# Beyond the Standard Model at LHC

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LHC is $pp$ collider with $E = 7 + 7\,\text{TeV}$, $L = 10^{33} – 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ scheduled to start in 2007 at CERN. Two main detectors, ATLAS and CMS, will probe physics at TeV mass scale.

Goals include searching for Higgs bosons and for other physics Beyond the Standard Model (BSM). Will concentrate on BSM topics motivated by electroweak symmetry breaking:

- SUSY

- "Little Higgs" models

- Extra space-time dimensions

Nothing on extra gauge bosons, other exotic states, or $B$ physics.

Shorter version of lectures at Corfu Summer School, September 2005.

Caveat: Talk is limited to work by ATLAS and CMS. Main emphasis is on results from analyses based on complete generation / simulation / reconstruction chain:

1. Generation of signal using pQCD cross sections linked (typically) to parton shower Monte Carlo generators;

2. Simulation of detector response based on GEANT;

3. Reconstruction of simulated events;

4. Analysis and comparison with Standard Model background.

But some fast simulation included.

Caveat: Am an ATLAS collaborator, so have easier access to ATLAS material. Do not want to use CMS results not officially blessed. Hence talk has ATLAS bias.

# SUSY

SUSY at TeV mass scale is perhaps most attractive extension of Standard Model. Provides naturally light Higgs, grand unification, and cold dark matter.
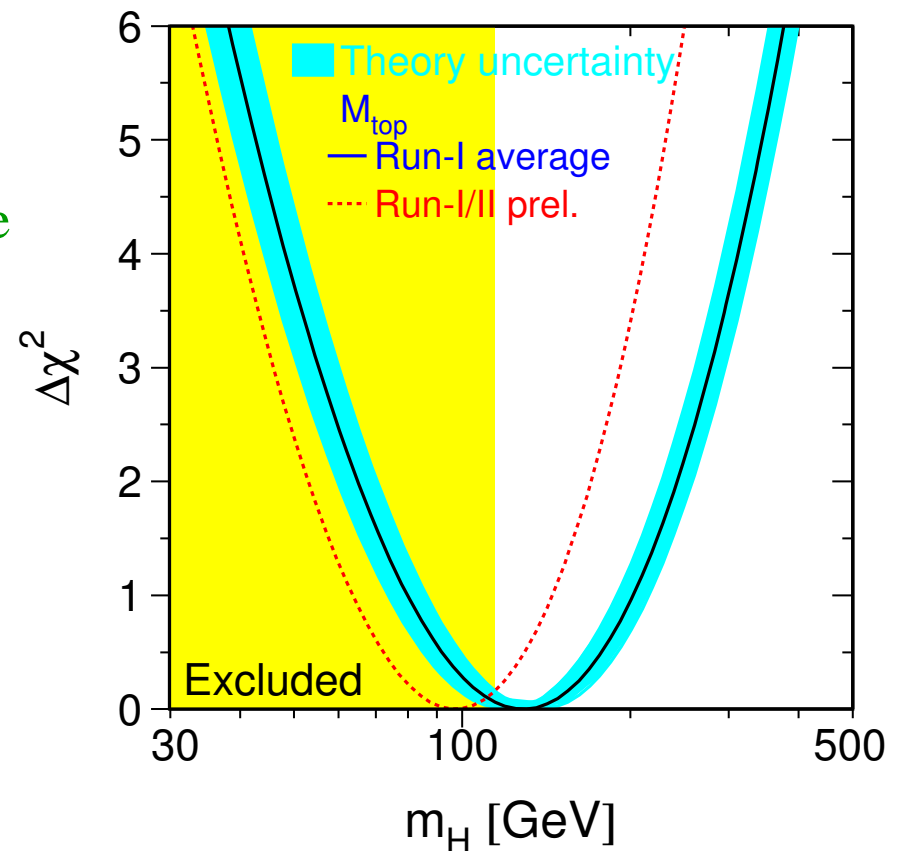
LEP/Tevatron data suggests light Higgs, $M_h \gtrsim 100\,\text{GeV}$. [LEPEW]

Radiative corrections in SUSY are

$$\Delta M_h^2 \sim g^2 M_{\text{SUSY}}^2 \sim M_h^2$$

In Standard Model

$$\Delta M_h^2 \sim g^2 M_{\text{Planck}}^2 \gg M_h^2$$

Hard to make this quantitative. Finding 1 TeV gluinos and squarks at LHC is easy; finding 3 TeV ones is much harder.
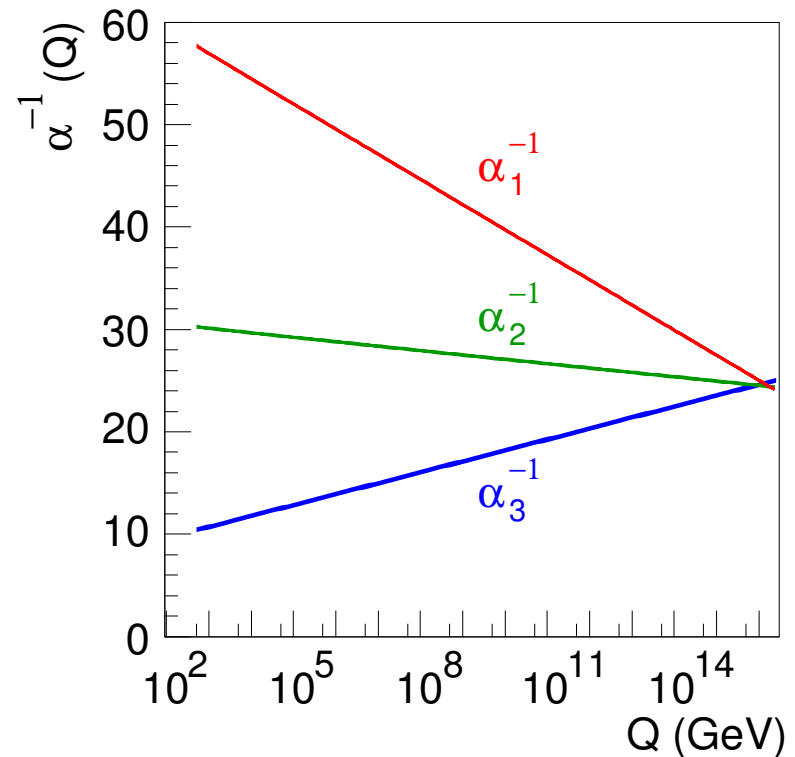
Similar argument applied to (apparent) cosmological constant would give $M_{SUSY} \sim 10^{-3}$ eV, clearly wrong.

Couplings measured at $Z$ scale unify with SUSY RGE's but not with Standard Model ones.

Unification of three lines likely with new parameter. But find

$$M_{SUSY} \sim 1 \text{ TeV}$$

consistent with naturalness, and $M_{GUT}$ more consistent with proton decay limits.

Accidental symmetries prevent proton decay in Standard Model but not in SUSY. Impose *R*-parity, where

$$
\begin{aligned}
R &\equiv (-1)^{3B-3L+2S} \\
&= +1 \quad \text{(all SM particles)} \\
&= -1 \quad \text{(all SUSY particles)}
\end{aligned}
$$

Implies SUSY particles always produced in pairs and decay to stable Lightest SUSY Particle (LSP), usually $\tilde{\chi}_1^0$. Must be neutral and weakly interacting, so escapes detector.

Conservation of just *B* or *L* rather than *R* possible.

WMAP results indicate cold dark matter:

$$
\Omega_b = 0.044 \pm 0.004, \quad \Omega_m = 0.27 \pm 0.04, \quad \Omega_\Lambda = 0.73 \pm 0.04
$$

LSP is good candidate: naturally gives about right $\Omega_m h^2$.

# Minimal Supersymmetric Standard Model

For each Standard Model particle $X$, MSSM has partner $\tilde{X}$ with $\Delta J = \pm \frac{1}{2}$:

$$\text{Each massless gauge boson} \quad \Leftrightarrow \quad \text{Massless gaugino}$$

$$\text{Each chiral fermion} \quad \Leftrightarrow \quad \text{Massless sfermion}$$

Also two Higgs doublets and corresponding $J = \frac{1}{2}$ Higgsinos.

$J = \frac{1}{2}$ gauginos and Higgsinos mix to give four neutralinos $\tilde{\chi}_i^0$ and two charginos $\tilde{\chi}_i^{\pm}$. LSP is lightest neutralino $\tilde{\chi}_1^0$.

$\tilde{f}_L$ and $\tilde{f}_R$ sfermions mix $\propto m_f$, so important only for third generation. Can have mixing among generations $\Rightarrow$ possible FCNC.

SUSY must be broken. Since all gauginos and sfermions have $SU(2) \times U(1)$ gauge invariant mass terms, can break SUSY by hand.

But then have 105 new mass and other soft parameters. Random choices give unobserved flavor and $CP$ violation at 1-loop level, e.g., to $\Delta M(K_L, K_S)$ or $B(\mu \to e\gamma)$.

Would like to break SUSY dynamically. Not possible just with MSSM; must communicate breaking in hidden sector via gravity or gauge interactions. Must avoid large flavor violation.

SUSY studies frequently use mSUGRA (or CMSSM) model. Uses simplest possible gravity-mediated breaking with just four parameters:

- Common scalar mass $m_0$ at GUT scale;

- Common gaugino mass $m_{1/2}$ at GUT scale;

- Common trilinear coupling parameter $A_0$ (not very important);

- Common ratio $\tan\beta$ of Higgs VEV's at weak scale.

Also $\text{sgn}\,\mu = \pm 1$ of Higgsino mass-squared.

Not generic prediction of gravity mediation. But does provide weak-scale spectrum consistent with low-energy constraints.

Must solve RGEs' to relate GUT and weak scale masses. Need iterative solution to handle thresholds from SUSY particles.

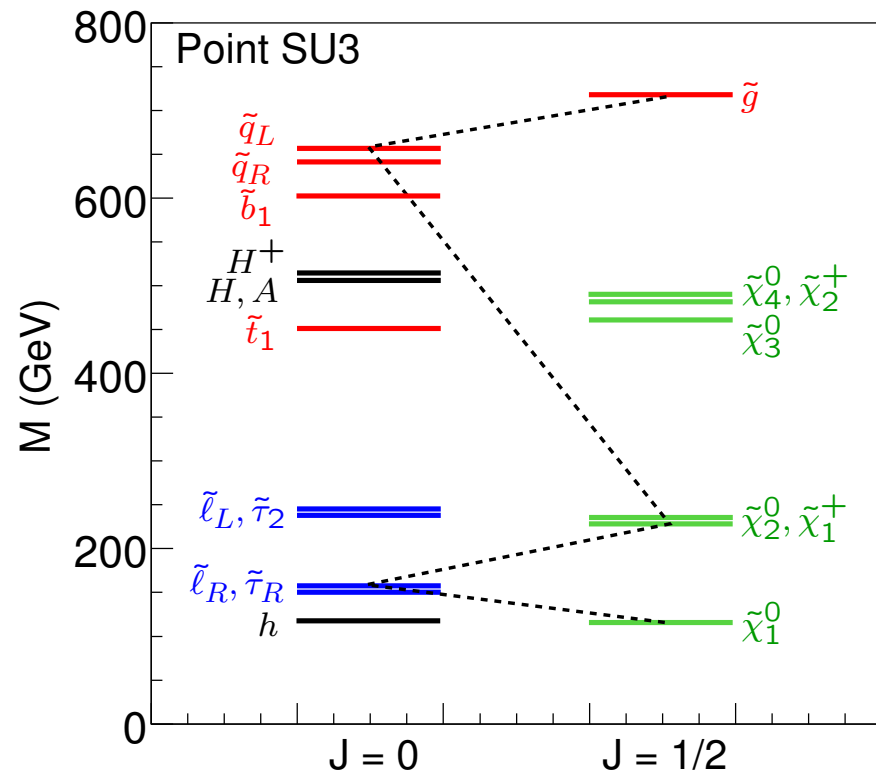Find complex spectrum at weak scale even for simple one at GUT scale.

Masses for mSUGRA with

$$m_0 = 100\,\text{GeV}, \quad m_{1/2} = 300\,\text{GeV}$$

Typically find in simple models

$$m_1 : m_2 : m_3 \approx \alpha_1 : \alpha_2 : \alpha_3$$

$$M(\tilde{\ell}) \sim m_0, \quad M(\tilde{q}) \gtrsim 0.9 M(\tilde{g})$$

But many patterns possible.



Point SU3

Generically expect $\tilde{g}$ and $\tilde{q}$ to be heavy, $\sim 1\,\text{TeV}$. In many cases, $\tilde{\chi}_3^0, \tilde{\chi}_4^0,$ $\tilde{\chi}_2^\pm, H, A,$ and $H^\pm$ also heavy. But model dependent.

While TeV-scale SUSY gives qualitatively right cold dark matter, detailed calculation $\Rightarrow$ need enhanced annihilation. Use mSUGRA as guide (qualitative picture — no mass scale) [bench]:

*Coannihilation:* Light $\tilde{\tau}_1$ in equilibrium with $\tilde{\chi}_1^0$, so annihilate via $\tilde{\chi}_1^0 \tilde{\tau}_1 \to \gamma\tau$.

*Bulk:* bino $\tilde{\chi}_1^0$; light $\tilde{\ell}_R$ enhances annihilation.

*Funnel:* $H,A$ poles enhance annihilation for $\tan\beta \gg 1$.

*Focus point:* Small $\mu^2$, so Higgsino $\tilde{\chi}_1^0$ annihilate. Heavy s-fermions, so small FCNC.
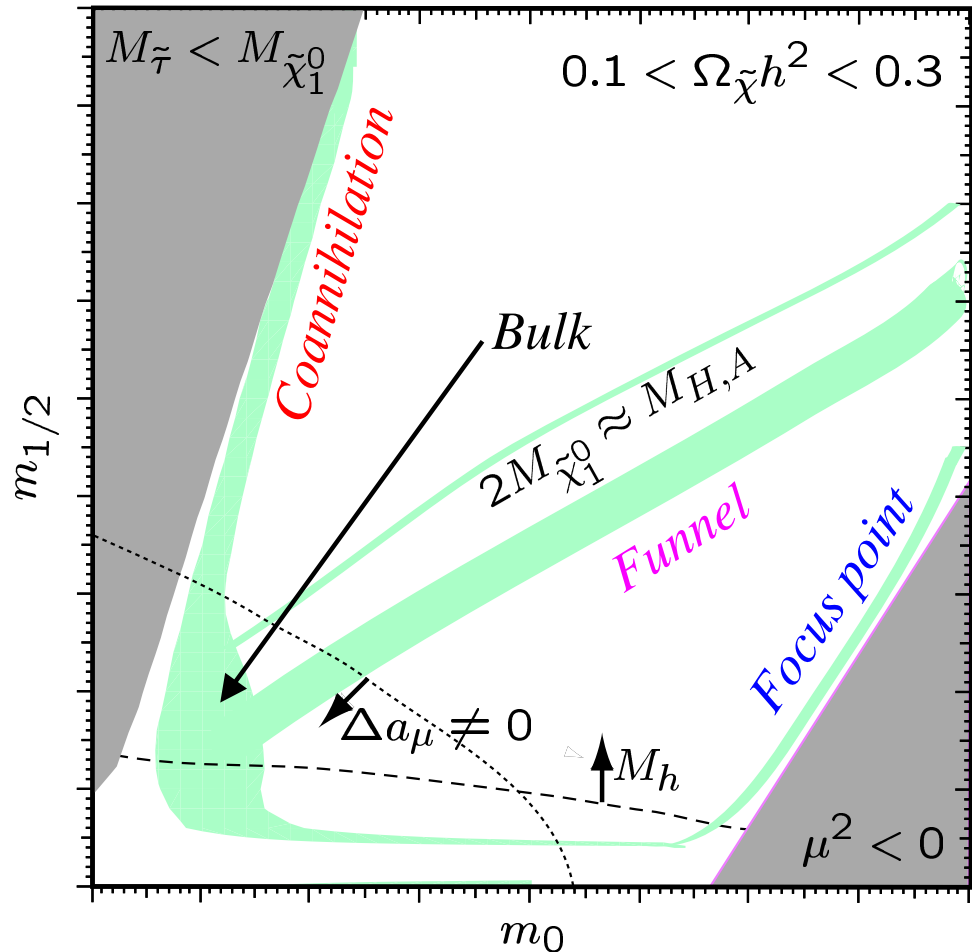
While mSUGRA consistent with WMAP is useful guide, no reason to think it is correct — even if SUSY with gravity-mediated breaking exists. Important to consider alternatives.

Want to explore all possible signatures. E.g., some SUSY models (GMSB, split SUSY) can give long-lived charged particles. Look like muons with $\beta < 1$.

Ultimate goal is to measure enough SUSY properties at weak scale to allow extrapolation of model to unification scale.

May be difficult at LHC: finding SUSY or other new physics at LHC would be strong argument for linear collider.

But should measure as much as possible at LHC.

# Inclusive SUSY Searches

"Typical" SUSY model has gluinos and squarks at $O\,(1\,\mathrm{TeV})$ decaying to $\tilde{\chi}_1^0$ at $O\,(100\,\mathrm{GeV})$.

Cross sections known to NLO; typically $\gtrsim 1\,\mathrm{pb}$ [Beenakker].

Generally decay to $\tilde{\chi}_1^0$ via several steps,

$$\tilde{g} \to \tilde{q}_L \bar{q} \to \tilde{\chi}_2^0 q \bar{q} \to \tilde{\ell}^{\pm} \ell^{\mp} q \bar{q} \to \tilde{\chi}_1^0 \ell^+ \ell^- q \bar{q}$$

Hence expect multiple jets plus large $E\!\!\!/_T$ from $\tilde{\chi}_1^0$. May also have leptons or $\tau$'s.
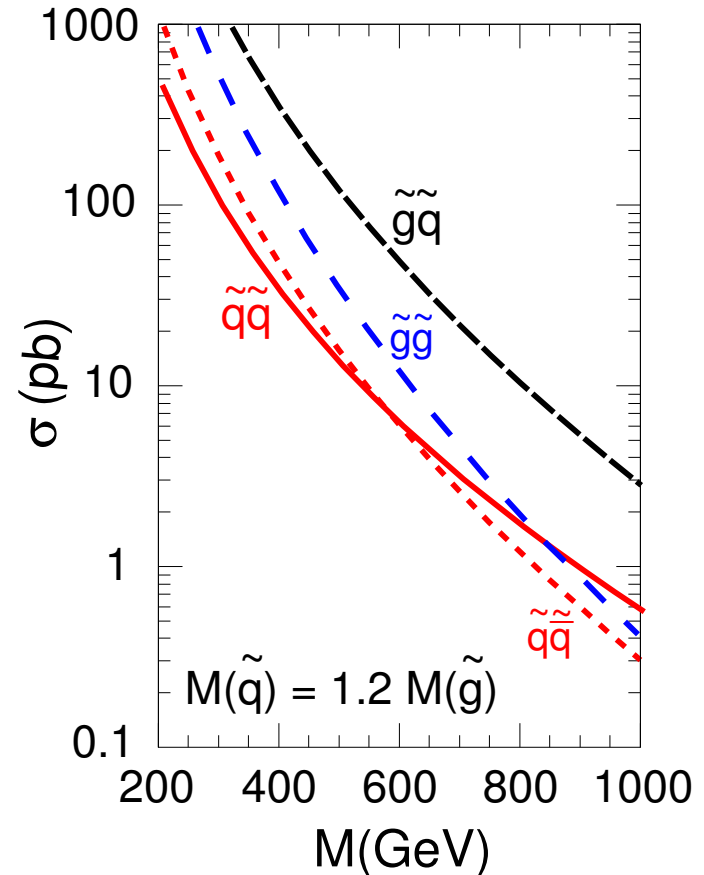
Standard Model backgrounds include $Z \to \nu\bar{\nu} + \mathrm{jets}$, $W + \mathrm{jets}$, $t\bar{t}$, $b$ jets with $b \to \nu X$, etc. Also backgrounds from mismeasured events.

Typical cuts: at least four jets with $p_T > 100, 50, 50, 50\,\text{GeV}$ and $\displaystyle{\not{E}_T} > 100\,\text{GeV}$. Then plot

$$M_{\text{eff}} \equiv {\not{E}_T} + \sum_j p_{T,j}$$

Scalar $p_T$ sum measures hardness of interaction better than invariant mass, which is sensitive to low-$p_T$ forward jets.
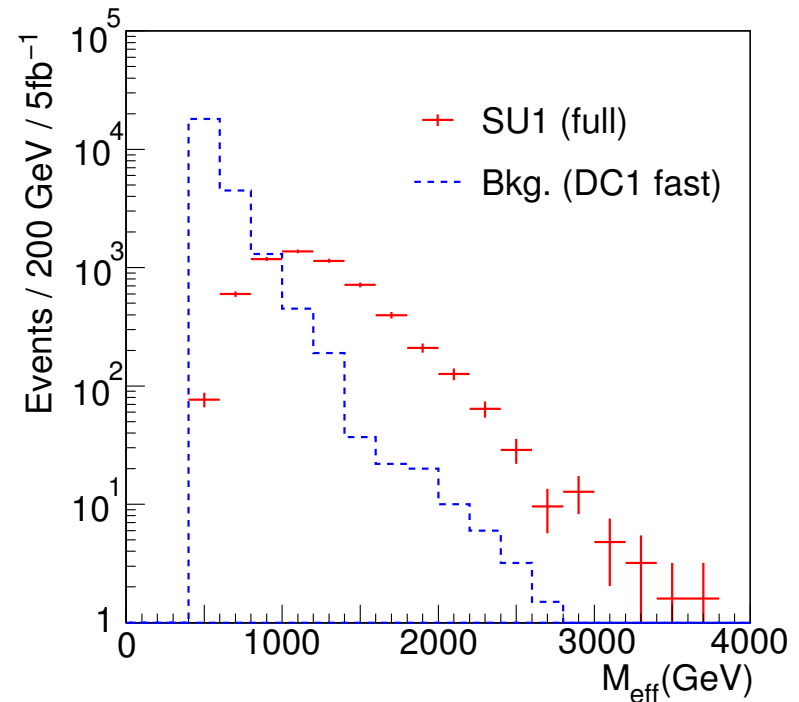
$M_{\text{eff}}$ distribution for mSUGRA with

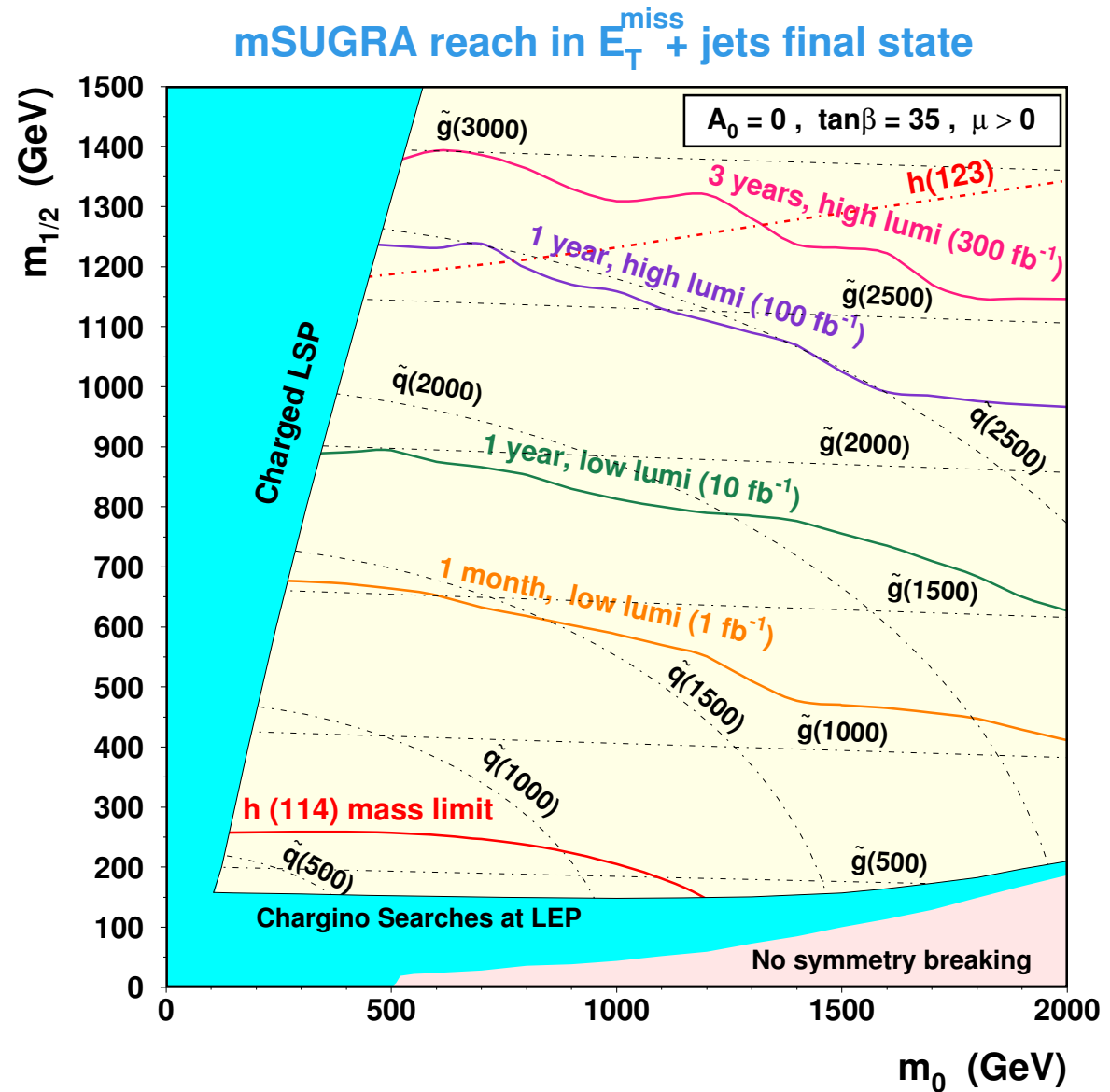$$m_0 = 70\,\text{GeV},\ m_{1/2} = 350\,\text{GeV},$$

$$\tan\beta = 10$$

and full reconstruction.

Standard Model backgrounds from parton shower Monte Carlo and fast simulation.

Note $S/B > 10$ for large $M_{\mathrm{eff}}$, so search limits depend mainly on signal, not on SM background.

mSUGRA search limits vs. luminosity shown based on parton showers and fast simulation [CMSSUSY].

**mSUGRA reach in $E_T^{miss}$ + jets final state**



$A_0 = 0$ , $\tan\beta = 35$ , $\mu > 0$

$\tilde{g}(3000)$

3 years, high lumi (300 fb$^{-1}$)

h(123)

1 year, high lumi (100 fb$^{-1}$)

$\tilde{g}(2500)$

Charged LSP

$\tilde{q}(2000)$

1 year, low lumi (10 fb$^{-1}$)

$\tilde{g}(2000)$

$\tilde{q}(2500)$

1 month, low lumi (1 fb$^{-1}$)

$\tilde{g}(1500)$

$\tilde{q}(1500)$

$\tilde{g}(1000)$

$\tilde{q}(1000)$

h (114) mass limit

$\tilde{q}(500)$

$\tilde{g}(500)$

Chargino Searches at LEP

No symmetry breaking

m$_{1/2}$ (GeV)

m$_0$ (GeV)

# Search limits in various lepton channels on same basis [CMSSUSY]:



mSUGRA reach in various final states for 100 fb$^{-1}$
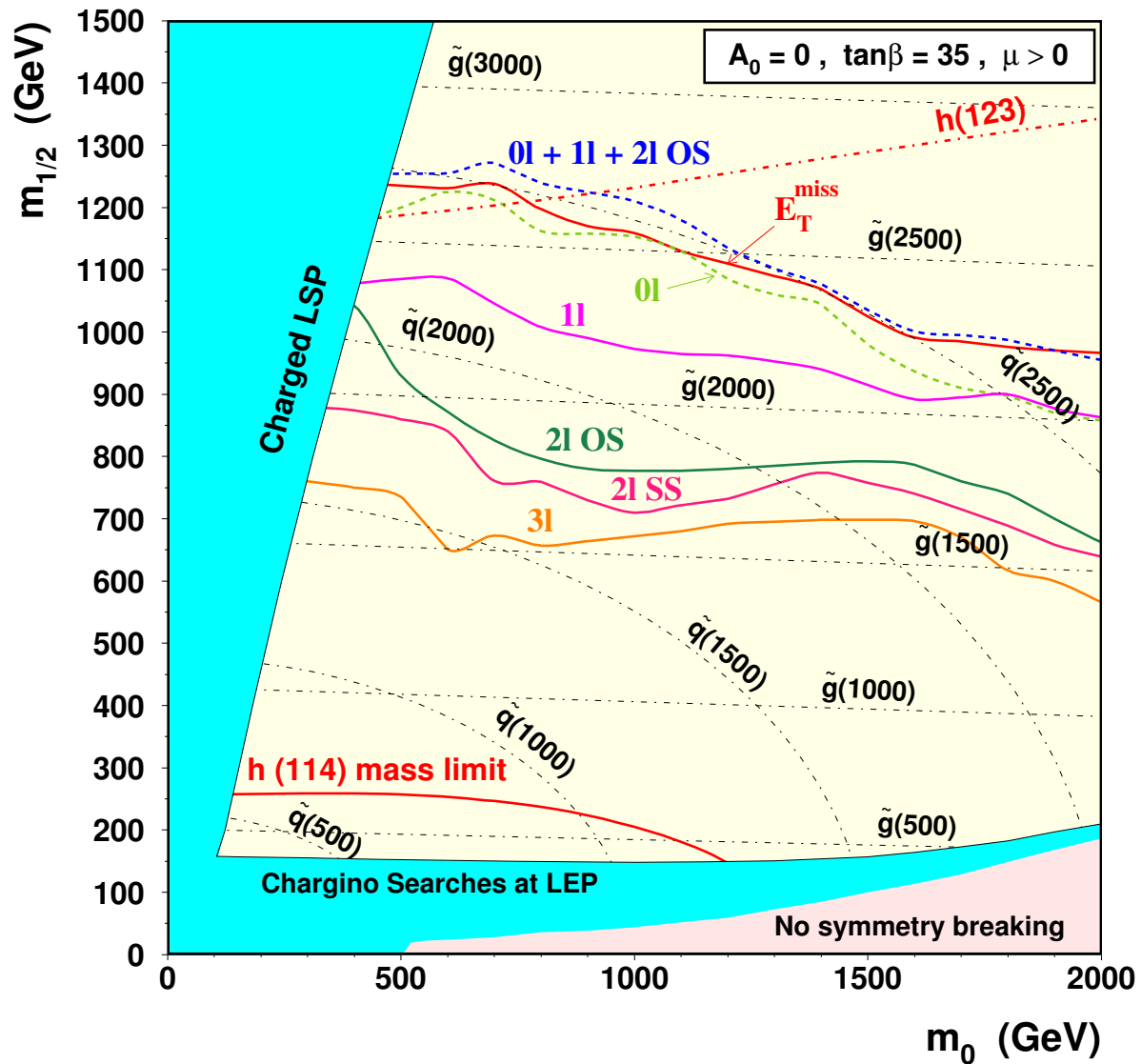
Search limits correspond to $> 5\sigma$ over Standard Model background. Limit for $1\,\mathrm{fb}^{-1}$ is $M(\tilde{q}) \lesssim 1.5\,\mathrm{TeV}$, $M(\tilde{g}) \lesssim 1.5\,\mathrm{TeV}$. Corresponds to one month at "initial" luminosity. But must understand detector and Standard Model processes first.

Ultimate reach is $\lesssim 2.5\,\mathrm{TeV}$. (Gaugino production might extend reach; should study this.)

Reach in inclusive, $0\ell$, and $1\ell$ channels is roughly comparable.

Gluino is self-conjugate Majorana fermion, so gluino pairs can give same-sign (SS) dileptons. Additional sources of opposite-sign dileptons, e.g., $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$.

Trileptons arise from leptonic decays of both gluinos or squarks or from more complex cascade decays.

Expect multiple signatures if SUSY exists at $O(1\,\mathrm{TeV})$ mass scale.

Standard Model backgrounds apparently underestimated in previous ATLAS/CMS inclusive search studies:

- Parton shower underestimates multi-jet backgrounds.

- Fast simulation underestimates resolution tails.

Parton shower algorithms based on singular parts of cross sections plus exact kinematics.

For massless quarks and gluons, QCD perturbation theory is singular. E.g., for collinear branching $q(p) \to q(p') + g(p - p')$ in collinear limit, $p^2 \to 0$, $z = p'/p$ fixed,

$$\sigma_{n+1} \approx \sigma_n \times \frac{\alpha_s(p^2)}{2\pi p^2} P_{qq}(z), \quad P_{qq}(z) = \frac{4}{3} \left( \frac{1 + z^2}{1 - z} \right)$$

Gives main QCD features, e.g., jets with (almost) fixed angular width.

But not reliable approximation for widely separated jets, $p^2 \not\to 0$ above.

ALPGEN generates $W + n$ jets and other processes using exact leading order matrix elements. Using it gives larger backgrounds for inclusive $M_{\text{eff}}$ distribution at large $M_{\text{eff}}$ [Asai]:
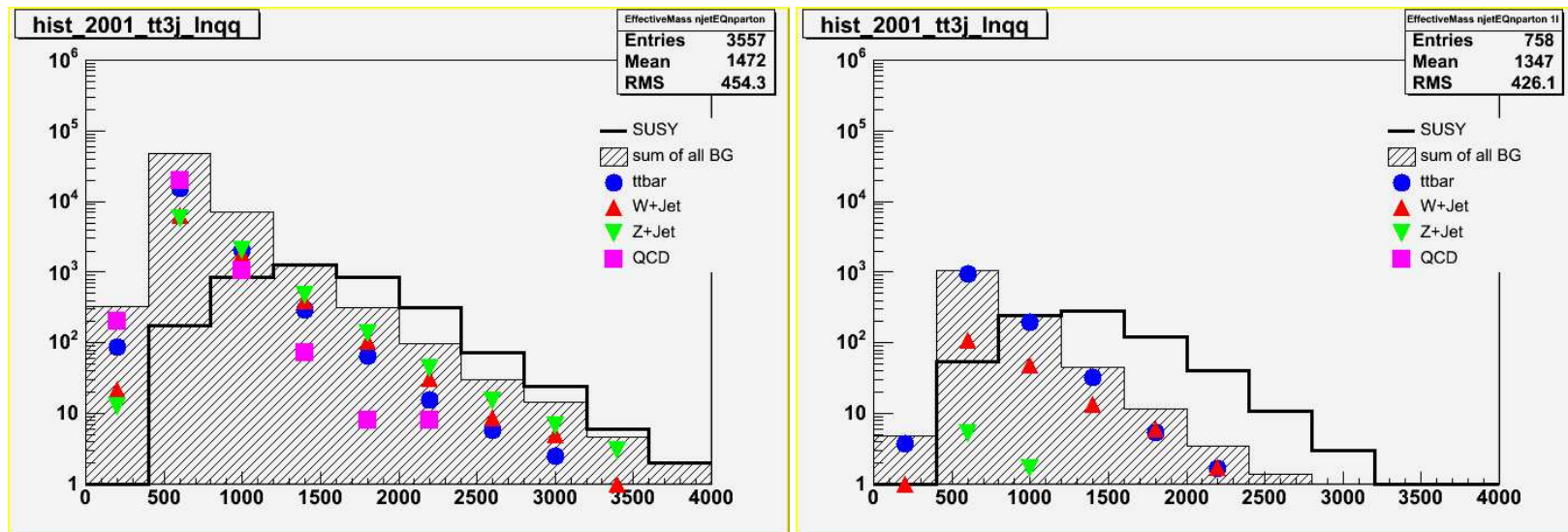


Much smaller effect on $M_{\text{eff}}$ with lepton (right). Dominated by $t\bar{t}$, so much less sensitive to high-order QCD.

Should probably avoid search based only on jets $+ \not{E}_T$.

Fast simulation typically assumes Gaussian resolution, but real detector has non-Gaussian resolution tails. Current ATLAS result for SUSY (SU1), QCD jet background (dash), and $t\bar{t}$ background (dot) with/without cut $\Delta\phi(E\!\!\!/_T, j_0) < 0.9\pi$:
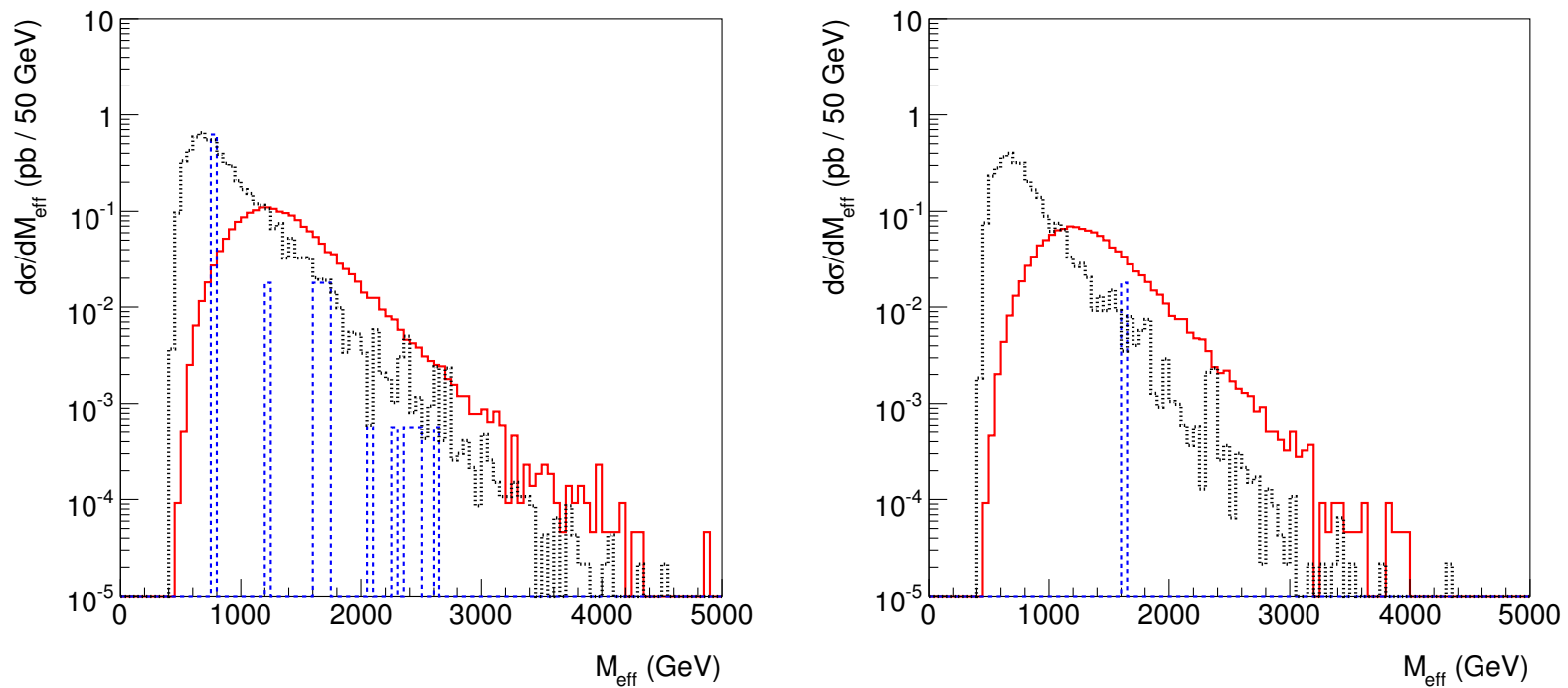


Work in progress — *not* indicator of ultimate ATLAS performance. But shows need to study $E\!\!\!/_T$ and similar resolution tails.

# Leptonic Endpoint Measurements

In mSUGRA and most SUSY models, all SUSY particles decay to invisible $\tilde{\chi}_1^0 \Rightarrow$ no mass peaks. Can often identify specific decays, use kinematic endpoints to measure mass combinations [Hinchcliffe,TDR].

Backgrounds dominated by other SUSY processes. Must choose SUSY model points and generate all processes consistently.

Very unlikely that any such point is real. Goal is to develop analysis techniques and reconstruction for complex events.

Simplest (trivial) endpoint example: for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$,

$$M(\ell^+\ell^-) \le M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)\,.$$

For $\tilde{\chi}_2^0 \to \tilde{\ell}^\pm \ell^\mp \to \tilde{\chi}_1^0 \ell^+ \ell^-$ find triangular mass distribution with

$$M(\ell^+\ell^-) \le \sqrt{\frac{\left(M^2(\tilde{\chi}_2^0) - M^2(\tilde{\ell})\right)\left(M^2(\tilde{\ell}) - M^2(\tilde{\chi}_1^0)\right)}{M^2(\tilde{\ell})}}\,.$$

Must avoid $e$ and $\mu$ flavor violation in $\tilde{\chi}_2^0$ decays to avoid $\mu \to e\gamma$ at 1-loop level. (Problem for SUSY model building.) Hence expect $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 e^+ e^-$ and $\tilde{\chi}_1^0 \mu^+ \mu^-$ with equal rates but no $\tilde{\chi}_1^0 e^{\pm} \mu^{\mp}$.

Backgrounds from two independent decays, either Standard Model (e.g., $t\bar{t}$) or SUSY (e.g., $\tilde{\chi}_1^+ \tilde{\chi}_1^-$) produce $e^+ e^-$, $\mu^+ \mu^-$, and $e^{\pm} \mu^{\mp}$ equally. Hence flavor subtraction

$$e^+ e^- + \mu^+ \mu^- - e^{\pm} \mu^{\mp}$$

cancels backgrounds up to statistics and acceptance differences.

ATLAS and CMS have comparable acceptance for $e$ and $\mu$. Details are different: cracks in EM calorimeter vs. gaps in muon chambers.

Point SU3 is mSUGRA model in "bulk" region:

$$m_0 = 100\,\text{GeV}, \; m_{1/2} = 300\,\text{GeV}, \; A_0 = -300\,\text{GeV}, \; \tan\beta = 10, \; \mu > 0.$$

DC1 full simulation result for $e^+ e^- + \mu^+ \mu^- - e^{\pm} \mu^{\mp}$ for $5\,\text{fb}^{-1}$ [DC1]:
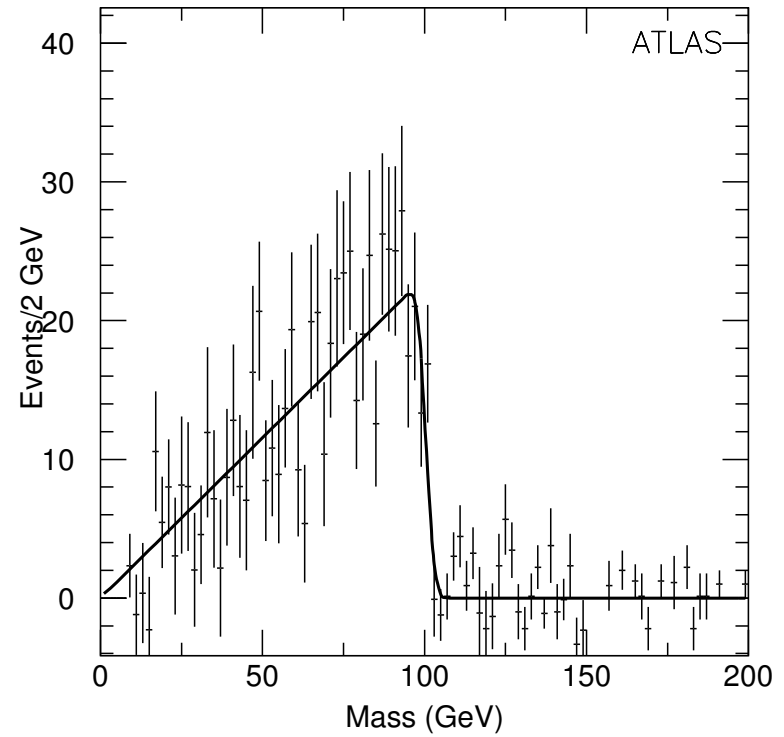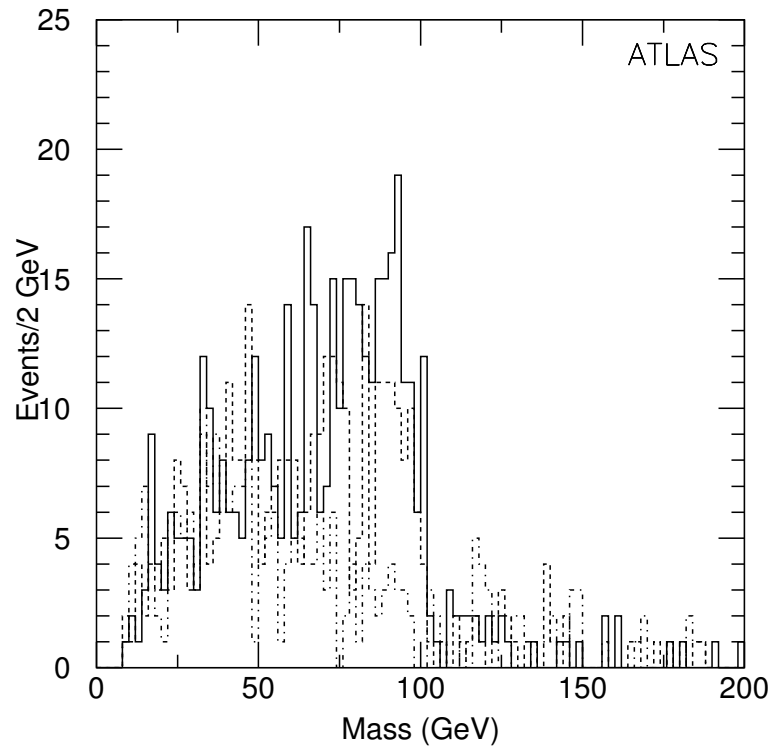
Fitted endpoint is $100.25 \pm 1.14\,\text{GeV}$; c.f. expected $100.31\,\text{GeV}$. Similar results at Rome [Aracena, Ozturk].

Dilepton endpoints observable over wide range of mSUGRA parameter
space scanned with fast simulation [CMSSUSY]:
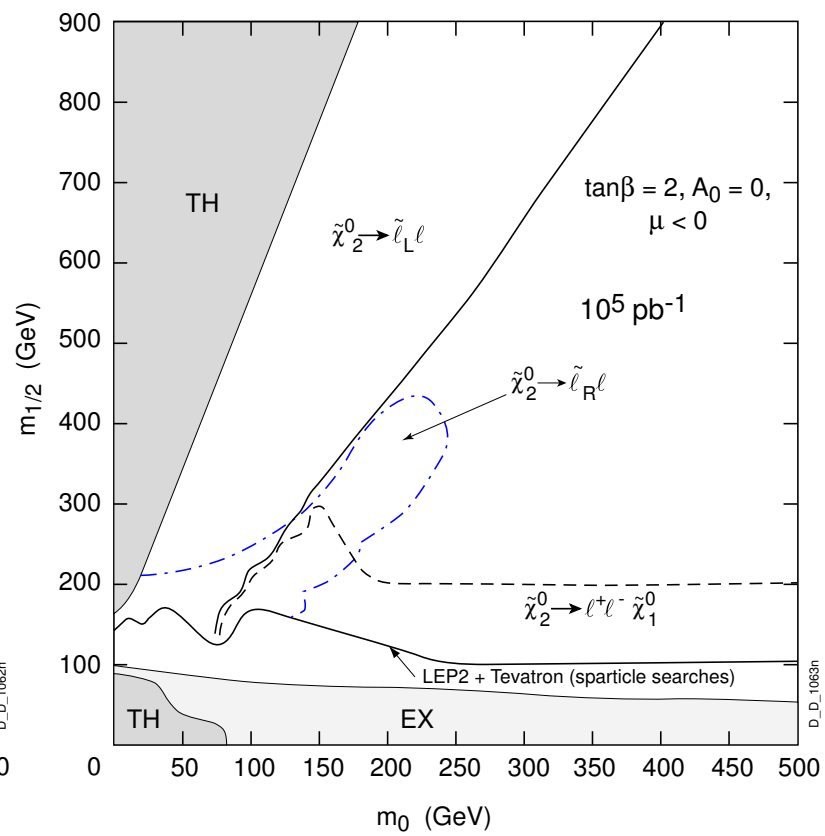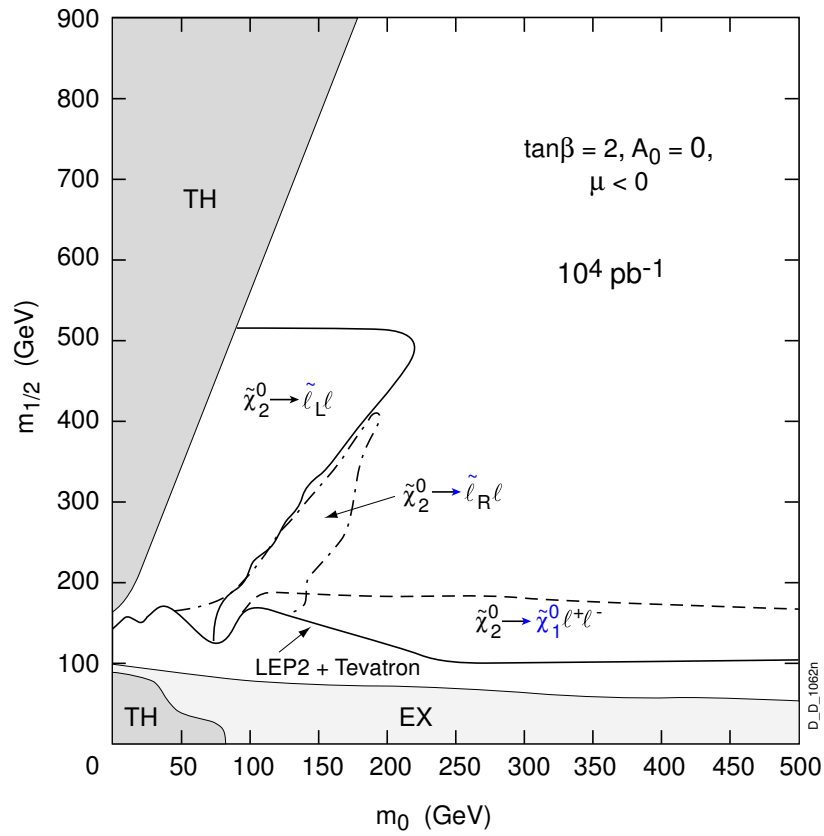
Sometimes have multiple endpoints. Point SU1 is mSUGRA Point in coannihilation region:

$$m_0 = 70\,\text{GeV},\ m_{1/2} = 350\,\text{GeV},\ A_0 = 0,\ \tan\beta = 10,\ \mu > 0$$

Small mass splitting for *both* $\tilde{\ell}_L$ and $\tilde{\ell}_R$:

$$M(\tilde{\chi}_2^0) - M(\tilde{\ell}_L) = 8.5\,\text{GeV},\ \ M(\tilde{\ell}_R) - M(\tilde{\chi}_1^0) = 17\,\text{GeV}$$

Problem is to reconstruct soft leptons.

Muons limited by minimum $p_T$ needed to penetrate calorimeter and make track through muon system: $p_T > 6\,\text{GeV}$ for ATLAS.

Low-$p_T$ electrons have backgrounds from jet fluctuations. Default ATLAS reconstruction is seeded from calorimeter, optimized for $p_T \gtrsim 20\,\text{GeV}$. Can do better using neural net and/or likelihood.

(Should also try track-seeded algorithm for low-$p_T$ electrons.)

## Results for SU1 after first attempt to optimize soft electrons:
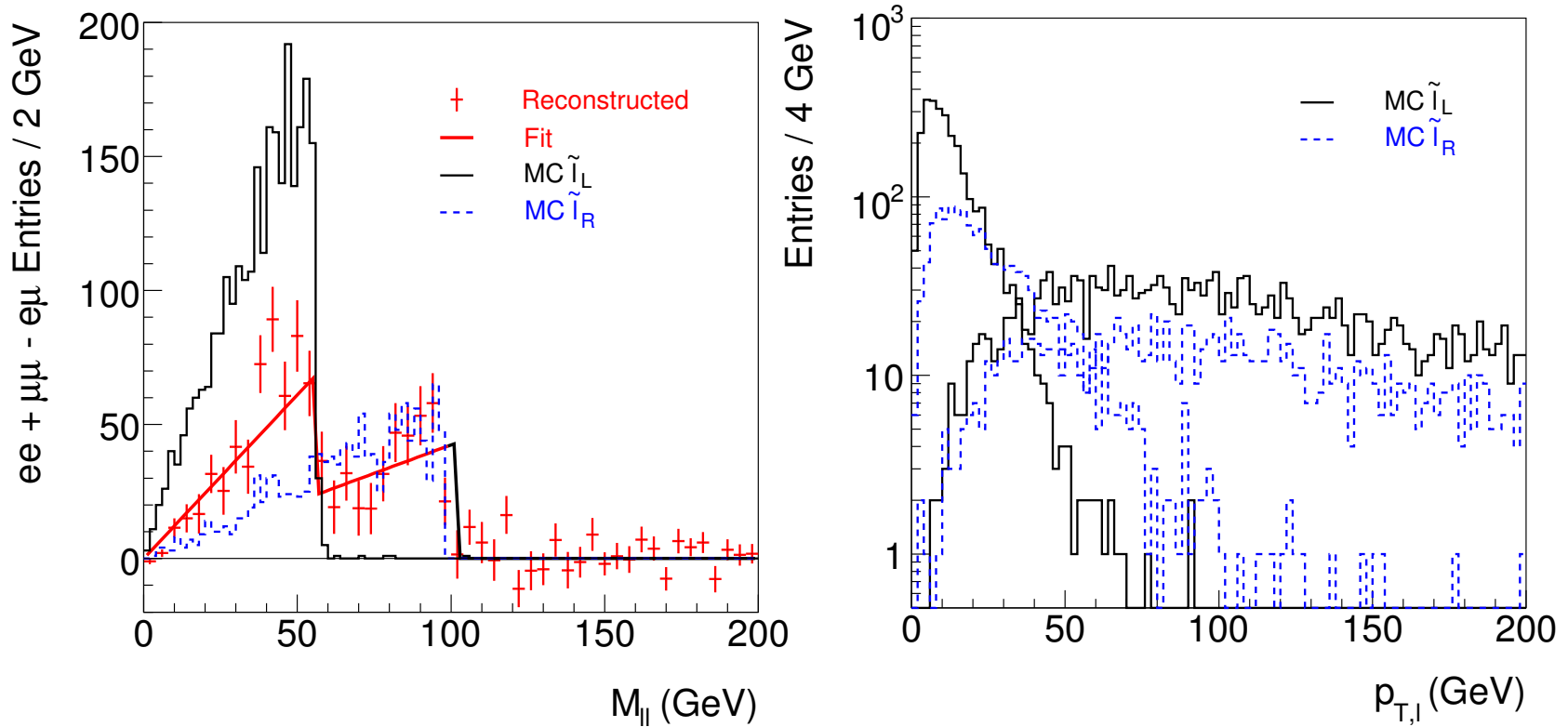


Reconstruction (points with errors) finds both edges. But poor efficiency for $\tilde{\ell}_L$ edge because "near" (first) lepton for this edge is very soft.

With small mass gaps, reconstruction is harder, but distinguishing which electron is "near" (first) and "far" (second) is easier.

Now combine leptons with jets for "bulk" point SU3. Dominant source of $\tilde{\chi}_2^0$ is $\tilde{q}_L$ decay:

$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\ell}_R^{\pm}\ell^{\mp} q \to \tilde{\chi}_1^0 \ell^+ \ell^- q.$$

Can make $\tilde{q}_L$ either directly or via $\tilde{g}$ decay. In either case expect hardest jets to be from $\tilde{q}_L$.

For above decay chain can calculate [Bachacou,TDR]

- $\ell\ell q$ endpoint $M_{\ell\ell q}$;

- Larger and smaller $\ell q$ endpoints $M_{\ell q}^<, M_{\ell q}^>$;

- $\ell\ell q$ threshold $T_{\ell\ell q}$ given $M_{\ell\ell}$ cut. ($T_{\ell\ell q} = 0$ without any $M_{\ell\ell}$ cut.)

Expressions depend on relative mass values [Allanach].

*Exercise:* Derive the expressions for the these endpoints/thresholds using techniques like those for the $\ell\ell$ endpoint.

# Distributions for various $\ell^+\ell^-$ plus jet distributions [Allanach]:
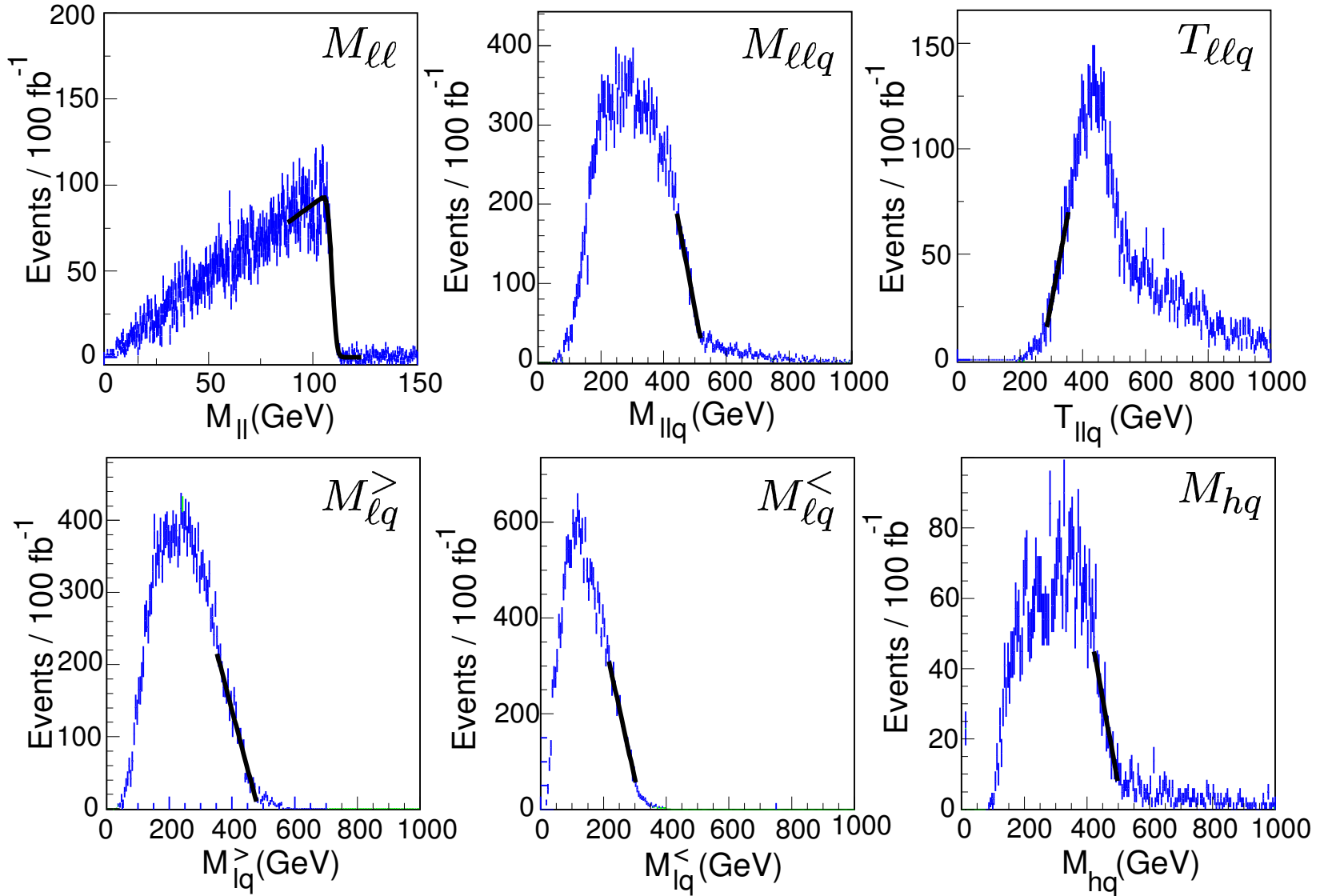
Generate masses in $\tilde{q}_L$ decay chain at random, compute edges, and compare with measured values and estimated errors. Result [Allanach]:
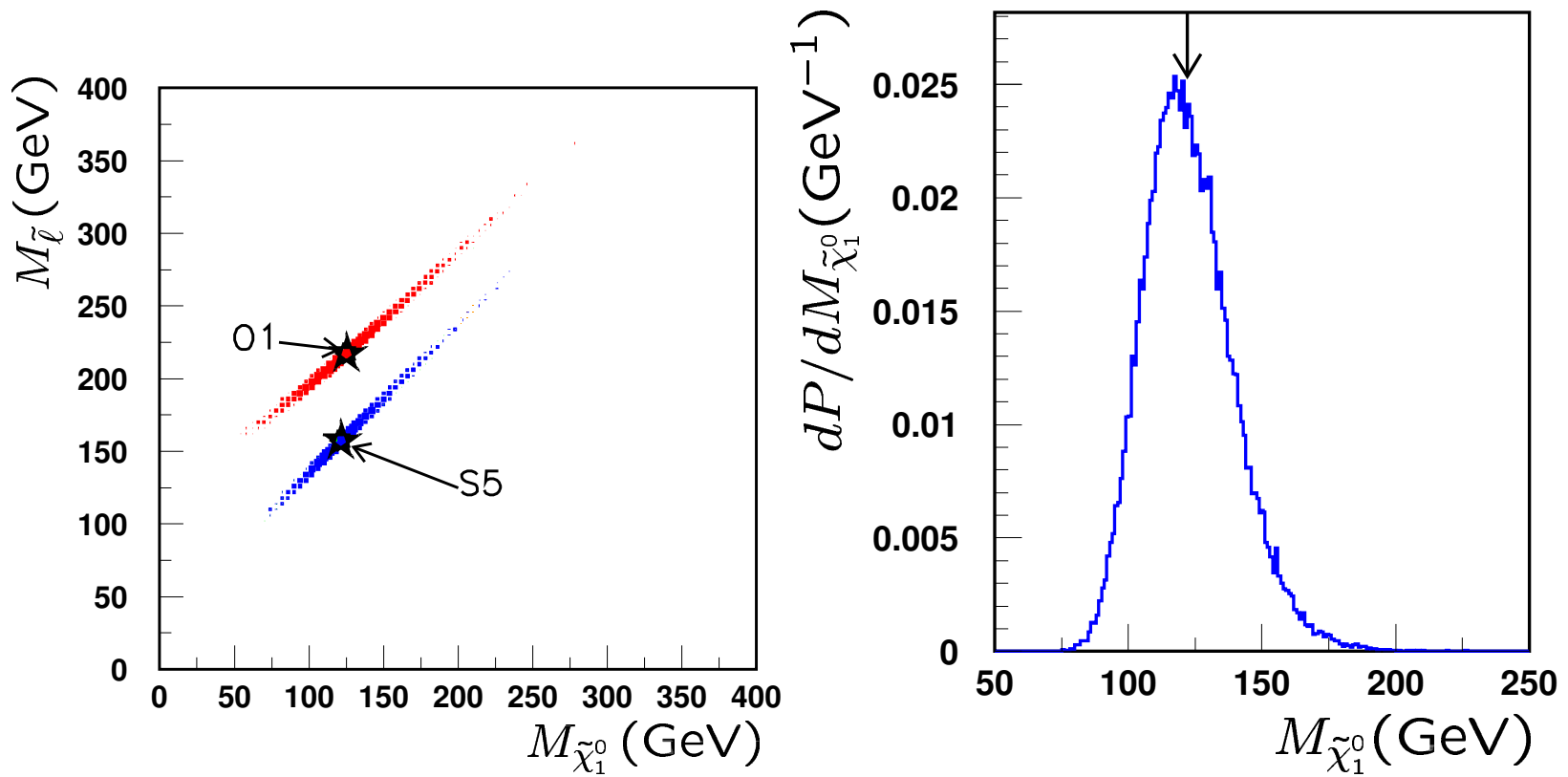


Measure relative masses to $\sim 1\%$, absolute $\tilde{\chi}_1^0$ mass to $\sim 10\%$. Endpoints measured to $\sim 1\%$, but $M(\tilde{\chi}_1^0)$ sensitivity vanishes as $M(\tilde{\chi}_1^0) \to 0$.

Similar analysis tried with full simulation for both DC1 and Rome. Results generally similar, but found more background below $T_{\ell\ell q}$ threshold.

Not understood, but threshold more sensitive to gluon radiation and to mis-reconstructed jets.

Without threshold measurement, relative mass measurements still possible, but cannot determine $M(\tilde{\chi}_1^0)$ just from these endpoints.

Might instead use $M(\tilde{q})$ from jet energy scale or rate. Needs both thought and work!

Can do similar analysis for Point SU1 with two dilepton edges. Instructive to look at $M_{\ell q}^{<}$ (left) and $M_{\ell q}^{>}$ (right) distributions:
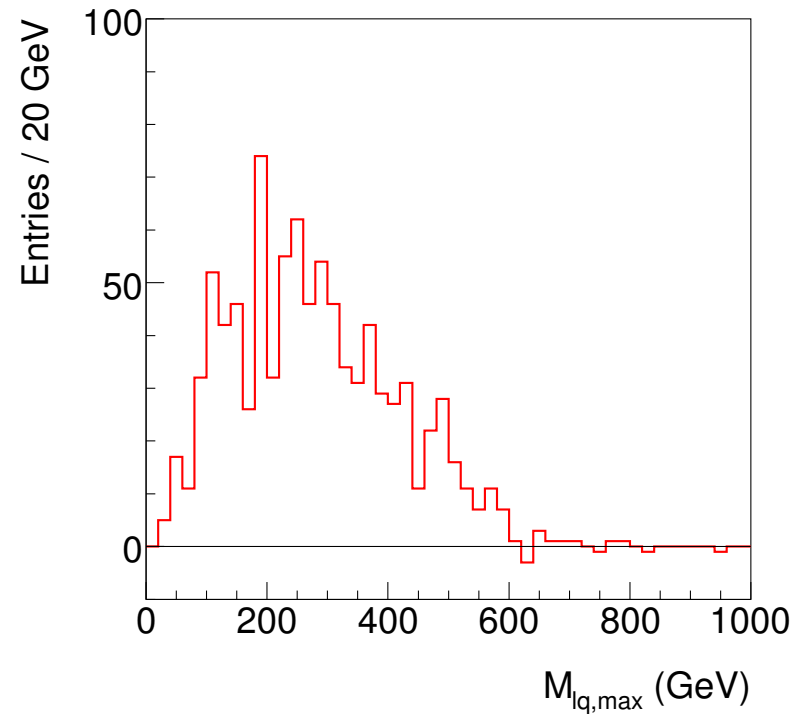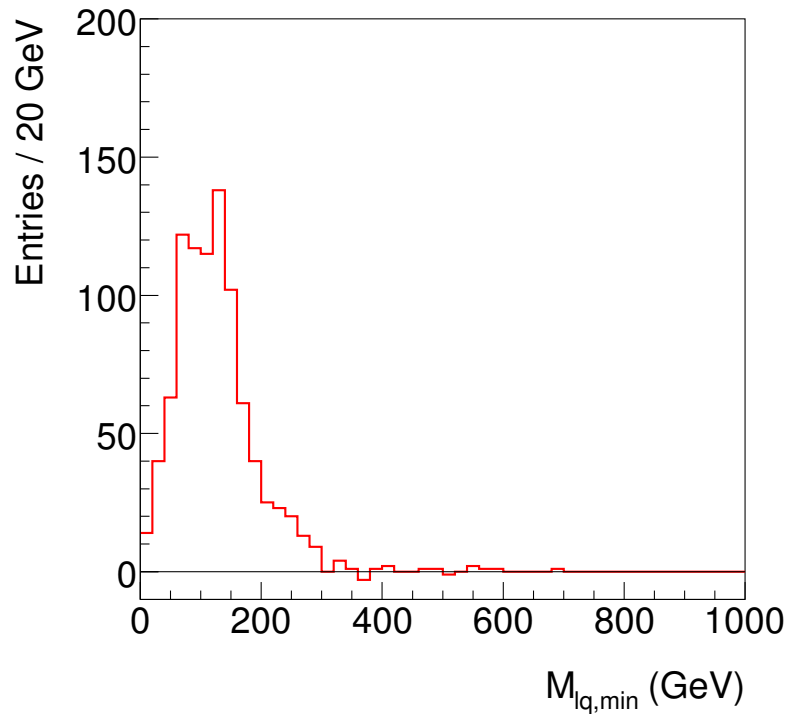


Soft lepton from $\tilde{\ell}_L$ is "near" (first) and gives triangular distribution smeared by resolution. Soft lepton from $\tilde{\ell}_R$ is "far" (second). Maximum $M_{\ell q}$ also requires maximum $M_{\ell\ell}$, so endpoint vanishes linearly.

Decompose measured distribution (points with errors) into contribution from $58.2 < M_{\ell\ell} < 100.9\,\text{GeV}$ ($\tilde{\ell}_R$, dashed) and $M_{\ell\ell} < 58.2\,\text{GeV}$ (mainly $\tilde{\ell}_L$, solid):
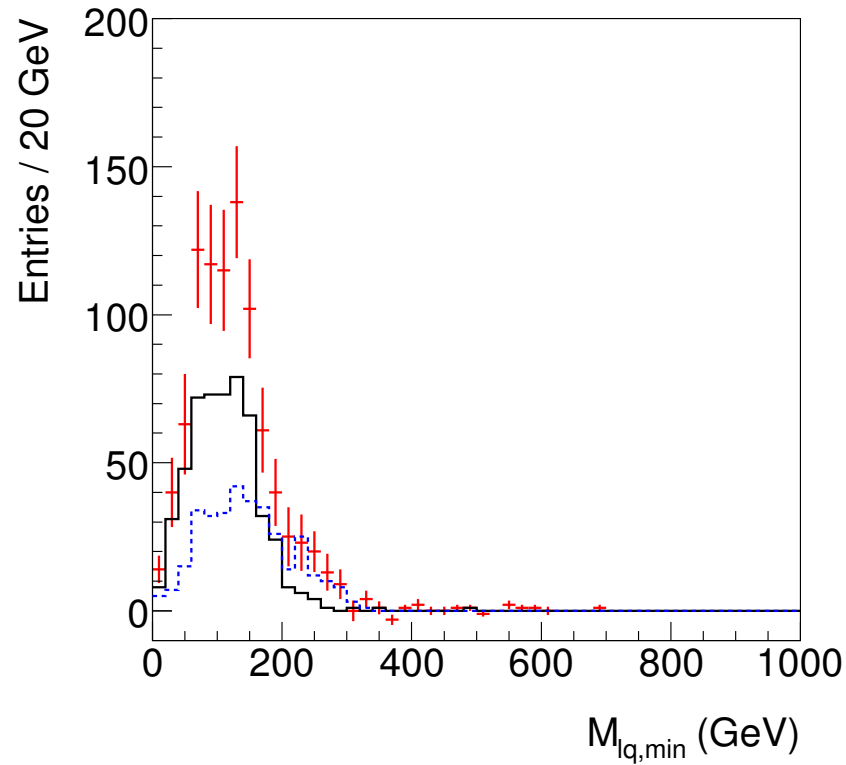


Clearly see both structures consistent with expected endpoints at $186.7\,\text{GeV}$ and $338.5\,\text{GeV}$. No error analysis yet.

If sleptons are heavy (e.g., focus point region), can have direct $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^+ \ell^-$ dominated by virtual $Z$.

Figure shows characteristic 3-body phase space with correct endpoint [CMSSUSY]. Not clear if matrix element was included.

$Z$ peak is mostly background from $WZ$; single $Z$ fails $\not{E}_T$ cut.

Shape could in principle determine $M(\tilde{\chi}^0_2)$ and $M(\tilde{\chi}^0_1)$ separately. Small effect; needs careful acceptance corrections.



*mSUGRA parameters*

$m_0 = 400$ GeV, $m_{1/2} = 150$ GeV, $\tan\beta = 2$, $A_0 = 0$, $\mu < 0$

$M(\tilde{\chi}^0_1) = 65$ GeV
$M(\tilde{\chi}^0_2) = 135$ GeV
Expected $M_{ll}^{max} = 70$ GeV

$L_{int} = 10^3$ pb$^{-1}$

$p_T^{1,2,3} > 15$ GeV
No tracks with
$p_T > 2$ GeV in $\Delta R < 0.3$

Events / 2 GeV

$M_{l+l-}$ (GeV)
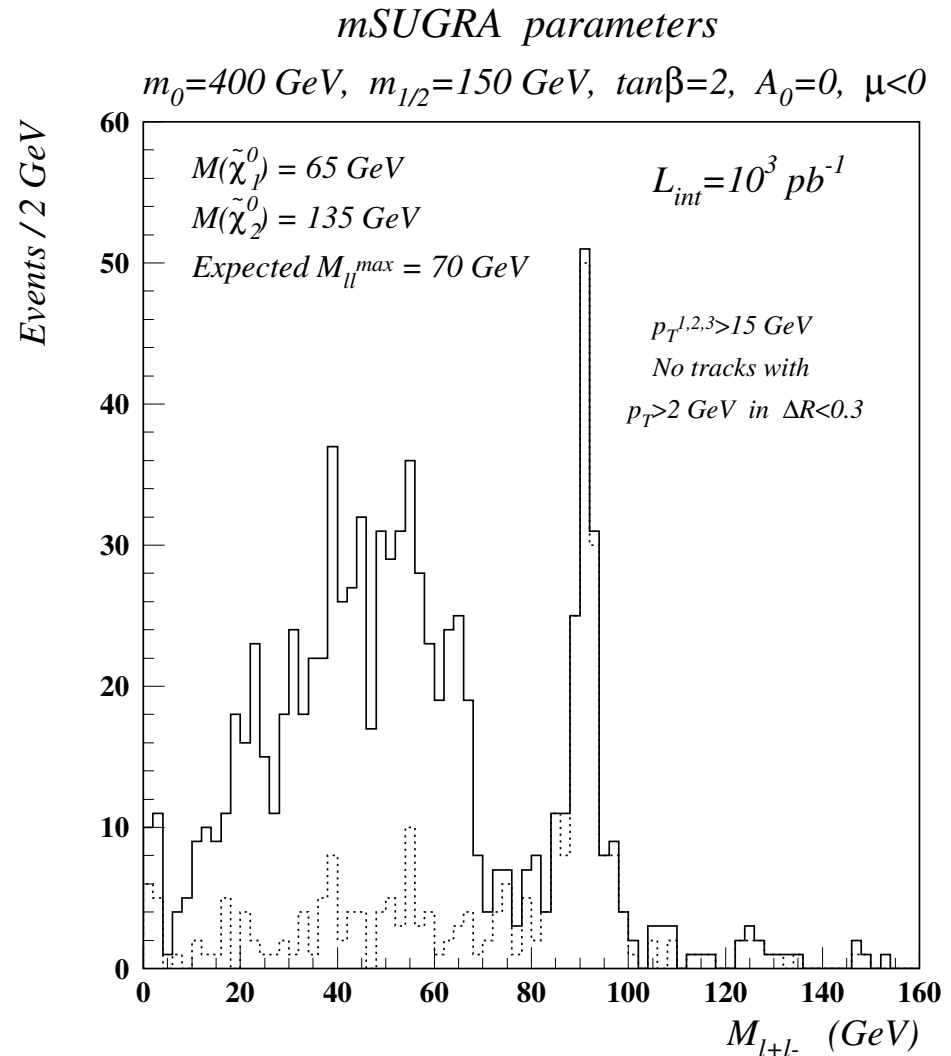
# (Hadronic) $\tau$ Signatures

$\tau$ decays can dominate over $e/\mu$ decays, especially for $\tan\beta \gg 1$, if light $\tilde{\tau}_1$ provides only 2-body mode.

Even in mSUGRA model with unification at GUT scale, $\tau$ decays provide independent information because:

- Yukawa terms in RGE running;

- Gaugino/Higgsino mixing for charginos/neutralinos;

- $\tau_L$–$\tau_R$ mixing ($\propto m_\tau \tan\beta$).

Inner layer of LHC vertex detectors at $R \sim 40\,\text{mm}$ to avoid radiation damage, so cannot tag $\tau \to \ell\nu\nu$. Must rely on hadronic $\tau$ decays $\to$ narrow, low-multiplicity jets. Background from QCD fluctuations.

Have $\not{E}_T$ from both $\tilde{\chi}_1^0$ and $\nu$, so can only measure visible hadronic $\tau$ momentum. Must deduce true $p_\tau$ from this.

DC1 full simulation analysis: parameterize visible $\tau\tau$ mass from $\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau$ decays and fit to reconstructed $\tau^+\tau^- - \tau^\pm\tau^\pm$ distribution:
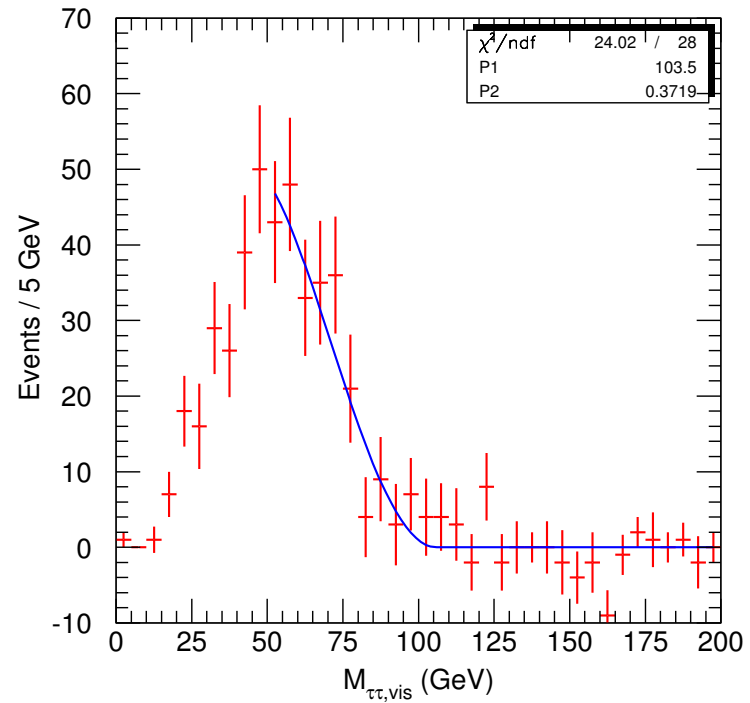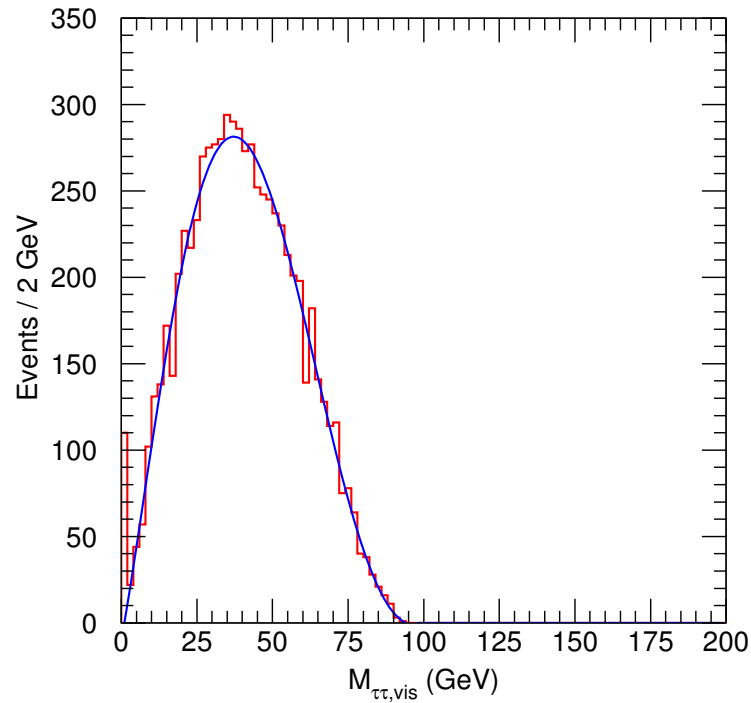


Sign subtraction assumes that fake tau background (mainly) random in sign. Fitted endpoint is $103.5 \pm 4.9\,\text{GeV}$ compared to true $98.3\,\text{GeV}$.

Caveat 1: Reconstructed $\tau\tau$ mass has different shape at low $M_{\tau\tau}$. Need to make acceptance correction for low-$p_T$ $\tau$'s — not done.

Caveat 2: Shape of Monte Carlo template distribution depends on $\tau$ polarization. Largest effect is for $\tau \to \pi\nu$:

$$\frac{dN}{d\cos\theta^*}(\tau^-_{L,R} \to \pi\nu) \propto 1 \mp \cos\theta^*\,.$$

I.e., single pi is soft for $\tau_L$, hard for $\tau_R$.

Polarization hard to measure $\Rightarrow$ not important for $M_{\tau\tau}$?

Still want to measure it: best handle on chiral structure at LHC. Perhaps possible: identify $\pi\nu$ decays using $E = p$ and compare with all decays [Vacavant]. Needs study.

$\tau$ decays can dominate, e.g., mSUGRA Point SU6 in funnel region, $(m_0 = 320\,\text{GeV}, m_{1/2} = 375\,\text{GeV}, A_0 = 0, \tan\beta = 50, \mu > 0)$ has 2-body decays only to $\tau$'s, so $B(\tilde{\chi}_2^0 \to \tilde{\tau}_1^{\pm}\tau^{\mp}) = 95.6\%$, $B(\tilde{\chi}_1^{\pm} \to \tilde{\tau}_1^{\pm}\nu_{\tau}) = 94.6\%$.

Fit to $\tau^+\tau^- - \tau^{\pm}\tau^{\pm}$ for 16k events $(3.6\,\text{fb}^{-1})$ using DC1/SU3 parameterization gives $135.6 \pm 8.3\,\text{GeV}$ compared to true $126.5\,\text{GeV}$:
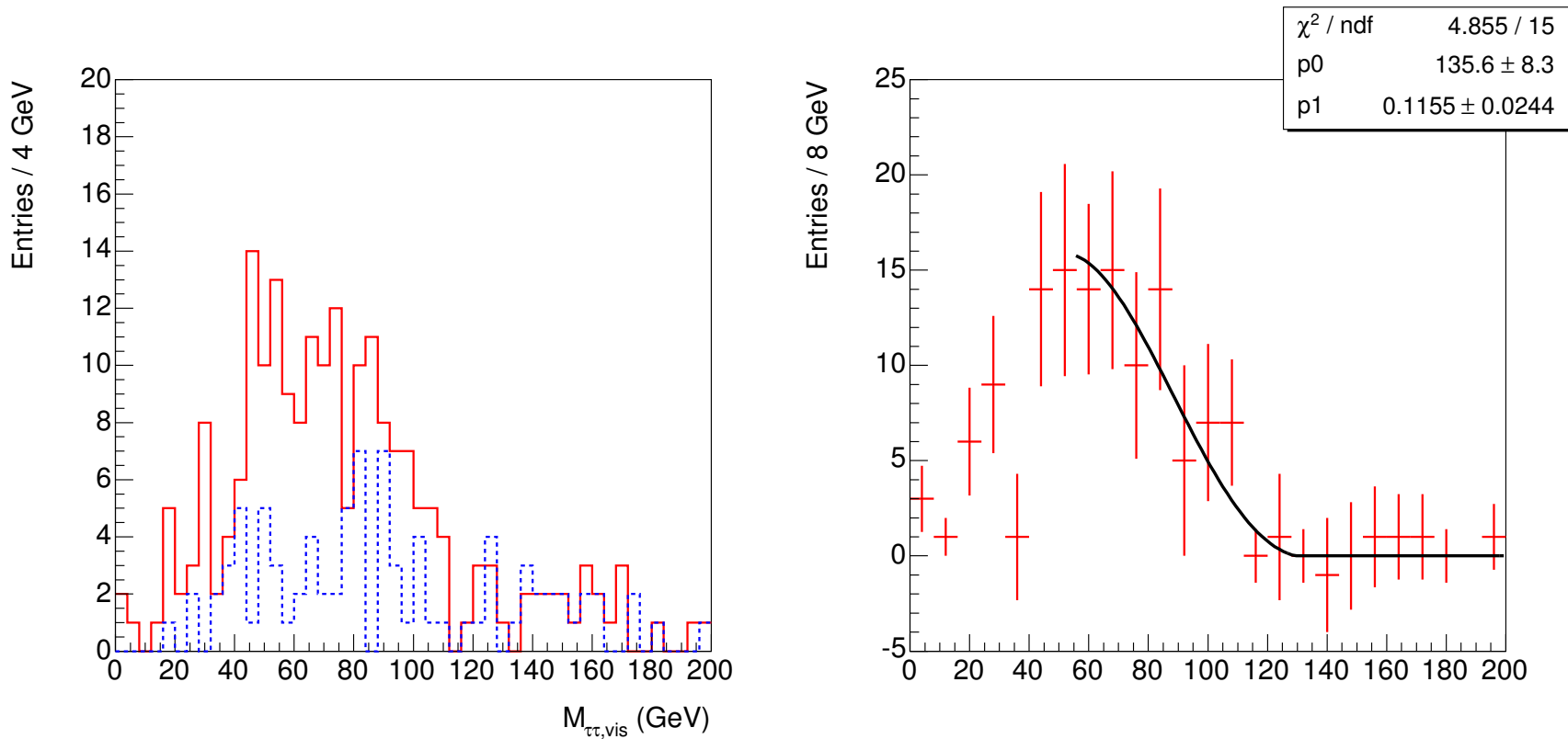
# Third Generation Squarks

Like $\tilde{\tau}$'s, third generation squarks $\tilde{t}_i, \tilde{b}_i$ are special:

- Large Yukawa terms in RGE's and couplings.

- Large left-right mixing proportional to $m_t$ or $m_b \tan\beta$.

Crucial for understanding SUSY model — needs work.

Rely on vertex detector to tag $b$ jets. Problems are efficiency/mistags and combinatorics.

Typical decay chain is $\tilde{g} \to \tilde{t}_1 \bar{t} \to \tilde{\chi}_j^+ b\bar{t} + \text{h.c.}$. Then $b\bar{t}$ endpoint with $t \to q\bar{q}b$ measures $M(\tilde{g}) - M(\tilde{\chi}_1^{\pm})$ [Hisano].

Fast simulation analysis. Large combinatorial background $\Rightarrow$ see nothing initially. But after sideband subtraction, endpoint emerges at right place $(471\,\text{GeV})$:
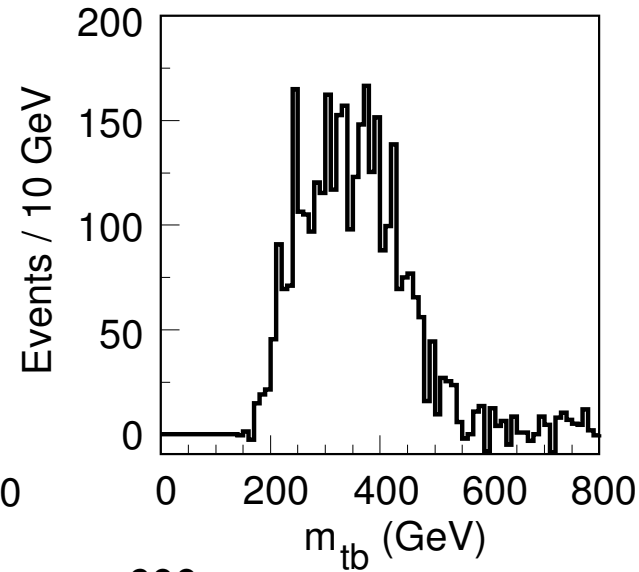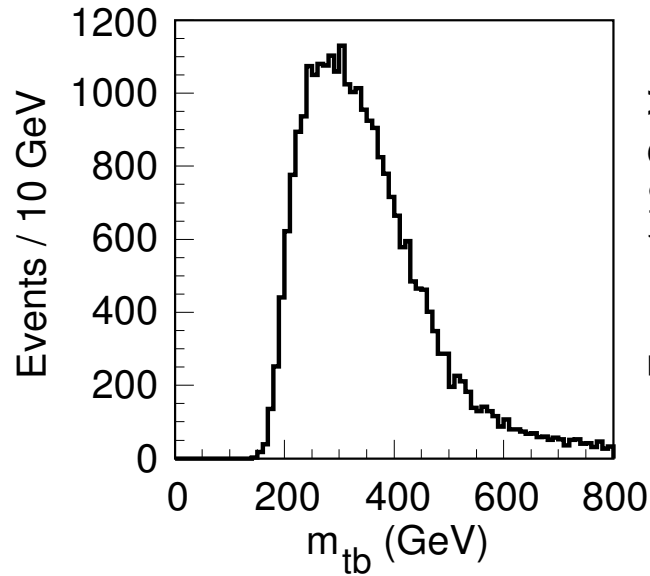
Analysis repeated for 10 points for both Herwig and Pythia.

Consistently find right endpoint to about ±2% (lines in figure).

Should try similar studies with full simulation.
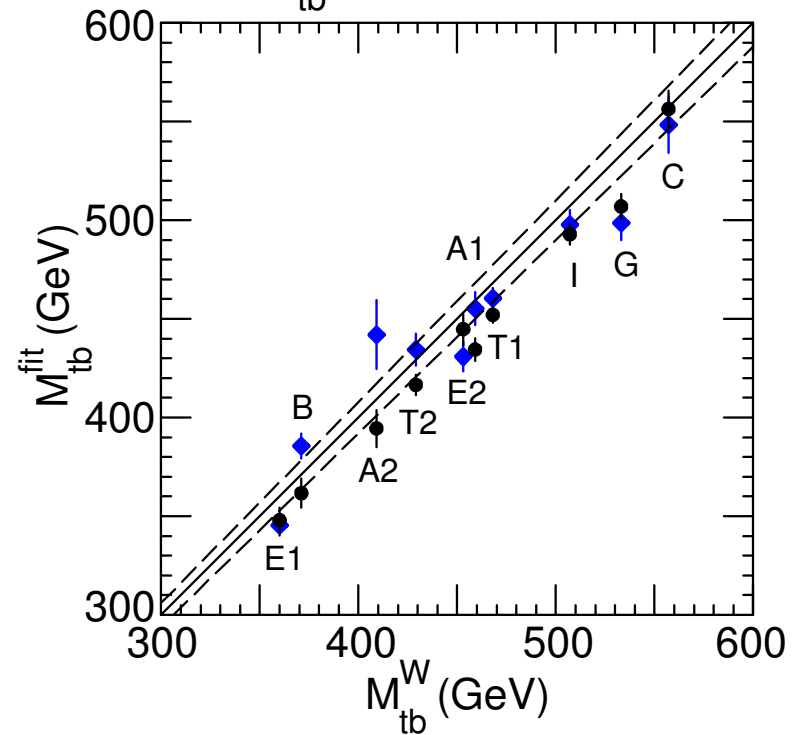
# "Stransverse Mass"

In mSIGRA $B(\tilde{q}_R \to \tilde{\chi}_1^0 q) \approx 1$. Generally expect some squarks to decay directly to $\tilde{\chi}_1^0$. If $M(\tilde{q}) < M(\tilde{g})$, expect events with two hard jets and $\not{E}_T$.

Form "stransverse mass" including $M(\tilde{\chi}_1^0)$:

$$M_{T2}^2 \equiv \min_{\not{p}_1 + \not{p}_2 = \not{p}_T} \left[ \max \left\{ m_T(p_{T\ell_1}, \not{p}_1; M(\tilde{\chi}_1^0)), m_T(p_{T\ell_2}, \not{p}_2; M(\tilde{\chi}_1^0)) \right\} \right]$$

Partition $\not{E}_T$ in all possible ways, form two $M_T$ for each partition, take larger, and minimize over all partitions.

Partitions include correct one, so $M_{T2}$ has endpoint at $M(\tilde{q})$. (Must be careful not to get stuck in false minima.)

*Exercise:* Think about it.

Very useful for signal and also to reject backgrounds with two neutrinos, e.g., $t\bar{t}$ or $W^+W^-$.

$M_{T2}$ distributions for mSUGRA points SU1 and SU3 with correct $M)\tilde{\chi}^0_1)$ and fitted endpoints:
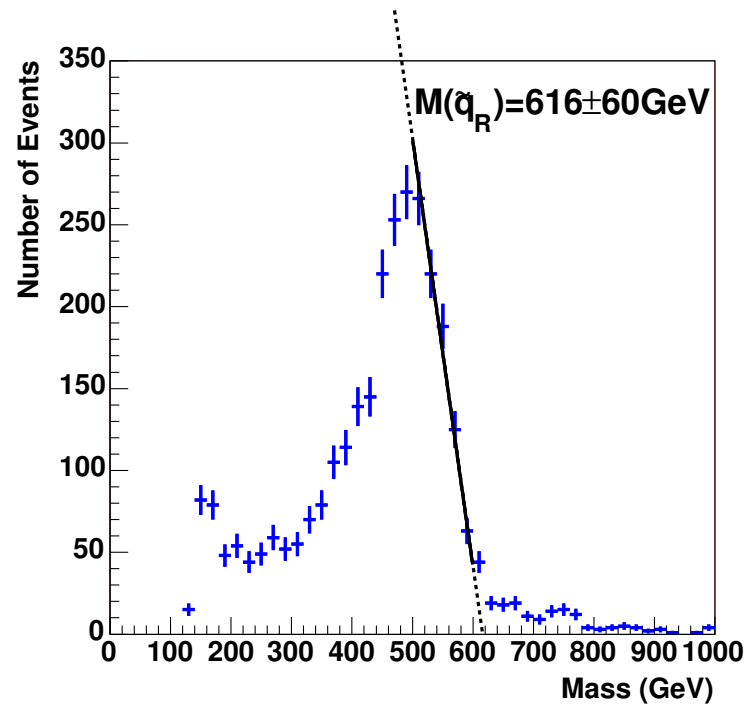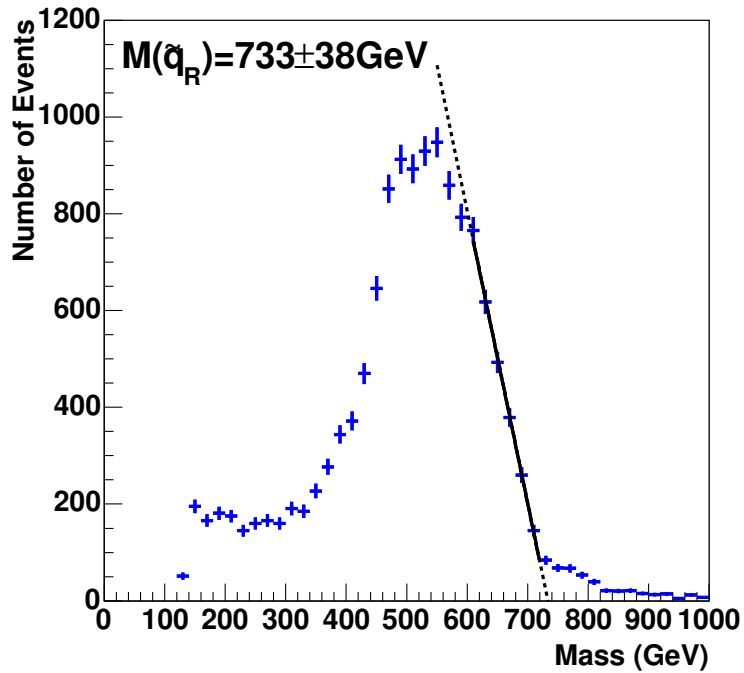


Compare with $\langle M(\tilde{q}_R)\rangle = 729$ and $638\,\mathrm{GeV}$ respectively.

Of course $M(\tilde{\chi}^0_1)$ not well known, at least from early data.

# SUSY Summary

Have shown many examples of SUSY signatures. Two goals:

- Develop techiniques for SUSY analysis.

- Test reconstruction on complex events.

Not yet ready to extract SUSY signatures from real LHC data, but getting close. Need a lot of work over next two years to be ready.

Must be prepared to find SUSY if it exists at TeV mass scale — and not to find it if it does not. Only experiment can decide whether SUSY, or any other BSM physics, is correct.

# Little Higgs Models

Only three large 1-loop quadratic divergences for Higgs mass:
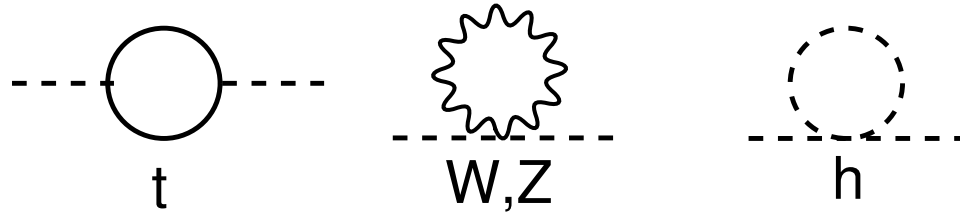


$$\delta m_H^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2 + \frac{g^2}{16\pi^2}\Lambda^2 + \frac{\lambda^2}{16\pi^2}\Lambda^2$$

Little Higgs models arrange to cancel these $\Rightarrow$ push cutoff to $\sim 10\,\text{TeV}$.

Studies have used "Littlest" Higgs. Break $SU(5)$ to $SO(5)$, giving 14 Goldstone bosons:

$$X(3,0),\ Y(1,0),\ h(2,\tfrac{1}{2}),\ h^\dagger(2,-\tfrac{1}{2}),\ \phi(3,1),\ \phi^\dagger(3,-1)$$

Gauge $SU(2)\times U(1)\times SU(2)\times U(1)$ and break to $SU(2)_L \times U(1)$. Remaining $SU(2)\times U(1)$ combines with $X,Y \Rightarrow$ massive $W_H^\pm, Z_H, A_H$. Also generate $\phi$ mass, but $h$ mass protected by two symmetries.

Add vector-like $SU(2)_L$ singlet $T_L, T_R$ with $SU(3)$ symmetry to guarentee cancellation of top loop.

Need additional (unknown) physics at $\sim 10\,\mathrm{TeV}$ to have complete theory.

Result is "naturally" light Higgs $h$: cancellation with particles of same spin, unlike SUSY. Have new particles at TeV scale:

- $T$ with $T \to Zt, Wb, ht$ in ratio $1:2:1$.

- New gauge bosons $W_H^\pm, Z_H, A_H$.

- Higgs triplet $\phi$ produced by $WW$ fusion.

"Littlest Higgs" model lacks custodial $SU(2)$, so ruled out. But still useful for LHC studies of such models.

Used by ATLAS for initial fast simulation study [Azuelos]. (CMS work in progress.)

Can have both $T\bar{T}$ and single $T$ production (via $W$ exchange).

Rate for single $T$ is model dependent but dominates for large mass.
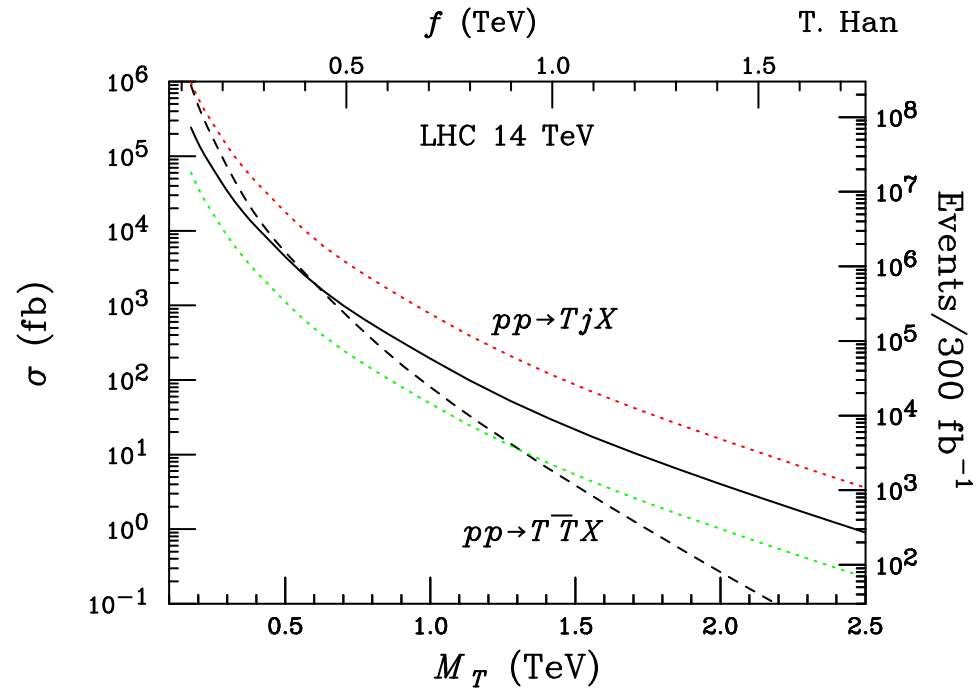


First consider $T \to Zt \to \ell^+\ell^-\ell\nu b$. Require

- Three isolated leptons with $p_T > 100, 40, 40\,\mathrm{GeV}$ and $|\eta| < 2.5$. No other leptons with $p_T > 15\,\mathrm{GeV}$.

- $\not{E}_T > 100\,\mathrm{GeV}$.

- At least one tagged $b$-jet with $p_T > 30\,\mathrm{GeV}$.

Standard Model backgrounds include $WZ$, $ZZ$, and dominant $t\bar{b}Z$. Latter generated by CompHep interfaced to Pythia. Determine $\vec{p}_\nu$ from $\not{E}_T$ plus $M_W$ and plot mass. Clean signal but small rate.

Analysis for $T \rightarrow Wb \rightarrow \ell\nu b$ like that for sequential quark. Backgrounds from $t\bar{t}$, single $t$, and $Wb\bar{b}$. Larger rate but worse $S/B$.
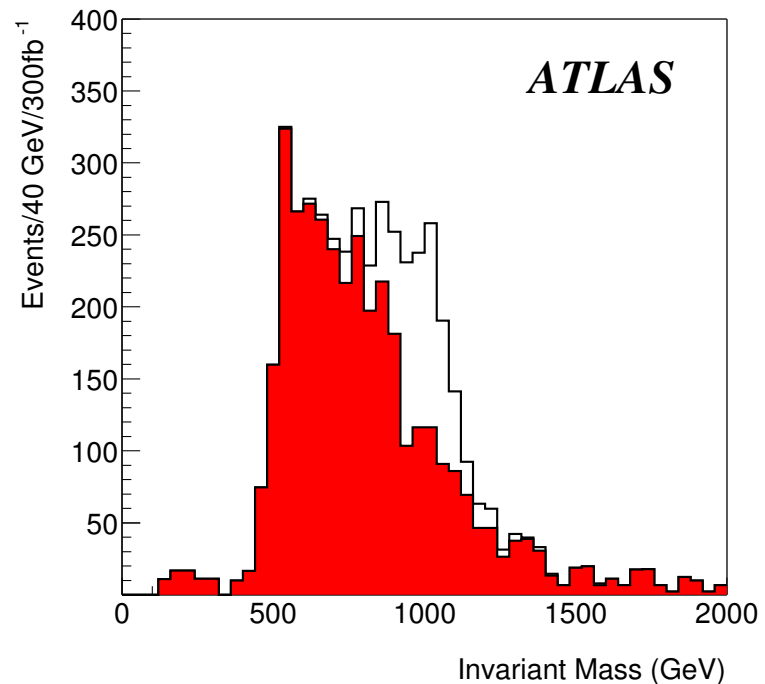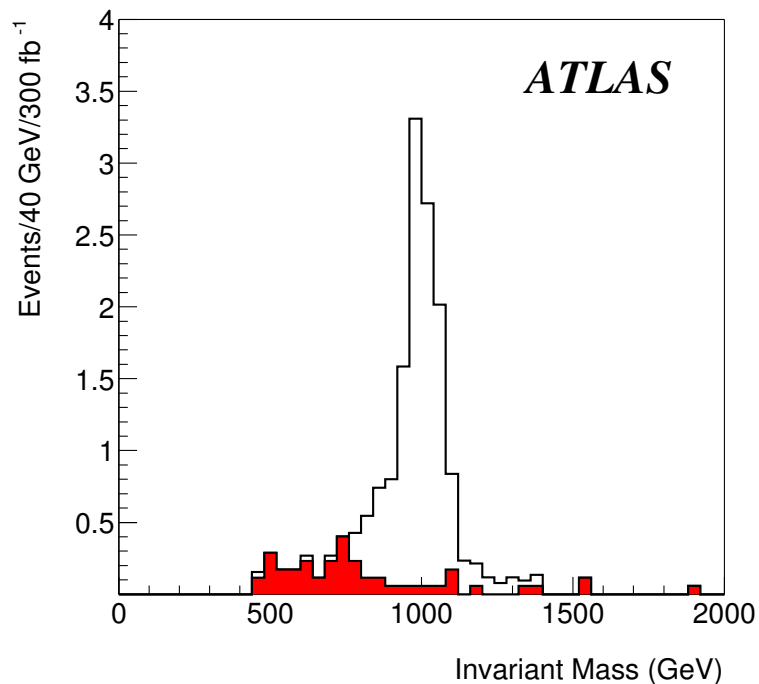
For $T \rightarrow ht$ assume $M_h = 120\,\mathrm{GeV}$ so $h \rightarrow b\bar{b}$. Select events with

- One isolated $e, \mu$ with $p_T > 100\,\mathrm{GeV}$, $|\eta| < 2.5$.

- Three jets with $p_T > 130\,\mathrm{GeV}$.

- At least one jet tagged as a $b-$jet.

Multiple $b$ tags just hurt efficiency. Background dominated by $t\bar{t}$.

Dijet mass after these cuts shows peak at $M_h$ even without $b$-tag. (Compare with 1 and 2 $b$-tags?) Require $110 < M_{jj}, 130\,\mathrm{GeV}$ and veto $70 < M_{jj} < 90\,\mathrm{GeV}$ to suppress $t\bar{t}$. Reconstruct $\vec{p}_{|}nu$ as above and form mass for $W + \mathrm{jet} + h$.

Find $\sim 4\sigma$ signal ("evidence") assuming $M(T)$ known from previous analysis and $t\bar{t}$ shape known from events reconstructed using tight constraints:
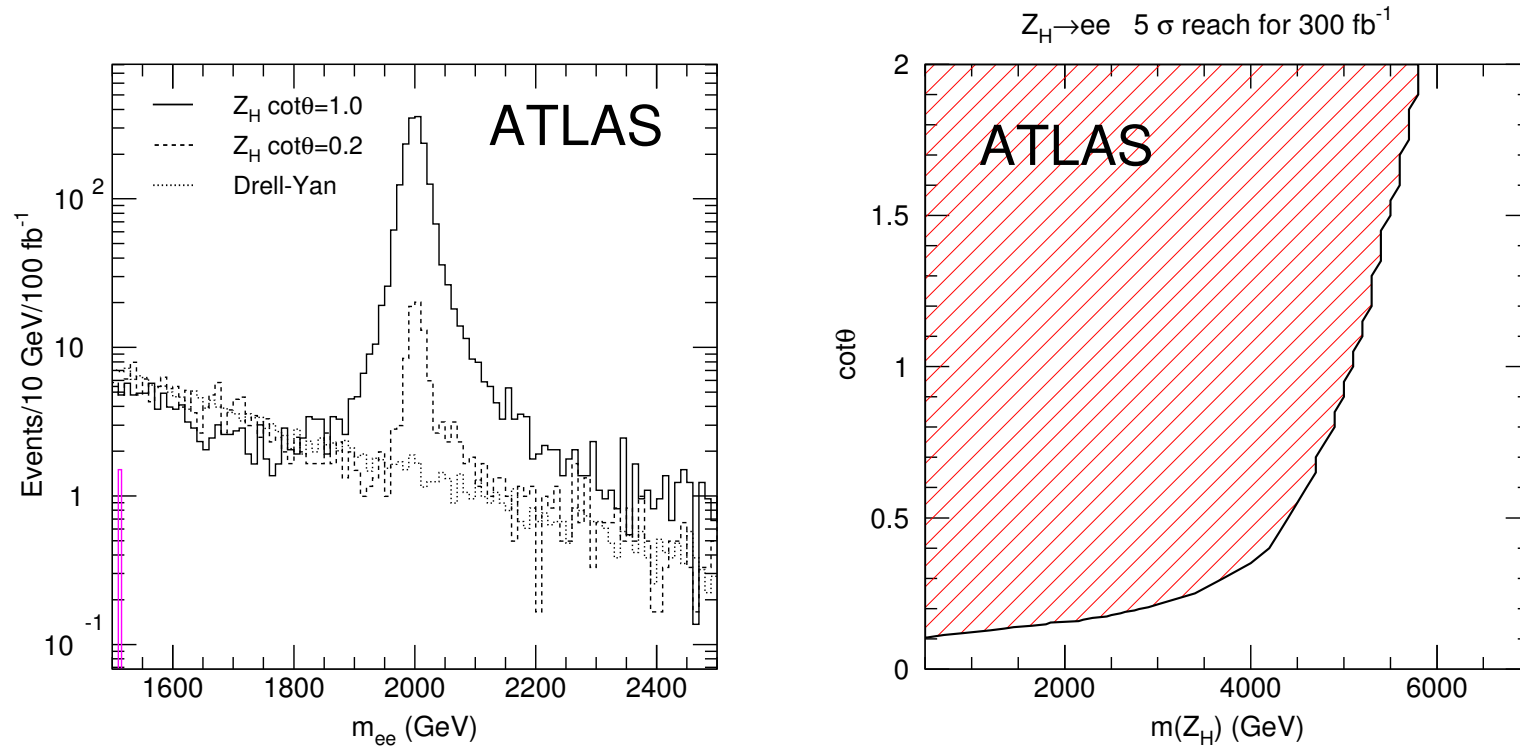
Plots of $M(jj)$ and $M(Wjh)$:
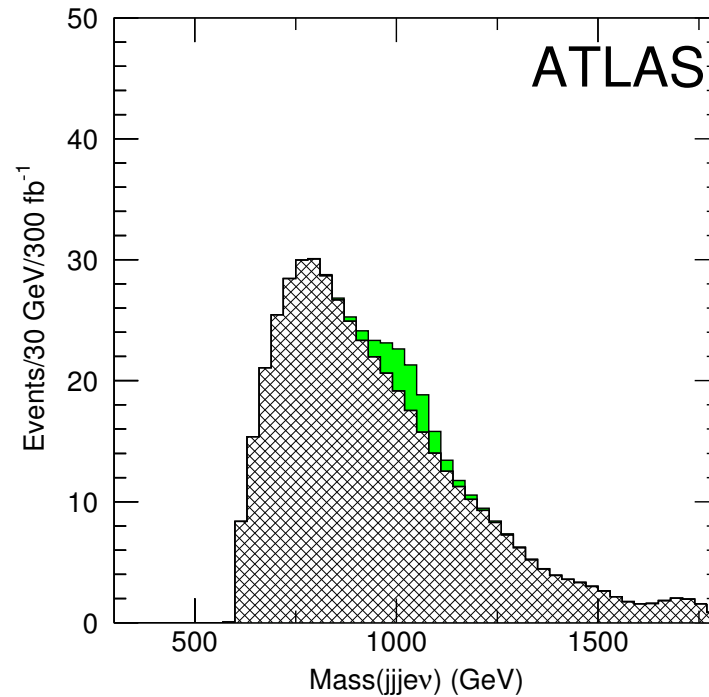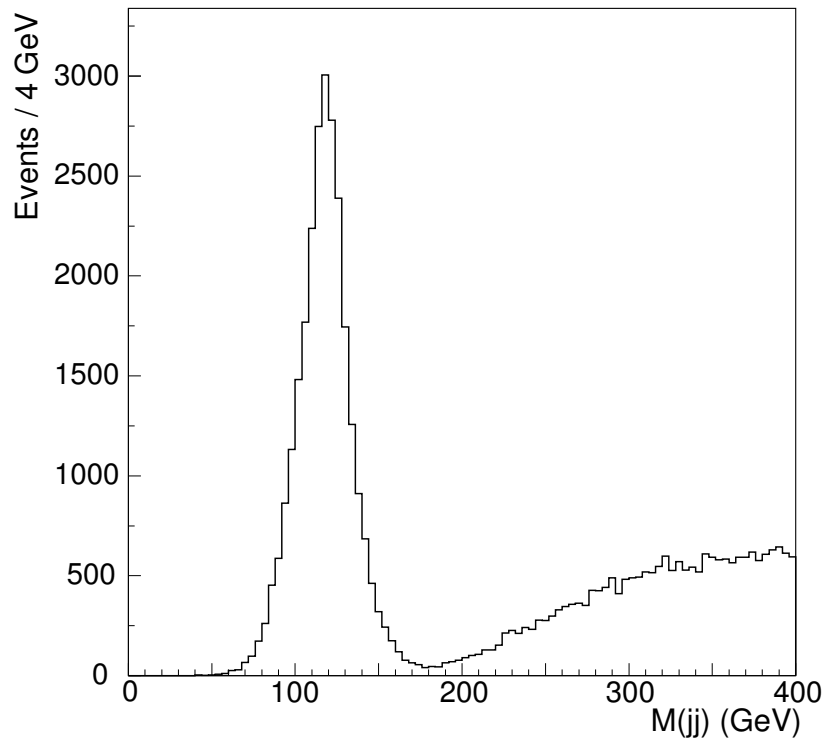


Signal is $\sim 4\sigma$ **if** mass known from previous analyses and $t\bar{t}$ background known. Note bin-to-bin fluctuations would be $\sim 20\%$ for $300\,\text{fb}^{-1}$..

"Challenging."

Search for $Z_H$ and $A_H$ in leptonic modes straightforward. Rely mainly on $e^+e^-$ because mass resolution is better at high mass. Only important background is Drell-Yan:



Rate depends on mixing parameter. Shaded region shows $5\sigma$ discovery reach for $300\,\mathrm{fb}^{-1}$.

Example: for $Z_H \to Zh$, assume $M_H = 120\,\mathrm{GeV}$ so $h \to b\bar{b}$. Require:

- Two OS,SF leptons with $P_T > 5(6)\,\mathrm{GeV}$ and $|\eta| < 2.5$, one with $p_T > 25\,\mathrm{GeV}$ for trigger, and $76 < M_{\ell\ell} < 106\,\mathrm{GeV}$.

- Two $b$-jets with $p_T > 25\,\mathrm{GeV}$, $|\eta| < 2.5$, $\Delta R < 1.5$, and $60 < M_{bb} < 180\,\mathrm{GeV}$.
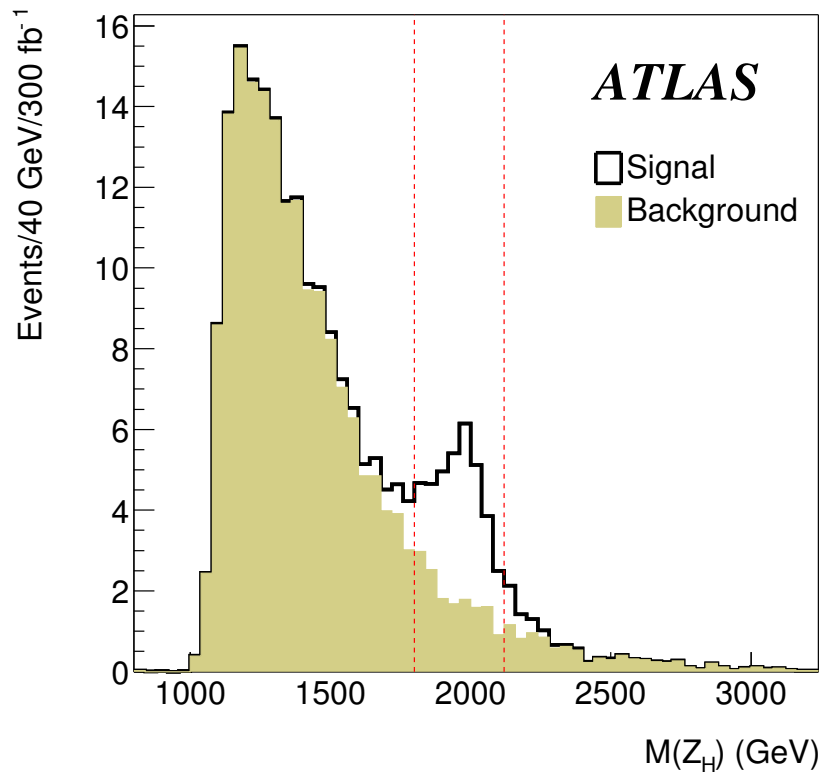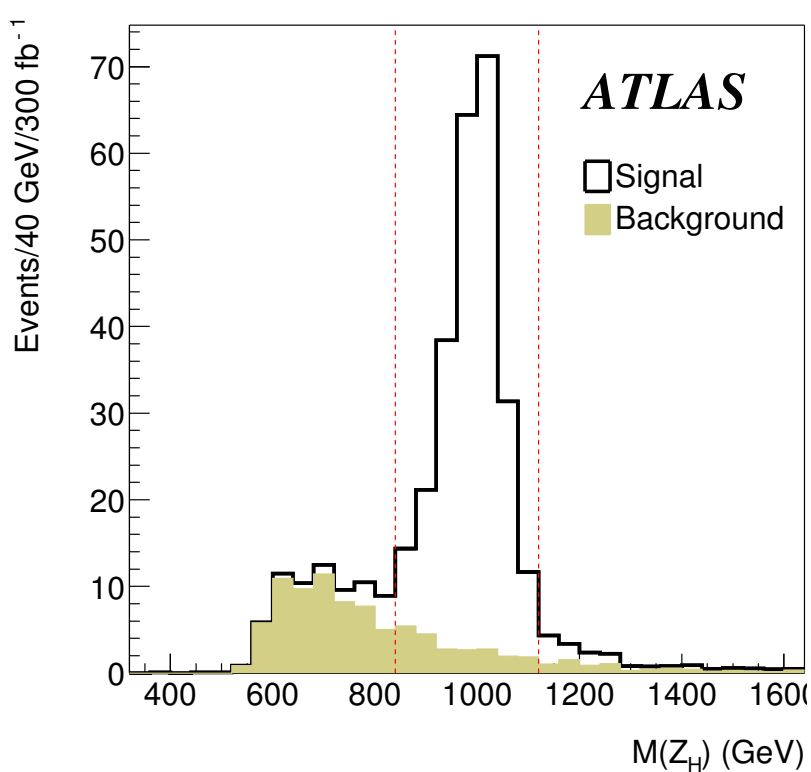
# Little Higgs Summary

Search much more difficult than for SUSY. Would be likely to find light Standard-Model-like Higgs first.

Rates are low, but detectors can do job with $300\,\text{fb}^{-1}$:

- $T$ observable in $h(120)t$ ($M < 1.2\,\text{TeV}$) and $Zt$ ($M < 1.0\,\text{TeV}$).

- $Z_H \to e^+ e^-$ observable ($M < 4.5\,\text{TeV}$ for $\cot\theta = 0.5$).

- $Z_H \to Zh(120)$ observable ($M < 2\,\text{TeV}$).

- Higgs triplet $\phi$ is difficult: $WW$ fusion violates custodial $SU(2)$, and Drell-Yan pair production rate is tiny.

Model invented after detectors were (mostly) designed. Illustrates importance of detecting all quanta of Standard Model.

# Extra Dimensions

Hierarchy problem comes from mismatch between reduced Planck scale ($\overline{M}_{\mathrm{Pl}} = M_{\mathrm{Pl}}/\sqrt{8\pi} = 2.43 \times 10^{18}\,\mathrm{GeV}$) and weak scale ($246\,\mathrm{GeV}$). Extra (space-like) dimensions aleviate this by reducing effective Planck scale.

At least three very different scenarios:

- TeV-scale extra dimensions, including universal extra dimensions;

- Warped extra dimensions;

- Large extra diimensions.

All scenarios imply new physics at TeV scale.

Studies by ATLAS and CMS much less complete than for SUSY. Needs work! Will discuss existing results — some more work in progress.

Models test generality of ATLAS/CMS trigger/reconstruction.

# Universal/TeV-Scale Extra Dimensions

In Universal Extra Dimension (UED) models, all Standard Model particles propagate in $4 + \delta$ dimensional "bulk." Implies in 4-dimensions that each has tower of Kaluza-Klein (KK) excitations with masses set by $1/R \sim 1\,\mathrm{TeV}$.

Conservation of momentum in extra dimension $\Rightarrow$ conservation of KK number. Broken by loop effects $\Rightarrow$ only lightest KK mode ($\gamma_1$) stable.
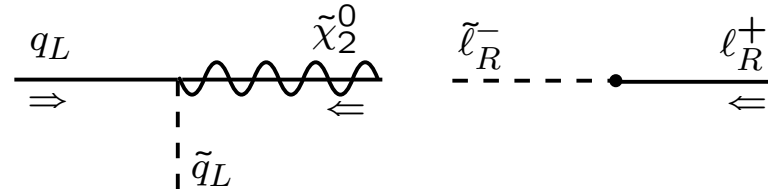
If only first KK modes seen, looks a lot like SUSY. Can have similar decay chains:

$$\mathrm{UED}: \qquad Q_1 \to Z_1 q \to \ell_1^{\pm} \ell^{\mp} q \to \gamma_1 \ell^+ \ell^- q$$

$$\mathrm{SUSY}: \qquad \tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\ell}^{\pm} \ell^{\mp} q \to \tilde{\chi}_1^0 \ell^+ \ell^- q$$

Only difference is the spins.

No public results from ATLAS or CMS (I think).

Can get some spin information: decay $\tilde{q}_L \to \tilde{\chi}_2^0 q$ produces $q_L$ and hence $\tilde{\chi}_2^0$ with helicity $\lambda = -1$:



Hence $\tilde{\chi}_2^0 \to \tilde{\ell}_R^\mp \ell^\pm$ distribution $\sim \left[ d_{-\frac{1}{2} \pm \frac{1}{2}}^{\left( \frac{1}{2} \right)} (\theta) \right]^2 \propto 1 \pm \cos\theta$.

Basic asymmetry suppressed by:

○ Cancellation between $\tilde{q}$ and $\bar{\tilde{q}}$. But for $pp$ machine valence quarks give excess of $\tilde{u}$ and $\tilde{d}$. (Suppresses effect of Higgsino mixing.)

○ Contribution of far (second) lepton.

Analysis done only for TDR Point 5 (fairly similar to SU3). Simulate detector response with Atlfast and make standard event selection cuts.

Even after dilutions, see difference between $\ell^+ q$ (red squares) and $\ell^- q$ (blue triangles). Clear asymmetry for $150\,\mathrm{fb}^{-1}$ [Barr]:
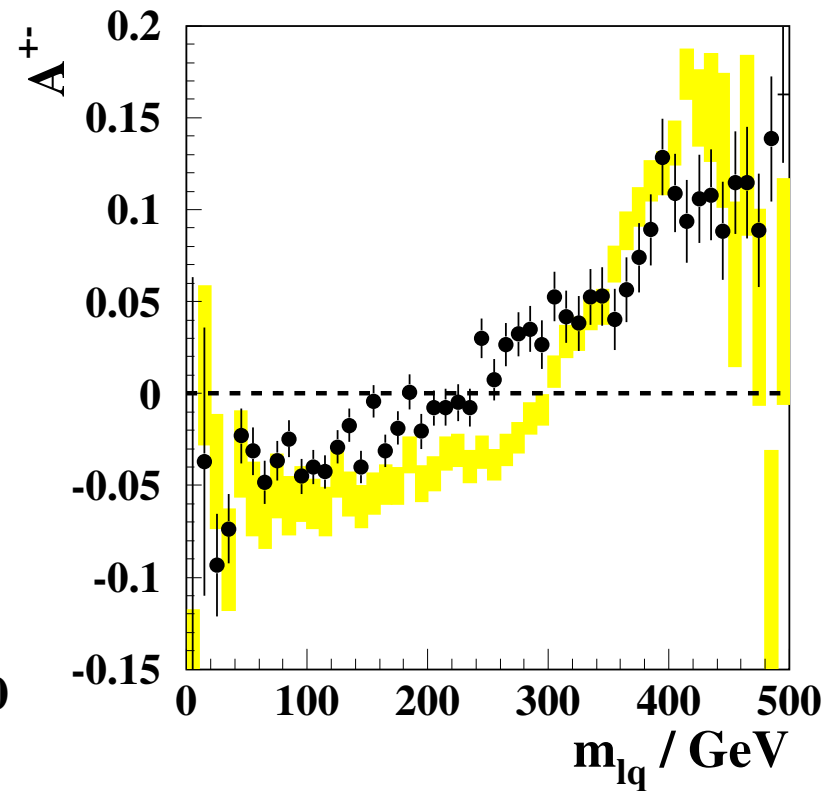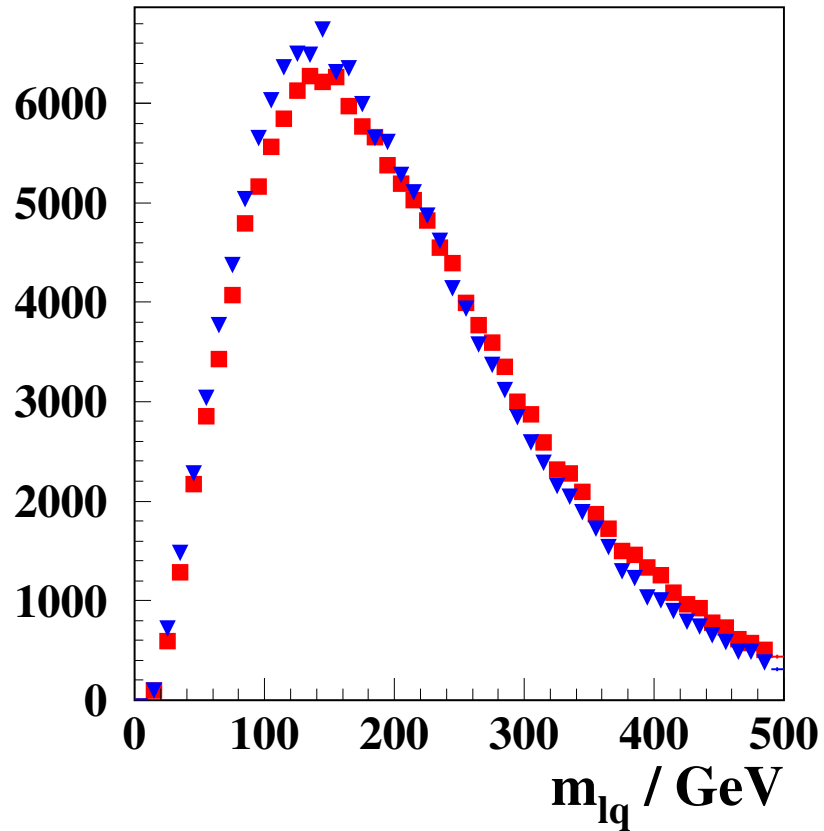
(Yellow rectangles show rescaled parton level distribution.)

Analysis shows non-zero spin for $\tilde{\chi}_2^0$ consistent with SUSY expectations. Comparison with UED?

What about $\tilde{\chi}_2^0 \to \tilde{\tau}^{\mp} \tau^{\pm}$?

TeV-scale extra dimensions can also have some particles in bulk and some on 3-brane, so KK parity not conserved. Two examples [Polesello]:
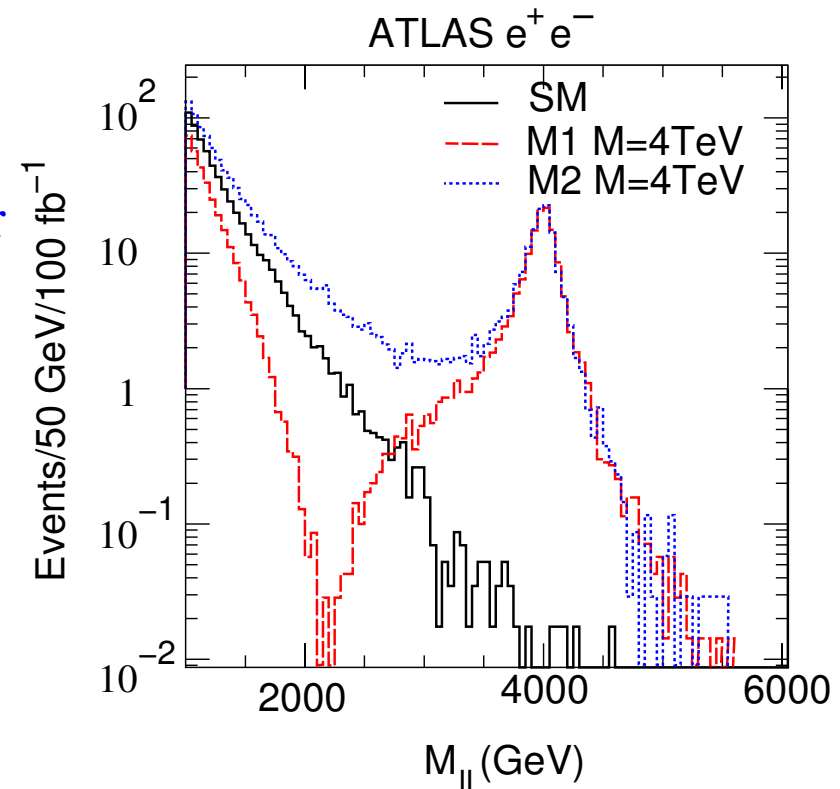
- M1: Gauge bosons in bulk, all fermions on same brane.

- M2: Gauge bosons in bulk, quarks and leptons on different branes.

Both give single prodcuction of KK gauge bosons interfering with SM.

If masses relatively low, see peak in $\ell^+\ell^-$ from KK production [Polesello].
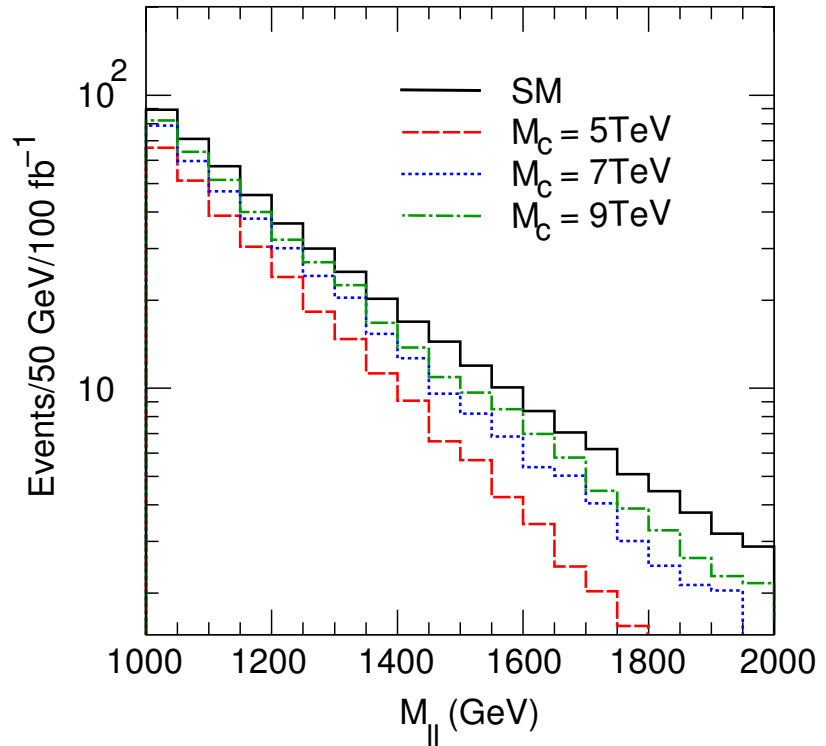
Destructive interence below peak for M1; constructive for M2.

Resolution better for $e^+e^-$ but $\mu^+\mu^-$ signal also observable.

Sensitive to masses beyond direct
production limit via interference
with SM continuum. Plot shows
results for model M1 with
destructive interference.

Error on fitted $M - c$ is $217\,\text{GeV}$ for
$M_c = 6\,\text{TeV}$ and $544\,\text{GeV}$ for
$M_c = 7\,\text{TeV}$.



ILC studies make frequent use of interference measurements like this.
Harder for $pp$ because of PDF uncertainties and large QCD corrections.
But still possible; needs further study.
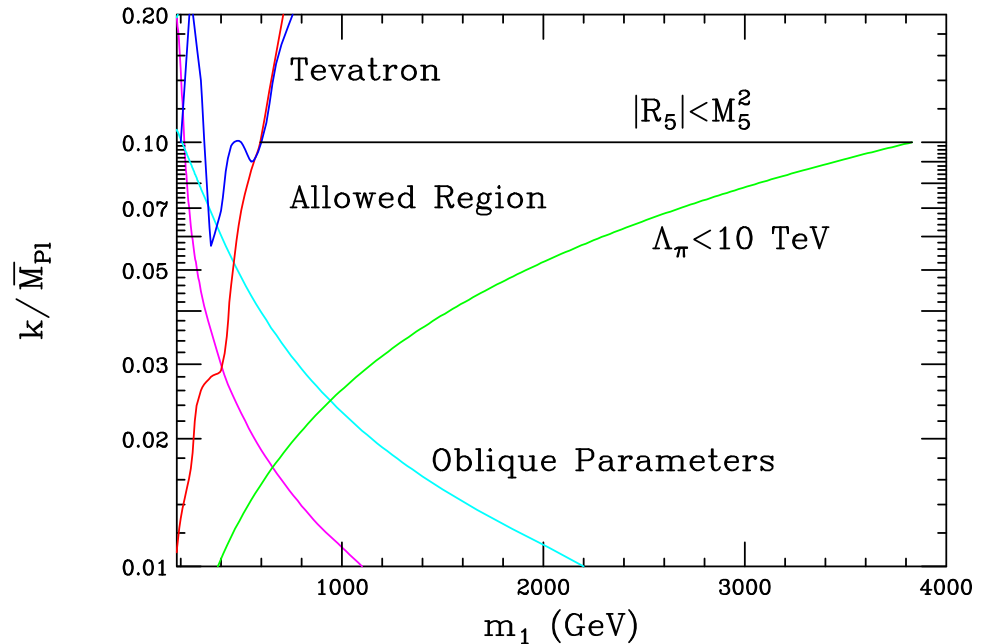
# Warped Extra Dimensions

Simplest version [RS1] has one (small) extra dimension with

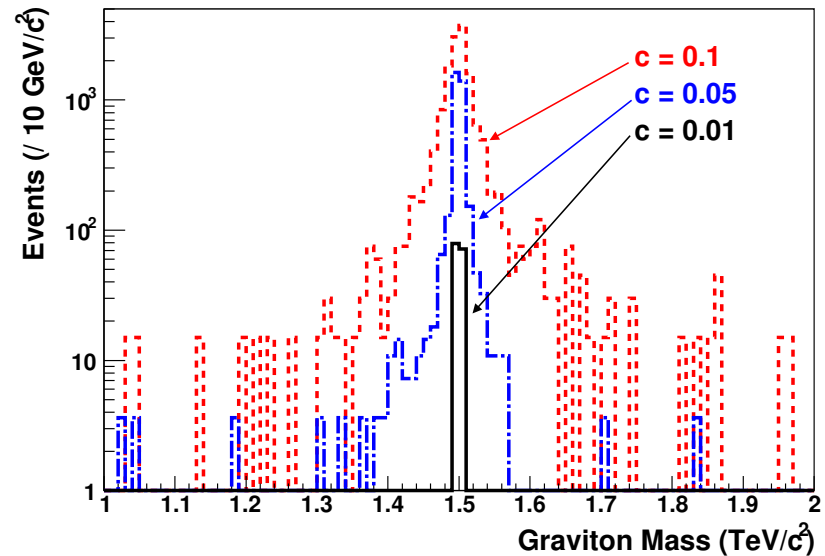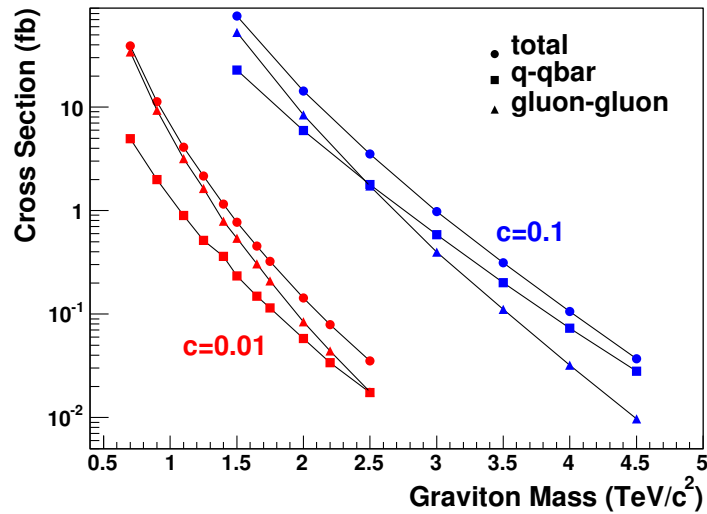$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2, \quad 0 < y < \pi.$$

Get $O(1\,\mathrm{TeV})$ masses on "TeV brane" if $kr_c \sim 10$. Predict graviton KK resonances with

$$m_n = kx_n e^{-kr_c\pi}, \quad J_1(x_n) = 0$$

Allowed region for lightest KK excitation and warp parameter $c = k/M_{\mathrm{Pl}}$ including theoretical and experimental constraints

[Davoudiasl].

Gravitons couple to everything: use $e^+e^-$ [Collard]. Cross sections are small $(0.1\text{--}10\,\text{fb}^{-1})$ but good signal:



Complication: CMS readout electronics saturate at such high energy. Correct highest energy crystal using 5 nearby ones. Important effect — *cannot* just use $\Delta E/E$ parameterization:
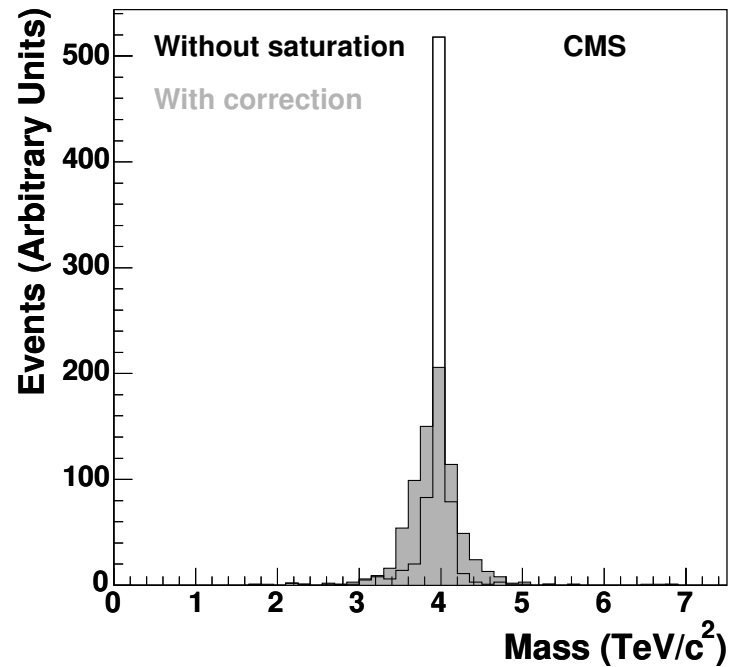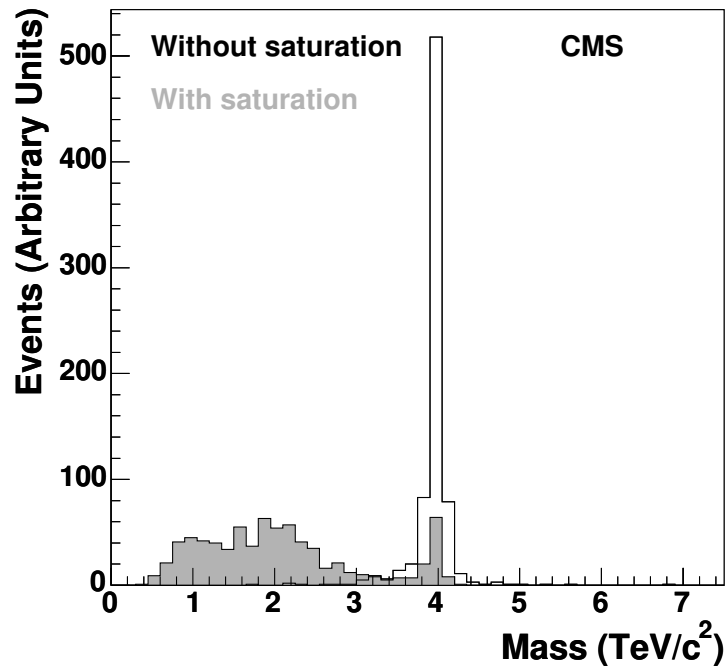
Obviously would see nothing with uncorrected performance. Corrected resolution worse than nominal, but not by much.

After correction can cover whole allowed range for Randall-Sundrum model with $100\,\mathrm{fb}^{-1}$:
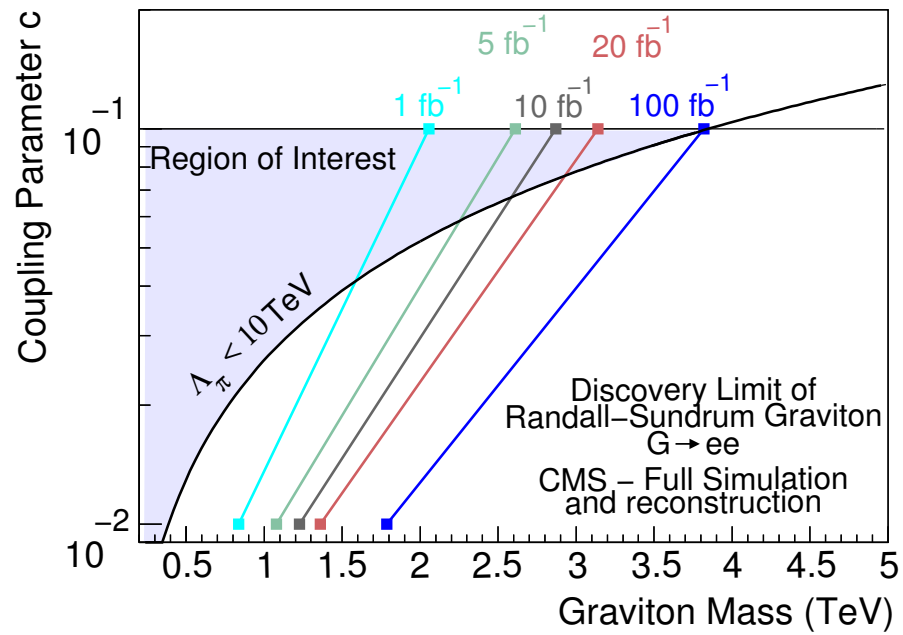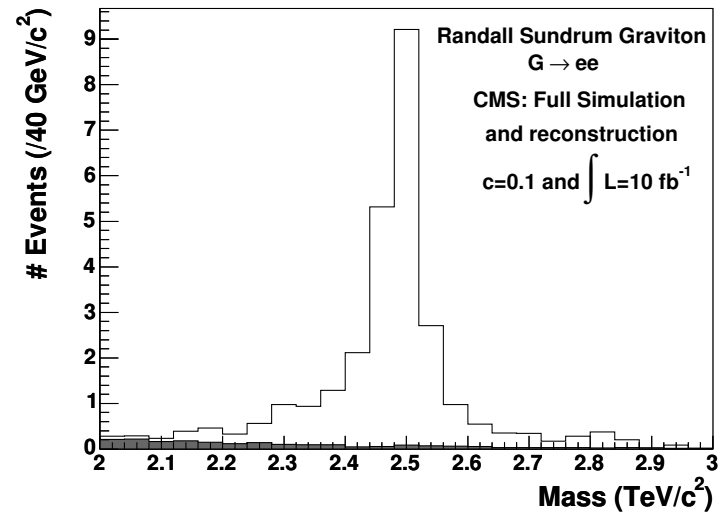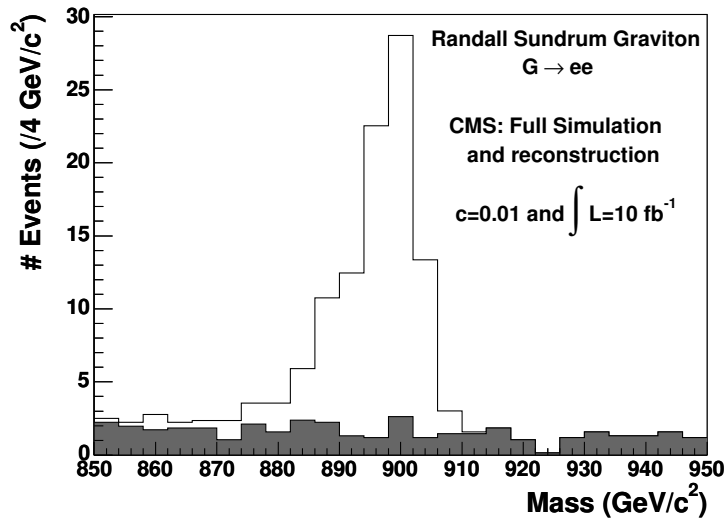
# Large Extra Dimensions

Large extra dimensions solve hierarchy problem by introducing $\delta$ large extra dimensions. Gauss's law $\Rightarrow$ 4-d Planck scale given by

$$\overline{M}_{\mathrm{Pl}}^2 = V_\delta \overline{M}_D^{2+\delta} \sim (2\pi R)^\delta \overline{M}_D^{2+\delta}$$
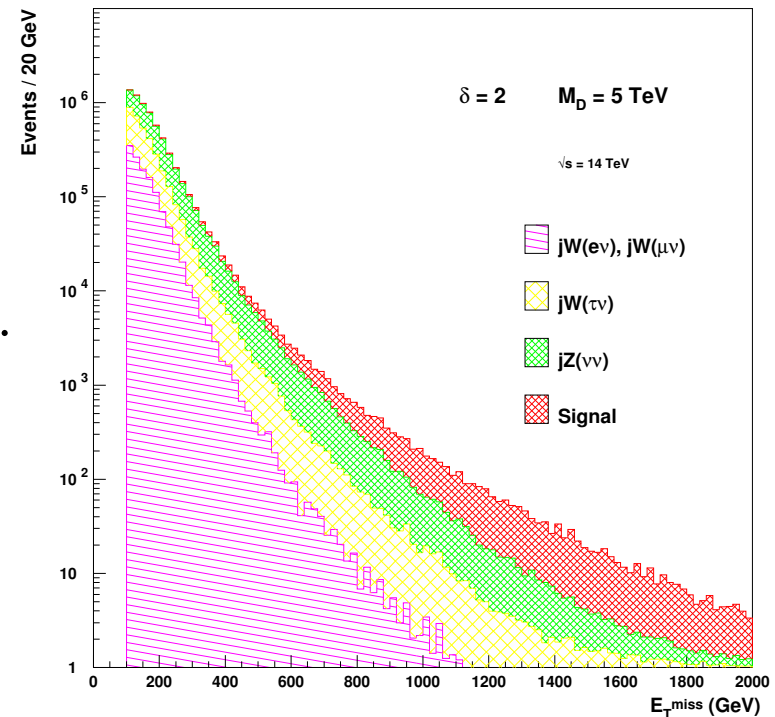
$\delta = 1$ ruled out by Newton, and $\delta = 2$ severely constrained.

For $Q \ll M_D$, signature is radiation of closely spaced KK gravitions.

Hence observe jet $+ \not{E}_T$, $\gamma + \not{E}_T$, etc. Good $S/B$ from fast simulation [Vacavant].

Need full simulation study to understand backgrounds from mismeasured jets.

Much more interesting physics if $Q \gtrsim M_D$. Schwarzschild radius for black hole in $4 + \delta$ dimensions is

$$r_{\text{BH}} = \frac{1}{\sqrt{\pi} M_D} \left( \frac{M_{\text{BH}}}{M_D} \right)^{\frac{1}{\delta+1}} \left( \frac{8 \Gamma \left( \frac{\delta+3}{2} \right)}{\delta+2} \right)^{\frac{1}{\delta+1}}$$

If partons collide with $\sqrt{\hat{s}} \gtrsim M_D$, expect to produce black holes with

$$\sigma \sim \pi r_{\text{BH}}^2.$$

Immediately decay via Hawking radiation with temperature

$$T_H = \frac{\delta+1}{4\pi R_{\text{BH}}}$$
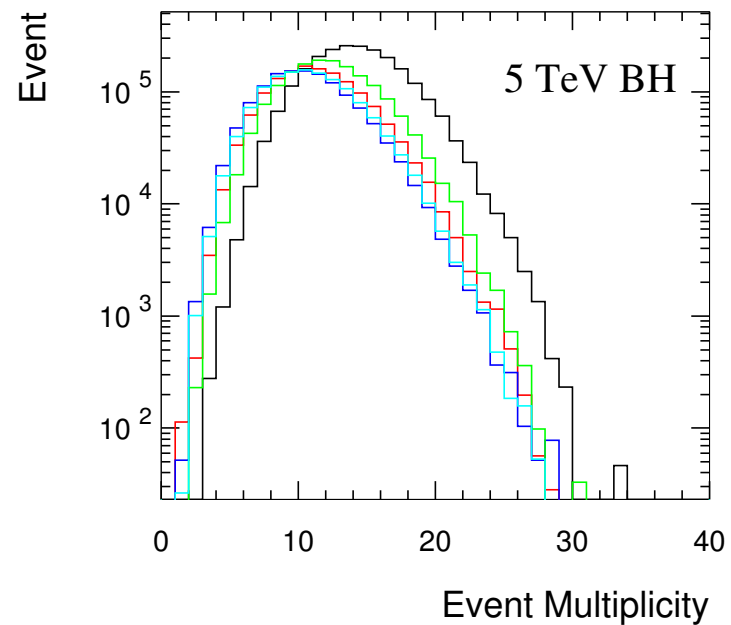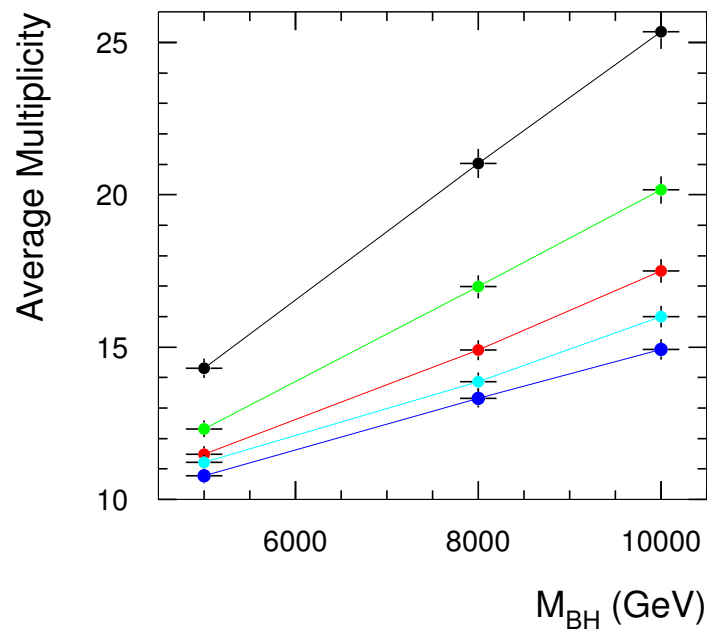
End of high-energy, short-distance physics … and start of experimental string physics.

Best available generator [Charybdis] includes black-body radiation modified by "grey-body" factors and simple model for remnant decay.

Expect stringy modifications for $Q \sim M_D$. Not understood.

Events have high multiplicity of Standard Model quanta ($\delta = 2$–$6$ from top to bottom):

Total transverse momentum is also large. Can reconstruct total mass by summing all reconstructed objects.

Require at least four jets, three with $p_T > 500, 400, 300\,\text{GeV}$. Also require $\not{E}_T < 100\,\text{GeV}$ to minimize neutrinos.

Find good agreement with true masses (shown for $\delta = 2$):



| Constant | 0.8685E+05 |
| Mean | -83.23 |
| Sigma | 202.1 |

5 TeV BH

| Constant | 373.9 |
| Mean | -285.9 |
| Sigma | 293.9 |

8 TeV BH

$M_{BH}^{rec.} - M_{BH}^{True}$ (GeV)
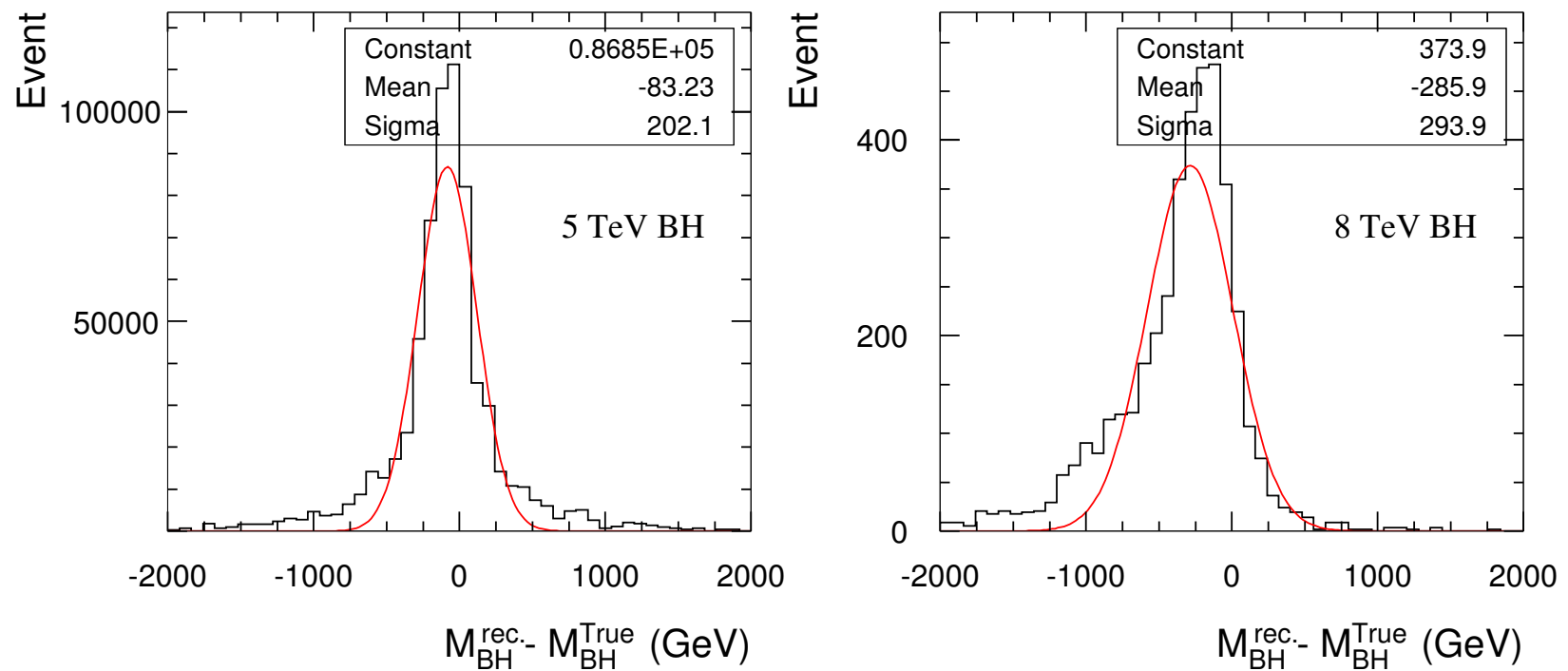
# Extra Dimension Summary

Many extra-dimension models. Based on string theory ideas, so less precise than SUSY models with well-defined field theory. But plausible candidates for new physics.

ATLAS/CMS have studied several examples. Need more systematic study with emphasis on signatures that stress detectors in new ways.

Most dramatic example is black hole production $\Rightarrow$ very complex events.

# Summary

Standard Model is very successful but fails to address several crucial issues. Speculation about physics beyond the Standard Model at TeV mass scale has been ongoing for at least 25 years.

Can only resolve such speculation by experiments capable of probing TeV mass scale. LHC can do this starting in about two years.

ATLAS and CMS are expending a lot of effort to understand how to extract physics from data.

Need more effort on new physics signatures and Standard Model backgrounds to optimize return on huge investment in LHC and detectors:

ATLAS/CMS will start in $\sim$ 2007 and dominate particle physics for many years. Huge potential for SM/BSM physics. US has good involvement in hardware and software, but still limited in physics. Please join!

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