Dark Matter and Sparticles at the LHC

The Hunt for Dark Matter

Symposium at Fermilab

May 12, 2007

Michael Schmitt
Northwestern University

The TEVATRON has discovered (so far)....

the top quark
(B_s oscillations)

The LHC will discover (perhaps)...

the Higgs boson
supersymmetric particles
Kaluza-Klein states

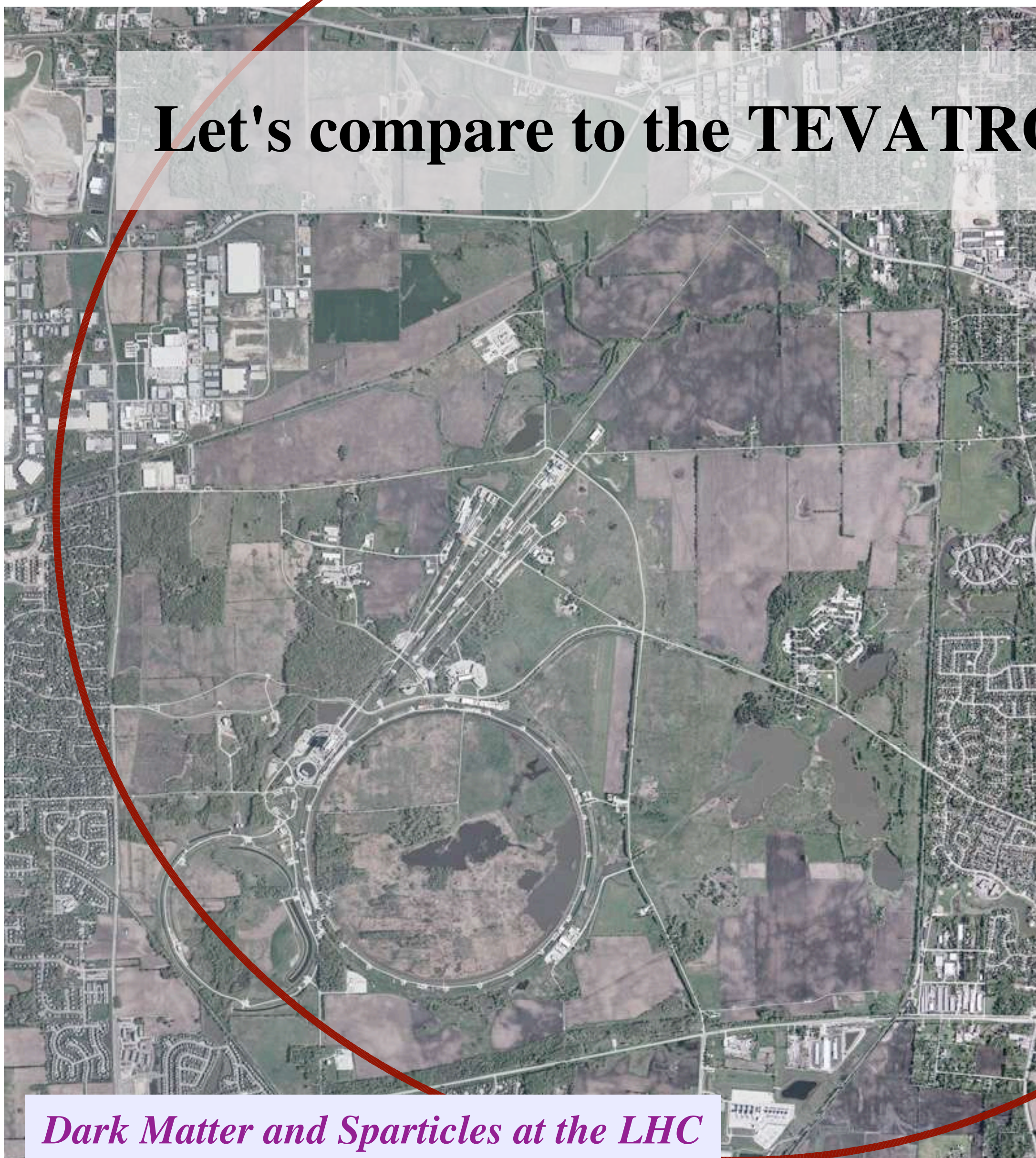
DARK MATTER ??

optimism abounds...

What is the LHC ?

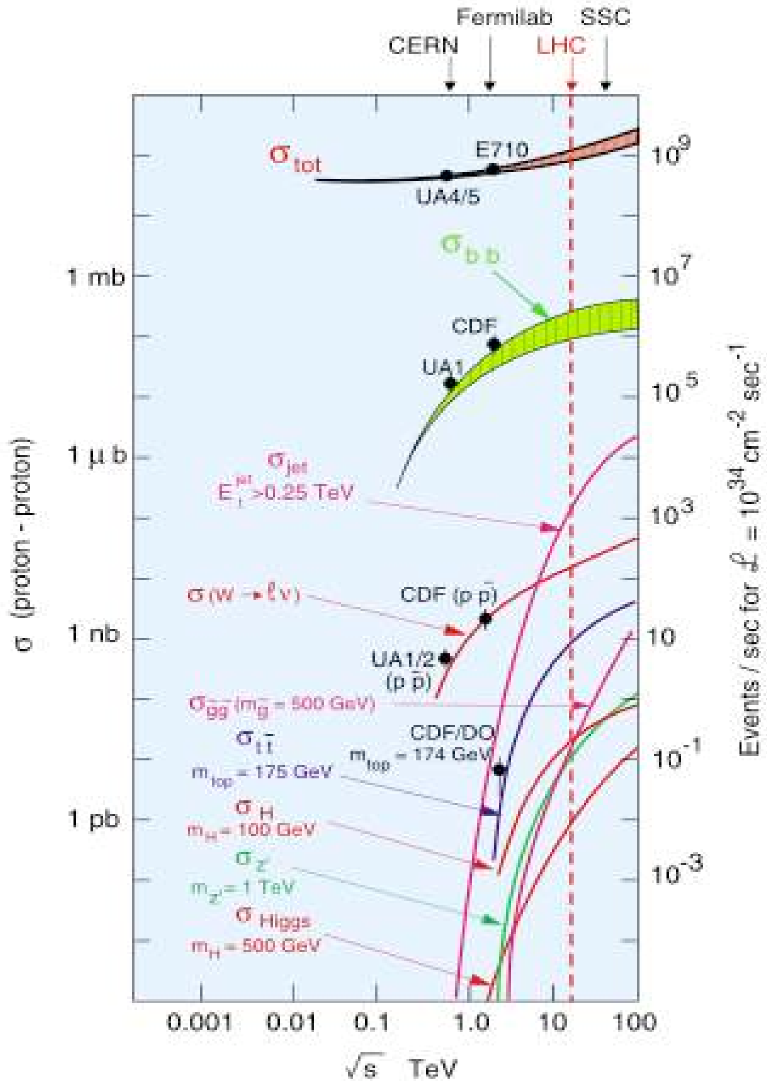
Let's compare to the TEVATRON $p\,\bar{p}$ collider:

see talk by Jane Nachtman



	TEVATRON	*LHC*
beams	p-pbar	p-p
circumference	6 km	27 km
energy	2 TeV	14 TeV
luminosity	10^{32}	10^{34} cm^{-2}s^{-1}
	8 fb^{-1}	300 fb^{-1}
bunch spacing	392 ns	25 ns
collisions/xing	6	20
collab'n size	600 each	2000 each
running mo/yr	12	6

What is the LHC ?



approximate event rates for 2×10^{33} cm^{-2} s^{-1}
(which would give 20 fb^{-1} in one year)

	events / s	*events/year*
$W \to e\nu$	40	4×10^8
$Z \to ee$	4	4×10^7
t tbar	1.6	1.6×10^7
QCD jets (E_T > 200 GeV)	10^2	10^9
b bbar	10^6	10^{13}
gluino pairs (1 TeV)	0.002	10^4
Higgs (120 GeV)	0.08	8×10^5

LHC Running Plan

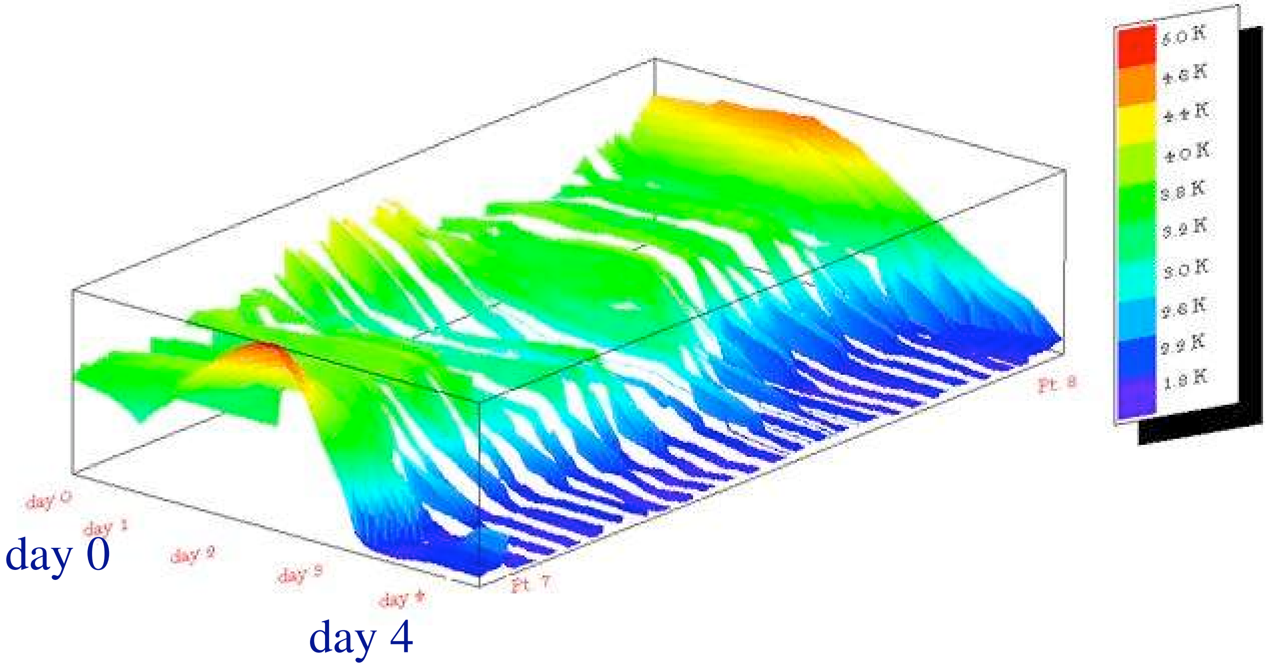
2007

- cool-down of LHC magnets proceeding nicely so far
- planned engineering run at 980 GeV is now *unlikely*
- failed quadrupole magnet – in-situ repair seems possible
- CMS and ATLAS will close up in November for CR's

2008

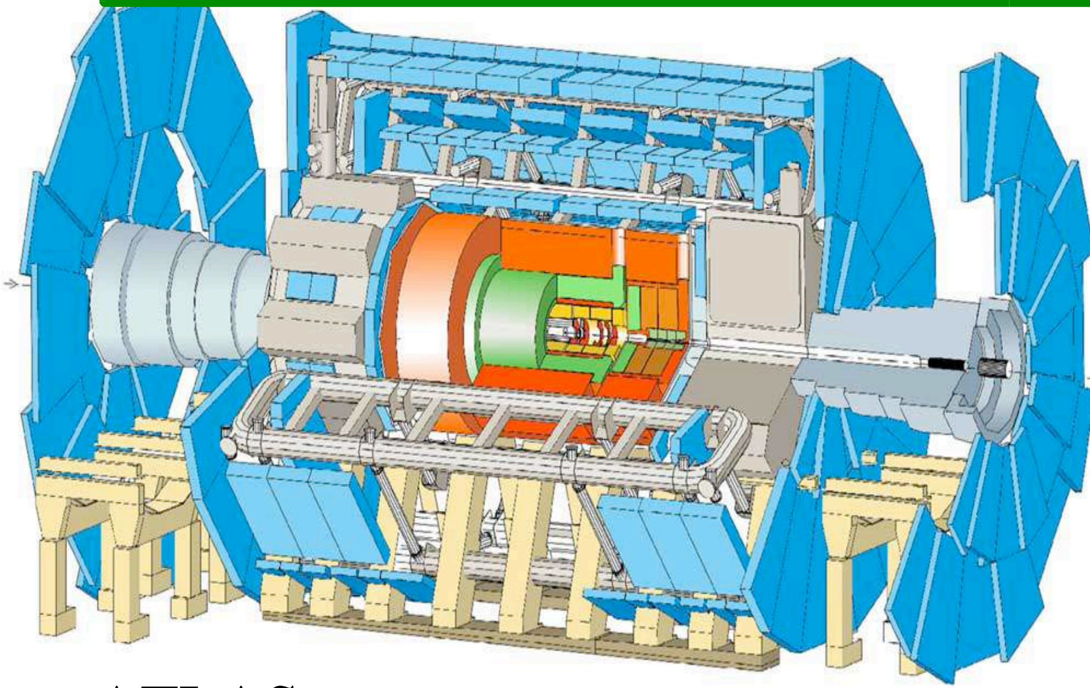
- **14 TeV** run planned for mid-2008
- aiming for a delivered luminosity of about **1 fb^{-1}**
- CMS and ATLAS both will be ready for collision data
- first calibrations & alignment to be done with 100 pb^{-1}

Cooling Sector 7-8

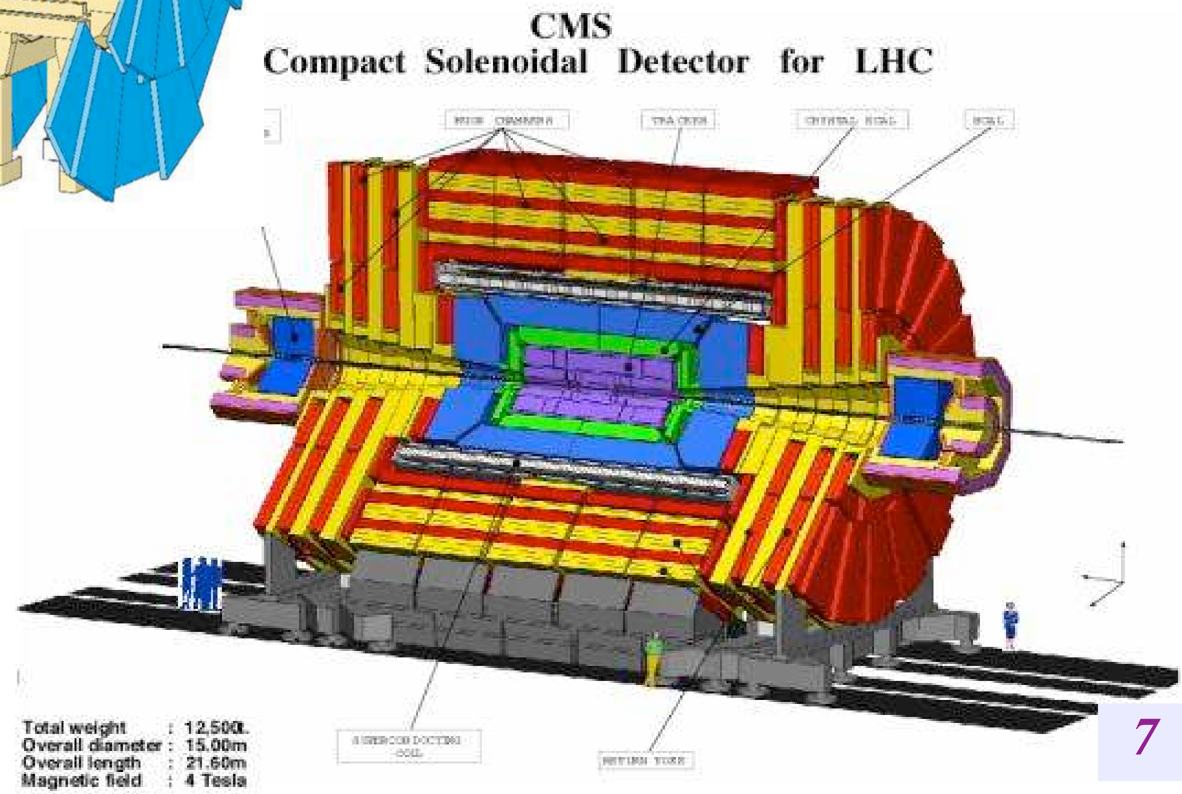


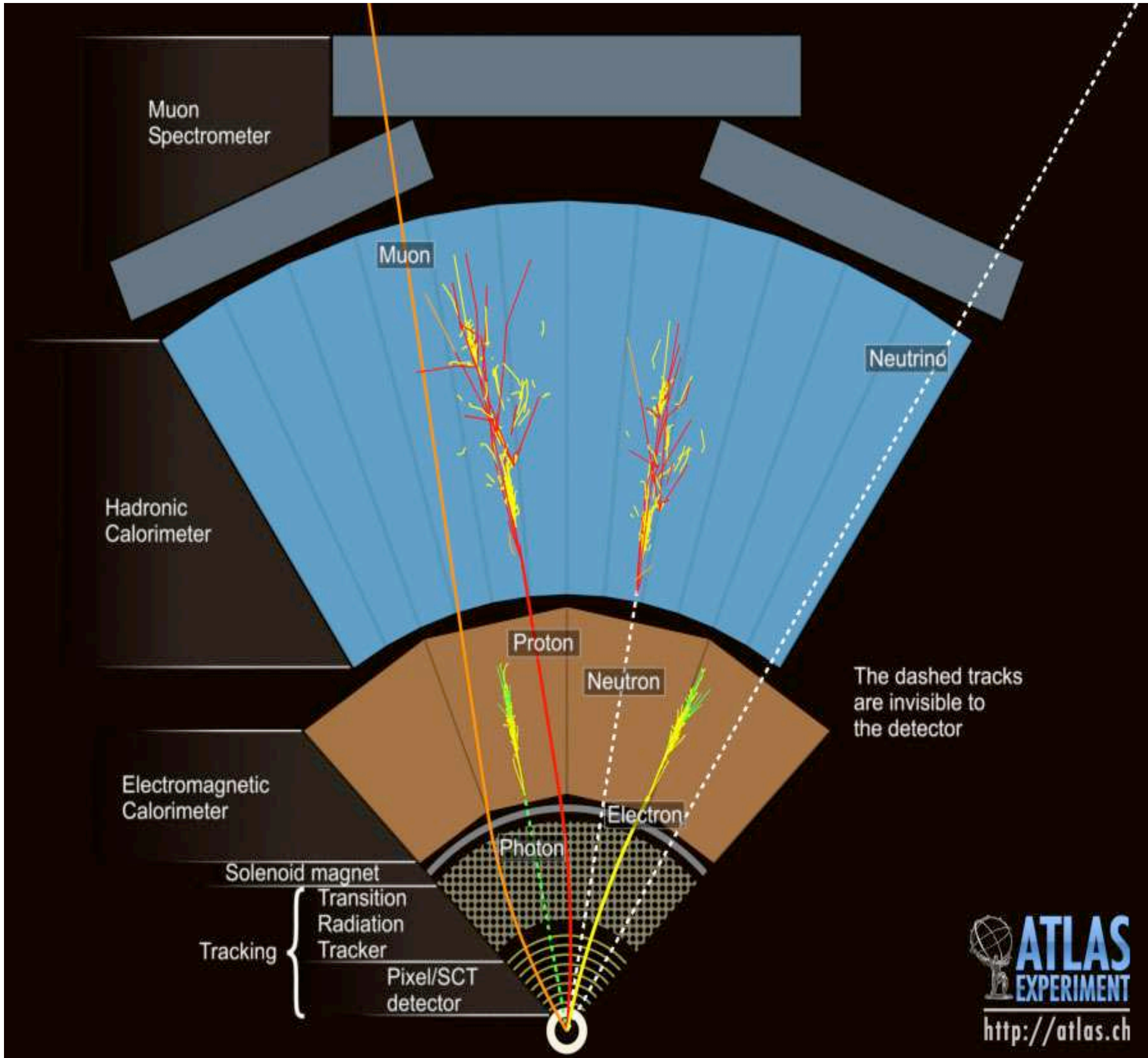
- slightly below 2º K
- 1/8 of the complete LHC ring
- 3.3 km long – <u>world's largest superconducting installation</u>
- 200 dipoles arranged in 30 cooling cells

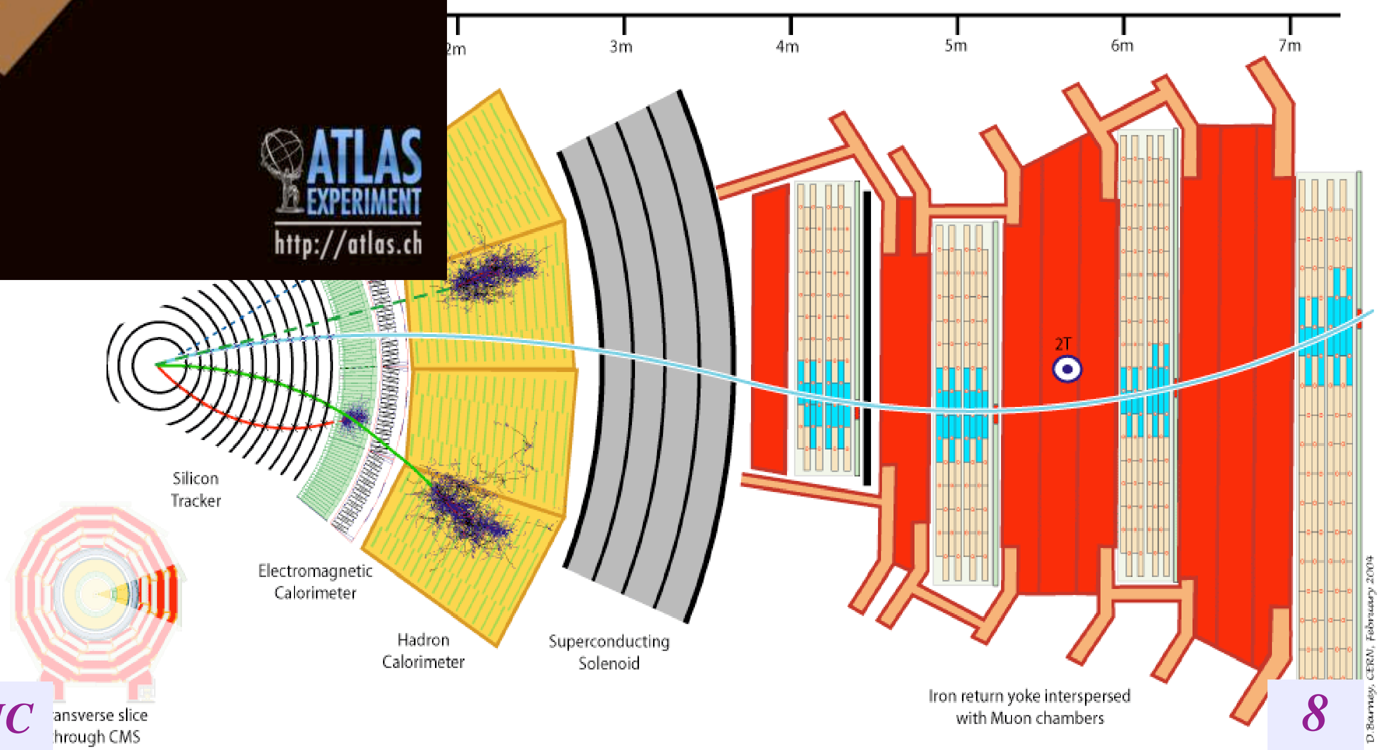
LHC Detectors / Collaborations



ATLAS




Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch


2m
3m
4m
5m
6m
7m
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
ansverse slice hrough CMS

Dark Matter at Colliders

"Dark Matter feels very close" - Pier Oddone
"The LHC will be a Dark Matter factory." - Bob McElrath

Apparently we should just run the LHC (+ILC).....

All evidence for Dark Matter is purely gravitational. (Dan Bauer)

→ *paradoxical that particle accelerator experiments can tell you anything about this.*

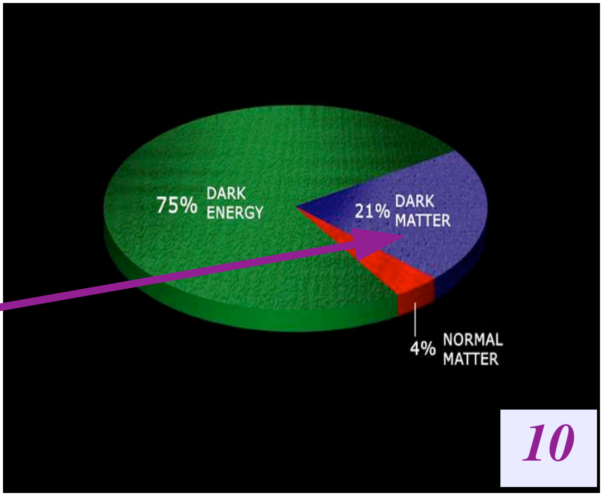
The key is Ted Baltz's "happy coincidence"

a.k.a. the "WIMP Miracle" - Jonathan Feng

→ *(assume dark matter is particulate),*
take TeV or EWK-scale masses,
take coupling constants of order 1,
you get the right annihilation cross-section.

DM (particle) paradigm

- **dark matter particles are weakly-interacting**
  - for sure no electric charge and no color,
  - and we *hope* that they will oblige us with weak interactions
- **they are massive**
  - happy coincidence argument: 50 – 5000 GeV
  - they could be much lighter or heavier, if we forget particle physics
- **there is only one type of dark matter**
  - and it can be produced directly or in "simple" cascades
- **there exists an efficient annihilation channel**
  - needed to obtain the observed relic density
  - implies the existence of *another* particle



simple composition?

Bridging Colliders to the Universe

- If the particle physics prejudices are correct, new particles are likely to be observed at the LHC.
- There may be evidence of massive, weakly-interacting, neutral particles.
- This would support a particle-physics explanation for dark matter.

Can we go from there to validating this paradigm?

- obviously, identify the LHC-WIMP and measure its properties
- essential to identify the particle(s) responsible for annihilation ←
- cannot prove long-term stability, so corroboration with direct-detection experiments is essential.
- don't know local dark matter density, so indirect-detection needed to tie direct-detection + collider information to astrophysics data

Colliders provide the means to measure particle properties, and one of these particles may turn out to be the dark matter particle.

LHC: testing the paradigm

Focus will not be on calculating relic densities...

- several studies show this is unlikely / very difficult – needs an ILC

Can the LHC rule out the standard paradigm?

- there should be a missing energy signal from particle X!
- more interesting: can we find the particle Y participating in annihilation?
- can we show that the mass difference $M_Y - M_X$ is appropriate?
- to what extent can we test the properties of X and Y?

Can the LHC fail to observe dark matter particles?

- yes, if it were very light or very heavy
- moreover, we could fail to find particle Y

example: Higgs decays invisibly or to jets
see talk by Carlos Wagner

be optimistic & hopeful

Despite these caveats, suppose this particle physics paradigm is true.

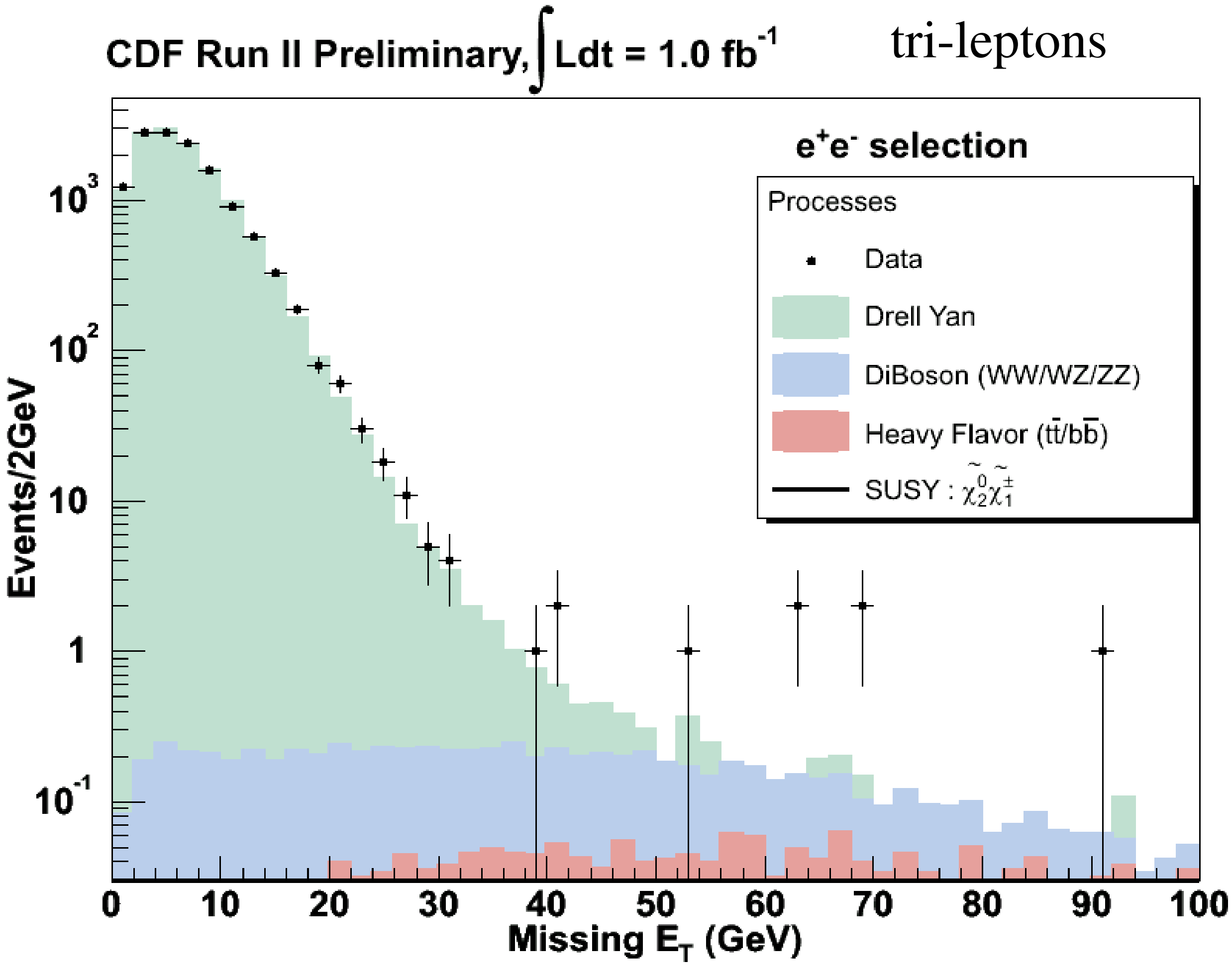
Or more conservatively, suppose there is no immediate “no” answer.

How can we make progress toward confirming this picture?

Establish a Missing Energy Signal

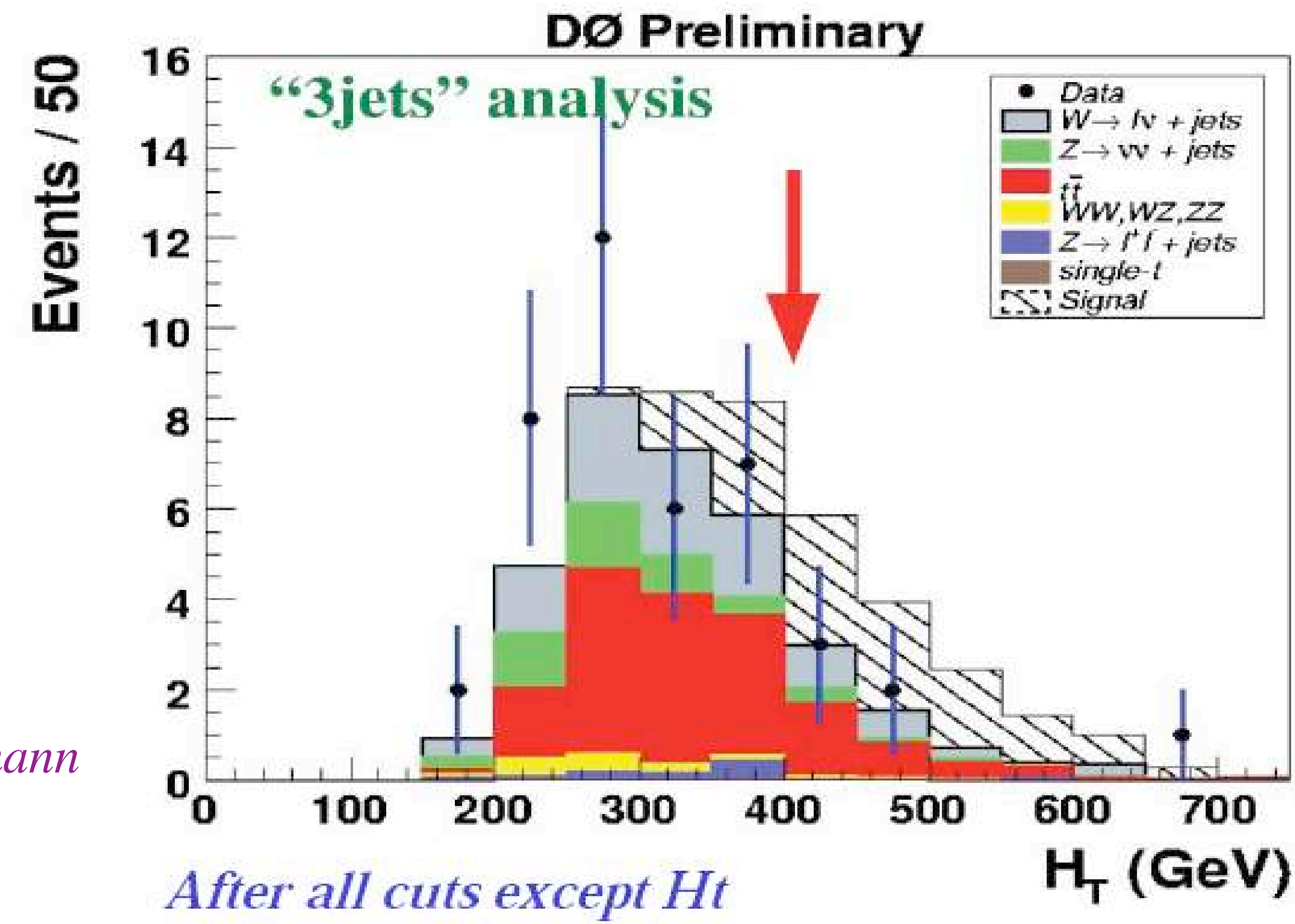
Here's one !!!

tri-leptons



Jane Nachtman

Here's another one !!!



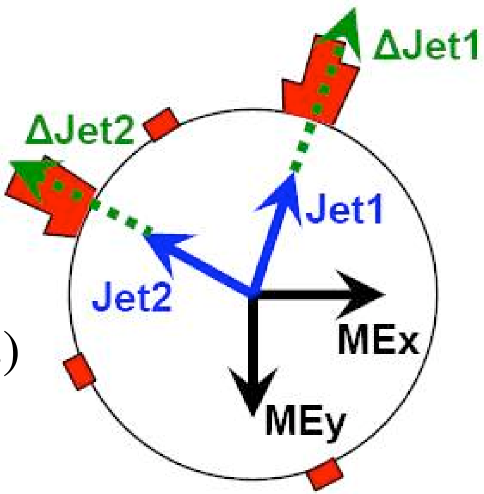
Jim Linnemann

How do they do it ???

Establish a Missing Energy Signal

How do we establish a genuine missing energy signal?

- missing energy is an apparent azimuthal imbalance in calorimeter energy.
- many sources of fake missing energy
  - muons
  - energy lost in uninstrumented regions
  - severe measurement errors (calorimetry, tracking)
  - energy from unrelated processes (other interactions, cosmics)



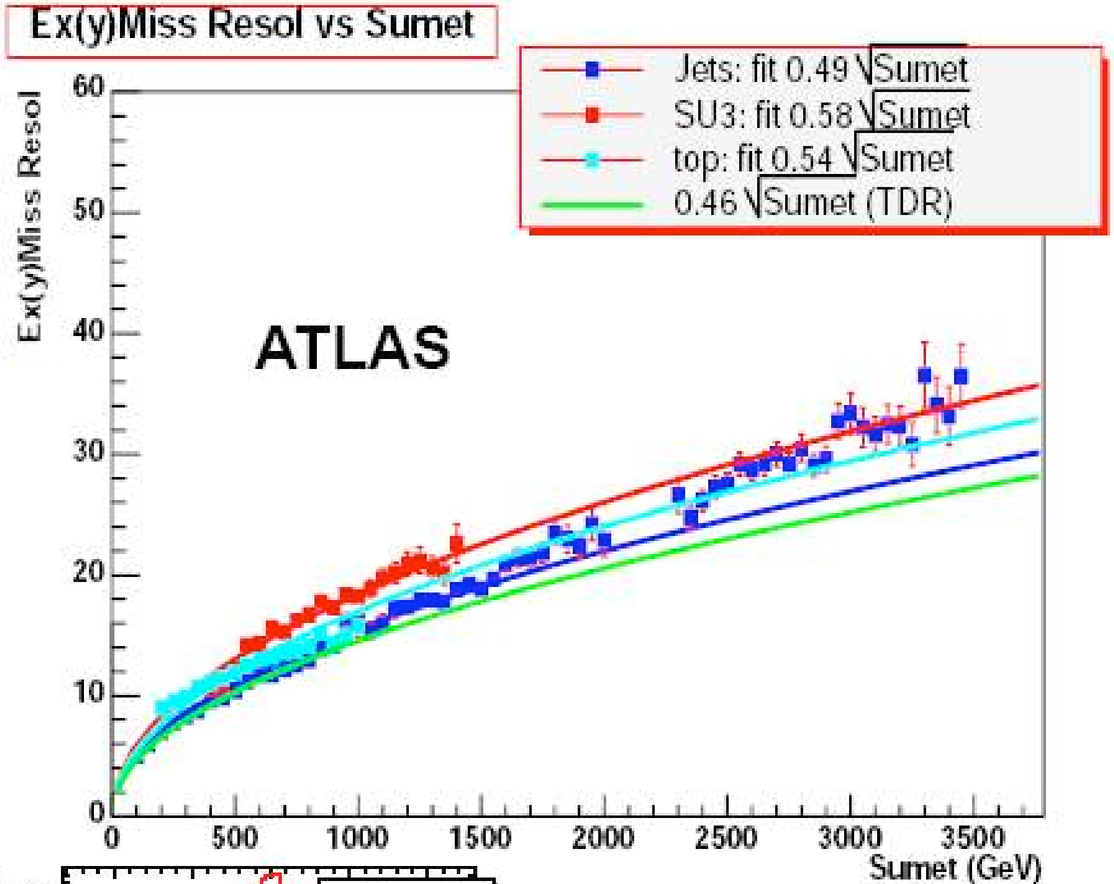
- neutrinos...
- resolution on MET determines the shape

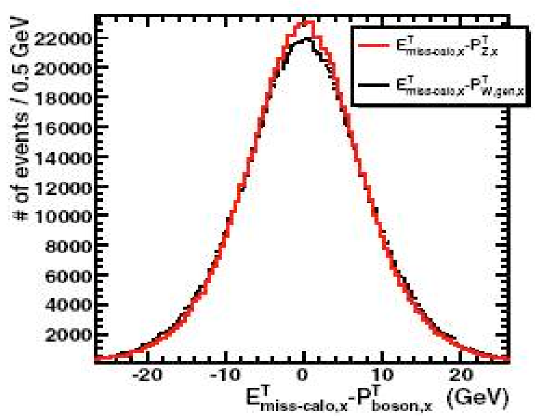
  → how long are the tails ??
- must calibrate the rates of all sources of fake MET

MET resolution is understood on basis of "SUMET"

SUMET = straight sum of calorimeter energies

- noise & stochastic terms important at low SUMET
- constant term in calor'y resolution at high SUMET
- resolution depends on event type due to differing particle content
- validate resolution using source of neutrinos: W's, Z's and top

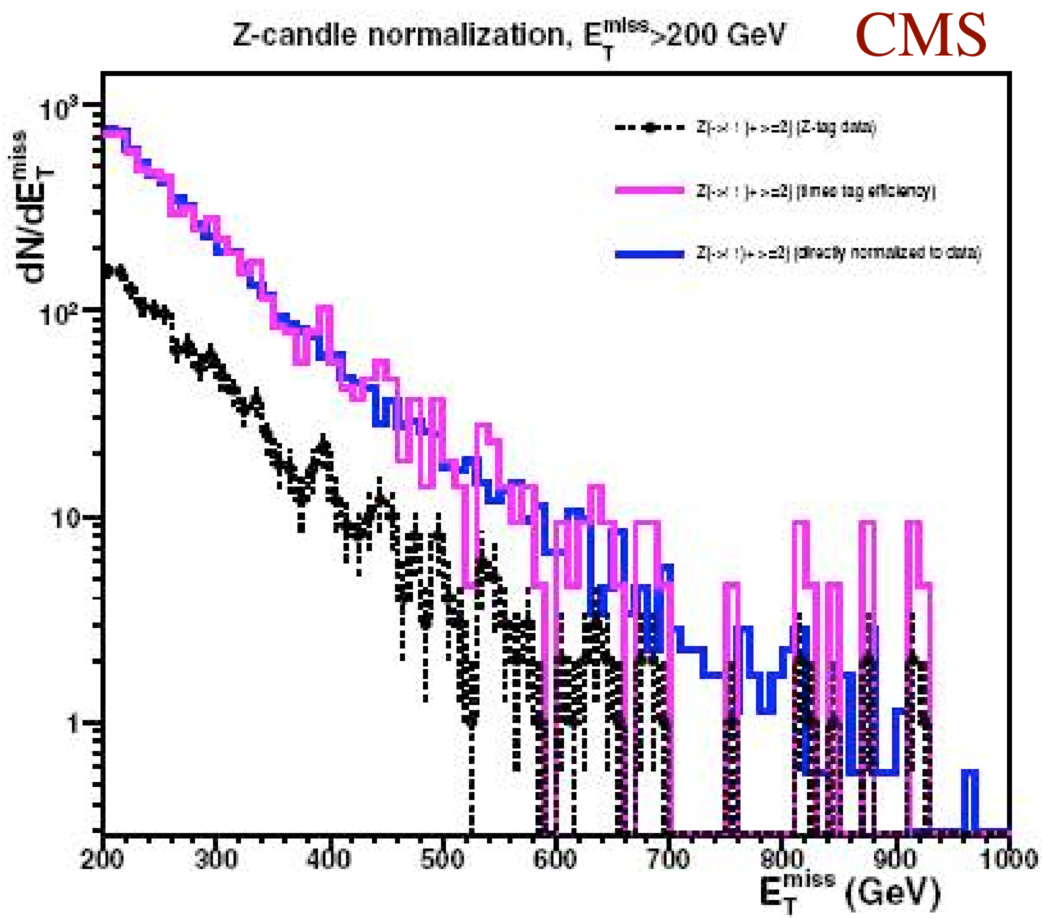


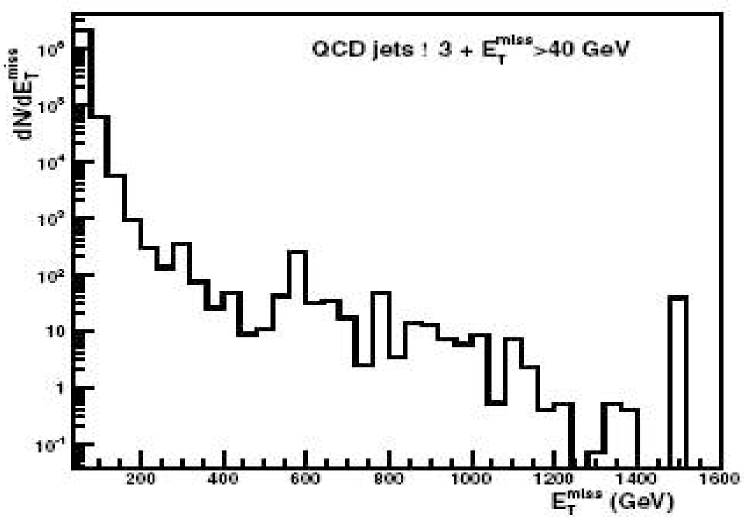


(Z→μμ, remove muons)

Backgrounds normalized by appropriate reference processes.

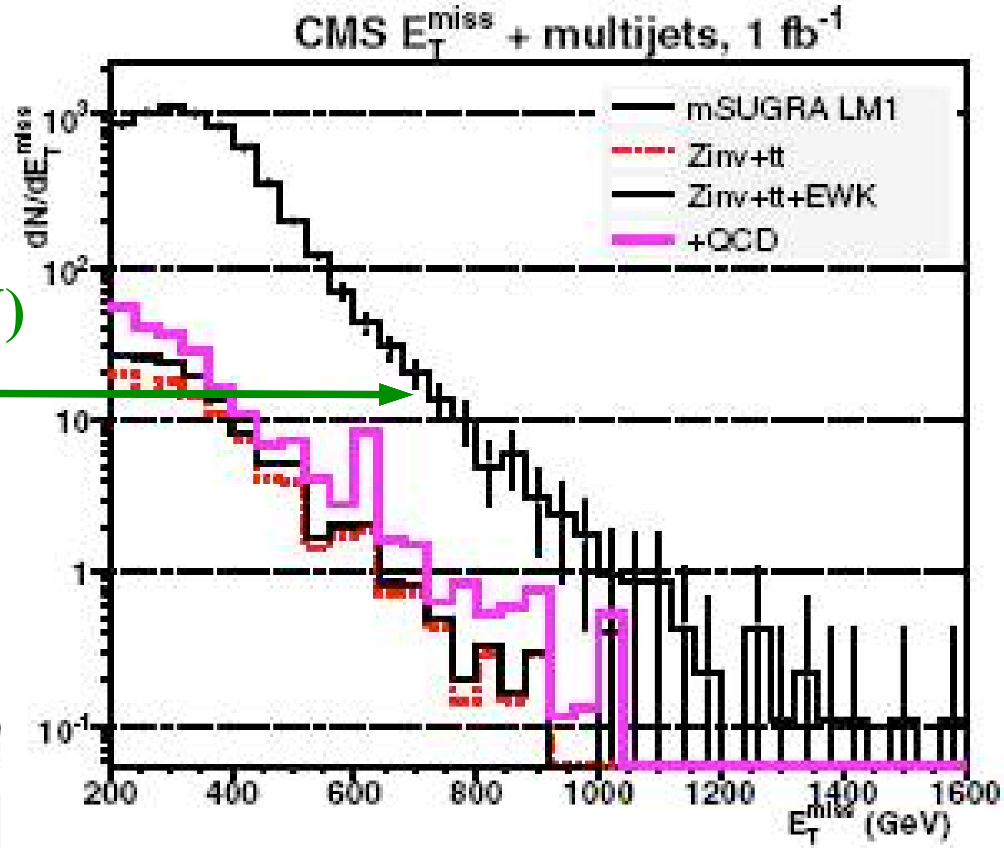
- important backgrounds:
  - t tbar
  - di-bosons   WW, WZ, ZZ
  - $Z \to \nu\nu$ + jets
  - multi-jet QCD
- normalize to similar processes
  - example: $Z \to \mu\mu$ + jets
  - similarly for t tbar



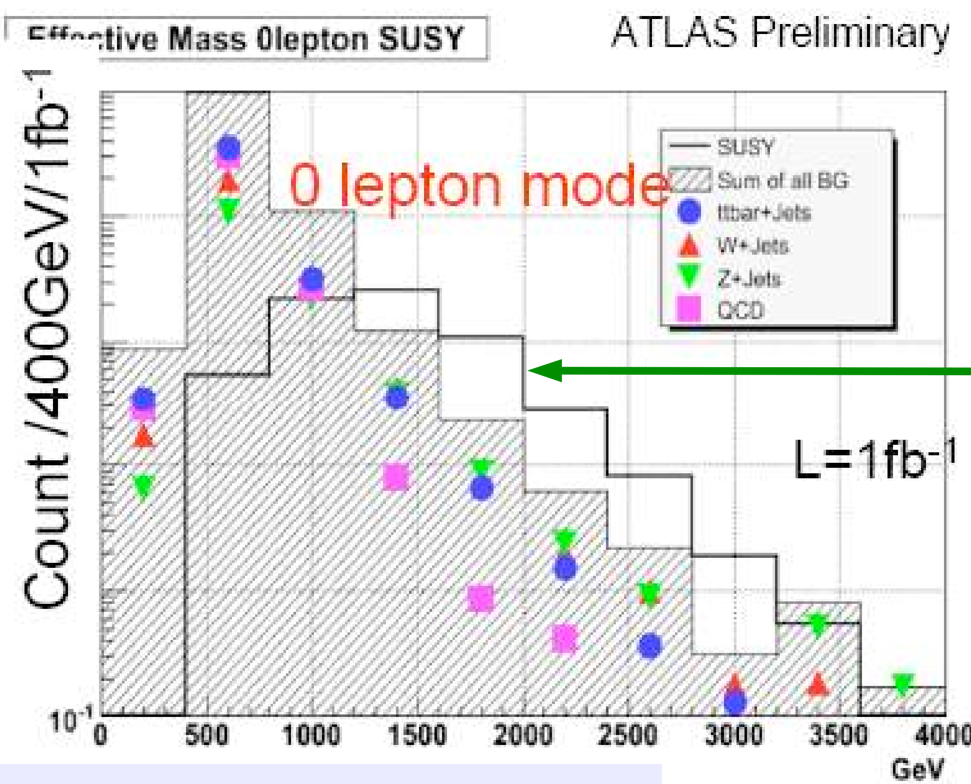


- shape of multi-jet background (scary!) obtained from reference samples
- (release certain topological cuts)

MET signals for 1 fb^{-1} (1^{st} year?)



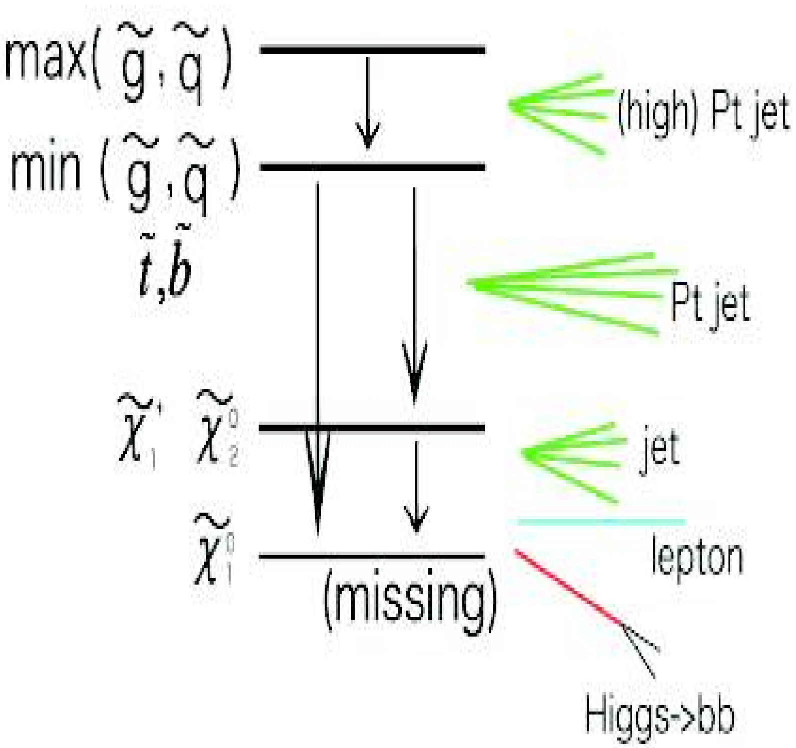
light mass point (M_{gluino} = 600 GeV)



high mass point (M_{gluino} = 1 TeV)

Measure Dark Matter Particle Properties

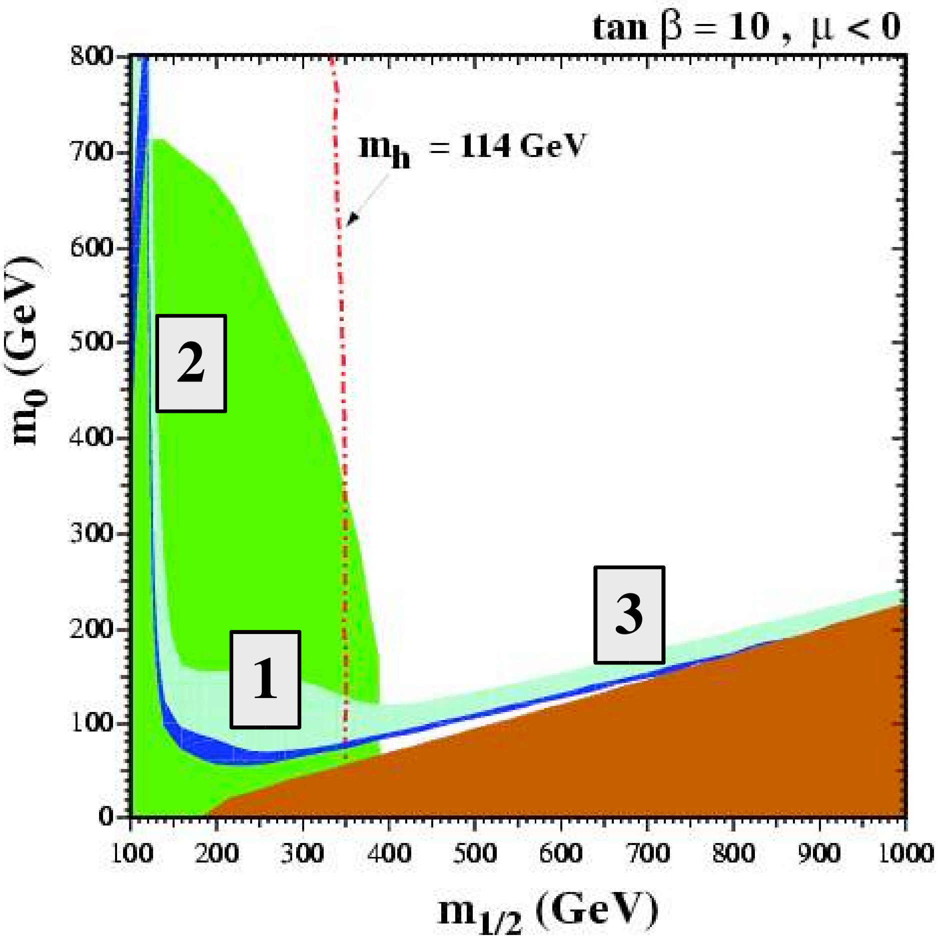
mass **spin** **couplings**

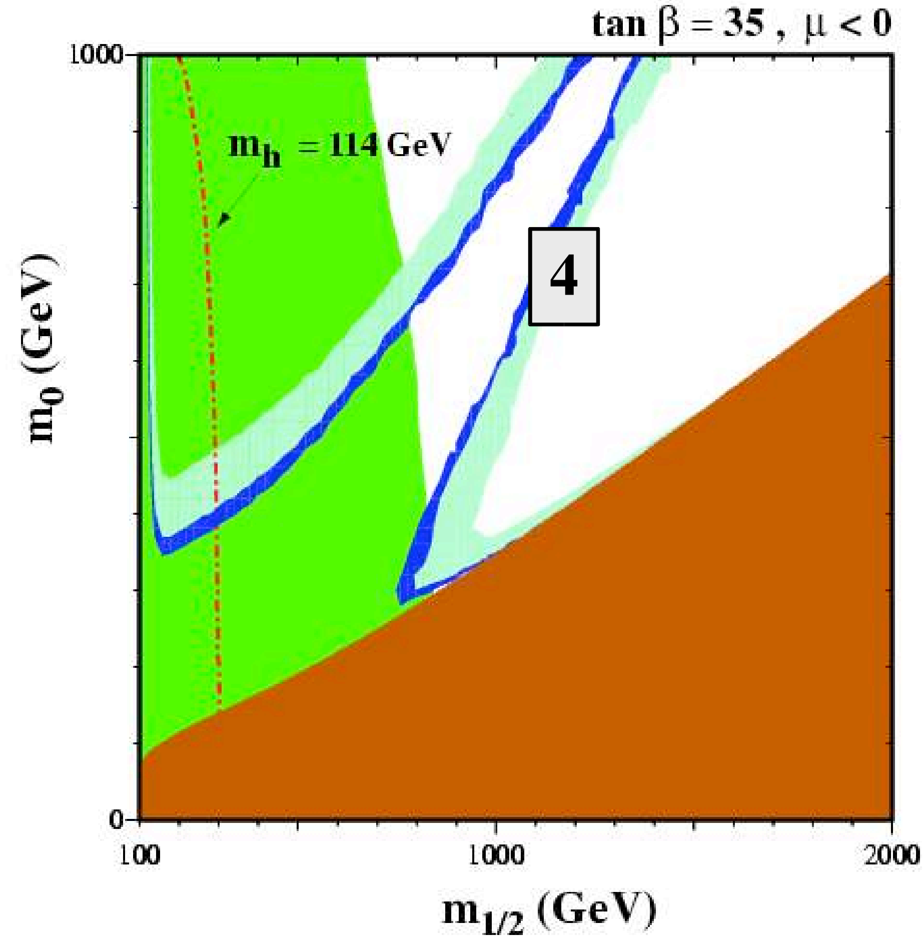


- **no general way to obtain the mass**
  - caveat: see interesting developments by Bob McElrath
- **no way to obtain spin and couplings**
- **no branching ratios....**

- **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

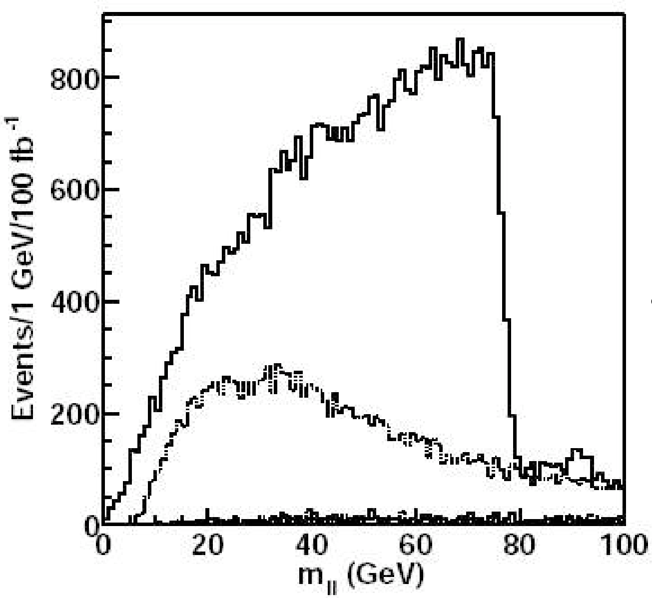
squarks around 550 GeV, gluino around 600, neutralino at 96 GeV

start here ↓ ↓ ***end here***

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

- 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}



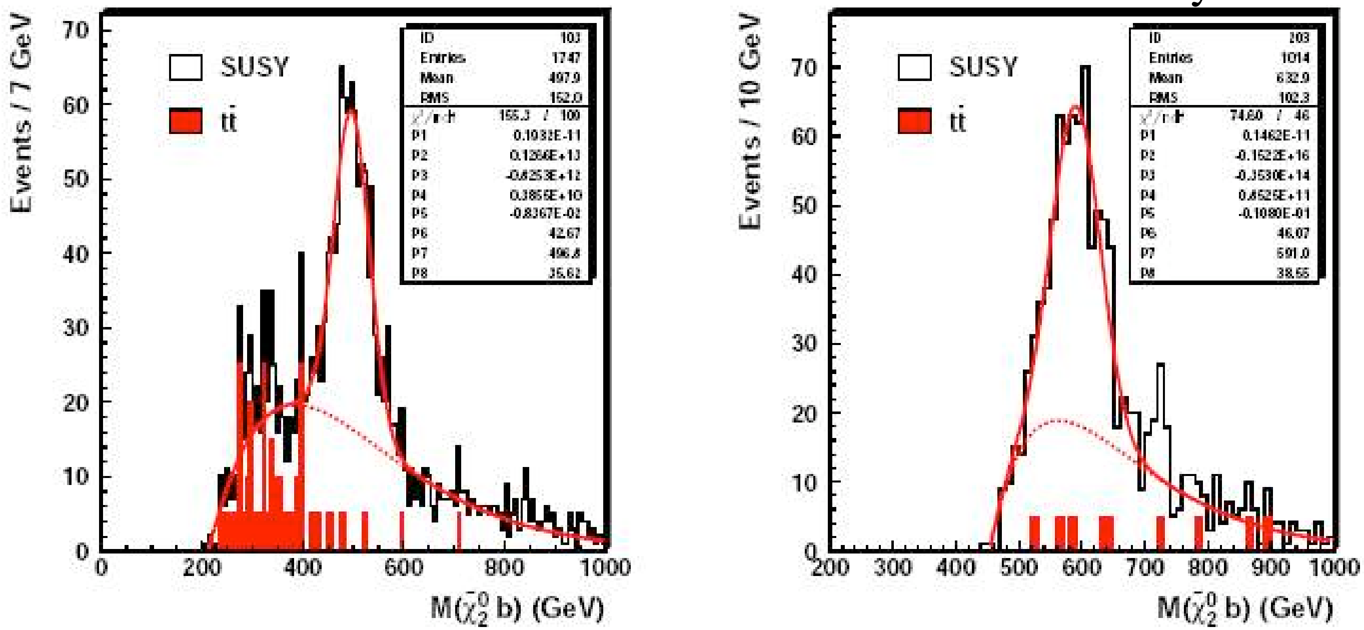
LHC-ILC study

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

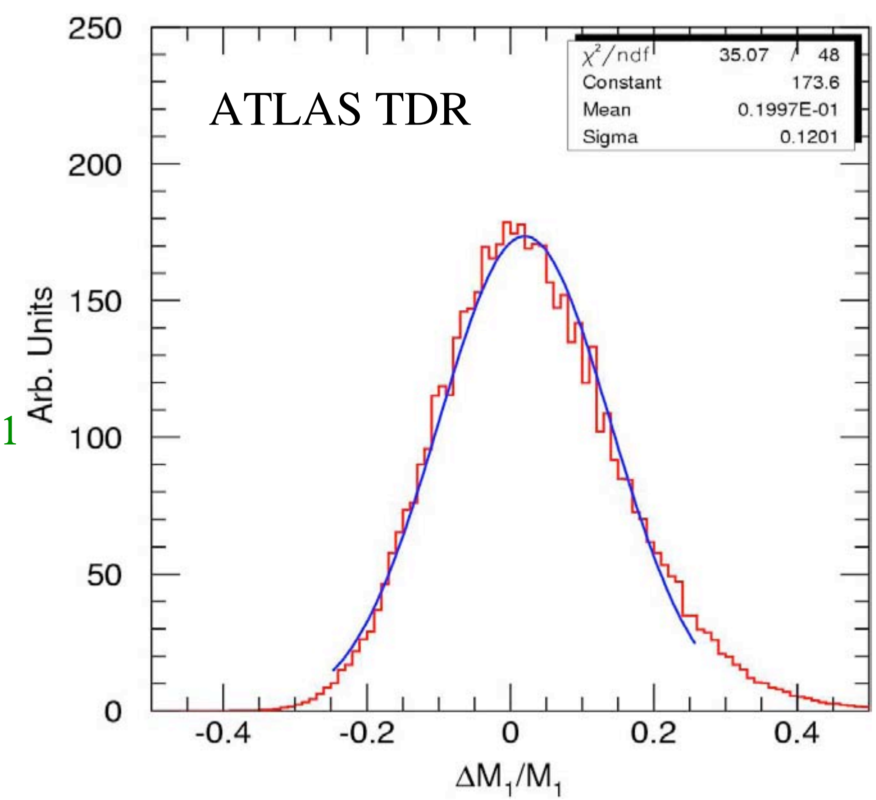
CMS study



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!
In general, no direct measurement is possible.



Other points are more difficult!

co-annihilation

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

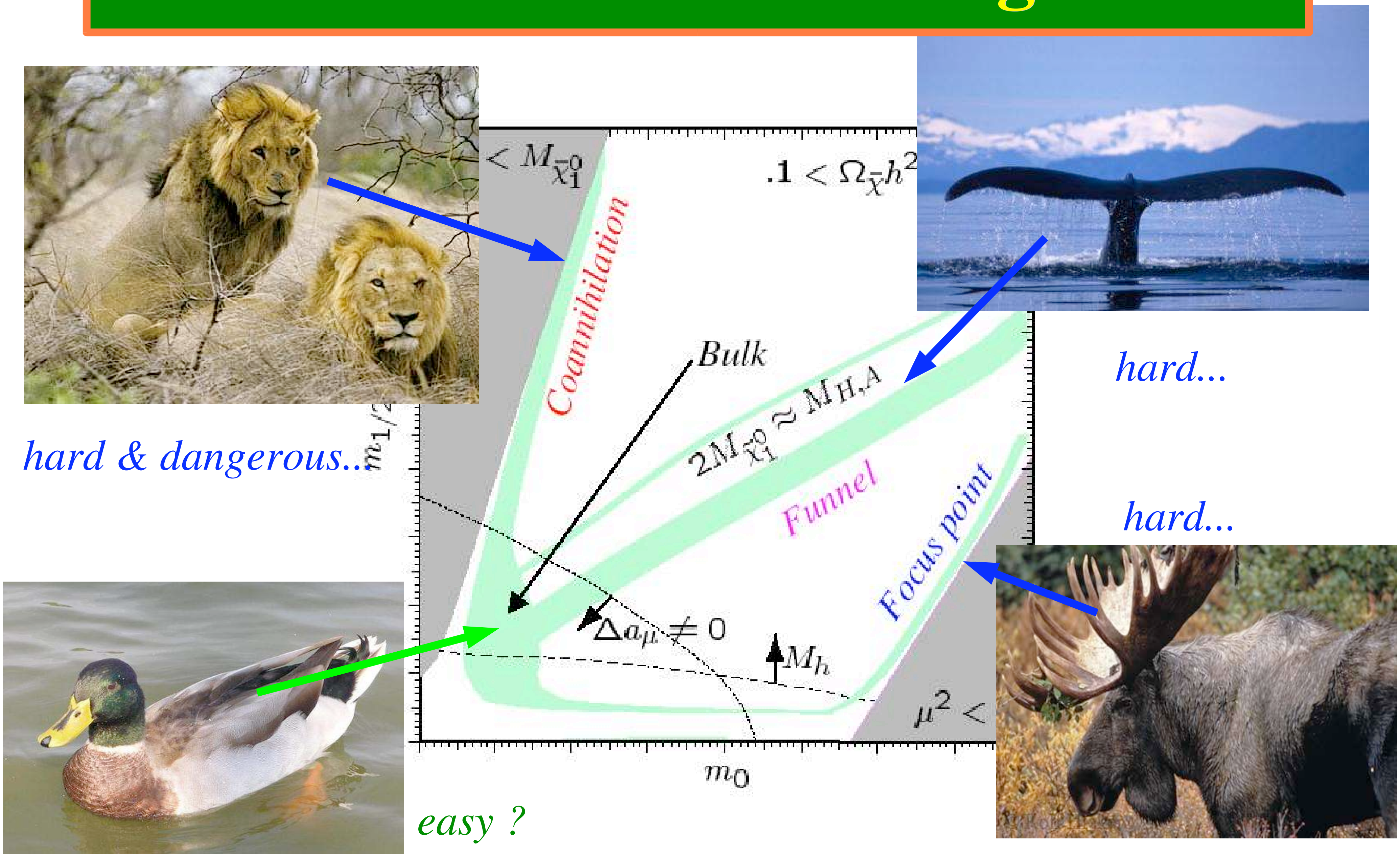
funnel(s)

- 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?



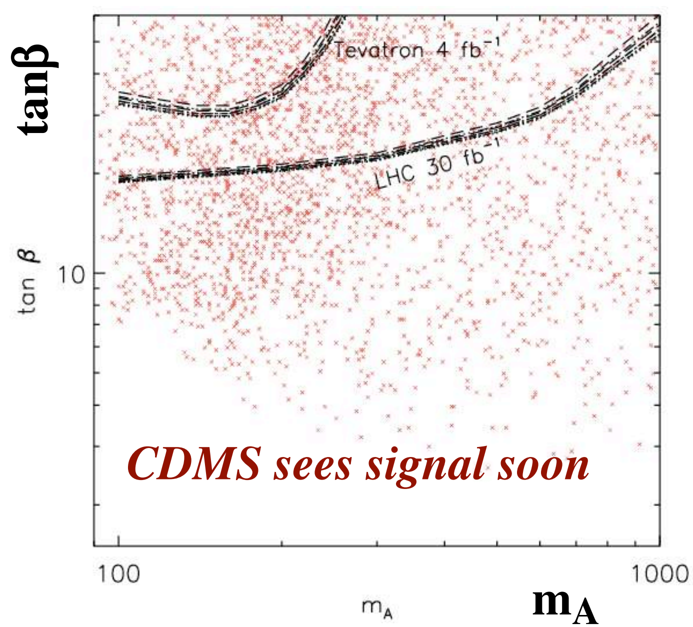
Find the "other" particle

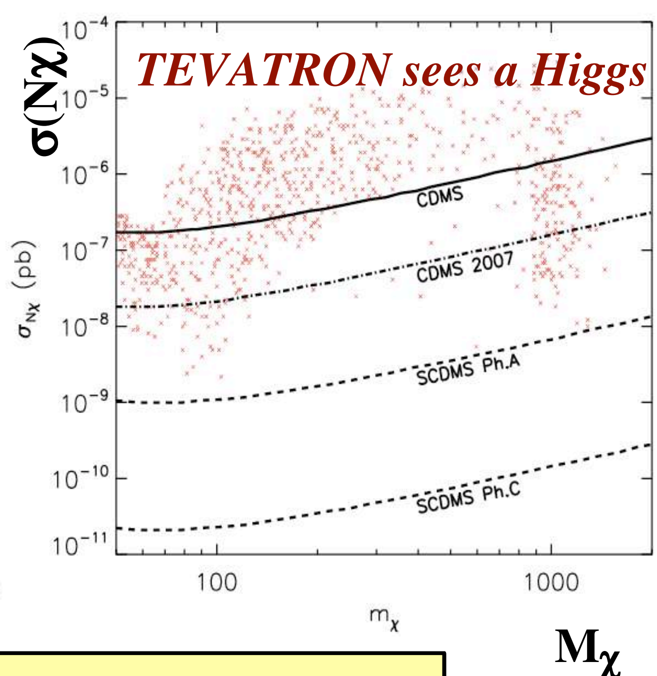
- interesting that Higgs sector is prominent in three out of four regions
- we need to validate the annihilation process directly from collider data a.f.a. possible
- perhaps understanding Higgs sector at LHC more important than constraining several SUSY parameters & calculating Ωh^2

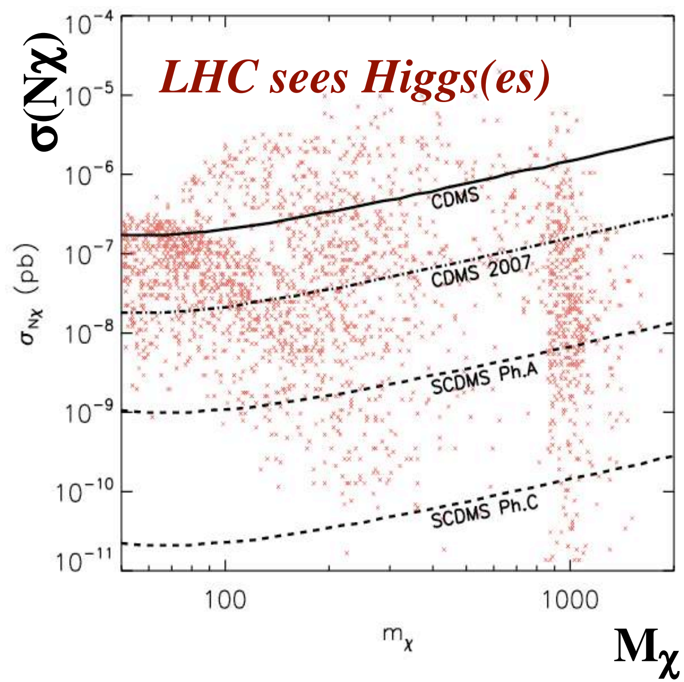
"Easy" Higgs signal in A,H $\rightarrow \tau^+\tau^-$

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 $\rightarrow \tau^+\tau^-$

Carena, Hooper, Vallinotto (2007)

hunting the Higgs bosons

- 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

- **even more interesting:**
  → connection w/ baryogenesis
- **light gauginos = a sitting duck?**
- **watch out: invisible Higgses!!**

see Carlos Wagner's talk

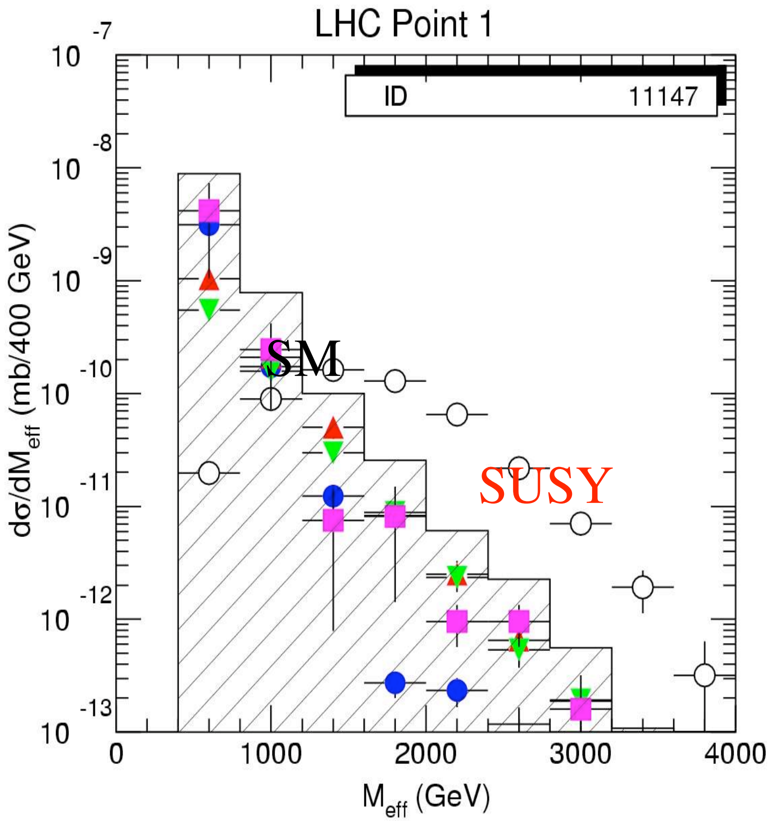
Overall Mass Scales

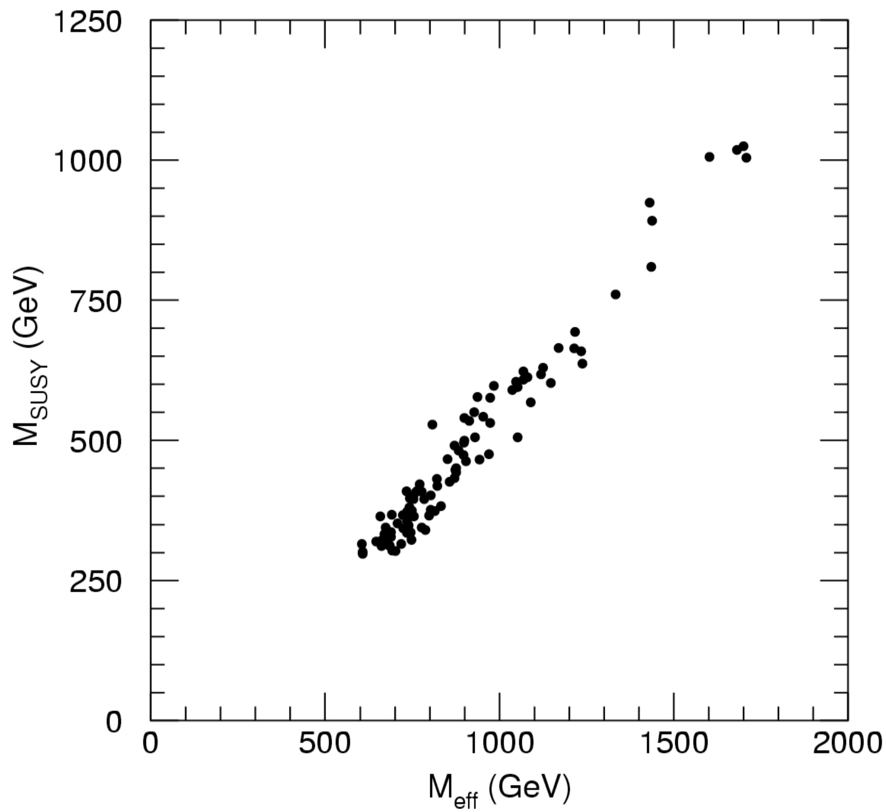
The production of squarks and gluons should be so copious that the simplest possible measure of "lots of energetic jets + MET" will already indicate SUSY mass scales.

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

correlates with SUSY mass scale

hep-ph/9610544





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

Conclusion

The LHC probably will not allow us to compute relic densities, but it will certainly set us on the path to understanding dark matter.

Soon we will all be on the hunt...

Here's another one !!!

search for squarks and gluinos