The latest and greatest tricks in studying missing energy events (Final)

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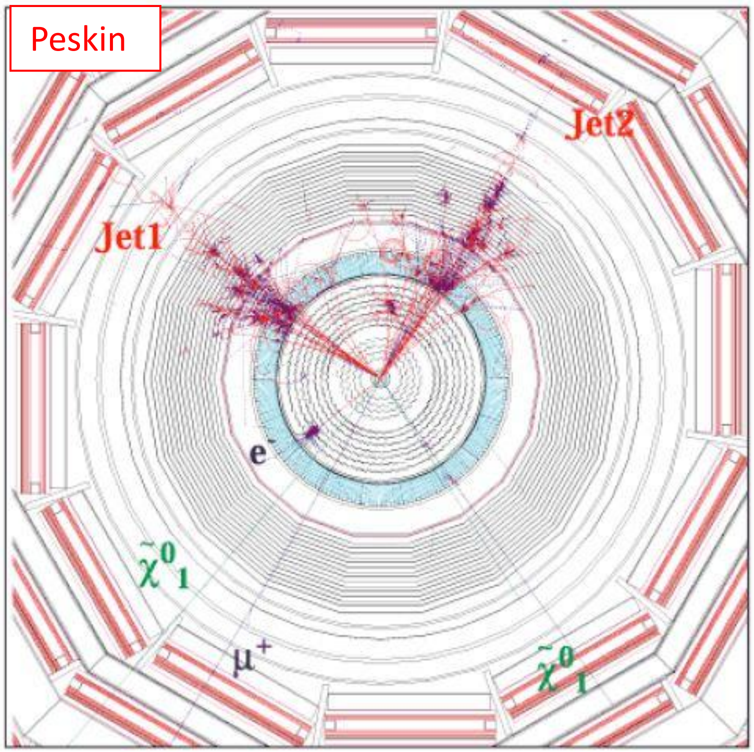
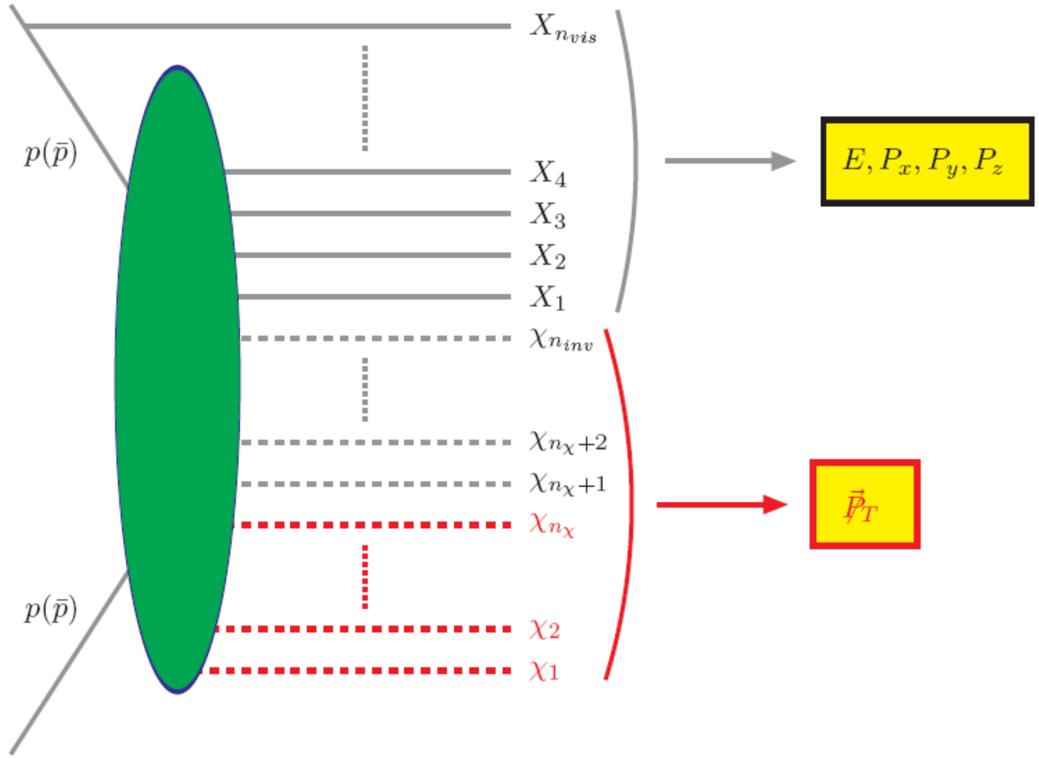
Source papers :

JHEP 0903:143,2009,
JHEP 0903:085,2009,
arXiv:090?.???? [hep-ph](s)

Events@LHC: experimentalist's view

- At the LHC, we expect to discover supersymmetry (or some similar theory) with a new spectroscopy and invisible particles.





- We will want to determine the masses of these particles precisely.

This is obviously impossible, because some of them are invisible. So how do we solve this problem ?

(Large) Hadron Colliders

1. Difficulties :
   (a) Uncertainty in production level
   - No idea of Pzs (Along the beam direction)
   - So, production Energy uncertainty

   (b) Huge number of JETs,
   (c) Expected "HUUGE" events from Standard model as backgrounds. (depending on expected signals)
2. We need to find and study the proper variables for "Hadron Colliders".

Contents

As suggestions for difficulties :

(a) THE VARIABLE for production Energy Scale : S_{min}

(b) Specific variables for mass spectrum : Subsystem M_{T2}

(c) Subsystem M_{T2} as a cut of Standard Model-background

As I promised :

(1) The LATEST studies

(2) Conclusion

(3) ?

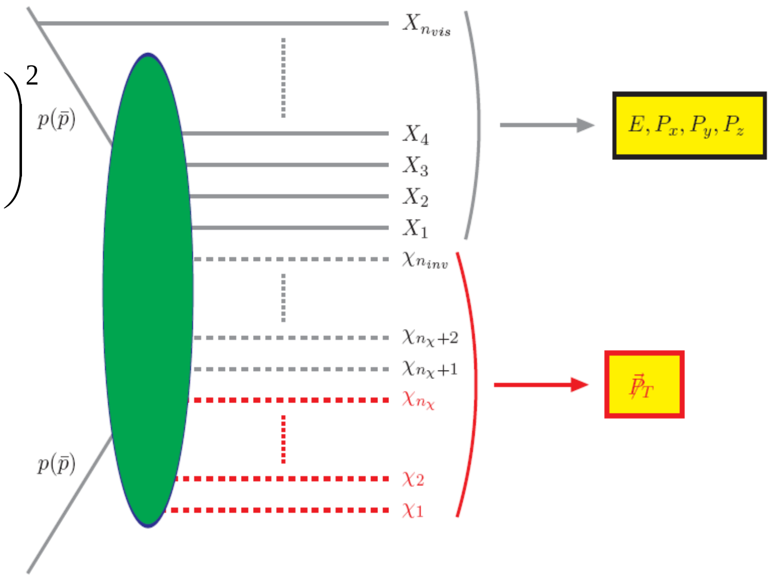
What is S_{min}?

- The minimum value of the Mandelstam variable consistent with the measured values of the total energy E and total visible momentum (P_x,P_y,P_z)

$$\hat{S} = \left(E + \sum_{i=1}^{n_{inv}} \sqrt{m_i^2 + \vec{p}_{iT}^{\,2} + p_{iz}^2} \right)^2 - \left(\vec{P}_T + \sum_{i=1}^{n_{inv}} \vec{p}_{iT} \right)^2 - \left(P_Z + \sum_{i=1}^{n_{inv}} p_{iz} \right)^2$$

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

$$M_{inv} \equiv \sum_{i=1}^{n_{inv}} m_i = \sum_{i=1}^{n_\chi} m_i$$

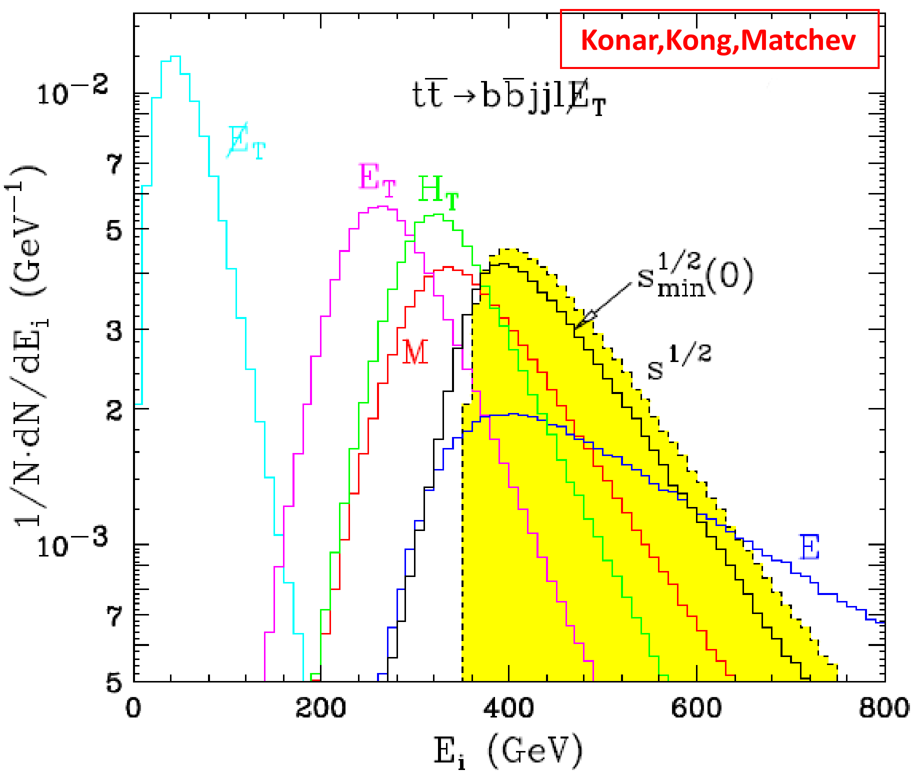


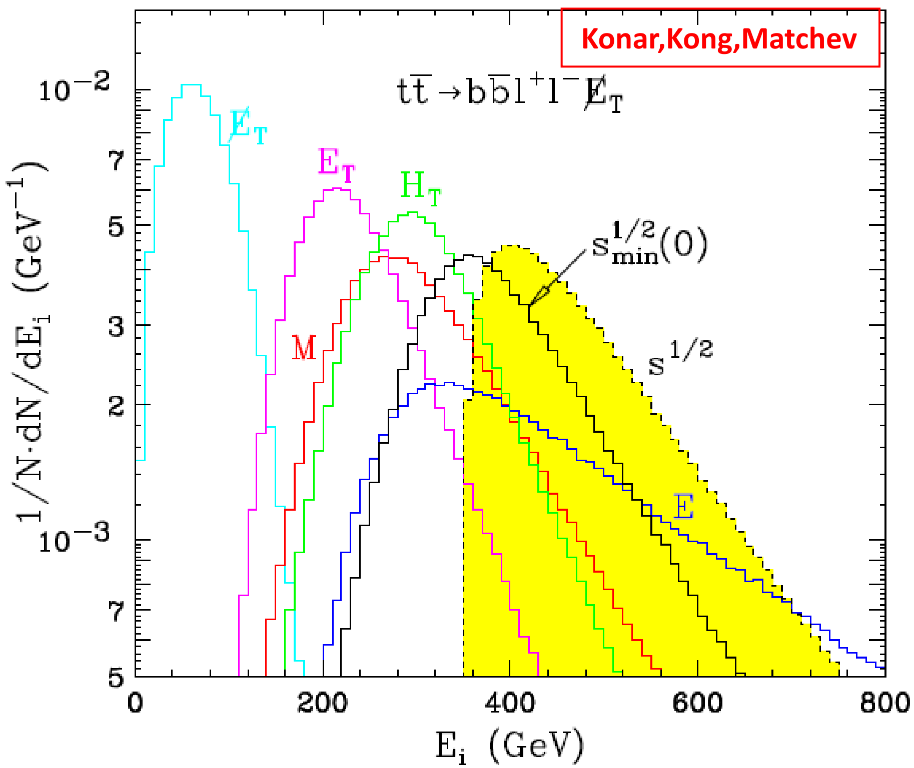
- Advantages:
  - Uses all available information (not just transverse quantities)
  - Model-independent: no need for any event reconstruction
  - Inclusive
  - Global
  - Clear physical meaning

What is S_{min} good for?

- As an approximation to the true value of S:

$$E \equiv \sum_\alpha E_\alpha \qquad E_T \equiv \sum_\alpha E_\alpha \sin\theta_\alpha \qquad H_T \equiv E_T + \not{E}_T \qquad M \equiv \sqrt{E^2 - P_x^2 - P_y^2 - P_z^2}$$

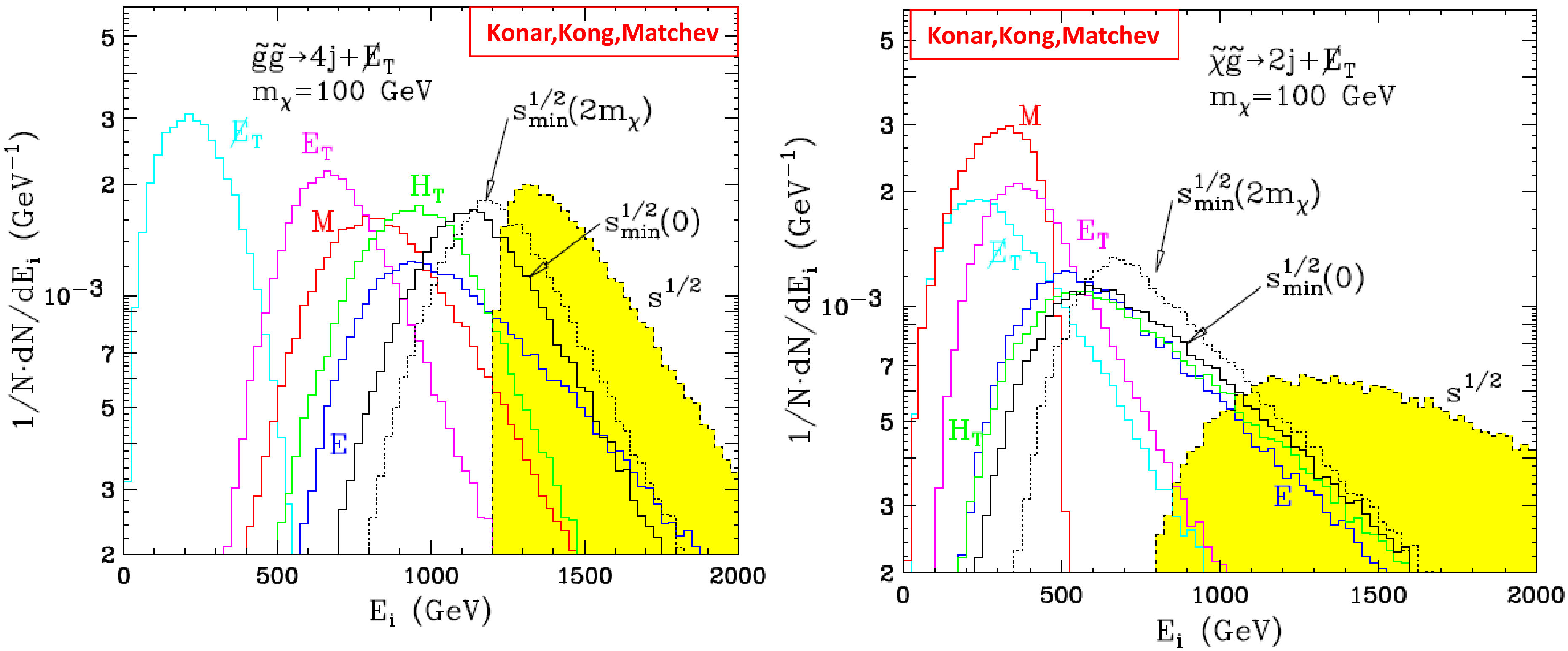




What is S_{min} good for?

- One can measure SUSY masses in terms of the LSP mass:

$$\left(\hat{s}^{1/2}\right)_{thr} \approx \left(\hat{s}^{1/2}_{min}(2m_\chi)\right)_{peak}$$

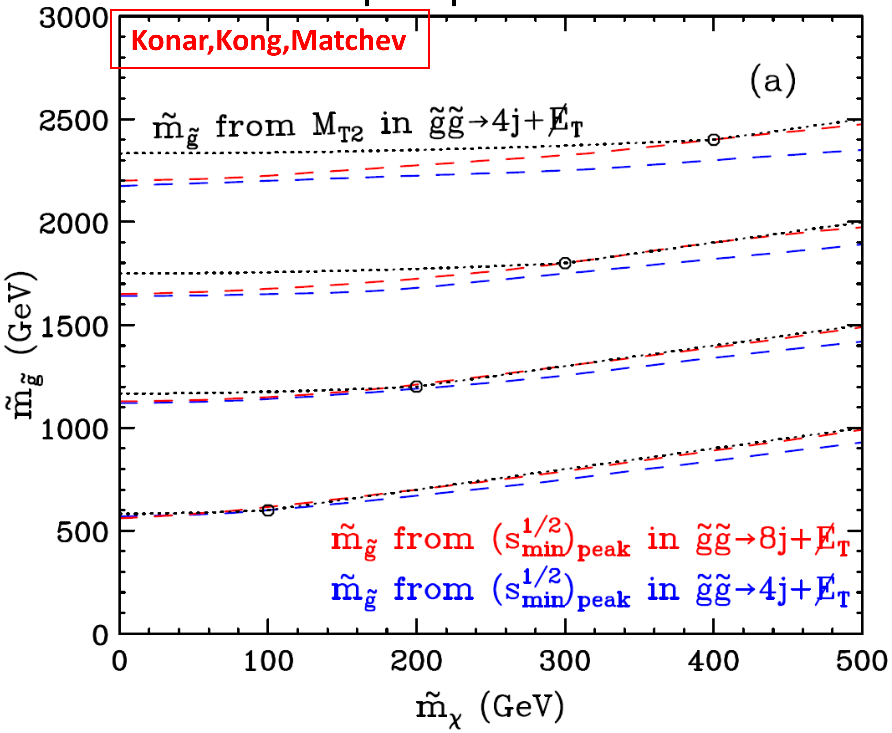


What is S_{min} good for?

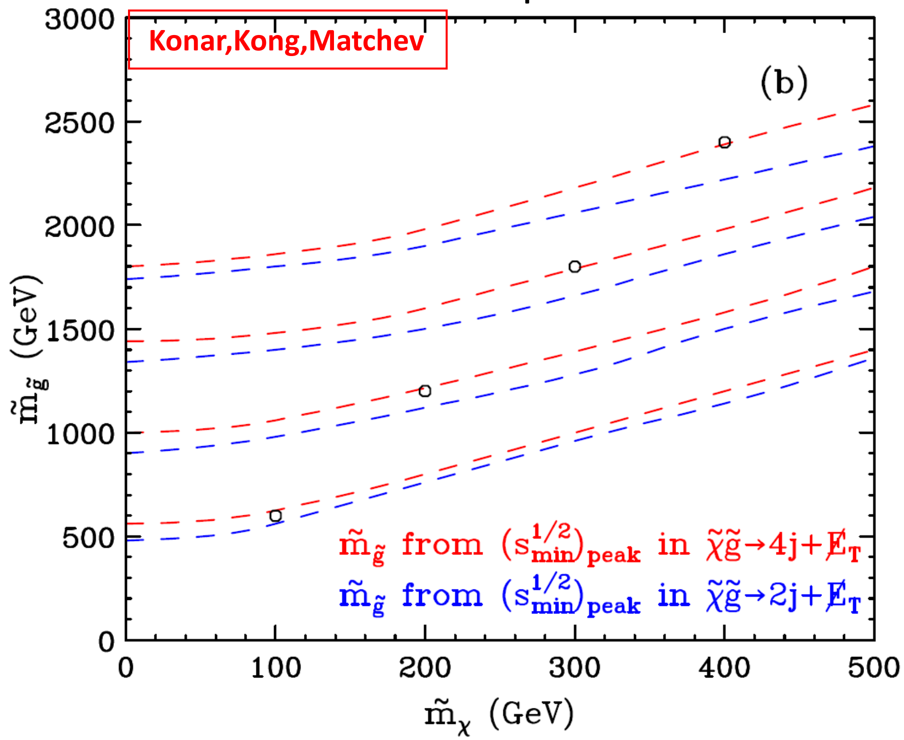
- One can measure SUSY masses in terms of the LSP mass:

$$\tilde{m}_{\tilde{g}}(\tilde{m}_\chi) \approx \frac{1}{2}\left(\hat{s}^{1/2}_{min}(2\tilde{m}_\chi)\right)_{peak} \qquad \tilde{m}_{\tilde{g}}(\tilde{m}_\chi) \approx \left(\hat{s}^{1/2}_{min}(2\tilde{m}_\chi)\right)_{peak} - \tilde{m}_\chi$$

Gluino pair production

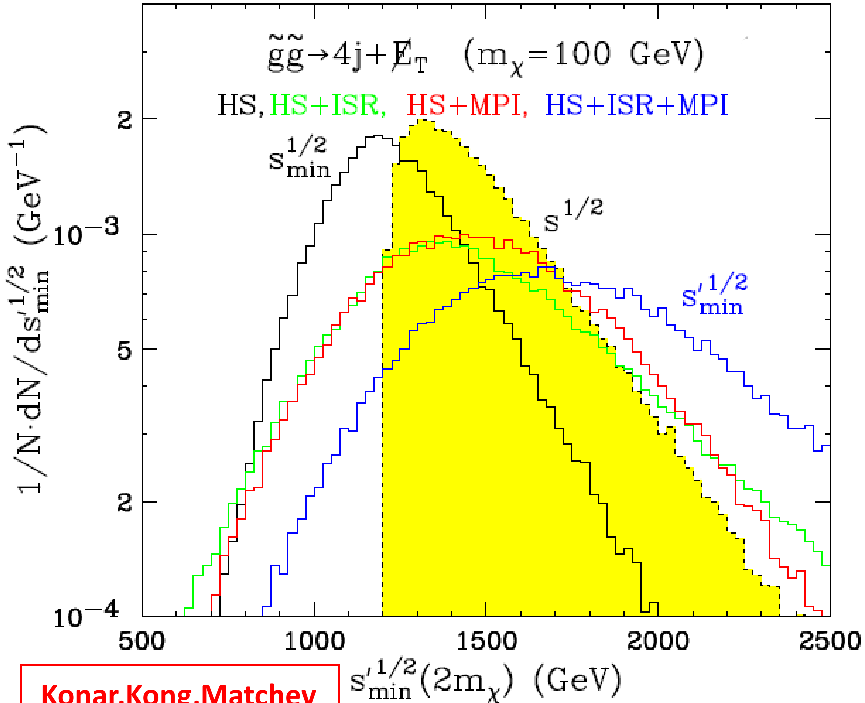


Gluino-LSP assoc. production

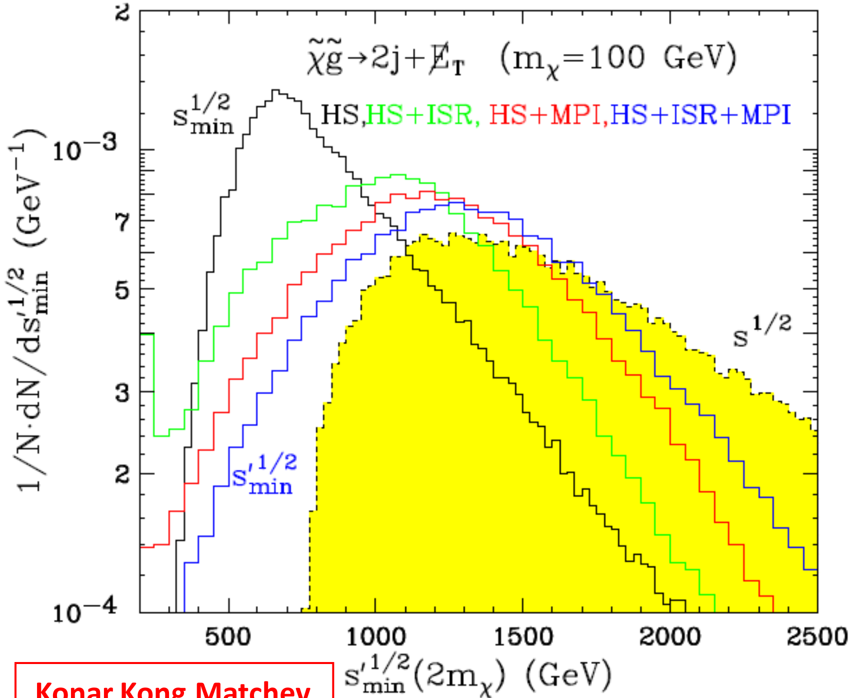


ISR/MPI effects on S_{min}

- If we can't isolate ISR jets :



Konar,Kong,Matchev



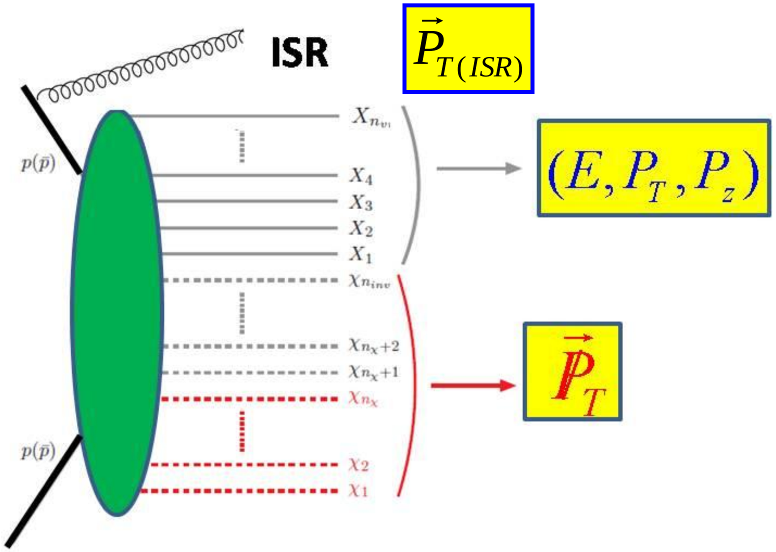
Konar,Kong,Matchev

Subsystem $(S_{min})^{1/2}$ versus M_T^{true}

- S_{min} introduced as a measure of the energy scale of interest

  Konar,Kong,Matchev 0812.1042

- Whenever the ISR contribution can be identified (e.g. leptonic signatures) the proper S_{min} is given by **Konar,Kong,Matchev,Park preliminary**



$$\sqrt{S}_{min} = \sqrt{\left(\sqrt{E^2 - P_z^2} + \sqrt{M_{inv}^2 + \vec{\not{P}}_T^2}\right)^2 - \vec{P}_{T(ISR)}^2}$$

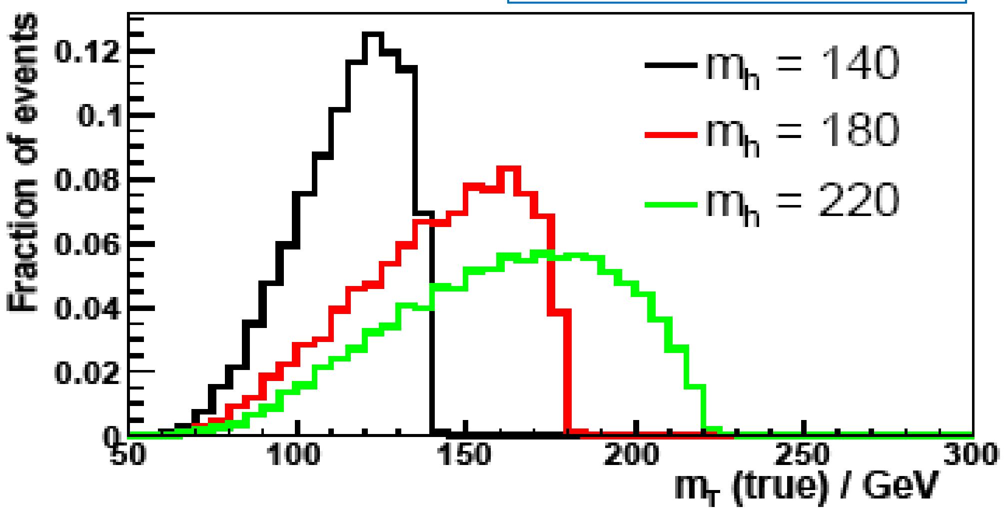
- M_T^{true} introduced as a measure of the Higgs mass in h->WW->2leptons+MET

  Tao Han hep-ph/0508097 Cluster variable
  Lester,Gripaios,Barr 0902.4864

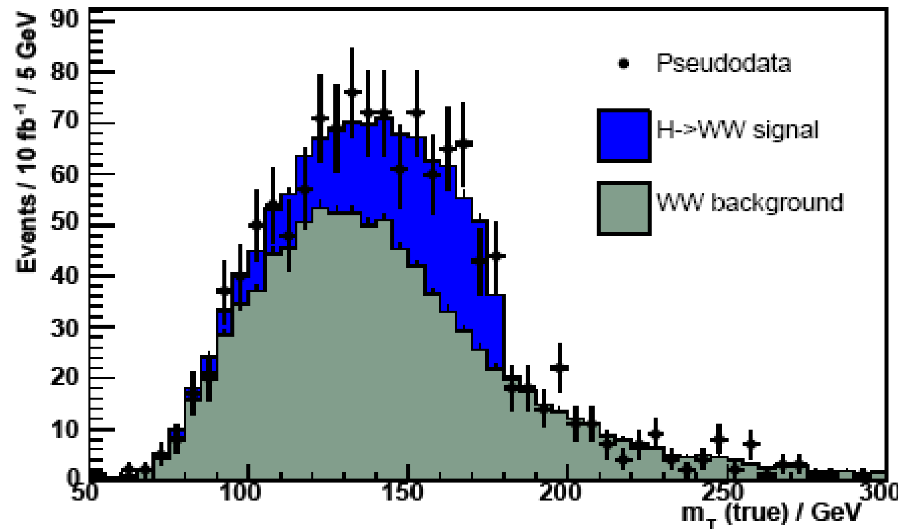
$$m_T^{true} \equiv m_T^2(m_i = 0) = m_v^2 + 2\left(e_v \left|\vec{\not{P}}_T\right| - \mathbf{p}_v \cdot \vec{\not{P}}_T\right)$$

Application to H → WW

Lester,Gripaios,Barr 0902.4864



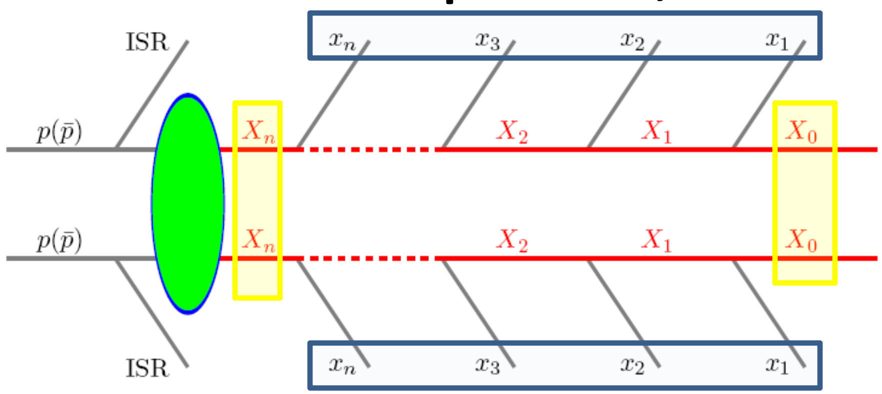
Lester,Gripaios,Barr 0902.4864



- How can two different variables be related ?

Different transverse Variables ?

- Without any assumptions on Events-topology, S_{min} is a very general transverse variable.
- If we add some assumptions, like :



then, S_{min} ⇒ M_{T2}

How can S_{min} go to the M_{T2} (or m_t^{true})? Is there any systematic study on those variables?

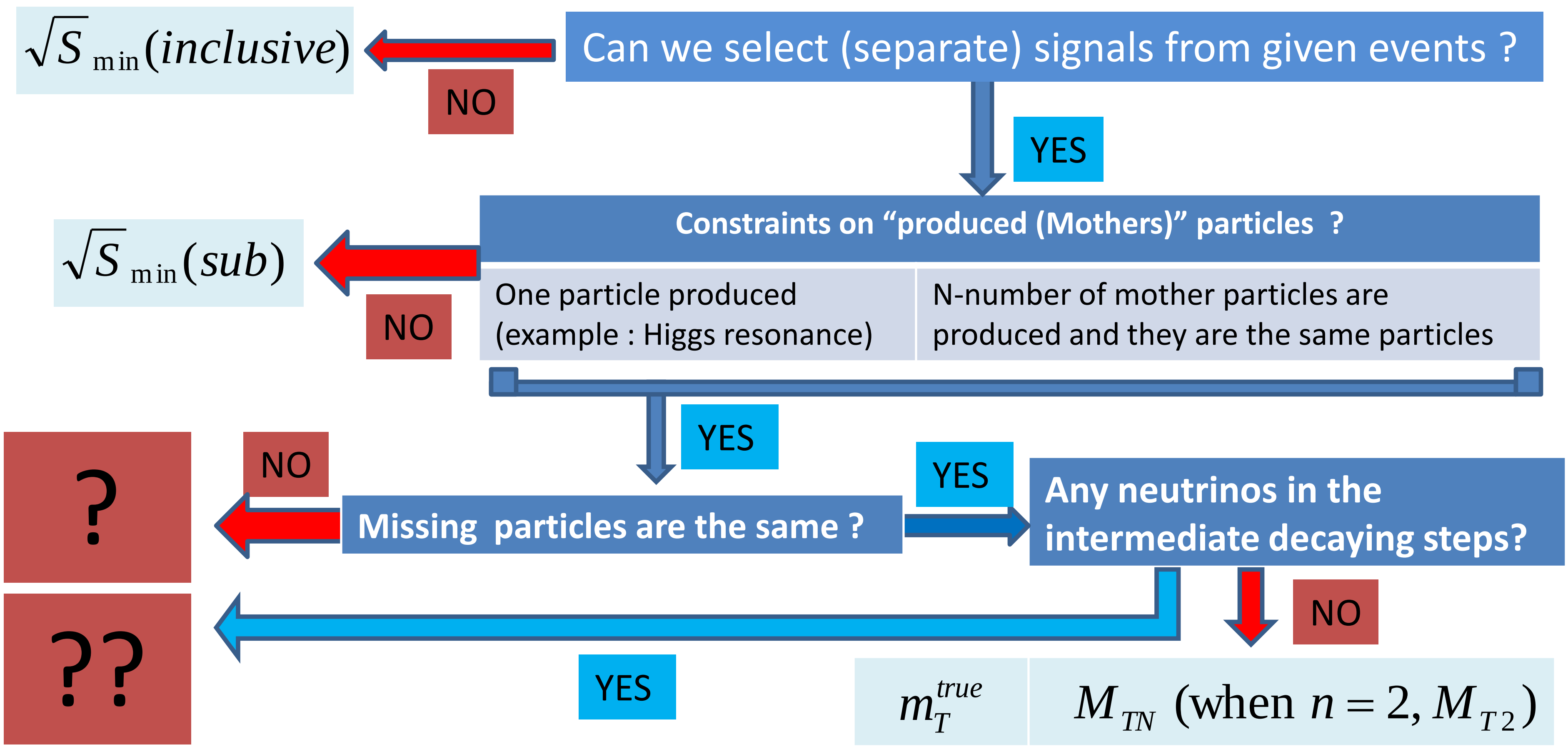
What constraint(s) will we give to event-topology ?

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

Can we select (separate) signals from given events ?

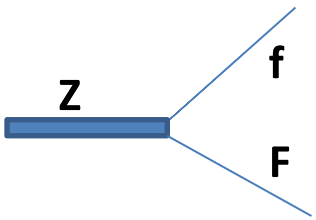
What constraint(s) will we give to event-topology ?

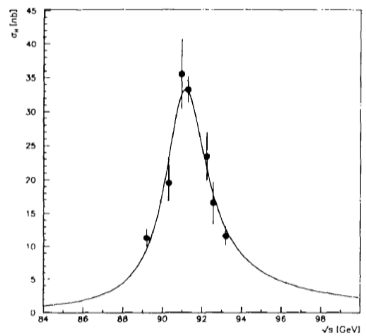
Minimizati on of $\sqrt{S}$ with Missing P_T constraint $(= \sqrt{S}_{min})$



Recap : M_{T2}

- If we can reconstruct the production particles, then like as Z - particle mass measurement: Using the invariant mass of two visible particles :





$$M_Z^2 = (f^\mu + F^\mu)(f_\mu + F_\mu)$$

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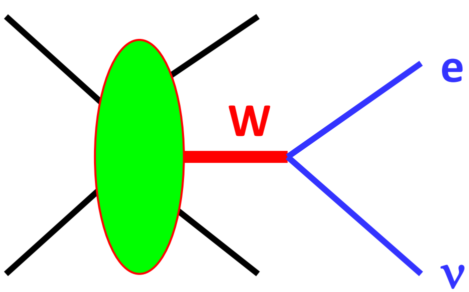
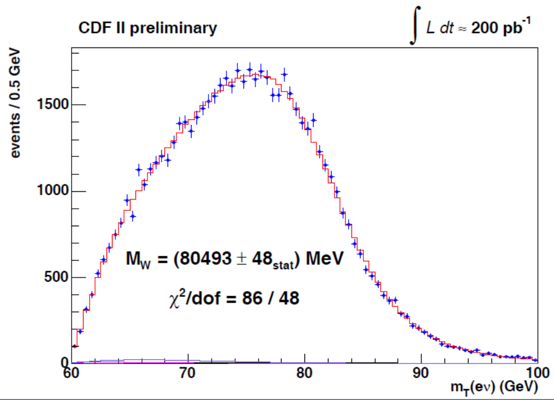
Volume 231, Issue 4, 16 November 1989, Pages 539-547

Measurement of the mass and width of the Z^0-particle from multihadronic final states produced in e^+e^- annihilations

- If we can't reconstruct the particles from resonance, then





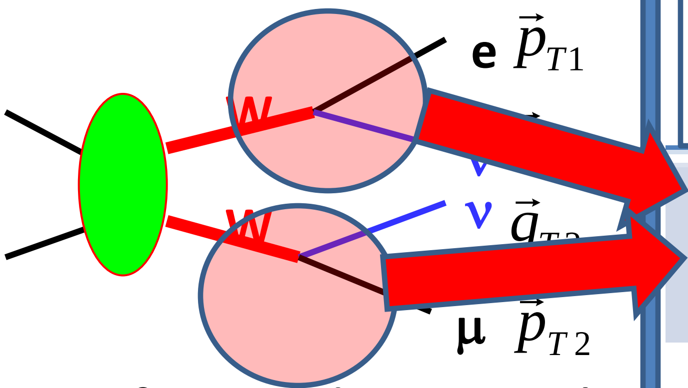
$$M_W^2 \geq m_T^2(e,\nu)$$

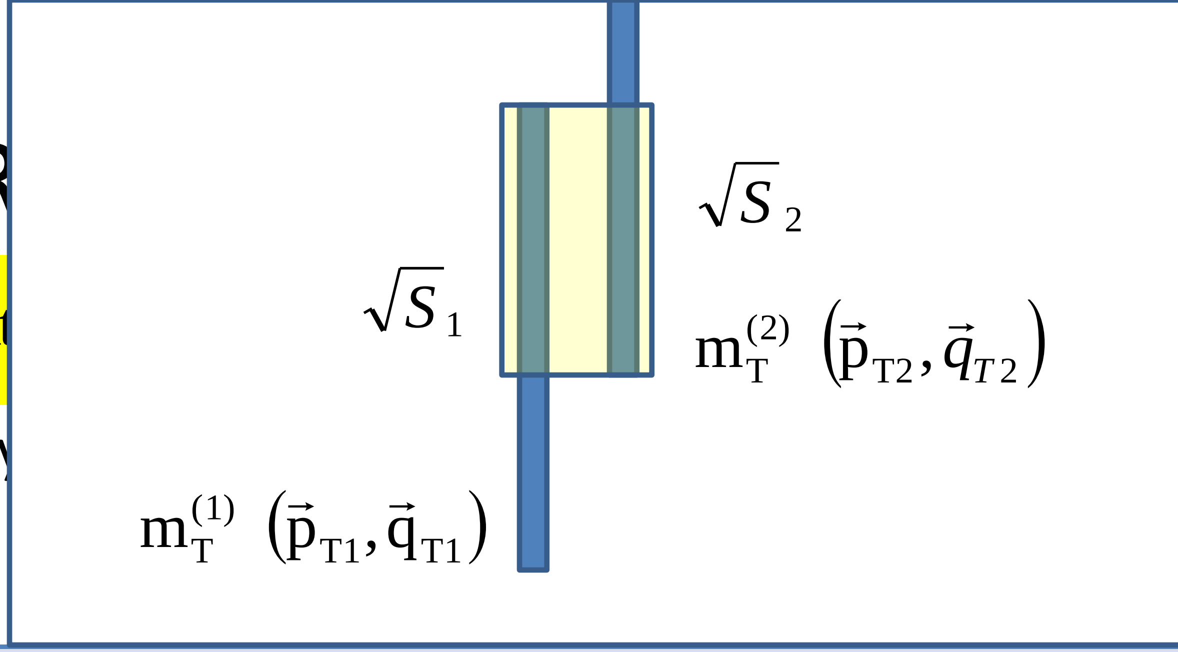
$$\equiv \left(\left|\vec{p}_{eT}\right| + \left|\vec{p}_{\nu T}\right|\right)^2 - \left(\vec{p}_{eT} + \vec{p}_{\nu T}\right)^2$$

R

Minimizati on of $\sqrt{S}$ wi

- A pair of semi-invisibly





N-number of mother particles are produced and they are the same particles

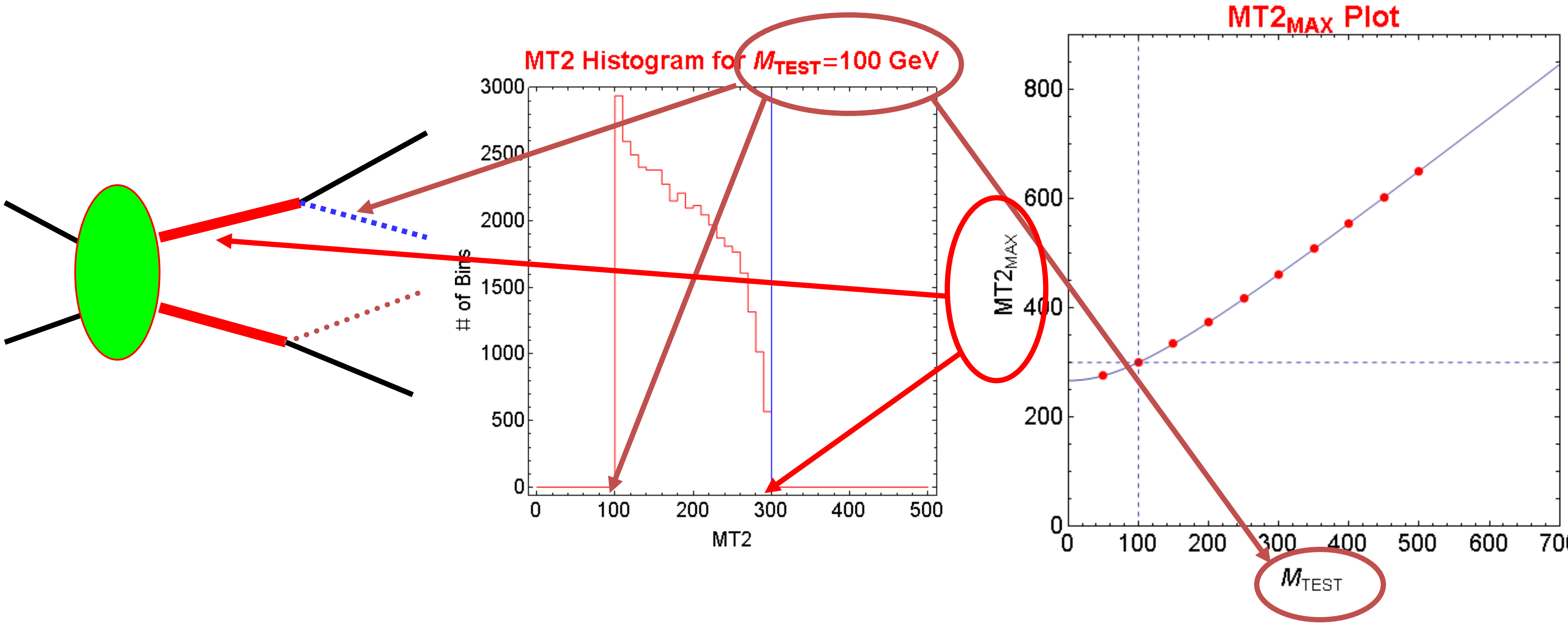
- If $\vec{q}_{T1}$ and $\vec{q}_{T2}$ are obtainable : $M_w \geq \max\{m_T(\vec{p}_{T1},\vec{q}_{T1}), m_T(\vec{p}_{T2},\vec{q}_{T2})\}$
- But since we don't get them, at most we can do :

$$M_W \geq M_{T2} = \min_{\vec{q}_{T1}+\vec{q}_{T2}=\not{E}_T}\left[\max\{m_T^{(1)}(\vec{p}_{T1},\vec{q}_{T1}), m_T^{(2)}(\vec{p}_{T2},\vec{q}_{T2})\}\right]$$

- Also , since we don't know the LSP(or Missing particles)' mass, we need to guess LSP's mass to formulate each $m_T(\vec{p}_T,\vec{q}_T)$

Recap : M_{T2}

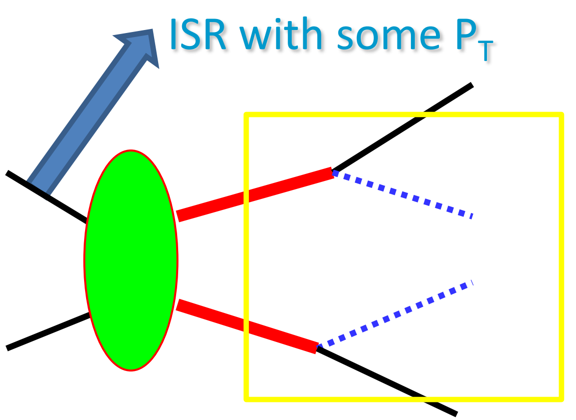
- Provides a relation between the two unknown masses of the parent (slepton) and child (LSP)
  - Vary the child (LSP) mass, read the endpoint of m_{T2}

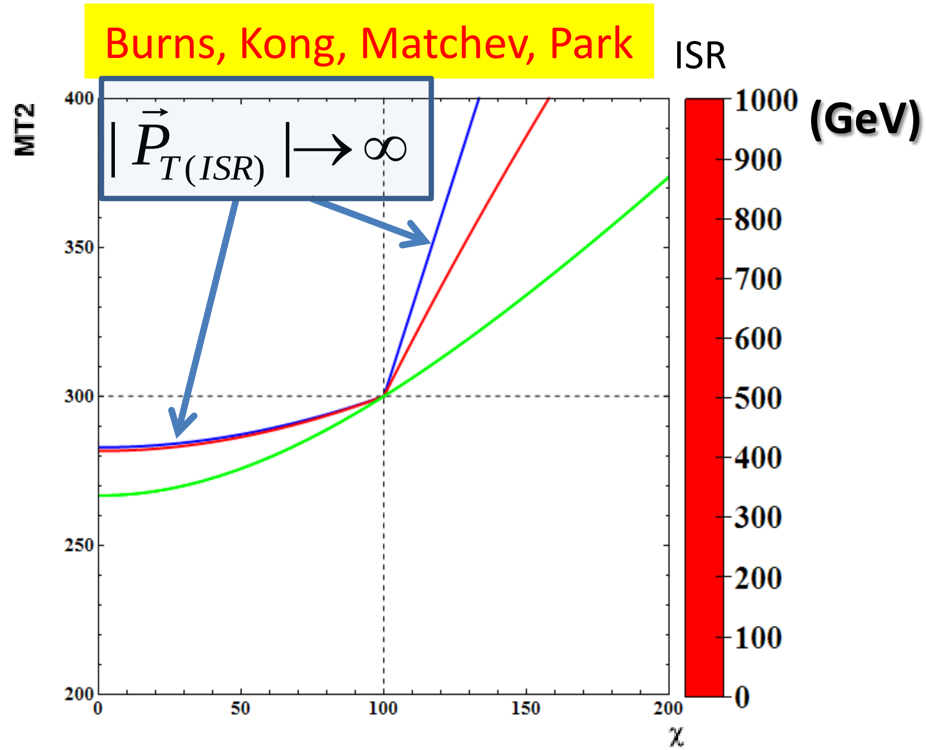


- So what? We still don't know exactly the LSP mass

Two important properties of M_{T2}

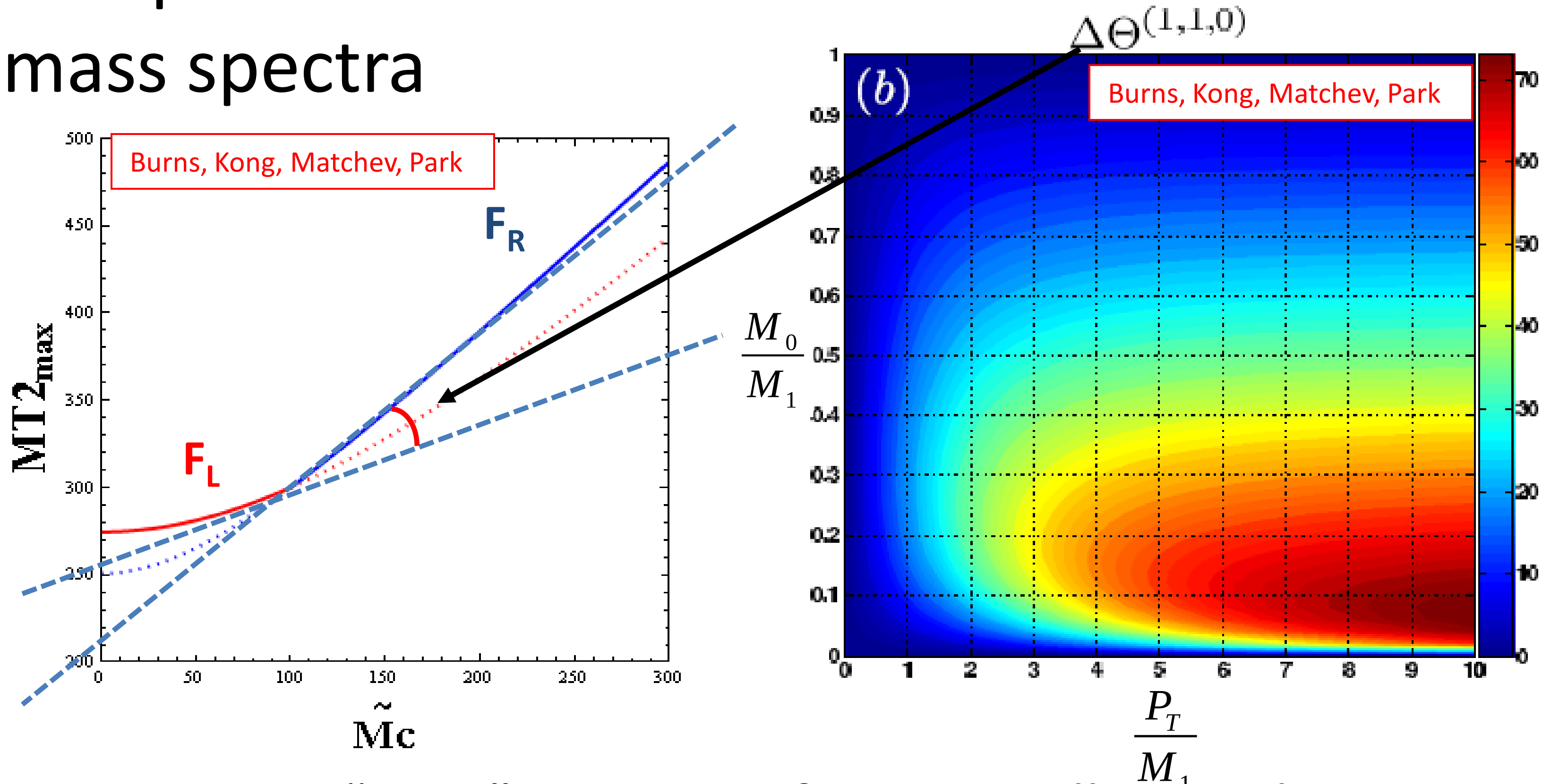
- "KINK" structure of M_{T2}
- "Boost"-invariance of M_{T2} at the true mass spectrum.





How big is this kink?

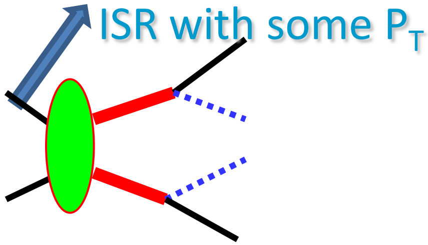
- It depends on the hardness of the ISR and the mass spectra



- We can use "KINK" structure if M_0 is small enough compared to M_1 or P_T is big enough compared to M_1

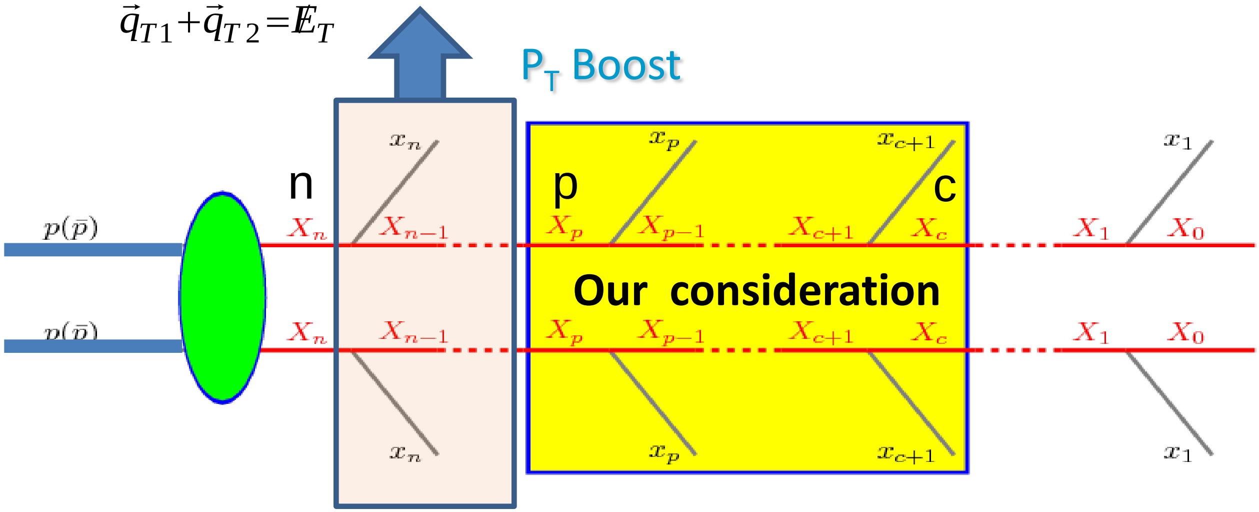
Understanding of P_T Effect

- P_T comes from
  (A) ISR



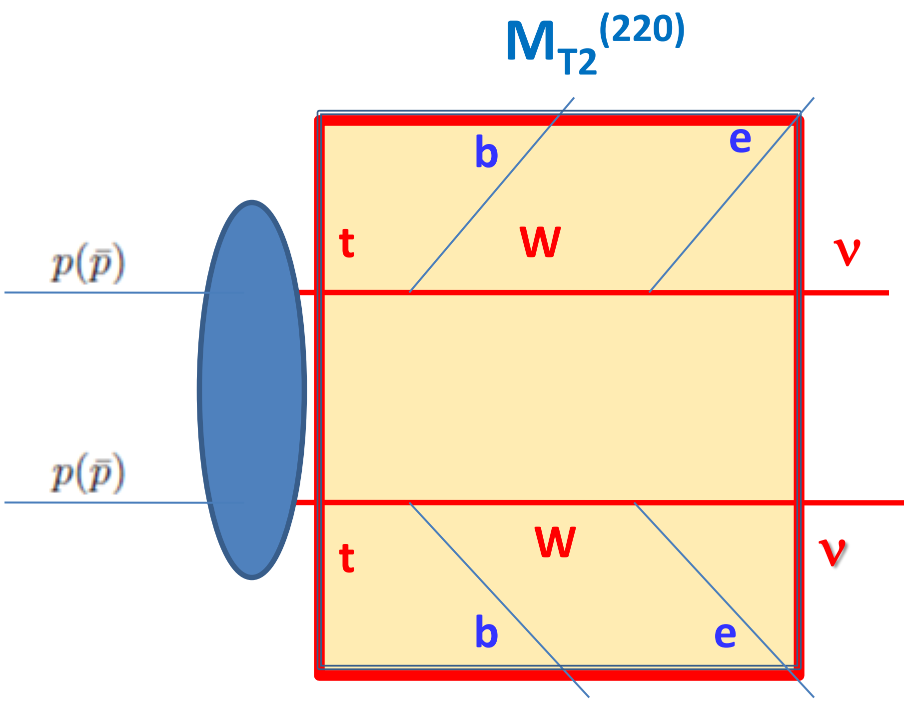
(B) upstream momentum from previous decaying steps.

$$M_{T2}^{(n,p,c)}(\tilde{M}_C) = \min_{\vec{q}_{T1}+\vec{q}_{T2}=\not{E}_T} [\max\{m_T(\vec{p}_{T1},\vec{q}_{T1},\tilde{M}_C), m_T(\vec{p}_{T2},\vec{q}_{T2},\tilde{M}_C)\}]$$



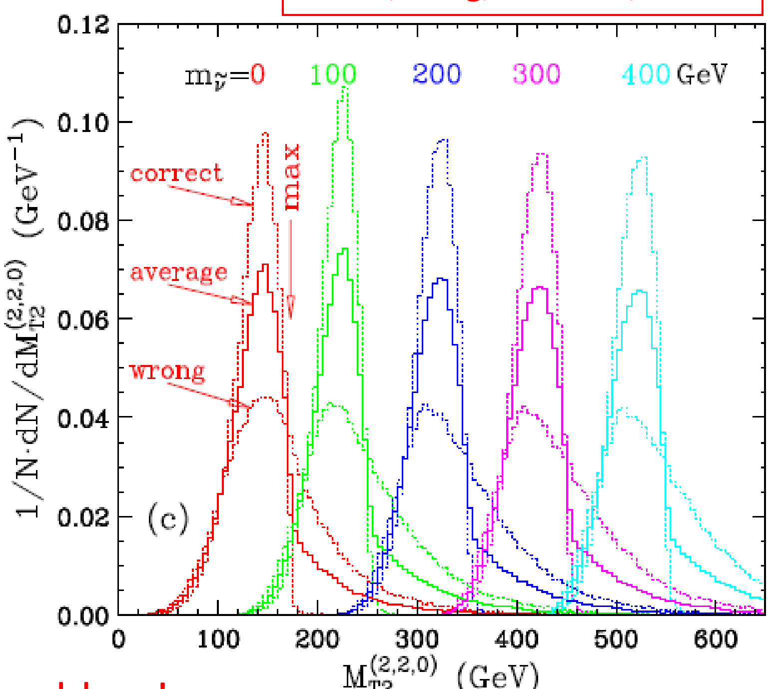
Subsystem M_{T2} applied to top pair

- Don't assume prior knowledge of the W and neutrino masses
- Traditional M_{T2} variable: $M_{T2}(2,2,0)$



Combinatorial problem!

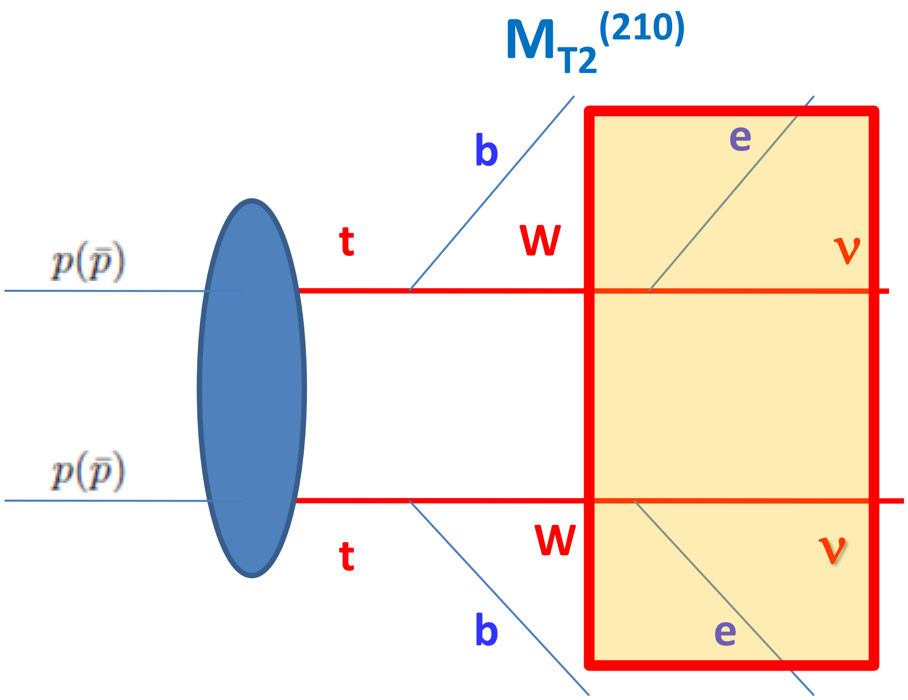
Burns, Kong, Matchev, Park

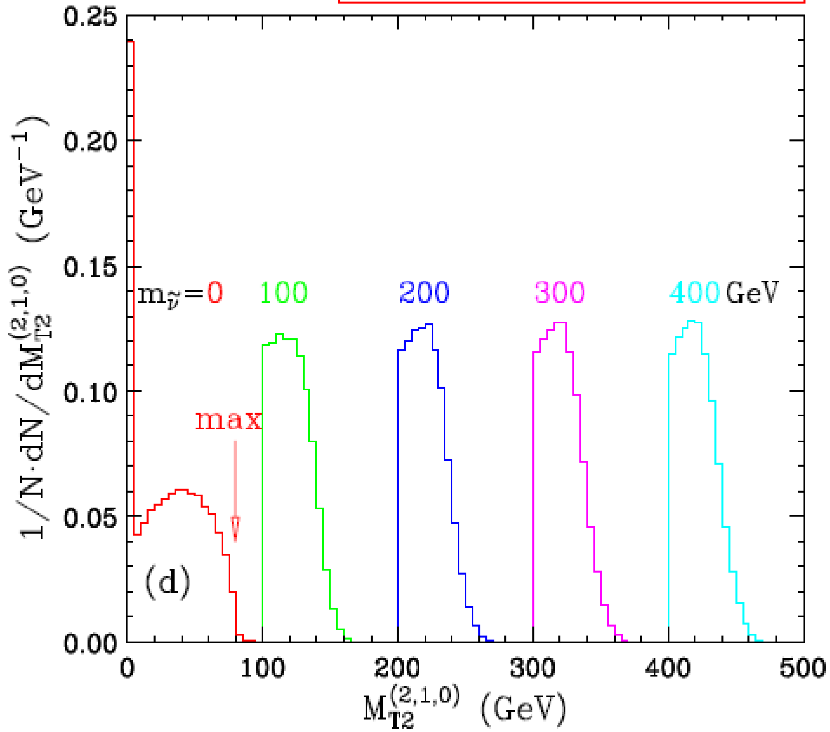


Subsystem M_{T2} applied to top pair

- Genuine subsystem variable: $M_{T2}(2,1,0)$

Burns, Kong, Matchev, Park

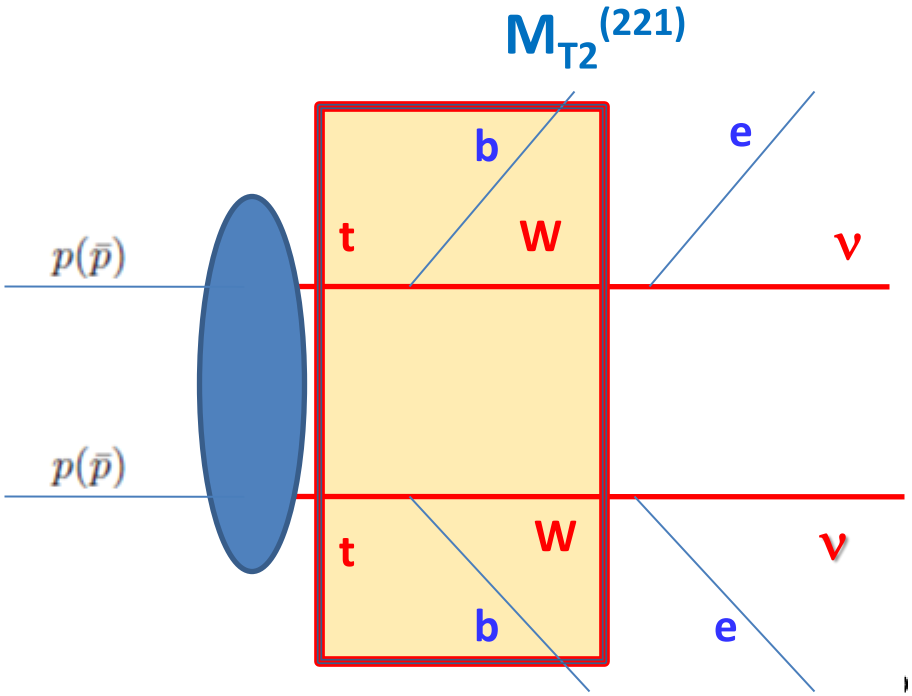




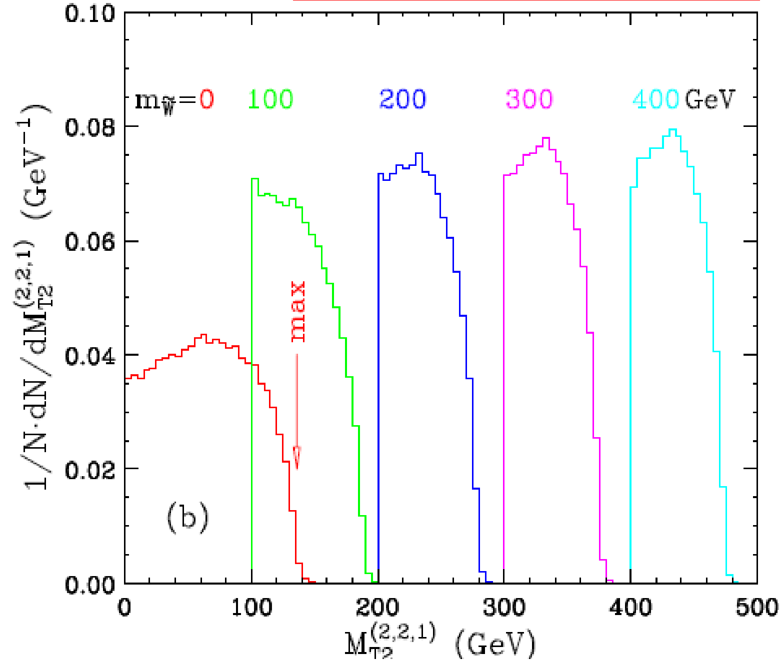
No combinatorial problem!

Subsystem M_{T2} applied to top pair

- Another genuine subsystem variable: $M_{T2}(2,2,1)$



Burns, Kong, Matchev, Park



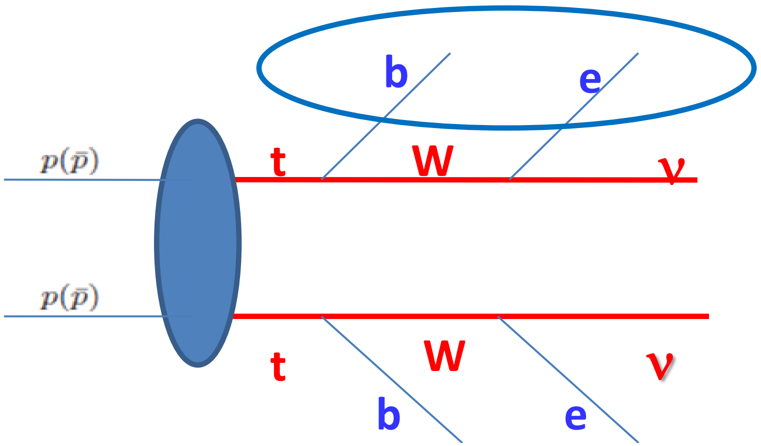
No combinatorial problem!

Mass measurements in the TTbar system

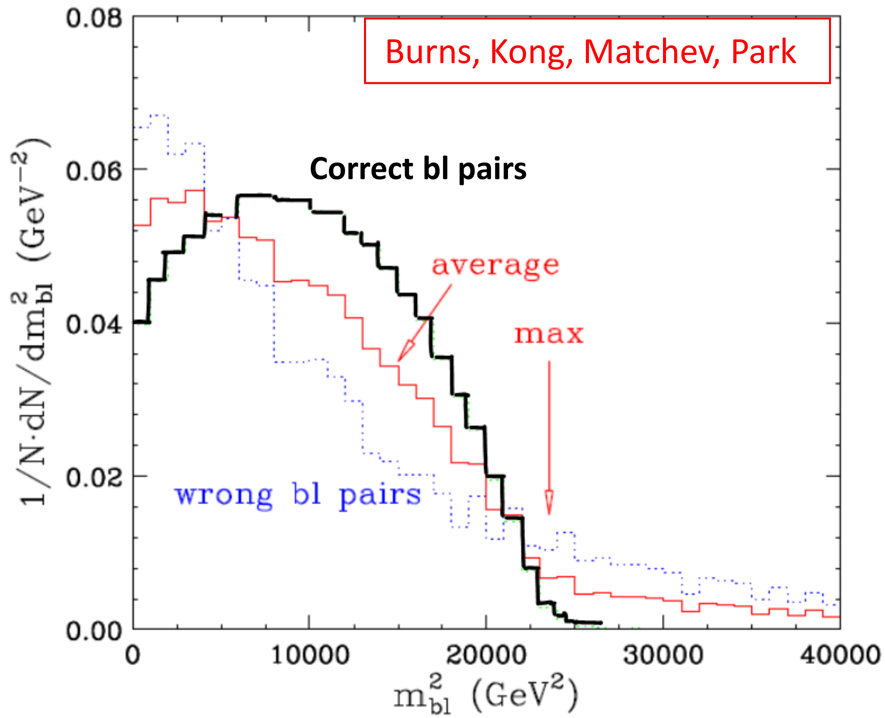
- We have just measured three M_{T2} endpoints which are known functions of the hypothesized Top, W and neutrino masses.
  - $M_{T2}(2,2,0)$ $(\tilde{M}_0 = 0)$ → $E_{220} = M_2\left(1 - \frac{M_0^2}{M_2^2}\right)$
  - $M_{T2}(2,1,0)$ $(\tilde{M}_0 = 0)$ → $E_{210} = M_1\sqrt{\left(1 - \frac{M_0^2}{M_2^2}\right)\left(1 - \frac{M_0^2}{M_1^2}\right)}$
  - $M_{T2}(2,2,1)$ $(\tilde{M}_1 = 0)$ → $E_{221} = M_2\left(1 - \frac{M_1^2}{M_2^2}\right)$
- Problem: they are not independent, $E_{210}^2 = E_{220}(E_{220} - E_{221})$ need an additional measurement. Endpoint of the lepton+b-jet inv. mass distribution

Full T, W, Nu mass determination

- Hybrid method: Inv. mass $\oplus$ Subsystem M_{T2}



M(bl)max = $E_{im}^2 = \frac{(m_t^2 - m_W^2)(m_W^2 - m_\nu^2)}{m_W^2}$



$$M_0 = \frac{\sqrt{2E_{221}}\,E_{im}\left(2E_{221}E_{210}^2 + E_{221}E_{im}^2 - E_{im}^2\sqrt{E_{221}^2+4E_{210}^2}\right)}{E_{221}^2 + 2E_{im}^2 - E_{221}\sqrt{E_{221}^2+4E_{210}^2}}$$

$$M_1 = \frac{\sqrt{2}\,E_{221}\,E_{im}\left(E_{221}\sqrt{E_{221}^2+4E_{210}^2} - E_{221}^2\right)^{\frac{1}{2}}}{E_{221}^2 + 2E_{im}^2 - E_{221}\sqrt{E_{221}^2+4E_{210}^2}},$$

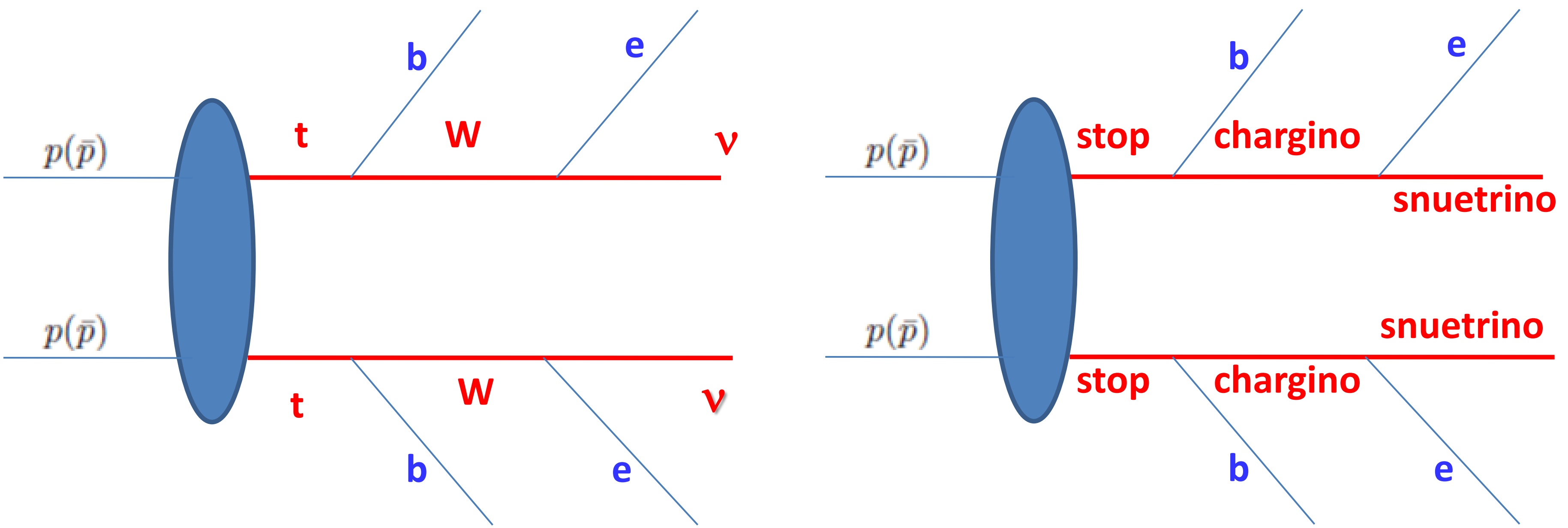
$$M_2 = \frac{2E_{221}E_{im}^2}{E_{221}^2 + 2E_{im}^2 - E_{221}\sqrt{E_{221}^2+4E_{210}^2}}.$$

MT2 as a Standard Model Killer

- MT2 can be used for background suppression

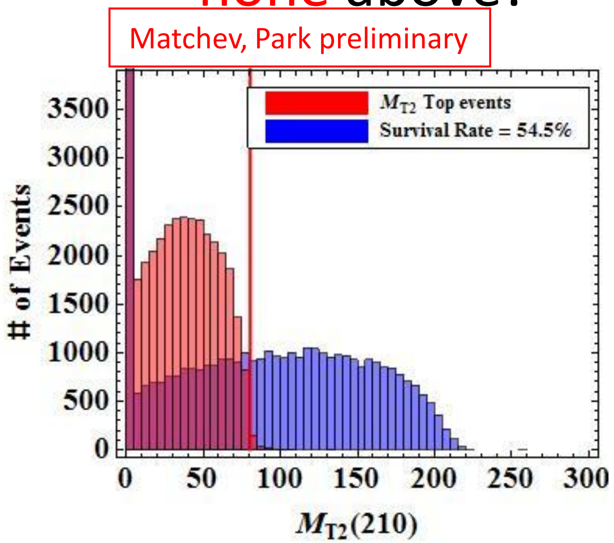
Barr, Gwenlan 2009

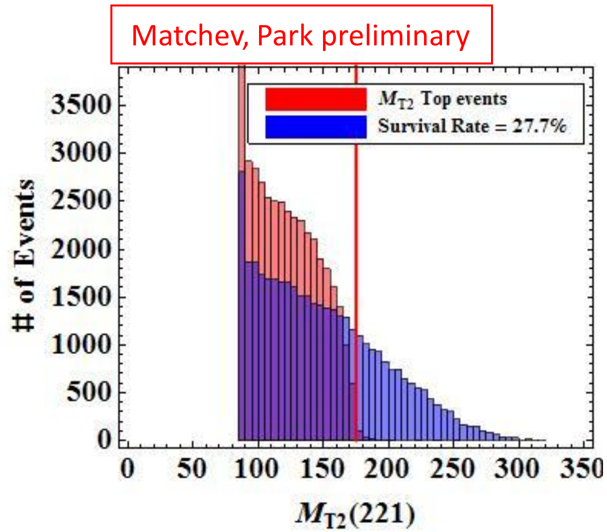
- The dominant background to SUSY is TTbar
- For illustration, let us choose a very challenging example with an identical signature
  - Stop pair production, with decays to chargino and LSP.

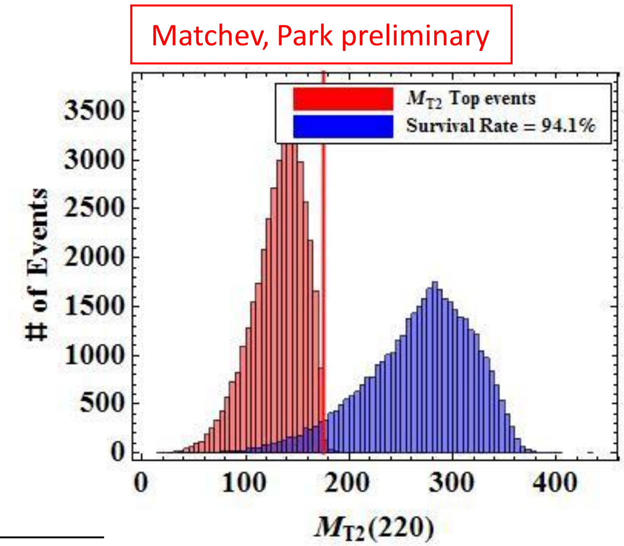


Top-Stop separation

- What do we know about the stop sample?
  - Absolutely nothing.
- What do we know about TTbar?
  - The endpoints of the subsystem M_{T2} variables that we just saw. All TTbar events fall below these endpoints, and there are none above!







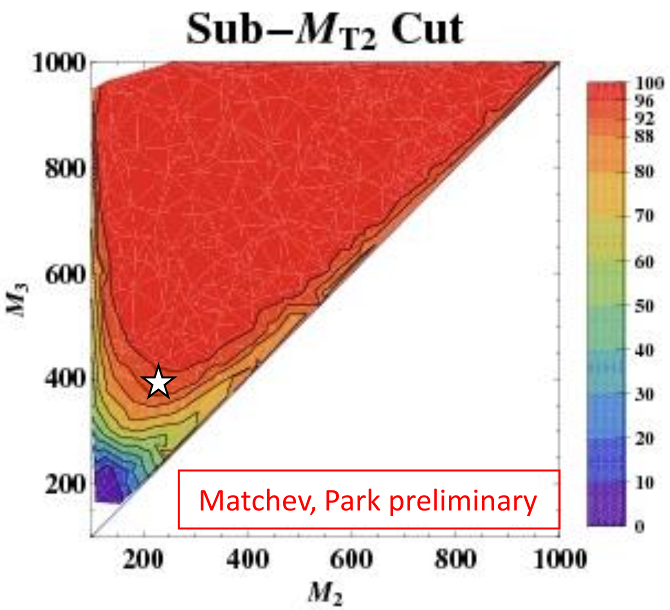
$$M_1\sqrt{\left(1-\frac{M_0^2}{M_2^2}\right)\left(1-\frac{M_0^2}{M_1^2}\right)}$$

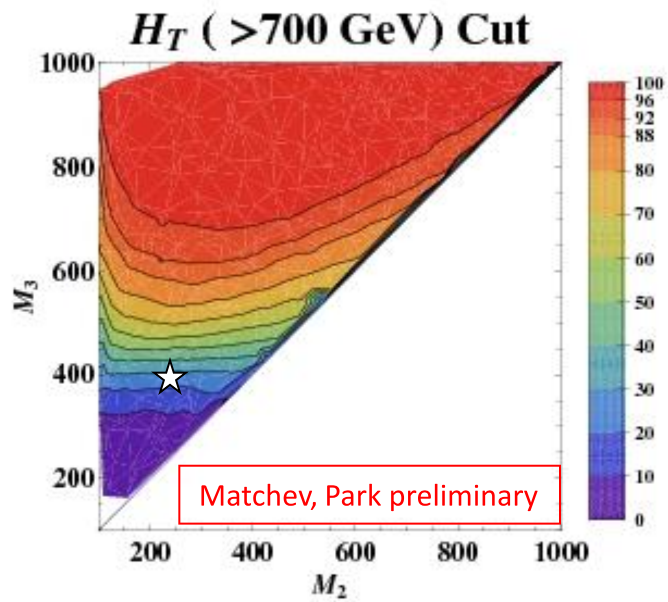
$$\frac{M_2}{2}\left(1-\frac{M_1^2}{M_2^2}\right)+\frac{M_2}{2}\sqrt{\left(1-\frac{M_1^2}{M_2^2}\right)^2+\frac{M_w^2}{4M_2^2}}$$

$$M_2\left(1-\frac{M_0^2}{M_2^2}\right)$$

Combination M_{T2} cut

- Accept the event if it is beyond at least one of the three subsystem M_{T2} endpoints.
- This greatly enhances the signal acceptance, compared to a single M_{T2} cut, or an H_T cut.





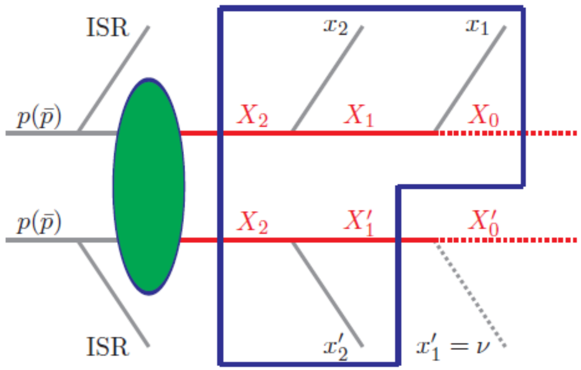
The LATEST Development(s)

- Are we sure that MISSING particles are "the same particles" ?

  - Question from Paddy

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

  (b) Some heavier particle may decay invisibly.



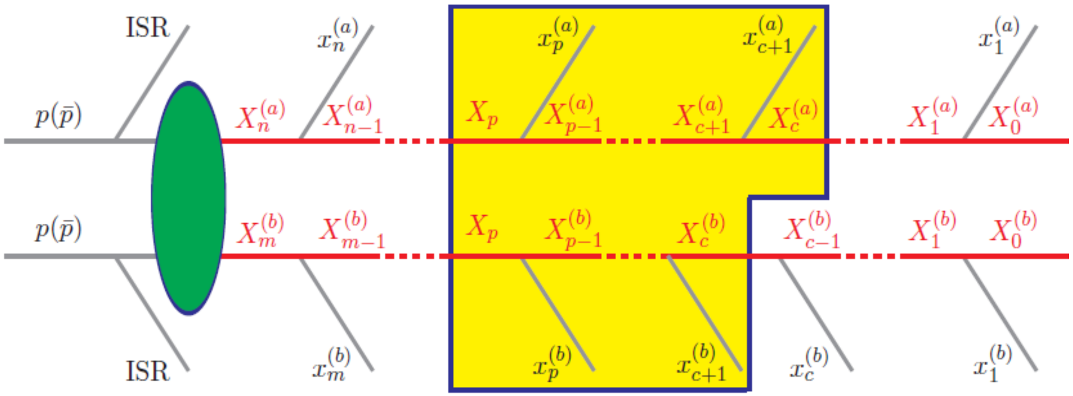
Generalize M_{T2} through S_{min}

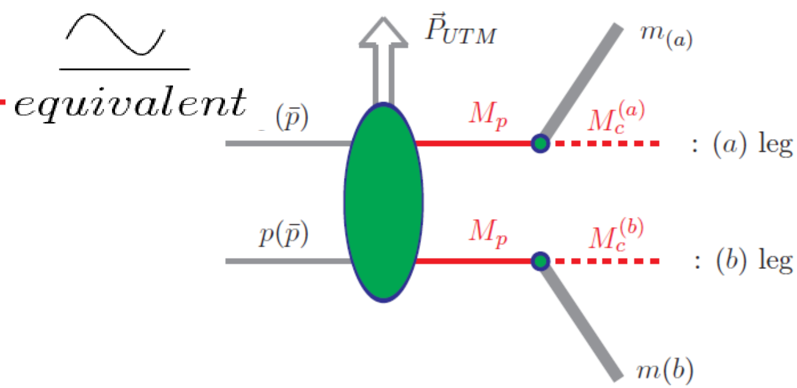
Constraints on "produced (Mothers)" particles to be the "SAME"

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

NO ↓

? = Generalized M_{T2}

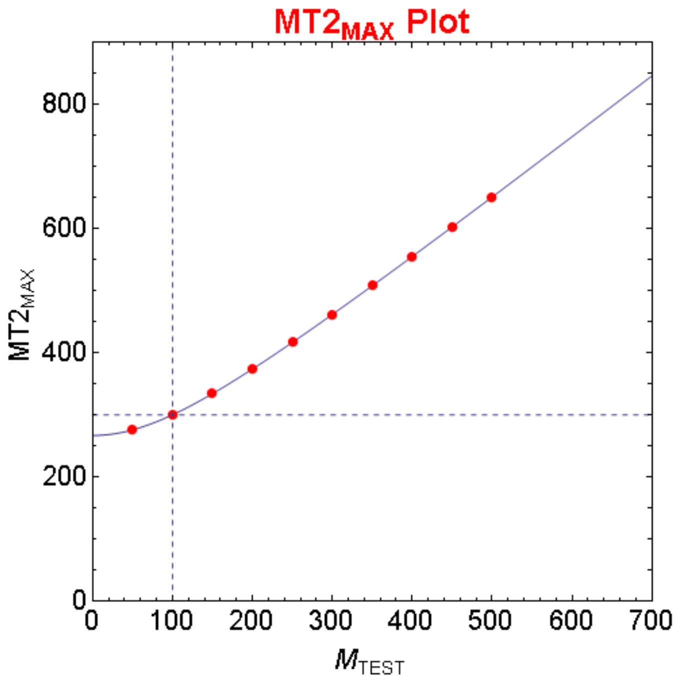


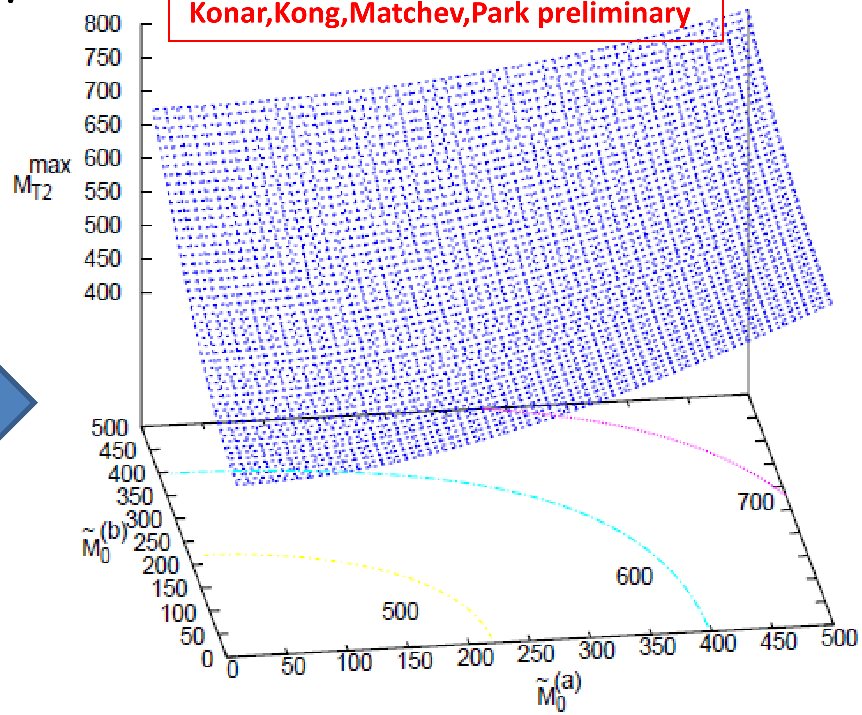


$$M_{T2}\left(\vec{p}_T^{\,(a)},\vec{p}_T^{\,(b)};m_{(a)},m_{(b)};\tilde{M}_c^{(a)},\tilde{M}_c^{(b)}\right) = \min_{\vec{q}_T^{\,(a)}+\vec{q}_T^{\,(b)}=\vec{P}_T}\left[\max\left\{M_T^{(a)}\left(\vec{p}_T^{\,(a)};\,\vec{q}_T^{\,(a)};\,m_{(a)};\,\tilde{M}_c^{\,(a)}\right),M_T^{(b)}\left(\vec{p}_T^{\,(b)};\,\vec{q}_T^{\,(b)};\,m_{(b)};\,\tilde{M}_c^{\,(b)}\right)\right\}\right]$$

Generalized M_{T2}

For example : $M_{T2}(1,1,0)$, namely No PT boost from earlier decaying step, and visible particles are massless case.





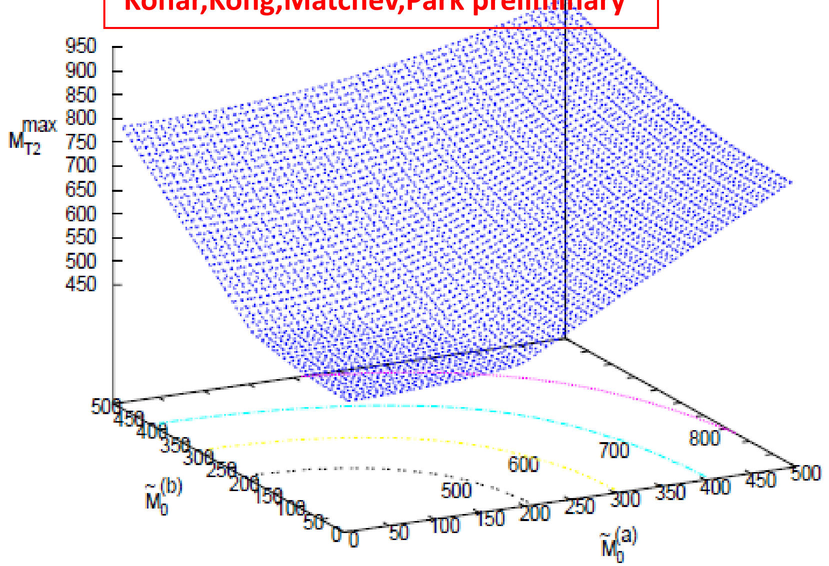
One dimensional relationship between M_1 and M_0

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

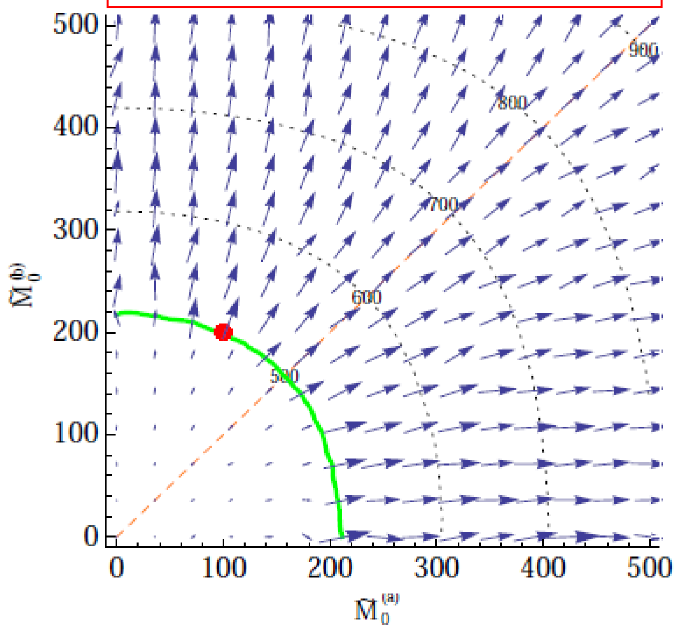
Way to pin down Mass spectrum

- Remember (a) : KINK structure

Konar,Kong,Matchev,Park preliminary



Konar,Kong,Matchev,Park preliminary

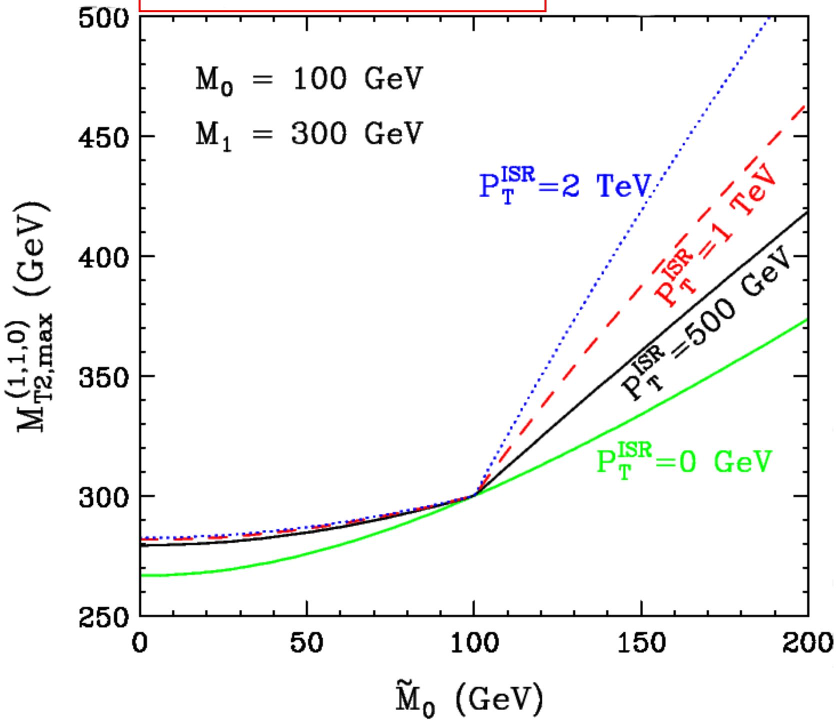


Like the "KINK" as in old M_{T2} ,the new generalized M_{T2} has a "Ridge" structure arising from the PT boost. But still we have can't pin down mass spectrum

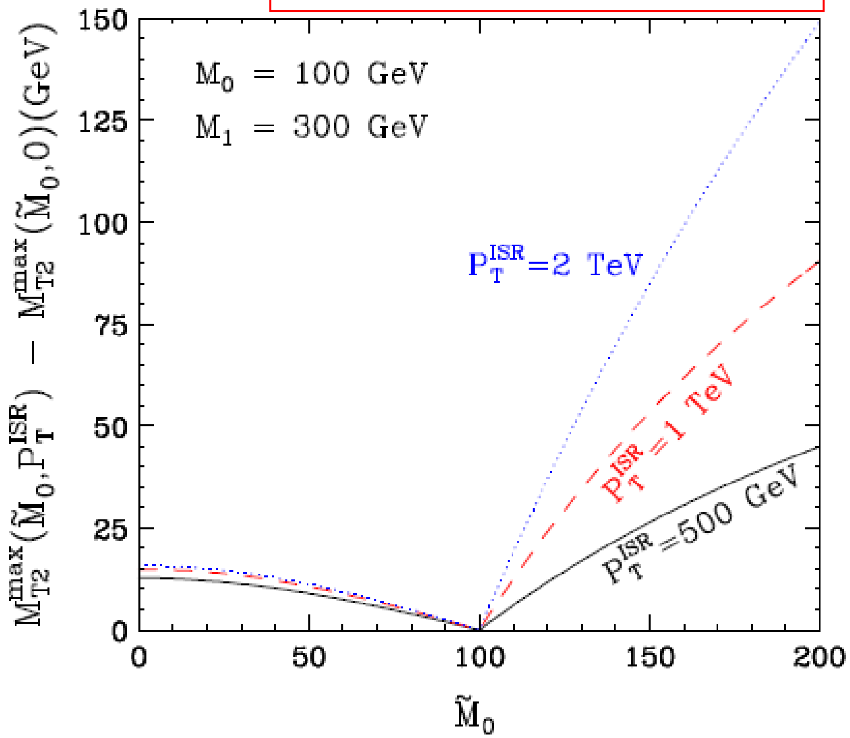
Way to pin down Mass spectrum

- Remember (b) :
  "Boost"-invariance of M_{T2} at the true mass spectrum.

Burns, Kong,Matchev,Park

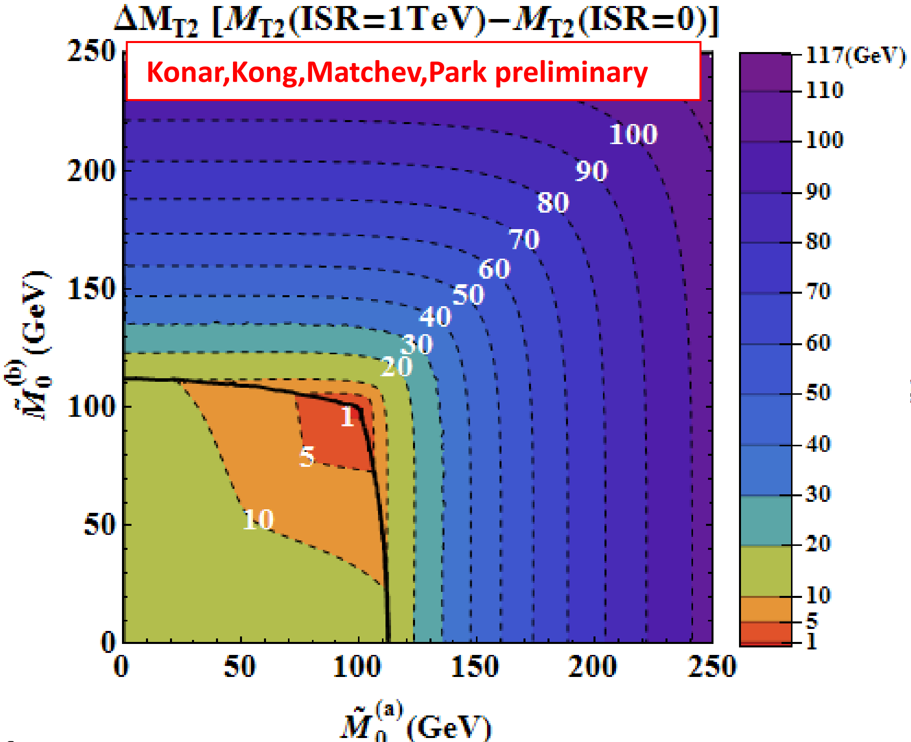


Konar,Kong,Matchev,Park preliminary



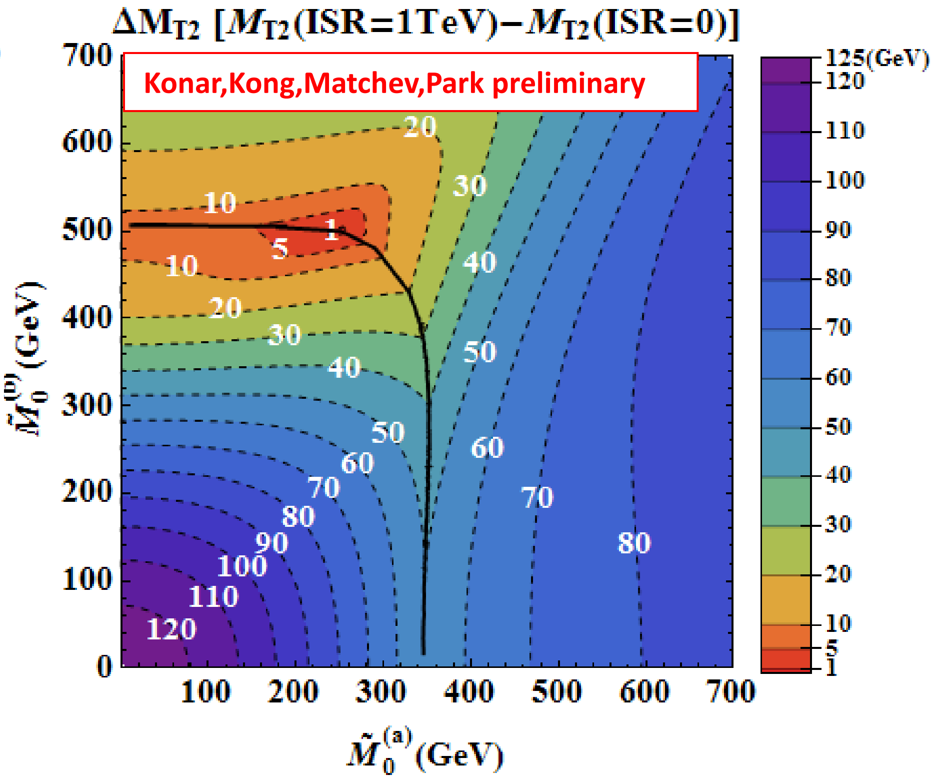
Way to pin down Mass spectrum

- Remember (b) :
  "Boost"-invariance of M_{T2} at the true mass spectrum.



Mass spectrum :

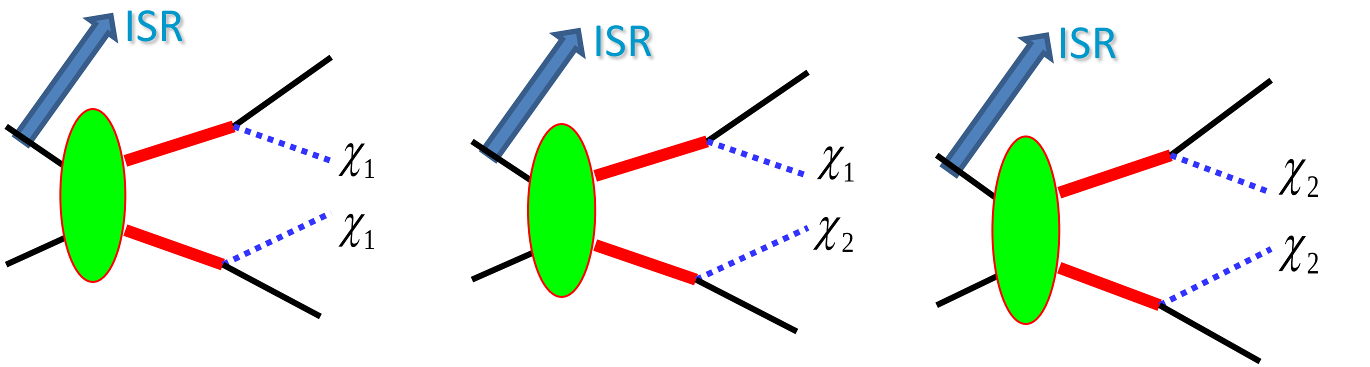
(M1, M^a_0 , M^b_0) = (300,100,100) GeV



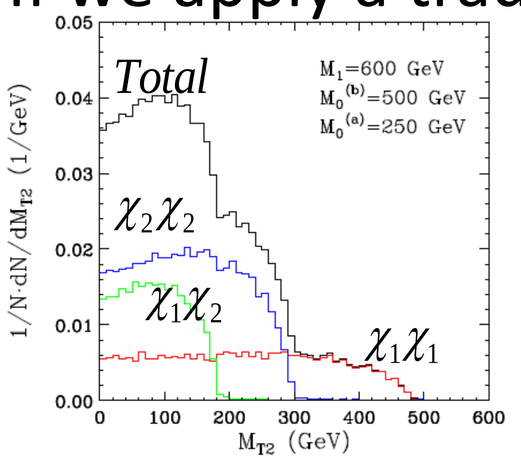
(M1, M^a_0 , M^b_0) = (600,250,500) GeV

Application

- Mother particle can decay into χ_1 or χ_2

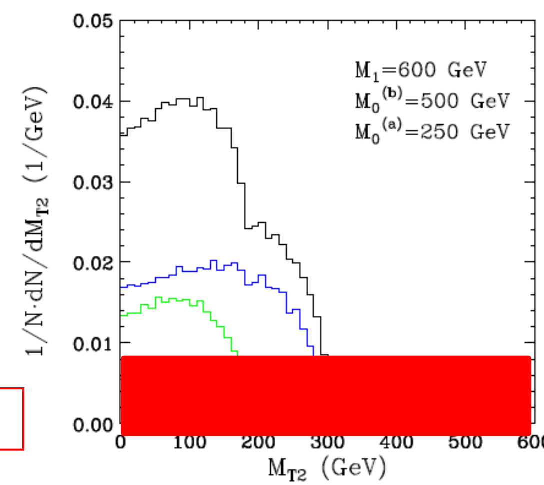


- If we apply a traditional M_{T2}



Depending on branch ratios, backgrounds, and errors in Missing E_T measurement

Konar,Kong,Matchev,Park preliminary



Handling neutrino !

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

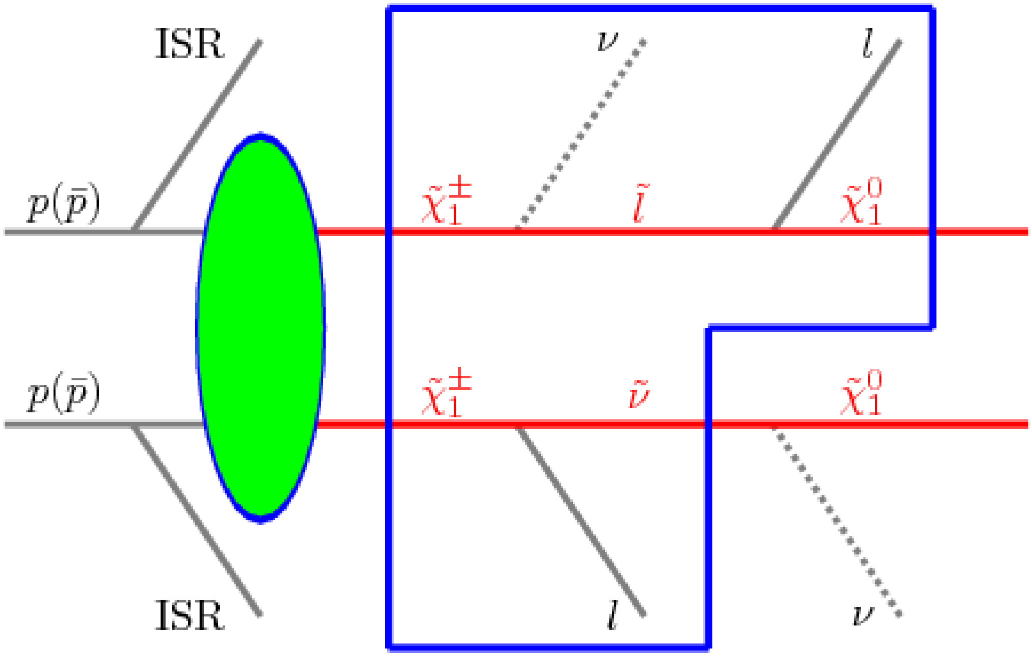
Require

$\sqrt{S}_{\min}(sub)$

Any neutrinos in the intermediate decaying steps?

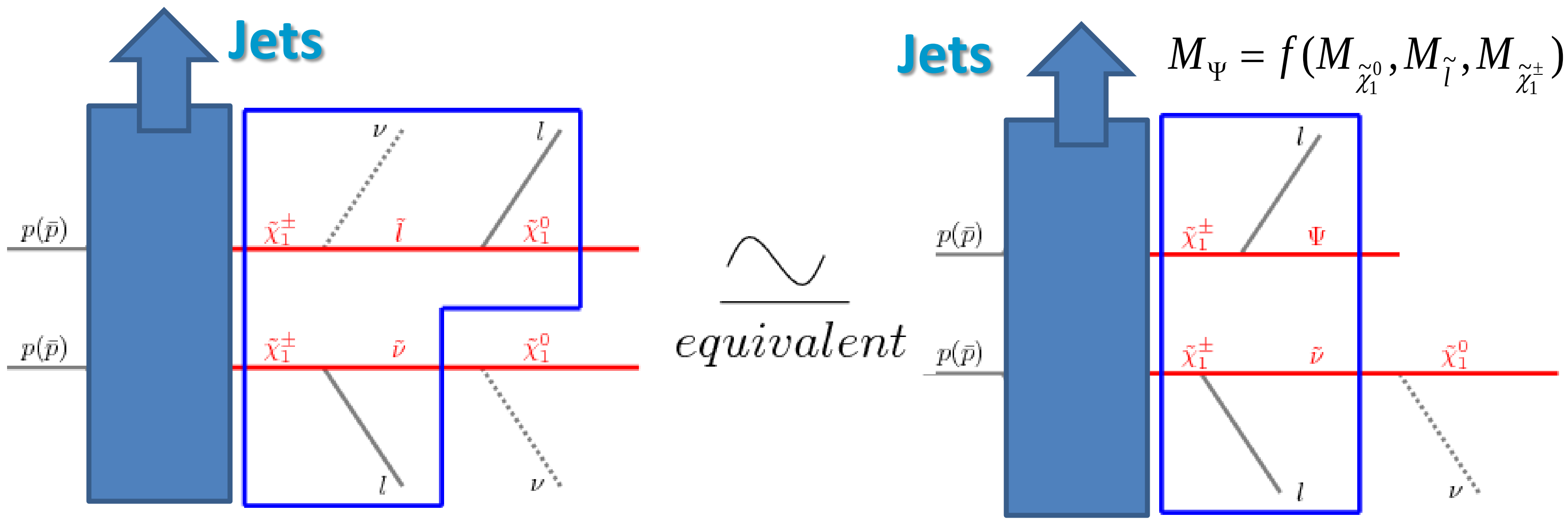
NO

?? = **Generalized M_{T2}**



Handling neutrinos !

- Thus, we need to apply our generalized M_{T2} to deal with neutrinos and more works are in progress with P. Konar, Konstantin Matchev (UF) KC. Kong (Fermilab) F. Moortgat, L. Pape (CERN)



CONCLUSION

- S_{min} is a very general and suitable variable for the hadron collider.
- M_{T2} can be generalized systematically through S_{min}
- We can't be sure whether WIMPs are the same type or not (only with Missing PT information)
- We need to consider a general case with admitting "Different-type" WIMPs case and if they are the same, we need to prove it at the first stage of analysis.
- Generalized M_{T2} can do its "JOB" for above case.