SUSY, UED, LHT at the LHC

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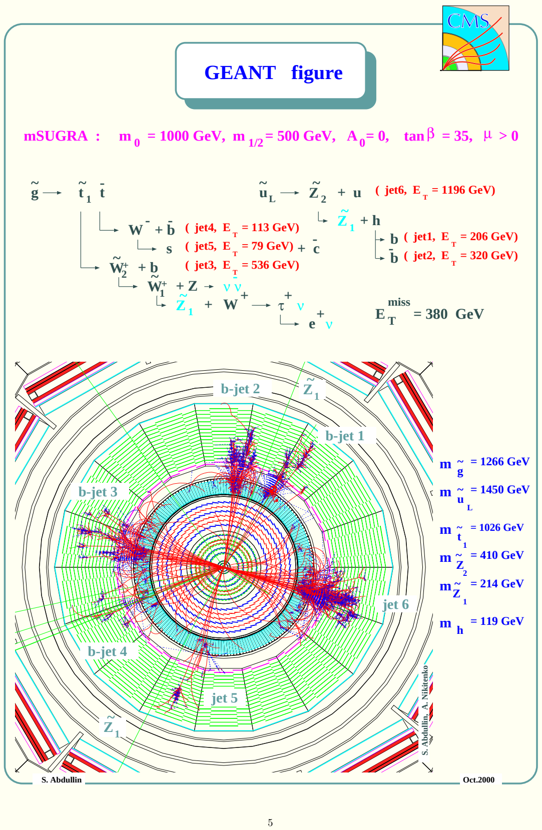
- ⋆ SUSY at LHC
  - SUSY signatures
  - SM backgrounds
  - cuts: optimizing signal/BG
  - LHC reach for SUSY
  - beyond discovery:
    - ∗ precision measurements
- ⋆ UED at LHC
- ⋆ LHT at LHC



SUSY signatures at LHC

- ⋆ $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV
- ⋆ lengthy cascade decays of $\tilde{g}$ $\tilde{q}$ are likely
- ⋆ events characterized by multiple hard jets, isolated and non-isolated leptons es and μs, and $\not{E}_T$ from $\widetilde{Z}_1$ or $\tilde{G}$ or νs escaping
- ⋆ many jets are b (displaced vertices due to long B lifetime) and τ (1 or 3 charged prongs) jets
- ⋆ one way to classify signatures is according to number of isolated leptons

Classify event topologies according to isolated leptons

- $\not\!\!E_T +$ jets
- $1\ell + \not\!\!E_T +$ jets
- $opposite - sign\ (OS)\ 2\ell + \not\!\!E_T +$ jets
- $same - sign\ (SS) 2\ell + \not\!\!E_T +$ jets
- $3\ell + \not\!\!E_T +$ jets
- $4\ell + \not\!\!E_T +$ jets
- $5\ell + \not\!\!E_T +$ jets

Backgrounds to SUSY events at LHC

★ numerous SM processes give same signature as SUSY!

★ SM BGs include:

- QCD: multi-jet qq, $q\bar{q}$, qg, gg production where $\not{E}_T$ comes from mis-measurement, cracks, etc.

– $t\bar{t}$, $b\bar{b}$, $c\bar{c}$

– W or $Z+$ multi-jet production

– WW, WZ, ZZ production, where $Z \to \nu\bar{\nu}$ or $\tau\bar{\tau}$

  * all of above embedded in Isajet, Pythia, Herwig

– four particle processes: *e.g.* $t\bar{t}t\bar{t}$, $ttbb$, etc.

– WWW, etc.

  * the $2 \to n$ for $n > 2$ processes usually need CalcHEP/Madgraph

– overlapping events; fake b-jets; fake leptons, etc

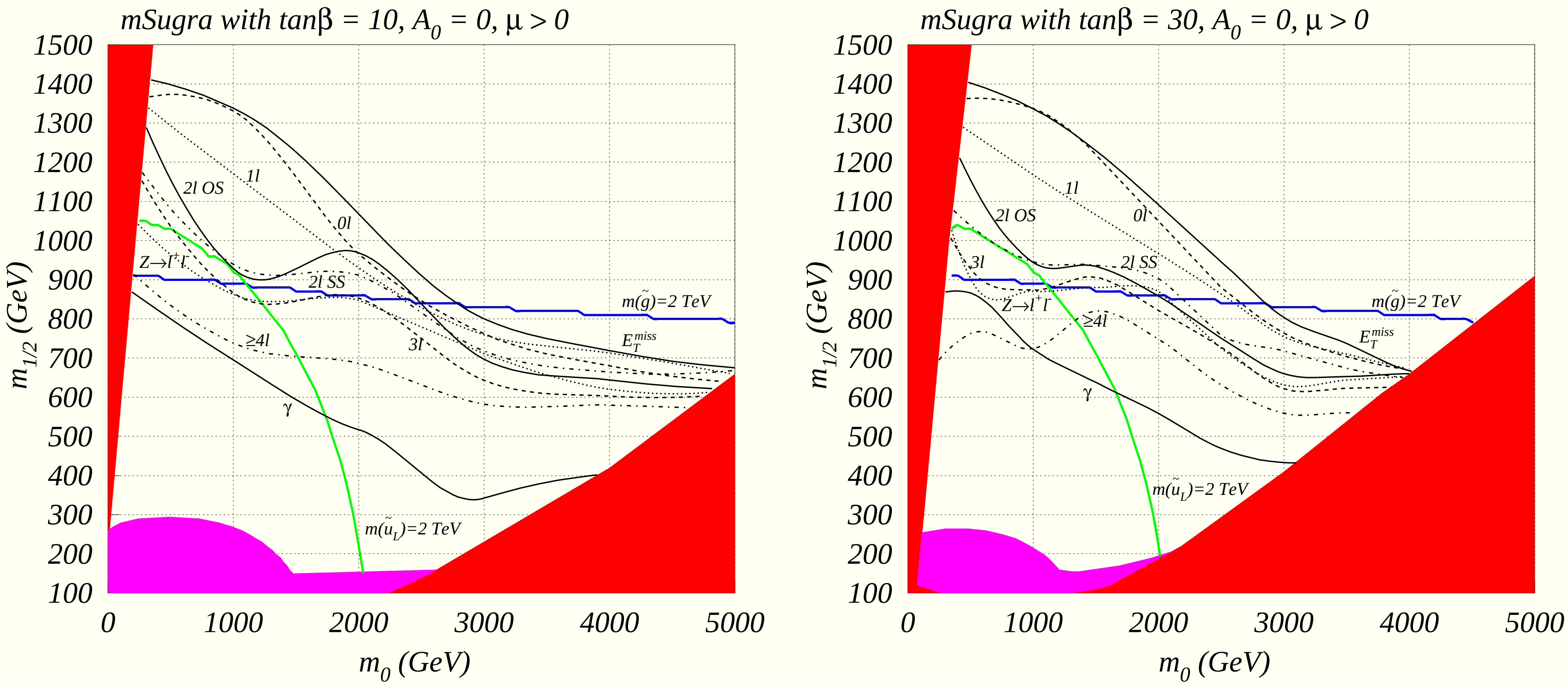
Background issues

- ⋆ The BGs must be estimated using full event simulation
  - jet broadening, interaction of particles with detectors
- ⋆ Must also simulate *detector*: GEANT or toy or...
- ⋆ If possible, use complete $2 \to n$-body matrix elements
- ⋆ matching of PS and HO-ME results? avoid double counting
  - VECBOS, AlpGEN, MCNLO , etc.
- ⋆ NLO QCD corrections?
- ⋆ matching the data: how well do we know SM BG rates?
- ⋆ first order of business at LHC: re-discover the SM!
  - calibrate detectors using Z+jets, W+jets, $t\bar{t}$ production

Example: calculate SUSY reach of LHC for 10, 100 fb^{-1}

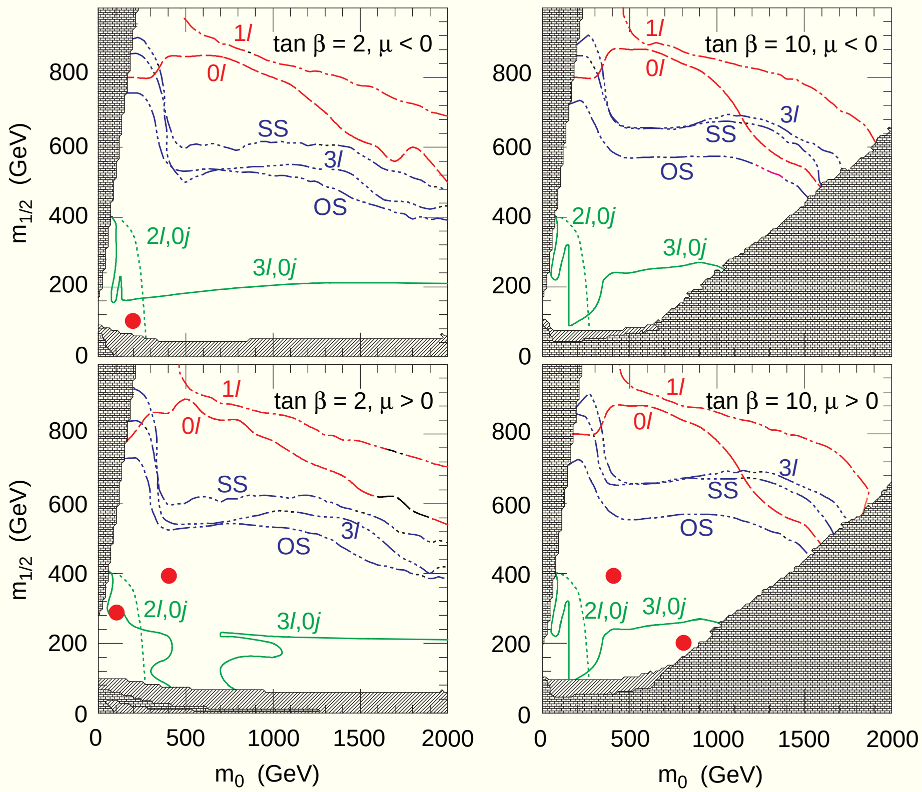
- ⋆ Cuts and pre-cuts:
- ⋆ $\not{E}_T > 200$ GeV
- ⋆ $N_j \geq 2$ (where $p_T(jet) > 40$ GeV and $|\eta(jet)| < 3$
- ⋆ Grid of cuts for optimized S/B:
  - $N_j \geq 2 - 10$
  - $\not{E}_T > 200 - 1400$ GeV
  - $E_T(j1) > 40 - 1000$ GeV
  - $E_T(j2) > 40 - 500$ GeV
  - $S_T > 0 - 0.2$
  - muon isolation
- ⋆ $S > 10$ events for 100 fb^{-1}
- ⋆ $S > 5\sqrt{B}$ for optimal set of cuts

Sparticle reach of LHC for 100^{-1} fb



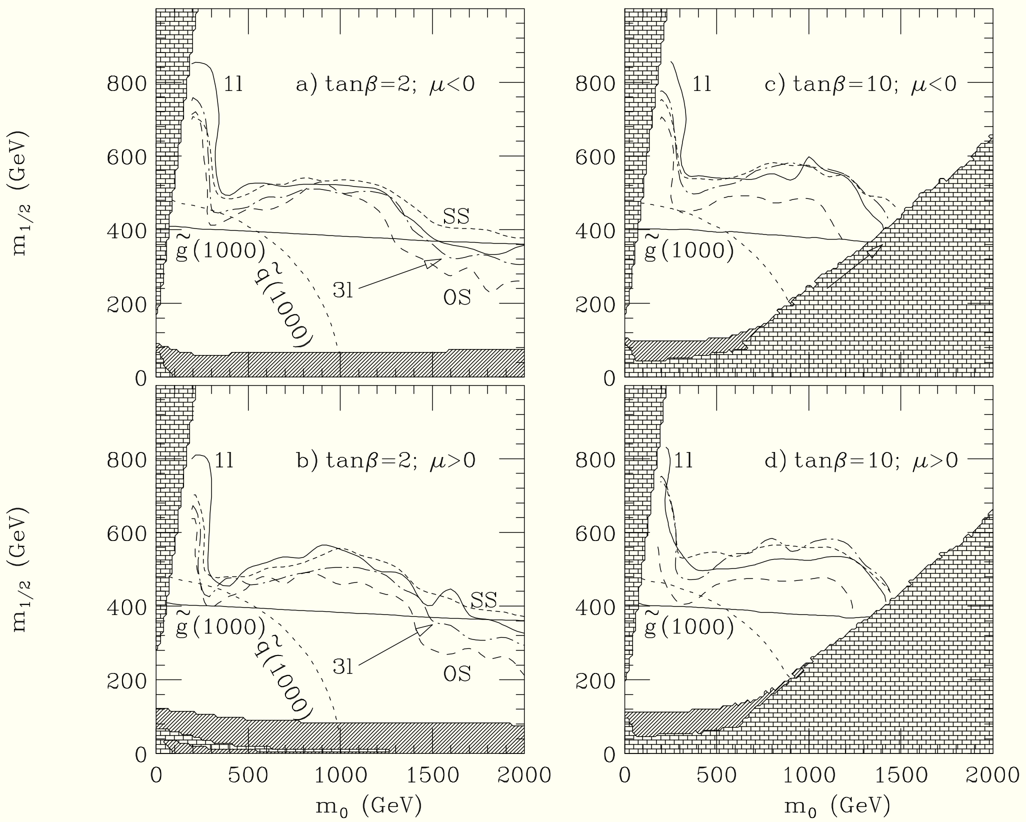
HB, Balazs, Belyaev, Krupovnickas, Tata: JHEP 0306, 054 (2003)

Old sparticle reach of LHC for 10^{-1} fb incl. 2ℓ and 3ℓ



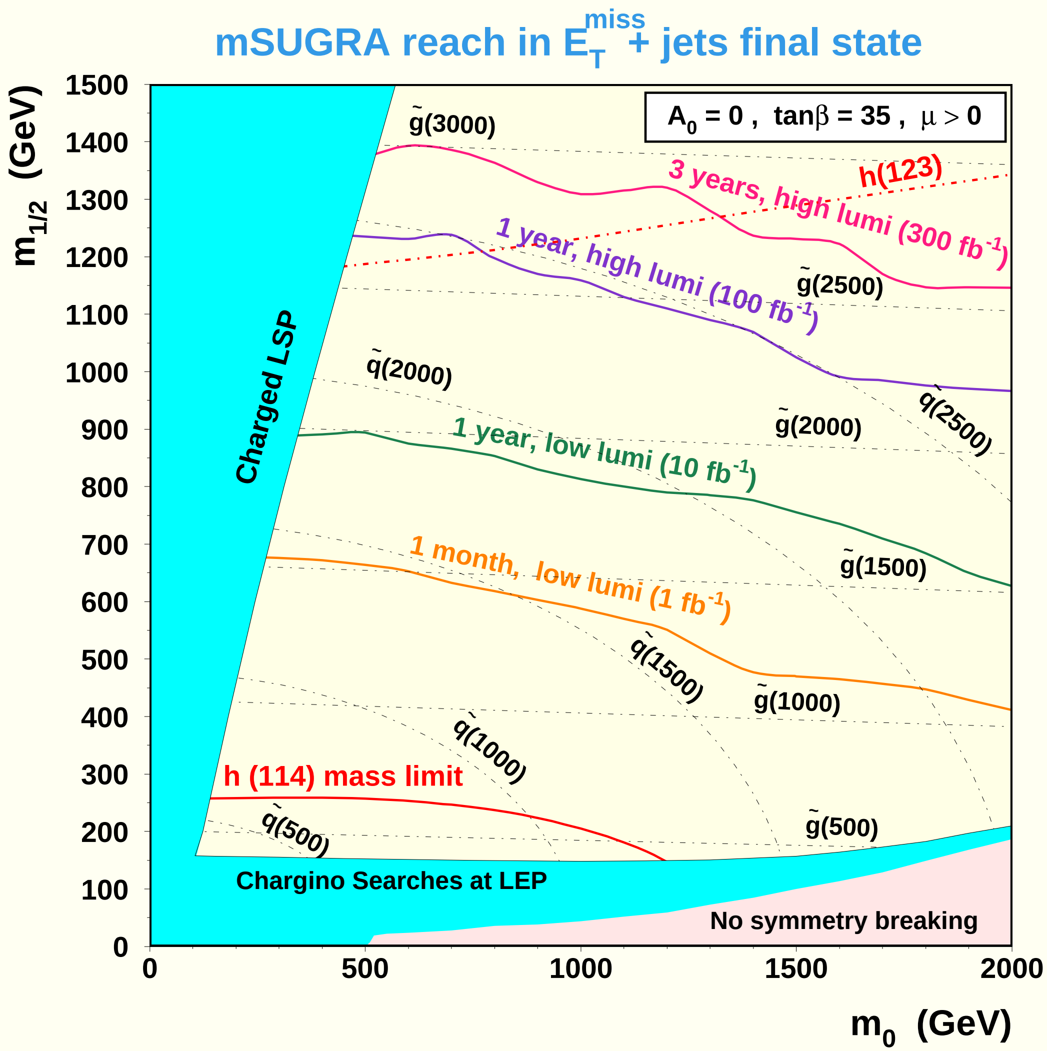
HB, Chen, Paige, Tata: PRD**53**, 6241 (1996)

Sparticle reach of LHC for 10^{-1} fb; RPV with $\widetilde{Z}_1 \to cds$

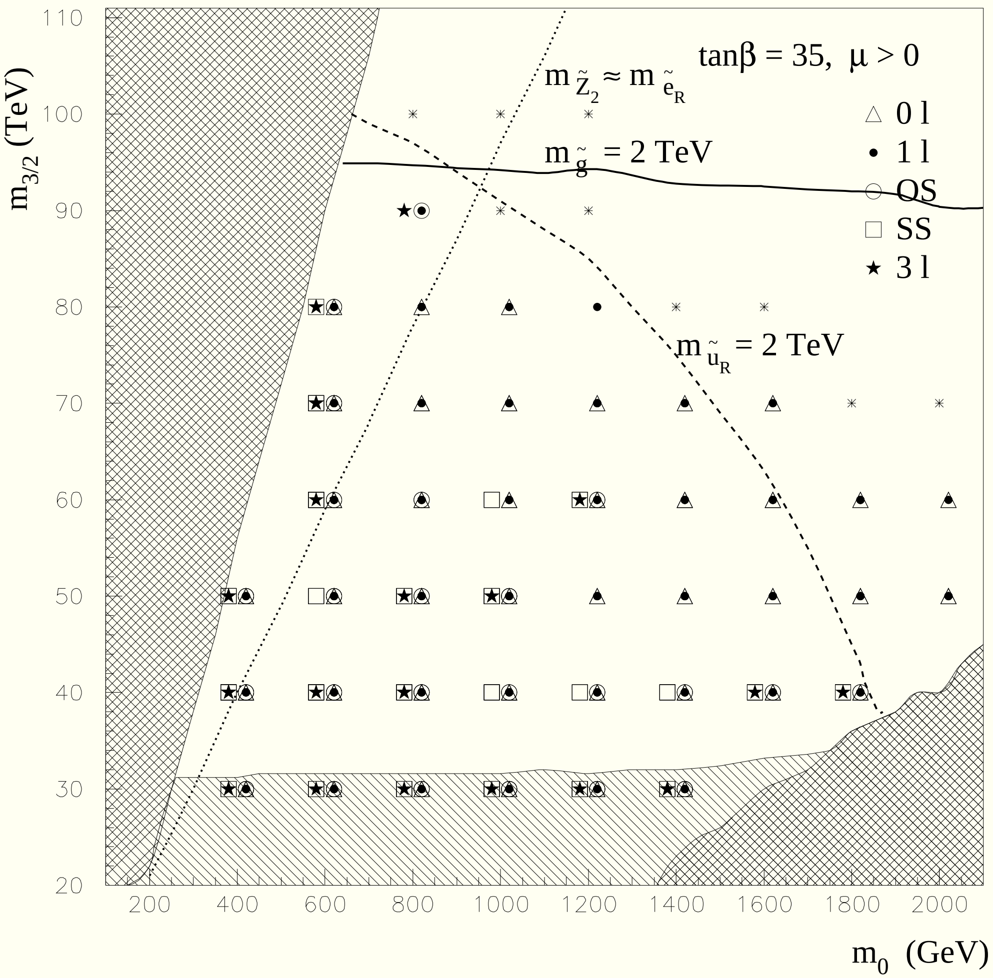


HB, Chen, Paige, Tata: PRD**55**, 1466 (1997)

Sparticle reach of CMS; various $\int \mathcal{L} dt$



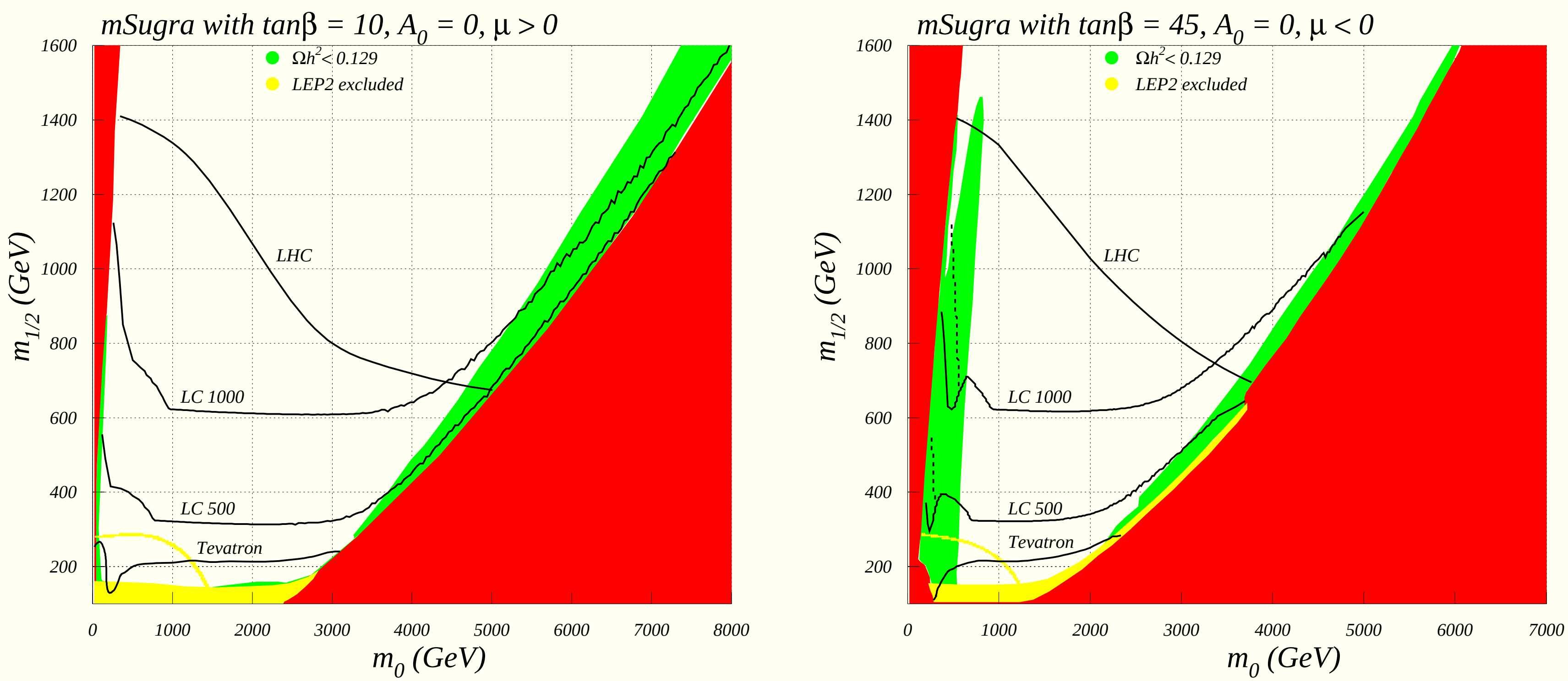
Sparticle reach in AMSB model



Sparticle reach in GMSB model: various model lines

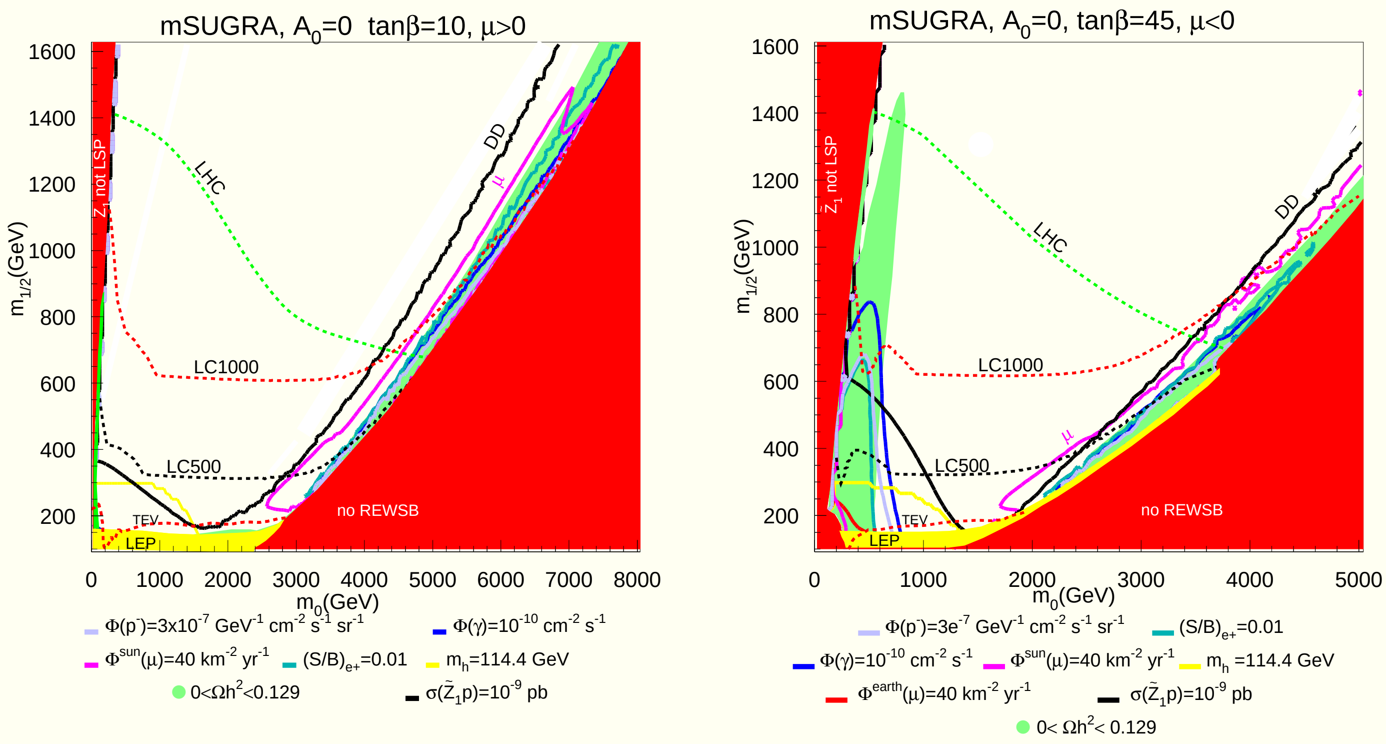
Model Line	NLSP	Tevatron ($25\ fb^{-1}$)	LHC ($10\ fb^{-1}$)
A	$\tilde{Z}_1 \sim \tilde{B}$ $\tilde{Z}_1 \to \gamma\tilde{G}$	$\Lambda \cong 115$ TeV, $m_{\tilde{g}/\tilde{q}} \sim 0.87$ TeV, $ll\gamma\gamma + E_T^{\rm miss}$	$\Lambda \cong 400$ TeV $m_{\tilde{g}/\tilde{q}} \sim 2.8$ TeV, $\gamma\gamma + E_T^{\rm miss}$
B	$\tilde{\tau}_1$	$\Lambda \cong 53$ TeV, $m_{\tilde{g}/\tilde{q}} \sim 0.82$ TeV, Clean channels $3l + 1\tau 2l + 1\tau 3l$ $+2\tau 1l + 3\tau 2l$	$\Lambda \cong 150$ TeV $m_{\tilde{g}/\tilde{q}} \sim 2.0$ TeV, $3l + E_T^{\rm miss}$

Sparticle reach of all colliders and relic density



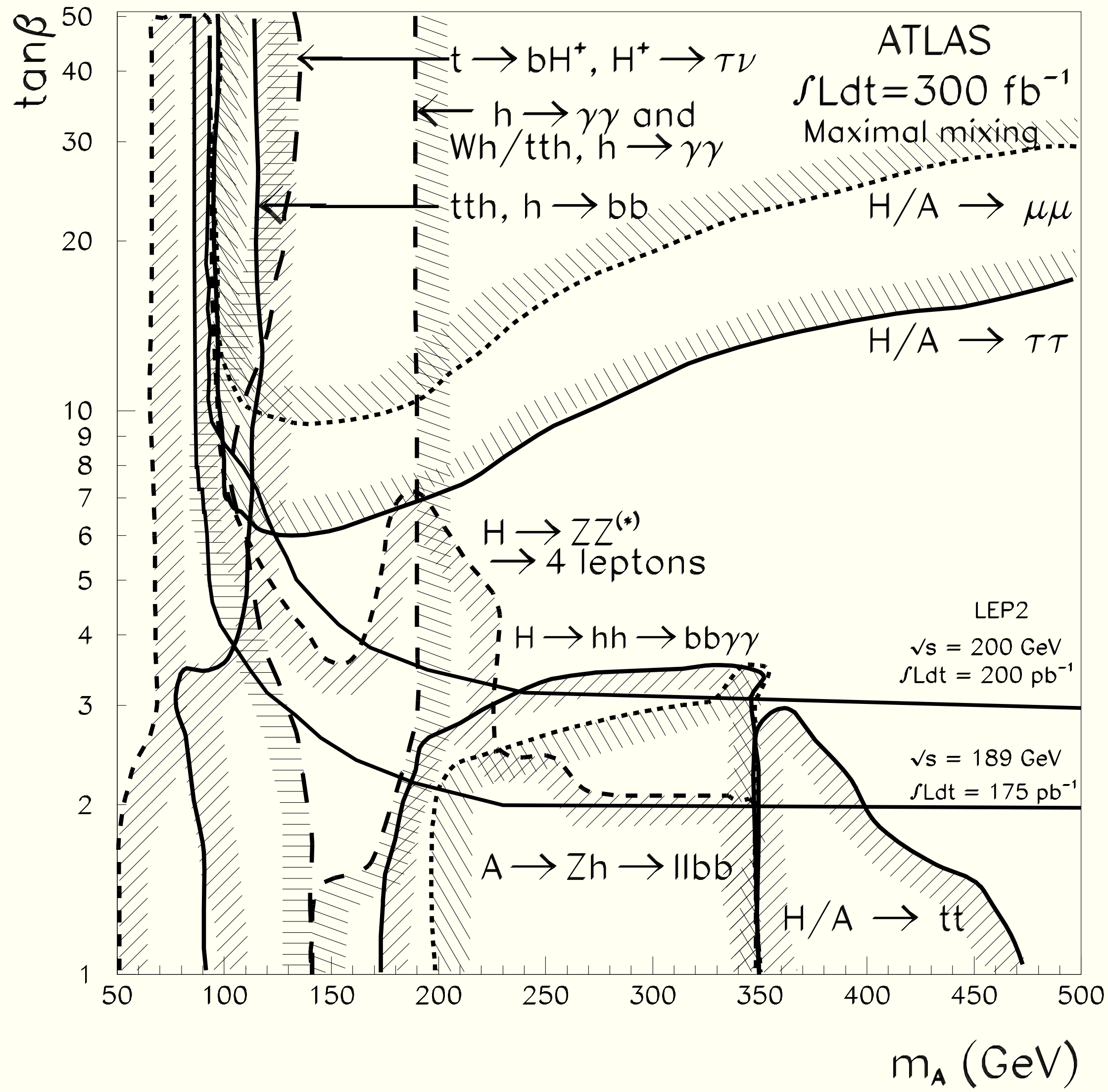
HB, Belyaev, Krupovnickas, Tata: JHEP 0402, 007 (2004)

Sparticle reach of colliders plus DM DD/IDD



HB, Belyaev, O'Farrill, Krupovnickas: JHEP 0408, 005 (2004)

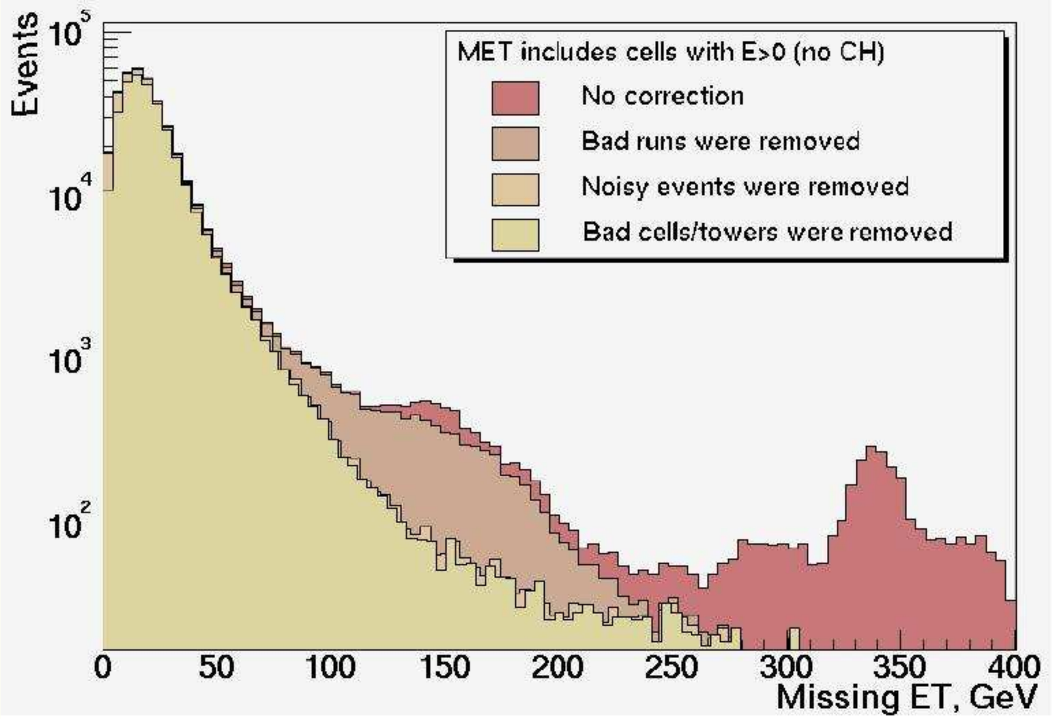
Reach of Atlas for SUSY Higgs: 300 fb^{-1}



Early SUSY discovery at LHC with just 0.1 fb^{-1}?

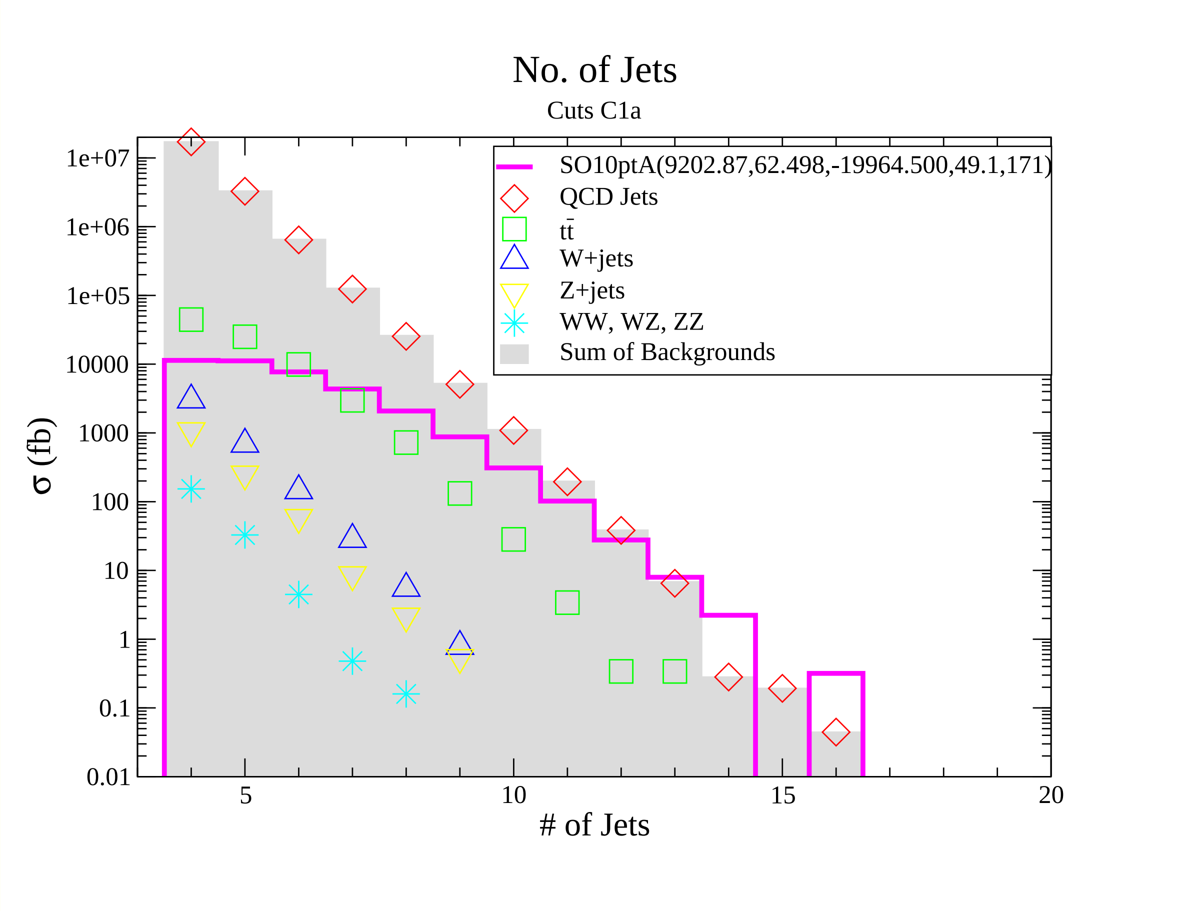
- To make $\not\!\!E_T$ cut, complete knowledge of detector needed
  - dead regions
  - "hot" cells
  - cosmic rays
  - calorimeter mis-measurement
  - beam-gas events
- Can we make early discovery of SUSY at LHC *without* $\not\!\!E_T$?
- Expect SUSY events to be rich in jets, b-jets, isolated ℓs, τ-jets,....
- These are *detectable*, rather than inferred objects
- Answer: YES! See HB, Prosper, Summy, arXiv:0801.3799

D0 saga with missing $\not{E}_T$

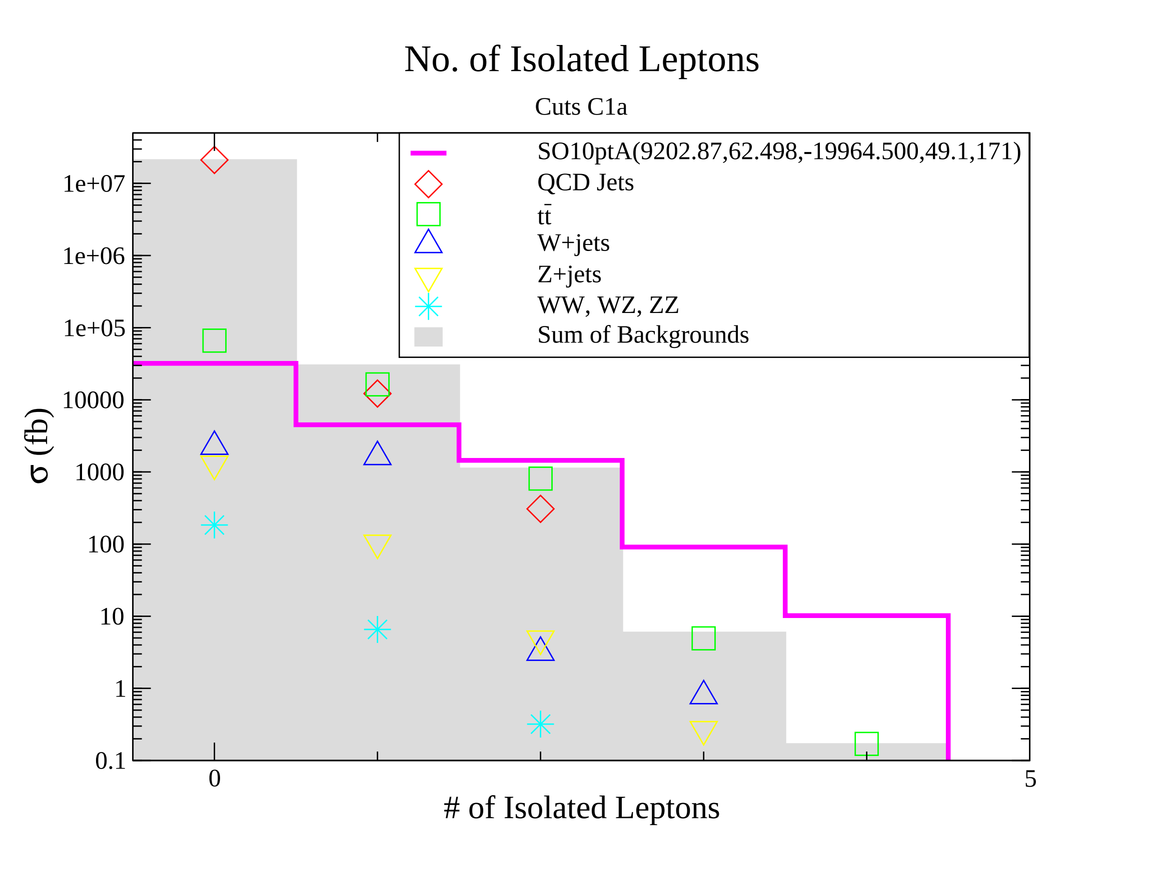


Require simple cuts: plot jet multiplicity

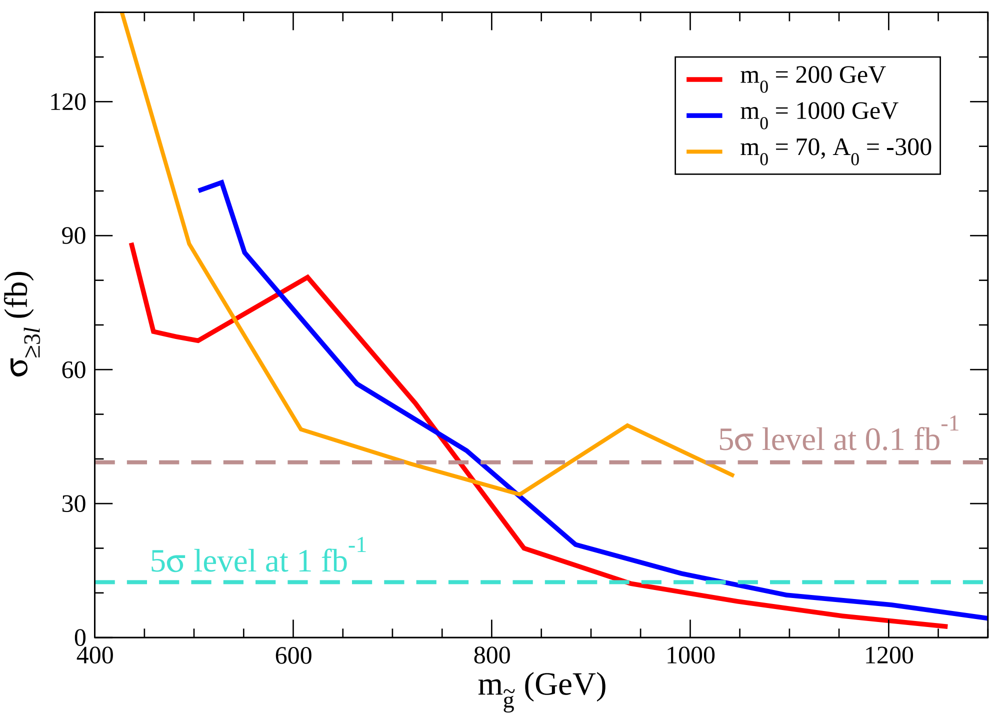
- $\geq$ 4-jets $E_T > 100, 50, 50, 50$ GeV; $S_T \geq 0.2$



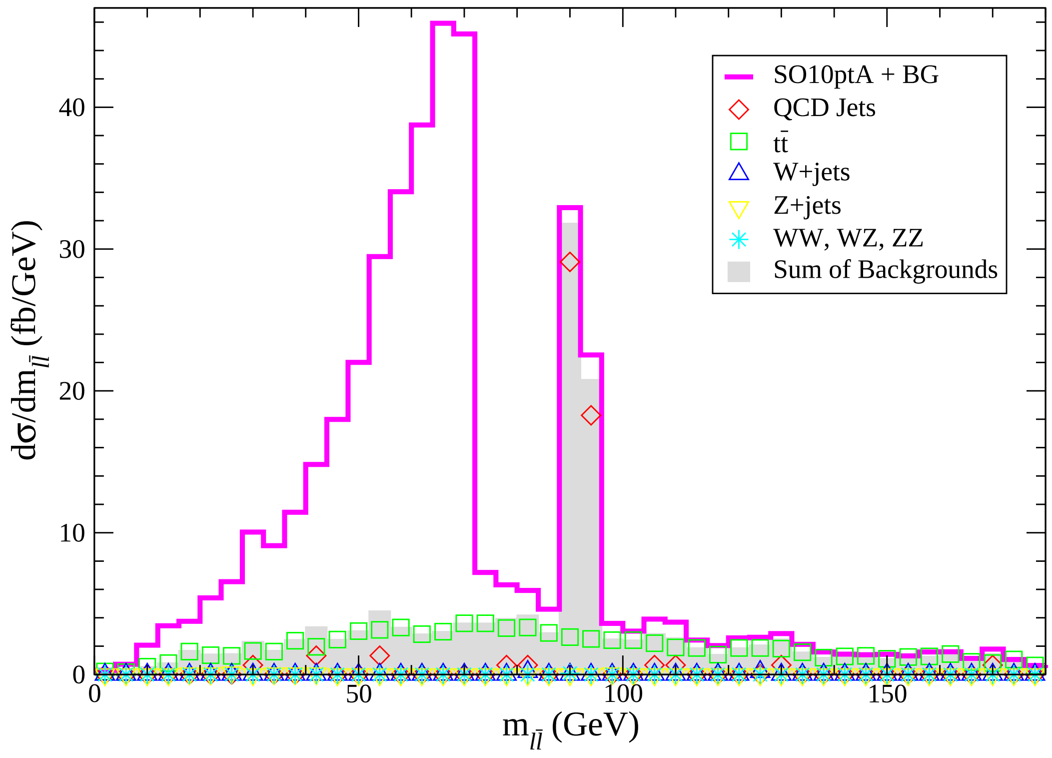
Simple cuts: lepton multiplicity



Cuts C1$'$ plus $\geq 3\ell$



Cuts C1′ plus $\geq 2\ OS/SF\ \ell$



Precision measurements at LHC

- $M_{eff} = \not{E}_T + E_T(j1) + \cdots + E_T(j4)$ sets overall $m_{\tilde{g}},\ m_{\tilde{q}}$ scale
- $m(\ell\bar{\ell}) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ mass edge
- $m(\ell\bar{\ell})$ distribution shape
- combine $m(\ell\bar{\ell})$ with jets to gain $m(\ell\bar{\ell}j)$ mass edge: info on $m_{\tilde{q}}$
- further mass edges possible *e.g.* $m(\ell\bar{\ell}jj)$
- Higgs mass bump $h \to b\bar{b}$ likely visible in $\not{E}_T + jets$ events
- in favorable cases, may overconstrain system for a given model

★ methodology very p-space dependent

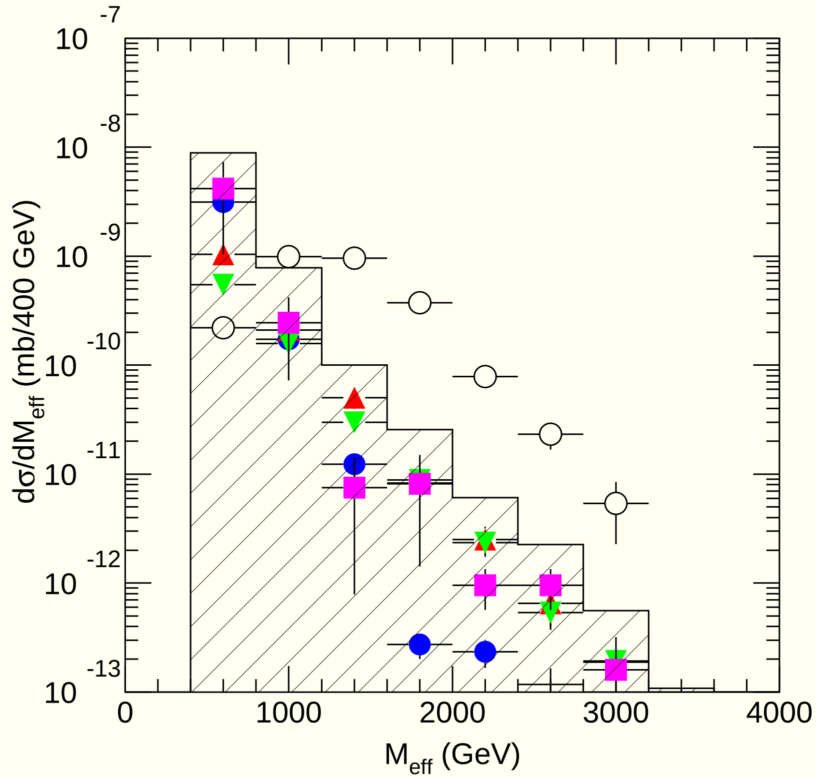
★ some regions are very difficult *e.g.* HB/FP

Paige, Hinchliffe *et al.* case studies:

- examined many model case studies in mSUGRA, GMSB, high $\tan\beta$...
- classic study: pt.5 of PRD**55**, 5520 (1997) and PRD**62**, 015009 (2000)
- $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu) = (100, 300, 0, 2, 1)$ in GeV
- dominant $\tilde{g}\tilde{g}$ production with $\tilde{g} \to q\tilde{q}_L \to qq\widetilde{Z}_2 \to q_1q_2\ell_1\tilde{\ell} \to q_1q_2\ell_1\ell_2\widetilde{Z}_1$ (string of 2-body decays)
- can reconstruct 4 mass edges; allows one to fit four masses: $m_{\tilde{q}_L},\ m_{\widetilde{Z}_2},\ m_{\tilde{\ell}},\ m_{\widetilde{Z}_1}$ to $3-12\%$
- can also find Higgs h in the SUSY cascade decay events
- if enough sparticle masses measured, can fit to MSSM/SUGRA parameters

$$M_{eff} = E_T(j1) + E_T(j2) + E_T(j3) + E_T(j4) + \not{E}_T$$

- rough estimate of $m_{\tilde{g}}, m_{\tilde{q}}$ can be gained from max of M_{eff}

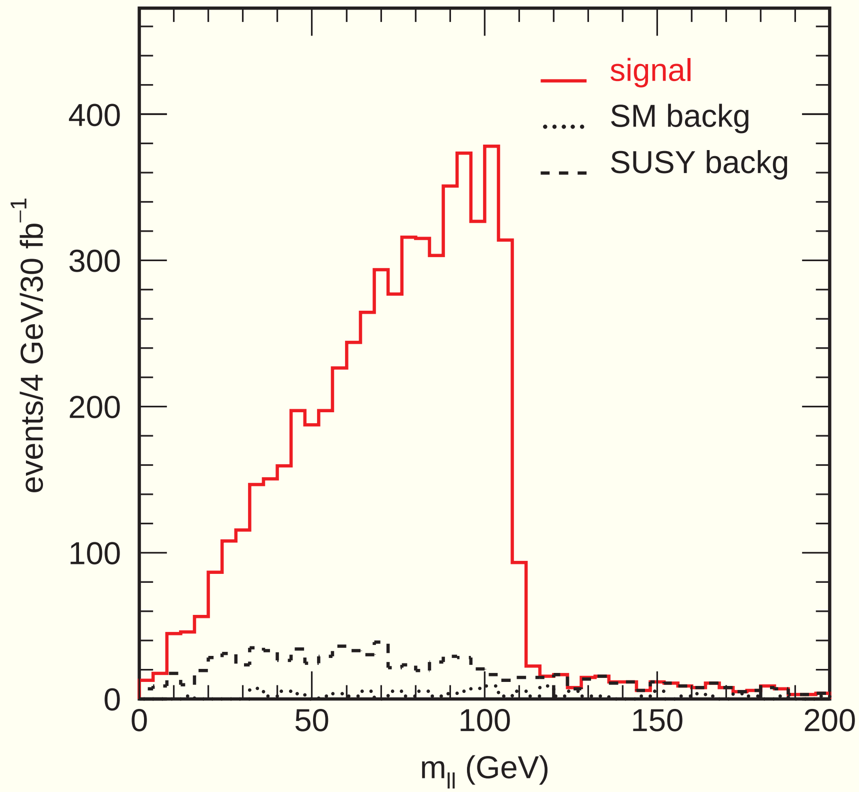


Atlas TDR (F. Paige)

$m(\ell^+\ell^-)$ mass edge from $\widetilde{Z}_2 \to \ell^+\ell^-\widetilde{Z}_1$

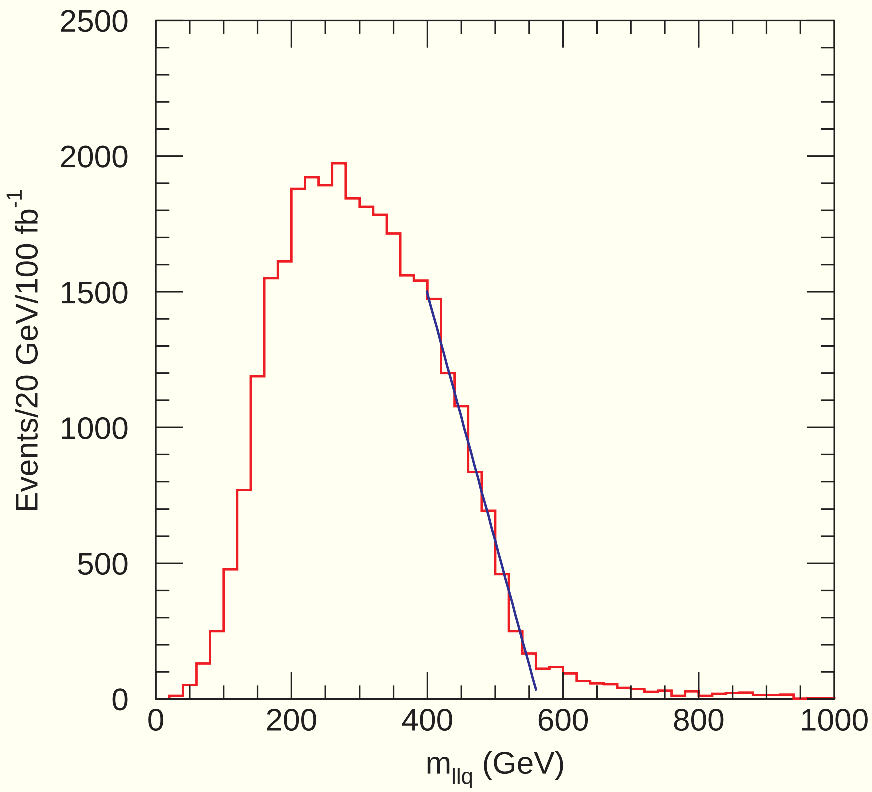
- kinematically, $m(\ell^+\ell^-) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$
- for $\widetilde{Z}_2 \to \tilde{\ell}^+\ell^- \to (\ell^+\widetilde{Z}_1)\ell^-$, have

$$m(\ell^+\ell^-) < m_{\widetilde{Z}_2}\sqrt{1-\frac{m^2_{\tilde{\ell}}}{m^2_{\widetilde{Z}_2}}}\sqrt{1-\frac{m^2_{\widetilde{Z}_1}}{m^2_{\tilde{\ell}}}} < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$$



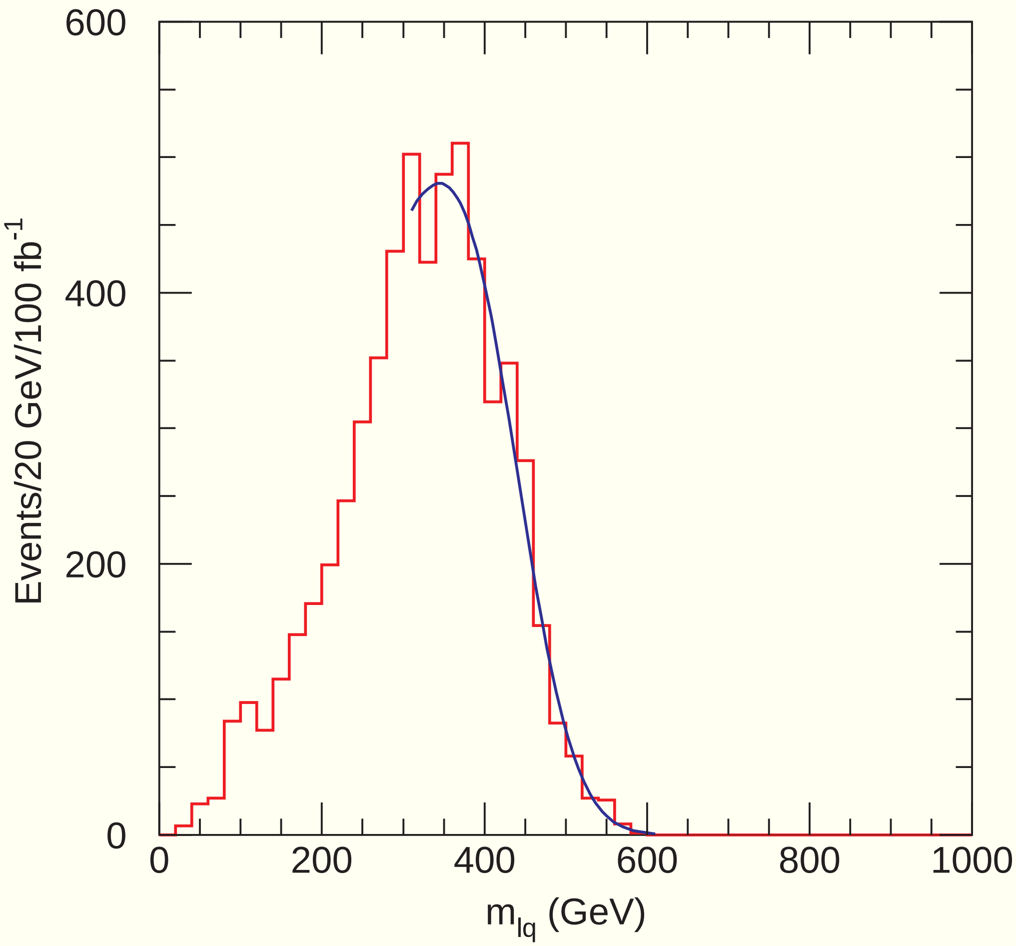
$m(\ell^+\ell^- q)$ **mass edge from** $\tilde{q} \to q\widetilde{Z}_2$

- $\tilde{q}_L \to q\widetilde{Z}_2 \to q\tilde{\ell}^\pm \ell^\mp \to q\ell^\pm\ell^\mp\widetilde{Z}_1$



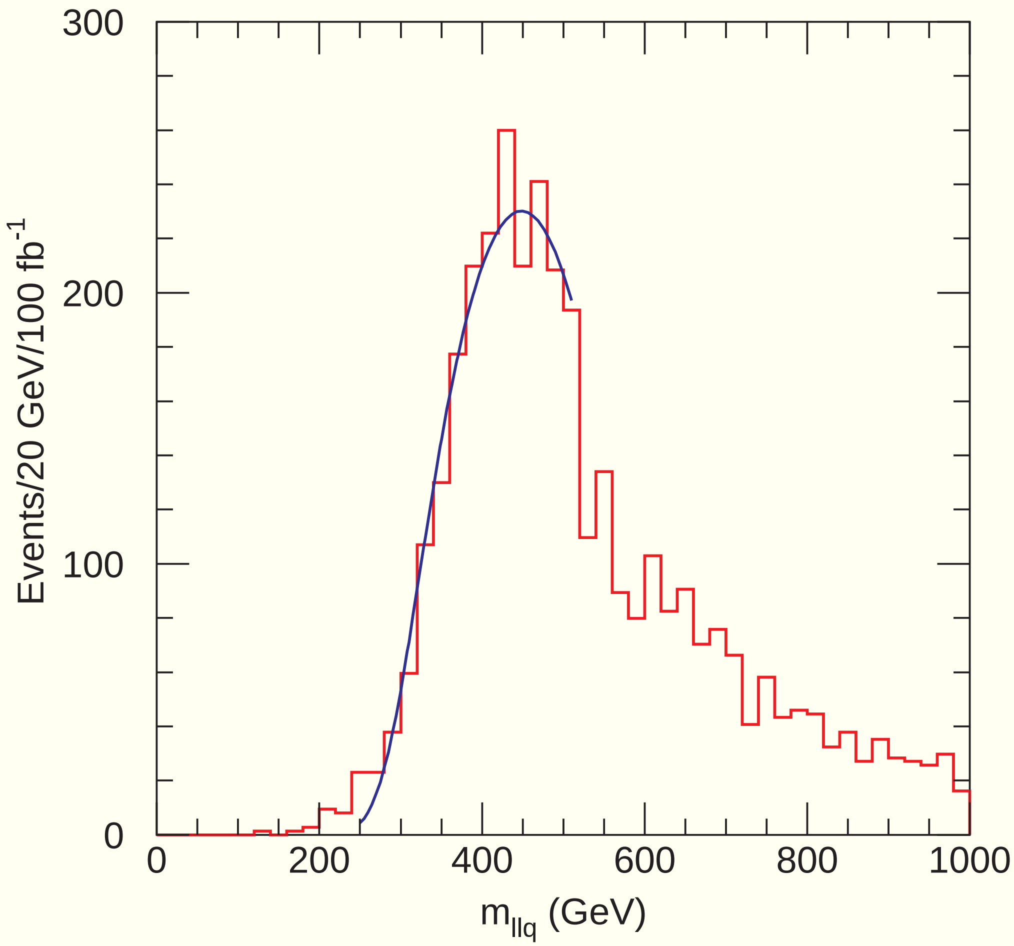
Atlas TDR (F. Paige)

$m(\ell q)$ **mass edge from** $\tilde{q} \to q\widetilde{Z}_2$



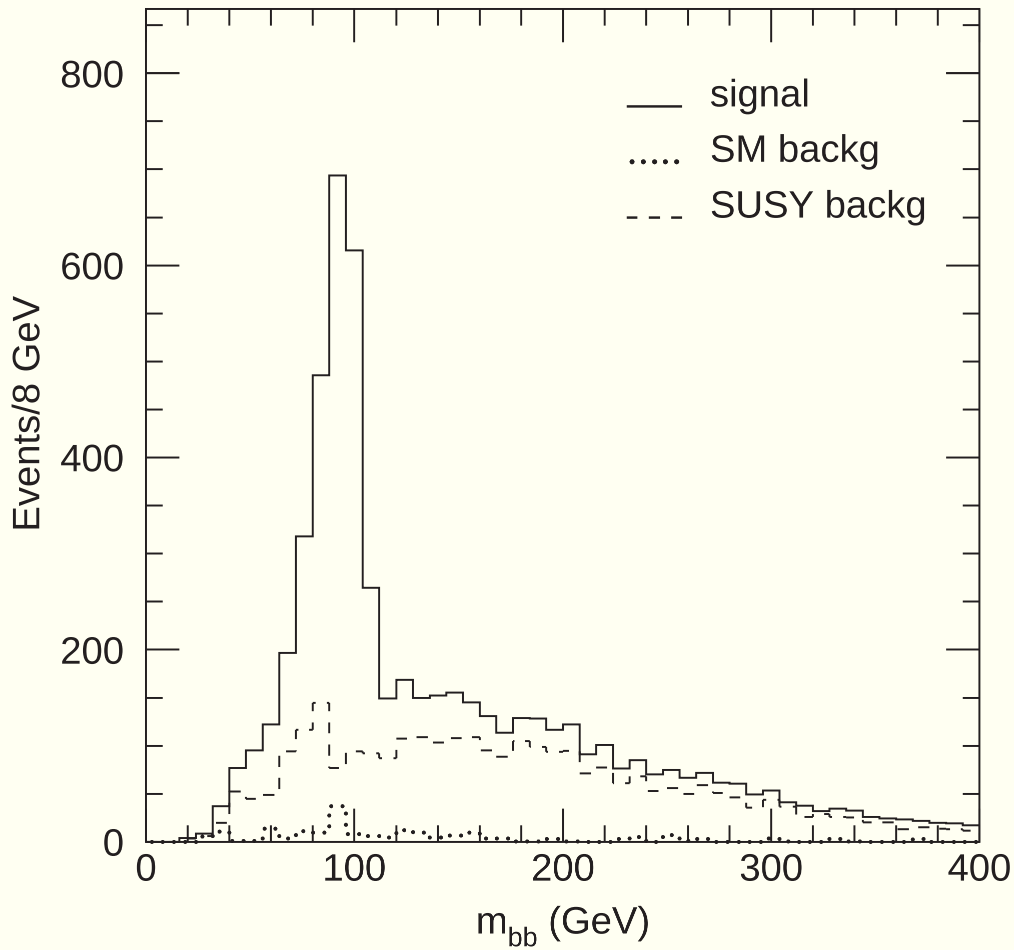
Atlas TDR (F. Paige)

$m(\ell q)$ mass edge from $\tilde{q} \to q\widetilde{Z}_2$



Atlas TDR (F. Paige)

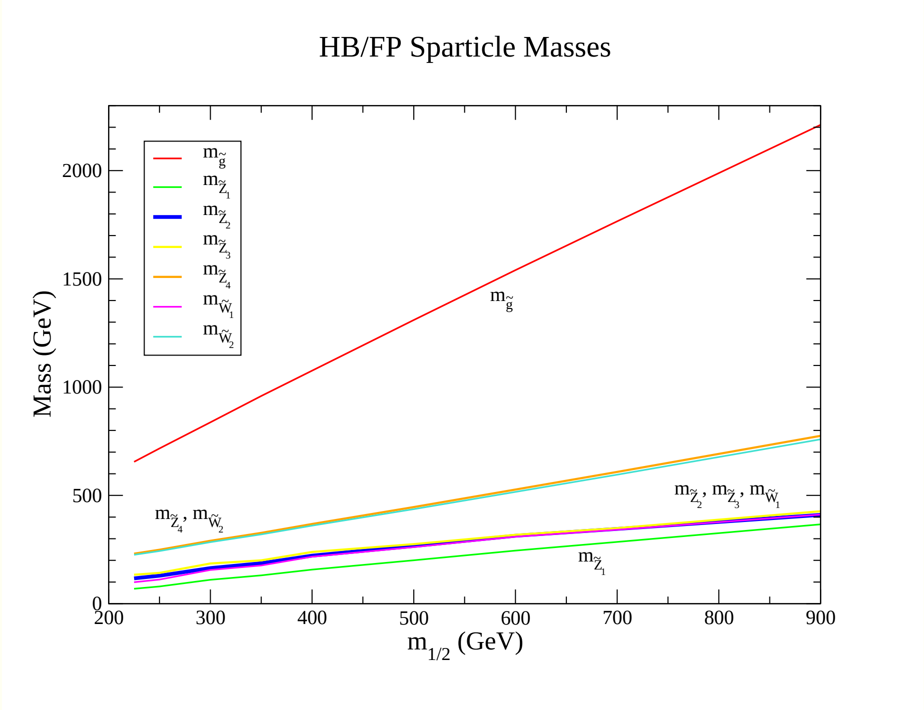
$m(b\bar{b})$ Higgs mass bump in SUSY jets $+ \not{E}_T$ events



Atlas TDR (F. Paige)

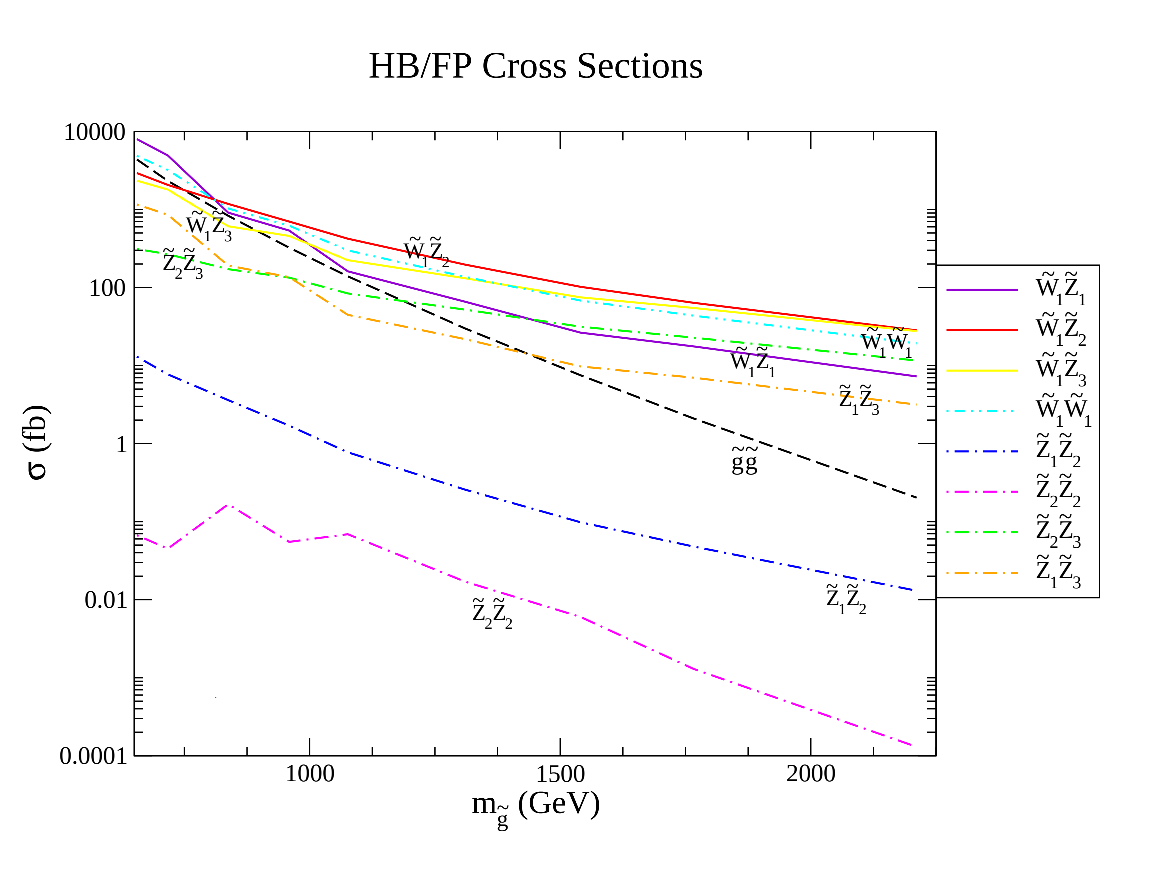
Case study of SUSY in the focus point region of mSUGRA

- $m_0 \sim 3$ TeV so squarks/sleptons decouple
- $m_{\tilde{g}} \sim 1$ TeV and $\mu \sim 226$ GeV so $\widetilde{W}_1,\ \widetilde{Z}_2$ light
- SUSY production: soft $(\widetilde{W}_1^+\widetilde{W}^-,\ \widetilde{W}^\pm\widetilde{Z}_2)$ and hard $(\tilde{g}\tilde{g})$ component



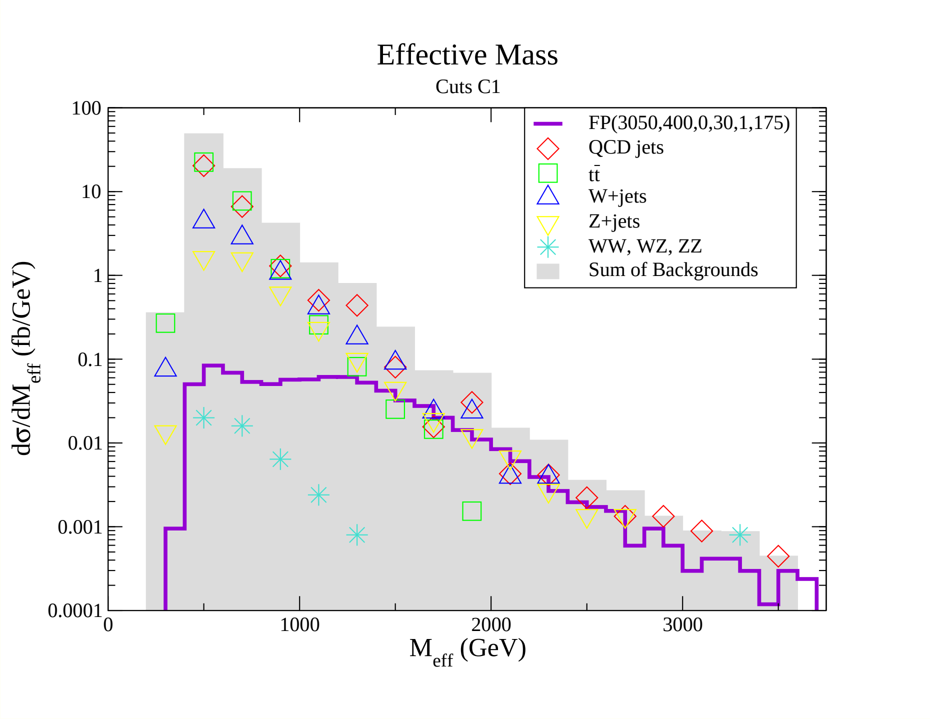
HB, Barger, Shaughnessy, Summy and Wang

FP case study: cross sections

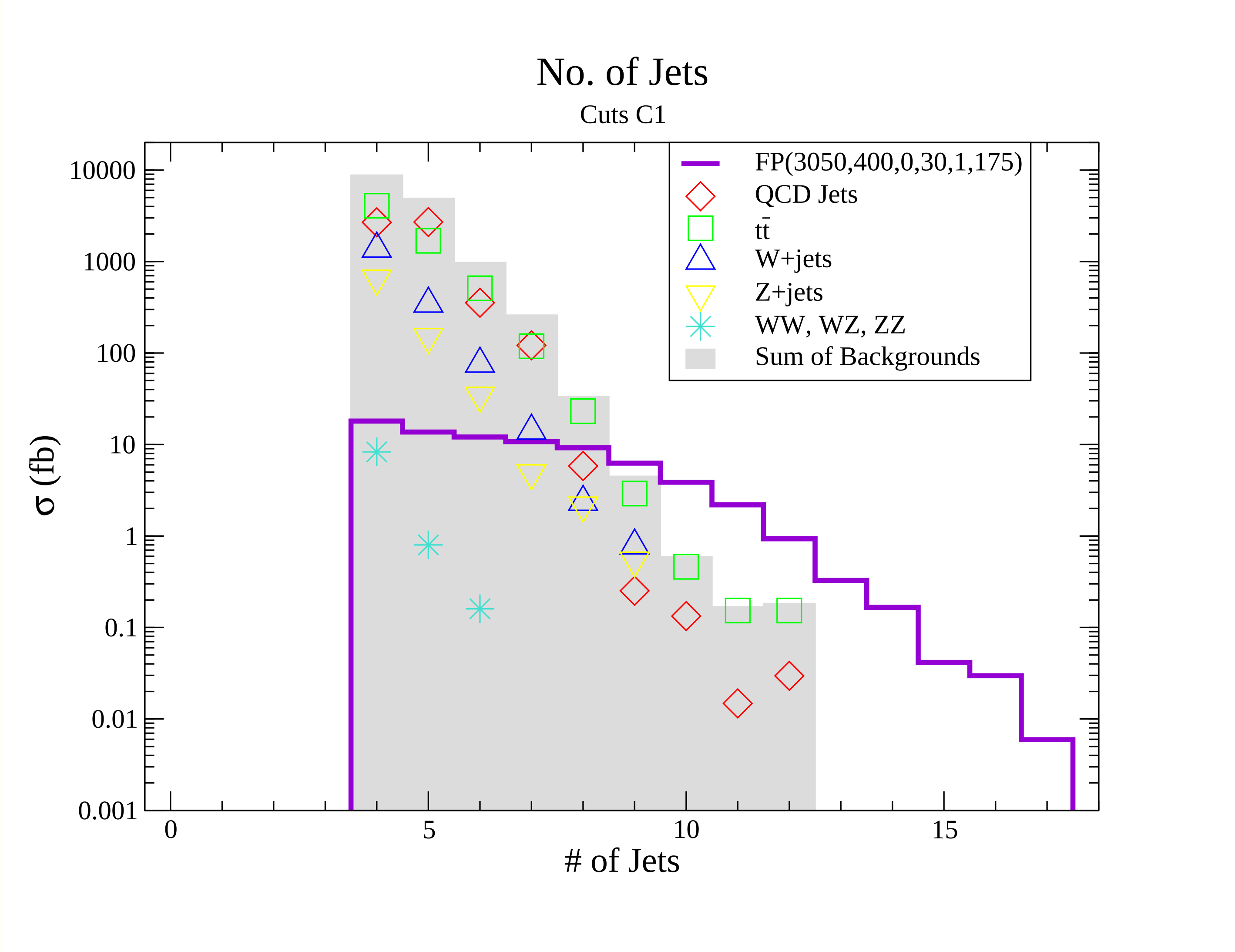


Apply cuts set C1

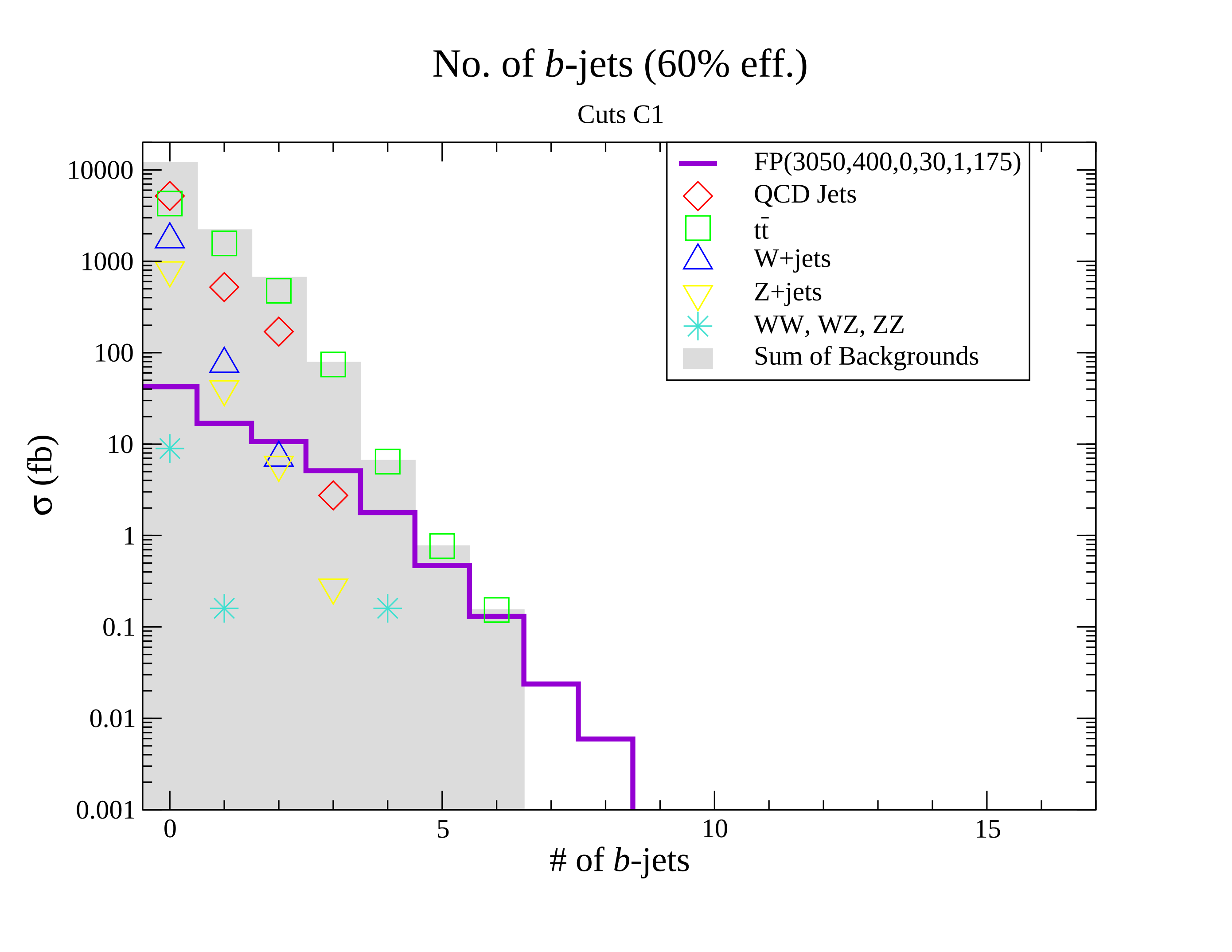
- $\not{E}_T > max(100\ GeV, 0.2 M_{eff}$
- $n_j \geq 4;\ S_T > 0.2$
- $E_T(j1, j2, j3, j4) > 100,\ 50,\ 50,\ 50$ GeV



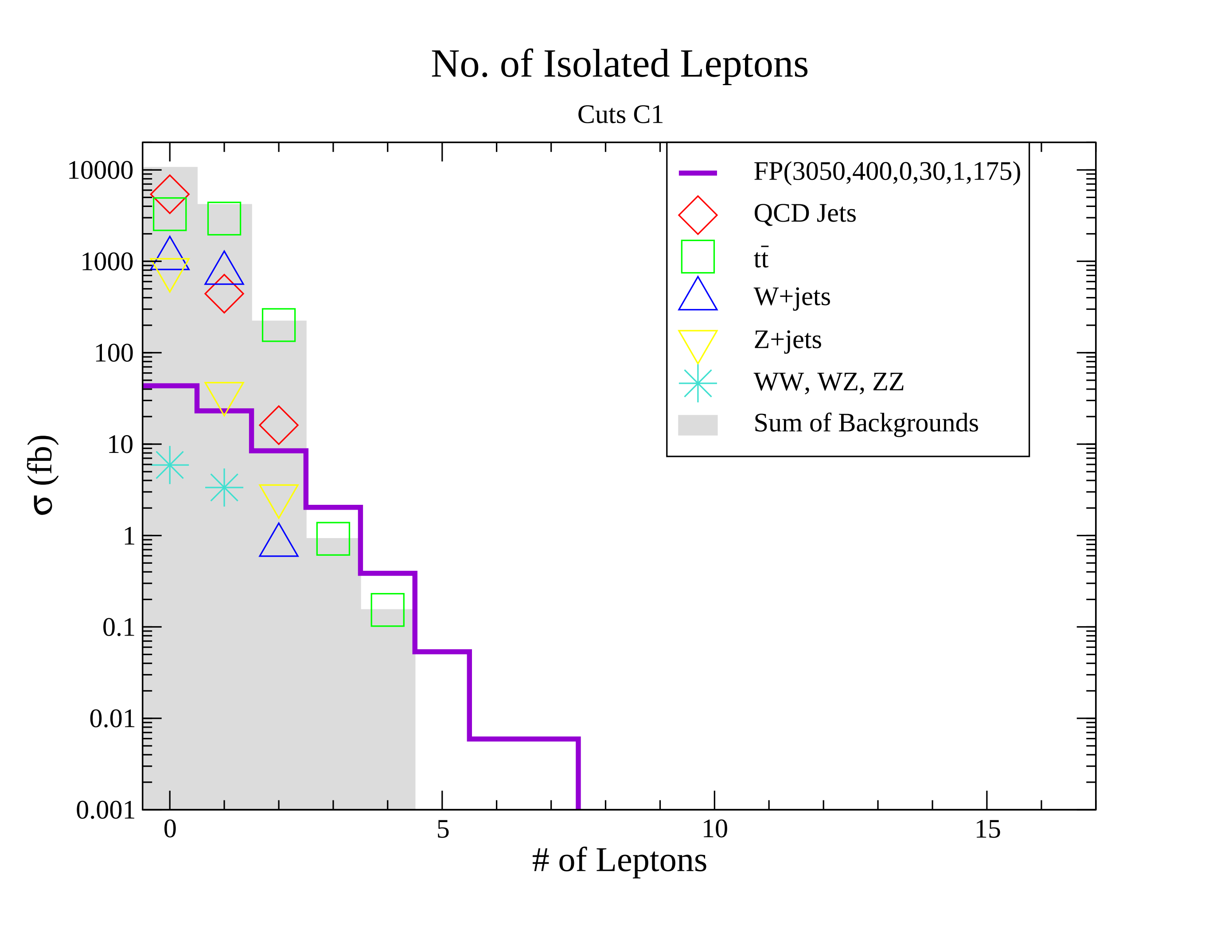
$n(jets)$ distribution



$n(b-jets)$ distribution

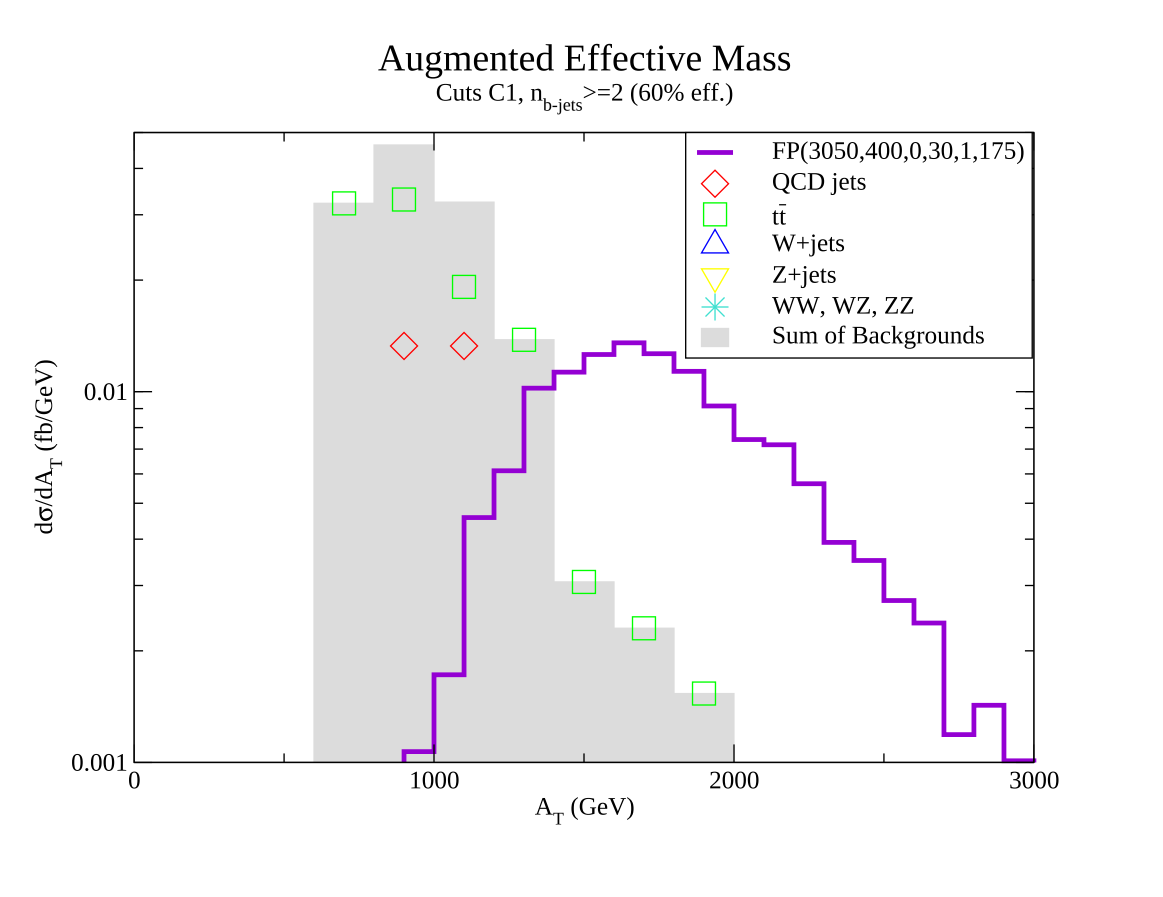


$n(leptons)$ **(isolated) distribution**



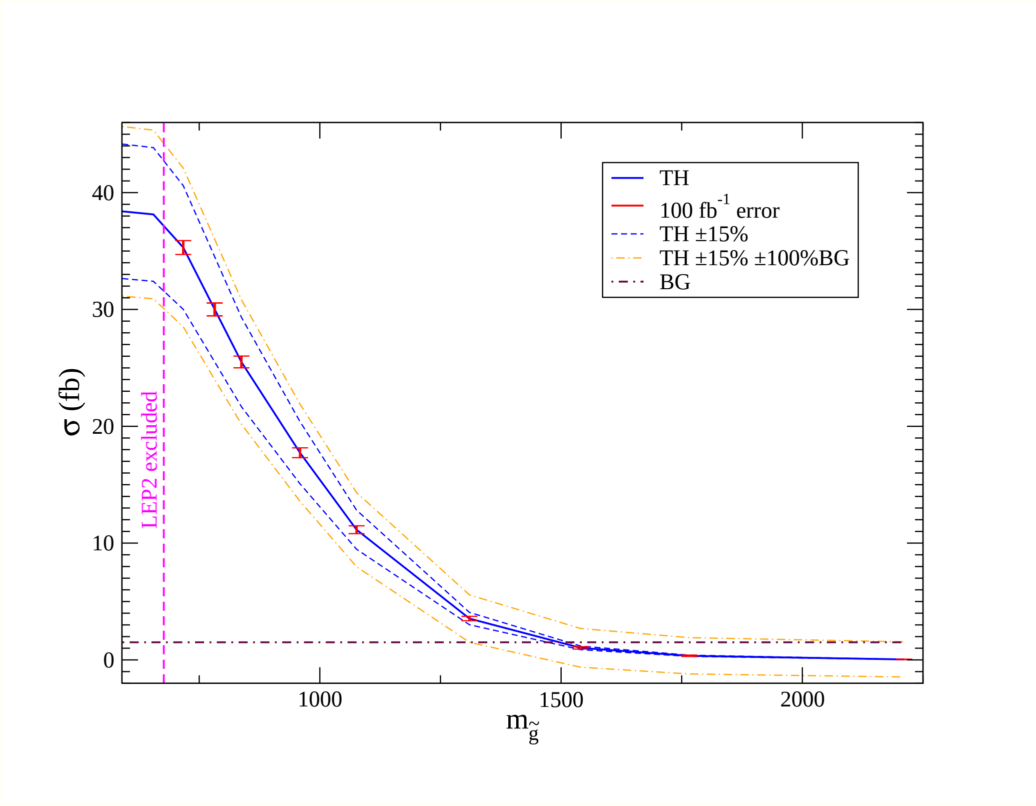
Augmented effective mass A_T

- $n(jets) \geq 7$
- $n(b - jets) \geq 2$



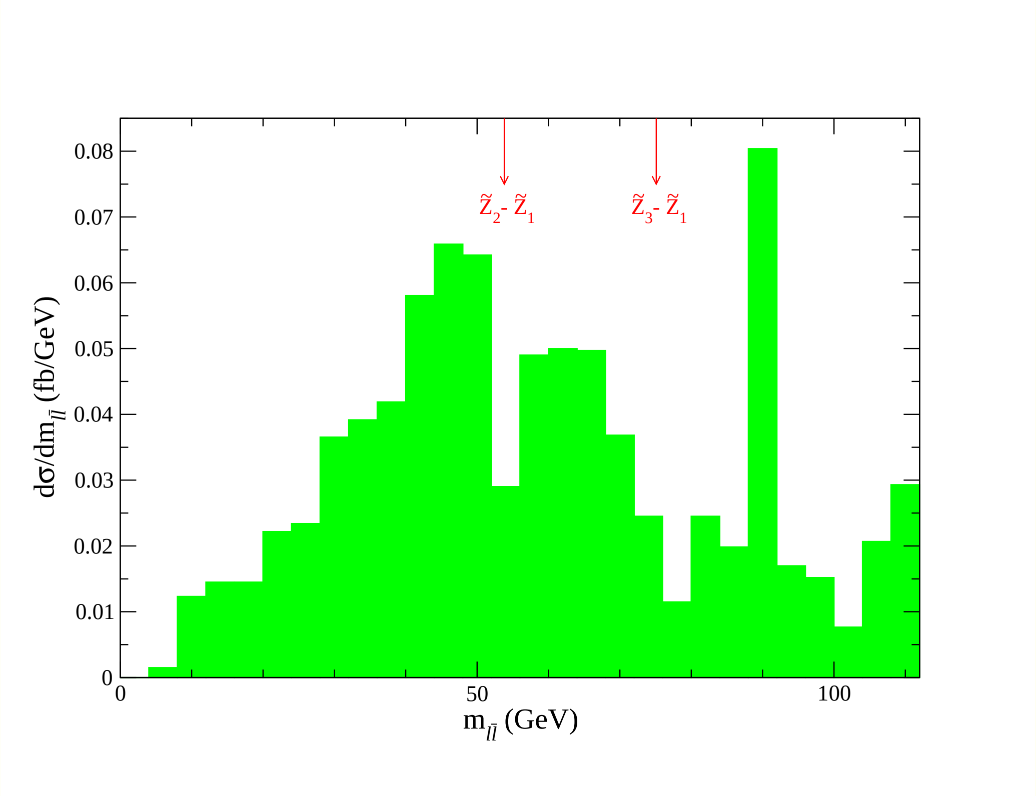
Remaining signal vs. $m_{\tilde{g}}$

- $n(jets) \geq 7$; $n(b-jets) \geq 2$; $A_T > 1400$ GeV
- signal way above BG; purely from $\tilde{g}\tilde{g}$ production
- extract $m_{\tilde{g}}$ from total rate to $\sim 8\%$



Same flavor/opposite sign dilepton mass distribution

- cuts C1; $n(leps) \geq 2$; $n(jets) \geq 4$; $n(b-jets) \geq 2$; $A_T > 1200$ GeV
- two mass edges stand out



Some aspects of Kaluza-Klein theory

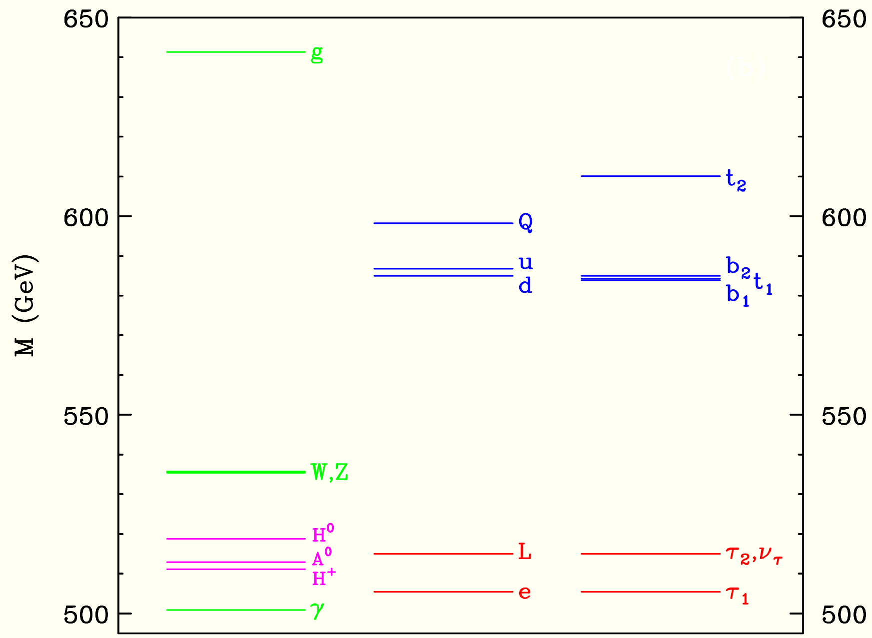
- ⋆ Write down Lagrangian, but in 5 space-time dimensions
- ⋆ Unify gravity plus E&M?
- ⋆ Compactification on manifold (circle) leads to zero modes plus KK-excitations with mass $m = \sqrt{m_0^2 + n^2/R^2}$ where R is compacification radius
  - get 2 KK excited states for each n value
  - excitations have same spin, couplings, charges as zero modes- just higher masses
- ⋆ instead, compactify on orbifold, *e.g.* S^1/Z_2
- ⋆ virtues of orbifolding:
  - reduction in # of KK excitations: no Z_2-odd modes
  - project out unwanted zero modes
  - can break symmetries of D-dimensional theory zero modes: alternative symmetry breaking mechanism to spontaneous SB

Universal Extra Dimensions (UED)

- ⋆ Write down SM action in 5-d
- ⋆ expand SM fields in terms of Z_2 odd/even functions
- ⋆ Compactify on S_1/Z_2 orbifold with radius R
- ⋆ Orbifolding eliminates "wrong helicity" SM zero modes to give chiral SM as zero mode theory
- ⋆ A_μ has zero mode; A_4 does not
- ⋆ low energy theory is SM zero modes
- ⋆ also get KK excitations starting at $m \sim 1/R$
- ⋆ KK-parity conserved: get DM candidate LKP
- ⋆ spectrum: $Q^1,\ u^1, d^1,\ L^1,\ e^1,\ W^{1\pm},\ Z^1,\ g^1,\ B^1,\ H^0,\ A^0,\ H^\pm$

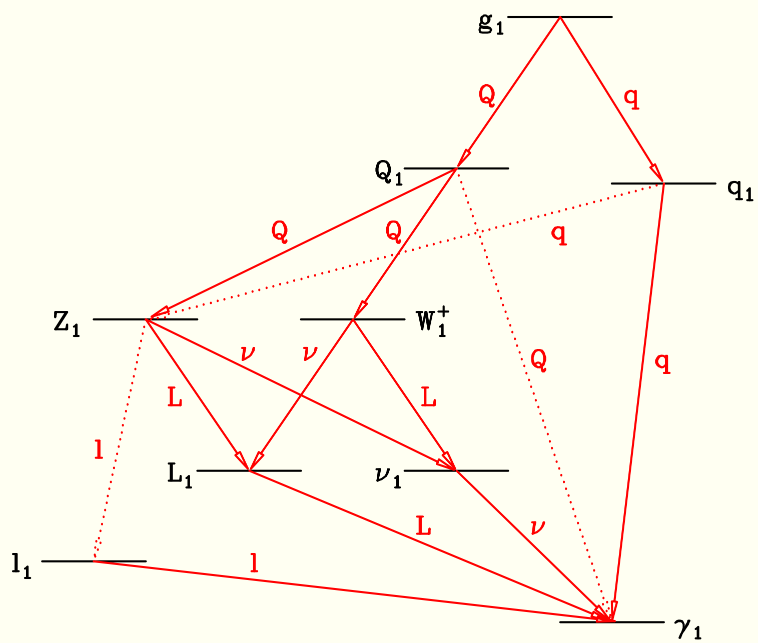
Universal Extra Dimensions (UED)

- tree level mass spectra nearly degenerate:
- radiative corrections give some splitting (Cheng, Matchev, Schmaltz)



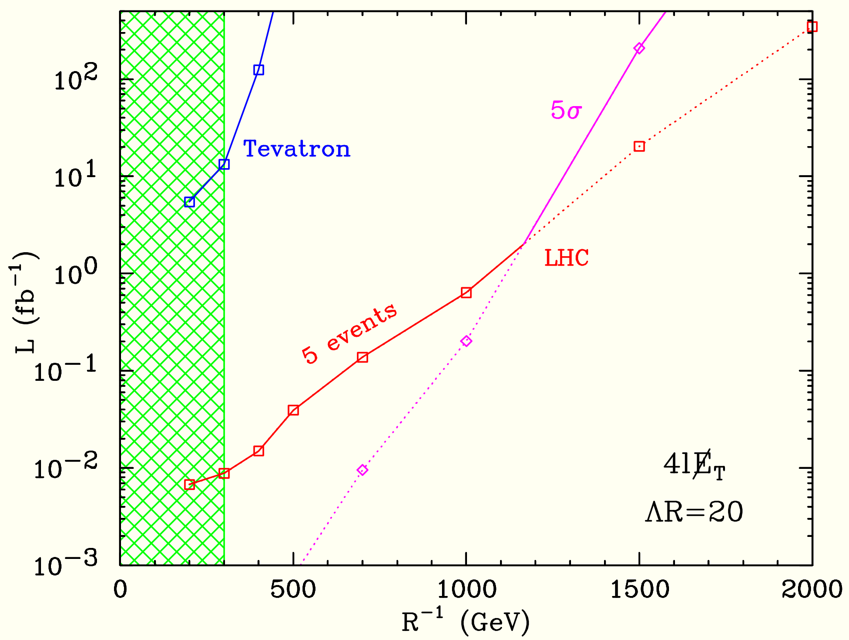
Universal Extra Dimensions (UED)

- decay modes (CMS)



LHC reach for UED theories in $4\ell + \not{E}_T$ channel

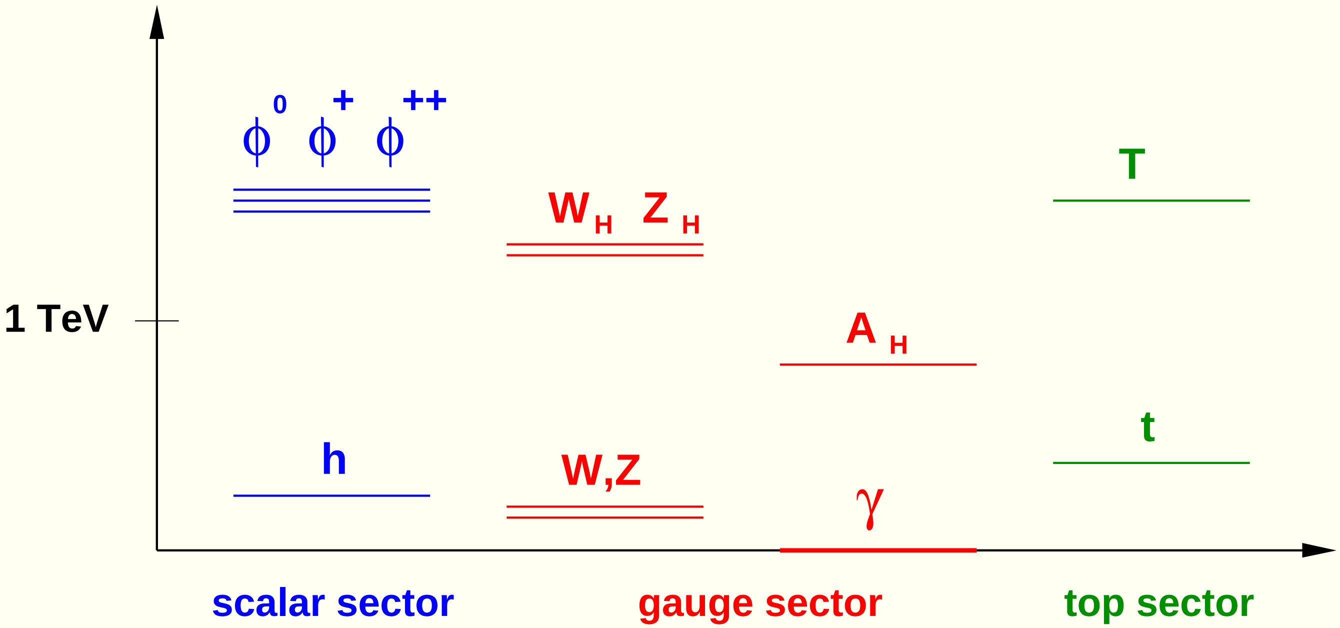
- $pp \to Z_1 Z_1 \to L_1 \bar{\ell} L_1 \bar{\ell} \to 4\ell + \not{E}_T$, etc.



Little Higgs theories

- for expert advice, see our TASI organizer, Prof. Tao Han!
- New approach to EWSB: Arkani-Hamed, Cohen, Georgi, 2001
- Higgs field arises as pseudo-Nambu-Goldstone boson from "collective" symmetry breaking
- Symmetry $\Rightarrow$ quadratic divergences to m_H^2 cancel at 1-loop (2-loop and higher quad. divergences remain)
- Natural cut-off of theory is ~ 10 TeV to avoid "little hierarchy problem"
- All LH theories predict new particles at 1-10 TeV scale
  - new gauge bosons A_H, $W_H^\pm$, W_H^0 to cancel gauge boson loops in m_H^2
  - new top partner fermions T to cancel top loop in m_H^2
  - new scalars to cancel Higgs self coupling loops
- precise details model-dependent: most popular: littlest Higgs with $SU(5)/SO(5)$

Spectrum from Little Higgs theories



T-parity in Little Higgs theories (LHT)

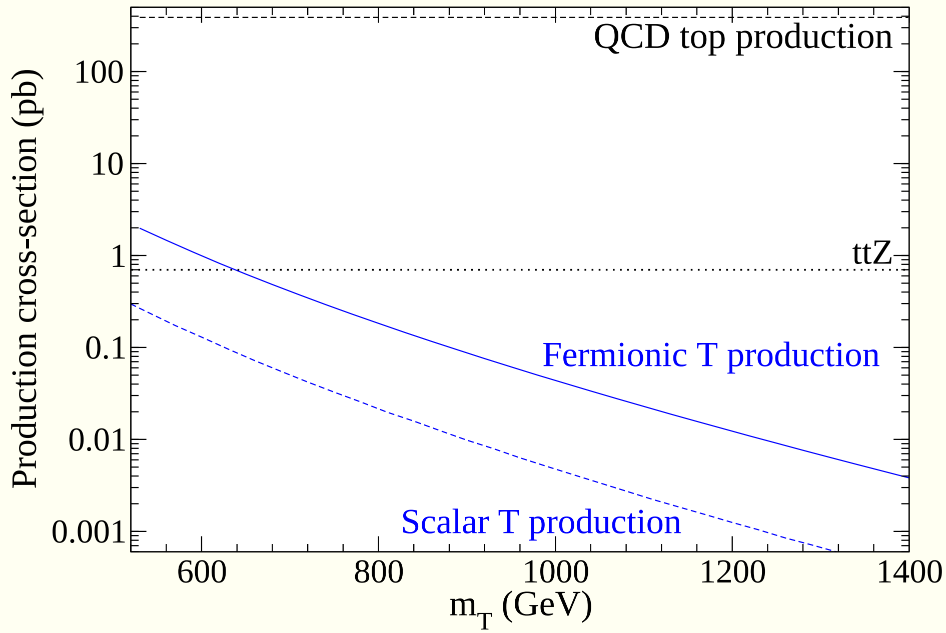
- It was found that LH models tend to give large corrections to precision EW observables unless $m_{LH} \to 10$ TeV
- This re-introduces fine-tunings in Higgs sector
- EWPOs can be saved by introducing T-parity (Cheng and Low)
  - SM particles: t-even
  - new GBs, scalars, some top-partners: t-odd
  - then contributions to EWPOs only occur at loop level
  - can allow much lighter new particle states
- t-odd particles produced in pairs
- $t$odd particles decay to other t-odd states
- Lightest t-odd particle absolutely stable: DM candidate, usually A_H (but see Hill+Hill anomalies paper)

LHT models at LHC

- main search channel: $pp \to T\bar{T}$ with $T \to tA_H$
- search for $t\bar{t}+ \not{E}_T$ states
- see Cheng, Low and Wang, PRD74, 055001 (2006)
- Matsumoto, Nojiri, Nomura, PRD75, 055006 (2007)
- Belyaev, Chen, Tobe and Yuan, PRD74, 115020 (2006)
- Carena, Hubisz, Perelstein, Verdier, PRD75, 091701 (2007)
- Han, Mahbubani, Walker, Wang, arXiv:0803.3820 (2008)

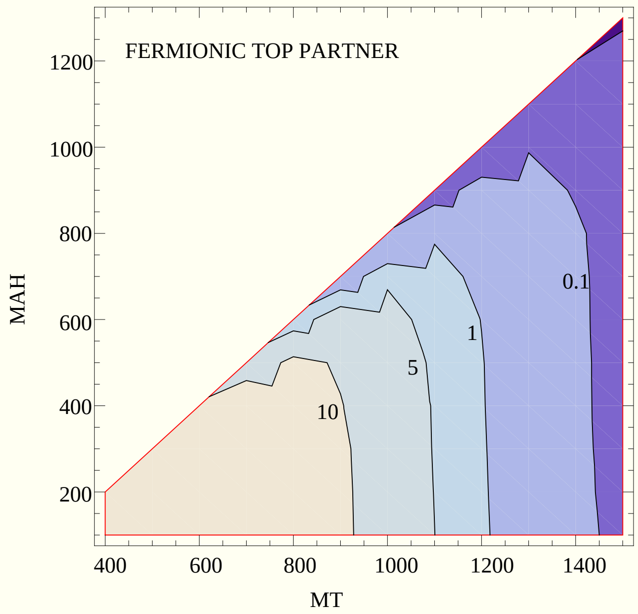
$T\bar{T}$ production at LHC

- Han, Mahbubani, Walker, Wang, arXiv:0803.3820 (2008)



$T\bar{T}$ discovery at LHC

- Han, Mahbubani, Walker, Wang, arXiv:0803.3820 (2008)
- significance after cuts with 100 fb^{-1} at LHC



Conclusions

- ⋆ SUSY at LHC
  - event signatures
  - backgrounds
  - reach
  - precision measurements
- ⋆ UED at LHC
- ⋆ LHT at LHC
- ⋆ We now have a good idea of what $\not{E}_T$ signatures will look like at the LHC for a variety of models
- ⋆ **in 2008, the road to discovery begins at the LHC: time to either discover or rule out models such as SUSY, UED, LHT at the weak scale, and resolve the physics behind electroweak symmetry breaking!**