LHC signals for SUSY discovery and measurements

Vasiliki A. Mitsou
(for the ATLAS and CMS Collaborations)
IFIC Valencia

PROMETEO I: LHC physics and cosmology
2-6 March, 2009
Department of Theoretical Physics, University of Valencia, Spain

Outline

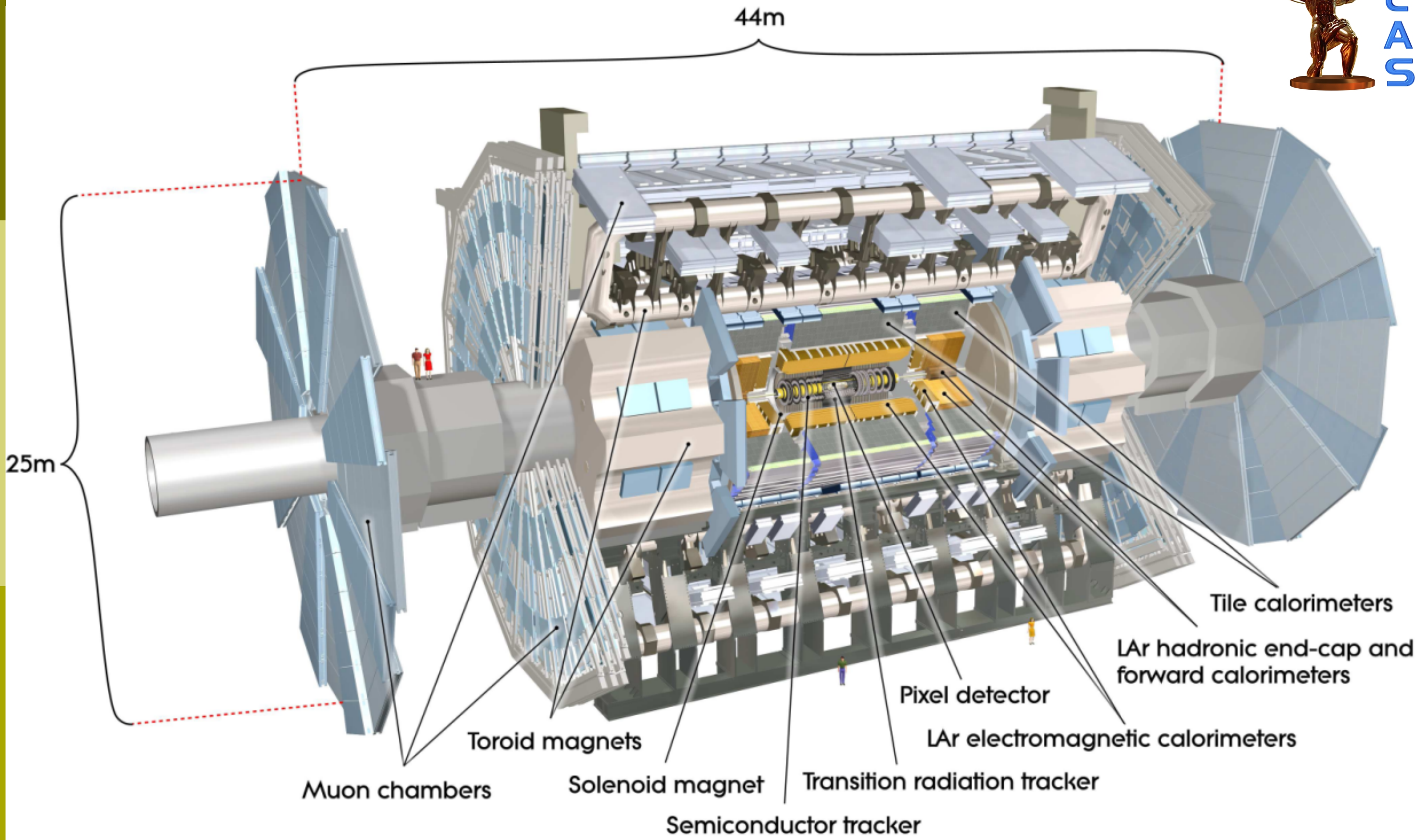
- Introduction
  - ATLAS & CMS detectors
  - Supersymmetry: motivation, framework, final states …
- LHC discovery potential
  - Background estimation from data
  - Inclusive signatures
  - Discovery reach
  - MSSM Higgs bosons
  - Long-lived particles
- SUSY measurements
  - End-point measurements
  - Spin determination
- Summary & outlook

Most studies presented here include:
- realistic detector geometry
- residual misalignments
- trigger efficiency

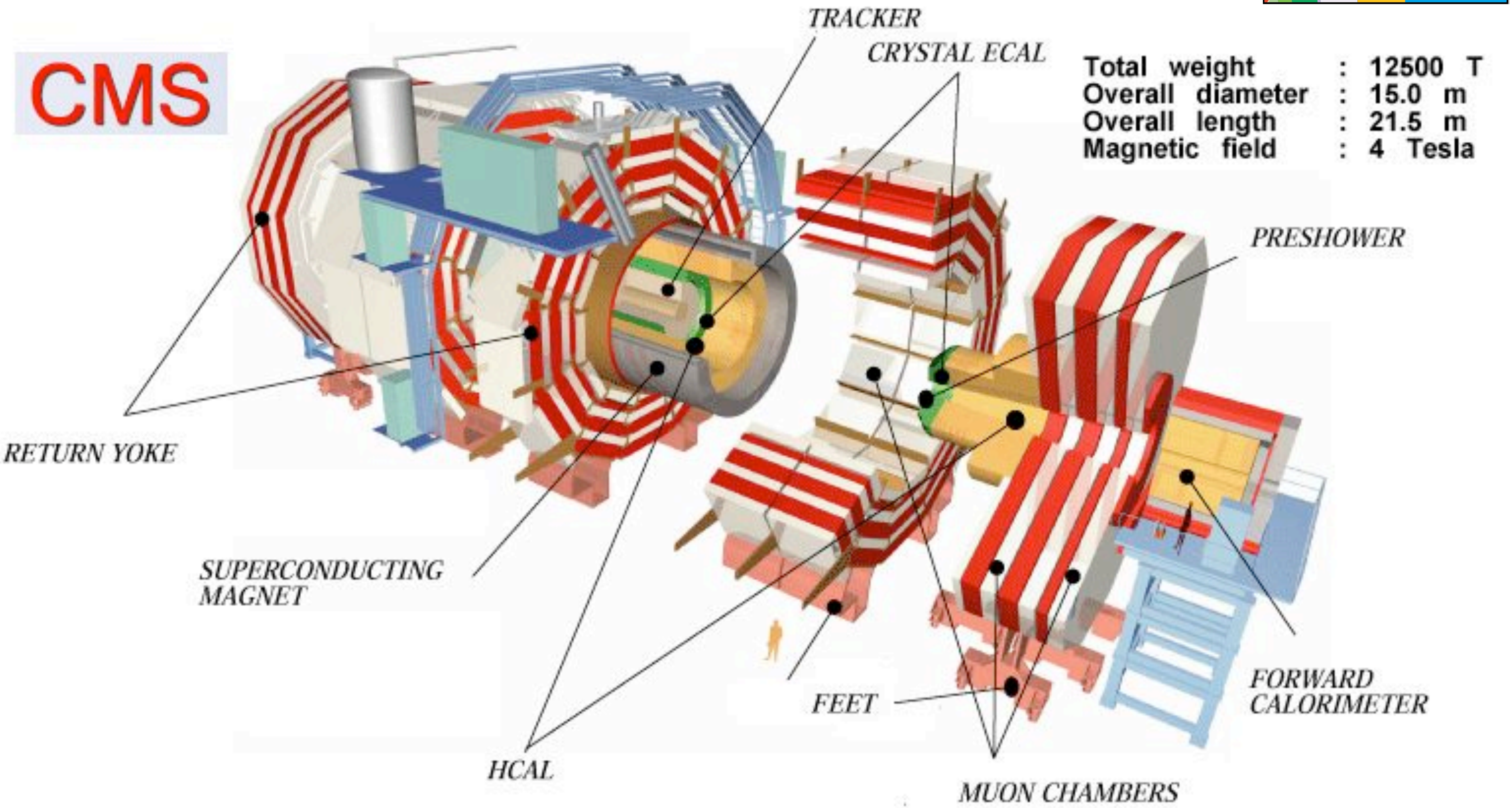
References

- CMS Collaboration, G.L. Bayatian et al, J. Phys. G, 34 (2007) 995
- ATLAS Collaboration, G. Aad et al, CERN-OPEN-2008-020 (2008) [arXiv:0901.0512]

The ATLAS detector

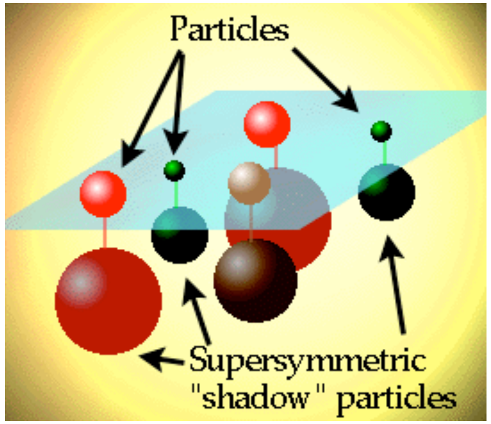


The CMS detector

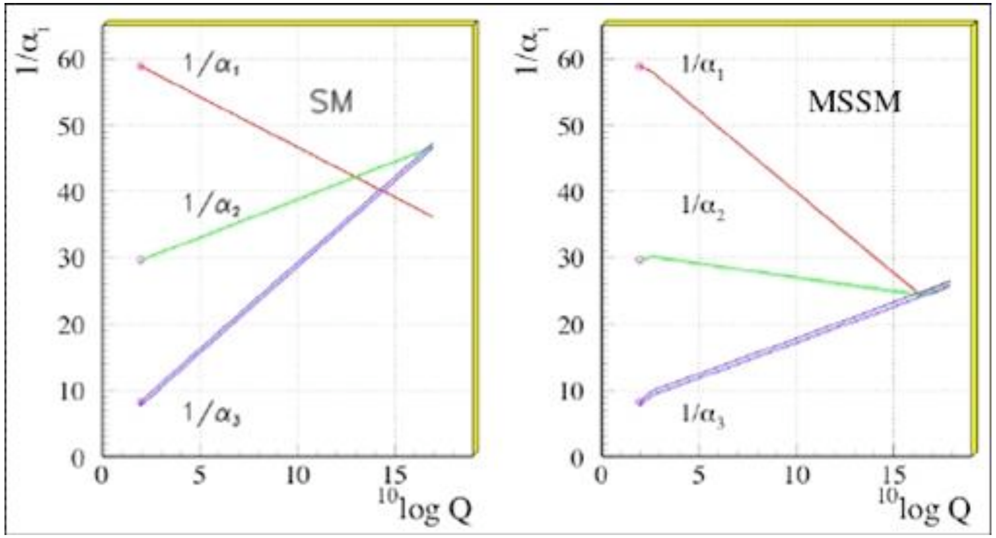


Supersymmetry (SUSY)

- Supersymmetry := fundamental global symmetry between fermions-bosons
  - all SM particles have SUSY-partners with spin difference of ±1/2



- Theoretical motivation
  - Higgs mass stabilisation against loop corrections (fine-tuning problem)
  - SUSY modifies running of SM gauge couplings 'just enough' to give Grand Unification at single scale
  - May explain Dark Matter
- Masses of SM states & SUSY partners cannot be degenerate in mass
  - Not observed
    ➔ SUSY must be a broken symmetry at low energy
  - Various possible SUSY SB mechanisms proposed



SUSY particle spectrum

(□ = super-partners)

spin $\frac{1}{2}$	spin 0	spin 1	spin $\frac{1}{2}$
quark $q_L,\ q_R$ lepton $\ell_L,\ \ell_R$	squark $\tilde{q}_L,\ \tilde{q}_R$ slepton $\tilde{\ell}_L,\ \tilde{\ell}_R$	W_3, B $W^{\pm}$	$\tilde{W}_3,\ \tilde{B}$ $\tilde{W}^{\pm}$
higgsino $\tilde{H}_1,\ \tilde{H}_2$	Higgs $H_1,\ H_2$	gluon g	gluino $\tilde{g}$

graviton (spin 2) $\leftrightarrow$ gravitino (spin 3/2)

charginos

$\tilde{W}^{\pm},\ \tilde{H}^{\pm} \Longleftrightarrow \tilde{\chi}_1^{\pm},\ \tilde{\chi}_2^{\pm}$

$\tilde{B},\ \tilde{W}_3,\ \tilde{H}_1,\ \tilde{H}_2 \Longleftrightarrow \tilde{\chi}_1^0, \ldots, \tilde{\chi}_4^0$

neutralinos

- *R*-parity: $R = (-1)^{3(B-L)+2s} \rightarrow R = \begin{cases} +1, \text{ for SM particles} \\ -1, \text{ for superpartners} \end{cases}$
  - *R*-parity conservation hinted by *not required* by proton stability
  - not a fundamental symmetry
- If *R*-parity is conserved:
  - SUSY-partners are always produced in pairs (*R* is a multiplicative quantum number)
  - Lightest SUSY-particle (LSP) is stable
    - should be colorless and neutral
    - weakly interacting → escapes the detector undetectable → *large missing energy*
    - dark matter candidate

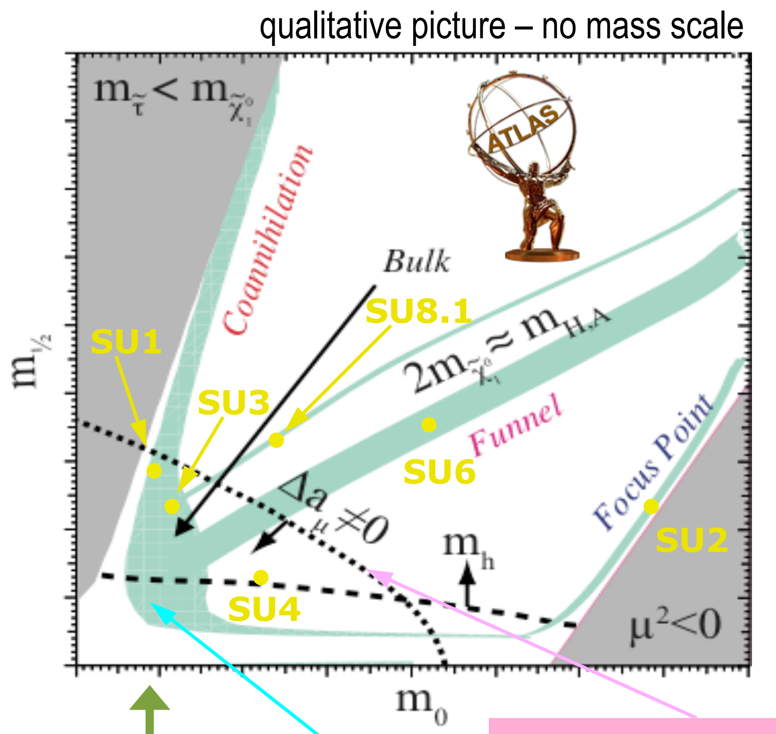
PART I

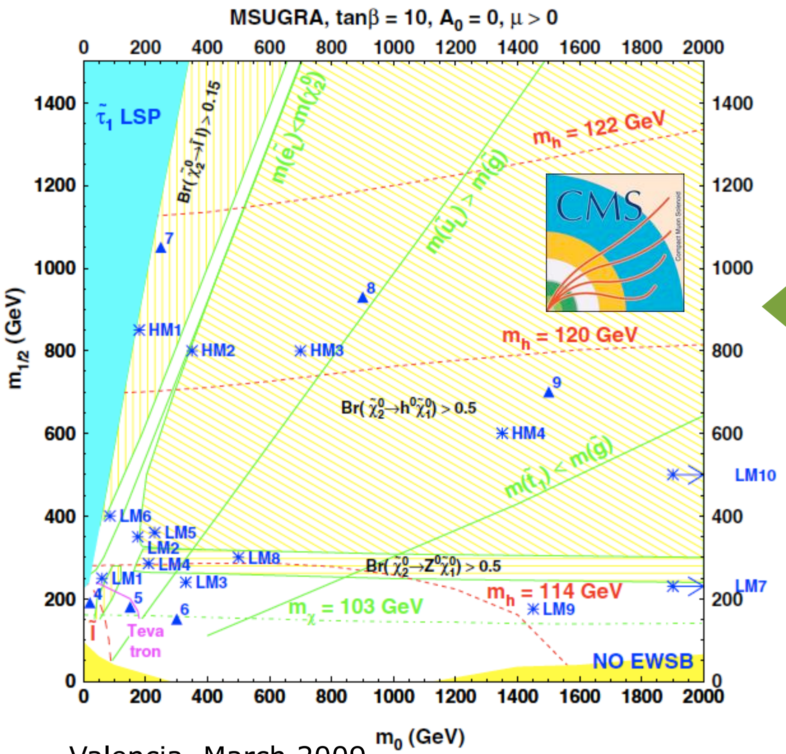
Discovering Supersymmetry

SUSY model framework

- Minimal SuperSymmetric Standard Model (MSSM) contains >100 free parameters
  → assume specific physically-motivated model (∋ gravity) for systematic studies
- Simplest: minimal SuperGravity (mSUGRA)
  - local SUSY with soft breaking mediated by gravitational interactions
  - universal masses and couplings at GUT scale
    → 5 free parameters: m_0, $m_{1/2}$, $\tan\beta$, A_0, $\mathrm{sgn}(\mu)$

qualitative picture – no mass scale





Benchmark points for detailed studies

$(g-2)_\mu$ measurements

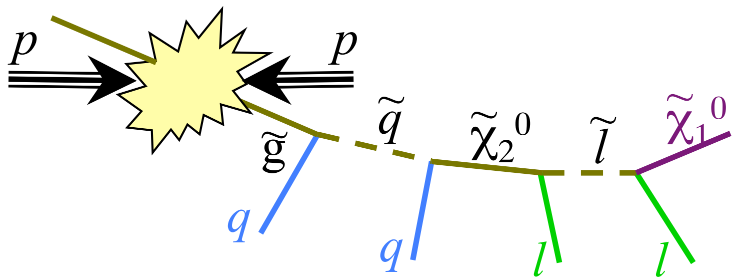
WMAP constraints on neutralino relic density

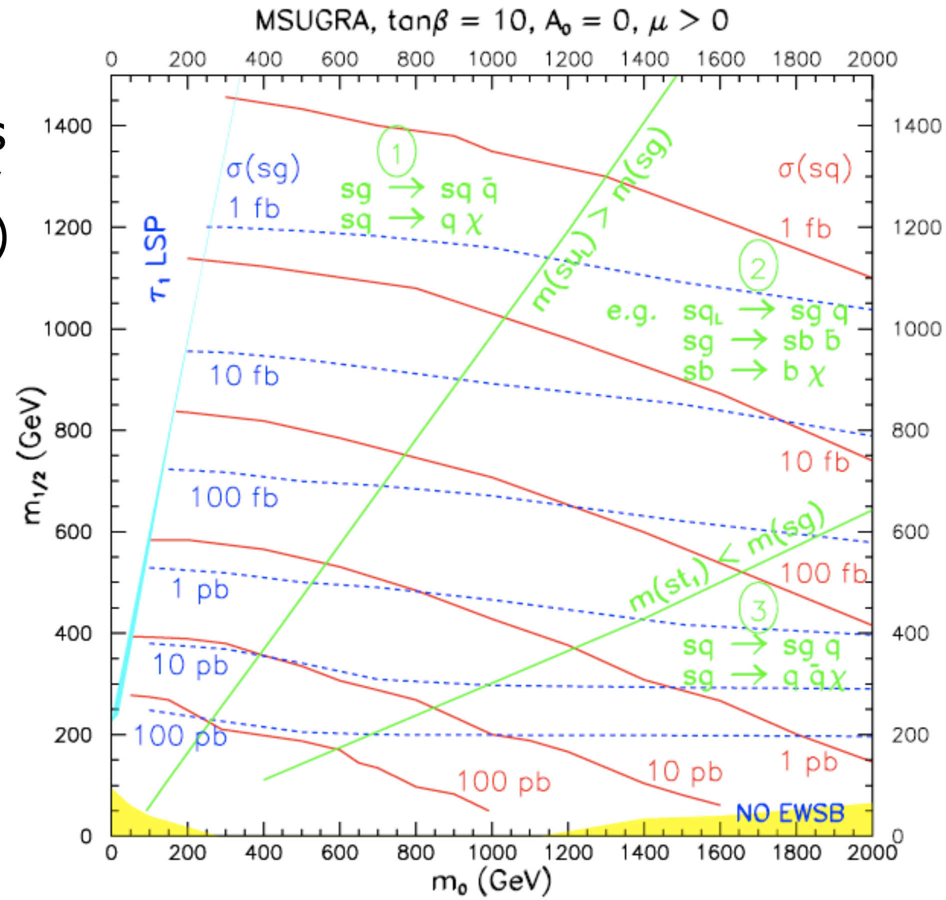
Other models also investigated
(not presented here)

- **GMSB**: gauge messengers; light gravitino LSP
- **AMSB**: anomalies in SUGRA $\mathcal{L}$; no flavour problem

SUSY signature at LHC

- SUSY search is one of the major topics for LHC
- Focus on the early SUSY searches ~1 fb^{-1}: one year running at very low luminosity (10^{31}–10^{32} $cm^{-2}s^{-1}$)
- Relatively large cross sections
- Strongly interacting sparticles (squarks, gluinos) dominate production
- Long cascade decay into the LSP: e.g. lightest neutralino, $\tilde{\chi}_1^0$





CMS Coll., J. Phys. G, 34 (2007) 995

- **'Golden discovery channel'** **multi jets + missing E_T + (leptons)**
- Other modes also studied: photons, tau leptons, b-jets

Strategy for SUSY searches @ LHC

- Model independent (as possible)
  - theoretically complicated
    - MSSM has > 100 parameters
    - many scenarios: mSUGRA, GMSB, AMSB, …
    - multi-dimensional parameter space: m_0, $m_{1/2}$, $\tan\beta$, …
  - experimentally rather simple
    - → search for multi-jets, large missing E_T and possibly high-p_T leptons
- Data-driven as possible
  - SUSY searches performed with early data at the LHC
    - poor understanding of detector (jet energy scale, fake missing E_T, …)
    - large uncertainty of SM backgrounds, especially in signal region
  - → try to estimate dominant background sources using real data wherever possible, instead of believing Monte Carlo estimates

Main SM background

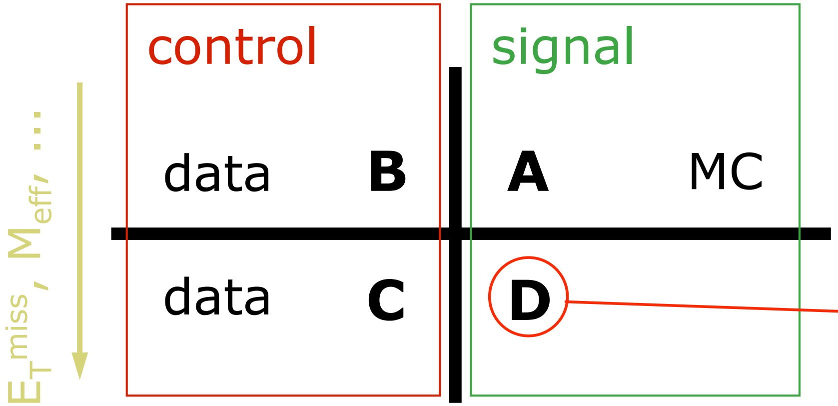
- top-antitop pairs
- W+jets
- Z+jets
- QCD jets
- diboson processes (ZZ, WW, WZ)

Baseline SUSY cuts

- At least 2 high-p_T jets
- High missing E_T
  - typically > 100 GeV
  - also > 0.2 M_{eff}
- High transverse sphericity (> 0.2)
- Leptons
  - either lepton veto
  - or exactly 1 or 2 leptons

Background estimation from data

General aim: estimate bkg in a `control' sample and propagate' this measurement to the `signal' sample



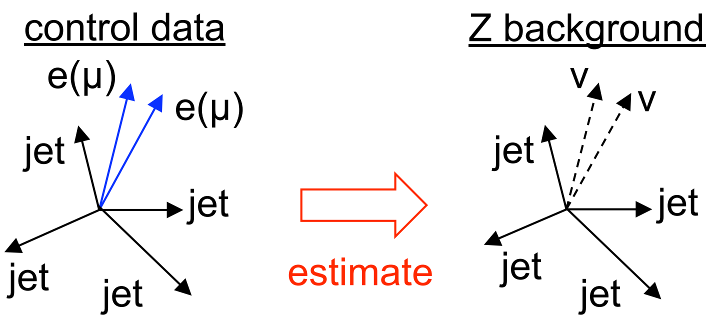
- Control region should be as close as possible to signal region
- SUSY contamination should be as low as possible

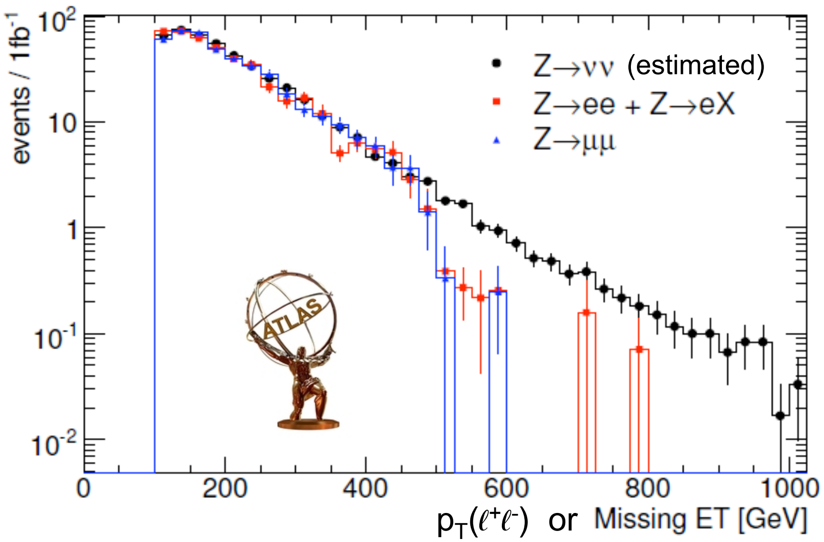
D = A × C/B

normalisation to data

Replace method in no-lepton mode

- estimate E_T^{miss} distribution of $Z \to \nu\nu$ from $p_T(\ell^+\ell^-)$ distribution of $Z \to \ell^+\ell^-$
- apply corrections for lepton reconstruction efficiency and coverage, additional cuts, …





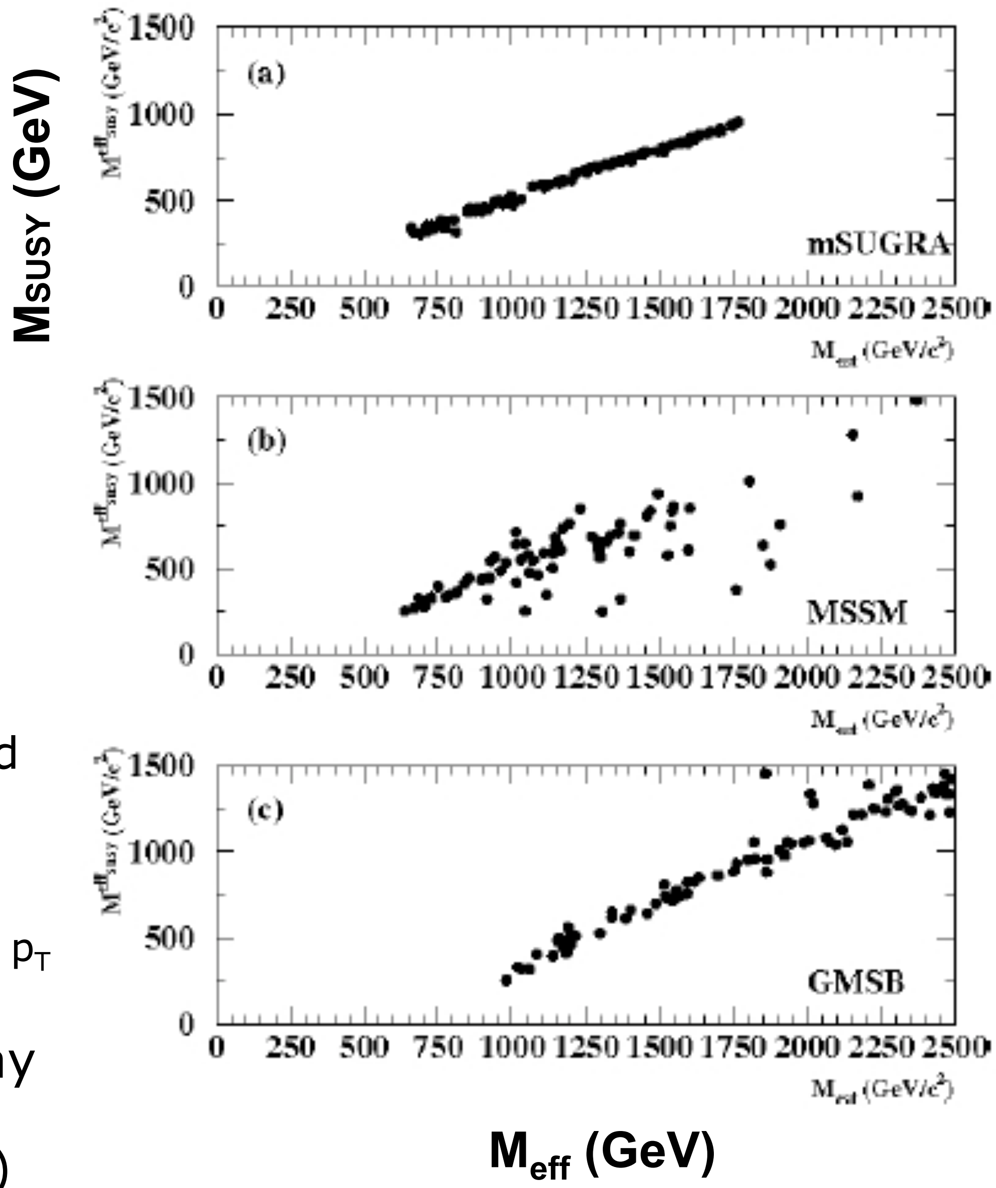
ATLAS Coll, arXiv:0901.0512 (2008)

SUSY mass scale versus M_{eff}

- SUSY mass scale, M_{SUSY} := average of squark and gluino masses

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

- M_{eff} peak strongly correlated to the SUSY mass scale
- Measurement of M_{SUSY} feasible with 10 fb^{-1}
  - 15% precision for mSUGRA
  - 40% precision for MSSM
  - also possible for GMSB with rapid decays to gravitino LSP
    - significantly increased statistics needed
    - *or* variables using photon or lepton p_T
- Total SUSY cross section, σ_{SUSY}, can be estimated in a similar way with 10 fb^{-1} with a precision of 15% (50%) in mSUGRA (MSSM)



D R Tovey, PLB 498 (2001) 1

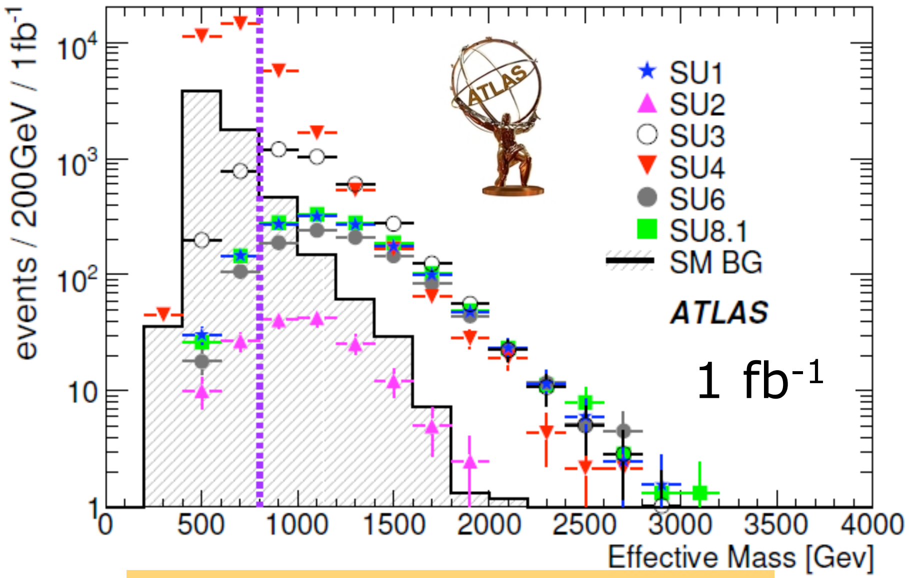
Inclusive search channels

- Lepton multiplicity exclusive (ATLAS) or inclusive (CMS)
- Inclusive in jet multiplicity
- **High missing transverse momentum (> 80-200 GeV)**

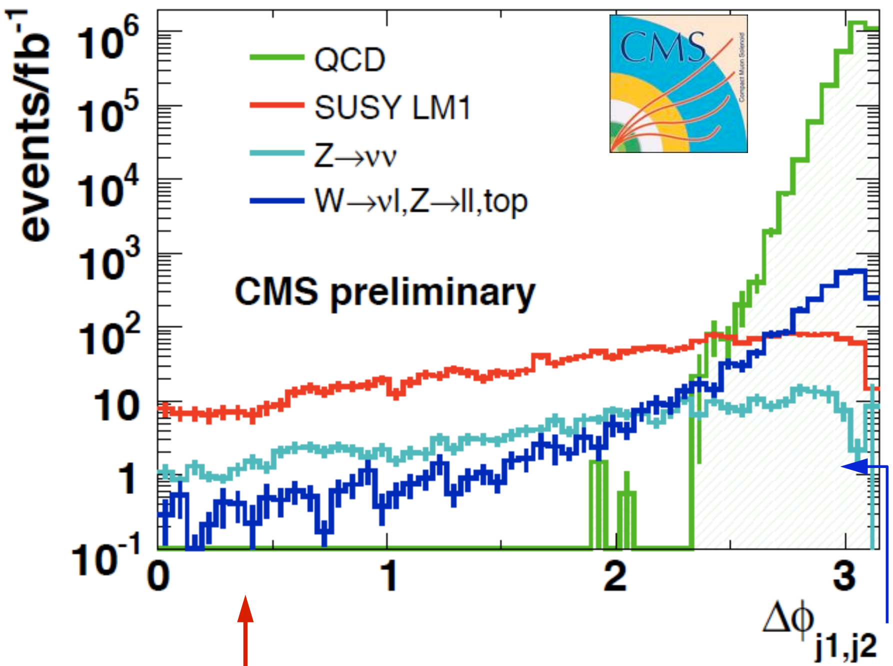
	No jets	1 jet	2 jets	3 jets	4 jets
lepton veto		split SUSY	✔	✔	✔
1 lepton			✔	✔	✔
2 leptons	LFV	LFV	✔	✔	✔
3 leptons	✔	✔			
tau(s)			✔	✔	✔
b-jets			✔	✔	✔
photons			✔	✔	✔

✔ : signatures studied by ATLAS and/or CMS

All-hadronic signature



ATLAS Coll, arXiv:0901.0512 (2008)



CMS Coll., note CMS-PAS-SUS-08-005 (2008)

ATLAS cuts

E_T^{miss} + 4 jets

- **Veto on electrons & muons**
- $\Delta\varphi(E_T^{miss}, jet_{1\text{-}3}) > 0.2$ against mismeasured jets (QCD bkg)
- at least 4 jets with $p_T > 50$ GeV
- $p_T(jet_1) > 100$ GeV
- $E_T^{miss} > \max(100 \text{ GeV}, 0.2M_{eff})$
- transverse sphericity $S_T > 0.2$

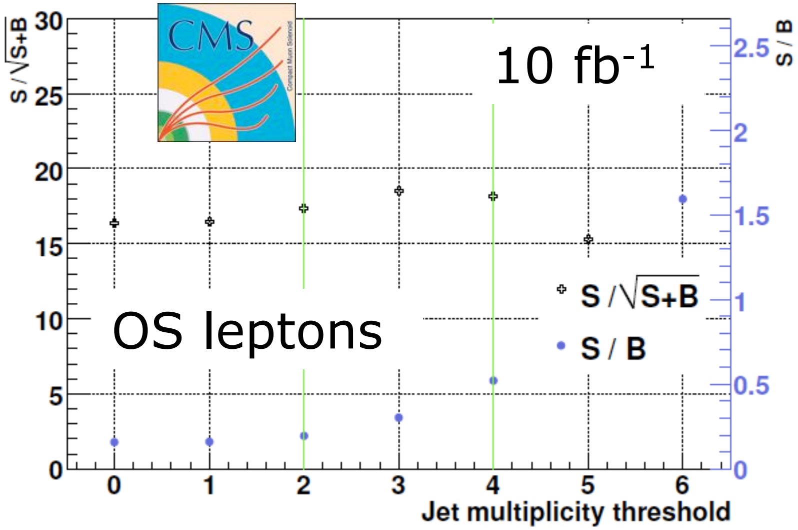
Clear excess of events is visible with 1 fb^{-1}

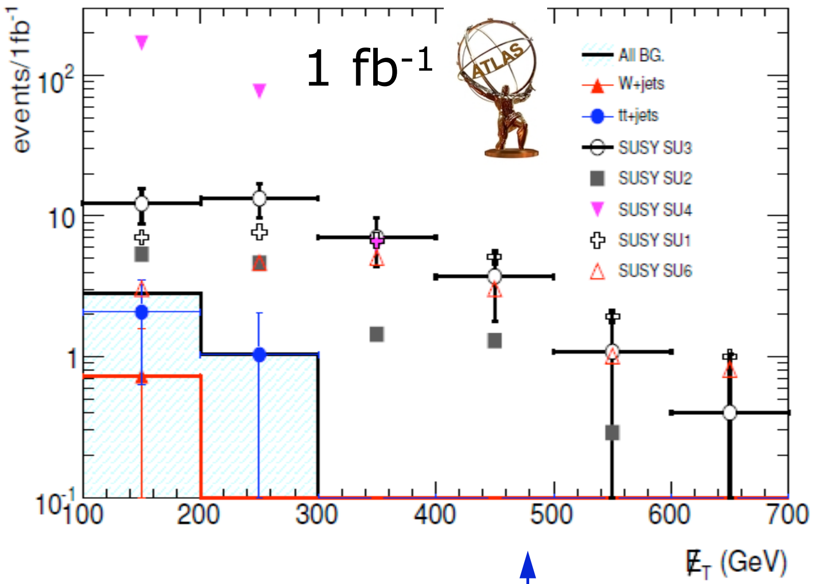
CMS: Further E_T^{miss} clean-up and QCD rejection cuts are applied

Di-leptons plus jets

- Opposite-sign (OS) and same-sign (SS) leptons (e or μ)
- Same flavour and different flavour (lepton flavour violation)

CMS Coll, noteCMS-PAS-2008/038 (2008)





ATLAS Coll, arXiv:0901.0512 (2008)

CMS: SS muons, 10 fb^{-1}

Sample(s)	Events	Signif.	Sample	Events	Signif.	Sample	Events	Signif.
SM	1.5	–	LM5	61	14.0	LM10	4	2.2
LM1	341	>37.0	LM6	140	22.3	HM1	4	2.2
LM2	94	17.6	LM7	82	16.3	HM2	2	1.1
LM4	90	17.2	LM8	294	35.9			

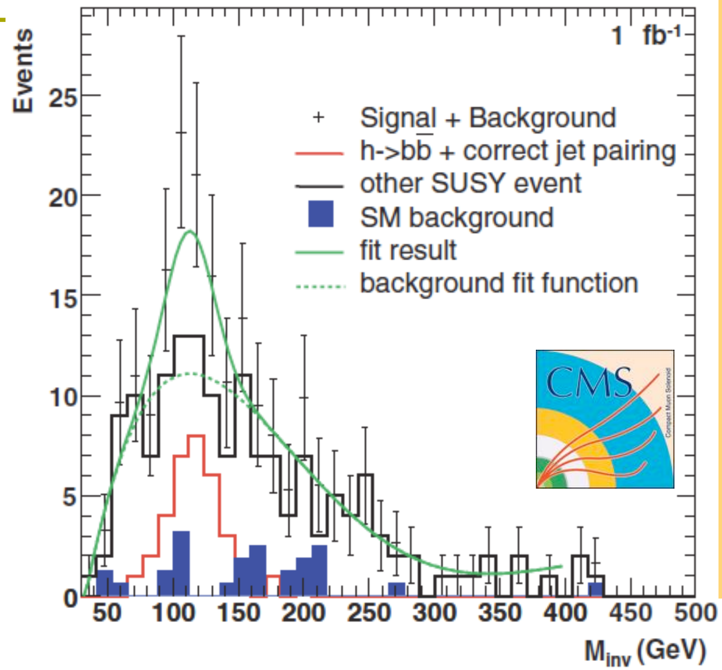
CMS Coll., J. Phys. G, 34 (2007) 995

ATLAS cuts

MET + 2 SFSS leptons + 4 jets
- Exactly two isolated **leptons** with p_T > 20 GeV
- at least 4 jets with p_T > 50 GeV
- $p_T(jet_1)$ > 100 GeV
- E_T^{miss} > max(100 GeV, 0.2M_{eff})
- transverse sphericity S_T > 0.2

Other modes: b-jets, taus, …

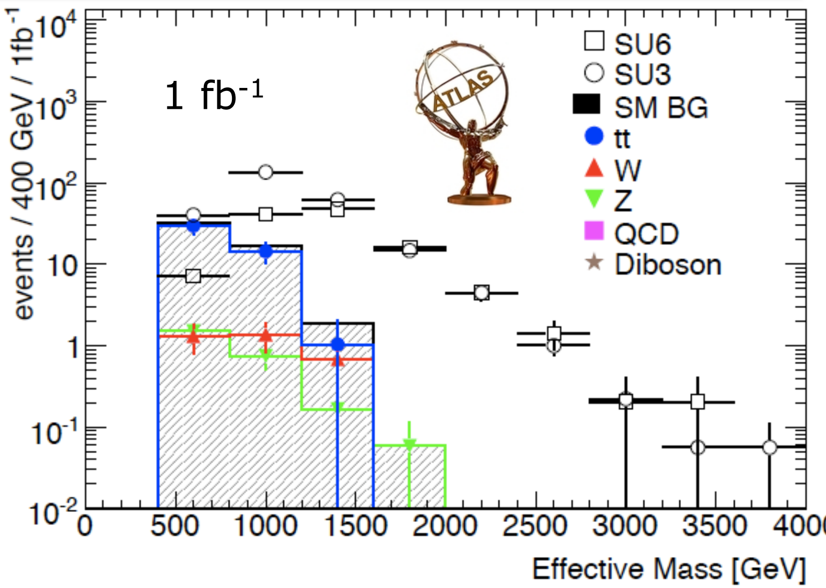
- CMS: h➔bb in cascade decay
- Crucial: b-tagging performance
  - mean efficiency 50%
  - mis-tagging: 1.6% (12%) for u,d,s,g (c-quarks)
- Hemisphere technique applied to reduce combinatorial bkg
- Higgs mass measured: ±7.5 GeV



CMS Coll., J. Phys. G, 34 (2007) 995

- ATLAS: ≥1 τ + 4 jets + E_T^{miss}
- τ reconstruction efficiency estimated from real data by replacing e or μ

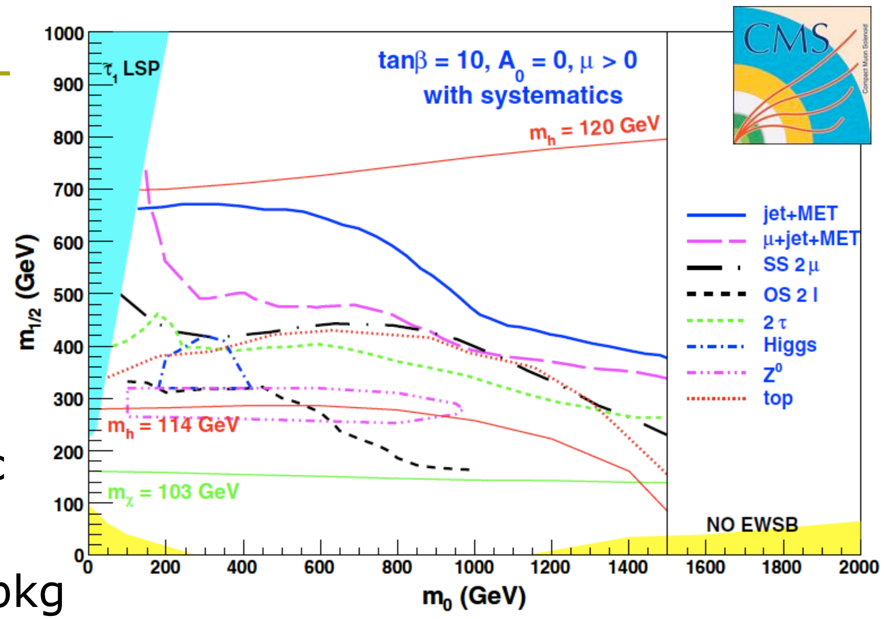
Sample	S	B	S/B	$S/\sqrt{B}$	Z_n
SU3	259	51	5.1	36.3	12
SU6	119	51	2.3	16.7	6.8



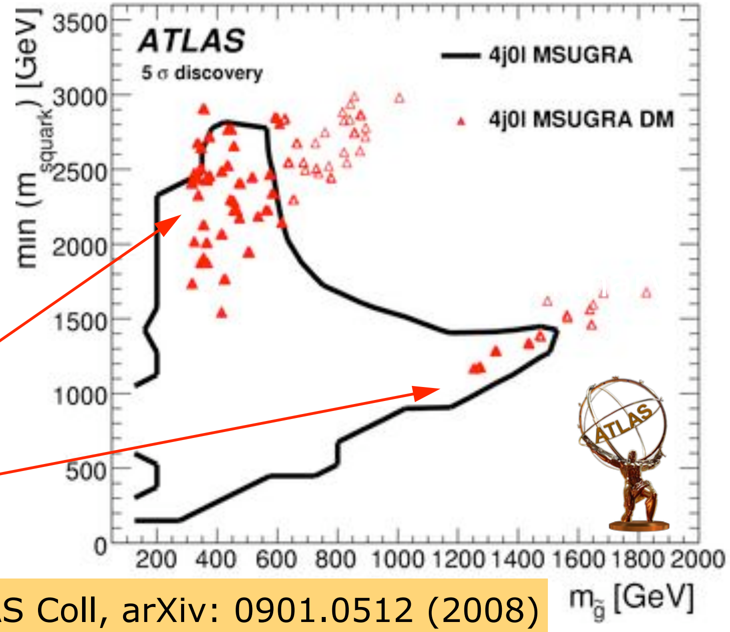
ATLAS Coll, arXiv:0901.0512 (2008)

Discovery reach @ 1fb^{-1}

- **Search for:**
  ***m* jets + E_T^{miss} (+ *n* leptons)**
- Sensitivity only weakly dependent on tanβ, A_0 & sgn(μ)
- Best reach achieved with 0-lepton mode
- Significance takes into account systematic uncertainties on bkg estimation
- 1-lepton mode more robust against QCD bkg
- **SUSY @ 2 TeV is accessible with 1 fb^{-1} (1 year of data taking)**
  - **result independent of chosen model (mSUGRA, AMSB, …)**
- Caveat: excess of events is not enough
  - possibly other physics beyond the Standard Model
  - further precision measurements required



CMS Coll., J. Phys. G, 34 (2007) 995



Random mSUGRA points compatible with various constraints (dark matter, $(g-2)_\mu$, …)

ATLAS Coll, arXiv: 0901.0512 (2008)

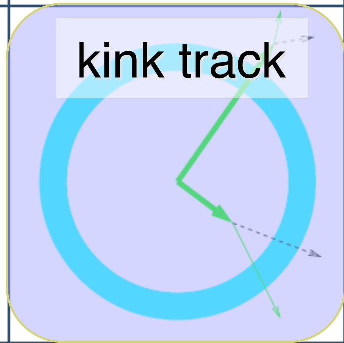
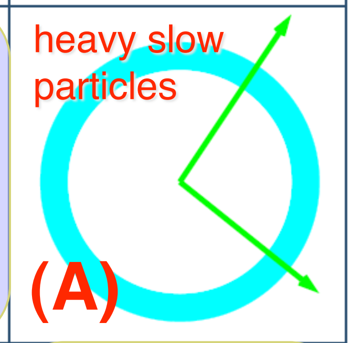
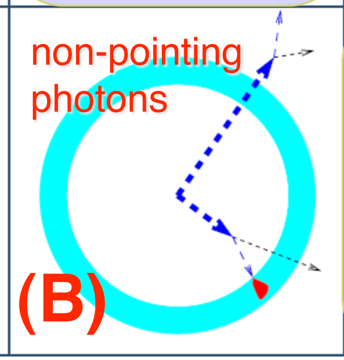
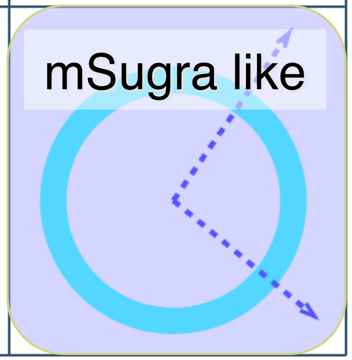
Long live the sparticle…

- Long-lived particles ≡ they live long enough to pass through detector or decay in it
- Predicted in many SUSY scenarios (GMSB, RPV, …) and not only!...
- Regardless of the model, categorised by event signature
  - Charge: electric? magnetic? colour?
  - Decay length?

Two general cases:

A. Sleptons, R-hadrons
   (heavy slow particles)
   - large ionisation energy loss
   - nuclear int. (R-hadron case)
   - delay (TOF) reconstructed in muon chambers

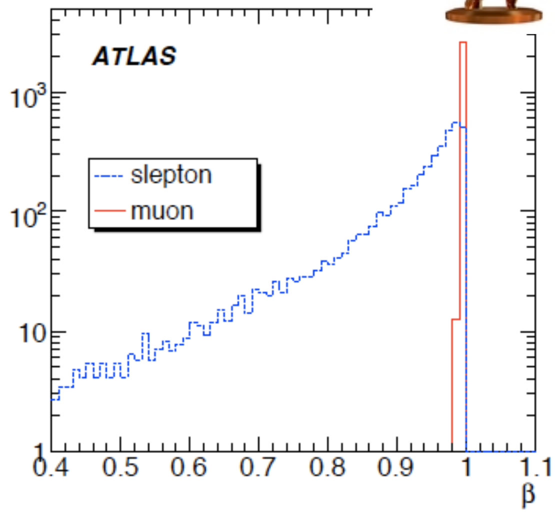
B. Long-lived neutralino
   (non-pointing photon)
   - decay vertex is somewhere in the inner tracker volume

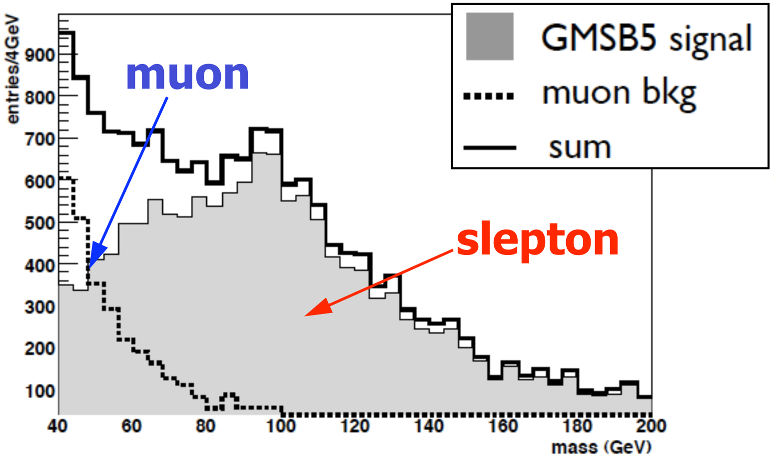
	$c\tau \simeq$ det. size	$c\tau >>$ det. size
$\tilde{\ell} \to \tilde{G}\ell$ $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 \pi^{\pm}$ R-hadrons		
$\tilde{\chi}_1^0 \to \tilde{G}\gamma$		

see e.g. Fairbairn *et al*, Phys Rept **438** (2007) 1 [hep-ph/0611040]

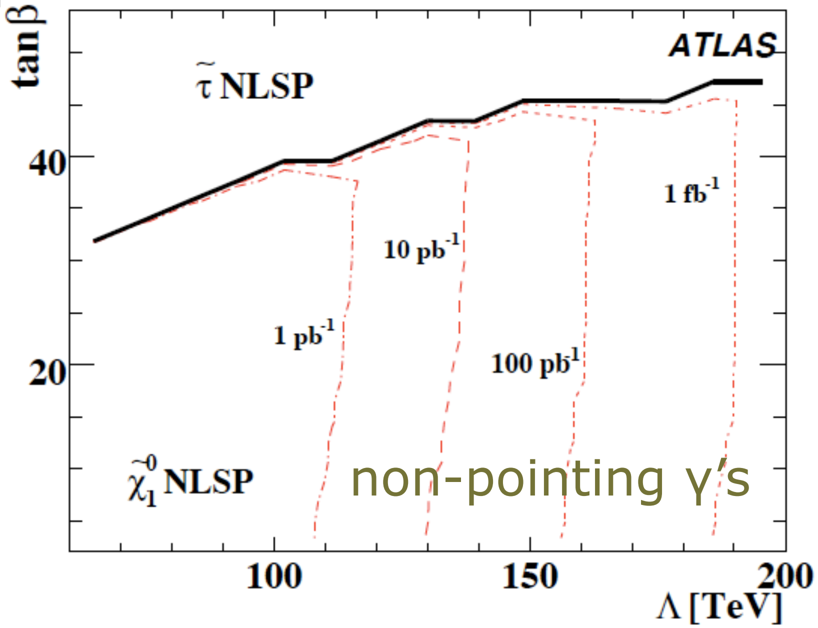
GMSB: sleptons & neutralinos

- **Slepton NLSP** couples weakly to gravitino
  -> long lifetime
- Detected as heavy, slow-moving muons
- Preselection of slepton-like events at trigger level
- β measurement: fast calculation with good resolution in the muon system





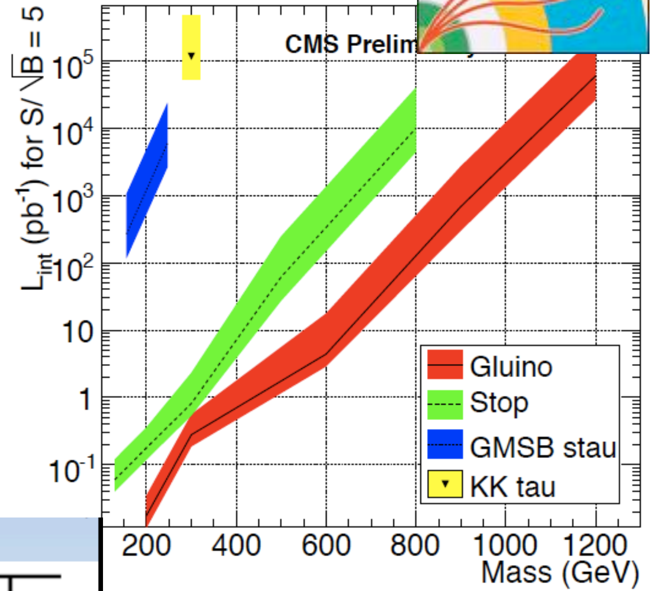
- **Neutralino NLSP** $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$
- Selection:
  - one or two non-pointing photons
  - two OS leptons (slepton decay)
  - high E_T^{miss} (gravitinos)



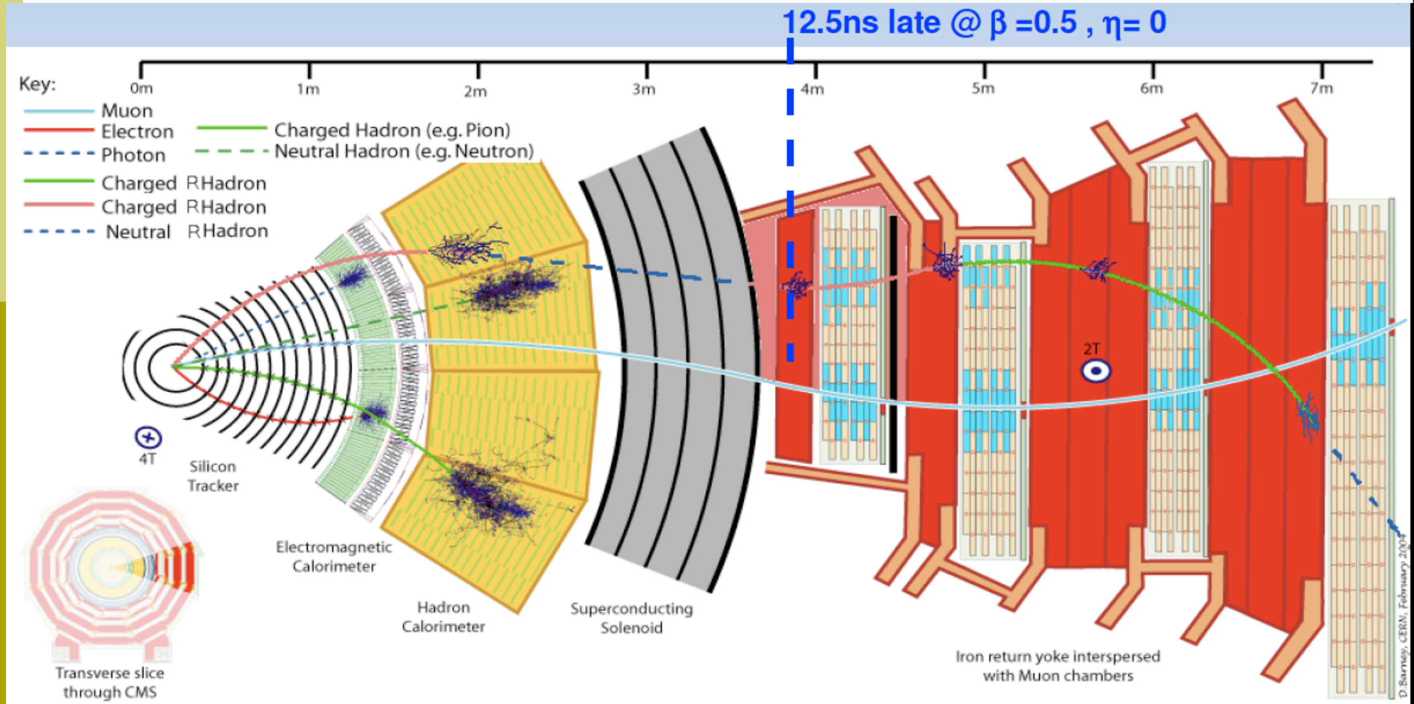
ATLAS Coll, arXiv: 0901.0512 (2008)

R-hadrons

- Massive exotic meta-stable hadrons, formed by gluinos or stops
- Split SUSY: if the gluino lifetime is long enough, it will hadronise forming an R-hadron
- Charge can change (`flip') in hadronic interactions with matter while crossing the detector
  -> unique signature
- Main background: cosmic muons



CMS Coll, note CMS-PAS-EXO-08-003 (2008)



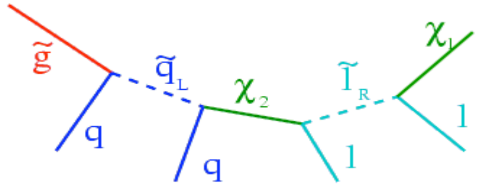
R-meson: $\tilde{g}q\bar{q}$
R-baryon: $\tilde{g}qqq$
R-Gluino-ball: $\tilde{g}g$

Mesino: $\tilde{t}\bar{q}$
Sbaryon: $\tilde{t}qq$

PART II

SUSY Measurements

Exclusive studies



- SUSY events contain two LSPs which escape the detector
  - reconstruction of mass peaks impossible
- Mass measurement strategy
  - apply kinematics on long decay chains to link endpoints with combinations of masses
  - measure endpoints (edges, thresholds) in invariant mass distributions
- $\tilde g, \tilde b_1, \tilde b_2$ masses: near di-lepton endpoint
- $\tilde\chi_1^0, \tilde\chi_2^0, \tilde l_R, \tilde q_L, \tilde q_R$ masses: kinematic endpoints and stransverse mass M_{T2} (variant of M_T for two-body decays)
- Comments:
  - cuts applied depend on the SUSY mass scale; has to be known from M_{eff} distribution
  - method does not depend on underlying model (pure kinematics)

Related edge	Kinematic endpoint
l^+l^- edge	$(m_{ll}^{max})^2 = (\tilde\xi - \tilde l)(\tilde l - \tilde\chi)/\tilde l$
l^+l^-q edge	$(m_{llq}^{max})^2 = \begin{cases} \max\left[\frac{(\tilde q-\tilde\xi)(\tilde\xi-\tilde\chi)}{\tilde\xi}, \frac{(\tilde q-\tilde l)(\tilde l-\tilde\chi)}{\tilde l}, \frac{(\tilde q\tilde l-\tilde\xi\tilde\chi)(\tilde\xi-\tilde l)}{\tilde\xi\tilde l}\right] \\ \text{except for the special case in which } \tilde l^2 < \tilde q\tilde\chi < \tilde\xi^2 \\ \text{and } \tilde\xi^2\tilde\chi < \tilde q\tilde l^2 \text{ where one must use } (m_{\tilde q} - m_{\tilde\chi_1^0})^2. \end{cases}$
Xq edge	$(m_{Xq}^{max})^2 = X + (\tilde q - \tilde\xi)\left[\tilde\xi + X - \tilde\chi + \sqrt{(\tilde\xi - X - \tilde\chi)^2 - 4X\tilde\chi}\right]/(2\tilde\xi)$
l^+l^-q threshold	$(m_{llq}^{min})^2 = \begin{cases} [2\tilde l(\tilde q-\tilde\xi)(\tilde\xi-\tilde\chi) + (\tilde q+\tilde\xi)(\tilde\xi-\tilde l)(\tilde l-\tilde\chi) \\ -(\tilde q-\tilde\xi)\sqrt{(\tilde\xi+\tilde l)^2(\tilde l+\tilde\chi)^2 - 16\tilde\xi\tilde l^2\tilde\chi}]/(4\tilde l\tilde\xi) \end{cases}$
$l^\pm_{near}\ q$ edge	$(m_{l_{near}\,q}^{max})^2 = (\tilde q - \tilde\xi)(\tilde\xi - \tilde l)/\tilde\xi$
$l^\pm_{far}\ q$ edge	$(m_{l_{far}\,q}^{max})^2 = (\tilde q - \tilde\xi)(\tilde l - \tilde\chi)/\tilde l$
$l^\pm q$ high-edge	$(m_{lq(high)}^{max})^2 = \max\left[(m_{l_{near}\,q}^{max})^2, (m_{l_{far}\,q}^{max})^2\right]$
$l^\pm q$ low-edge	$(m_{lq(low)}^{max})^2 = \min\left[(m_{l_{near}\,q}^{max})^2, (\tilde q - \tilde\xi)(\tilde l - \tilde\chi)/(2\tilde l - \tilde\chi)\right]$
M_{T2} edge	$\Delta M = m_{\tilde l} - m_{\tilde\chi_1^0}$

$\tilde\chi = m^2_{\tilde\chi_1^0}, \tilde l = m^2_{\tilde l_R}, \tilde\xi = m^2_{\tilde\chi_2^0}, \tilde q = m^2_{\tilde q}$ and X is m_h^2 or m_Z^2

Allanach *et al.*, JHEP 09 (2000) 004

Dilepton endpoint

$$\tilde{\chi}_2^0 \to \tilde{l}^{\pm} l^{\mp} \to \tilde{\chi}_1^0 l^{\pm} l^{\mp}$$

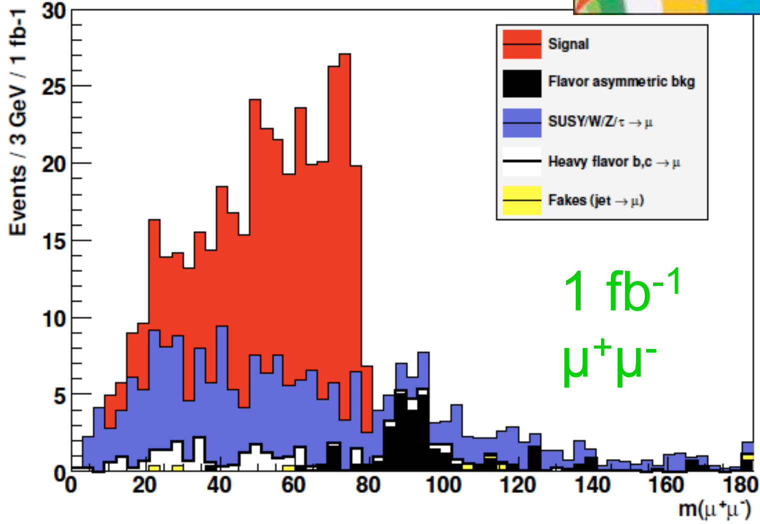
$$M_{ll}^{max} = \sqrt{\frac{(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{l}}^2)(M_{\tilde{l}}^2 - M_{\tilde{\chi}_1^0}^2)}{M_{\tilde{l}}^2}}$$

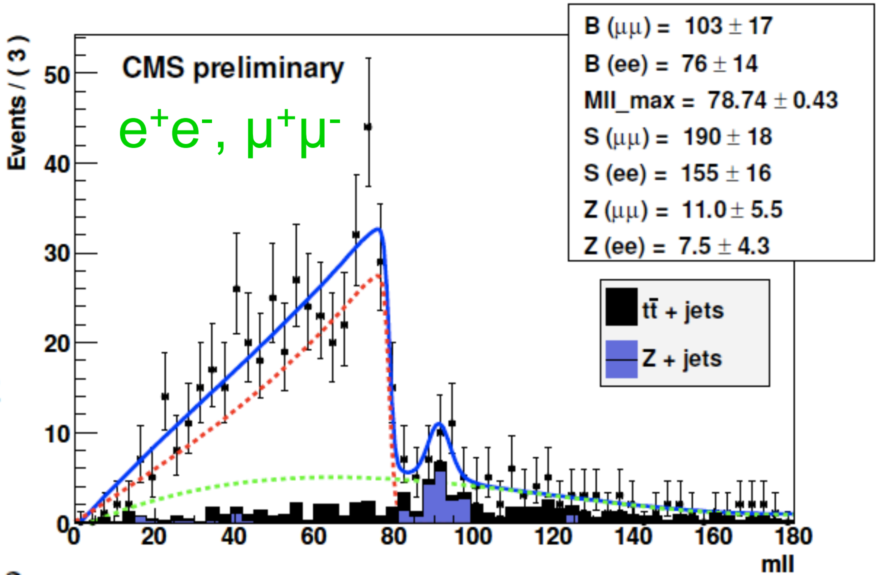
$$m_{\ell\ell}^{max}(TH) = 78.15\ GeV/c^2$$

- Event selection:
  - 2 OS isolated leptons with p_T > 10 GeV, $|\eta|$ < 2.4
  - at least 3 jets with p_T > 30 GeV, $|\eta|$ < 3
  - p_T^{j1} > 120 GeV, p_T^{j2} > 80 GeV
  - E_T^{miss} > 200 GeV
- Background
  - Flavour –symmetric: SF & DF
  - Flavour-asymmetric: SF dileptons only
  - Fake leptons

$$m_{ee}^{max} = 77.90\ GeV/c^2$$
$$\Delta m_{ee}^{max} = \pm 1.07(stat.) \pm 0.36(syst.) GeV/c^2$$

$$m_{\mu\mu}^{max} = 78.03\ GeV/c^2$$
$$\Delta m_{\mu\mu}^{max} = \pm 0.75(stat.) \pm 0.18(syst.) GeV/c^2$$

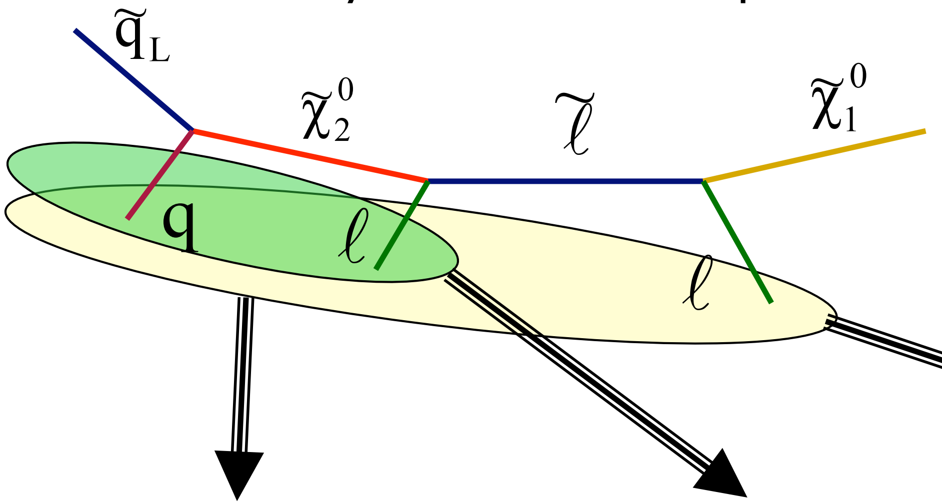




CMS Coll, CMS-PAS-2008/038 (2008)

Adding the squarks

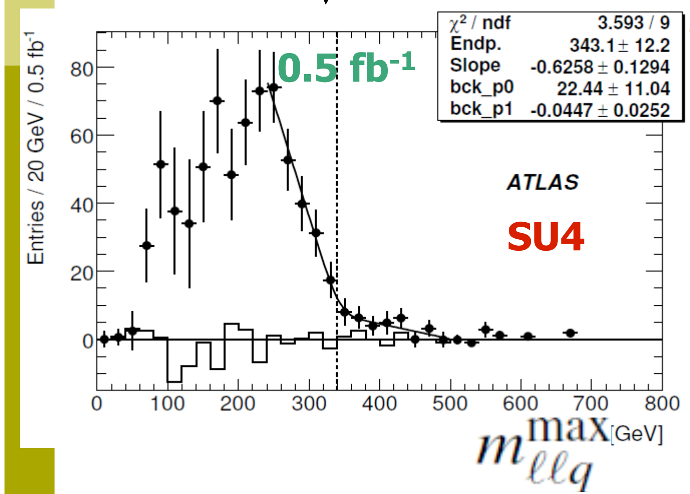
- Di-lepton edge starting point for reconstruction of decay chain
- Make invariant mass combinations of leptons and jets
- Gives multiple constraints on combinations of four masses
- Sensitivity to individual sparticle masses

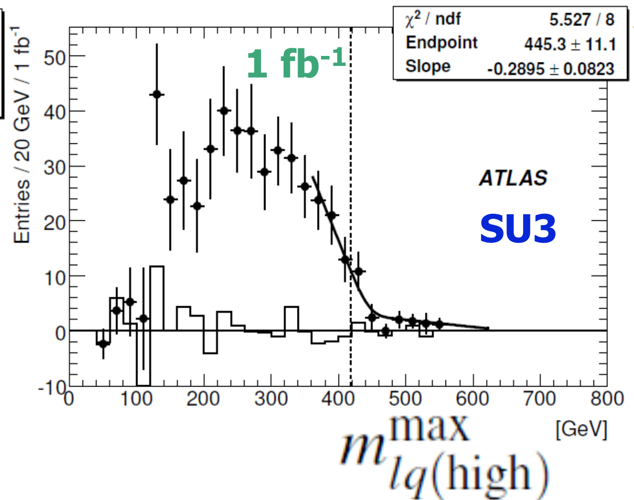


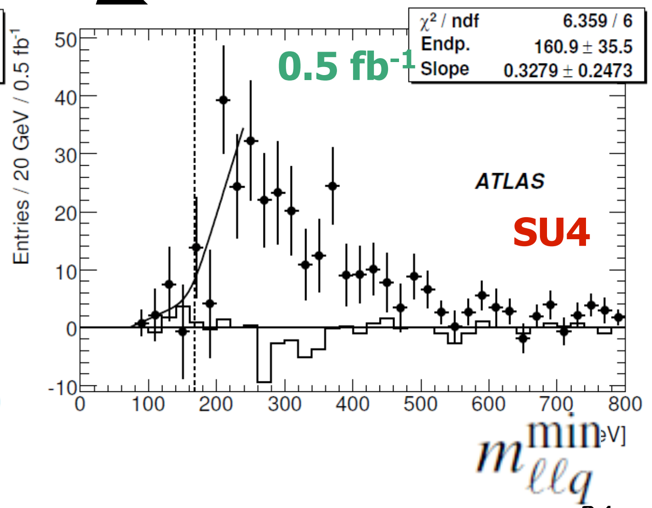
with 1 fb^{-1}

Endpoint	SU3 truth	SU3 measured
$m_{\ell\ell q}^{max}$	501	$517 \pm 30 \pm 10 \pm 13$
$m_{\ell\ell q}^{min}$	249	$265 \pm 17 \pm 15 \pm 7$
$m_{lq(low)}^{max}$	325	$333 \pm 6 \pm 6 \pm 8$
$m_{lq(high)}^{max}$	418	$445 \pm 11 \pm 11 \pm 11$

ATLAS Coll, arXiv: 0901.0512 (2008)







mSUGRA masses/parameters determination

ATLAS collab, CSC note, ATL-COM-PHYS-2008-063

Measurement of mass combinations - `endpoints'

$m_{\ell\ell q}^{max}$ $m_{lq(high)}^{max}$ $m_{\ell\ell q}^{min}$ ...

1 fb^{-1}

Sparticles masses determination with high uncertainty even for SU3 (optimum case)

$\delta m(\tilde{\chi}_1^0) = 70\%$ $\delta m(\tilde{q}) = 15\%$

$\delta m(\tilde{\chi}_2^0) = 30\%$ $\delta m(\tilde{\ell}) = 50\%$

1 fb^{-1}

mSUGRA parameters determination:

- m_0, $m_{1/2}$ at 1–3%
- $\tan\beta$, A_0 only order of magnitude
- *BUT:* Higgs width measurement

➔ $\tan\beta$ determination

Fitting mass combinations with Sfitter program

	SPS1a	error
m_0	100	**1.2 (1%)**
$m_{1/2}$	250	**1.0 (0.4%)**
$\tan\beta$	10	**0.9 (9%)**
A_0	-100	**20 (20%)**

If sgn(μ) fixed

300 fb^{-1}

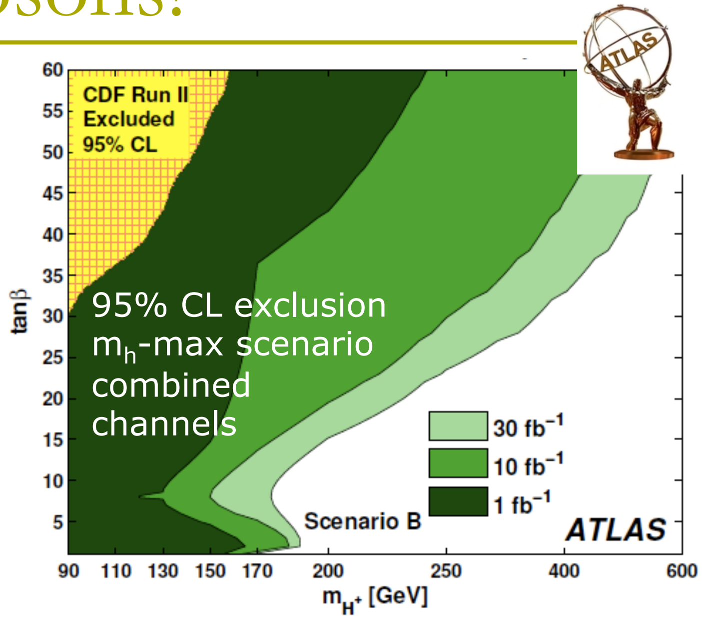
Determination of mSUGRA parameters with a precision at the percent level

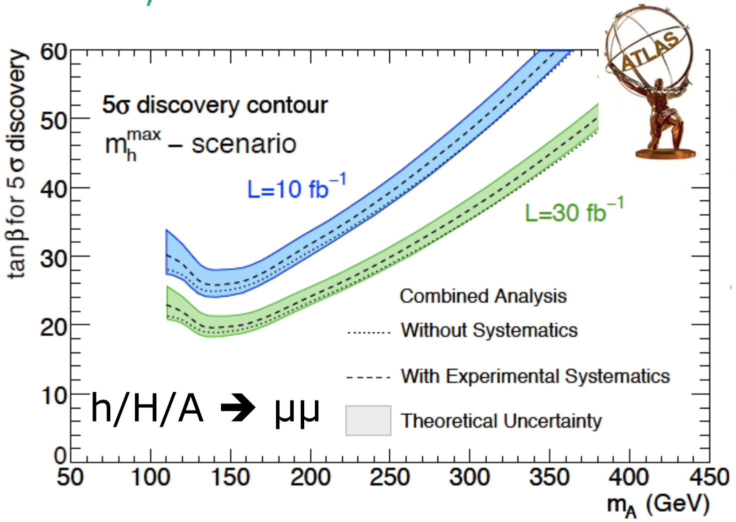
Lafaye *et al,* hep-ph/0512028

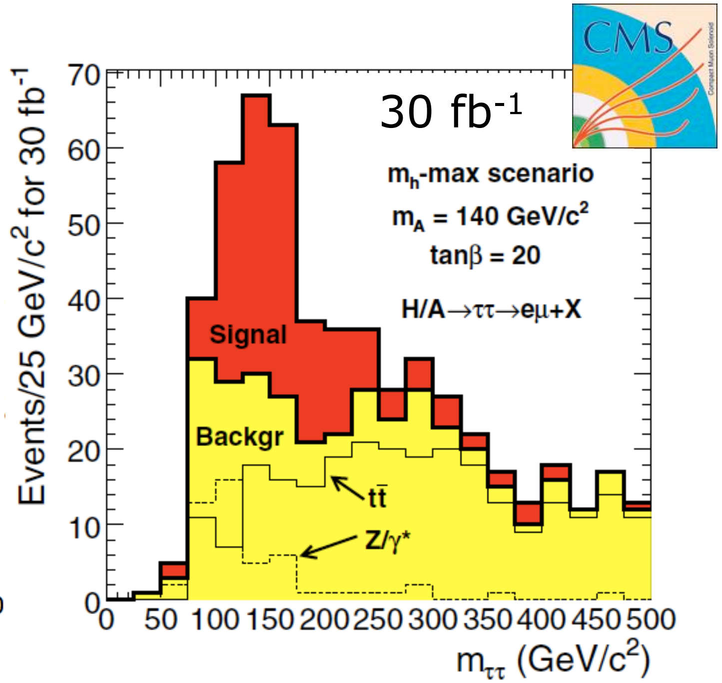
For a more precise parameter determination, SLHC, ILC is needed

What about the (SUSY) Higgs bosons?

- Supersymmetry requires two Higgs doublets
  ➔ five physical states
  - three neutral: two CP-even (h and H) and one CP-odd (A)
  - two charged: H^+, H^-
- The lightest Higgs, h, can be discovered in the whole (m_A, tanβ) plane
  - however, indistinguishable from a light SM Higgs
  - discovery of other (heavy) Higgs bosons (➔SUSY) should be necessary
- Searches for MSSM Higgs boson
  - decay modes: h/H/A ➔ ττ, h/H/A ➔ μμ
  - charged Higgs: $H^\pm$ ➔ τν, $H^\pm$ ➔ tb
- Measurement of Higgs properties with 300 fb^{-1}:
  - mass (~0.1%)
  - width / tanβ (5–10%)
  - couplings (~20%)
  - spin / **CP**







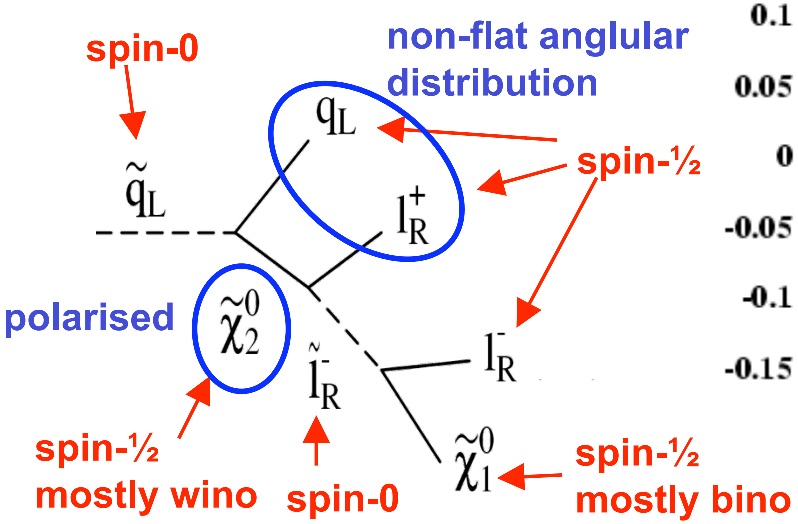
Is it Supersymmetry?

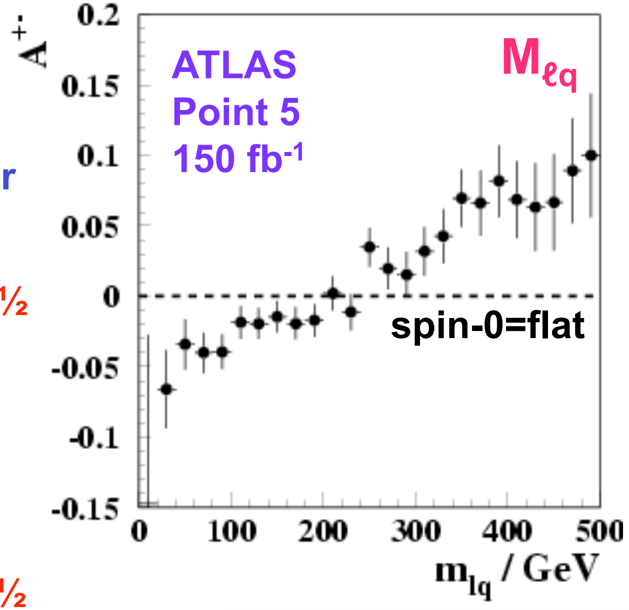
Q: How do we know that a SUSY signal is really due to SUSY?
Other models (e.g. UED with Kaluza-Klein parity) can mimic SUSY mass spectrum
A: Measure spin of new particles!

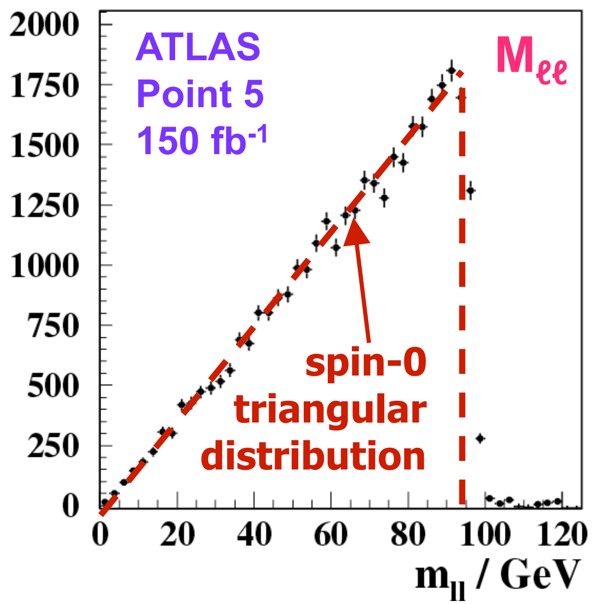
- Angular distributions in sparticle decays ➔ charge asymmetry in lepton-jet invariant mass distributions
- Charge asymmetry reflects the primary production asymmetry between squarks and anti-squarks (LHC: proton–proton collider)
- Consider usual two-body slepton decay chain
  - charge asymmetry of lq pairs sensitive to spin of $\tilde{\chi}_2^0$
  - shape of dilepton invariant mass spectrum is an indication of slepton spin
  - results consistent with spin-½ $\tilde{\chi}_2^0$ and spin-0 slepton

A J Barr, PLB 596 (2004) 205

$$A^{\pm} = \frac{N(l^+q) - N(l^-q)}{N(l^+q) + N(l^-q)}$$







See next talk for more on SUSY look-alikes…

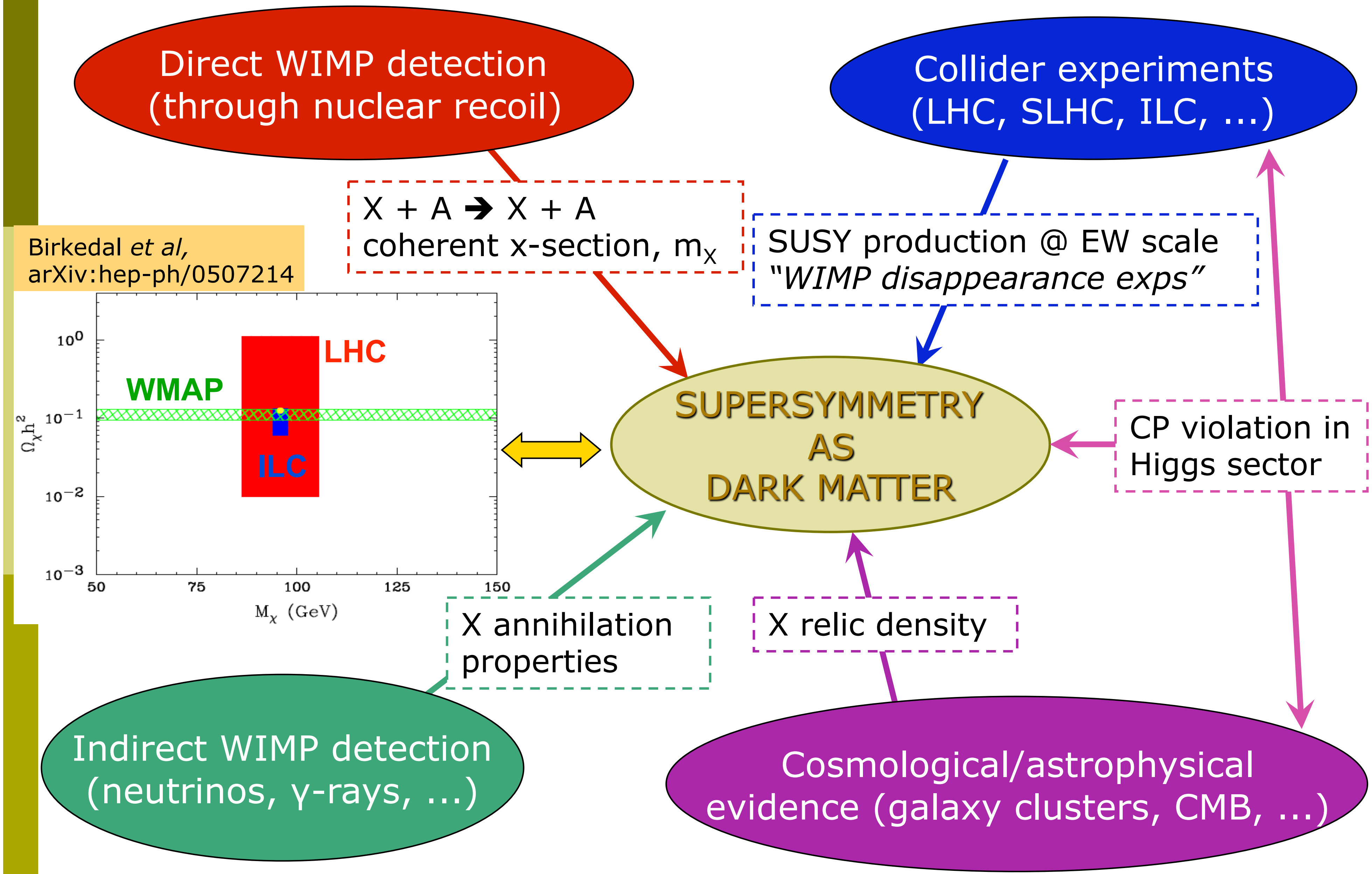
Recap: What LHC can(not) tell us about SUSY?

- SUSY discovery potential
  - SUSY @ 1 TeV with 0.1 fb^{-1} – could be first discovery
  - SUSY @ 2 TeV with 1-10 fb^{-1} – within 1 year of data taking
  - SUSY @ 5 TeV – may need SLHC
- Measurement of effective mass ➔ mass scale, total SUSY cross section
- Endpoint measurements
  - sparticle masses at 10% level
  - model parameters at 1 – 10% level (assuming specific model!)
- How can we distinguish various SUSY models?
  - E_T^{miss} spectrum ➔ *R*-parity
  - hard photons, NLSPs, long-lived gluinos ➔ GMSB, split SUSY
  - τ leptons ➔ large $\tan\beta$
- Higgs sector
  - discovery of SM Higgs: observable for the whole allowed mass range
  - additional Higgs bosons from the MSSM can be discovered on a large fraction of the parameter space
  - measurement of Higgs bosons properties is possible with 300 fb^{-1}
    - masses, total width, ratios of couplings, spin / CP properties
- *And what it cannot tell us ...*
  - *observe and measure the full gaugino spectrum (in particular charginos)*
  - *constrain model parameters to < 1%*
  - *define directly the nature of neutralino & chargino (higgsino / bino / wino -like?)*

Outlook: SUSY / Dark Matter @ LHC

- Discovery: search for deviation from SM in inclusive signatures like **missing energy + jets (+leptons)**
  - Inclusive studies: establish SUSY discovery
  - Exclusive studies: rough determination of model parameters
- Scheme developed for SUSY, but applicable to other BSM scenarios, e.g. UED, T-parity Little Higgs, ...
- LHC should discover general WIMP dark matter, but it is non-trivial to prove that it has the right properties
  ➔ SLHC, ILC: extend discovery potential of LHC
    - improve on LHC capability of identifying DM model
    - more precise determination of model parameters
- Complementarity between LHC and cosmo/astroparticle experiments
  - uncorrelated systematics
  - measure different parameters
- In the following years we expect a continuous interplay between particle physics experiments (LHC, SLHC, ILC) and astrophysical/cosmological observations
  - either for model exclusion or discovery of New Physics

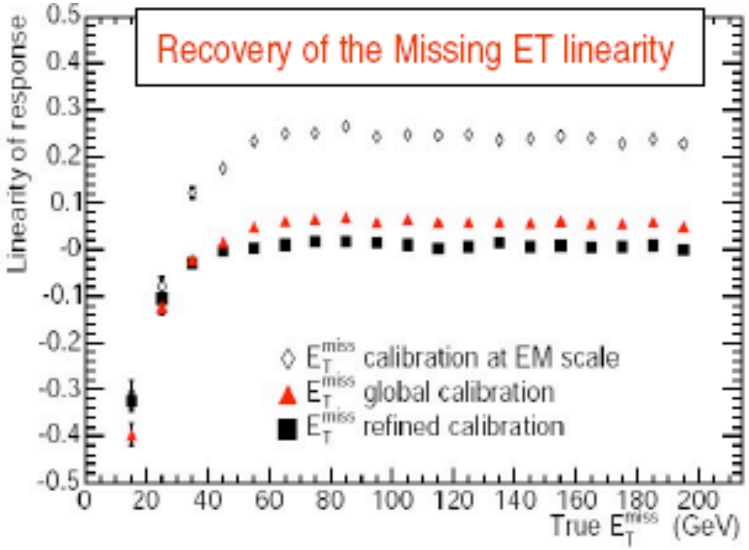
SUSY&DM: the complete (?) picture

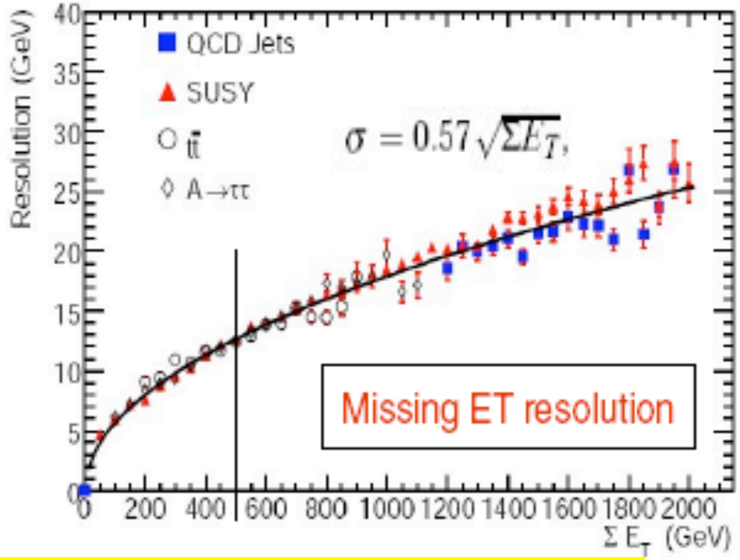


Backup…

Missing transverse energy resolution

- **Missing ET calculation:**
  - Raw Missing ET
    - Default: Cell-based
    - Alternate: Cluster-based
  - Noise suppression
    - Use only cells within topo clusters
  - Refinement:
    - Cell associated with electrons, muons, taus and jets are calibrated according to the energy scale of the respective object
    - Correct for dead material

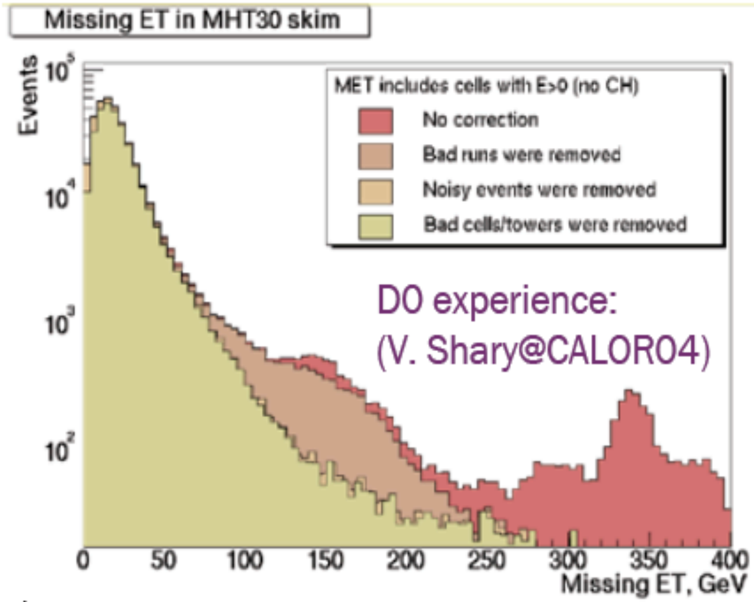




Ulla Blumenschein (IFAE), QCD Moriond, 18.03.2008

Fake missing energy

- ✓ E_T^{miss} is a discriminating variable for SUSY discovery
  - Our searches rely on the excess in the $E_T^{miss}(M_{eff})$ distribution.
- ✓ However, controlling its energy scale and resolution is very difficult experimentally.
  - Fake muons
  - Dead material and crack
  - Industrial effects in the detector (hot, dead and noisy calorimeter cells)
- ✓ Large tail in E_T^{miss} due to the fake is serious for SUSY searches.
  - Especially for QCD-jet background (almost no truth E_T^{miss}, but large x-section)



In-situ measurements for E_T^{miss} scale/resolution determination and understanding of fake E_T^{miss} sources are our priorities straight.

Shimpei Yamamoto, SUSY07, Kalrsruhe, 06.07.2007

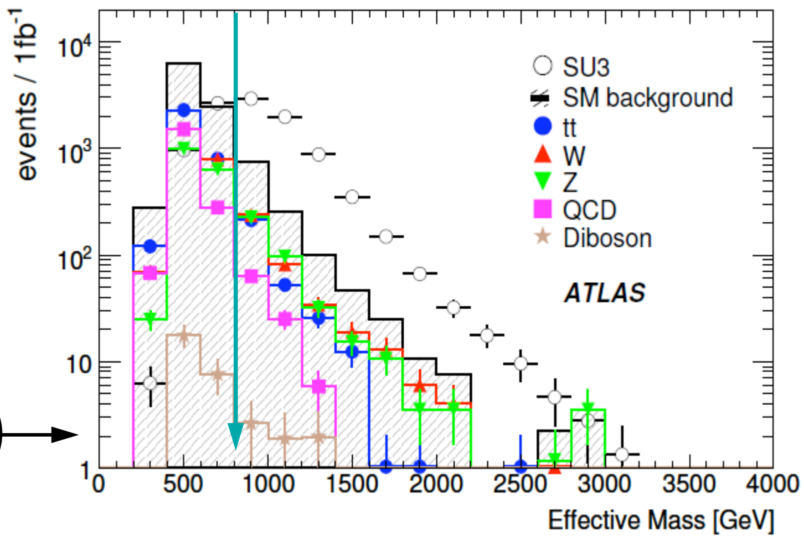
Discriminating variables

- Effective mass, M_{eff}

$$M_{\mathrm{eff}} = \sum_{4\ \mathrm{jets}} p_{\mathrm{T}} + \sum_{\mathrm{leptons}} p_{\mathrm{T}} + E_{\mathrm{T}}^{miss}$$

  - correlates with SUSY mass scale
  - example: no-lepton mode @ 1 fb^{-1}
    - lepton veto (no e or μ)
    - $p_T^{j1} > 150$ GeV
    - $p_T^{j2} > 100$ GeV
    - $E_T^{miss} > 0.3\ M_{eff}$
    - $\delta\varphi(jet_i, E_T^{miss}) > 0.2$
    - **$M_{eff} > 800$ GeV**

0-lepton plus 2 jets analysis after all cuts have been applied



ATLAS collab, CSC note, ATL-COM-PHYS-2008-063

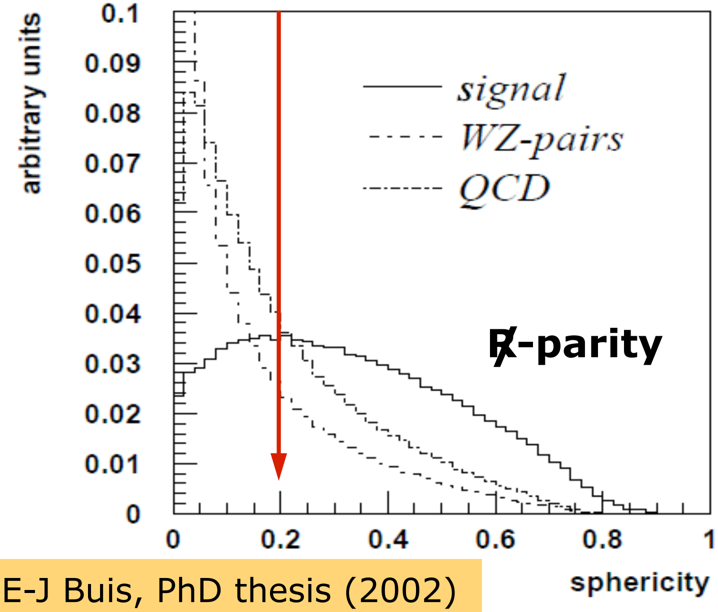
- Transverse sphericity, S_T

$$S_T = 2\min(\lambda_1, \lambda_2)/(\lambda_1 + \lambda_2)$$

  - λ_1, λ_2 eigenvalues of the 2×2 sphericity tensor

$$S_{ij} = \sum_k p_{ki} p^{kj}$$

    calculated over all jets ($p_T^{jet} > 20$ GeV) and leptons
  - SUSY events are more `spherical'
  - Common cuts in SUSY analyses: **$S_T > 0.2$**



E-J Buis, PhD thesis (2002)

Models faking SUSY

- Universal Extra Dimensions
- Compactified extra dimensions (compactification scale 1/R)
  - Randall-Sundrum
- Kaluza Klein excitations

J Hubitz *et al*, PRD **78** (2008) 075008