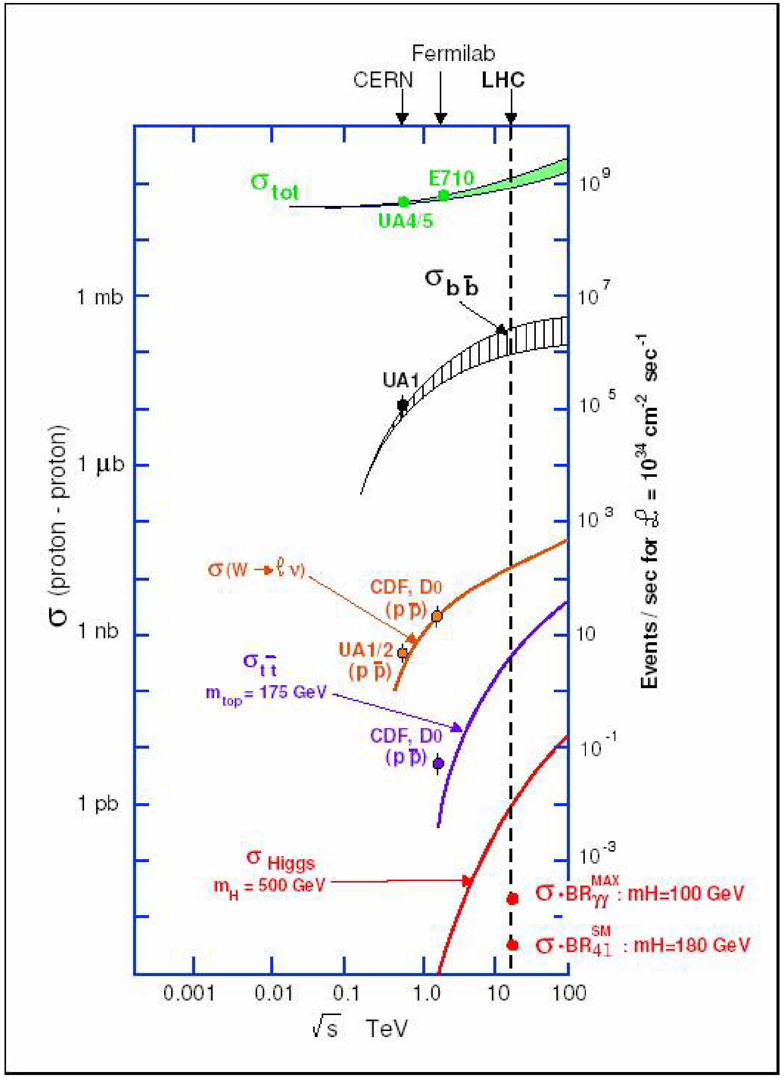
Physics with the CMS Detector

Dan Green
Fermilab

“each man’s grief my own”

Higgs Cross Section



CDF and D0 successfully found the top quark, which has a cross section ~ 10^{-10} the total cross section.

A 500 GeV Higgs has a cross section ratio of ~ 10^{-11}, which requires great rejection power against backgrounds and a high luminosity.

Rate = luminosity * cross section

LHC has ~ 20 times the luminosity of the Tevatron and 7 times the energy.

Outline

- Establish the Standard Model (100 pb^{-1})
  - Minbias, Underlying event
  - Dijets and balance, photon + J
  - B tagging
  - Dilepton resonances: ψ, Y, W, Z – mass scale and resolution
  - Top pairs
  - Tau
- Look for the new Physics along the way (< 1 fb^{-1})
  - Excited quarks
  - W’, Z’ in dileptons
  - Diphoton gravitons
  - SUSY spectroscopy (dark matter)
- Then a jumping off point (> 1 fb^{-1})
  - Higgs
  - V+V Scattering
  - …….

Typical Statistics for a 10 TeV Run

Assume 200 pb^{-1}, include acceptance, initial reconstruction and id efficiency

Establish Standard Model cross sections and distributions

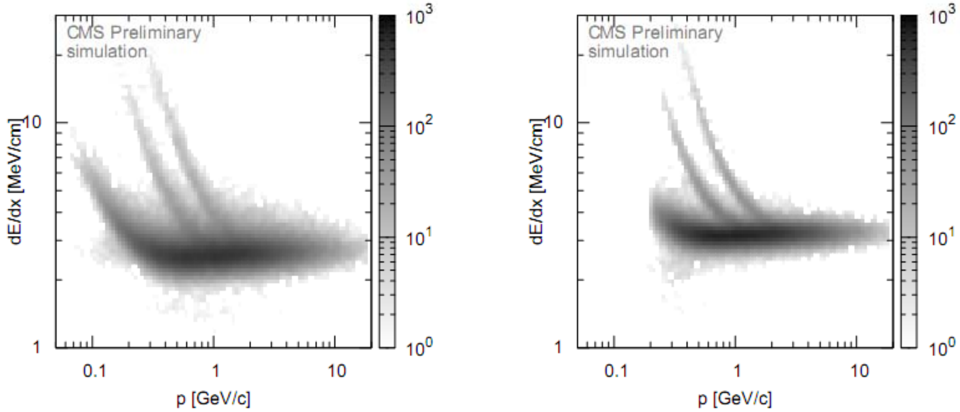
Log ~ 200 pb^{-1} at 10 TeV in 2009. This should be reliable data taking without Physics penalty for masses < 2 TeV

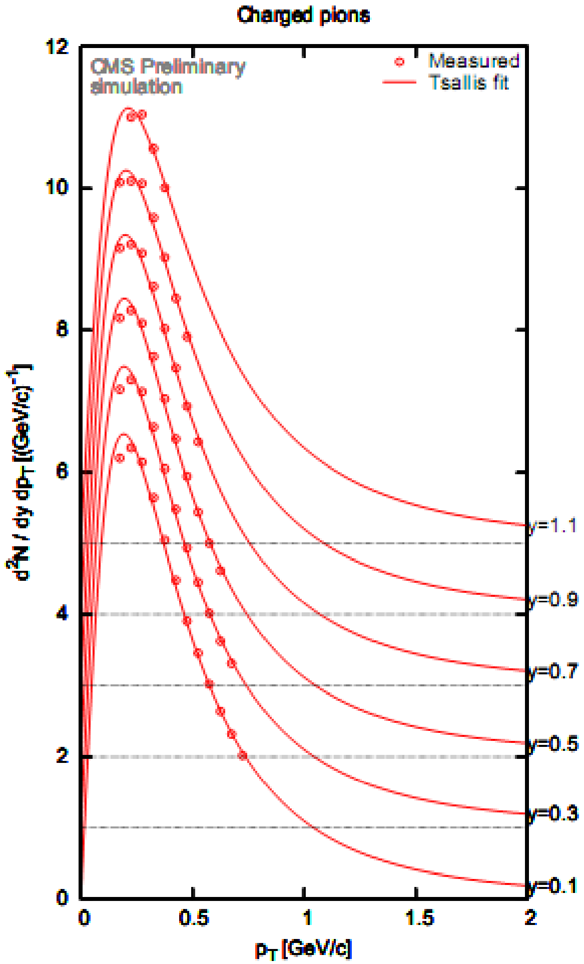
min bias	2×10^{13}
Jet Et>25	6×10^{11}
Jet Et>140	6×10^{7}
γ+Jet Et>20	6×10^{7}
W ->$l\nu$	600,000
Z -> ll	60,000
tt-> $l\nu$4q	2000

2009, Rediscover the SM

L for 1 month run (10^6 sec)	Integrated L	Trigger	Process	Comments
10^{23}	100 mb^{-1}	None σ_I~ 50 mb	Inelastic non-diff	Input to tweak Pythia
10^{24}	1 μb^{-1}	Setup Jet	Inelastic non-diff	Calib in azimuth
10^{25}	10 μb^{-1}	Jet $\sigma(gg) \sim 90\ \mu b$ $\sigma(ggg) \sim 6\ \mu b$	g+g -> g+g g+g -> g+g+g	Establish JJ cross section
10^{26}	100 μb^{-1}	Jet	g+g -> g+g g+g -> g+g+g	Dijet balance for polar angle – Establish MET
10^{27}	1 nb^{-1}	Jet Setup Photon $\sigma(q\gamma) \sim 20$ nb	g+g -> g+g g+g -> g+g+g q+g -> q+γ	Dijet masses > 2 TeV, start discovery search. J+γ calib

Minimum Bias Events

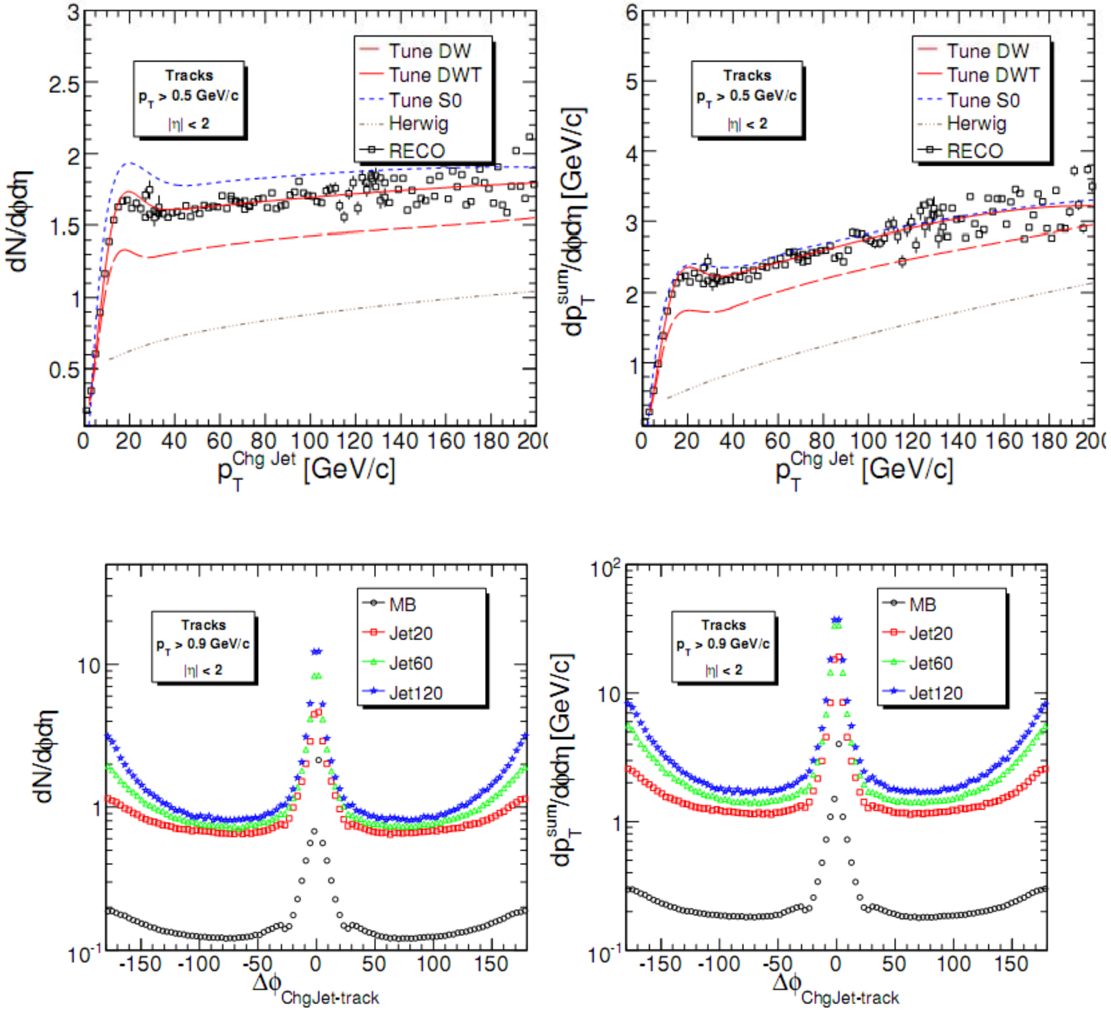




Use dE/dx in the CMS tracking system to do particle identification. Extract the charged particle cross section vs. particle type as a function of y and Pt

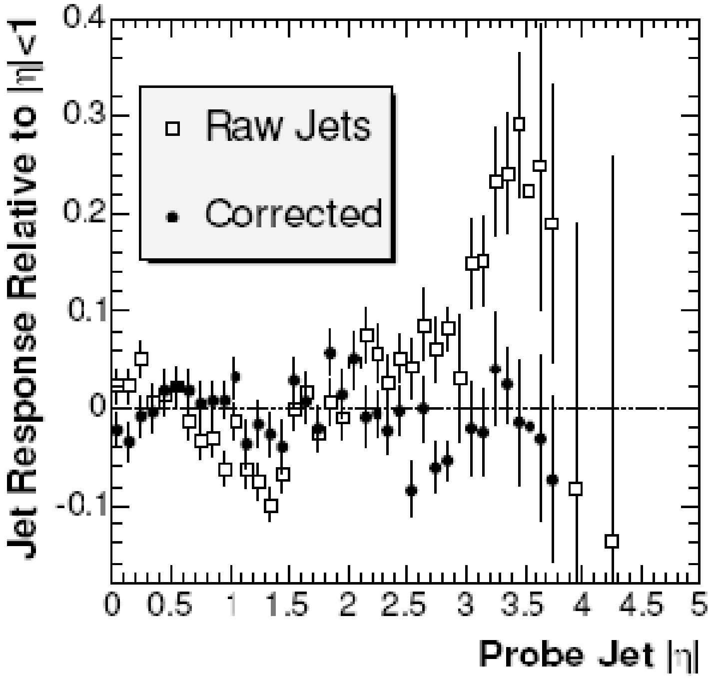
Useful for overlap to simulate high luminosity pileup.

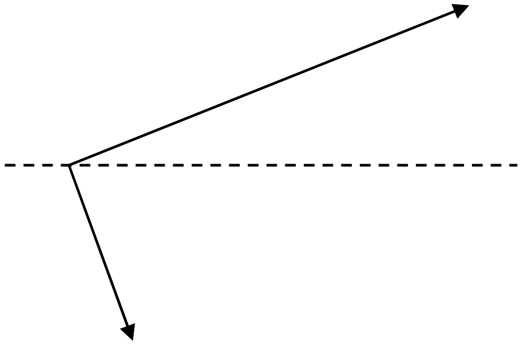
The Underlying Event



Extrapolation of the UE is uncertain. The UE is crucial for trigger strategy – e.g. lepton isolation. Must tune the CMS Monte Carlo to have a valid representation of the UE

Dijet Balance





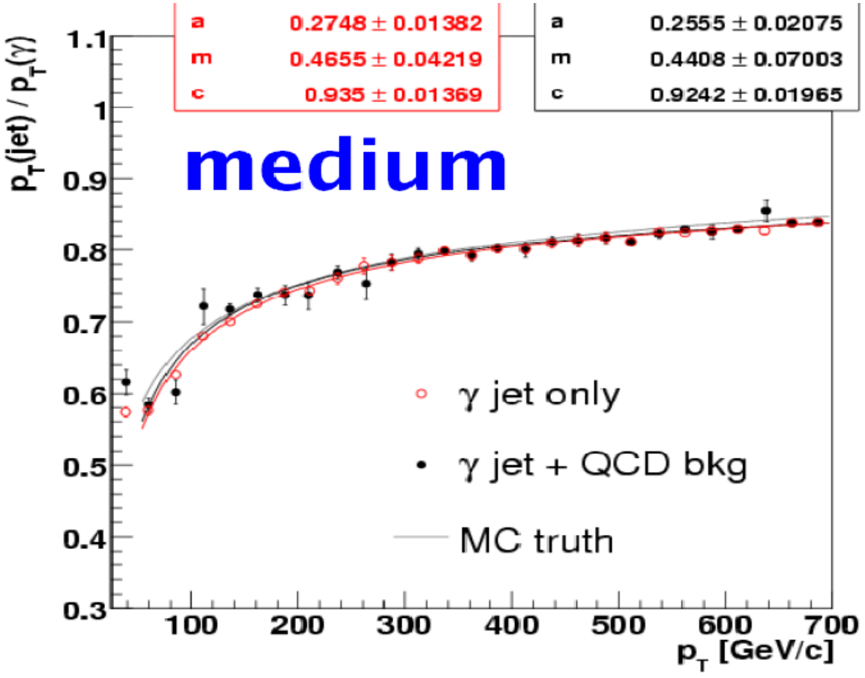
Use azimuthal symmetry for "rings" in y. Use dijet balance for equalizing the rings.
We can quickly equalize at " low Et" until we run out of statistics.

Photon + Jet Balance

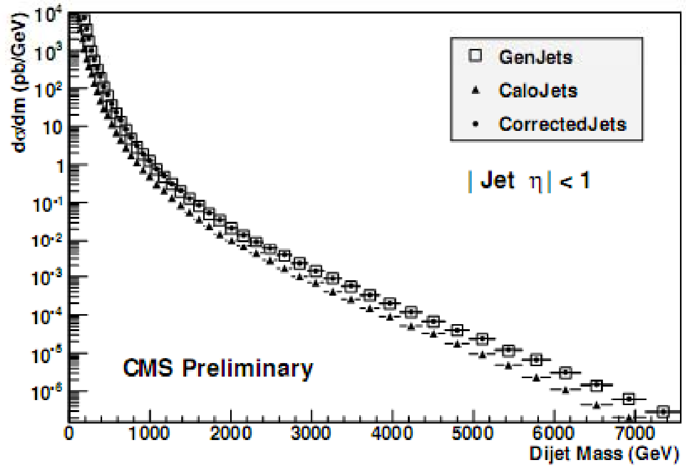
Photon + jet balance analysis is ready for data

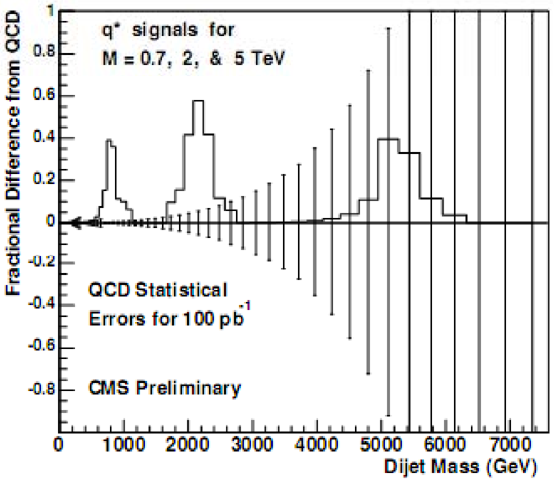
Ready to combine γ + jet and Z + jet and extrapolate using the MC

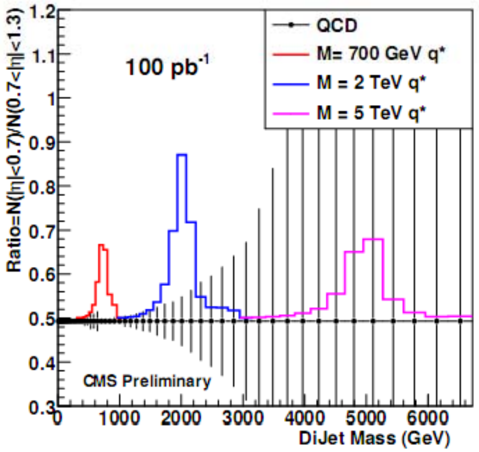
- Z + jet balance will give valuable confirmation but samples will be small

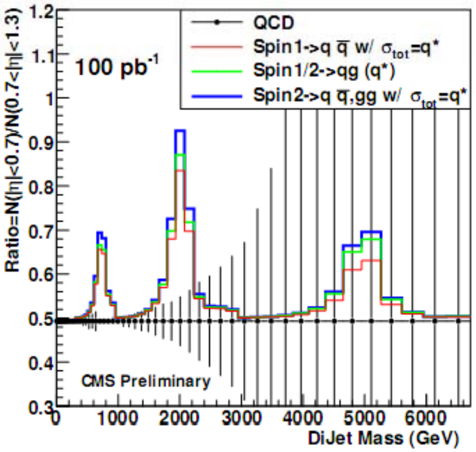


Jets and Dijets









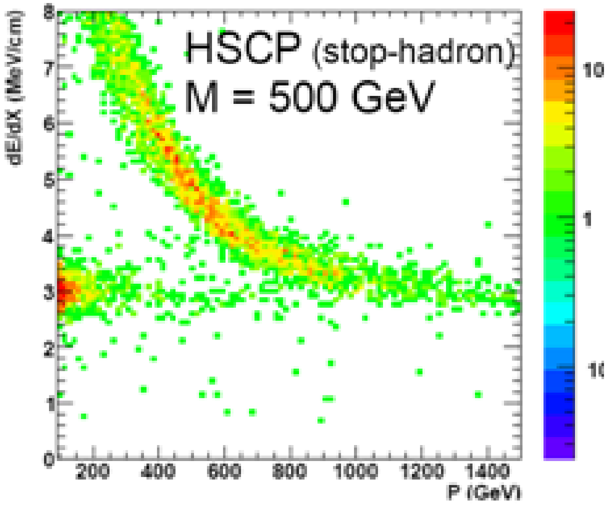
Establish low Pt cross section, mass distribution and angular distribution. Then look at high mass. Discovery possible very quickly - ~ 3 TeV for 100 pb^{-1}

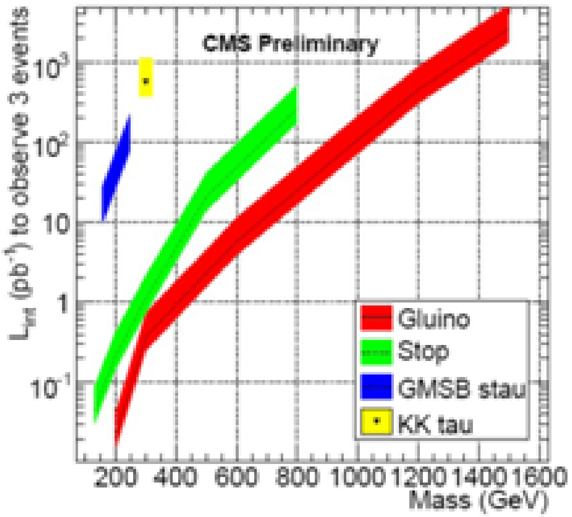
LHC – 2009 Run, 10-100 pb^{-1}

L for 1 month run	Integrated L	Trigger	Process	Comments
10^{28}	$10 nb^{-1}$	σ_{bB} ~ 600 nb. Setup – run single electron, muon, photon	g+g -> b+B ψ	900,000 JJ, 6000 bB, 1200 1μ, 60 2μ Establish μ jet tag 80 2e and 2μ events from ψ
10^{29}	100 nb^{-1}	Setup dimuon, dielectron $\sigma_{\mu v}$ ~ 10 nb	q+Q->W->μ+v (D-Y) Υ	1000 μ from W->μ + v Lumi – standard candle (look at high Mt tail) 100 2e and 2μ events from Υ
10^{30}	1 pb^{-1}	Run dilepton trigger $\sigma_{\mu\mu}$ ~ 1.5 nb σ_{tT} ~ 630 pb	q+Q->Z->μ+μ (D-Y) g+g->t+T	1500 dimuons from Z-mass scale, resolution Lumi- standard candle, high M 600 t + T produced
10^{31}	10 pb^{-1} End of '07 Pilot Run	Setup, J*MET $\sigma_{q\mu\mu}$ ~ 40 pb $\sigma_{\gamma\gamma}$ ~ 24 pb	g+q->Z+q->μ+μ+q q+Q->γ+-γ (tree) τ	400 Z + J events with Z->dimuons – Z+J balance, calib Estimate J + MET (q + v) 240 diphoton events with M > 60 GeV 6000 t + T 150 Z->tau pairs into dileptons > 8 GeV * MET > 15 GeV
10^{32}	100 pb^{-1}	σ_{qQZ} ~ 170 pb σ_{qgZg} ~ 32 pb σ_{tT} ~ 630 pb	g+g->q+Q+Z g+q->q+g+Z+g	3000 J+J+Z->vv events, Pt>30 500 J+J+Z->μ+μ events, Pt>30 600 J+J+J+Z->vv events 10000 J+J+J+J+μ+v events
10^{33}	1 fb^{-1} (1% of design L for 1 yr) End of '08 Physics Run			M of dijet in 100000 top events, W-> μ +v – set Jet energy scale with W mass. Dimuon mass > 1 TeV, start discovery search, diphoton search, SUSY search

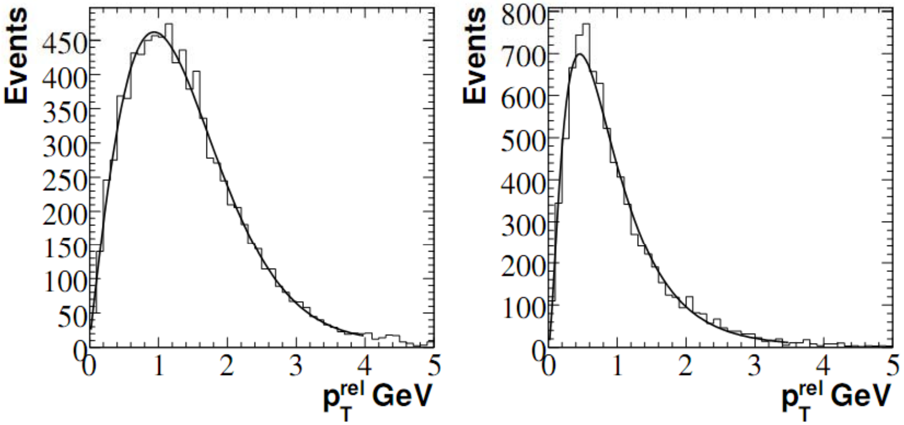
Heavy Stable Particles?

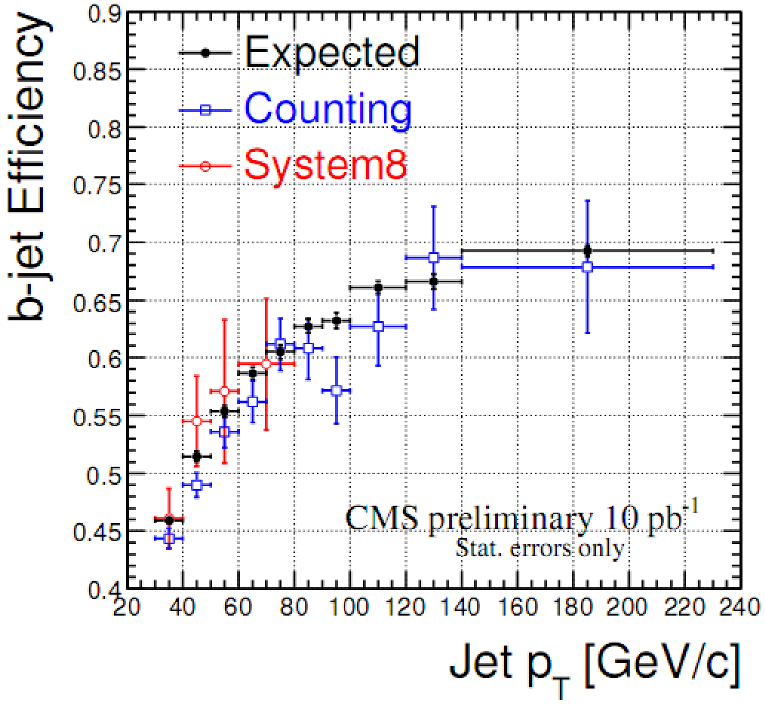
- Several SUSY variants predict metastable or stable charged particles
  - Slepton: “heavy muons”
  - Gluino, squark: “R-hadrons”
    - nuclear interactions!
- Signatures: dE/dx, Time Of Flight
- dE/dx: Tracker
  - >10 independent samplings in Si
  - Estimate the Most Probable Value
- TOF: Muon Chambers
  - δt additional parameter in the track fit
  - Main bkg: cosmics





B Tagging

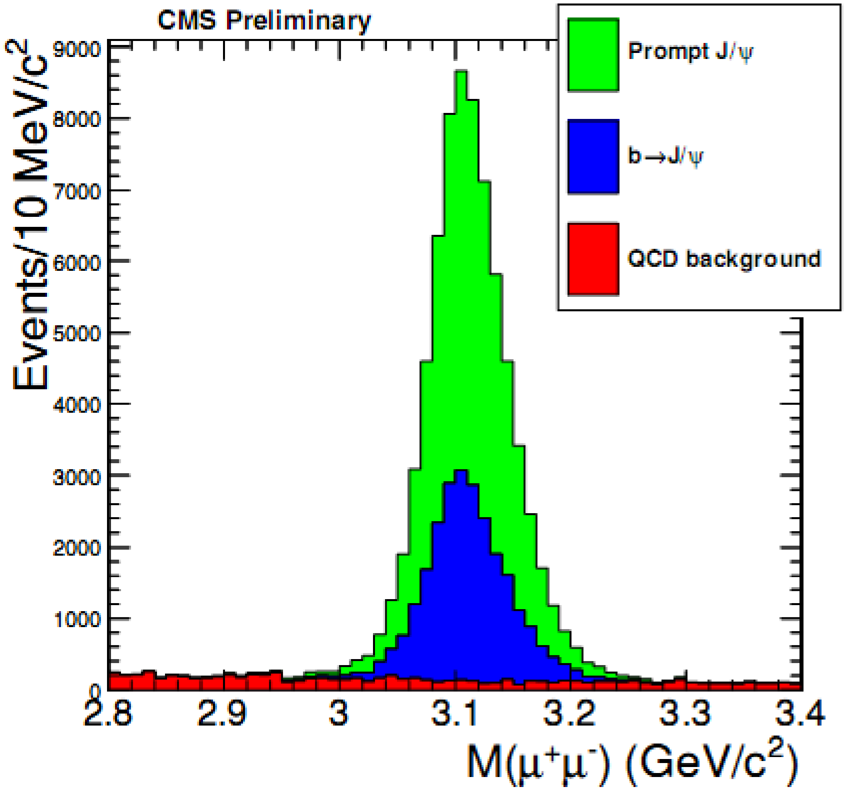


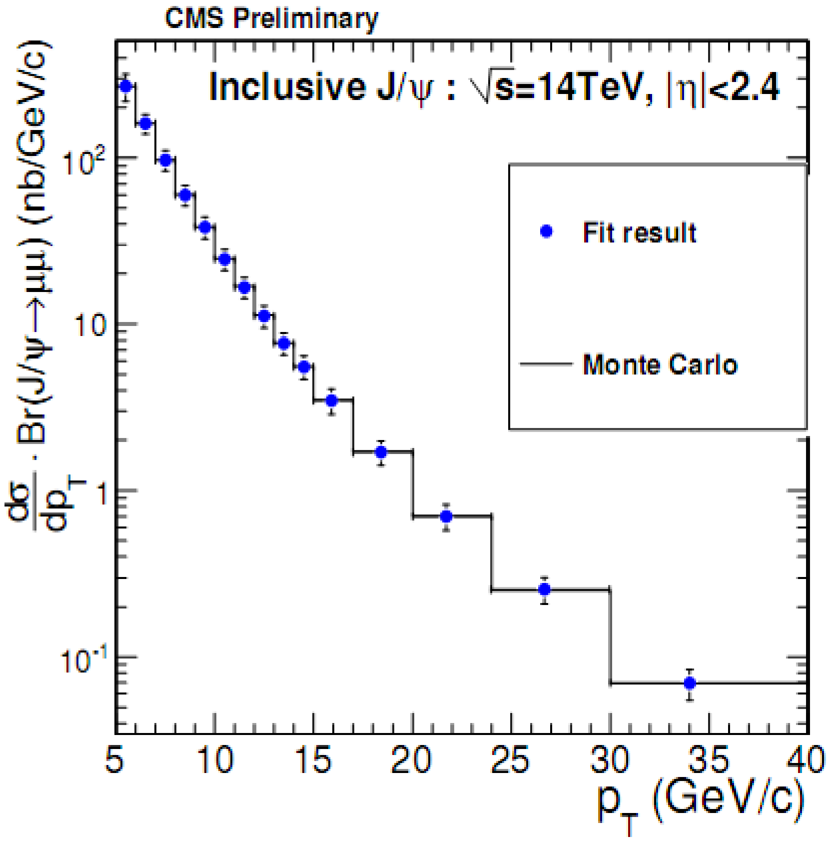


Identify b Jets using Pt relative to jet axis. Tracking alignment crucial.

Establish b tagging. Check with top pair events.

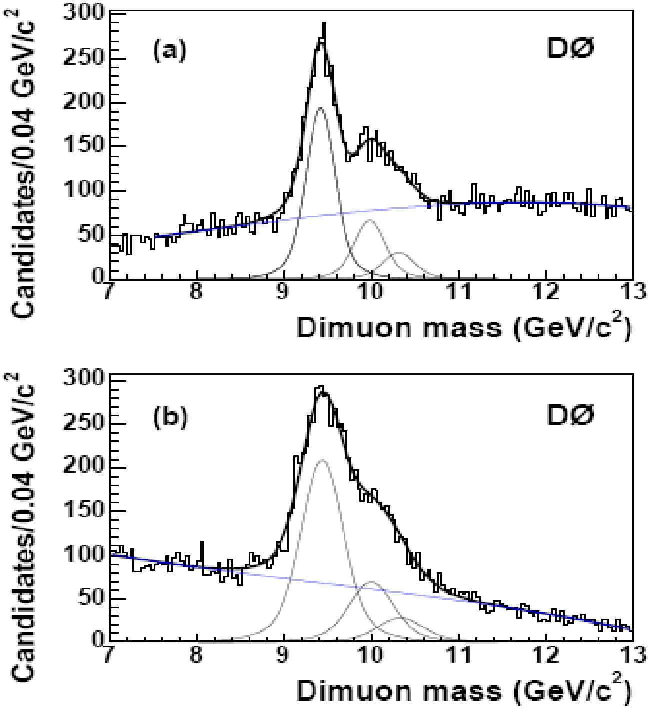
Psi Production

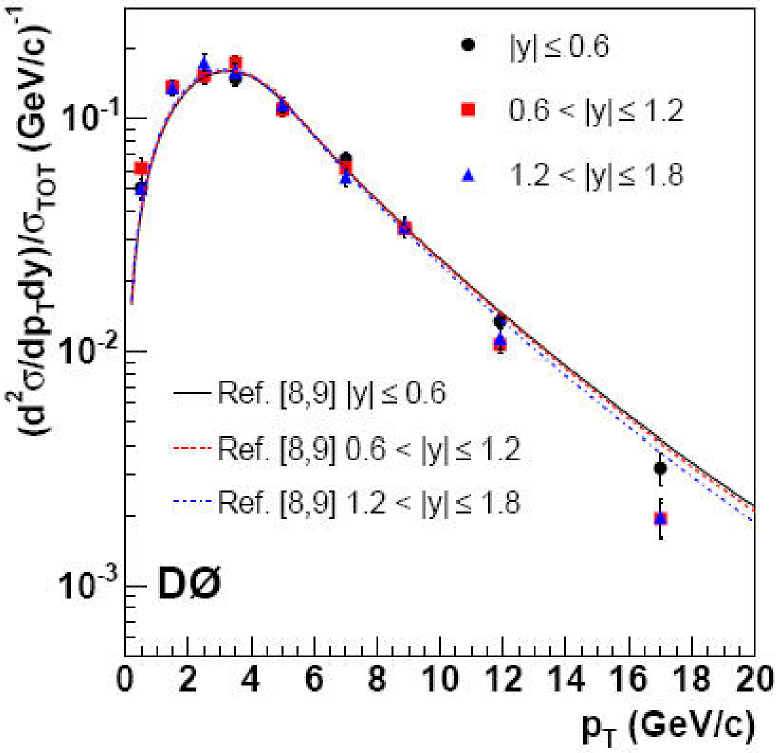




Largest cross section resonant dilepton state. Set momentum scale for tracker. Note the cross section scale is nb.

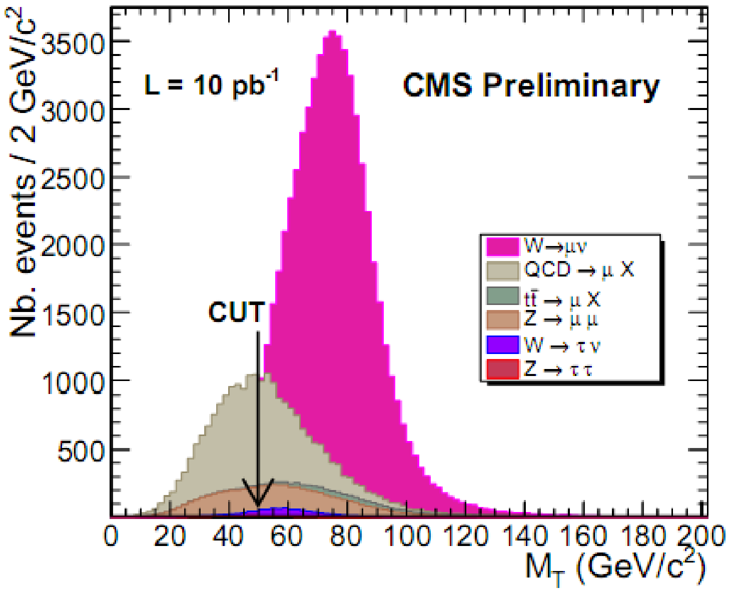
Upsilon Calibration – D0

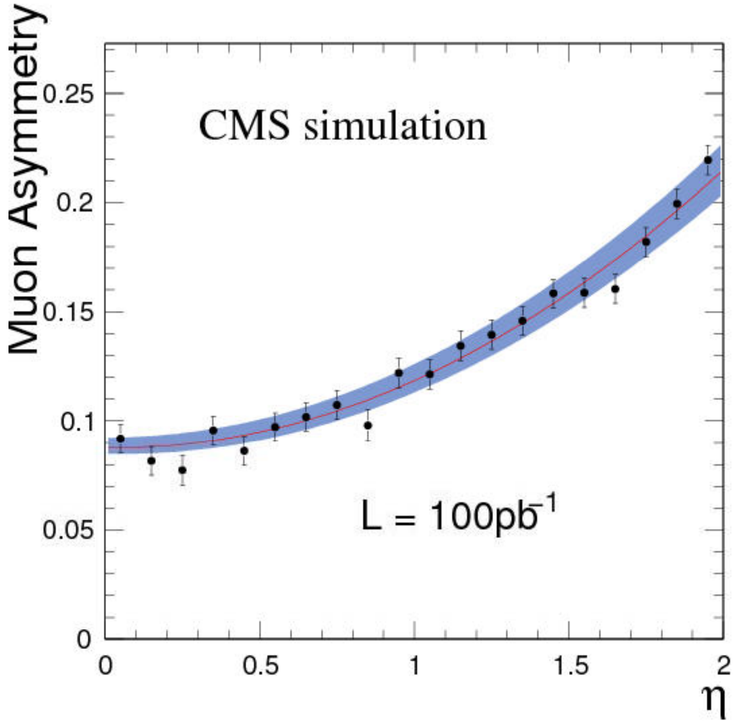




Cross section * BR about 1 nb. Resolve the spectral peaks? Mass scale correct? Moving to higher P scale.

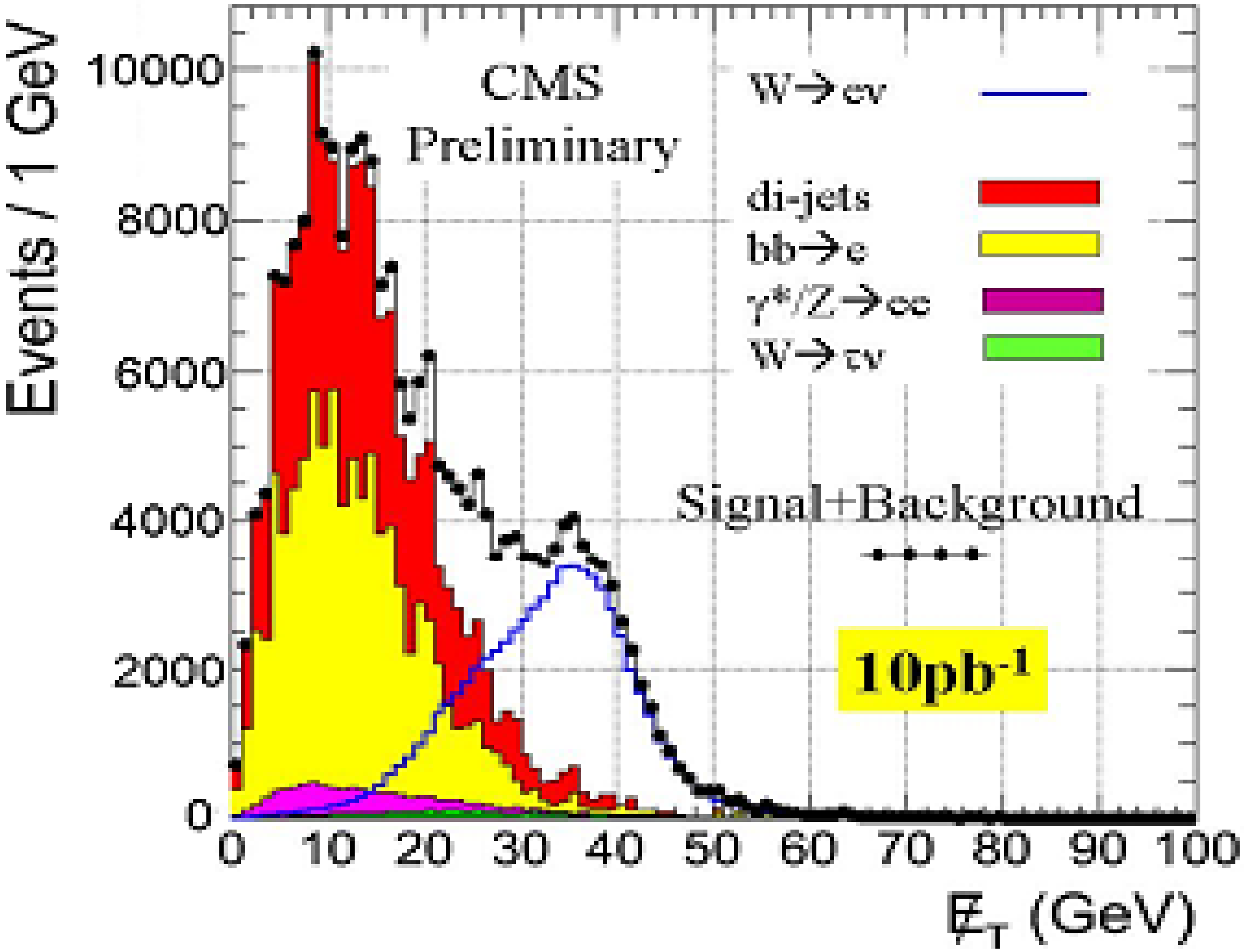
W Production - Muons



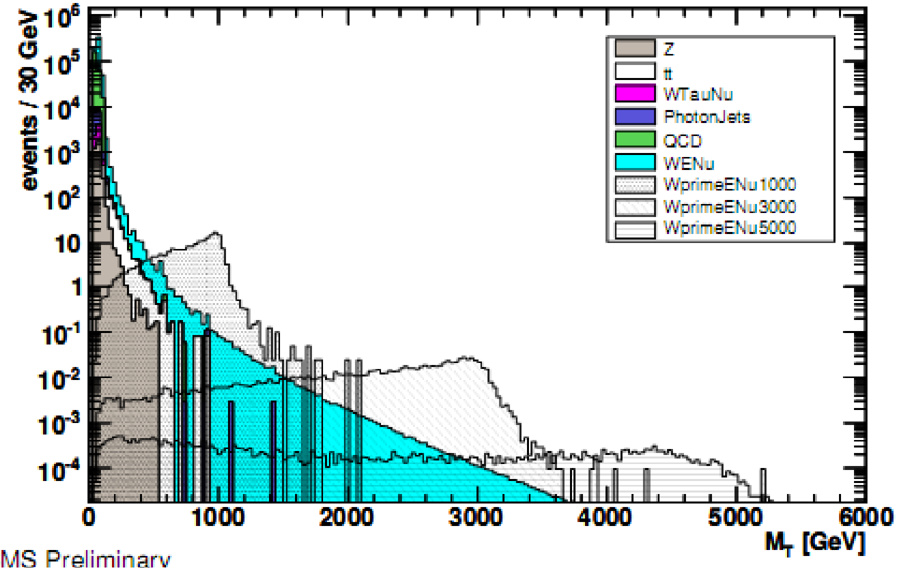


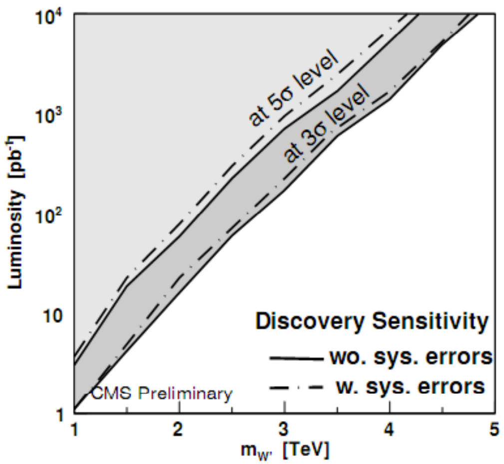
Check W cross section and y distribution. The PDF predictions are quite constrained. Charge asymmetry is a ratio – many efficiencies cancel out. The cross section is ~ 20 nb.

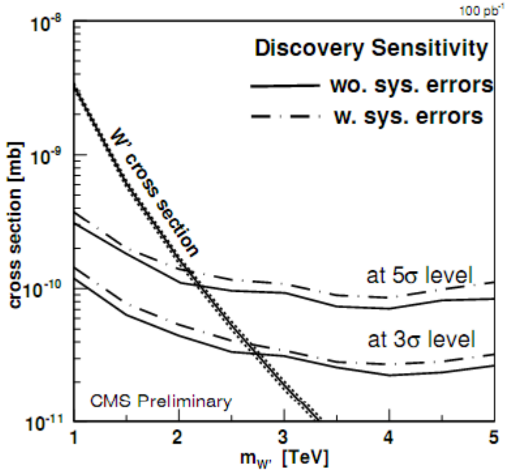
W Production - Electrons



W’ Search

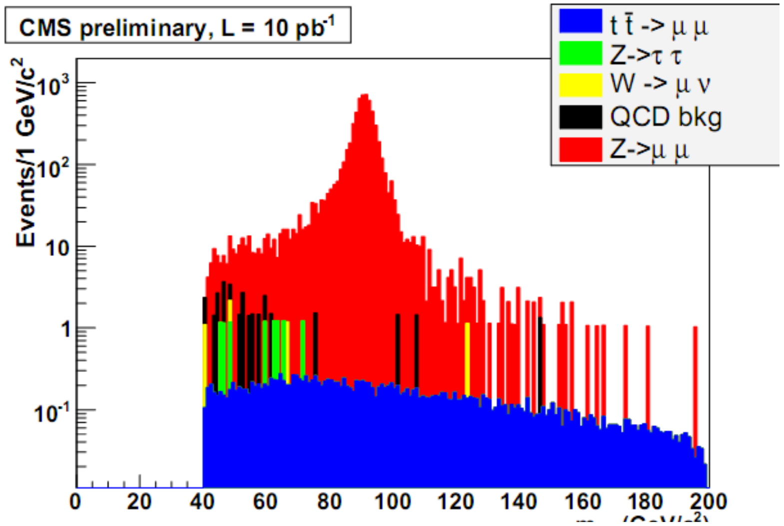


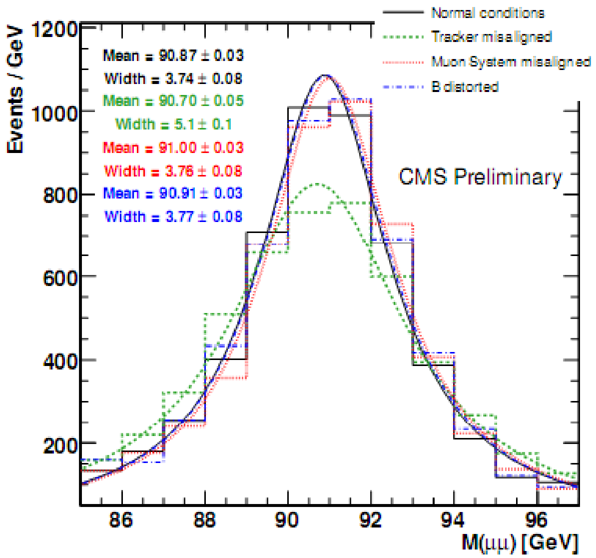


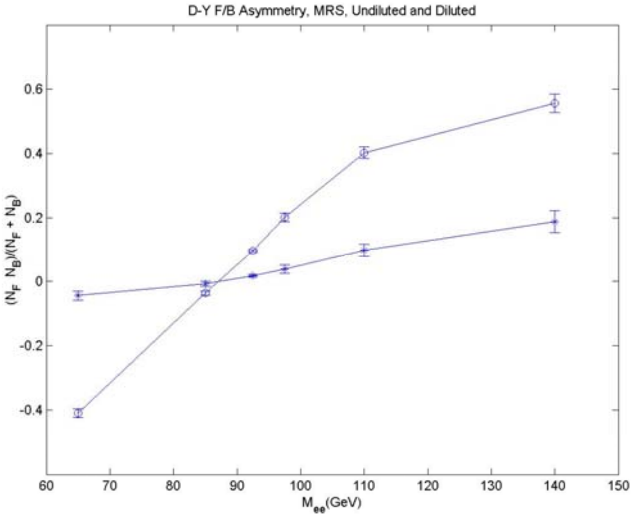


With SM W in hand, look in BW tail of the W. At 100 pb^{-1}, the W′ mass limit is ~ 2 TeV

Z Production - Muons

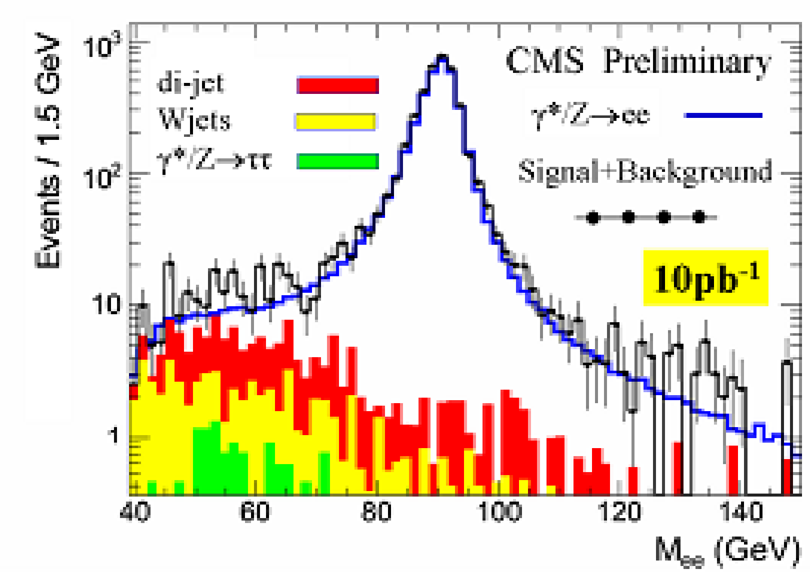






SM Z – check mass scale, Z resolution, width and FB Asymmetry. Use Z signal for “tag and probe” to get lepton efficiencies.

Z Production - Electrons



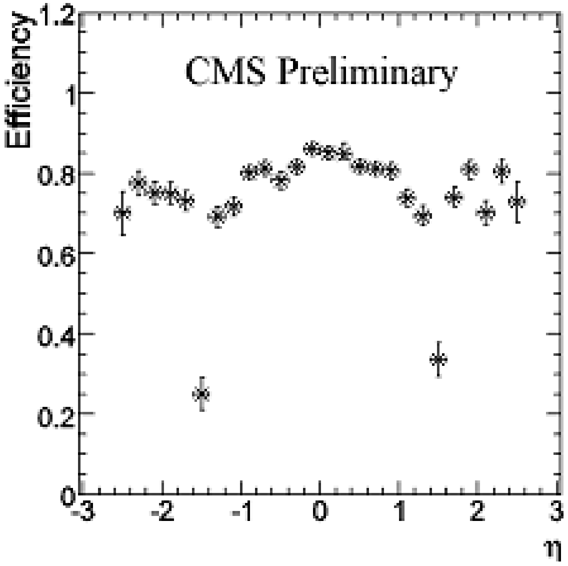
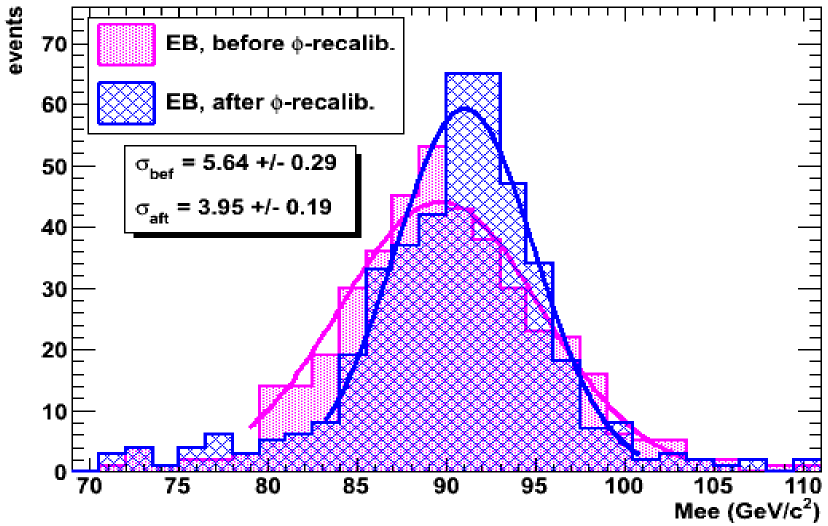


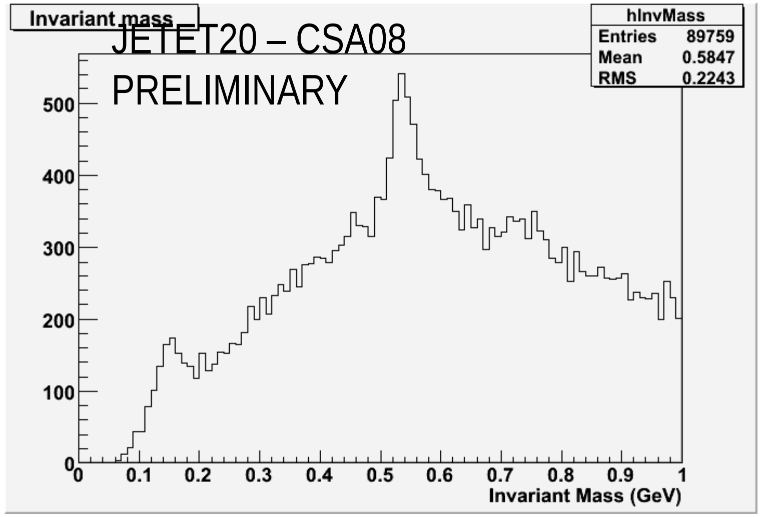
Figure 4: Trigger efficiency versus supercluster η.

The dilepton "tag and probe" – extract data driven efficiencies for leptons – e.g. e trigger efficiency. Backgrounds are small so purity for tagging is very high.

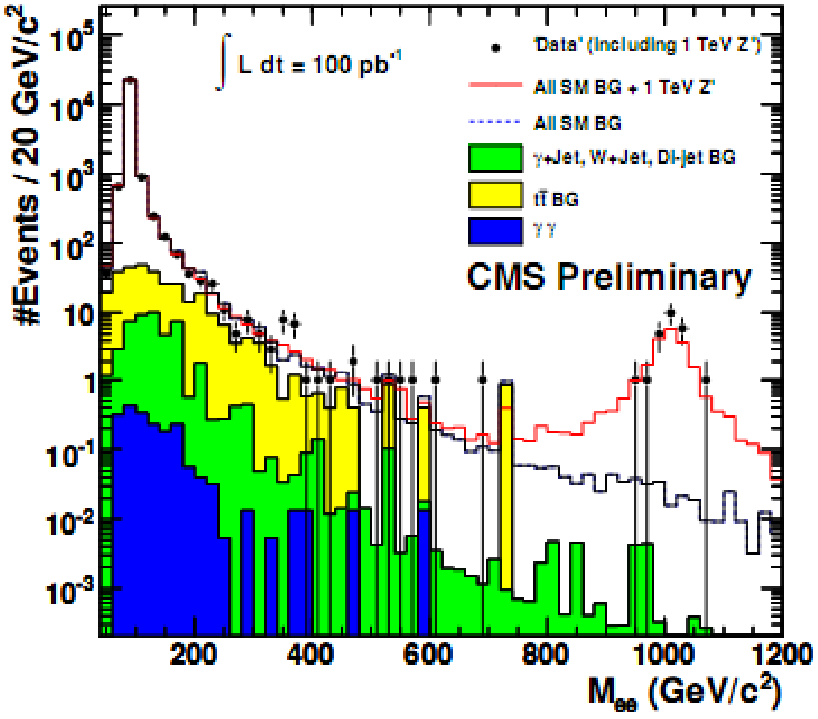
Calibration Validation - Photons

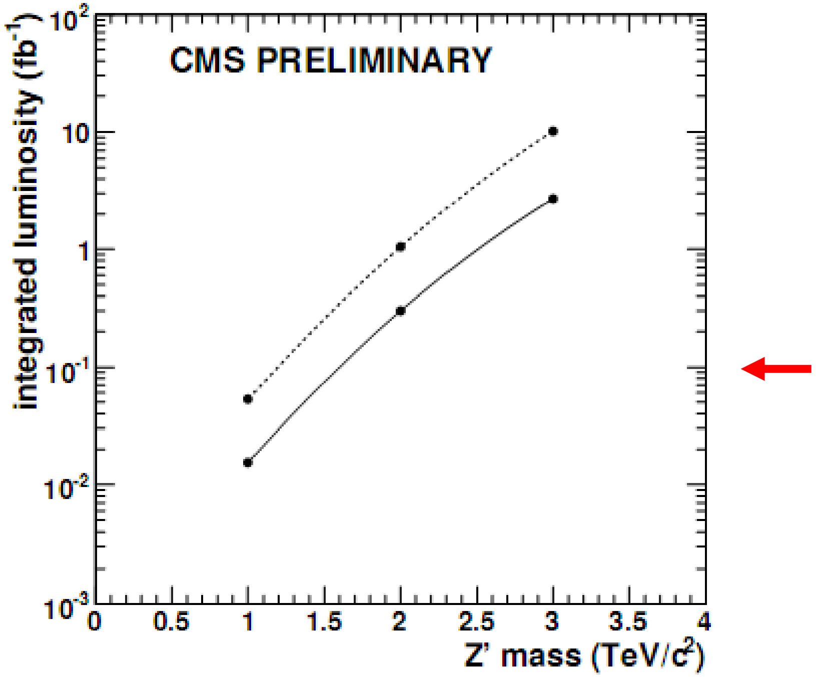
- Zee mass peak useful to test “ϕ-symmetry” in EE
- π^0 peak: in EE (insufficient for EB: small energy & opening angle)
- $\pi^0 \rightarrow \gamma ee$ (Dalitz): electrons well measured in TK (low pt)
- $\eta \rightarrow \gamma\gamma$: rate 1/20 of $\pi^0 \rightarrow \gamma\gamma$ but better mass resolution





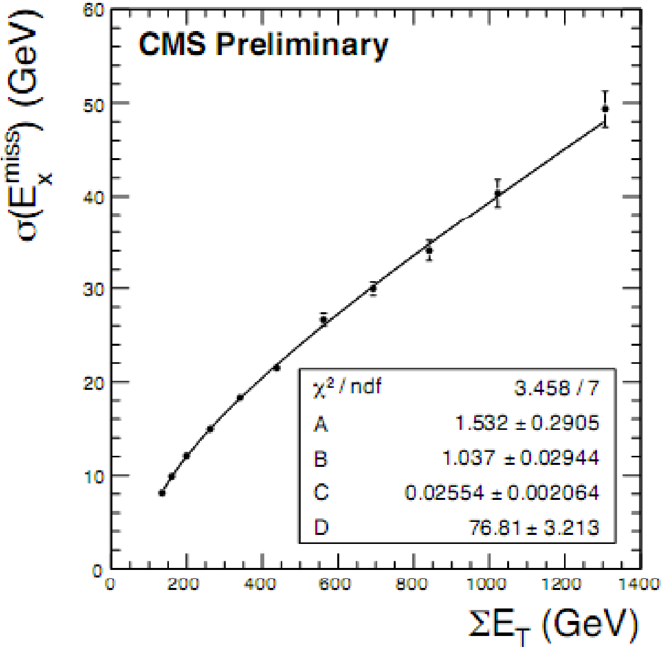
Z' Search

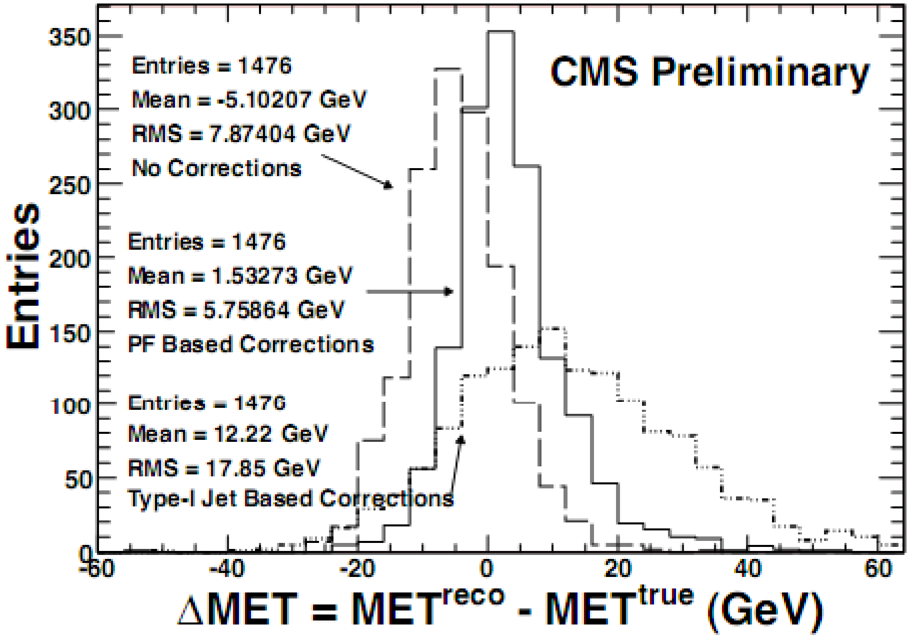




Having established Z decays into dileptons, look in the BW tail of the Z for new physics. At 100 pb^{-1} start to probe the "terascale" – masses ~ 2 TeV.

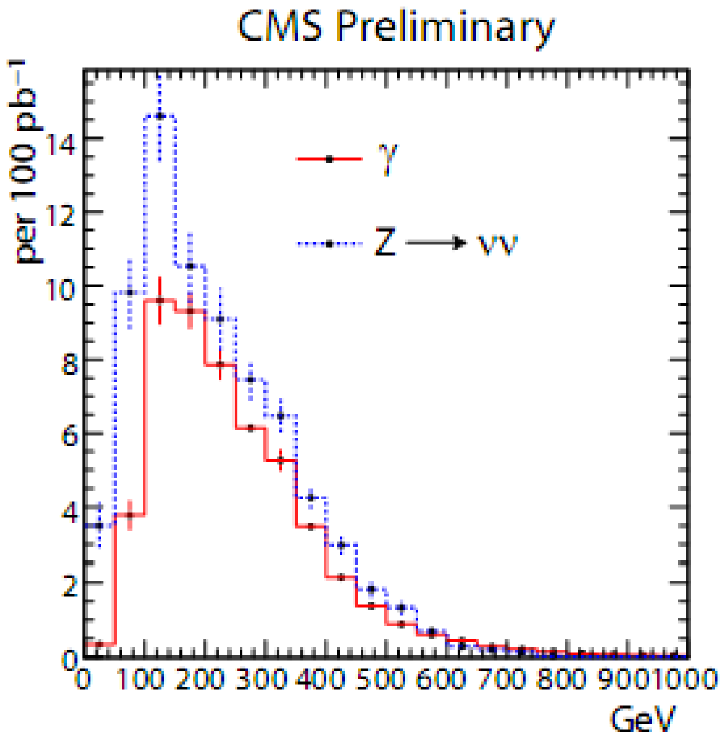
Missing Transverse Energy

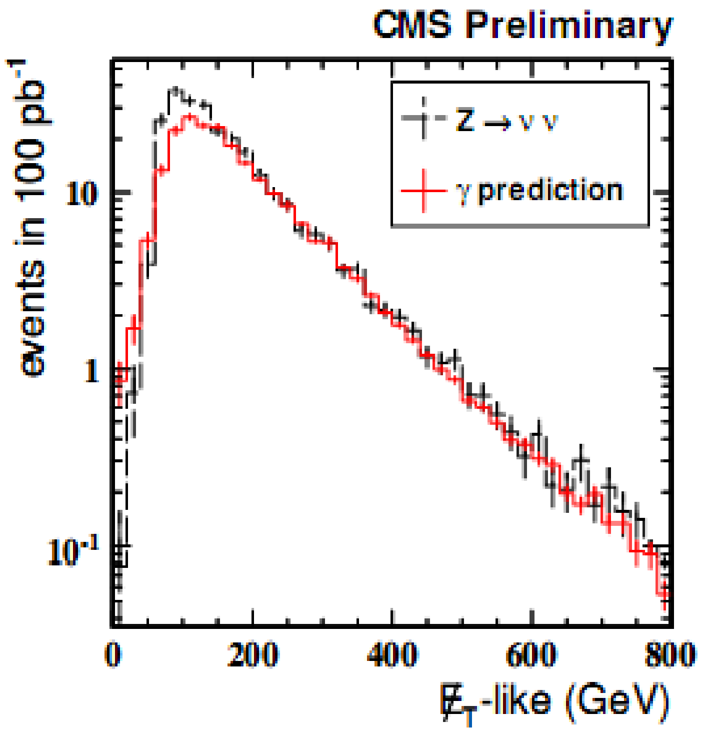




Establish MET with SM processes: e.g. W leptonic decay, Z -> v + v and top decays. When validated use MET as a tool for probing new physics. Use particle flow and tracking information to improve MET resolution by ~ 2x.

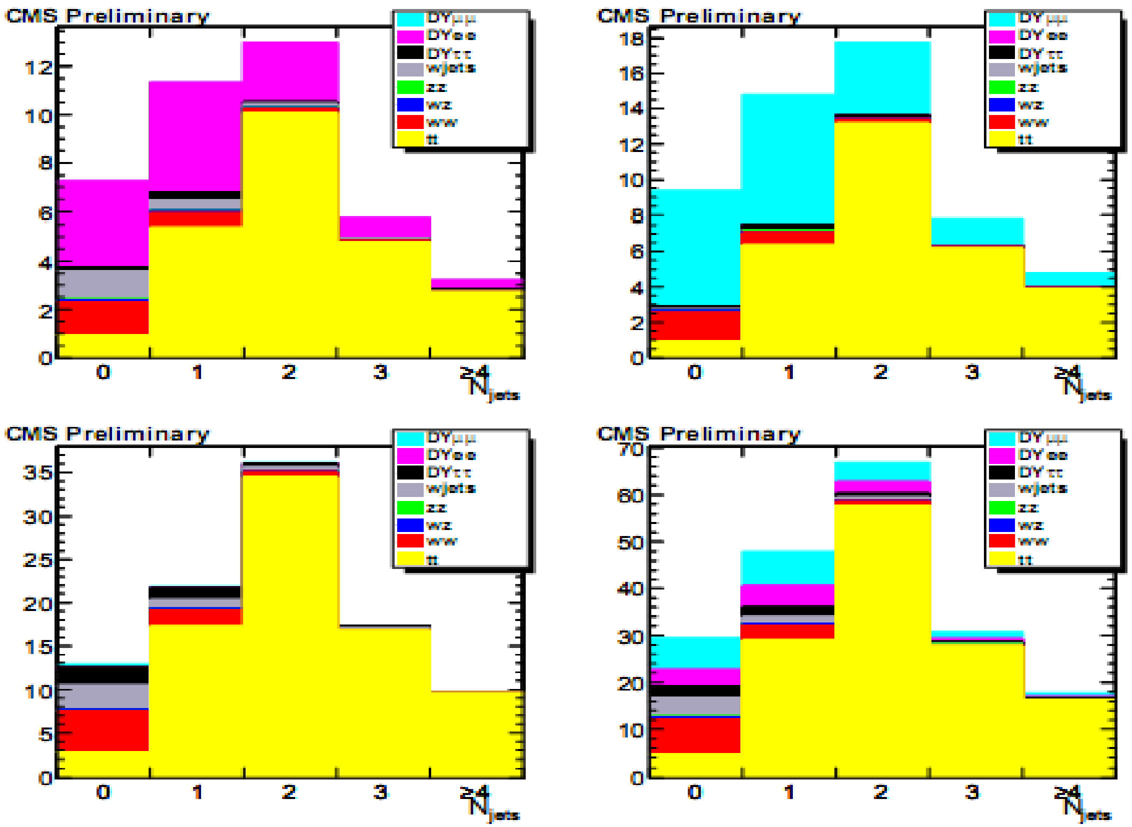
Irreducible SM MET Background





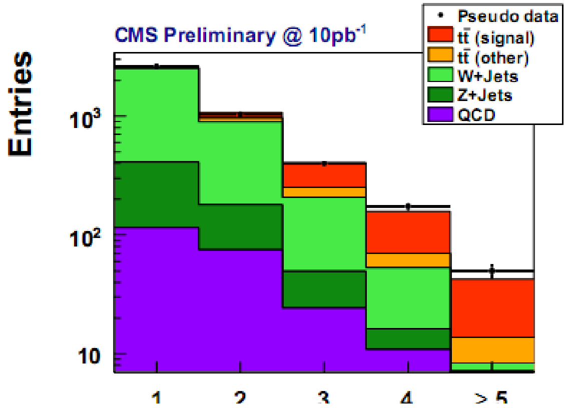
Z -> v + v is irreducible. Use leptonic Z decay to estimate (low statistics) or use photon as a signal which is dynamically similar to Z.

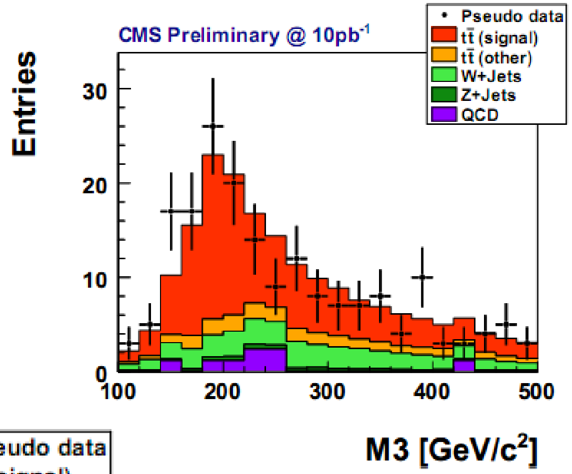
Top - Dileptons

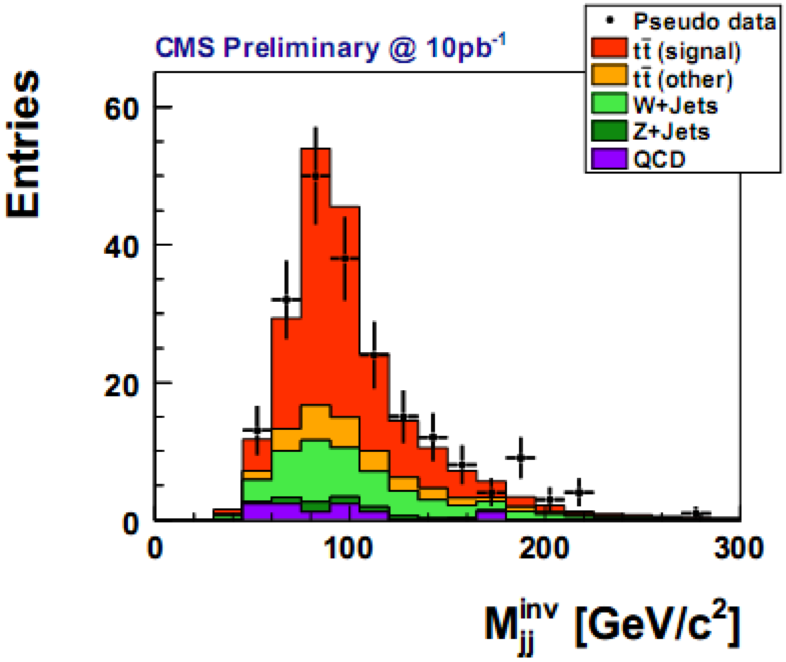


Establish top pair SM signal in dilepton final state – clean but low statistics. Top has SM “candle” with leptons, jets, MET and b jets.

Top – Jets + Leptons + MET

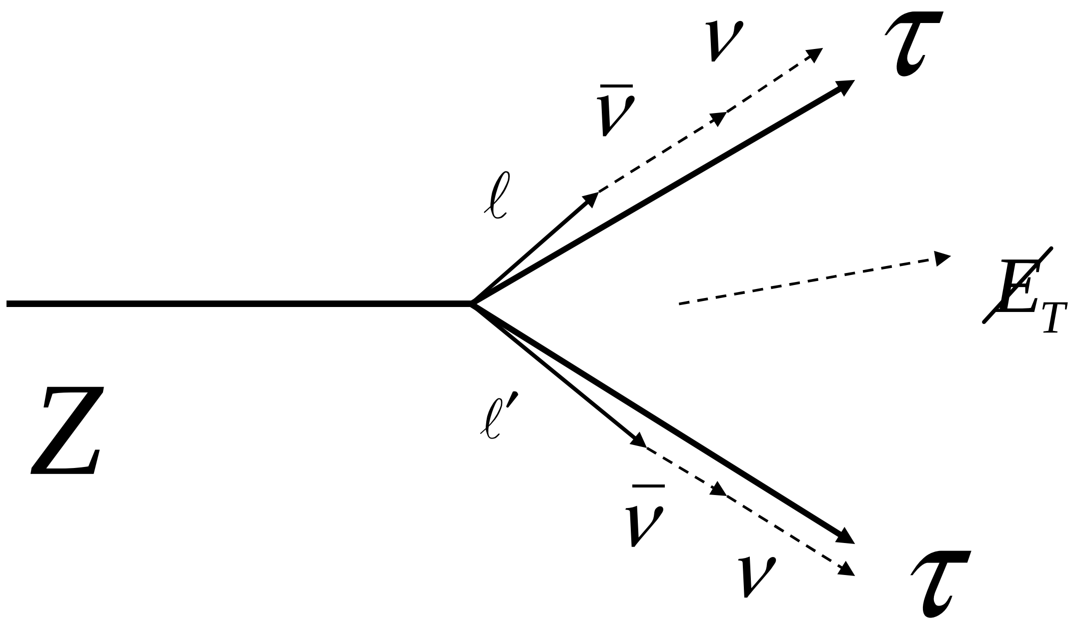






Check jet energy scale with hadronic decay of the W. Check b tag efficiency with 2 b in final state. Establish MET scale.

Z Decay to Tau Pairs - Collinear



$$M_{\tau\tau} \sim \sqrt{2(E_{\ell 1}+E_{\nu\nu 1})(E_{\ell 2}+E_{\nu\nu 2})(1-\cos\theta_{\ell 1\ell 2})}$$

$$METx = E_{\nu\nu 1}\alpha_{x\ell 1} + E_{\nu\nu 2}\alpha_{x\ell 2}$$

$$METy = E_{\nu\nu 1}\alpha_{y\ell 1} + E_{\nu\nu 2}\alpha_{y\ell 2}$$

SM "candle" for tau – third generation lepton important in many BSM scenarios.

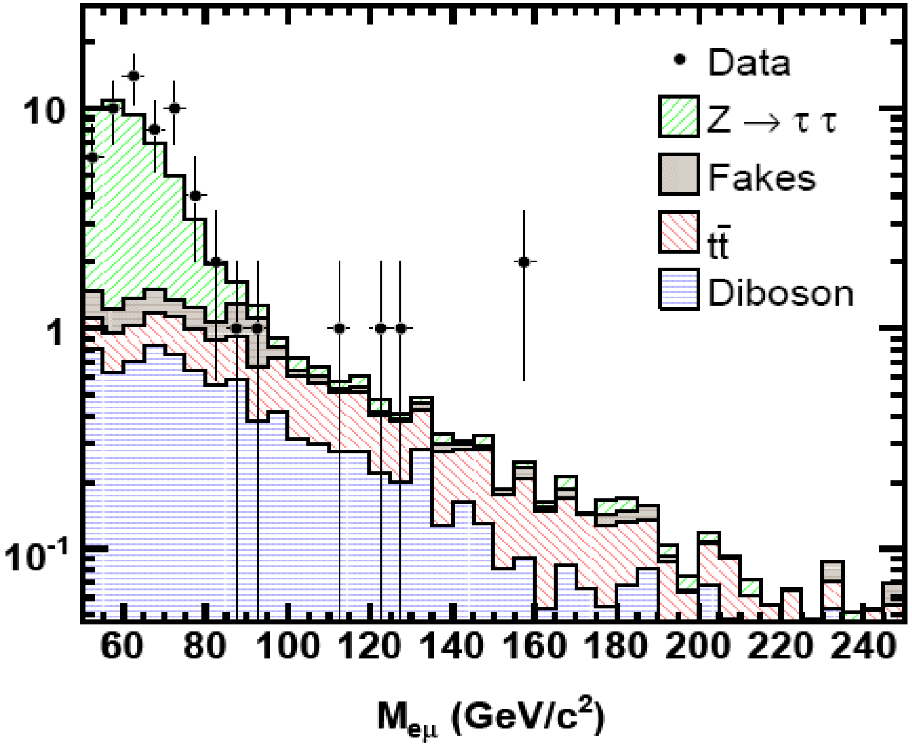
Assume collinear neutrinos. Then have 2 Eqs in 2 unknowns. Must cut on determinant

$$\det = \sin\theta_{\ell 1}\sin\theta_{\ell 2}\sin(\phi_{\ell 1}-\phi_{\ell 2})$$

$|\det|$>0.005 is ~ 70% efficient after cuts on Pt of the leptons and MET.

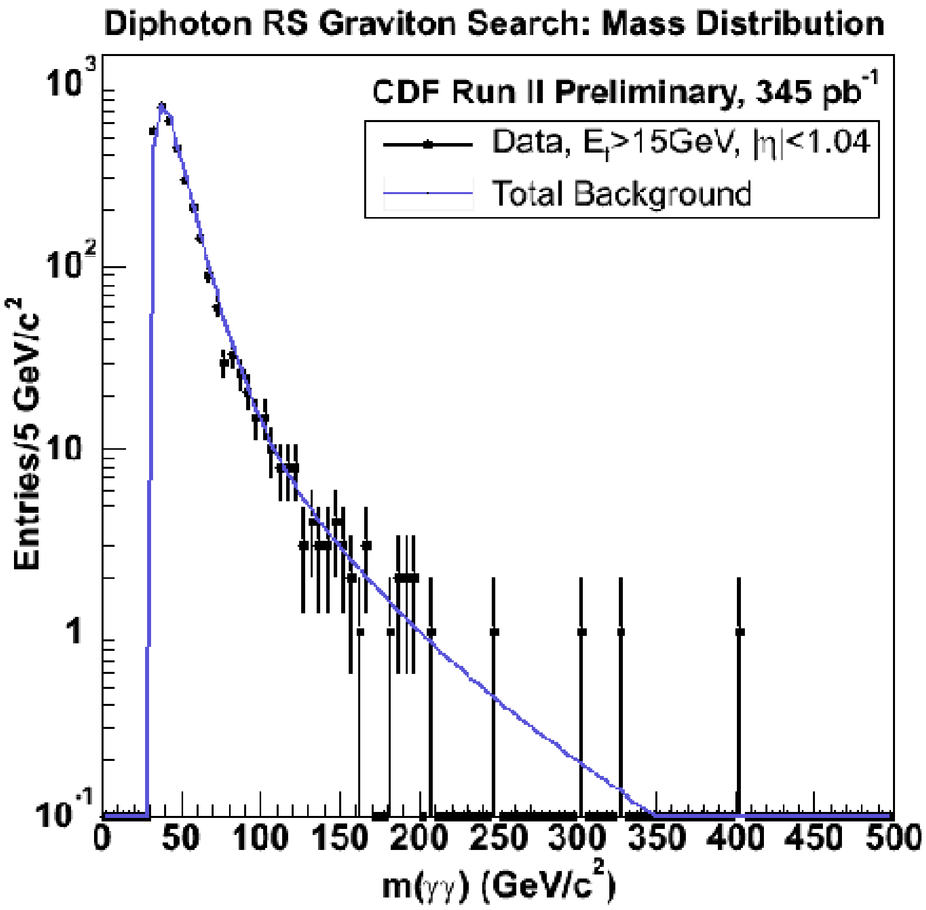
Di-lepton Search for Z -> $\tau + \tau$

Tevatron

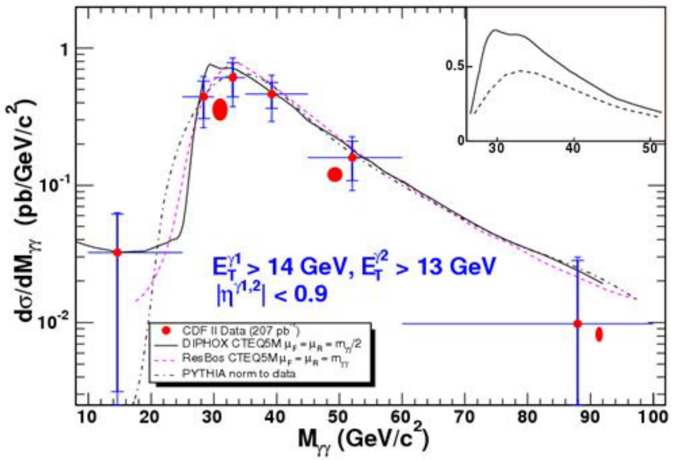


Having established clean electron, muon and tau "objects" a look at di-lepton masses can be taken with some confidence. The top pair background dominates the dilepton mass spectrum at high masses - SUSY.

Tevatron - Diphotons

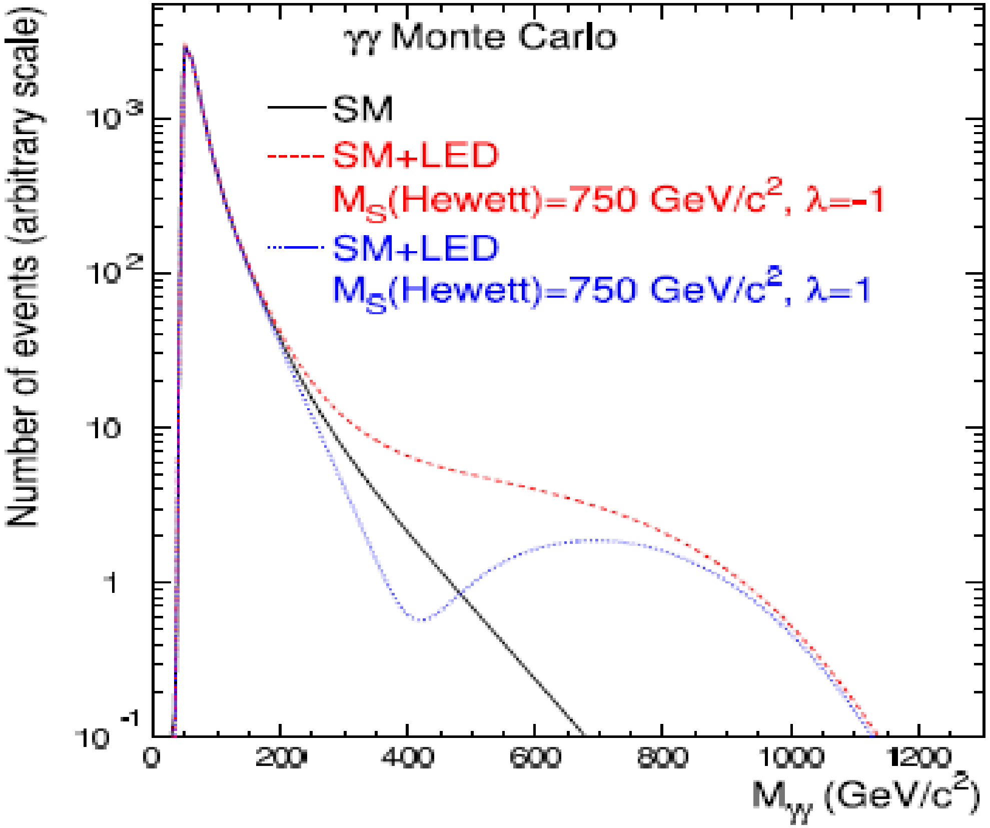


Mass spectrum explored to ~ 300 GeV. Large increase in mass reach at the LHC.



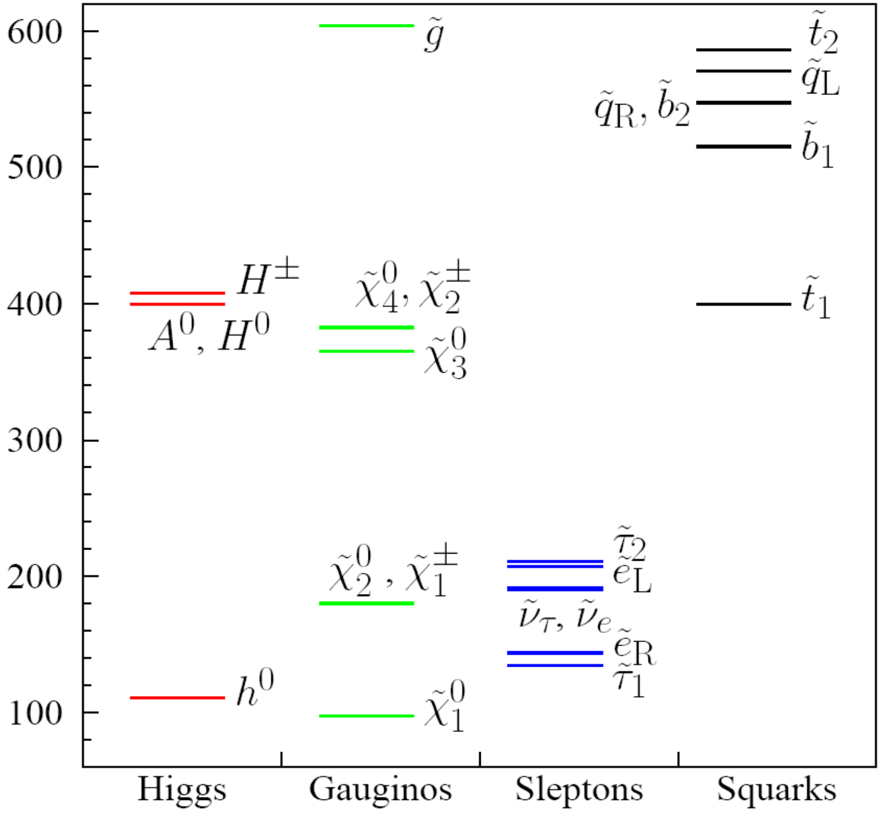
● COMPHEP – tree diagrams

Di-photons at High Mass



Gravity couples to all mass "democratically". Therefore look at rare processes with SM weak couplings. LHC will be in new territory by 100 pb^{-1}.

SUSY MSSM Mass Spectrum

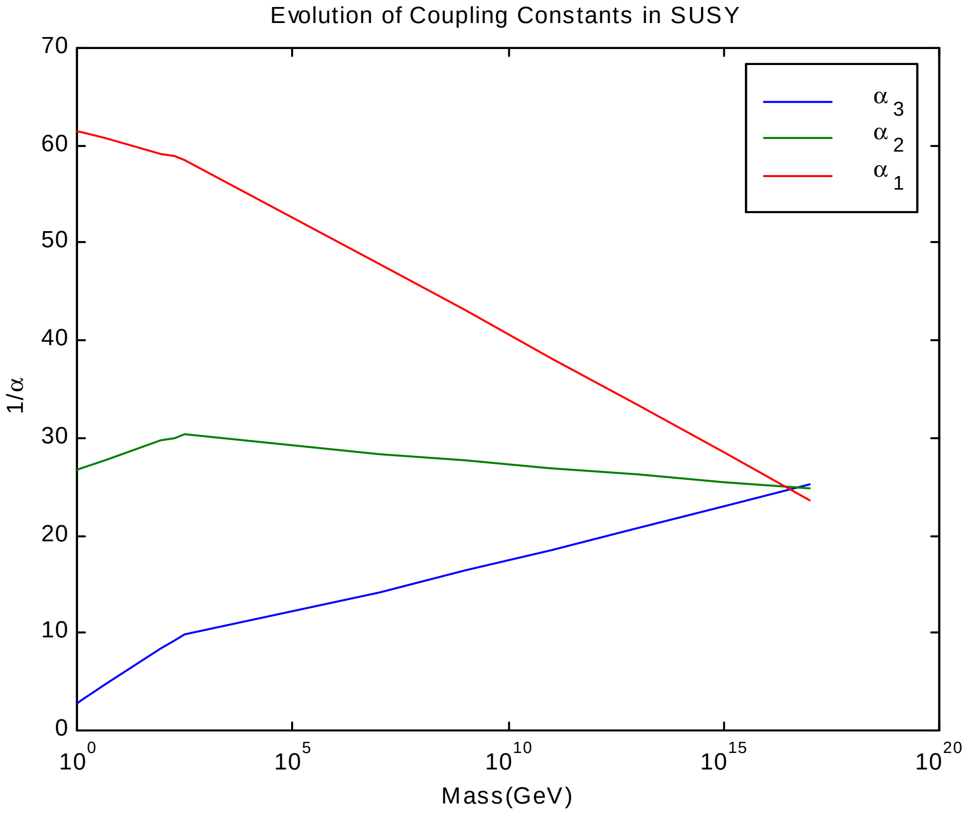


MSSM has ~ SM light h and ~ mass degenerate H,A. LSP is a neutralino. Squarks and gluinos are heavy, sleptons are light.

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.**

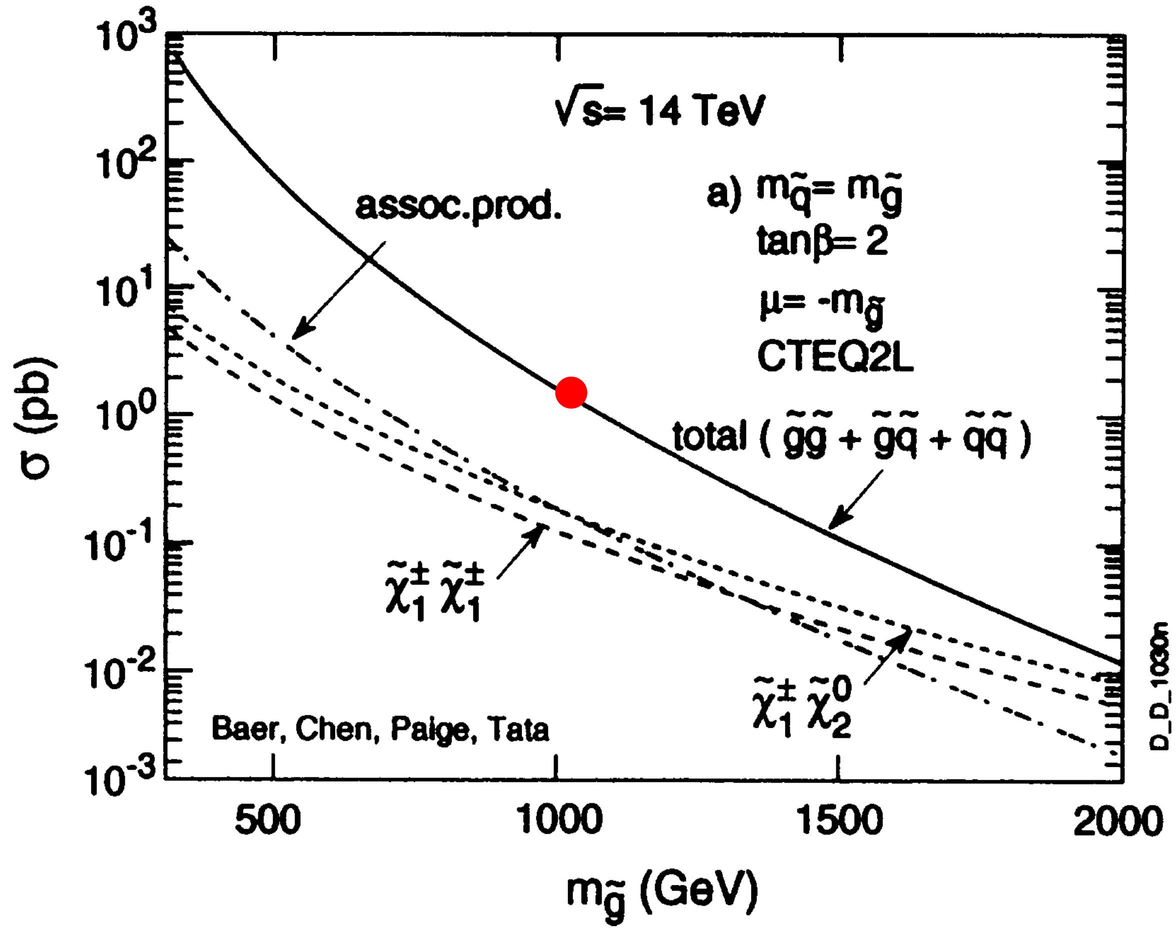
GUT and Evolution of α


Evolution of Coupling Constants in SUSY

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

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

SUSY Cross Sections



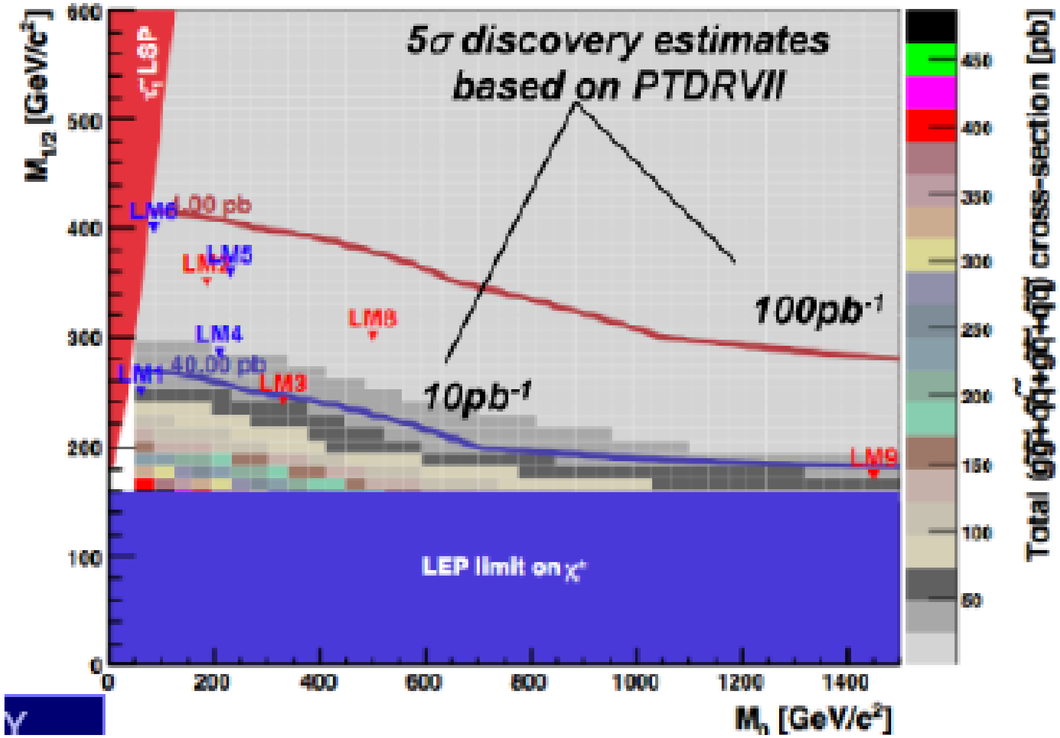
The SUSY cross sections for squarks and gluinos are large because they have strong couplings. R parity means cascade decays to LSP. Simplest signature is jets and MET, independent of specific SUSY model.

Dimensionally

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

or ~ 1 pb for M = 1 TeV.

SUSY and 2009 Run



Very Early Discovery Potential:

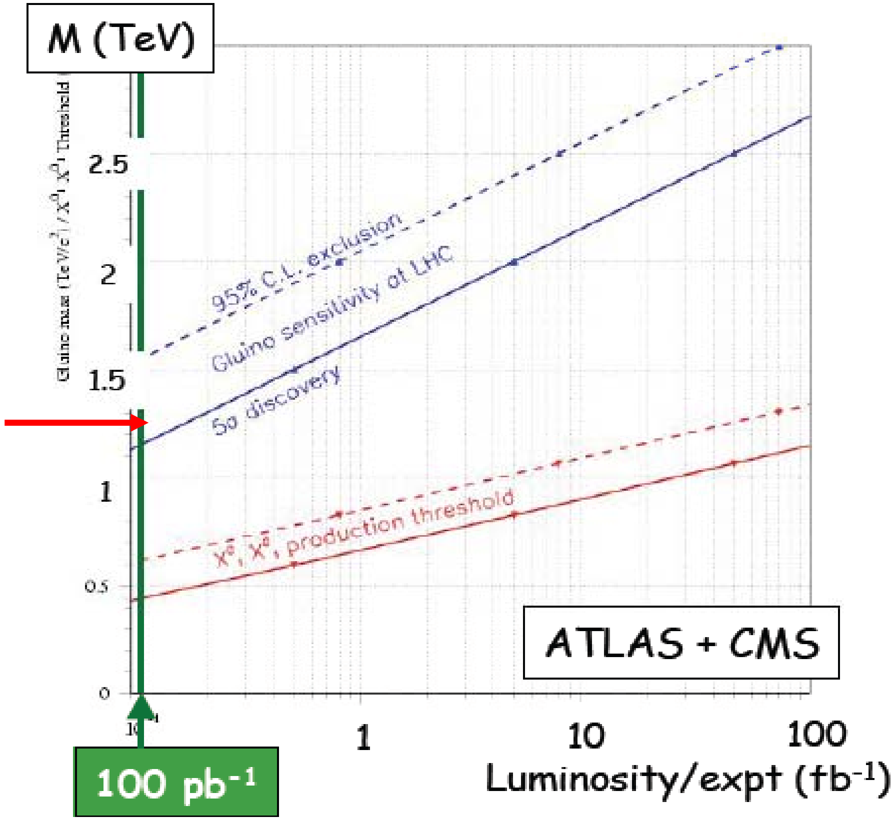
10 pb^-1 : ~50pb production XS

100 pb^-1: ~4pb production XS

Already with O(10pb^{-1}) we are probing very interesting SUSY parameter space

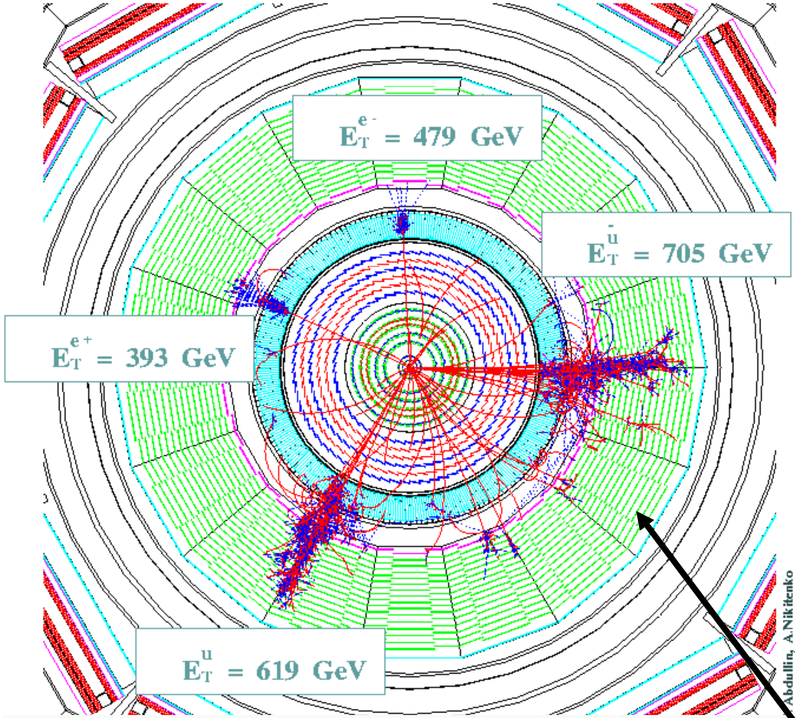
Energy is important. Quickly surpass Tevatron discovery reach.

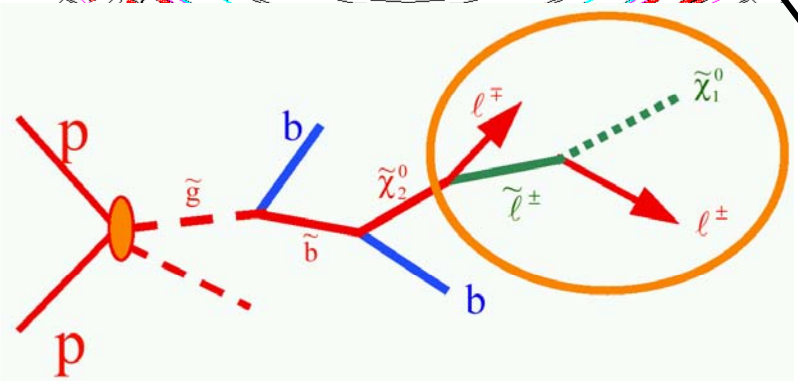
Getting to the Terascale



Very early for SUSY CMS will exceed the CDF/D0 mass reach – for strongly produced squark/gluino even in 2009 at 100 pb^{-1}.

Sparticle Cascades





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

Decay chain used is :

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

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

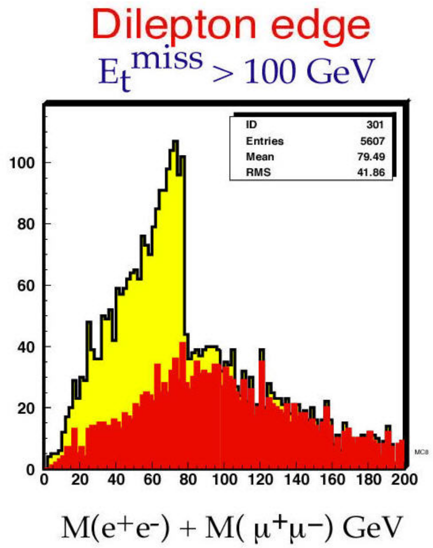
$$\tilde{b} \to \tilde{\chi}_2^0 + b$$

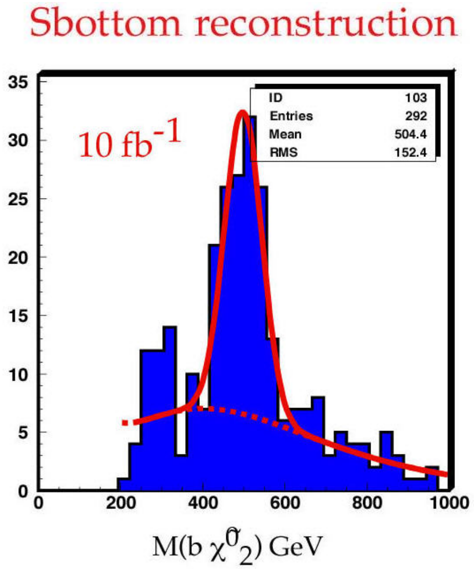
$$\tilde{g} \to \tilde{b} + b$$

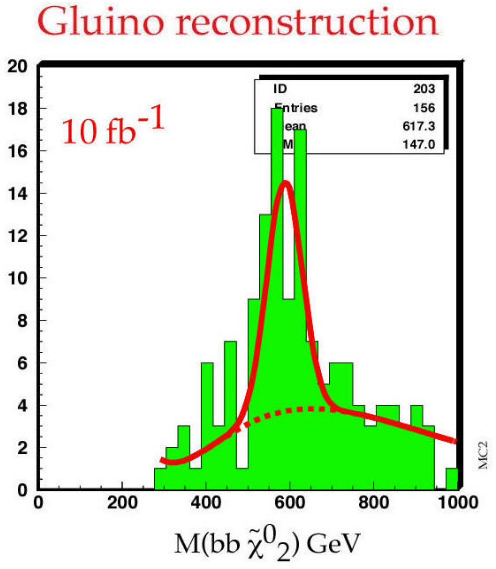
Final state is

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

SUSY Reconstruction







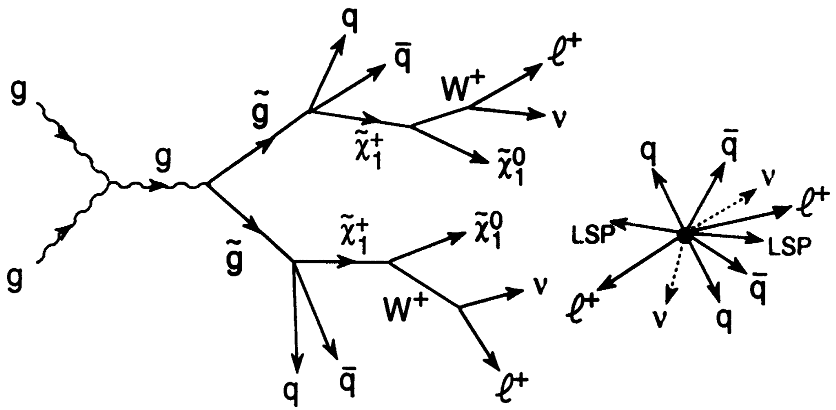
$$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \ell^+ + \ell^-$$

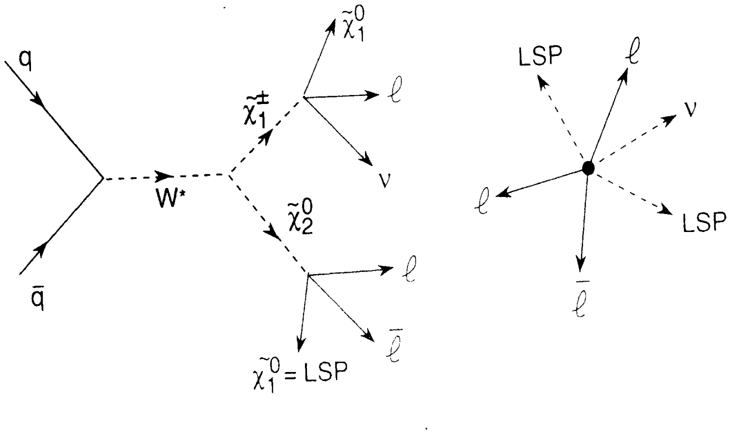
$$\tilde{b} \rightarrow \tilde{\chi}_2^o + b$$

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

Mass of $\tilde{\chi}_1^0$ from MET, 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.

SUSY Signatures

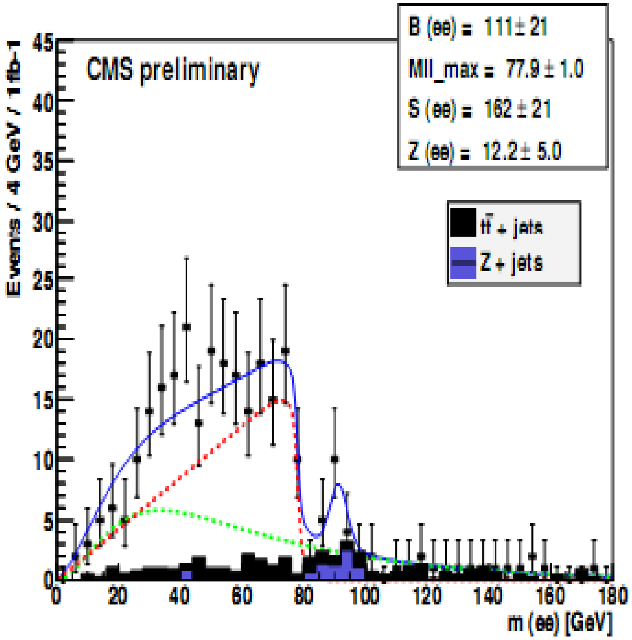


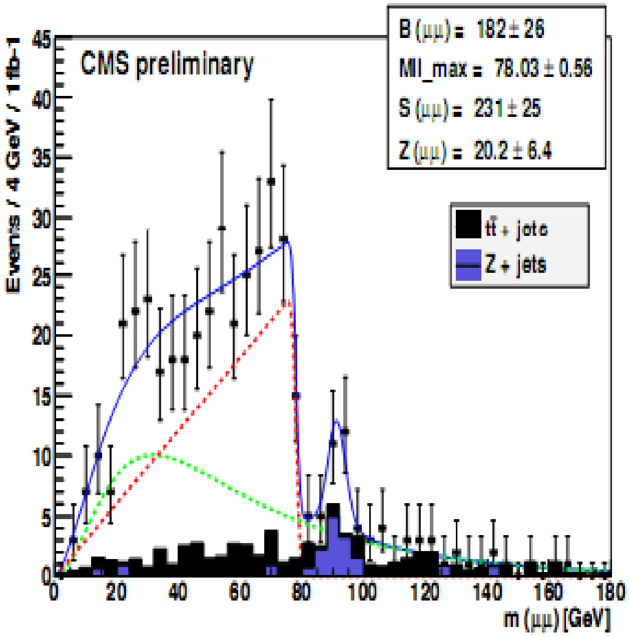


The gluino pair production cascade decays to jets + leptons + missing Et. Gluino is a Majoran, like sign ~ same sign for dileptons

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

Dilepton Kinematic Edges



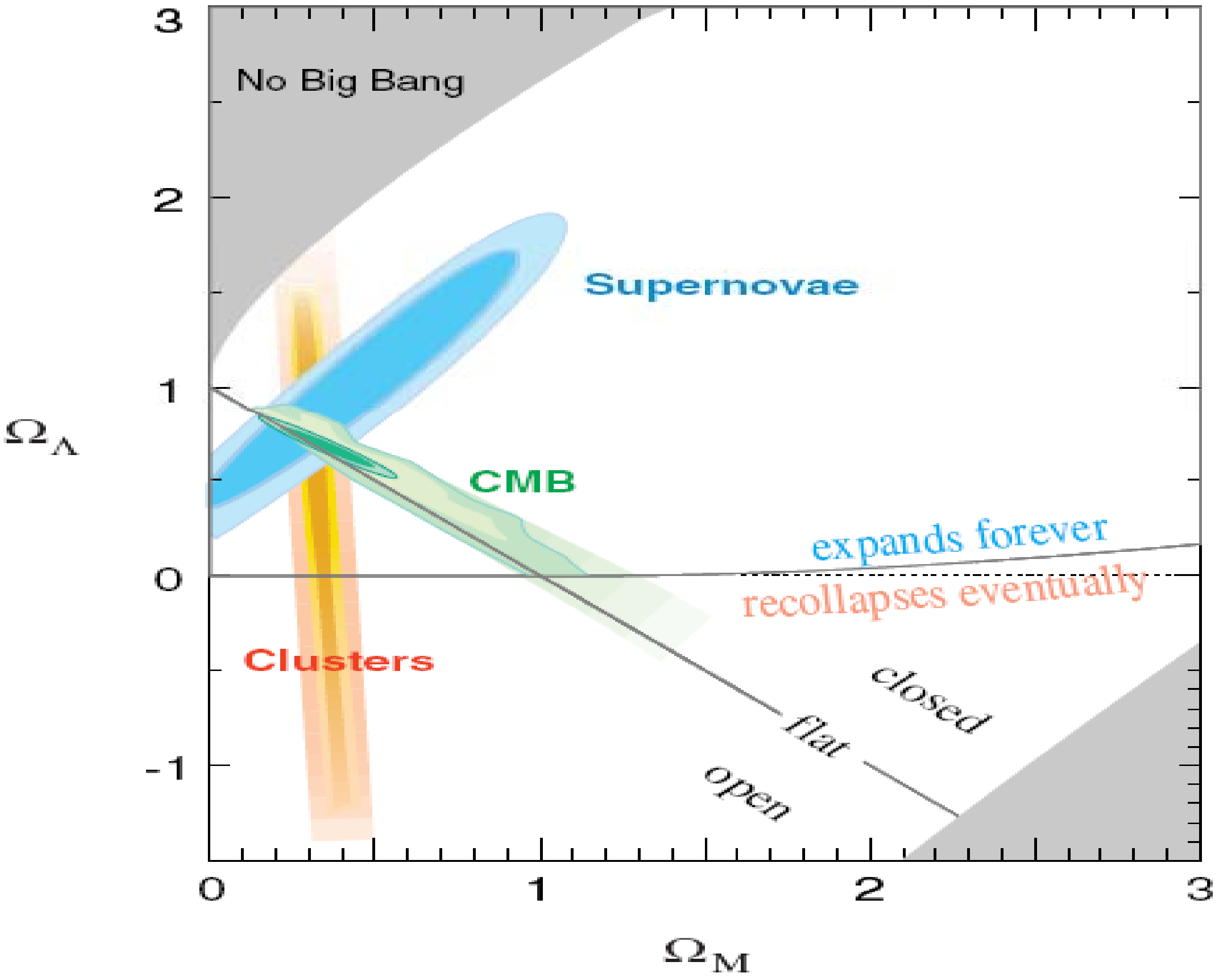


$$M^{\max}_{\ell^+\ell^-} = \frac{\sqrt{(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\tilde{\chi}^0_1})}}{M_{\tilde{\ell}}}$$

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

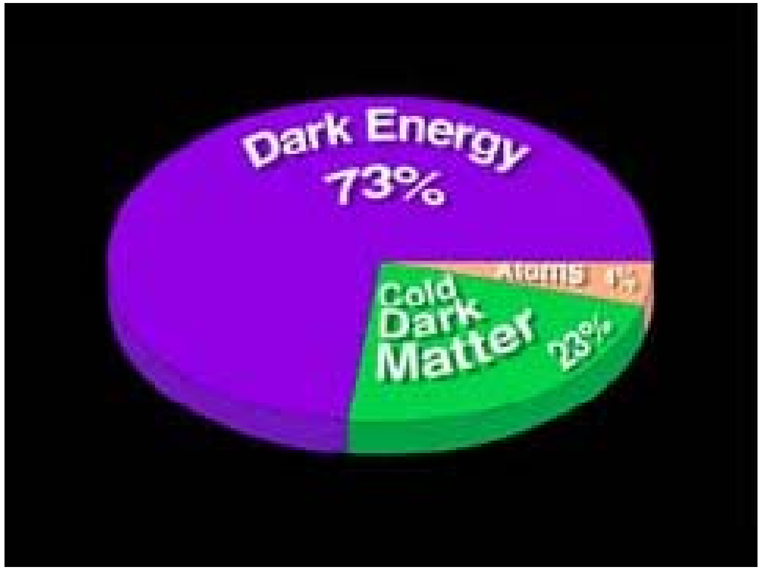
Edges give mass information. Signals for 1 fb^{-1}. Use flavor of lepton and charge pairing to extract signal (Majorana)

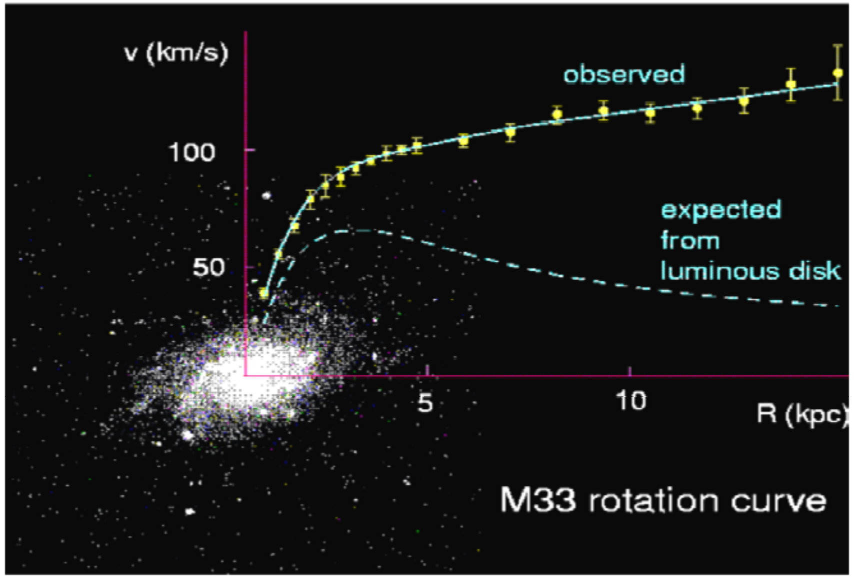
Cosmology and CMS



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 !

Dark Matter ?





There is no SM candidate. Can we produce DM in CMS? Is it the SUSY LSP? Searches at LHC, in direct (recoil) measures – e.g CDMS, in annihilations - e.g GLAST , in flavor loops – e.g. LHCb and in annihilations (e.g. GLAST) 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.

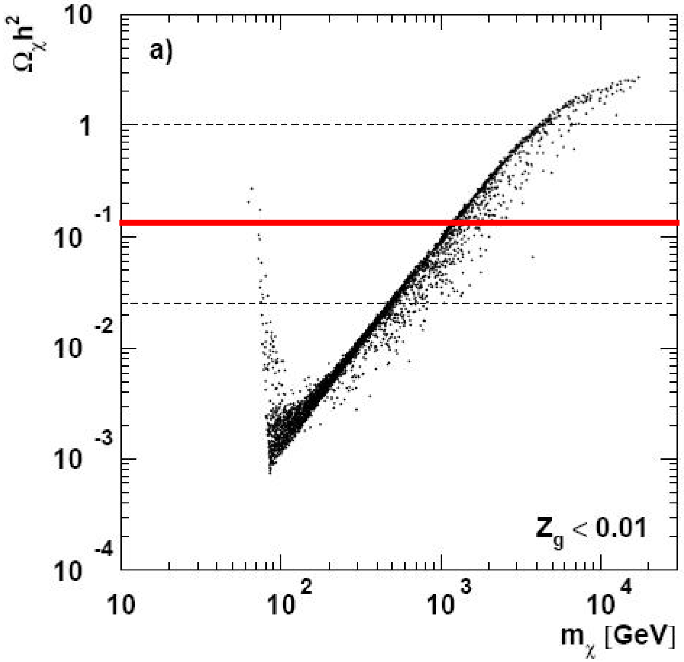
$$\sigma_A \sim \alpha_W^2 / 2M_W^2[y/(1+y)^2]$$

$$y = s/M_W^2$$

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

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? What is the thermally averaged annihilation cross section times velocity?

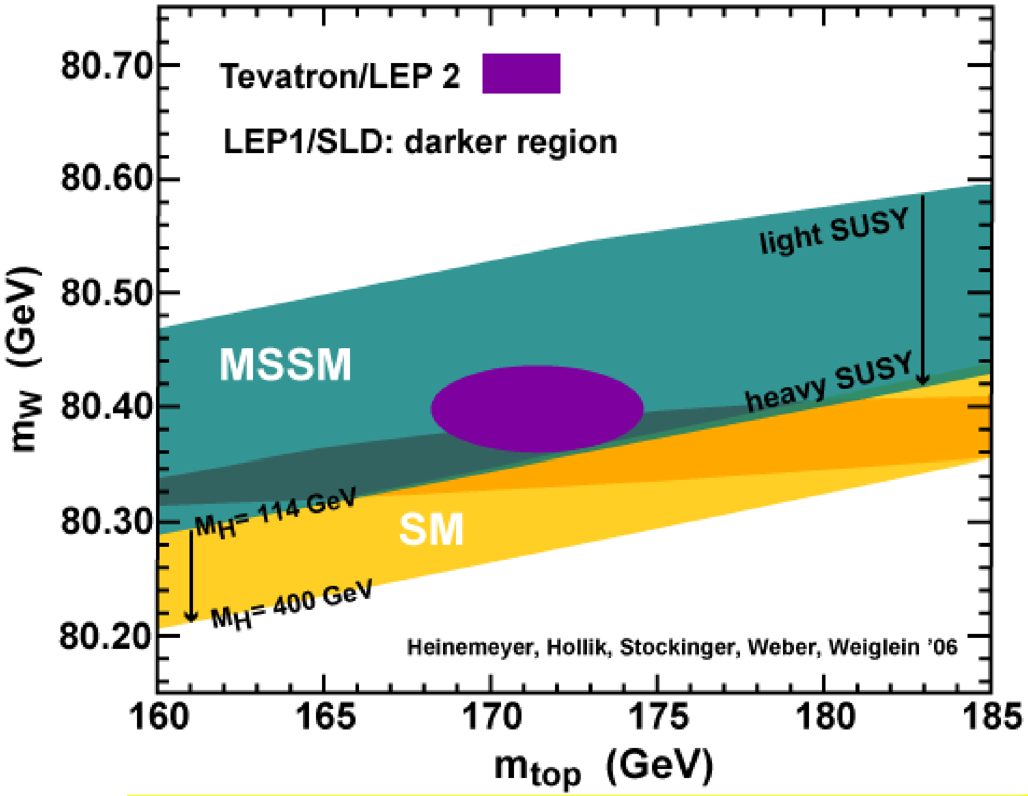
Dark Matter and SUSY

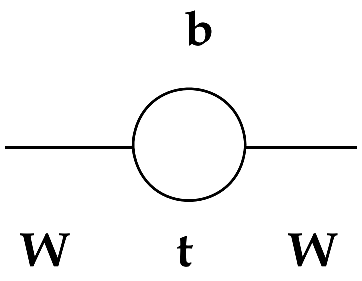


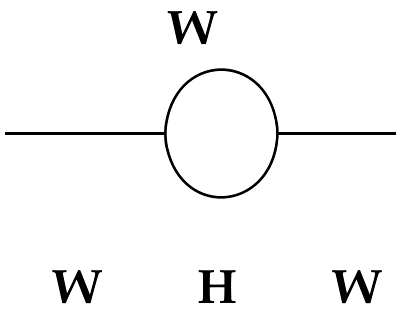
SUSY = dark matter? We need an ensemble of experiments

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. The memory of the Big Bang is stored in the vacuum waiting to be reignited at the LHC.

LEP,CDF D0 Data Indicate Light Higgs – 2009 and Beyond

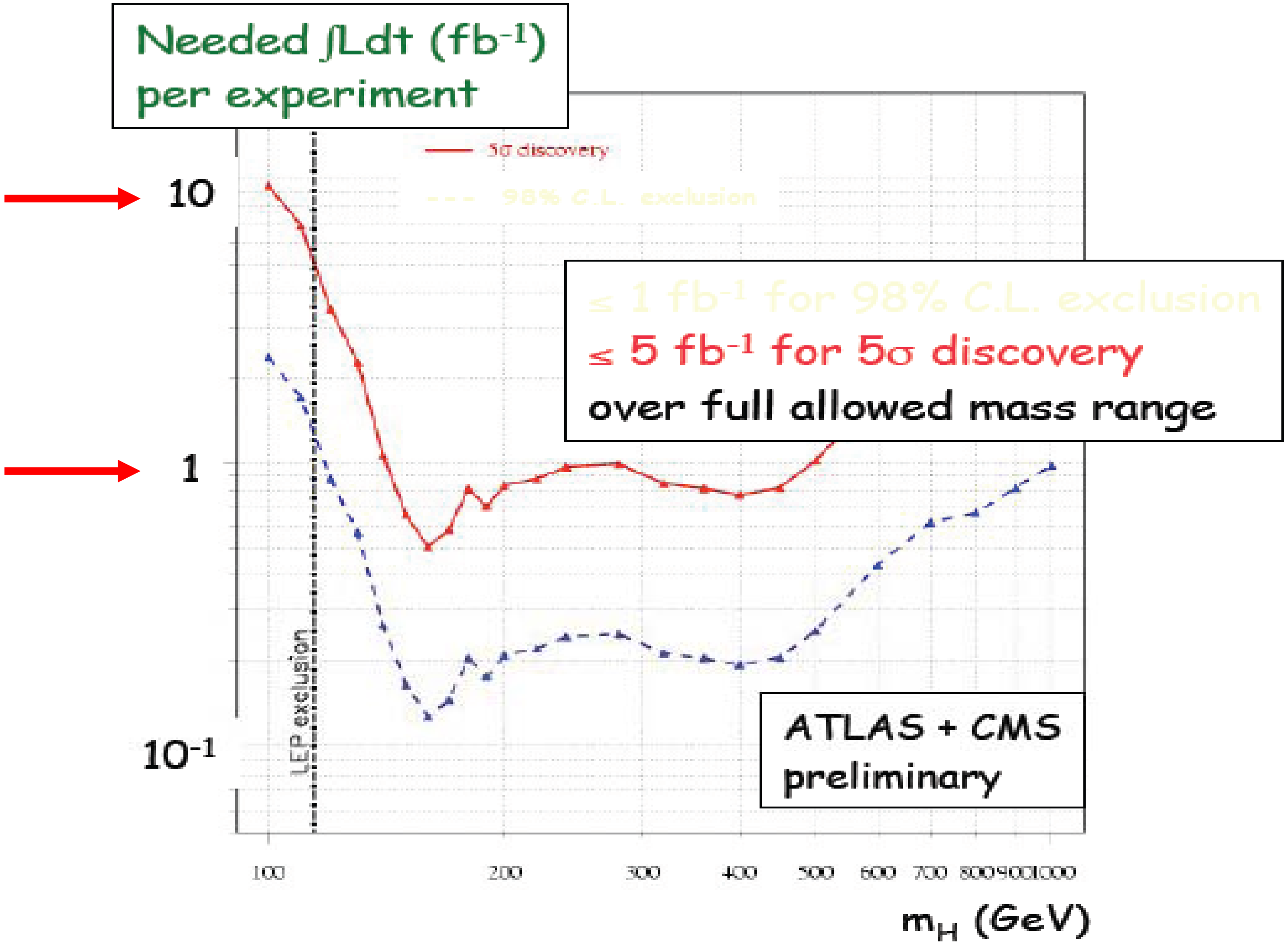






Quantum mechanics: traces of higher mass states are seen in radiative corrections due to virtual quantum loops, e.g. Lamb shift in atomic spectrum due to virtual e pairs. Note sign – fermion, boson (Quantum Amplitude – phase matters) - SUSY. Data indicates light Higgs (SM) or heavy SUSY.

Early Physics Reach - 2009



≤ 1 fb^{-1} for 98% C.L. exclusion

≤ 5 fb^{-1} for 5σ discovery

over full allowed mass range

ATLAS + CMS preliminary

CMS was designed to find the SM Higgs boson at design luminosity in less than 1 year (100 fb^{-1}).

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,

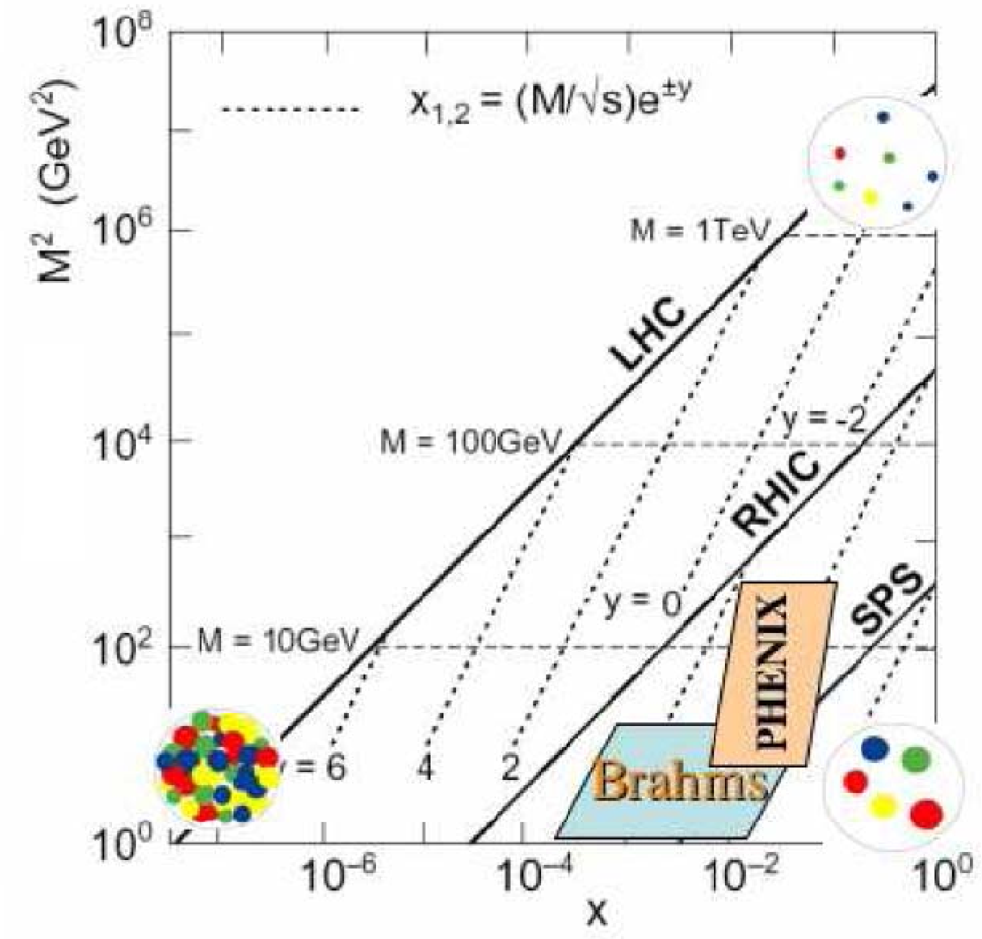
$<\phi>=246\,GeV, M_W = g_W <\phi>$ - Landau-Ginzberg

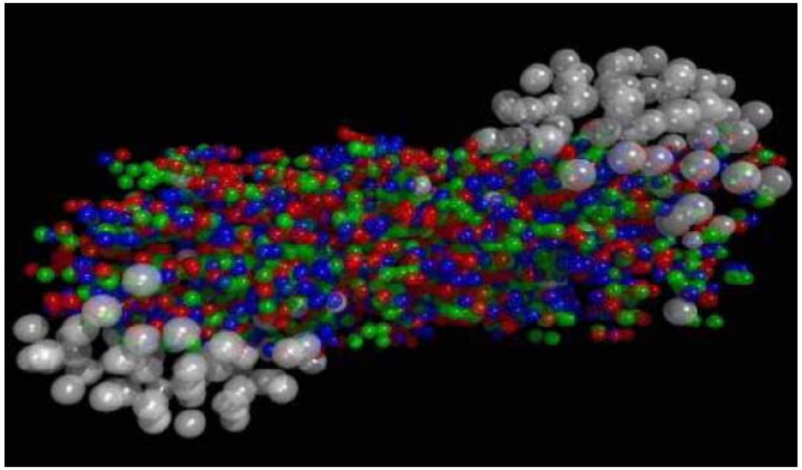
- If so, there is a cosmological mass density ~

$<\phi>^4$ This is ~ 10^{52} larger than the observed dark energy density!

- 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"?

Is There a Quark-Gluon Plasma?



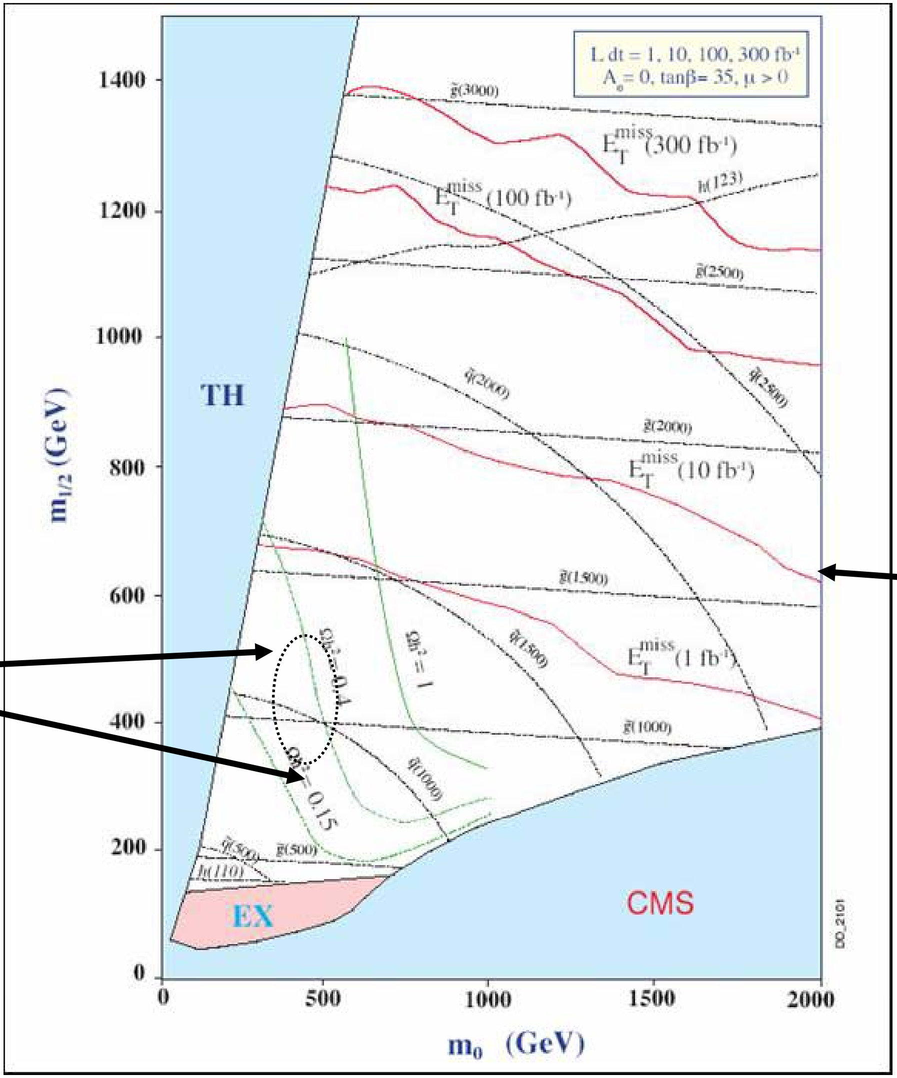


The LHC and CMS offer a ~ 35 fold increase in C.M. energy for heavy ion collisions w.r.t. RHIC. Will that allow the formation of a true plasma?

Summary

- CMS will be ready for data taking in 2009
- We will first re-establish the Standard Model through a variety of “standard candles”.
- While doing this we will make multiple signature based searches for new Physics at a scale ~ 2 TeV.
- At higher luminosities (> 2009?) the exploration of the TeV scale will become even wider and more inclusive.

SUSY – Squark/Gluino Mass "Reach"

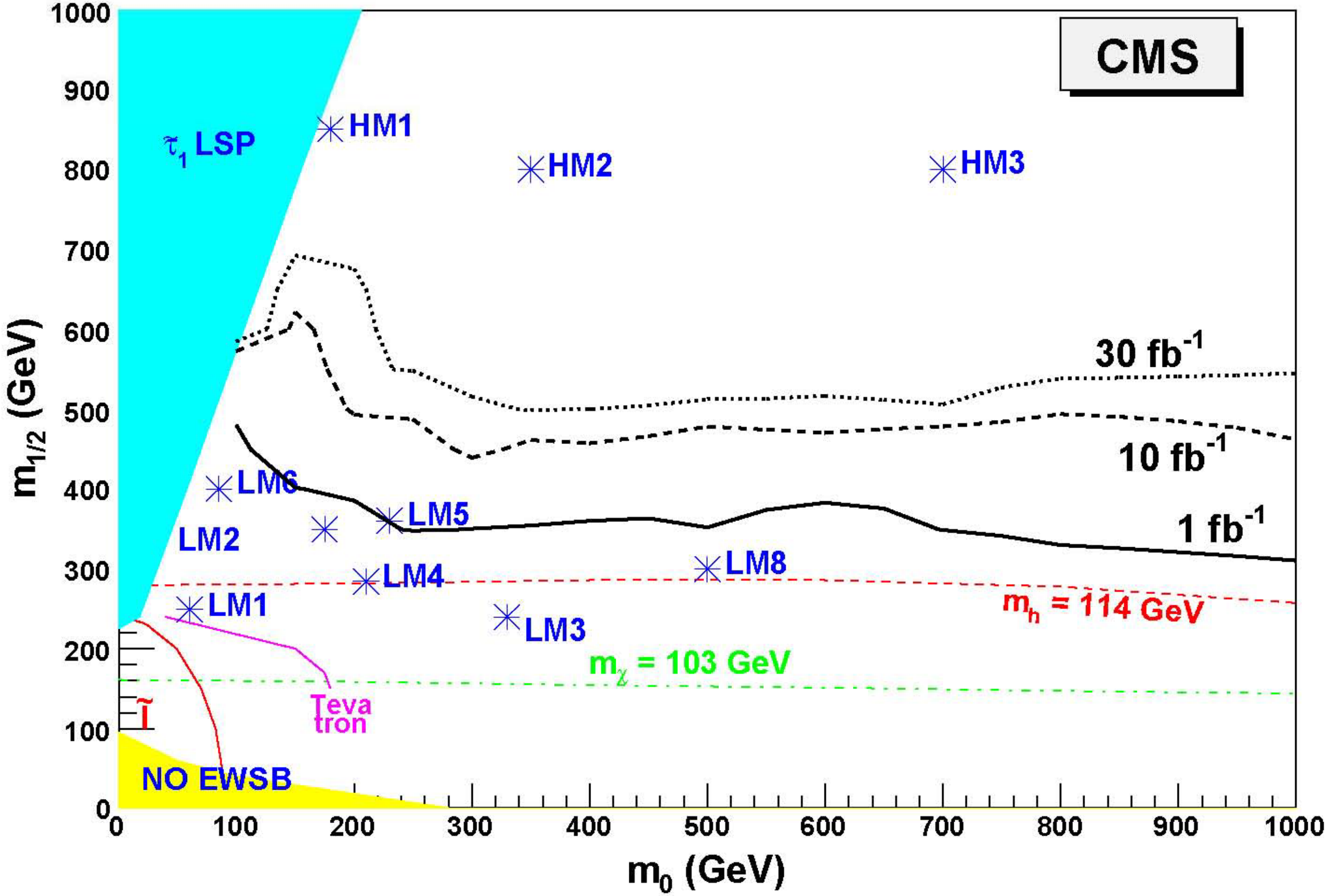


WMAP

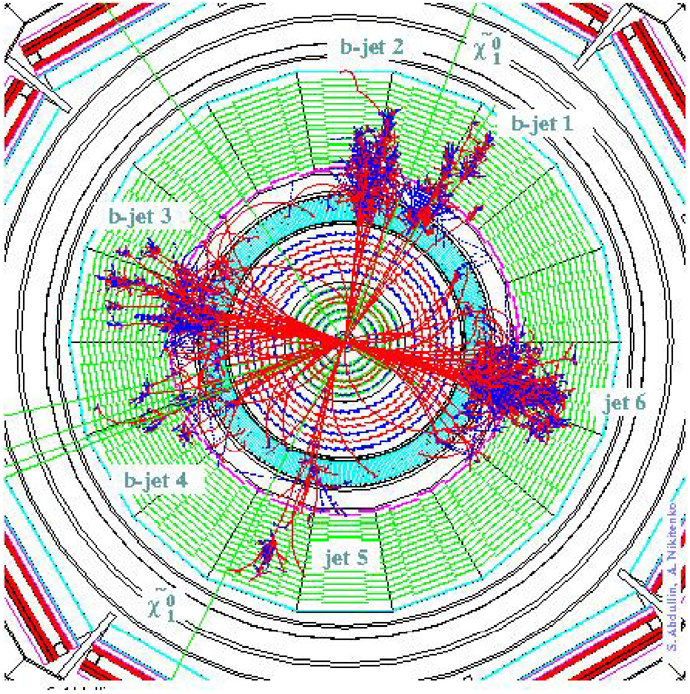
1 year at 1/10 design luminosity.

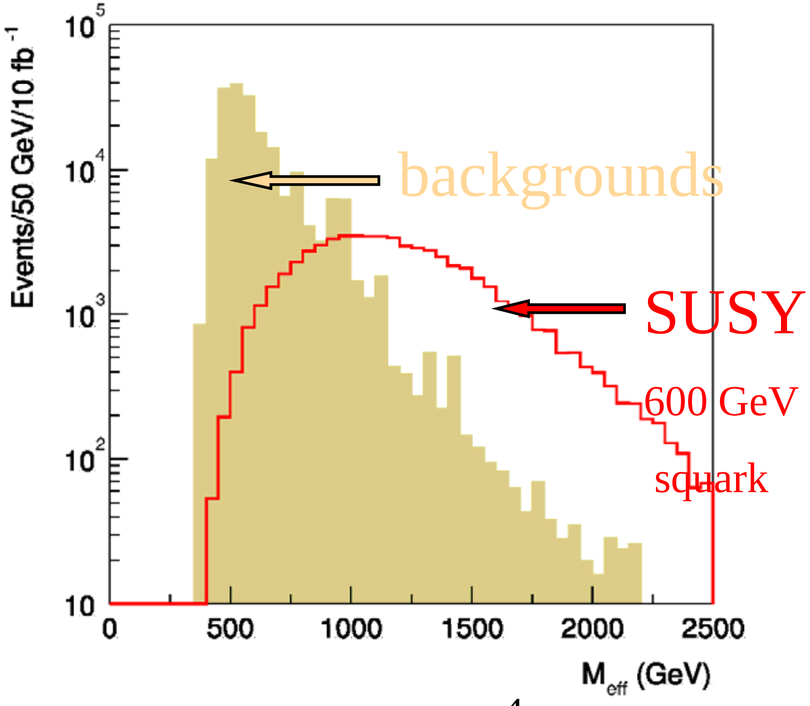
SUSY discovery would happen quickly.

Region explored for Low Mass SUSY



SUSY - Discovery





$$M_{eff} = P_T(\nu) + \sum_{1}^{4} P_T(\text{jets})$$

Assuming a conserved SUSY quantum number, the lightest SUSY particle (LSP) is stable. A neutral weakly interacting LSP escapes the detector. Dramatic event signatures (cascade to LSP -> jets + Missing Et) and large cross section mean we will discover SUSY quickly, if it exists.

Sparticle Masses

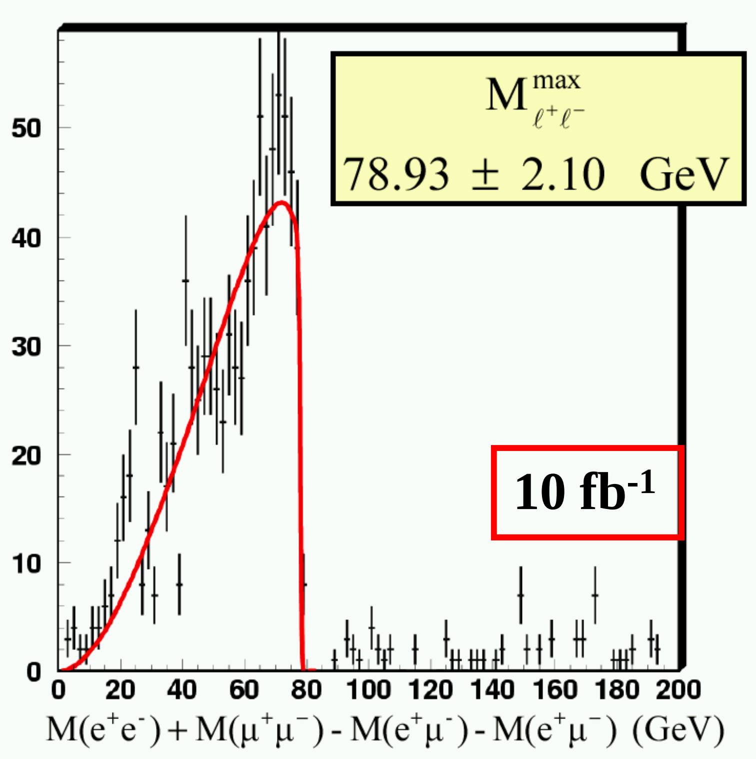
An example of the kind of analysis done, from 1 year at 1/10th design luminosity.

Sequential

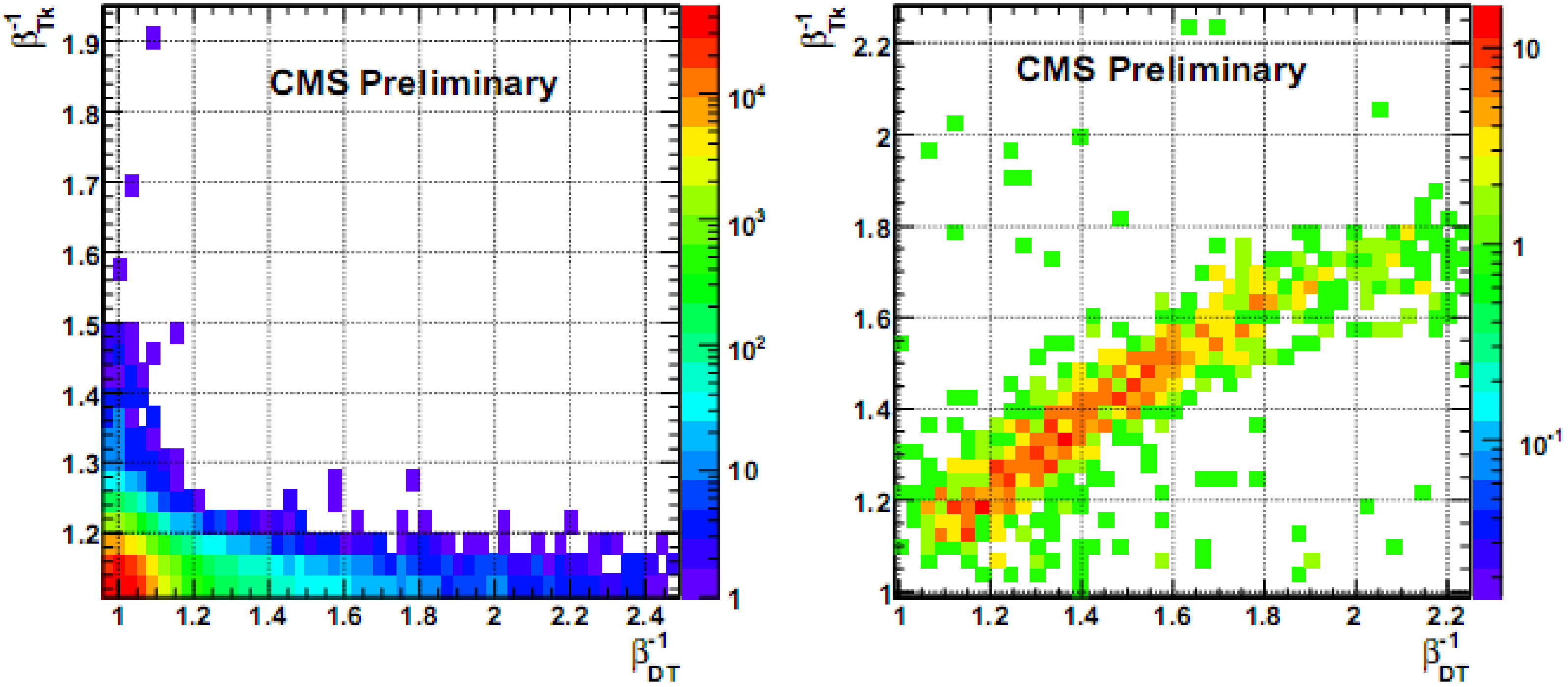
2-body decay: edge in M_{ll}

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

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



Heavy Stable Particles



Use tracker with dE/dx vs. P and TOF. Also have a TOF measure in the Muon subsystem. Plots shown for a 500 GeV SUSY top.

SUSY Cascades

Production of SUSY Particles at LHC is dominated by gluinos and squarks

The production is followed by a SUSY+SM cascade.