Collider Signatures of Dark Matter

Lecture 2

- **Multi-Lepton Signatures**
  - **Tevatron**
  - **LHC**
- **Models**
- **ILC**

Michael Schmitt
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SLAC Summer Institute, August 3, 2007

conclusions from lecture 1

- A missing-energy signal is required if the WIMP-miracle paradigm is true.
- So far, no sign for dark matter particles at the Tevatron.
- We plan to follow the same approach at the LHC, and we expect to see a signal...

Suppose we observe a signal in the Jets+MET channel - how do we confirm that we are producing DM particles?

→ **We need to confirm the underlying theory in detail.**

Find additional signals for new physics → reveal the theory.

Example: The "tri-Lepton" Search

Rare SM processes can be identified by the presence of leptons, so let's try that strategy with SUSY processes, too.

Charginos and neutralinos are the spin-1/2 SUSY partners of (W and charged Higgs), and (γ, Z and neutral Higgs bosons).

Schematically speaking, their decays will resemble those of their SM partners, except for the "extra" LSP at the end of the decay chain.

e.g., charginos decay to 2 fermions + LSP

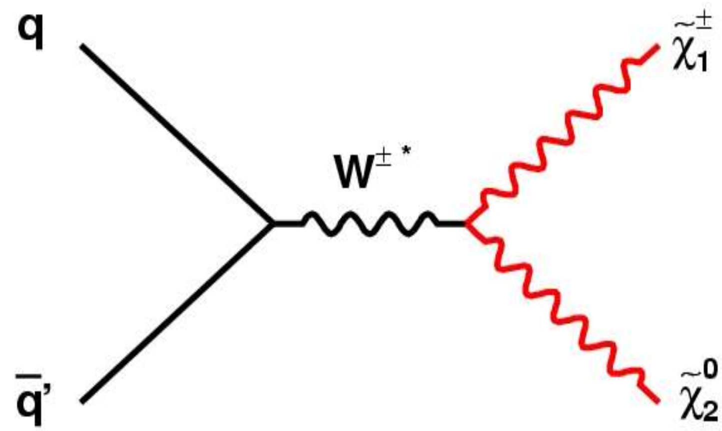
DM particle

- Single-lepton events come from inclusive W production and ttbar.
- Double-lepton events come from inclusive Z (Drell-Yan) and ttbar.
- So, ***look for triple-lepton events***...

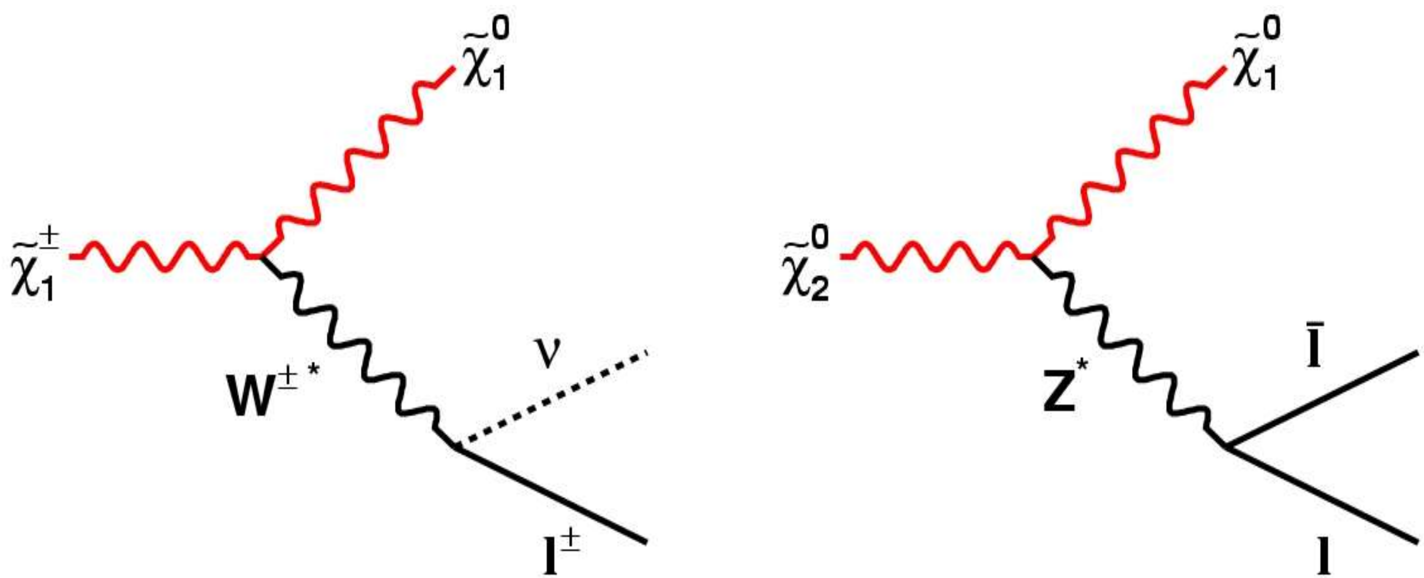
The tri-lepton Search

To be more specific, this is what we are after:

production:



decay:



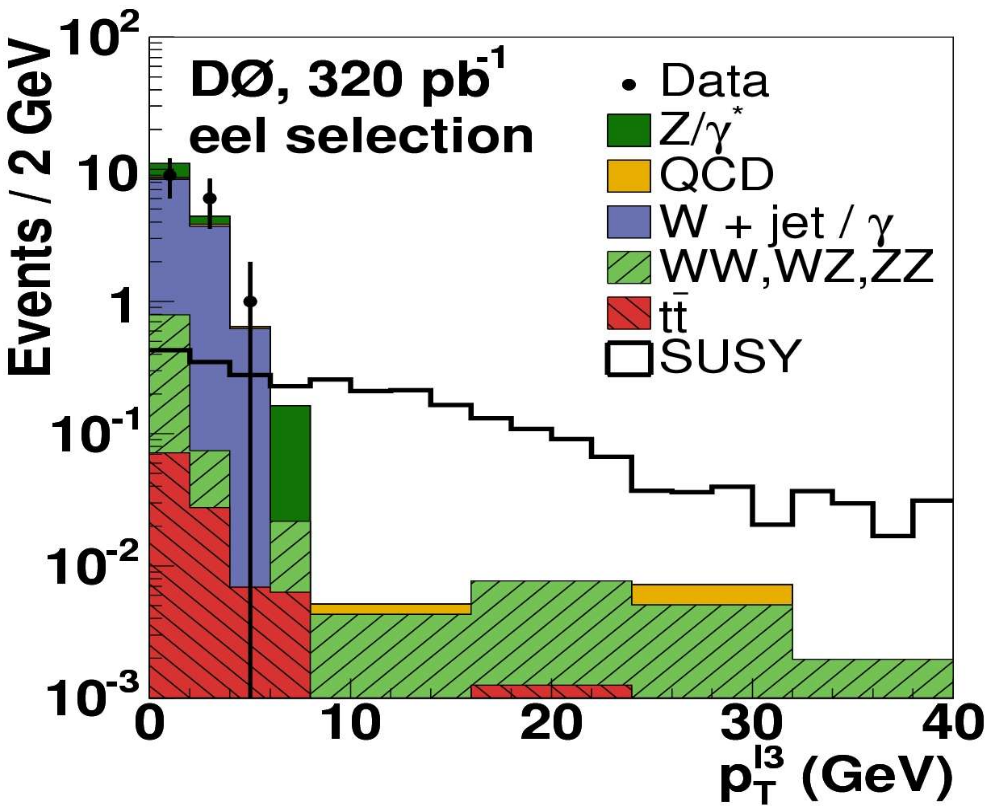
One lepton comes from the chargino, and two leptons come from the neutralino.
There is lots of missing transverse energy, too!

Again, we know that charginos and neutralinos are heavy (> 100 GeV).

This ensures that the leptons will be **energetic.**

They will also tend to be **isolated** in the sense that they will not be part of a jet.

(A troublesome source of leptons are jets with b-hadrons or c-hadrons, which sometimes decay semileptonically, giving us a lepton and a neutrino (=MET). The key point is that the leptons from b- or c-decays come associated with hadrons that are produced with the b- or c-quarks, and also in the b- and c-decays. So, we veto any leptons which have hadrons near by.)



This plot shows the discriminating power of the energy cuts (p_T) on the third lepton.

The SUSY curve corresponds to an optimistic but not crazy scenario.

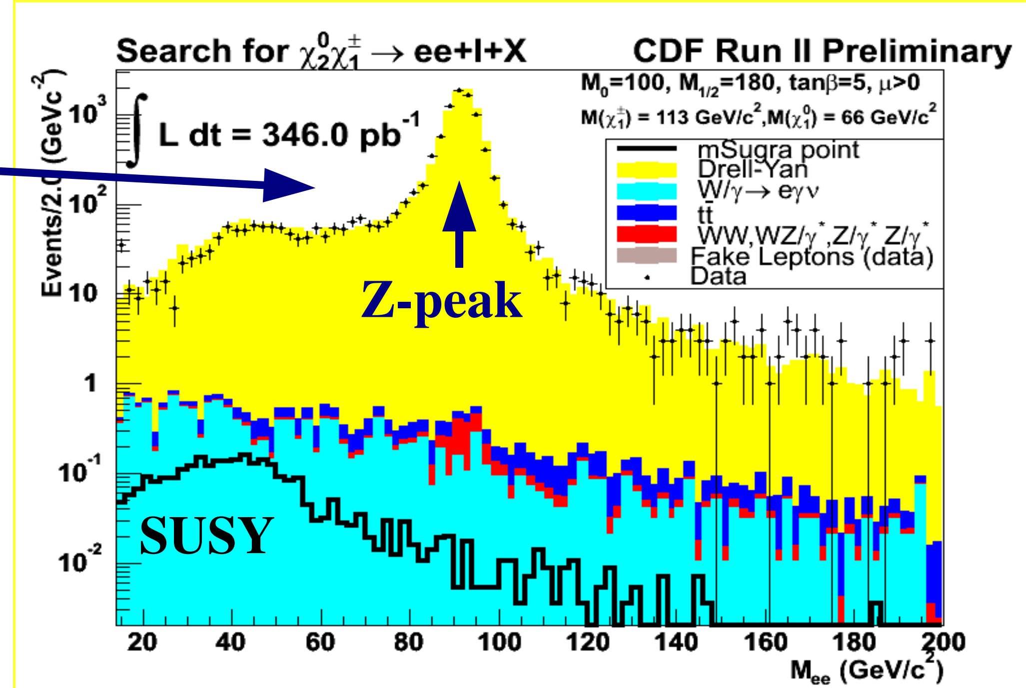
D0 published! hep-ex/0504032

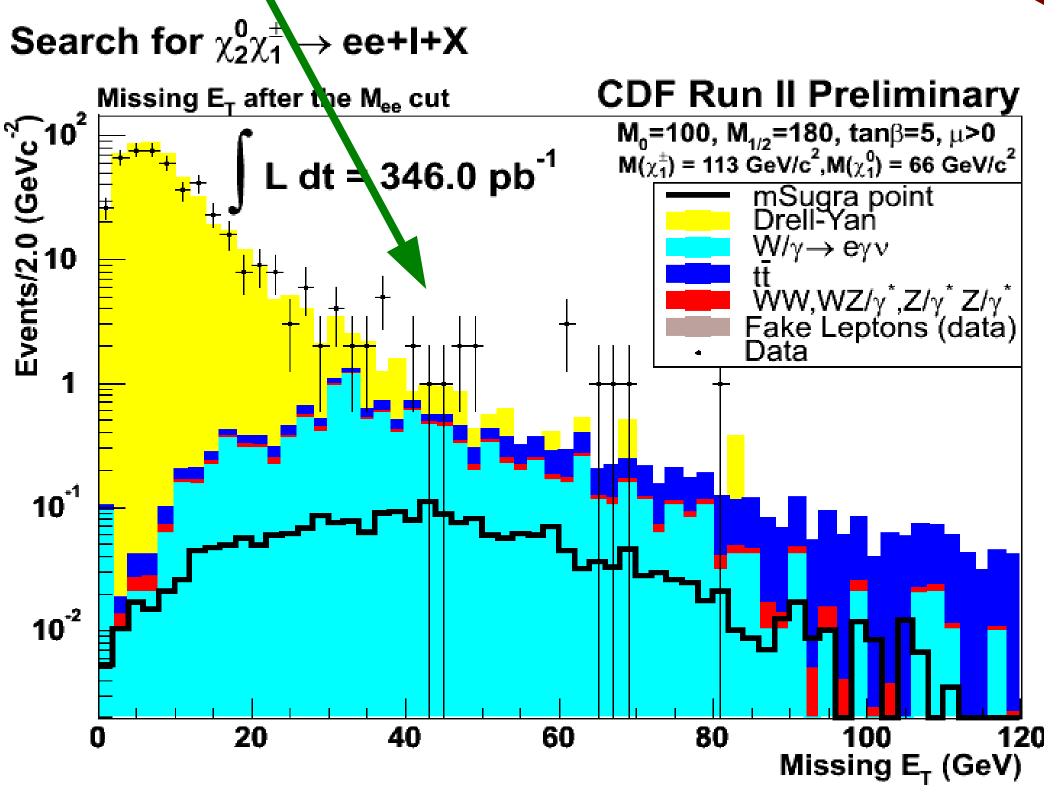
These plots show the power of the other cuts.

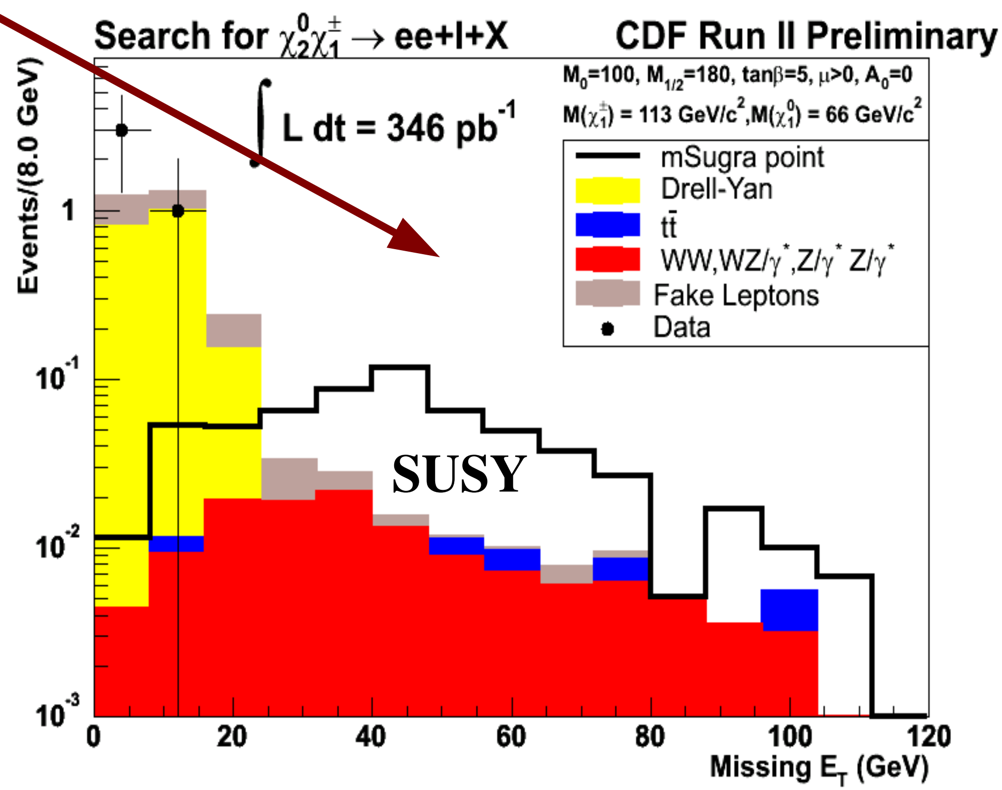
Overall di-electron mass spectrum.

MET distribution after cutting out the Z-peak.

MET distribution after all cuts.

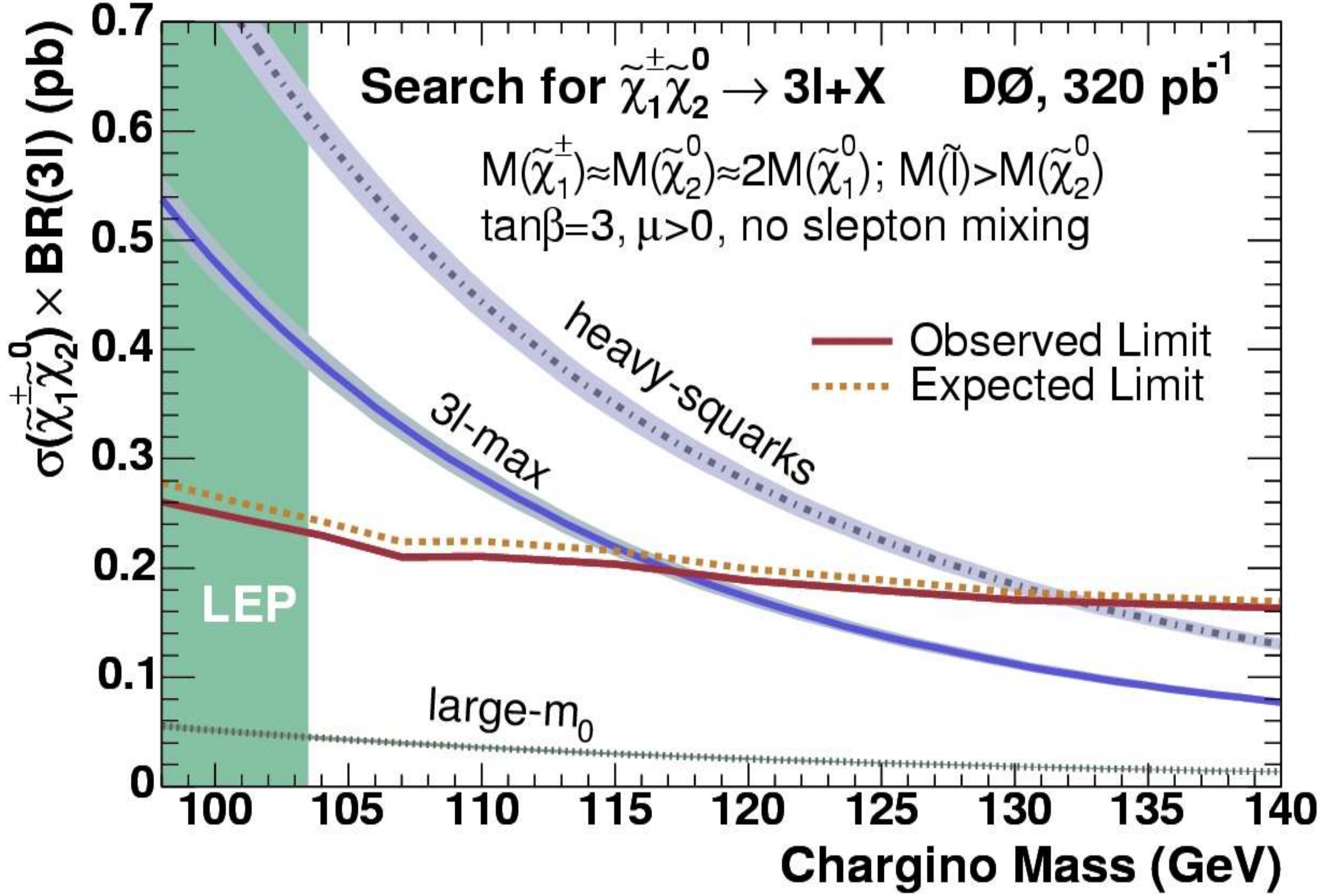






Limits from the tri-Lepton Search

Again, no evidence for any excess, so we can only place limits on SUSY cross sections, or equivalently, masses.



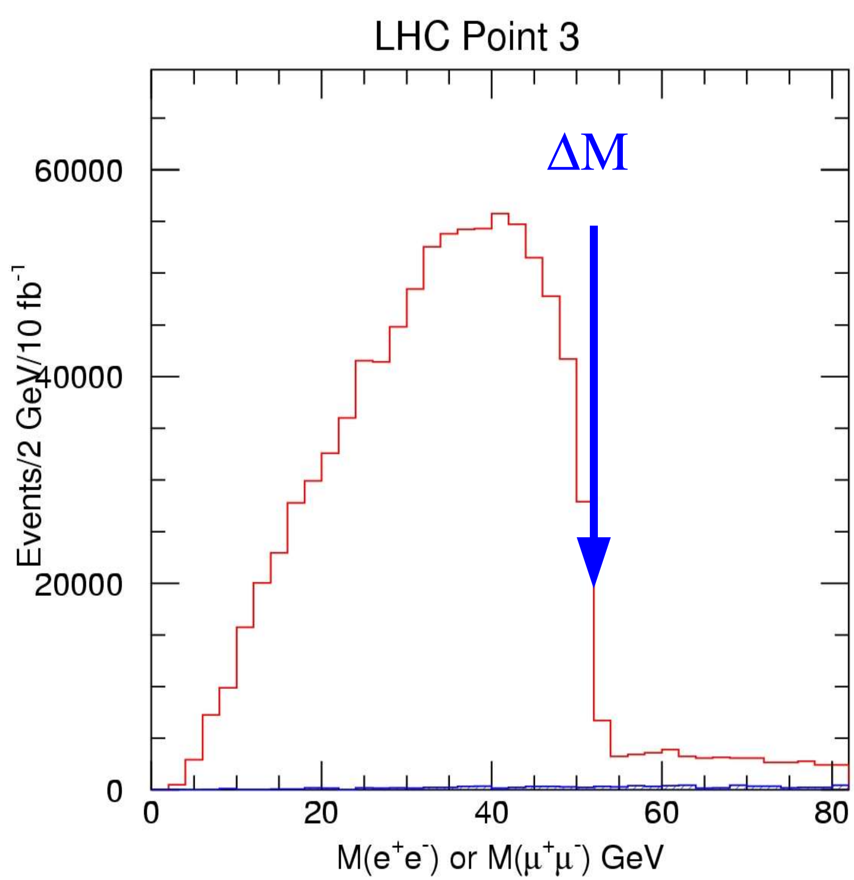
hep-ex/0504032

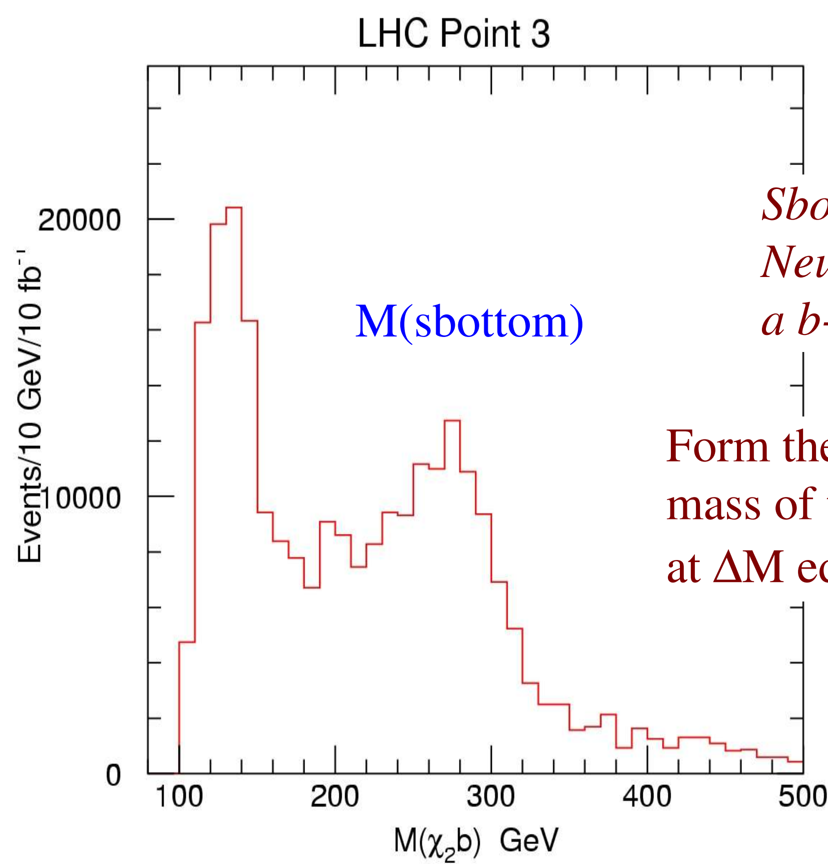
Lepton-based Searches at the LHC

Lepton-based signals at the LHC could be very impressive –
even the di-lepton + MET signature might be background-free!

With large distinctive signatures, we might be able to infer masses of SUSY particles (or combinations of SUSY particles).

Here is an example of a neutralino signal: Neutralino(2) $\rightarrow$ $\mu^+\mu^-$ + Neutralino(1)





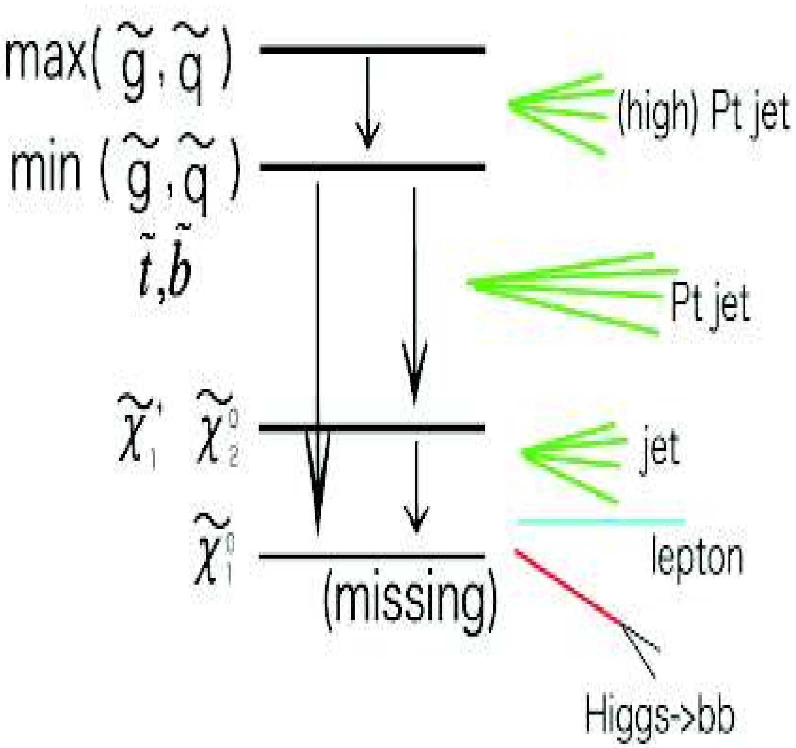
hep-ph/9610544

Sbottom decays to Neutralino(2) and a b-quark.

Form the invariant mass of the Neutralino(2) at ΔM edge, and a b-jet.

Measure Dark Matter Particle Properties

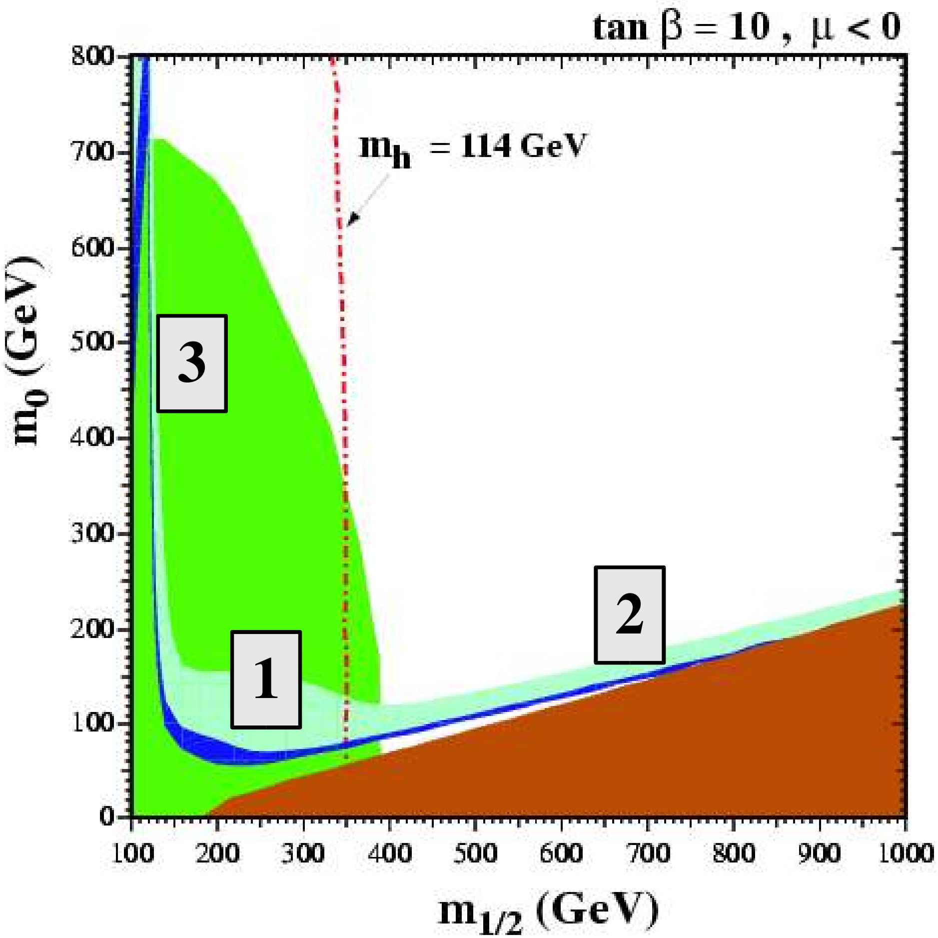
mass **spin** **couplings**

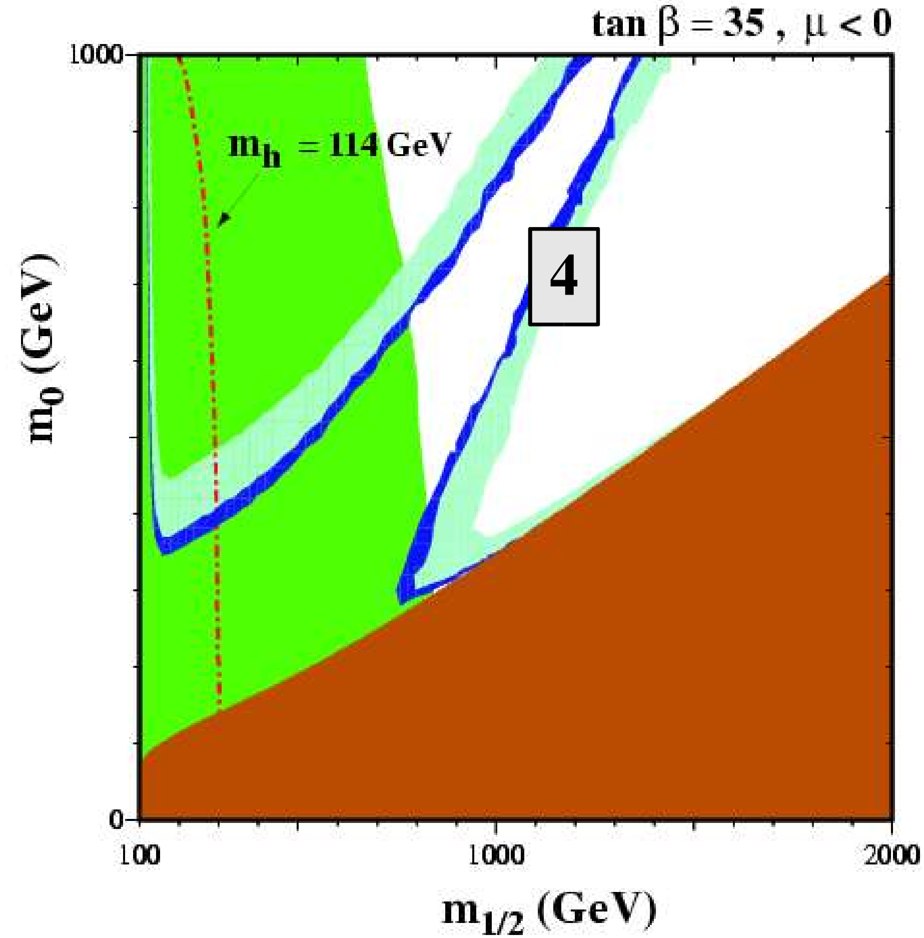


- **no general way to obtain the mass, yet.**
- **no way to obtain spin and couplings**
- **no branching ratios....**

- **must infer these quantities indirectly, assume relations among "similar" particles**
- **before we have data, case studies.**

One Model out of Many





Ellis *et al.*, Baer & Tata, for example

Identify several regions giving the right relic density ("WIMP Miracle"), distinguished by the method for efficient annihilation.

1) "bulk" ***2) "co-annihilation"*** ***3) "focus-point"*** ***4) "funnel"***

light sfermions *degeneracy w/ stau or stop* *gauge bosons* *CP-odd Higgs*

"Easy" Point in the Bulk Region

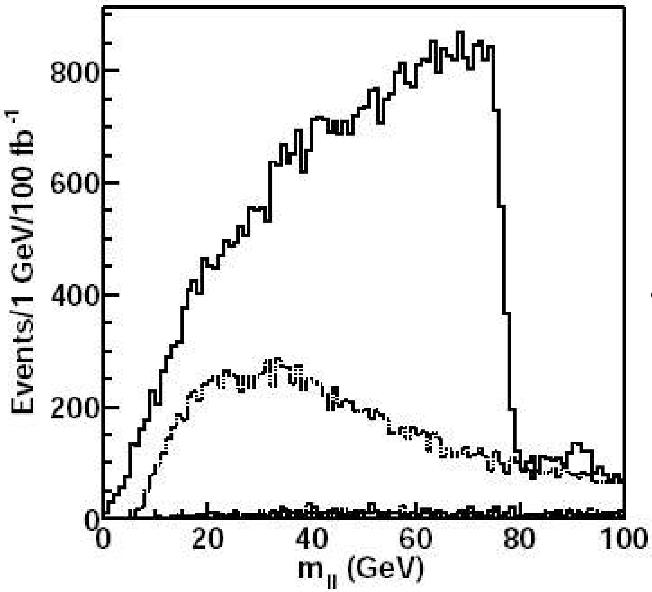
squarks around 550 GeV, gluino around 600, neutralino at 96 GeV

start here ↓ ... ↓ *end here*

$$\tilde{g} \to \tilde{q}_L q \qquad \tilde{q}_L \to \tilde{\chi}_2^0 q \qquad \tilde{\chi}_2^0 \to \tilde{l}_R l \qquad \tilde{l}_R \to \tilde{\chi}_1^0 l$$

- reconstruct chain from bottom up, use kinematic features opportunistically
- ask for 4 high-E_T jets, larget MET and two opposite-sign leptons (e or μ)
- only serious background: ttbar, which gives eμ as often as ee+μμ
- di-lepton invariant mass has a sharp edge:
  - depends on masses of two neutralinos and the (light) slepton mass
  - edge measured to a fraction of a GeV
  - talk about "miracles"

ATLAS 100 fb^{-1}



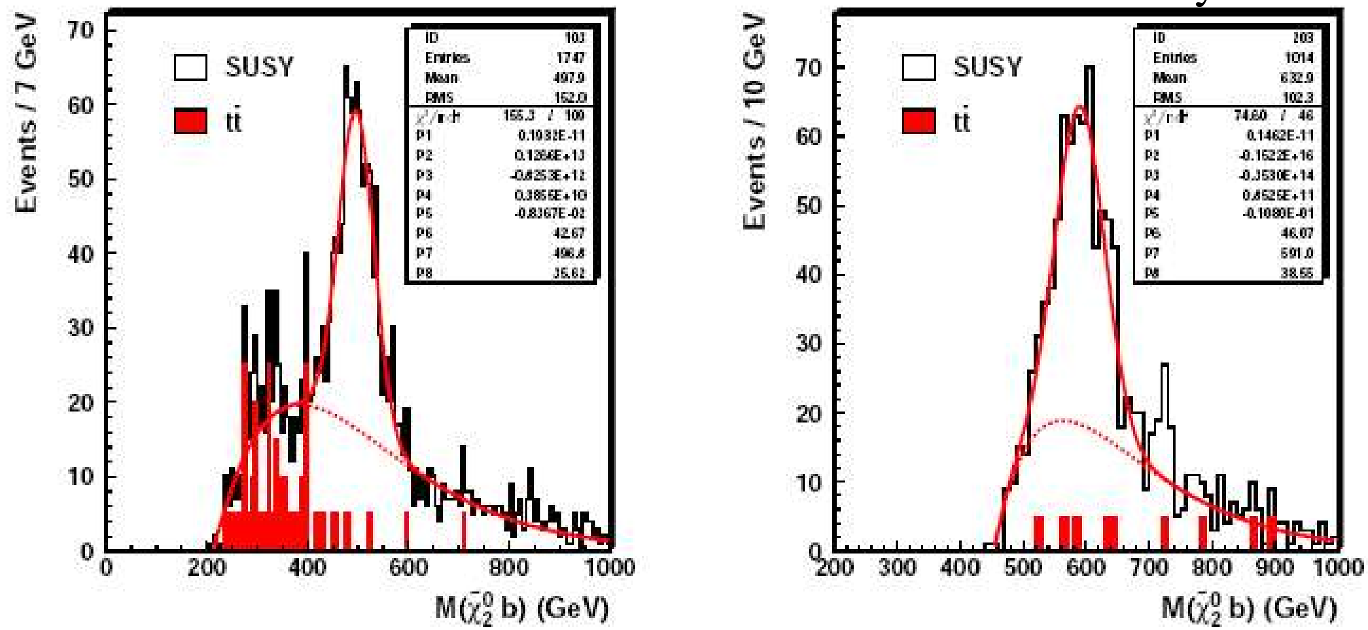
LHC-ILC study

Make clever use of kinematic extremes, possible when event samples are very large.

One can reconstruct squark masses, and then gluino masses.

does not give M_χ

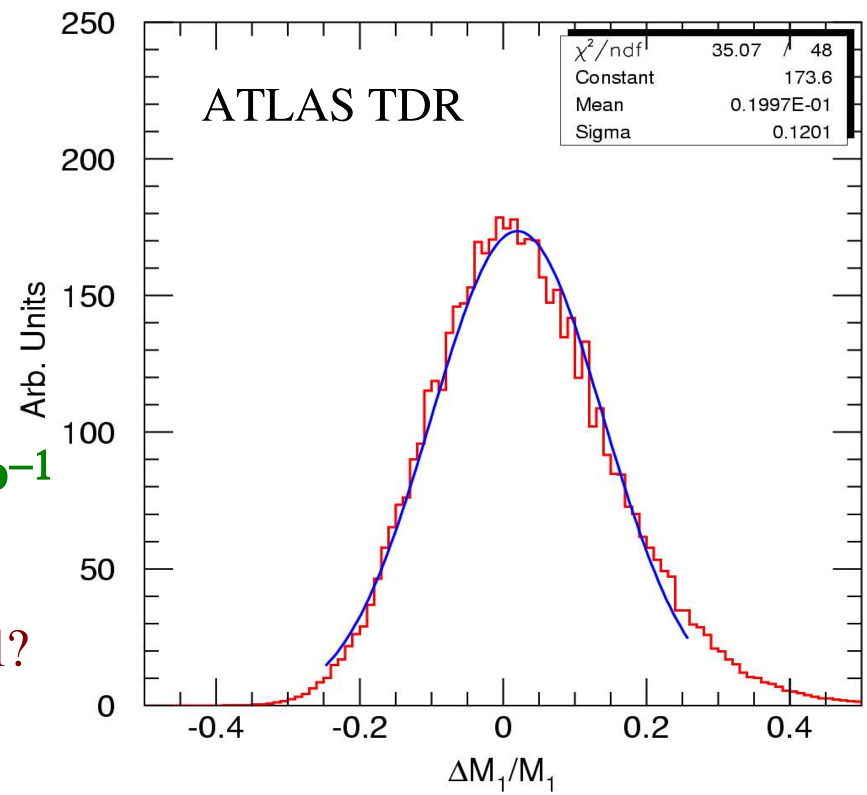
CMS study



Even more clever – and complex – analysis.

- use both min and max kinematic endpoints
- crucial is min(l^+l^-q) measurement
- conclusion:

  measure M_χ to about 10% for 100 fb^{-1}



This is a very special case study!
Are there more methods that succeed in general?

Are there more methods that succeed in general?

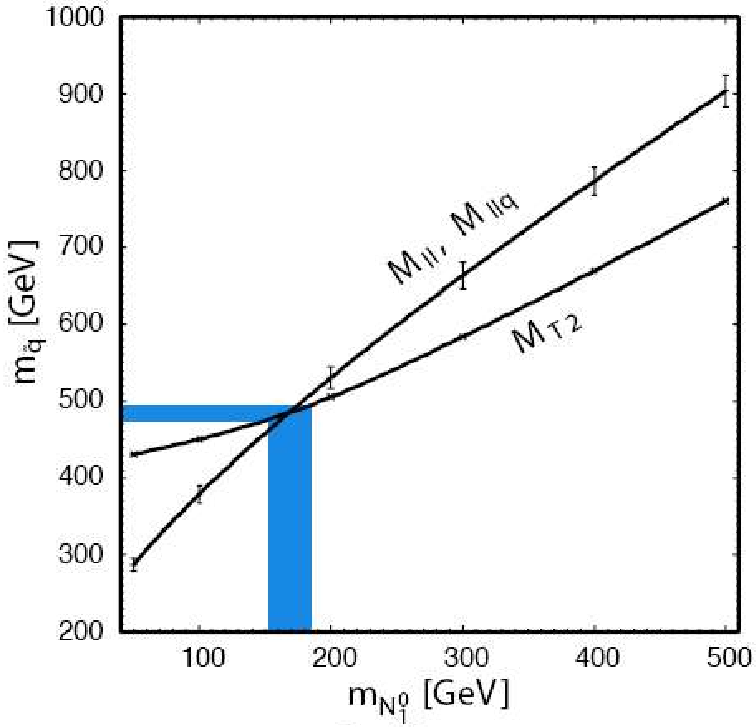
- This is an active area of investigation.
- Typically one has several masses in terms of $M_{\tilde{\chi}_0^1}$
- There are several interesting ideas about exploiting special kinematic features of events in certain channels.
- See Michael Peskin's Lecture #3 at PITP / Princeton (July 2007) for nice overview.
  http://www.admin.ias.edu/pitp/
- Various clever approaches give different functional dependencies on

  $M_{\tilde{\chi}_0^1}$ and $M_{\tilde{q}}$

- Demand consistency!

→ 10% mass measurements

The endpoint positions have a different functional dependence on the squark and neutralino masses. Demand consistency:



(M. Peskin's lecture)

$$m_{N_1} = 169 \pm 17 \text{ GeV} \qquad m_{\tilde{q}} = 486 \pm 11 \text{ GeV}$$

Phys. Rev. D73 095004 (2006) Kitano-Nomura

Other points are more difficult!

co-annihilation

- squarks and gluinos heavy
- staus impossible to find
- stops very challenging, but not impossible...

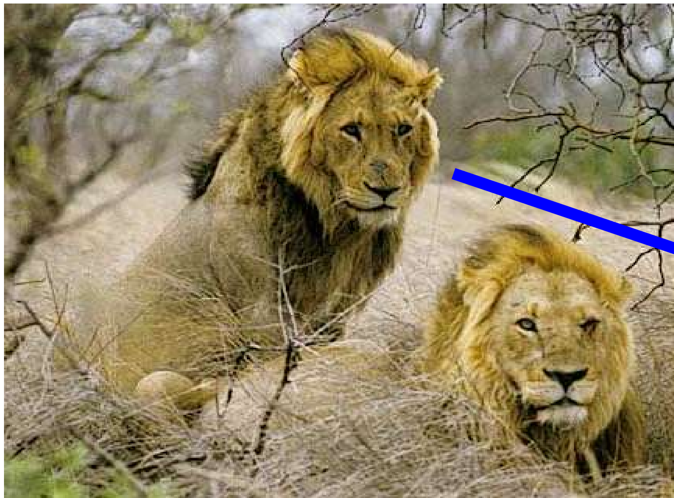
funnel(s)

- most important: pseudo-scalar Higgs, A
- likely to be found in $\tau^+\tau^-$ or other channels
- other sparticles difficult to analyze in detail
- detailed, precise kinematic studies unlikely

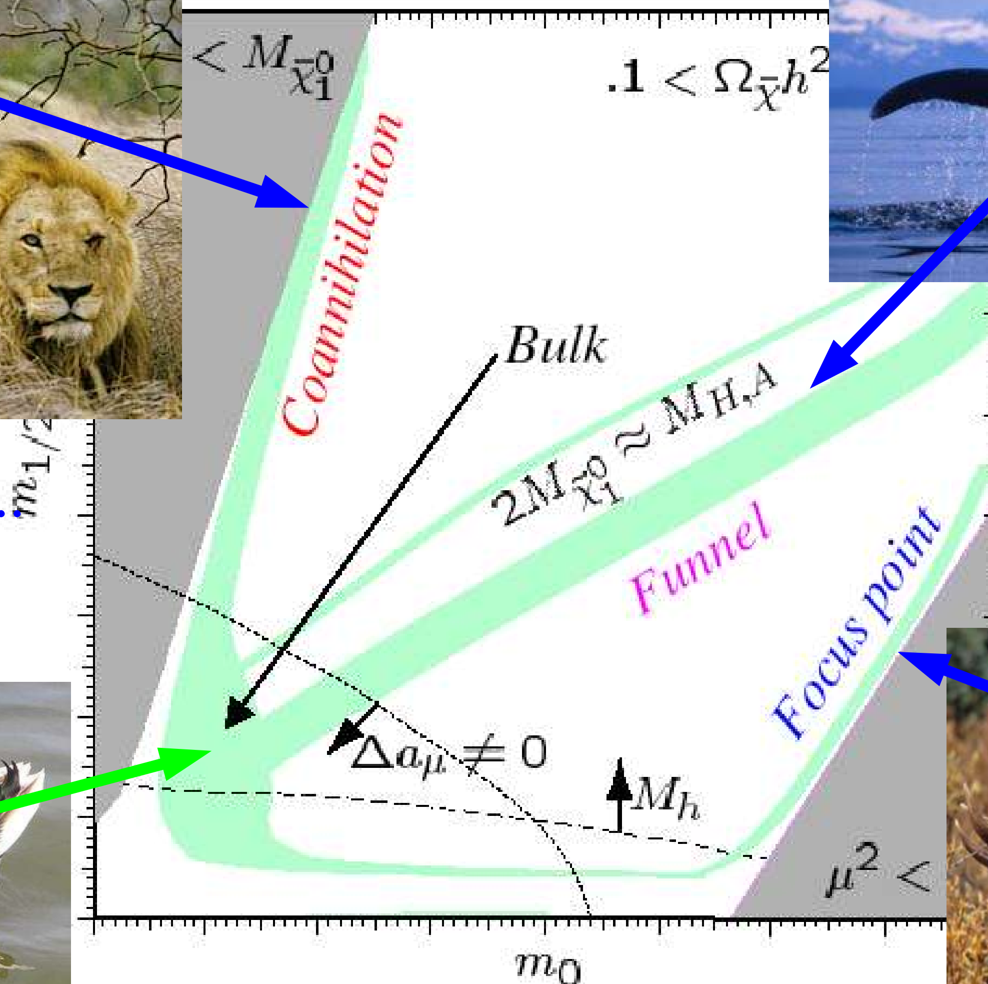
focus-point

- few sparticles can be observed
- lepton branching ratios are small
- neutralinos = mixed bino-higgsino

What are we hunting?

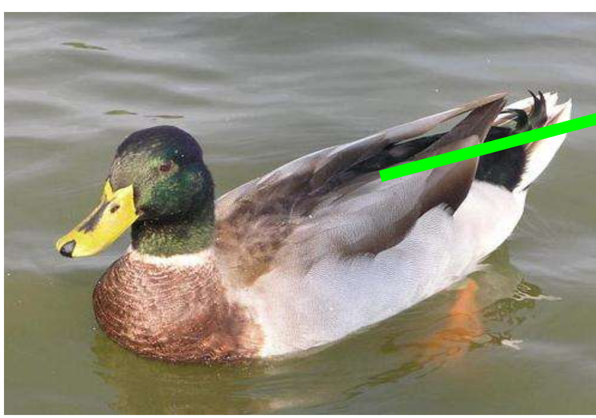


hard & dangerous...



hard...

hard...



easy ?

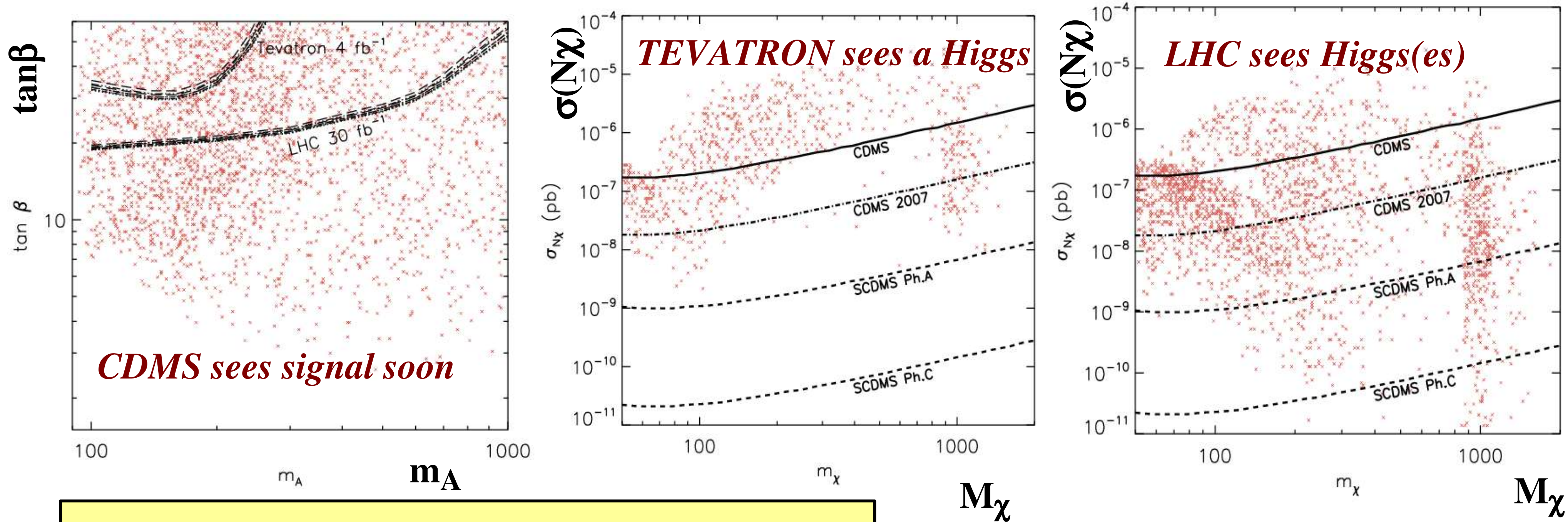
Find the "other" particle

- interesting that Higgs sector is prominent in three out of four regions
- we need to validate the annihilation process directly from collider data a.f.a. possible
- perhaps understanding Higgs sector at LHC more important than constraining several SUSY parameters & calculating Ωh^2

"Easy" Higgs signal in A or H $\rightarrow \tau^+\tau^-$

Higgs Bosons Bridge Colliders and Direct-detection experiments

- nice interplay between, say, CDMS and Tevatron/LHC
- mixed bino-Higgsino state is good for both
- if one or the other does not see DM particles, interesting....



"Easy" Higgs signal in A,H $\to \tau^+\tau^-$

Carena, Hooper, Vallinotto (2007)

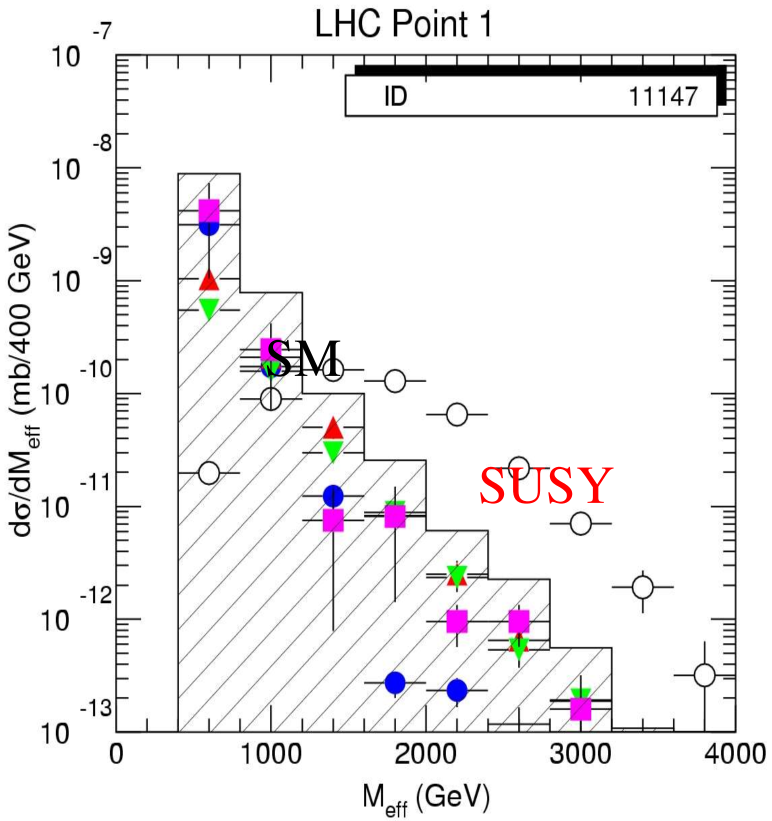
Overall Mass Scales

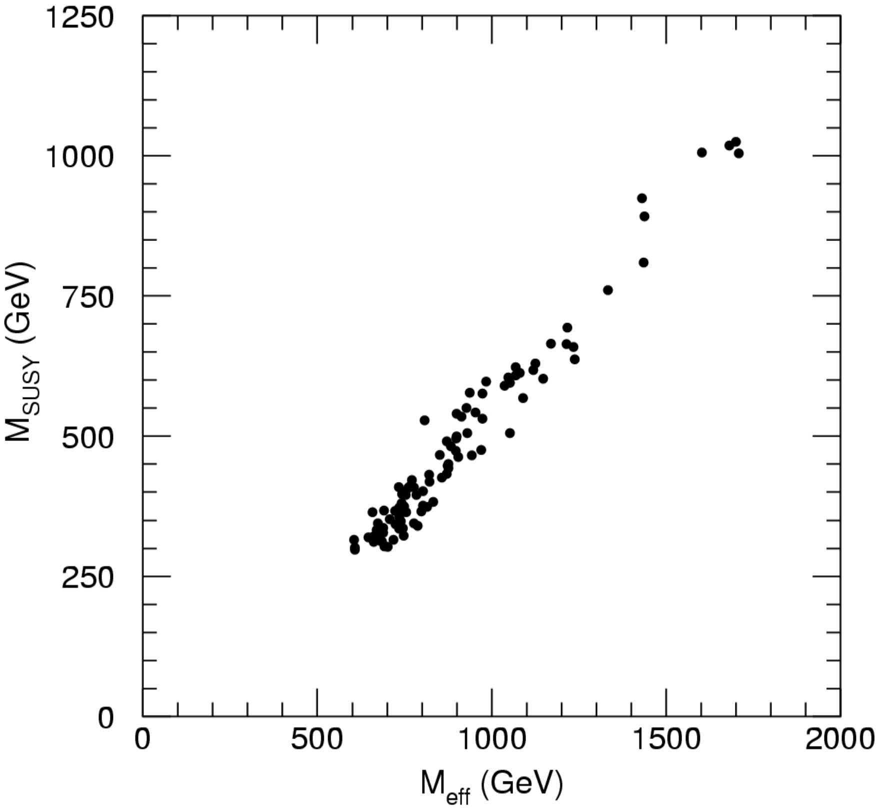
The production of squarks and gluons should be so copious that the simplest possible measure of "lots of energetic jets + MET" will already indicate SUSY mass scales.

$$M_{eff} = E_{T1} + E_{T2} + E_{T3} + E_{T4} + MET$$

correlates with SUSY mass scale

hep-ph/9610544

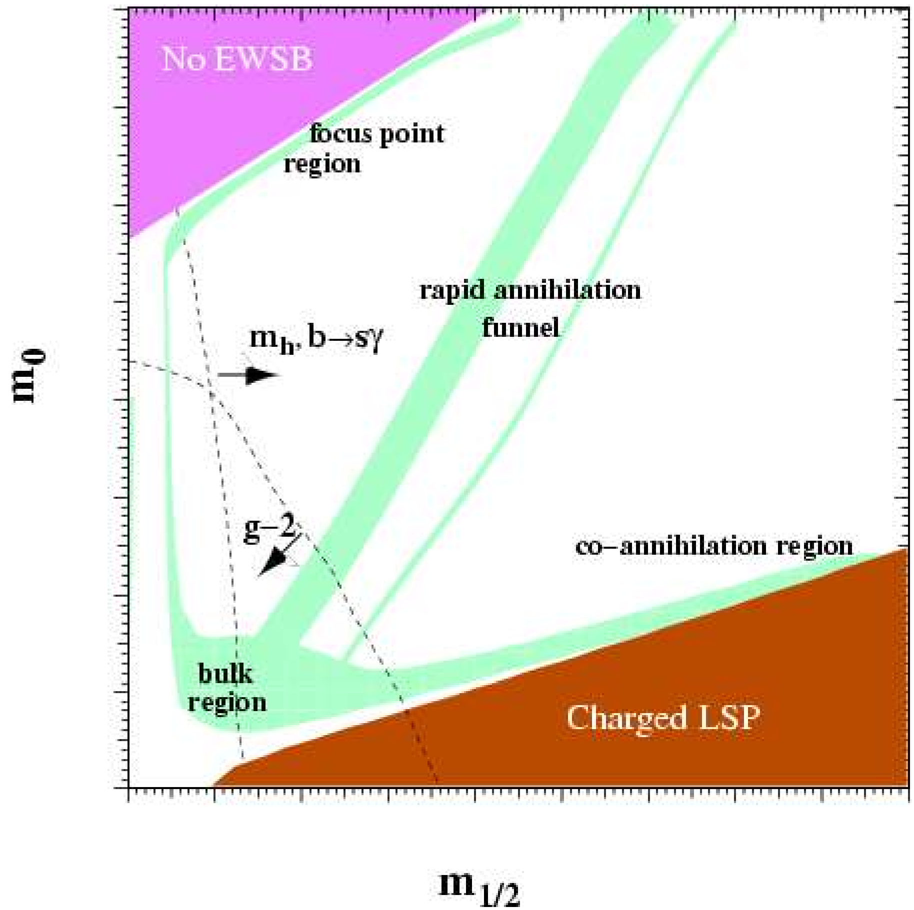




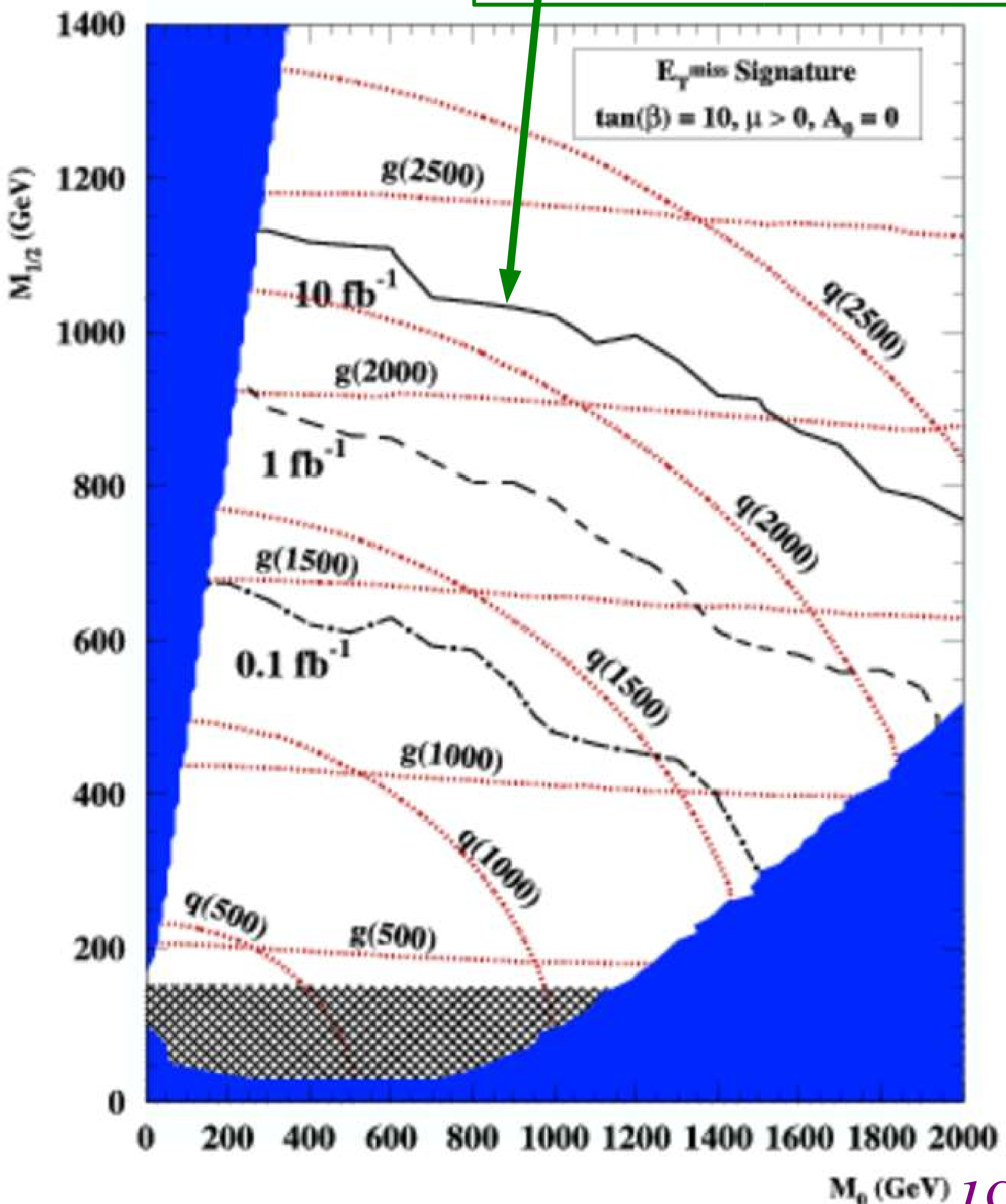
This kind of inclusive measure will help us identify which region we are in.

m_0 and $M_{1/2}$ are fundamental SUSY parameters in the CMSSM model.
They control the masses of squarks and gluinos, and other particles.

Once the LHC is running, it will log a luminosity 10 fb^{-1} in one year.



ATLAS



“Observation” of Dark Matter at the LHC

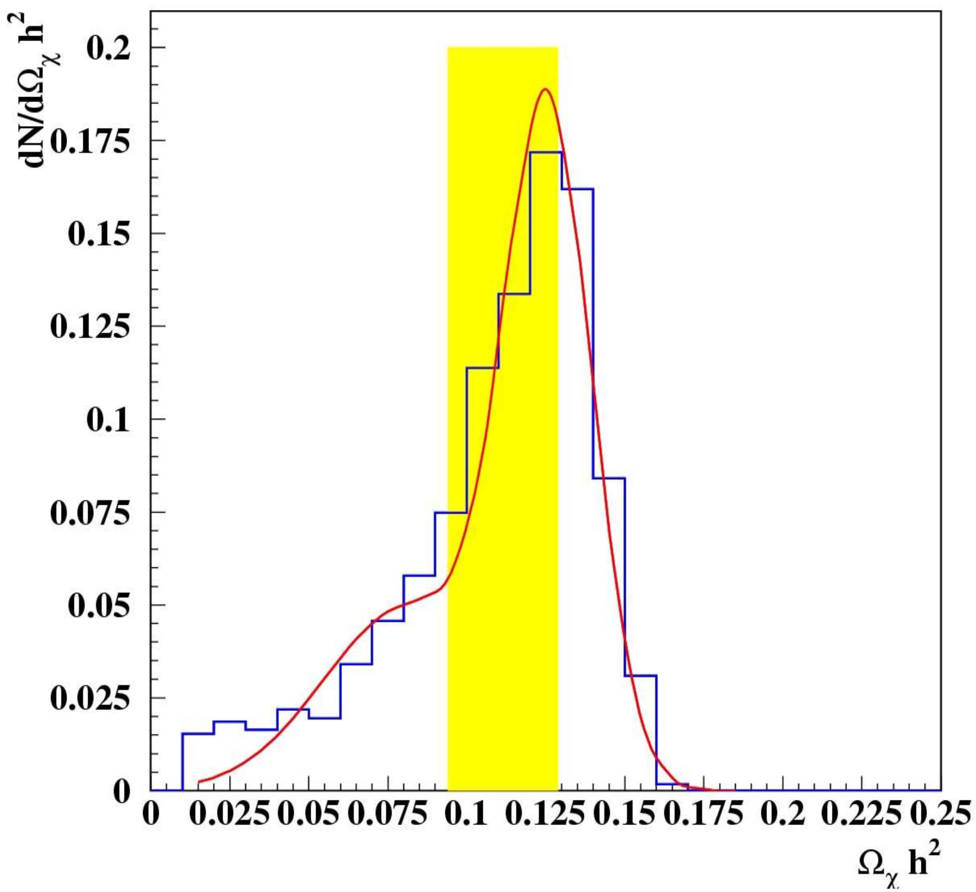
If SUSY is discovered and elucidated at the LHC,
can we confirm that it explains **Dark Matter**?

not always..

The fundamental SUSY parameters can be inferred with fairly good precision, and then used to calculate the DM relic density.

Finally, check the result against astrophysical observations:

hep-ph/0406147



Example analysis based on LHC “measurements” of sparticles masses, etc.
in a very fortuitous case.

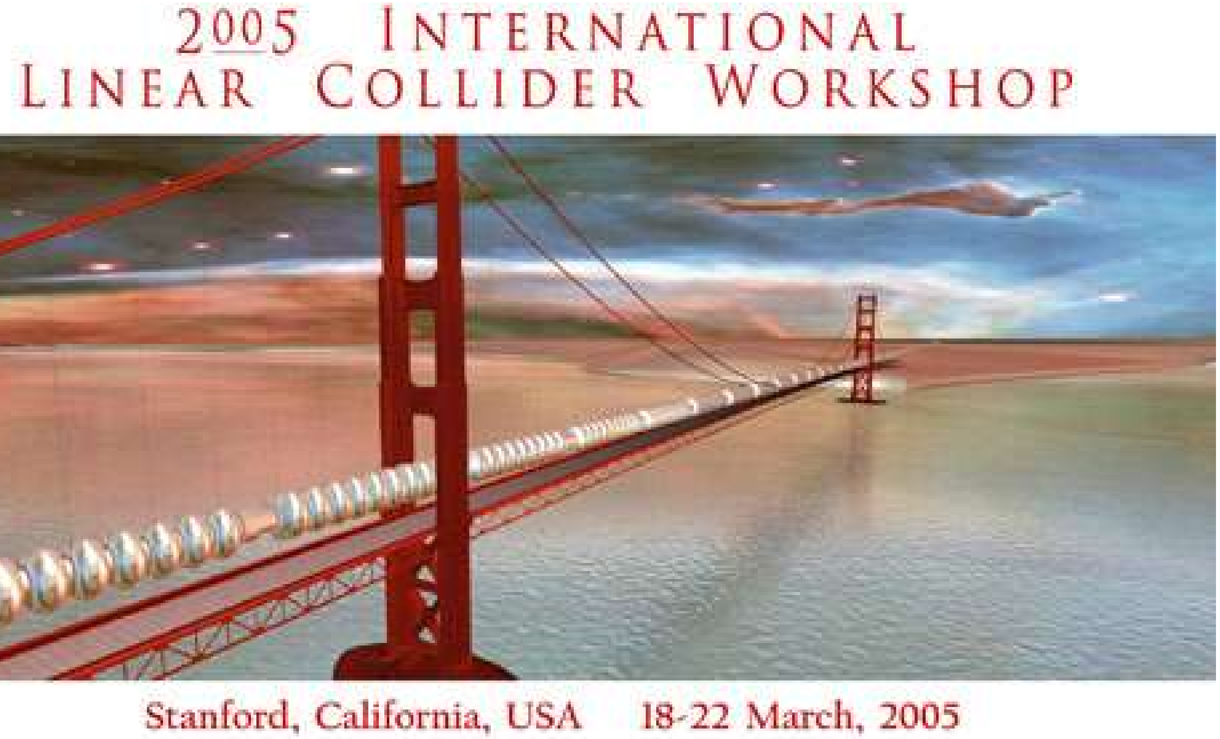
Histogram and curve show distribution of $\Omega_\chi h^2$ from such calculations compared to WMAP measurement.

ILC

- The problem is the inherent "fuzziness" of hadron collider events.
  - must work extensively with jets and MET
  - kinematics are severely smeared or incomplete
  - only some channels are visible, often with low statistical power
- One can assume a model and try to explain the LHC data, and from there, calculate $\Omega_\chi h^2$.
- But this does not constitute a scientific explanation.
- We want a unique answer before we claim we understand something.
- In fact, virtually any set of observations at the LHC that can be explained by Supersymmetry can also be explained by extra-dimensional theories!
- Evidently a better tool is needed, such as a high-energy e^+e^- collider.

⟶ **International Linear Collider**

The SLAC Community have played a leading role in future Linear Colliders:

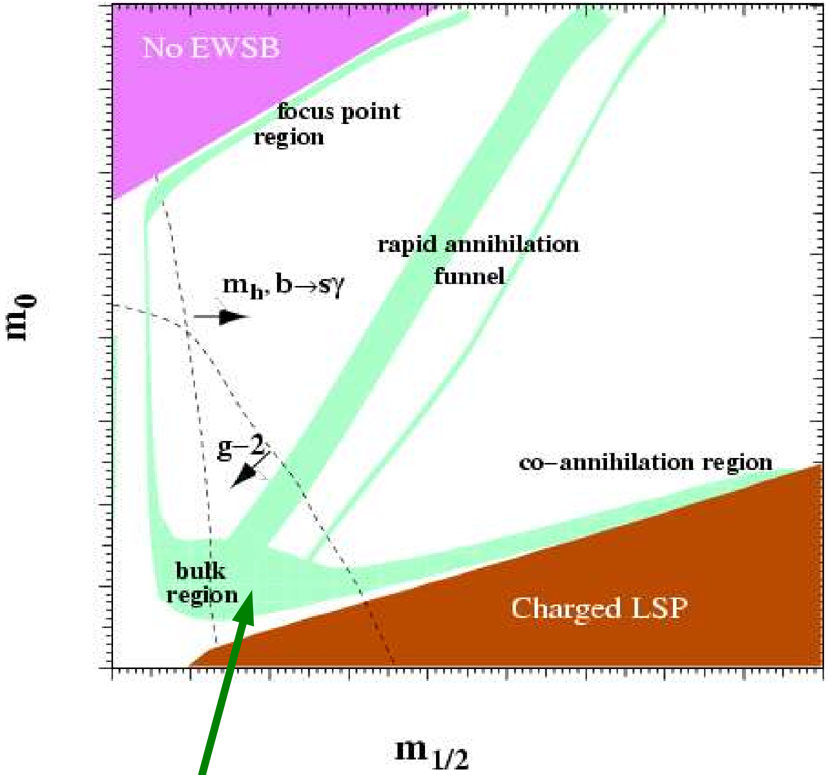


- A technical design has been selected for the ILC.
- Energy will range 500 GeV – 1 TeV.
- There will be one interaction point and one detector.
- The lab and experiment will be truly international (already is).
- A site has not yet been chosen – Fermilab is a leading candidate.

The ILC Approach

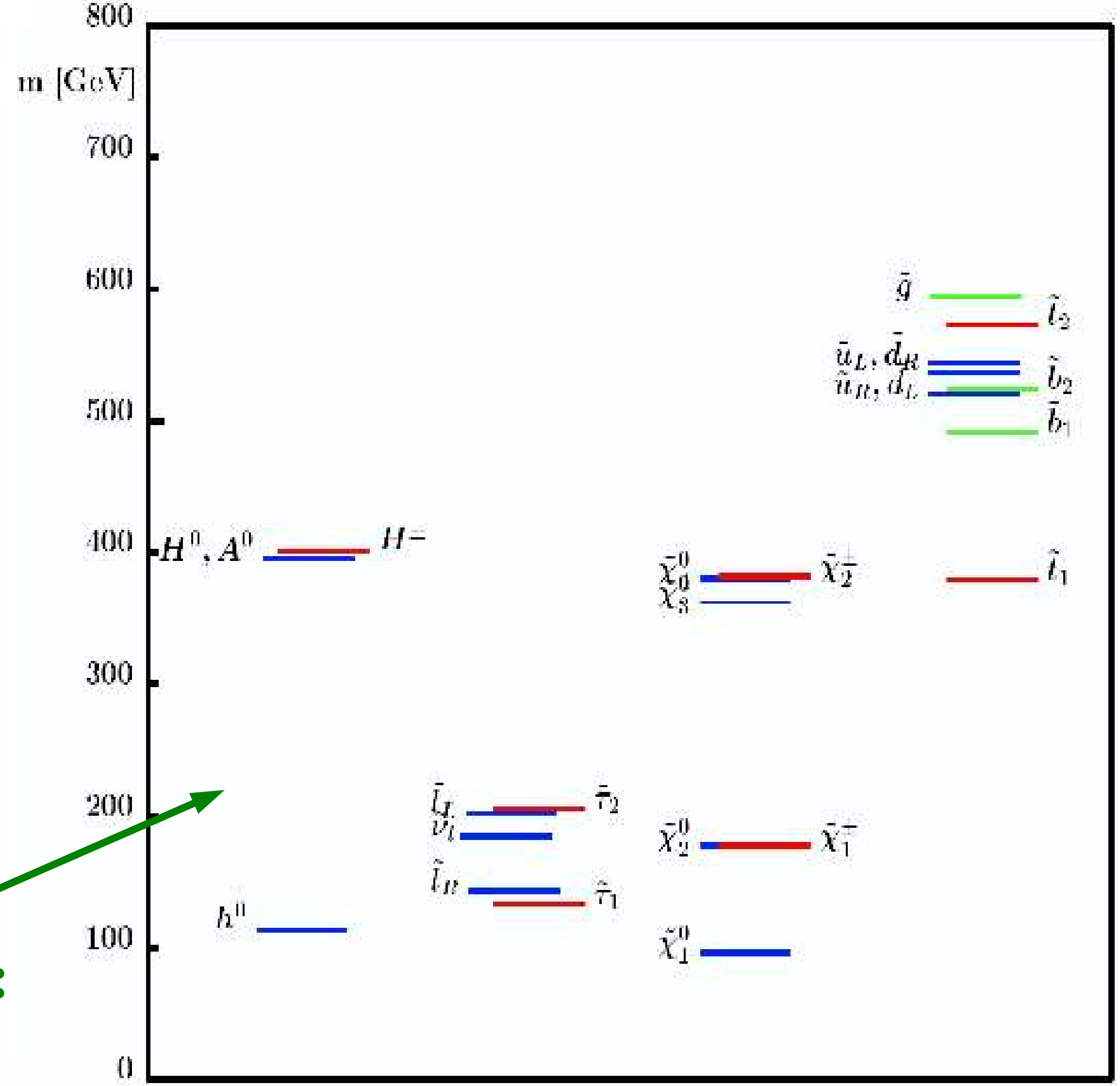
- Find the particles already discovered at the LHC.
- Measure their quantum numbers:

  mass *spin* *coupling constants*
- Decide whether we have Supersymmetry, Extra-Dimensions, or ???
- On the basis of existing data and a corresponding theoretical fit, go after the unobserved particles, and measure their quantum numbers.
  - charginos and neutralinos (a total of six)
  - (light?) stop squarks
  - Higgs bosons (four distinct states)
  - etc.
- Combine a myriad of such measurements into a global minimization in theoretical parameter space $\rightarrow$ infer the correct description of nature.
- Perform other tests of the theory: unification, Yukawa couplings, etc.



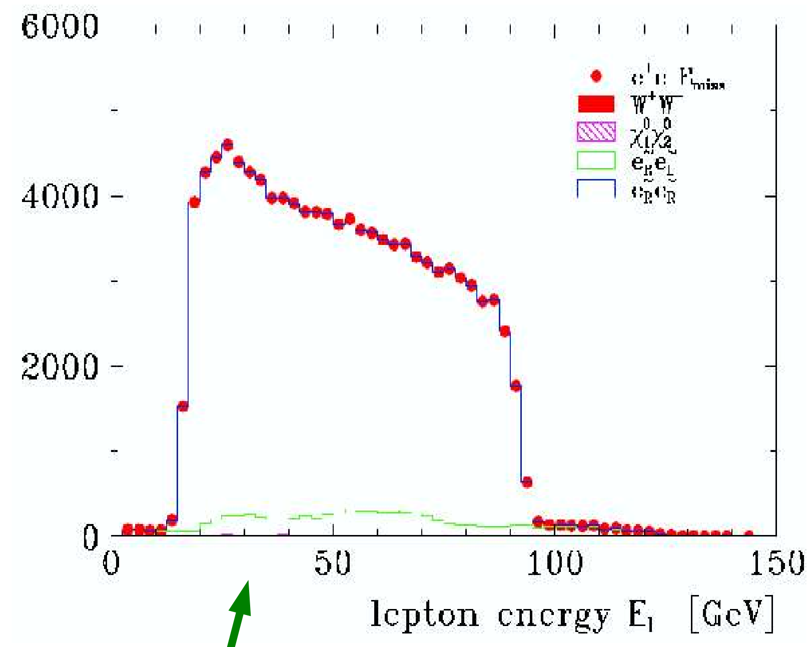
a point in parameter space

gives this spectrum:

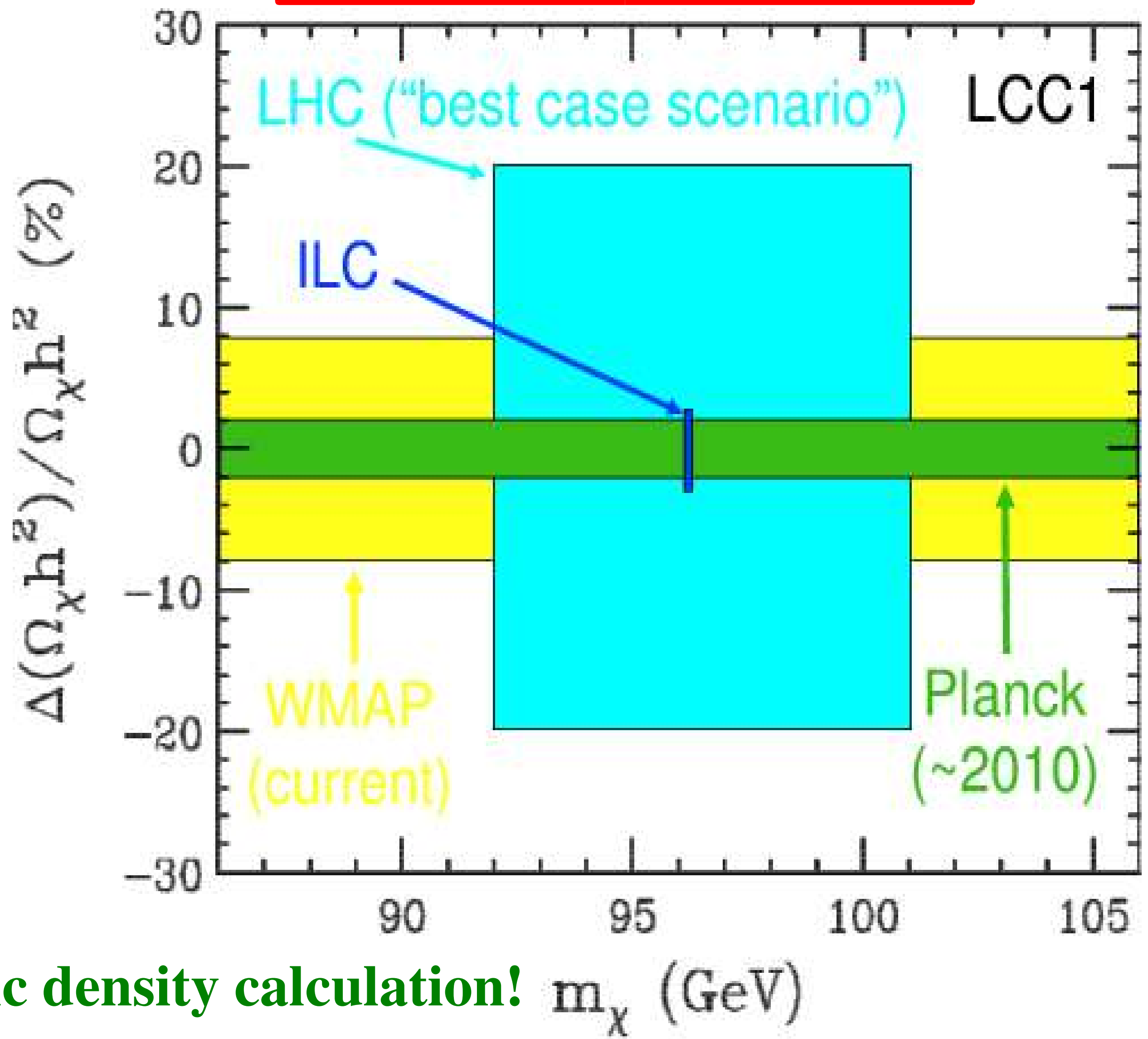


In this scenario, most particles can be directly produced.

(1 TeV machine)



How general is this result?



Exquisite measurements of endpoints and other kinematic features are envisioned...

⟶ remarkably accurate relic density calculation!

The ILC and the LHC are like a Mouse and an Elephant!

Phys. Rev. D74 103521 (2006)

Seminal Study by Baltz *et al.*

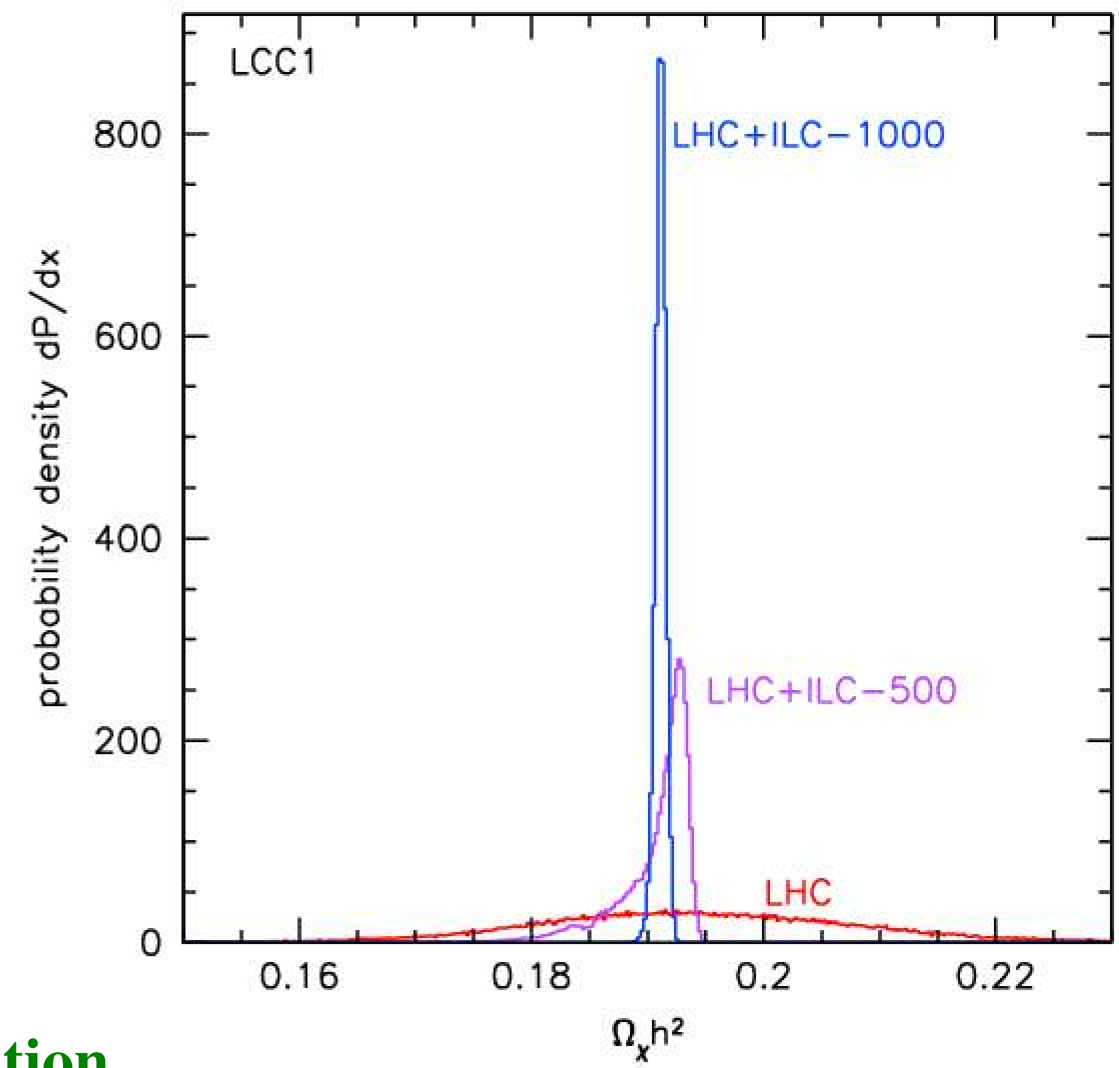
Example point in parameter space and estimates of mass and difference measurements.

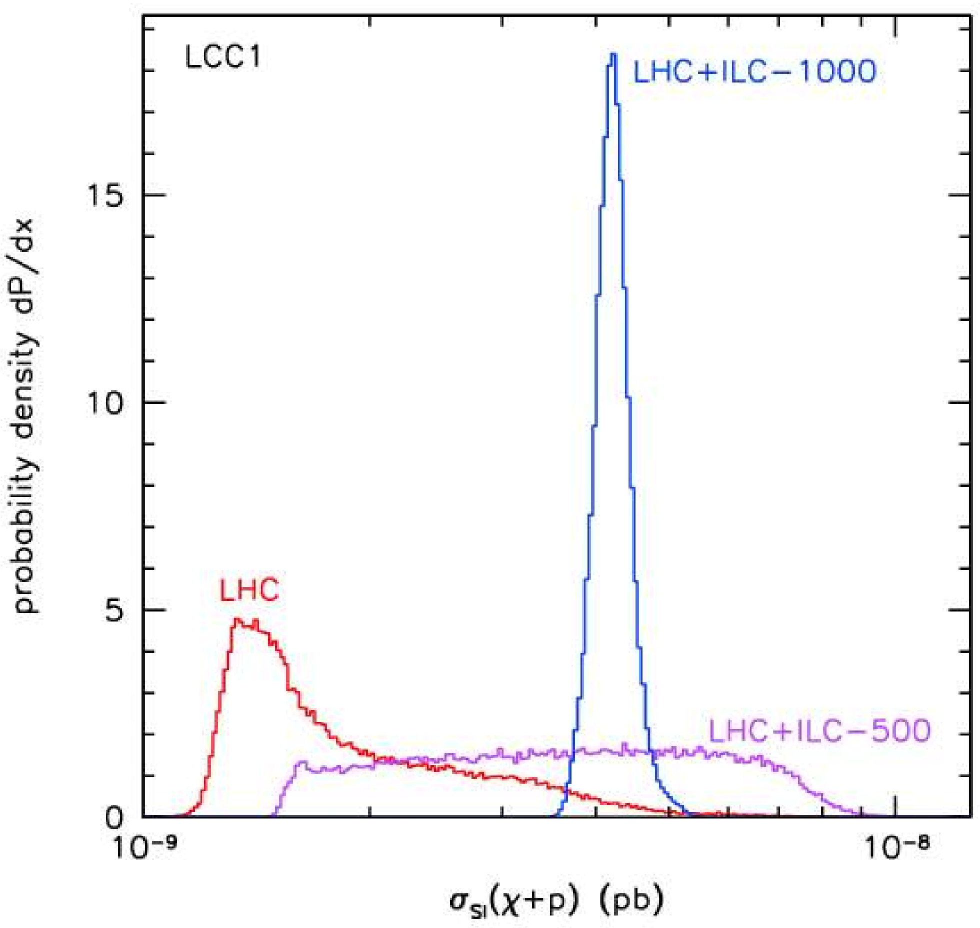
Notice huge improvement in crucial low-mass states such as LSP.

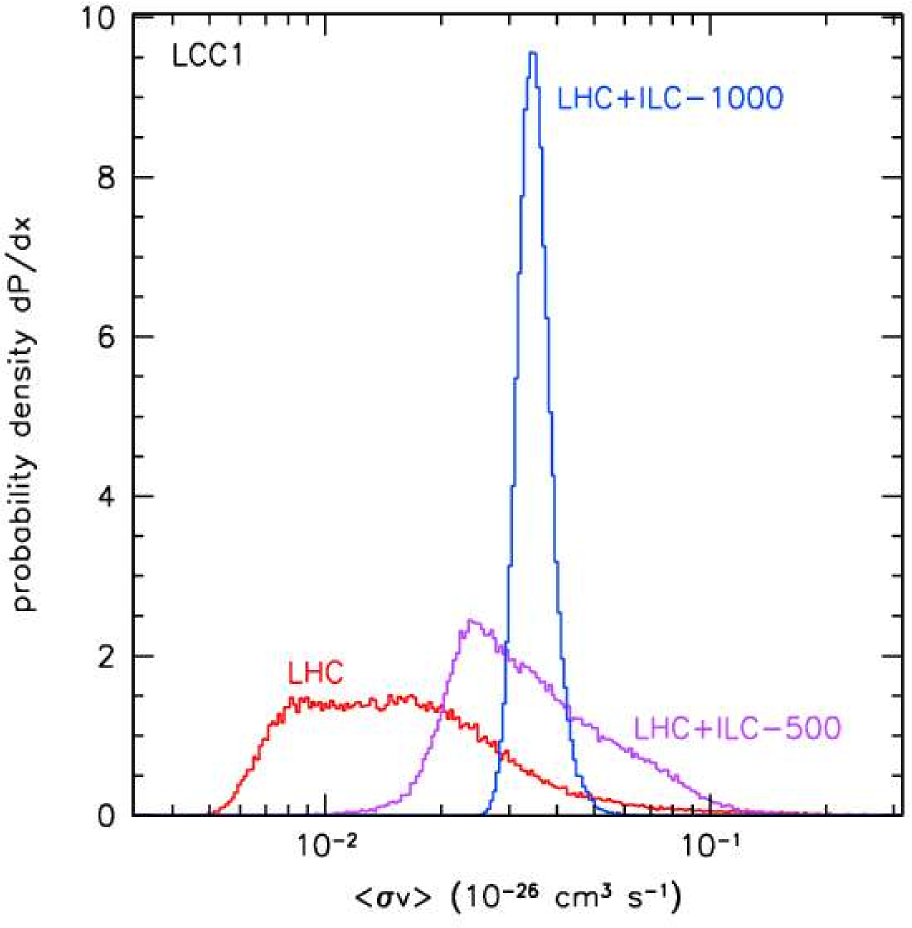
mass/mass splitting	LCC1 Value		LHC	ILC 500	ILC 1000
$m(\tilde{\chi}_1^0)$	95.5	$\pm$	4.8	0.05	
$m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$	86.1	$\pm$	1.2	0.07	
$m(\tilde{\chi}_3^0) - m(\tilde{\chi}_1^0)$	261.2	$\pm$	$@^a$	4.0	
$m(\tilde{\chi}_4^0) - m(\tilde{\chi}_1^0)$	280.1	$\pm$	2.2^a	2.2	
$m(\tilde{\chi}_1^+)$	181.7	$\pm$	-	0.55	
$m(\tilde{\chi}_2^+)$	374.7	$\pm$	-	-	3.0
$m(\tilde{e}_R)$	143.1	$\pm$	-	0.05	
$m(\tilde{e}_R) - m(\tilde{\chi}_1^0)$	47.6	$\pm$	1.0	0.2	
$m(\tilde{\mu}_R) - m(\tilde{\chi}_1^0)$	47.5	$\pm$	1.0	0.2	
$m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0)$	38.6	$\pm$	5.0	0.3	
$BR(\tilde{\chi}_2^0 \to \tilde{e}e)/BR(\tilde{\chi}_2^0 \to \tilde{\tau}\tau)$	0.077	$\pm$	0.008		
$m(\tilde{e}_L) - m(\tilde{\chi}_1^0)$	109.1	$\pm$	1.2	0.2	
$m(\tilde{\mu}_L) - m(\tilde{\chi}_1^0)$	109.1	$\pm$	1.2	1.0	
$m(\tilde{\tau}_2) - m(\tilde{\chi}_1^0)$	112.3	$\pm$	-	1.1	
$m(\tilde{\nu}_e)$	186.2	$\pm$	-	1.2	
$m(h)$	113.68	$\pm$	0.25	0.05	
$m(A)$	394.4	$\pm$	*	(> 240)	1.5
$m(\tilde{u}_R)$, $m(\tilde{d}_R)$	548.	$\pm$	19.0	16.0	
$m(\tilde{s}_R)$, $m(\tilde{c}_R)$	548.	$\pm$	19.0	16.0	
$m(\tilde{u}_L)$, $m(\tilde{d}_L)$	564., 570.	$\pm$	17.4	9.8	
$m(\tilde{s}_L)$, $m(\tilde{c}_L)$	570., 564.	$\pm$	17.4	9.8	
$m(\tilde{b}_1)$	514.	$\pm$	7.5	5.7	
$m(\tilde{b}_2)$	539.	$\pm$	7.9	6.2	
$m(\tilde{t}_1)$	401.	$\pm$	(> 270)	-	2.0
$m(\tilde{g})$	611.	$\pm$	8.0	6.5	

Table 2: Superparticle masses and their estimated errors or lower limits for the parameter point LCC1. Lower limits are indicated in parentheses. The ILC columns contain the measurements added or improved by the ILC at that energy. The symbol '-' denotes that the measurement is not yet available. The symbol '*' denotes the formula: $m_A > 200$ GeV, or $\tan\beta < 7.0(m_A/200.0)$. The notation '$@^a$' indicates that the mass measurement marked with a superscript ^{a} could equally well be ascribed to this particle. All values are quoted in GeV.

- Direct comparison of LHC, ILC-500, ILC-1000
- probability for $\Omega_\chi h^2$ after integrating over all parameter space
- careful treatment of statistics issues
- ILC-500 adds a lot!
- ILC-1000 very powerful
- best to combine all information



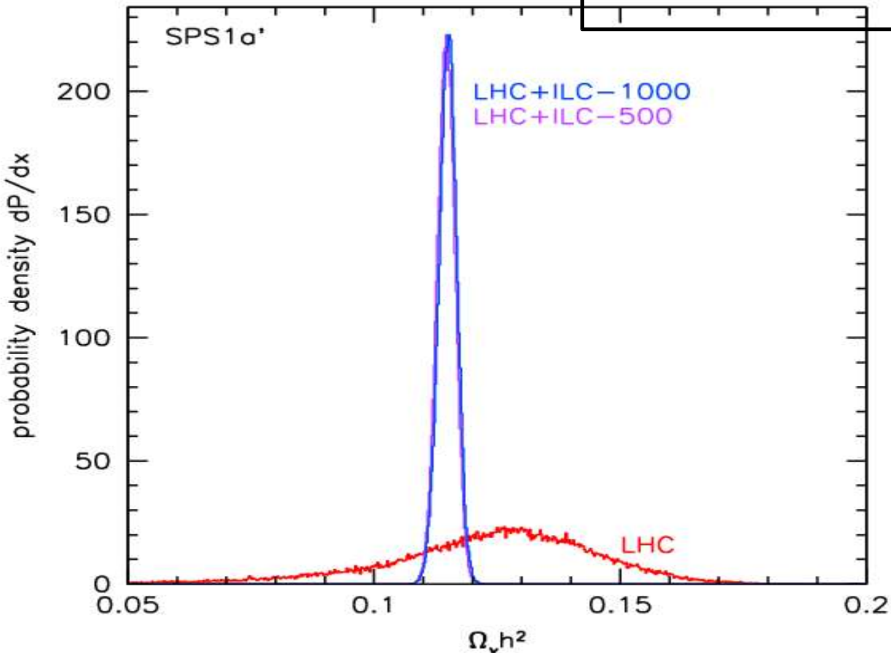


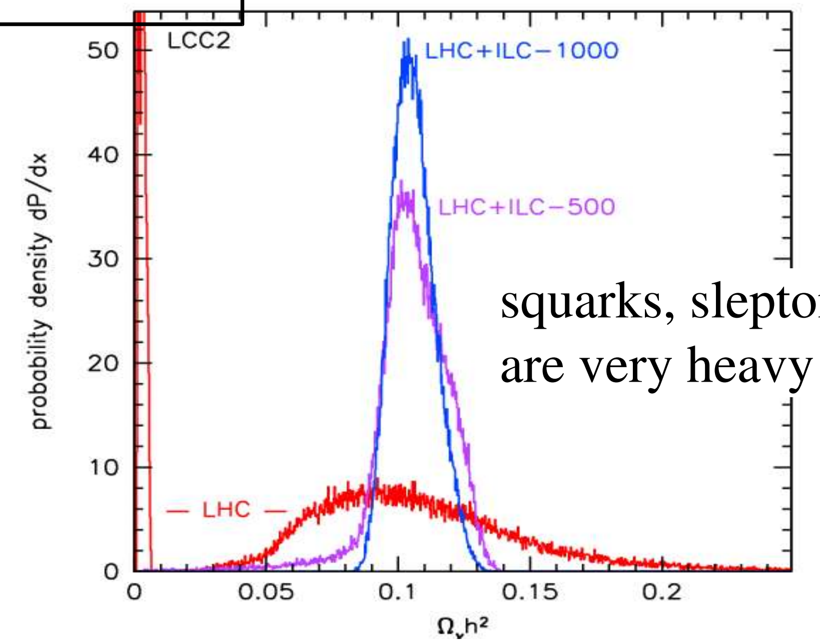


scattering cross-section for direct-detection experiments

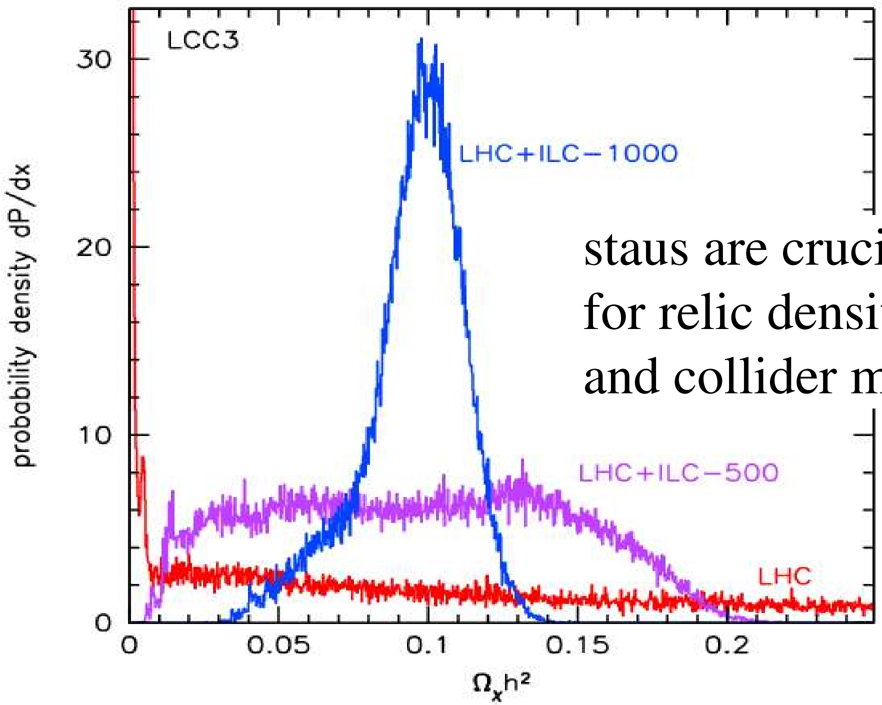
WIMP annihilation cross-section at threshold

Check out four other cases:

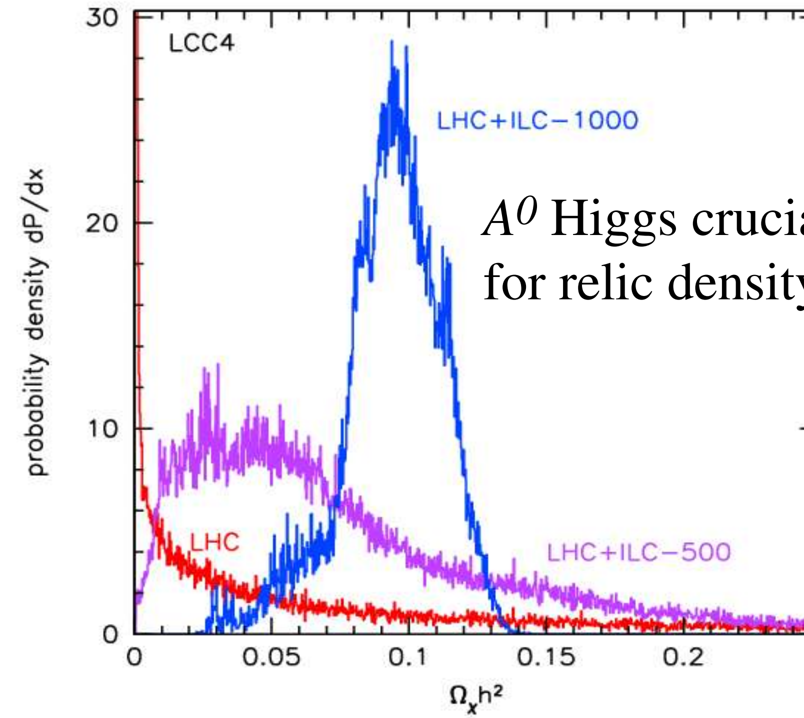




squarks, sleptons are very heavy



staus are crucial for relic density and collider meas.



A^0 Higgs crucial for relic density.

Conclusions of Baltz et al., study:

- if complete spectrum found, precise relic density can be calculated.
- if some of the spectrum is too high, can still do 20% calculation since key sparticles are the lighter ones, which can be observed.
- Agreement of a even a 20% calculation with the known relic density would be a major triumph, lending strong support to the particle physics interpretation of dark matter.
- Furthermore, we can hope for agreement with results from direct-detection experiments and indirect-detection observations, making the case even stronger.

- This will be a major scientific enterprise joining high-energy, low-energy particle physics, and astrophysical observations, for the next 10 – 15 years!

Maybe, in the mean time, some data analysis methods will improve the picture.

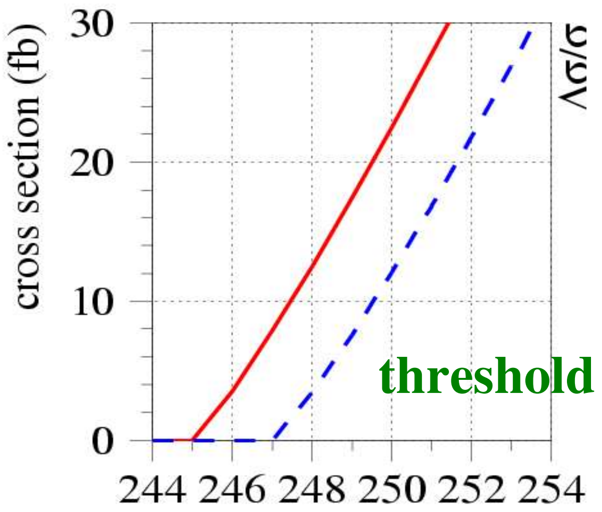
Improved Methods

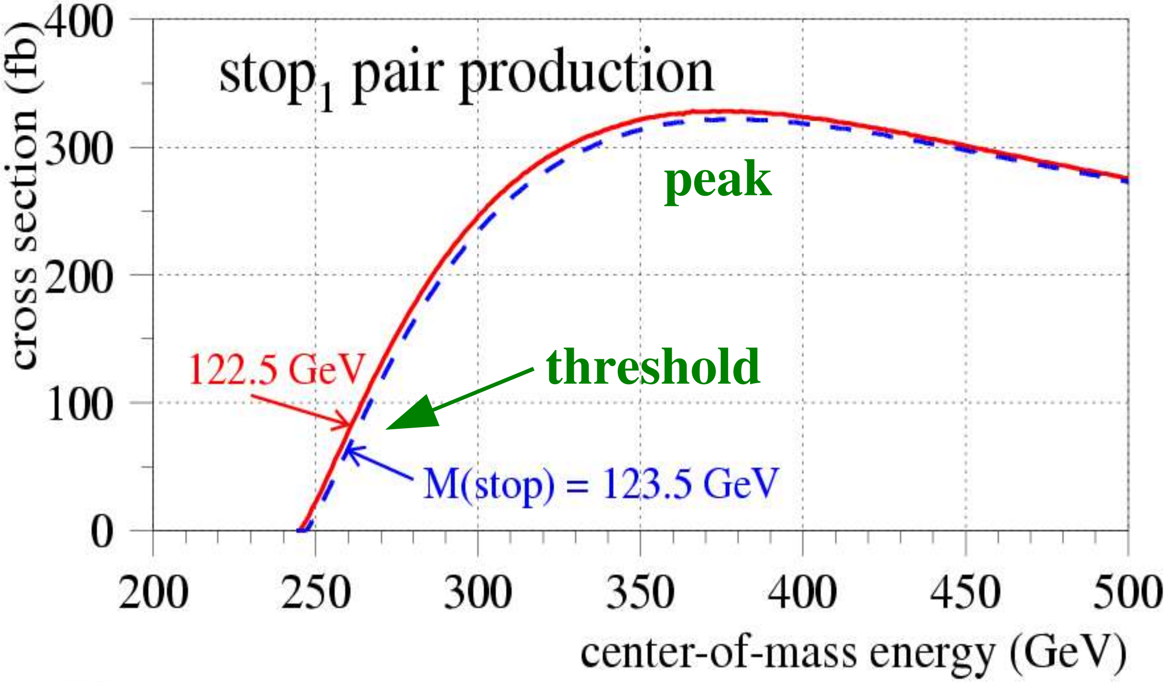
Carena, Quiros, Wagner, Nucl. Phys. B524 (1998) 3

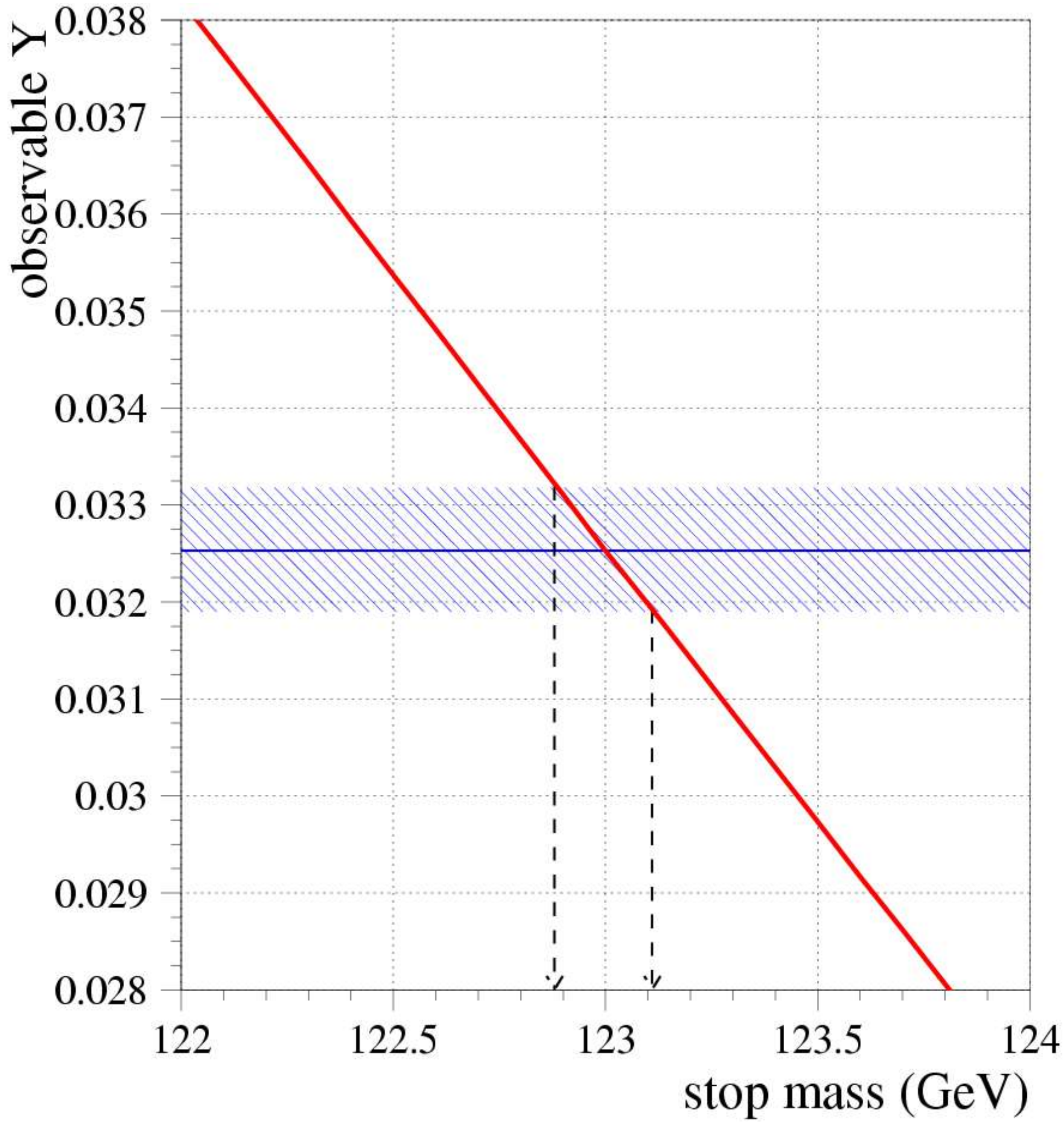
- One special theoretical model purports to explain
  both **Dark Matter** and the **Baryon Asymmetry** .
- A special feature is the co-annihilation with light stop squarks
  (scalar SUSY partners of the top quark).
  M(stop) < 175 GeV
- Measurement of the stop squark mass and couplings is crucial for a calculation of the relic density.
- At a 500-GeV ILC, $e^+ e^- \rightarrow \tilde{t}_1 \tilde{t}_1^*$ $\tilde{t}_1 \rightarrow c\, \tilde{\chi}_1^0$ *(two jets and missing energy)*
- Typical methods for measuring M(stop) include
  - measuring the kinematic endpoints for the jets
  - measuring the cross-section at 500 GeV
  - performing a threshold scan

- These methods tend to be limited by experimental systematics.
  - event selection efficiency (modeling of kinematics)
  - efficiency for charm-jet tagging
  - background estimation
- The impact of such uncertainties can be reduced when taking ratios.
- New Method:
  - take data at two c.m. energies
  - at the peak in the cross-section vs. mass, insensitive to mass
  - at the rapidly rising part, near threshold, large sensitivity to mass
  - take the ratio of yields at these two c.m. energies

$$Y = \frac{N^{th}_{obs} - B^{th}_{est}}{N^{ph}_{obs} - B^{pk}_{est}} = \frac{\sigma^{th}}{\sigma^{pk}} \times \frac{\epsilon^{pk} L^{pk}}{\epsilon^{th} L^{th}}$$







$$Y = \frac{N_{obs}^{th} - B_{est}^{th}}{N_{obs}^{ph} - B_{est}^{pk}} = \frac{\sigma^{th}}{\sigma^{pk}} \times \frac{\epsilon^{pk} L^{pk}}{\epsilon^{th} L^{th}}$$

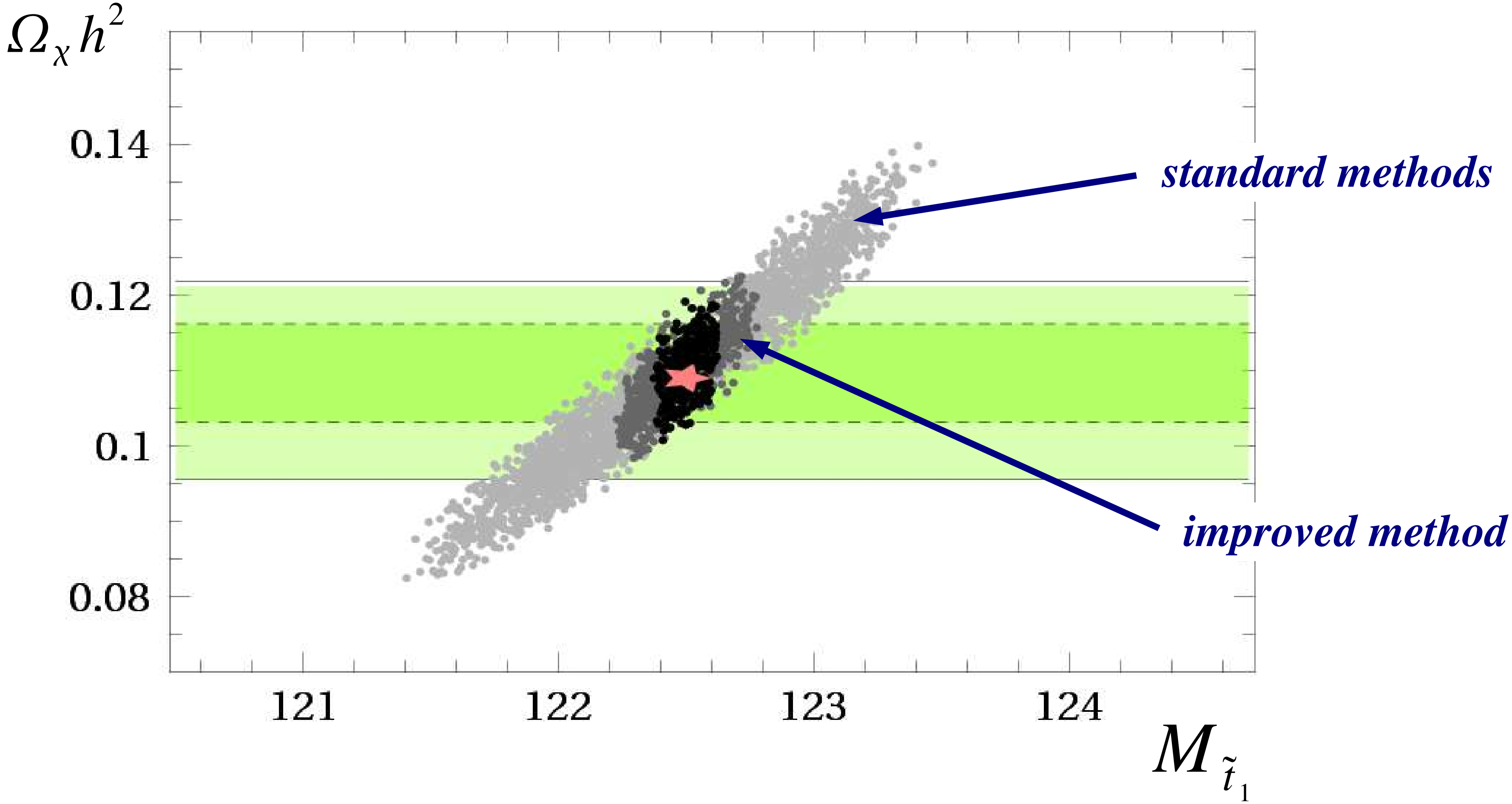
- A measurement of observable Y translates directly into M(stop).

$$\Delta M_{\tilde{t}_1} = 0.2\,GeV$$

- Systematic uncertainties are very low (below 3%).
- Statistical uncertainty is low, thanks to running near threshold.
- Significant theoretical uncertainty enters, for predicting σ^{th}.

A. Freitas, C. Milstene, M.S., A. Sopczak, in preparation

In this special scenario,
a very good precision can be obtained with a 500-GeV ILC.



The stop squark mass no longer dominates the uncertainty of the relic density calculation.

Conclusion

- The prospect of a particle physics explanation for DM is exciting!
- Collider experiments will play a crucial role, but
  they cannot unravel this mystery on their own.
- A high-energy e^+e^- collider is essential, but success not guaranteed.

Soon the hunt will begin...