SUSY Studies at CMS

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For CMS Collaboration

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Outline

- SUSY-related preamble
  - Introduction
  - Recent news : PTDR and TB'06
- Inclusive SUSY searches
  - Jets + missing E_T
  - Leptons + jets + missing E_T
  - Inclusive Higgs searches
  - Z0 + missing E_T
  - Top + missing E_T
- SUSY particle spectroscopy
- Conclusions

Supersymmetry

- Implies a symmetry between fermions and bosons
  - Avoids fine-tuning, can lead to GUTs, prerequisite for String Theories provides Dark Matter candidate (LSP)

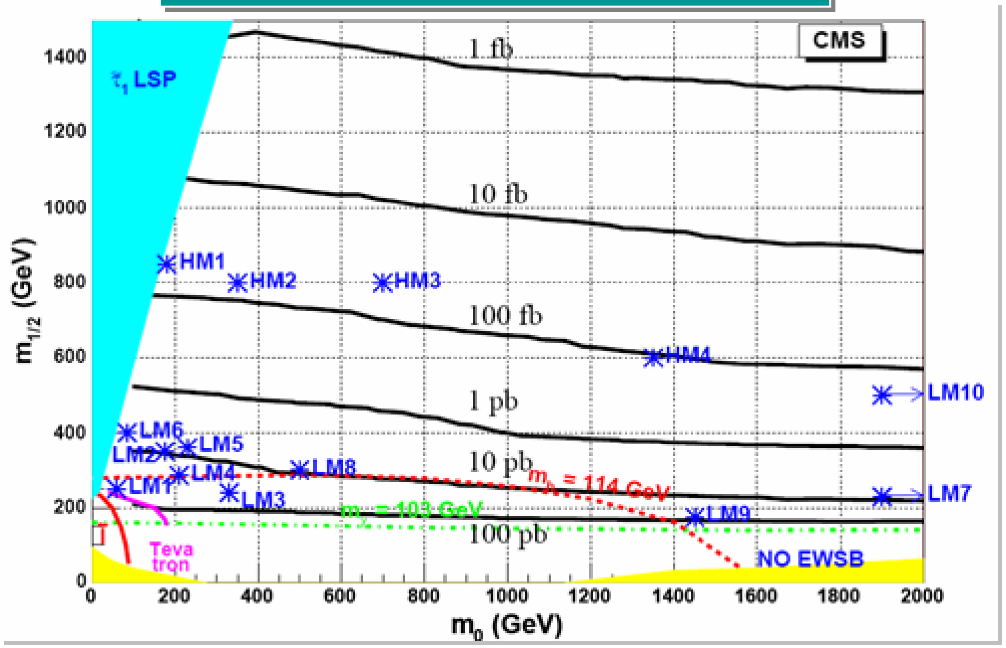
SM Particles	SUSY Particles			
quarks: q	q	squarks: $\tilde{q}$		
leptons: l	l	sleptons: $\tilde{l}$		
gluons: g	g	gluino: $\tilde{g}$		
charged weak boson: $W^{\pm}$	$W^{\pm}$	Wino: $\widetilde{W}^{\pm}$	$\tilde{\chi}^{\pm}_{1,2}$	chargino
Higgs: H^{0}	$H^{\pm}$	charged higgsino: $\widetilde{H}^{\pm}$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

  - Usually assume LSP is stable - R-parity= $(-1)^{3(B-L)+2S}$ conservation
  - SUSY breaking mechanism is unknown $\Rightarrow$ many parameters (105)
  - Gravity-inspired model mSUGRA : **m0, m1/2, A0, tan β, Sign(μ)**

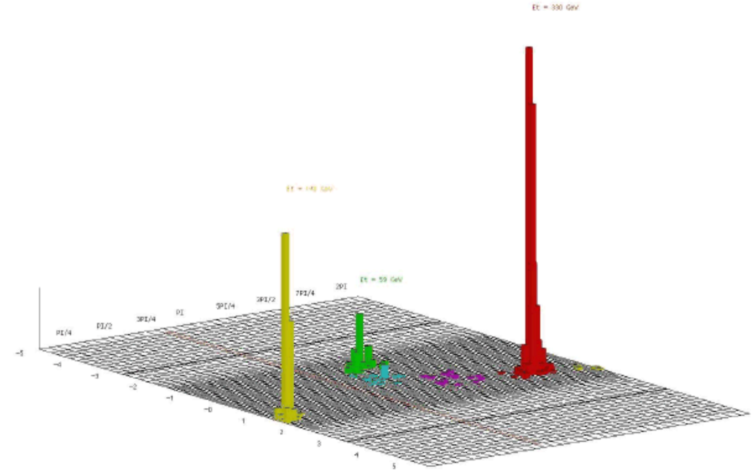
Are Raklev. “Overview of SUSY Phenomenology at LHC” (Monday)

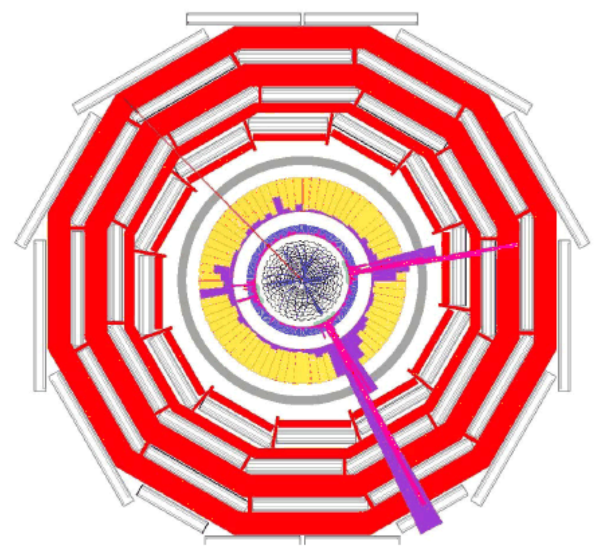
Cross Section and Signatures

$A_0 = 0$, $\tan(\beta) = 10$, $\mathrm{sign}(\mu) = +1$



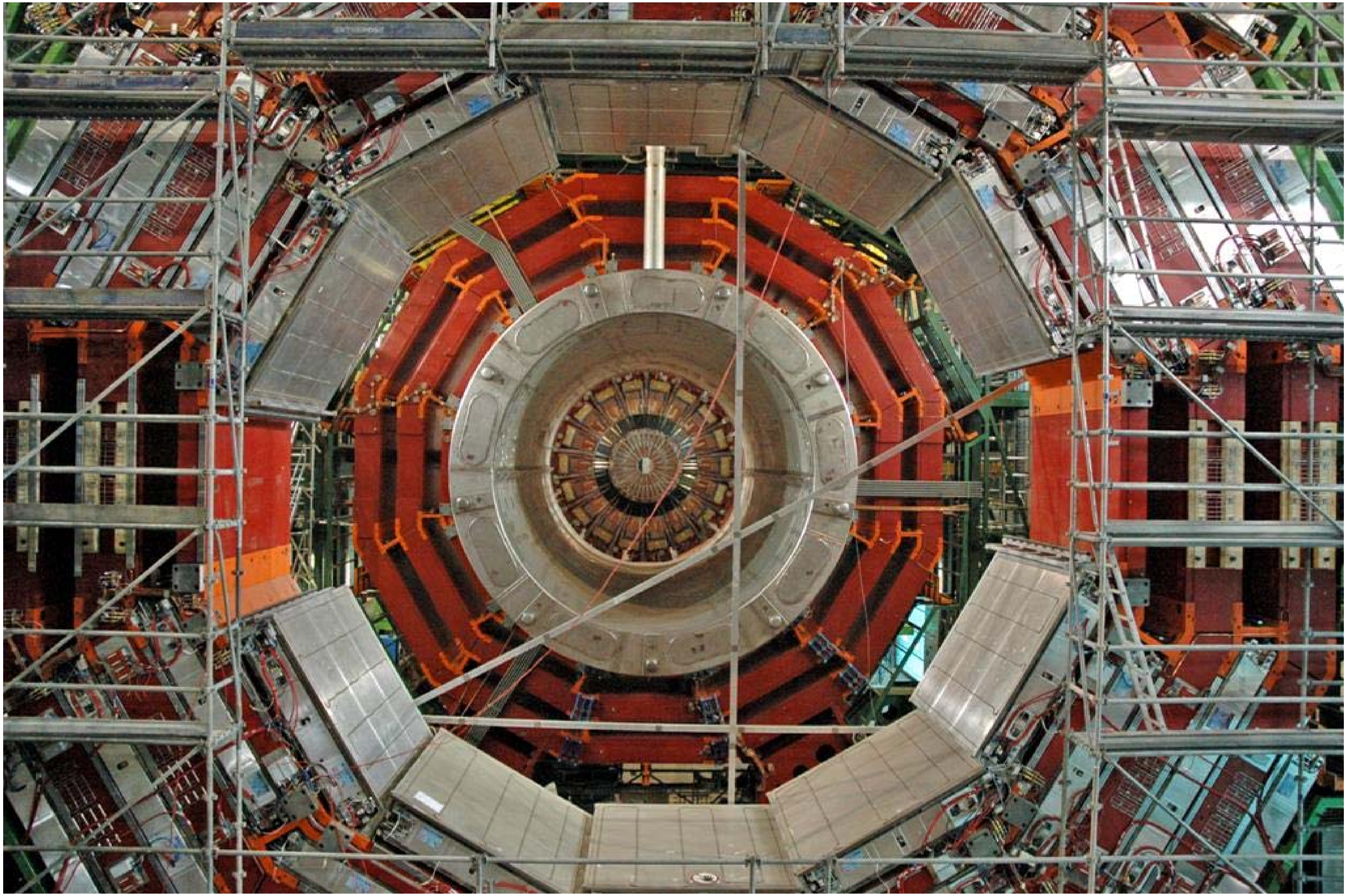
E_T^{miss}=360 GeV, $E_T(1)$=330 GeV, $E_T(2)$=140 GeV, $E_T(3)$=60 GeV



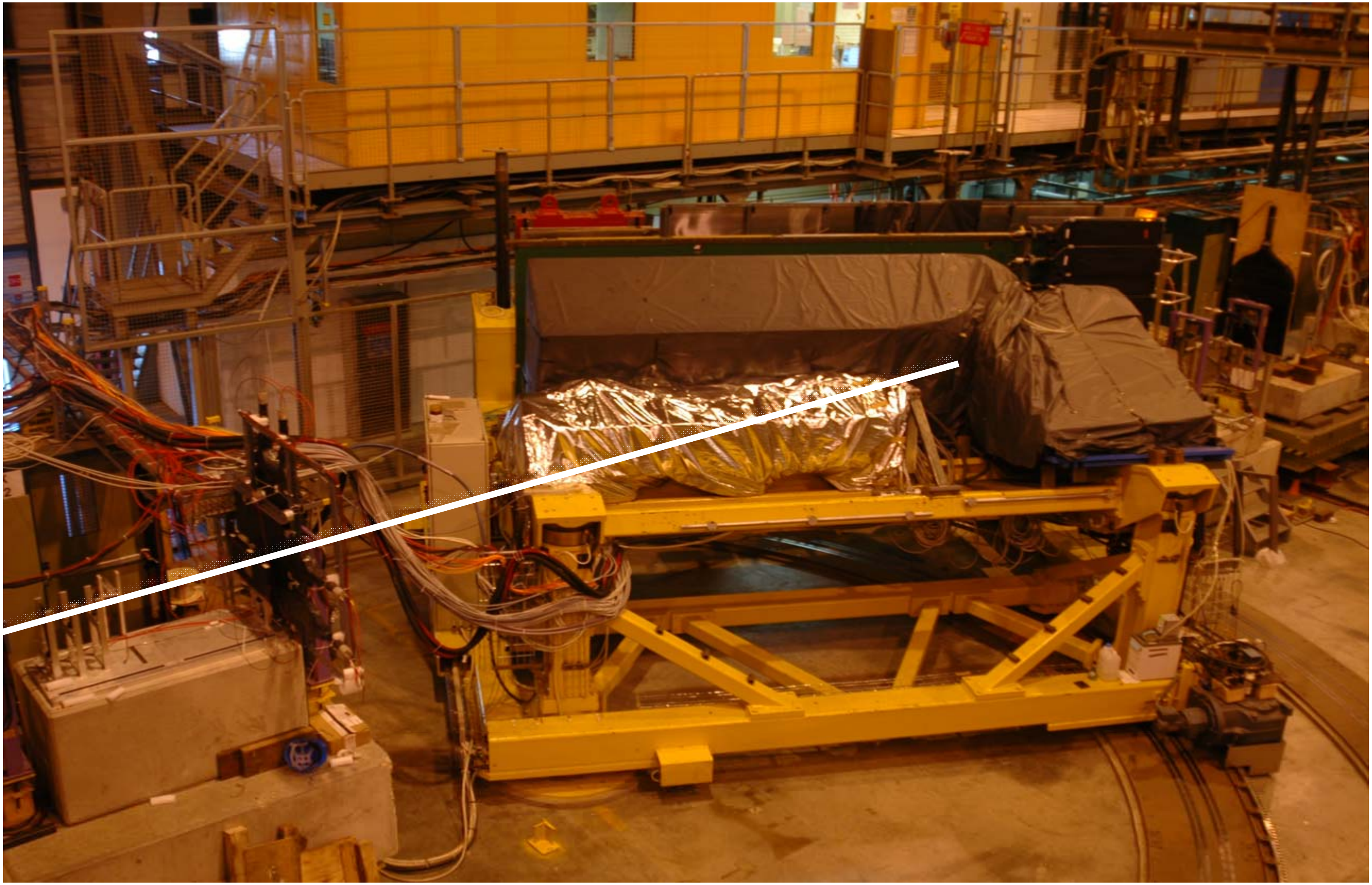


- Complex decays chains
  - MET (LSP)
  - High PT jets ($\tilde{q}$, $\tilde{g}$)
  - Leptons ($\tilde{\chi}$, $\tilde{l}$, W, Z)
  - Heavy flavor (high tanβ)

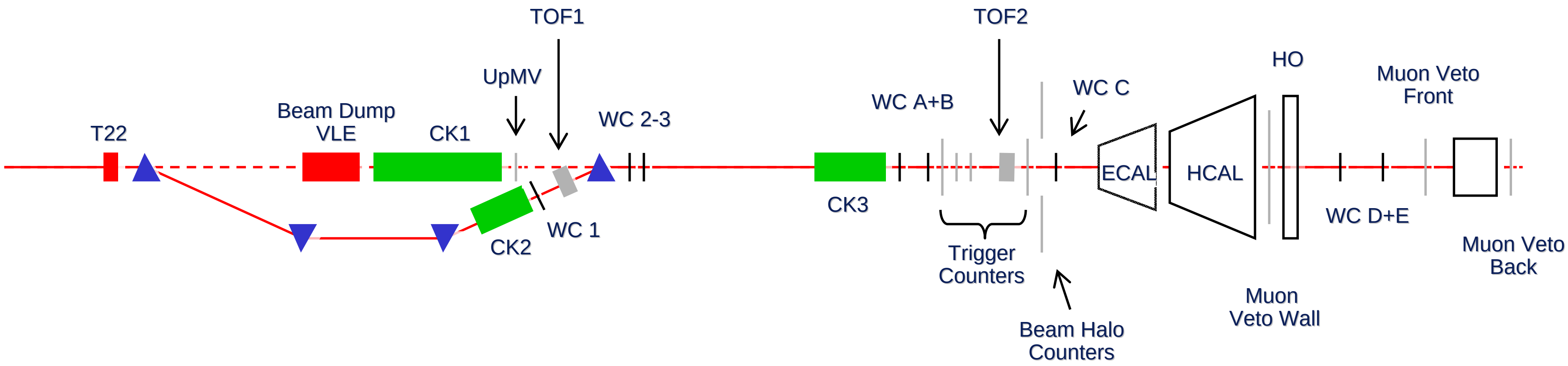
CMS at Surface Assembly Hall



CMS ECAL+HCAL Test Beam Setup



CMS ECAL+HCAL TB'06 Setup



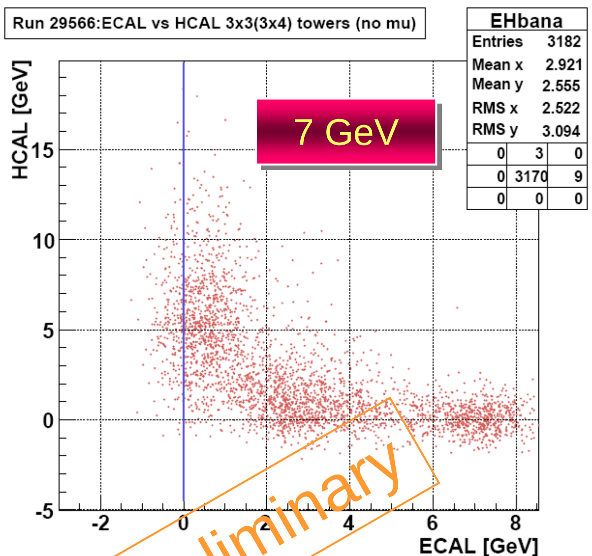
- Very Low Energy (VLE) line is able to give 1 to 9 GeV/c h+, h-, e+ and e- with good rate, a few hundred/spill using a tertiary target (T22). At lower end of the range, particles are mostly electrons. There is a significant muon contamination as well.

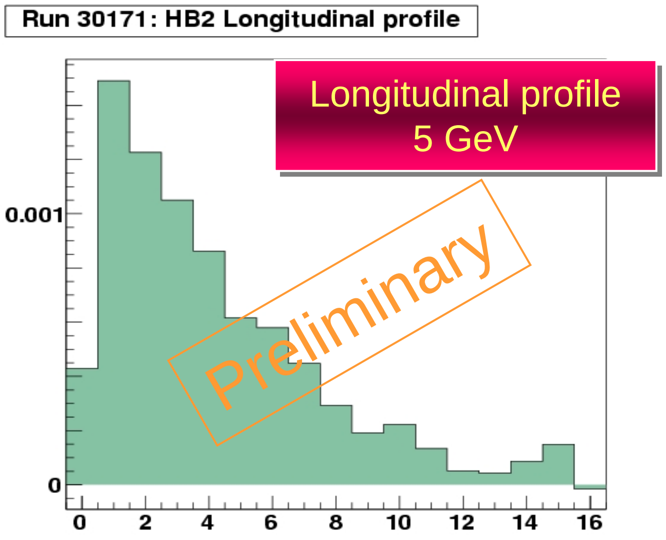
- Particle ID is accomplished by TOFs, CKs and muon veto counters.

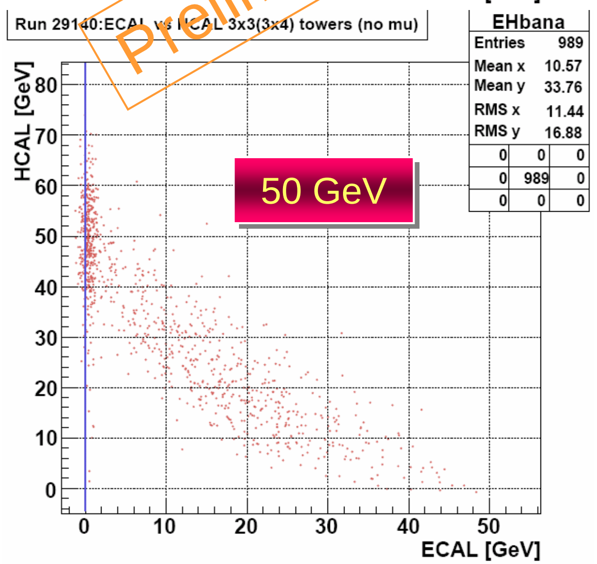
- High energy line covers a momentum range from 10 to 300 GeV/c for hadrons through secondary particle production.

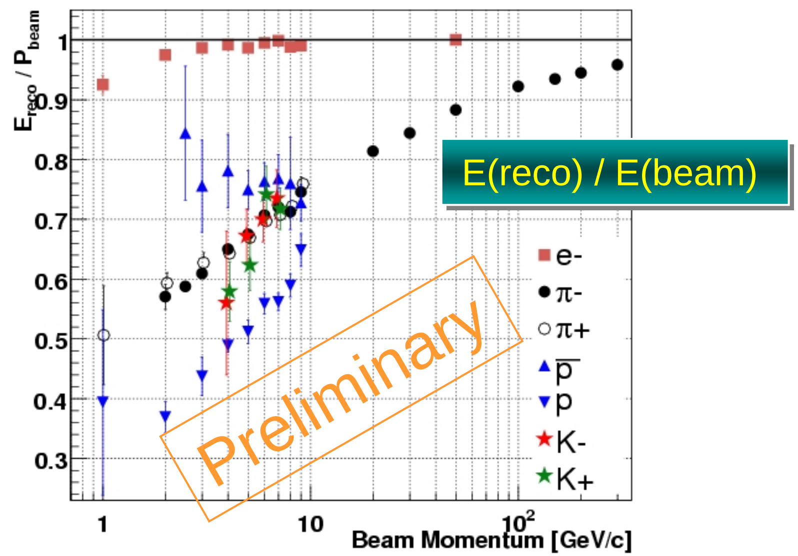
  For electrons/positrons, the range is 10 to 150 GeV/c.

Some ECAL+HCAL TB'06 Results

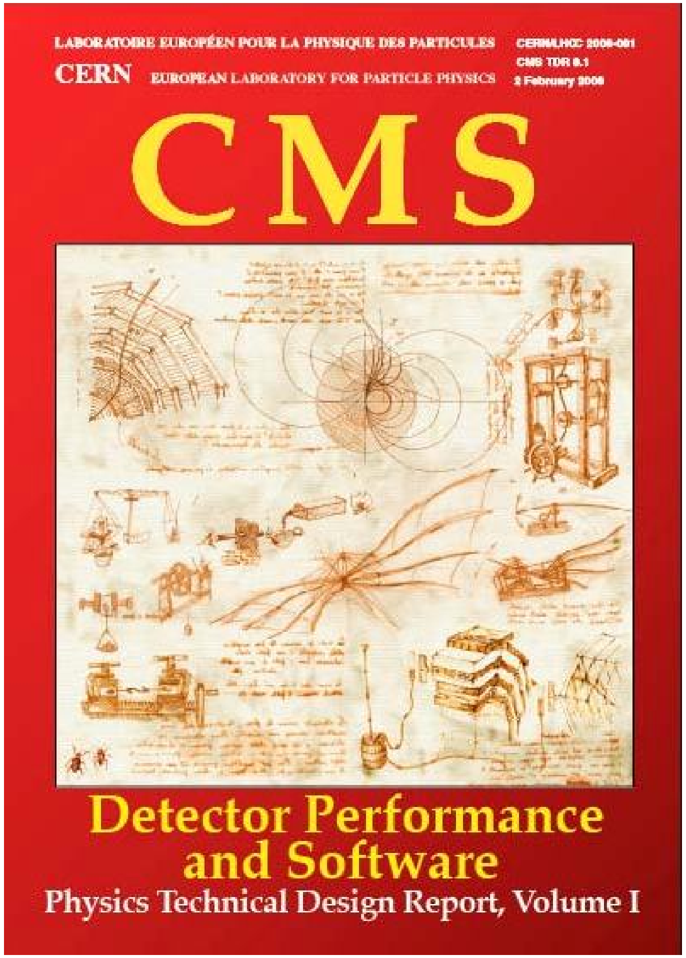


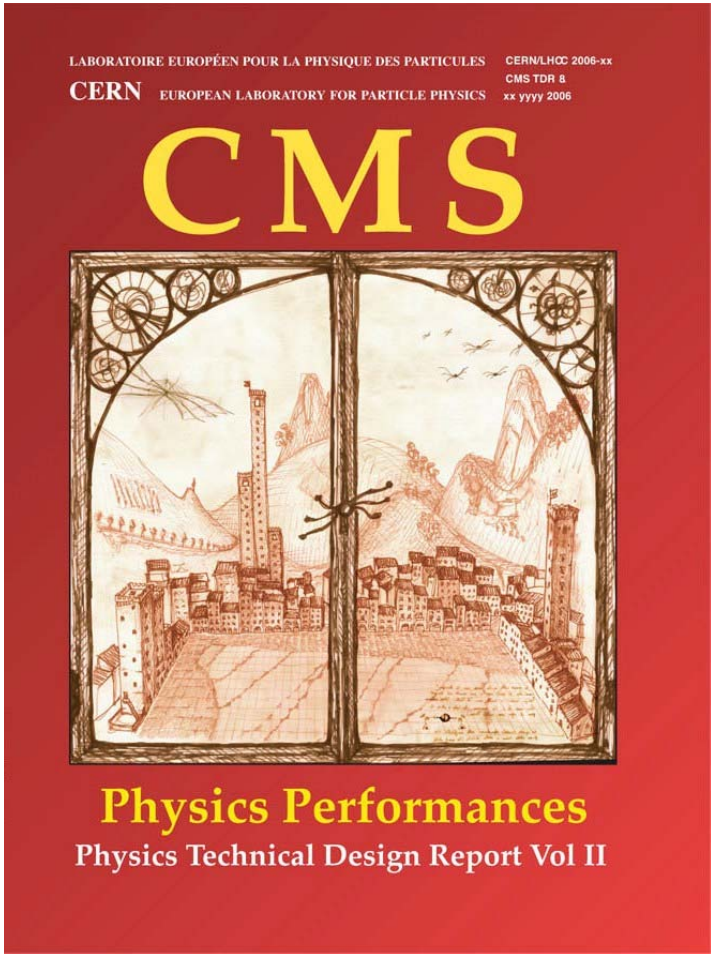






New Analysis Developments





http://cmsdoc.cern.ch/cms/cpt/tdr/

CERN/LHCC 2006-001 CERN/LHCC 2006-021

Physics TDR

- Volume 1:
  - Compendium of detector performance, calibration & alignment strategies, and reconstruction algorithms for physics objects (e, γ, μ, τ, b, jet, MET)
- Volume 2:
  - Detailed study of several benchmark analyses, including SUSY, to demonstrate key performances of the detector and including all the methodology of a real data analysis
  - Background estimation, systematic uncertainties, etc.
  - Comprehensive collection of analyses that span most final state topologies to determine overall reach (e.g. mSUGRA)
  - Analyses based on GEANT4 detector simulations (or derived parameterizations) for backgrounds and signals and real reconstruction algorithms studied in Vol.1

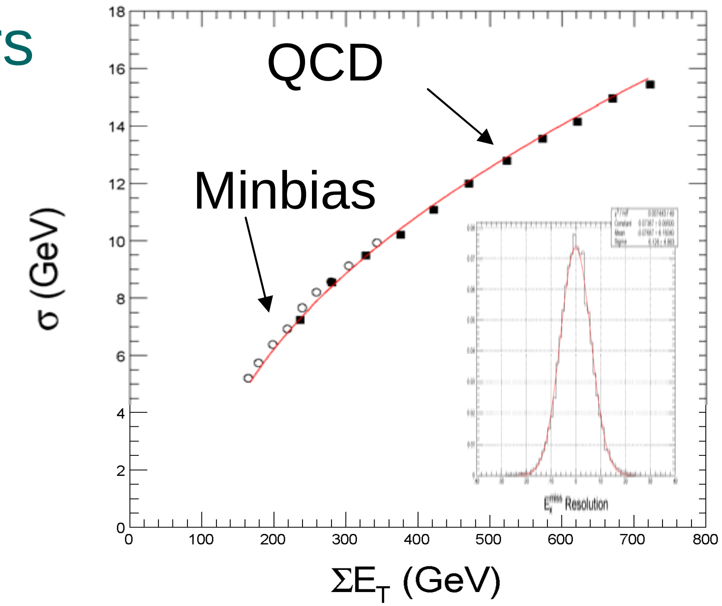
Inclusive Search Strategies for Final Sates with MET

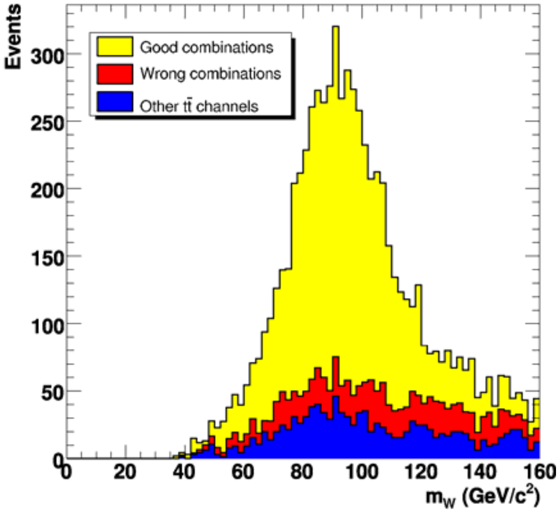
Strategy

- Use Missing Transverse Energy (MET) – a key signature For SUSY in analyses presented here
  - R-parity conservation, neutral LSP
- SUSY benchmark points studied in details using GEANT-based detector simulation and full reconstruction algorithms
- Consider all backgrounds as well as lepton fakes
  - QCD multi-jets, W/Z+jets, t-tbar, diboson
- Optimize significance to determine cuts at particular benchmark point(s)
- Determine 5σ reach in mSUGRA parameter space using fast simulation (FAMOS)

MET Reconstruction

- Sum of tr.momentum over calo towers
  - MET is a measure of imbalance
  - Can be corrected for jets, muons
- MET resolution
  - Measure from data:
    min.bias and prescaled jet triggers
  - CMS stochastic term ~ 0.6-0.7
- Jet calibration important to improve resolution and reduce systematic uncertainties, variety of techniques
  - γ-jet balancing, di-jet balancing
  - W-mass constraint in hadronic decays of W in top-pair production
  - CMS achieve 3% of JES uncertainty for $E_T > 50$ GeV with 1-10 fb^{-1}

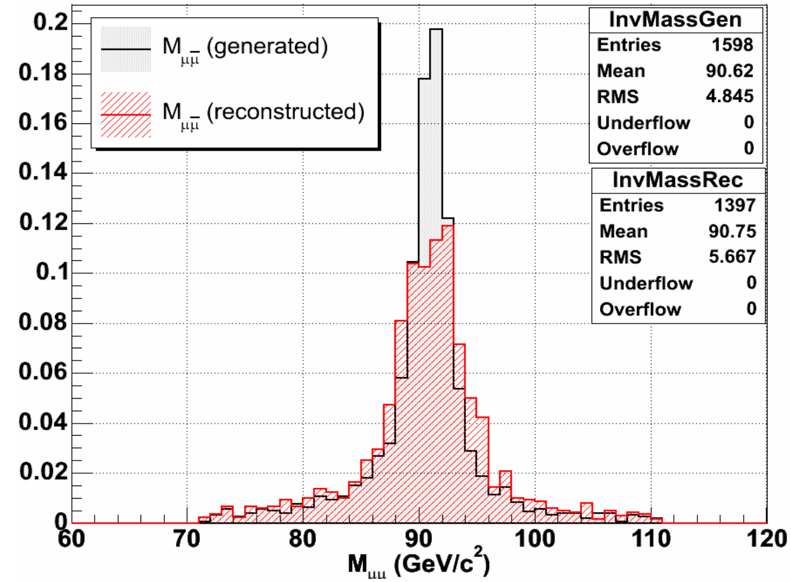


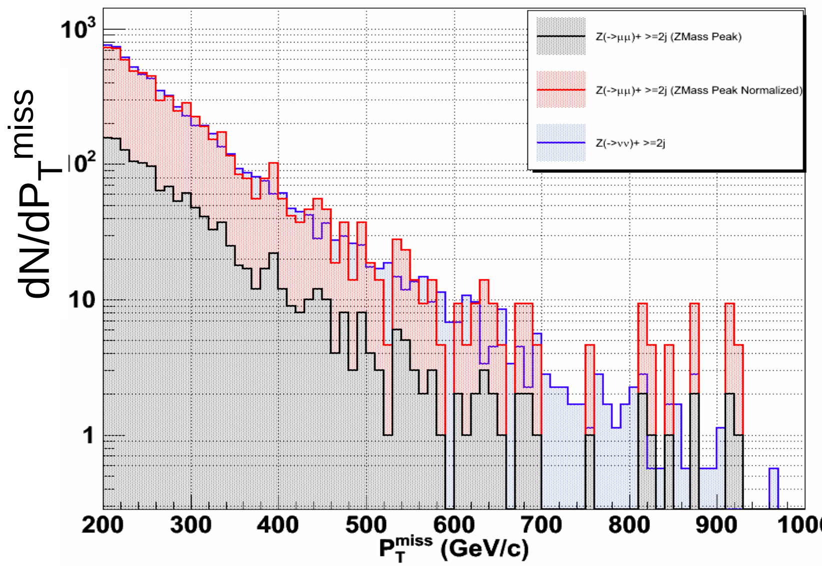


MET Calibration Using Z-Candle

- Measure Z+jets with $Z \to \mu\mu$ in data to normalize $Z \to \nu\nu$ (invisible) contribution and calibrate MET spectrum

- With ~1fb-1 we will have enough Z+jets in the PT(Z)>200 GeV region of interest to normalize within 5% the invisible Z process as well as W+jets through the W/Z ratio and lepton universality



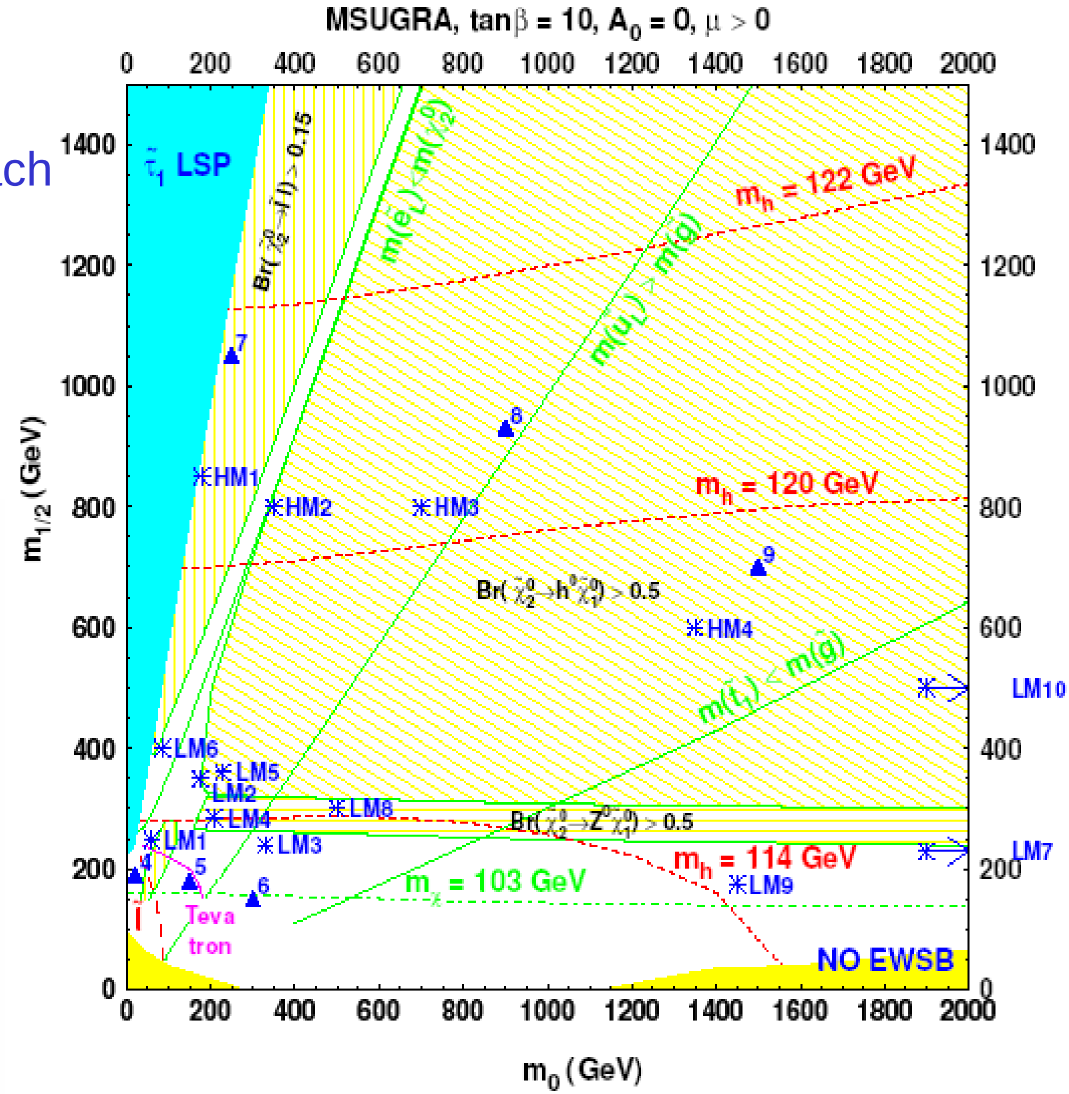


Benchmark Points

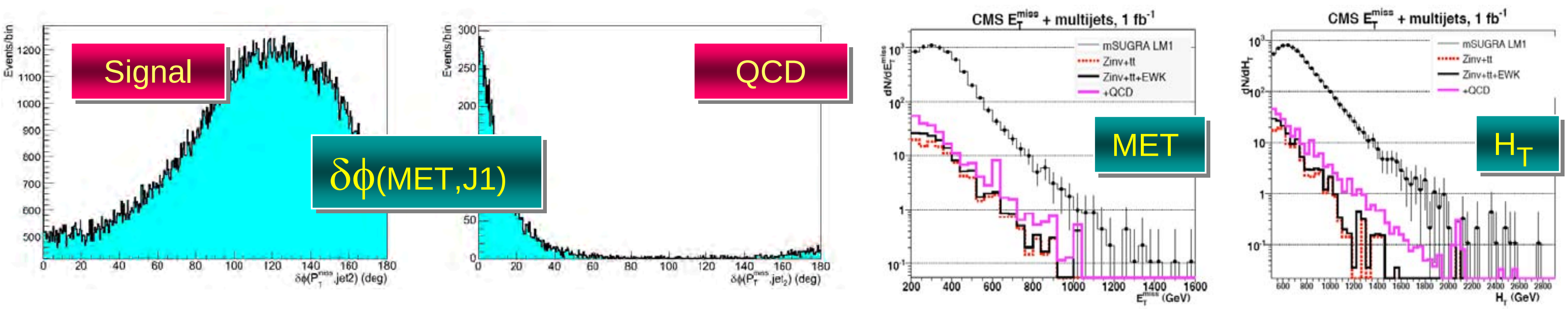
Basis of detailed studies

- Low mass points for early LHC running but above Tevatron reach
- High-mass points for ultimate LHC reach
- Indirect WMAP constraints except LM1, 2, 6, 9 (in favor of signatures)

Point	m_0	$m_{1/2}$	$\tan\beta$	sgn(μ)	A_0
LM1	60	250	10	+	0
LM2	185	350	35	+	0
LM3	330	240	20	+	0
LM4	210	285	10	+	0
LM5	230	360	10	+	0
LM6	85	400	10	+	0
LM7	3000	230	10	+	0
LM8	500	300	10	+	-300
LM9	1450	175	50	+	0
LM10	3000	500	10	+	0
HM1	180	850	10	+	0
HM2	350	800	35	+	0
HM3	700	800	10	+	0
HM4	1350	600	10	+	0



Inclusive MET + Jets Example (LM1)



Requirement	Remark
Level 1	Level-1 trigger eff. parameter.
HLT, $E_T^{miss} > 200\,\mathrm{GeV}$	trigger/signal signature
primary vertex ≥ 1	primary cleanup
$F_{em} \geq 0.175$, $F_{ch} \geq 0.1$	primary cleanup
$N_j \geq 3, \lvert\eta_d^{1j}\rvert < 1.7$	signal signature
$\delta\phi_{min}(E_T^{miss} - jet) \geq 0.3$ rad, $R1, R2 > 0.5$ rad, $\delta\phi(E_T^{miss} - j(2)) > 20°$	QCD rejection
$Iso^{ltrk} = 0$	ILV (I) $W/Z/t\bar{t}$ rejection
$f_{em(j(1))}$, $f_{em(j(2))} < 0.9$	ILV (II), $W/Z/t\bar{t}$ rejection
$E_{T,j(1)} > 180\,\mathrm{GeV}, E_{T,j(2)} > 110\,\mathrm{GeV}$	signal/background optimisation
$H_T > 500\,\mathrm{GeV}$	signal/background optimisation
SUSY LM1 signal efficiency 13%	

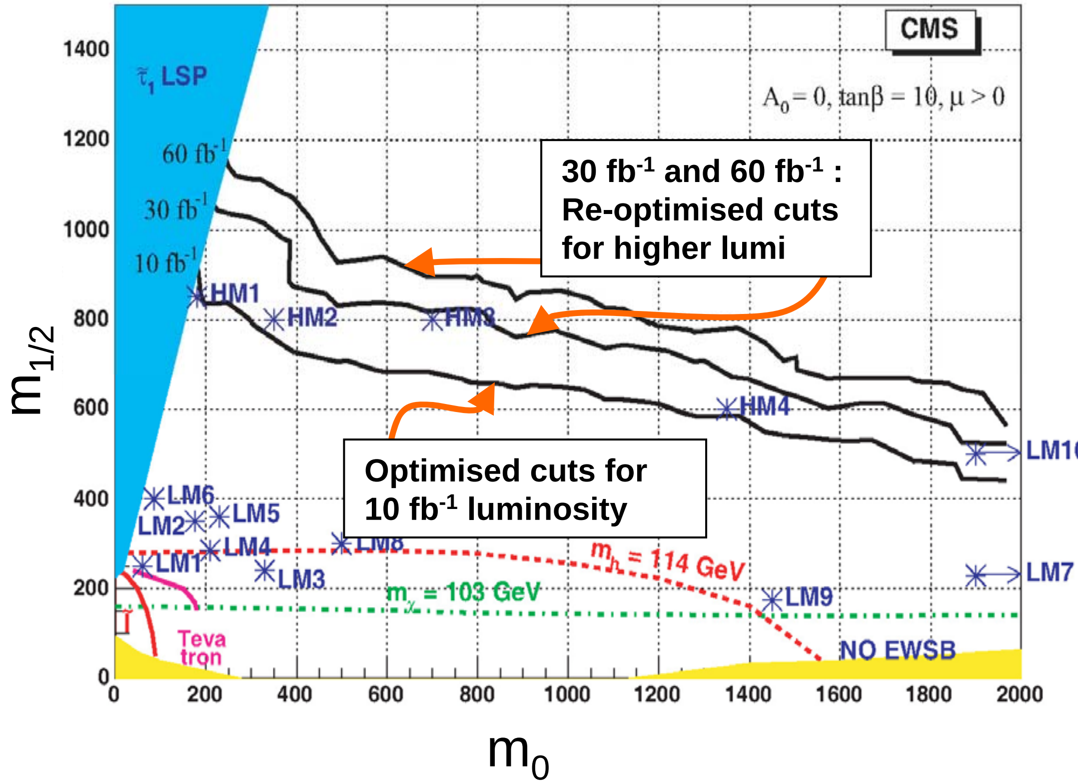
S/B ~ 26

Inclusive MET + Jets + Muons

- Add lepton ⇒ clean trigger

$A_0 = 0$, $\tan(\beta) = 10$, $\text{sign}(\mu) = +1$

- Cuts optimized @LM1
  - ≥1 isolated muon
  - pT > 30 GeV
  - MET > 130 GeV
  - ≥3 jets:
  - ET> 440, 440, and 50 GeV
  - $|\eta|$< 1.9, 1.5, and 3
  - Cuts on $\Delta\phi$ between jets and MET

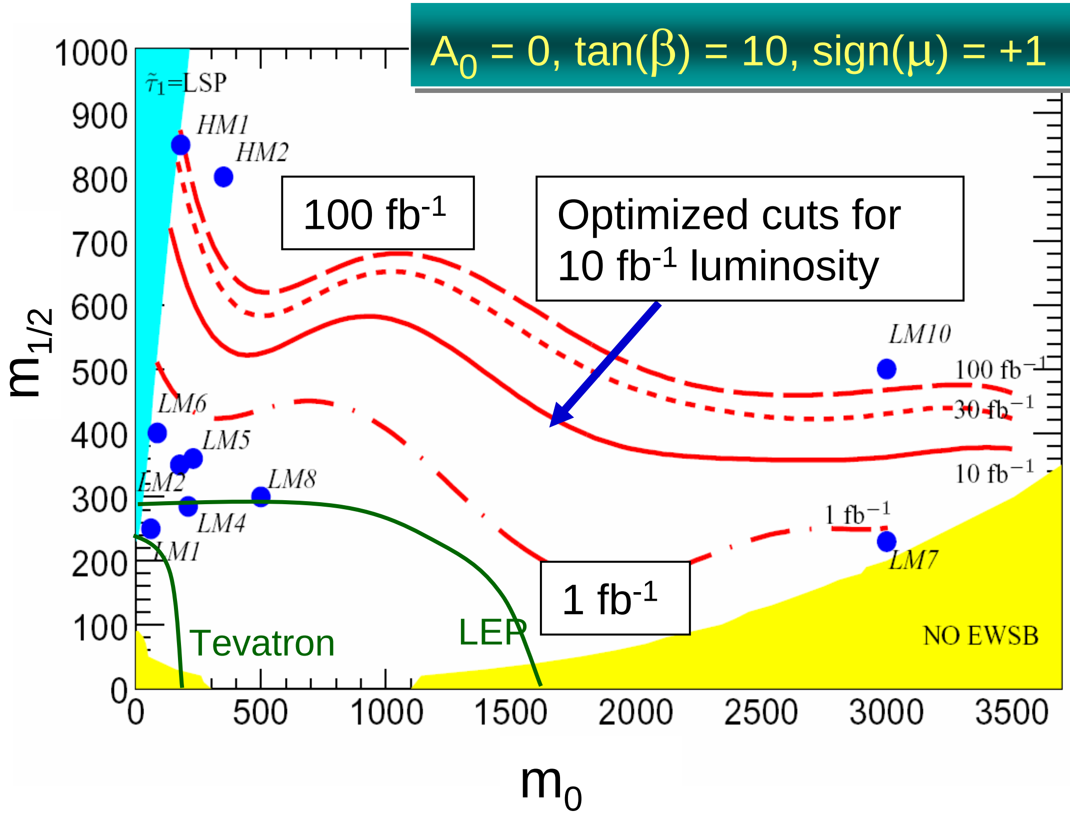


- Background (10 fb^{-1})
  - 2.5 ev, systematic uncertainty ~20%

Sample(s)	Events	Sample	Events	Sample	Events
SM	2.54	LM4	246	LM6	277
LM1	311	LM5	165	HM1	13

Same-Sign Muon Reach

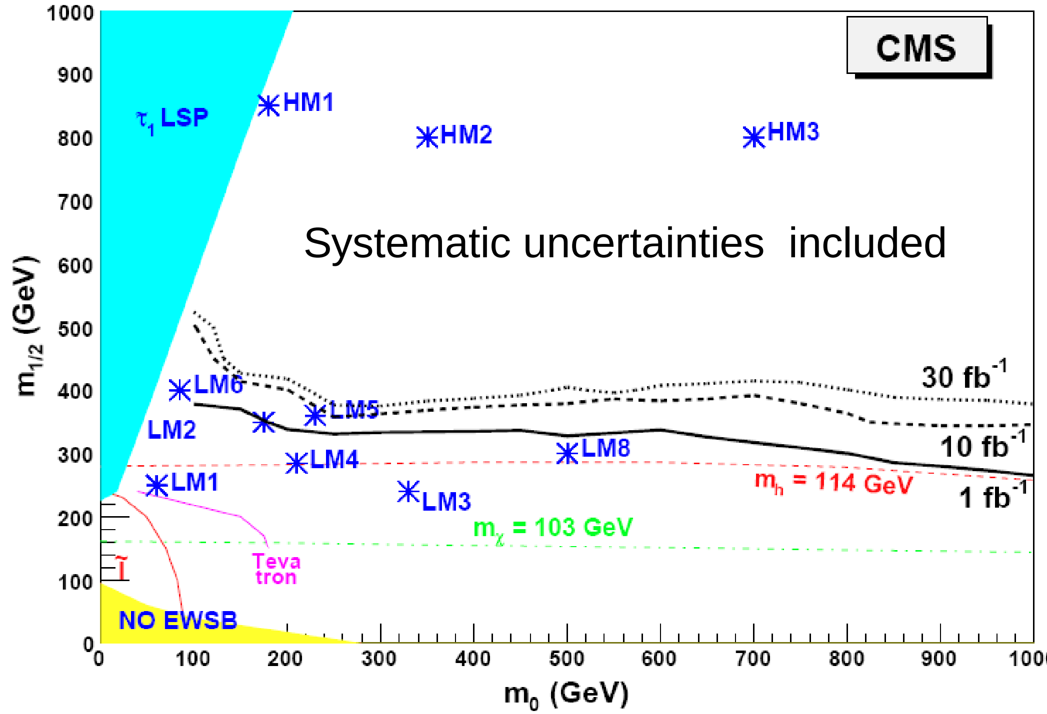
- Even cleaner signature with low background due to same-sign requirement
- Cuts optimized @LM1
  - 2 SS isolated muons
    - pT > 10 GeV
  - MET > 200 GeV
  - ≥3 jets:
    - ET1>175 GeV
    - ET2>130 GeV
    - ET3>55 GeV
- Background (10 fb^{-1})
  - 1.5 ev, systematic uncertainty ~23%



Sample(s)	Events	Sample	Events	Sample	Events
SM	1.5	LM5	61	LM10	4
LM1	341	LM6	140	HM1	4
LM2	94	LM7	82	HM2	2
LM4	90	LM8	294		

MET + Opposite Sign Leptons

- Cuts optimized @LM1
  - 2 OS SF isolated leptons (e,μ)
    - pT > 10 GeV
  - MET > 200 GeV
  - ≥2 jets:
    - ET1>100 GeV
    - ET2>60 GeV
    - |η| < 3

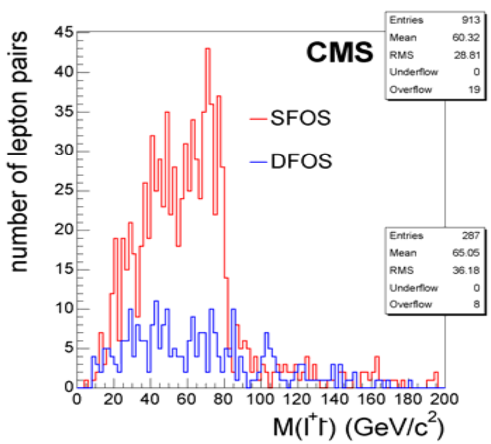


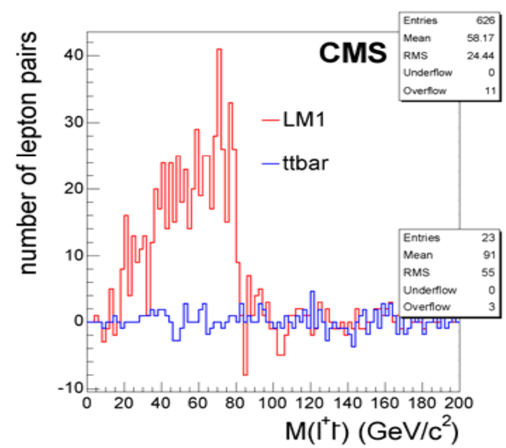
- Background (1 fb^{-1})
  - 200 events, ttbar : WW+jets : Z+jets : others = 6:1:1:1
    Systematic uncertainty 20%

- Signal (1 fb^{-1})
  - 850 events
    5 σ discovery at 20 pb^{-1}

Di-Lepton Mass Edge

- Measure invariant mass distribution of same-flavor opposite-sign (SFOS) leptons as evidence for
  - $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$
  - $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^+ \ell^- \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$
- Endpoint in mass spectrum exhibits sharp edge dependent on sparticle masses
  - $m_{\ell\ell}^{\max} = m\left(\tilde{\chi}_2^0\right) - m\left(\tilde{\chi}_1^0\right)$
  - $m_{\ell\ell}^{\max} = \sqrt{\left[m^2\left(\tilde{\chi}_2^0\right) - m^2\left(\tilde{\ell}\right)\right]\left[m^2\left(\tilde{\ell}\right) - m^2\left(\tilde{\chi}_1^0\right)\right]} / m\left(\tilde{\ell}\right)$

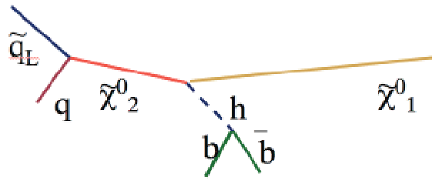




Subtract different flavour leptons

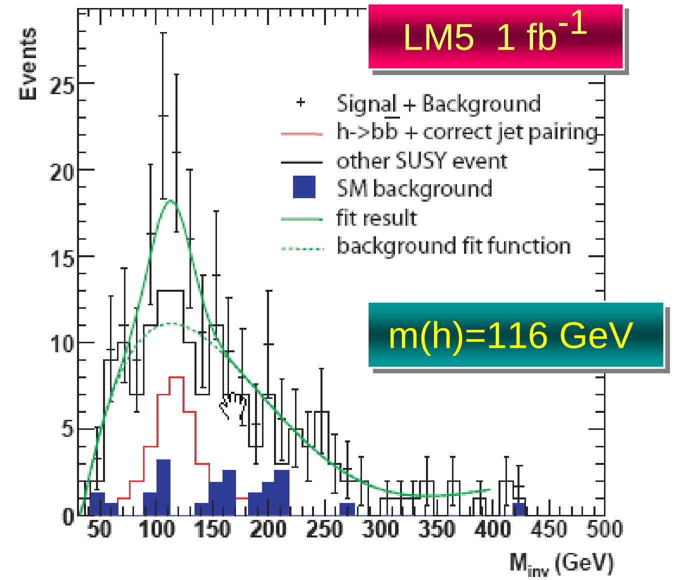
- LM with 1 fb^{-1}, fit result (expected 81 GeV):
  - $m_{\ell\ell}^{\max} = 80.4 \pm 0.5\ (\text{stat})\ \pm 1.0\ (\text{misalign})\ \pm 0.8\ (\text{EM scale})\ \text{GeV}$

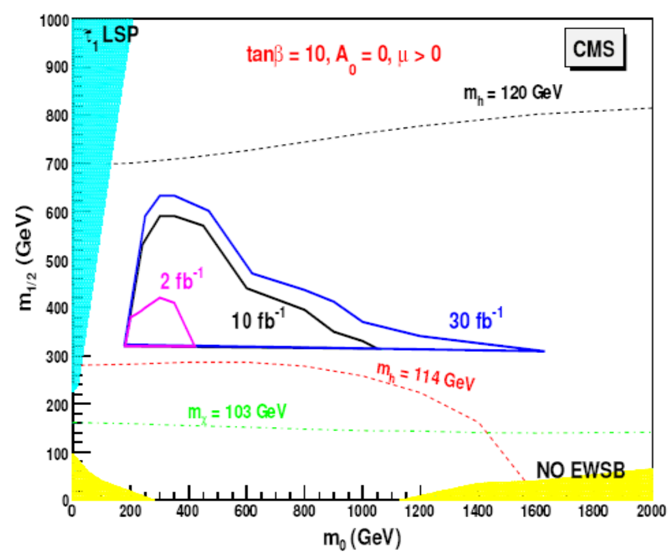
Inclusive Higgs Search



- Consider
  - Dominant
    squark decay chain
    in a significant domain of mSUGRA
    parameter space

- LM5 full simulation selection
  - MET > 200 GeV
    E_T (jet 1,2,3,4) > 200,150,50,30 GeV
    2 tagged hi-quality b-jets
    in the same hemisphere
    closest in $\eta-\phi$-space
  - Signal efficiency ~ 8%, main bkgd. – ttbar
  - 5 σ excess with 1.5 fb^{-1}
  - m(h) = 112.9 ± 6.6(stat.) ± 7.5(syst.) GeV



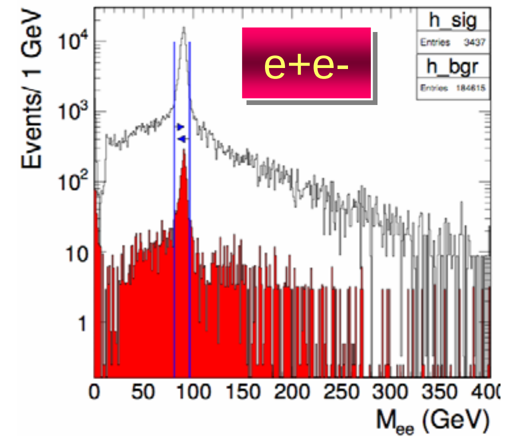


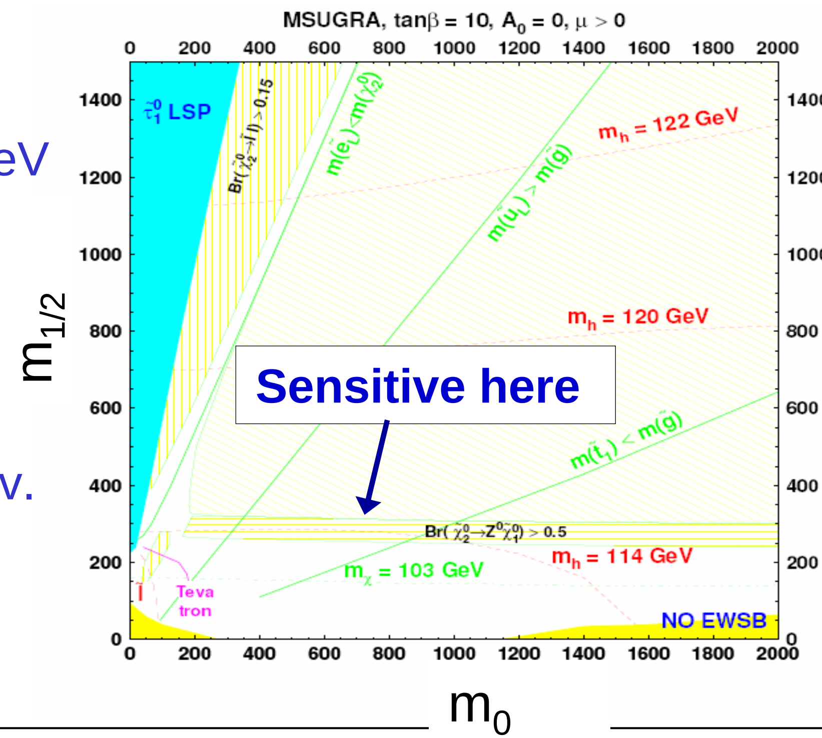
Inclusive MET + Z^0

- Consider $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + Z^0$
  - Mostly from squark-gluino decays
  - Z0 gives extra handle against non-resonant di-lepton background
- Cuts optimized @LM1

  MET > 230 GeV
  2 OS SF leptons
  $p_T(e) > 17$ GeV, or $p_T(\mu) > 7$ GeV
  $81 < M_{ll} < 96.5$ GeV
  $\Delta\phi < 2.65$ rad

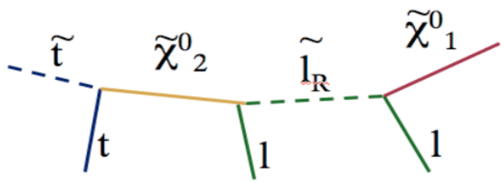
- Background (10 fb^{-1})
  - 200 ± 40 (top pairs + di-bosons) ev.
- LM1 signal (10 fb^{-1})
  - 1550 ± 30 events





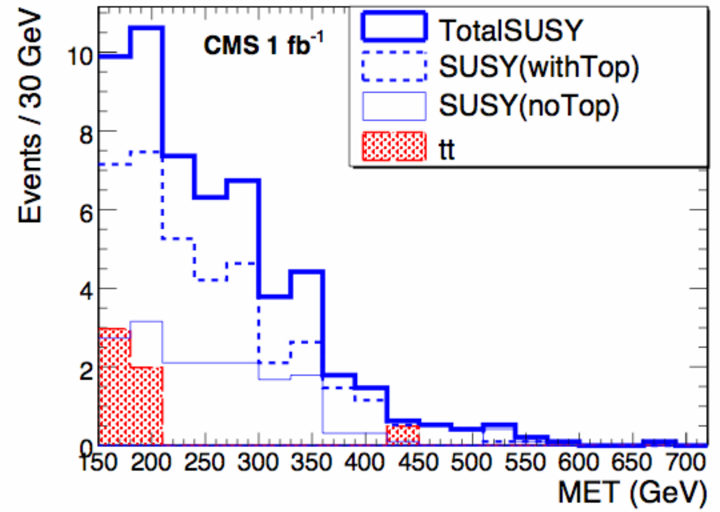
Inclusive MET + Top

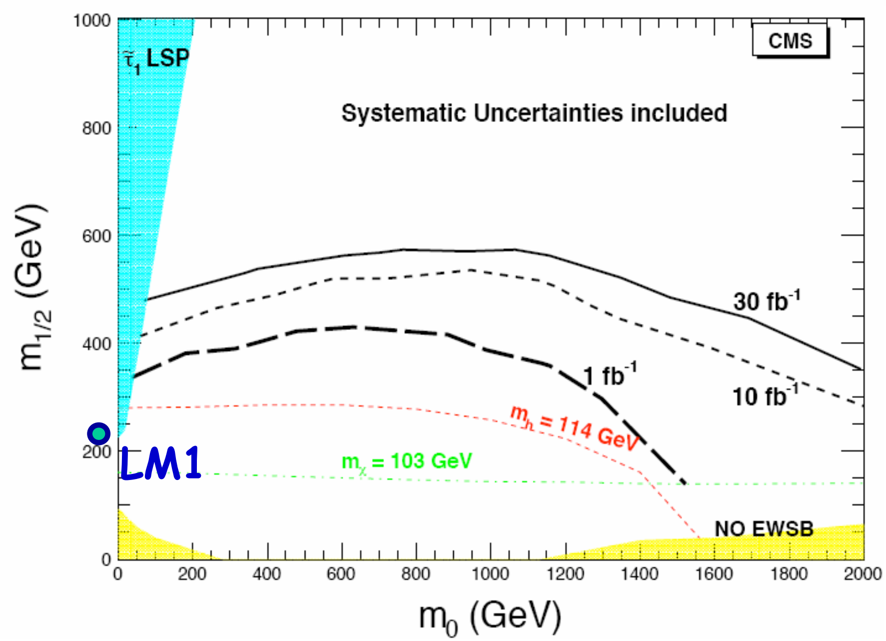
- Catch stop decays to top



- Cuts optimized @LM1

  MET>150 GeV
  Hadronic top selection and 2C fit
  1 b-jet + 2 non-b jets
  Use the W and top mass
  constraints to fit top
  and require good $\chi 2$

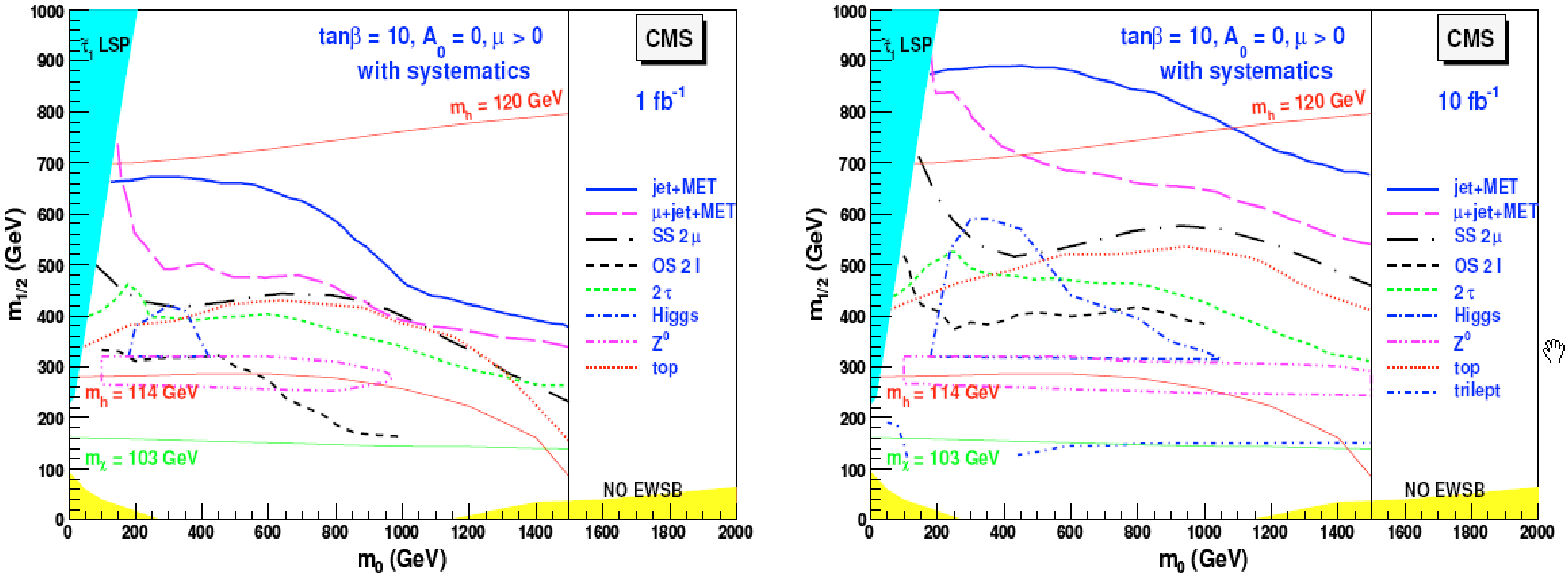




- LM1 signal
  - ~200 pb^{-1} for 5σ observation
    sys. uncertainty ~12%

Low-Luminosity Reach Summary

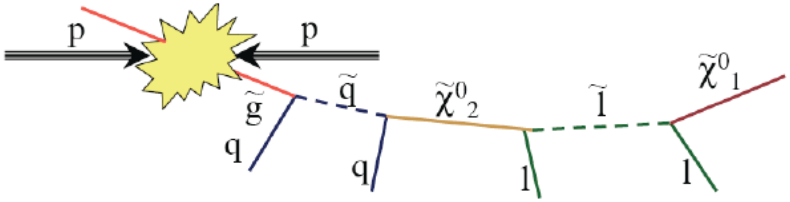
- Discovery map including background systematics



SUSY Particle Spectroscopy

General Consideration

- With stable LSP cannot fully reconstruct squark or gluino decay chains in general
  But endpoints in invariant mass distributions give information on sparticle masses

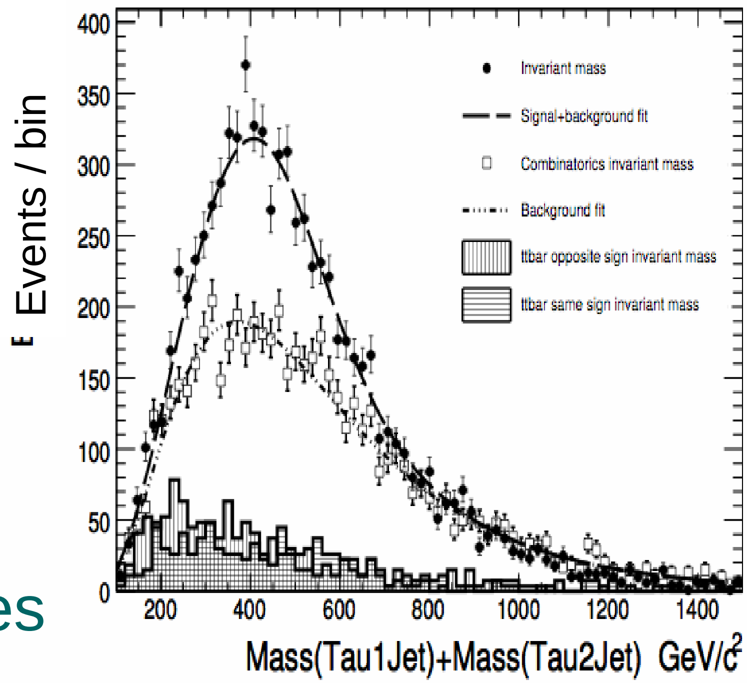


- Discussed dileptons from
  $\tilde{\chi}_2^0$ (mll)
  Add quark jet to get squark (mllq)
  Add another jet to get gluino (mllqq)

- These and other combinations (e.g. mlq) have endpoints that are functions of the sparticle masses

One Example : Di-Tau Ananlysis

- Consider $\tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow q\tau\tilde{\tau} \rightarrow q\tau\tilde{\tau}\tilde{\chi}_1^0$
- Measure di-tau endpoint and infer sparticle masses
- But no sharp reconstructed endpoint due to ν_τ
  - Fit to signal + background can be translated to endpoint measurement
- Measure several invariant masses
  - 2-tau, tau1+jet, tau2+jet, tau1+tau2+jet



- Extract the masses of the sparticles by solving for the kinematics of the decay chain; example measurement at 40 fb-1 at LM2

	LM2 benchmark point	
	measured	theory
$M(\chi_1^0)$	$147 \pm 23(\text{stat}) \pm 19(\text{sys})$	138.2
$M(\chi_2^0)$	$265 \pm 10(\text{stat}) \pm 25(\text{sys})$	265.5
$M(\tilde{\tau})$	$165 \pm 10(\text{stat}) \pm 20(\text{sys})$	153.9
$M(\tilde{q})$	$763 \pm 33(\text{stat}) \pm 58(\text{sys})$	753-783 (light $\tilde{q}$)

First Data and SUSY

General Stategy

Maria Spiropulu, “SUSY at the Large Hadron Collider”
(plenary talk, Physics at LHC, Krakow, 3-8 July 2006)

- Choose signatures identifying well defined decay chains
- Extract constraints on masses, couplings, spin from decay kinematics/rates (especially for spin, need clever ideas!)
- try to match emerging pattern to tentative template models
- having adjusted template models to measurements, try to find additional signatures to discriminate different options

Conclusions

- LHC opens up a very large energy frontier for SUSY searches
- Low-mass SUSY visible almost immediately in many channels according to the latest detailed simulations taking into account all backgrounds and systematic uncertainties
- Difficult part is to disentangle decay chains and measure spins, but constraints from endpoints and asymmetries are available (not to mention cross section measurements as well)
- LHC is coming soon - focus on commissioning and startup scenarios

Acknowledgements

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