BSM at LHC

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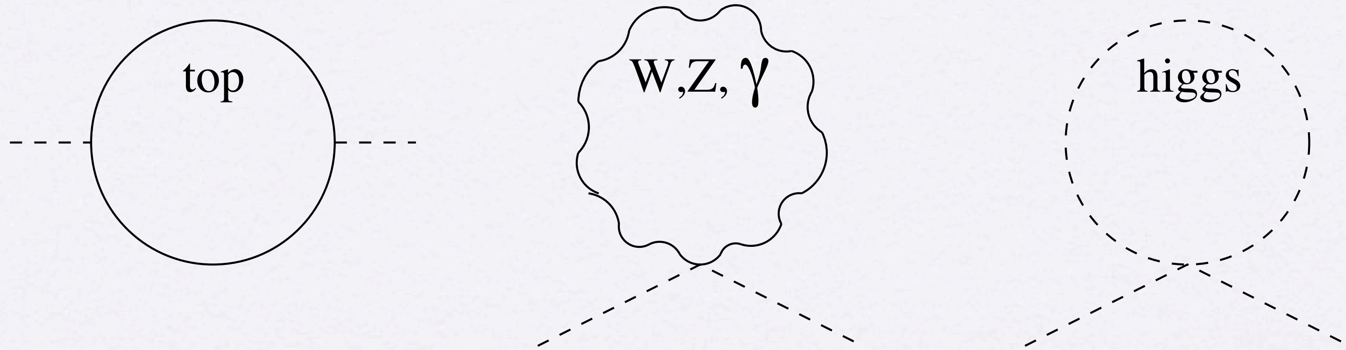
On the theories in the market
and how LHC tackle them

LHC is far more important than any experiment in the past

- Expand experimental reach significantly
- Cutting into TeV scale first time. **Last chance** to solve naturalness problem.
- We have solid observational evidence of DM in our Universe. A new particle!
- future experimental projects are now tied up with "LHC discovery", ILC, Super B factory, DM searches....**Huge responsibility to provide correct scientific results quickly**.

New Physics, Clue

Fine tuning in the Higgs sector

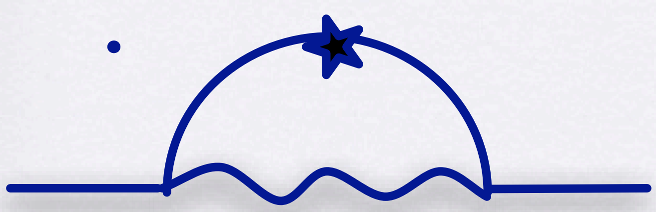


$$
\begin{array}{rcl}
\text{top loop} & -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 & \sim \; -(2\ \text{TeV})^2 \\
SU(2)\ \text{gauge boson loops} & \frac{9}{64\pi^2}g^2\Lambda^2 & \sim \; (700\ \text{GeV})^2 \\
\text{Higgs loop} & \frac{1}{16\pi^2}\lambda^2\Lambda^2 & \sim \; (500\ \text{GeV})^2.
\end{array}
$$

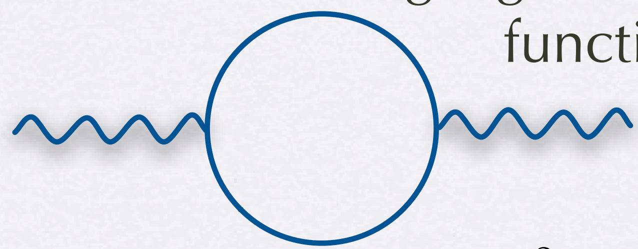
Others are reasonable

Why Higgs vev is O(200) GeV??

$m_f \log \Lambda$ fermion mass



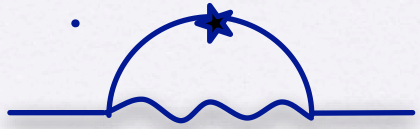
gauge two point function



$$\Pi_{\mu\nu} = (g_{\mu\nu}p^2 - p_\mu p_\nu)\Pi$$

New Symmetry →New Particle

- Need control on the radiative correction to the Higgs sector



- ideas
  - chiral symmetry (extended to boson sector)
  - global symmetry(little Higgs model)
  - gauge symmetry (gauge higgs unification)

- **Or planck scale is low (Extra dimension model)**

- On the other hand< we see no effect of BSM in radiative correction

$$\delta L = \frac{(h^\dagger D_\mu h)^2}{\Lambda^2} \quad \Lambda > 5\mathrm{TeV}$$

Classic Solution:Supersymmetry

- exchange boson and fermion. $\phi \leftrightarrow \psi$
  - sfermions(0), gaugino(1/2), higgsinos(1/2)
- SUSY change "dimension" (1 for boson 3/2 for fermion), relate mass and couplings

$$\Phi = \frac{1}{g^2} + M\theta^2 \qquad \Phi WW = \frac{1}{g^2} F_{\mu\nu}F^{\mu\nu} + M\tilde{g}\tilde{g}$$

- chiral symmetry is extended to boson sector. No quadratic divergence

$$\lambda\psi_L\psi_R H \to \lambda\phi_L\psi_R\tilde{H} + \lambda\psi_L\phi_R\tilde{H}$$

- R parity conservation. New stable particle→ DM candidate.

SUSY breaking scenarios and mass spectrum

- Low energy phenomenology is not the end of the story .

- Hidden sector break supersymmety. “flavor and CP” problem

  - gravity mediation, gauge mediation, anomaly mediation(string inspired mixed cases) , “geometric separation”

Rich Field!

- Problems (why alternatives are searched for)

  - Light higgs boson (hope and/or worry) little hierarchy

  - DM constraints

  - gravitino, string moduli.....

Alternative: Extra-dimension

- matter on brane, gravity in the bulk (Arkani-Hamed at al 1998)
  - fundamental gravity scale may be small. gravity effects at colliders
- extra space may not be flat (Randall and Sundrum, 99)

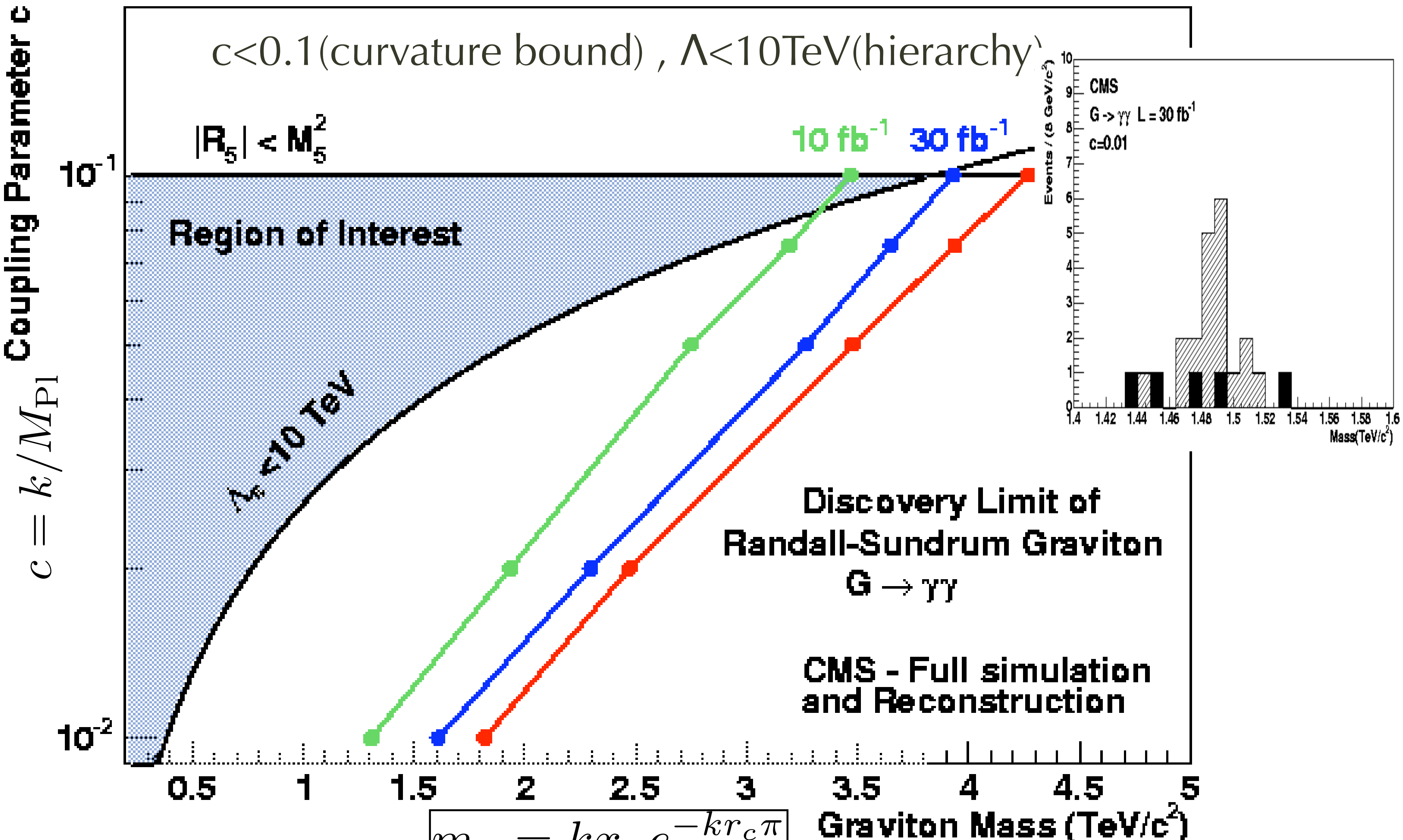
$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2$$

$$\Lambda = M_{\rm Pl}e^{-kr_c\pi} \qquad m_n = kx_n e^{-kr_c\pi}$$

$kr_c\pi$ → O(10)

- Universal Extra dimension (Appelquist et al 2000)
  - particles also in the bulk, Translation is violated only at the boundary. KK level works as parity. LKK particles is stable
- Black Hole at collider.
- difficulty: divergence (higher dimension), cosmology

Discovery potential



$$m_n = k x_n e^{-k r_c \pi}$$

Litvin talk in Moriond

see also EPJ C40 Collard et al

Dynamical symmetry breaking ?

- Technicolor→ Little Higgs model
  - Higgs boson is goldstone boson of a large symmetry. SU(5)→SO(5)

$$\Sigma(x) = e^{i\Pi(x)/f}\Sigma_0 e^{i\Pi^T(x)/f} \qquad \frac{f^2}{8}\mathrm{Tr} D_\mu \Sigma (D^\mu \Sigma)^\dagger$$

  - Gauge symmetry: $SU(2)_1 x SU(2)_2 x U(1)_1 x U(1)_2$

$$(g_1, g_2, g_1', g_2')$$

  - quadratic correction to Higgs sector starts from 2 loop
  - top sector must be extended (extra top quark). afterall top-higgs coupling is the source of fine tuning.

$$\chi = (b_3, t_3, \tilde{t})$$

$$\tilde{t}, \tilde{t}'$$

$$\frac{1}{2}\lambda_1 f \epsilon_{ijk}\epsilon_{xy}\chi_i \Sigma_{jx}\Sigma_{ky} u_3^{'c} + \lambda_2 f \tilde{t}\tilde{t}^c + hc$$

- However it is rather difficult to make simple Little Higgs model and LEP data consistent .

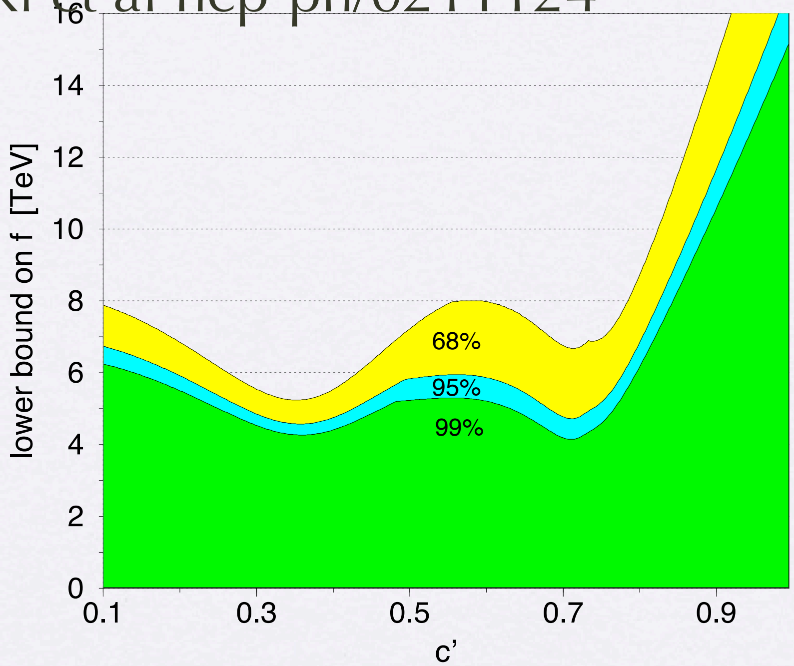
LEP Anchor

difficulty comes from tree level Heavy-Light mixing

$$L_2 \to -\frac{g_1 g_2 (g_1^2 - g_2^2)}{4(g_1^2 + g_2^2)} W^a_{\mu L} W^{a\mu}_H h^2 \quad \longrightarrow \quad -\frac{g^2 (s^2 - c^2)^2}{8 f^2} W_L W_L h^4$$

$$(W^a_L = s W^a_1 + c W^a_2)$$

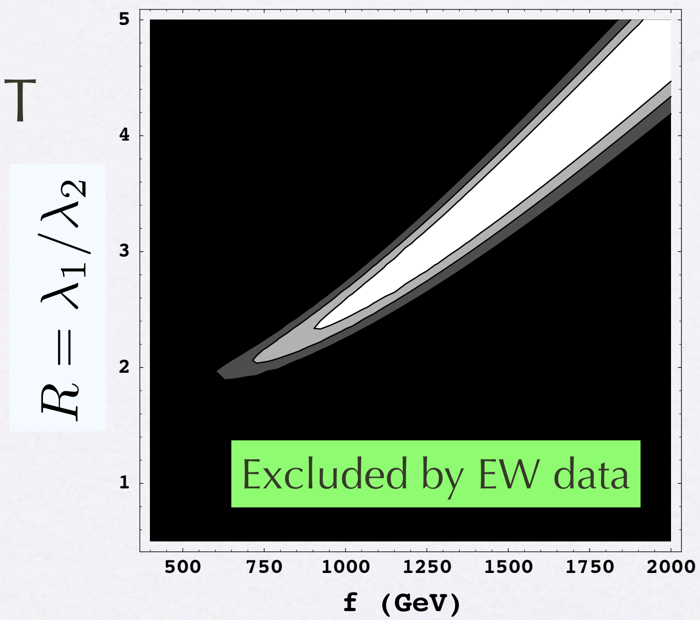
Csaki et al hep-ph/0211124



- Various v^2/f^2 corrections. proportional to the coupling difference, $\Delta g = g_1 - g_2$
- $M^2(W_H) = (g_1^2 + g_2^2) f^2/4 \sim (gf/2)^2 > 2.7$TeV
- f>4TeV m(t')>7TeV, (Hewett et al JHEP, 2003) Fine turning is reintroduced

Little Higgs with T-parity

Hubisz et al 0411264



$m_{T_-} = \lambda_2 f$

- gauge groups and matter contents respect T parity. $SU(2)_1 \rightleftarrows SU(2)_2$ $U(1)_1 \rightleftarrows U(1)_2$
- T-odd matters are introduced. Looks like SUSY without gluino
- LEP constraint is weaker.
    - Heavy gauge bosons and triplet higgs boson live in T-odd sector. No tree level mixing
- **Need more attempts to construct a model including symmetry breaking sector. (cf. the study of SUSY breaking sector.)**
- UED has similar nature.

The Lesson is ......

- LEP constraint (small radiative correction)
  - New Physics scale Λ is high, suggesting fine tuning.
  - Need symmetry to cancel divergence
  - top partner $\rightarrow$ top must be involved in the symmetry.
- "DM" and "radiative correction"$\rightarrow$parity structure

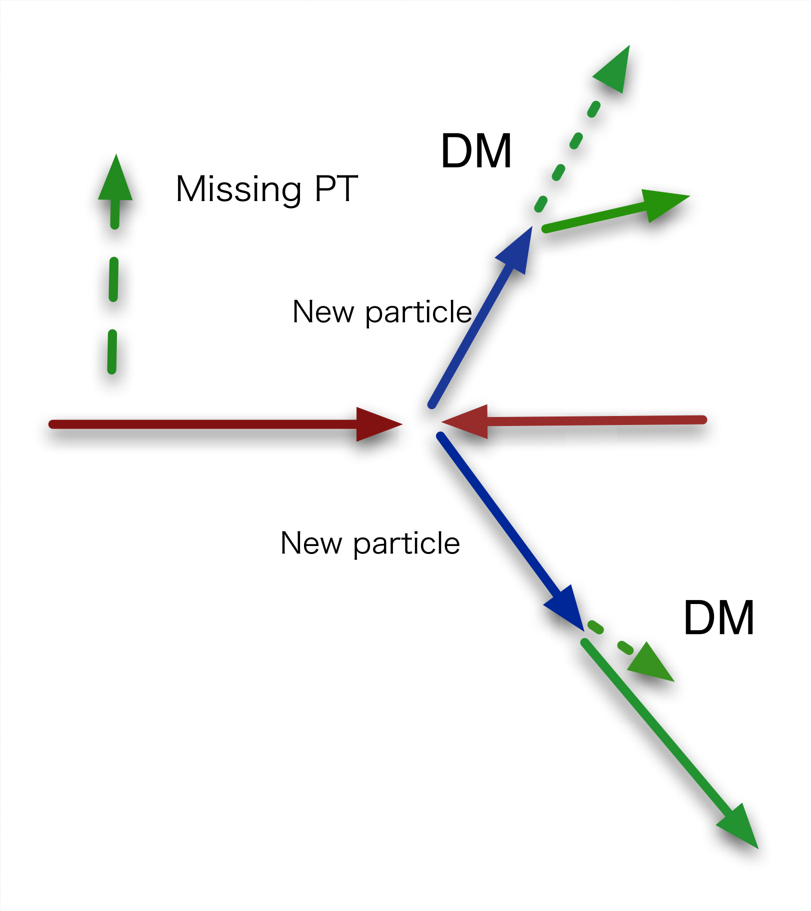
LHC signature:strongly interacting particle decay into DM
(and flavor sector involving b quark.....)

Basic objects at LHC

- jet and lepton momenta

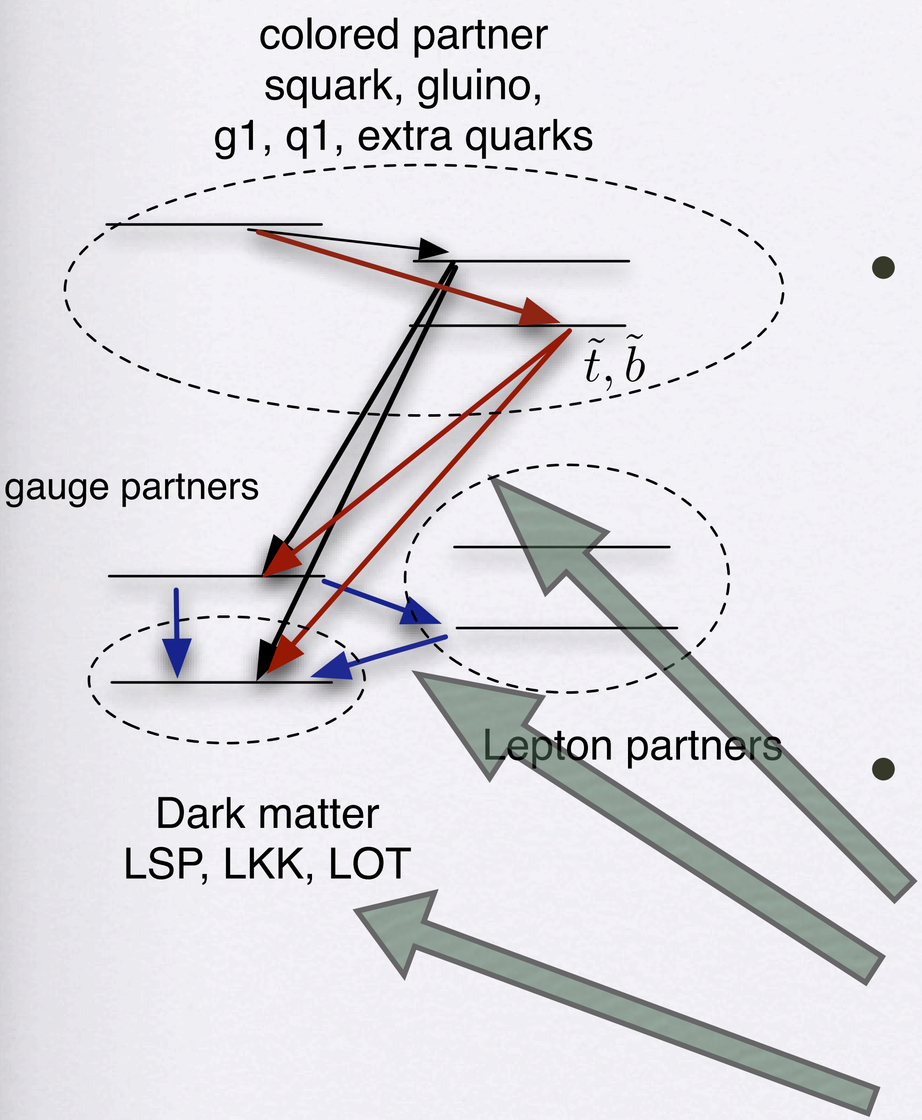
  $p_{j1}, p_{j2},\ldots. p_{l1}, p_{l2}\ldots.$
- Jet and lepton transverse momenta (to the beam)

  $p_{T1}, p_{T2}, p_{T3}\ldots..$
- E_{Tmiss}: Sum of the transverse momenta of all particles.
- M_{eff} Sum of the transverse energies of first 4 jets + E_{Tmiss}



$$M_{\rm eff} \equiv \sum_{i=1,\ldots4} p_{Ti} + \sum_{\rm leptons} p_{Tl} + E_{\rm Tmiss}$$

DM and collider signature



- **“SUSY signature”**
  “Models with new colored particles decaying into a stable neutral particle--LSP”
- “New physics” are migrated into SUSY category.
  - Universal extra dimension lightest of first level KK is stable. .
  - Little Higgs model with T parity. T parity in the model, T odd sector has stable particle (B_H)
- Signal: assume mass difference is large

High P_T jets (p_{T1}>100GeV, $p_{T2,3,4}$>50GeV)

p_{Tl}>20GeV, S_T>0.2

E_{Tmiss}> max(100GeV, 0.2M_{eff})

Background and discovery

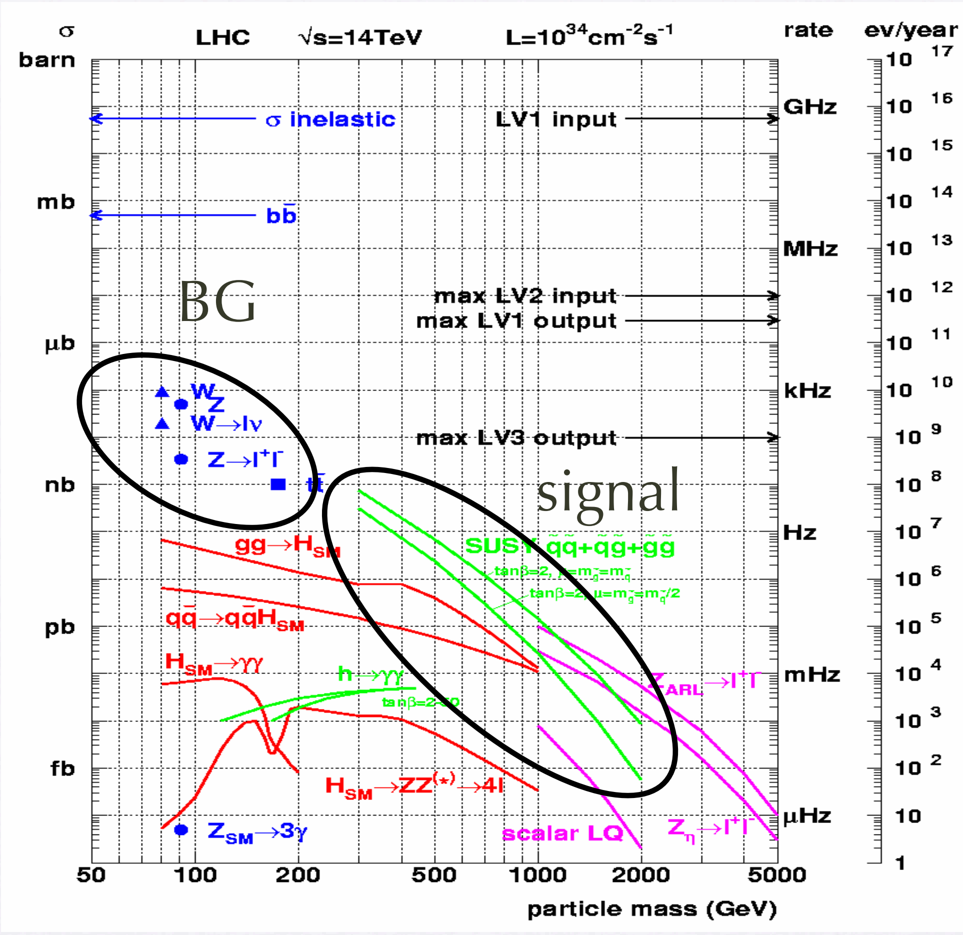
- The typical number of SUSY events are 10^5 for 10 fb^{-1}, while BG rate is 10^{9-8} for W, Z and ttbar productions. 10^{-4} rejection of SM process is required.

- Understanding of the distribution is the key issue

  - P_T distribution of the jets, M_{eff} distribution. (theoretical complexities)

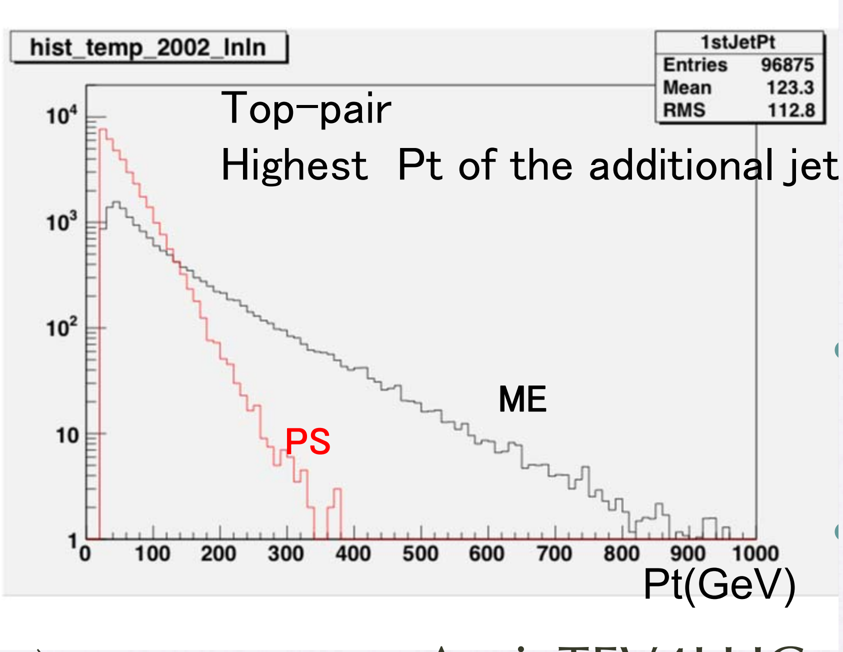
  - E_{tmiss} distributions (Experimental complexities)

CMS

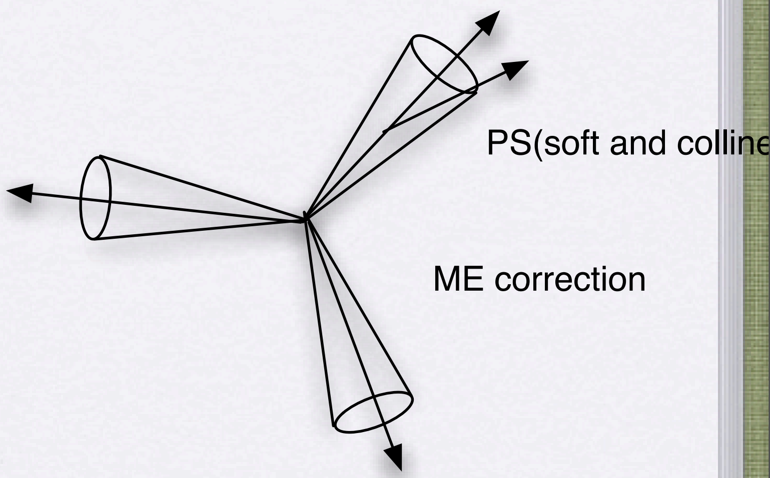


Discovery and Recent BG issues

- Bg process pp→W(Z)+X, ttbar ....
- Lowest order process (ex gq→W q) +"multiple parton final states" (ex. gq→ W+ n jet not in soft and collinear region (ME collections, CKKW, Mangano)
- Some generators(ALPGEN, MADevent..) allow to simulate multi-parton final state. Matching between PS and ME is an issue. (Lessons from Tevatron)
- up to ttbar + 3 jet, W(Z) +6 jet (!) have been included in BG estimation. Results with full detector simulations are getting ready.

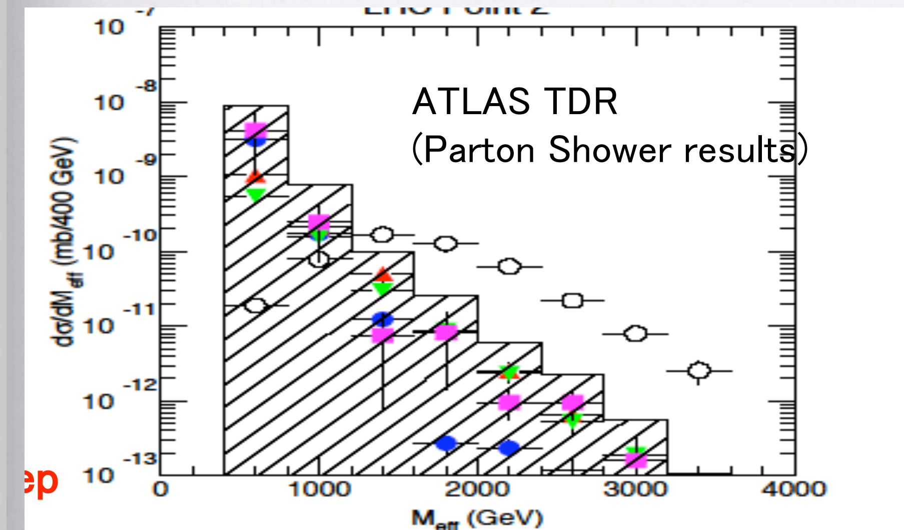


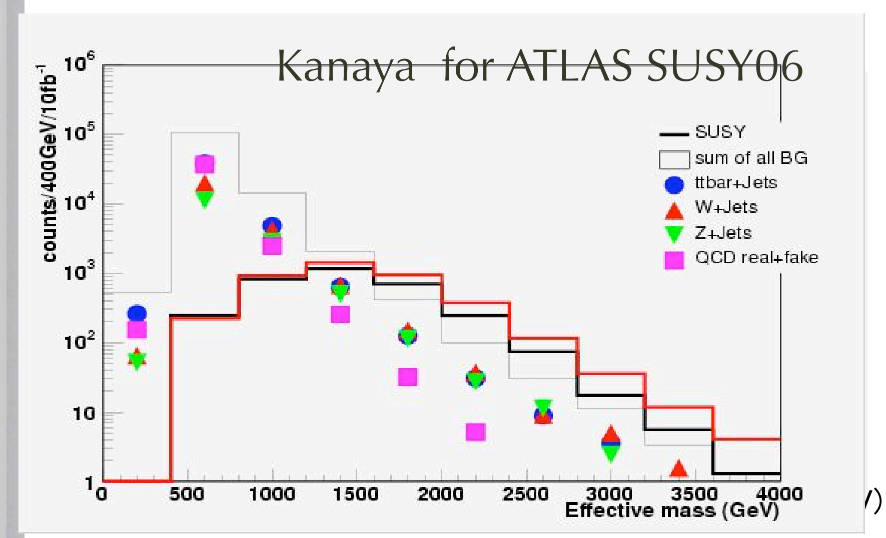
Asai TEV4LHC



Simulation study of ME corrections

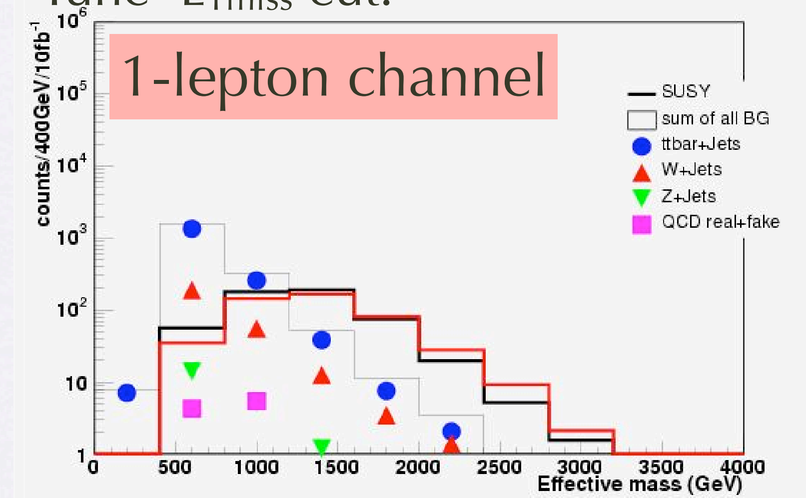
zero lepton channel





- High P_T jets increase drastically when taking into ME.
- K factor is 2~4 for large M_{eff} .
- scale uncertainty still remains(order of $\alpha^n(\mu)$), easily gets factor 2.
- BG is smaller in 1 lepton channel and dominated by ttbar. calibration is easier) Tune E_{Tmiss} cut.

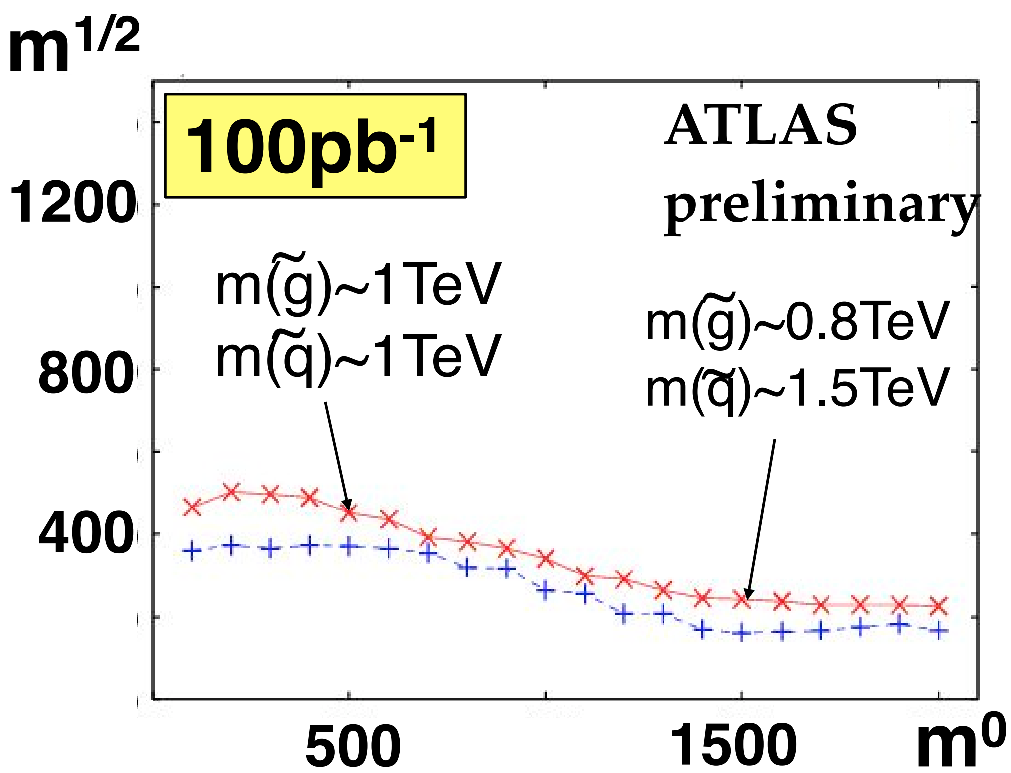
1-lepton channel

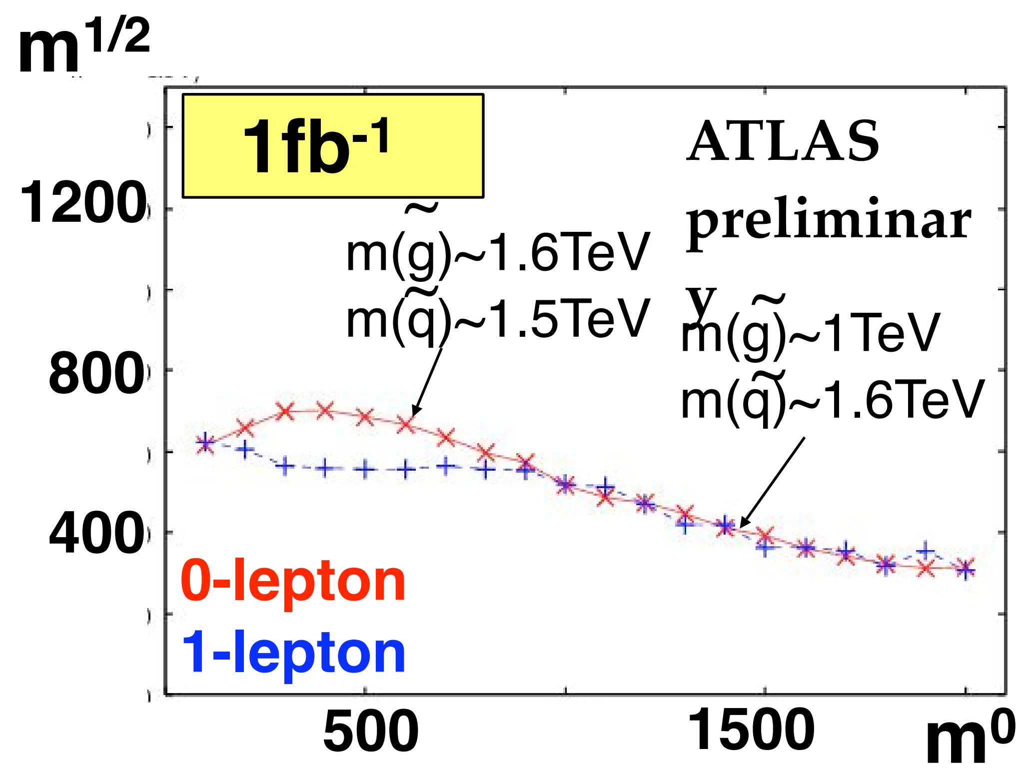


From Kanay's Slide in SUSY06

Discovery Potential

5-sigma discovery potential on m_0-$m_{1/2}$ plane





Fast simulation result
Signal : Isawig/Jimmy
Background : Alpgen

- **Only statistical error is included.**
- **Backgound is estimated by Alpgen.**
- **0-lepton mode : More statistics is available.**
- **1-lepton mode : Relatively smaller background uncertainty.**
  Major background is tt(+njets) is comparatively predictable.

Getting off from MSUGRA

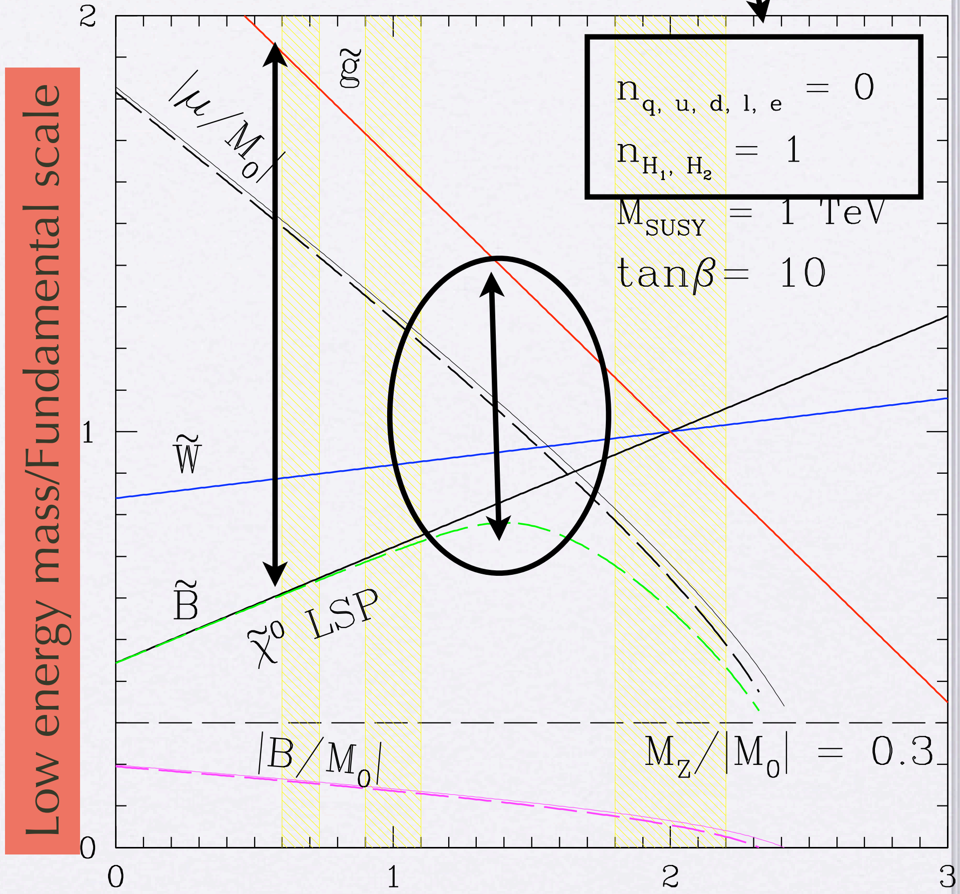
choice for large μ

Choi et al (2005)

- If both volume modulas T and compensator C contribute to the SUSY breaking.

$$M_a = \left(\frac{l_a}{R} + \frac{b_a g_{GUT}^2}{16\pi^2}\right) m_{3/2}$$

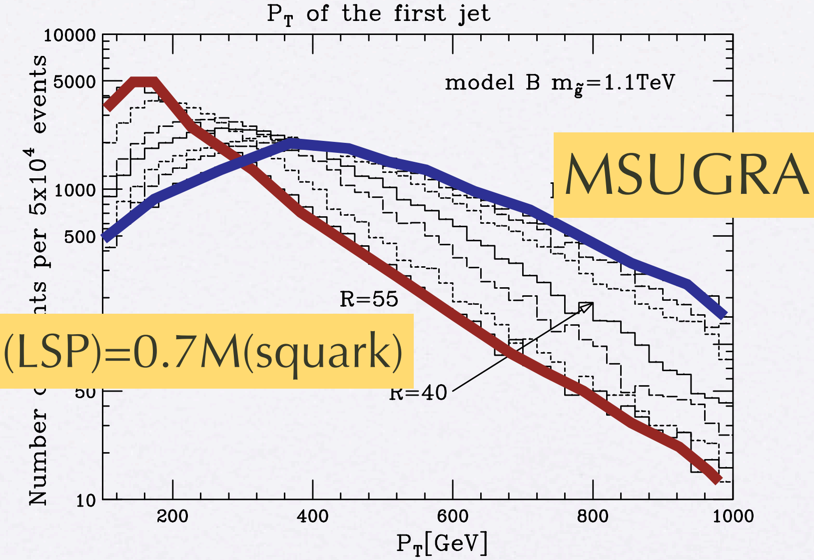
- mass spectrum can be quite degenerated. Change FT/FC, MSUGRA→ UED like→ AM

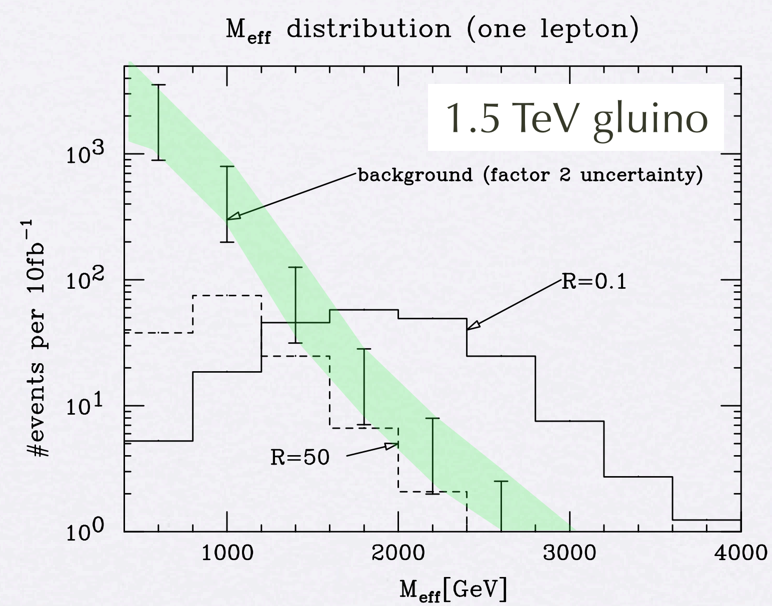


$$\alpha = \frac{m_{3/2}(T+T^*)}{F_T \log(M_{pl}/m_{3/2})}$$

SUSY at LHC in degenerated limit

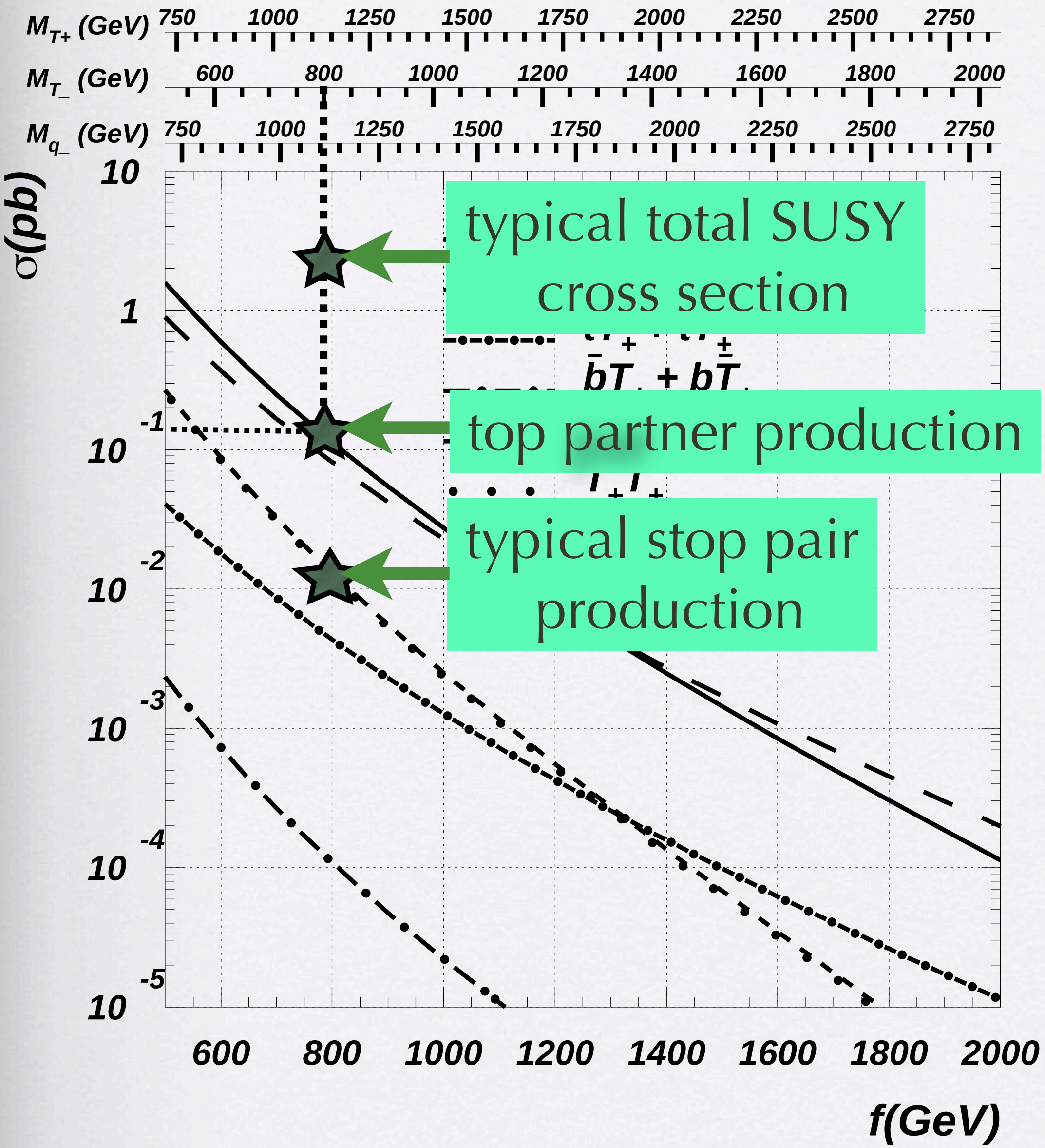
- degenerate SUSY= lower P_T jets, small M_{eff}. Discovery gets difficult (no chance if all masses are same)
- "Benchmark" of degenerate scenario
- Need to take into account the background seriously
- S/N<1, discovery is in ?? because of the background uncertainty





Kawagoe and Nojiri

Little Higgs model with T parity



- fermion partner instead of top partner
- Typical "fermion" top partner production cross section is 0.2 pb at m(T)=800GeV.
- σ(boson) /σ(fermion)=0.1
- The difference comes from spin structure. stop production is "mostly" p wave.
-

from Belyaev et al hep-ph 060917

Reconstruction of top partners at LHC

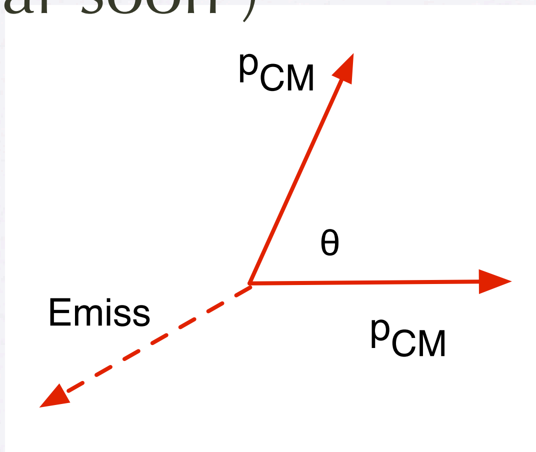
(Matsumoto, Nojiri, Nomura.... to appear soon)

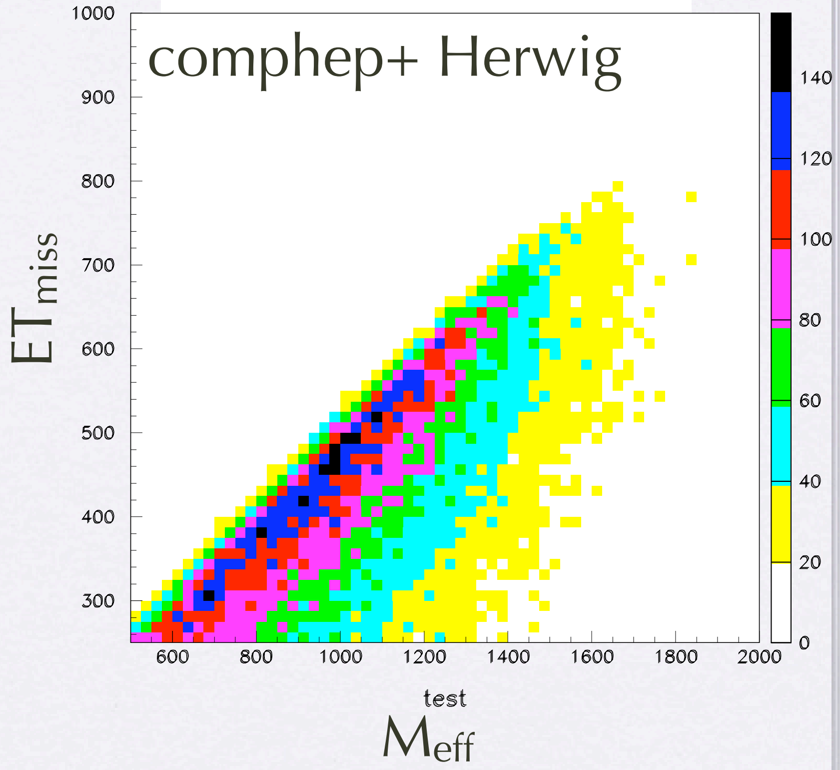
Top partner : Key particle of Little higgs model with T parity

$$gg \to T_- T_-^*, T_- \to t B_H$$

$\sigma = 0.2\text{pb for } m(T_-) = 800 \text{ GeV}$

BG is huge $\sigma(tt) \sim 1\text{nb}$





- Clue: E_{Tmiss} tend to be ~0.5 M_{eff} for the events with 2 DM.
  - 2 "uncorrelated" top with same energy $|p_{CM}|$. Large M_{eff} means large E_{Tmiss} for fixed M(T_).

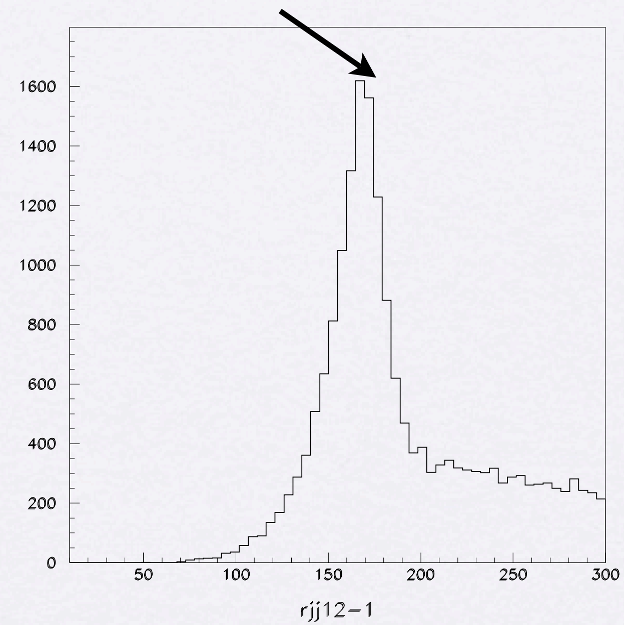
Top reconstruction

- hemisphere analysis: find two axes in a event

F. Moortgat and L. Pape, CMS Physics TDR

- algorithm
  - take highest PT jet as seed of an axis. (A)
  - take 2nd jet with max PxΔR from the 1st jet as the seed of the 2nd axis (B)
  - assign jet and lepton activities to the “closer axis”. (C)
  - recalculate “axis=sum of particle in the hemisphere” , repeat . (D,E)

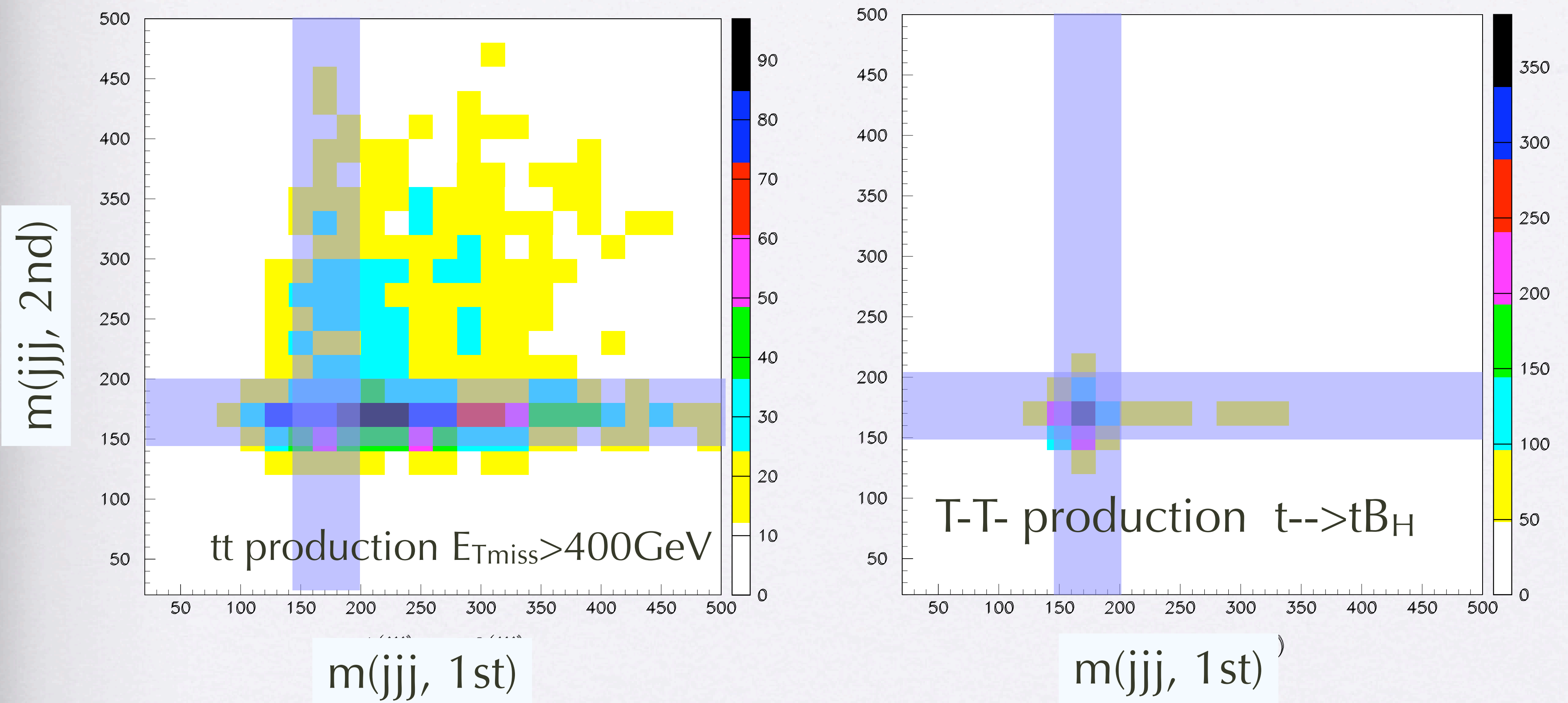
top peak!



3 jet invariant mass distribution in a 1st hemisphere

This is an unbiased selection

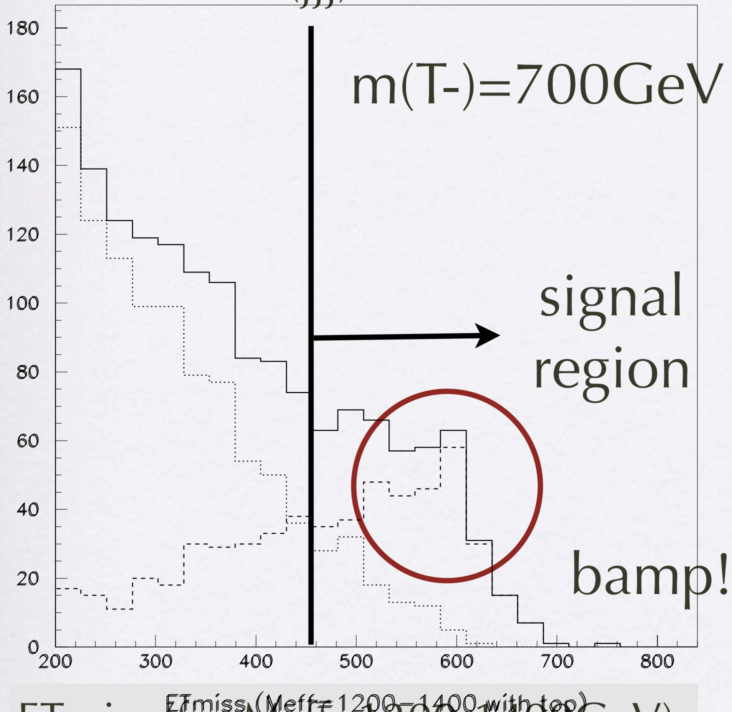
Signal and BG



- tops are seen in both of the hemisphere
- probability of top reconstruction is small for the ttbar background (because of E_{Tmiss} cut)
- Need b tag to make ttbar is a dominant background (not applied)

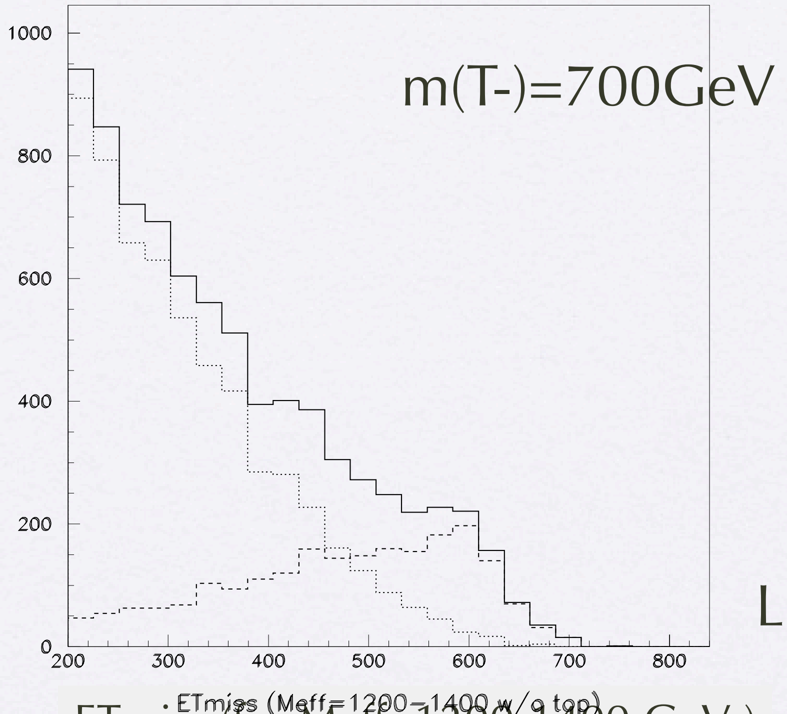
signal distribution & top background

no K factor for signal and background
one of m(jjj) is consistent to mt



ETmiss (for Meff=1200-1400GeV)

top is not required



ETmiss (for Meff=1200-1400 GeV)

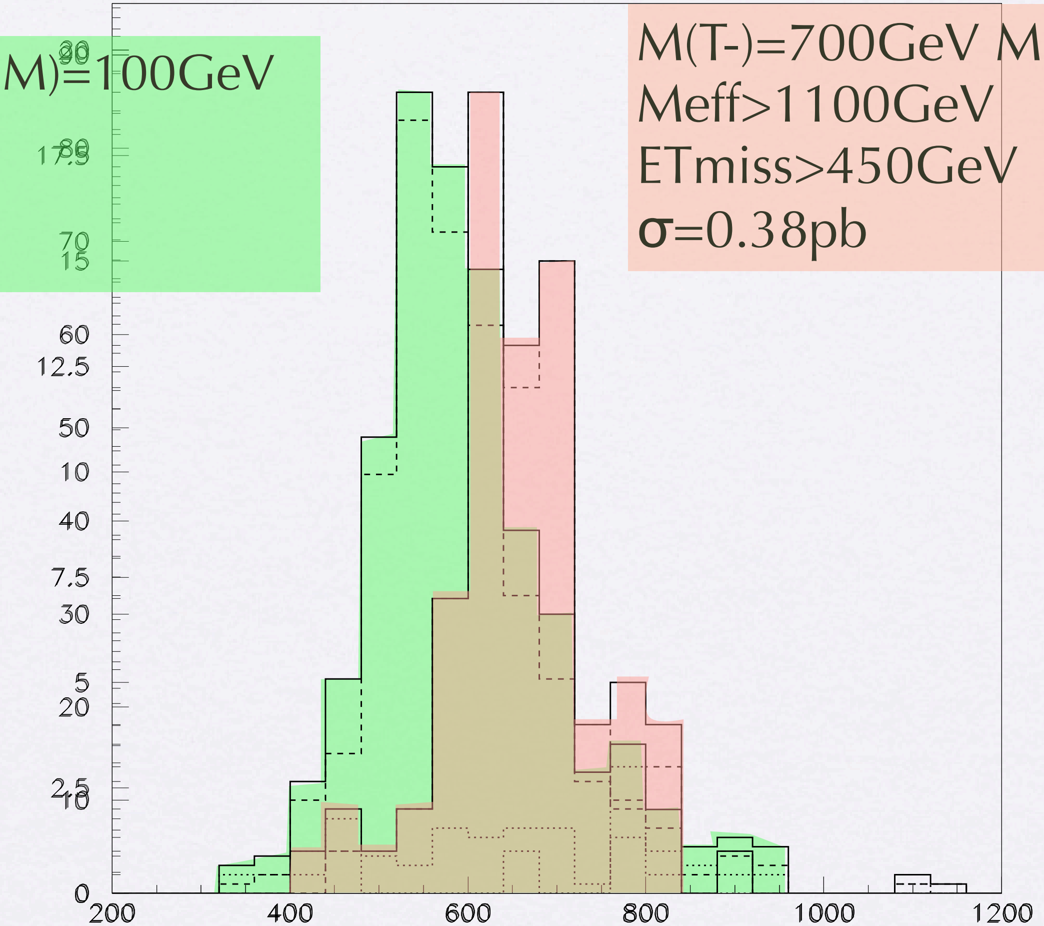
L= 50fb-1

- signal E_{Tmiss} distribution has a peak near $M_{eff}/2$
- BG peaks at $E_{tmiss} << M_{eff}$
- good margin for discovery due to the bump structure.

Sensitivity to the mass

M(T-)=600GeV M(DM)=100GeV
Meff>1000GeV
ETmiss>400GeV
σ=0.98pb

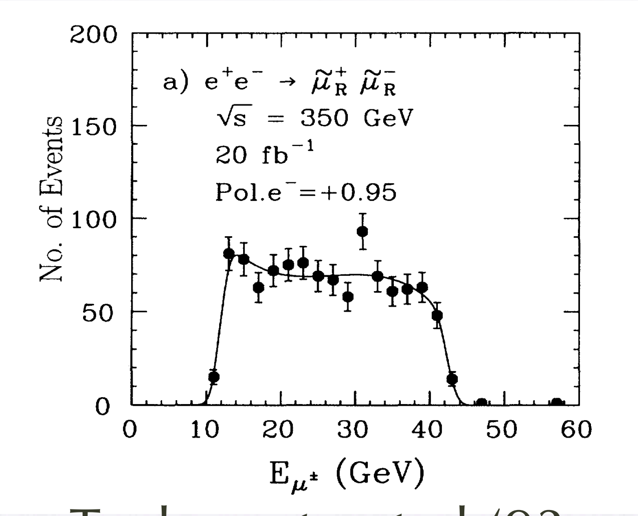
M(T-)=700GeV M(DM)=125GeV
Meff>1100GeV
ETmiss>450GeV
σ=0.38pb



MT2 for $M(B_H)$=150 GeV

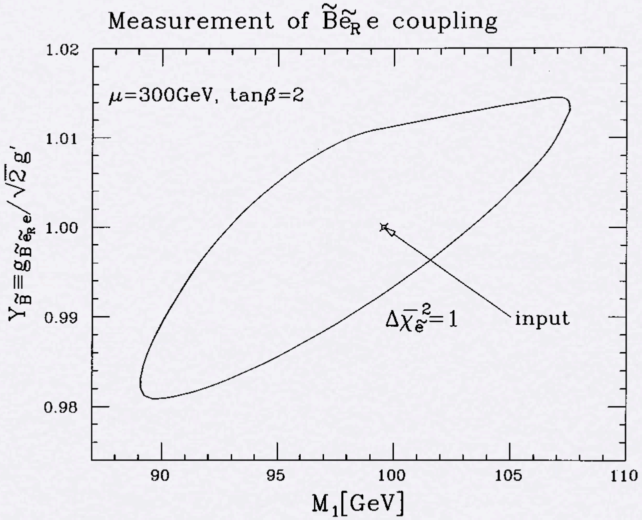
SUSY parameter measurement
A brief history

- early 1990
  - JLC study: define LC as the machine to measure SUSY parameters, spin, and interaction. check GUT relation M_1:M_2
  - LHC as a discovery machine.



Tsukamoto et al '93

- Snowmass 1996:
  - Trying to establish US participation at LHC, "(ex-)Theorists"(Hinchliffe, Paige, ...) took LC concepts. Techniques for mass reconstruction were established at that time.
  - ILC: SUSY coupling measurements ('96 Nojiri et al , Feng et al....): physics point of LC over LHC



Nojiri et al '96

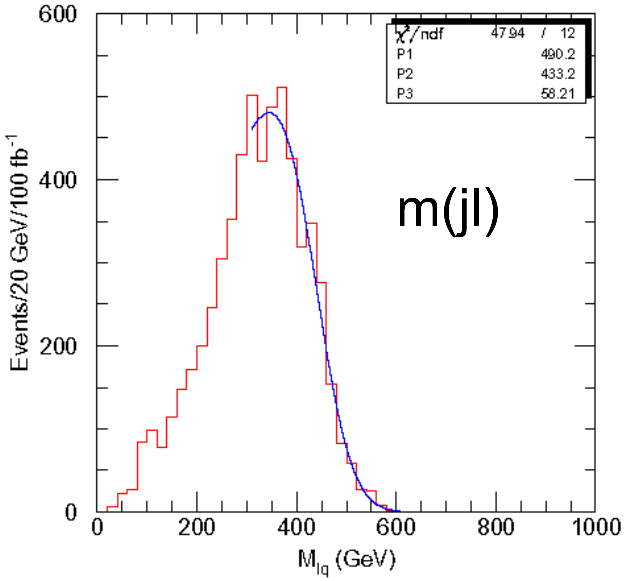
Mass reconstruction at LHC

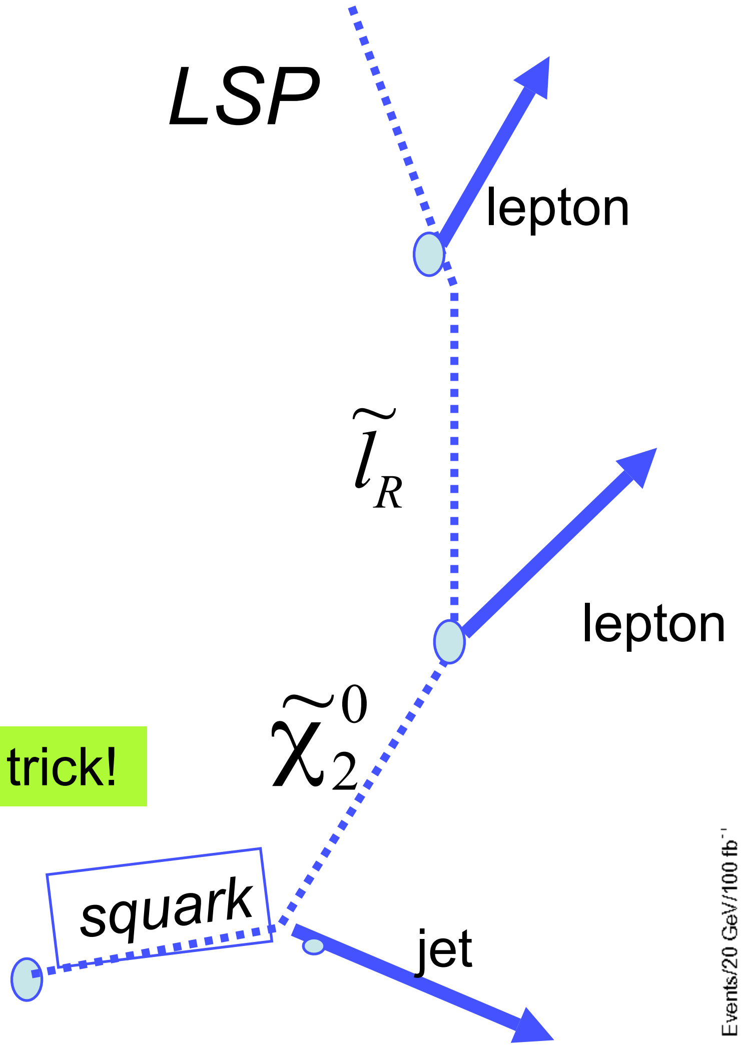
- Invariant mass distributions instead of energy distribution
  - Tag particles from a SUSY particle decay chains (jet selections are essential)
  - end point of distributions or distributions near the end point (momentums are aligned)
  - Exact Kinematical relation (long decay chains)

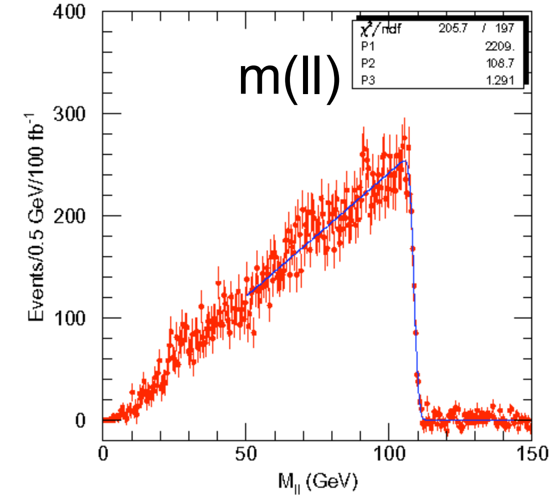
  } mass information

- P_T of the jets (Peaks at typical scale) ⇒ M_{T2}
- SUSY distributions" are not correction of the 1 dim distributions. It lives in multi-dimensional space---momentum space of jets and leptons.

determination of the boundary of phase space for mass determination.

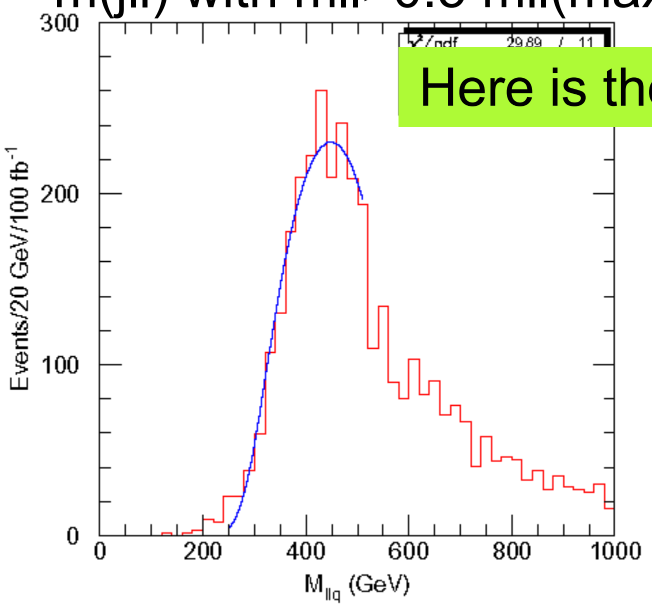


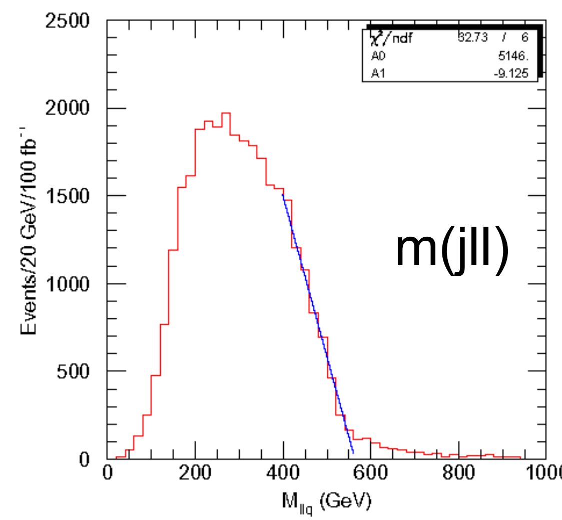




ee+μμ-eμ subtraction is effective to select single channel

m(jll) with mll>0.5 mll(max)



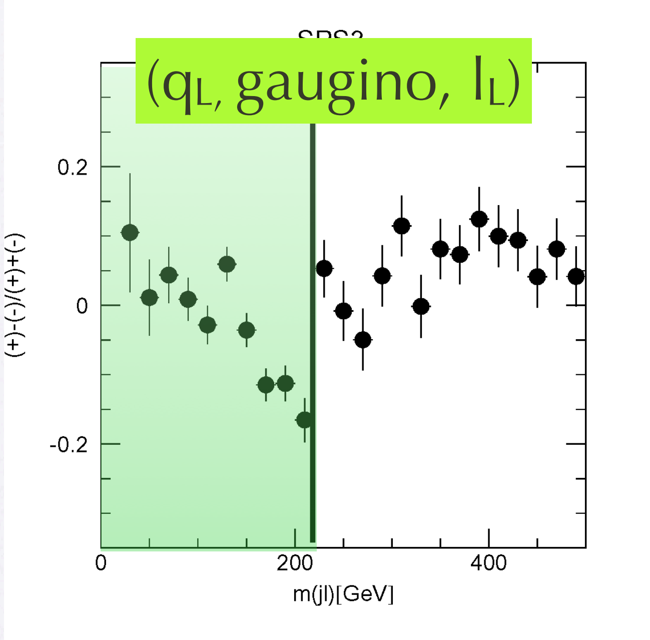


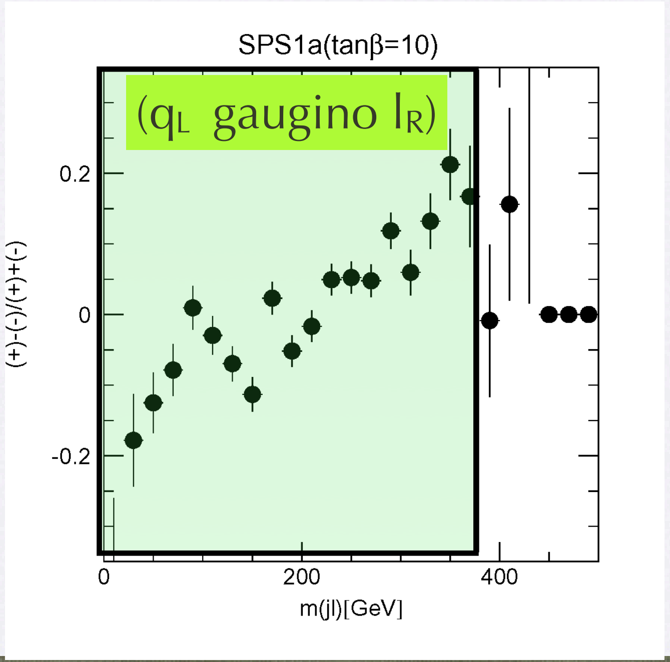
Hinchliffe et al (97)

fermion/boson? Left/Right?

- charge asymmetry in jl(+ or -) distributions (Barr, Goto et al....) in SUSY
- To have this asymmetry
  - pp collider (squark> anti-squark)
  - squark /sleptons are dominantly left or right.
  - **neutralino is spin 1/2**
  - SUSY is the chiral theory , gaugino-sL-L vertex
- Distribution would be different for UED cases (Smillie and Webber, hep-ph 0406317, Alves et al hep-ph/0605067)
- general discussion (by Athanasious et al hep-ph 0605286) for general decays involving 4 new particles

from Goto et al (2004)





Summary in SPS1a (most lucky case)

from LHC/LC study

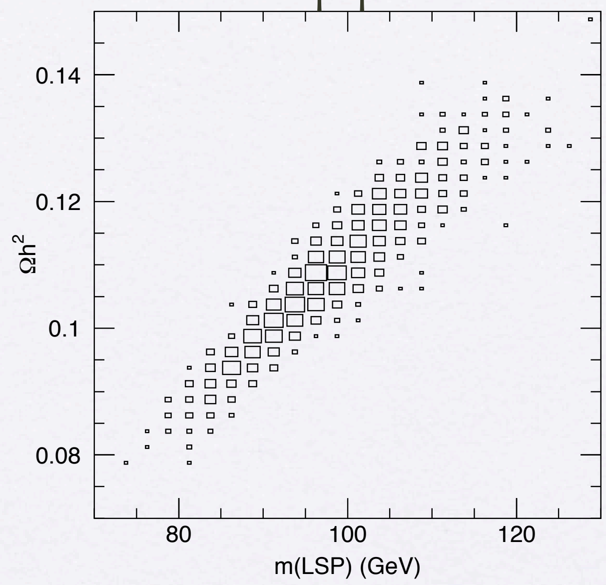
particle	mass	error(low)	error(high)	
gluino	595	16.3	8.0	bbll
squark(L)	540	21.2	8.7	jll
squark(R)	520	17.7	11.8	M_{T2} 10GeV sys
$\tilde{\chi}_4^0$	378	14.6	5.1	
$\tilde{\chi}_2^0$	177	13.4	4.7	
$\tilde{\chi}_1^0$	96	13.2	4.7	

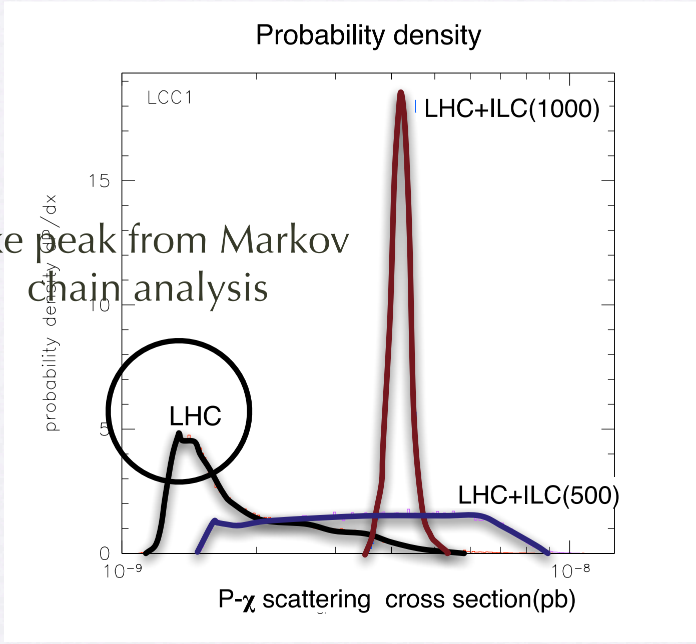
- LSP mass error is large, but mass differences are known precisely
- Access to 3 neutralino mass, information on 3 of (M1,M2,μ, tanβ)
- selectron and smuon mass error is about same to that of N02
- stau mass also can be measured from tau tau end point. many fake tau background. Need more study, but don’t be nervous.

Trying to pin down Dark matter nature

- DM density: for SPS1a
  - slepton exchange (^^)v
  - stau co-annihilation (^^; not enough in co-annihilation region because dependence is so large. (Discussed in Baltz et al)
  - higgs s-channel exchange (; ;) Heavy higgs is not accessible in many cases.
  - higgsino component (^^)

MN, Polesello and Tovey
hep-ph/0512204





Baltz et al (2006)

top in SUSY events

Hisano, Kawagoe , Nojiri(2003)

- N(jet)>>7 typically (not as simple as tt +missing events.)

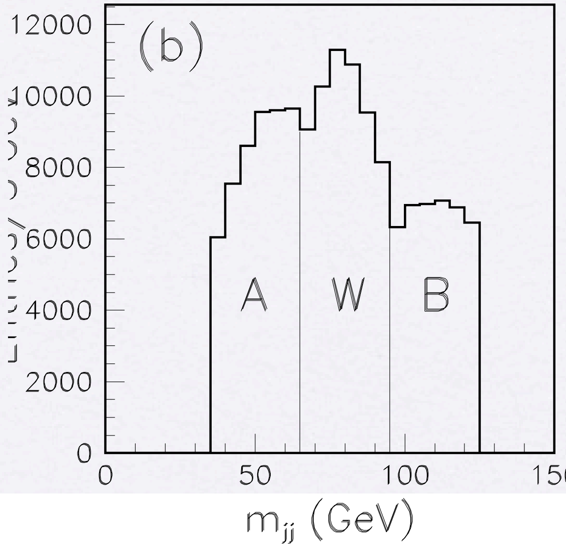
Look for jet pairs with m(jj)~Mw and m(bjj) ~Mt (biased analysis)

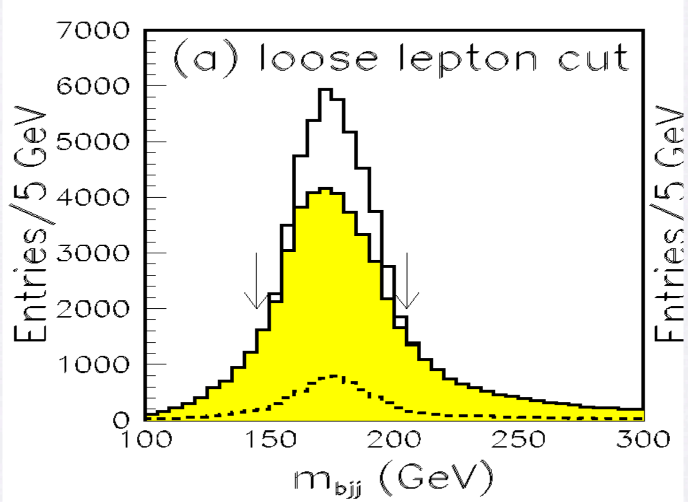
- Background to t ⇨bW⇨bjj is estimated from events in the sideband m_{jj}<Mw-15GeV m_{jj}>Mw+15 GeV.

- Reconstructed top quarks are used to study tb distribution

- Warning about jet background (more high pT jet) We may have to require leptons.

ATLFAST

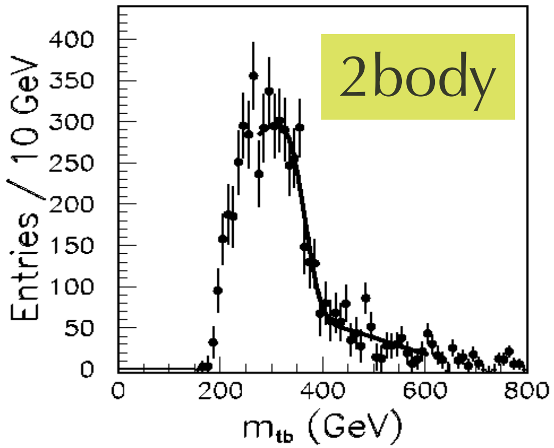


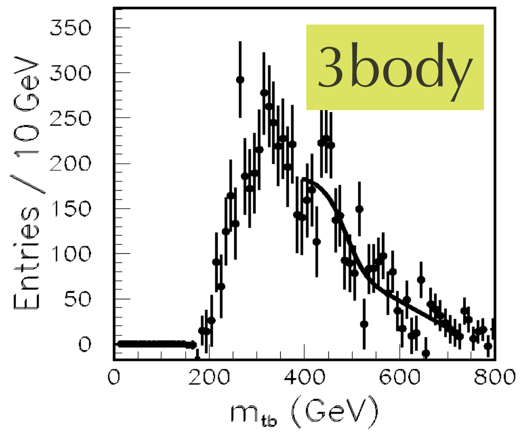


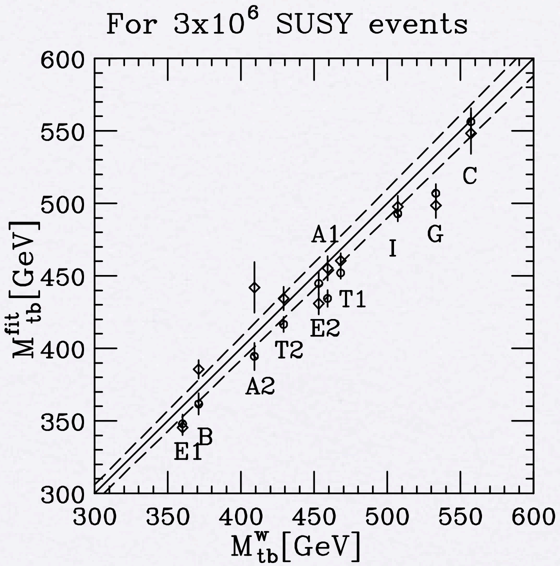
gluino→stop reconstruction

Hisano, Kawagoe , Nojiri(2003)

$$\tilde{g} \rightarrow (t\tilde{t} \text{ or } b\tilde{b}) \rightarrow tb\tilde{\chi}_1^{\pm}$$







depends on stop mass and mixing angles->edge hights and end point* gives constraints to 3rd generation SUSY breaking, B physics....

$$M_{tb}^w = \frac{Br(\tilde{t})M_{tb}(\tilde{t}) + Br(\tilde{b})M_{tb}(\tilde{b})}{Br(\tilde{t}) + Br(\tilde{b})}$$

Uncertainty(QCD): fragmentation (Herwig : Phythia =1.3:1)

jet finding algorithm.... How to tune MC?

Thoughts

- New physics at LHC will be in top sector with missing momentum (LEP precision+hierarchy+DM+wish)
    - fermionic top partner -> discovery. Kinematical understanding is necessary. Don't just count S/B.
    - scalar top (SUSY) -> Other partners...
- Models are increasing. (They will disappear quickly once LHC starts...) **How to feed back the theoretical ideas to experimentalists?**, especially when we start to see deviation from SM/SUSY.
- Need model independent output from experimentalists (not only MSSM, MSUGRA)
- **How to feedback reality to the theorists?:** Need quick publication from experimental side in accessible format. Learning from astrophysicists ?