Dark Matter and Missing Energy at the LHC

Tilman Plehn

Heidelberg

MPI für Kernphysik 11/2009

Outline

Mass reconstruction (relativistic kinematics)

Underlying parameters (statistics and errors)

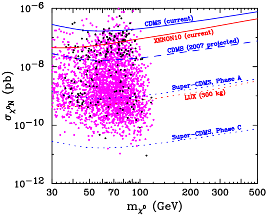
Effective Standard Model in the LHC era

Expectations from the LHC [Uli Baur's rule: 'there is always new physics at higher scales']

- find light Higgs?
- find new physics stabilizing Higgs mass?
- see dark–matter candidate (WIMP)?

Particle theory and new physics

- model–independent analyses likely not helpful
- testing testable hypotheses [theory: e.g. Higgs sector and underlying theory?]
  discrete hypotheses: spins,....
  continuous hypotheses: masses,...
- link to other observations [DM+Tevatron: Hooper, TP, Valinotto]
- reconstruction of Lagrangian [theory+experiment]



Effective Standard Model in the LHC era

Expectations from the LHC [Uli Baur's rule: 'there is always new physics at higher scales']

- find light Higgs?
- find new physics stabilizing Higgs mass?
- see dark–matter candidate (WIMP)?

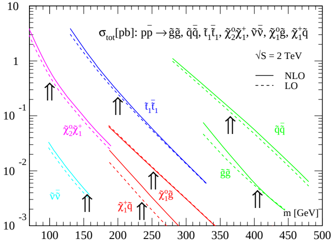
Particle theory and new physics

- model–independent analyses likely not helpful
- testing testable hypotheses [theory: e.g. Higgs sector and underlying theory?]
  discrete hypotheses: spins,....
  continuous hypotheses: masses,...
- link to other observations [DM+Tevatron: Hooper, TP, Valinotto]
- reconstruction of Lagrangian [theory+experiment]

Special about LHC [except bigger than Tevatron]

- beyond inclusive searches [that was Tevatron]
  lots of strongly interacting particles
  cascade decays to DM candidate
- survive QCD (serious theory problem)

$\Rightarrow$ aim at underlying theory



Effective Standard Model in the LHC era

Expectations from the LHC [Uli Baur's rule: 'there is always new physics at higher scales']

– find light Higgs?

– find new physics stabilizing Higgs mass?

– see dark–matter candidate (WIMP)?

Particle theory and new physics

– model–independent analyses likely not helpful

– testing testable hypotheses [theory: e.g. Higgs sector and underlying theory?]
discrete hypotheses: spins,....
continuous hypotheses: masses,...

– link to other observations [DM+Tevatron: Hooper, TP, Valinotto]

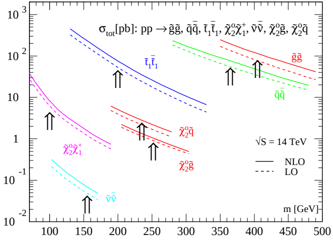
– reconstruction of Lagrangian [theory+experiment]

Special about LHC [except bigger than Tevatron]

– beyond inclusive searches [that was Tevatron]
lots of strongly interacting particles
cascade decays to DM candidate

– survive QCD (serious theory problem)

$\Rightarrow$ aim at underlying theory



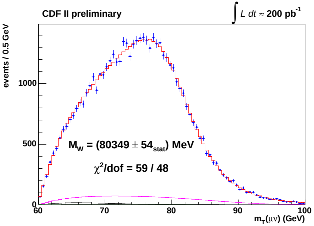
Transverse mass

Learning from neutrinos...

- $W \to \ell\nu$ decay to invisible particles
- longitudinal boost unobserved at hadron colliders
- transverse instead of invariant W mass $[E_T^2 = \vec{p}_T^2 + m^2$, observed 2D $\vec{p}_T]$

$$m_{T,W}^2 = \left(E_T^{\text{miss}} + E_{T,\ell} \right)^2 - \left(\vec{p}_T^{\text{miss}} + \vec{p}_{T,\ell} \right)^2$$
$$= m_\ell^2 + m_{\text{miss}}^2 + 2 \left(E_{T,\ell} E_T^{\text{miss}} - \vec{p}_{T,\ell} \cdot \vec{p}_T^{\text{miss}} \right) \le m_W$$

$\Rightarrow$ m_W from endpoint and shape



Transverse mass

Learning from neutrinos...

- $W \to \ell\nu$ decay to invisible particles
- longitudinal boost unobserved at hadron colliders
- transverse instead of invariant W mass [$E_T^2 = \vec{p}_T^2 + m^2$, observed 2D $\vec{p}_T$]

$$m_{T,W}^2 = \left(E_T^{\text{miss}} + E_{T,\ell}\right)^2 - \left(\vec{p}_T^{\text{miss}} + \vec{p}_{T,\ell}\right)^2$$
$$= m_\ell^2 + m_{\text{miss}}^2 + 2\left(E_{T,\ell}E_T^{\text{miss}} - \vec{p}_{T,\ell}\cdot\vec{p}_T^{\text{miss}}\right) \le m_W$$

$\Rightarrow$ m_W from endpoint and shape

- two invisible particles: $H \to WW \to \ell\nu\,\ell\nu$

$$m_{T,WW}^2 = \left(E_T^{\text{miss}} + E_{T,\ell\ell}\right)^2 - \left(\vec{p}_T^{\text{miss}} + \vec{p}_{T,\ell\ell}\right)^2$$
$$= m_{\ell\ell}^2 + m_{\text{miss}}^2 + 2\left(E_{T,\ell\ell}E_T^{\text{miss}} - \vec{p}_{T,\ell\ell}\cdot\vec{p}_T^{\text{miss}}\right)$$

- assumption needed:
  $m_{\text{miss}} = m_{\ell\ell}$ sharp peak
  $m_{\text{miss}} = 0$ endpoint [general $m_T < m$]

$\Rightarrow$ $H \to WW$ at Tevatron and LHC [Kauer, TP, Rainwater, Zeppenfeld; Barr, Gripaios, Lester]

$\Rightarrow$ massive invisible particles and decay chains...?

Transverse masses

M_{T2} algorithm [Lester, Summers; Barr, Lester, Stephens]

– SUSY process $pp \to \tilde{\ell}\tilde{\ell}^* \to \ell\tilde{\chi}_1^0\ \ell\tilde{\chi}_1^0$ [massive particles, balancing $\vec{p}_T^{\,\text{miss}}$]

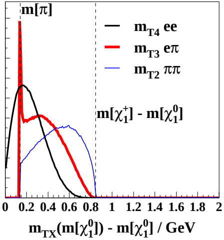
– (in)famous m_{T2} [for m_{miss} hypothesis]

$$m_{T2}(m_{\text{miss}}) = \min_{\vec{p}_T^{\,\text{miss}} = \not{q}_1 + \not{q}_2} \left[\max_j \ m_{T,j}(\not{q}_j; m_{\text{miss}}) \right]$$

– $m_{\text{daughter}}^{(1)} + m_{\text{daughter}}^{(2)} < m_{T2} < m_{\text{mother}}$ sharp endpoint [for correct m_{miss}]

– constraint in $m_{\tilde{\ell}} - m_{\tilde{\chi}_1^0}$ plane

m_{TX} with more invisible particles not as promising [$\nu\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$ etc]



Transverse masses

M_{T2} algorithm [Lester, Summers; Barr, Lester, Stephens]

– SUSY process $pp \to \tilde\ell\tilde\ell^* \to \ell\tilde\chi_1^0\ \ell\tilde\chi_1^0$ [massive particles, balancing $\vec{p}_T^{\rm miss}$]

– (in)famous m_{T2} [for $m_{\rm miss}$ hypothesis]

$$m_{T2}(m_{\rm miss}) = \min_{\vec{p}_T^{\rm miss}=\not{q}_1+\not{q}_2} \left[\max_j \ m_{T,j}(\not{q}_j; m_{\rm miss}) \right]$$

– $m_{\rm daughter}^{(1)} + m_{\rm daughter}^{(2)} < m_{T2} < m_{\rm mother}$ sharp endpoint [for correct $m_{\rm miss}$]

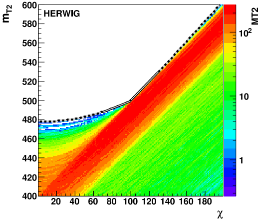
– constraint in $m_{\tilde\ell} - m_{\tilde\chi_1^0}$ plane
m_{TX} with more invisible particles not as promising [$\nu\nu\tilde\chi_1^0\tilde\chi_1^0$ etc]

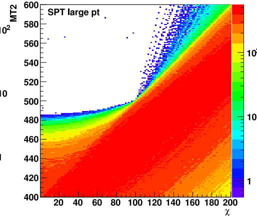
– m_{T2} boost invariant only for correct $m_{\rm miss}$

– scan over $m_{\rm miss}$
accumulation points for many events [Cho, Choi, Kim, Park; Barr, Gripaios, Lester]

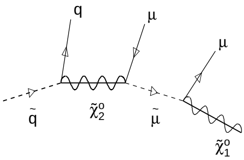
– kink for pairwise three-particle decays $pp \to \tilde\chi_2^0\tilde\chi_2^0 \to f\bar{f}\tilde\chi_1^0\ f\bar{f}\tilde\chi_1^0$

$\to$ determine missing mass





Mass relations



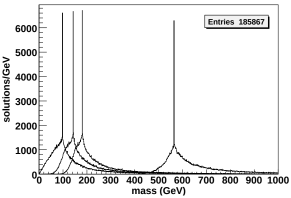
Same masses in all events [Nojiri, Tovey; McElrath etal; Webber]

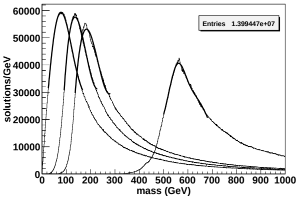
– on-shell decay chain $\tilde{q}_L \to \tilde{\chi}_2^0 \to \tilde{\ell} \to \tilde{\chi}_1^0$

$$(p_1 + p_2 + p_3 + \vec{p}^{\text{miss}})^2 = m_{\tilde{q}_L}^2$$
$$(p_2 + p_3 + \vec{p}^{\text{miss}})^2 = m_{\tilde{\chi}_2^0}^2$$
$$(p_3 + \vec{p}^{\text{miss}})^2 = m_{\tilde{\ell}}^2$$
$$(\vec{p}^{\text{miss}})^2 = m_{\tilde{\chi}_1^0}^2$$

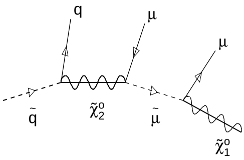
– pair production, $\vec{p}_T^{\text{miss}}$ measured: 4+2 constraints for 8 unknowns [McElrath etal]

– two events: 12+4 constraints for 16 unknowns
solve for invisible momenta, extract masses [quantum effects, detector effects]





Mass relations



Same masses in all events [Nojiri, Tovey; McElrath etal; Webber]

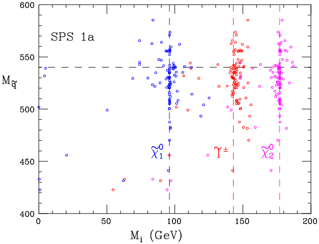
– on-shell decay chain $\tilde{q}_L \to \tilde{\chi}_2^0 \to \tilde{\ell} \to \tilde{\chi}_1^0$

$$(p_1 + p_2 + p_3 + \vec{p}^{\text{miss}})^2 = m_{\tilde{q}_L}^2$$
$$(p_2 + p_3 + \vec{p}^{\text{miss}})^2 = m_{\tilde{\chi}_2^0}^2$$
$$(p_3 + \vec{p}^{\text{miss}})^2 = m_{\tilde{\ell}}^2$$
$$(\vec{p}^{\text{miss}})^2 = m_{\tilde{\chi}_1^0}^2$$

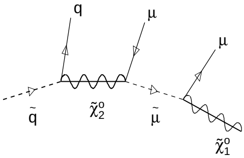
– pair production, $\vec{p}_T^{\text{miss}}$ measured: 4+2 constraints for 8 unknowns [McElrath etal]

– two events: 12+4 constraints for 16 unknowns
solve for invisible momenta, extract masses [quantum effects, detector effects]

– alternative: samples of 25 events [Webber]
fast numerical inversion/goodness of fit



Mass relations



Same masses in all events [Nojiri, Tovey; McElrath etal; Webber]

– on-shell decay chain $\tilde{q}_L \to \tilde{\chi}_2^0 \to \tilde{\ell} \to \tilde{\chi}_1^0$

$$\begin{aligned}(p_1 + p_2 + p_3 + \vec{p}^{\text{miss}})^2 &= m^2_{\tilde{q}_L} \\ (p_2 + p_3 + \vec{p}^{\text{miss}})^2 &= m^2_{\tilde{\chi}_2^0} \\ (p_3 + \vec{p}^{\text{miss}})^2 &= m^2_{\tilde{\ell}} \\ (\vec{p}^{\text{miss}})^2 &= m^2_{\tilde{\chi}_1^0}\end{aligned}$$

– pair production, $\vec{p}_T^{\text{miss}}$ measured: 4+2 constraints for 8 unknowns [McElrath etal]

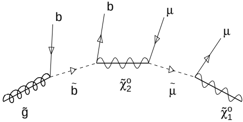
– two events: 12+4 constraints for 16 unknowns
solve for invisible momenta, extract masses [quantum effects, detector effects]

– alternative: samples of 25 events [Webber]
fast numerical inversion/goodness of fit

$\to$ working scheme for LHC [backgrounds etc to be checked]

$\delta p/p$	ξ^2_{max}	f_ξ	f_{cor}	$M_{\tilde{q}}$ (540)	$M_{\tilde{\chi}_2^0}$ (177)	$M_{\tilde{\ell}}$ (143)	$M_{\tilde{\chi}_1^0}$ (96)
0	∞	100%	72%	538 ± 20	176 ± 12	143 ± 7	95 ± 10
0	100	80%	76%	539 ± 7	177 ± 1	144 ± 1	96 ± 2
5%	∞	100%	52%	534 ± 28	176 ± 11	143 ± 10	95 ± 13
5%	100	57%	55%	539 ± 9	178 ± 3	144 ± 2	96 ± 4
10%	∞	100%	40%	522 ± 37	171 ± 18	140 ± 17	88 ± 26
10%	200	42%	43%	530 ± 22	173 ± 12	140 ± 12	89 ± 20

Kinematic endpoints

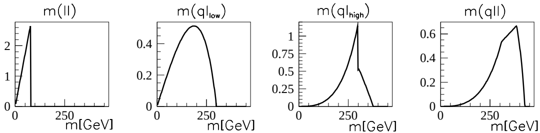


Cascade decays [Atlas-TDR, Cambridge people]

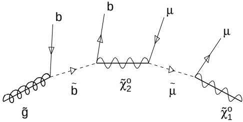
- new particles strongly interacting and LSP weakly interacting
- long chain $\tilde g \to \tilde b \bar b \to \tilde\chi^0_2 b\bar b \to \mu^+\mu^- b\bar b \tilde\chi^0_1$
- tough: $(\sigma \mathrm{BR})_1/(\sigma \mathrm{BR})_2$ [model dependence, QCD uncertainty] easier: kinematics
- thresholds & edges

$$0 < m^2_{\mu\mu} < \frac{m^2_{\tilde\chi^0_2} - m^2_{\tilde\ell}}{m_{\tilde\ell}} \; \frac{m^2_{\tilde\ell} - m^2_{\tilde\chi^0_1}}{m_{\tilde\ell}}$$

- new–physics mass spectrum from endpoints
- new–physics spins from shapes [Barr, Lester, Smillie, Webber; Alves, Eboli, TP;...]



Kinematic endpoints



Cascade decays [Atlas-TDR, Cambridge people]

– new particles strongly interacting and LSP weakly interacting

– long chain $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$

– tough: $(\sigma \mathrm{BR})_1/(\sigma \mathrm{BR})_2$ [model dependence, QCD uncertainty]
easier: kinematics

– thresholds & edges

$$0 < m^2_{\mu\mu} < \frac{m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}}}{m_{\tilde{\ell}}} \; \frac{m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}$$

– new–physics mass spectrum from endpoints

– new–physics spins from shapes [Barr, Lester, Smillie, Webber; Alves, Eboli, TP;...]

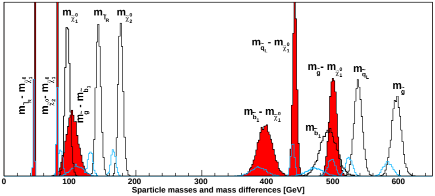
Gluino decay [Gjelsten, Miller, Osland, Raklev...]

– only b jets [otherwise dead by QCD]

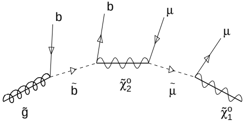
– no problem: off-shell [Catpiss]

– no problem: jet radiation?

– gluino mass to $\sim 1\%$



Kinematic endpoints



Cascade decays [Atlas-TDR, Cambridge people]

- new particles strongly interacting and LSP weakly interacting
- long chain $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$
- tough: $(\sigma\mathrm{BR})_1/(\sigma\mathrm{BR})_2$ [model dependence, QCD uncertainty]
  easier: kinematics
- thresholds & edges

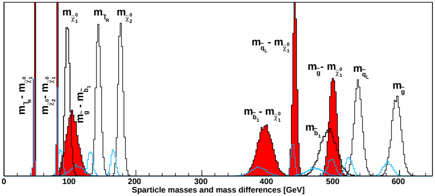
$$0 < m_{\mu\mu}^2 < \frac{m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2}{m_{\tilde{\ell}}} \; \frac{m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\ell}}}$$

- new–physics mass spectrum from endpoints
- new–physics spins from shapes [Barr, Lester, Smillie, Webber; Alves, Eboli, TP;...]

Gluino decay [Gjelsten, Miller, Osland, Raklev...]

- only b jets [otherwise dead by QCD]
- no problem: off-shell [Catpiss]
- no problem: jet radiation?
- gluino mass to $\sim 1\%$

$\Rightarrow$ but why physical masses?



Underlying parameters

From kinematics to weak–scale parameters [Fittino; SFitter: Lafaye, TP, Rauch, Zerwas]

– parameters: weak-scale Lagrangian

– measurements: edges or masses,
branching fractions, rates,... [NLO, of course]
ew precision, dark matter,...

– errors: general correlation, statistics & systematics & theory [flat theory errors!]

– problem in grid: no local maximum
problem in fit: no global maximum
problem in interpretation: bad observables, secondary maxima?

Probability maps of new physics [Baltz,...; Roszkowski,...; Allanach,...; SFitter]

– want probability of model being true $p(m|d)$

– can do exclusive likelihood map $p(d|m)$ over m

– LHC challenge: poor data [e.g. endpoints vs rates]

– Bayesian: $p(m|d) \sim p(d|m)\, p(m)$ [cosmology, BSM]
frequentist: best–fitting point $\max_m p(d|m)$ [flavor, Higgs@LHC]

– LHC era: (1) compute high-dimensional map $p(d|m)$
(2) find and rank local best-fitting points
(3) predict additional observables

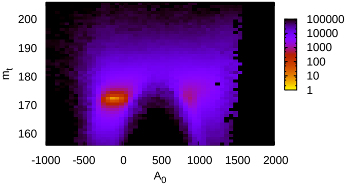
Correlations and errors

Toy model: MSUGRA map from LHC [LHC endpoints with free y_t]

– model unrealistic but useful testing ground

– SFitter output #1: fully exclusive likelihood map
  SFitter output #2: ranked list of local maxima

$\Rightarrow$ correlations and secondary maxima significant



χ^2	m_0	$m_{1/2}$	$\tan\beta$	A_0	μ	m_t
0.3e-04	100.0	250.0	10.0	-99.9	+	171.4
27.42	99.7	251.6	11.7	848.9	+	181.6
54.12	107.2	243.4	13.3	-97.4	-	171.1
70.99	108.5	246.9	13.9	26.4	-	173.6
88.53	107.7	245.9	12.9	802.7	-	182.7
...						

Correlations and errors

Toy model: MSUGRA map from LHC [LHC endpoints with free y_t]

– model unrealistic but useful testing ground

– SFitter output #1: fully exclusive likelihood map
SFitter output #2: ranked list of local maxima

$\Rightarrow$ correlations and secondary maxima significant

A word on errors

– statistical errors Gaussian
systematic errors Gaussian, correlated
theory errors flat

– RFit scheme

[CKMFitter, profile likelihood inspired]

$$\chi^2 = -2 \log \mathcal{L} = \vec{\chi}_d^T \, C^{-1} \, \vec{\chi}_d$$

$$\chi_{d,i} = \begin{cases} 0 & |d_i - \bar{d}_i| < \sigma_i^{\text{(theo)}} \\ \frac{\mathcal{D}|d_i - \bar{d}_i| - \sigma_i^{\text{(theo)}}}{\mathcal{D}\sigma_i^{\text{(exp)}}} & |d_i - \bar{d}_i| > \sigma_i^{\text{(theo)}} \end{cases},$$

$$C_{i,i} = 1 \qquad C_{i,j} = C_{j,i} = \frac{0.99 \, \sigma_i^{(\ell)} \, \sigma_j^{(\ell)} + 0.99 \, \sigma_i^{\text{(j)}} \, \sigma_j^{\text{(j)}}}{\sigma_i^{\text{(exp)}} \, \sigma_j^{\text{(exp)}}}$$

Correlations and errors

Toy model: MSUGRA map from LHC [LHC endpoints with free y_t]

– model unrealistic but useful testing ground
– SFitter output #1: fully exclusive likelihood map
  SFitter output #2: ranked list of local maxima
⇒ correlations and secondary maxima significant

A word on errors

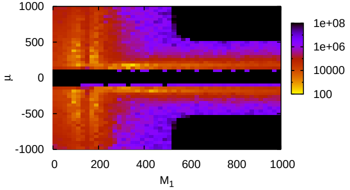
– statistical errors Gaussian
  systematic errors Gaussian, correlated
  theory errors flat
– theory error sizeable
⇒ endpoints instead of masses

	SPS1a	$\Delta^{\rm theo-exp}_{\rm zero}$	$\Delta^{\rm expNoCorr}_{\rm zero}$	$\Delta^{\rm theo-exp}_{\rm zero}$	$\Delta^{\rm theo-exp}_{\rm gauss}$	$\Delta^{\rm theo-exp}_{\rm flat}$
		masses	endpoints			
m_0	100	4.11	1.08	0.50	2.97	2.17
$m_{1/2}$	250	1.81	0.98	0.73	2.99	2.64
$\tan\beta$	10	1.69	0.87	0.65	3.36	2.45
A_0	-100	36.2	23.3	21.2	51.5	49.6
m_t	171.4	0.94	0.79	0.26	0.89	0.97

TeV-scale MSSM: SFitter

MSSM map from LHC mass measurements

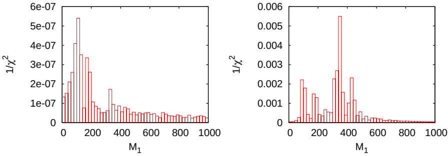
– 19D parameter space [Markov chain globally + hill climber locally]
– SFitter outputs #1 and #2 still the same
– three neutralinos observed [left: Bayesian — right: likelihood]



TeV-scale MSSM: SFitter

MSSM map from LHC mass measurements

- 19D parameter space [Markov chain globally + hill climber locally]
- SFitter outputs #1 and #2 still the same
- three neutralinos observed [left: Bayesian — right: likelihood]



- quality of fit all the same...

	$\mu < 0$				$\mu > 0$			
M_1	96.6	175.1	103.5	365.8	98.3	176.4	105.9	365.3
M_2	181.2	98.4	350.0	130.9	187.5	103.9	348.4	137.8
μ	-354.1	-357.6	-177.7	-159.9	347.8	352.6	178.0	161.5
$\tan\beta$	14.6	14.5	29.1	32.1	15.0	14.8	29.2	32.1
M_3	583.2	583.3	583.3	583.5	583.1	583.1	583.3	583.4
$M_{\tilde{\mu}_L}$	192.7	192.7	192.7	192.9	192.6	192.6	192.7	192.8
$M_{\tilde{\mu}_R}$	131.1	131.1	131.1	131.3	131.0	131.0	131.1	131.2
$A_t\ (-)$	-252.3	-348.4	-477.1	-259.0	-470.0	-484.3	-243.4	-465.7
$A_t\ (+)$	384.9	481.8	641.5	432.5	739.2	774.7	440.5	656.9
m_A	350.3	725.8	263.1	1020.0	171.6	156.5	897.6	256.1
m_t	171.4	171.4	171.4	171.4	171.4	171.4	171.4	171.4

$\Rightarrow$ combination with astro-particle measurements...

Outlook

Once we actually see LHC data...

– from neutrinos we know invisible particles

– WIMP the same, but massive

– transverse masses for short decays
mass relations for pure samples
cascade endpoints including spin info

– missing: co-transverse mass [Tovey]

– missing: dark matter sectors [Dama, Pamela, Atic, Fermi]

$\Rightarrow$ LHC more than a discovery machine!