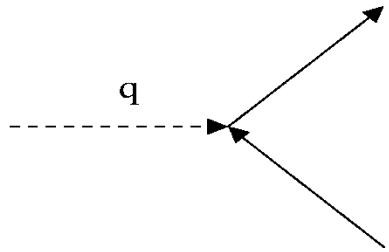
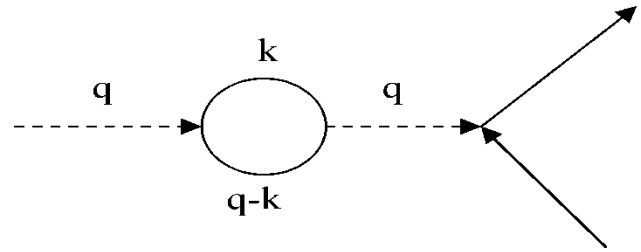
Outline – IV, GUTS, SUSY, Dark Matter, Dark Energy

- Running Coupling Constants
  - QED
  - Standard Model
  - Unification
- SUSY
  - Unification
  - Production
  - LHC Searches
  - SUSY Spectroscopy at the LHC
- Dark Matter
  - SUSY DM
  - Direct Searches
  - Annihilation
- Dark Energy

Running of α in QED





$$A \sim < f\,|V(r)|\,i > \sim \int e^{i\vec{k}_f\cdot\vec{r}} V(r) e^{-i\vec{k}_i\cdot\vec{r}} d\vec{r} \sim \int e^{i\vec{q}\cdot\vec{r}} V(r) d\vec{r} = V(\vec{q})$$

$$\delta A \sim \alpha^2 \int dk^4 (1/q^2)[1/(\not{k}+m)][1/((\not{q}-\not{k})+m)](1/q^2)$$

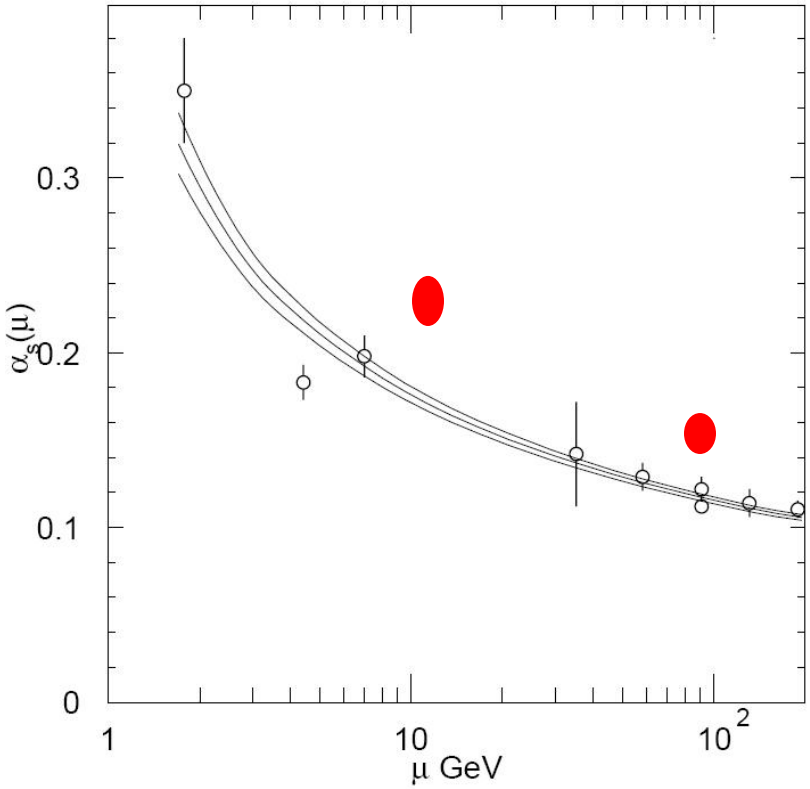
$$A \sim \alpha / q^2 \{1 - \alpha / 12\pi [\ln(\Lambda^2/m^2) + \ln(-q^2/m^2)]\}$$

$$A \sim \alpha_R(m^2)/q^2 [1 + \alpha_R(m^2)/12\pi \ln(-q^2/m^2)]$$

$$1/\alpha_R(Q^2) = 1/\alpha_R(m^2) - 1/12\pi \ln(Q^2/m^2)$$

Diverges – need a cutoff. However, can still connect different scales, Q and m. Done to all orders in perturbation theory. The ln(Q²) behavior is typical. Lamb shift

"Running" of α_s



$$1/\alpha_s(\Lambda_{QCD}^2) = 0$$

$$\Lambda_{QCD} \sim 0.2\ GeV \sim 1\ fm$$

Energy below which strong interaction is strong

$$\alpha_S((1\ \ GeV)^2) = 0.55$$

$$\alpha_S((10\ \ GeV)^2) = 0.23$$

$$\alpha_S(M_Z{}^2) = 0.15$$

$$1/\alpha_s(Q^2) = 1/\alpha_s(\Lambda^2) + b\ln(Q^2/\Lambda^2)$$

$$\alpha_s(Q^2) = [12\pi/(33-2n_f)]/\ln(Q^2/\Lambda_{QCD}{}^2)]$$

Running of EW and QCD Coupling "Constants"

In electromagnetism the e+e- vacuum pairs shield the "bare" charge which means that electromagnetism gets stronger at shorter distances; b = - 2nf/12π, where nf is the number of fermions that can make virtual pairs at a scale Q. In SU(3) the strong interactions become weak at short distances. This is because the gluons themselves carry a color charge whereas the photon is uncharged. Likewise the W and Z, SU(2), self-couple having triplet vertices - because they carry weak "charge". Thus we expect that the SU(2) coupling strength also gets weaker with increasing mass scale due to an anti-screening of the weak charge

$$1/\alpha(Q^2) = 1/\alpha(m^2) + b[ln(Q^2/m^2)].$$

$$b_3 = (33 - 2n_f)/12$$

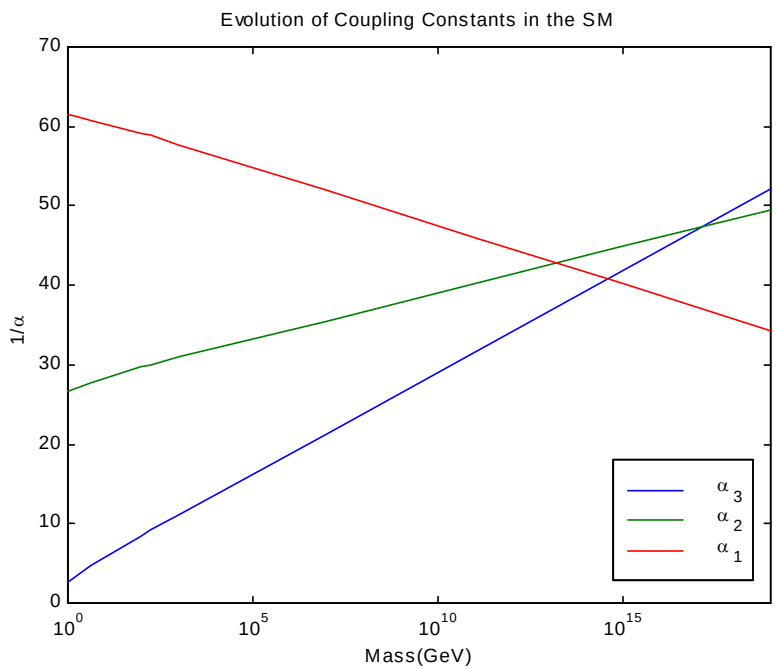
$$b_2 = (22 - 2n_f - ½)/12$$

$$b_1 = -2n_f/12$$

+ factors ➔ antiscreening by bosons, - factors ➔ screening by fermions.

Grand Unified Theories

- Perhaps the strong and electroweak forces are related. In that case leptons and quarks would make transitions and p would be unstable. The unification mass scale of a GUT must be large enough so that the decay rate for p is < the rate limit set by experiment.
- The coupling constants "run" in quantum field theories due to vacuum fluctuations. For example, in EM the e charge is shielded by virtual γ fluctuations into e^+e^- pairs on a distance scale set by, $\lambda_e \sim 1/m_e$. Thus α increases as M increases (logarithmically), $\alpha(0) = 1/137$, $\alpha(M_Z) = 1/128$.



Assume no new Physics. "Run" the coupling "constants" to a high mass. Observe approximate unification of the forces. Note smallness of neutrino masses is consistent with a high mass scale (see-saw).

Why is the Universe Made of Matter?

- The present state of the Universe is very matter-antimatter asymmetric.
- The necessary conditions for such an asymmetry are that CP is violated, that Baryon number is not conserved, and that the Universe went through a phase out of thermal equilibrium.
- The existence of 3 generations allows for CP violation and it has been observed in decays of K and B mesons.
- The GUT has, of necessity, baryon non-conserving reactions due to lepto-quarks.
- Thus the possibility to explain the asymmetry exists in GUTs, although agreement with the data, $N_B/N_\gamma \sim 10^{-9}$, and calculation may not be plausible.

Why is Charge Quantized?

- There appears to be approximate unification of the couplings at a mass scale $M_{GUT} \sim 10^{14}$ GeV.
- Then we combine quarks and leptons into GUT multiplets - the simplest possibility being SU(5).

$$[d_R\ d_B\ d_G\ e\ \nu] = 3(-1/3\ ) + 1 + 0 = 0$$

- Since the sum of the projections of a group generator in a group multiplet is = 0 (e.g. the angular momentum sum of m), then charge must be quantized in units of the electron charge.
- In addition, we see that quarks must have 1/3 fractional charge because there are 3 colors of quarks - SU(3).

A GUT Mass Scale?

$$m_\nu \sim m_q^2/M_{GUT} \sim 10^{-12} - 10^{-6} - 10^{-2}\ eV$$

The smallness of the neutrino masses implies a large mass scale – the "seesaw" mechanism

$$m_d = m_e \quad (3\text{-}9)\ \text{MeV} = 0.5\ \text{MeV}$$
$$m_s = m_\mu \quad (60 - 170)\ \text{MeV} = 105\ \text{MeV}$$
$$m_b = m_\tau \quad (4.1 - 4.8)\ \text{GeV} = 1.78\ \text{GeV}$$

The quarks and leptons differ only in color – so at a GUT scale they should have the same mass in the same generation

Why is Matter (protons) ~ Stable?

- There is no gauge motivated conservation law making protons stable.
- Indeed, SU(5) relates quarks and leptons and possesses "leptoquarks" with masses ~ the GUT mass scale.
- Thus we expect protons (uud) to decay via $u+u \rightarrow e^{+}+\bar{d}$,
- $u+d \rightarrow \bar{\nu}_e+\bar{d}$. Thus $p \rightarrow e^{+} + \pi^{o}$ or $\nu + \pi^{+}$, $\pi^{o} = u\bar{u}, d\bar{d}$ and $\pi^{+} = u\bar{d}$
- Looking at the GUT extrapolation, we find $1/\alpha \sim 40$ at a GUT mass of ~ 10^{15} GeV.
- One dimensional grounds, the proton lifetime should be
- $\Gamma_p = 1/\tau_p \sim \alpha_{GUT}^2 (m_p/M_{GUT})^4 m_p$ or $\tau_p \sim 4 \times 10^{31}$ *yr*.
- Recall the m^5 quark weak decay widths.
- The current experimental limit is 10^{32} yr The limit is in disagreement with a careful estimate of the p decay lifetime in simple SU(5) GUT models. Thus we need to look a bit harder at the grand unification scheme.

GUT Predicts θ_W

- A GUT has a single gauge coupling constant for the single gauge group – SU(5) ?. Thus, α and α_W must be related. The SU(5) prediction is that $\sin(\theta_W) = e/g = \sqrt{3/8}$, $\sin^2\theta_W = 0.375$.
- This prediction applies only at M_{GUT}
- Running α_1 and α_2 back down to the Z mass, the prediction becomes;

$$\sin^2\theta_W(M_Z^2) \sim (3/8)/[1 + b\ln(M_Z^2/M_{GUT}^2)], \text{ with } b = 55\alpha(M_{GUT}^2)/18\pi$$

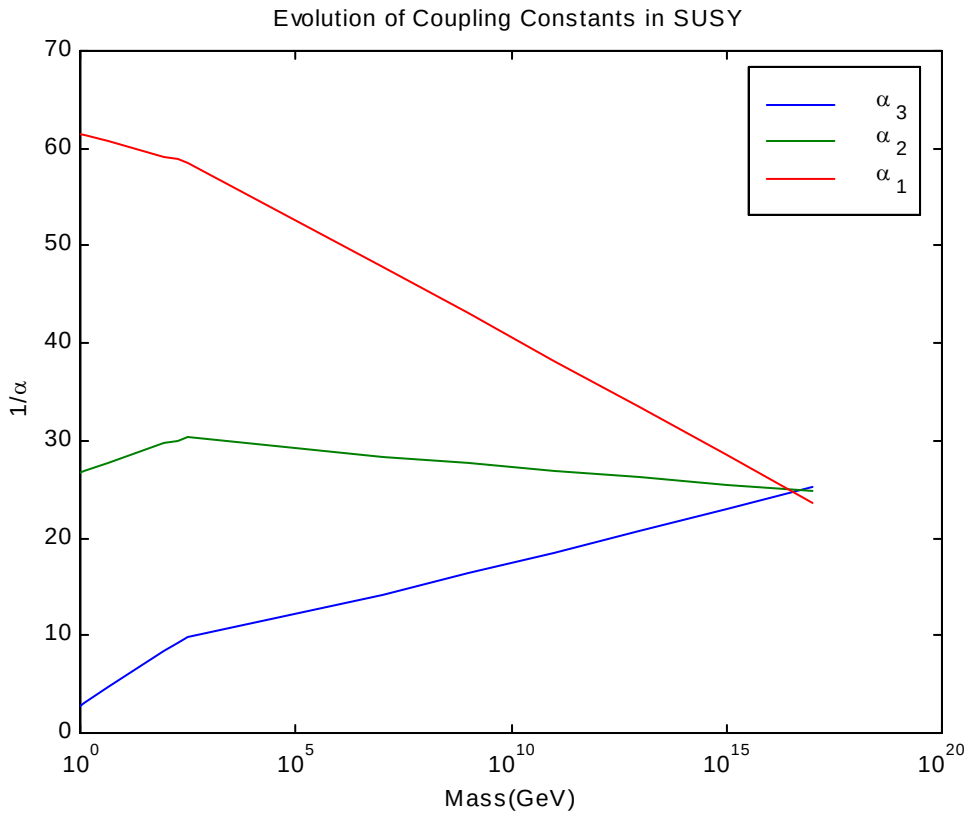
- This prediction, 0.206, is in ~ agreement with the measurement of θ_W from the W and Z masses, $\sin^2\theta_W = 0.231$. Recall that in the SM the Weinberg angle is a free parameter.

SUSY - Fermion/Boson Symmetry, a Specific GUT

Why SUSY?

- **GUT Mass scale - unification works with SUSY**
- **Improved Weinberg angle prediction**
- **p decay rate slowed consistent with present limits.**
- **Mass hierarchy protected Planck/EW**
- **Dark matter candidate**
- **String connections, local SUSY and gravity.**
- **Last possible Poincare symmetry - if not prohibited a symmetry is mandatory**

GUT and Evolution of α



SUSY particles intervene at masses ~ (100,1000) GeV. The modified loop running improves the convergence at the GUT mass.

$$M_{GUT} = 2 \times 10^{16} \text{ GeV and } 1/\alpha_{GUT} \sim 24$$

Unification?

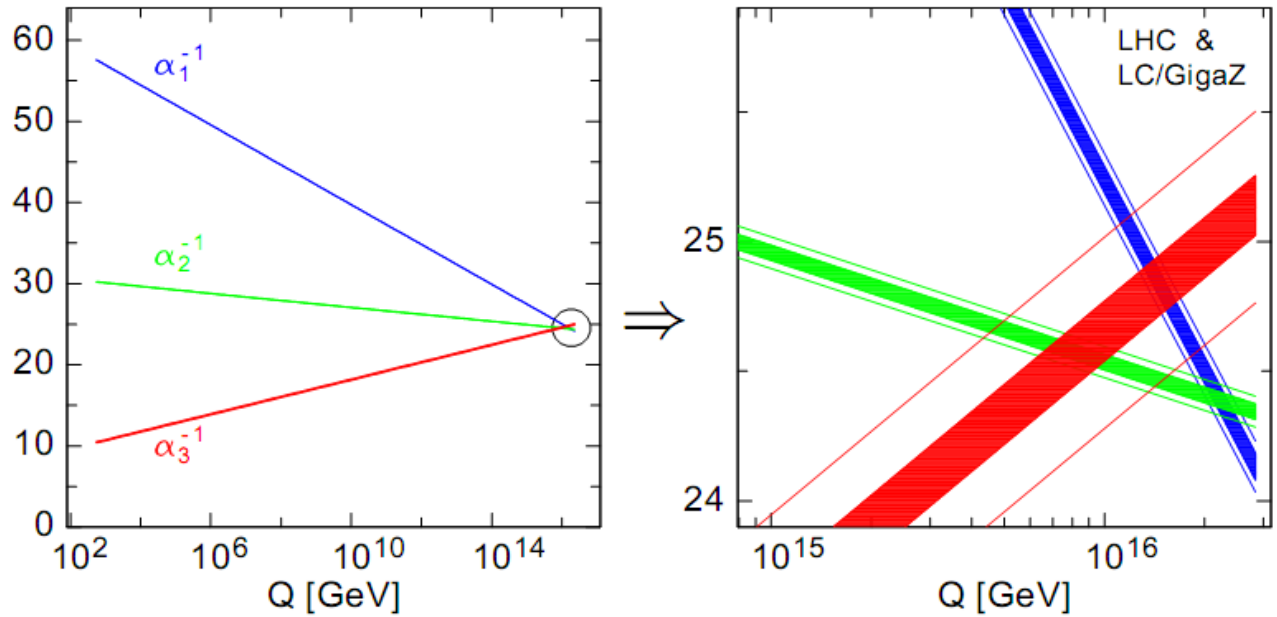


Figure 3: *(a) Running of the inverse gauge couplings from low to high energies. (b) Expansion of the area around the unification point M_U defined by the meeting point of α_1 with α_2. The wide error bands are based on present data, and the spectrum of supersymmetric particles from LHC measurements within mSUGRA. The narrow bands demonstrate the improvement expected by future GigaZ analyses and the measurement of the complete spectrum at "LHC+LC".*

Within present errors there is unification. Better measurements (especially at LHC) would sharpen the conclusion

SUSY Predictions

- The decay of protons is slowed (recall M_{GUT}^{-4} dependence) in SUSY-GUT removing the conflict with experimental upper limits. The proton is quasi-stable because M_{GUT} is very large.
- The 2 mass scales, M_{GUT} and M_Z make SU(5) without SUSY difficult to keep stable under radiative (loop) corrections. If the Higgs mass is fixed at the GUT scale, then there is a quadratic divergence in running down to the Z mass scale. Thus 2 numbers of order M_{GUT} must subtract to a number of order M_Z. $\delta M_H^2 \sim (\alpha_{GUT}/\pi)(M_{GUT}{}^2)$
- In unbroken SUSY the SUSY partners of the SM particles are mass degenerate, and thus the loop corrections vanish, solving the "hierarchy problem".
- With SUSY breaking, the Higgs mass gets radiative corrections due to the differences of masses of the SUSY and SM partners.

$$\delta M_H^2 \sim (\alpha_{GUT}/\pi)(M_{SUSY}^2 - M^2)$$

- SUSY requires that the Higgs has a mass ~ the Z mass. Radiative corrections --> M_H < 130 GeV. Thus in SUSY a light Higgs is expected.
- Therefore, SUSY solves the hierarchy problem, but only if M_{SUSY} is < 1 TeV, and hence also accessible at the LHC.

$$\delta M_H^2 \sim 3\alpha_W / 2\pi (m_t / M_W)^2 m_t^2 [\ln(M_{SUSY}^2 / m_t^2)]$$

SUSY Search Strategy

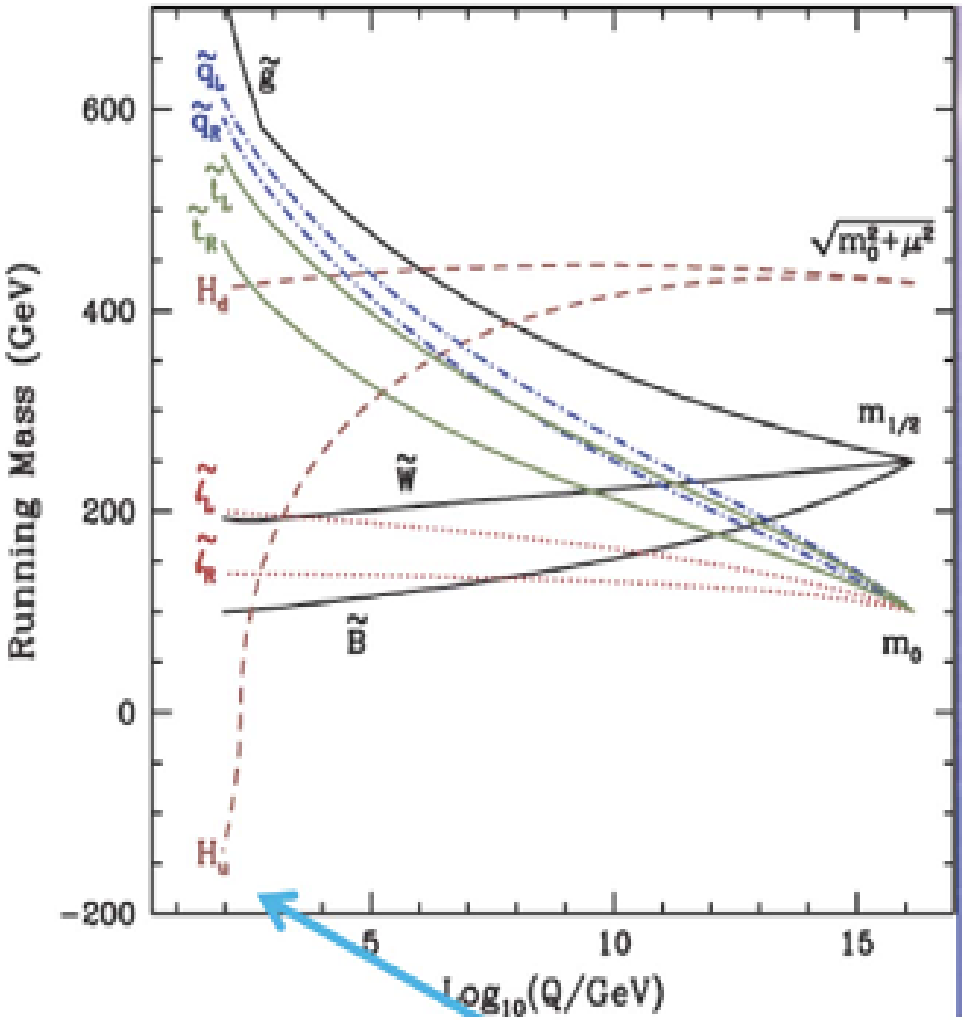
inclusive supersymmetry

- the dominant production of superparticles at LHC is through pairs of gluinos and squarks
- their cascade decays produce high PT jets and large missing energy
- a simple discriminant for inclusive SUSY searches is the effective mass defined as

$$M_{eff} = E_T^{miss} + \sum_{i=1}^{4} P_T^{jet}$$

- an excess of events with large M_{eff} or H_T could be the initial discovery of supersymmetry

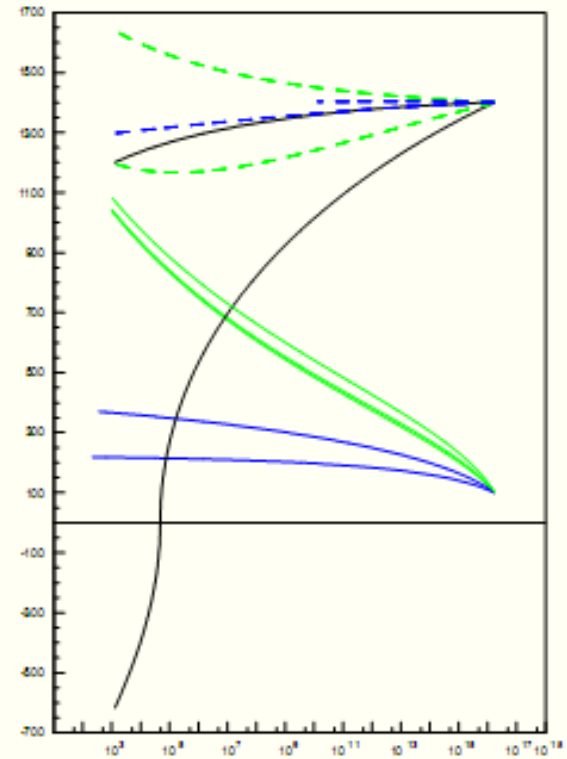
Running of SUSY Masses



Assume 2 masses at GUT scale. When particles run down to TeV scale the strongly interacting squarks and gluinos acquire the largest masses. They are produced strongly and cascade decay to ligher particles giving the classic "SUSY signature"

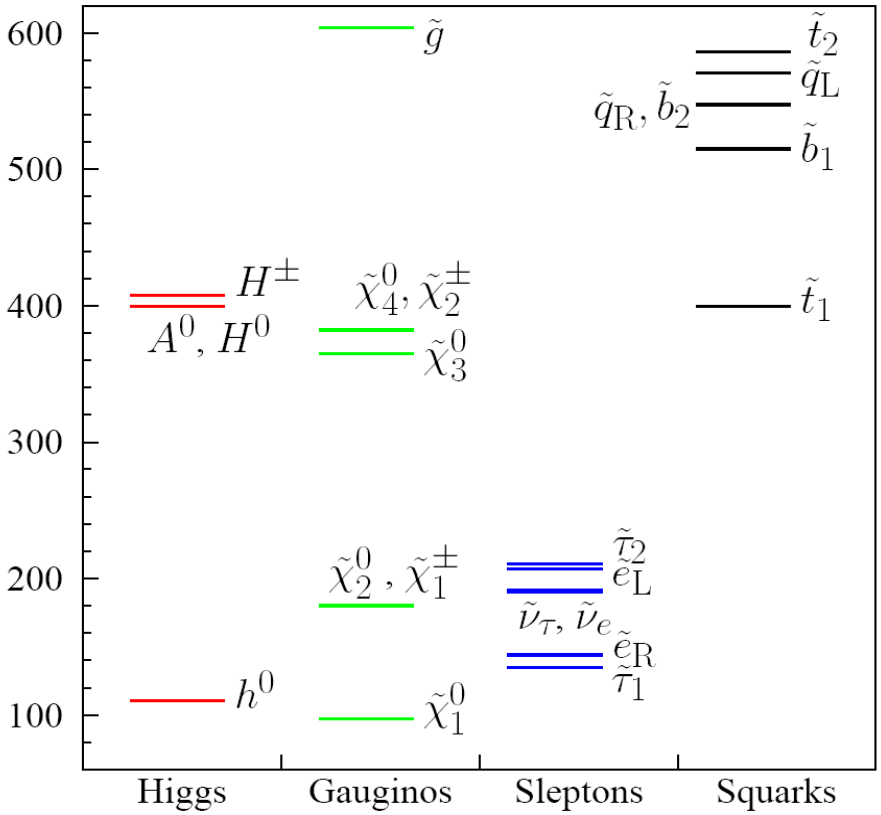
SUSY – MSSM Constraints

- Normal scalar mass hierarchy (NMH):
- $BF(b \to s\gamma)$ prefers heavy 3rd gen. squarks
- $(g-2)_\mu$ prefers light 2nd gen. sleptons
- $m_0(1) \simeq m_0(2) \ll m_0(3)$
  - (preserve FCNC bounds)
- motivation: reconcile $BF(b \to s\gamma)$ with $(g-2)_\mu$
  - HB, Belyaev, Krupovnickas, Mustafayev
  - JHEP 0406, 044 (2004)



SUSY is simple; it is the details of the breaking that allow so many possibilities. There are also experimental constraints due to loop contributions of SUSY. -> NMSSM

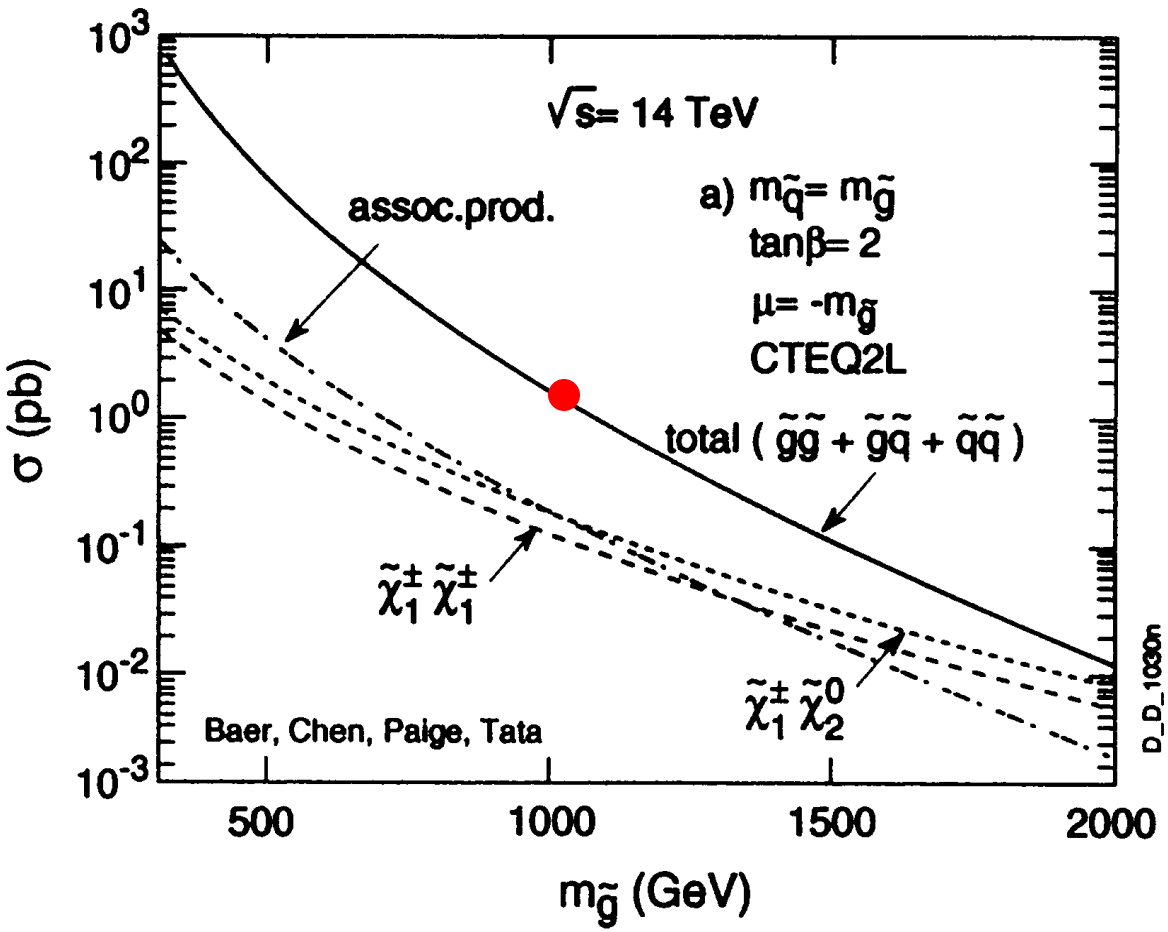
MSSM Mass Spectrum



SM Particles	SUSY Particles		
quarks: q	$\tilde{q}$	squarks: $\tilde{q}$	
leptons: l	$\tilde{l}$	sleptons: $\tilde{l}$	
gluons: g	$\tilde{g}$	gluino: $\tilde{g}$	
charged weak boson: $W^\pm$	$W^\pm$	Wino: $\tilde{W}^\pm$	$\tilde{\chi}^\pm_{1,2}$ chargino
Higgs: H^0	$H^\pm$	charged higgsino: $\tilde{H}^\pm$	
	h^0, A^0, H^0	neutral higgsino: $\tilde{h}^0, \tilde{A}^0$	
neutral weak boson: Z^0	Z^0	Zino: $\tilde{Z}^0$	$\tilde{\chi}^0_{1,2,3,4}$ neutralino
photon: γ	γ	photino: $\tilde{\gamma}$	

MSSM has ~ SM light h and ~ mass degenerate H,A. LSP is a neutralino. Squarks and gluinos are heavy, sleptons are light. Recall in EW the Wo and B mix to make the Z and γ

SUSY Cross Sections



The SUSY cross sections for squarks and gluinos are large because they have strong couplings. R parity means cascade decays to LSP. Simplest signature is jets and MET, independent of specific SUSY model.

Dimensionally

$\sigma \sim \alpha_s^2/(2M)^2$

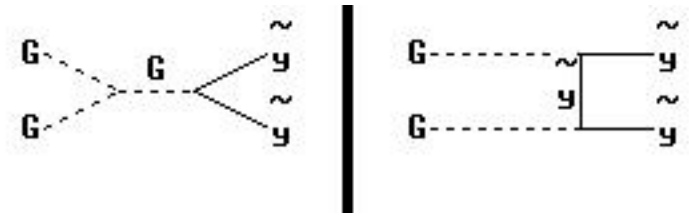
or ~ 1 pb for M = 1 TeV.

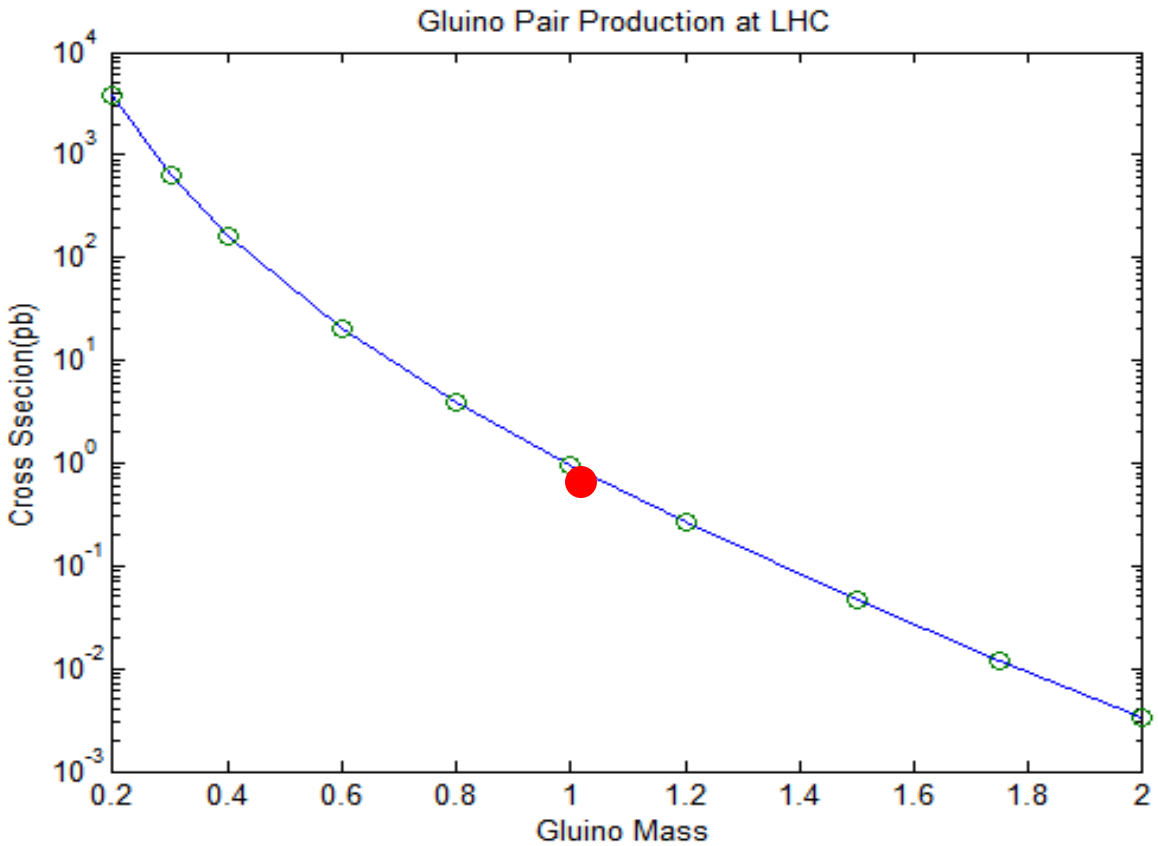
SUSY Models in CalcHEP

Full name	P	aP	2*spin	mass	width	color
photon	A	A	2	0	0	1
Z boson	Z	Z	2	MZ	wZ	1
W boson	W+	W-	2	MW	wW	1
gluon	G	G	2	0	0	8
neutrino	n1	N1	1	0	0	1
electron	e1	E1	1	0	0	1
mu-neutrino	n2	N2	1	0	0	1
muon	e2	E2	1	Mm	0	1
tau-neutrino	n3	N3	1	0	0	1
tau-lepton	e3	E3	1	Mt	0	1
u-quark	u	U	1	0	0	3
d-quark	d	D	1	0	0	3
c-quark	c	C	1	Mc	0	3
s-quark	s	S	1	Ms	0	3
t-quark	t	T	1	Mtop	wtop	3
b-quark	b	B	1	Mb	0	3
Light Higgs	h	h	0	Mh	wh	1
Heavy higgs	H	H	0	MHH	wHh	1
CP-odd Higgs	H3	H3	0	MH3	wH3	1
Charged Higgs	H+	H-	0	MHc	wHc	1
chargino 1	~1+	~1-	1	MC1	wC1	1
chargino 2	~2+	~2-	1	MC2	wC2	1
neutralino 1	~o1	~o1	1	MNE1	0	1
neutralino 2	~o2	~o2	1	MNE2	wNE2	1
neutralino 3	~o3	~o3	1	MNE3	wNE3	1
neutralino 4	~o4	~o4	1	MNE4	wNE4	1
gluino	~g	~g	1	MSG	wSG	8
1st selectron	~e1	~E1	0	MSe1	wSe1	1
2nd selectron	~e4	~E4	0	MSe2	wSe2	1
1st smuon	~e2	~E2	0	MSmu1	wSmu1	1
2nd smuon	~e5	~E5	0	MSmu2	wSmu2	1
1st stau	~e3	~E3	0	MStau1	wStau1	1
2nd stau	~e6	~E6	0	MStau2	wStau2	1
e-sneutrino	~n1	~N1	0	MSne	wSne	1
m-sneutrino	~n2	~N2	0	MSnmu	wSnmu	1
t-sneutrino	~n3	~N3	0	MSntau	wSntau	1
u-squark 1	~u1	~U1	0	MSu1	wSu1	3
u-squark 2	~u2	~U2	0	MSu2	wSu2	3
d-squark 1	~d1	~D1	0	MSd1	wSd1	3
d-squark 2	~d2	~D2	0	MSd2	wSd2	3

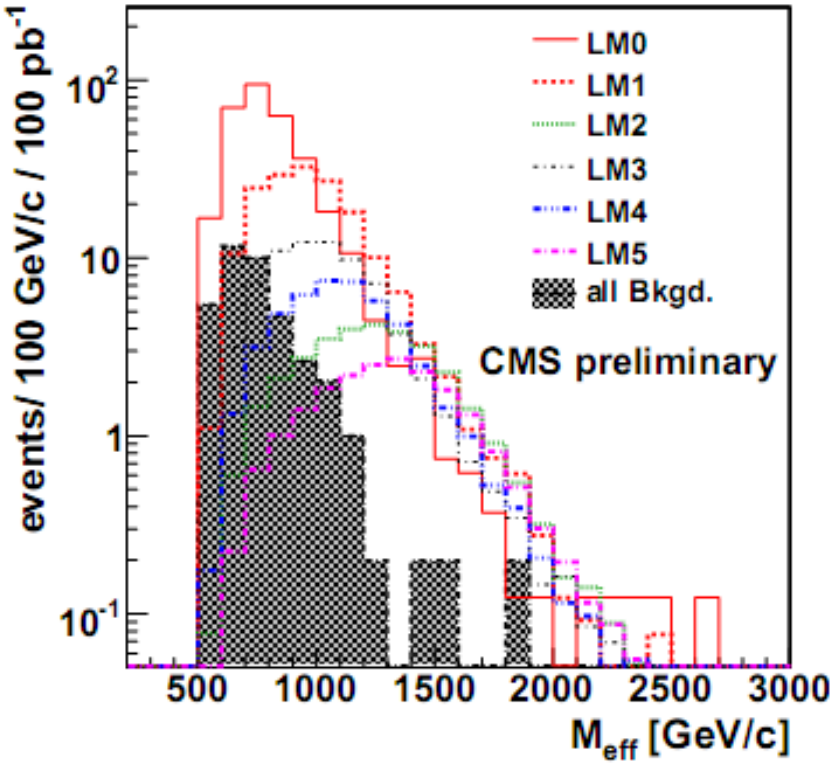
With CalcHEP there are many possibilities to look at parameter changes in MSSM and NMMSM

COMPHEP – Gluino Pairs at LHC



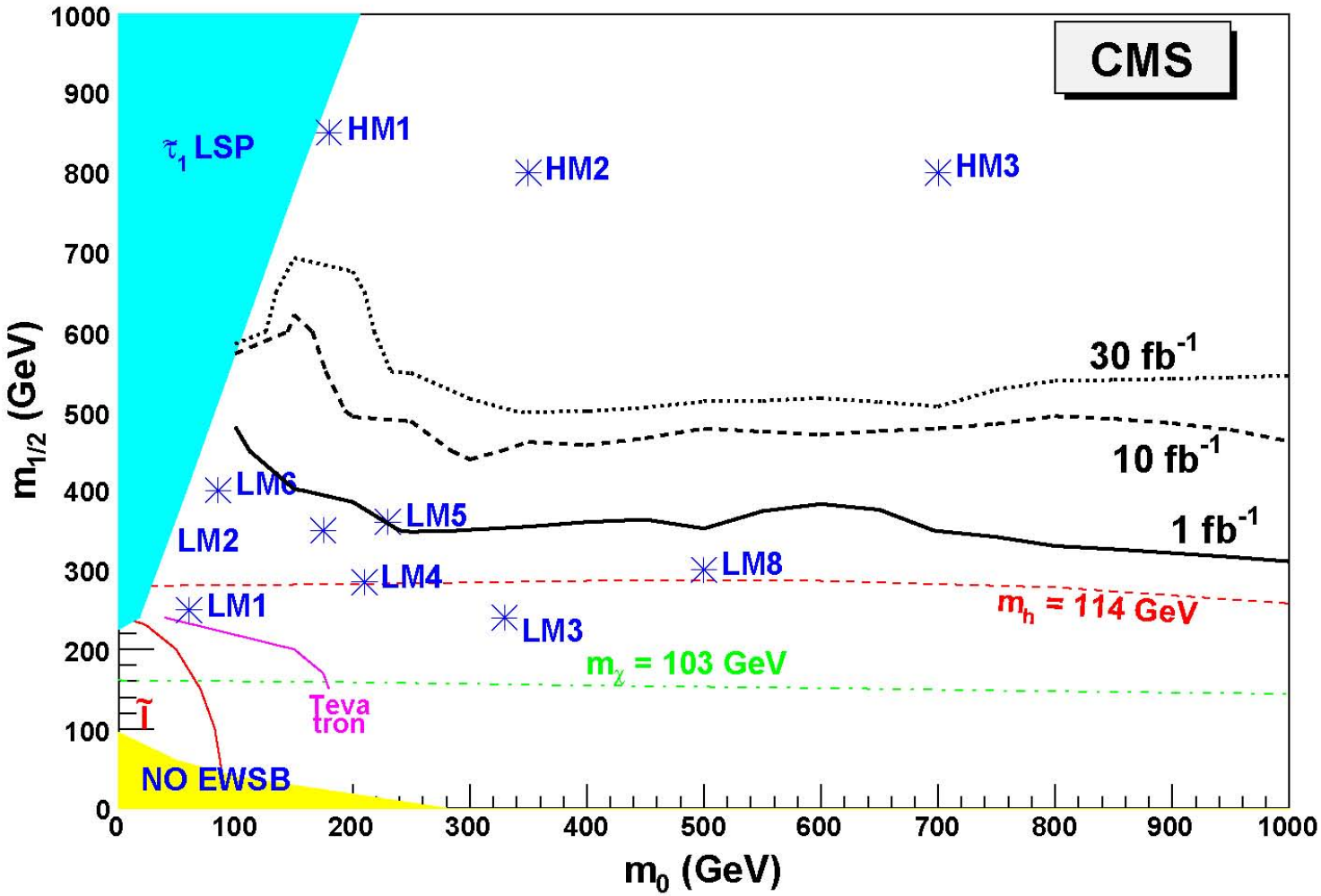


SUSY in Jets + MET

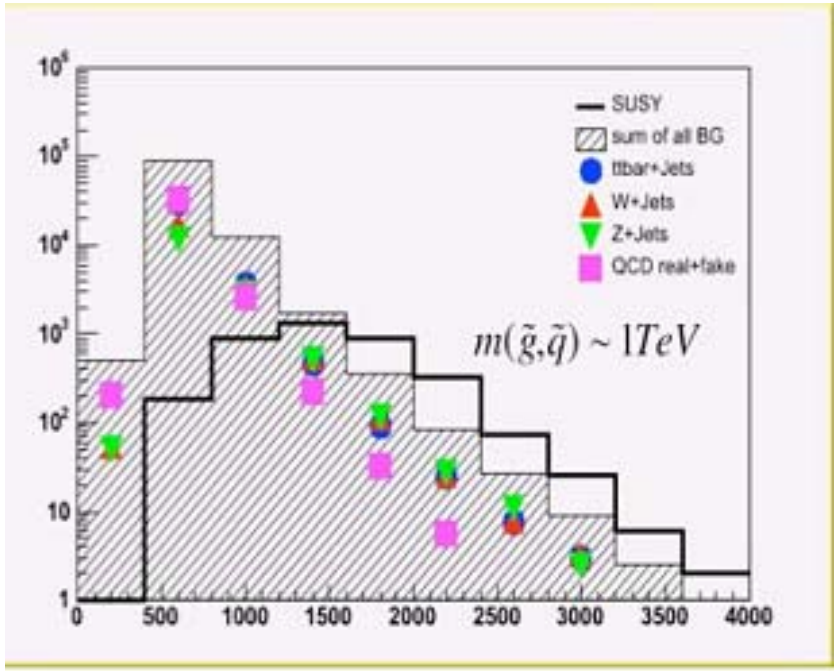


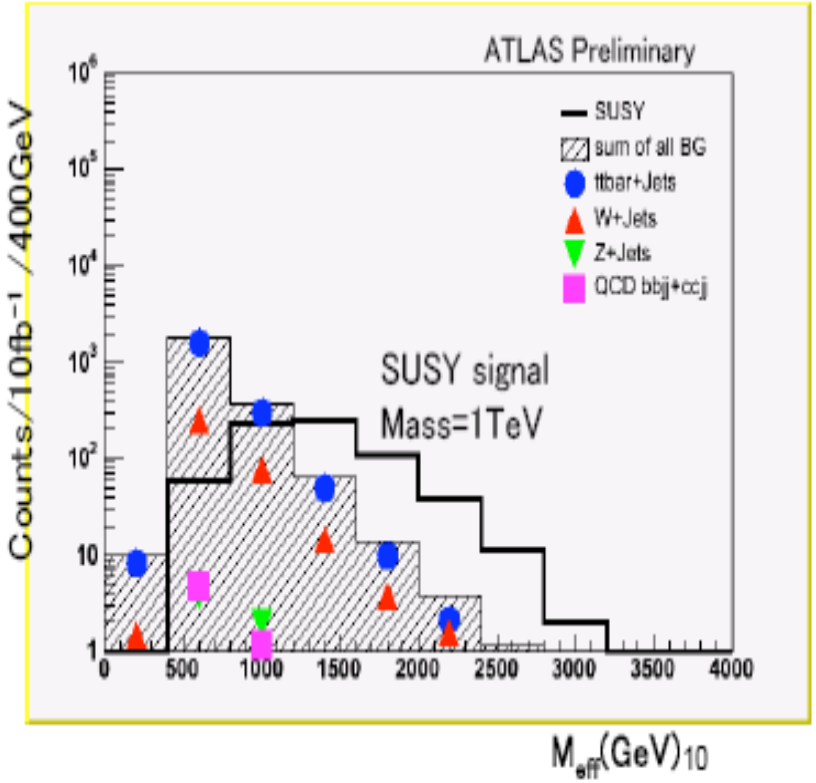
Classic signature is jets (cascade) + MET (the LSP). At low masses, just outside the Tevatron reach the signals are quite large.

Region Explored for Low Mass SUSY



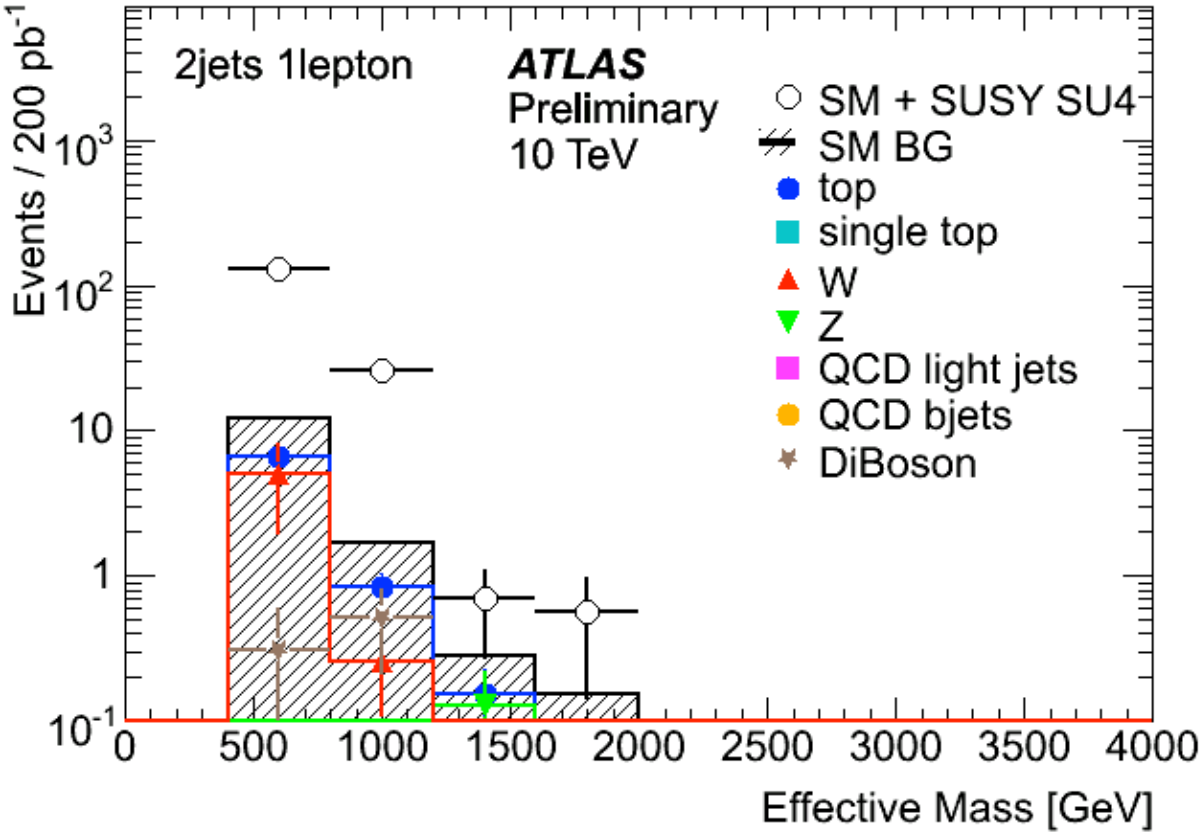
ATLAS Search – Need 1 Lepton





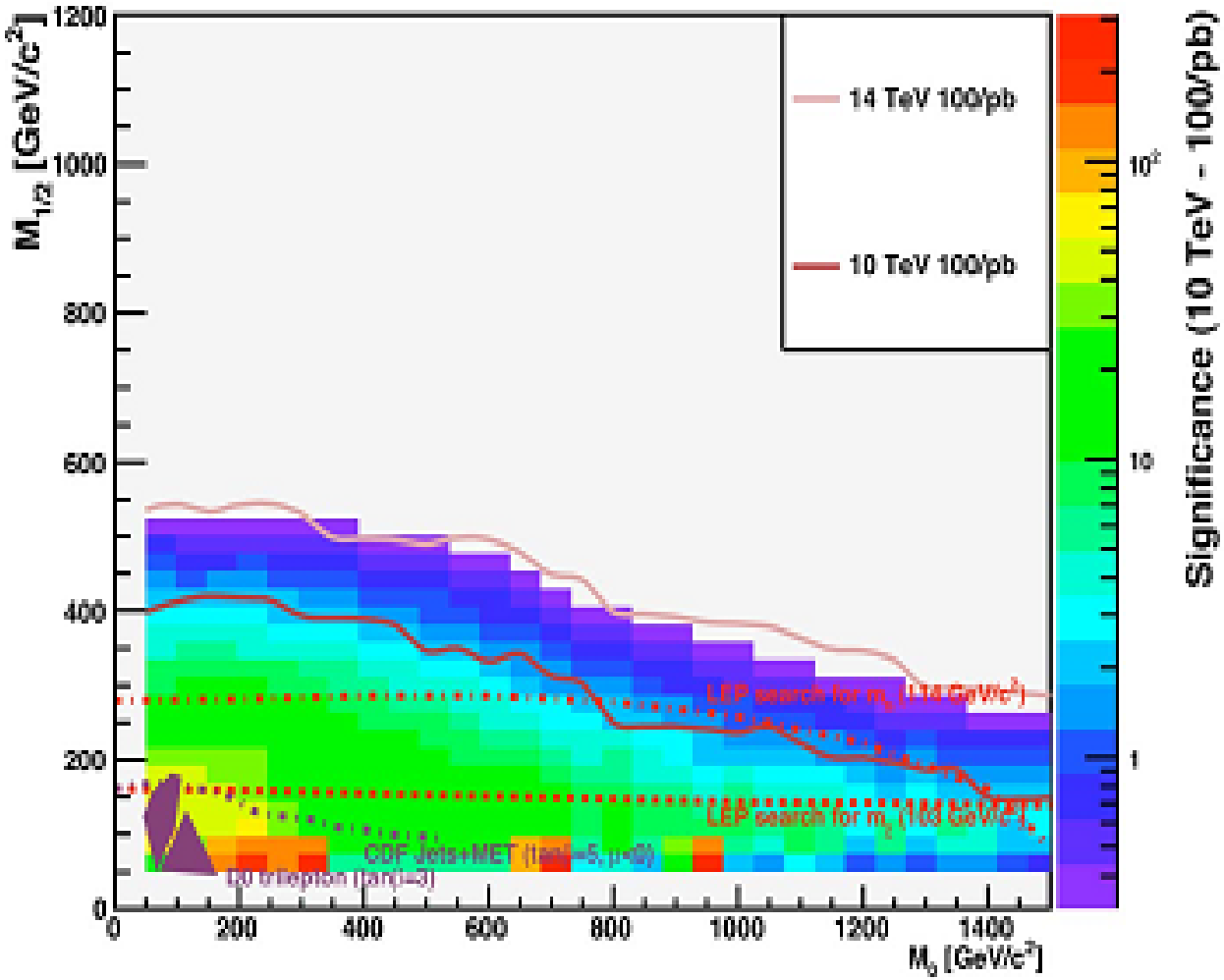
Monte Carlo studies for V + multijets need to have hard matrix elements, not 2 -> 2 + radiation (soft). Studies showed SUSY was harder to see than thought. JETs + MET may require an additional lepton

ATLAS – 10 TeV



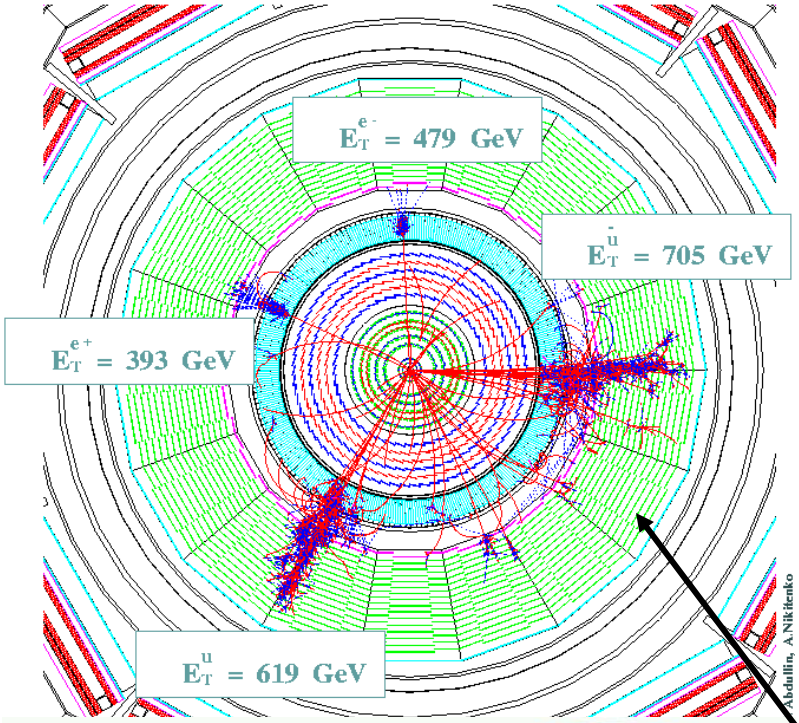
$$M_{eff} = \sum_{jets} p_T^{jet} + \sum_{lep} p_T^{lep} + E_T^{miss}$$

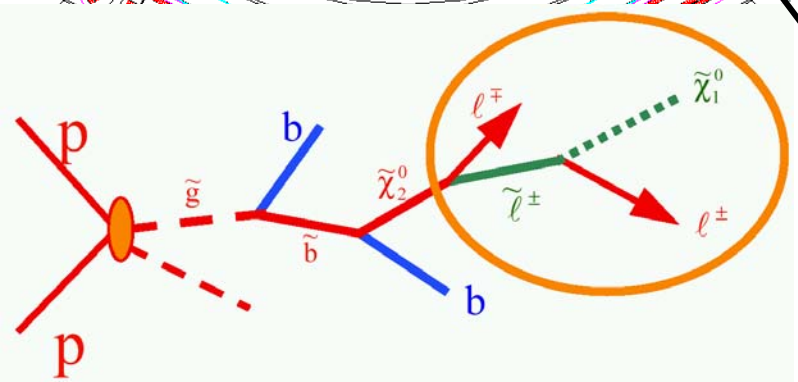
SUSY Limits – Gluinos, Squarks



Energy is important. Quickly surpass Tevatron discovery reach for LM points.

Sparticle Cascades





Use SUSY cascades to the stable LSP to sort out the new spectroscopy.

Decay chain used is :

$$\tilde{\ell}^{+-} \rightarrow \tilde{\chi}_1^o + \ell^{+-}$$

$$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^+ + \ell^-$$

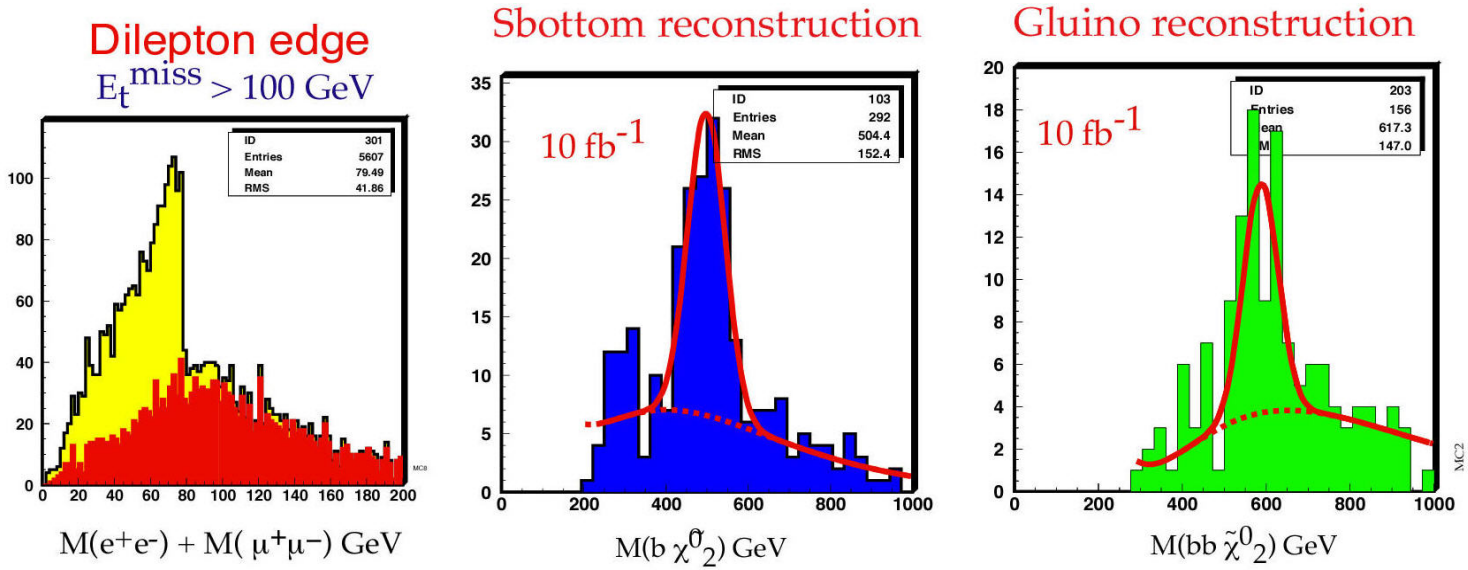
$$\tilde{b} \rightarrow \tilde{\chi}_2^0 + b$$

$$\tilde{g} \rightarrow \tilde{b} + b$$

Final state is

$$b + b + \ell^- + \ell^+ + \tilde{\chi}_1^0$$

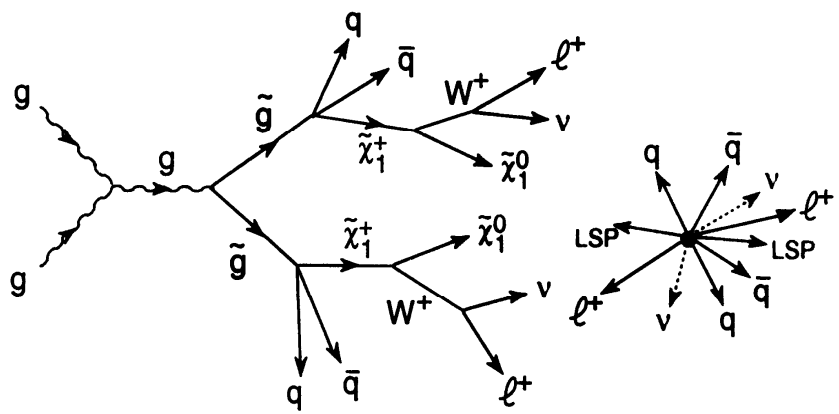
SUSY Reconstruction

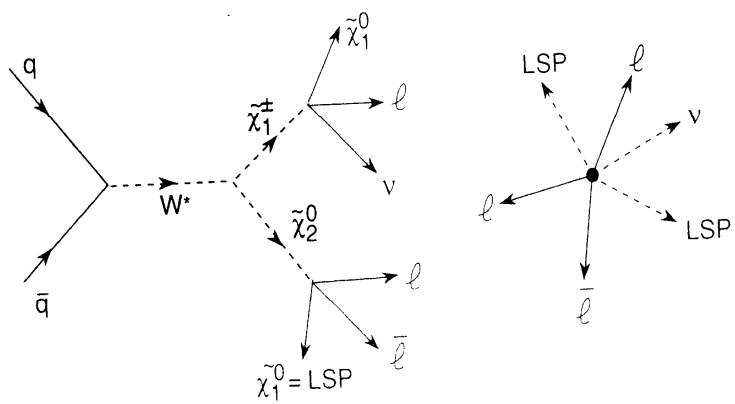


$$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \ell^+ + \ell^- \qquad \tilde{b} \rightarrow \tilde{\chi}_2^o + b \qquad \tilde{g} \rightarrow \tilde{b} + b$$

from MET, $\tilde{\chi}_1^0$ then others from observed decay products. Earliest searches are with jets + MET, semi-inclusive. Here use dilepton end point? Note plots are for 1 year at 10% of design luminosity. Worked harder since this study.

SUSY Signatures



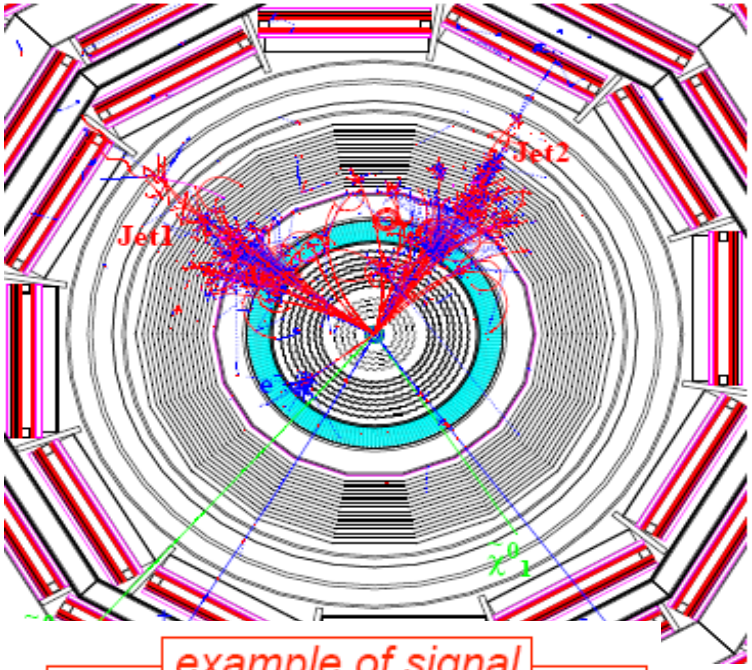


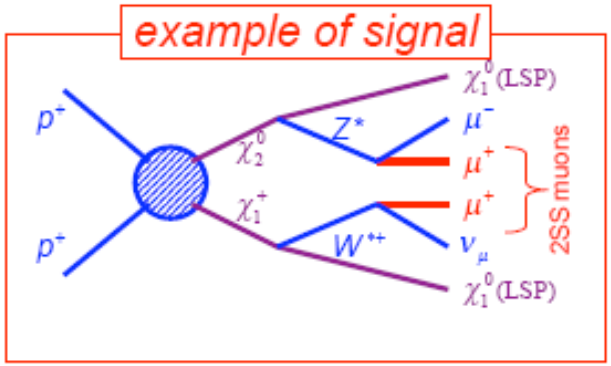
The gluino pair production cascade decays to jets + leptons + missing Et. Gluino is a Majoran, like sign ~ same sign for dileptons

The gaugino pairs cascade decay to missing Et + 3 leptons which is a very clean signature, but with smaller cross section

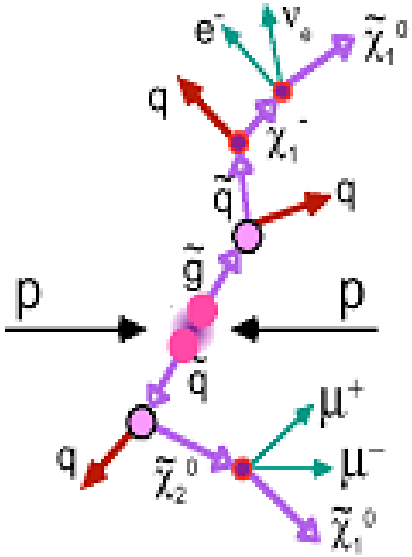
Di, Tri-Lepton Signatures

$$\tilde{\chi}_1^0 + \tilde{\chi}_1^0 + (\mu^+ + \mu^-)_Z + (J + J)_W$$

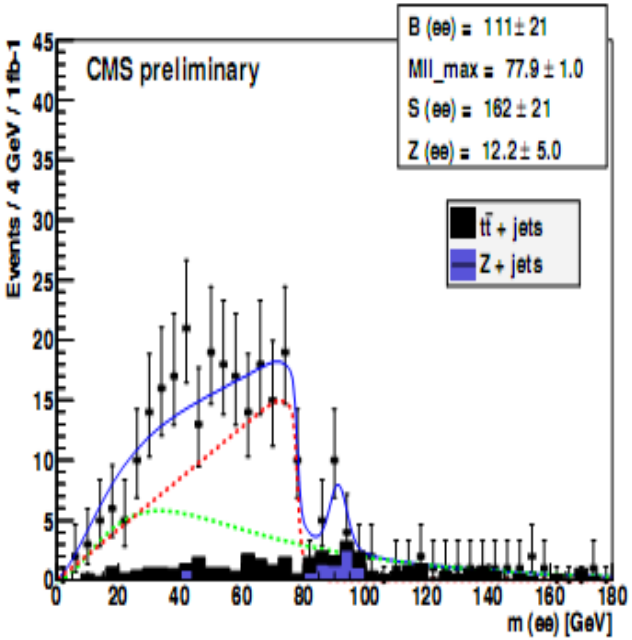


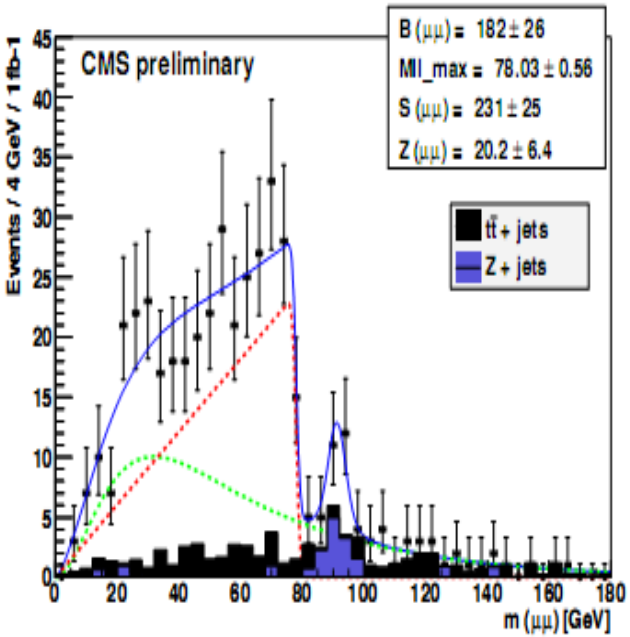


At lower cross section there are more spectacular topologies, such as MET + 3 leptons or MET + 2 jets + 2 leptons. If you see an enhancement above the SM is it MSSM SUSY?



Dilepton Kinematic Edges





$$M^{max}_{\ell^+\ell^-} = \frac{\sqrt{(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\tilde{\chi}^0_1})}}{M_{\tilde{\ell}}}$$

$$\tilde{\chi}^0_2 \rightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \tilde{\chi}^0_1 \ell^{\pm}\ell^{\mp}$$

Edges give mass information. Signals for 1 fb^{-1}. Use flavor of lepton and charge pairing to extract signal (Majorana). First the discovery then the spectroscopy.

The SUSY Spectroscopy

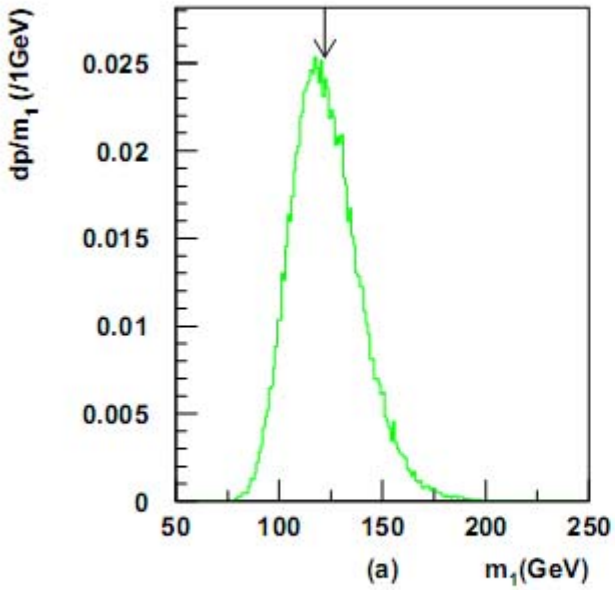


Figure 4: $M(\chi_1^0)$ distribution for ATLAS point 5.

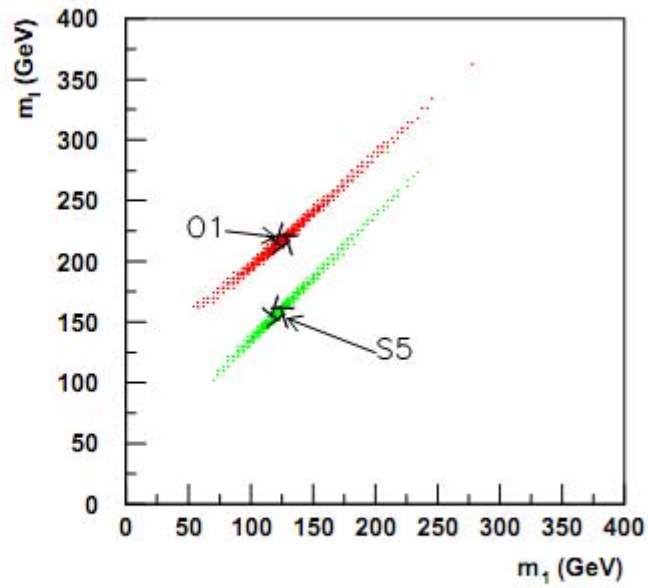
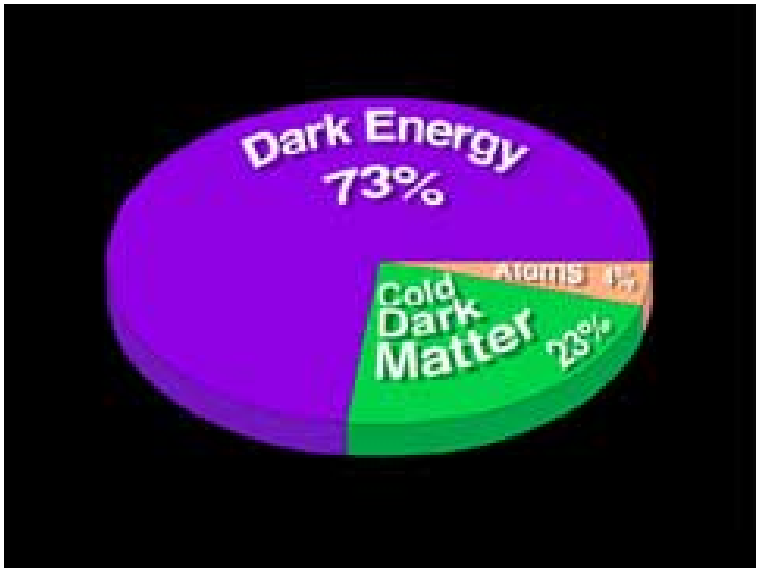
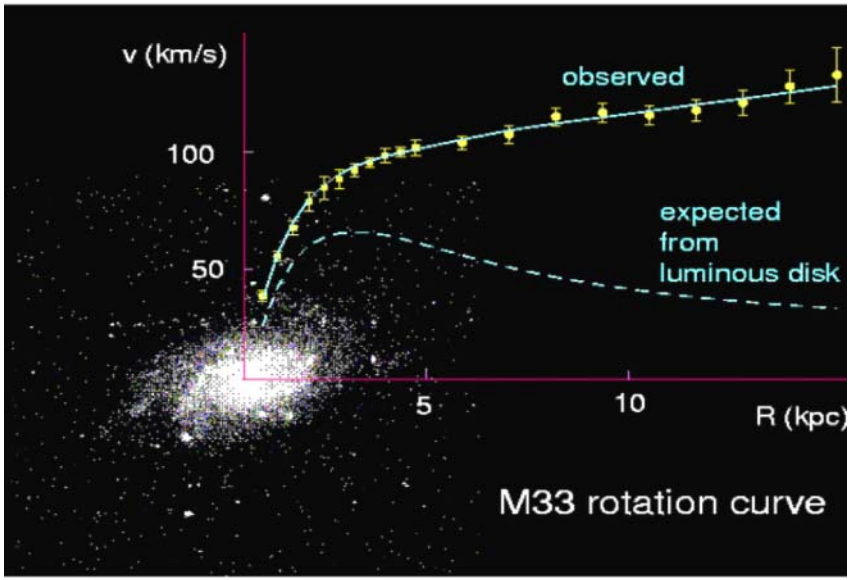


Figure 5: Reconstructed $M(\tilde{\ell})$ vs $M(\chi_1^0)$ for O1 and S5 (see text). The stars show the true mass for each model.

Given that the LSP is not detected, the overall mass scale is limited by the MET resolution. Nevertheless, mass differences can be well determined – e.g. kinematic edges, multi-jet spectroscopy.

Dark Matter ?





There is no SM candidate. Can we produce DM in LHC? Is it the SUSY LSP? Searches at LHC, in direct (recoil) measures – e.g CDMS , in flavor loops – e.g. LHCb and in annihilations (e.g. PAMELA, FERMI) may find new aspects of DM

Dark Matter and SUSY

$$dY/dx = -x < \sigma_A v > s[Y^2 - Y_{EQ}^2]$$

$$Y = n/s,\ x = M/T,\ Y_{EQ}|_{NR} \sim x^{3/2} e^{-x}$$

$$\Gamma_A(T_F) \sim H(T_F)$$

Boltzmann Eq. Freezout of relic when annihilation rate ~ expansion rate.

$$\sigma_A \sim \alpha_W^2 / 2M_W^2 [y/(1+y^2)]$$

$$y = s/M_W^2$$

$$q + \bar{q} -> \tilde{\chi}_1^o + \tilde{\chi}_1^o$$

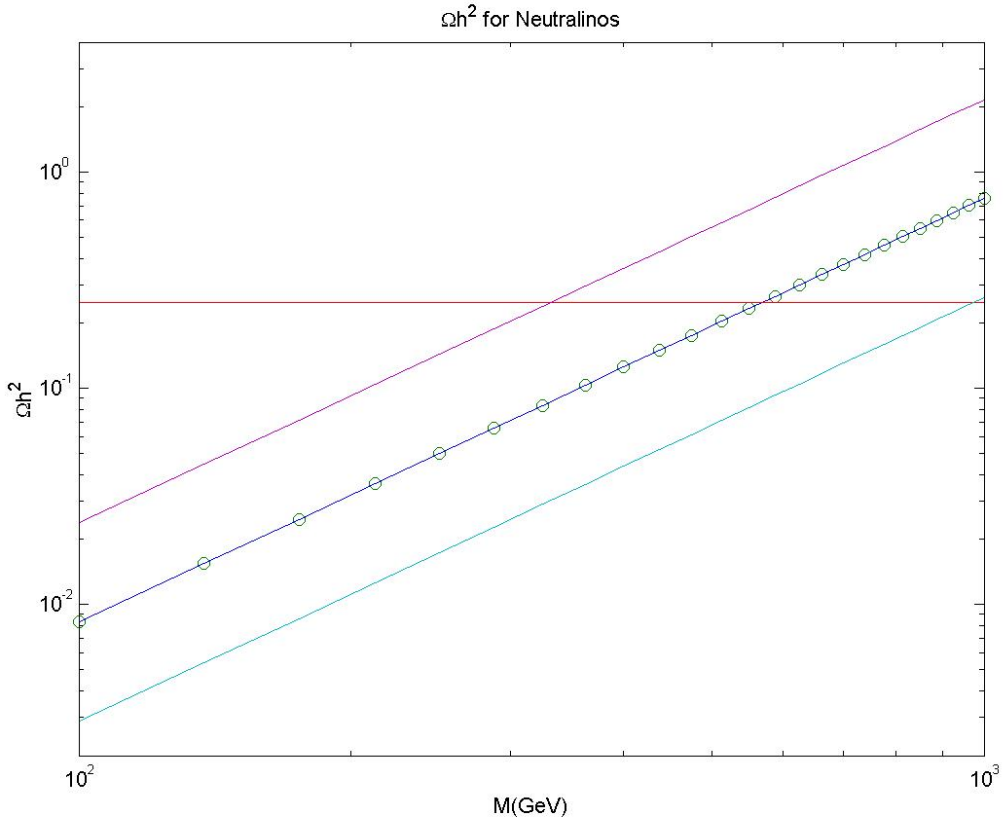
$$\sigma_A \to \alpha_W^2 s / 2M_W^4, \quad \textit{Fermi Theory}$$

$$\sigma_A \to \alpha_W^2 / 2s$$

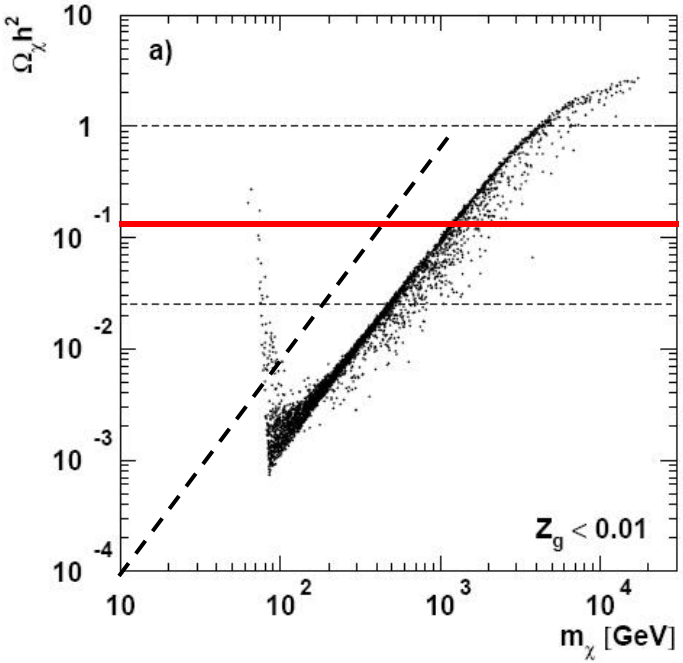
Neutralino annihilation rate into quark pairs. A weakly interacting particle with a mass (100, 1000) GeV has the correct relic density to be dark matter. Thus DM (lensing, rotation curves), plus cosmology (thermal relic) implies a weakly interacting, TeV scale stable (R parity) object. Can we be more incisive? Not yet.

Simple Model- by Hand

Cross section at the EW scale _ 1 pb is about right for a particle relic of about 300 GeV. Details of annihilation are very messy. As mass increases the cross section decreases and the LSP "freezes out" earlier, leaving a larger relic density. Density goes as relic mass squared



Dark Matter and SUSY



SUSY = dark matter? We need an ensemble of experiments. Line is mass squared behavior

It may be a big hint that a SUSY LSP with a mass O(TeV) with a weak cross section (neutralino ?) decouples from the Big Bang expansion to give roughly the correct relic density to be "dark matter". The hope is then to produce and detect dark matter at the LHC.

Numerical Values

Evolution of the Dark Matter Density

- Produced in big bang, but also annihilate with each other.
- Annihilation stops when number density drops to the point that

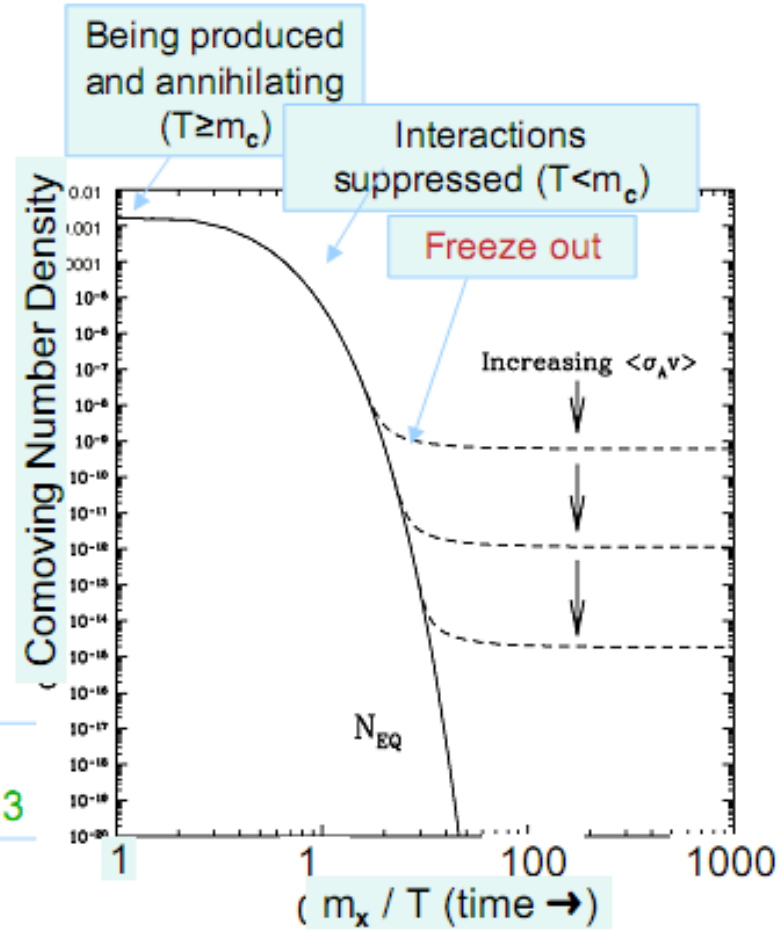
$$H > \Gamma_A \approx n_\chi < \sigma_A v >$$

- i.e., annihilation too slow to keep up with Hubble expansion ("freeze out")
- Leaves a relic abundance:

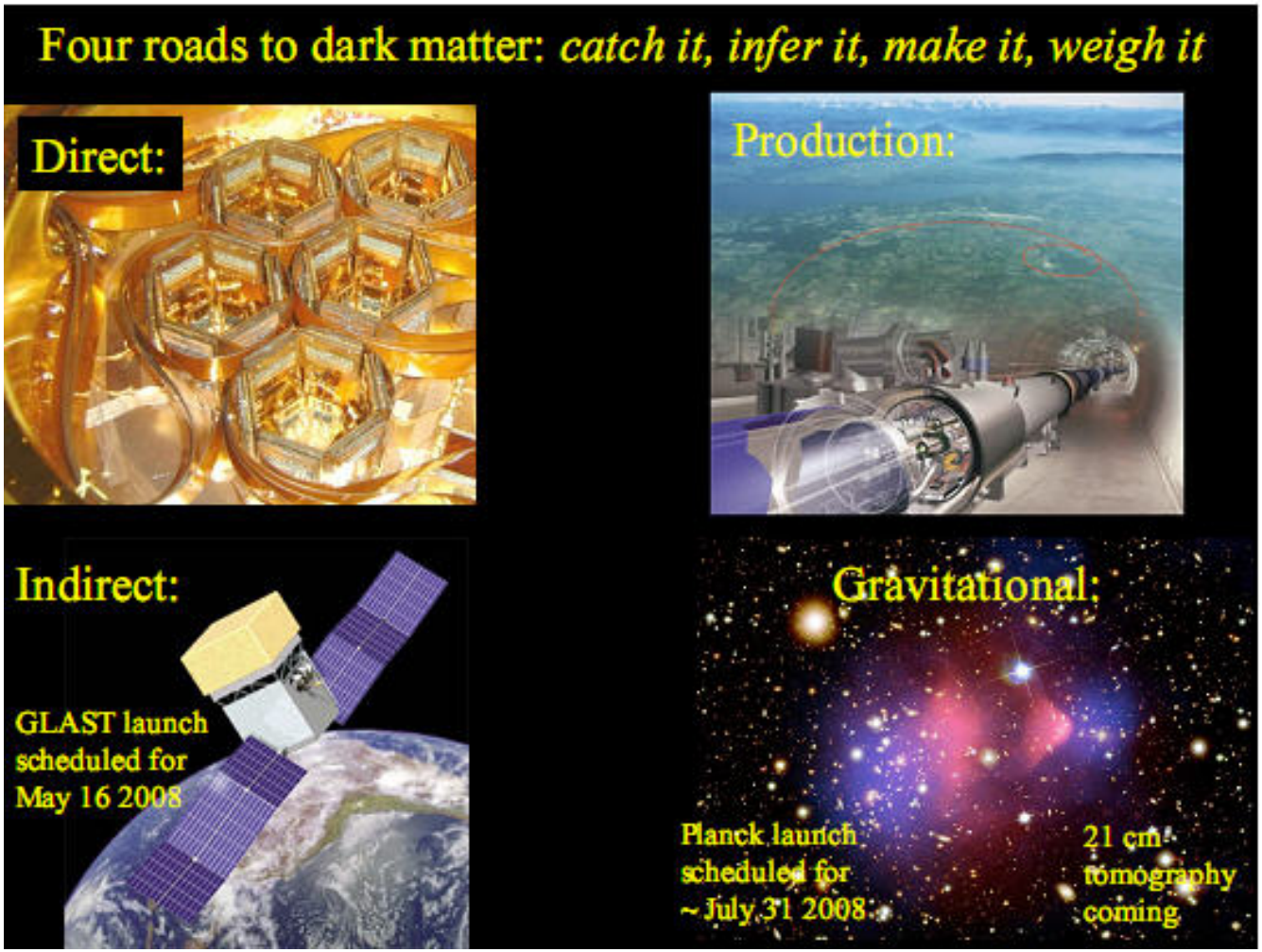
$$\Omega_\chi h^2 \approx 10^{-27} cm^3 s^{-1} / < \sigma_A v >_{fr}$$

if m_x and σ_A determined by electroweak physics, then $\Omega_x \sim 0.3$

$$\sigma_{ann.} \approx \text{a few pb} \approx \alpha_W^2 / M_W^2$$



DM – "Full Court Press"



DM - Direct

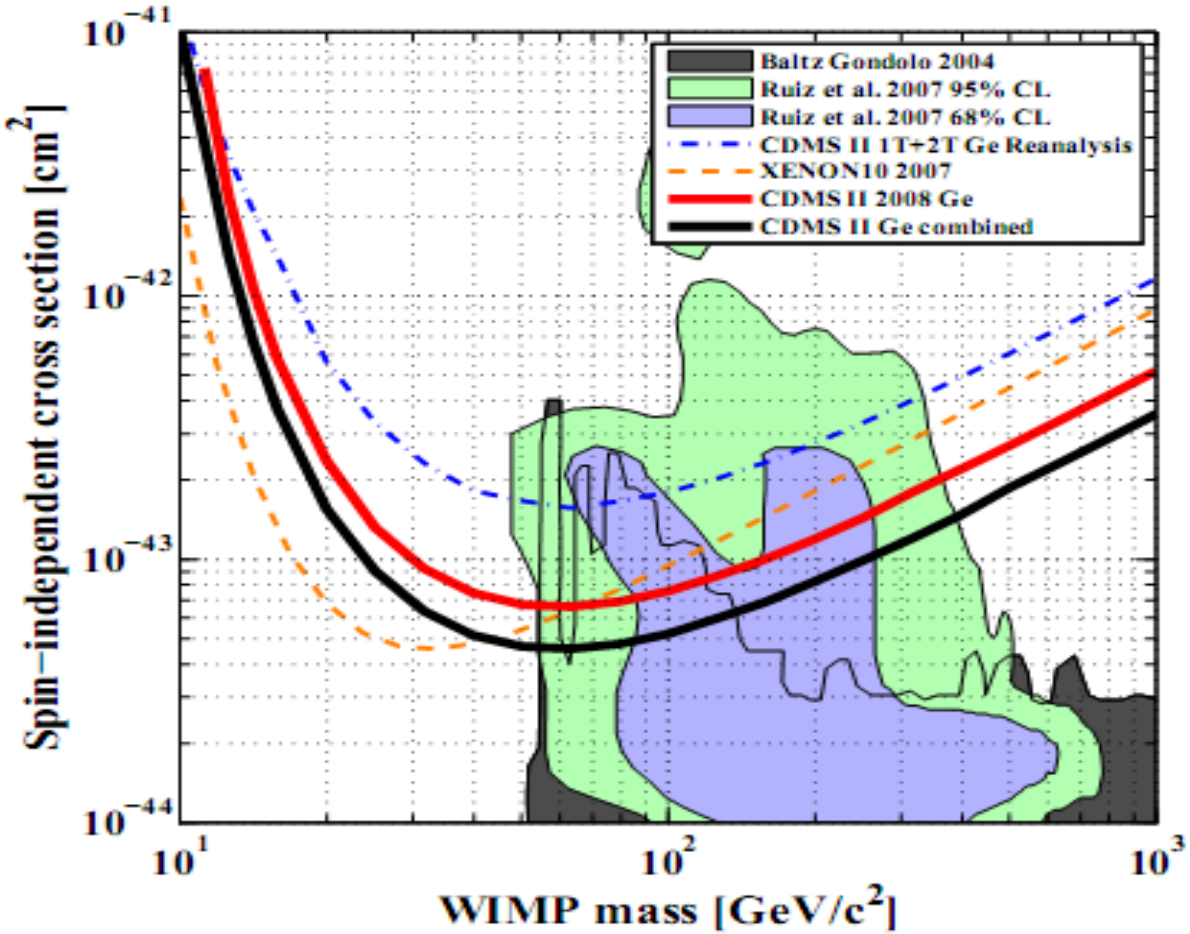
- Look for recoil of nucleus in elastic scatter of LSP off detector.
- Low energy weak cross section -> difficult search
- Take velocity of LSP to be 100 km/sec. A VERY, VERY rough estimate is then:

$$\sigma \sim G^2 s / \pi$$

$$s \sim m_p M_{LSP} \beta_{LSP}^2$$

$$\sigma \sim 10^{-46} cm^2$$

DM - CDMS

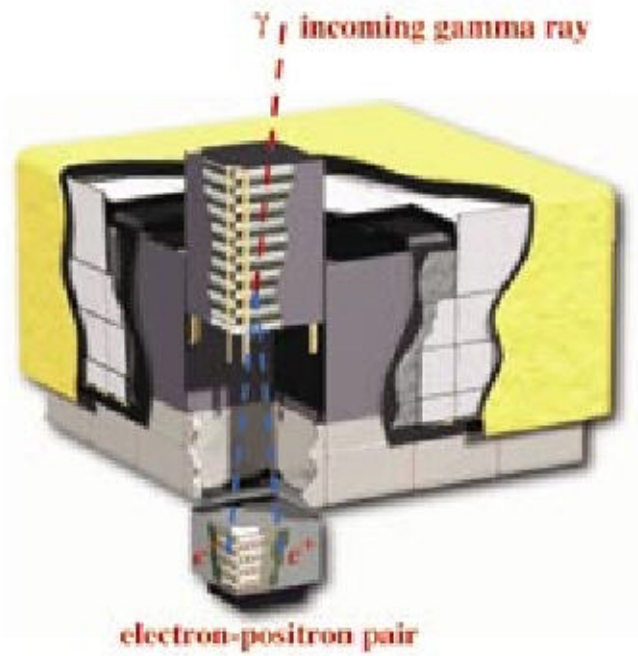


Solid State or Nobel Liquids – scaleable?

DM- Annihilations

Instrument Design

The instruments on the GLAST mission are the Large Area Telescope (LAT) and the GLAST Burst Monitor (GBM). The LAT has four subsystems: a solid state detector (silicon strip) pair conversion tracker for gamma-ray detection and direction measurement, a CsI calorimeter for measurement of the energies, a plastic scintillator anticoincidence system to provide rejection of the intense background of charged particles, and a flexible trigger and dataflow system. The LAT is modular, consisting of a 4 × 4 array of identical towers with 880,000 silicon-strip detector channels. The GBM has 12 NaI scintillators and two BGO scintillators mounted on the sides of the spacecraft. The GBM will view the entire sky not occulted by Earth, with keV to 30 MeV, overlapping with the lower energy limit of the LAT and with the range of GRB dete



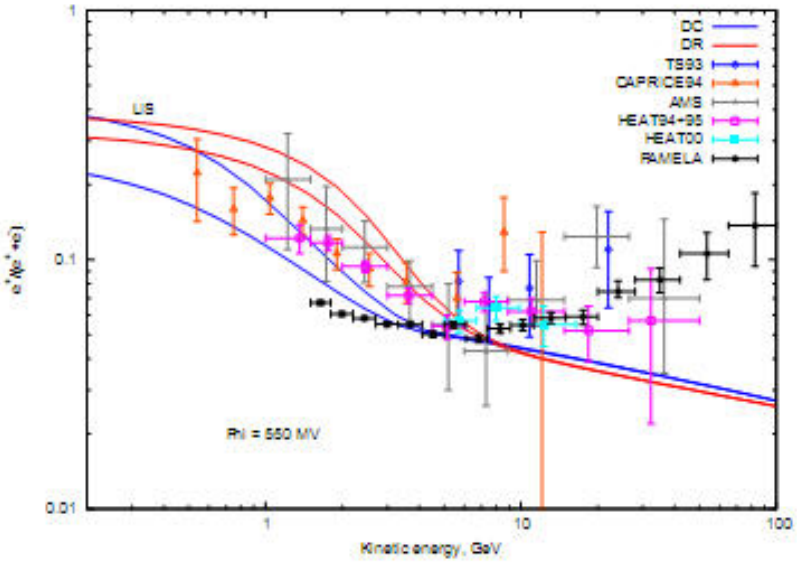
LAT

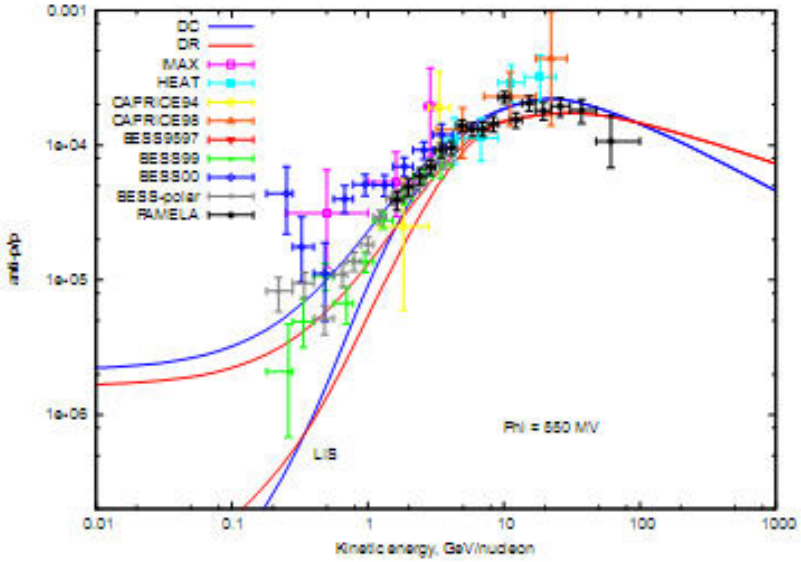
GBM - HE BGO
(1 of 2)

GBM - LE NaI
(3 of 12)

Silicon strips + CsI +NaI + BGO. Use Crab to calibrate with high energy photons in the 0.1 GeV to 10 TeV range. Launched in June 2008

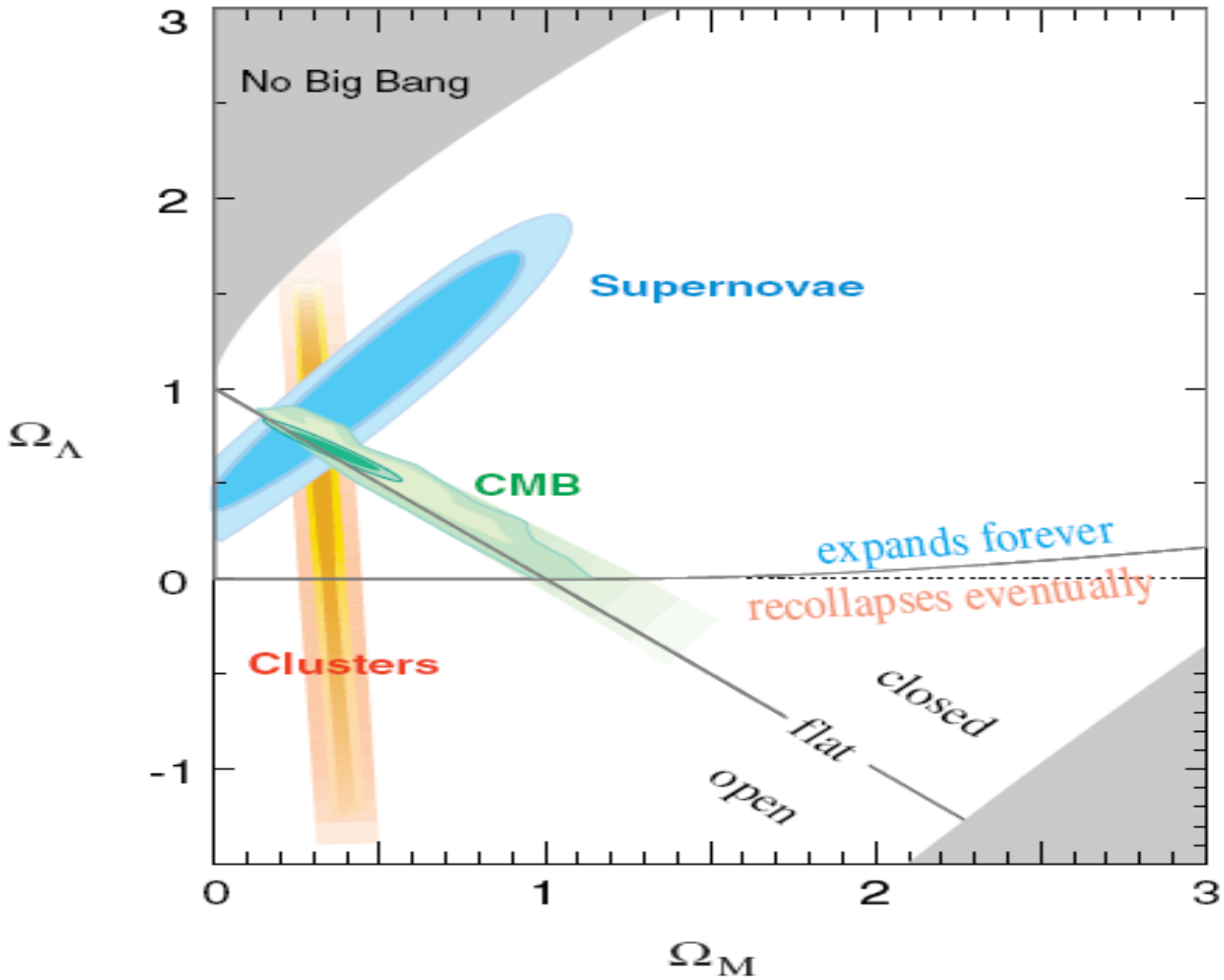
PAMELA Results





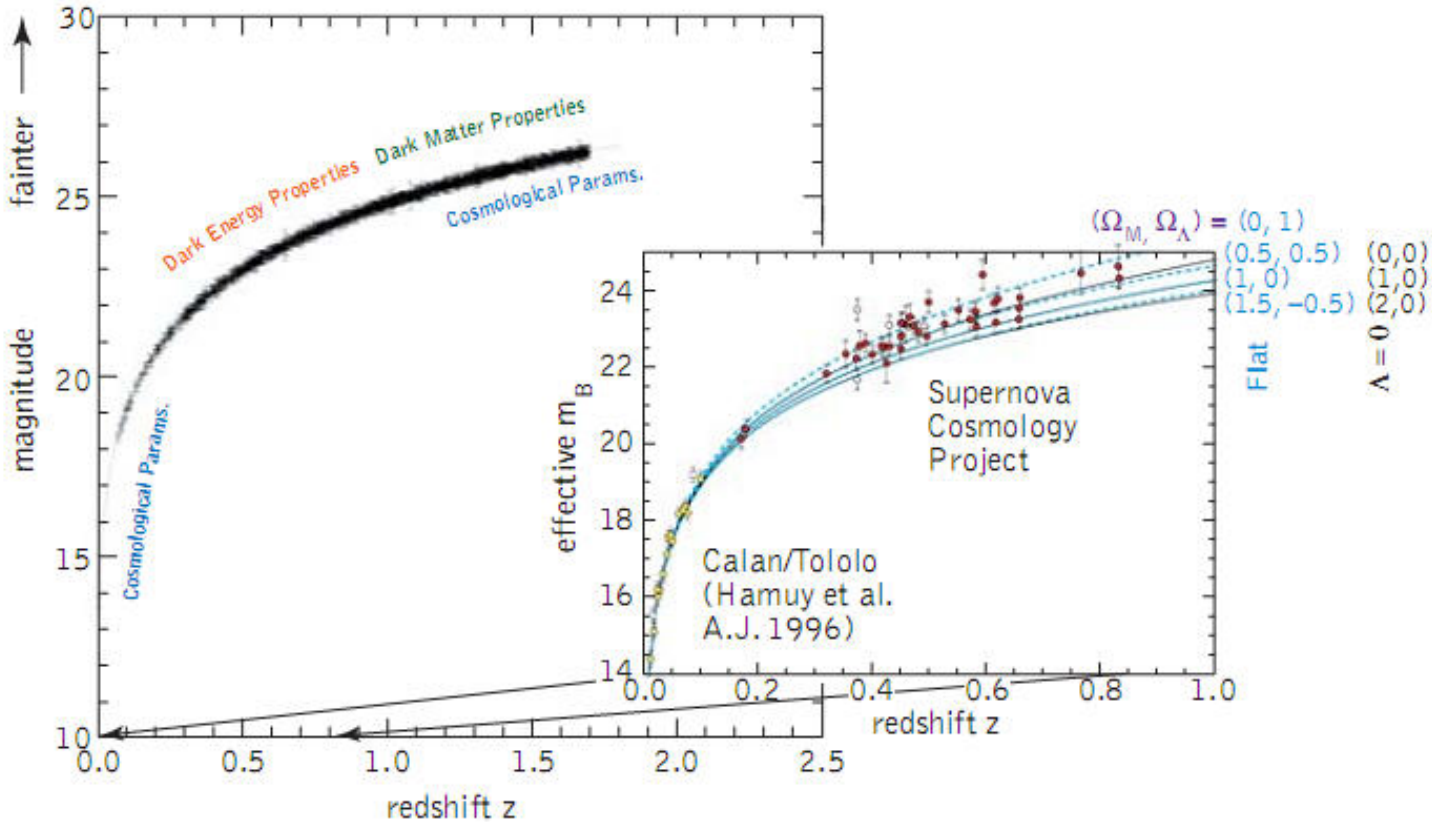
The high energy positron data is not well modeled at present. Is this DM annihilation? Stay tuned

Cosmology and CMS



The universe is flat and composed largely of dark energy (73%) and dark matter (22 %). What are they? We understand only about 5% of the Universe by weight !

SNAP "Reach"



Use supernovae as a "standard candle". Will yield > 100x improvement. Main aim is to study Eq. of State of DE. Is it just a vacuum energy?

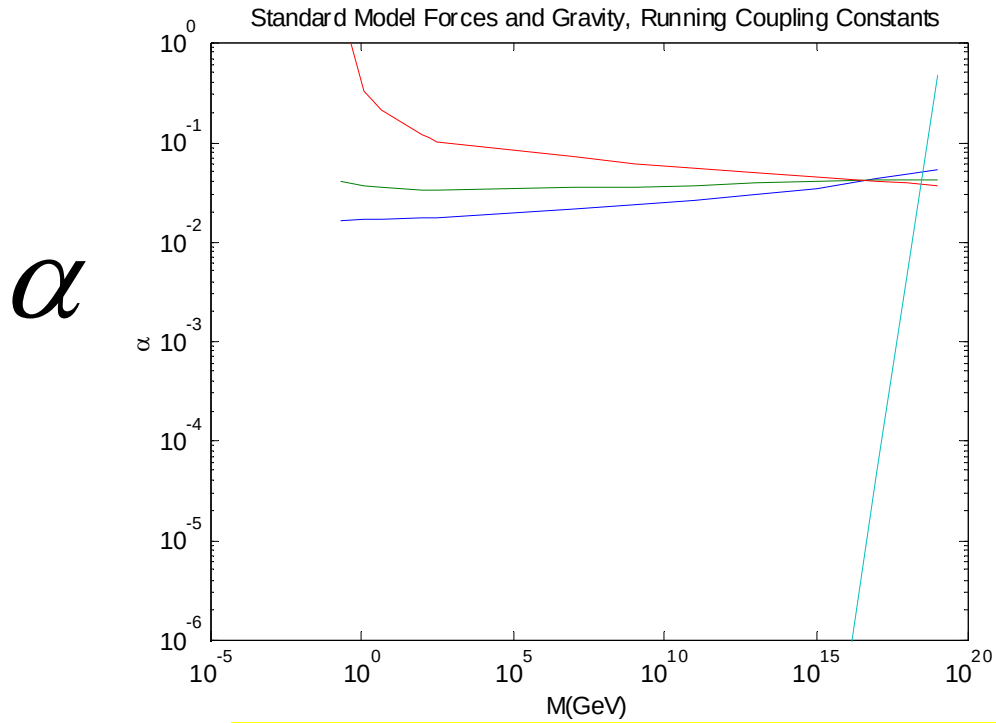
Cosmological Constants

- The dark energy is observed to be ~ 73% of the closure density of the Universe.
- But we have measured the W and Z mass, so we "know" that there is a vacuum Higgs field,

  $<\phi>=174\,GeV, M_W = g_W <\phi>$ - Landau-Ginzberg
- If so, there is a cosmological mass density ~

  $<\phi>^4$ This is ~ 10^{52} larger than the observed dark energy density which is ~ 20 meV compared to 174 GeV!
- What is going on? Is the Higgs field gravitationally inert? Try to study the Higgs mass and couplings (especially self couplings). Will we really find a SM Higgs "ether"? Do we understand the "vacuum"?

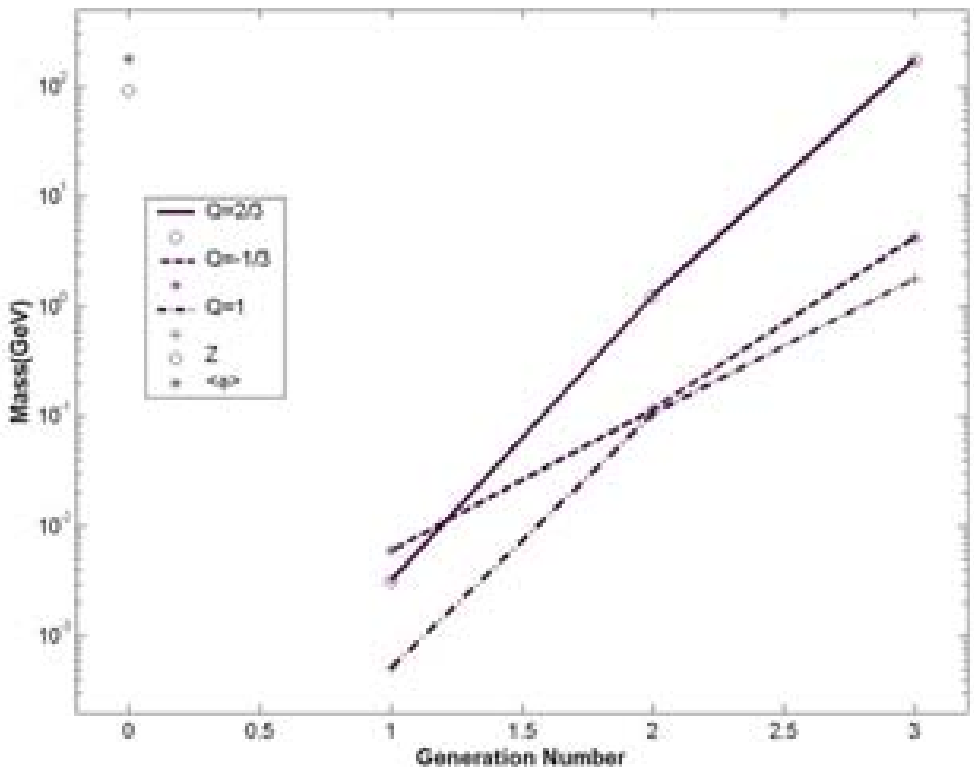
Gravity and SM Forces



A completely naïve classical extrapolation of gravity comes close to the GUT mass scale. Is that a hint? Note that $\alpha_G \sim M^2$

We expect fundamental issues with quantum gravity as it defines the geometry of space-time. It appears that point particles are not possible, but rather strings existing in many dimensions, with those > 4 curled up or "compactified" to dimensions ~ 1/M. Gravity is very, very weak – a small magnet can overcome the whole Earth and pick up a nail. Is that because gravity spreads out thinly into additional dimensions?

Generations?



$$M_{gen} \sim M_o e^{6 n_{gen}}$$

Do we have a clue about all the parameters having to do with generations? Masses, CKM elements…. What is the dynamics that splits the generation masses? A Balmer series with only 3 terms?

What will we find at the LHC?

•There is a single fundamental Higgs scalar field. This appears to be incomplete and unsatisfying.

•Another layer of the "cosmic onion" is uncovered. Quarks and/or leptons are composites of some new point like entity. This is historically plausible – atoms → nuclei → nucleons → quarks.

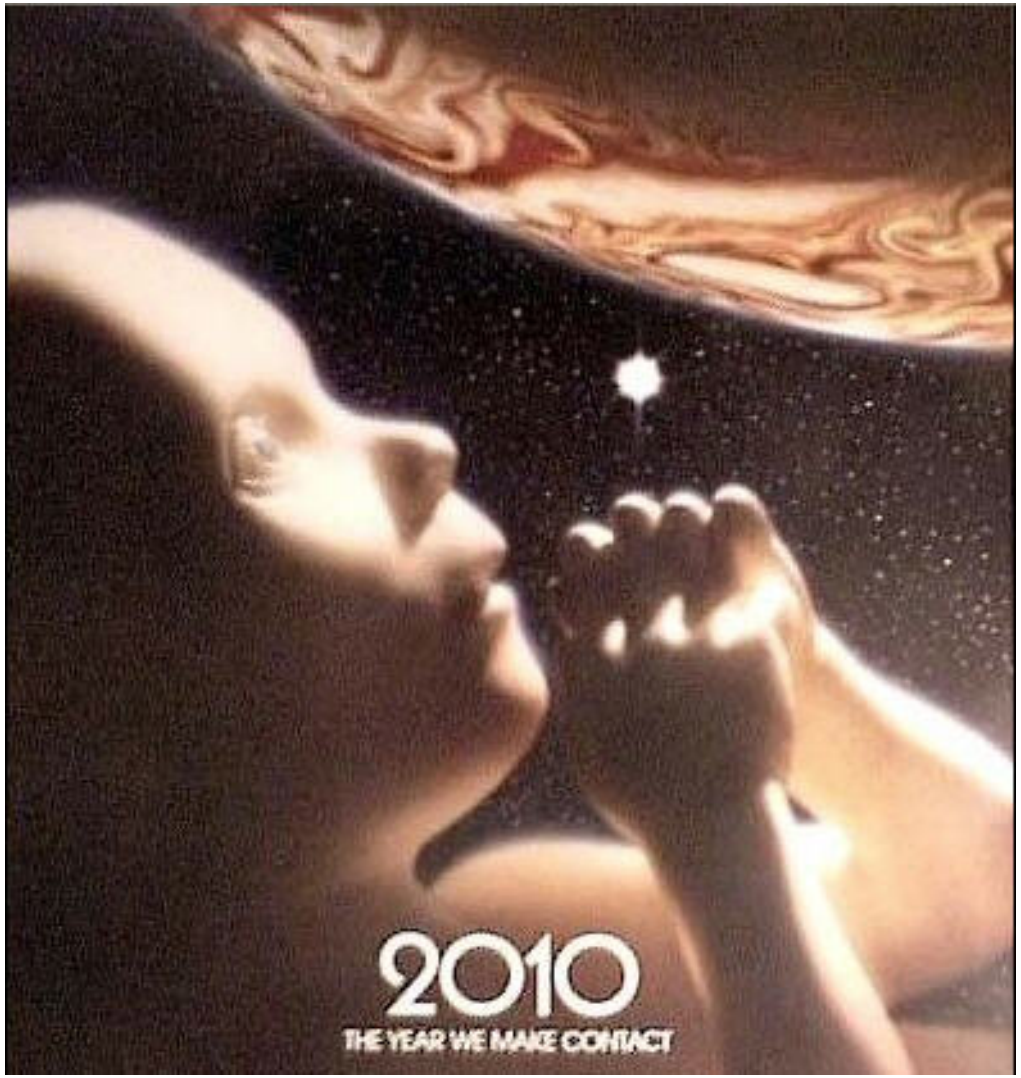
•There is a deep connection between Lorentz generators and spin generators. Each known SM particle has a "super partner" differing by ½ unit in spin. An extended set of Higgs particles exists and a whole new "SUSY" spectroscopy exists for us to explore.

•The weak interactions become strong (unitarity). Resonances appear in WW and WZ scattering as in $\pi + \pi \rightarrow \rho$. A new force manifests itself, leading to a new spectroscopy.

•There are extra dimensions at the ~ 1 TeV mass scale, so there is no hierarchy problem. Gravity is weak because it exists in the complete space-time geometry, while SM forces are only in 4 - d.

•"There are more things in heaven and earth than are dreamt of in your philosophy"

Something Wonderful



"Nothing is too wonderful to be true" - Michael Faraday

Problems - IV

1. Evaluate the Weinberg angle going from the value of 3/8 at GUT mass to 100 GeV
2. Use Calchep to compute the gluino cross section at 1 and 1.5 TeV gluino mass.
3. Show that a 1 TeV LSP yields a reasonable relic abundance to be DM.