New Physics at the Weak Scale:

From Collider Physics to Cosmology

C.E.M. Wagner

EFI & KICP , Univ. of Chicago
HEP Division, Argonne National Lab.

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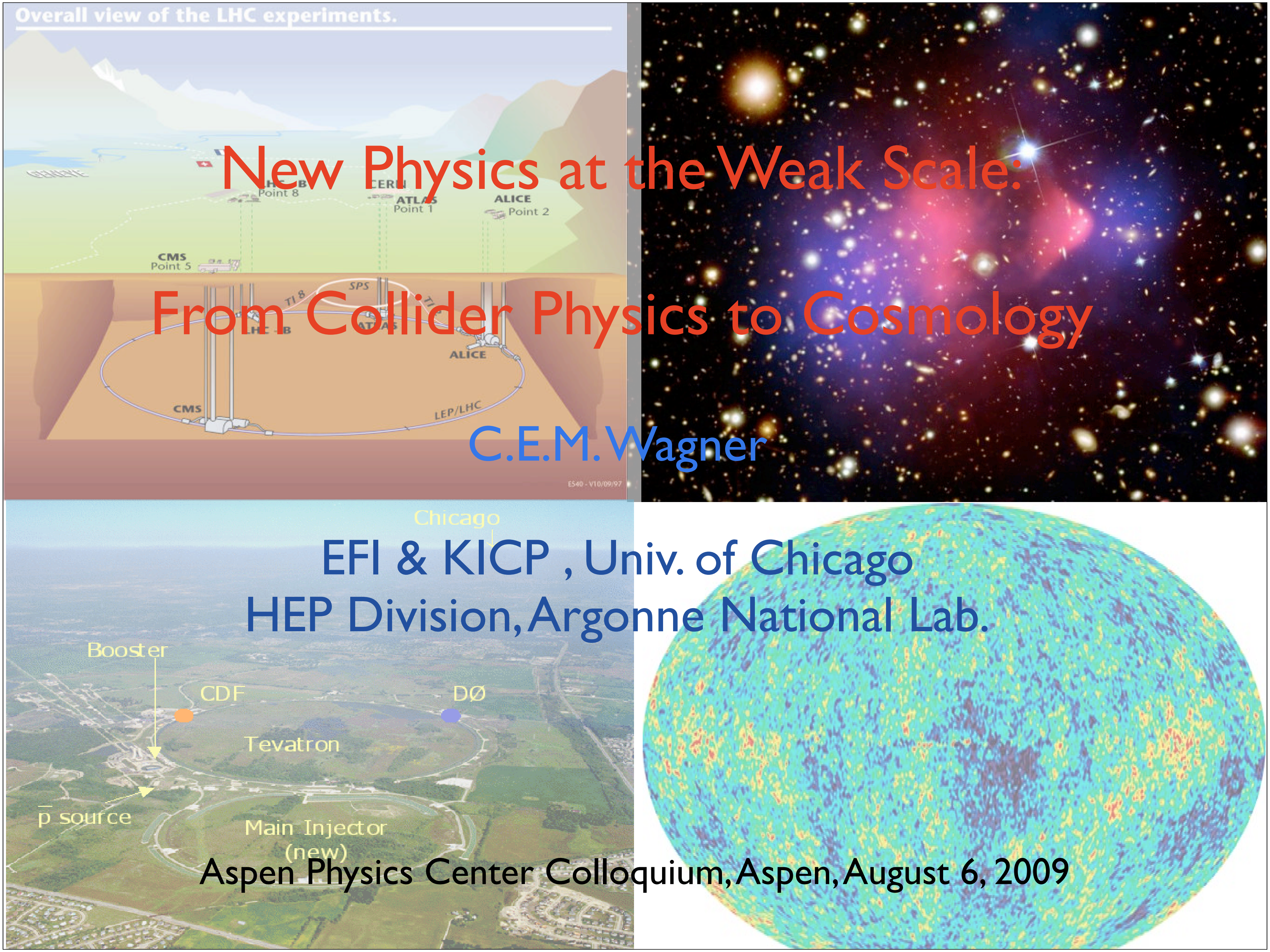


Physics at the Weak Scale

- The Standard Model (SM) has provided an understanding of all data collected in low and high energy physics experiments
- However, there are reasons to believe that there is new physics at the weak scale. They are related to both particle physics and cosmology:
- Electroweak Symmetry Breaking
- Source of Dark Matter
- Origin of the Matter-Antimatter asymmetry
- There are other open questions in the SM, like the explanation of the fermion mass hierarchies and mixing angles (including the tiny neutrino masses) and dark energy. The first has been the subject of last week colloquium. I will not concentrate on these questions.

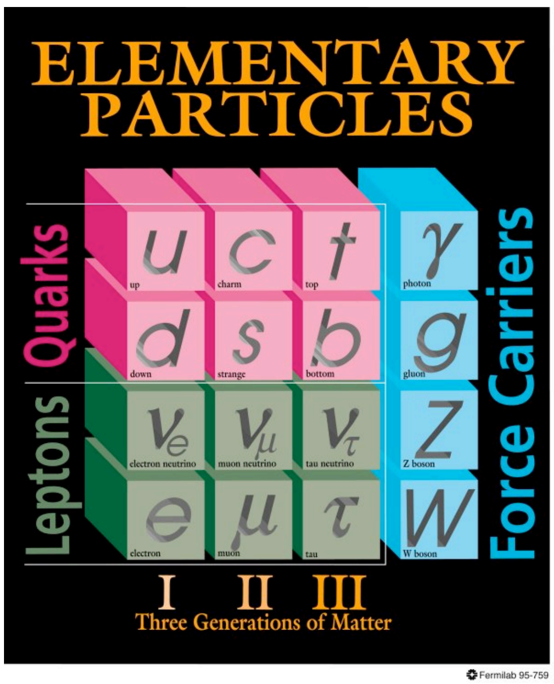
Standard Model Particles

There are 12 fundamental gauge fields:

8 gluons, 3 W_μ's and B_μ
and 3 gauge couplings g_1, g_2, g_3

The matter fields:

3 families of quarks and leptons with same quantum numbers under gauge groups



But very different masses!

m_3/m_2 and $m_2/m_1 \simeq$ a few tens or hundreds
$m_e = 0.5\ 10^{-3}$ GeV, $\frac{m_\mu}{m_e} \simeq 200$, $\frac{m_\tau}{m_\mu} \simeq 20$

Largest hierarchies
$m_t \simeq 175$ GeV $\quad m_t/m_e \propto 10^5$
neutrino masses smaller than as 10^{-9} GeV!

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	<1×10^{-8}	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

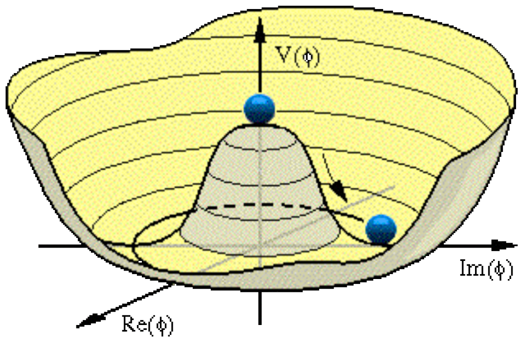
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Only left handed fermions transform under the weak SM gauge group
$SU(3) \times SU(2)_L \times U(1)_Y$
Fermion and gauge boson masses forbidden by symmetry

Electroweak Symmetry Breaking:

The Higgs Mechanism and the Origin of Mass

A scalar (Higgs) field is introduced. The Higgs field acquires a nonzero value to minimize its energy



Spontaneous Breakdown of the symmetry : $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\mathrm{em}}$

Vacuum becomes a source of energy = a source of mass

$$\langle H^0 \rangle = \mathrm{v}$$

A physical state (Higgs boson) appear associated to fluctuations in the radial direction . Goldstone modes: Longitudinal component of massive Gauge fields.

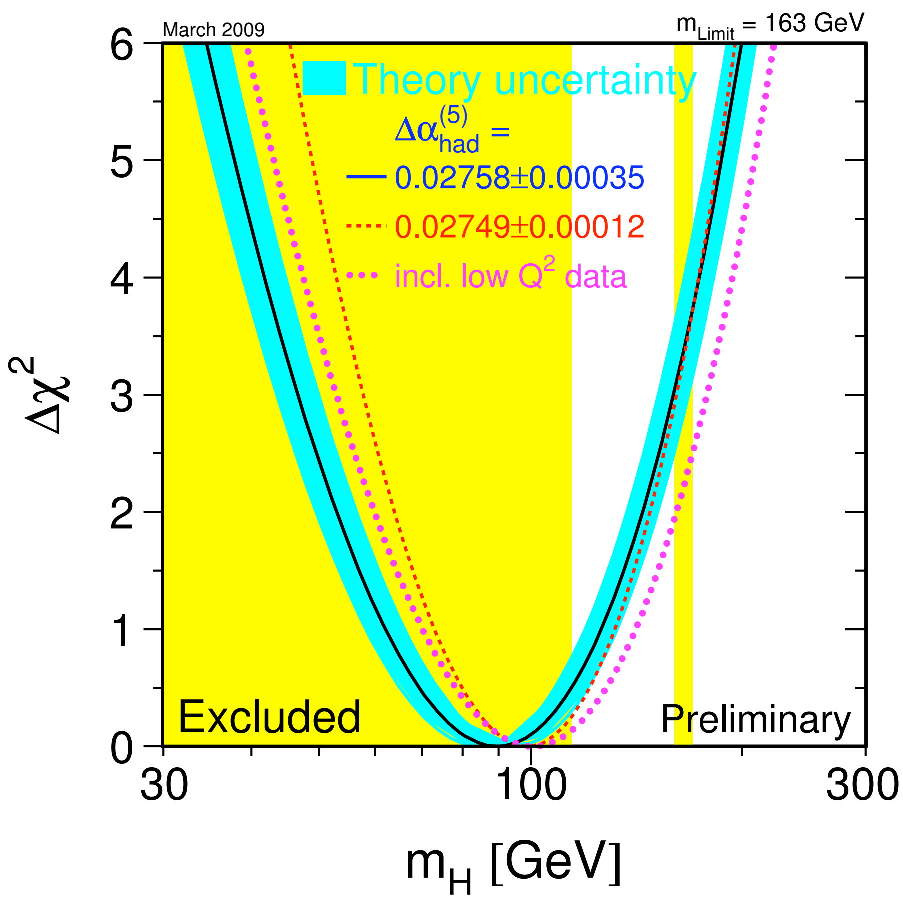
Masses of fermions and gauge bosons proportional to their couplings to the Higgs field:

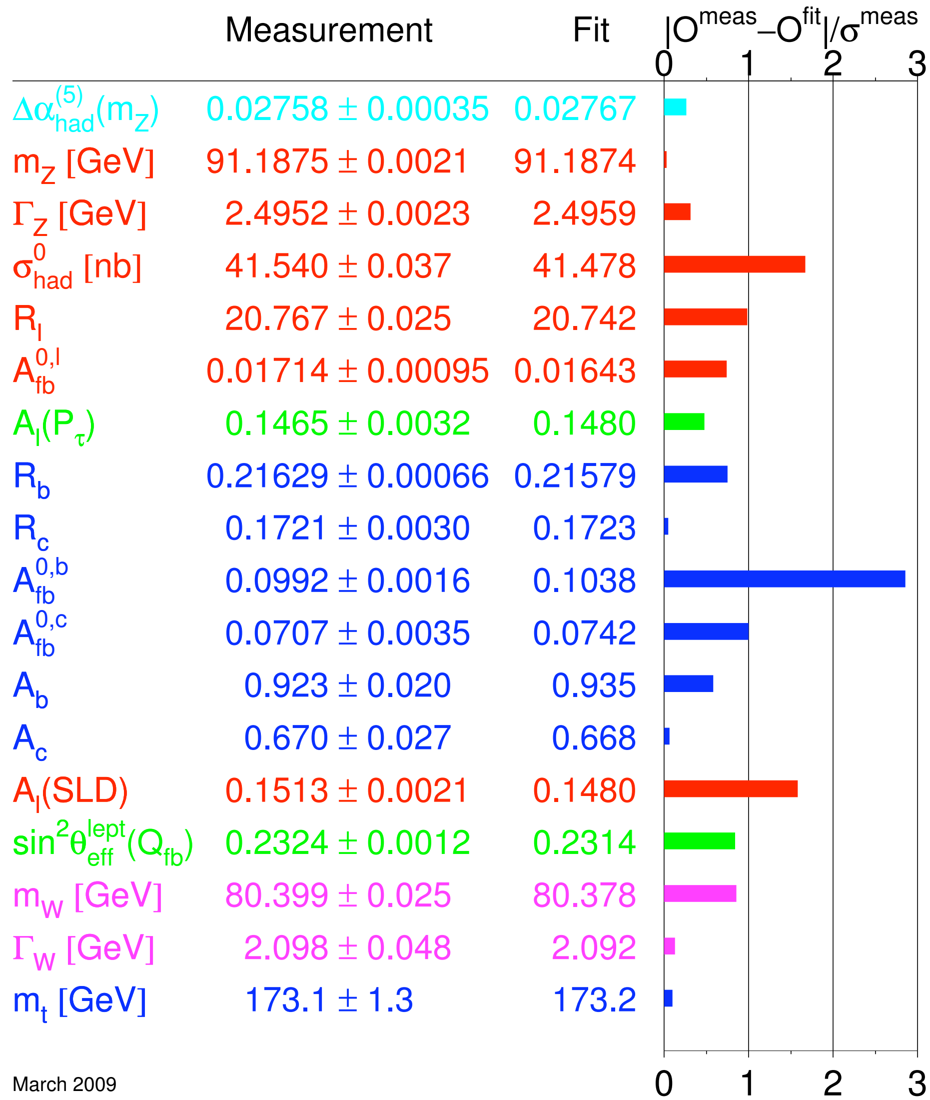
$\mathbf{M_W = g_{W,Z}\, v}$ $\quad m_{top} = h_{top}\, v$ $\quad m_H^2 = \lambda\, v^2$

$$\mathcal{L} = \sum_i i\bar{\Psi}^i_{L,R}\mathcal{D}^\mu\gamma_\mu\Psi^i_{L,R} - \sum_{i,j}\left(\bar{\Psi}^i_L h^d_{ij} H d^j_R + \bar{\Psi}^i_L h^u_{ij}(i\sigma_2 H^*) u^j_R + h.c.\right)$$

SM: Consistent picture of physics at or below the weak scale

Sensitivity to the loop-induced Higgs quantum corrections





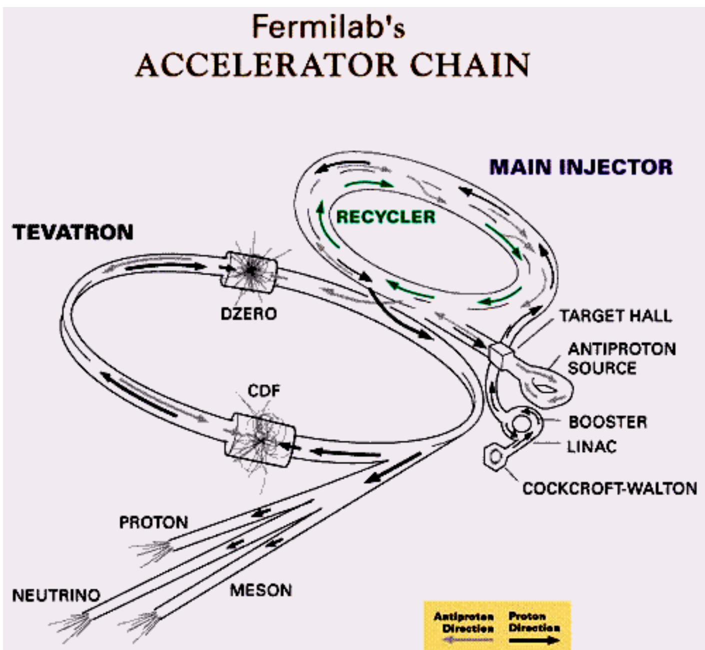
Discovering the Higgs will put the final piece of the Standard Model in place

It will prove that our simplest explanation for the origin of mass is indeed correct.

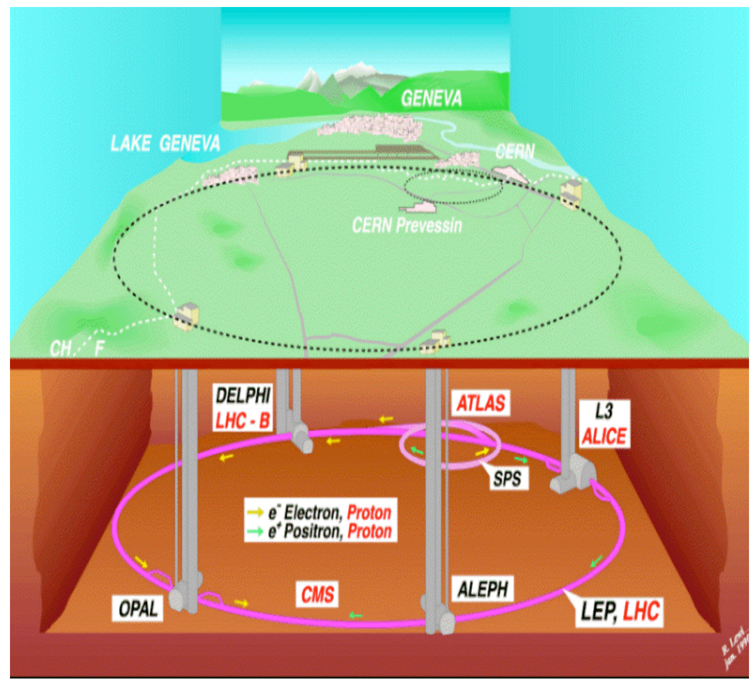
How do we search for the Higgs?

Colliding particles at High Energy Accelarators: LEP, the Tevatron, the LHC

$p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV



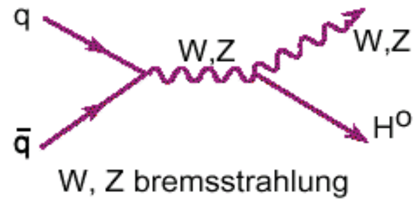
e^+e^- at $\sqrt{s}$ = 210 GeV and pp at $\sqrt{s}$ = 14 TeV



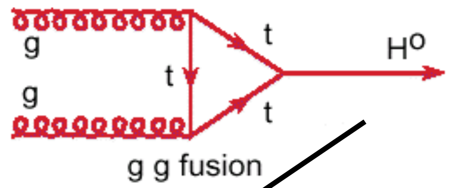
Direct Higgs searches at the Tevatron

Tevatron can search for the Higgs in all the mass range preferred by precision data

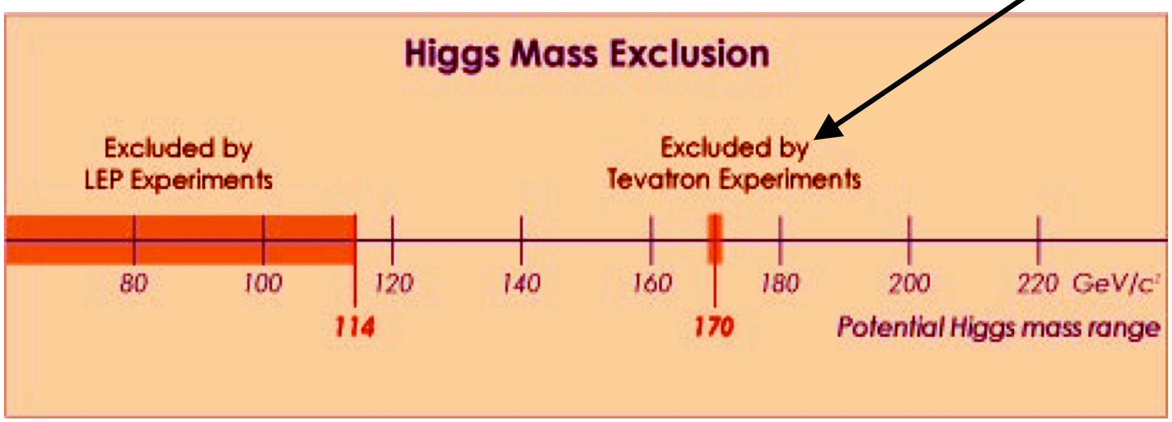
Many Possible production Processes



with $H \to b\bar{b}, WW$

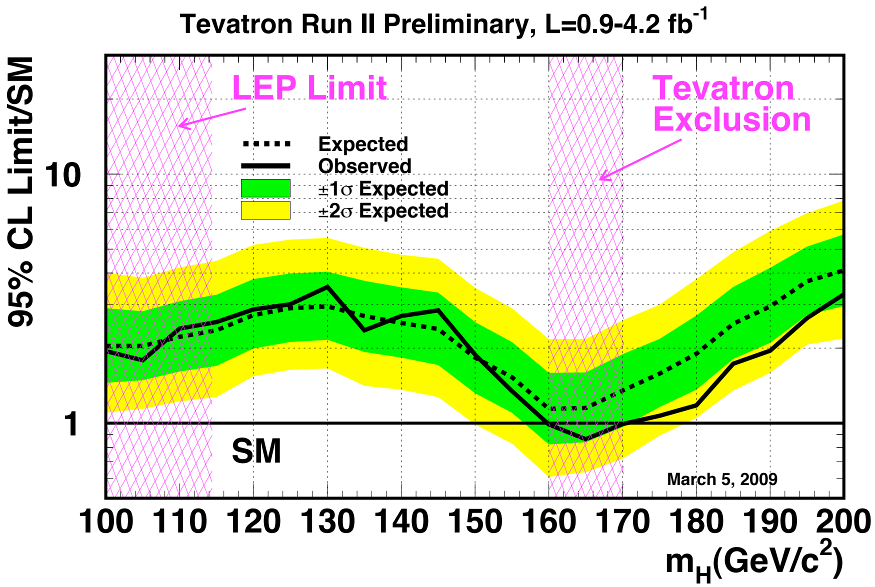


with $H \to WW$



Press release: 9/08

Tevatron achieves sensitivity to exclude a Higgs with mass 170 GeV

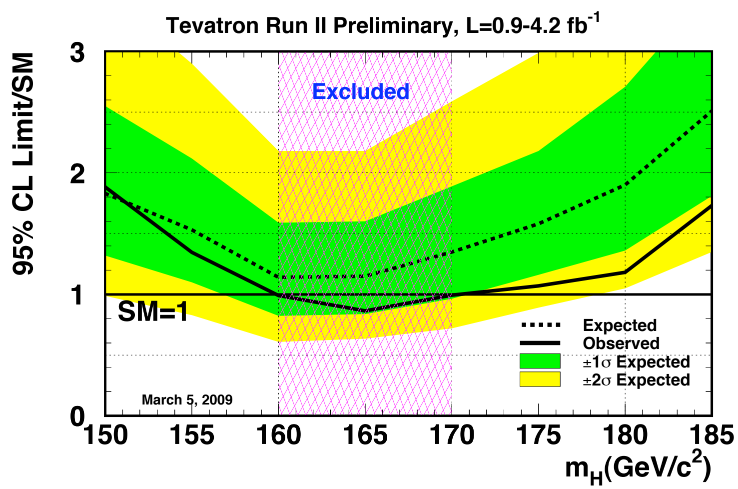


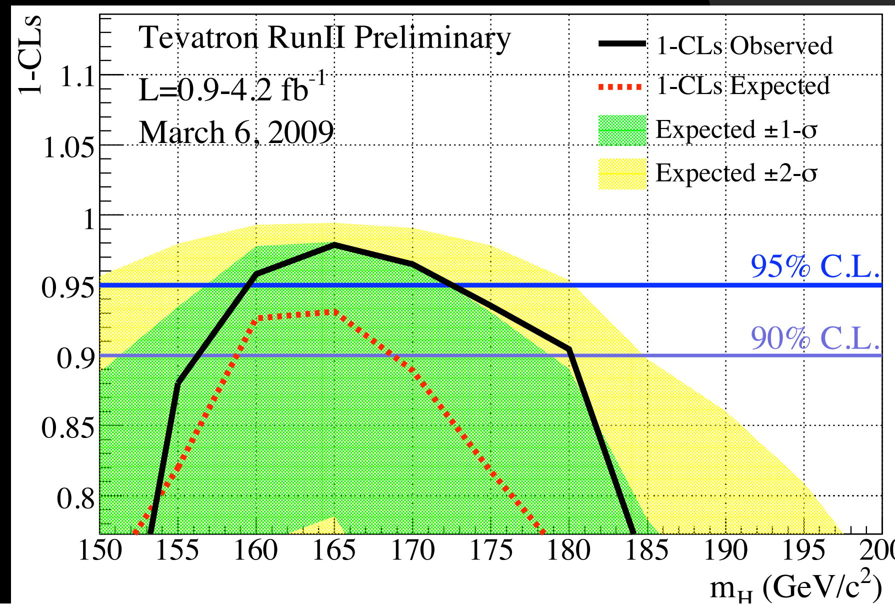
Very recent news:

Tevatron sets the first significant bounds on a heavy Higgs boson

Higgs with SM properties, in mass range 160–170 GeV is excluded at 95% C.L.

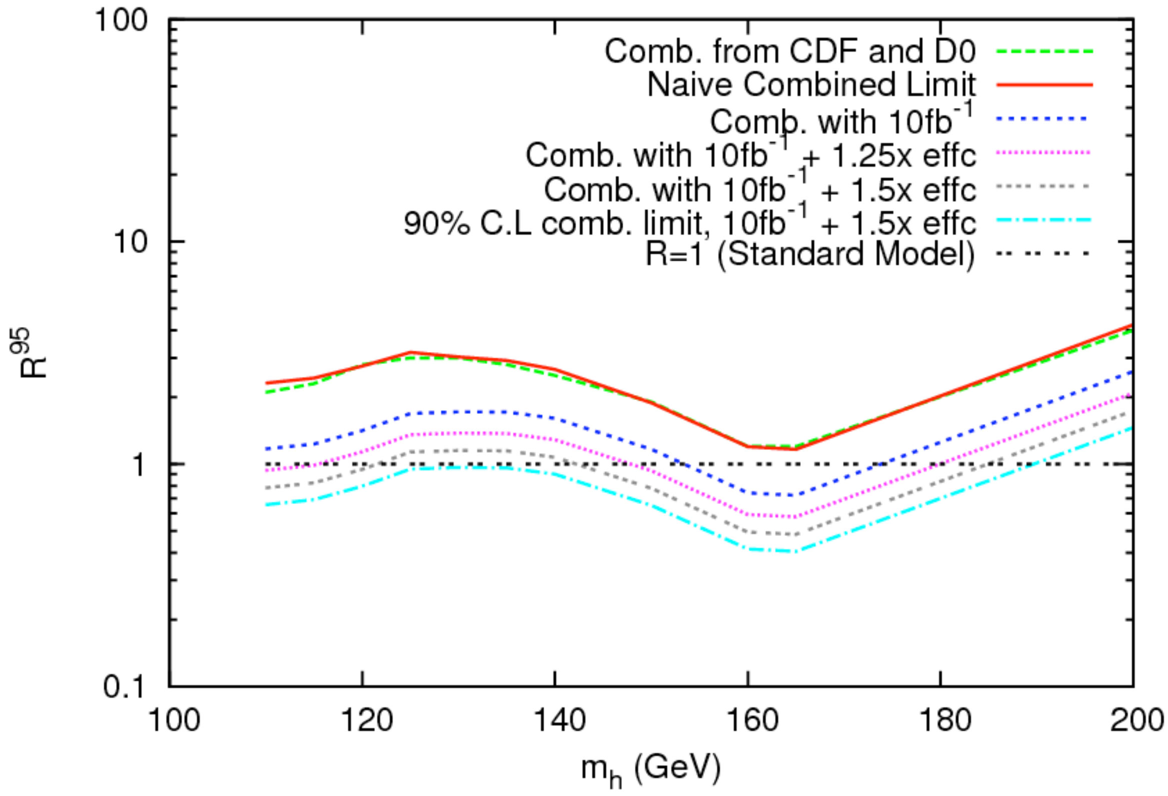
http://tevnphwg.fnal.gov/results/SM_Higgs_Winter_09/





Prospects for Higgs Searches at the Tevatron

P. Draper, T. Liu and C. Wagner'09

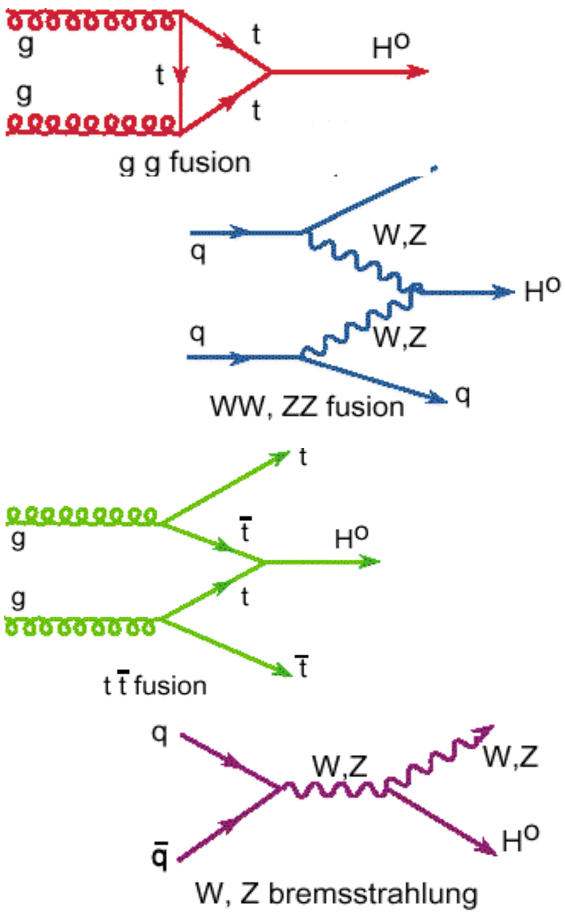


Running for two years more, the Tevatron should collect more than 10 fb^{-1}
With expected detector/analysis performance, $m_H < 185$ GeV may be probed.

LHC

- After an accidental start last year, the LHC is expected to start running by the end of 2009.
- The center of mass energy will be lower than the expected one, 14 TeV, reaching only up to 7 to 10 TeV depending on the magnets performance.
- The plan is to run for a whole year, until the end of the fall of 2010, accumulating about 200 inverse pb of luminosity.
- Due to the limited energy and luminosity, this will make LHC superior to the Tevatron only in certain search analyses, like the search for TeV scale resonances decaying to leptons.
- Higgs searches beyond the Tevatron reach will demand higher luminosities and higher energies.
- After the first run, LHC plans to shut down for about 6 months. Higher luminosity/energy run will start in the spring of 2011. It is yet unclear what the highest energy achievable will be.

The search for the Standard Model Higgs at the LHC

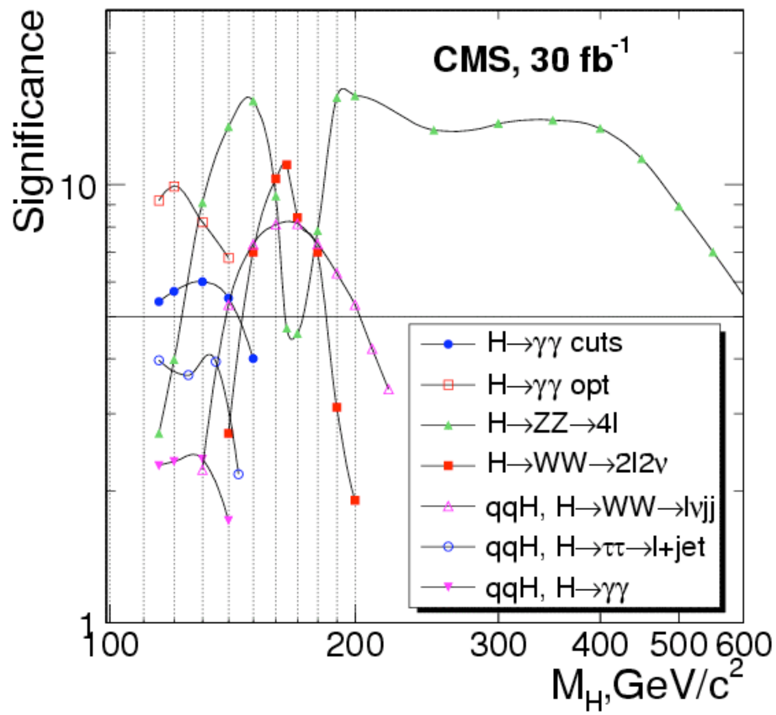


- **Low mass range** $m_{H_{SM}} < 200$ GeV

$$H \to \gamma\gamma, \tau\tau, bb, WW, ZZ$$

- **High mass range** $m_{H_{SM}} > 200$ GeV

$$H \to WW,\ ZZ$$



Results for 14 TeV. In most of the channels presented here, the Higgs search at 10 TeV will demand higher luminosities.

Dark Matter and Electroweak Symmetry Breaking

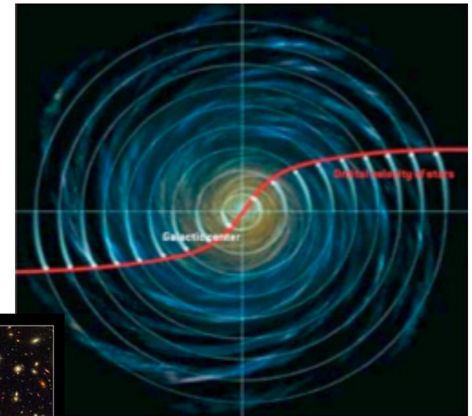
Physics Beyond the SM ? Dark Matter

- Cosmological measurements provided "precision tests" of the Universe energy density composition, making the case for Dark Matter quite compelling.
- Today we know that Dark Matter makes most of the matter of the Universe and there are experiments looking for its direct (and indirect) detection.
- The detection of Dark Matter may just be the tip of the Iceberg of a whole new world of additional particles
- High Energy Physics experiments could provide clues toward the understanding of the nature of these particles: This will depend on their energy range and interaction strength with SM particles.

The Mystery of Dark Matter

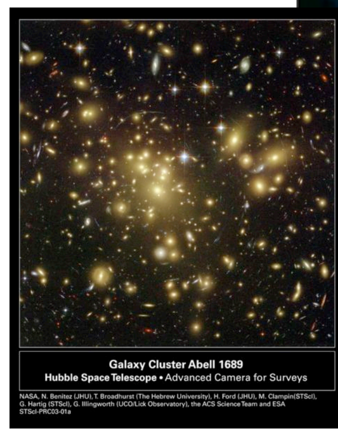
- Rotation curves from Galaxies.

  Luminous disk → not enough mass to explain rotational velocities of galaxies → Dark Matter halo around the galaxies



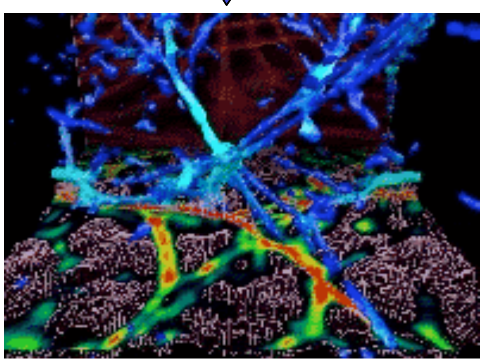
- Gravitational lensing effects

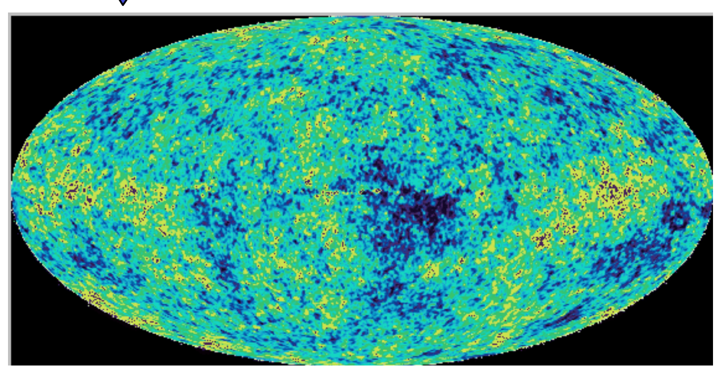
Measuring the deformations of images of a large number of galaxies, it is possible to infer the quantity of Dark Matter hidden between us and the observed galaxies



- Structure formation:

Large scale structure and CMB Anisotropies

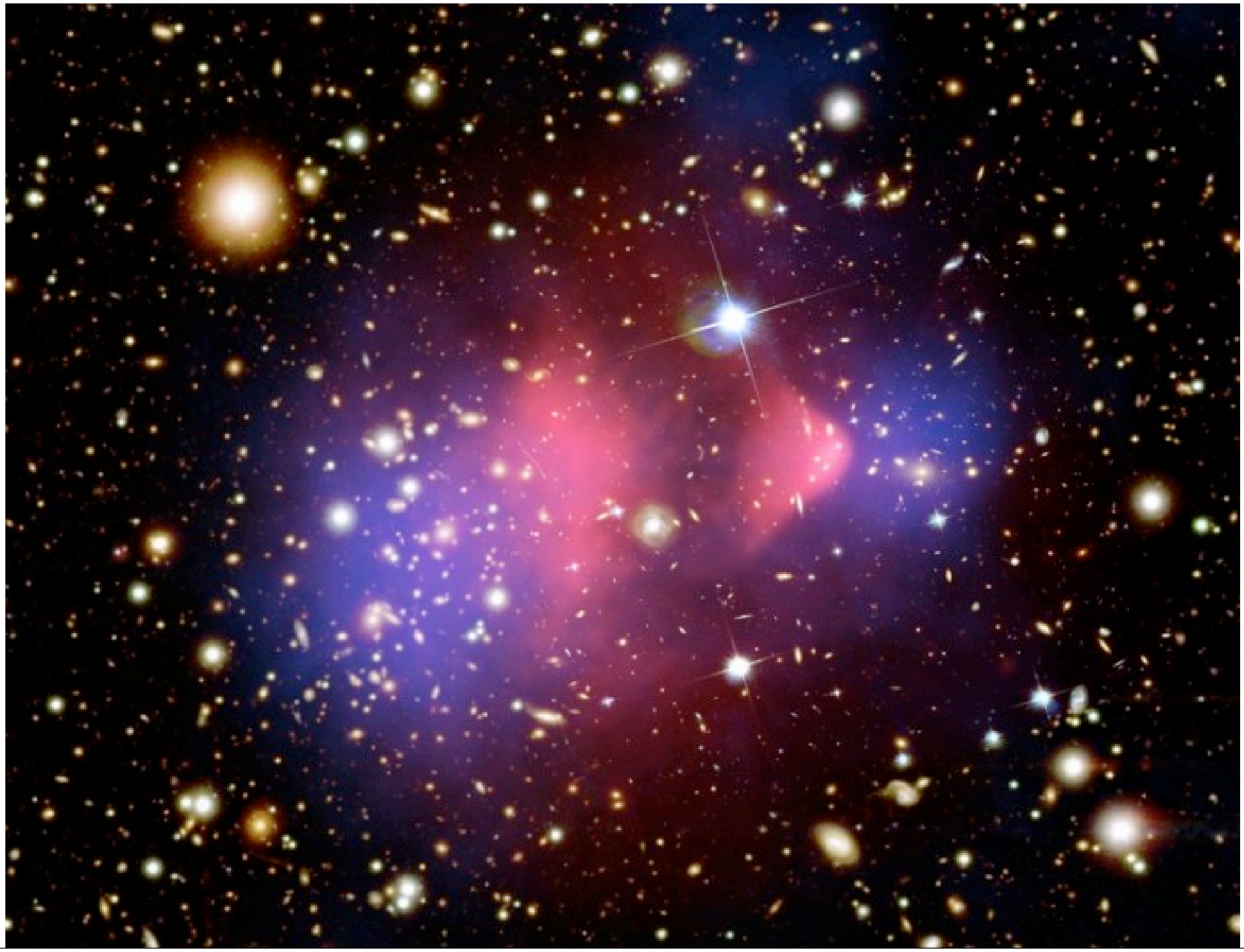




The manner in which structure grows depends on the amount and type of dark matter present. All viable models are dominated by cold dark matter.

Bullet Cluster

Position of X-ray emitting hot gas (red) different from main mass concentration detected by lensing (blue) after collision of two clusters of galaxies. Clear separation between the "dark matter" and the gas clouds is considered one of the best evidences that dark matter exists.

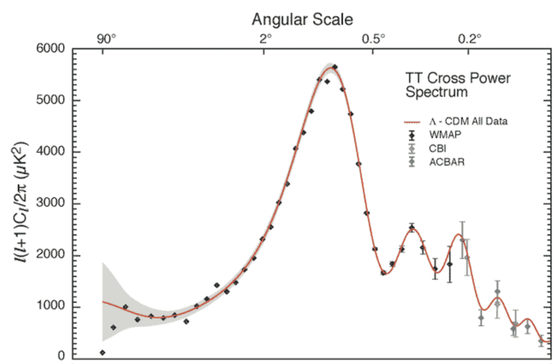


Results from WMAP

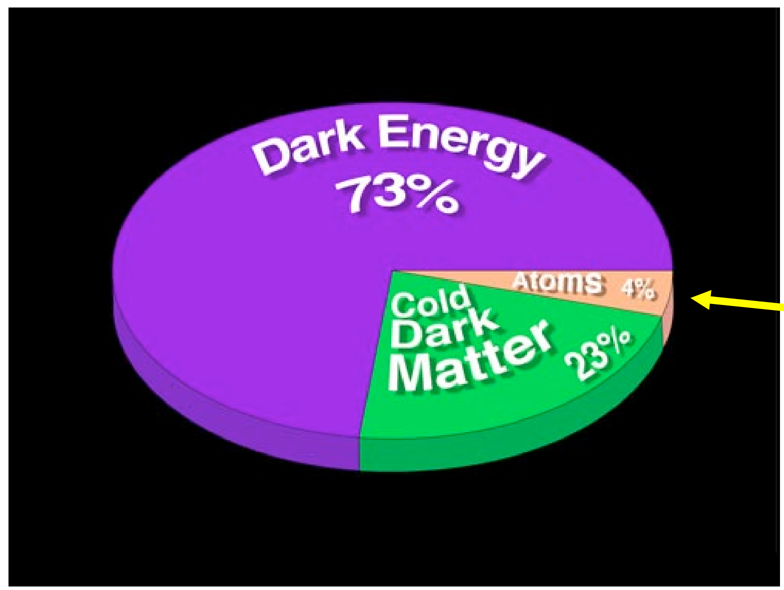
Ω_i : Fraction of critical density

Universe density	$\Omega_0 = 1.02 \pm 0.02$
Dark energy density	$\Omega_\Lambda = 0.73 \pm 0.04$
Total matter density	$\Omega_M = 0.27 \pm 0.05$
Baryon matter density	$\Omega_b = 0.044 \pm 0.004$

→ Dark matter is non-baryonic



Our Universe:



us

Why do we think that Dark Matter may be accessible at high energy physics experiments ?

- Dark Matter is most likely associated with new particles

- Many dark matter candidates have been proposed. They differ in mass and in the range of interaction with SM particles.

- However, if the relic density proceeds from the primordial thermal bath, there are reasons to believe that it must be part of the dynamics leading to an explanation of electroweak symmetry breaking.

- It is likely to interact with (annihilate into) ordinary matter at an observable rate

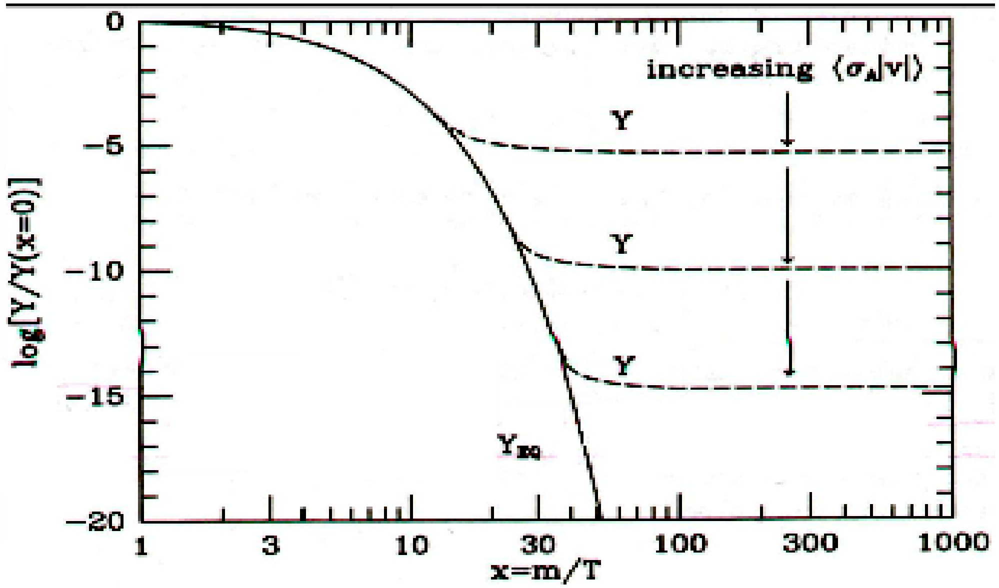
Evolution of Dark Matter Density

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v \rangle (n^2 - n_{eq}^2), \qquad n_{eq} \approx \exp(-m/T)$$

$\langle \sigma_{eff} v \rangle$ Thermal average of (co-)annihilation cross section

$$Y = \frac{n}{s}$$

$$s \approx g_* T^3$$



$$\Omega \simeq \frac{2\ 10^{-10}\text{GeV}^{-2}}{\sigma_{\text{eff}} v}$$

Dark Matter Annihilation Rate

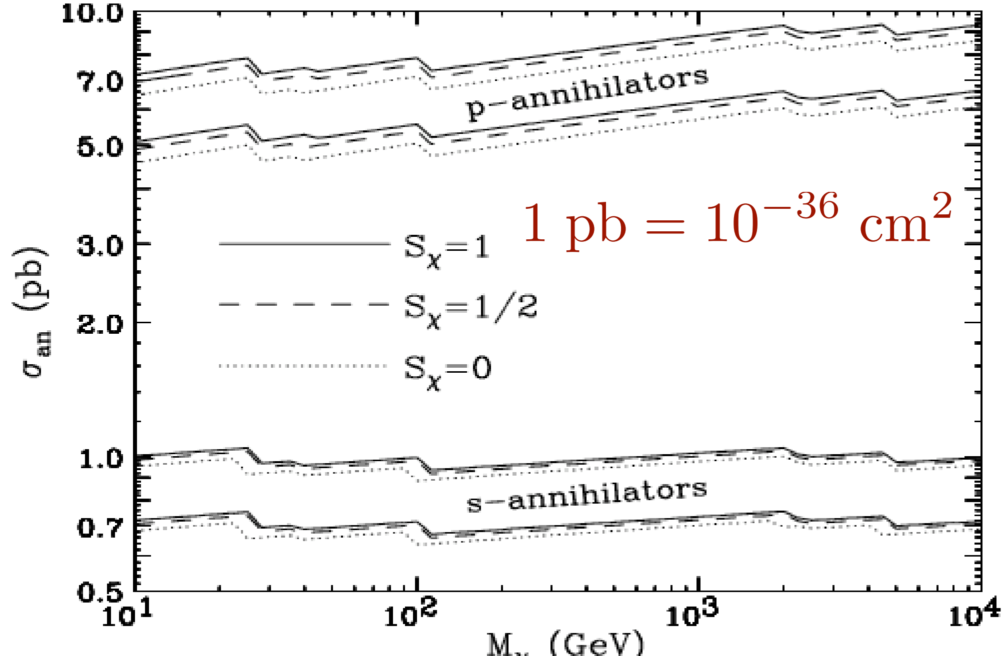
- The main reason why we think there is a chance of observing dark matter at colliders is that, when we compute the annihilation rate, we get a cross section

$$\sigma_{\mathrm{ann.}}(\mathrm{DM\ DM} \to \mathrm{SM\ SM}) \simeq 1\ \mathrm{pb}$$

- This is approximately

$$\sigma_{\mathrm{ann.}} \simeq \frac{\alpha_W^2}{\mathrm{TeV}^2}$$

This suggests that it is probably mediated by weakly interacting particles with weak scale masses



(A.B., K. Matchev and M. Perelstein, PRD 70:077701, 2004)

- Connection of Thermal Dark Matter to the weak scale and to the mechanism of electroweak symmetry breaking

Weak Scale Models and Dark Matter

- Motivated by the question of electroweak symmetry breaking, many different models of particle physics at the weak scale have been proposed.

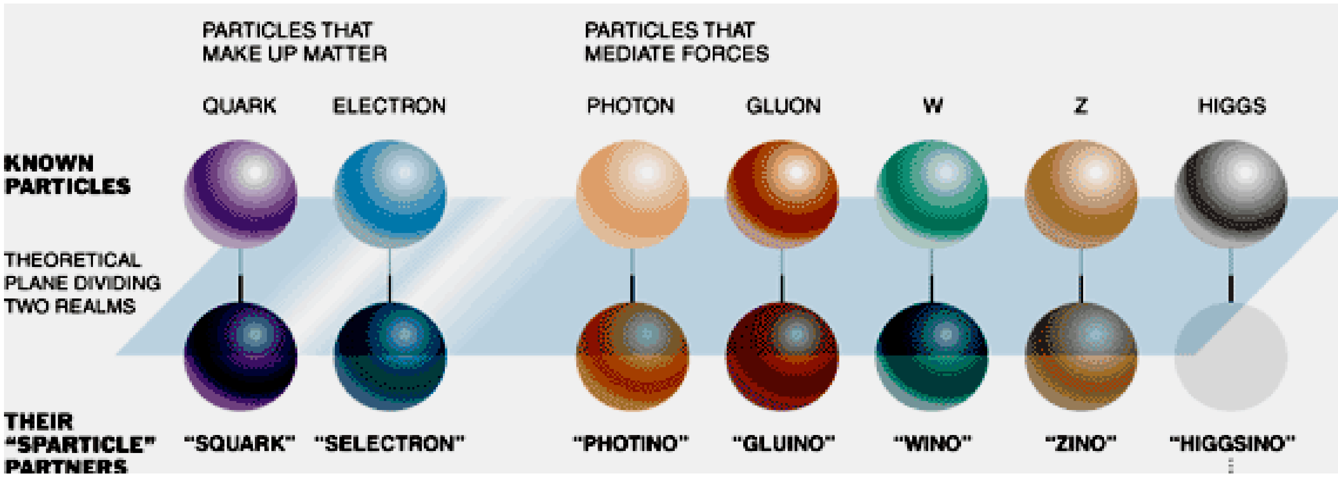
- Most of them lead to problems of flavor changing transitions, disagreement with precision electroweak observables and/or rapid proton decay (baryon and lepton number violating processes), unless extra symmetries are invoked.

- These extra symmetries lead usually to the stability of the lightest new particle, which tend to be neutral and weakly interacting and therefore a good candidate for dark matter

- I'll concentrate, as an example, on the supersymmetric case as a well motivated example of this kind of models, but I'll comment on other models, too.

Supersymmetry

fermions   bosons



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

$$\text{Two Higgs doublets necessary} \rightarrow \tan\beta = \frac{v_2}{v_1}$$

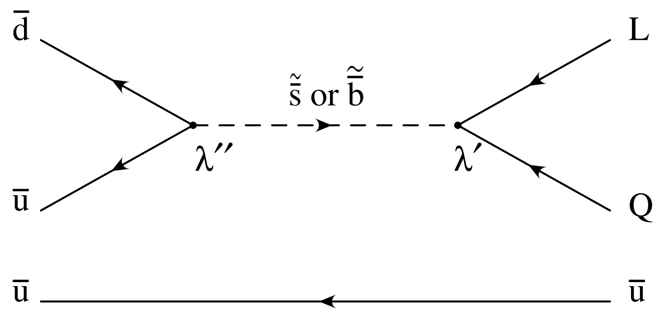
Why Supersymmetry ?

- Helps to stabilize the weak scale—Planck scale hierarchy: $\delta\, m_H^2 \approx (-1)^{2 S_i} \frac{n_i\, g_i^2}{16\pi^2} \Lambda^2$
- Supersymmetry algebra contains the generator of space-time translations.
  Possible ingredient of theory of quantum gravity.
- Minimal supersymmetric extension of the SM :
  Leads to Unification of gauge couplings.
- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.

G.G. Ross, last week Colloquium

Proton Decay Problem :

$$\mathrm{L} = \begin{pmatrix} \nu \\ l^- \end{pmatrix} \qquad \mathrm{Q} = \begin{pmatrix} u \\ d \end{pmatrix}$$



If all the couplings allowed by supersymmetry and gauge invariance are present, and take values of order one, the proton would present a very fast decay rate.

- Both lepton and baryon number violating couplings involved.
- Proton: Lightest baryon. Lighter fermions: Leptons

R-Parity

- A solution to the proton decay problem is to introduce a discrete symmetry, called R-Parity. In the language of component fields,

$$R_P = (-1)^{3B+2S+L}$$

- All Standard Model particles have $R_P = 1$.
- All supersymmetric partners have $R_P = -1$.
- All interactions with odd number of supersymmetric particles, like the Yukawa couplings inducing proton decay are forbidden.
- Supersymmetric particles should be produced in pairs.
- The lightest supersymmetric particle is stable.
- Good dark matter candidate. Missing energy at colliders.

Missing Energy at Colliders

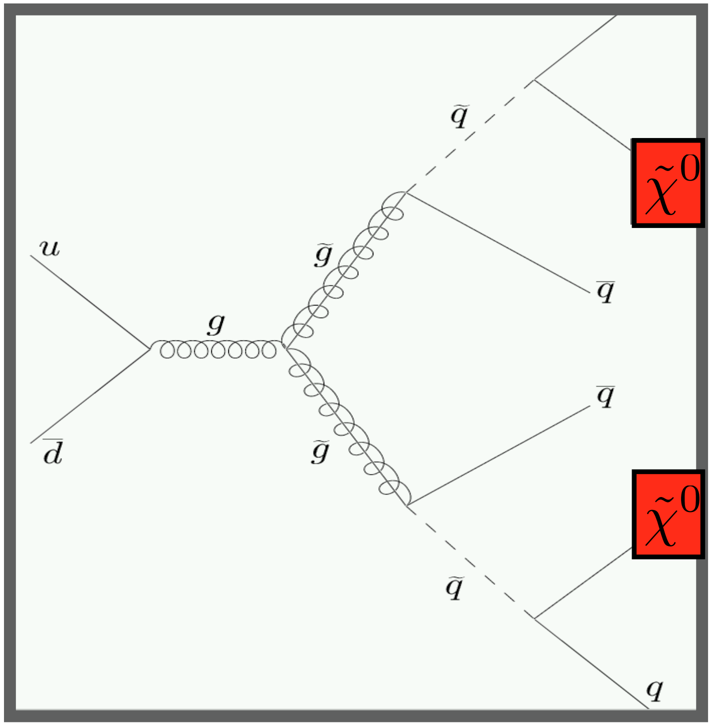
- In general, if the dark matter particle is neutral and weakly interacting, it will not be detected at current lepton and hadron colliders.
- Just like when the neutrino was discovered, evidence of the production of such a particle will come from an apparent lack of conservation of the energy and momentum in the process.
- Missing Energy and (transverse) momentum signatures, beyond the ones expected in the Standard Model, should be sizable and will be the characteristic signatures of theories with a thermal WIMP as a Dark Matter Candidate.

Supersymmetry at colliders

Gluino production and decay: Missing Energy Signature

Supersymmetric Particles tend to be heavier if they carry color charges.

Charge-less particles tend to be the lightest ones.

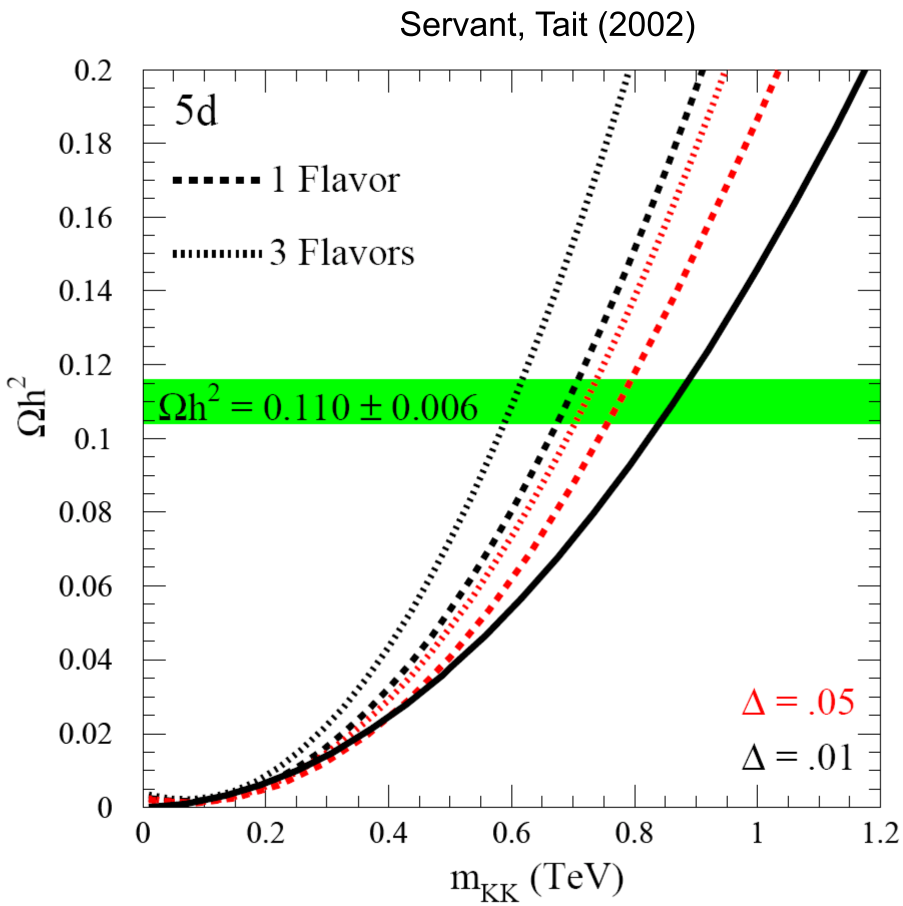


Lightest Supersymmetric Particle: Excellent cold dark matter candidate

Other WIMP candidates

- For most electroweak symmetry breaking models proposed, a possible dark matter candidate has been found. These include
- The Lightest KK particle (LKP) in Universal Extra Dimensions
- The lightest T-odd Particle in little Higgs models
- Lightest mirror KK particle in warped extra dimensional models
- Lightest neutral particle in inert doublet models
- The game is quite simple. If a discrete symmetry exists that ensures the stability of a light neutral weakly interacting particle of the model, then the numbers will probably work well in certain region of parameter space of such a model.

Dark Matter in Universal Extra Dimensions



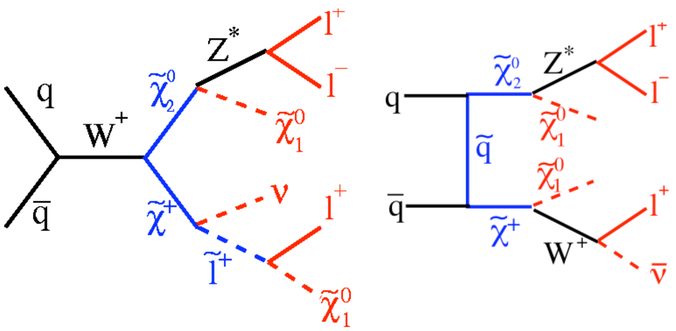
LKP in UED: $B^{(1)}$

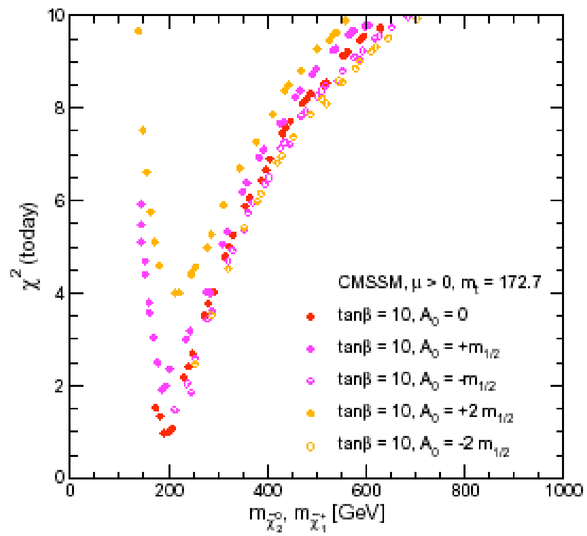
Searches at Colliders


Chicago
Booster
CDF
DØ
Tevatron
p̄ source
Main Injector
(new)

Searches at the Tevatron: Trileptons

- **"Golden" Trilepton Signature**
  - **Chargino–neutralino production**
  - **Low SM backgrounds**
- **3 leptons and large Missing E_T:**
  - **Neutralino χ^0_1 is LSP**
- **Recent analysis of electroweak precision and WMAP data (J. Ellis, S. Heinemeyer, K. Olive, G. Weiglein: hep-ph/0411216)**
  - **Preference for "light SUSY"**
  - **Chargino mass around 200 GeV/c²**
- **Current DØ analysis:**
  - **2 l (l=e,μ,τ) + isolated track or $\mu^\pm\mu^\pm$**
  - **$\not{E}_t$ +topological cuts**
  - **Analysis most sensitive at low tanβ**
  - **BG expectation: 2.9±0.8 events**
  - **Observed: 3 events**





M(chargino)

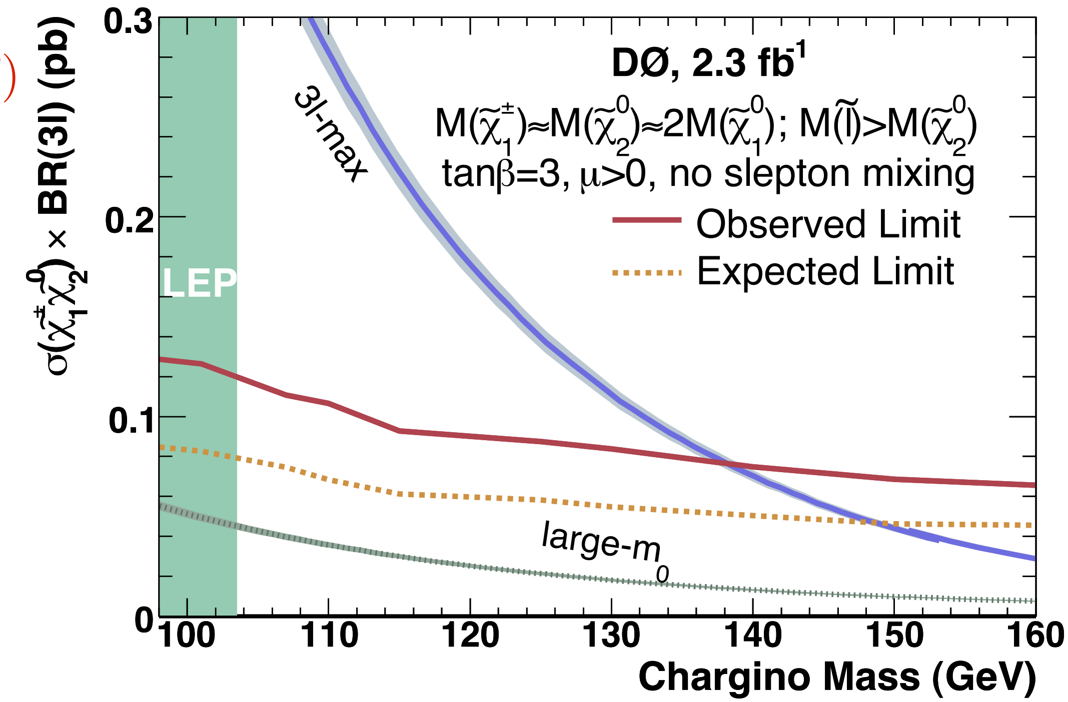
Comment: Preferred region strongly depends on muon anomalous magnetic moment

Result

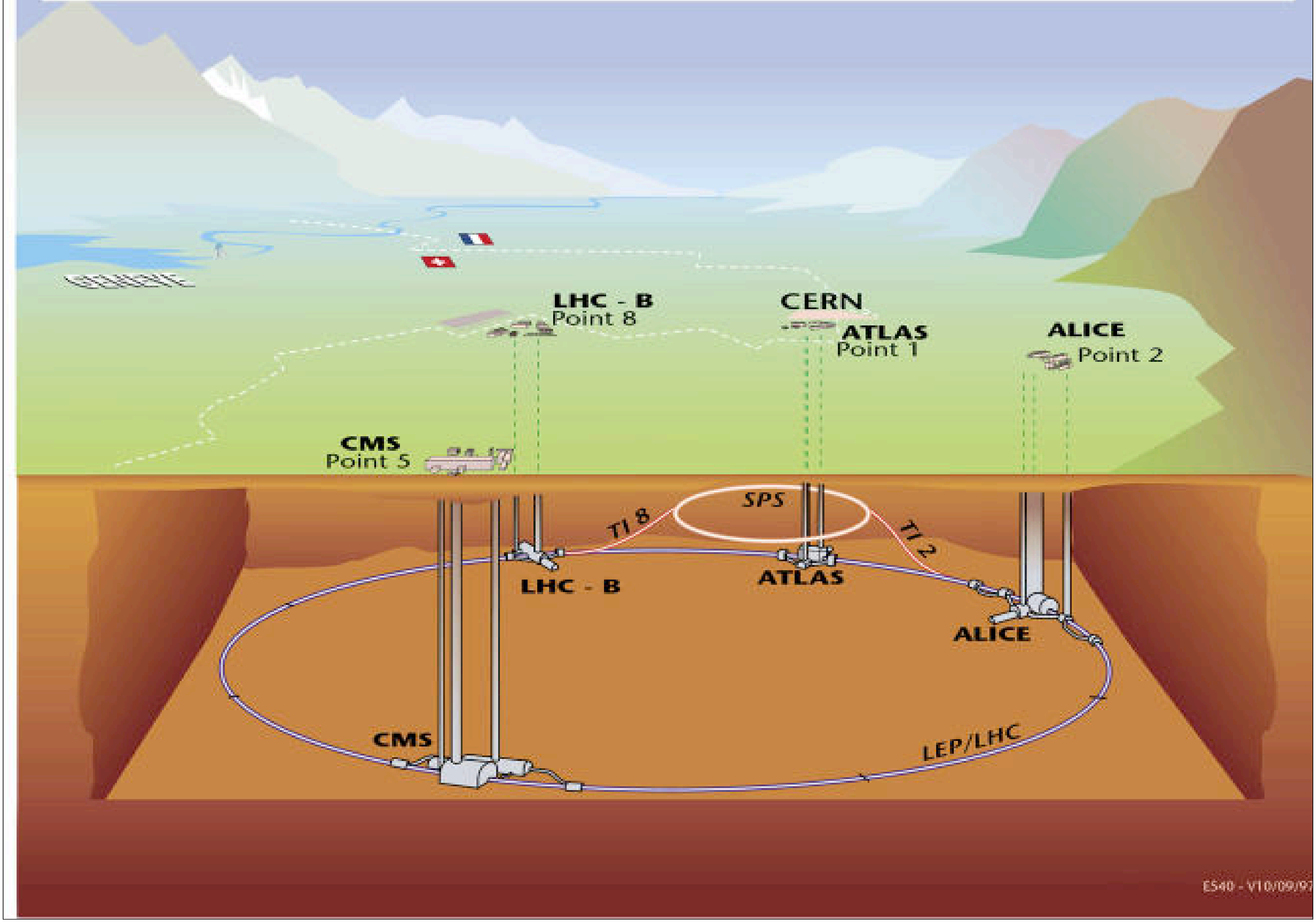
- No evidence for SUSY observed
  - ▲ Set limit on production cross sections times branching ratio $\sigma \times BR(3\ell)$
  - ▲ 3ℓ–max scenario
    - ▶ $m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_2^0} \approx 2m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\ell}}$ slightly heavier than $m_{\tilde{\chi}_2^0}$
    - ▶ Maximized branching ratio into three leptons

- Cross section limit $\sigma \times BR(3\ell)$
  - ▲ Observed: 0.06–0.12 pb
  - ▲ Expected: 0.04–0.08 pb

- Mass limits for $m_{\tilde{\chi}_1^\pm}$
  - ▲ Observed: 138 GeV
  - ▲ Expected: 148 GeV



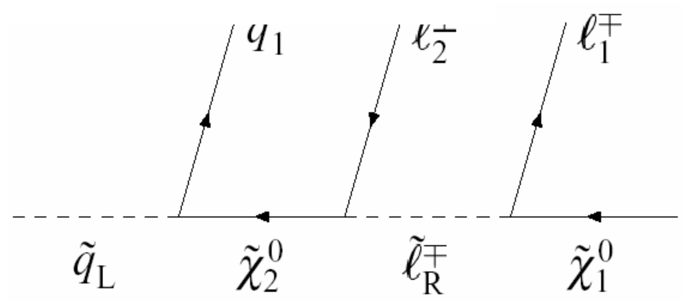
Overall view of the LHC experiments.



Searches at the LHC

New particle searches at the LHC are induced by the cascade decay of strongly interacting particles.

By studying the kinematic distributions of the decay products one can determine the masses of produced particles, including the LSP.



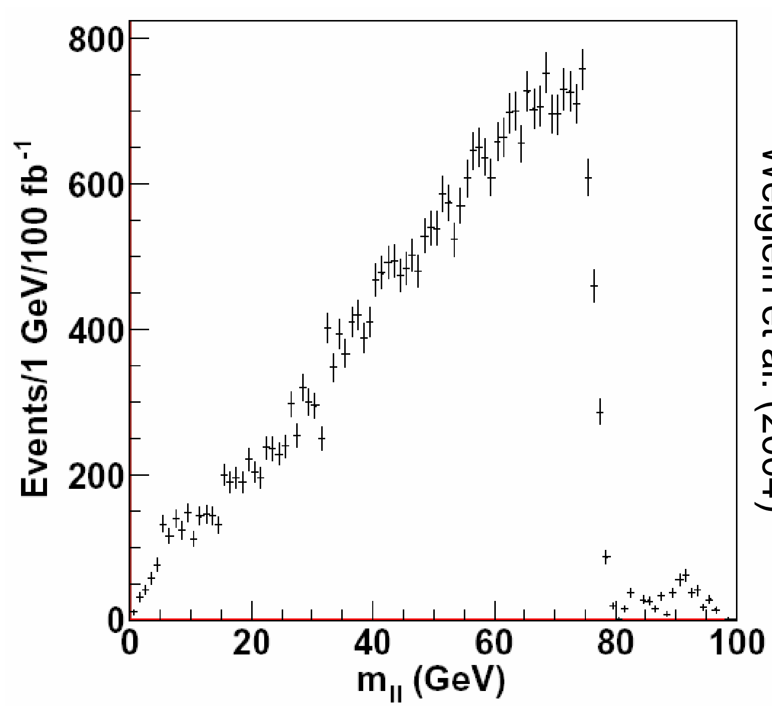
$$(m^2_{ll})^{\rm edge} = \frac{(m^2_{\tilde\chi^0_2} - m^2_{\tilde l_R})(m^2_{\tilde l_R} - m^2_{\tilde\chi^0_1})}{m^2_{\tilde l_R}}$$

$$(m^2_{qll})^{\rm edge} = \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde\chi^0_1})}{m^2_{\tilde\chi^0_2}}$$

$$(m^2_{ql})^{\rm edge}_{\rm min} = \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde l_R})}{m^2_{\tilde\chi^0_2}}$$

$$(m^2_{ql})^{\rm edge}_{\rm max} = \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde l_R} - m^2_{\tilde\chi^0_1})}{m^2_{\tilde l_R}}$$

$$\begin{aligned}(m^2_{qll})^{\rm thres} = {} & [(m^2_{\tilde q_L} + m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde l_R})(m^2_{\tilde l_R} - m^2_{\tilde\chi^0_1}) \\ & -(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})\sqrt{(m^2_{\tilde\chi^0_2} + m^2_{\tilde l_R})^2(m^2_{\tilde l_R} + m^2_{\tilde\chi^0_1})^2 - 16 m^2_{\tilde\chi^0_2} m^4_{\tilde l_R} m^2_{\tilde\chi^0_1}} \\ & +2m^2_{\tilde l_R}(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde\chi^0_1})]/(4m^2_{\tilde l_R} m^2_{\tilde\chi^0_2})\end{aligned}$$

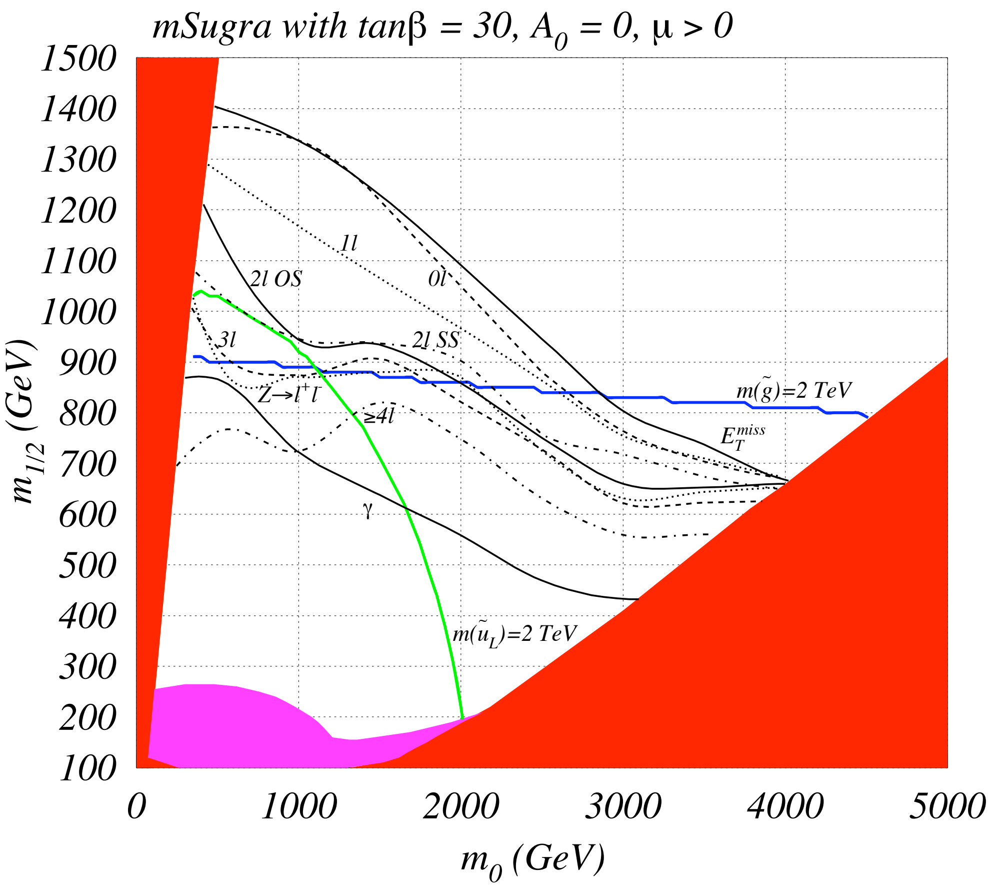


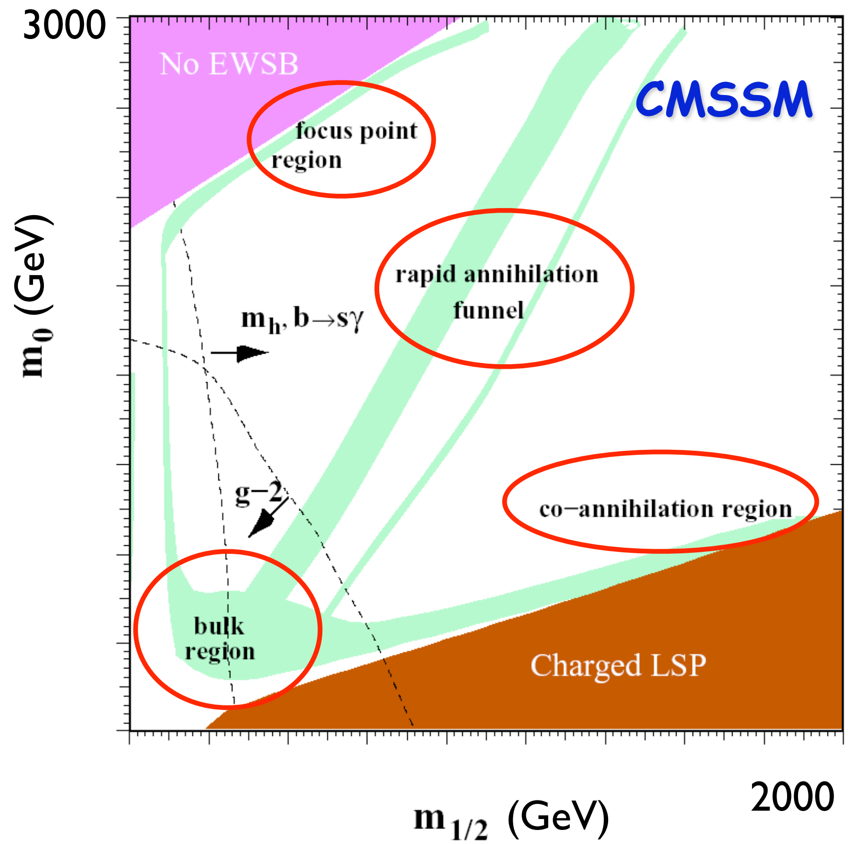
Weiglein et al. (2004)

How well can the LHC do ?

Example in the Minimal Supergravity Model

Baer, Balazs, Belyaev, Kropovnickas and Tata, Ellis, Olive et al;
Arnowitt, Dutta et al'02--08





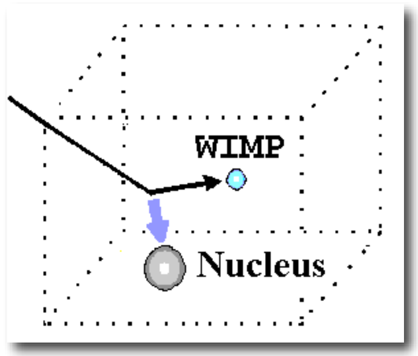
Indirect and Direct Dark Matter Detection Searches

Direct Detection Dark Matter Experiments

• **Collider experiments can find evidence of DM through $\not{E}_T$ signature but no conclusive proof of the stability of a WIMP**

- Direct Detection Experiments can establish the existence of Dark Matter particles

✸ WIMPs elastically scatter off nuclei in targets, producing nuclear recoils

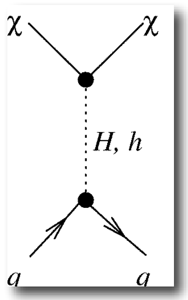


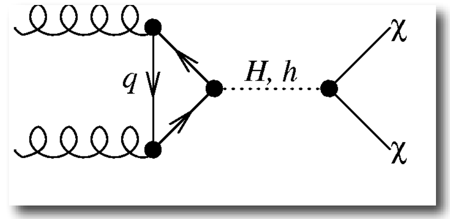
$$R = \sum_i N_i \; \eta_\chi \langle \sigma_{i\chi} \rangle$$

Direct DM experiments:
sensitive mainly to spin-independent elastic scattering cross section ($\sigma_{SI} \leq 10^{-8}\, pb$)

==> dominated by virtual exchange of H and h

- $\tan\beta$ enhanced couplings of H to strange, and to gluons via bottom loops

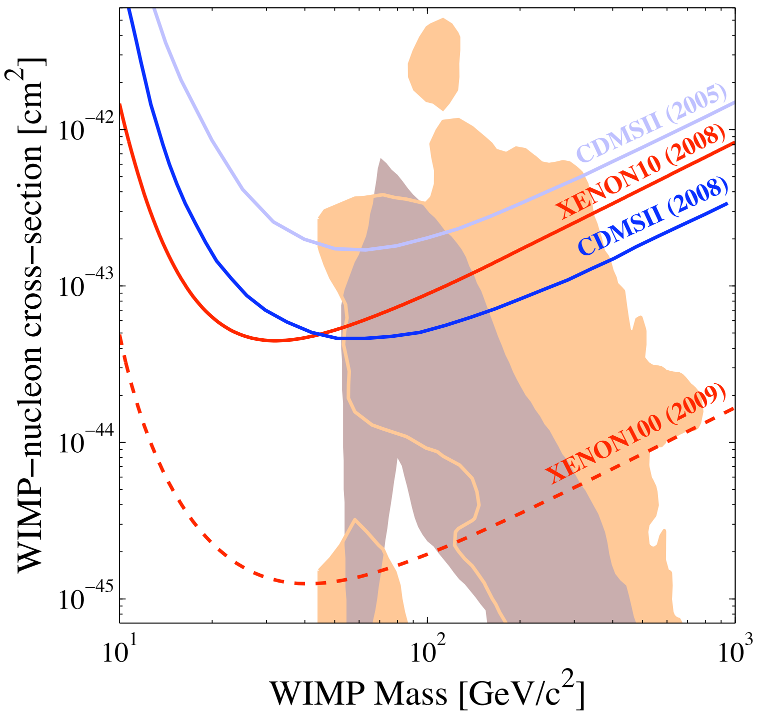




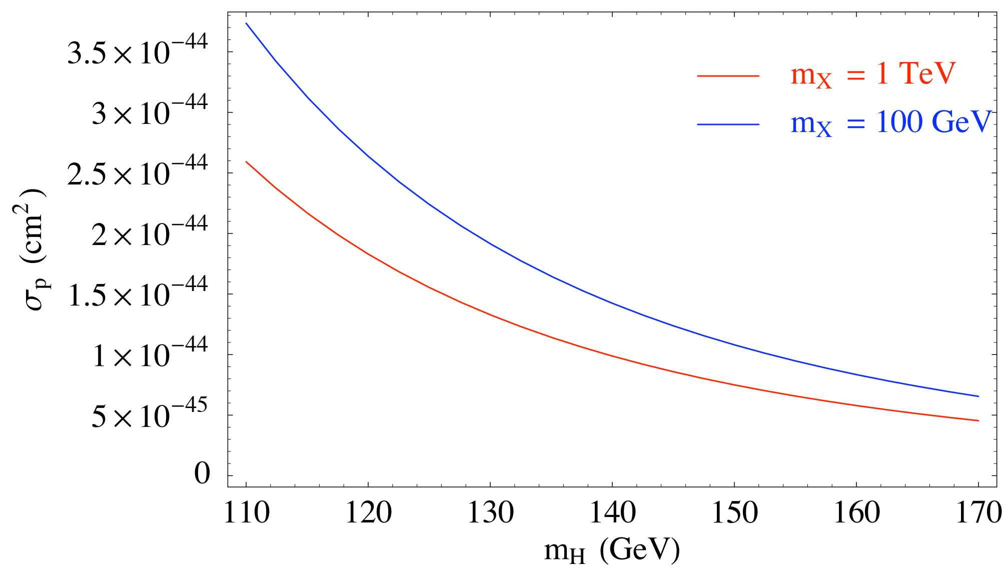
$$\frac{\sigma_{SI}}{A^4} \approx \frac{0.1 g_1^2 g_2^2 N_{11}^2 N_{13}^2 m_p^4 \tan^2\beta}{4\pi m_W^2 M_A^4}$$

Prospects for direct Dark Matter Detection

The XENON experiment in Grand Sasso will test soon models in which the suppression of flavor violation is due to the heaviness of the sfermions, CP-odd and charged Higgs boson states. Two other experiments will explore the same region, CDMS (Ge crystal) in Soudan, MN and LUX (similar to XENON) in Homestake, SD.



XENON100 projected sensitivity



$$\sigma_p = \frac{8}{\pi}\left[\frac{G_F M_W m_p \mu_\chi}{9 m_H^2}\left(2 + 7\sum_{q=u,d,s} f_q^{(p)}\right)\gamma\right]^2 = \left(\frac{115\ \text{GeV}}{m_H}\right)^4 \gamma^2\ 5.4\times10^{-43}\,\text{cm}^2$$

$$\gamma = \frac{1}{g}\left(\tilde{g}_u N_{\chi 2} N_{\chi 4} - \tilde{g}_d N_{\chi 2} N_{\chi 3} - \tilde{g}'_u N_{\chi 1} N_{\chi 4} + \tilde{g}'_d N_{\chi 1} N_{\chi 3}\right)\ .$$

Arkani-Hamed, Dimopoulos, Giudice, Romanino'04

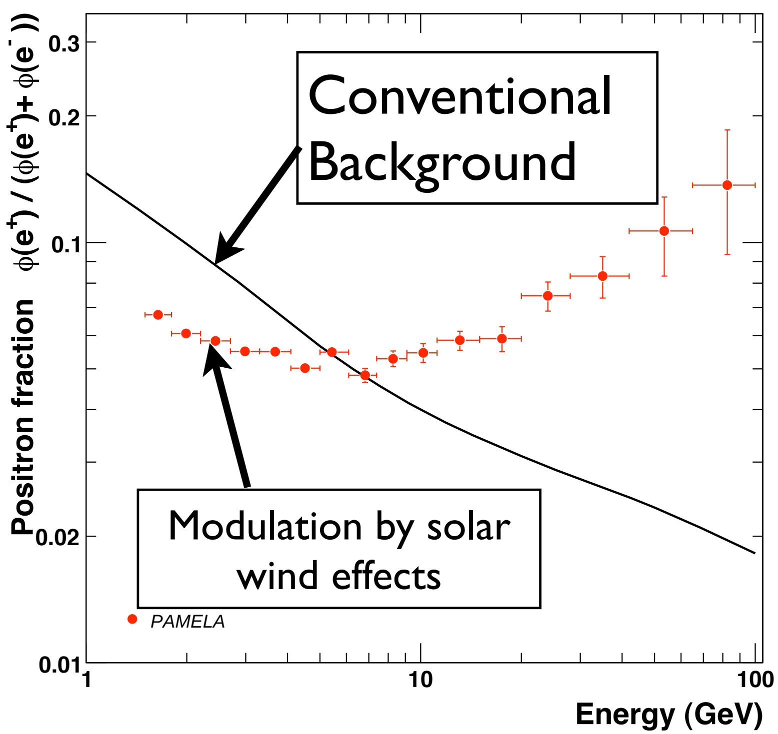
XENON: Scintillation plus ionization
CDMS: Phonons plus ionization

Search for DM annihilation signals

Although cosmological dark matter stop annihilating in the early Universe, the situation with the dark matter in the galaxy may be different. Compare the critical density $\rho_c \simeq 0.5\ 10^{-5}\ GeV/cm^3$ with the local dark matter density $\rho_{\rm DM} \simeq 0.7\ {\rm GeV/cm^3}$. Since dark matter annihilates into high energy particles, one looks for anomalies in high energy cosmic rays.

PAMELA: Positron fraction excess 10-100 GeV

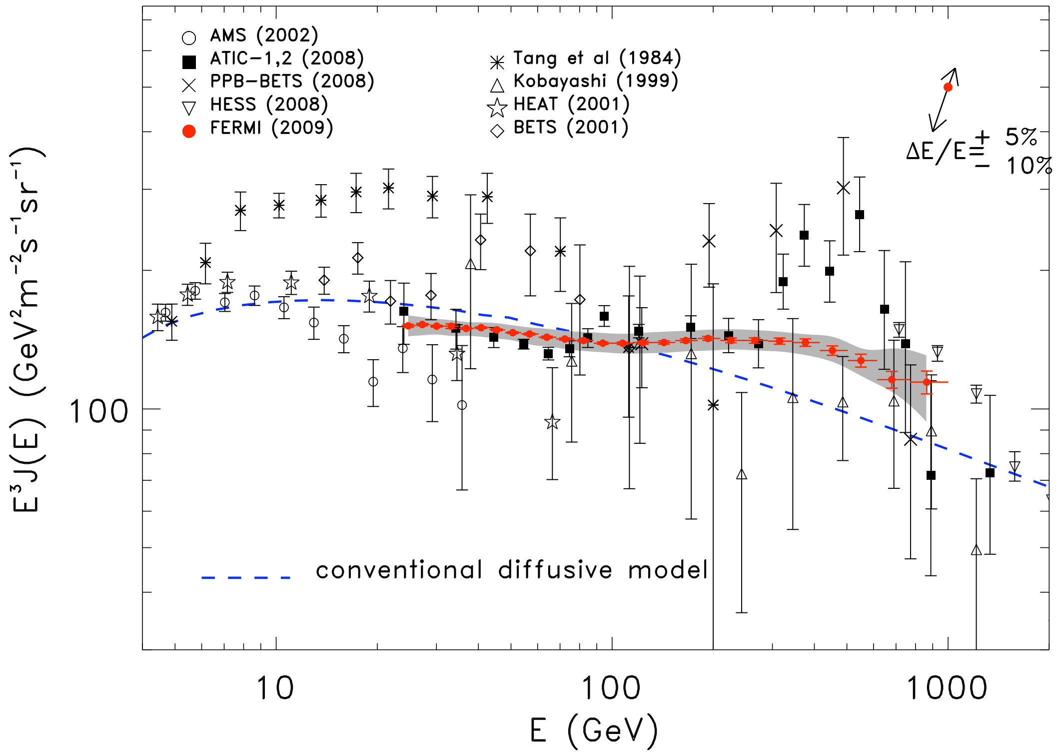
PAMELA:
Magnetic spectrometer and electromagnetic calorimeter mounted on a satellite



Searches for an excess in high energy electrons

FERMI: $e^+ + e^-$ spectrum 20 GeV to 1 TeV

FERMI -LAT
measured the spectrum
with better accuracy:
first $e^+ + e^-$ results
in the April APS Meeting
(May 4 2009)

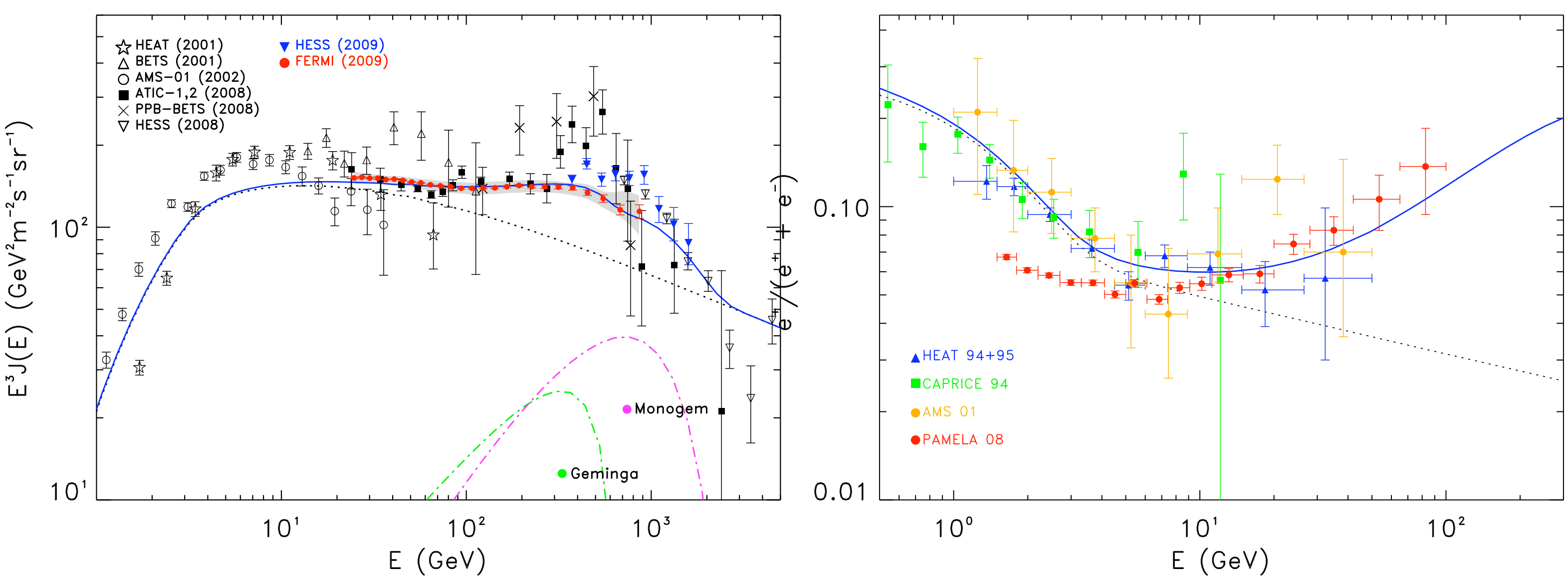


Fermi: Silicon tracker and electromagnetic calorimeter mounted on satellite. No magnetic field, implying no possible charge identification

Dark Matter ? Possible explanations

- Possible proton contamination may be a problem for PAMELA positron excess. A rejection factor larger than about 4 orders of magnitude needed.
- Astrophysical objects, like pulsars, have the power to produce the high energy electron spectrum. For this, they should be nearby and have the proper "age". Positron excess can also be explained by the same astrophysical sources.
- Uncertainties on high energy electron conventional background can lead to an explanation of the FERMI data (no "ATIC profile" observed).
- Dark Matter Annihilation: A large "Enhancement" factor, of order of a few hundreds, with respect to thermal annihilation cross section needed. Boost factor can come from Sommerfeld enhancement or from variations in DM density distribution. If astrophysics is the source of the excess, standard thermal dark matter models would not have an observable effect on data. To explain all data by annihilations dark matter must be heavier than 1TeV.
- Dark Matter Decays : A large lifetime, of order of $10^{26}\ s$ would be necessary. Easy to obtain such large lifetimes by GUT scale suppressed higher order operators. To explain all data a heavy dark matter needed.

Few near-by "mature" pulsars: $d < 1$ kpc, $t > 5 \times 10^4$y so e's can be released into the ISM- Monogem (290pc, 1.1×10^4 y) and Geminga (160pc, 3.7×10^5 y) with 40% efficiency to produce $e\pm$ and $E_{cut} = 1.1$ TeV (Grasso et al. Fermi Coll, 09)



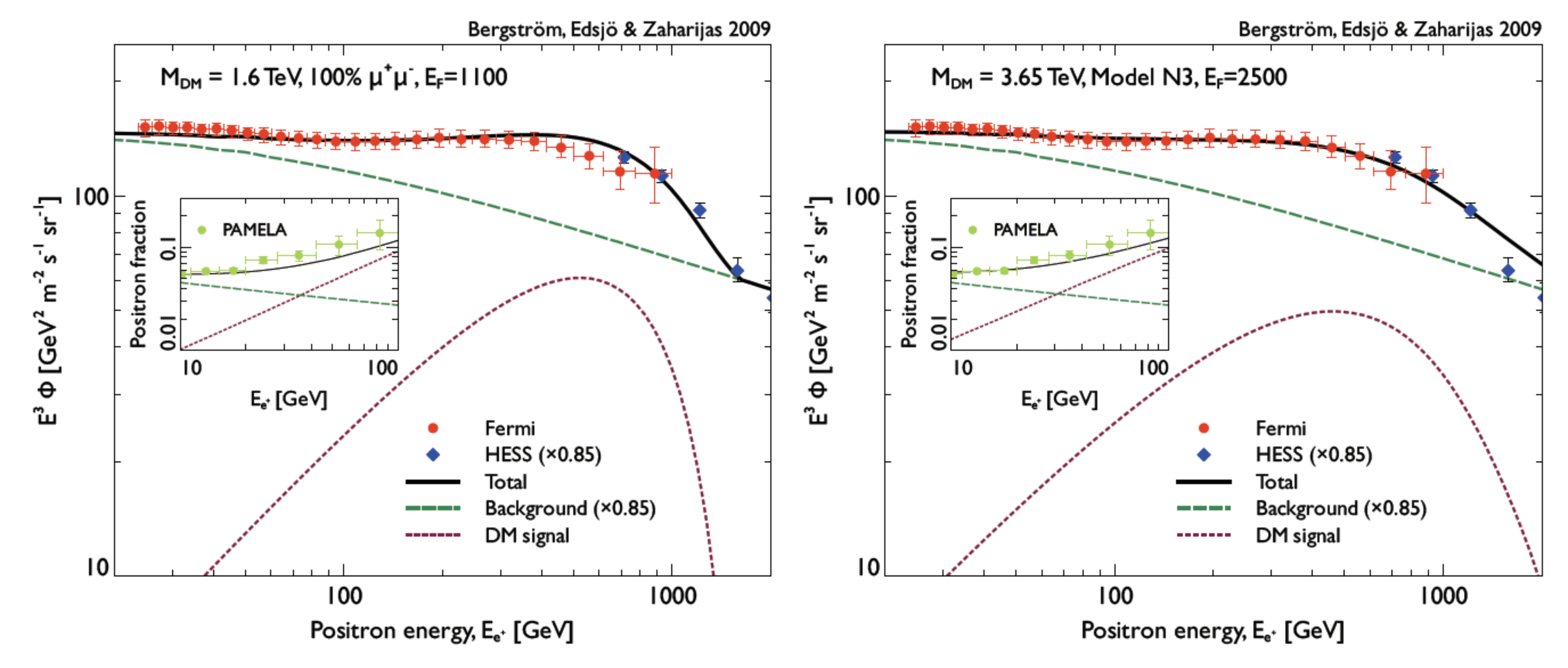
G. Gelmini, Aspen 09

Including somewhat more distant mature pulsars, within a few kpc, decreases the efficiency requirements to 10 to 30 %.

Examples of **Dark Matter** models that also fit the Fermi/Pamela data

1.6 TeV particle annihilating directly into two high energy muons

3.65 TeV particle annihilations into light scalars that decay into muons



Bergstrom, Edsjo and Zaharijas, 0905.0333

Role of **Fermi** to assess the **origin** of high-energy **CRE**:

1. Accurate CRE **Spectral Information** (probably not conclusive by itself)

2. **Local** CRE **source** ? → Compare the **Inverse Compton** and Bremss. emis. predicted from the measured CRE spectrum with diffuse **gamma-ray data**

3. Discovery and improved understanding of **gamma-ray pulsars**

4. **Constraints** on **DM** interpretation with **gamma-ray** data (e.g. nearby clump)

5. **Anisotropy**: search for excess CRE from bright nearby **pulsars**

Profumo SUSY 09

Further weak scale anomalies

Signals which are two to three standard deviations away from the expected SM predictions.

- 100 GeV Higgs signal excess. Rate about one tenth of the corresponding SM Higgs one.
- 115 GeV Higgs signal, seen only by Aleph experiment at LEP.
- DAMA/LIBRA annual modulation signal, direct DM detection searches (sodium iodide NaI scintillation crystal). Cross section far above the limit set by XENON/CDMS.
- Anomalous magnetic moment of the muon.
- Forward-backward asymmetry of the bottom quark at LEP.
- Forward-backward asymmetry of the top quark at the Tevatron.
- Apparent heavy quark events, with mass about 450 GeV, together with a top quark pair resonance at about 900 GeV at the Tevatron.
- CP-violation in the Bs mixing seen by D0 and CDF
- Disagreement between values of the CKM $\sin 2\beta$ phase obtained through different B-physics processes at B factories.
- Apparent 214 MeV muon pair resonance in the decay $\Sigma \to p\, \mu^+ \mu^-$
- Apparent 250 GeV electron pair resonance at CDF

Where did the Antimatter Go ?

Matter-Antimatter Asymmetry

- The four percent of ordinary matter present in the Universe introduces additional challenges to our understanding of the evolution of the Universe

- Two puzzling questions are raised:

- Why is anti-matter absent in the observable Universe ?

- What explains the smallness of the baryon number density when compared to photons or neutrinos ?

- There is a third question, related to the relatively close values of the baryon, dark matter and dark energy densities, that I will not discuss in this talk.

Theory vs. Observation

- Baryons annihilate with antibaryons via strong interactions mediated by pions
- This is a very efficient annihilation channel and the equilibrium density is

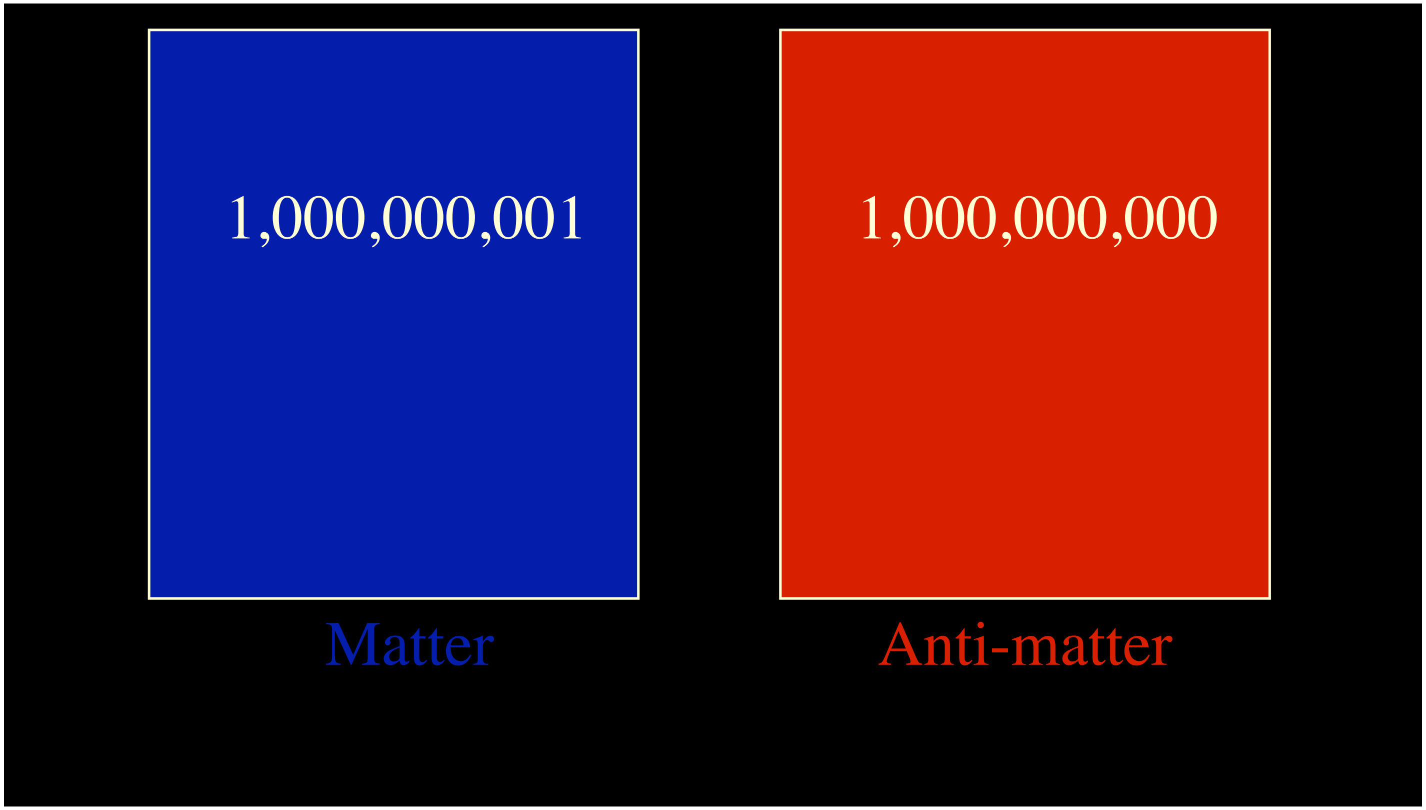
$$\frac{n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} \simeq 10^{-20}$$

- The first conflict with experience is the equality of baryon and antibaryon number density. Even obviating this problem, how does this compare to experiment ?

$$\frac{n_B}{n_\gamma} \approx 6\ 10^{-10}$$

- How to explain the absence of antimatter and the appearence of such a small asymmetry ?

Small Asymmetry must be generated primordially



Murayama

Annihilation will occur efficiently and finally the small asymmetry will be the only remaining thing left in the Universe

Additional Information on New Physics at the weak scale

Baryogenesis at the weak scale

- Under natural assumptions, there are three conditions, enunciated by Sakharov, that need to be fulfilled for baryogenesis. The SM fulfills them :

- Baryon number violation: Anomalous Processes

- C and CP violation: Quark CKM mixing

- Non-equilibrium: Possible at the electroweak phase transition.

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(- \frac{10^{16}}{T_c(\mathrm{GeV})} \exp\left(- \frac{E_{sph}(T_c)}{T_c} \right)\right)$$

$$\mathbf{E_{sph}} \propto \frac{8\pi\, \mathbf{v}}{\mathbf{g}}$$

Kuzmin, Rubakov and Shaposhnikov, '85—'87

Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

Therefore, to preserve the baryon asymmetry, a strongly first order phase transition is necessary: $\frac{v(T_c)}{T_c} > 1$

Finite Temperature Higgs Potential

$$V(T) \quad = \quad D(T^2 - T_0^2)\phi^2 - E_B T\phi^3 + \frac{\lambda(T)}{2}\phi^4$$

D receives contributions at one-loop proportional to the sum of the couplings of all bosons and fermions squared, and is responsible for the phenomenon of symmetry restoration

E receives contributions proportional to the sum of the cube of all light boson particle couplings

$$\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

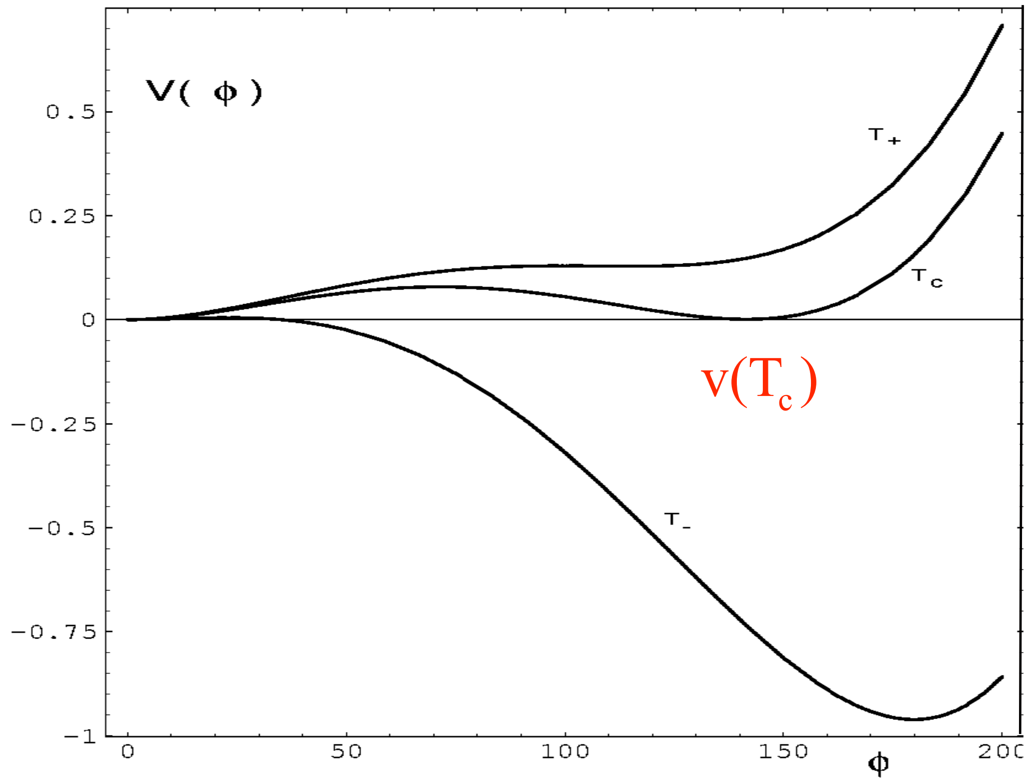
Since in the SM the only bosons are the gauge bosons, and the quartic coupling is proportional to the square of the Higgs mass,

$$\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H \quad < 40 \text{ GeV.}$$

In the SM, Electroweak Baryogenesis scenario is not viable

Electroweak Phase Transition

Higgs Potential Evolution in the case of a first order Phase Transition



Baryon Number Generation

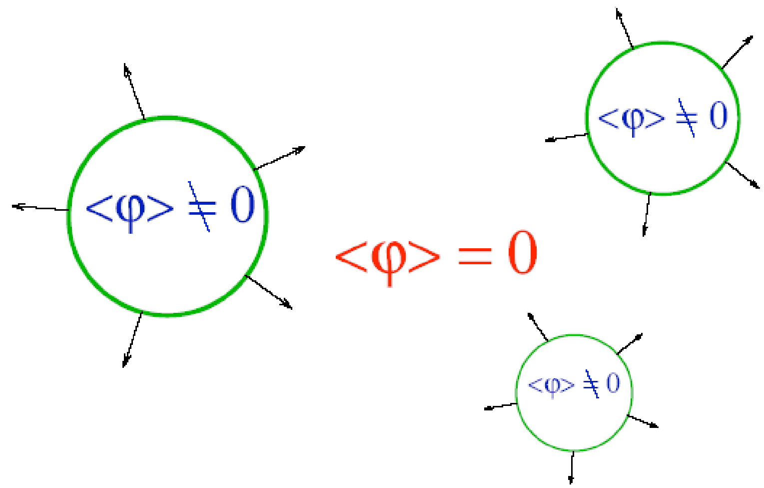
- Baryon number violating processes out of equilibrium in the broken phase if phase transition is sufficiently strongly first order.

Cohen, Kaplan and Nelson, hep-ph/9302210; A. Riotto, M. Trodden, hep-ph/9901362;
Carena, Quiros, Riotto, Moreno, Vilja, Seco, C.W.'97--'03,

Konstantin, Huber, Schmidt,Prokopec'00--'06

Cirigliano, Profumo, Ramsey-Musolf'05--06

Baryon number is generated by reactions in and around the bubble walls.



CP-Violation sources

- Another problem for the realization of the SM electroweak baryogenesis scenario:

- Absence of sufficiently strong CP-violating sources

- Even assuming preservation of baryon asymmetry, baryon number generation several order of magnitues lower than required

$$\Delta_{CP}^{max} = \left[\sqrt{\frac{3\pi}{2}}\frac{\alpha_W T}{32\sqrt{\alpha_s}}\right]^3 J\,\frac{(m_t^2-m_c^2)(m_t^2-m_u^2)(m_c^2-m_u^2)}{M_W^6}\,\frac{(m_b^2-m_s^2)(m_s^2-m_d^2)(m_b^2-m_d^2)}{(2\gamma)^9}$$

$$J \equiv \pm Im[K_{li}K_{lj}^*K_{l'j}K_{l'i}^*] = c_1c_2c_3s_1^2s_2s_3s_\delta$$

γ : Quark Damping rate

Gavela, Hernandez, Orloff, Pene and Quimbay'94

How to make EWBG work ?

Simplest cases studied:

- Introduce new boson degrees of freedom strongly coupled to the Higgs (larger E for the same Higgs mass). Example: MSSM with light stops. Masses of light stop and Higgs boson must be smaller than 130~GeV.

  Huet, Nelson '91; Giudice '93, Espinosa et al'93, Laine '98, Losada and Farrar '98, Carena, Nardini, Quiros, C.W.'96--08

- Introduce new Higgs scalars, that mix with the conventional Higgs and induce a change of the Higgs potential at tree-level. Example: NMSSM. Mass of new singlet must be smaller than about 250 GeV.

  Pietroni '93, Langacker and Liu '04; Menon, Morrissey, C.W. '04, Huber et al'07, Ramsey Musolf et al '09

- Introduce new CP-violating phases, associated with a new sector of the theory. Example: Charginos in the MSSM/NMSSM. Masses of charginos must be smaller than 500 GeV.

  Huet, Nelson '91, Riotto '96, Carena, Moreno, Seco, Quiros, C.W. '98--04, Cline, Rummukainen '98, Schmidt et al '98--07, Cirigliano et al '07

- Introduce baryogenesis at an earlier TeV scale phase transition or delay the EW one

  Shu, Tait, C.W. '07; Quiros and Naridini '07

Possible Signatures of EWBG

- Light Higgs boson, with mass smaller than about 150 GeV and SM-like couplings to the electroweak gauge bosons.

- Production of new scalar (colored) degrees of freedom.

Kraml '06, Martin '08, Freitas, Carena, C.W. '08, Hiller and Nir '08

- Modification of SM-like Higgs production rate at the LHC via mixing or new loop induced processes. New decay modes possible.

Djouadi '98, Menon, Morrissey, C.W. '04, Freitas, Carena, C.W.'08, Ramsey Musolf et al '08, Menon and Morrissey '08

- Electric dipole moments of the electron and the neutron induced by the new CP-violating phases.

Pilaftsis, Chang and Keung '98, Pilaftsis '02

- Gravitational waves at LISA, induced by the presence of a first order phase transition.

Kosowsky, Turner, Watkins'92; Servant and Grojean '06

Conclusions

- Higgs Searches at hadron colliders are reaching maturity. The Tevatron is already achieving significant results and the LHC will start at the end of 2009.
- Recent cosmological observations have lead to a surge in the interest of the HEP to observe signatures of the Dark Matter candidate at colliders. Missing energy would be an important ingredient.
- Anomalies in the cosmic ray data may be induced by DM decay/annihilation. Strong interest in direct and indirect DM searches.
- Electroweak Baryogenesis provides a very interesting, additional possibility
- Searches at the Tevatron become difficult, due to energy limitations and large backgrounds, but it is still possible to observe new physics in the near future.
- Searches at the LHC become quite promising, particularly if there are light colored particles in the spectrum.
- If nature is favorable, we may soon learn something about the nature of dark matter, the origin of mass and/or the source of the baryon asymmetry.

Backup Slides

Preservation of the Baryon Asymmetry

- EW Baryogenesis requires new boson degrees of freedom with strong couplings to the Higgs.

- Supersymmetry provides a natural framework for this scenario. Huet, Nelson '91; Giudice '91, Espinosa, Quiros,Zwirner '93.

- Relevant SUSY particle: Superpartner of the top

- Each stop has six degrees of freedom (3 of color, two of charge) and coupling of order one to the Higgs

$$E_{SUSY} = \frac{g_w^3}{4\pi} + \frac{h_t^3}{2\pi} \approx 8\, E_{SM}$$

M. Carena, M. Quiros, C.W. '96, '98
Delepine et al '96
J. Cline, K. Kainulainen '96
M. Laine '96; M. Losada '96

- Since

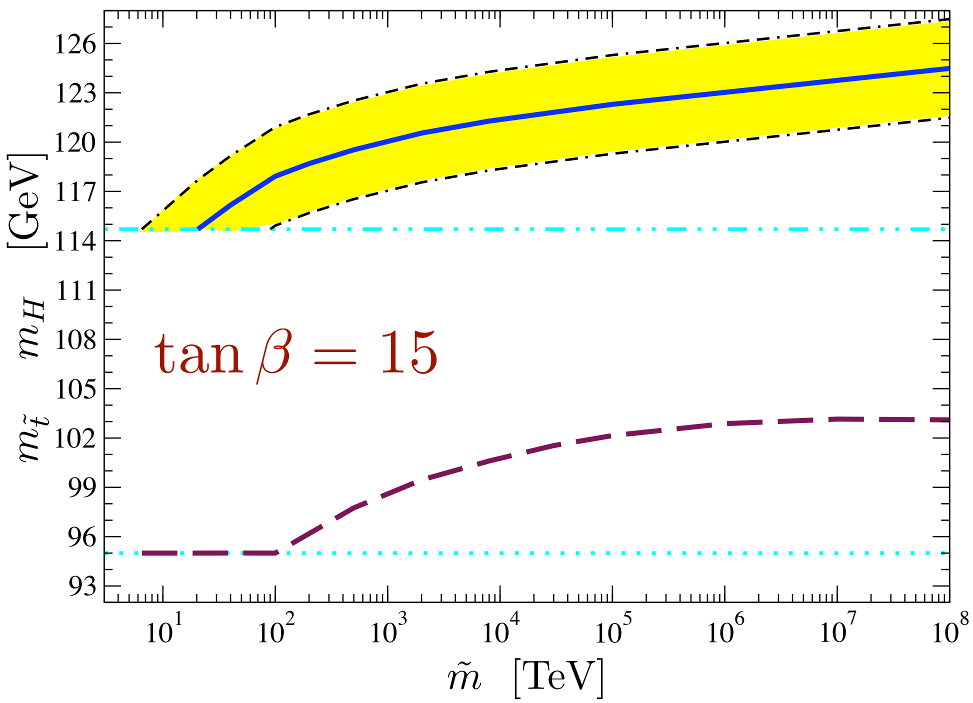
$$\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

Higgs masses up to 120 GeV may be

Allowed parameter space for Electroweak Baryogenesis

M. Carena, G. Nardini, M. Quiros, C.W. '08

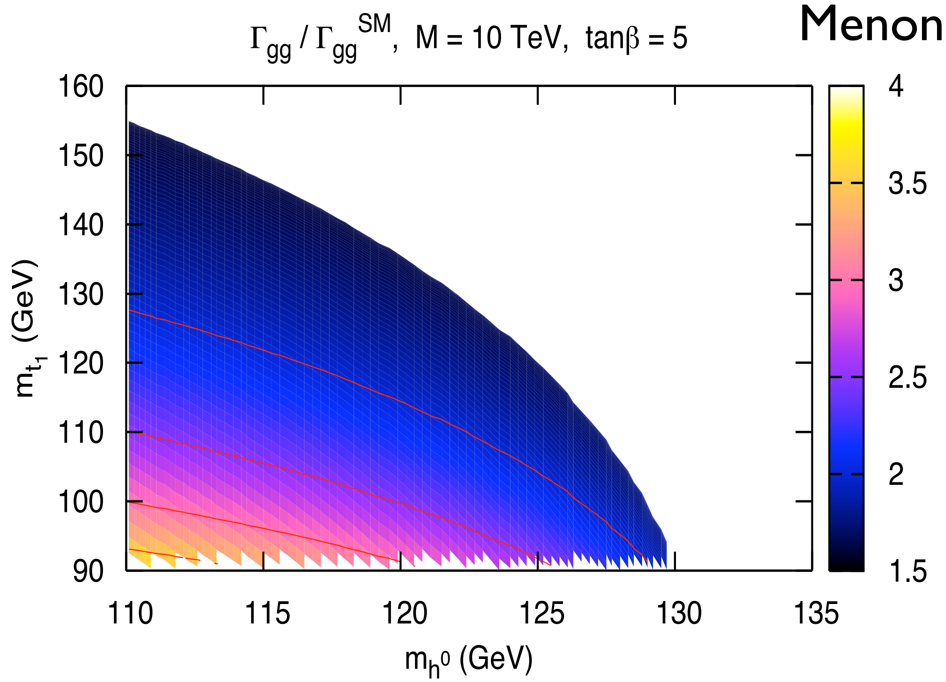
- Values of $\tan\beta \geq 5$ preferred to keep the Higgs mass large
- Values of At, the stop-Higgs coupling, cannot be too large to keep the phase transition strongly first order
- Higgs remains light, and so does the stop, with masses below 125 GeV.



Higgs Boson Production via $gg \to h^0$

- $\sigma(gg \to h^0) \propto \Gamma(h^0 \to gg)$.
- Stop loops interfere constructively with tops.

Menon and Morrissey '09

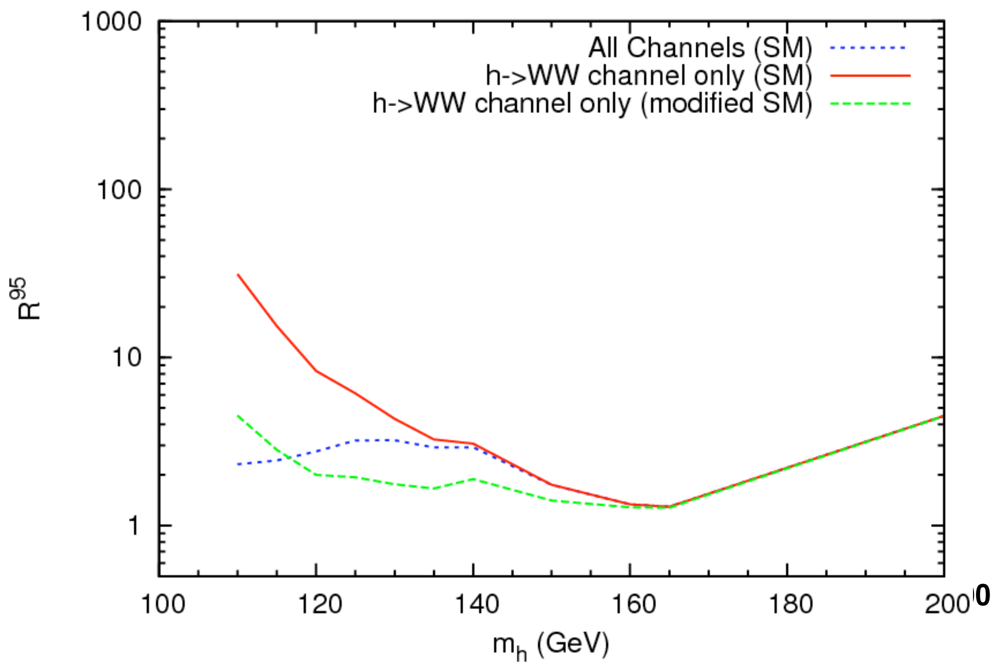


- MSSM EWBG Region: $m_{\tilde{t}_1}, m_{h^0} \lesssim 125\,\text{GeV}$.

  [Carena,Nardini,Quirós,Wagner '08]

Tevatron Search Prospects

- Light Higgs search dominated by $h^0\, W/Z$ with $h^0 \to b\bar{b}$.



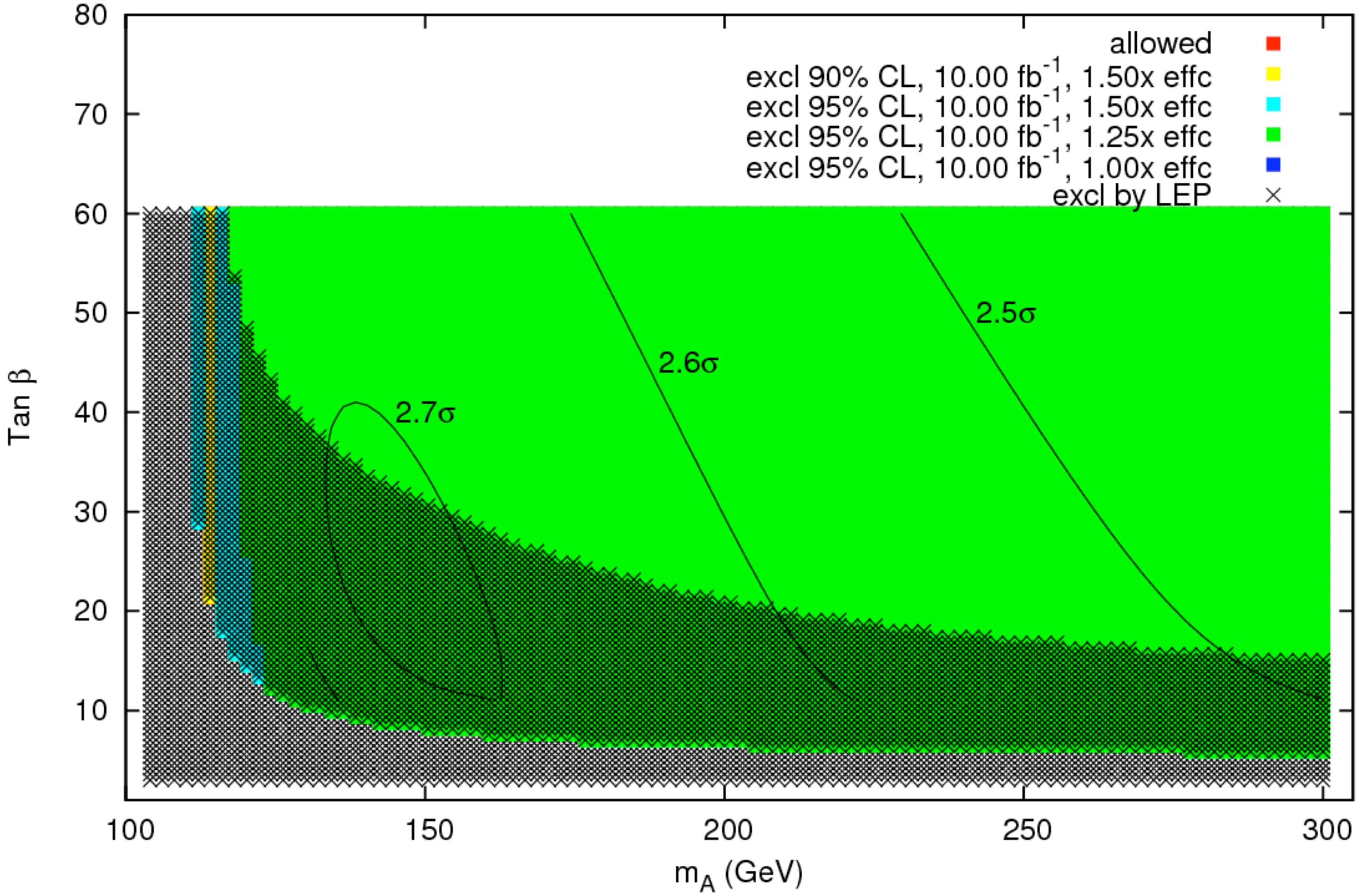
- $\sigma\, BR(h^0 \to WW)/\sigma\, BR_{SM} \lesssim 8$ for $m_{h^0} < 125\,\mathrm{GeV}$.

  MSSM EWBG $\Rightarrow$ enhancement by 2–4.

- Tevatron could be sensitive with $10\, fb^{-1}$.

Minimal Mixing Scenario

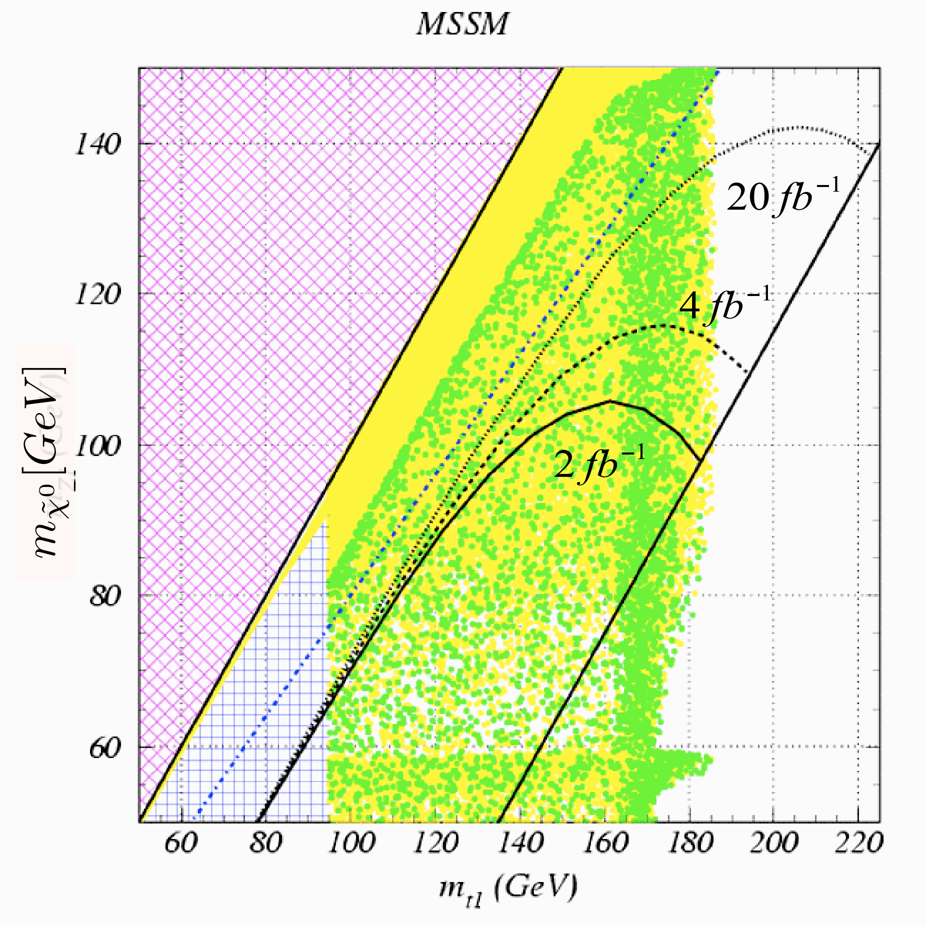
P. Draper, T. Liu and C.W. '09



Higgs mass small, $m_h < 120$ GeV. Easily probed at the Tevatron. More than 2.5 σ evidence in most of parameter space (WW enhancement will further improve reach).

Tevatron stop searches and dark matter constraints

$\tilde{t}_1 \rightarrow c\, \tilde{\chi}_1^0$



Carena, Balazs and C.W. '04

Green: Relic density consistent with WMAP measurements.

Searches for light stops difficult in stop-neutralino coannihilarion region.

LHC will have equal difficulties.

But, LHC can search for stops from gluino decays into stops and tops.
Stops may be discovered for gluino masses lower than 900 GeV, even if the stop-neutralino mass difference is as low as 10 GeV !

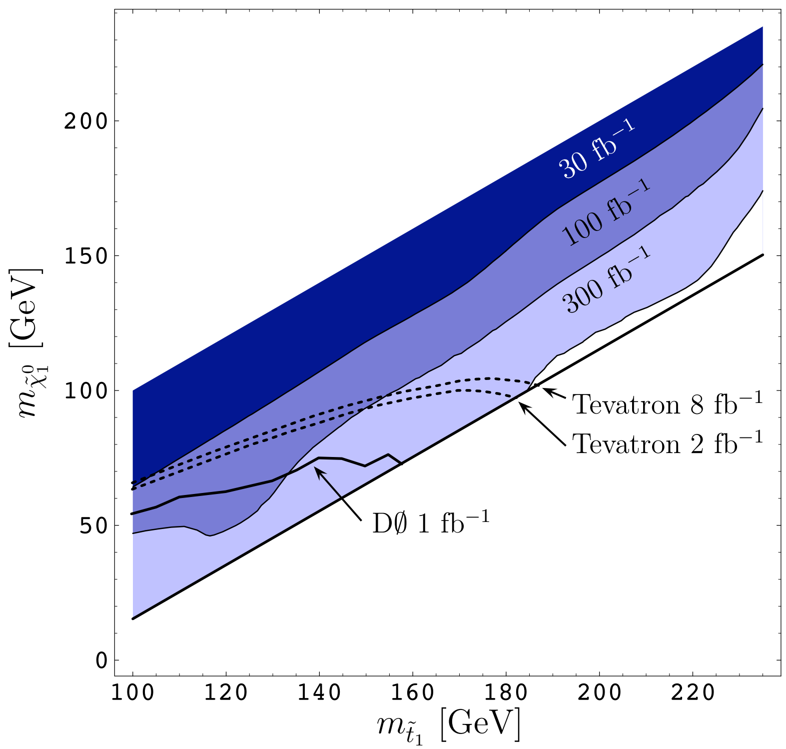
Kraml, Raklev '06, Martin 08

Jets plus missing Energy

M. Carena, A. Freitas, C.W.'08

1. Require one hard jet with $p_T > 100$ GeV and $|\eta| < 3.2$ for the trigger.

2. Large missing energy $\not{E}_T > 1000$ GeV.



Including systematics associated with jet and missing energy determination. Dominant missing energy background, coming from Z's, calibrated with the electron channel.

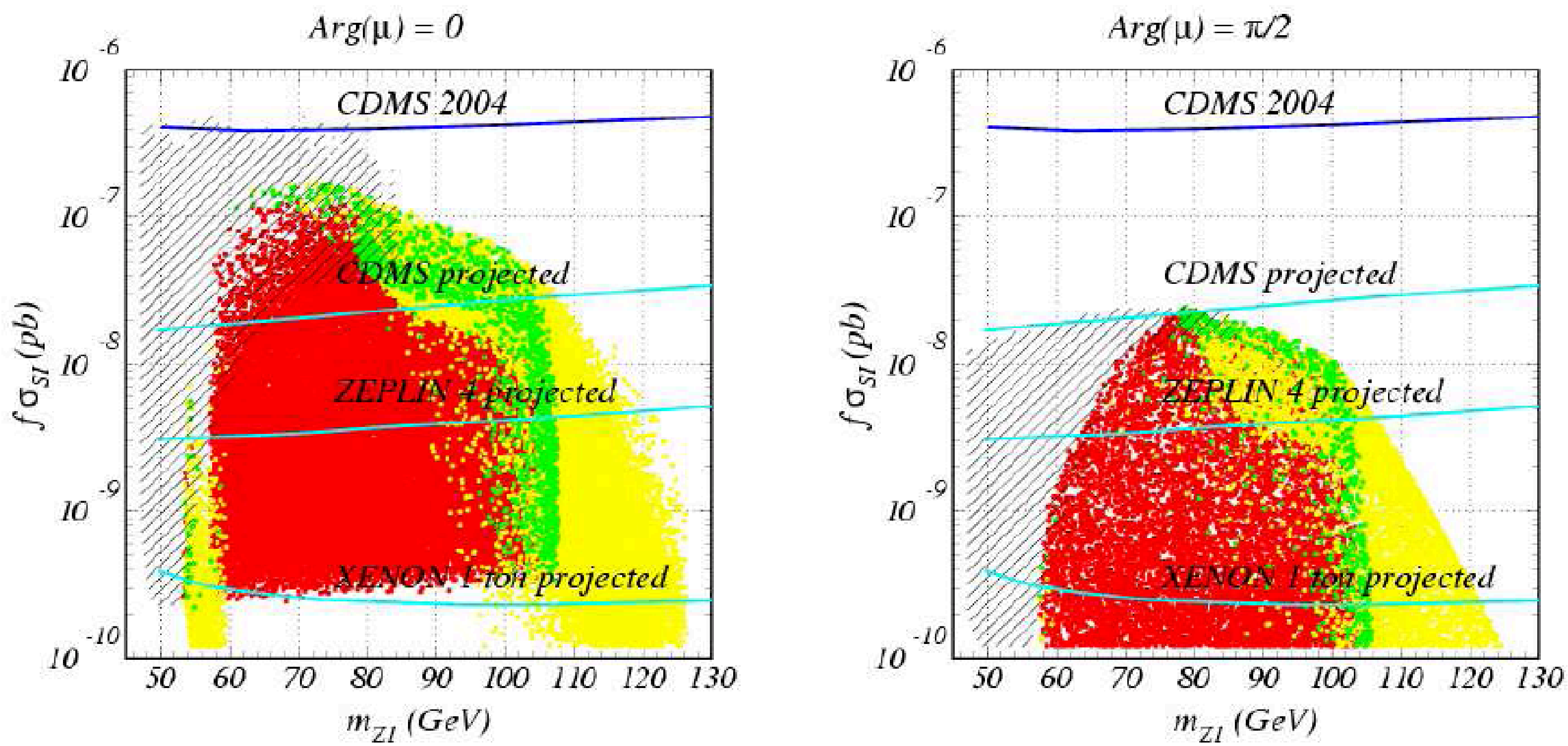
Excellent reach until masses of the order of 220 GeV and larger.

Full region consistent with EWBG will be probed by combining the LHC with the Tevatron searches.

Direct Dark Matter Detection

- Neutralino DM is searched for in neutralino-nucleon scattering exp. detecting elastic recoil off nuclei
- Hatched region: Excluded by LEP2 chargino searches

Balazs, Carena, Menon, Morrissey, C.W.'05



Baryon Abundance

- Information on the baryon abundance comes from two main sources:
- Abundance of primordial elements. When combined with Big Bang Nucleosynthesis tell us

$$\eta = \frac{\mathrm{n_B}}{\mathrm{n}_\gamma} \quad , \qquad \mathrm{n}_\gamma = \frac{421}{\mathrm{cm}^3}$$

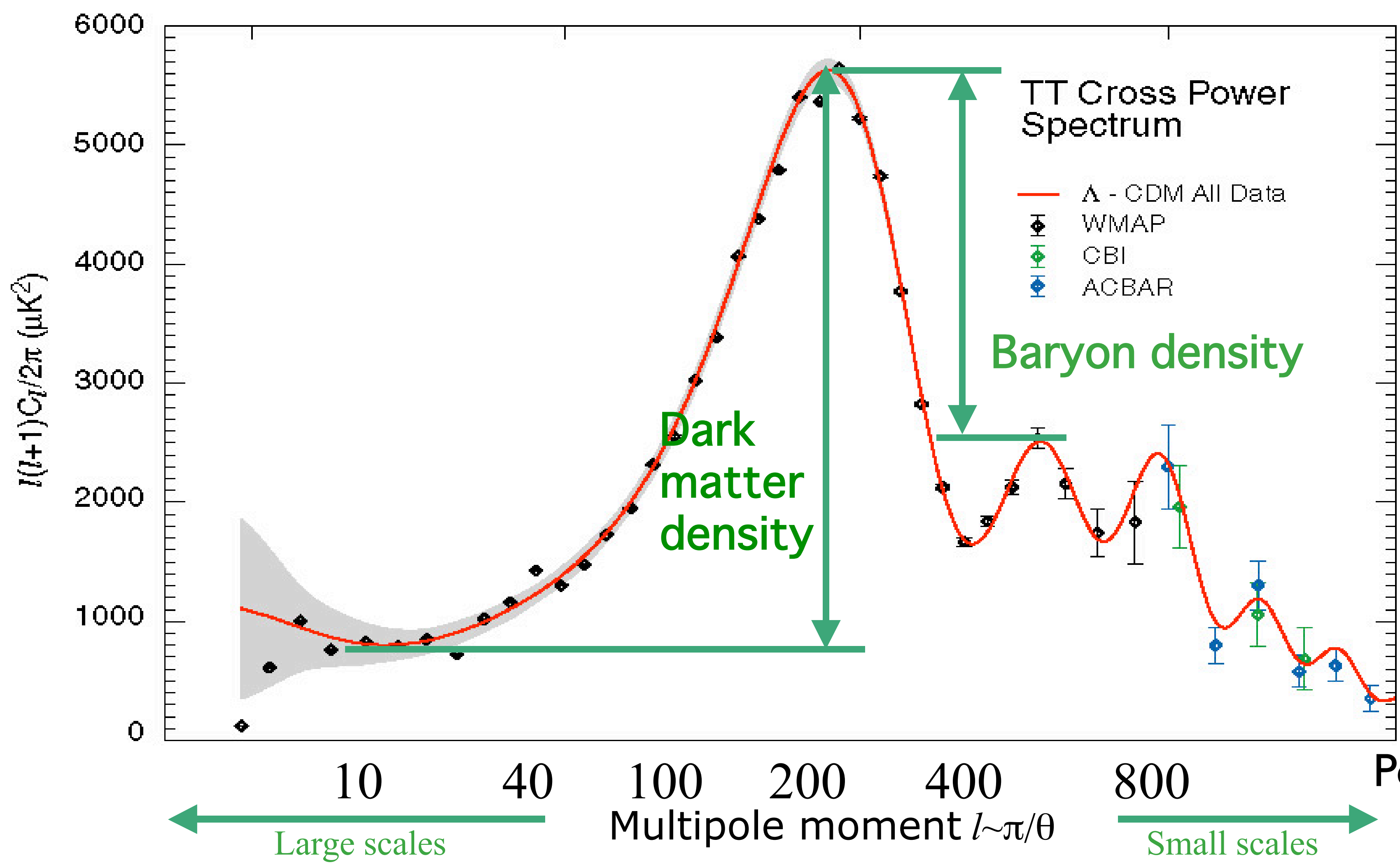
- CMBR, tell us ratio

$$\frac{\rho_\mathrm{B}}{\rho_\mathrm{c}} \equiv \Omega_B, \qquad \rho_\mathrm{c} \approx 10^{-5} h^2 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

- There is a simple relation between these two quantities

$$\eta = 2.68\ 10^{-8}\,\Omega_B h^2$$

Information coming from the CMBR



Peris

Comment on WIMP Hypothesis

- Let us stress that the condition we just obtained only relates the masses and the couplings of the particles

- One can have a sector which interacts more strongly than the weak interactions, provided it has masses of the order of a few TeV instead of few hundred GeV (example: gauge mediation)

$$\frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M} \rightarrow \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

right relic density !
(irrespective of its mass)

Feng and Kumar'08

- The range is then, even in the thermal case, quite large. Moreover, the annihilation can proceed into a hidden sector and therefore say nothing about collider physics.

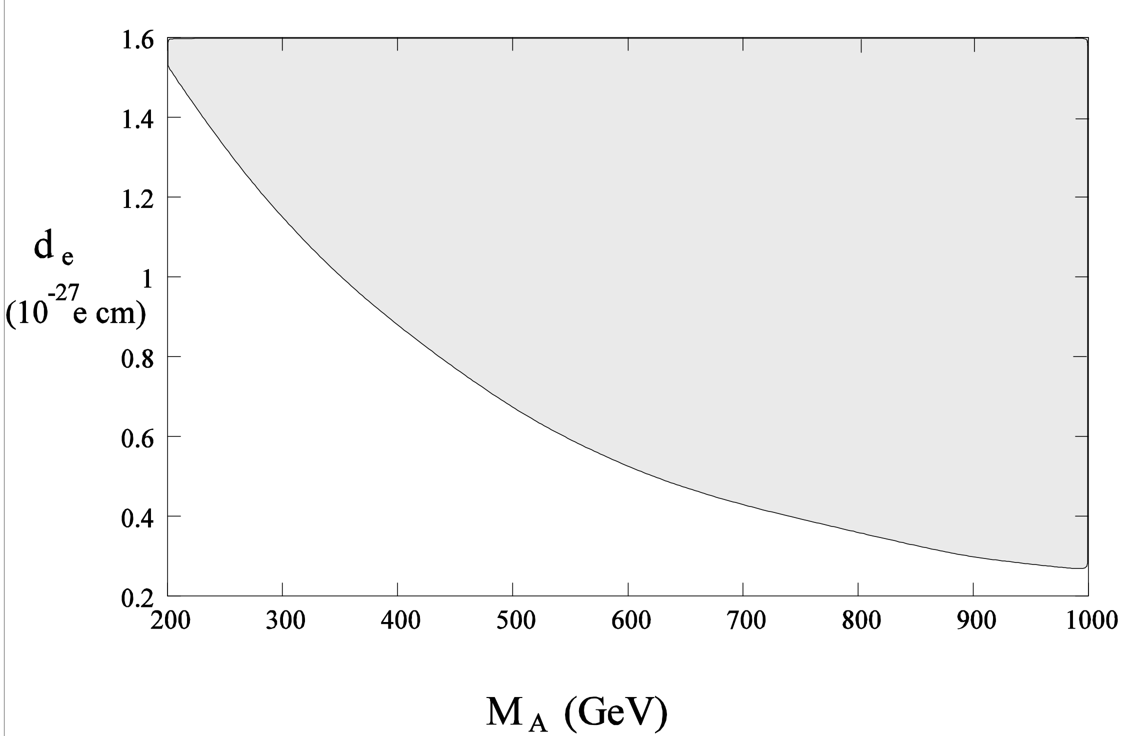
- The LHC will therefore probe a large class of weak scale extensions of the Standard Model, but even in the case of thermal dark matter, no guarantee of its detection may be established.

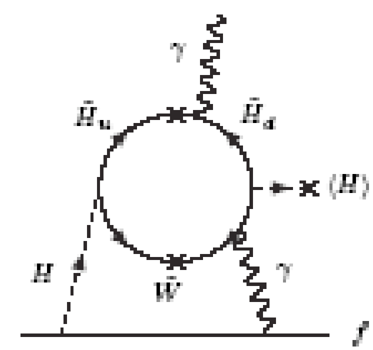
Electron electric dipole moment

- Asssuming that sfermions are sufficiently heavy, dominant contribution comes from two-loop effects, which depend on the same phases necessary to generate the baryon asymmetry. (Low energy spectrum is like a Stop plus Split Supersymmetry).
- Chargino mass parameters scanned over their allowed values. The electric dipole moment is constrained to be smaller than

$$d_e < 1.6\ 10^{-27}\ \text{e cm}$$

Balazs, Carena, Menon, Morrissey, C.W.'05





Pilaftsis' 02

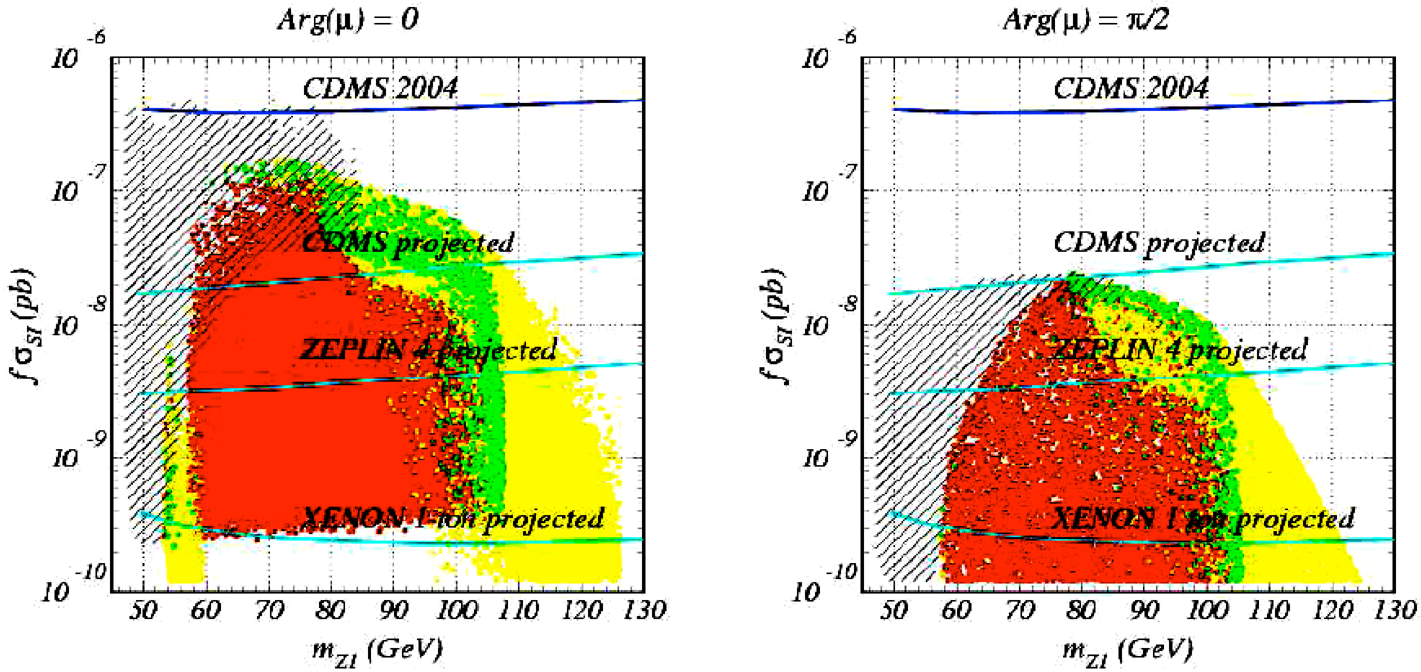
Direct detection

- Searches at colliders will be complemented by direct (and indirect) detection experiments
- These are based on nuclei--dark matter collisions and hence strongly dependent on these cross sections
- It is possible that these experiments will lead to a dark matter signature in the near future.

Direct Dark Matter Detection

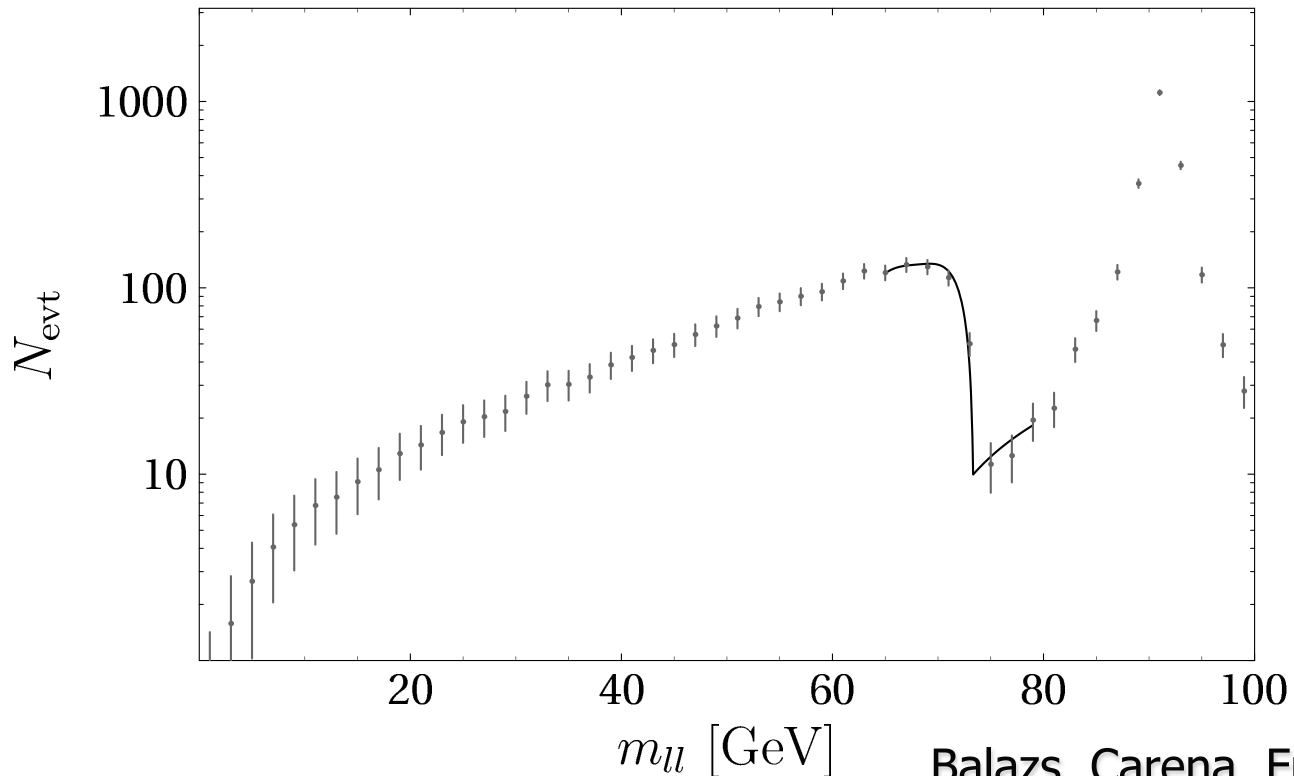
- Neutralino DM is searched for in neutralino-nucleon scattering exp. detecting elastic recoil off nuclei
- Hatched region: Excluded by LEP2 chargino searches

Balazs, Carena, Menon, Morrissey, C.W.'04



$$pp \to \tilde{g}\tilde{g}, \qquad \tilde{g} \to b\tilde{b}^* \text{ or } \bar{b}\tilde{b} \to b\bar{b}\tilde{\chi}_2^0 \qquad \tilde{\chi}_2^0 \to Z^*\,\tilde{\chi}_1^0$$

$$m_{ll,\max,2} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \qquad m^2_{jll,\max,2} = \frac{1}{m^2_{\tilde{\chi}_2^0}}(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\chi}_1^0})(m^2_{\tilde{b}} - m^2_{\tilde{\chi}_2^0})$$

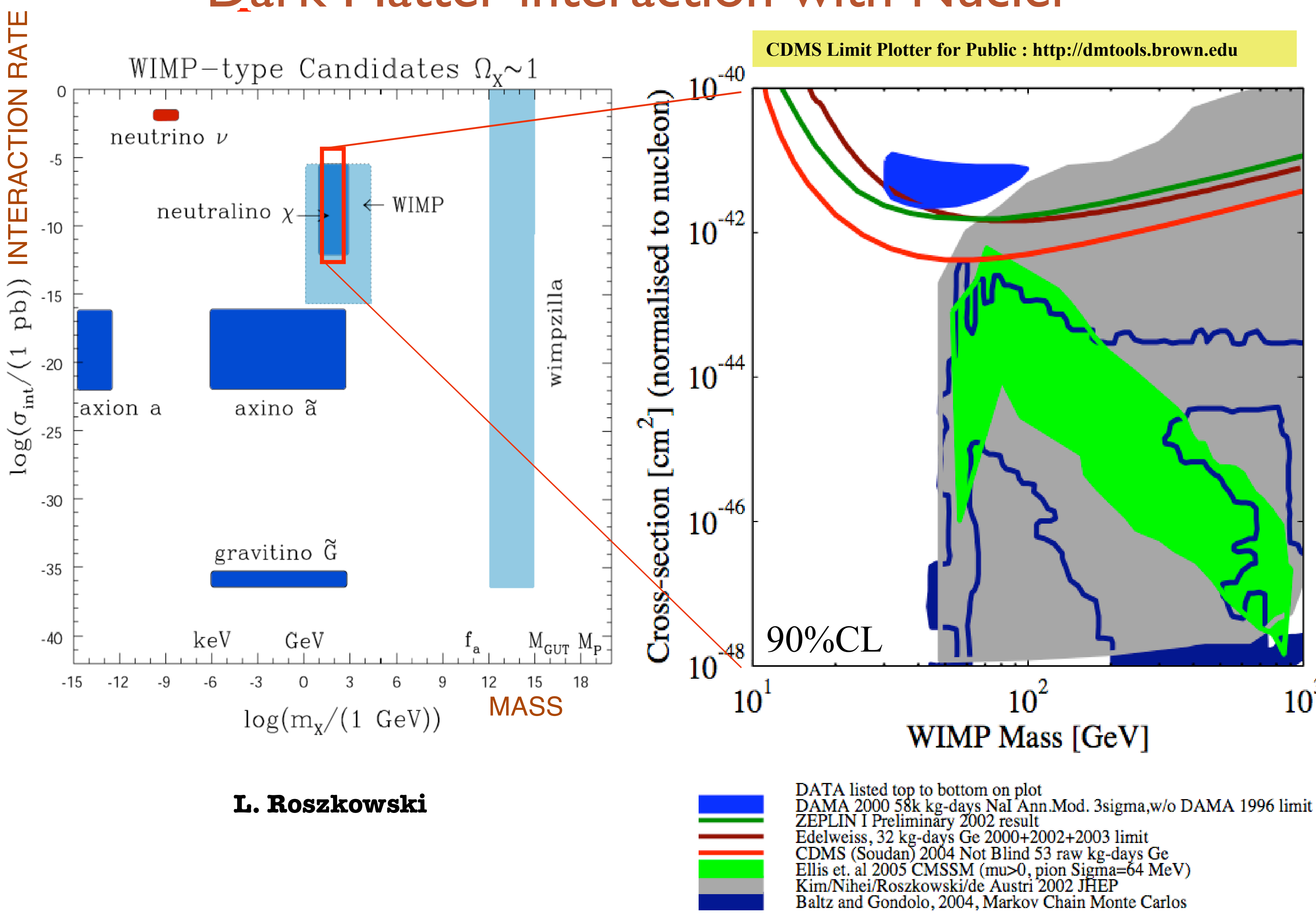


Balazs, Carena, Freitas, C.W. '07

Using similar methods for $\tilde{\chi}_3^0$, one obtains

$$m_{\tilde{\chi}_1^0} = 33^{+32}_{-17.5}\ \text{GeV}, \quad m_{\tilde{\chi}_2^0} = 106.5^{+32.5}_{-17.5}\ \text{GeV}, \quad m_{\tilde{\chi}_3^0} = 181^{+20}_{-10}\ \text{GeV}, \quad m_{\tilde{b}} = 499^{+30}_{-17}\ \text{GeV}$$

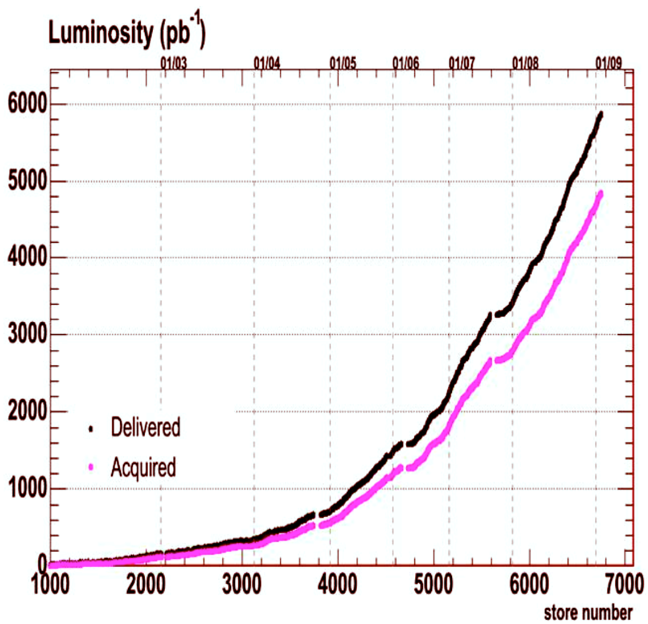
Dark Matter interaction with Nuclei

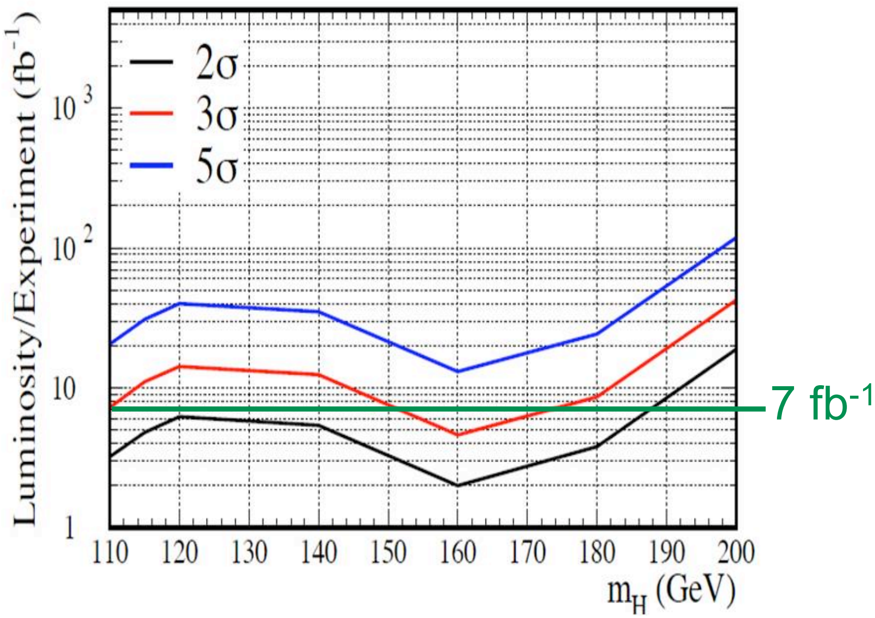


L. Roszkowski

E. Ramberg, Argonne 2006

Higgs mass reach at the Tevatron: exciting times ahead





Accelerator performance implies $9fb^{-1}$ of data available in 2010

Expected detector/analysis performance

==> m_H < 185 GeV will to be probed at the Tevatron

Evidence of a signal will mean that the Higgs has SM-like couplings to the W and Z