Prospects for SUSY at the LHC

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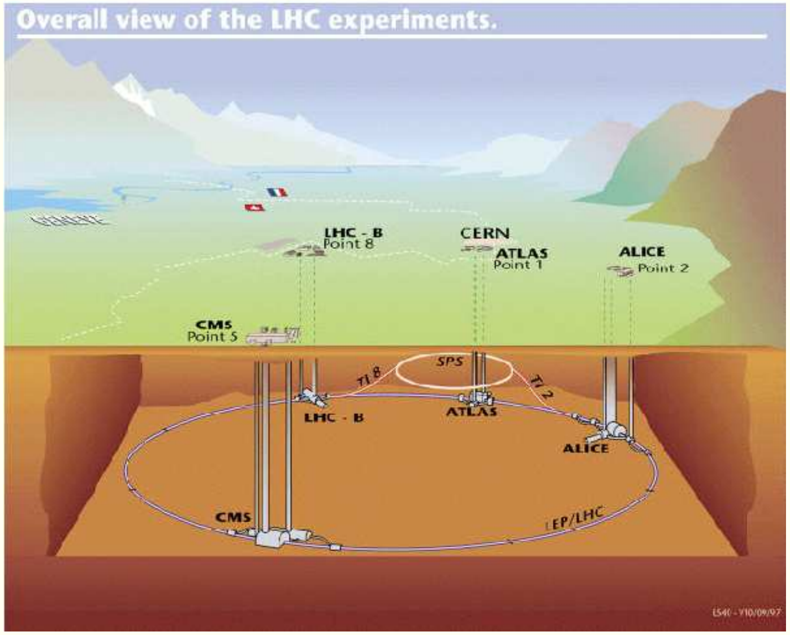
OUTLINE

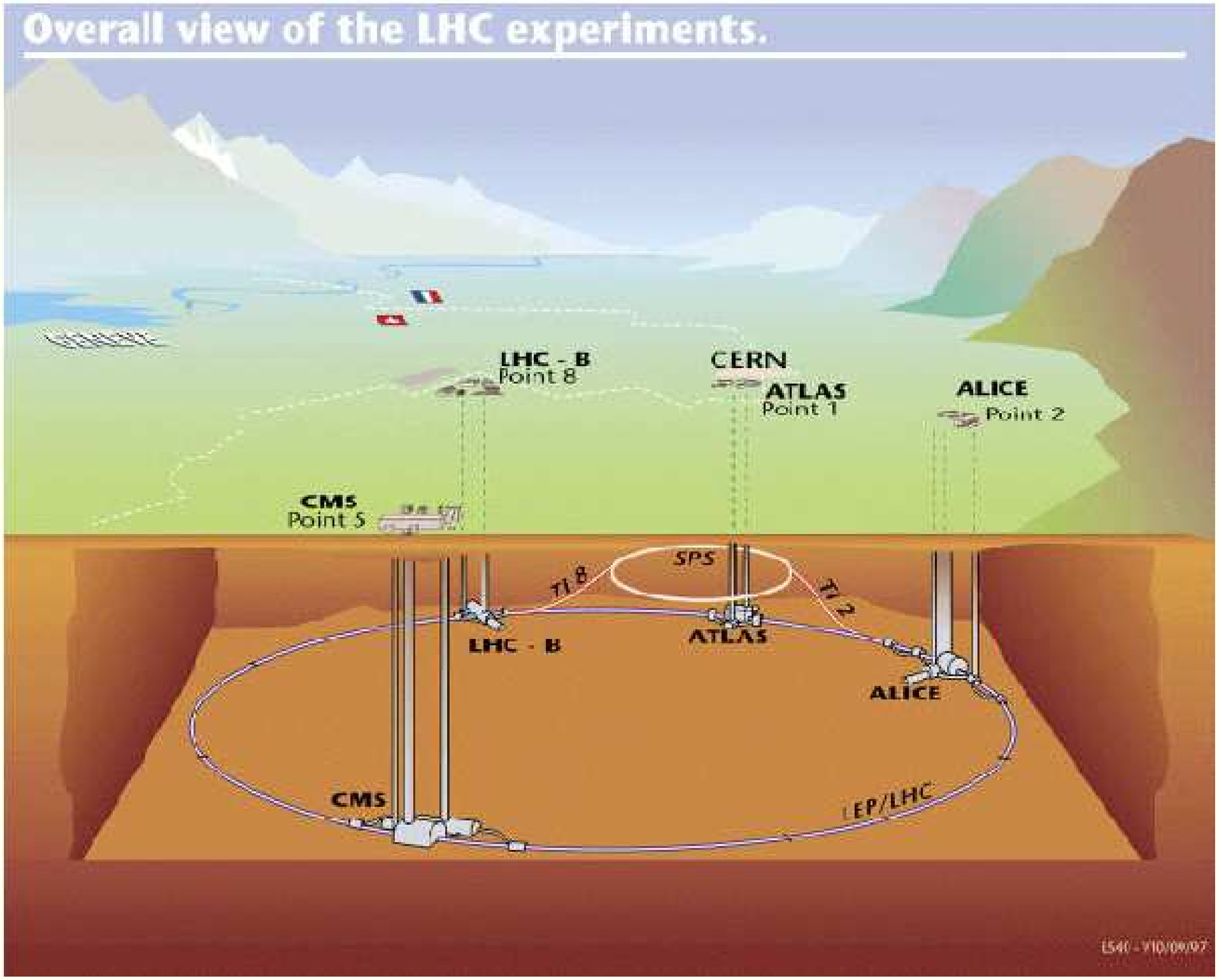
- ⋆ LHC details
- ⋆ Sparticle production
- ⋆ Sparticle decay
- ⋆ Event generation
- ⋆ LHC reach and year 1
  - Multi-muons + jets
  - RT-S dijet signal
- ⋆ precision measurements



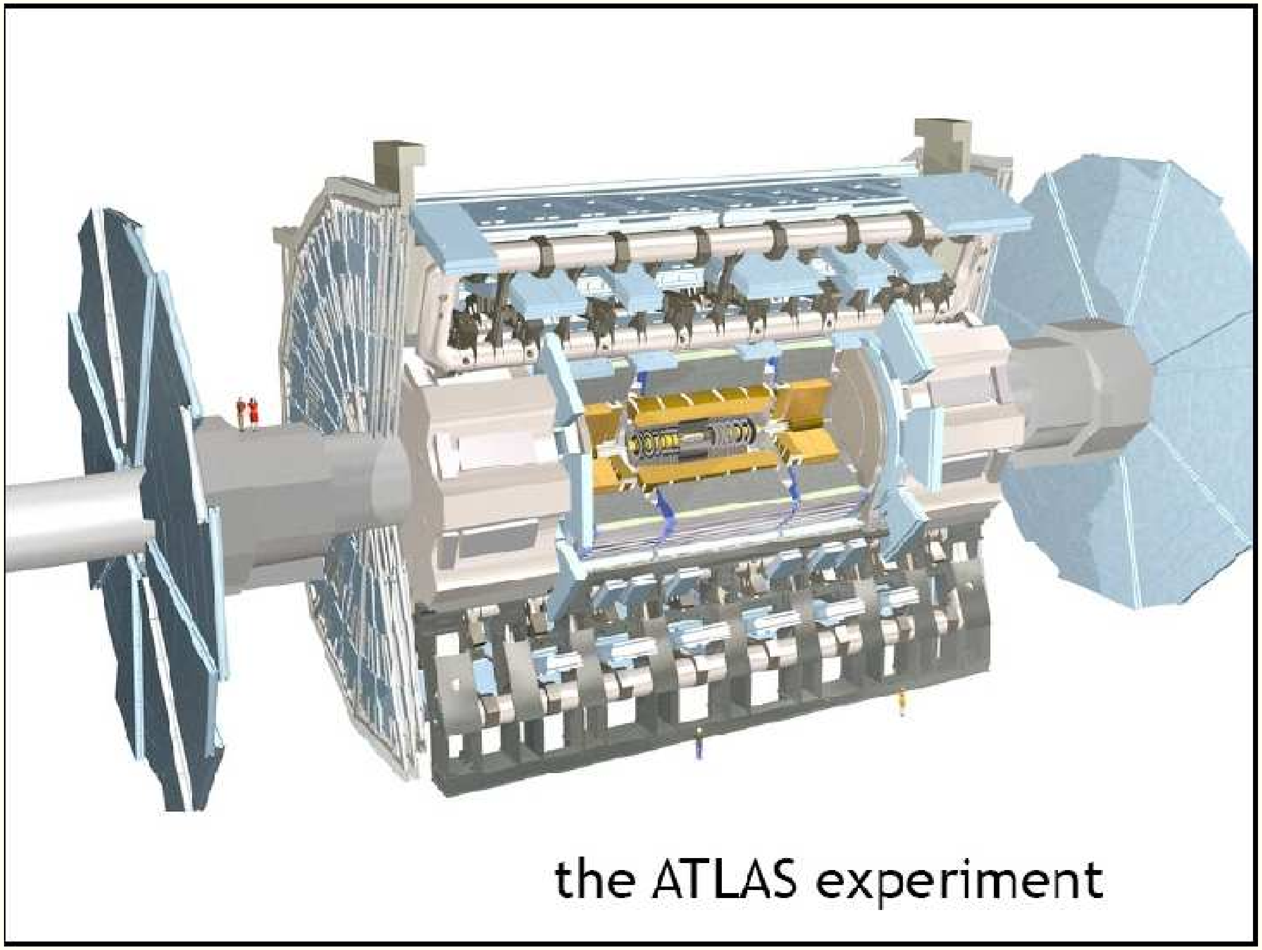
The role of the CERN Large Hadron Collider (LHC)

- The LHC is a proton-proton collider (pp)
- Each beam will have $E = 3.5 \to 7$ TeV (trillion electron volts)
- Center-of-mass energy $E \equiv \sqrt{s} = 7 \to 14$ TeV
- The collider is on a circular tunnel 27 km in circumference
- It is nearly ready: turn-on expected in November 2009!
- Protons are not fundamental particles: made of quarks q and gluons g
- The quark and gluon collisions should have enough energy to produce TeV-scale superparticles at a large enough rate that they should be detectable above SM background processes
- LHC should be able to discover SUSY or other new physics: but probably can't rule SUSY out if just a Higgs or nothing new is found

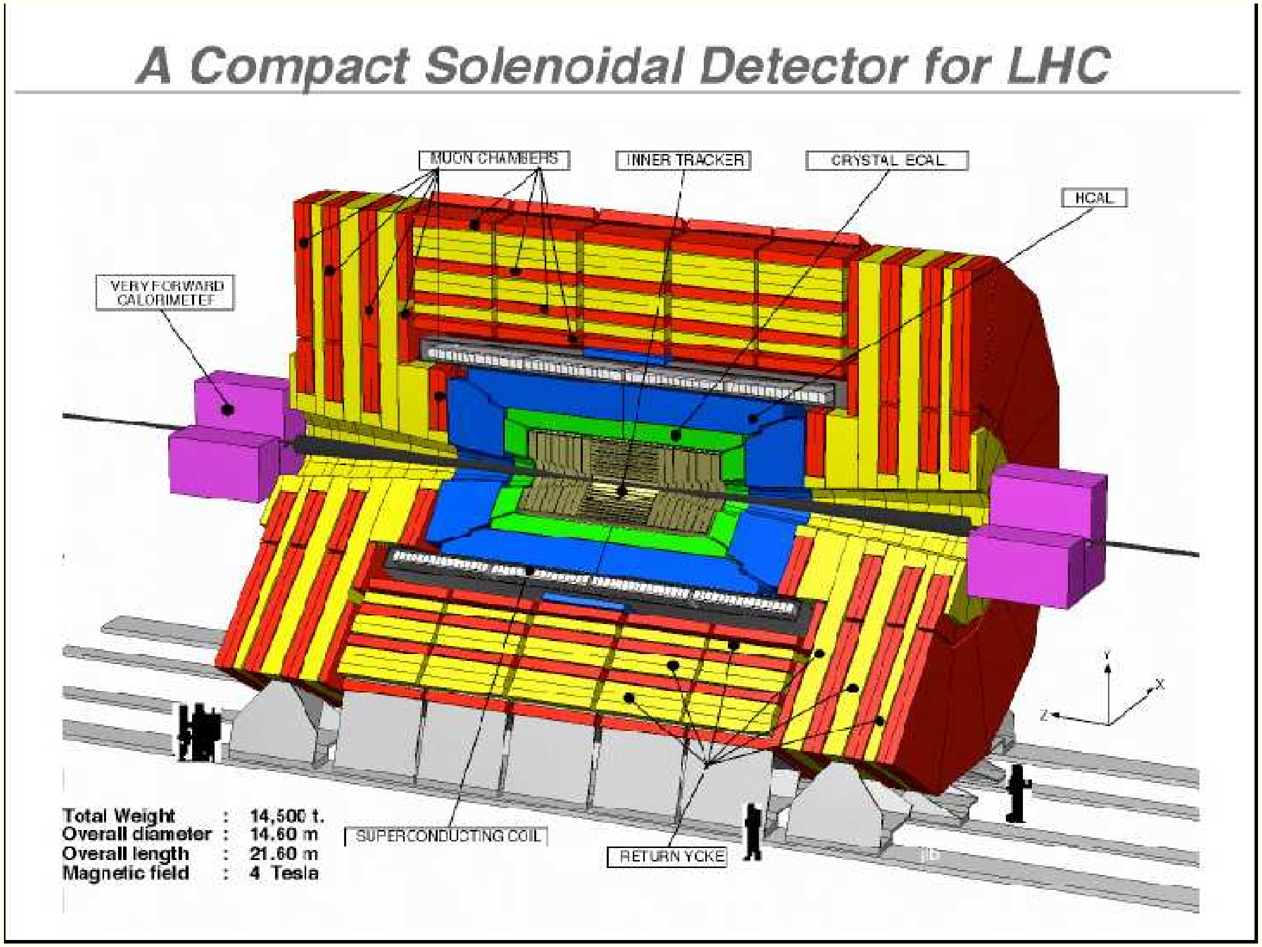
Layout of the LHC:two main detectors: Atlas and CMS



The Atlas detector



The CMS (Compact Muon Solenoid) detector



Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

Parton model of hadronic reactions

For a hadronic reaction,

$$A + B \to c + d + X,$$

where c and d are superpartners and X represents assorted hadronic debris, we have an associated subprocess reaction

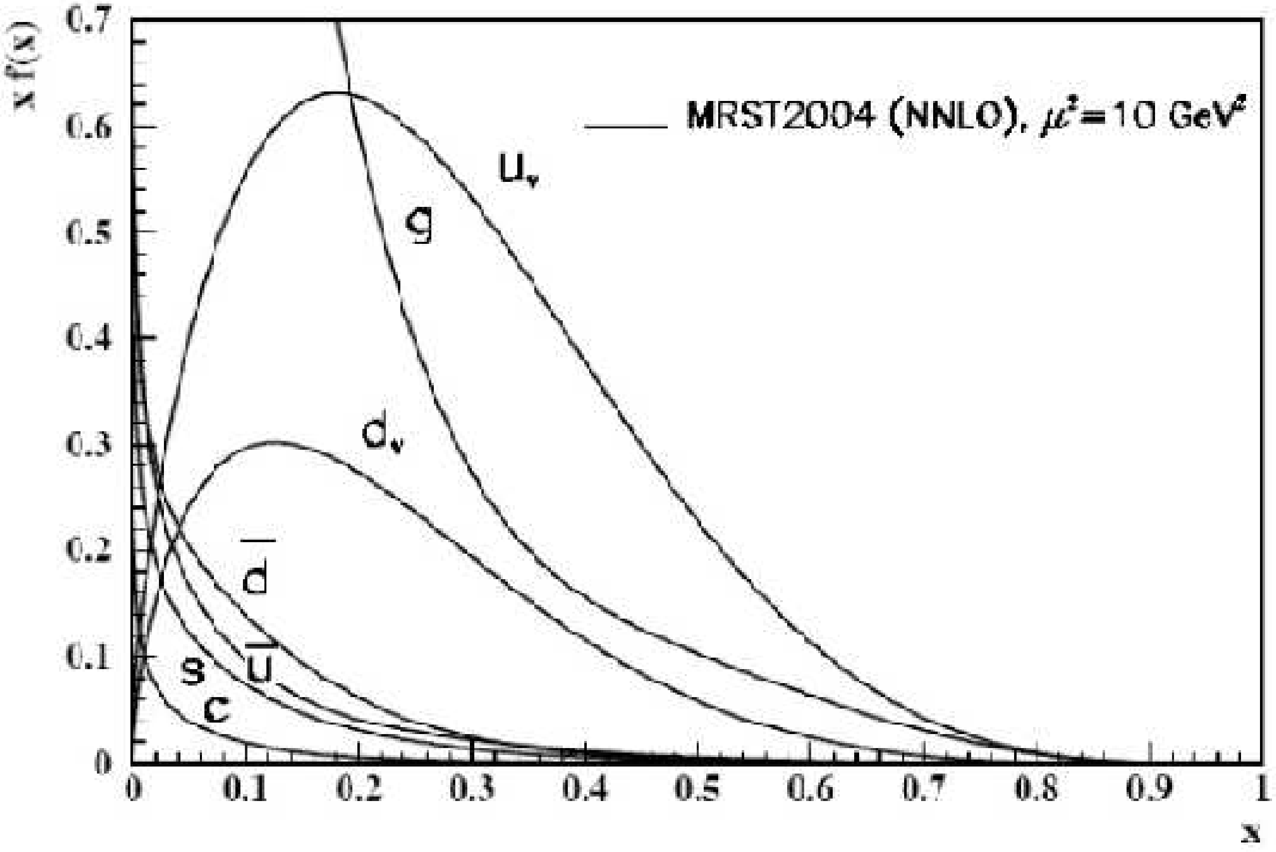
$$a + b \to c + d,$$

whose cross section can be computed using the Lagrangian for the MSSM. To obtain the final cross section, we must convolute the appropriate subprocess production cross section $d\hat{\sigma}$ with the parton distribution functions:

$$d\sigma(AB \to cdX) = \sum_{a,b} \int_0^1 dx_a \int_0^1 dx_b f_{a/A}(x_a, Q^2)\ f_{b/B}(x_b, Q^2)\ d\hat{\sigma}(ab \to cd).$$

where the sum extends over all initial partons a, b whose collisions produce the final state $c + d$.

Parton Distribution Functions (PDFs)



Calculating subprocess cross sections/decay rates in QFT

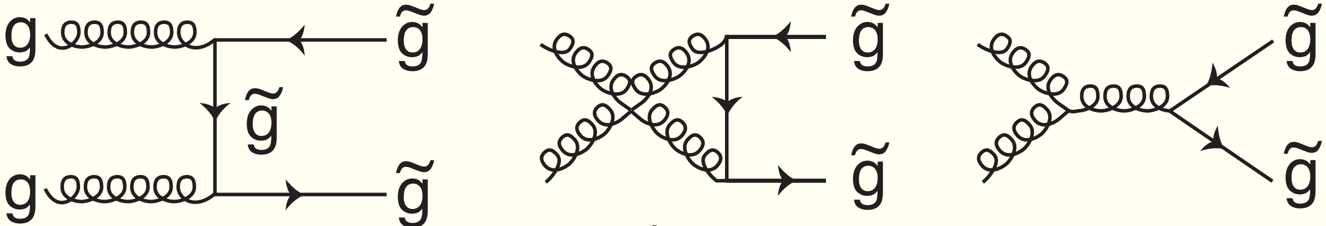
- The fundamental calculable object in QM is the *amplitude* $\mathcal{M}$ for a process to occur
- A pictorial representation of $\mathcal{M}$ is given by a *Feynman diagram*
- Feynman rules for many theories can be found in standard texts: *e.g.* Peskin& Schroeder, *Introduction to Quantum Field Theory*
- In the MSSM, an additional complication occurs due to presence of *Majorana* spinors
- Methods for handling these given *e.g.* in *Weak Scale Supersymmetry* (HB, X. Tata), or book by M. Drees, Godbole& Roy
- total amplitude $\mathcal{M}$ is sum of all different ways a process can occur
- $\mathcal{M}$ is a complex number; $|\mathcal{M}|^2$ gives probability
- must normalize and sum (integrate) over all momentum configurations to gain cross section, usually in *femtobarns*:

Calculating subprocess cross sections/decay rates in QFT

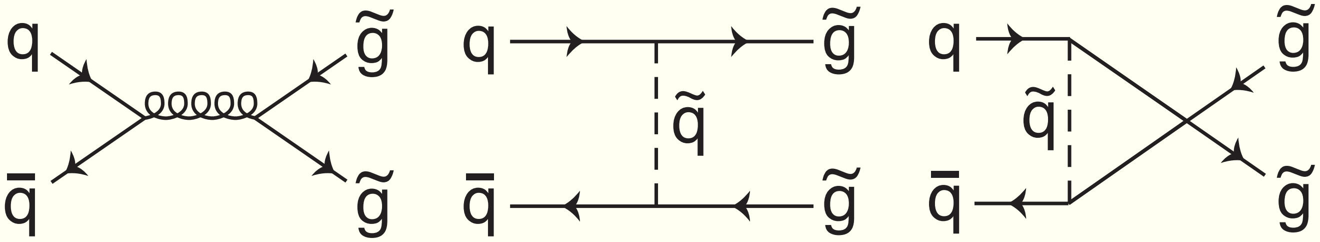
$$d\hat{\sigma} \quad = \quad \frac{1}{2\hat{s}}\frac{1}{(2\pi)^2}\int \frac{d^3p_c}{2E_c}\frac{d^3p_d}{2E_d}\delta^4(p_a+p_b-p_c-p_d)\cdot F_{\rm color}F_{\rm spin}\sum|\mathcal{M}|^2,$$

- Must sum (integrate) over all final state momentum configurations
- May be done analytically for simple processes $e.g.\ 2 \to 2$
- Usually done using Monte Carlo method for $n \geq 3$
- Monte Carlo well suited for adding on particle decays so one has really $2 \to n$ processes where n can be very large
- Convolution of subprocess cross section with PDFs must be done numerically, since PDFs distributed as *subroutines*

Gluino pair production

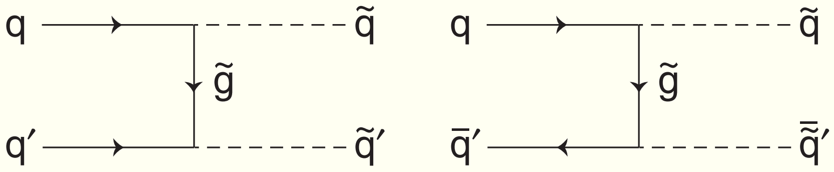


a)

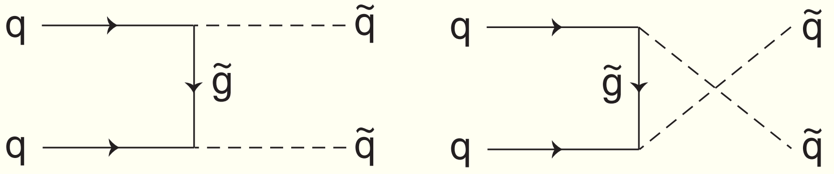


b)

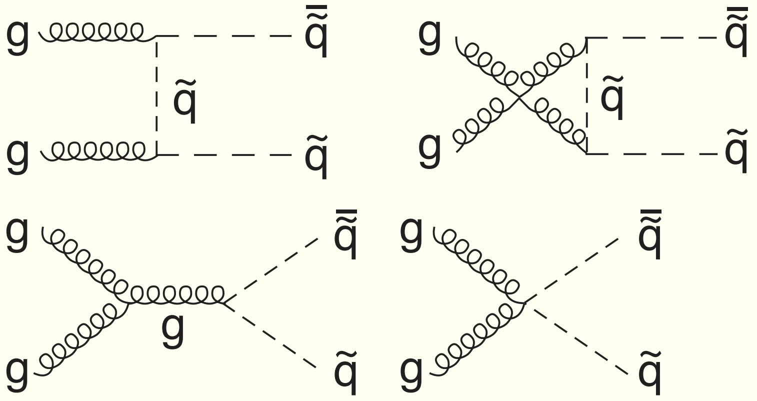
Squark pair production

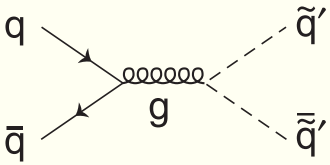


a)



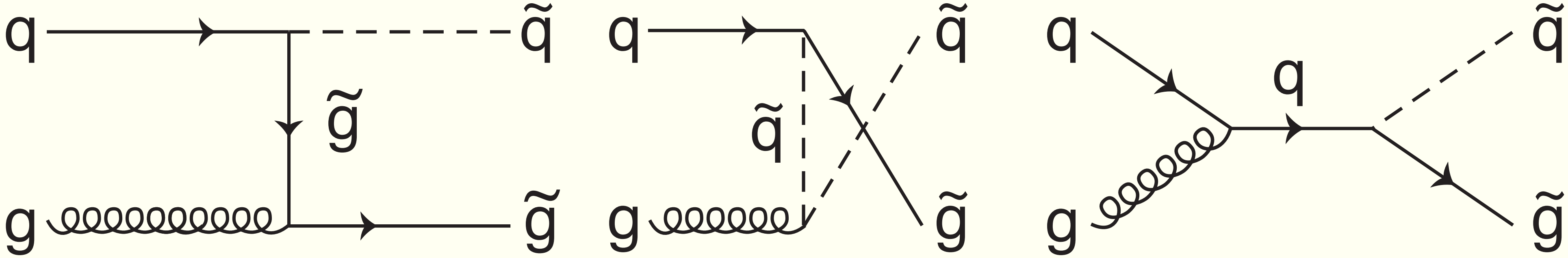
b)



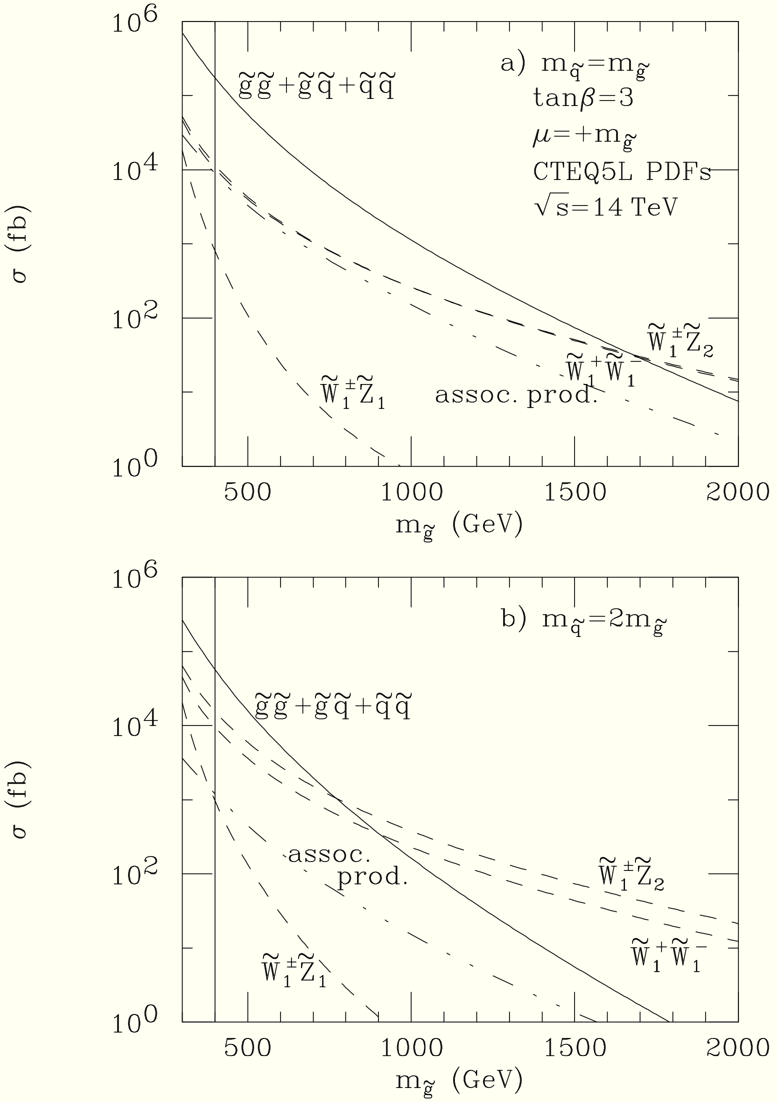


c)

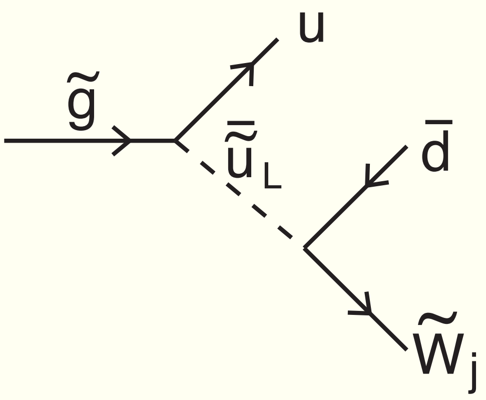
Gluino-squark associated production



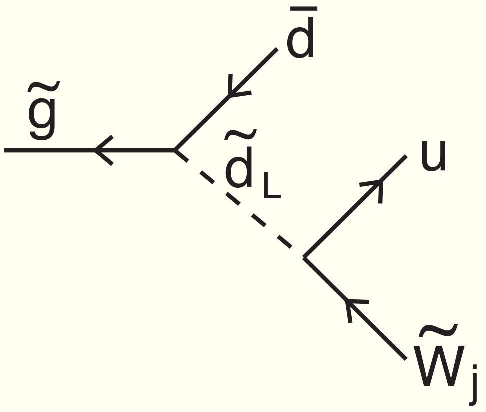
Production at LHC



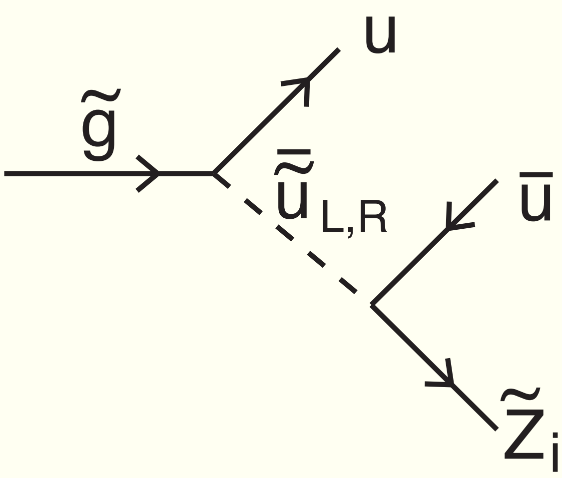
Gluino decays: $\tilde{g} \to q\tilde{q}$ or 3-body

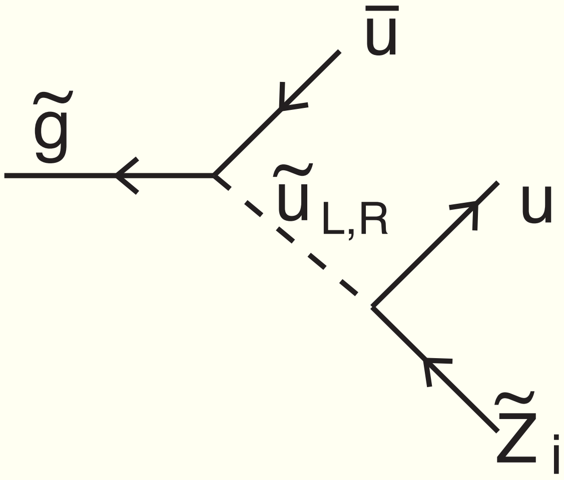


(1)

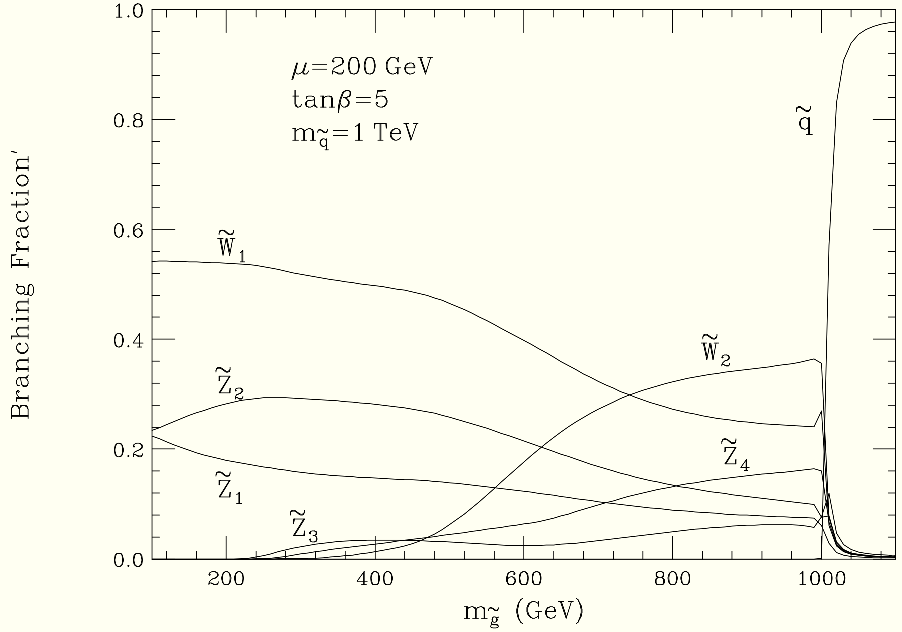


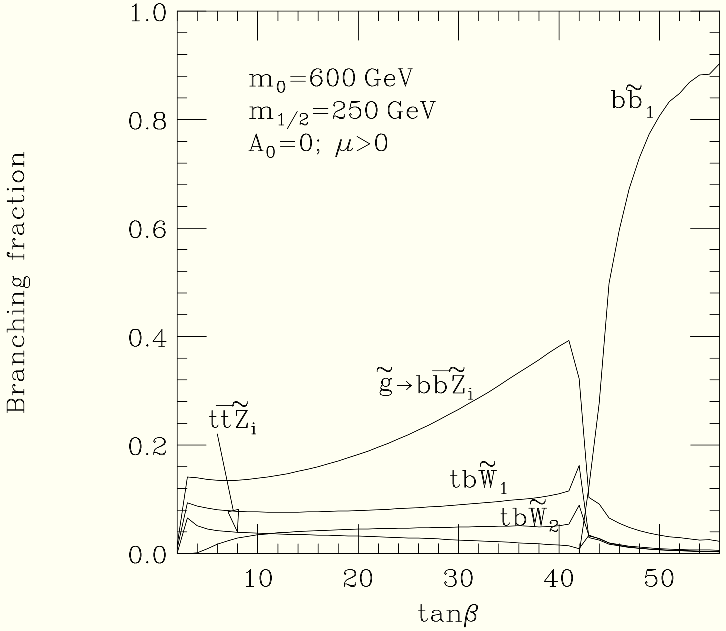
(2)





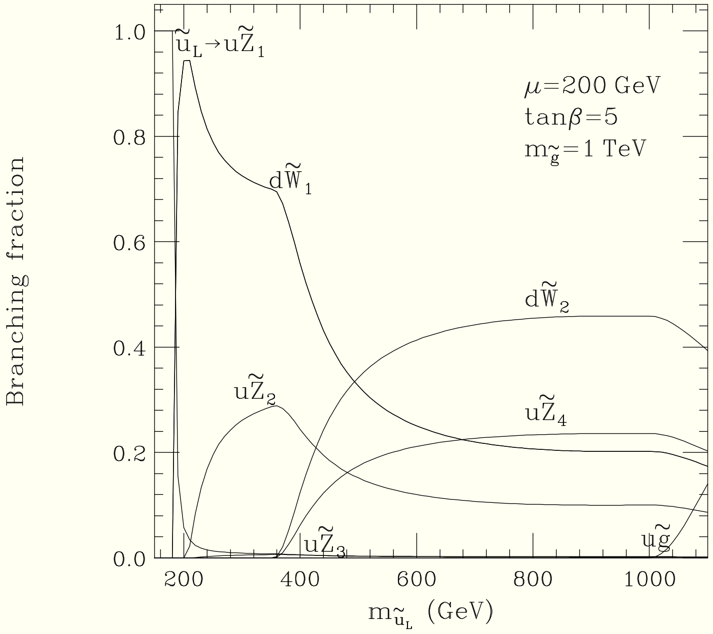
Gluino decays: branching fractions

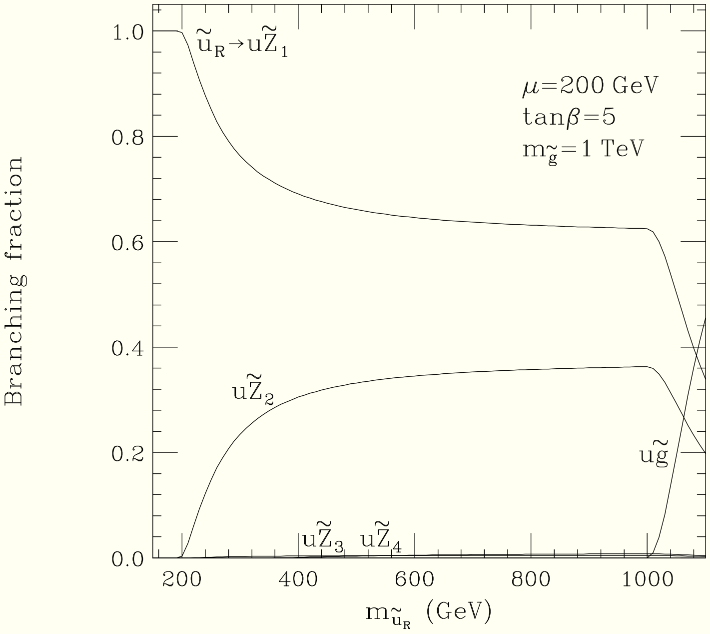




Squark decays

$$\begin{aligned}
\tilde{u}_L &\to u\widetilde{Z}_i,\ d\widetilde{W}_j^+,\ u\tilde{g},\\
\tilde{d}_L &\to d\widetilde{Z}_i,\ u\widetilde{W}_j^-,\ d\tilde{g},\\
\tilde{u}_R &\to u\widetilde{Z}_i,\ u\tilde{g},\\
\tilde{d}_R &\to d\widetilde{Z}_i,\ d\tilde{g}.
\end{aligned}$$



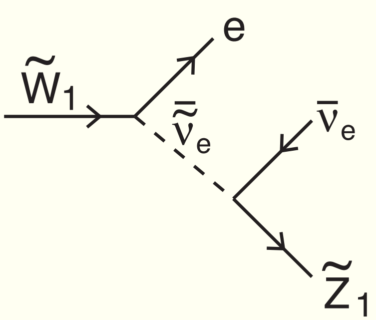


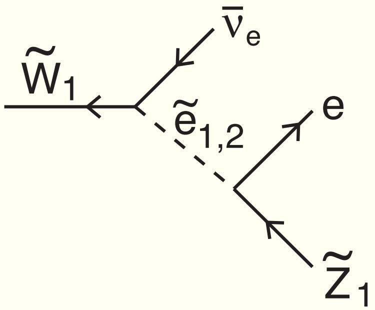
Chargino decays

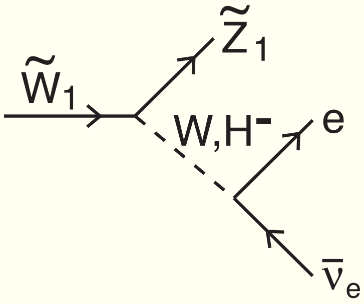
$$\begin{aligned}
\widetilde{W}_j &\rightarrow W\widetilde{Z}_i,\ H^-\widetilde{Z}_i, \\
&\rightarrow \tilde{u}_L\bar{d},\ \bar{\tilde{d}}_L u,\ \tilde{c}_L\bar{s},\ \bar{\tilde{s}}_L c,\ \tilde{t}_{1,2}\bar{b},\ \tilde{b}_{1,2}t, \\
&\rightarrow \tilde{\nu}_e\bar{e},\ \bar{\tilde{e}}_L\nu_e,\ \tilde{\nu}_\mu\bar{\mu},\ \bar{\tilde{\mu}}_L\nu_\mu,\ \tilde{\nu}_\tau\bar{\tau}, \bar{\tilde{\tau}}_{1,2}\nu_\tau,\ \text{and} \\
\widetilde{W}_2 &\rightarrow Z\widetilde{W}_1,\ h\widetilde{W}_1,\ H\widetilde{W}_1 \text{ and } A\widetilde{W}_1.
\end{aligned}$$

Charginos may decay to a lighter neutralino via

$$\widetilde{W}_j \rightarrow \widetilde{Z}_i + f\bar{f}' \ , \tag{1}$$





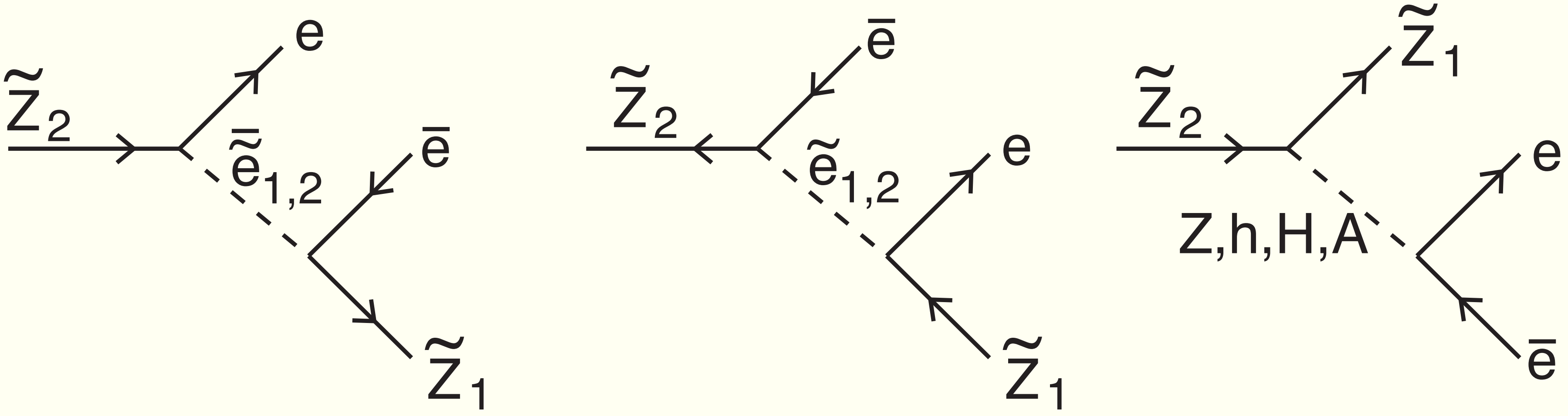


Neutralino decays

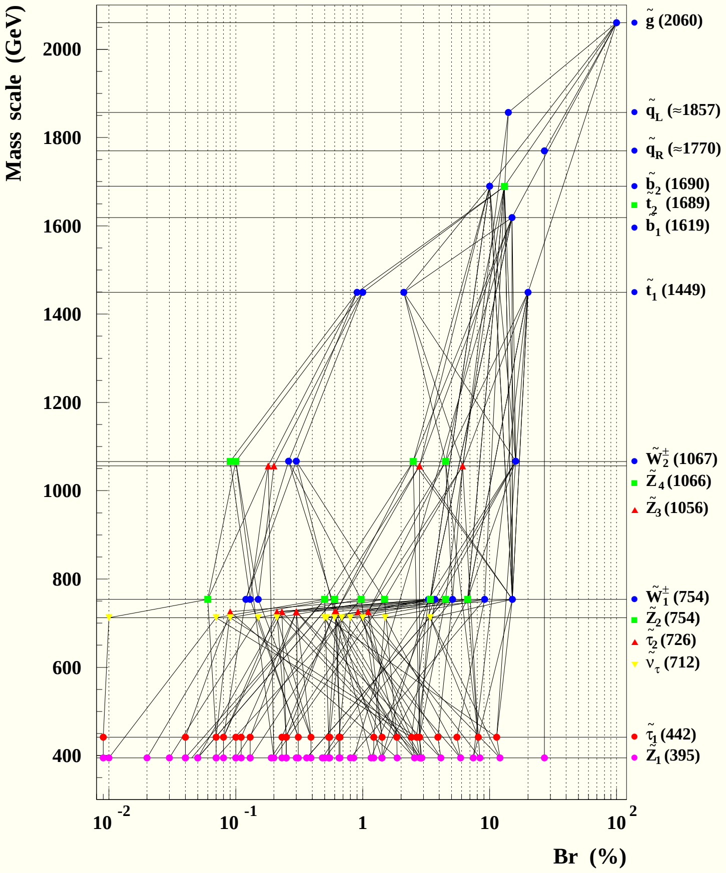
$$\begin{aligned}\widetilde{Z}_i &\rightarrow W\widetilde{W}_j,\ H^-\widetilde{W}_j,\ Z\widetilde{Z}_{i'},\ h\widetilde{Z}_{i'},\ H\widetilde{Z}_{i'},\ A\widetilde{Z}_{i'} \\ &\rightarrow \tilde{q}_{L,R}\bar{q},\ \bar{\tilde{q}}_{L,R}q,\ \tilde{\ell}_{L,R}\bar{\ell},\ \bar{\tilde{\ell}}_{L,R}\ell,\ \tilde{\nu}_\ell\bar{\nu}_\ell,\ \bar{\tilde{\nu}}_\ell\nu_\ell.\end{aligned}$$

If 2-body modes are closed,then the neutralino can decay via

$$\widetilde{Z}_i \rightarrow \widetilde{Z}_{i'} + f\bar{f} \tag{2}$$



Sparticle cascade decays

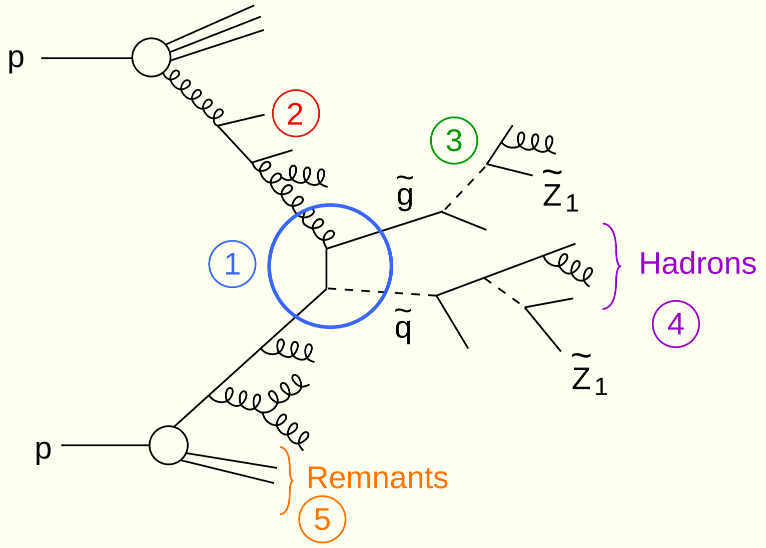


$\tilde{Z}_1$ qq	(27.0 %)	$\tilde{Z}_1$ τνWWWbb	(4.1 %)
$\tilde{Z}_1$ τνWbb	(12.1 %)	$\tilde{Z}_1$ ττbb	(2.9 %)
$\tilde{Z}_1$ ττWWbb	(8.4 %)	$\tilde{Z}_1$ ττqq	(2.9 %)
$\tilde{Z}_1$ WWbb	(7.4 %)	$\tilde{Z}_1$ τνZWbb	(2.8 %)
$\tilde{Z}_1$ τνqq	(5.9 %)	$\tilde{Z}_1$ τνhWbb	(2.6 %)

A realistic picture of what SUSY matter looks like at LHC

- ⋆ Counting different flavor states (which are potentially measurable), there are well over 1000 subprocess reactions expected at LHC from the MSSM
- ⋆ on average, each sparticle has 5-20 decay modes
- ⋆ rough estimate of distinct SUSY $2 \to n$ processes:
  - $\sim 1000 \times 10 \times 10 \sim 10^5$
  - this is actually a gross underestimate since each daughter of a produced sparticle has multiple decay modes, and so on...
- ⋆ the way forward: Monte Carlo program
  - calculate *all* prod'n cross sections: generate according to relative weights
  - calculate all branching fractions, and generate decays according to them
  - interface with parton shower, hadronization, underlying event
  - computer generated events should look something like what we would expect from the MSSM at the LHC

Event generation for sparticles



Event generation in LL - QCD

1) Hard scattering / convolution with PDFs

2) Intial / final state showers

3) Cascade decays

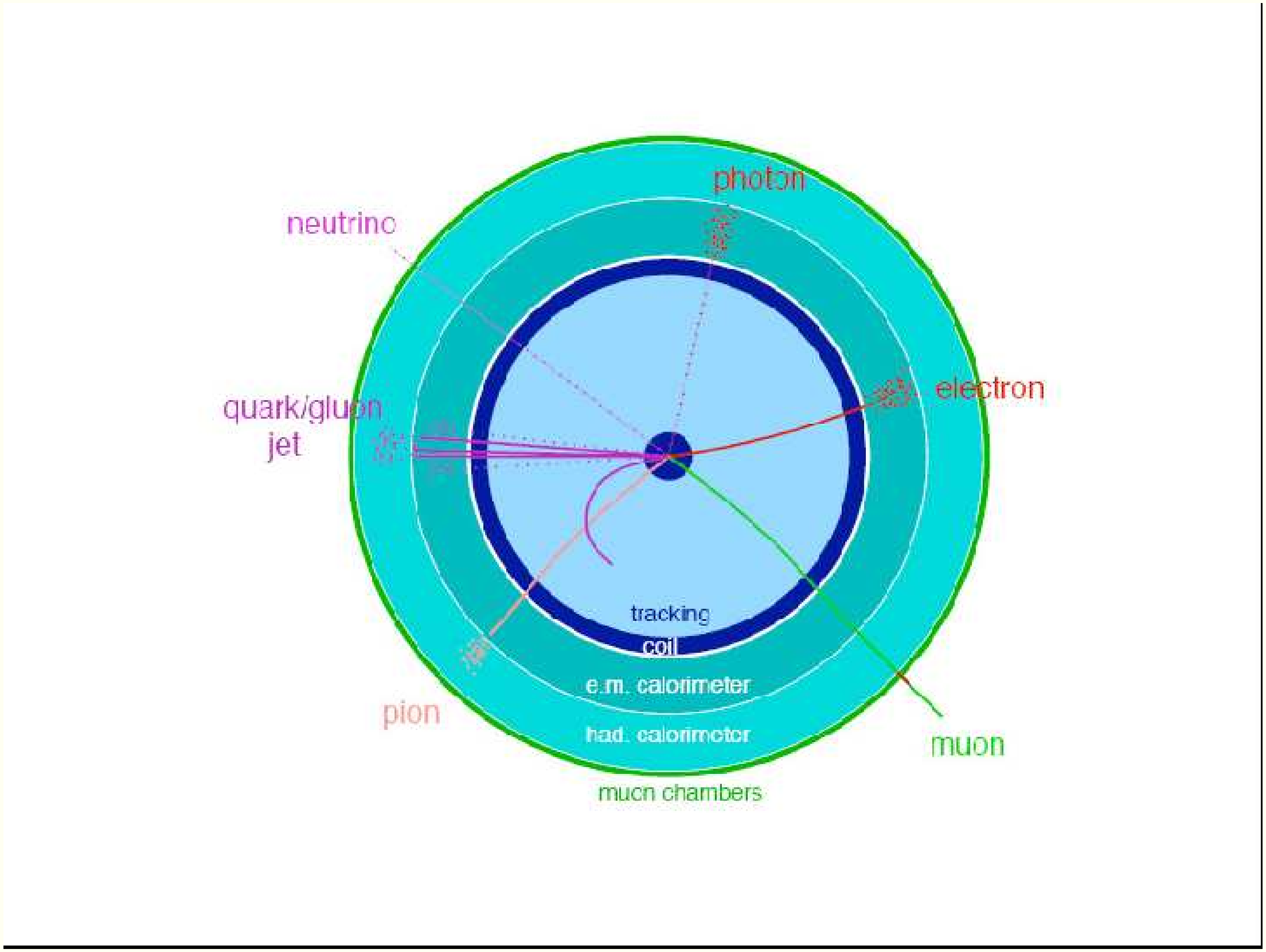
4) Hadronization

5) Beam remnants

Event generations for SUSY

- ⋆ Isajet (HB, Paige, Protopopsecu, Tata)
  - IH, FW-PS, n-cut Pomeron UE
- ⋆ Pythia (Sjöstrand, Lönnblad, Mrenna)
  - SH, FW-PS, multiple scatter UE, SUSY at low $\tan\beta$ only
- ⋆ Herwig (Marchesini, Webber, Seymour, Richardson,...)
  - CH, AO-PS, Phen. model UE, Isawig, Spin corr.!
- ⋆ SUSYGEN (Ghodbane, Katsanevas, Morawitz, Perez)
  - mainly for e^+e^-; interfaces to Pytha
- ⋆ SHERPA (Gleisberg, Hoche, krauss, Schalicke, Schumann, Winter)
  - $C++$ code for various $2 \to n$ processes
- ⋆ CompHEP, CalcHEP, Madgraph: for automatic Feynman diagram evaluation: interface via LHA

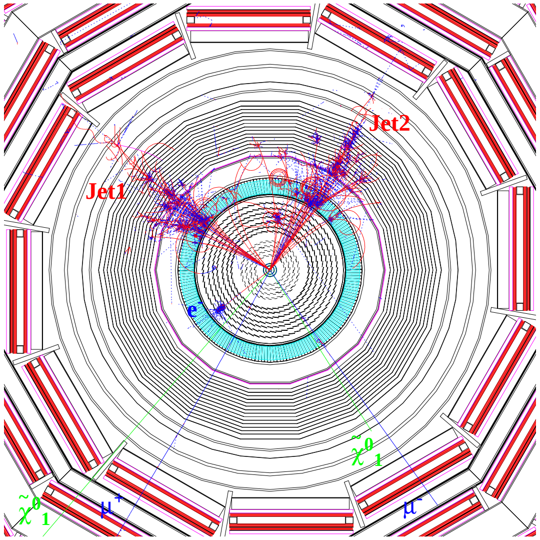
Briefly: particle interactions with detector



SUSY scattering event: Isajet simulation

SUSY event with 3 lepton + 2 Jets signature

m_0 = 100 GeV, $m_{1/2}$ = 300 GeV, $\tan\beta$ = 2, A_0 = 0, $\mu < 0$,
$m(\tilde{q})$ = 686 GeV, $m(\tilde{g})$ = 766 GeV, $m(\tilde{\chi}^0{}_2)$ = 257 GeV,
$m(\tilde{\chi}^0{}_1)$ = 128 GeV.



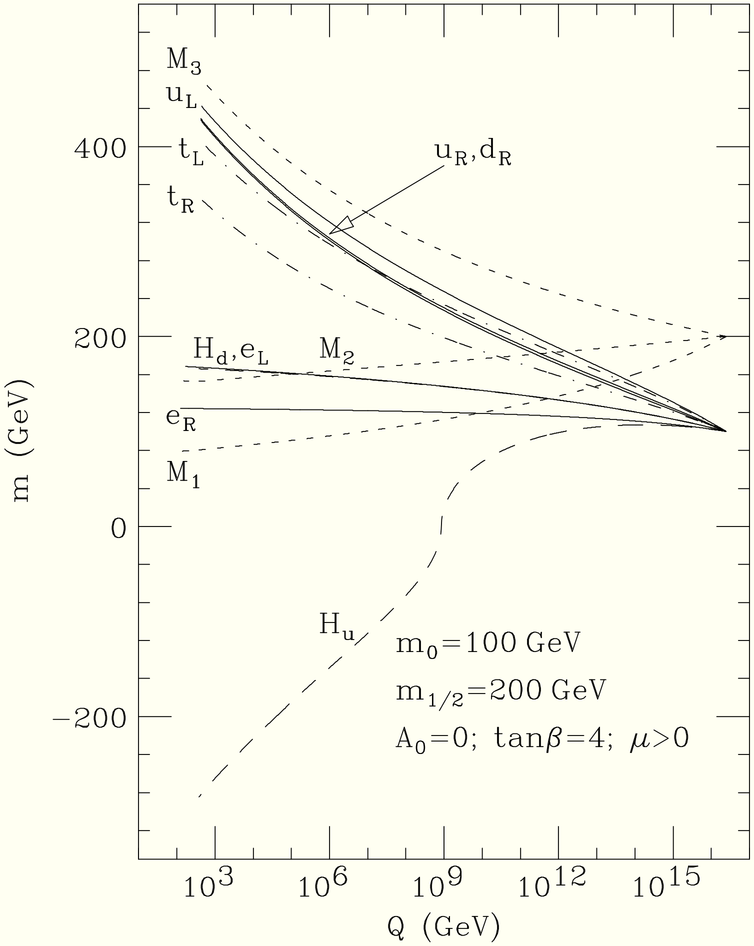
Leptons:	Jets:	Sparticles:
$p_t(\mu^+)$ = 55.2 GeV	E_t(Jet1) = 237 GeV	$p_t(\tilde{\chi}^0{}_1)$ = 95.1 GeV
$p_t(\mu^-)$ = 44.3 GeV	E_t(Jet2) = 339 GeV	$p_t(\tilde{\chi}^0{}_1)$ = 190 GeV
$p_t(e^-)$ = 43.9 GeV		

Charged particles with p_t > 2 GeV, $|\eta|$ < 3 are shown;
neutrons are not shown; no pile up events superimposed.

Search for SUSY at LHC: model dependent

- ⋆ GMSB
- ⋆ AMSB
  - MM-AMSB (mirage mediation)
  - hypercharged-AMSB (HCAMSB)
  - deflected AMSB
  - deflected mirage mediation
- ⋆ gravity-mediated models
  - mSUGRA or CMSSM
  - NUHM1, NUHM2
  - non-universal gaugino masses: MWDM, BWCA, LM3DM, HM2DM, ...
  - normal scalar mass hierarchy $(m_0(1,2) > m_0(3))$
  - compressed SUSY
- ⋆ Split SUSY, pMSSM, NMSSM, $\cdots$

Right or wrong, most analyses work in mSUGRA model



- $m_0,\ m_{1/2},\ A_0,\ \tan\beta, sign(\mu)$

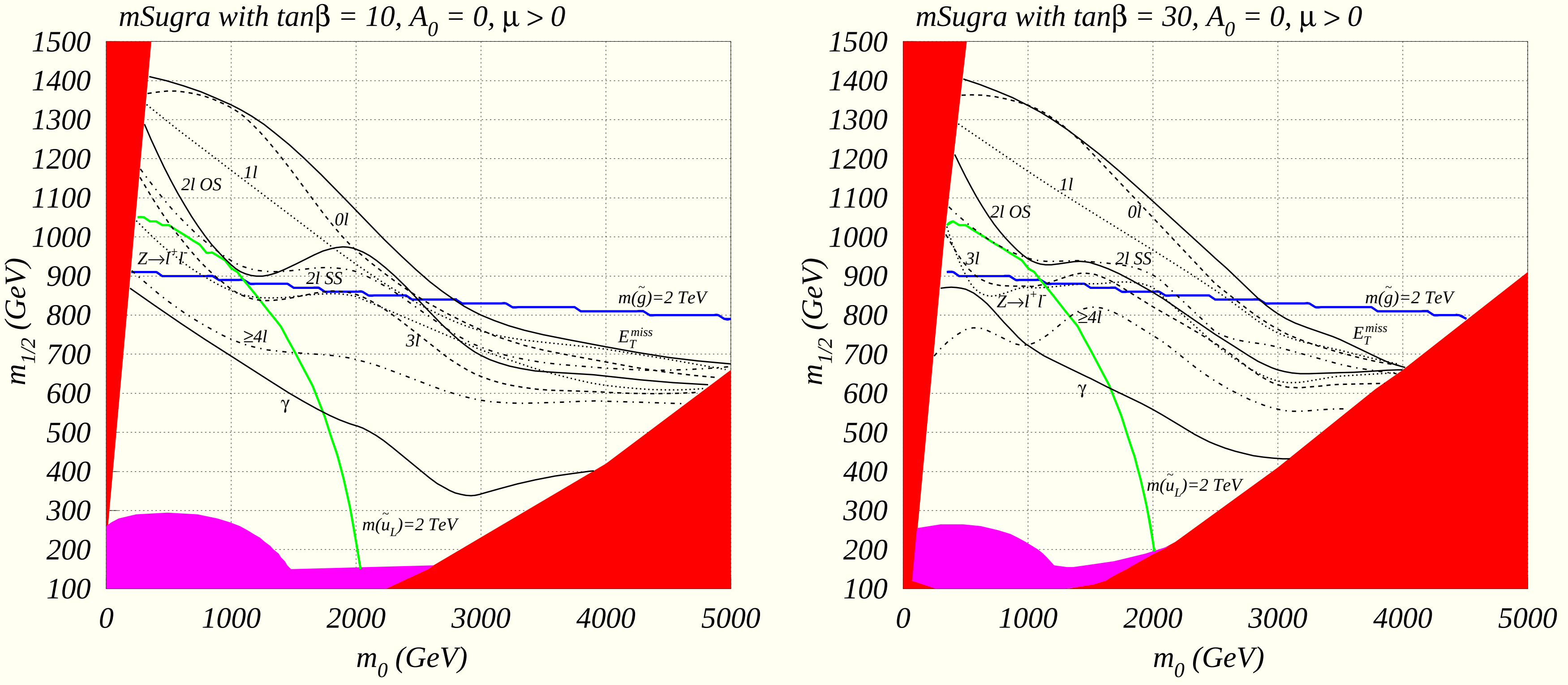
Search for SUSY at CERN LHC

- ⋆ $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV
- ⋆ lengthy cascade decays are likely
  - $\not{E}_T+$ jets
  - $1\ell+\not{E}_T+$ jets
  - $OS\ 2\ell+\not{E}_T+$ jets
  - $SS2\ell+\not{E}_T+$ jets
  - $3\ell+\not{E}_T+$ jets
  - $4\ell+\not{E}_T+$ jets
- ⋆ BG: $W+jets$, $Z+jets$, $t\bar{t}$, $b\bar{b}$, WW, $4t$, $\cdots$
- ⋆ Grid of cuts gives optimized S/B

Pre-cuts and cuts

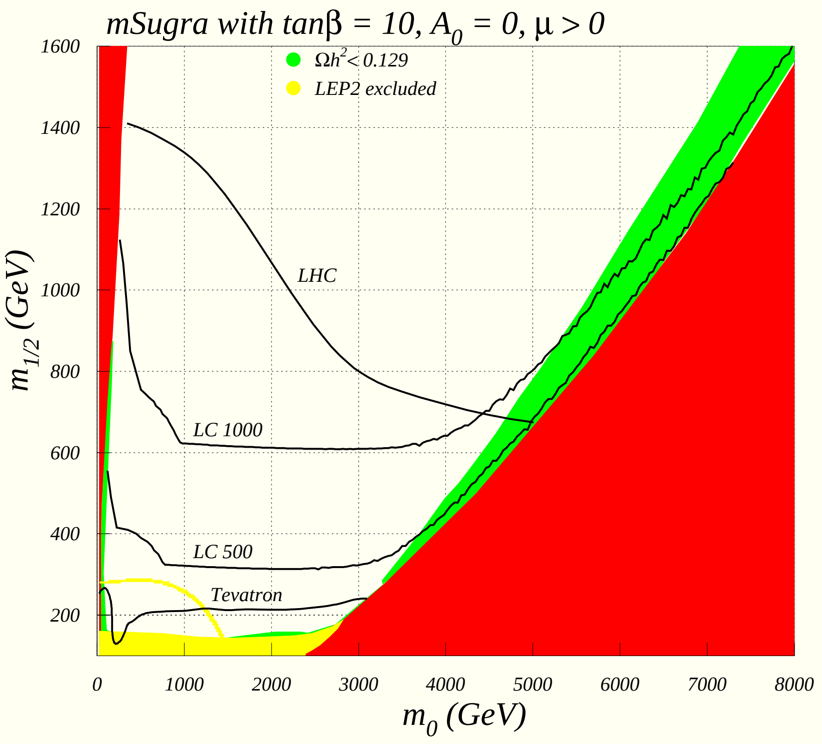
- ⋆ $\not{E}_T > 200$ GeV
- ⋆ $N_j \geq 2$ (where $p_T(jet) > 40$ GeV and $|\eta(jet)| < 3$
- ⋆ Grid of cuts for optimized S/B:
  - $N_j \geq 2 - 10$
  - $\not{E}_T > 200 - 1400$ GeV
  - $E_T(j1) > 40 - 1000$ GeV
  - $E_T(j2) > 40 - 500$ GeV
  - $S_T > 0 - 0.2$
  - muon isolation
- ⋆ $S > 10$ events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

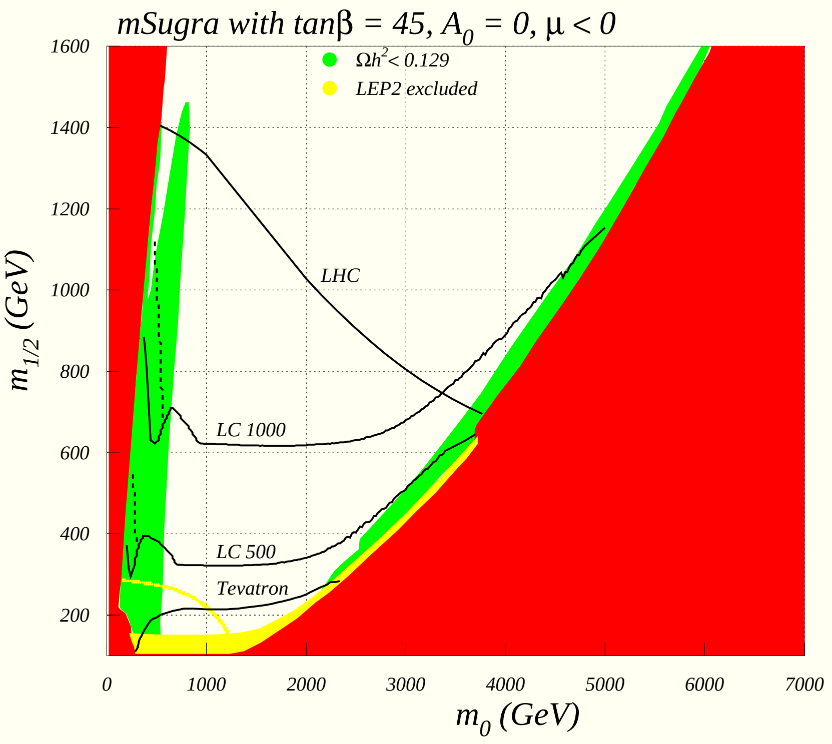
Sparticle reach of LHC for 100^{-1} fb



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

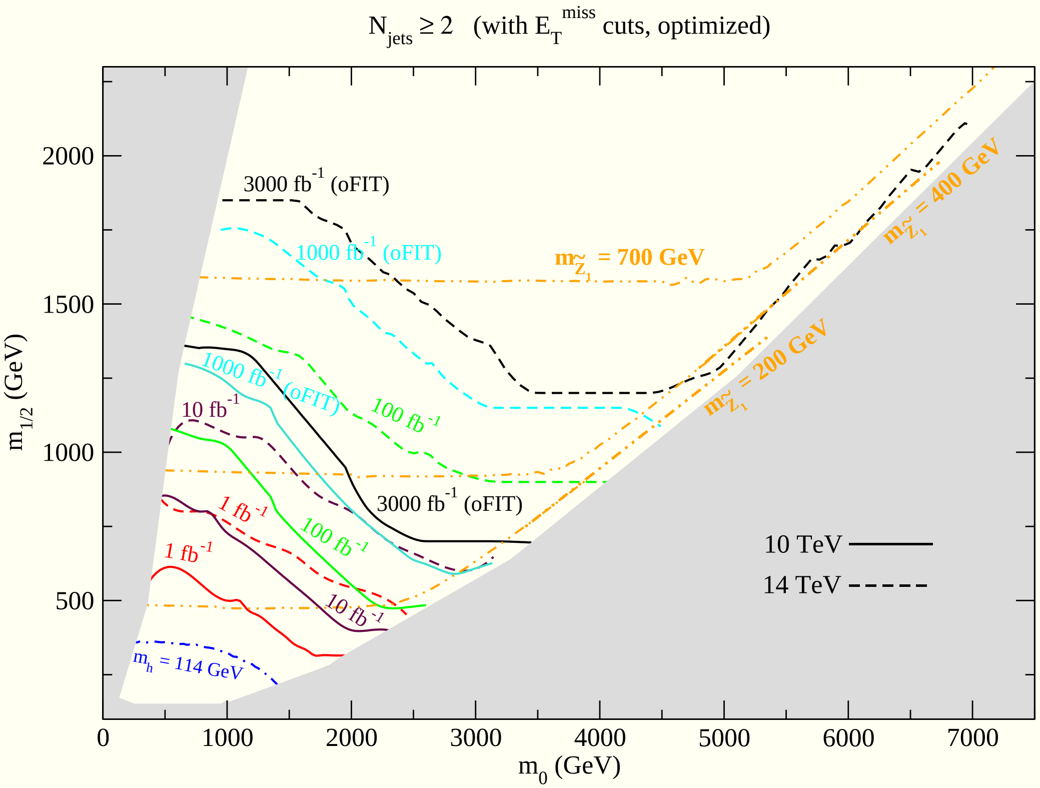
Sparticle reach of all colliders with relic density


mSugra with tanβ = 10, A_0 = 0, μ > 0


mSugra with tanβ = 45, A_0 = 0, μ < 0

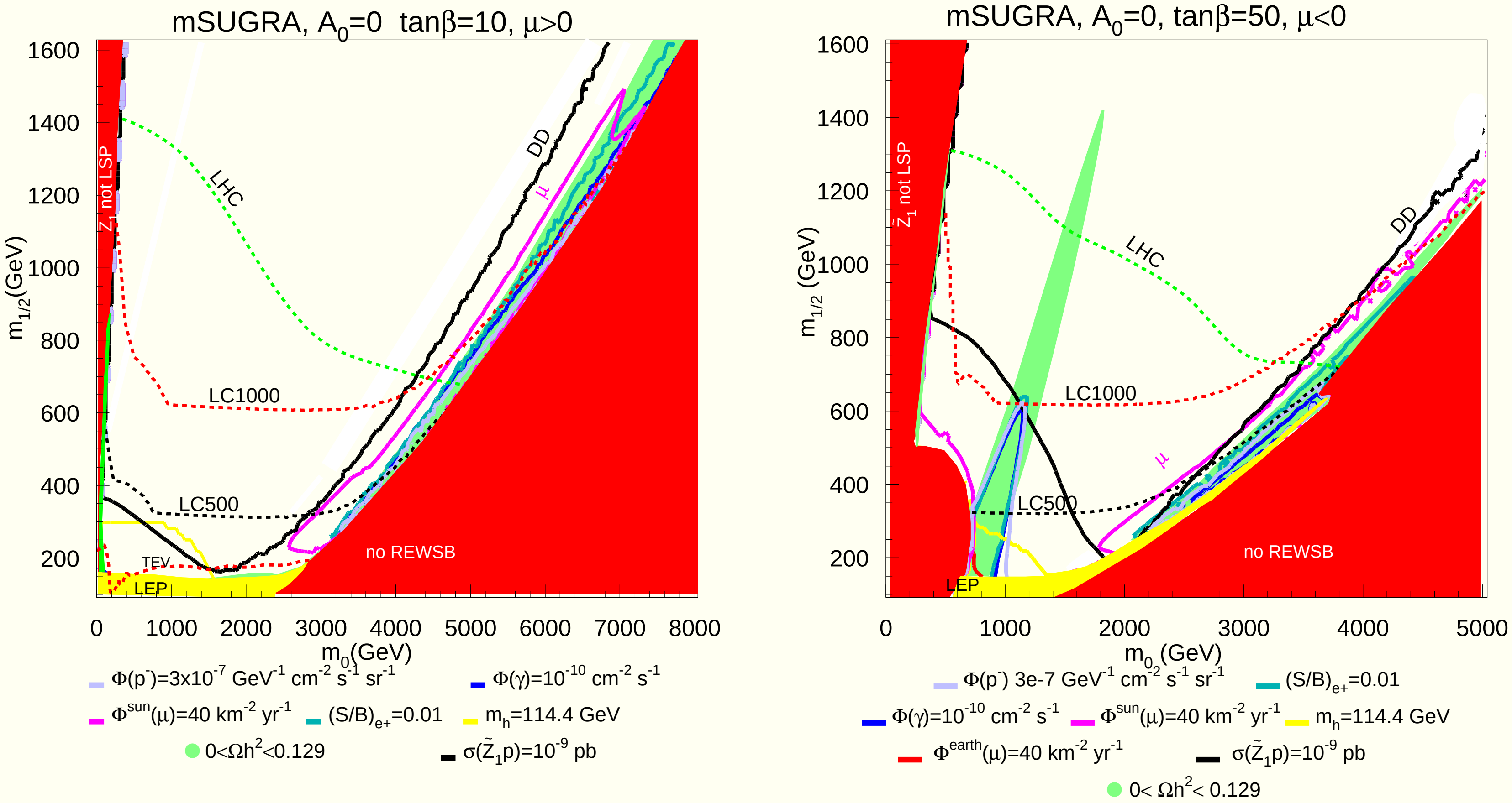
HB, Belyaev, Krupovnickas, Tata: JHEP 0402, 007 (2004)

Sparticle reach for various integrated luminosity



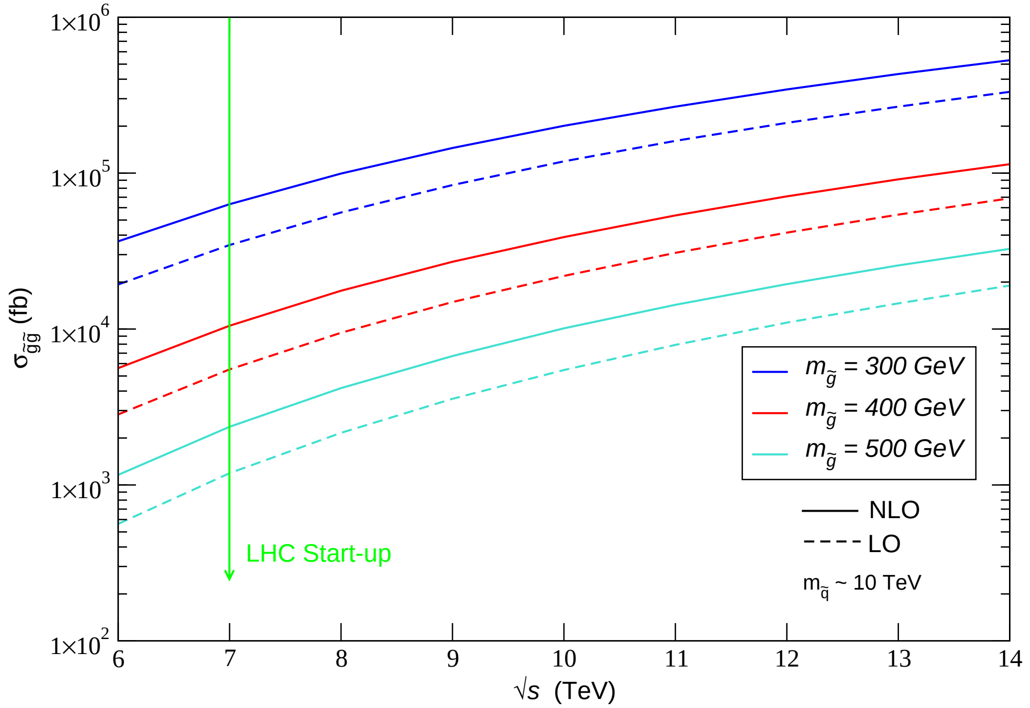
HB, Barger, Lessa, Tata (2009)

Direct and indirect detection of neutralino DM



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

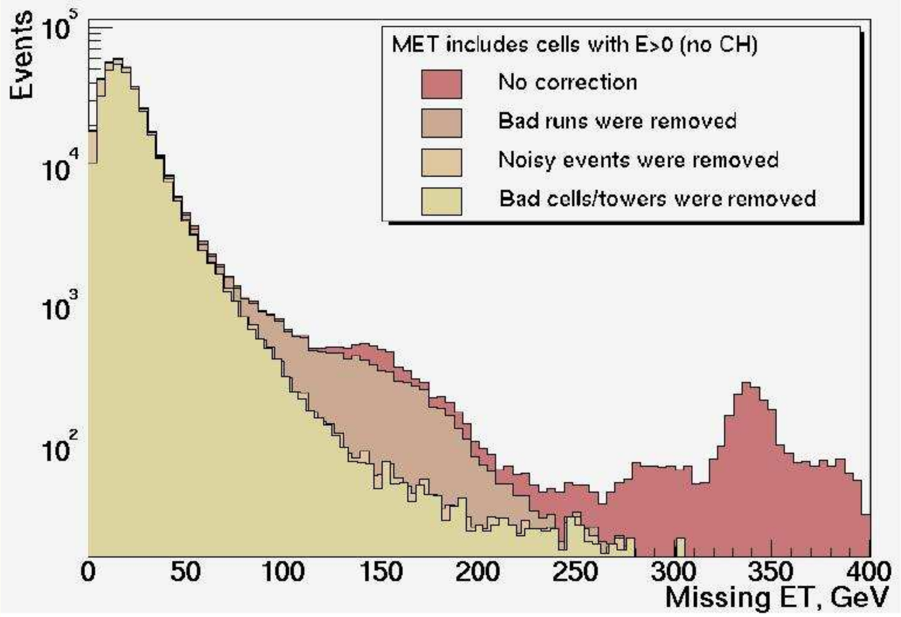
Issues in early search for SUSY: beam energy



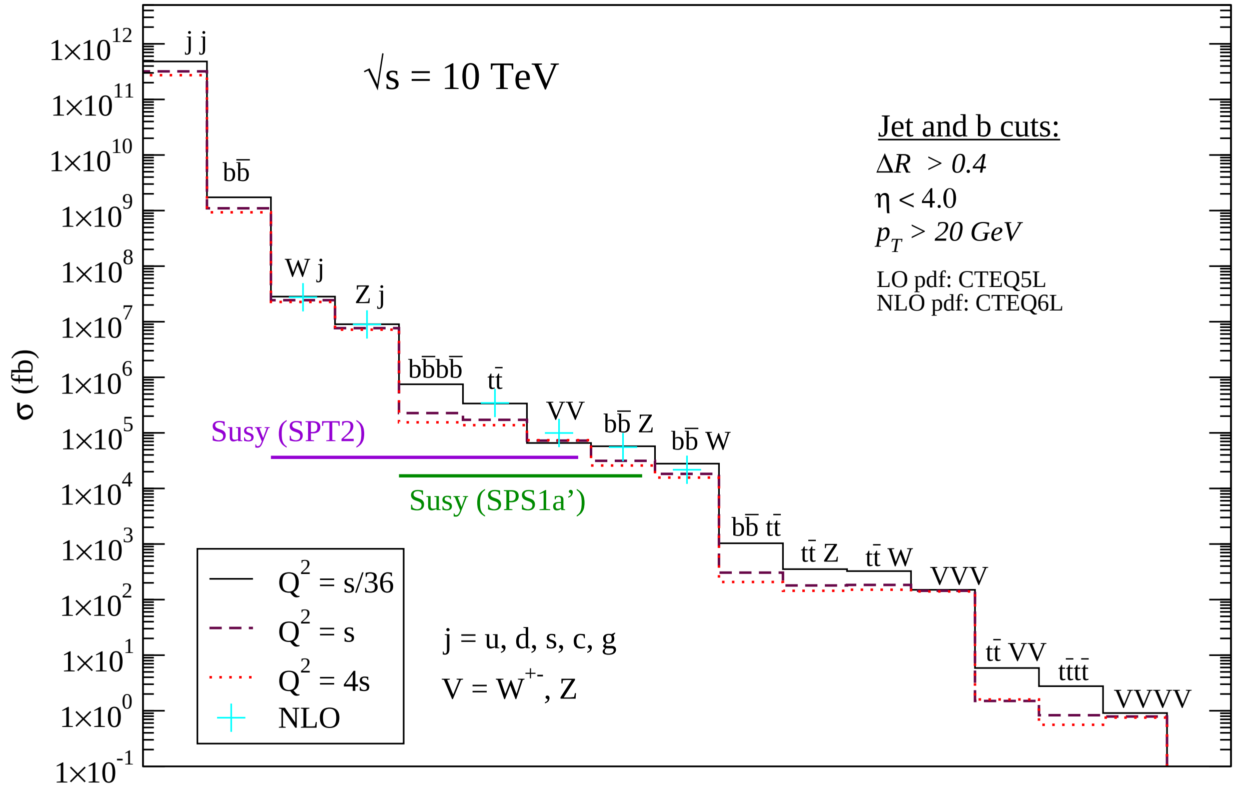
Early SUSY discovery at LHC with just 0.1 fb^{-1}?

- 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,....
- Use multiplicity of isolated muons rather than $\not\!\!E_T$
- HB, Prosper, Summy, PR**D77**, 055017 (2008); HB, Lessa, Summy, PL**B674**, 49 (2009)
- HB, Barger, Lessa, Tata, JHEP**0909**, 063 (2009)

D0 saga with missing E_T

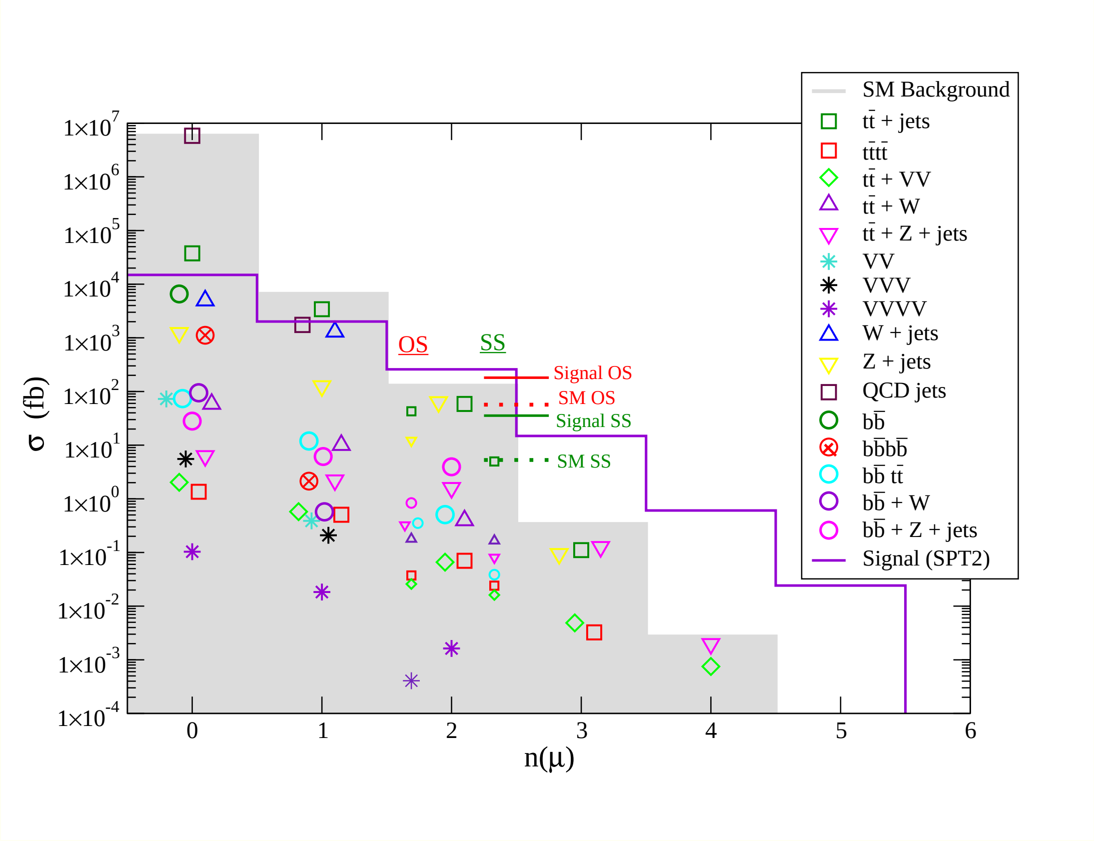


Possible SM sources of multi-muon events: $\sqrt{s} = 10$ TeV

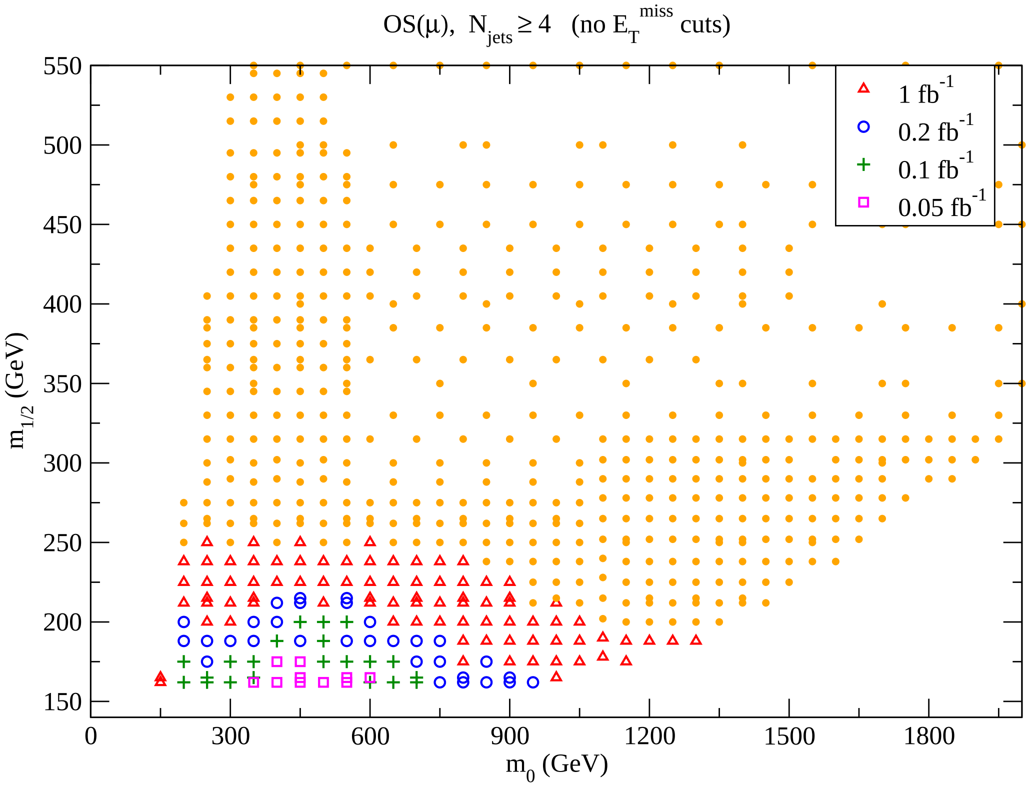


Simple cuts: ≥ 4 jets plus isolated muons: no $\not\!\!E_T$-cut

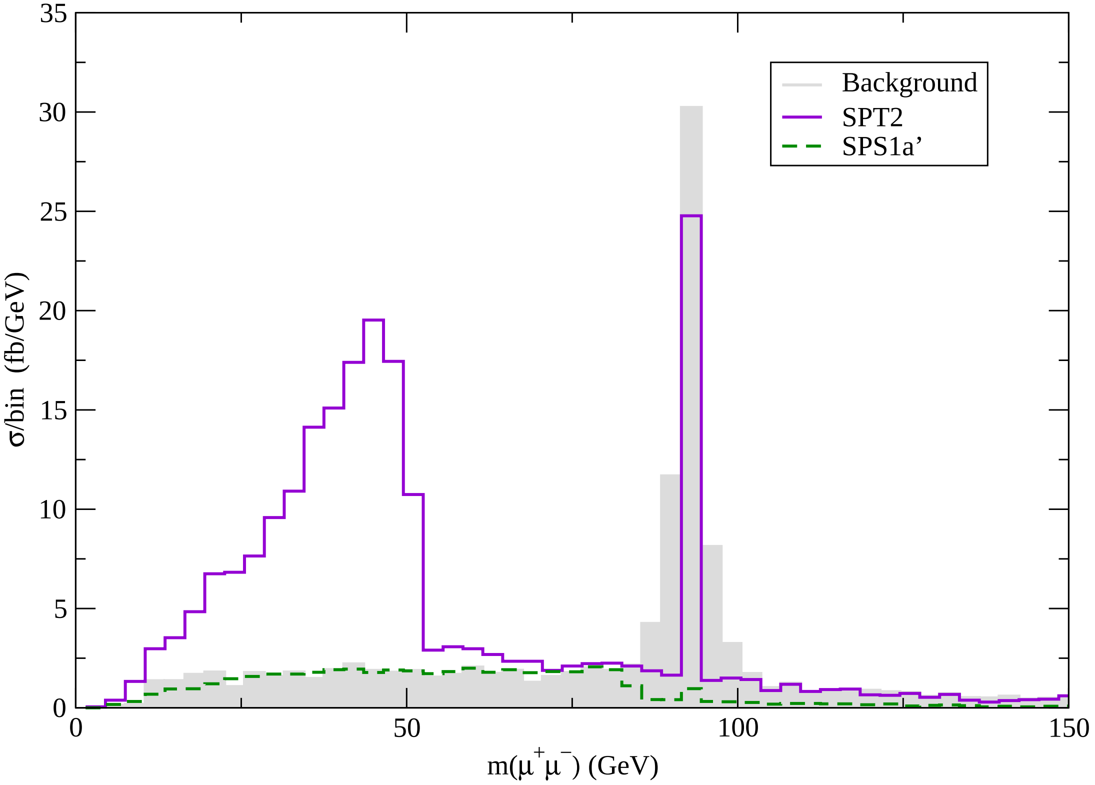
- SPT2 point: $(m_0, m_{1/2}, A_0, \tan\beta, sgn(\mu)) = (450\ \mathrm{GeV}, 170\ \mathrm{GeV}, 0, 45, +1)$
- note: dis-allowed by $\widetilde{Z}_1$ CDM but allowed for mixed $a/\tilde{a}$ CDM



Require $n(jets) \geq 4$ and $\mu^+\mu^-$ pair: no $\not\!\!E_T$

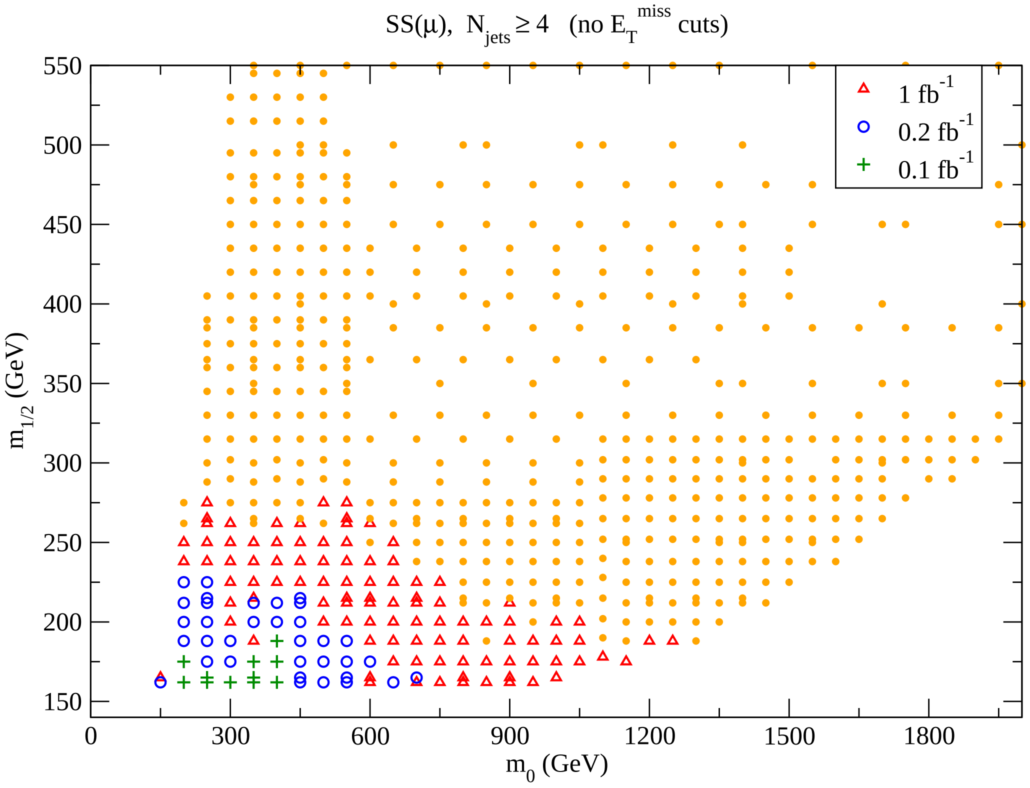


Case of isolated $\mu^+\mu^-$ events

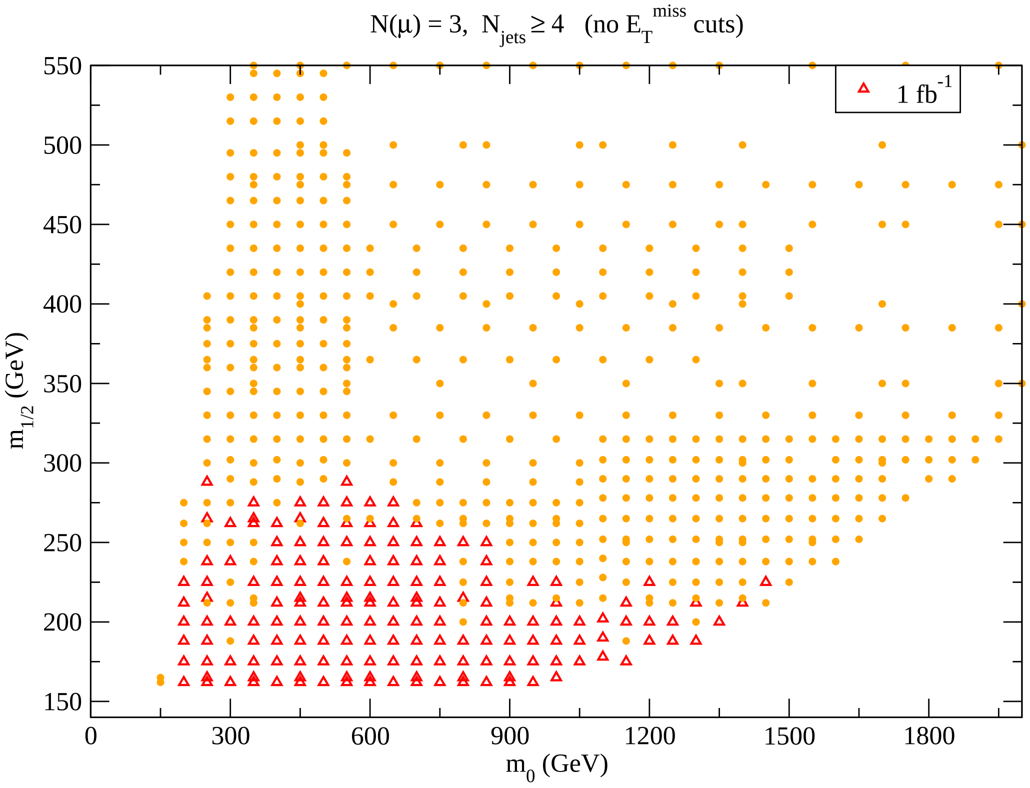


- mSUGRA $= (450, 170, 0, 45, +1)$

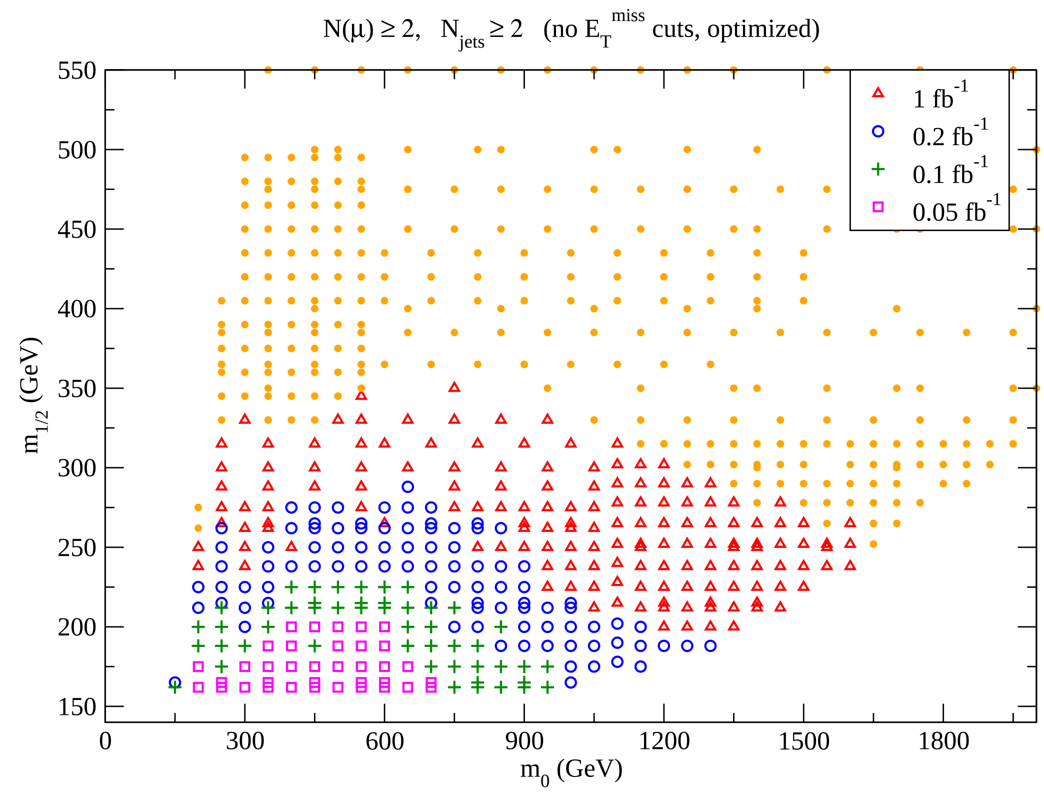
Require $n(jets) \geq 4$ **and** $\mu^{\pm}\mu^{\pm}$ **pair: no** $\not\!\!E_T$



Require $n(jets) \geq 4$ and 3μ: no $\not{E}_T$



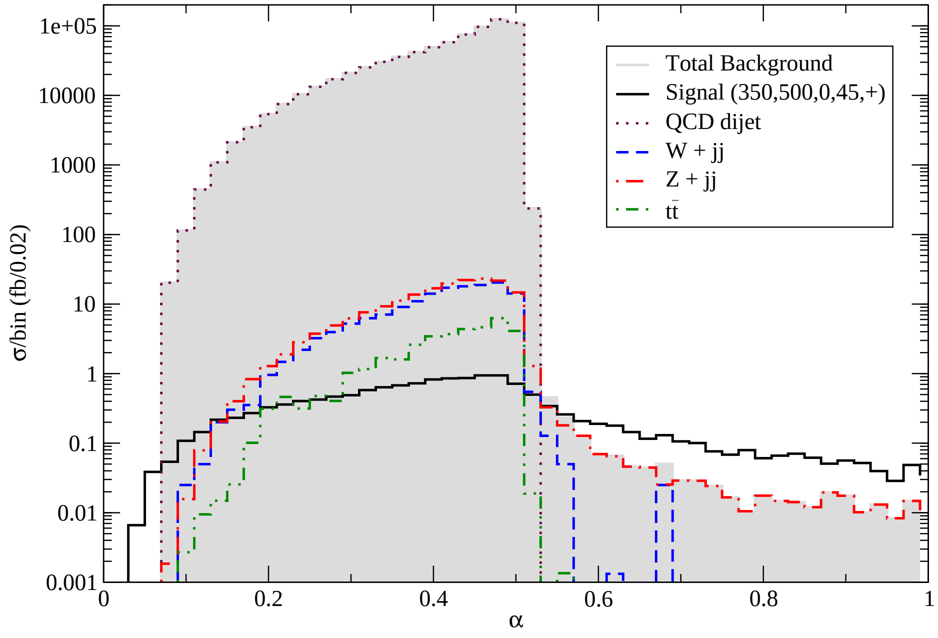
Cuts optimized with $n(jets) \geq 2$ and $n(\mu) \geq 2$: no $\not{E}_T$



Randall-Tucker-Smith dijet signal

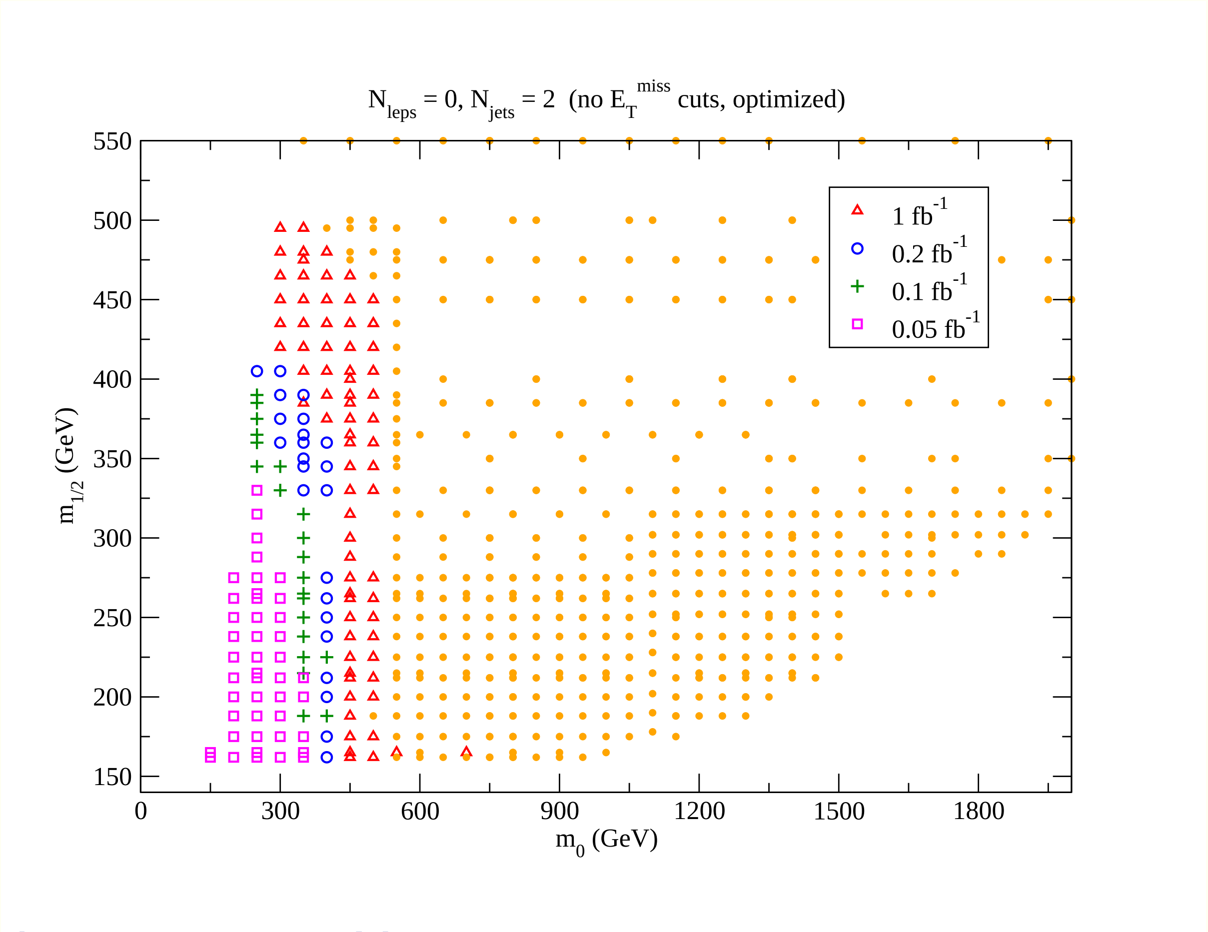
- ⋆ propose simplest thing: can we see SUSY in di-jet channel
- ⋆ knee-jerk reaction: no, QCD di-jet BG is too large
- ⋆ reality: SUSY di-jets from squark pair production: do not lie in one plane
- ⋆ L. Randall and Tucker-Smith exploit this: PRL**101** (2008) 221803
  - $\Delta\phi(j1,j2)$
  - $\alpha = E_T(j2)/m(jj)$
  - $MT2(jj+\not{E}_T)$ (though not needed)

Randall-Tucker-Smith dijet signal



- $(m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu) = 350, 500, 0, 45, +1)$ at $\sqrt{s} = 10$ TeV
- We require that $E_T(j_1) + E_T(j_2) > 700$ GeV, but make no restriction on $\not{E}_T$.

Cuts optimized for Randall-Tucker-Smith dijet signal



- HB, Barger, Lessa, Tata, arXiv:0907.1922

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

Conclusions

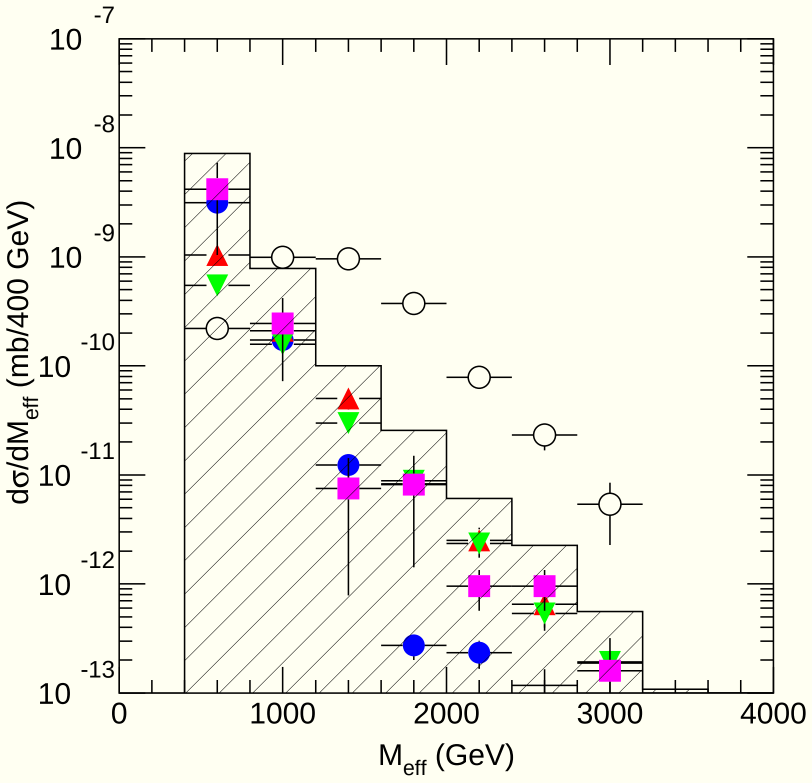
- ⋆ mSUGRA: right or wrong?
- ⋆ LHC slepton pair reach to $m_{\tilde{\ell}} \sim 350$ GeV
- ⋆ LHC clean trilepton from $\widetilde{W}_1\widetilde{Z}_2$ production (no spoiler modes)
- ⋆ LHC reach via cascade decay to multi-leptons
  - reach at $\sqrt{s} = 10$ TeV vs. $\sqrt{s} = 14$ TeV
  - early reach via OS, SS, 3μ or jj events *without* need for $\not{E}_T$ cut
- ⋆ Precision measurements possible for LHC

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}

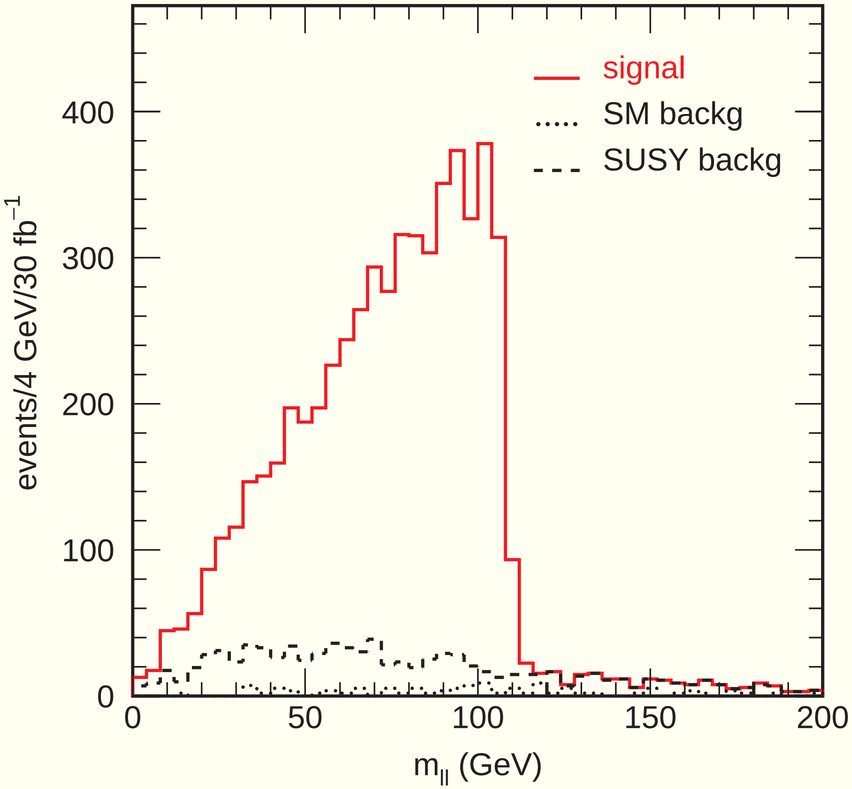


Atlas TDR (F. Paige)

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

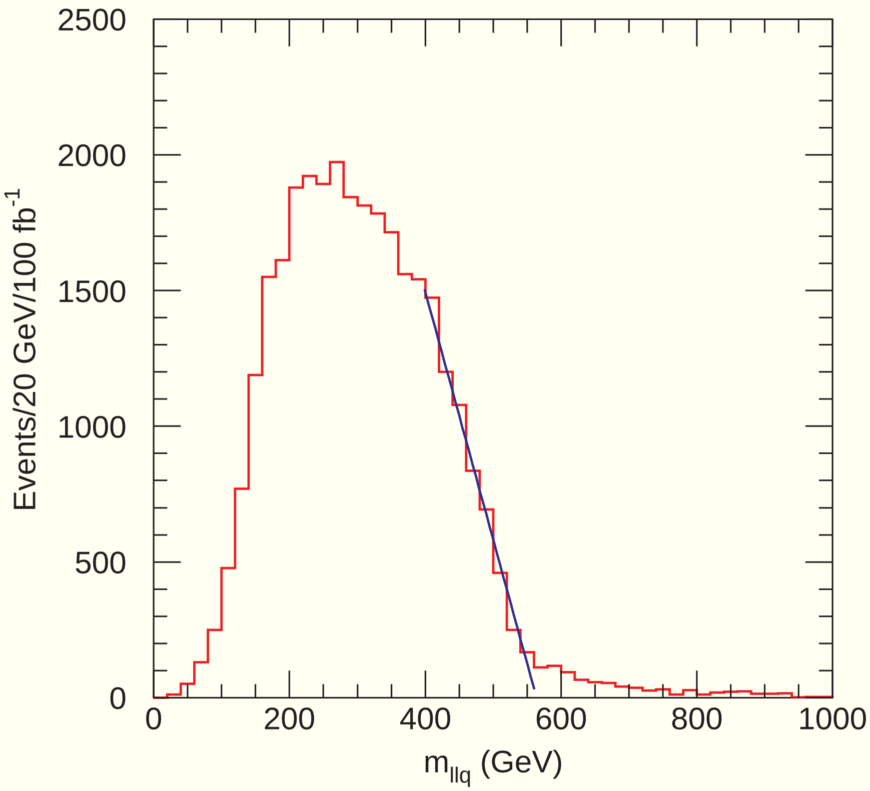
- kinematically, $m(\ell^+\ell^-) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$
- for $\widetilde{Z}_2 \to \tilde{\ell}^+\ell^- \to (\ell^+\widetilde{Z}_1)\ell^-$, have

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



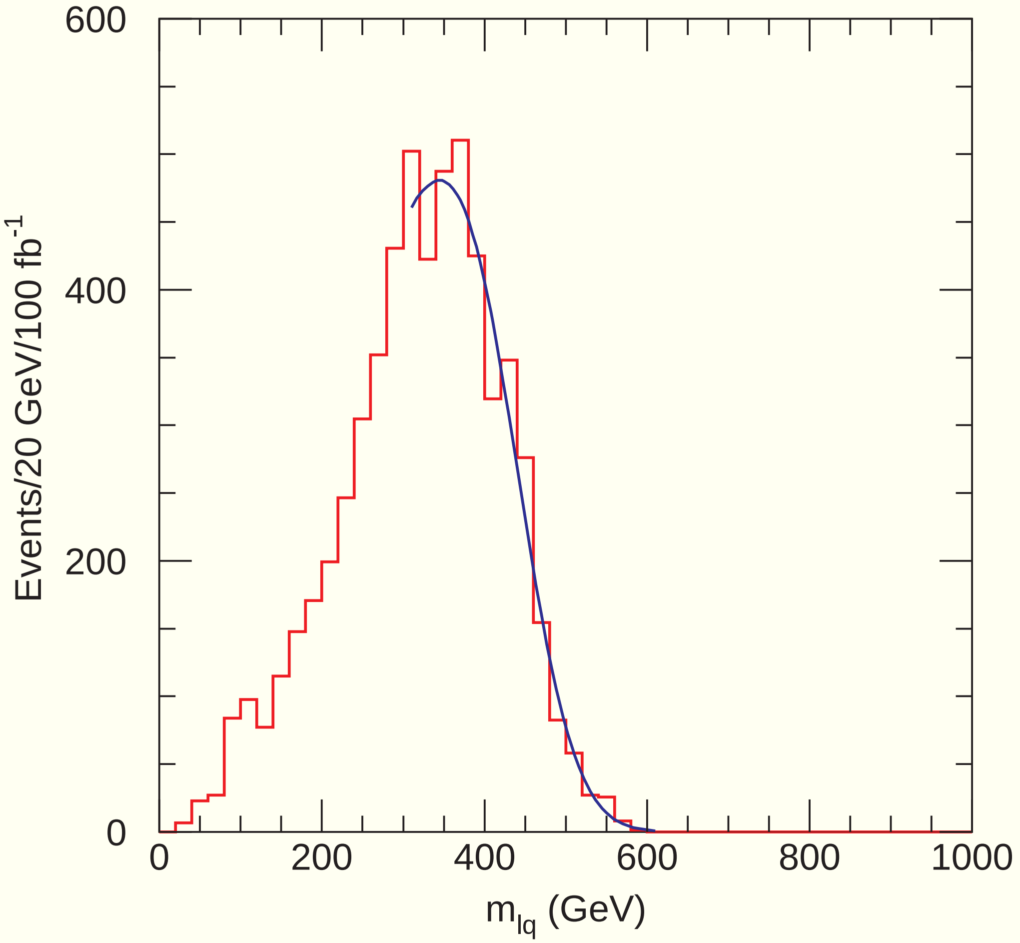
$m(\ell^+\ell^- q)$ **mass edge from** $\tilde{q} \to q\widetilde{Z}_2$

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



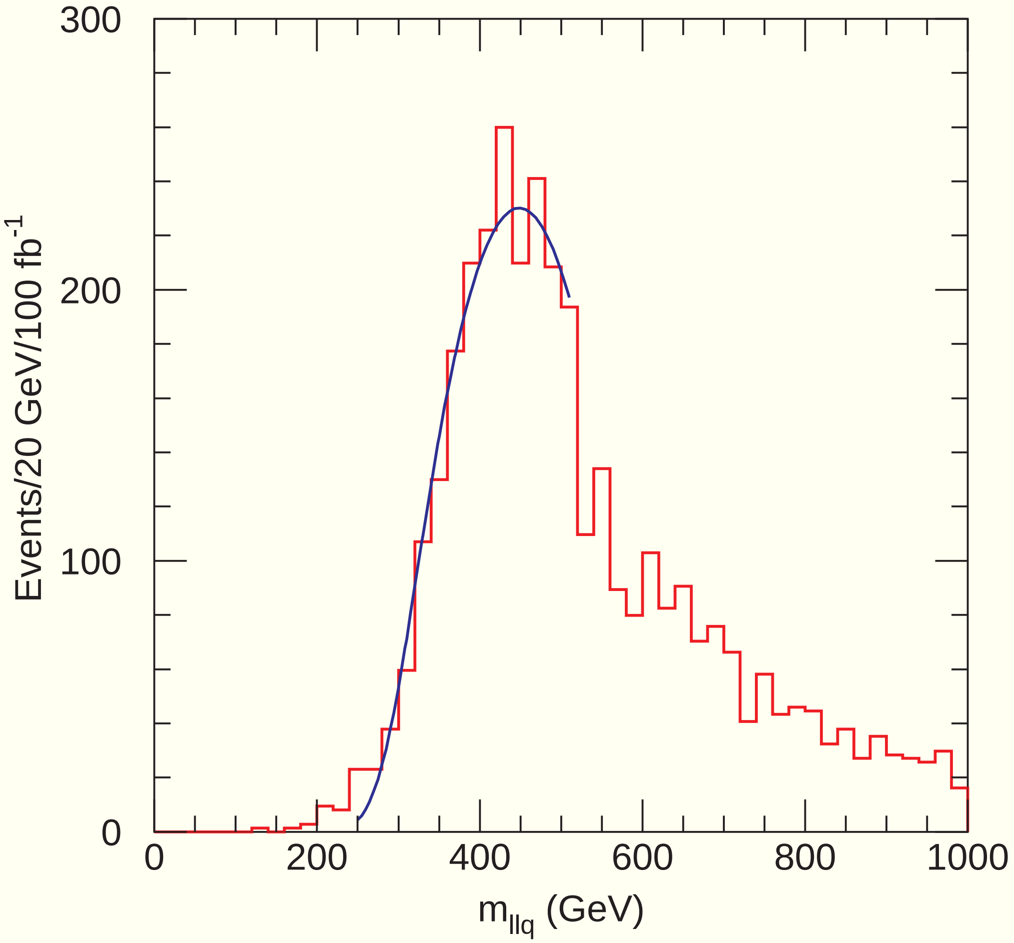
Atlas TDR (F. Paige)

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



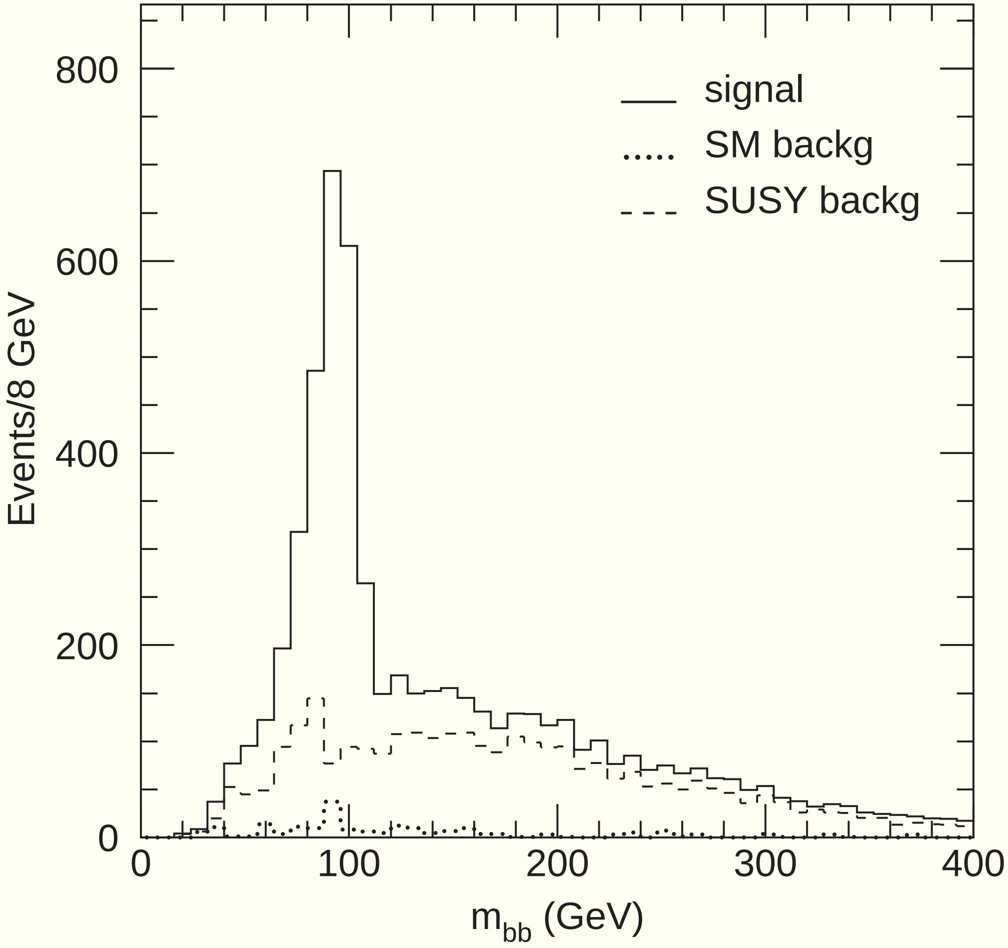
Atlas TDR (F. Paige)

$m(\ell q)$ 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)