DARK MATTER AND THE LHC

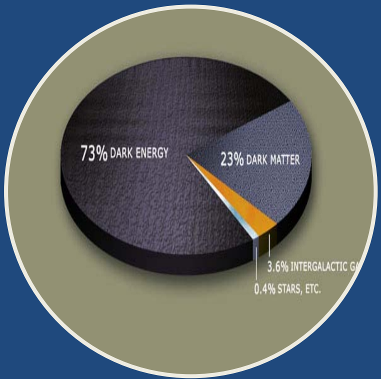
Launch09

Sascha Caron (Freiburg)

Outline

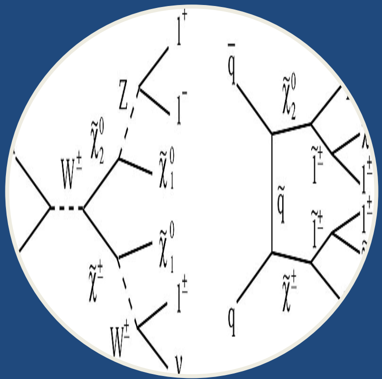
- Dark Matter (DM) production at LHC
- LHC , ATLAS and CMS status
- Search strategies and prospects
- Measurement of DM properties
- Summary and Outlook

Dark Matter and the LHC



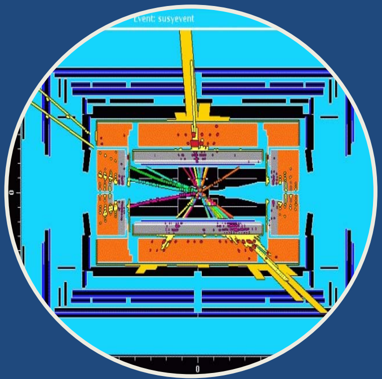
Evidence from Astroparticle physics

- Dark Matter
- Assumptions



Theoretical connections

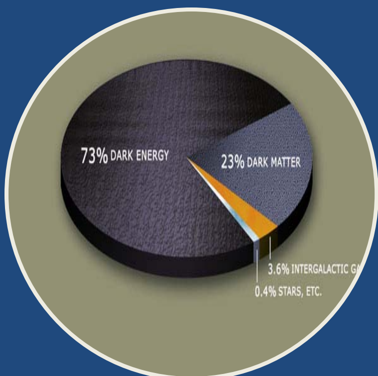
- Supersymmetry
- Extra Dimensions
- … , ??

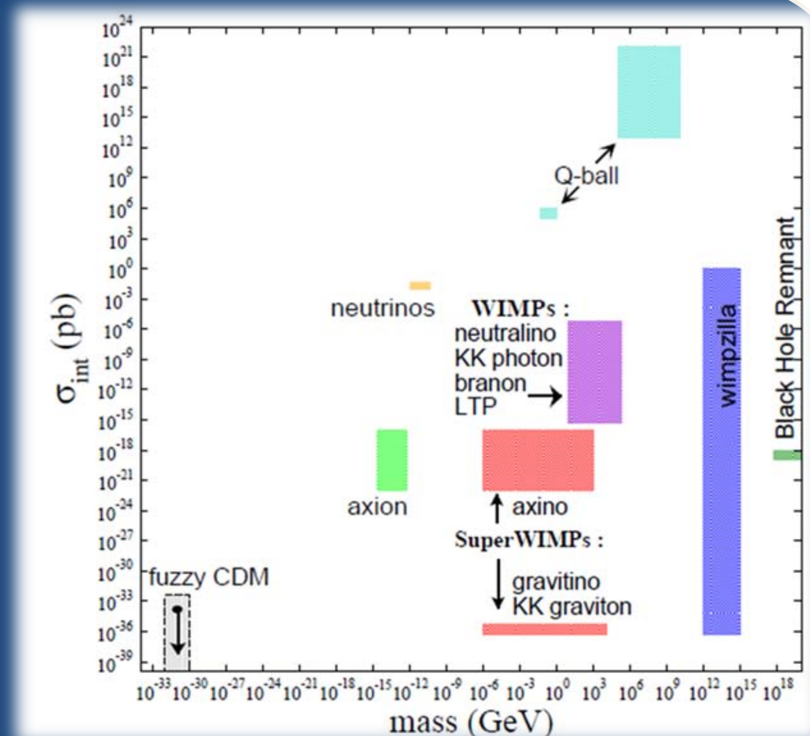


Consequences for LHC

- LHC phenomenology
- Model testing

Dark Matter and the LHC : Astro





Evidence from Astroparticle physics mainly based on gravitational interactions

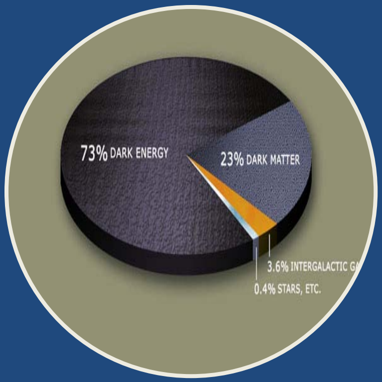
Good candidate:

- Non-relativistic (Cold Dark Matter)
- Massive
- Electrically and color neutral

Furthermore mainly concentrate on:

- Weakly interacting (WIMP)
- The amount of WIMP DM suggests a new particle (in thermal equilibrium in early Universe) with a mass of O(100 GeV) at an electroweak annihilation cross section

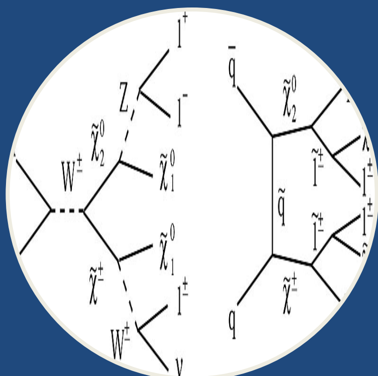
Dark Matter and the LHC : Astro



O(100 GeV): This is the Electroweak scale
According to some of the most interesting theories describing DARK MATTER it might be visible at LHC energies

No particle in the Standard Model of particle physics has the right properties

Dark Matter and the LHC : Theory



Connection from Astrophysics and LHC physics via theoretical models:

Many theoretical models developed to solve other mysteries of the SM like the fine-tuning problem of EWSB turn out to deliver perfect candidates for cold dark matter

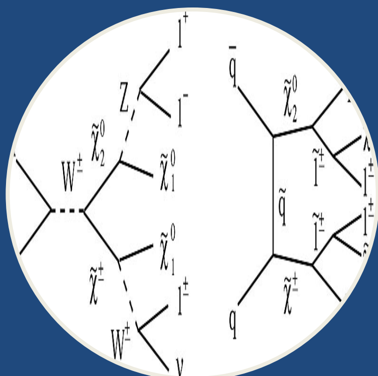
Huge amount of models on the market, the most popular *classes of models* are:

-Supersymmetry

-Extra Dimensions

-Others (Little Higgs, etc.)

Dark Matter and the LHC : Theory



SUPERSYMMETRY (SUSY) is an extension of the Standard Model with a new symmetry between half-integer spin fermions and integer spin bosons.

Most studied new physics theory at LHC for several reasons :

-Fermion and Boson loops protect the Higgs mass at large energies (solves "fine tuning")

-SUSY is a broken symmetry and thus offers (with R-parity conservation) perfect candidates for DM

-Gauge couplings unification, "radiative" EWSB, …

SUSY Reminder

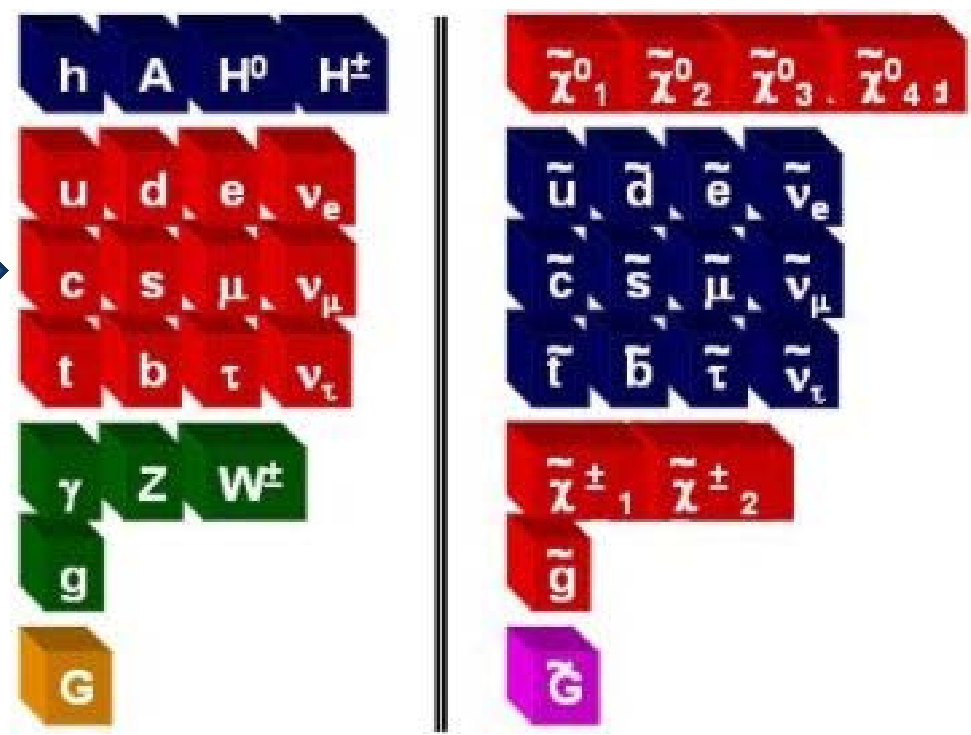
Models of SUSY breaking

>100 parameters in MSSM

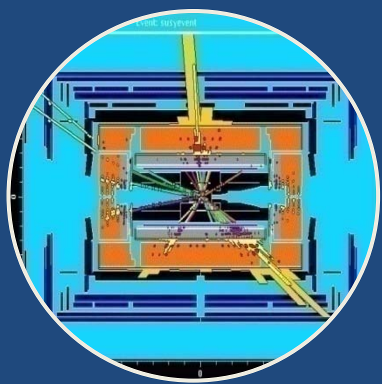
Sub-models with Less parameter:
mSUGRA
GMSB
AMSB
etc.

SUSY breaking mechanisms generate masses

MSSM particle Zoo

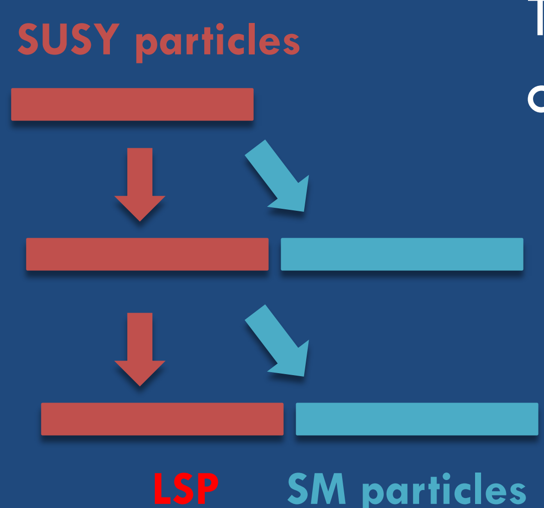


Dark Matter and the LHC : Signal



SUSY leads to a huge increase in the number of particles and parameters which makes it *a priori* not so predictive for LHC phenomenology.
Searches need to be quite general and model-parameter-independent

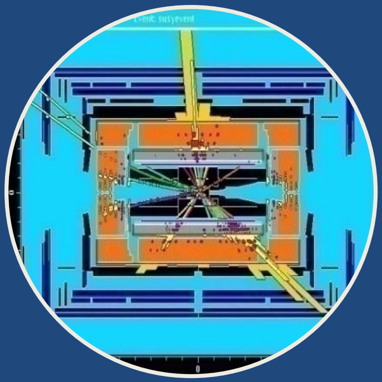
Typically production of SUSY particles which cascade decay to Lightest SUSY particle (LSP)



DM candidates in Minimal Supersymmetric SM:

- Lightest Neutralino (the WIMP candidate)
- Gravitino (gravitational interacting spin 3/2)
- *Sneutrinos (largely excluded by direct DM searches)*

Dark Matter and the LHC : Signal



If R-Parity is conserved then SUSY particles are pair produced.

LHC:

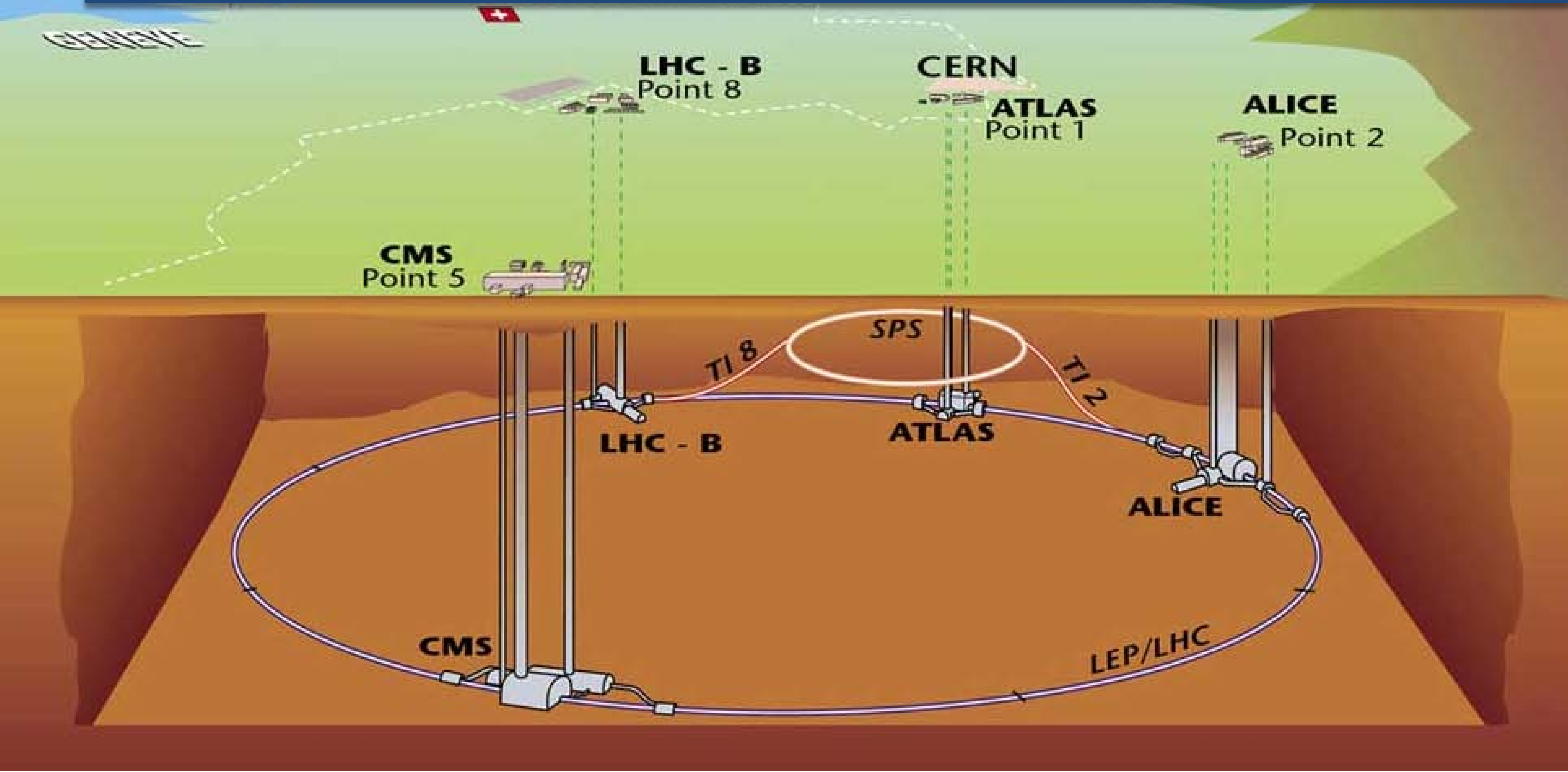
Due to strong force dominant production of squarks and gluinos (if not too heavy)
Cascade decay to lighter SUSY particles and finally the lightest SUSY particle (LSP)

The "Standard signals":
Missing transverse energy (MET), maybe jets, maybe leptons, maybe photons
The "non-standard signals":
New heavy particles with lifetime, non pointing photons , no MET, ….

Interesting: Similar conclusions for Universal Extra Dimension, ADD, Little Higgs, ….

LHC is a proton-proton (and lead nuclei) collider with a design centre-of-mass energy of 14 TeV and an integrated luminosity of 10^{34} $cm^{-2}s^{-1}$

- 10. September 2008: LHC Start with single beam energy of 450 GeV
- 19. September 2008: During 5 TeV magnet commisioning a high resistance appeared in a faulty interconnection between two magnets
  ➔Serious incident (He released, large forces displaced magnets)
- Since then various preventive systems installed, √s initially reduced



LHC schedule

What happened till today ?

- All sectors are cold again

(magnets operate at 1.7 Kelvin, liquid Helium)

- During 23.-25.October injection tests for protons and ions were successful

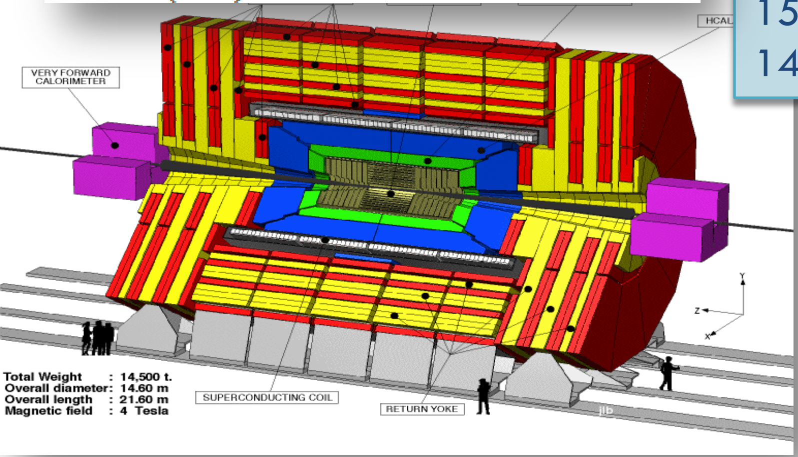
Further schedule:

- End of 2009: 450 GeV (SPS energy) collisions
- Begin of 2010: collisions at 3.5 TeV beam energy ($\sqrt{s}$=7 TeV)
- Mid of 2010 : perhaps increase of beam energy ($\sqrt{s}$=8-10 TeV)

Most physics studies assume now 100- 200pb^{-1} at $\sqrt{s}$=10 TeV

CMS and ATLAS

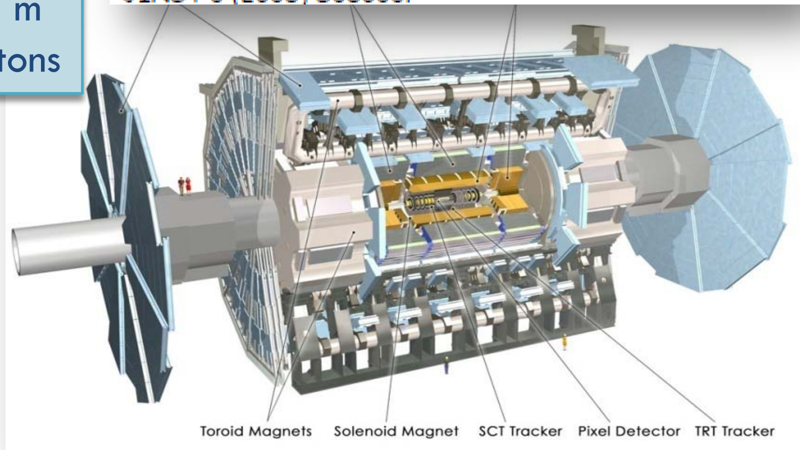
The CMS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08004.



15*21 m
14500 tons

25*44 m
7000 tons

The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003.



CMS

Huge silicon detector (pixel and strips)

4 Tesla solenoid

Crystal EM calorimeter: $\sigma(E)/E \sim 3\%/\sqrt{E} + 0.003$

Brass and scintillator had. Calorimeter: $\sigma(E)/E \sim 100\%/\sqrt{E} + 0.05$

Muon Chambers: $\sigma(p)/p < 10\%$ at 1TeV

Level 1 + higher level trigger

ATLAS

Silicon detector (pixel and strips) and Transition Radiation Tracker (TRT)

2 Tesla solenoid + barred and endcap toroid

Em. calorimeter (PB+Lar) : $\sigma(E)/E \sim 10\%/\sqrt{E} + 0.007$

Hadronic calorimeter (Iron Tile + Scint., Cu +Lar HEC): $\sigma(E)/E \sim 50\%/\sqrt{E} + 0.03$

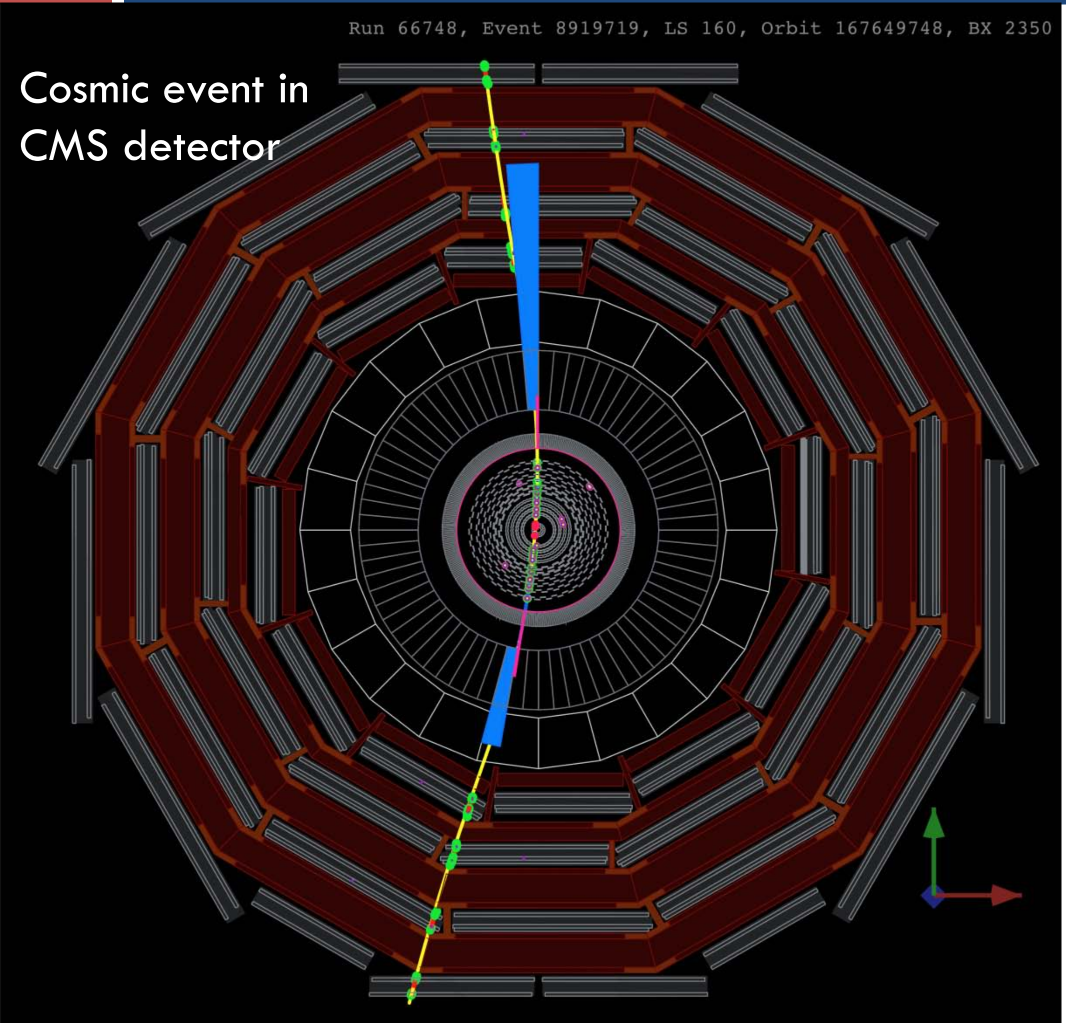
Muon Chambers (Drift Tubes): $\sigma(p)/p < 10\%$ at 1TeV

3 level trigger system

Resolutions might be measured in different experimental environments

ATLAS and CMS are ready
- all major detectors installed and commissioned
- cosmics, splash events, technical runs, milestone runs

First data

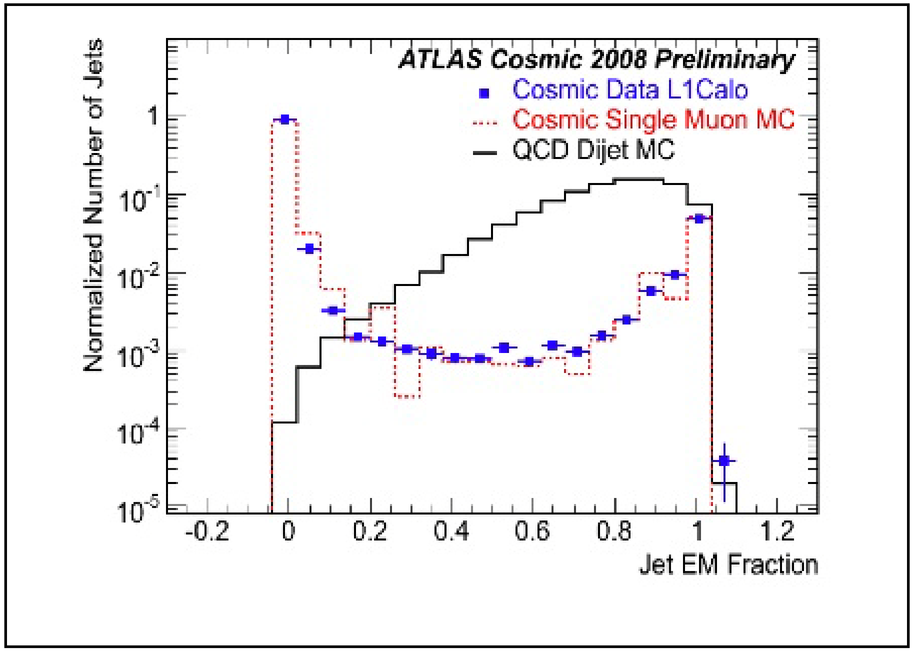


ATLAS and CMS analyzed about 300M cosmic events each with good data taking efficiency

Alignment of tracking detectors

Analysis of these data was good test for GRID and Software infrastructure

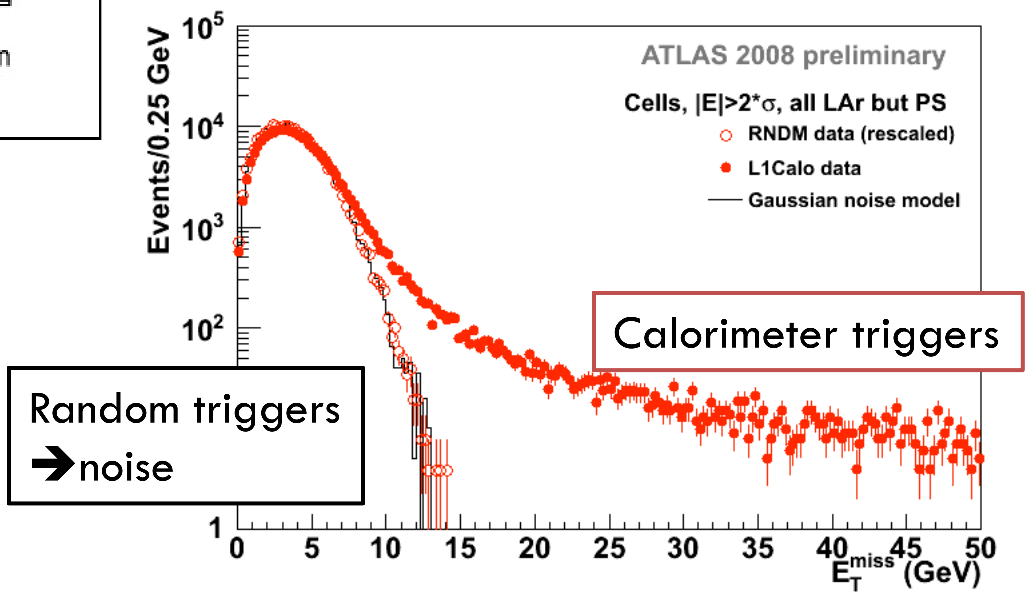
First data



Cosmic muons mimic jets

Define jet clean up cuts
from calorimeter variables

Study fake missing transverse energy from calorimeter noise and cosmics



First collisions at 7 TeV

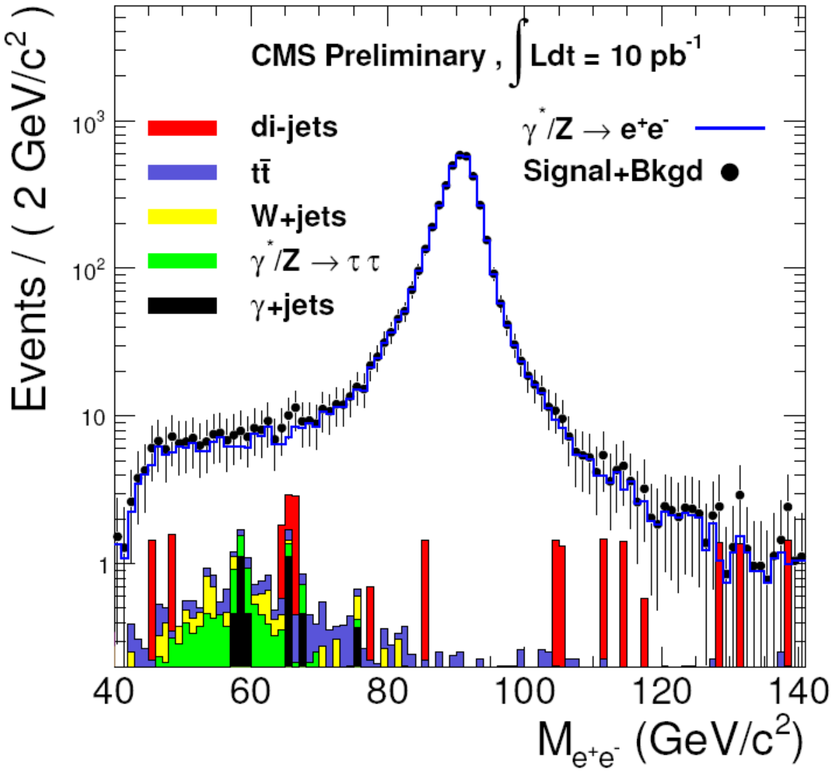
Before claiming any discovery we need to understand our expectations (MC, detector response for tails of distributions)

- Understand the ATLAS detector by measuring known SM processes
- Reduce backgrounds and validate background expectations

→First signals are the known SM particles (Z, W, top)

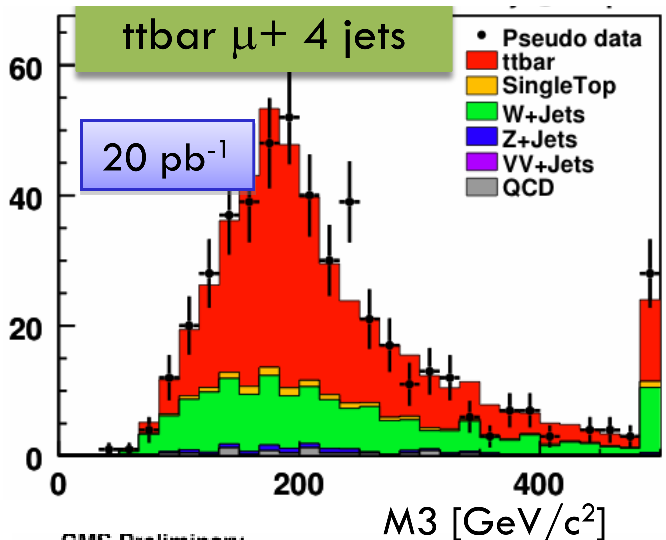
First collisions at 7 TeV

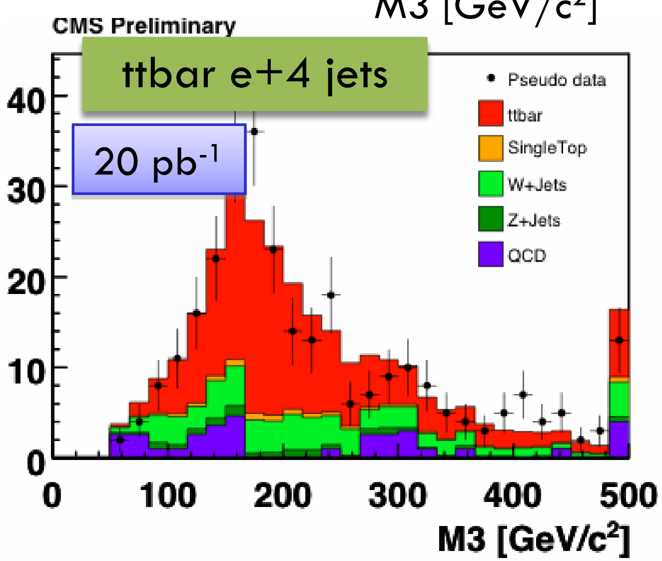
Clear Z and W events with 10 pb^{-1}



Z events can be used to study all kinds of efficiencies, e.g. using so called tag and probe methods

First data: Top production in Europe





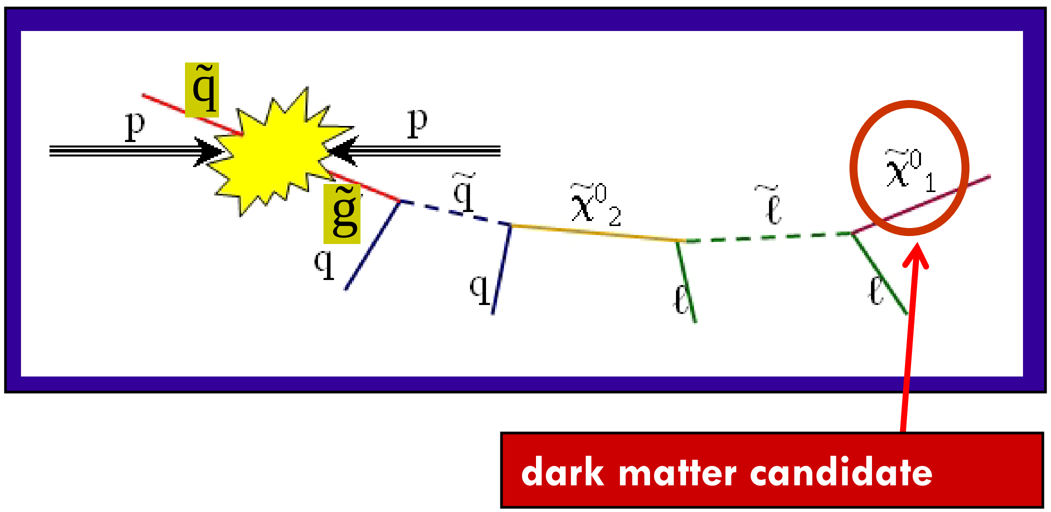
Tops are most important SUSY background and needed to understand reconstruction efficiencies in busy events

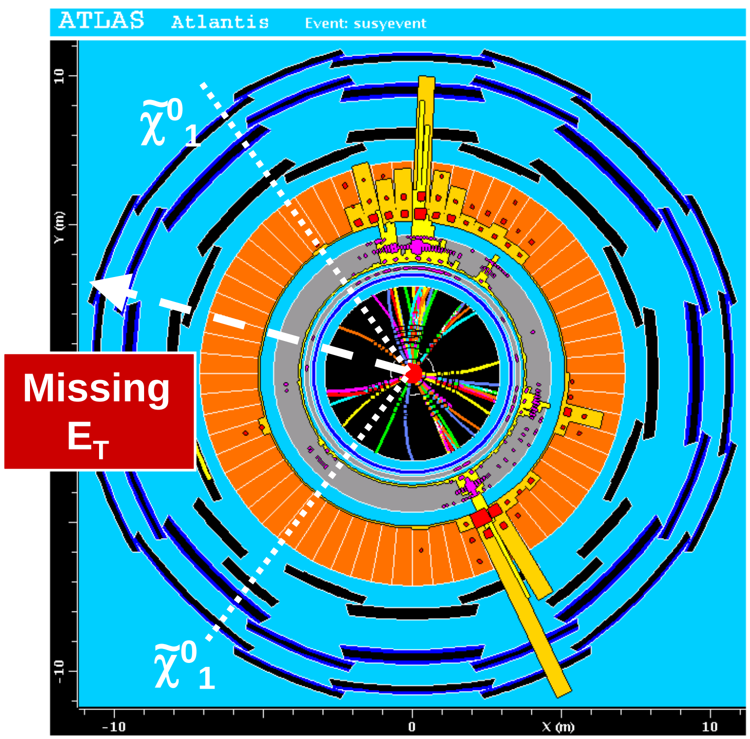
M3 = inv. mass of 3 jets with highest vector sum

Inclusive SUSY searches

The "Standard signals":

Missing transverse energy, maybe jets, maybe leptons, maybe photons





SUSY might have huge cross section of O(1000 pb)

Might be visible next year ?

Inclusive SUSY searches

The “Standard signals”:

General Approach:
Find more events than expected and search in many channels since masses and parameters of new particles unknown

Challenge :
control the background expectation for a new experiment

Study first some benchmark points, then try make analyses less parameter dependent

Selections

- 0 leptons + 4 jets + large missing E_T

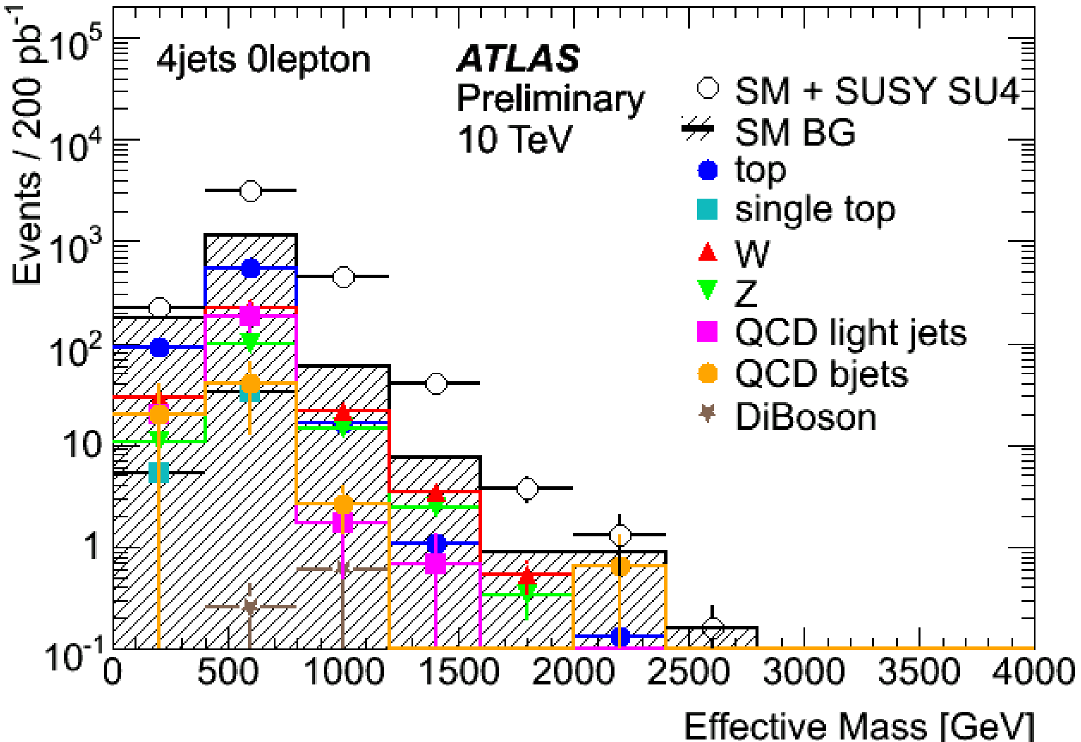
ATLAS baseline selection:

Trigger :

- Jet + MET or multi jets

Offline:

- 4 jets with E_T > 100, 40, 40, 40 GeV
- large MET
- Exclusive in lepton multiplicity
- Various cuts to reduce QCD background



$$M_{\mathrm{eff}} \equiv \sum_{i=1}^{4} p_T^{\mathrm{jet},i} + \sum_{i=1} p_T^{\mathrm{lep},i} + E_{\mathrm{T}}^{\mathrm{miss}}$$

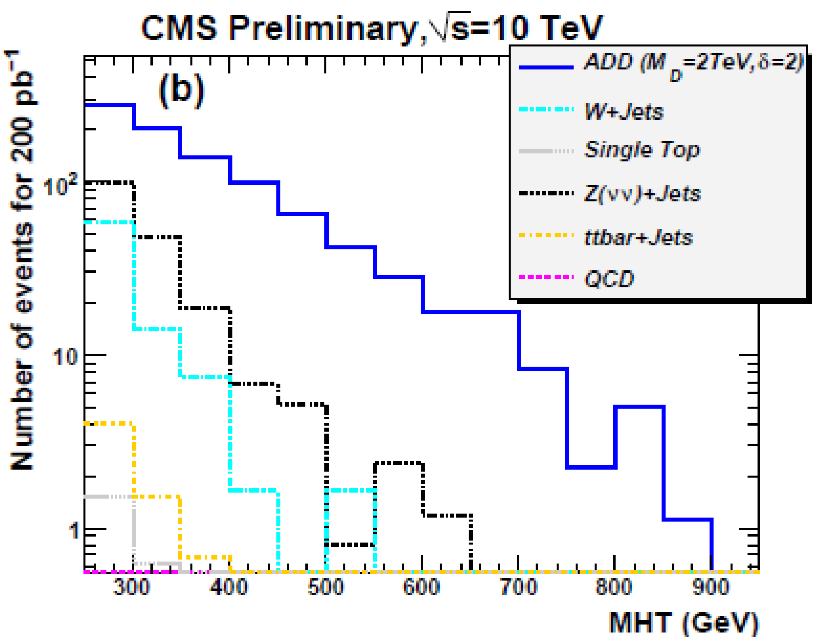
ATLAS benchmark point SU4

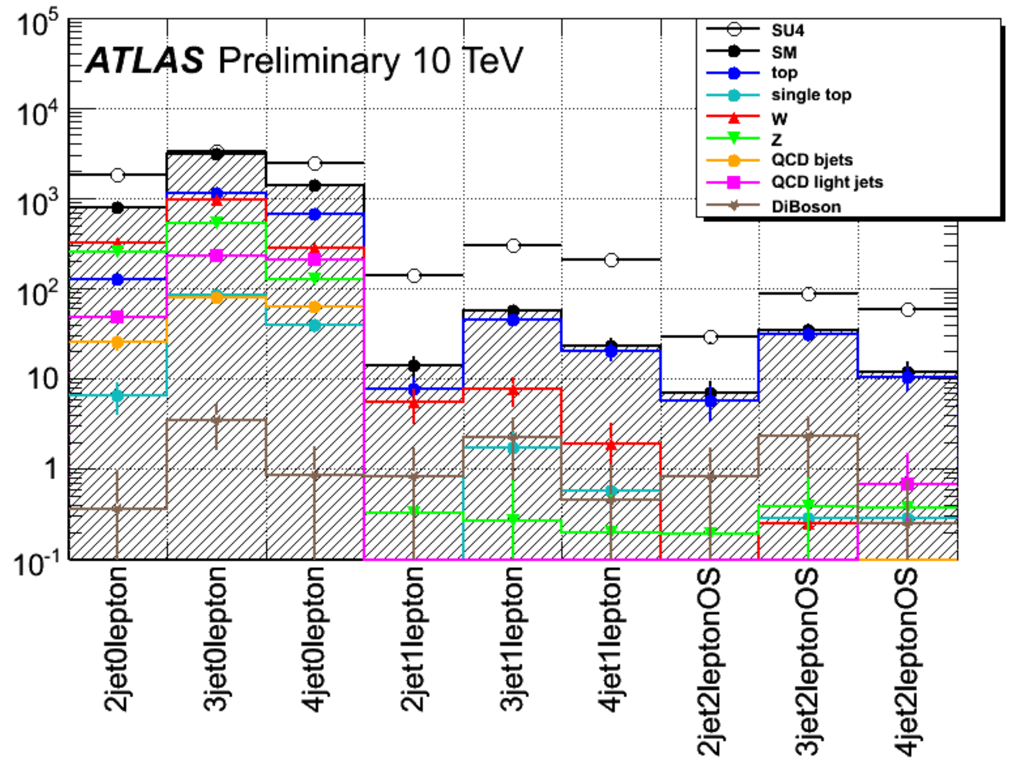
$m(\tilde{q},\tilde{g}) \sim 410$ GeV

visible !

Selections

1,2,3,4,5,6 Jets + 0,1,2 same and opposite sign, 3 leptons, tau, b-jets





MHT = |Vectorial sum of jet transverse momenta|
- Monojets sensitive to Large Extra Dimensions (ADD), Split SUSY, Unparticles, …

ED can be excluded for discovered for fundamental scale M_D < 3.1 TeV for 2 ED

Important: Control Measurements

Both ATLAS and CMS implemented many ways to verify each background:

Top :

Reconstruction of top events in SUSY signal region, define SUSY top control selections

W+jets :

Estimate in control selections and from Z+jets

Z+jets :

Estimate from Z➔ee or Z➔μμ or photon+jet events

QCD :

Derive calorimeter response function and apply it to good data,

find variables to remove QCD events most efficiently, …

Not beam induced :

study e.g. with overlayed cosmics

….

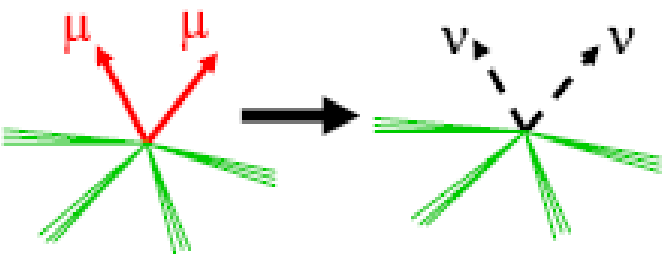
….

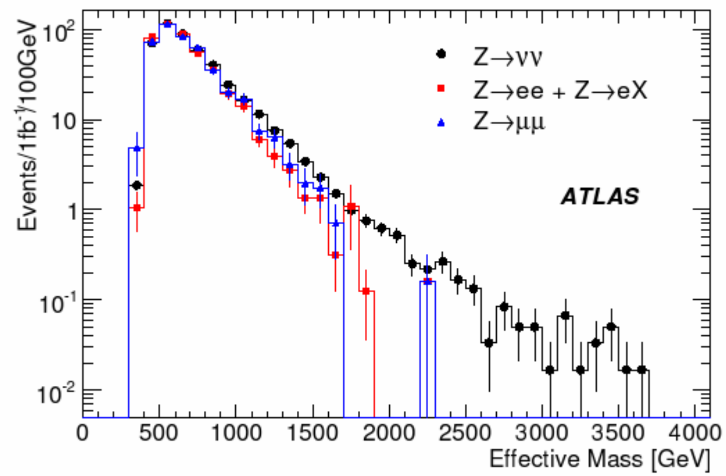
Students working hard…

Control Measurements and new variables

Estimate Z ➔ neutrinos background from data for 0 lepton channels

ATLAS/CMS: From Z➔ ee or μμ events





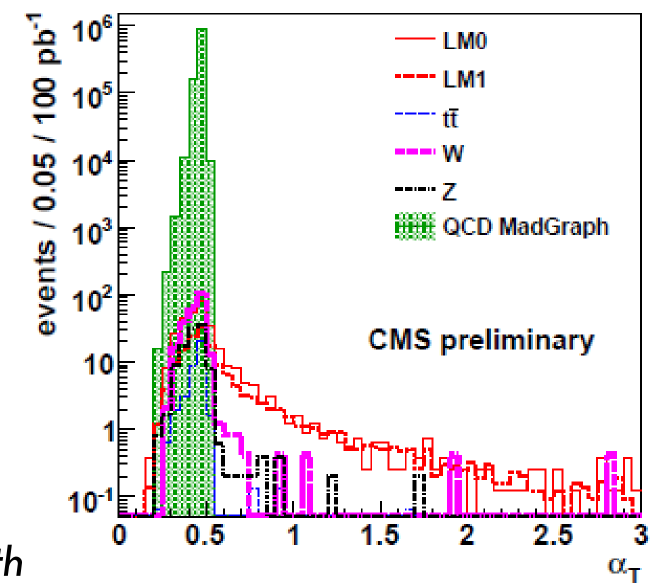
Find new variables to reduce QCD jet background

CMS:

$$\alpha_T = E_T^{j2} / M_T$$

- Exploits that QCD dijet events are back to back with equal P_T
- M_T is transverse mass
- Does also work for multijet events

Randall, Tucker-Smith



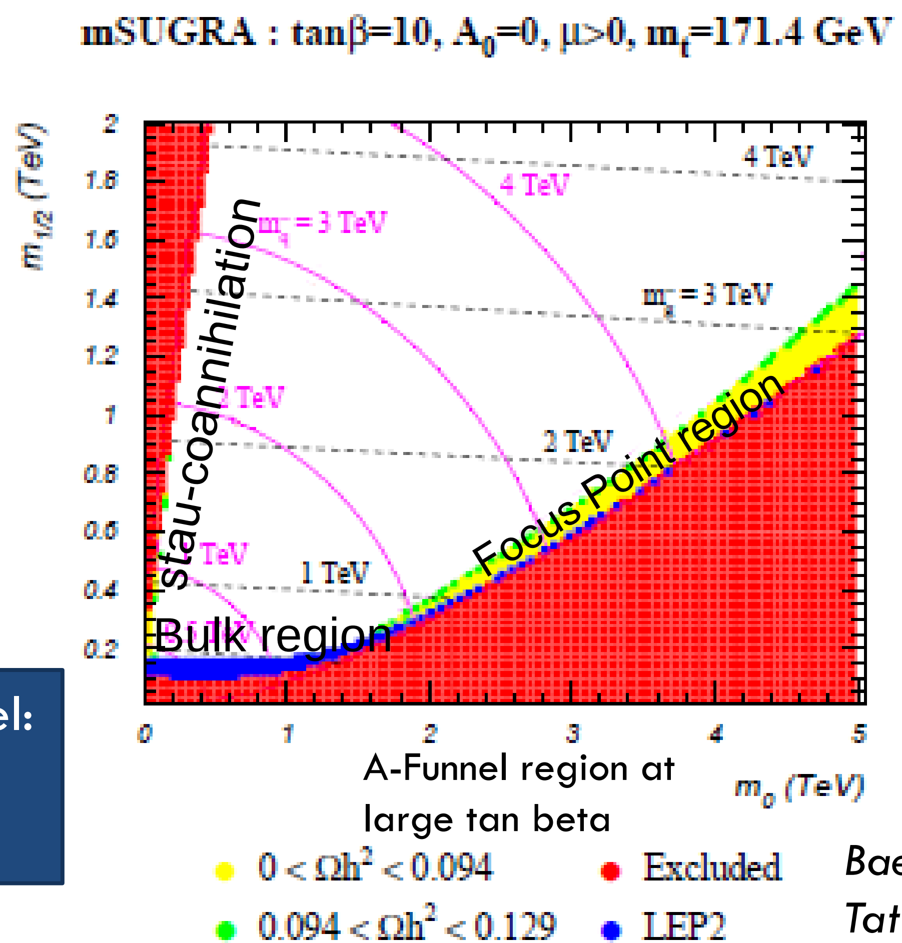
mSUGRA : Learning from DM for LHC

Most studied scenario is the 5 parameter mSUGRA model

M_0: common boson mass at GUT scale
$M_{1/2}$: common fermion mass at GUT scale
tan β: ratio of higgs vacuum expectation values
A_0: common GUT trilinear coupling
μ : sign of Higgs potential parameter

Large LSP annihilation cross section required by DM constraints
Huge restriction of parameter space in restrictive models

But if we are not in this restrictive model:
No stringent constraint on allowed SUSY masses from cosmology

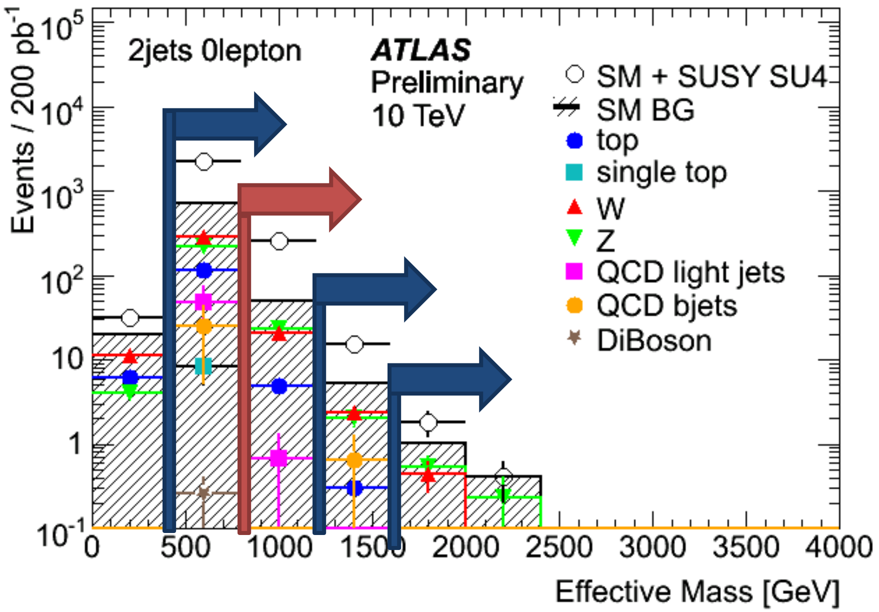


Baer, Tatta

Search for new physics

Example from ATLAS:

Cut on effective mass optimized to get best signal significance



A set of cuts

➔ Sensitive to full mass range

HEP jargon:

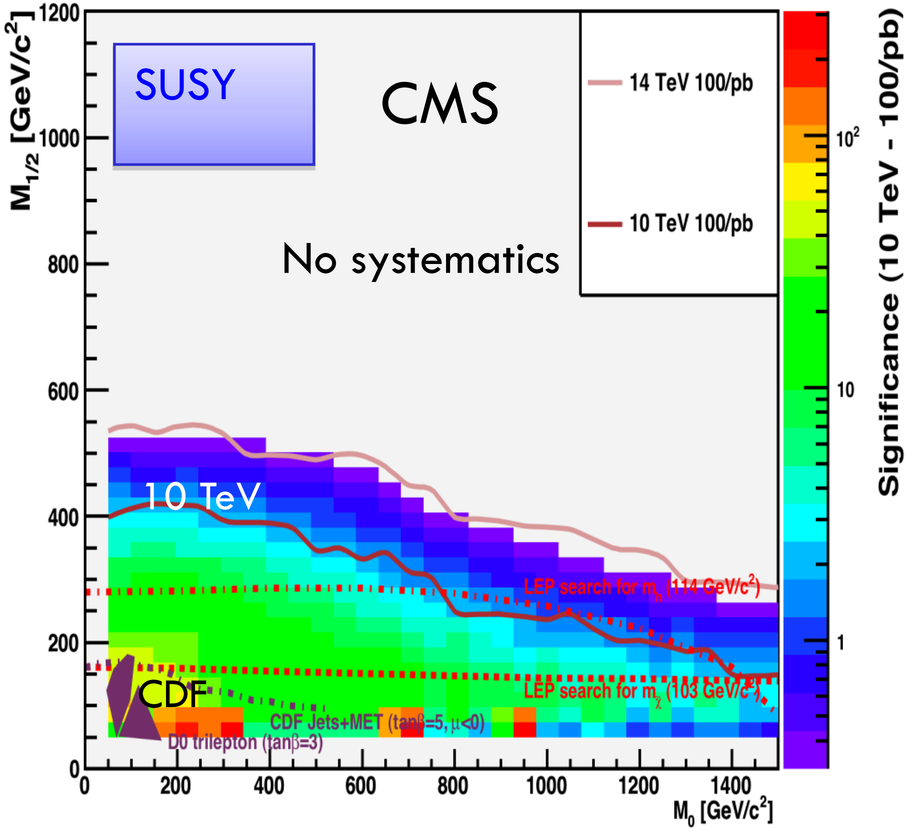
- *> 5 sigma deviation means discovery*

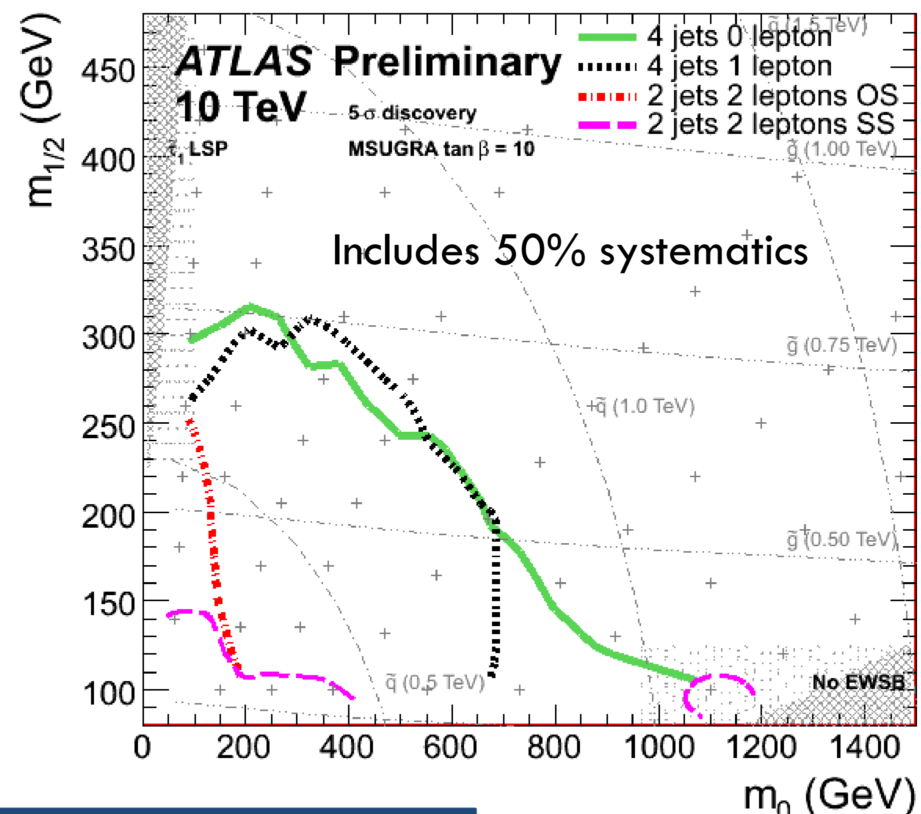
Some further information:

-Significance corrected for multiple tests

-Significance includes syst. error
(about 50% for first data)

mSUGRA reach



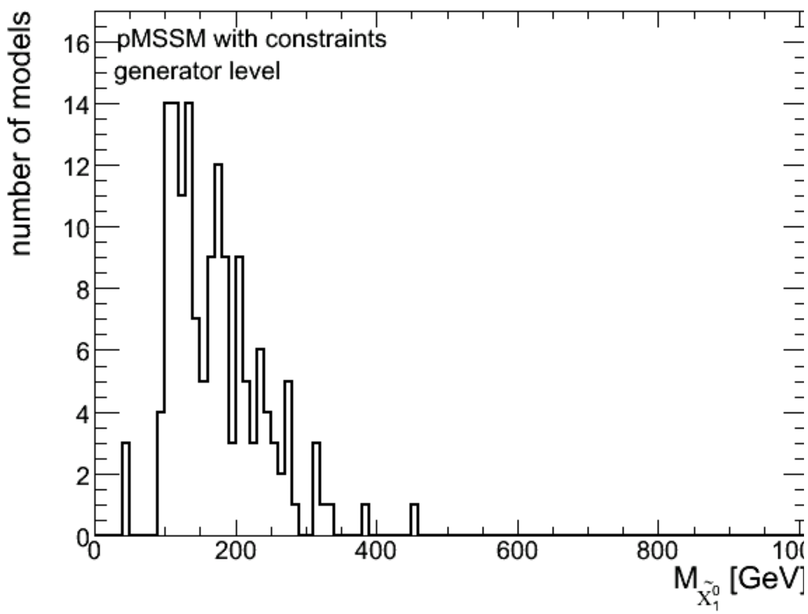


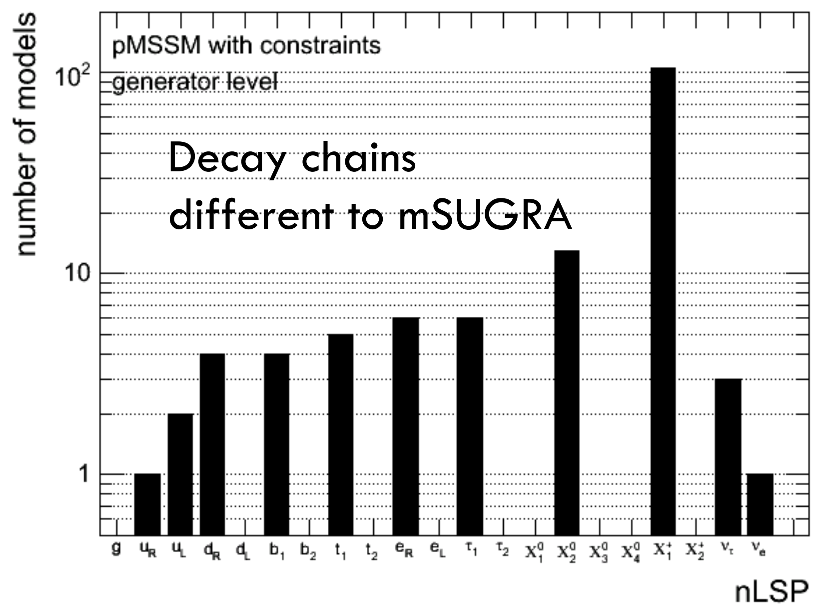
0 and 1 lepton channel have largest reach
With O(100 pb^{-1}) well understood data ATLAS and CMS reach well above Tevatron limits (300-400 GeV for squarks/gluinos)

Beyond mSUGRA

Parameter space of 19 parametric phenomenological MSSM was sampled with mass scale < 1TeV *(Berger, Gainer, Hewitt, Rizzo)*

ATLAS analyzed 200 points fulfilling all constraints from direct searches, DM and collider experiments

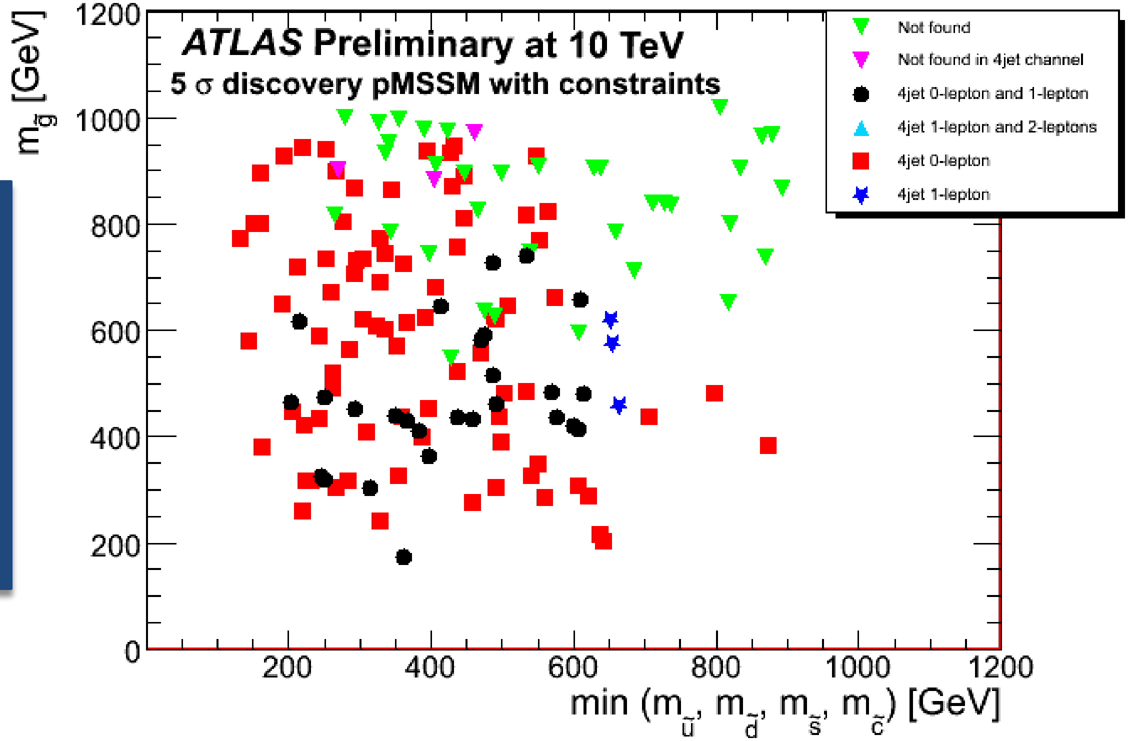




Beyond mSUGRA

Most models can be discovered also in this scenario

There are MSSM scenarios where no signal is discovered even though mass scale is small



Red, Black, Blue, Pink discovered

Green points are <u>not</u> discovered

Beyond SUSY: UED reach

Universal

Extra Dimension

Model

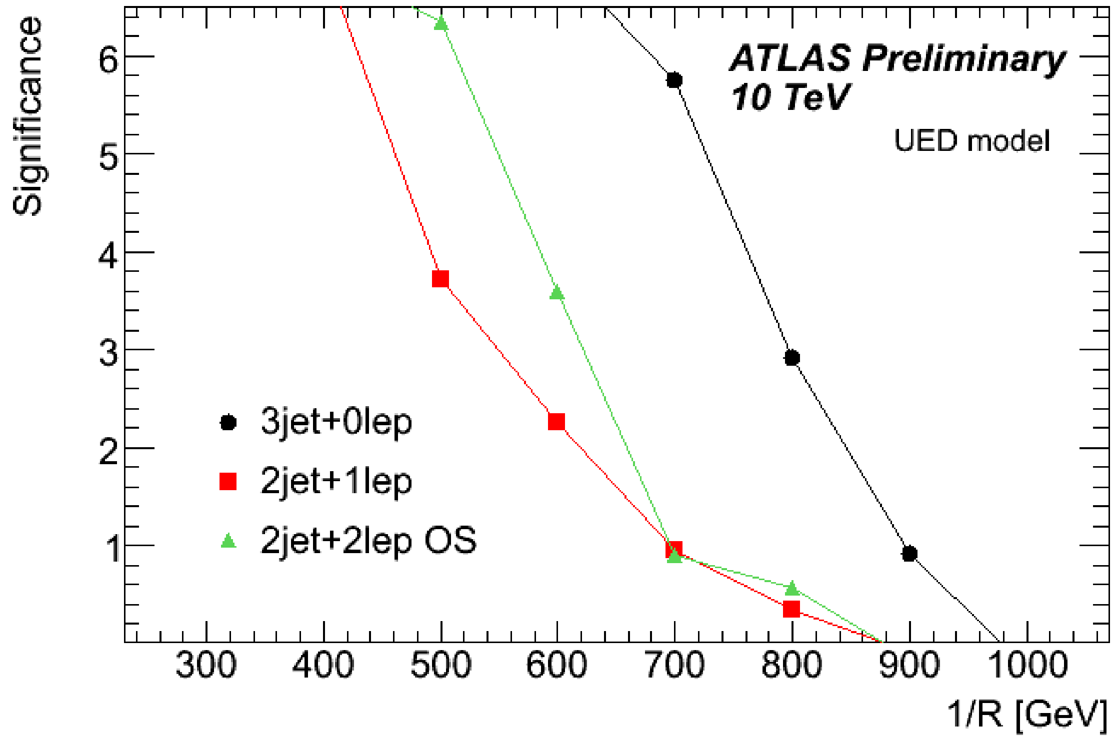
SM fields can

propagate into extra

dimensions with radius R.

➔Kaluza Klein Towers of SM particles (same spin as SM)

➔ Here lightest KK particle is DM candidate



- Mass of new particles of O(1/R)
- Analysis identical with SUSY search
- Similar discovery reach

Not shown today

- Searches with photons
- Searches with b-jets
- Searches with taus
- Searches for stops
- Multilepton
- Searches for SUSY Higgs
- Searches for R-Parity violating SUSY
- ….

Examples of non-standard signals

Long lived particles appear if decay is only possible via loops, via highly virtual particles or if coupling is small

Some studied examples are long lived hadrons, sleptons, neutralinos

•Long lived SUSY particles can form R-hadrons
➔ Signal of (slowly) travelling heavy hadron (muon like)

•Signal from long lived sleptons
➔late muon like track (wrong bunch crossing)

•Neutralino (with lifetime) could in GMSB decay to photon and gravitino (non-pointing photons)

Challenging, but discovery possible in CMS and ATLAS in many scenarios in early data due to small backgrounds

After discovery: Models and Parameters

"Observation of events with high missing transverse energy in pp collisions"

Is it really Supersymmetry ? Is it any of the known candidates?

Perform a great many of exclusive measurements

-Measurement of possible decay chains
-Measurement of 3rd generation signals
-Measurement of mass differences
-Measurement of signal strenght and mass scale (is it comparable with assumed cross section)
-Measurement of Majorana nature of gluino via dileptons of same sign
-Measurement of particles spin
- ....

Test models against all those measurements
Determine "best fit values" for each model
Determine which model fits best

→ Model predicts then DM relic density from LHC

Exclusive measurements

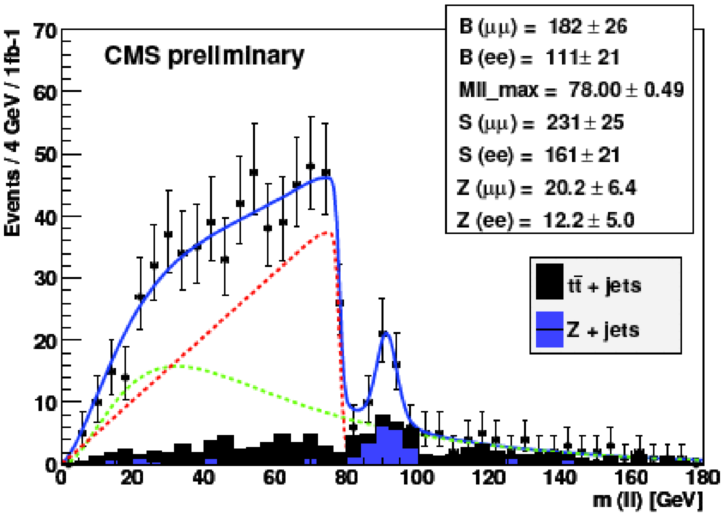
Perform a great many of exclusive measurements

Example : Measurement of $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_{L,R}\ell \rightarrow \ell\ell\tilde{\chi}_1^0$ in OS dilepton events

Due to missing energy no mass peaks, but shapes and endpoints of mass distribution provide mass information

$$m_{\ell\ell}^{max} = m_{\tilde{\chi}_2^0}\sqrt{1-\frac{m_{\tilde{\ell}_R}^2}{m_{\tilde{\chi}_2^0}^2}}\sqrt{1-\frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\ell}_R}^2}}$$

CMS



$$\Delta m_{ee}^{max} = \pm 1.07(stat.) \pm 0.36(syst.) GeV/c^2$$

$$\Delta m_{\mu\mu}^{max} = \pm 0.75(stat.) \pm 0.18(syst.) GeV/c^2$$

SUSY Masses & Model parameters

Measure various endpoints of mass distributions from dilepton and lepton + jets signals

Use position of all edges to fit for sparticle masses

Fit assumes we know mass hierarchy

ATLAS

	Measured $[\mathrm{GeV}/c^2]$	Monte Carlo $[\mathrm{GeV}/c^2]$
$m_{\tilde{\chi}_1^0}$	$88 \pm 60 \mp 2$	118
$m_{\tilde{\chi}_2^0}$	$189 \pm 60 \mp 2$	219
$m_{\tilde{q}}$	$614 \pm 91 \pm 11$	634
$m_{\tilde{\ell}}$	$122 \pm 61 \mp 2$	155
Observable	SU3 Δm_{meas} $[\mathrm{GeV}/c^2]$	SU3 Δm_{MC} $[\mathrm{GeV}/c^2]$
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$	$100.6 \pm 1.9 \mp 0.0$	100.7
$m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$	$526 \pm 34 \pm 13$	516.0
$m_{\tilde{\ell}} - m_{\tilde{\chi}_1^0}$	$34.2 \pm 3.8 \mp 0.1$	37.6

mSUGRA bulk region, 1 fb^{-1}

Or fit parameter of SUSY model, e.g. mSUGRA
(M_0 and $M_{1/2}$ good constraint, tan β and A0
order of magnitude right, sign μ unconstrained with 1 fb^{-1})
or fit in pMSSM

…we can then calculate neutralino mass, coupling and DM relic density within model

Example: DM parameter estimation

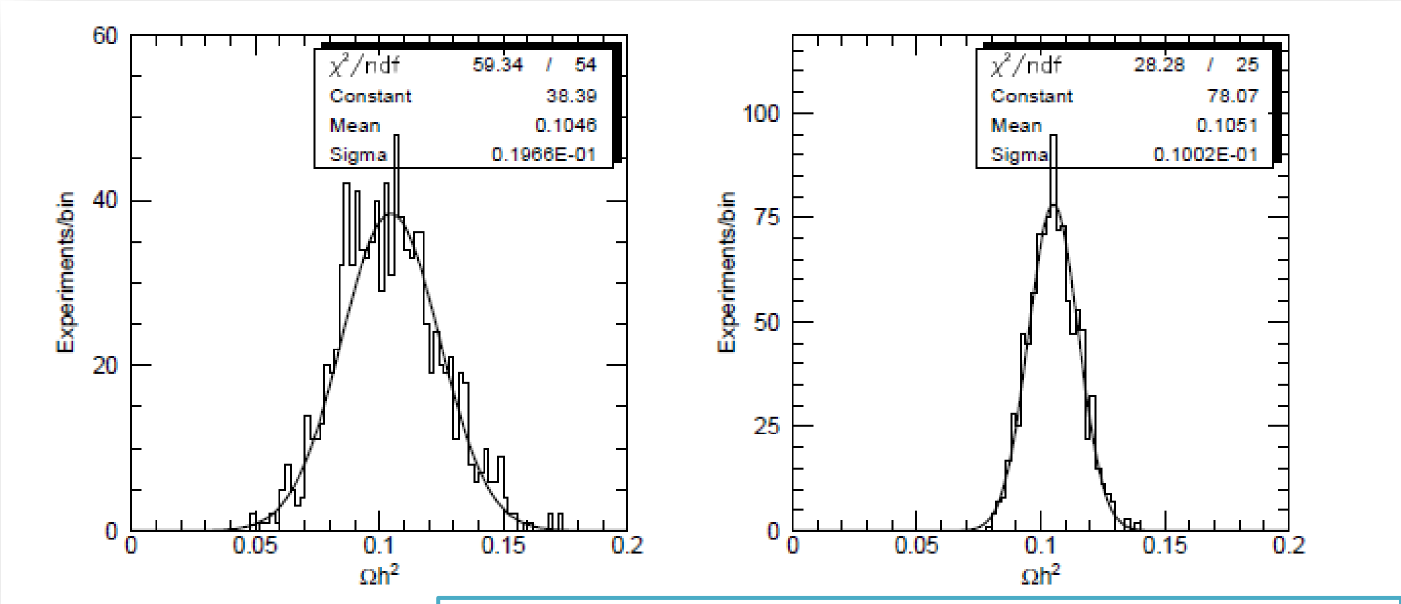
(Nojiri, Polesello, Tovey, 2006)

Explored how well the LHC measurements can predict the dark matter relic density
Important to measure all parameters essential for the DM annihilation, e.g.
Neutralino components, sleptons especially taus and Higgs sector (also heavy Higgses)

Considered a “bulk region” SUSY model (SPS1a) where neutralino annihilation is dominated by diagrams involving light sleptons

Good prediction with 300 fb^{-1} if heavy H/A are discovered with m>300 GeV

Otherwise upper limit possible



Error on tau-tau edge 5 GeV …. or 0.5 GeV

Example: DM parameter estimation

(Baltz, Battaglia, Peskin, Wizansky)

Explored how well LHC and ILC measurements can predict the dark matter relic density

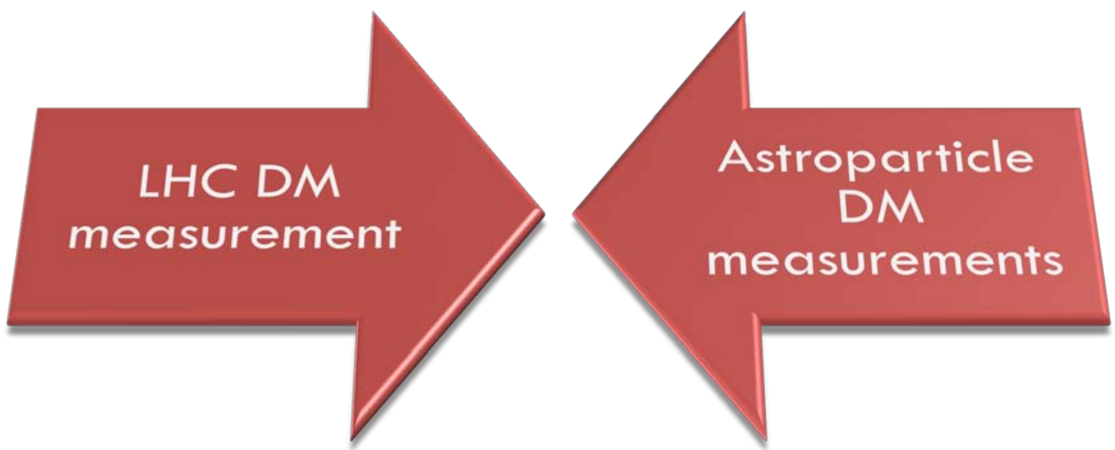
- Detailed studied of various points in the SUSY parameter space
- Performed a "scan" over the MSSM parameters to calculate probability density distributions for relic density and cross sections for direct detection

	Ωh^2	LHC	ILC-500	ILC-1000	LHC (mean)	ILC-500	ILC-1000
LCC1	0.192	7.2%	1.8%	0.24%			
LCC2	0.109	82.%	14.%	7.6%	0.074		
LCC3	0.101	167%	50.%	18.%	0.24		
LCC4	0.114	405%	85.%	19.%	0.26	0.083	0.094

→ Predict cross sections relevant for direct DM detection from LHC data

Summary and Conclusions

- Some of the most interesting theories for Dark Matter yield large signals for LHC
- Signals might show up early … and LHC will exclude a huge region in parameter space of many models
- LHC gives information which theory is how likely
- LHC will start up again in the next month(s)



ATLAS benchmark points

SU1 $m_0 = 70$ GeV, $m_{1/2} = 350$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Coannihilation region where $\tilde{\chi}_1^0$ annihilate with near-degenerate $\tilde{\ell}$.

SU2 $m_0 = 3550$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Focus point region near the boundary where $\mu^2 < 0$. This is the only region in mSUGRA where the $\tilde{\chi}_1^0$ has a high higgsino component, thereby enhancing the annihilation cross-section for processes such as $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to WW$.

SU3 $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -300$ GeV, $\tan\beta = 6$, $\mu > 0$. Bulk region: LSP annihilation happens through the exchange of light sleptons.

SU4 $m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$ GeV, $\tan\beta = 10$, $\mu > 0$. Low mass point close to Tevatron bound.

SU6 $m_0 = 320$ GeV, $m_{1/2} = 375$ GeV, $A_0 = 0$, $\tan\beta = 50$, $\mu > 0$. The funnel region where $2m_{\tilde{\chi}_1^0} \approx m_A$. Since $\tan\beta \gg 1$, the width of the pseudoscalar Higgs boson A is large and τ decays dominate.

SU8.1 $m_0 = 210$ GeV, $m_{1/2} = 360$ GeV, $A_0 = 0$, $\tan\beta = 40$, $\mu > 0$. Variant of coannihilation region with $\tan\beta \gg 1$, so that only $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ is small.

SU9 $m_0 = 300$ GeV, $m_{1/2} = 425$ GeV, $A_0 = 20$, $\tan\beta = 20$, $\mu > 0$. Point in the bulk region with enhanced Higgs production

CMS LM benchmark points

- Point LM1 :
  - Same as post-WMAP benchmark point B′ and near DAQ TDR point 4.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \rightarrow \tilde{q}q$ is dominant
  - $B(\tilde{\chi}_2^0 \rightarrow \tilde{l}_R l) = 11.2\%$, $B(\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau) = 46\%$, $B(\tilde{\chi}_1^{\pm} \rightarrow \tilde{\nu}_l l) = 36\%$
- Point LM2 :
  - Almost identical to post-WMAP benchmark point I′.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \rightarrow \tilde{q}q$ is dominant ($\tilde{b}_1 b$ is 25%)
  - $B(\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau) = 96\%$ $B(\tilde{\chi}_1^{\pm} \rightarrow \tilde{\tau}\nu) = 95\%$
- Point LM3 :
  - Same as NUHM point γ and near DAQ TDR point 6.
  - $m(\tilde{g}) < m(\tilde{q})$, hence $\tilde{g} \rightarrow \tilde{q}q$ is forbidden except $B(\tilde{g} \rightarrow \tilde{b}_{1,2} b) = 85\%$
  - $B(\tilde{\chi}_2^0 \rightarrow ll\tilde{\chi}_1^0) = 3.3\%$, $B(\tilde{\chi}_2^0 \rightarrow \tau\tau\tilde{\chi}_1^0) = 2.2\%$, $B(\tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^0) = 100\%$
- Point LM4 :
  - Near NUHM point α in the on-shell Z^0 decay region
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \rightarrow \tilde{q}q$ is dominant with $\tilde{g} \rightarrow \tilde{b}_1 b = 24\%$
  - $B(\tilde{\chi}_2^0 \rightarrow Z^0\tilde{\chi}_1^0) = 97\%$, $B(\tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^0) = 100\%$
- Point LM5 :
  - In the h^0 decay region, same as NUHM point β.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \rightarrow \tilde{q}q$ is dominant with $B(\tilde{g} \rightarrow \tilde{b}_1 b) = 19.7\%$ and $B(\tilde{g} \rightarrow \tilde{t}_1 t) = 23.4\%$
  - $B(\tilde{\chi}_2^0 \rightarrow h^0\tilde{\chi}_1^0) = 85\%$, $B(\tilde{\chi}_2^0 \rightarrow Z^0\tilde{\chi}_1^0) = 11.5\%$, $B(\tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^0) = 97\%$
- Point LM6 :
  - Same as post-WMAP benchmark point C′.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \rightarrow \tilde{q}q$ is dominant
  - $B(\tilde{\chi}_2^0 \rightarrow \tilde{l}_L l) = 10.8\%$, $B(\tilde{\chi}_2^0 \rightarrow \tilde{l}_R l) = 1.9\%$, $B(\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau) = 14\%$, $B(\tilde{\chi}_1^{\pm} \rightarrow \tilde{\nu}_l l) = 44\%$

Point LM7 :
  - Very heavy squarks, outside reach, but light gluino.
  - $m(\tilde{g}) = 678\,\mathrm{GeV/c^2}$, hence $\tilde{g} \rightarrow$ 3-body is dominant
  - $B(\tilde{\chi}_2^0 \rightarrow ll\tilde{\chi}_1^0) = 10\%$, $B(\tilde{\chi}_1^{\pm} \rightarrow \nu l\tilde{\chi}_1^0) = 33\%$
  - EW chargino-neutralino production cross-section is about 73% of total.

Point LM8 :
  - Gluino lighter than squarks, except $\tilde{b}_1$ and $\tilde{t}_1$
  - $m(\tilde{g}) = 745\,\mathrm{GeV/c^2}$, $M(\tilde{t}_1) = 548\,\mathrm{GeV/c^2}$, $\tilde{g} \rightarrow \tilde{t}_1 t$ is dominant
  - $B(\tilde{g} \rightarrow \tilde{t}_1 t) = 81\%$, $B(\tilde{g} \rightarrow \tilde{b}_1 b) = 14\%$, $B(\tilde{q}_L \rightarrow q\tilde{\chi}_2^0) = 26 - 27\%$,
  - $B(\tilde{\chi}_2^0 \rightarrow Z^0\tilde{\chi}_1^0) = 100\%$, $B(\tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^0) = 100\%$
- Point LM9 :
  - Heavy squarks, light gluino. Consistent with EGRET data on diffuse gamma ray spectrum, WMAP results on CDM and mSUGRA [674]. Similar to LM7.
  - $m(\tilde{g}) = 507\,\mathrm{GeV/c^2}$, hence $\tilde{g} \rightarrow$ 3-body is dominant
  - $B(\tilde{\chi}_2^0 \rightarrow ll\tilde{\chi}_1^0) = 6.5\%$, $B(\tilde{\chi}_1^{\pm} \rightarrow \nu l\tilde{\chi}_1^0) = 22\%$
- Point LM10 :
  - Similar to LM7, but heavier gauginos.
  - Very heavy squarks, outside reach, but light gluino.
  - $m(\tilde{g}) = 1295\,\mathrm{GeV/c^2}$, hence $\tilde{g} \rightarrow$ 3-body is dominant
  - $B(\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_4^0) = 11\%$, $B(\tilde{g} \rightarrow tb\tilde{\chi}_2^{\pm}) = 27\%$

Other benchmark points

- SPS1: bulk region

  m0 = 100 GeV, m1/2 = 250 GeV,

  tan = 10, A = 100 GeV, sign mu > 0

(Baltz, Battaglia, Peskin, Wizansky 2006, page 25)

Point	m_0	$m_{\frac{1}{2}}$	$\tan\beta$	A_0	sign mu	m_t	reference	$\Omega_\chi h^2$
LCC1	100	250	10	−100	+	175	[86]	0.192
LCC2	3280	300	10	0	+	175	[87]	0.109
LCC3	213	360	40	0	+	175	[88]	0.101
LCC4	380	420	53	0	+	178	[90]	0.114
SPS1a′	70	250	10	−300	+	175	[91]	0.115

Table 1: mSUGRA parameter sets for four illustrative models of neutralino dark matter. Masses are given in GeV. The table also lists the value of $\Omega_\chi h^2$. The references given are the primary references for simulation studies of the accuracy of spectrum measurements at colliders. The point SPS1a′ has a phenomenology similar to that of LCC1 but gives a more correct value of the relic density.

e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$. The sleptons are not quite light enough; the spectrum achieves a relic density $\Omega h^2 = 0.19$, almost doubly the WMAP value. Point LCC2 is chosen as a point with substantial gaugino-Higgsino mixing at which the neutralino annihilation is dominated by annihilation to W^+W^-, Z^0Z^0, and Z^0h^0. Point LCC3 is chosen in the region where coannihilation with the $\tilde{\tau}$ plays an important role. Point LCC4 is chosen in a region where the A^0 resonance makes an important contribution to the neutralino annihilation cross section.

Cross sections for direct detection

		LHC	ILC-500	ILC-1000	LHC (mean)	ILC-500	ILC-1000
	Ωh^2						
LCC1	0.192	7.2%	1.8%	0.24%			
LCC2	0.109	82.%	14.%	7.6%	0.074		
LCC3	0.101	167%	50.%	18.%	0.24		
LCC4	0.114	405%	85.%	19.%	0.26	0.083	0.094
	σv				(mean)		
LCC1	0.0121	165.%	54.%	11.%	0.0069		
LCC2	0.547	143.%	32.%	8.7%	8.47		
LCC3	0.109	154.%	178.%	10.%	24.2	0.311	
LCC4	0.475	557.%	228.%	20.%	82.5	1.83	0.57
	$\sigma(\chi p)$				(mean)		
LCC1	0.418	44.%	45.%	5.7%	0.20		
LCC2	1.866	62.%	63.%	22.%	3.57	2.82	2.19
LCC3	0.925	184.%	146.%	8.6%	13.2	1.86	
LCC4	1.046	150.%	190.%	7.5%	23.2	3.59	

Table 11: Fractional errors in the determination of the most important microscopic WIMP parameters derived from the MCMC scans: Ωh^2, the predicted relic density, σv, the annihilation cross section at threshold (in pb), and $\sigma(\chi p)$, the spin-independent neutralino-proton cross section (in units of 10^{-8} pb). The second column lists the values predicted by the benchmark models. Columns 3–5 give the fractional error (σ/mean) from the MCMC scans. Columns 6-8 give the mean value found from the MCMC data when this deviated by more than 10% from the nominal value in column 2. As discussed in Appendix A, the quoted errors are accurate to 10% or better, e.g. a 20% error is $20\% \pm 2\%$.

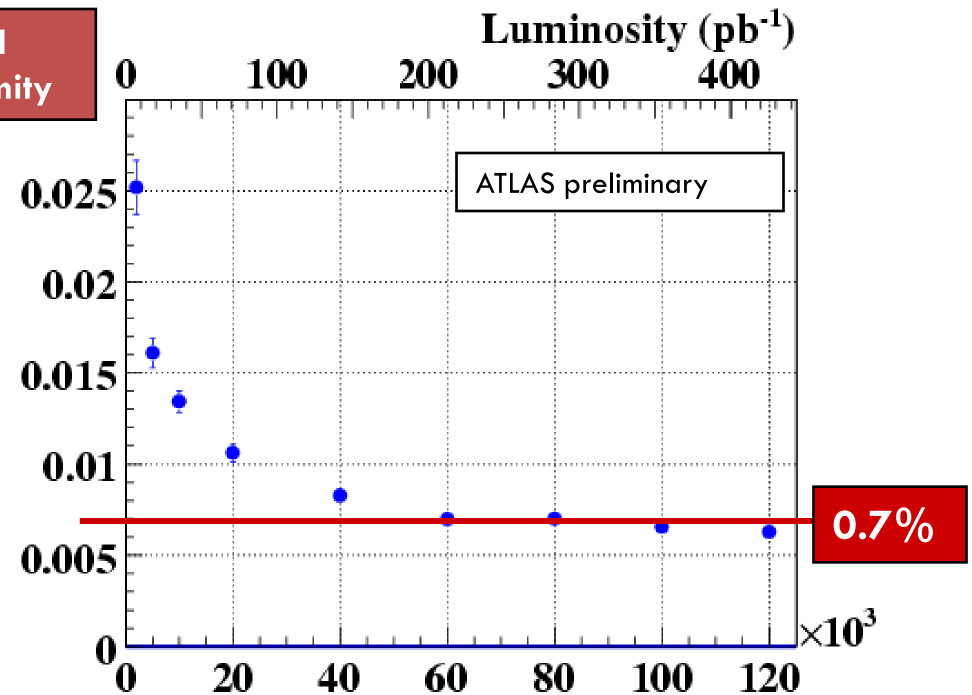
(Baltz, Battaglia, Peskin, Wizansky)

Expected ATLAS performance on "Day-1"

(examples based on test-beam, simulation, and cosmics results)

	Initial Day-1	Ultimate goal	Physics samples to improve(examples)
ECAL uniformity	~2.5%	0.7%	Isolated electrons, $Z \to ee$
e/γ E-scale	2-3%	<0.1%	J/ψ, $Z \to ee$, E/p for electrons
Jet E-scale	5-10%	1%	γ/Z + 1j, $W \to jj$ in tt events
ID alignment	20-200 μm	5 μm	Generic tracks, isolated μ, $Z \to \mu\mu$
Muon alignment	40-1000 μm	30 μm	Straight μ, $Z \to \mu\mu$

Overall uniformity



Number of $Z \to ee$ events

ECAL uniformity:

- local uniformity by construction/test: 0.5%
- residual long-range non-uniformities (upstream material, etc.): ~ few percent
  → use Z-mass constraint to correct
  ~ 10^5 $Z \to ee$ events enough to achieve the goal response uniformity of ~ 0.7%

Inclusive SUSY searches

Example : jets + 0 lepton channel baseline channel

Main backgrounds for 0 lepton search

QCD : missing PT due to jet mis-measurements and jet resolutions

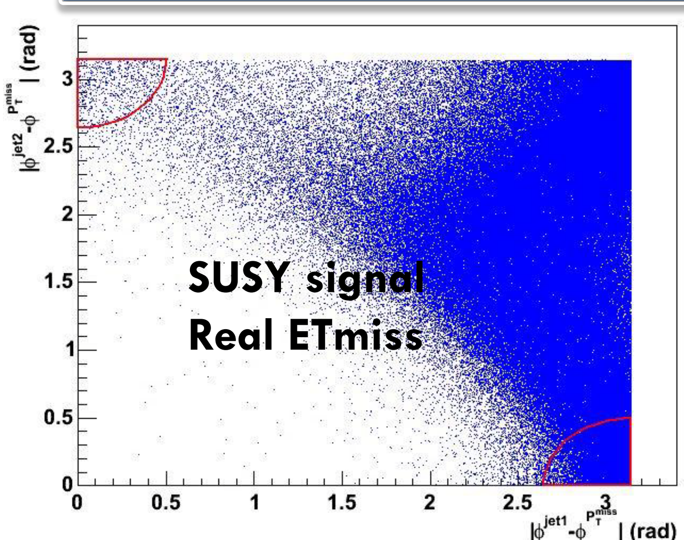
Z → neutrinos : irreducible, we need to measure

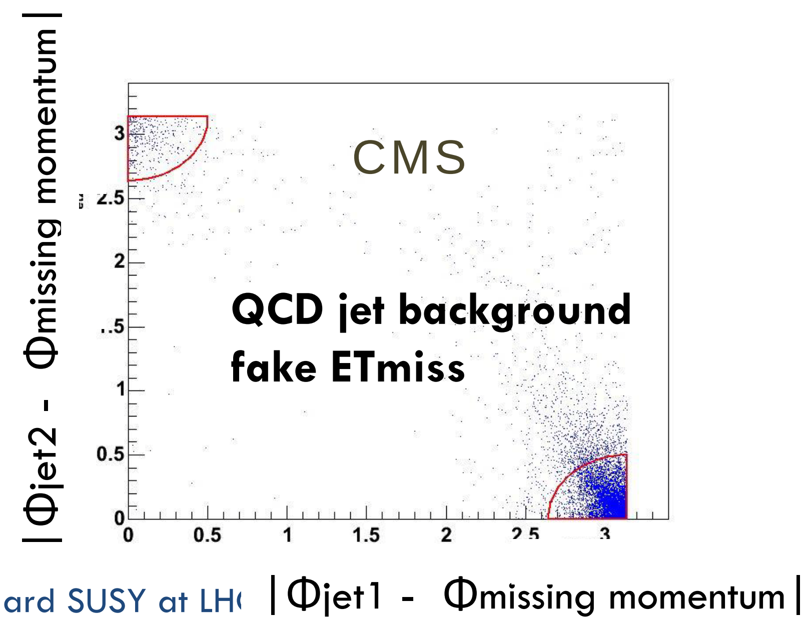
Top : 1 or 2 leptons not identified

W : 1 lepton not identified

QCD background reduction and control

Clean-up cuts against fake E_T^{miss}





Control Measurements

- 1 leptons + 2/3/4 jets + large missing E_T

ATLAS:
control region with M_T < 100 GeV
Here we have more SM events than new physics signal

effective mass distribution in control region can be used to predict distribution in signal region (M_T > 100 GeV)