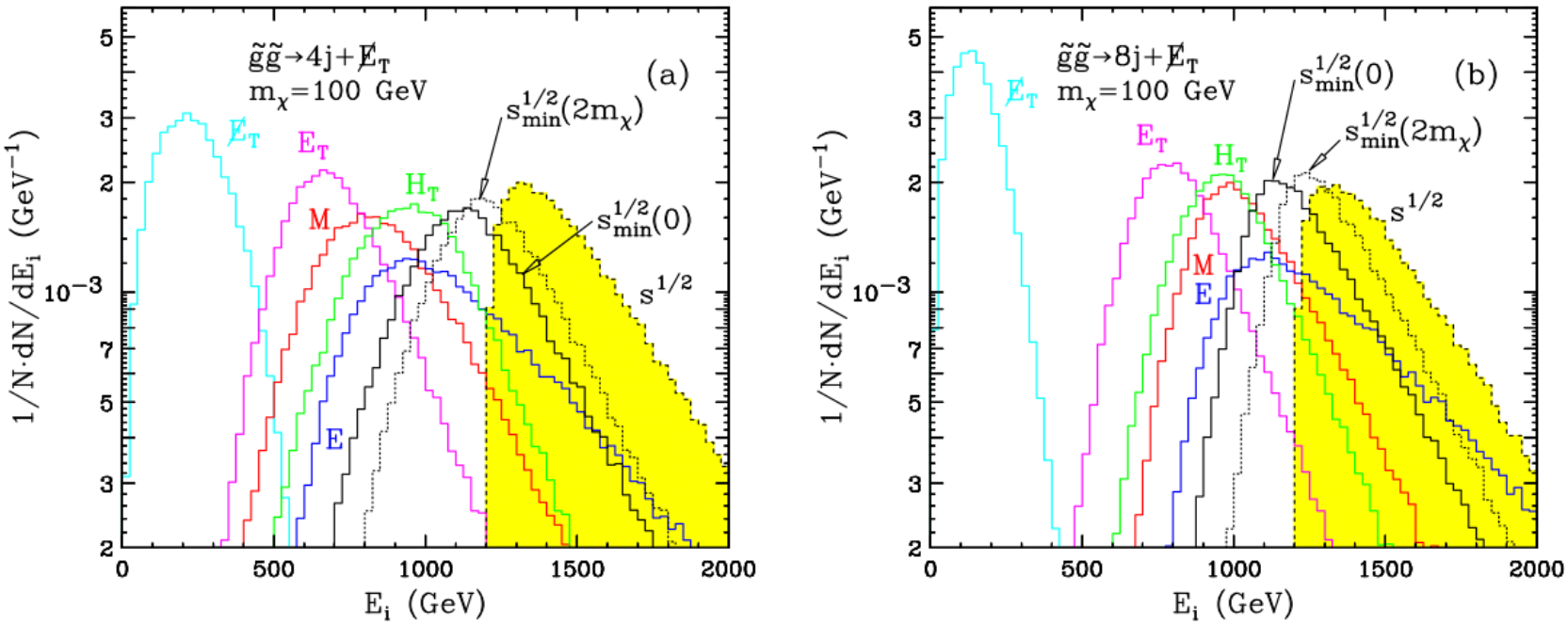
$$\hat{s}_{min}^{1/2}(M_{inv}) = \sqrt{E^2 - P_z^2} + \sqrt{\not{P}_T^2 + M_{inv}^2}$$

# $S_{min}$




- Better indicator of the relevant energy scale
- The peak of $S_{min}$ ~ sum of Mother particles' mass, even without reconstructing objects.

# $S_{min}$

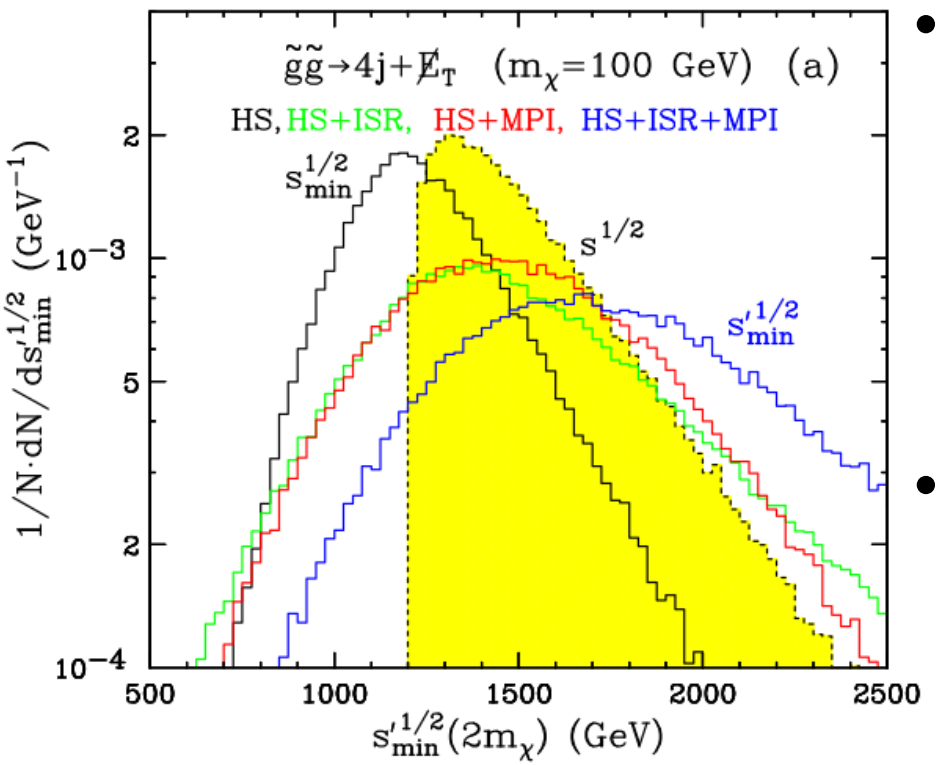



- Problems : Contaminated by underlying events

  + dependency on unknown mass

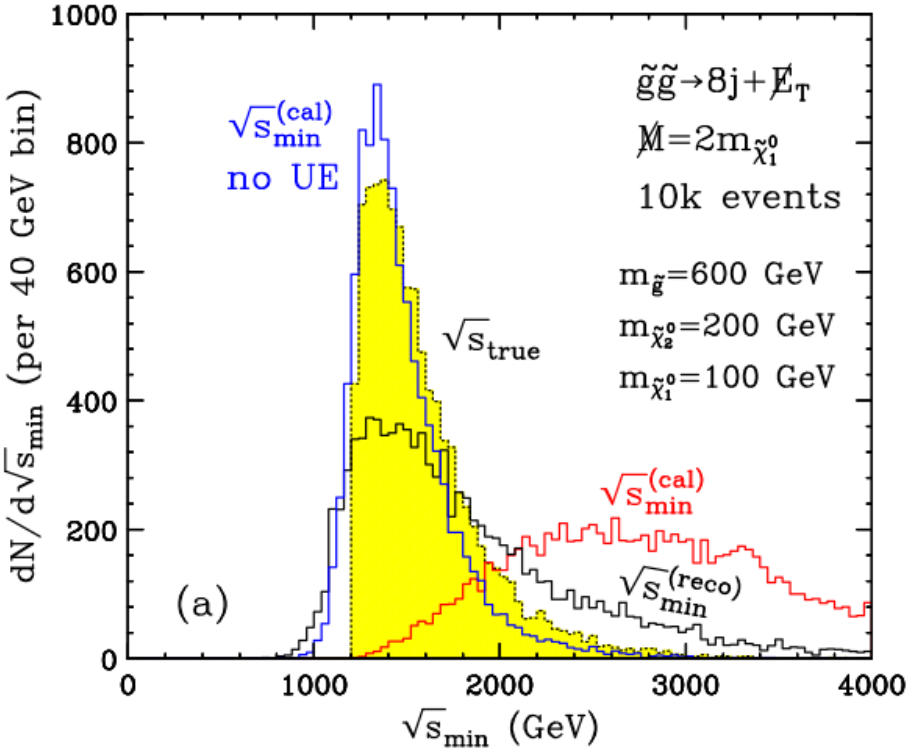
  (missing particles) $\hat{s}_{min}^{1/2}(M_{inv}) = \sqrt{E^2 - P_z^2} + \sqrt{\not{P}_T^2 + M_{inv}^2}$

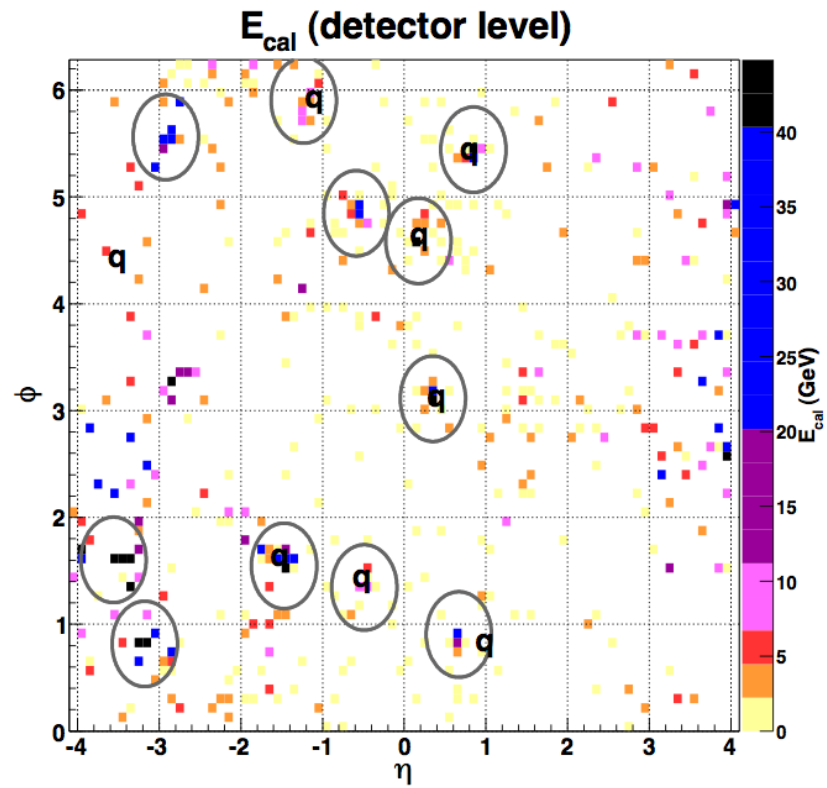
# ISR/MPI effect on $S_{min}$




- Real event can have Initial state radiation (ISR), multiple parton interactions (MPI) and pile-up.
- If not controlled, these extra contributions can increase $S_{min}$

# Removal of ISR/MPI effect on $S_{min}$



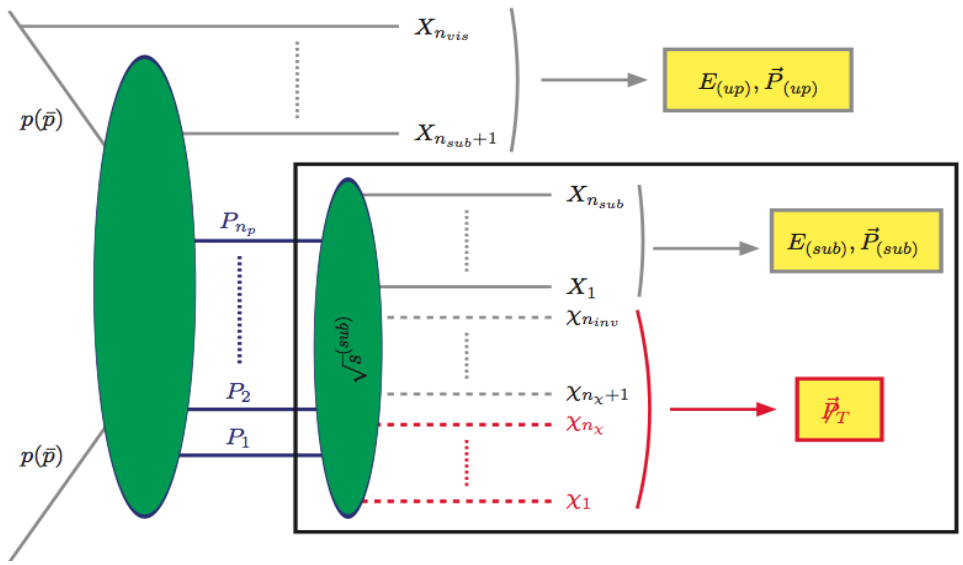




We can use only reconstructed objects.

Or we can use only relevant objects in some signals like as t->b+W

# Subsystem $S_{min}$

- If we divide objects into two categories.

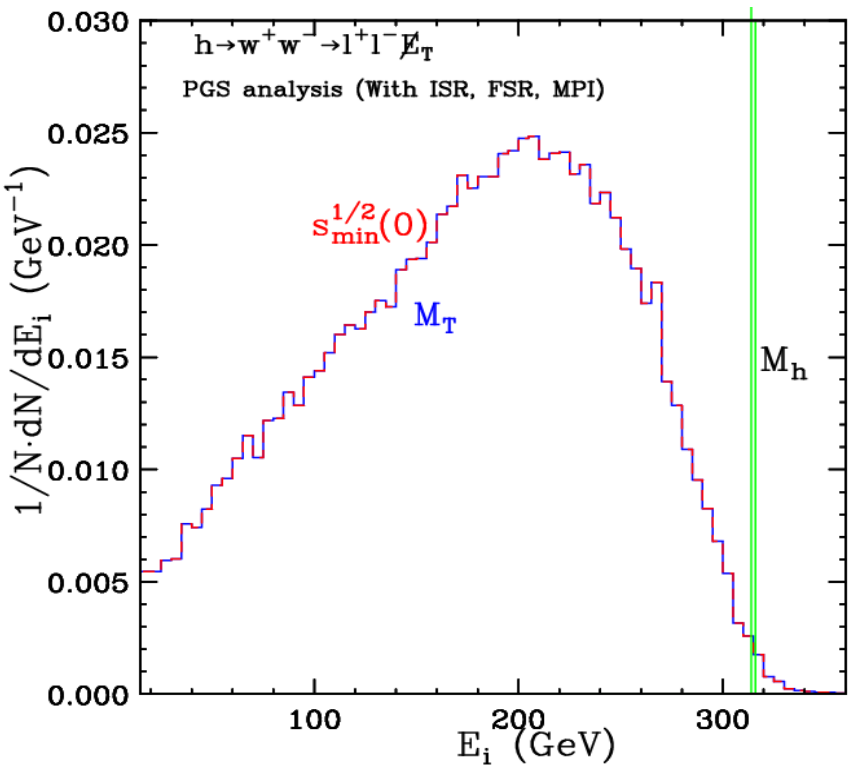


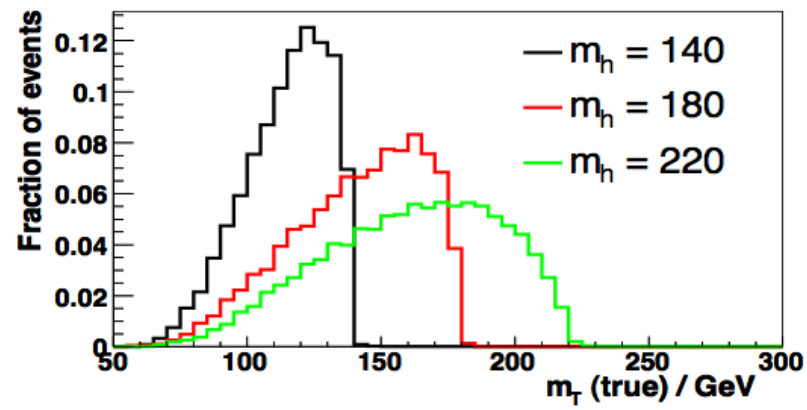

$$\sqrt{s}^{(sub)}_{min}(\not{M}) = \left\{ \left( \sqrt{E^2_{(sub)} - P^2_{z(sub)}} + \sqrt{\not{M}^2 + \not{P}^2_T} \right)^2 - P^2_{T(up)} \right\}^{\frac{1}{2}}$$

- We can remove ISR effects, introducing another applications.

# Subsystem $S_{min}$

- Higgs to W's and 2lepton+ 2 neutrino system.




This application was known as $m_T$(true) by Alan J. Barr et.al (JHEP 0907:072,2009)

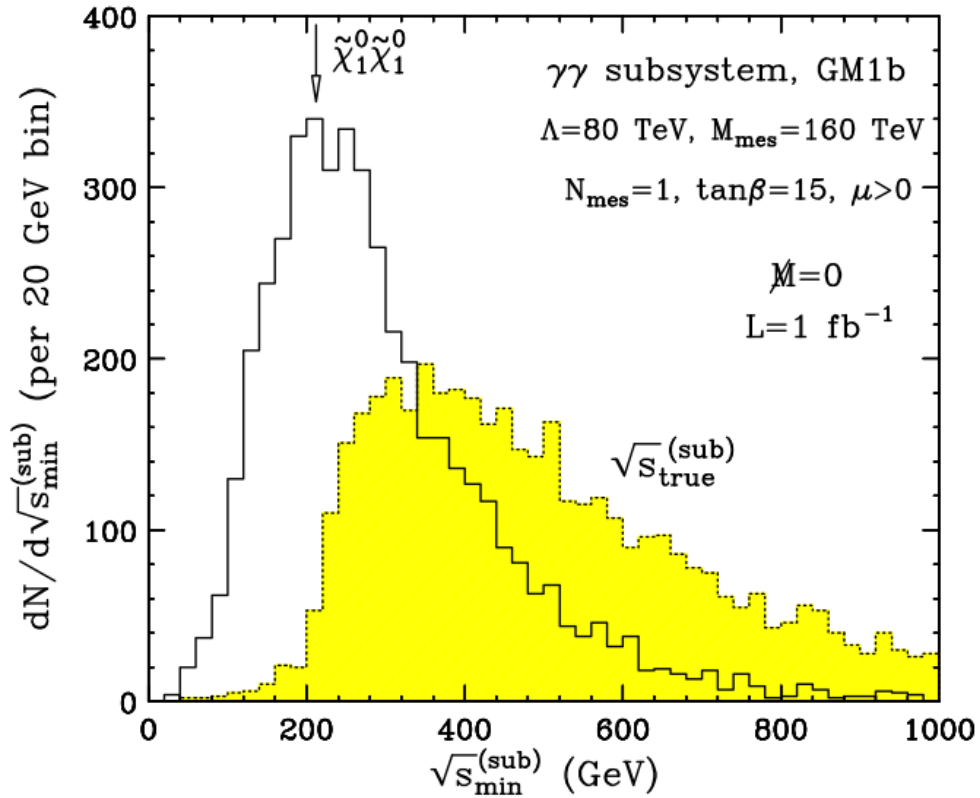
$$m_T^{\text{true}} \equiv m_T^2(m_i = 0) = m_v^2 + 2(e_v|\vec{\not{P}}_T| - \mathbf{p}_v \cdot \vec{\not{P}}_T)$$

# Subsystem $S_{min}$

- GMSB with subsystem $\tilde{\chi}_1^0 \to \tilde{G} + \gamma$

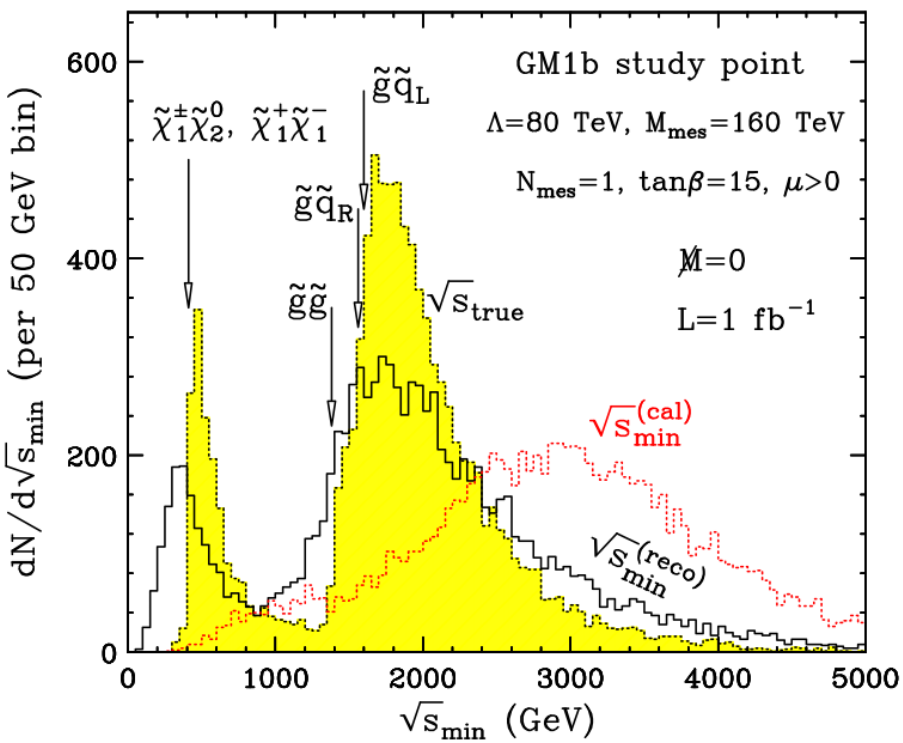
| Points | $\Lambda$ | $M$ | $\tan\beta$ | $N_5$ | sgn($\mu$) | $C_{grav}$ | $M(\tilde{\chi}_1^0)$ | $c\tau(\tilde{\chi}_1^0)$ |
|---|---|---|---|---|---|---|---|---|
| GM1b | 80 TeV | $2\Lambda$ | 15 | 1 | + | 1 | 109.6 GeV | 0.14 mm |
| GM1c | 100 TeV | $2\Lambda$ | 15 | 1 | + | 1 | 138.8 GeV | 0.10 mm |
| GM1e | 140 TeV | $2\Lambda$ | 15 | 1 | + | 1 | 196.8 GeV | 0.06 mm |
| GM1f | 160 TeV | $2\Lambda$ | 15 | 1 | + | 1 | 225.7 GeV | 0.05 mm |
| GM1g | 180 TeV | $2\Lambda$ | 15 | 1 | + | 1 | 254.7 GeV | 0.04 mm |

Table 1: GMSB model parameters for $pp \to \tilde{g}\tilde{g}$ production. The following minimal GMSB parameters are used: $\Lambda$ determines the scale of the SUSY breaking; messenger mass scale $M = 2\Lambda$; the ratio of the Higgs vev's $\tan\beta = 15$; number of messengers $N_5 = 1$; the sign of Higgsino mass term sgn($\mu$)$> 0$; and the $C_{grav}$ is used to set NLSP lifetime.



# Back to $S_{min}$

- We can reconstruct mass parameters.

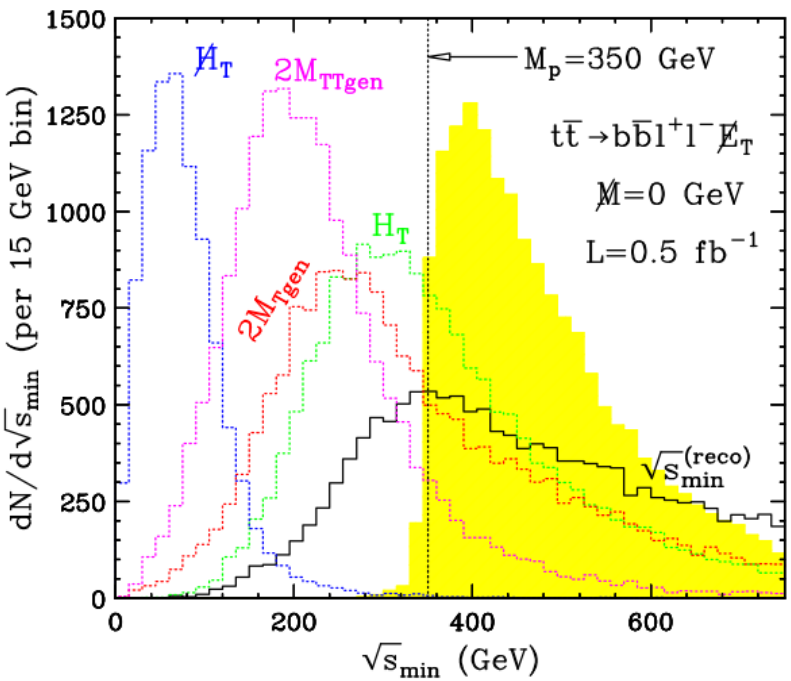


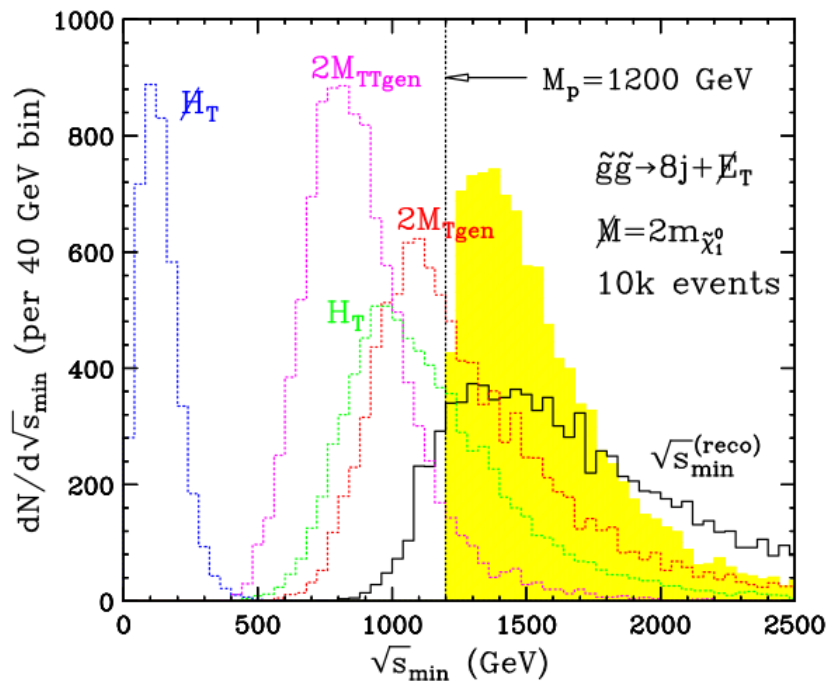

| $\tilde{u}_L$ | $\tilde{d}_L$ | $\tilde{u}_R$ | $\tilde{d}_R$ | $\tilde{\ell}_L$ | $\tilde{\nu}_\ell$ | $\tilde{\ell}_R$ | $\tilde{\chi}_2^\pm$ | $\tilde{\chi}_4^0$ | $\tilde{\chi}_3^0$ | $\tilde{g}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 908 | 911 | 872 | 870 | 289 | 278 | 145 | 371 | 371 | 348 | 690 |
| $\tilde{t}_1$ | $\tilde{b}_1$ | $\tilde{t}_2$ | $\tilde{b}_2$ | $\tilde{\tau}_2$ | $\tilde{\nu}_\tau$ | $\tilde{\tau}_1$ | $\tilde{\chi}_1^\pm$ | $\tilde{\chi}_2^0$ | $\tilde{\chi}_1^0$ | $\tilde{G}$ |
| 806 | 863 | 895 | 878 | 290 | 277 | 138 | 206 | 206 | 106 | 0 |

| Process | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ | $\tilde{\chi}_1^+\tilde{\chi}_1^-$ | $\tilde{g}\tilde{g}$ | $\tilde{g}\tilde{q}_R$ | $\tilde{g}\tilde{q}_L$ | $\tilde{q}_R\tilde{q}_R$ | $\tilde{q}_L\tilde{q}_R$ | $\tilde{q}_L\tilde{q}_L$ |
|---|---|---|---|---|---|---|---|---|
| $\sigma$ (pb) | 0.83 | 0.43 | 2.03 | 2.17 | 1.90 | 0.36 | 0.50 | 0.28 |
| $M_p$ (GeV) | 412 | 412 | 1380 | $\sim 1560$ | $\sim 1600$ | $\sim 1740$ | $\sim 1780$ | $\sim 1820$ |

# Comparison with other variables

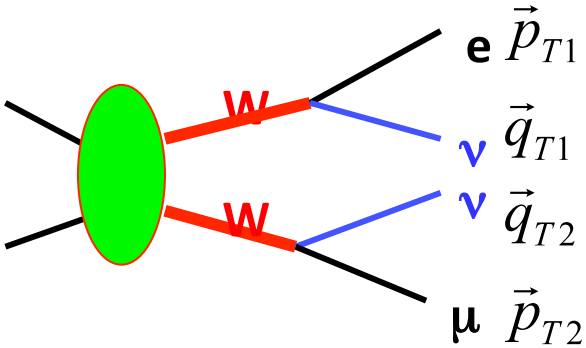
- HT suppose to track the peak, while $M_{Tgen}$ has endpoint to measure the mass spectrum.



# Model-Dependent variable: $M_{T2}$

- A pair of semi-invisibly decaying particles



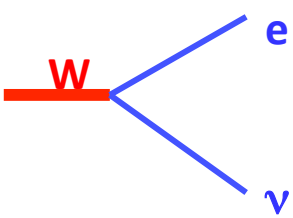

*Lester,Summers 99*
*Barr,Lester,Stephens 03*

The Best thing that we have : MET constraint

$$\not{E}_T = \vec{q}_{T1} + \vec{q}_{T2} = -\sum \vec{p}_{T(vis_k)}$$

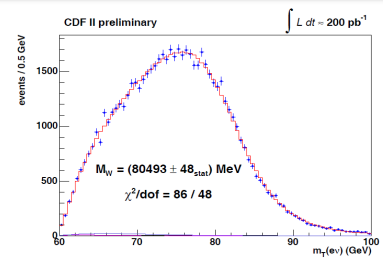
- If $\vec{q}_{T1}$ and $\vec{q}_{T2}$ are obtainable : $M_w \geq \max\{m_T(\vec{p}_{T1},\vec{q}_{T1}), m_T(\vec{p}_{T2},\vec{q}_{T2})\}$
- But since we don't get them, we can do partition !:

$$M_W \geq M_{T2} = \min_{\vec{q}_{T1}+\vec{q}_{T2}=\not{E}_T} [\max\{m_T(\vec{p}_{T1},\vec{q}_{T1}),\ m_T(\vec{p}_{T2},\vec{q}_{T2})\}]$$



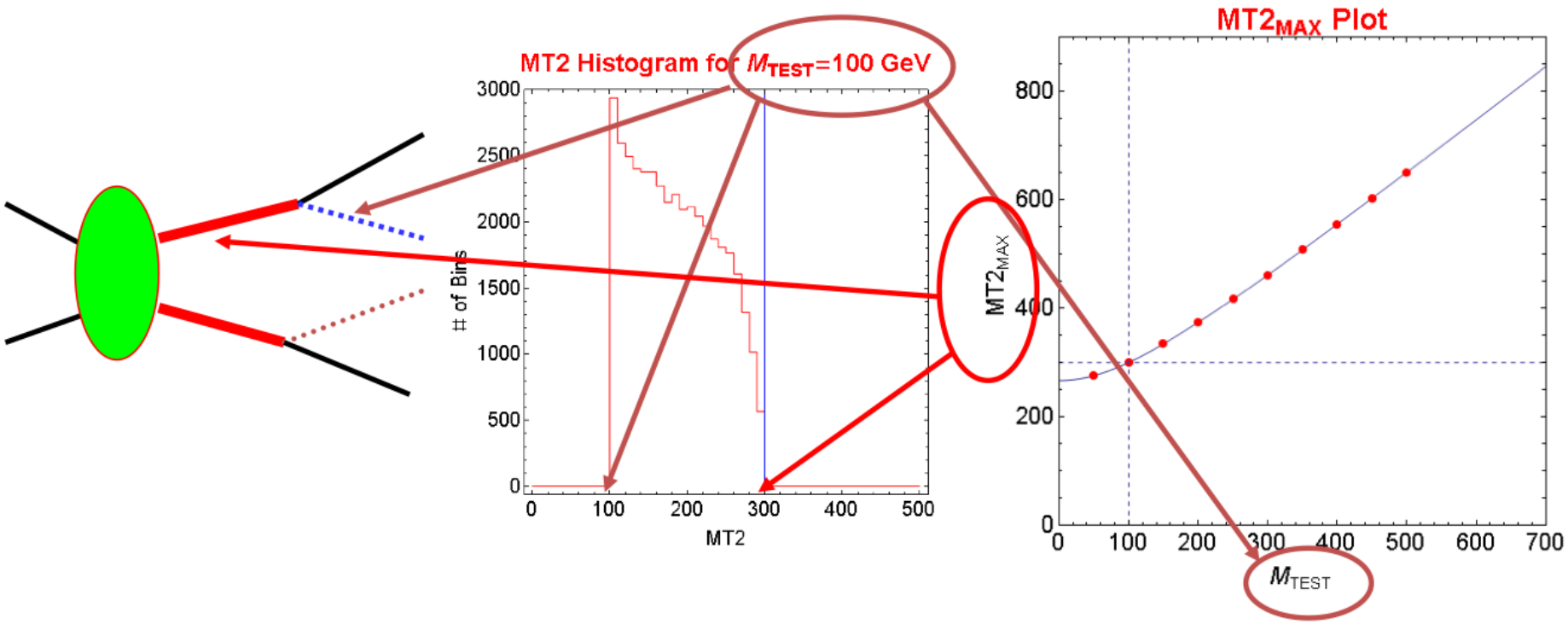

$$M_W^2 \geq m_T^2(e,\nu)$$

$$\equiv \left(\left|\vec{p}_{eT}\right| + \left|\vec{p}_{\nu T}\right|\right)^2 - \left(\vec{p}_{eT} + \vec{p}_{\nu T}\right)^2$$



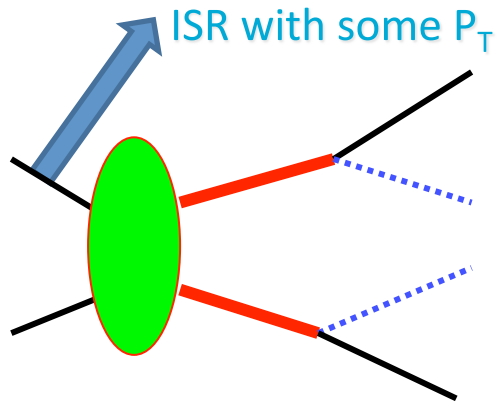
# MT2

- Even though MT2 is a constrained observable, still it is very powerful.

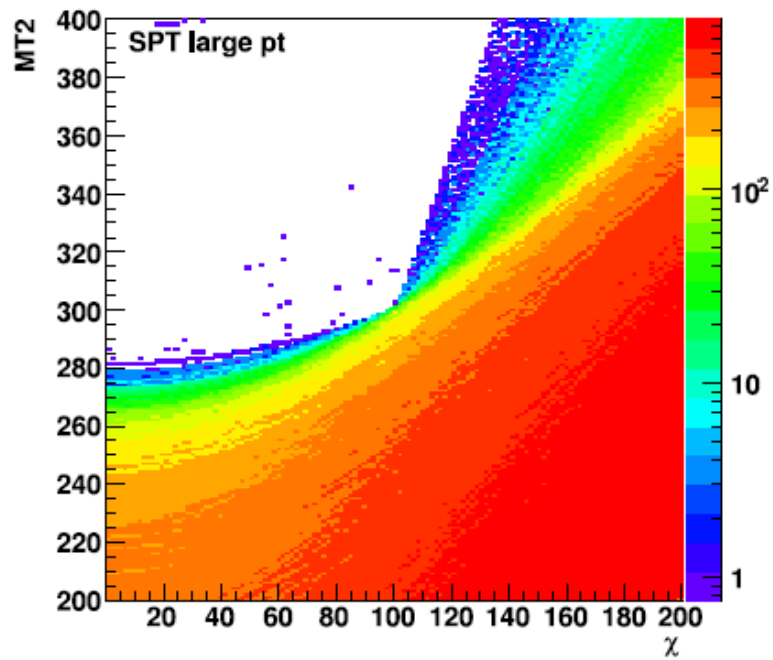


# Two important properties of Original $M_{T2}$

- "KINK" structure of $M_{T2}$
- "Boost"-invariance of $M_{T2}$ at the true spectrum.




(Barr, Gripaios, Lester, arXiv:0711.4008)



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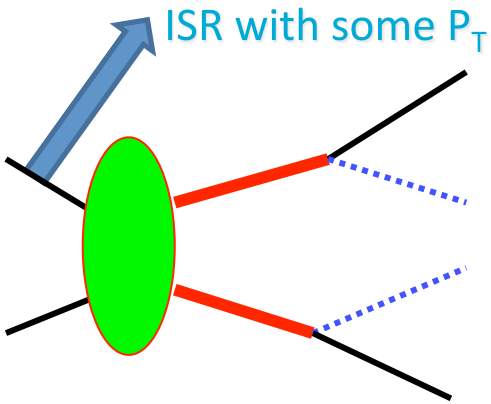
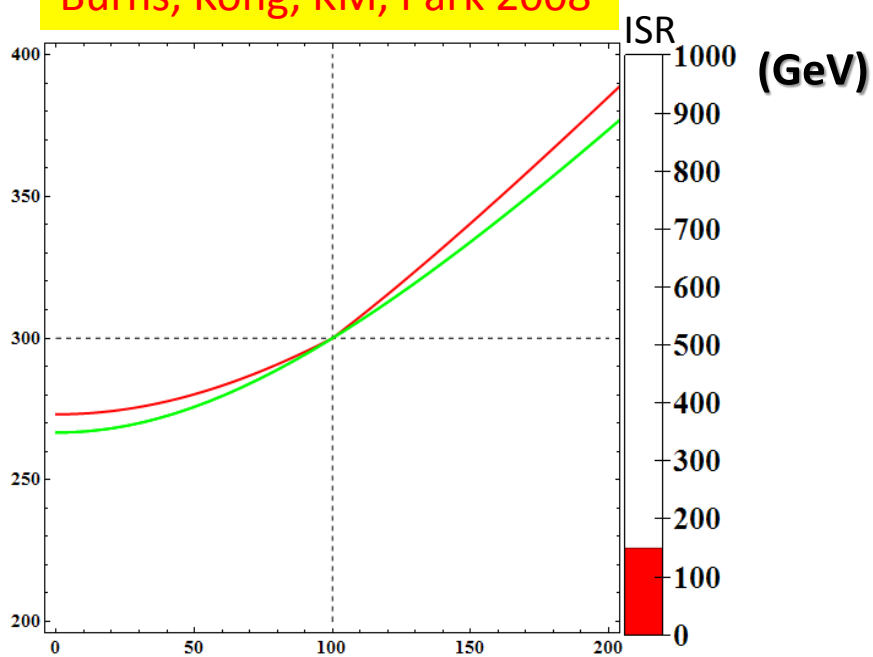
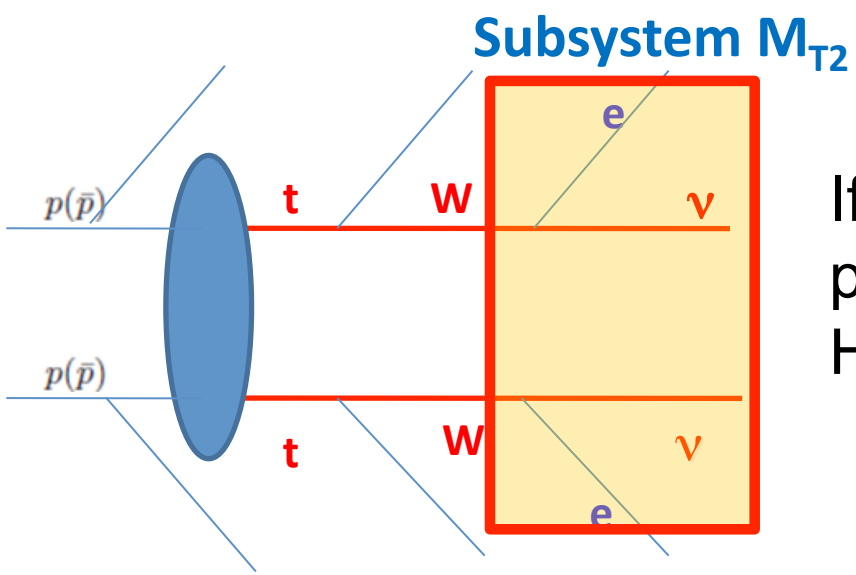



Burns, Kong, KM, Park 2008



# Revising of MT2

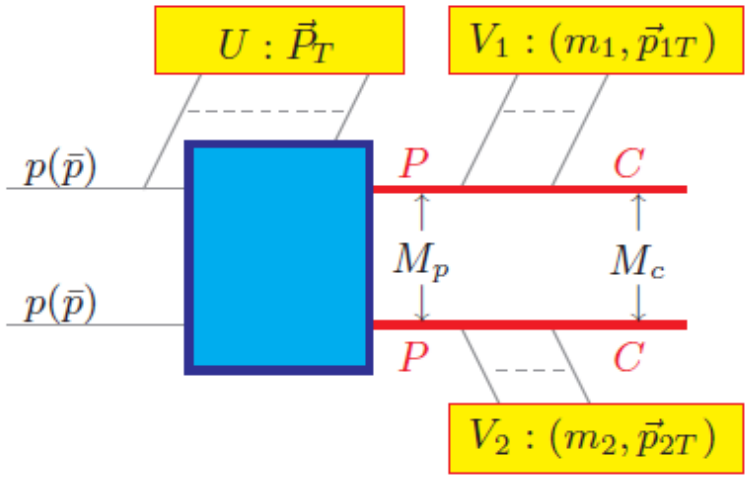
- @ LHC, there is problem called "Jet combinatorics" including ISR/FSR
- Thus the analysis using jets is challenging.
- How about using non-jet signal ?

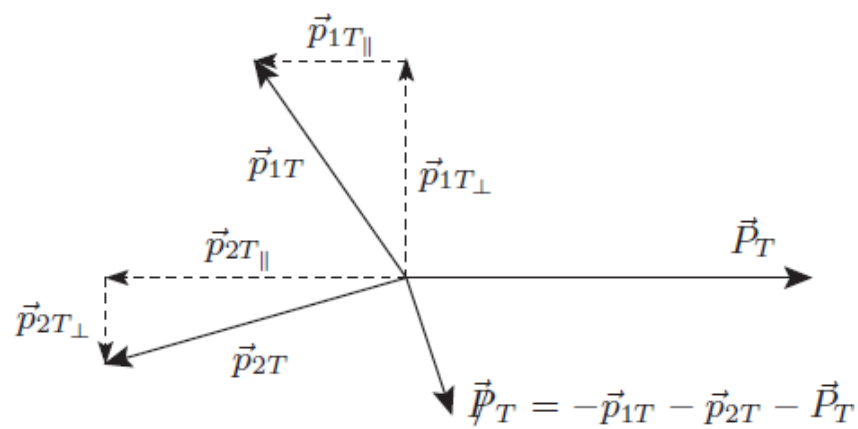



If we can measure missing particles' mass, then we can Handle this information to $S_{min}$

# Decompose the MT2

- We can use subsystem MT2 more wisely.

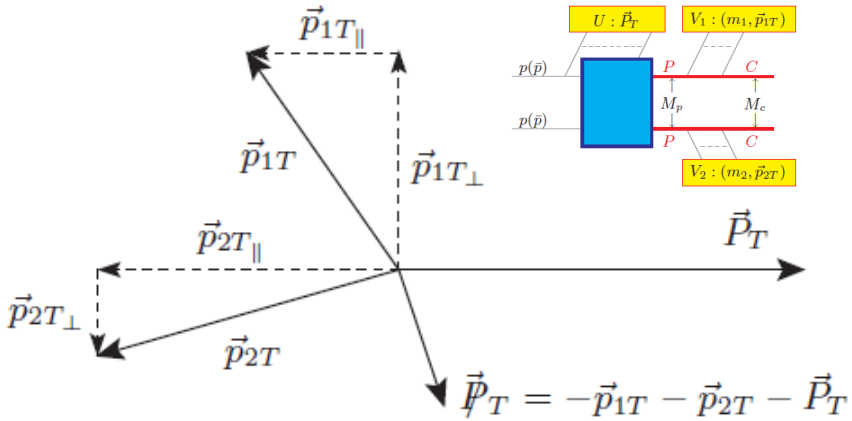



- If we decompose transverse direction into perpendicular and parallel to PT (jets) direction

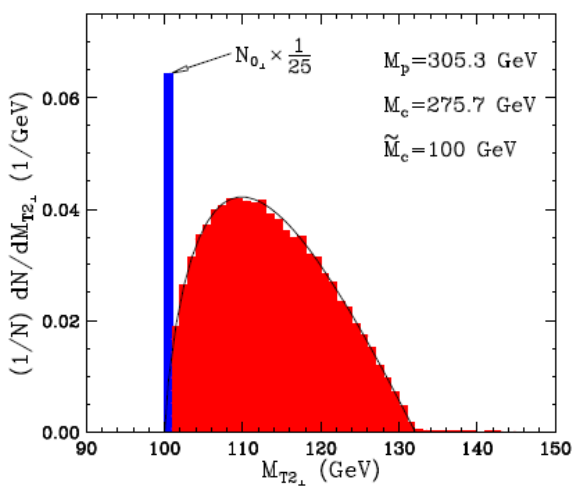
# Decompose the MT2

Decompose the visible section along the UTM direction




$$M_{T_\parallel}^{(i)} \equiv \sqrt{\tilde{M}_c^2 + 2\left(e_{iT_\parallel}\sqrt{\tilde{M}_c^2 + |\vec{p}_{cT_\parallel}^{(i)}|^2} - \vec{p}_{iT_\parallel}\cdot\vec{p}_{cT_\parallel}^{(i)}\right)},$$

$$M_{T_\perp}^{(i)} \equiv \sqrt{\tilde{M}_c^2 + 2\left(e_{iT_\perp}\sqrt{\tilde{M}_c^2 + |\vec{p}_{cT_\perp}^{(i)}|^2} - \vec{p}_{iT_\perp}\cdot\vec{p}_{cT_\perp}^{(i)}\right)},$$




$$M_{T2_\parallel}(\tilde{M}_c, \vec{P}_T, \vec{p}_{iT_\parallel}) \equiv \min\left\{\max\left\{M_{T_\parallel}^{(1)}, M_{T_\parallel}^{(2)}\right\}\right\}$$

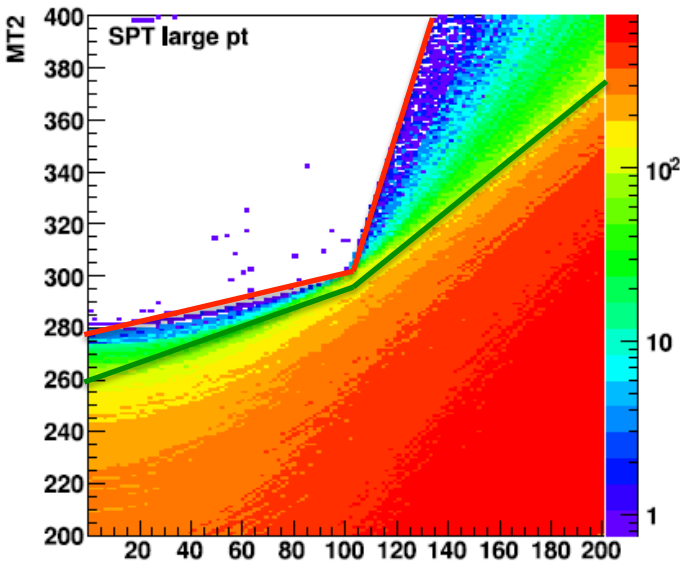
$$M_{T2_\perp}(\tilde{M}_c, \vec{p}_{iT_\perp}) \equiv \min\left\{\max\left\{M_{T_\perp}^{(1)}, M_{T_\perp}^{(2)}\right\}\right\}$$

1. We can get information purely independent of PT
   ( For example : lepton sector. )

2. We can get information depend on PT

# Let’s count !

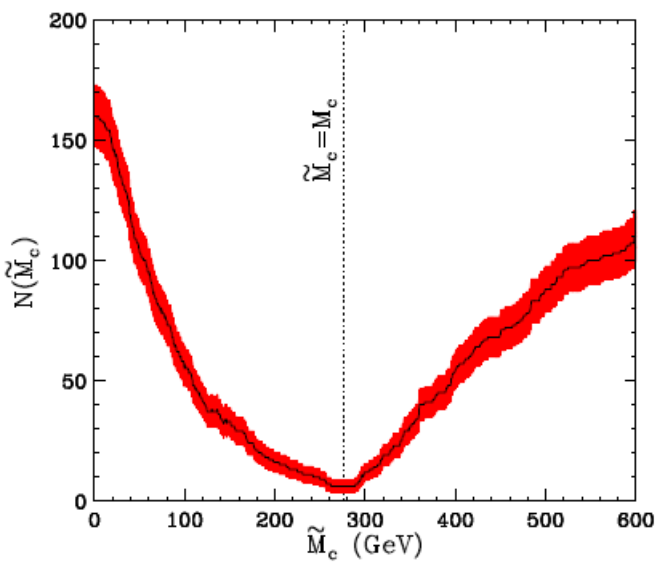
(Barr, Gripaios, Lester, arXiv:0711.4008)



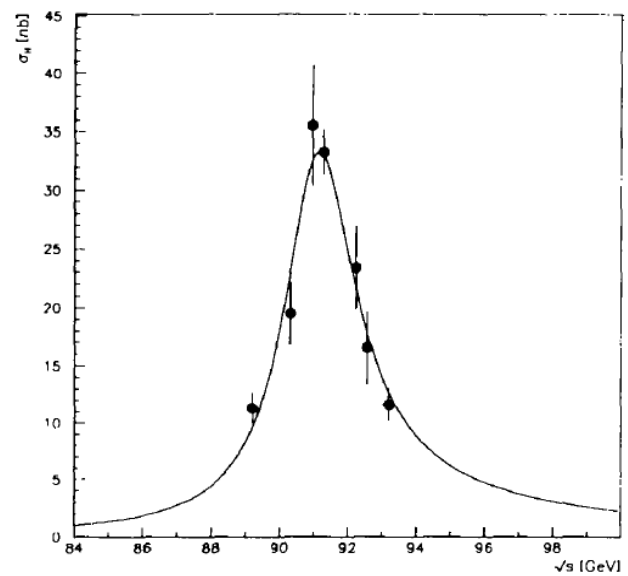

**Superpartner mass measurements with 1D decomposed M(T2).**
Partha Konar, (Florida U.) , Kyoungchul Kong, (SLAC) , Konstantin T. Matchev, Myeonghun Park, (Florida U.)
e-Print: **arXiv:0910.3679** [hep-ph]

$$N(\tilde{M}_c) \equiv \sum_{\text{all events}} H\left(M_{T2} - M_{T2_\perp}^{max}(\tilde{M}_c)\right)$$

Let’s count events whose MT2 is larger than MT2perp !

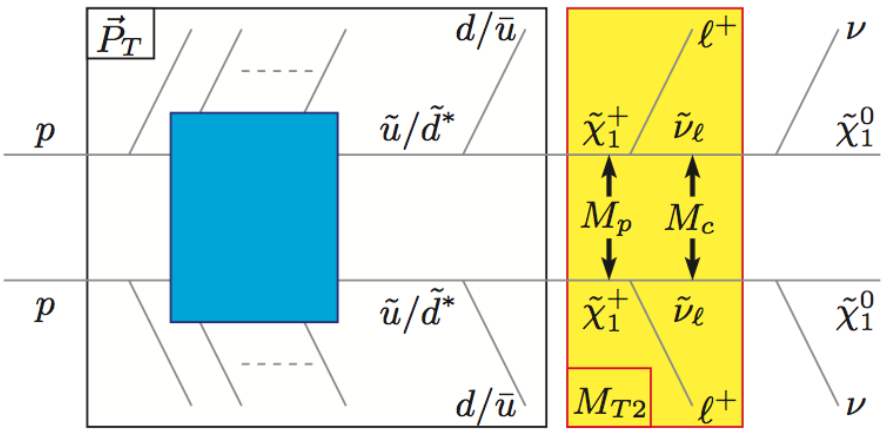



V.S.

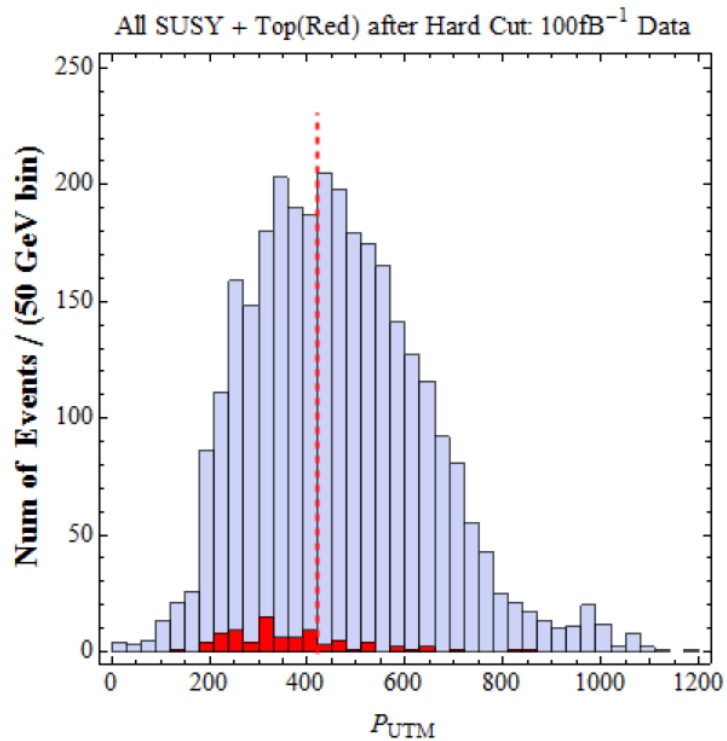


# Collider Study

- CMS LM6 study point




| $M_{\tilde{g}}$ | $M_{\tilde{q}_L}$ | $M_{\tilde{\chi}_1^+}$ | $M_{\tilde{\ell}_L}$ | $M_{\tilde{\nu}_\ell}$ | $M_{\tilde{\chi}_1^0}$ |
|---|---|---|---|---|---|
| 939.8 | 862 | 305.3 | 291.0 | 275.7 | 158.1 |

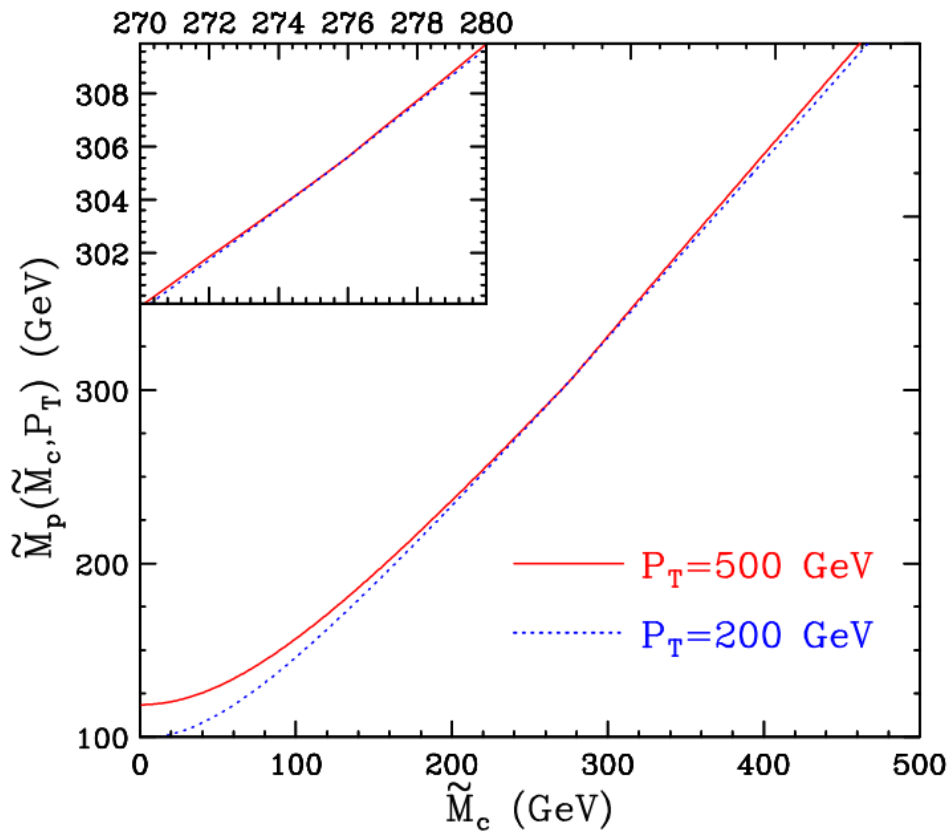



: hard cut: to remove SM backgrounds:

Two isolated leptons with pT > 10 GeV, at least three jets with pT>(175, 130, 55)GeV, MET>200GeV and a veto on tau jets.

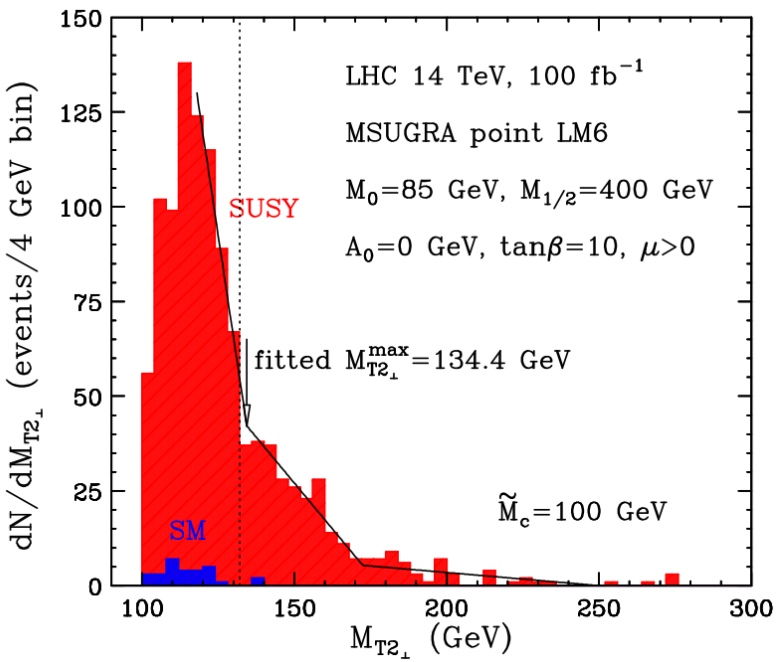
# Collider Study

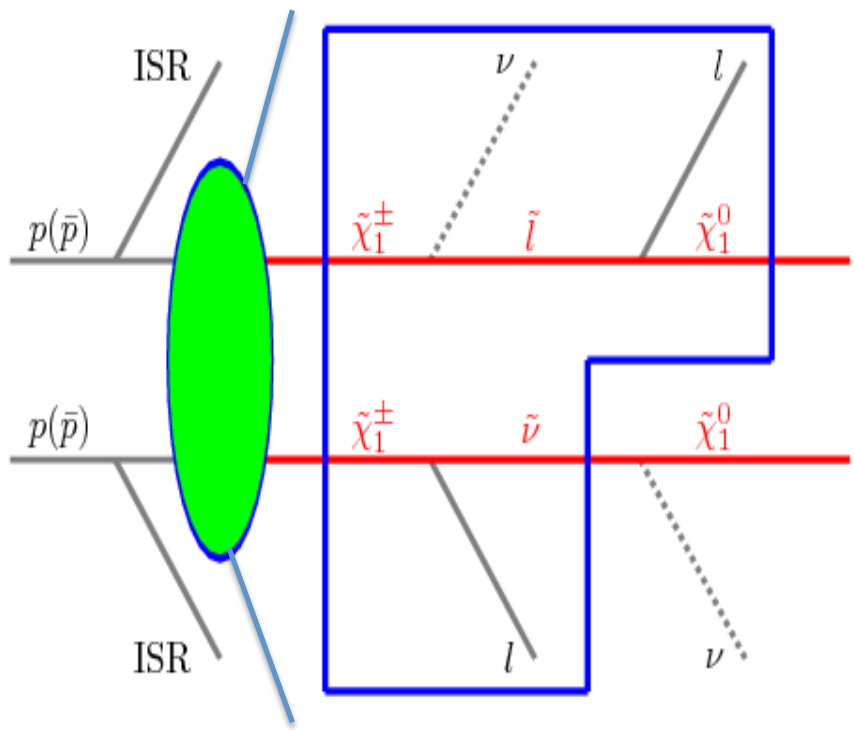
- Even though the MT2 KINK structure is not so clear



# Collider Study

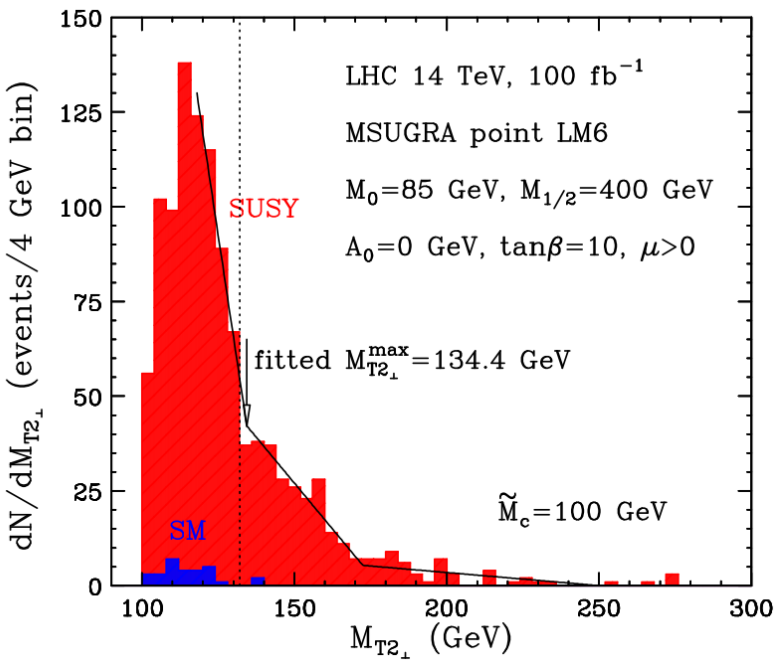
- We can apply our method to measure mass spectrum



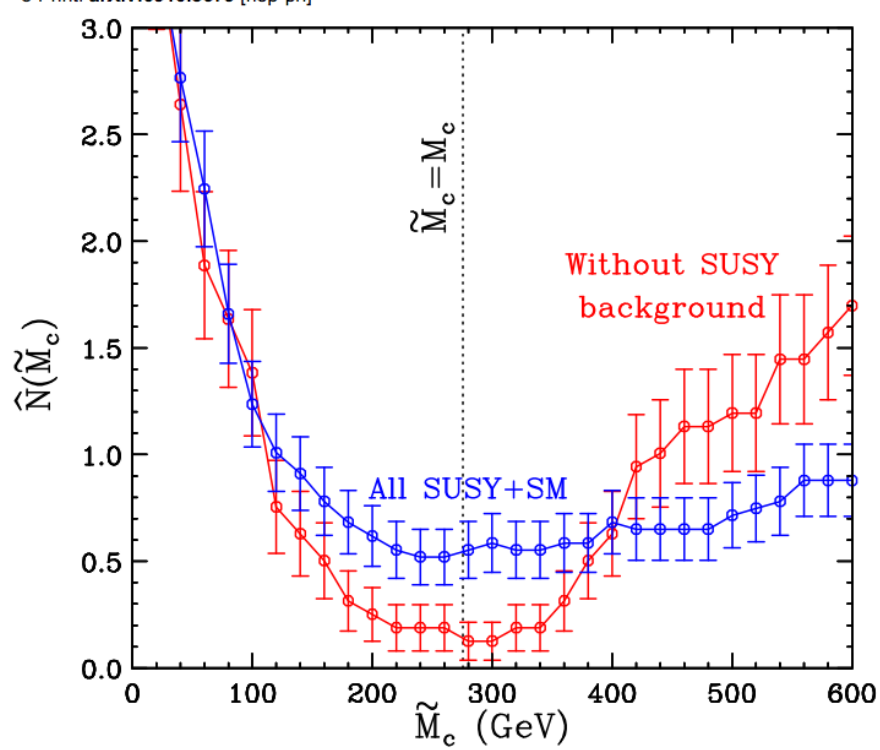



# Collider Study

- We can apply our method to measure mass spectrum

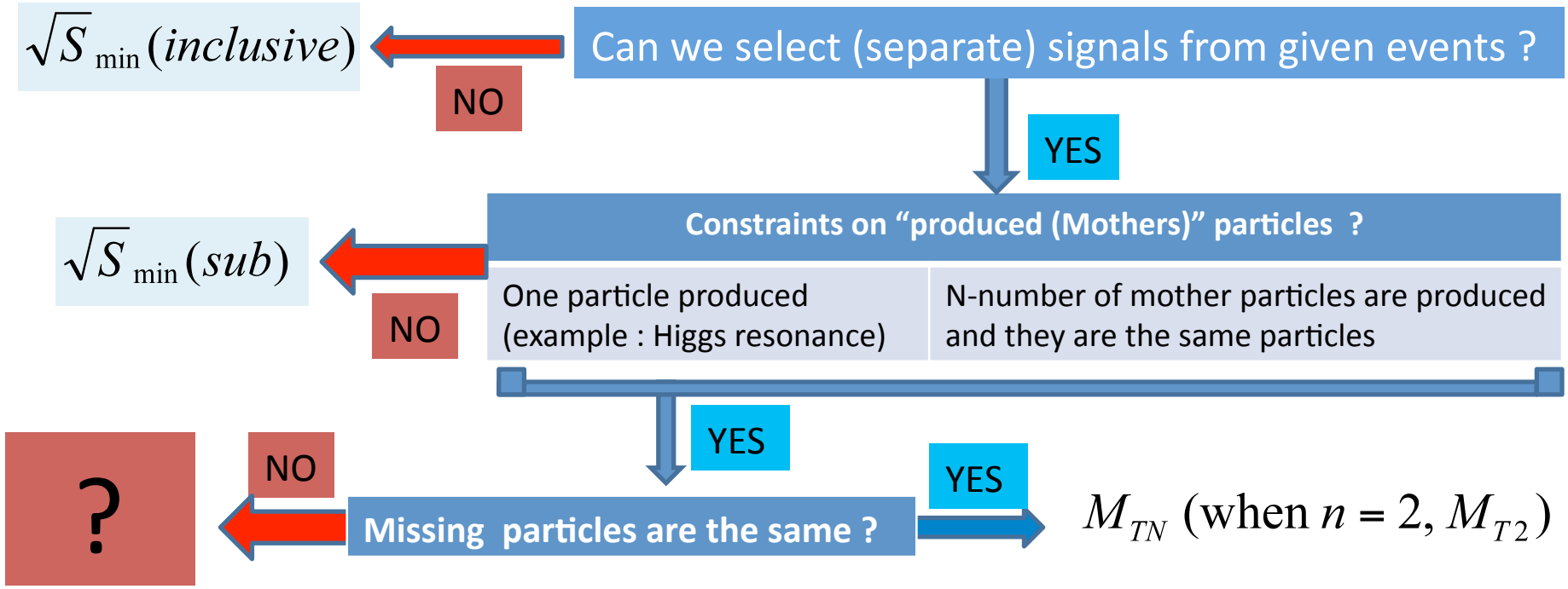



**Superpartner mass measurements with 1D decomposed M(T2).**
Partha Konar, (Florida U.) , Kyoungchul Kong, (SLAC) , Konstantin T. Matchev, Myeonghun Park, (Florida U.)
e-Print: **arXiv:0910.3679** [hep-ph]



# Relationship between $S_{min}$ and $M_{TN}$

Minimization of $\sqrt{S}$ with Missing $P_T$ constraint $(= \sqrt{S}_{\min})$



# Generalize $M_{T2}$ through $S_{min}$

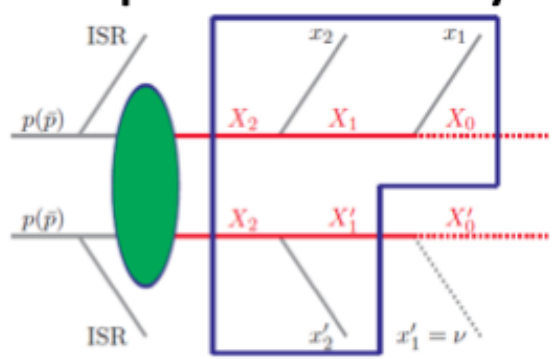
Constraints on "produced (Mothers)" particles to be the "SAME"

$\sqrt{S}_{\min}(sub)$ → Require → Missing particles are the same ?

NO → ? = **Generalized $M_{T2}$**

(a) There are maybe different types of WIMPS.
(Multiple Dark matters ?)

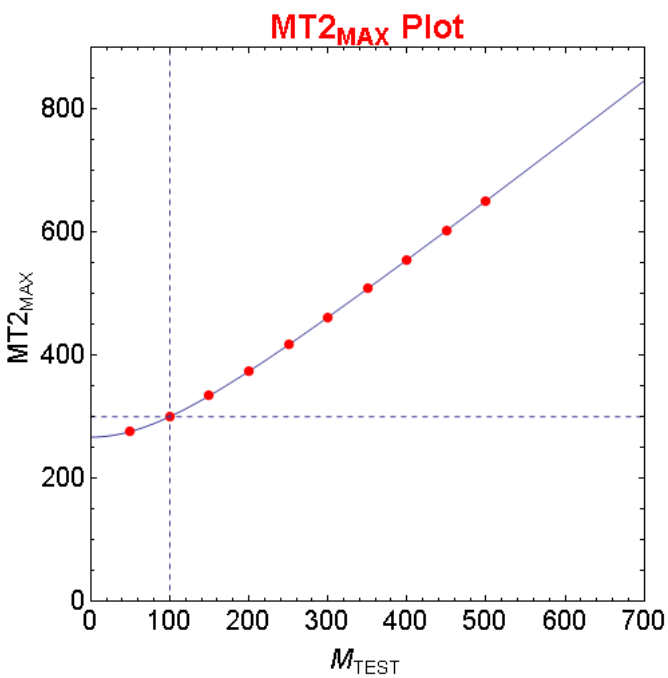
(b) Some heavier particle may decay invisibly.



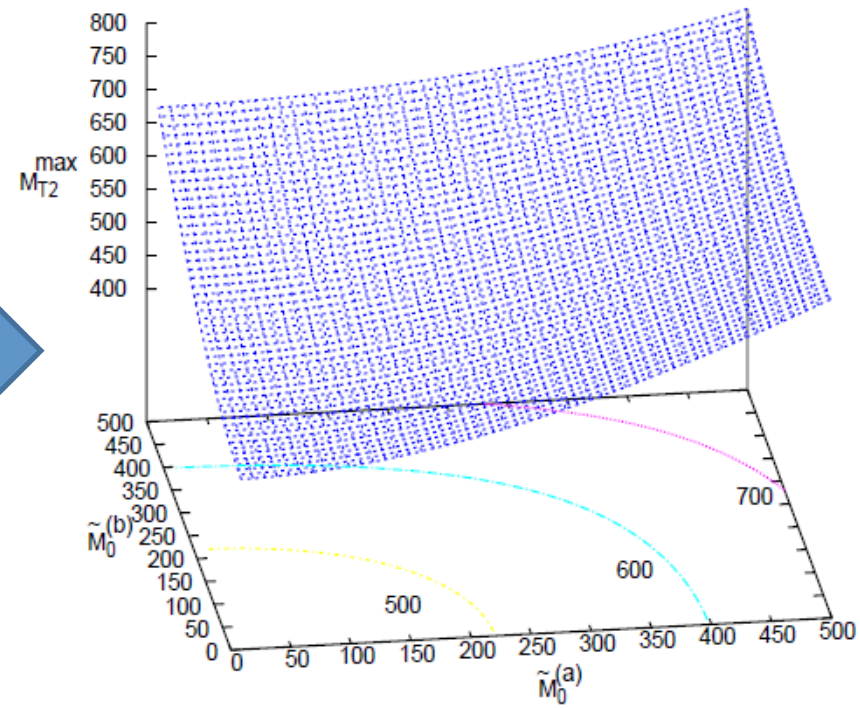
# Generalized $M_{T2}$

$$M_{T2}\left(\vec{p}_T^{\,(a)},\vec{p}_T^{\,(b)};m_{(a)},m_{(b)};\tilde{M}_c^{(a)},\tilde{M}_c^{(b)}\right) =$$

$$\min_{\vec{q}_T^{\,(a)}+\vec{q}_T^{\,(b)}=\vec{\not{p}}_T}\left[\max\left\{M_T^{(a)}\left(\vec{p}_T^{\,(a)};\,\vec{q}_T^{\,(a)};\,m_{(a)};\,\tilde{M}_c^{\,(a)}\right),M_T^{(b)}\left(\vec{p}_T^{\,(b)};\,\vec{q}_T^{\,(b)};\,m_{(b)};\,\tilde{M}_c^{\,(b)}\right)\right\}\right]$$




One dimensional relationship between $M_1$ and $M_0$



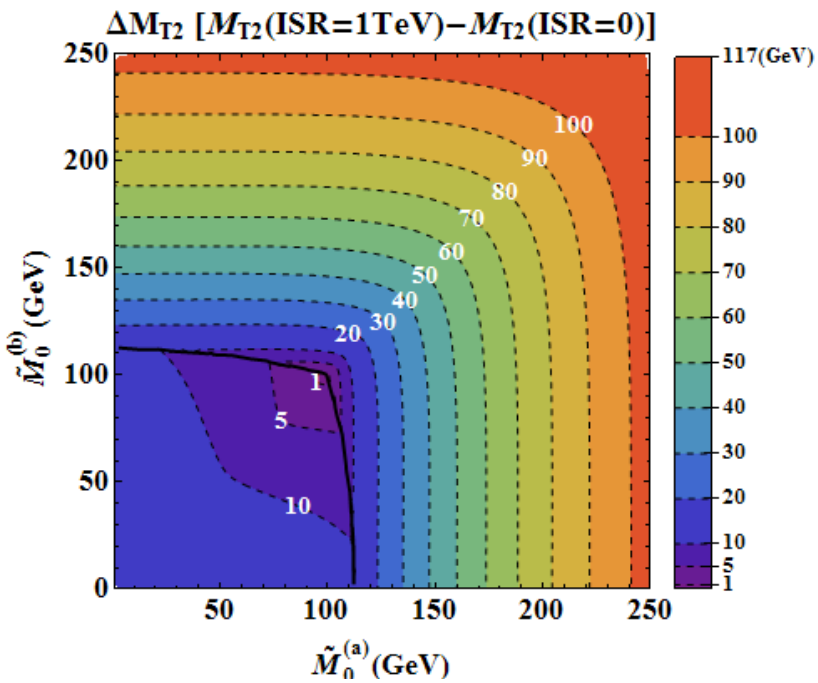

Two dimensional relationship between $M_1$ and $M^a_0$ , $M^b_0$

# 1D decomposition to Generalized MT2

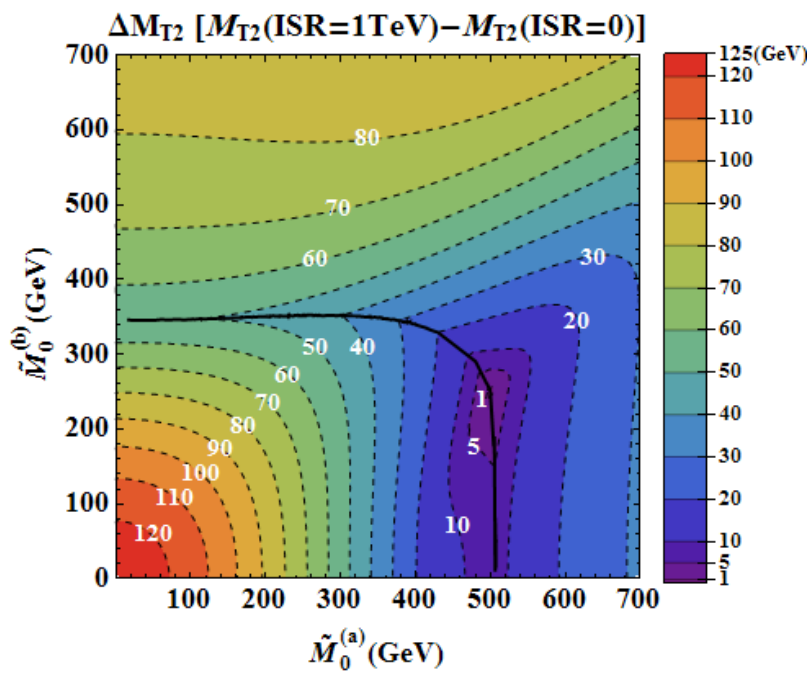
- Using MT2-perpendicular, we can have :

Mass spectrum :

$(M1, M^a_0, M^b_0) = (300,100,100)$ GeV




$(M1, M^a_0, M^b_0) = (600,500,250)$ GeV




**Dark Matter Particle Spectroscopy at the LHC: Generalizing M(T2) to Asymmetric Event Topologies.**
Partha Konar, (Florida U.) , Kyoungchul Kong, (SLAC) , Konstantin T. Matchev, Myeonghun Park, (Florida U.)
Published in **JHEP 1004:086,2010**.
e-Print: **arXiv:0911.4126** [hep-ph]

# SUMMARY

- Even though there are difficulties in LHC (Hardron collider) experiments, using the decomposition-methods, we can have controlled information of mass scale.
- $S_{min}$ can determine mass spectrum without any assumption becoming the most general tool for LHC