From first LHC Data to a Possible Understanding of the Terascale

Philip Bechtle

7. September 2010

1. On the way to the Terascale
   - The Search for the System behind Matter
   - SUSY: The missing link at the Terascale?
   - First Experiments at the Terascale
2. Measurements at the LHC
   - Understanding Reconstruction and Identification
   - Searches for Supersymmetry (or else . . .)
   - One Possibility to Measure Features of SUSY
3. Towards understanding the physics of the Terascale
   - SUSY below $\sqrt{s} = 7\,\mathrm{TeV}$
   - The Terascale in the Light of the LHC
   - Ultimative Precision at the ILC?

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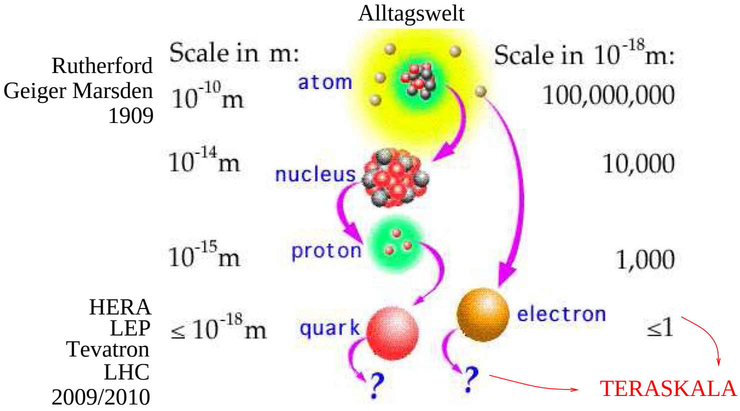
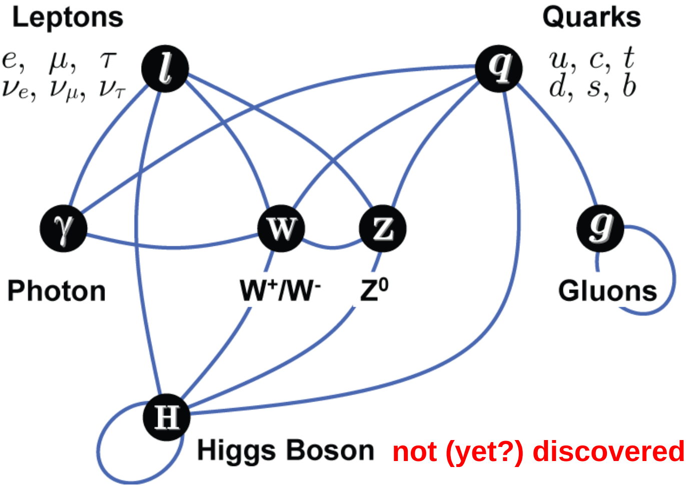
The Search for the Fundamental Buildung Blocks



A new era with the LHC, almost exactly 100 years after the first look into the atom

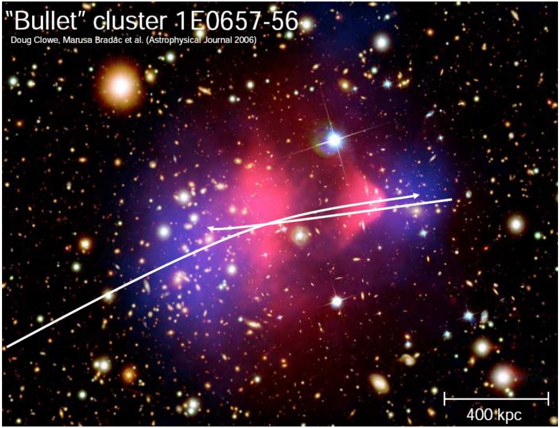
The Standard Model of Elementary Particles



not (yet?) discovered!

Why we know we missed something fundamental

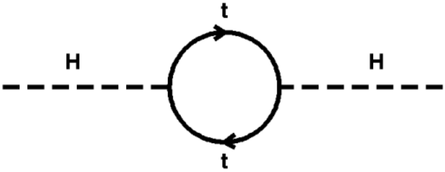
- Experimentally known: The SM is incomplete!



- We do not experimentally know any particle or field which could explain dark matter or dark energy

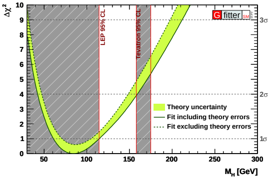
Supersymmetry

- Even if we find the Higgs, we still have a problem . . .



$$\Delta m_h \sim \Lambda^2$$
natural $m_h = M^2_{Planck}$
Finetuning:

- From indirect measurements:
  $m_h < 140$ GeV



$$m_{h,obs} = \underbrace{10^{2\cdot19}\,\mathrm{GeV}}_{\text{nat. mass}} - \underbrace{(1-\epsilon)10^{2\cdot19}\,\mathrm{GeV}}_{Renormalisation} \approx 100\,\mathrm{GeV}$$

Supersymmetry

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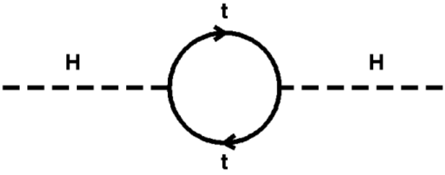


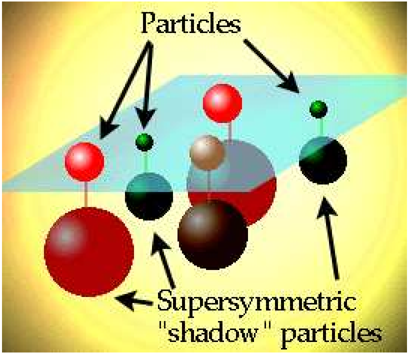
$$\Delta m_h \sim \Lambda^2$$

$$\Delta m_h \sim \ln \Lambda$$

- From indirect measurements: $m_h < 140$ GeV
- To prevent quadratic divergencies: Introduce shadow world: One SUSY partner for each SM d.o.f.
- Nice addition for free: If R-parity conserved, automatically the Lightest SUSY Particle (LSP) is a stable DM candidate
- But: Where are all those states?

Supersymmetry

- Even if we find the Higgs, we still have a problem . . .



In any case: $m_{Hlike} < 1\,\mathrm{TeV}$
$m_{SUSY} \leq \mathcal{O}(\mathrm{TeV})$
$\Rightarrow$ Terascala

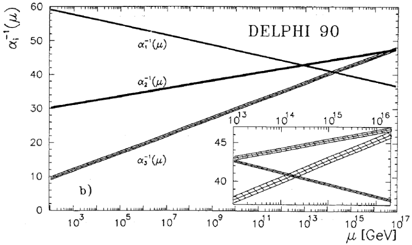
- From indirect measurements: $m_h < 140$ GeV
- To prevent quadratic divergencies: Introduce shadow world: One SUSY partner for each SM d.o.f.
- Nice addition for free: If R-parity conserved, automatically the Lightest SUSY Particle (LSP) is a stable DM candidate
- But: Where are all those states?
- SUSY breaking introduces a lot of additional parameters
  Understand model: Measure parameters!

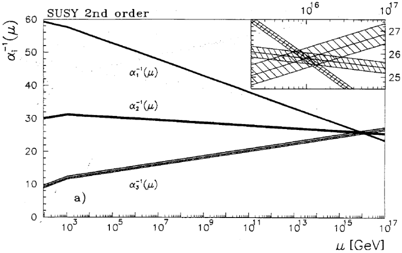
Why try (trust?) SUSY?

Wim de Boer *et al.* (1991):

It was shown that the evolution of the coupling constants within the minimal Standard Model with one Higgs doublet does not lead to Grand Unification, but if one adds five additional Higgs doublets, unification can be obtained at a scale below $2 \cdot 10^{14}$ GeV. However, such a low scale is excluded by the limits on the proton lifetime.

On the contrary, the minimal supersymmetric extension of the Standard Model leads to unification at a scale of $10^{16.0\pm0.3}$ GeV. Such a large unification scale is compatible with the present limits on the proton lifetime of about 10^{32} years. Note that the Planck mass (10^{19} GeV) is well above the unification scale of 10^{16} GeV, so presumably quantum gravity does not influence our results.

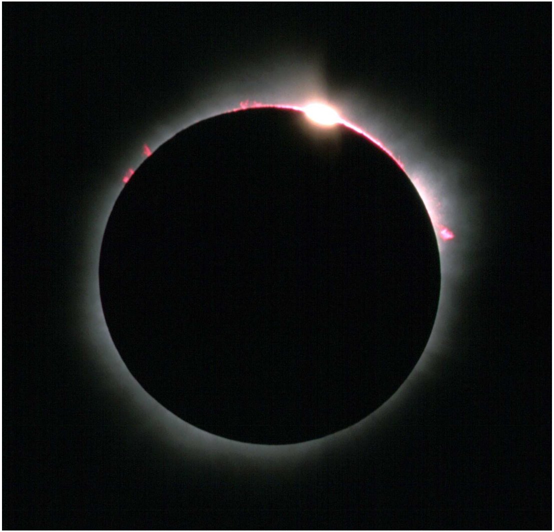


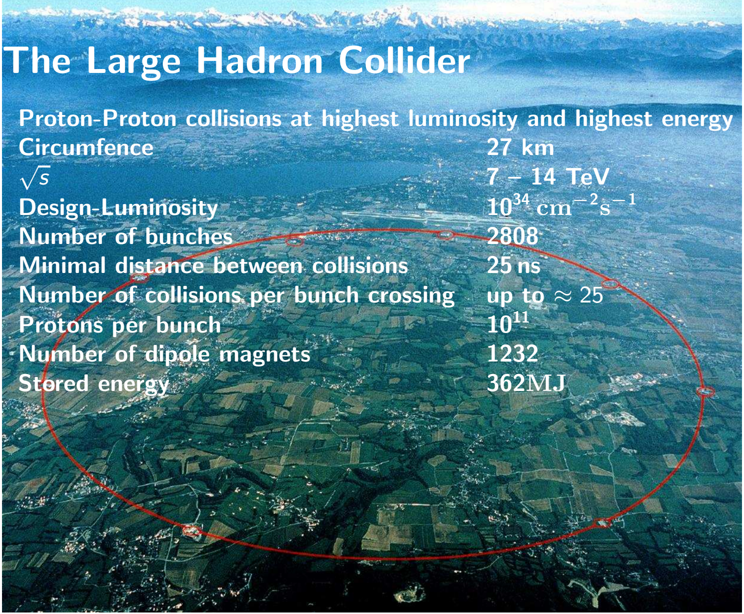


„Prediction" of $\sin^2\theta_W$:

$$\sin^2\theta_W^{SUSY} = 0.2335(17), \qquad \sin^2\theta_W^{exp} = 0.2315(02)$$

A Warning: Apparent Finetuning





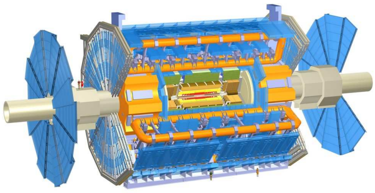
The Large Hadron Collider

Proton-Proton collisions at highest luminosity and highest energy

Circumfence	27 km
$\sqrt{s}$	7 – 14 TeV
Design-Luminosity	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Number of bunches	2808
Minimal distance between collisions	25 ns
Number of collisions per bunch crossing	up to ≈ 25
Protons per bunch	10^{11}
Number of dipole magnets	1232
Stored energy	$362\mathrm{MJ}$

The ATLAS Experiment

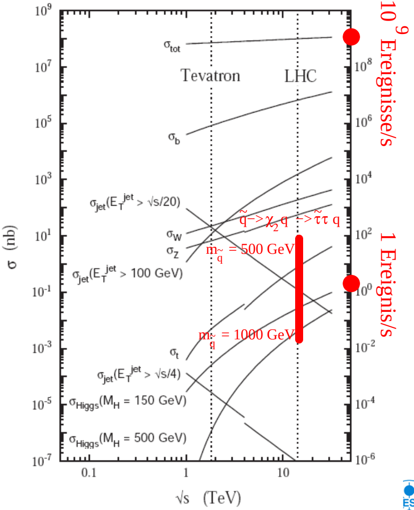
- ATLAS and CMS: First direct experimental access to the Terascale



Diameter	25 m
Length	46 m
Weight	7000 t

≈ 100 Million readout channels

≈ 3000 km cables



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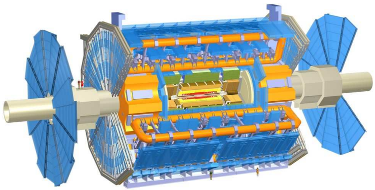
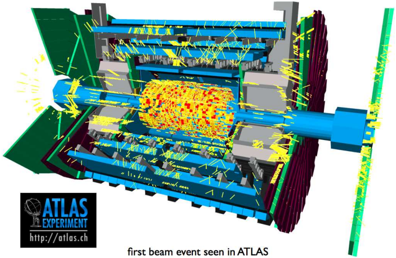
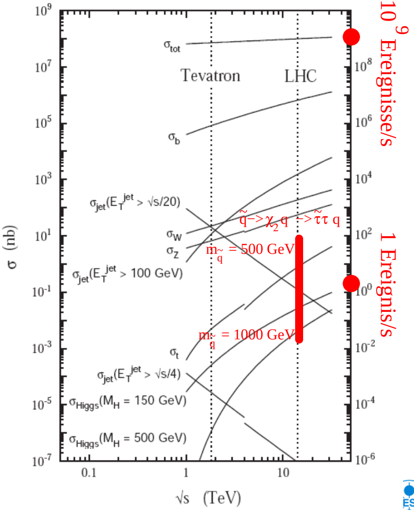
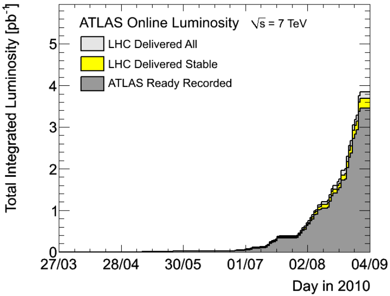


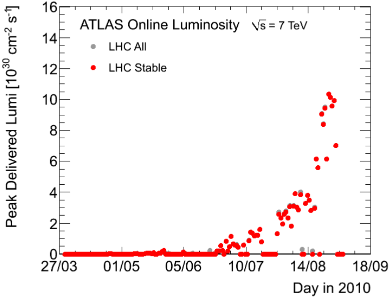


first beam event seen in ATLAS



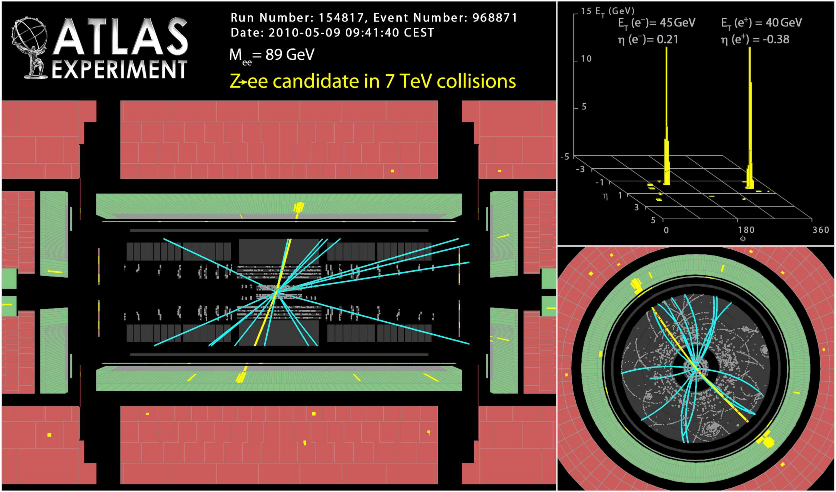
Successful Data Taking





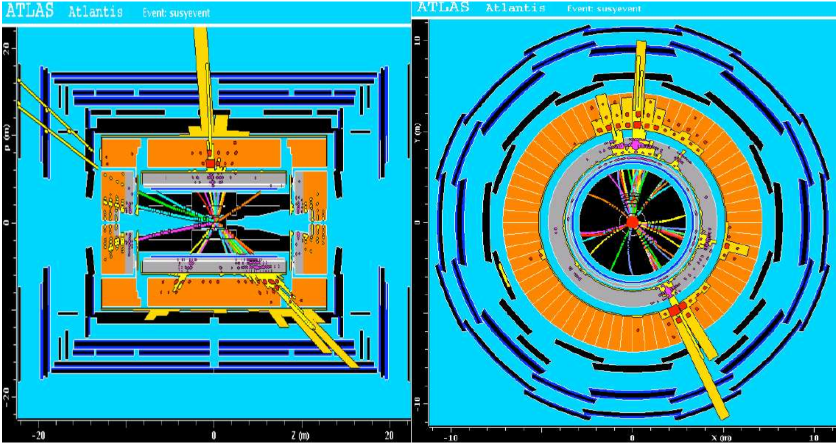
- The experiments are taking data with high efficiency and very good understanding of the data
- Quite successful delivery of luminosity
- Expectations for the rest of 2010 around $40\,\mathrm{pb}^{-1}$ with large uncertainty

Re-Discovery of almost all known SM-Particles



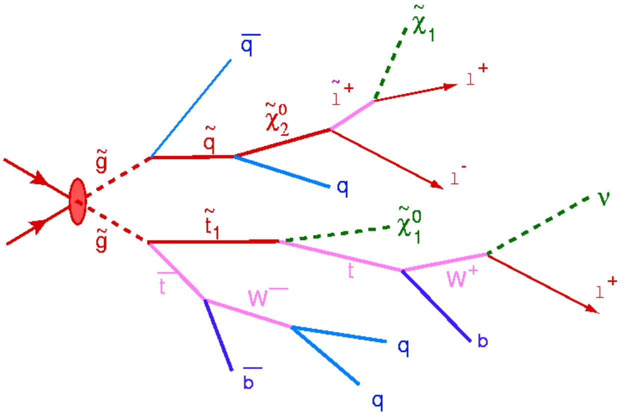
e.g. a few hundred Z boson candidates

. . . but what we're looking for is a bit more complicated . . .



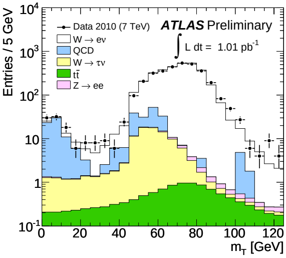
simulated SUSY event (no pileup)

What do we hope to find?

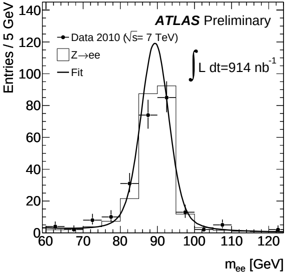


Need everything: MET, Jets, B-Jets, elektrons, myons, taus

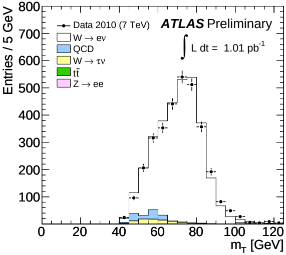
A few first Measurements of Heavy Objects



W



Z



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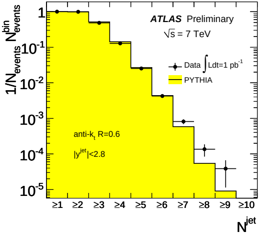


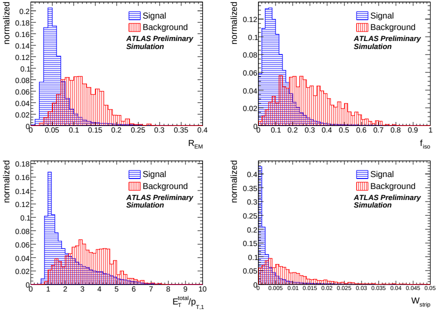
jets

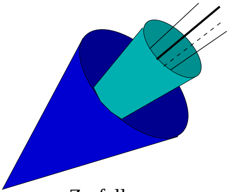
Reconstructing τ Lepton Candidates in Early Data

- Distinguish hadronic decays from *QCD* jets
- e.g.

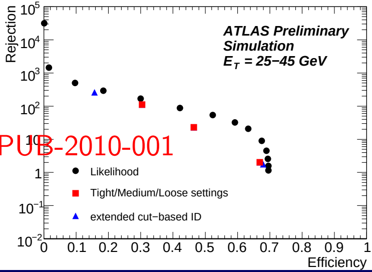
$$\Delta E_T^{12} = \sum_{\Delta R<0.2} E_T \Bigg/ \sum_{\Delta R<0.4} E_T$$

- Concentrate currently on least systematics, not most theoretical sensitivity





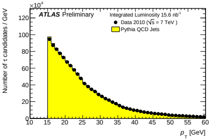
τ Zerfall

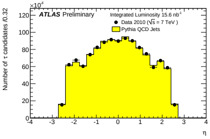


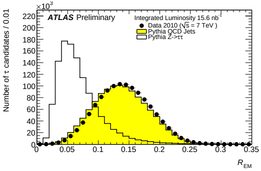
ATL-PHYS-PUB-2010-001

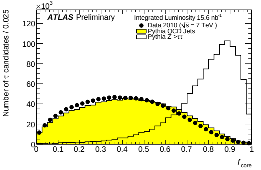
Understanding First Data: τ Identification

The first $\approx 17\,nb^{-1}$ of 7 TeV data: ATLAS-CONF-2010-059







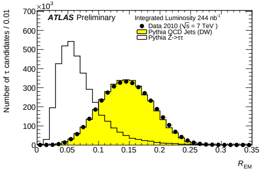


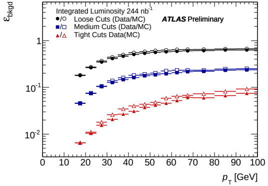
- No significant number of real τ leptons
- Use τ lepton candidates from QCD instead
- Compare data and MC in detail

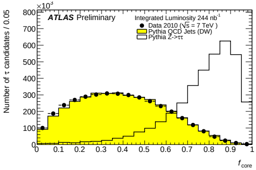
Already quite good agreement – but the standard ATLAS Pythia tune with k_T ordered showers shows some small deviations

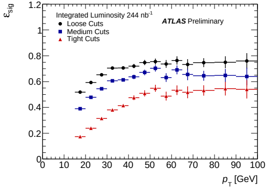
More data and a different simulation . . .

The first $\approx 244\, nb^{-1}$ of 7 TeV data: ATLAS-CONF-2010-086



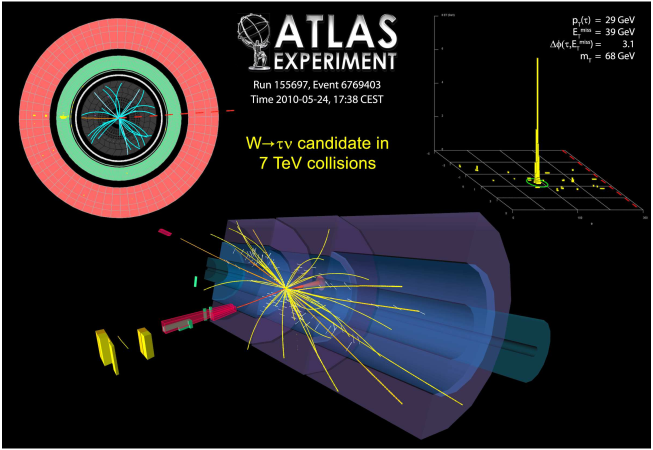






- Great data-MC agreement (including minimal pileup)
- Strong separation between signal and background expected
- Slightly different tune with q^2 ordered showers seems to work much better – probably only due to tuning, nothing to do with shower

The first very good hadronic τ Candidate



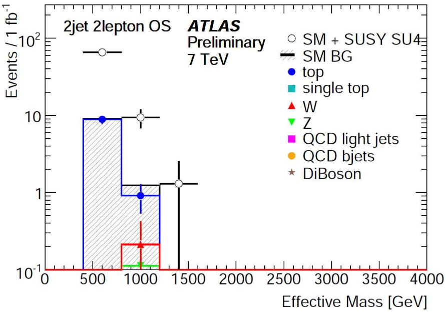
- Single prong candidate
- $p_T(\tau) = 29$ GeV
- $E_{Tmiss} = 39$ GeV
- $\Delta\phi(\tau, E_{Tmiss}) = 3.1$
- $m_T = 68$ GeV
- No μ or electron candidate in the event

Current Focus:

Work on understanding fake rates and efficiencies in detail

The possible discovery of Physics at the Terascale

- inclusive spectra: probably fastest way to discover SUSY-like physics
- Challenging because very good detector understanding with relatively little data needed (ca. $\mathcal{L} \approx 1\,\mathrm{fb}^{-1}$)



$$M_{eff} = \sum_i p_{T,i} + E_{Tmiss}$$

ATLAS MC $1\,\mathrm{fb}^{-1}$ @ $7\,\mathrm{TeV}$

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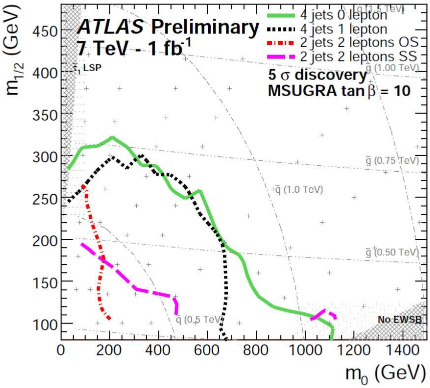
- Which particles, which masses, which decay chains?
- Quantum numbers, couplings?



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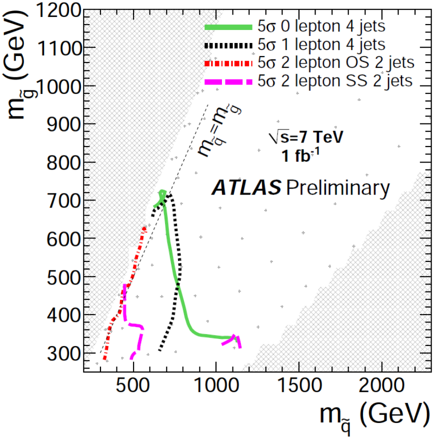

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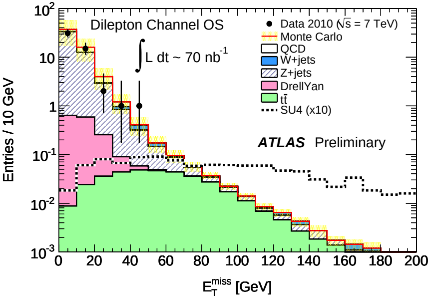

ATLAS data @ $7\,\mathrm{TeV}$ only 70 nb!

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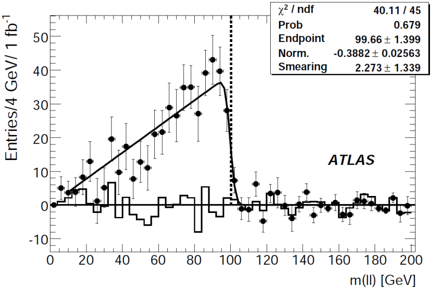
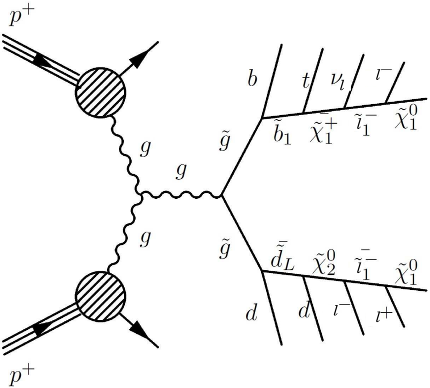


ATLAS MC $1\,\mathrm{fb}^{-1}$ @ $14\,\mathrm{TeV}$

kinematic edges

$\Rightarrow$ mass information

Typical SUSY Process in the Expected Region

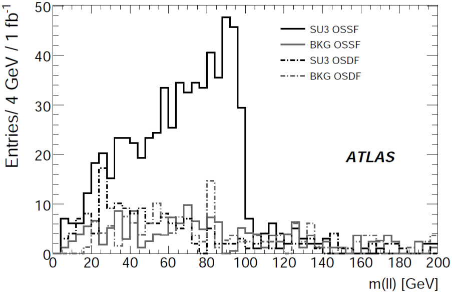


- Cannot detect LSP
- Only SM-particles visible:
  - Leptons (3)
  - Jets (at least 4)
  - missing transverse momentum
- Observable: Inavriant mass $m^2_{\ell^+\ell^-}(m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1}, m^2_{\tilde{\chi}^0_1})$

- Cannot reconstruct any sparticle mass directly
- Observable $m^2_{\ell\ell}$ depends on sparticle masses $(m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1}, m^2_{\tilde{\chi}^0_1})$
- Combinatoric background from second decay chain

Measurement of the invariant $\ell\ell$ mass

ATLAS MC arXiv:0901.0512 [hep-ex]

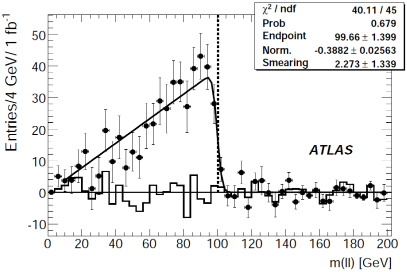


$$
\begin{array}{lcrl}
m_0 & = & 100 & \text{GeV} \\
m_{12} & = & 300 & \text{GeV} \\
A_0 & = & -300 & \text{GeV} \\
\tan\beta & = & 6 &
\end{array}
$$

- Select events with E_{Tmiss}, hard jets and at least 2 ℓ
- Sharp edge in the $m_{\ell\ell}$ spektrum smeared due to finite resolution
  $\Rightarrow$ E.g. calibrate inflection point to edge
- Use data itself to subtract background:
  $OS - SS$ or $OSSF - QSDF$

Measurement of the invariant $\ell\ell$ mass

ATLAS 14TeV MC, update in progress!



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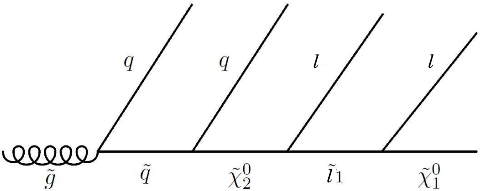
More Mass Edges

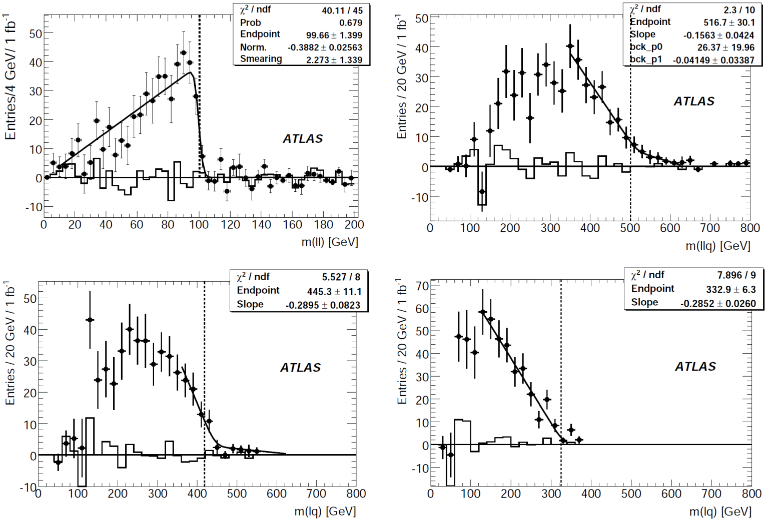
- One observables $m^2_{\ell\ell}$ epends on 3 sparticle masses $(m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1}, m^2_{\tilde{\chi}^0_1})$



Mass edges:
$m^2_{\ell^+\ell^-}(m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1}, m^2_{\tilde{\chi}^0_1})$
$m^2_{q\ell^+\ell^-}(m^2_{\tilde{q}}, m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1}, m^2_{\tilde{\chi}^0_1})$
$m^2_{q\ell_{near}}(m^2_{\tilde{q}}, m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1})$
$m^2_{q\ell_{far}}(m^2_{\tilde{q}}, m^2_{\tilde{\chi}^0_2}, m^2_{\tilde{\ell}_1}, m^2_{\tilde{\chi}^0_1})$
$m^2_{q\ell_{low}} = min[(m^2_{q\ell_{near}}), (m^2_{q\ell_{far}})]$
$m^2_{q\ell_{high}} = max[(m^2_{q\ell_{near}}), (m^2_{q\ell_{far}})]$

- e.g. by adding a reconstructed jet:
  - **1** additional sparticle mass
  - But **3** additional observables!
- ℓ_{near} and ℓ_{far} cannot be resolved $\rightarrow$
  - $q\ell_{high}$ and $q\ell_{low}$ edges
- Di-leptonic final states: $\rightarrow$ **4**(5) observables and **4** sparticle masses $\rightarrow$ distinct solution(s)

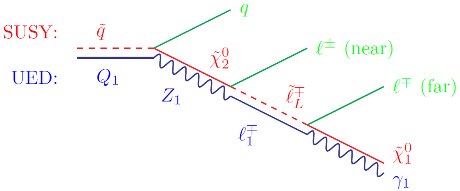
Expected mass spectra

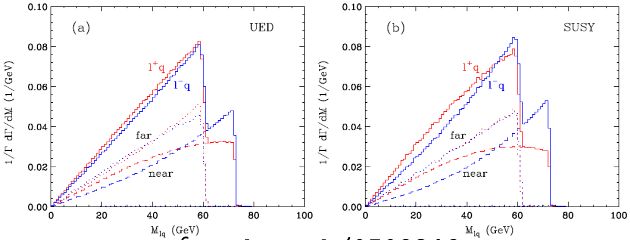


ATLAS 14TeV 1 fb^{-1}, updates at 7TeV in progress!

Are we done yet?

Not only SUSY causes kinematic edges





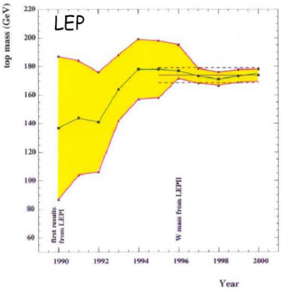
from hep-ph/0509246

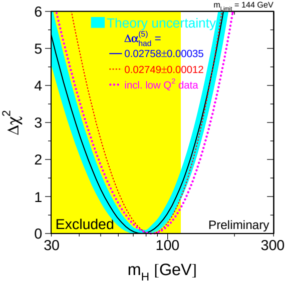
Need much more complex measurements (angular distributions, polarizations ($\Rightarrow \tau$))

Multi-Messenger

Experiments at highest precision

- Babar
- Belle
- BES, CLEO
- Aleph
- Delphi
- L3
- OPAL
- SLC
- $(g-2)_\mu$
- m_W, m_t, B bei CDF
- m_W, m_t, B bei D0
- Indirect Detection, Satellites
- SuperBelle
- ILC?





Experimente at highest energies

- SUSY-search at Tevatron
- Higgs-search at Tevatron
- ATLAS
- CMS
- Cosmology of the early universe
- ...

Fits using Fittino

- Measure properties of New Physics ⇒ Check confidencde in different models ⇒ measure parameters
- Fittino is a framework to perform χ^2-Fits of model parameters and to compare models/interpretations
- Momentarily: concentrate on MSSM/nMSSM/...
- Modular expandable
- Modular combination with programs to calculate observables in NP models (SPheno, micromegas, mastercode, etc...)
- Fittino does determine best fit values, $\mathcal{P}$-values, uncertainties, comparisons of confidence levels of different models/interpretations
- Advanced statistical Methods (GA, Simulated Annealing, Markov Chains)

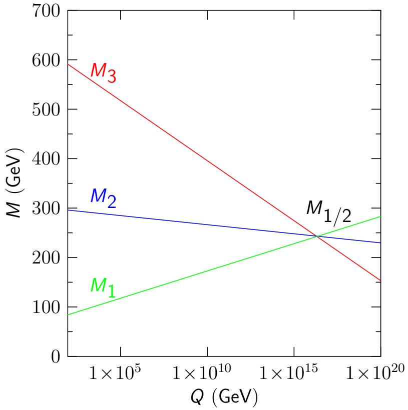
- See e.g. arXiv:0907.2589 [hep-ph]
- Older work in hep-ph/0412012, hep-ph/0511006
- Lots of other work in this field, e.g. arXiv:0907.5568 [hep-ph], arXiv:0910.2601 [astro-ph.CO]

Simplified SUSY Models

Reduction of the number of parameters: Assume unification at M_{GUT}

Example

Universal gaugino mass $M_{1/2}$



Unified model: mSUGRA

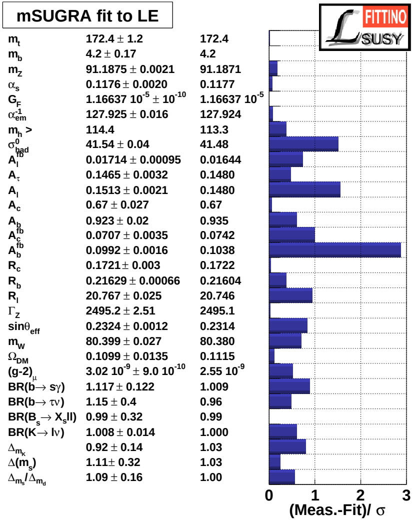
4 additional continuous parameters

- universal gaugino mass $M_{1/2}$
- universal scalar mass M_0
- universal trilinear coupling A_0
- $\tan\beta = v_2/v_1$
- signμ

Typical model point forLHC,ILC studies: SPS 1a

$M_{1/2} = 250$ GeV, $M_0 = 100$ GeV,
$A_0 = -100$ GeV, $\tan\beta = 10$, sign$\mu = 1$

Experimental Status of SUSY

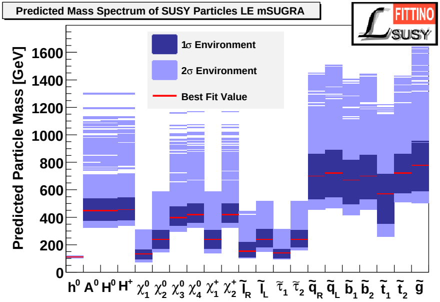


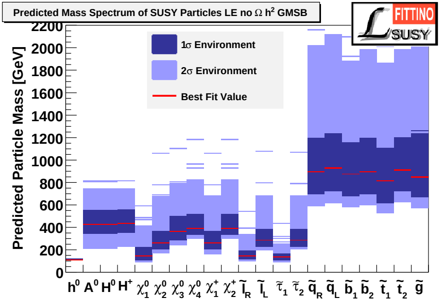
- Fit SM+mSUGRA to measured observables
- $\chi^2 = 20.6$ at 23 d.o.f. $\Rightarrow$ $\mathcal{P}$-Value $= 60.5\,\%$
- Best fit for sign$\mu = +1$ und

Parameter	Value and Uncertainty
$\tan\beta$	13.2 ± 7.2
M_{12}	331.5 ± 86.6
M_0	$76.2^{+79.8}_{-29.2}$
A_0	383.1 ± 647.0
α_s	0.1177 ± 0.0020
α_{em}	127.924 ± 0.014
m_Z	91.1871 ± 0.0020
m_t	172.4 ± 1.1
G_F	$1.16637 \cdot 10^{-5} \pm 1 \cdot 10^{-10}$

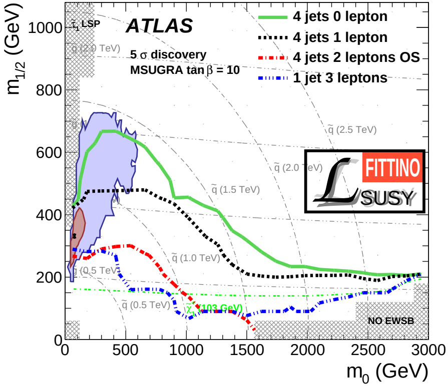
Experimental Status of GMSB & mSUGRA

Almost the same $\mathcal{P}$ value for different models
similar expectations for the sparticle masses at LHC:





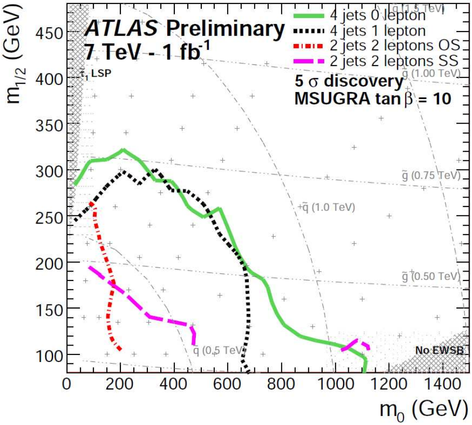
Experimental Statements on the Allowed Parameters



$$1\,\mathrm{fb}^{-1}\,@\,14\,\mathrm{TeV}$$

Still chances for early discovery at LHC . . .

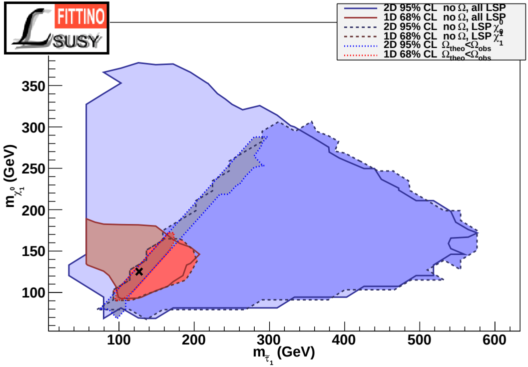
Experimental Statements on the Allowed Parameters



$$1\,\mathrm{fb}^{-1}\,@\,7\,\mathrm{TeV}$$

Still chances for early discovery at LHC . . .

Experimentelle Statements on Observables

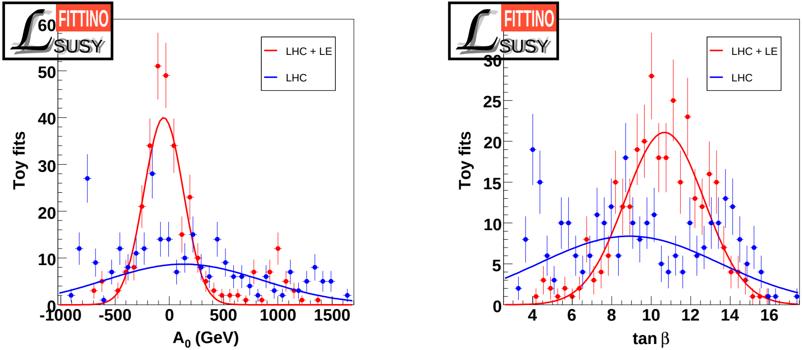


Challenging final states expected for the reconstruction of model properties

small $m_{NSLP} - m_{LSP}$

Many τ leptons

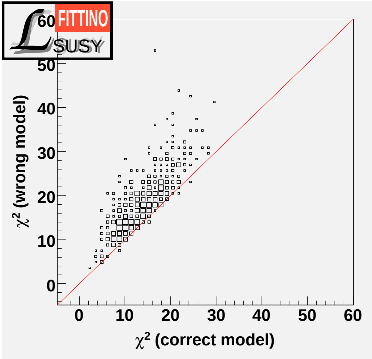
mSUGRA-Fits including LHC Expectations

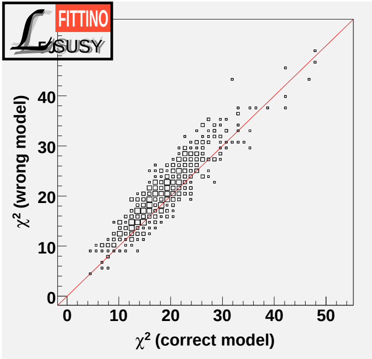


For small LHC luminosities: $1\,\mathrm{fb}^{-1}$ @ $14\,\mathrm{TeV}$

- Non-gaussian parameter uncertainties
- Very clear improvement when combining LHC with low energy precision observables $\Rightarrow$ Multi-Messenger
- More improvements possible using higher precision $\Rightarrow$ SuperB-Factories, GigaZ . . .

Distinguishing Models/Interpretations





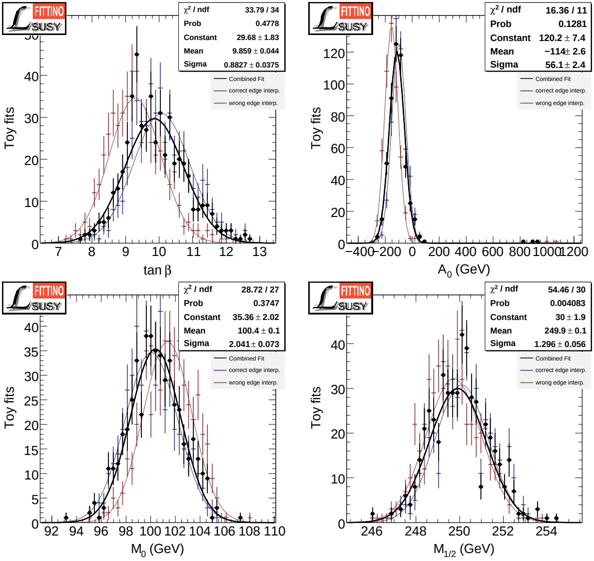
Digital parameters at 1 fb^{-1}

- Fit the "wrong" models with signμ = -1
- Probability to prefer right over wrong: 96 % C.L.

Interpretation of mass edges at 10 fb^{-1}

- Change interpretation of measured mass edge ($m_{\tilde{e}_R} \leftrightarrow m_{\tilde{e}_L}$)
- Probability to prefer right over wrong: 77 % C.L.

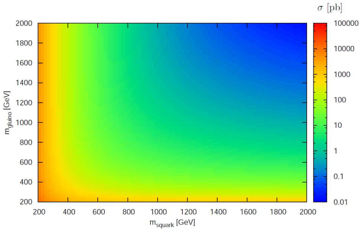
Assignments: Measurements and Observables



- Observed mass edges cannot automatically be assigned uniquely to exactly one decay chain
- New precedure allows to extract CL and to study the effect of these uncertainties on the parameter uncertainties

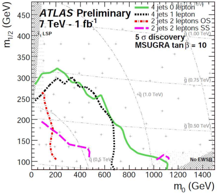
Expected Future Developments

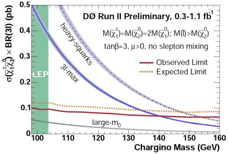
- Expectations for 7 TeV data
- Correlated treatment of RGE uncertainties
- Complete χ^2 information of Higgs searches from HiggsBounds arXiv:0811.4169 [hep-ph]
- Complete Treatment of assignment uncertainties
- Using rate information on SUSY final states



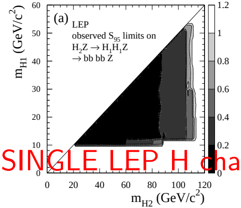
- Parametrise σ in $m_{\tilde{g}}, m_{\tilde{q}}$, parametrise ϵ (fast sim), calculate $\mathcal{B}$ arXiv:1003.2648 [hep-ph]
- Direct/Indirect Detection Limits/Discoveries?

Challenges for Interpretation and Data Preservation

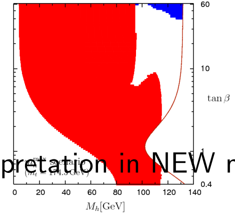




Not very useful, sincde channels are convoluted



One SINGLE LEP H channel

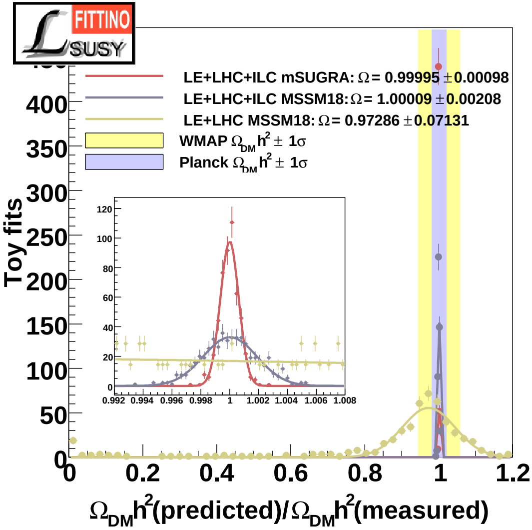


Interpretation in NEW model

Can only go from experimental result to new interpretation if detector resonse to each signature is known individually

Precise collider "prediction" of Ω_{CDM}

- Compare without assuming unification at the GUT scale:



Summary

- The SM (w/o Higgs) will have to be expanded by at least one feature at the Terascale
- SUSY solves many challenges, in theory and experiment
- SUSY has a rich phenomenology: Perfect for preparing for New Physics
- LHC Experiments are starting with exceptional understanding of the detectors
- Many analyses ongoing to completely understand the detectos, the beams and the reconstruction
- Discovery of SUSY unsing $1\,\mathrm{fb}$ @ $7\,\mathrm{TeV}$ is possible
- Available data prefers LE SUSY (mainly $(g-2)_\mu$ and Ω_{CDM} though . . .)
- Many activities and advancements on the field of trying to understand New Physics