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SUSY
AND
DM

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THE DRUNK'S LOST KEYS
and
OUR SEARCH FOR TEV NEW PHYSICS

LHC : NEW PHYSICS =

THE DRUNK : THE LOST KEYS

$M_W = 10^2$ GeV $\qquad M_{PLANCK} = 10^{19}$ GeV

Why new physics should sit where our lamppost is, i.e. just at the TeV scale?

TEVATRON → LHC → I L C

DM - FLAVOR

for DISCOVERY

and/or FUND. TH.

RECONSTRUCTION

NEW PHYSICS AT THE ELW SCALE

A MAJOR LEAP AHEAD IS NEEDED

DARK MATTER

$m_\chi\ n_\chi\ \sigma_\chi \ldots$

DARK ENERGY

LINKED TO COSMOLOGICAL EVOLUTION

LEPTOGENESIS

GW

INFLATION

"LOW ENERGY" PRECISION PHYSICS

FCNC, CP ≠, (g-2), $(\beta\beta)_{0\nu\nu}$

LFV, CPV B PHYSICS

NEUTRINO PHYSICS

WHY TO GO BEYOND THE SM

"OBSERVATIONAL" REASONS

- HIGH ENERGY PHYSICS

NO (but $A_{FB}^{Z \to b\bar{b}}$……., $A_{FB}^{t\bar{t}}$)

- FCNC, CP≠

NO (but $b \to s q\bar{q}$ penguin …)

- HIGH PRECISION LOW-EN.

NO (but $(g-2)_\mu$ …)

- **NEUTRINO PHYSICS**

YES $m_\nu \neq 0$, $\theta_\nu \neq 0$

- **COSMO - PARTICLE PHYSICS**

YES (DM, ΔB_{cosm}, INFLAT., DE)

THEORETICAL REASONS

- INTRINSIC INCONSISTENCY OF SM AS QFT

NO (spont. broken gauge theory without anomalies)

- NO ANSWER TO QUESTIONS THAT "WE" CONSIDER "FUNDAMENTAL" QUESTIONS TO BE ANSWERED BY "FUNDAMENTAL" THEORY

YES **(hierarchy, unification, flavor)**

PROLOGUE

… **no firm experimental indication that some NEW PHYSICS sets in at the electroweak scale (i.e., with new particles and phenomena at the TeV mass scale) and**

… **yet, we are strongly convinced that TeV New Physics is present**

Is it possible that there is "only" a light higgs boson and no NP?

- **This is acceptable if one argues that no ultraviolet completion of the SM is needed at the TeV scale** simply because there is **no actual fine-tuning related to the higgs mass stabilization** (**the correct value of the higgs mass is "environmentally" selected**). This explanation is similar to the one adopted for the cosmological constant

- Barring such wayout, **one is lead to have TeV NP to ensure the unitarity of the elw. theory at the TeV scale**

% FINE-TUNING FOR THE NEW PHYSICS AT THE ELW. SCALE

- **Elementary Higgs** →In the **MSSM** % fine-tuning among the SUSY param. to avoid light SUSY particles which would have been already seen at LEP and Tevatron

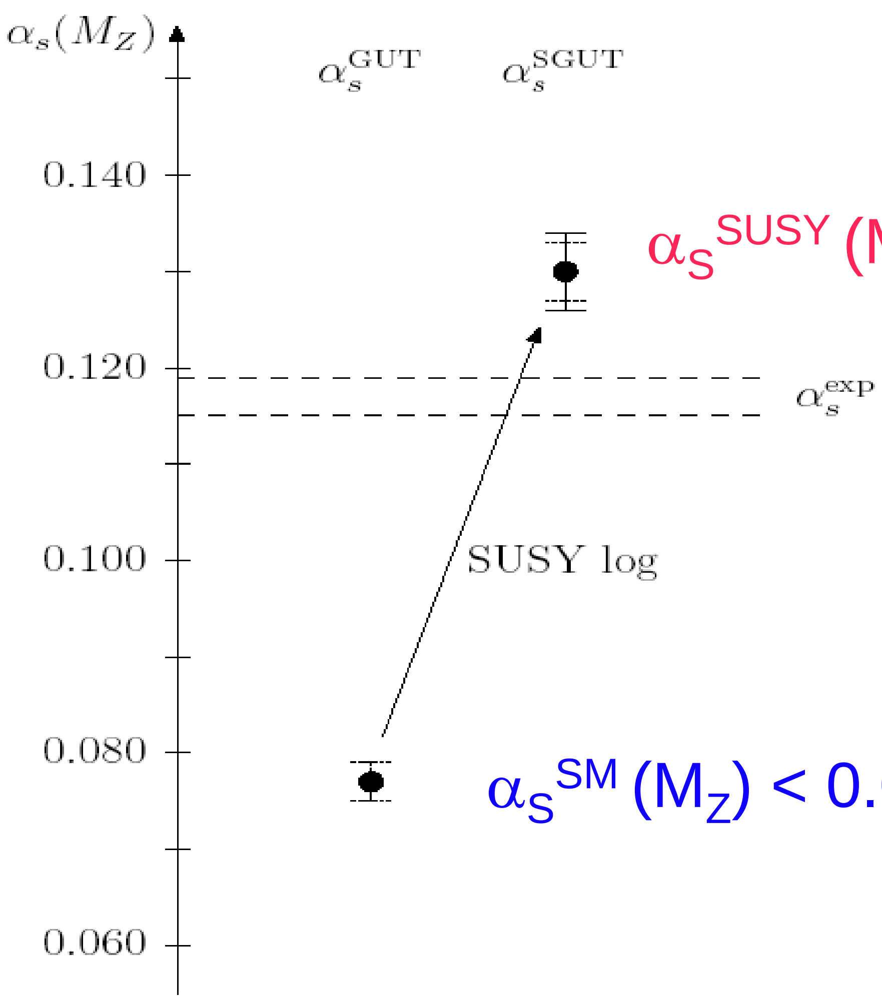
- **Elementary Higgs** → **PSEUDO-GOLDSTONE boson in the LITTLE HIGGS model** → Λ^2 div. cancelled by new colored fermions, new W,Z, γ, 2Higgs doublets… → % fine-tuning to avoid too large elw. corrections

- **COMPOSITE HIGGS** in **a 5-dim**. holographic theory: the Higgs is a **PSEUDO-GOLDSTONE** boson and the elw. symmetry breaking is triggered by bulk effects (in 5 dim. the theory is **WEAKLY** coupled, but in 4 dim. the bulk looks like a **STRONGLY** coupled sector) → also here % fine-tuning needed to survive the elw. precision tests

GENERAL FEATURES OF NEW PHYSICS AT THE ELW. SCALE

- Some amount of **fine-tuning** (typically at the % level) is required to pass unscathed the elw. precision tests, the higgs mass bound and the direct search for new particles at accelerators.
- The **higgs is typically rather light** (<200 GeV) apart from the extreme case of the “Higgsless proposal”
- All models provide **signatures which are (more or less) accessible to LHC physics** (including the higgsless case where new KK states are needed to provide the unitarity of the theory)

Fundamental interactions unify



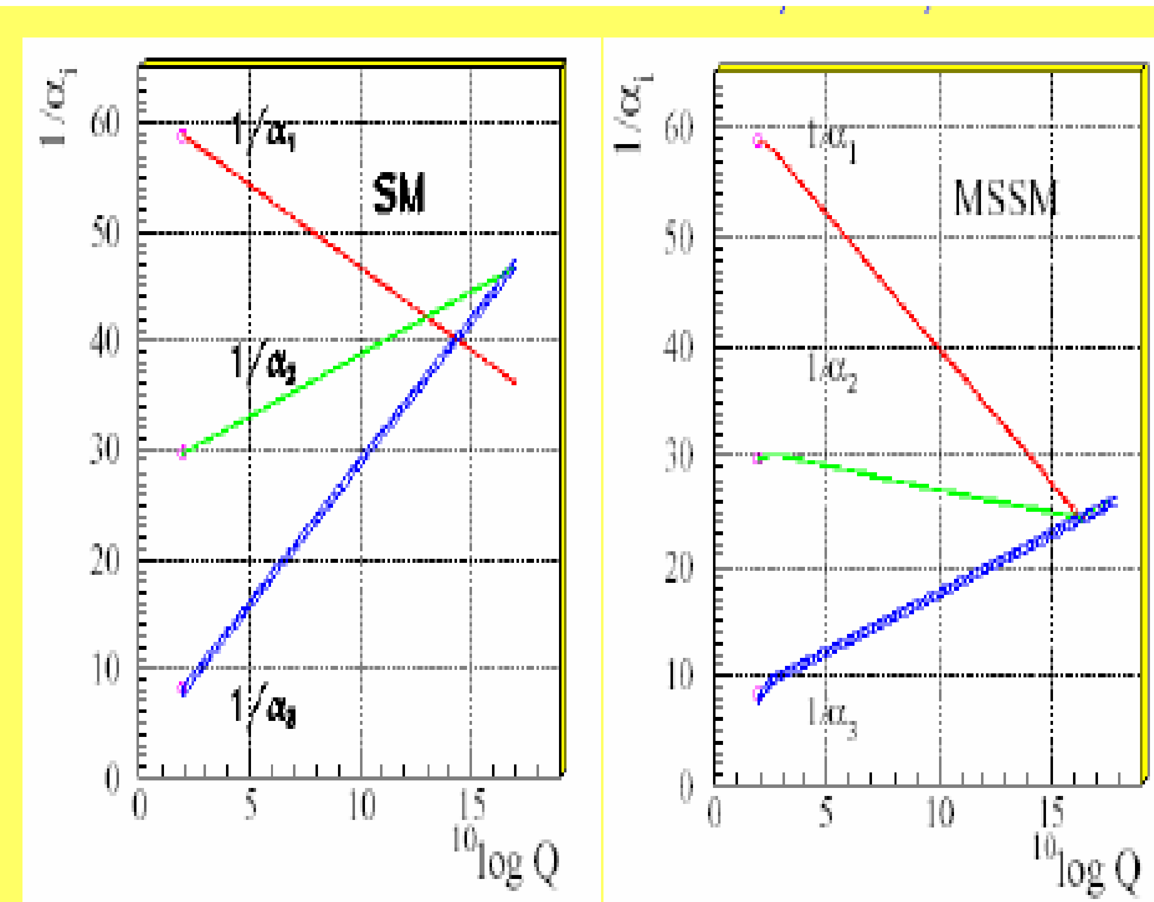
$\alpha_S^{SUSY}(M_Z)$

$\alpha_S^{exp}(M_Z) = 0.117 \pm 0.002$

$\alpha_S^{SM}(M_Z) < 0.080$

Hall, Nomura

LOW-ENERGY SUSY AND UNIFICATION



Input

$$\alpha^{-1}(M_Z) = 128.978 \pm 0.027$$

$$\sin^2 \theta_{\overline{MS}} = 0.23146 \pm 0.00017$$

$$\alpha_s(M_Z) = 0.1184 \pm 0.0031$$

Output

$$M_{SUSY} = 10^{3.4 \pm 0.9 \pm 0.4} \text{ GeV}$$

$$M_{GUT} = 10^{15.8 \pm 0.3 \pm 0.1} \text{ GeV}$$

$$\alpha_{GUT}^{-1} = 26.3 \pm 1.9 \pm 1.0$$

"*MASS PROTECTION*"

For FERMIONS, VECTOR (GAUGE) and SCALAR BOSONS

SIMMETRY PROTECTION

- -FERMIONS → chiral symmetry

  $f_L f_R$ not invariant under SU(2)x U(1)

- -VECTOR BOSONS → gauge symmetry

→ FERMIONS and W,Z VECTOR BOSONS can get a mass only when the elw. symmetry is broken m_f, $m_W \leq$ <H>

NO SYMMETRY PROTECTION FOR SCALAR MASSES

POSSIBLE SOLUTION ⇓

"INDUCED MASS PROTECTION"

→ Create a symmetry (SUPERSIMMETRY)

Such that FERMIONS ↔ BOSONS

So that the fermion mass "protection" acts also on bosons as long as SUSY is exact

⇒ SUSY BREAKING ~ SCALE OF 0 (10^2-10^3 Gev)

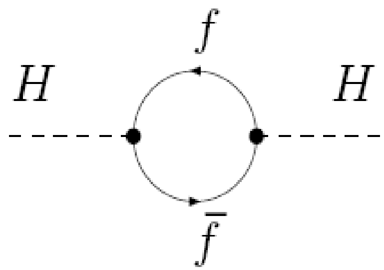
→ LOW ENERGY SUSY

ON THE RADIATIVE CORRECTIONS TO THE SCALAR MASSES

Free propagation:

inverse propagator: $i(p^2 - M_H^2)$

Loop corrections:



inverse propagator: $i(p^2 - M_H^2 + \Sigma_H^f)$

$$\Sigma_H^f \sim N_f\, \lambda_f^2 \int d^4k \left(\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right)$$

for $\Lambda \to \infty$:
$$\Sigma_H^f \sim N_f\, \lambda_f^2 \left(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_f^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \right)$$

DESTABILIZATION OF THE ELW. SYMMETRY BREAKING SCALE

For $\Lambda = M_{\text{Pl}}$:

$$\Sigma_H^f \approx \delta M_H^2 \sim M_{\text{Pl}}^2 \quad \Rightarrow \quad \delta M_H^2 \approx 10^{30}\, M_H^2$$

(for $M_H \lesssim 1$ TeV)

SCALAR MASSES ARE "UNPROTECTED" AGAINST LARGE CORRECTIONS WHICH TEND TO PUSH THEM UP TO THE LARGEST ENERGY SCALE PRESENT IN THE FULL THEORY

EX: Grand Unified Theory (GUT): $\delta M_H^2 \approx M_{\text{GUT}}^2$

SYMMETRY → MASS = 0 LIMIT

NO NEW SYMMETRY IN THE LIMIT $M_H = 0$

On the contrary, in the limit of massless electron one recovers the chiral symmetry, i.e. the invariance under a separate rotation of the LH and RH components of the electron

FERMION AND GAUGE BOSON MASSES →

WHEN SENT TO ZERO THE THEORY ACQUIRES A NEW

SYMMETRY OR, EQUIVALENTLY, THEY ARISE ONLY

WHEN A CERTAIN SYMMETRY IS BROKEN, i.e. **THEIR**

VALUE CAN NEVER EXCEED THE SCALE AT WHICH

SUCH SYMMETRY IS BROKEN

THE FINE-TUNING PROBLEM
OR
NATURALNESS PROBLEM

When SM is embedded in a larger theory where a new scale M>> the electroweak scale → the SM higgs mass receives corrections of O(M), i.e.

M higgs= M higgs tree-level+ aM +bM +…

Need a and b to cancel each other with a precision of O(elw. scale / M)

IS THE FINE-TUNING A ***REAL PROBLEM?***

- WARNING: THERE EXISTS AN EVEN “LARGER” HIERARCHY OR FINE -TUNING OR NATURALNESS PROBLEM: THE COSMOLOGICAL CONSTANT PROBLEM (“ THE MOTHER” OF ALL NATURALNESS PROBLEMS
- QUANTUM CORRECTIONS PUSH THE VALUE OF THE COSMOLOGICAL CONSTANT UP TO THE LARGEST SYMMETRY SCALE PRESENT IN THE THEORY, I.E. THE “NATURAL” VALUE OF THE COSM. CONST. SHOULD BE OF O(MPLANCK) OR O(MGUT)
- WE DON’T HAVE ANY SOLUTION FOR THE COSMOLOGICAL CONSTANT PROBLEM SO FAR, I.E. WE “ACCEPT” THE FINE TUNING IN THIS CASE
- YET I THINK THAT WE NEED TO “SOLVE” THESE FINE TUNINGS PROBLEMS AND NOT SIMPLY ACCEPTING THEM AS GIVEN VALUES FOR DIFFERENT MASS PARAMETRS OF THE FINAL THEORY

The Higgs problem is central in particle physics today

Altarelli LP09

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

Vacuum energy
$V_{0exp} \sim (2.10^{-3}\ \mathrm{eV})^4$

Possible instability depending on m_H

Origin of quadratic divergences. Hierarchy problem

The flavour problem: large unexplained ratios of Y_{ij} Yukawa constants

HOW TO COPE WITH THE HIERARCHY PROBLEM

- LOW-ENERGY SUSY
- LARGE EXTRA DIMENSIONS
- DYNAMICAL SYMMETRY BREAKING OF THE ELW. SYMMETRY
- LANDSCAPE APPROACH (ANTHROPIC PRINCIPLE)

ROADS TO GO BEYOND THE STANDARD MODEL (I)

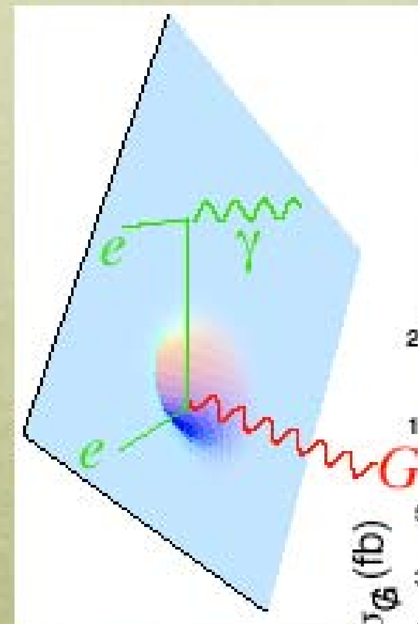
1) **THERE EXISTS NO NEW PHYSICAL ENERGY SCALE ABOVE THE ELW. SCALE**: gravity is an extremely weak force not because of the enormous value of the Planck scale, but because of the existence of **NEW DIMENSIONS** beyond the usual 3+1 space-time where (most of) the gravity flux lines get "dispersed"

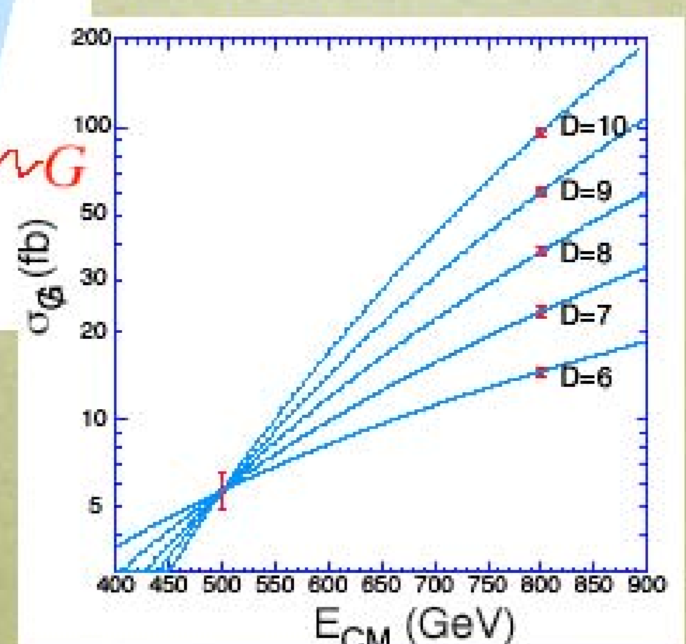
→ **VISIBILITY AT LHC**: there exist "excited" states of the ordinary particles (**Kaluza-Klein states**) and some of them are accessible at LHC (the lightest KK state may be a stable particle and it can constitute the DM)

Hidden Dimensions

- *Hidden dimensions*
- *Can emit graviton into the bulk*
- *Events with apparent energy imbalance*

How many extra dimensions are there?





ROADS TO GO BEYOND THE STANDARD MODEL (II)

- **2) NO NEED TO "PROTECT" THE HIGGS MASS AT THE ELW. SCALE: THE HIGGS IS A COMPOSITE OBJECT (for instance, a fermion condensate) WHOSE COMPOSITENESS SCALE IS THE ELW. SCALE (cfr. the pion mass case)**

→ **VISIBILITY AT LHC: THERE EXIST NEW (STRONG) INTERACTIONS AT THE ELW. SCALE WHICH PRODUCE THE HIGGS CONDENSATE** (new resonances,, new bound states, a new rescaled QCD at 1 TeV)

ROADS TO GO BEYOND THE STANDARD MODEL (III)

- **3) THE MASS OF THE ELEMENTARY HIGGS BOSON IS "PROTECTED" AT THE ELW. SCALE BECAUSE OF THE PRESENCE AT THAT ENERGY OF A NEW SYMMETRY, THE SUPERSYMMETRY (SUSY)**

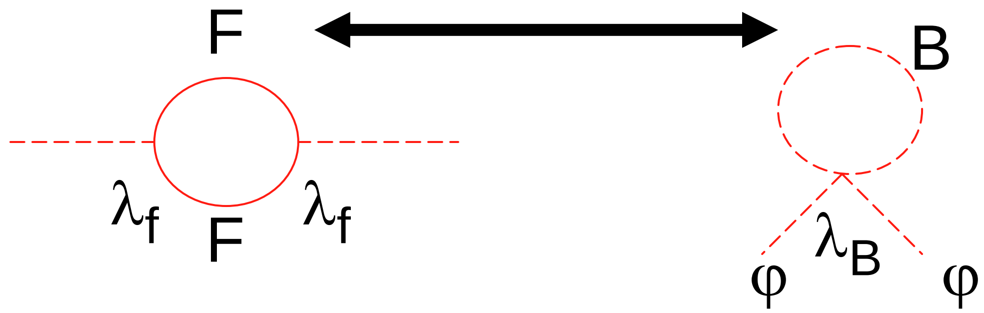
  → **VISIBILITY AT LHC**: WE'LL SEE (SOME OF) THE **SUSY PARTICLES AND THEIR INTERACTIONS**. THE LIGHTEST SUSY PARTCILE (**LSP**) IS LIKELY TO BE STABLE AND PROVIDE THE **DM**. **AT THE SAME TIME, WE COULD DISCOVER SUSY AND THE SOURCE OF 90% OF THE ENTIRE MATTER PRESENT IN THE UNIVERSE.**

HIERARCHY PROBLEM:

THE SUSY WAY

SUSY HAS TO BE BROKEN AT A SCALE CLOSE TO 1TeV → LOW ENERGY SUSY

$m_\varphi^2 \propto \Lambda^2$ → Scale of susy breaking



$$Sm^2_\varphi \sim \frac{(\lambda_B - \lambda^2_f)}{16\,\pi^2}\,\Lambda^2$$

$$\longrightarrow [m^2_B - m^2_F]^{1/2} \sim 1/\sqrt{G_F}$$

$\begin{pmatrix} B \\ F \end{pmatrix}$ In SUSY multiplet

SPLITTING IN MASS BETWEEN B and F of O (ELW. SCALE)

THE SUSY PATH

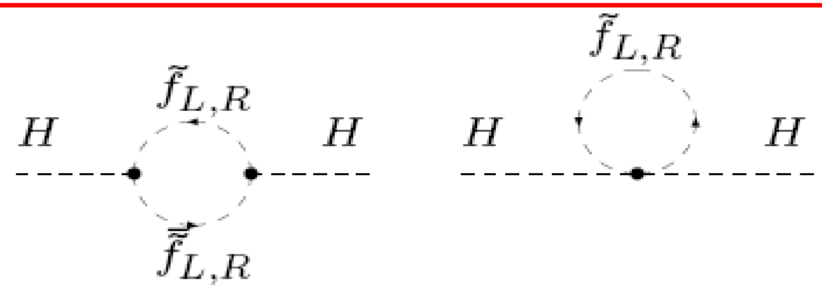
$$Q\,|\,boson>=|\,fermion> \qquad Q\,|\,fermion>=|\,boson>$$

$$[b,b]=0,\quad \{f,f\}=0 \;\Rightarrow$$

$$\{Q^i_\alpha, \overline{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta}P_\mu$$

Effectively: SM particles have SUSY partners (e.g. $f_{L,R} \rightarrow \tilde{f}_{L,R}$)

SUSY: additional contributions from scalar fields:



$$\Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\,\lambda_{\tilde{f}}^2 \int d^4k \left(\frac{1}{k^2 - m^2_{\tilde{f}_L}} + \frac{1}{k^2 - m^2_{\tilde{f}_R}}\right) + \text{ terms without quadratic div.}$$

for $\Lambda \rightarrow \infty$: $\quad \Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\,\lambda_{\tilde{f}}^2\,\Lambda^2$

⇒ quadratic divergences cancel for

$$N_{\tilde{f}_L} = N_{\tilde{f}_R} \; = \; N_f$$
$$\lambda_{\tilde{f}}^2 \; = \; \lambda_f^2$$

complete correction vanishes if furthermore

$$m_{\tilde{f}} = m_f$$

Soft SUSY breaking: $m_{\tilde{f}}^2 = m_f^2 + \Delta^2, \quad \lambda_{\tilde{f}}^2 = \lambda_f^2$

$$\Rightarrow \; \Sigma_H^{f+\tilde{f}} \sim N_f \, \lambda_f^2 \, \Delta^2 + \ldots$$

⇒ correction stays acceptably small if mass splitting is of weak scale

⇒ realized if mass scale of SUSY partners

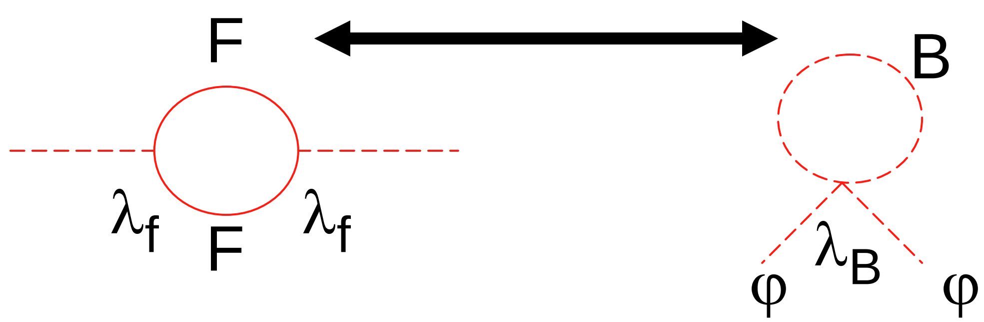
$$M_{\mathrm{SUSY}} \lesssim 1\,\mathrm{TeV}$$

⇒ SUSY at TeV scale provides attractive solution of hierarchy problem

HIERARCHY PROBLEM: THE SUSY WAY

SUSY HAS TO BE BROKEN AT A SCALE CLOSE TO 1TeV $\longrightarrow$ LOW ENERGY SUSY

$m_\varphi^2 \propto \Lambda^2 \longrightarrow$ Scale of susy breaking



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$$\longrightarrow [m^2_B - m^2_F]^{1/2} \sim 1/\sqrt{G_F}$$

$\begin{pmatrix} B \\ F \end{pmatrix}$ In SUSY multiplet

SPLITTING IN MASS BETWEEN B and F of O (ELW. SCALE)

NO – GO AND NO NO-GO ON THE ROAD TO GET A SUSY SM

Theorem # 1: No-go theorem [*Coleman, Mandula '67*]

Any Lie-group containing Poincaré group P and internal symmetry group $\tilde{G}$ must be direct product $P \otimes \tilde{G}$

$$\Big|\underbrace{m, s; \vec{p}, s_3}_{\text{space–time}}; \underbrace{\tilde{g}, \ldots}_{\text{internal}}\Big\rangle$$

quantum numbers

New group $\tilde{G}$ with generators Q^α and

$$[\Lambda^{\mu\nu}, Q^\alpha] \neq 0, \quad [P^\rho, Q^\alpha] \neq 0$$

impossible

Theorem # 2: How-To-Avoid-the-No-go theorem

[Gol'fand, Likhtman '71] [Volkov, Akulov '72] [Wess, Zumino '73]

No go theorem can be evaded if instead of Lie-group (generators fulfill commutator relations):

$$[\ldots,\ldots] \rightarrow \{\ldots,\ldots\}$$

Anticommutator: $\{A, B\} = AB + BA$

$\Rightarrow$ Generator Q^α is fermionic (i.e. it has spin $\frac{1}{2}$)

$\Rightarrow$ Particles with different spin in one multiplet possible

Simplest case: only one fermionic generator Q_α (and conjugate $\bar{Q}_{\dot\beta}$)

$\Rightarrow$ $N = 1$ SUSY algebra:

$$
\begin{aligned}
[Q_\alpha, P_\mu] = \left[\bar{Q}_{\dot\beta}, P_\mu\right] &= 0 \\
[Q_\alpha, M^{\mu\nu}] &= i(\sigma^{\mu\nu})_\alpha{}^\beta Q_\beta \\
\left\{Q_\alpha, Q_\beta\right\} = \left\{\bar{Q}_{\dot\alpha}, \bar{Q}_{\dot\beta}\right\} &= 0 \\
\left\{Q_\alpha, \bar{Q}_{\dot\beta}\right\} &= 2(\sigma^\mu)_{\alpha\dot\alpha} P_\mu
\end{aligned}
$$

Energy $= H = P_0$, $\Rightarrow$ $[Q_\alpha, H] = 0$ $\Rightarrow$ conserved charge

$\Rightarrow$ SUSY: symmetry that relates bosons to fermions

unique extension of Poincaré group of symmetries of $D = 4$ relativistic QFT

ON THE WAY TO SUPERSYMMETRIZE THE SM

SUSY Multiplets

Chiral multiplet $N=1,\ \lambda=0$

helicity	-1/2	0	1/2
# of states	1	2	1

(φ, ψ) — scalar, spinor

Vector multiplet $N=1,\ \lambda=1/2$

helicity	-1	-1/2	1/2	1
# of states	1	1	1	1

(λ, A_μ) — spinor, vector

Simplest (N=1) SUSY Multiplets

Bosons and Fermions come in pairs

$$(\varphi, \psi) \qquad (\lambda, A_\mu) \qquad (\tilde{g}, g)$$

Spin 0 Spin 1/2 Spin 1/2 Spin 1 Spin 3/2 Spin 2

D. KAZAKOV

Particle Content of the MSSM

Superfield	Bosons	Fermions	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge					
G^a	gluon g^a	gluino $\tilde{g}^a$	8	1	0
V^k	Weak $W^k(W^\pm, Z)$	wino, zino $\tilde{w}^k(\tilde{w}^\pm, \tilde{z})$	1	3	0
V'	Hypercharge $B(\gamma)$	bino $\tilde{b}(\tilde{\gamma})$	1	1	0
Matter					
L_i	sleptons $\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons $L_i = (\nu, e)_L$	1	2	-1
E_i	sleptons $\tilde{E}_i = \tilde{e}_R$	leptons $E_i = e_R$	1	1	2
Q_i	squarks $\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks $Q_i = (u, d)_L$	3	2	$1/3$
U_i	squarks $\tilde{U}_i = \tilde{u}_R$	quarks $U_i = u_R^c$	3^*	1	$-4/3$
D_i	squarks $\tilde{D}_i = \tilde{d}_R$	quarks $D_i = d_R^c$	3^*	1	$2/3$
Higgs					
H_1	Higgses H_1	higgsinos $\tilde{H}_1$	1	2	-1
H_2	Higgses H_2	higgsinos $\tilde{H}_2$	1	2	1

$$\mathcal{L}_{\mathrm{SM}} = \underbrace{m_d \bar{Q}_L H d_R}_{\text{d-quark mass}} + \underbrace{m_u \bar{Q}_L \tilde{H} u_R}_{\text{u-quark mass}}$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \tilde{H} = i\sigma_2 H^\dagger, \quad H \to \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \tilde{H} \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

In SUSY: term $\bar{Q}_L H^\dagger$ not allowed

Superpotential is holomorphic function of chiral superfields, i.e. depends only on φ_i, not on φ_i^*

IN SUSY WE NEED TO INTRODUCE AT LEAST TWO HIGGS DOUBLETS IN ORDER TO PROVIDE A MASS FOR BOTH THE UP- AND DOWN- QUARKS

BREAKING SUSY

- The world is clearly not supersymmetric:

  for instance, we have not seen a scalar of Q=1 and a mass of ½ MeV, i.e. the selectron has to be heavier than the electron and, hence, SUSU has to be broken

→

SUSY HAS TO BE BROKEN AT A SCALE > 100 GeV

SINCE NO SUSY PARTNERS HAVE BEEN SEEN

UP TO THOSE ENERGIES, roughly

COLORED S-PARTICLE MASSES > 200 GeV

UNCOLORED S- PARTICLE MASSES > 100 GeV

Little digression: how to break a symmetry

- **EXPLICIT BREAKING**: add to a Lagrangian invariant under a certain symmetry S some terms which do not respect such symmetry S.

  Advantage: freedom in choosing such terms and possibility to adapt them to the phenomenological requests one has

  Disadvantage: losing the virtues related to the presence of a symmetry in the theory (ex: if S is the elw. symmetry, adding an explicit mass tem to the W boson would spoil the renormalizability of the theory)

SPONTANEOUS BREAKING:: THE THEORY IS INVARIANT UNDER A CERTAIN SYMMETRY S (i.e., the FULL Lagrangian respects S), however **THE VACUUM OF THE THEORY IS NOT INVARIANT UNDER S** TRANSFORMATIONS.

ADVANTAGE: POSSIBILITY OF PRESERVING THE NICE PROPERTIES RELATED TO THE PRESENCE OF A SYMMETRY (EX: SPONTANEOUSLY BROKEN GAUGE THEORIES ARE RENORMALIZABLE)

DISADVANTAGE: SCHEME IS MORE CONSTRAINED; ONE CANNOT CHOOSE THE BREAKING TERMS “ARBITRARILY”

SPONTANEOUS BREAKING OF SUSY

- FIRST ATTEMPT: **SPONTANEOUS BREAKING OF SUSY** (letting history teach: since spontaneous breaking of the electroweak symmetry was so successful, try to repeat it in the SUSY case) → PROBLEM: **NO phenomenologically viable model** results from spontaneously broken SUSY (ex: one of the two selectrons remains lighter than the electron…)

2^{nd} ATTEMPT TO BREAK SUSY: THE EXPLICIT BREAKING

- WISH: add to the SUSY version of the SM Lagrangian some terms which are **NOT** SUSY invariant, i.e. add an explicit breaking of SUSY, but try to PRESERVE the nice properties of having SUSY in the game (for instance, still quadratic divergences should be absent even when SUSY is explicitly broken) $\longrightarrow$ special class of explicitly breaking terms called **SOFT BREAKING TERMS OF SUSY**

THE BASKET WHERE TO PICK UP

THE WANTED (OR NEEDED) SUSY SOFT BREAKING TERMS

Classification of possible soft breaking terms:

[*L. Girardello, M. Grisaru '82*]

- scalar mass terms: $m^2_{\phi_i}\,|\phi_i|^2$
- trilinear scalar interactions: $A_{ijk}\phi_i\phi_j\phi_k + \text{h.c.}$
- gaugino mass terms: $\frac{1}{2}m\bar{\lambda}\lambda$
- bilinear terms: $B_{ij}\phi_i\phi_j + \text{h.c.}$
- linear terms: $C_i\phi_i$

$\Rightarrow$ relations between dimensionless couplings unchanged

no additional mass terms for chiral fermions

THE SOFT BREAKING TERMS OF THE MINIMAL SUSY SM (MSSM)

$$-L_{Soft} = \sum_{\alpha} M_i \tilde{\lambda}_i \tilde{\lambda}_i + \sum_i m_{0i}^2 |A_i|^2 + + \sum_{ijk} \mathrm{A}_{ijk} A_i A_j A_k + \sum_{ij} \mathrm{B}_{ij} A_i A_j$$

gauginos

scalar fields

WHICH SUSY

HIDDEN SECTOR SUSY BREAKING AT SCALE $\sqrt{F}$

MESSENGERS

$F = M_W M_{Pl}$

GRAVITY

$M_{gravitino} \sim F/M_{Pl} \sim (10^2 - 10^3)$ GeV

$F = (10^5 - 10^6)$ GeV

GAUGE INTERACTIONS

$M_{gravitino} \sim F/M_{Pl} \sim (10^2 - 10^3)$eV

OBSERVABLE SECTOR

SM + superpartners

MSSM : minimal content of superfields

The MSSM Lagrangian

$$L = L_{gauge} + L_{Yukawa} + L_{SoftBreaking}$$

The Yukawa Superpotential

Superfields

$$W_R = y_U Q_L H_2 U_R + y_D Q_L H_1 D_R + y_L L_L H_1 E_R + \mu H_1 H_2$$

Yukawa couplings

Higgs mixing term

$$W_{NR} = \lambda_L L_L L_L E_R + \lambda_L^{'} L_L Q_L D_R + \mu^{'} L_L H_2 + \lambda_B U_R D_R D_R$$

Violate: Lepton number Baryon number

These terms are forbidden in the SM

$$\lambda_L, \lambda_L^{'} < 10^{-6}, \quad \lambda_B < 10^{-9}$$

THE FATE OF B AND L IN THE SM AND MSSM

- **IN THE SM B AND L ARE "AUTOMATIC" SYMMETRIES**: NO B or L VIOLATING OPERATOR OF DIM.≤ 4 INVARIANT UNDER THE GAUGE SIMMETRY SU(3) X SU(2) X U(1) IS ALLOWED (B AND L ARE CONSERVED AT ANY ORDER IN PERTURBATION THEORY, BUT ARE VIOLATED AT THE QUANTUM LEVEL (ONLY B – L IS EXACTLY PRESERVED)
- **IN THE MSSM**, THANKS TO THE EXTENDED PARTICLE SPECTRUM WITH NEW SUSY PARTNERS CARRYING B AND L, **IT IS POSSIBLE TO WRITE (RENORMALIZABLE) OPERATORS WHICH VIOLATE EITHER B OR L**
- → IF BOTH B AND L VIOLATING OPERATORS ARE PRESENT, GIVEN THAT SUSY PARTNER MASSES ARE OF O(TEV), THERE IS NO WAY TO PREVENT A **TOO FAST PROTON DECAY** UNLESS THE YUKAWA COUPLINGS ARE INCREDIBLY SMALL!

ADDITIONAL DISCRETE SYMMETRY IN THE MSSM TO SLOW DOWN P - DECAY

- SIMPLEST (and nicest) SOLUTION: ADD A SYMMETRY WHICH **FORBIDS ALL B AND L VIOLATING OPERATORS**

$\longrightarrow$ **R PARITY**

- SINCE B AND L 4-DIM. OPERATORS INVOLVE 2 ORDINARY FERMIONS AND A SUSY SCALAR PARTICLE, THE SIMPLEST WAY TO ELIMINATE ALL OF THEM:

R = +1 FOR ORDINARY PARTICLES

R = - 1 FOR SUSY PARTNERS

IMPLICATIONS OF IMPOSING R PARITY:

i) The superpartners are created or destroyed in pairs;

ii) **THE LIGHTEST SUPERPARTNER IS ABSOLUTELY STABLE**

BROKEN R PARITY

- PROTON DECAY REQUIRES THE VIOLATION OF BOTH B AND L

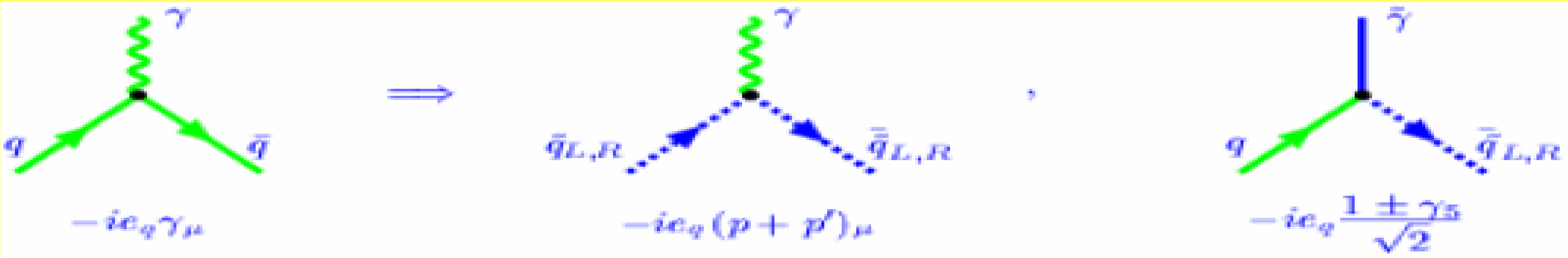
→ **NOT NECESSARY TO HAVE R PARITY TO KILL B AND L VIOLATING OPERATORS**

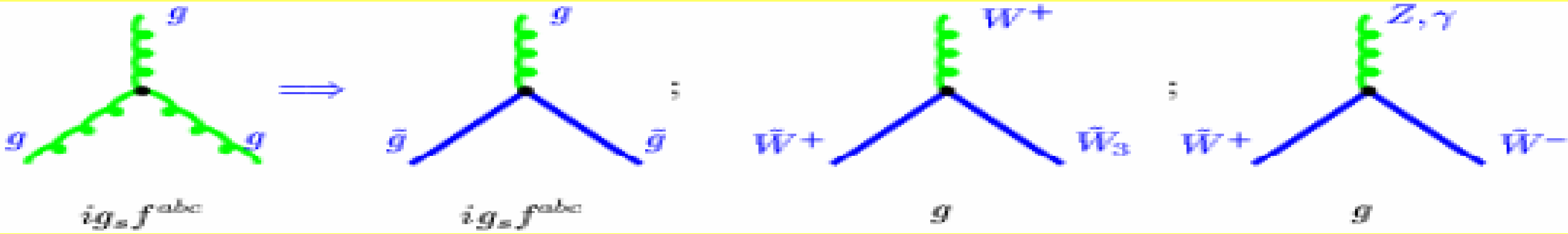
→ ENOUGH TO IMPOSE AN **ADDITIONAL DISCRETE SYMMETRY TO FORBID EITHER B OR L VIOLATING OPERATORS**; RESTRICTIONS ON THE YUKAWA COUPLINGS OF THE SURVIVING B OR L VIOLATING OPERATORS

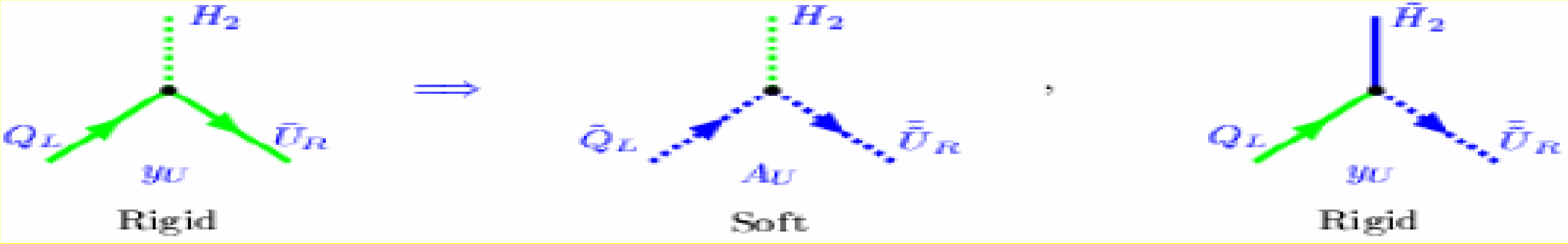
Interactions in the MSSM

SM → **MSSM**

D. KAZAKOV







FROM THE MSSM TO THE CMSSM (constrained MSSM)

- PROLIFERATION OF PARAMETRS IN THE SOFT BREAKING SECTOR OF THE MSSM: OVERALL NUMBER OF PARAM. IN THE MSSM IS **124** (large number, but are we sure that a fundamental theory should have a “small” number of parameters?)

- MOST OF THIS ENORMOUS PARAM. SPACE IS IN ANY CASE ALREADY RULED OUT BY THE VARIOUS PHENOMENOLOGICAL CONSTRAINTS ON SUSY)

- POSSIBLE TO DRASTICALLY REDUCE THE NUMBER OF PARAM. IMPOSING (REASONABLE?) THEORETICAL ASSUMPTIONS ON THE SOFT BREAKING SECTOR:

FLAVOR UNIVERSALITY IN THE SCALAR SOFT TERMS

AND

GAUGINO MASS UNIVERSALITY

AT THE GRAND UNIFICATION SCALE

MSSM Parameter Space

- Three gauge couplings
- Three (four) Yukawa matrices
- The Higgs mixing parameter
- Soft SUSY breaking terms

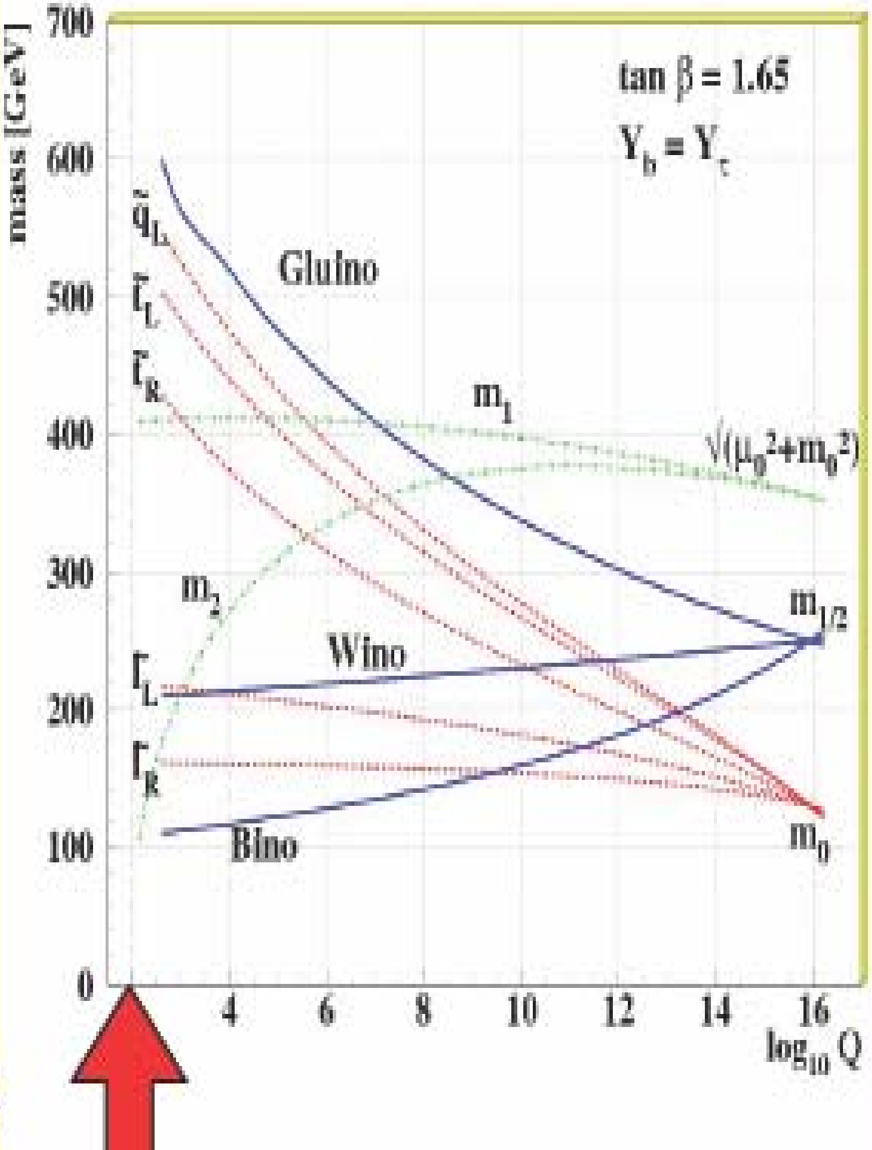
mSUGRA Universality hypothesis (gravity is colour and flavour blind):
Soft parameters are equal at Planck (GUT) scale

$$-L_{Soft} = A\{y_t Q_L H_2 U_R + y_b Q_L H_1 D_R + y_L L_L H_1 E_R\} + B\mu H_1 H_2$$
$$+ m_0^2 \sum_i |\varphi_i|^2 + \tfrac{1}{2} M_{1/2} \sum_\alpha \tilde{\lambda}_\alpha \tilde{\lambda}_\alpha$$

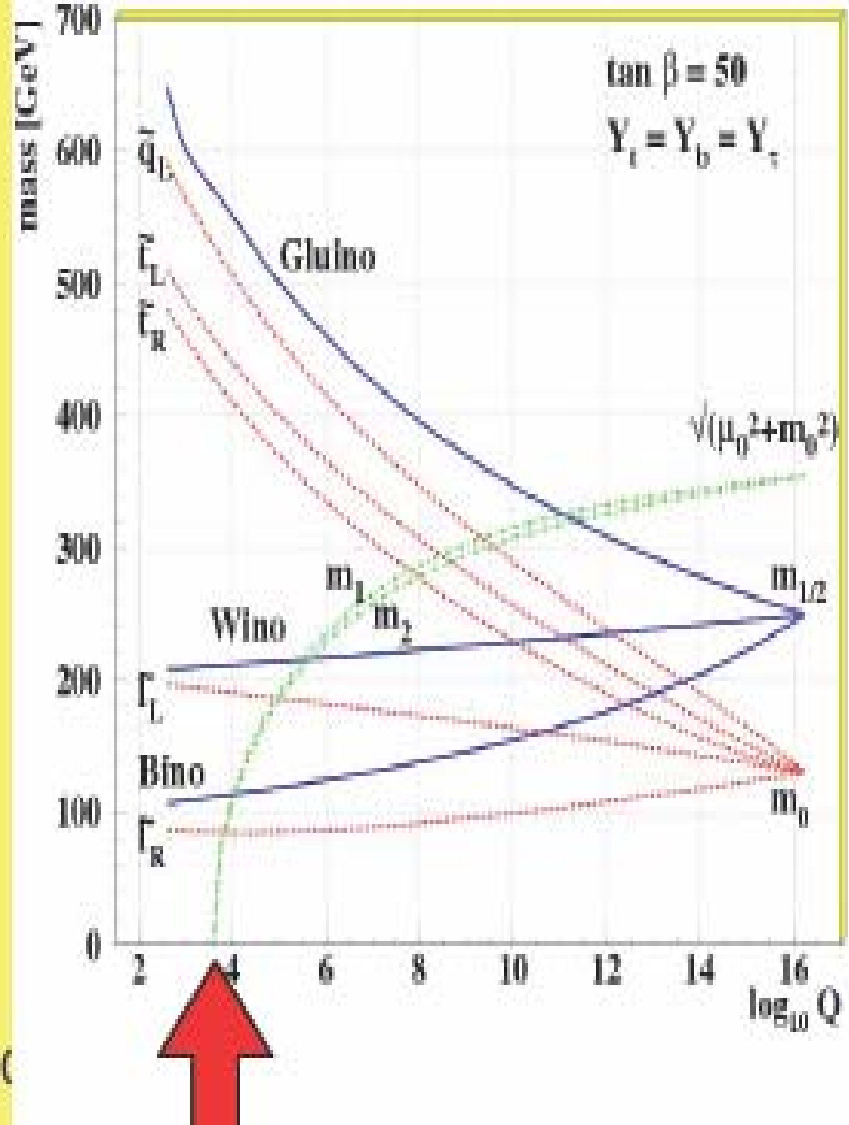
D. KAZAKOV

RADIATIVE ELECTROWEAK SYMMETRY BREAKING IN MSSM

- CMSSM → both higgses have positive masses squared at the GUT scale (like having μ^2 positive in the SM scalar potential), hence **the tree level potential of the CMSSM does not lead to the spontaneous breaking of the elw. symmetry**
- **The masses squared of the higgses decrease during the running from the GUT scale down to lower energies**; in particular, the decrease is enhanced for the mass of the higgs coupled to the top quark given the large value of the top Yukawa coupling


mass [GeV]
tan β = 1.65
$Y_b = Y_\tau$
Gluino
$\tilde{q}_L$
$\tilde{t}_L$
$\tilde{t}_R$
m_1
$\sqrt{(\mu_0^2+m_0^2)}$
m_2
$m_{1/2}$
Wino
$\tilde{l}_L$
$\tilde{l}_R$
Bino
m_0
$\log_{10} Q$

sch


mass [GeV]
tan β = 50
$Y_t = Y_b = Y_\tau$
Gluino
$\tilde{q}_L$
$\tilde{t}_L$
$\tilde{t}_R$
$\sqrt{(\mu_0^2+m_0^2)}$
m_1
m_2
$m_{1/2}$
Wino
$\tilde{l}_L$
Bino
$\tilde{l}_R$
m_0
$\log_{10} Q$

CMSSM + RADIATIVE ELW. BREAKING: A 4 – PARAMETER WORLD

- FREE PARAM. IN THE CMSSM :

$$A,\ m_0,\ M_{1/2},\ B \leftrightarrow \tan\beta = v_2 / v_1 \quad \text{and} \quad \mu$$

IMPOSING THE RAD. BREAKING OF THE ELW. SYMMETRY ONE ESTABLISHES A RELATION BETWEEN THE ELW. BREAKING SCALE AND THE SOFT SUSY PARAMETERS **FURTHER REDUCING THE NUMBER OF THE FREE PARAM. IN THE CMSSM TO FOUR** , FOR INSTANCE THE FIRST FOUR PARAM. ABOVE + THE SIGN OF μ (THE ELW. SYMM. BREAKING FIXES ONLY THE SQUARE OF μ

The Higgs Bosons Masses

CP-odd neutral Higgs A

CP-even charged Higgses $H^{\pm}$

CP-even neutral Higgses h,H

$$m_A^2 = m_1^2 + m_2^2$$

$$m_{H^\pm}^2 = m_A^2 + M_W^2$$

$$M_W^2 = \frac{g^2}{2} v^2$$

$$M_Z^2 = \frac{g^2 + g'^2}{2} v^2$$

$$m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + M_Z^2 \pm \sqrt{(m_A^2 + M_Z^2)^2 - 4 m_A^2 M_Z^2 \cos^2 2\beta}\right]$$

$$m_h \approx M_Z |\cos 2\beta| < M_Z \ !$$

➡ Radiative corrections

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 g^2 m_t^4}{16\pi^2 M_W^2} \log \frac{\tilde{m}_{t_1}^2 \tilde{m}_{t_2}^2}{m_t^4} + 2\ loops$$

D. KAZAKOV

Upper bound on m_h in the MSSM:

"Unconstrained MSSM":

M_A, $\tan\beta$, 5 parameters in $\tilde{t}$–$\tilde{b}$ sector, μ, $m_{\tilde{g}}$, M_2

$$m_h \lesssim 135 \text{ GeV}$$

for $m_t = 171.4 \pm 2.1\,\text{GeV}$

(including theoretical uncertainties from unknown higher orders)
$\Rightarrow$ observable at the LHC

Obtained with:

FeynHiggs

[S.H., W. Hollik, G. Weiglein '98, '00, '02]

[T. Hahn, S.H., W. Hollik, G. Weiglein '03 – '06]

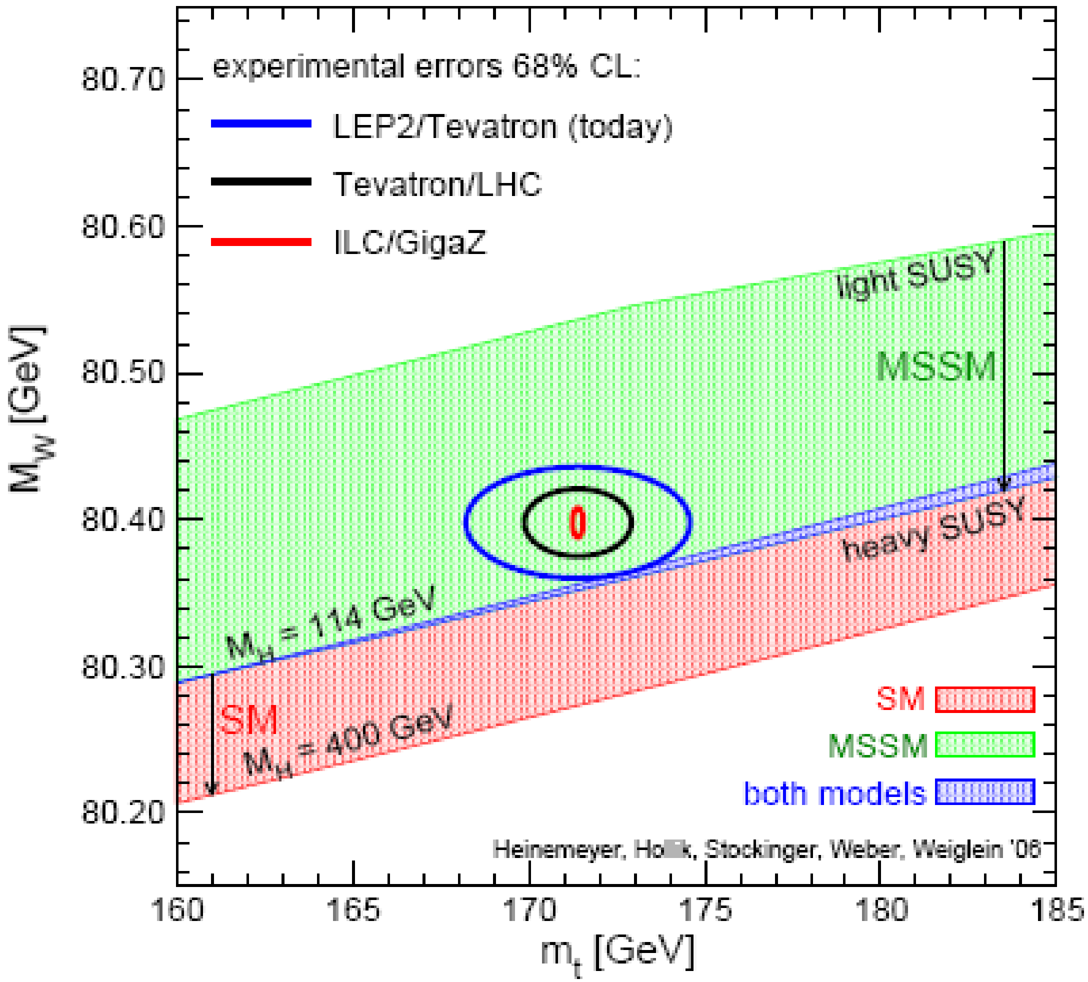
`www.feynhiggs.de`

$\to$ all Higgs masses, couplings, BRs (easy to link, easy to use :-)

Property VII: M_W NEW CDF value: $M_W = 80.413 \pm 0.048$ GeV

Prediction for M_W in the SM and the MSSM :

[S.H., W. Hollik, D. Stockinger, A.M. Weber, G. Weiglein '06]

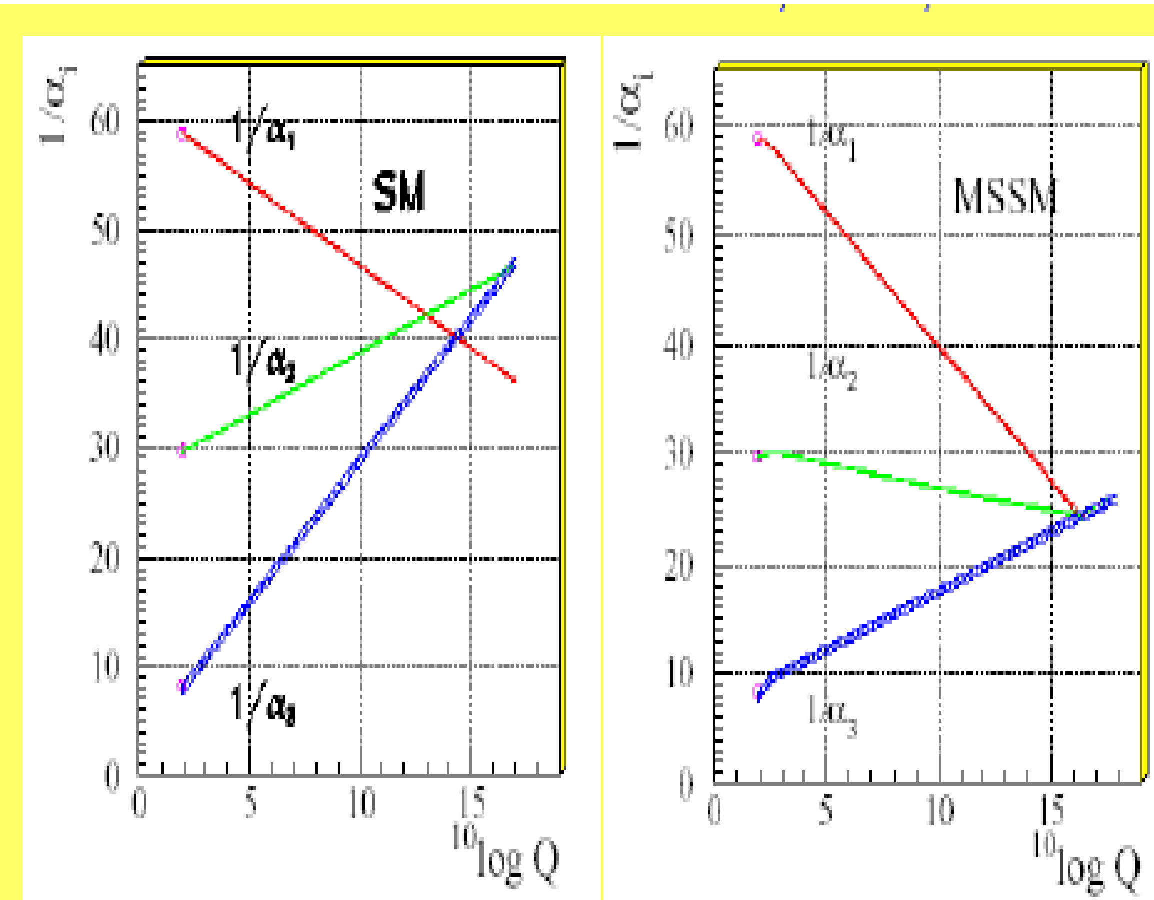


MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of M_H^{SM}

LOW-ENERGY SUSY AND UNIFICATION



Input

$$\alpha^{-1}(M_Z) = 128.978 \pm 0.027$$

$$\sin^2\theta_{\overline{MS}} = 0.23146 \pm 0.00017$$

$$\alpha_s(M_Z) = 0.1184 \pm 0.0031$$

Output

$$M_{SUSY} = 10^{3.4\pm0.9\pm0.4}\ \text{GeV}$$

$$M_{GUT} = 10^{15.8\pm0.3\pm0.1}\ \text{GeV}$$

$$\alpha_{GUT}^{-1} = 26.3 \pm 1.9 \pm 1.0$$

MICRO

PARTICLE PHYSICS

GWS STANDARD MODEL

MACRO

COSMOLOGY

HOT BIG BANG
STANDARD MODEL

HAPPY MARRIAGE
Ex: NUCLEOSYNTHESIS

BUT ALSO POINTS OF FRICTION

- -COSMIC MATTER-ANTIMATTER ASYMMETRY
- -INFLATION
- - DARK MATTER + DARK ENERGY

"OBSERVATIONAL" EVIDENCE FOR NEW PHYSICS BEYOND THE **(PARTICLE PHYSICS)** STANDARD MODEL

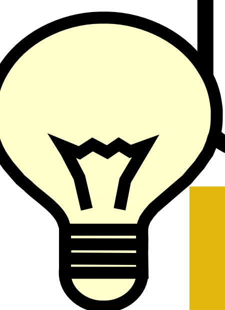
Present "Observational" Evidence for New Physics

- NEUTRINO MASSES ☆☆☆
- DARK MATTER ☆☆☆
- MATTER-ANTIMATTER ASYMMETRY ☆☆
- INFLATION ☆

COULD (AT LEAST SOME OF) THE "OBSERVATIONAL" NEW PHYSICS BE LINKED TO THE ULTRAVIOLET COMPLETION OF THE SM AT THE ELW. SCALE, in particular that UV completion known as LOW-ENERGY SUSY extension of the SM?

The Energy Scale from the “Observational” New Physics

- neutrino masses
- dark matter
- baryogenesis
- inflation



NO NEED FOR THE NP SCALE TO BE CLOSE TO THE ELW. SCALE

The Energy Scale from the “Theoretical” New Physics

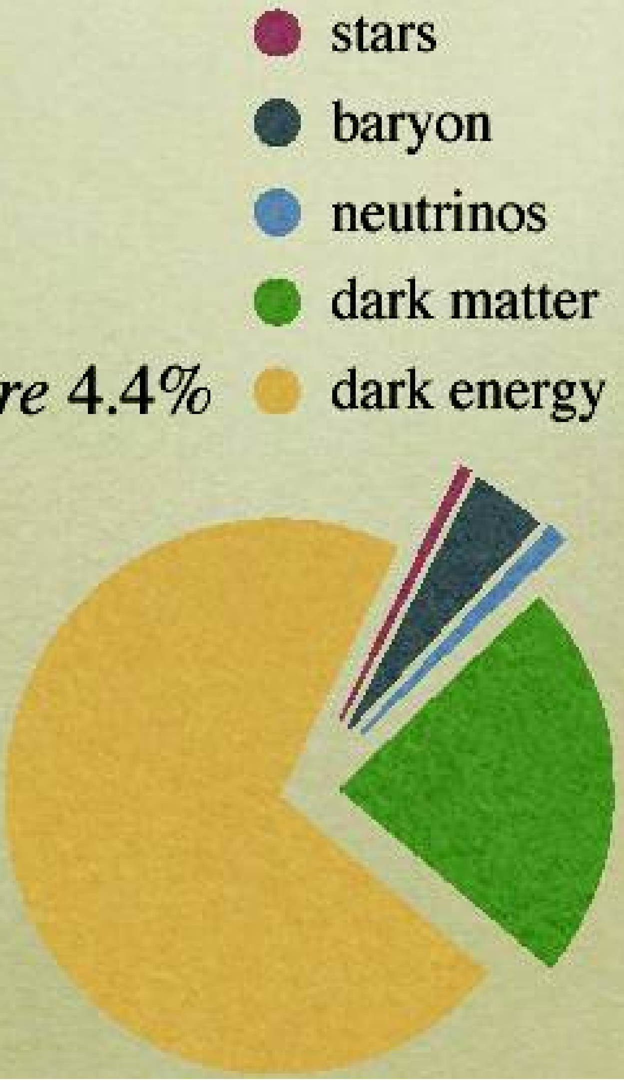
☆ ☆ ☆ **Stabilization of the electroweak symmetry breaking at M_W calls for an ULTRAVIOLET COMPLETION of the SM already at the TeV scale**

+

☆ **CORRECT GRAND UNIFICATION “CALLS” FOR NEW PARTICLES AT THE ELW. SCALE**

DM, DE, ANTIMATTER AND VACUUM ENERGY

- *Stars and galaxies are only ~0.5%*
- *Neutrinos are ~0.1–1.5%*
- *Rest of ordinary matter (electrons, protons & neutrons) are 4.4%*
- *Dark Matter 23%*
- *Dark Energy 73%*
- *Anti-Matter 0%*
- *Higgs Bose-Einstein condensate ~10^{62}%??*

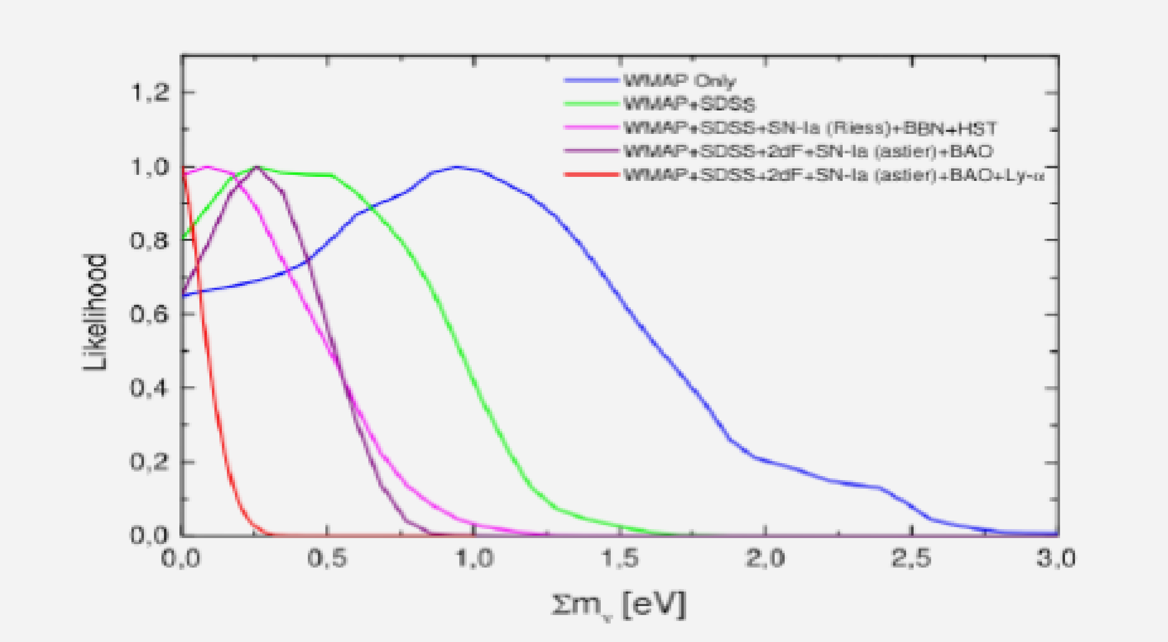


Courtesy of H. Murayama

DM: the most impressive evidence at the "quantitative" and "qualitative" levels of **New Physics beyond SM**

- QUANTITATIVE: Taking into account the latest WMAP data which in combination with LSS data provide stringent bounds on Ω_{DM} and Ω_B → **EVIDENCE FOR NON-BARYONIC DM AT MORE THAN 10 STANDARD DEVIATIONS!! THE SM DOES NOT PROVIDE ANY CANDIDATE FOR SUCH NON-BARYONIC DM**

- QUALITATIVE: it is NOT enough to provide a mass to neutrinos to obtain a valid DM candidate; LSS formation requires DM to be COLD → **NEW PARTICLES NOT INCLUDED IN THE SPECTRUM OF THE FUNDAMENTAL BUILDING BLOCKS OF THE SM !**



Cosmological Bounds on the sum of the masses of the 3 neutrinos from increasingly rich samples of data sets

Case	Cosmological data set	Σ bound (2σ)
1	WMAP	< 2.3 eV
2	WMAP + SDSS	< 1.2 eV
3	WMAP + SDSS + SN_{Riess} + HST + BBN	< 0.78 eV
4	CMB + LSS + SN_{Astier}	< 0.75 eV
5	CMB + LSS + SN_{Astier} + BAO	< 0.58 eV
6	CMB + LSS + SN_{Astier} + Ly-α	< 0.21 eV
7	CMB + LSS + SN_{Astier} + BAO + Ly-α	< 0.17 eV

Fogli et al., Phys. Rev. D 75, 053001 (2007)

TEN COMMANDMENTS TO BE A "GOOD" DM CANDIDATE

BERTONE, A.M., TAOSO

- **TO MATCH THE APPROPRIATE RELIC DENSITY**
- **TO BE COLD**
- **TO BE NEUTRAL**
- **TO BE CONSISTENT WITH BBN**
- **TO LEAVE STELLAR EVOLUTION UNCHANGED**
- **TO BE COMPATIBLE WITH CONSTRAINTS ON SELF – INTERACTIONS**
- **TO BE CONSISTENT WITH DIRECT DM SEARCHES**
- **TO BE COMPATIBLE WITH GAMMA – RAY CONSTRAINTS**
- **TO BE COMPATIBLE WITH OTHER ASTROPHYSICAL BOUNDS**
- **"TO BE PROBED EXPERIMENTALLY"**

***THE DM ROAD TO NEW PHYSICS BEYOND THE SM*:**

IS **DM** A PARTICLE OF THE ***NEW PHYSICS AT THE ELECTROWEAK ENERGY SCALE*** **?**

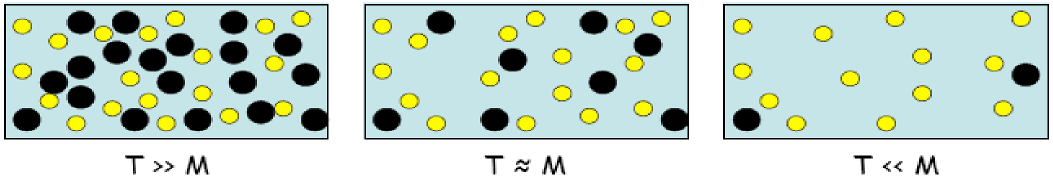
THE "*WIMP MIRACLE*"

Bergstrom

Table 1. Properties of various Dark Matter Candidates

Type	Particle Spin	Approximate Mass Scale
Axion	0	μeV-meV
Inert Higgs Doublet	0	50 GeV
Sterile Neutrino	1/2	keV
Neutralino	1/2	10 GeV - 10 TeV
Kaluza-Klein UED	1	TeV

Many possibilities for DM candidates, but WIMPs are really special: peculiar coincidence between particle physics and cosmology parameters to provide a VIABLE DM CANDIDATE AT THE ELW. SCALE



WIMPS (Weakly Interacting Massive Particles)

$\#\chi \; \exp(-m_\chi/T_\chi)$

$\#\chi$ does not change any more

$\#\chi \sim \#\gamma$ $\quad m_\chi$

$T_{decoupl.}$ typically ~ m_χ /20

Ω_χ depends on particle physics ($\sigma_{annih.}^\chi$) and "cosmological" quantities (H, T_0, …

$$\Omega_\chi h^2 \simeq \frac{10^{-3}}{<(\sigma_{annih.}) V \chi > \quad TeV^2}$$

$<(\sigma_{annih.}) V\chi>$ ~ α^2 / M^2_χ

TeV^2 → From $T^0 M_{Planck}$

COSMO – PARTICLE CONSPIRACY

$\Omega_\chi h^2$ in the range 10^{-2} -10^{-1} to be cosmologically interesting (for DM)

$m_\chi \sim 10^2 - 10^3$ GeV (weak interaction) $\quad \Omega_\chi h^2 \sim 10^{-2}$ -10^{-1} !!!

THERMAL RELICS (WIMP in thermodyn.equilibrium with the plasma until $T_{decoupl}$)

STABLE ELW. SCALE WIMPs from PARTICLE PHYSICS

	SUSY	EXTRA DIM.	LITTLE HIGGS.
1) **ENLARGEMENT OF THE SM**	(x^{μ}, θ)	(x^{μ}, j^{i})	SM part + new part
	Anticomm. Coord.	New bosonic Coord.	to cancel Λ^2 at 1-Loop
2) **SELECTION RULE**	**R-PARITY LSP**	**KK-PARITY LKP**	**T-PARITY LTP**
→ **DISCRETE SYMM.**	Neutralino spin 1/2	spin1	spin0
→ **STABLE NEW PART.**	↓	↓	↓
3) FIND REGION (S) PARAM. SPACE WHERE THE “L” NEW PART. IS NEUTRAL + $\Omega_L h^2$ OK	m_{LSP} ~100 - 200 GeV *	m_{LKP} ~600 - 800 GeV	m_{LTP} ~400 - 800 GeV

* But abandoning gaugino-masss unif. → Possible to have m_{LSP} down to 7 GeV

Bottino, Donato, Fornengo, Scopel

SUSY & DM : a successful marriage

- Supersymmetrizing the SM does not lead necessarily to a stable SUSY particle to be a DM candidate.
- However, the mere SUSY version of the SM is known to lead to a too fast p-decay. Hence, necessarily, the SUSY version of the SM has to be **supplemented with some additional (ad hoc?) symmetry to prevent the p-decay catastrophe.**
- Certainly the simplest and maybe also the most attractive solution is **to impose the discrete R-parity** symmetry
- MSSM + R PARITY ⟶ LIGHTEST SUSY PARTICLE (LSP) IS STABLE .
- The LSP can constitute an interesting DM candidate in several interesting realizations of the MSSM (i.e., with different SUSY breaking mechanisms including gravity, gaugino, gauge, anomaly mediations, and in various regions of the parameter space).

FROM THE MSSM TO THE CMSSM (constrained MSSM)

PROLIFERATION OF PARAMETRS IN THE SOFT BREAKING SECTOR OF THE MSSM:

OVERALL NUMBER OF PARAM. IN THE MSSM IS

1 2 4

At $M_{GUT} \simeq 2 \times 10^{16}$ GeV:

- gauginos $M_1 = M_2 = m_{\tilde{g}} = m_{1/2}$
- scalars
  $m^2_{\tilde{q}_i} = m^2_{\tilde{l}_i} = m^2_{H_b} = m^2_{H_t} = m^2_0$
- 3–linear soft terms $A_b = A_t = A_0$
- radiative EWSB
  $\mu^2 = \frac{m^2_{H_b} - m^2_{H_t} \tan^2\beta}{\tan^2\beta - 1} - \frac{m^2_Z}{2}$
- five independent parameters:
  $m_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)$

CMSSM

$m_{\tilde{\tau}_1} \simeq \sqrt{0.15 m^2_{1/2} + m^2_0}$

bino: $m_\chi \simeq 0.4 m_{1/2}$

gluino $\tilde{g}$: $m_{\tilde{g}} \simeq 2.7 m_{1/2}$

MSSM Parameter Space

- Three gauge couplings
- Three (four) Yukawa matrices
- The Higgs mixing parameter
- Soft SUSY breaking terms

mSUGRA Universality hypothesis (gravity is colour and flavour blind):
Soft parameters are equal at Planck (GUT) scale

$$-L_{Soft} = A\{y_t Q_L H_2 U_R + y_b Q_L H_1 D_R + y_L L_L H_1 E_R\} + B\mu H_1 H_2$$
$$+ m_0^2 \sum_i |\varphi_i|^2 + \tfrac{1}{2} M_{1/2} \sum_\alpha \tilde{\lambda}_\alpha \tilde{\lambda}_\alpha$$

D. KAZAKOV

CMSSM + RADIATIVE ELW. BREAKING: A 4 – PARAMETER WORLD

- FREE PARAM. IN THE CMSSM :

$$A,\ m_0,\ M_{1/2},\ B \leftrightarrow\ \tan\beta = v_2 / v_1 \quad \text{and} \quad \mu$$

IMPOSING THE RAD. BREAKING OF THE ELW. SYMMETRY ONE ESTABLISHES A RELATION BETWEEN THE ELW. BREAKING SCALE AND THE SOFT SUSY PARAMETERS **FURTHER REDUCING THE NUMBER OF THE FREE PARAM. IN THE CMSSM TO FOUR** , FOR INSTANCE THE FIRST FOUR PARAM. ABOVE + THE SIGN OF μ (THE ELW. SYMM. BREAKING FIXES ONLY THE SQUARE OF μ

IS SUSY PRESENT IN NATURE?

- I think that **it is very likely that SUSY is present as a fundamental symmetry of Nature**: it is the most general symmetry compatible with a good and honest QFT, it is likely to be needed to have a consistent STRING theory (super-string), in its local version (local supersymmetry or supergravity) it paves the way to introduce and quantize GRAVITY in a unified picture of ALL FUNDAMENTAL INTERACTIONS
- Much more debatable is whether it should be a **LOW-ENERGY SYMMETRY** (i.e. effectively broken at the elw. Scale) or a HIGH-ENERGY SYMMETRY (i.e. broken at the Planck scale, or at the string compactification scale)

WHO IS THE LSP?

- **SUPERGRAVITY** (transmission of the SUSY breaking from the hidden to the obsevable sector occurring via gravitational interactions): best candidate to play the role of LSP:

  NEUTRALINO (i.e., the lightest of the four eigenstates of the 4x4 neutralino mass matrix)

In **CMSSM**: the LSP neutralino is almost entirely a BINO

WHICH SUSY

HIDDEN SECTOR SUSY BREAKING AT SCALE $\sqrt{F}$

MESSENGERS

$F = M_W M_{Pl}$

GRAVITY →

$\mathbf{M_{gravitino}} \sim F/M_{Pl} \sim$

$(10^2 - 10^3)$ GeV

$F = (10^5 - 10^6)$ GeV

→ GAUGE INTERACTIONS

$\mathbf{M_{gravitino}} \sim F/M_{Pl} \sim$

$(10^2 - 10^3)$ eV

OBSERVABLE SECTOR

SM + superpartners

MSSM : minimal content of superfields

GRAVITINO LSP?

- **GAUGE MEDIATED SUSY BREAKING**

(GMSB) : LSP likely to be the GRAVITINO (it can be so light that it is more a warm DM than a cold DM candidate)

Although we cannot directly detect the gravitino, there could be interesting signatures from the **next to the LSP (NLSP)** : for instance the s-tau could decay into tau and gravitino, Possibly with a very long life time, even of the order of days or months

DIFFERENT FROM THE THERMAL HISTORY OF WIMPS

SWIMPS (Super Weakly Interacting Massive Particles)

- - LSP Gravitino in SUSY
- - First excitation of the graviton in UED …

They inherit the appropriate relic density through the decay of a more massive thermal species that has earlier decoupled from the thermal bath

$$\Omega_{\rm SWIMP} = \frac{m_{\rm SWIMP}}{m_{\rm NLP}} \Omega_{\rm NLP}$$

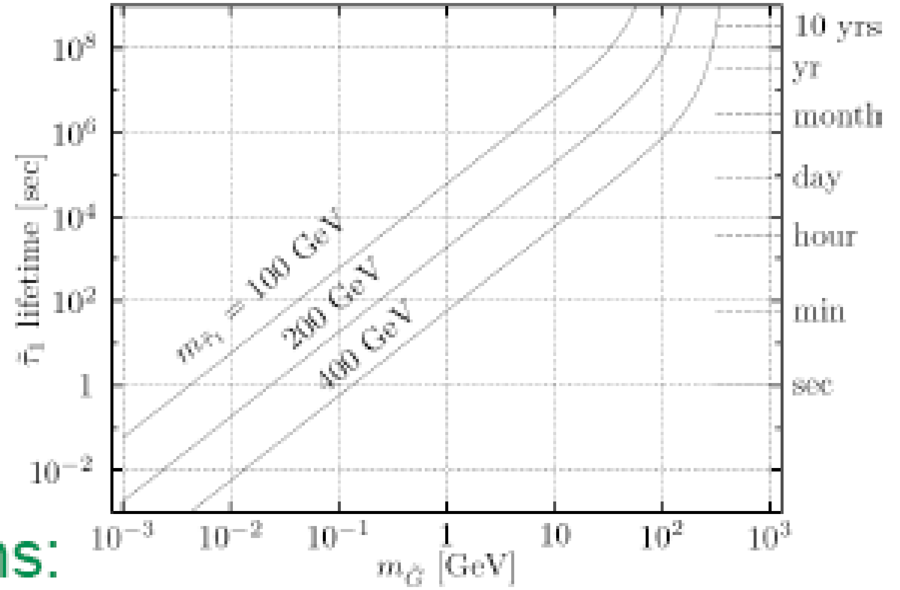
Collider experiments do not distinguish between stable ($\tau > 10^{17}$ s) and long-lived ($\tau > 10^{-7}$ s) particle

$$P' \rightarrow P \;\; \Rightarrow \quad \Omega_{P'} = \frac{m_{P'}}{m_P} \Omega_P$$

Gravitino

Long-lived charged particle at the LHC ($\tilde{\tau} \rightarrow \tau \tilde{G}$)

Hamaguchi-Kuno-Nakaya-Nojiri; Feng-Smith; Ellis-Raklev-Øye; Hamaguchi-Nojiri-de Roeck



Distinctive ToF and energy loss signatures

"Stoppers" in ATLAS/CMS caverns:

- Measure position and time of stopped $\tilde{\tau}$; time and energy of τ
- Reconstruct susy scale and gravitational coupling

G. GIUDICE

IS THE "*WIMP MIRACLE*" AN ACTUAL MIRACLE?

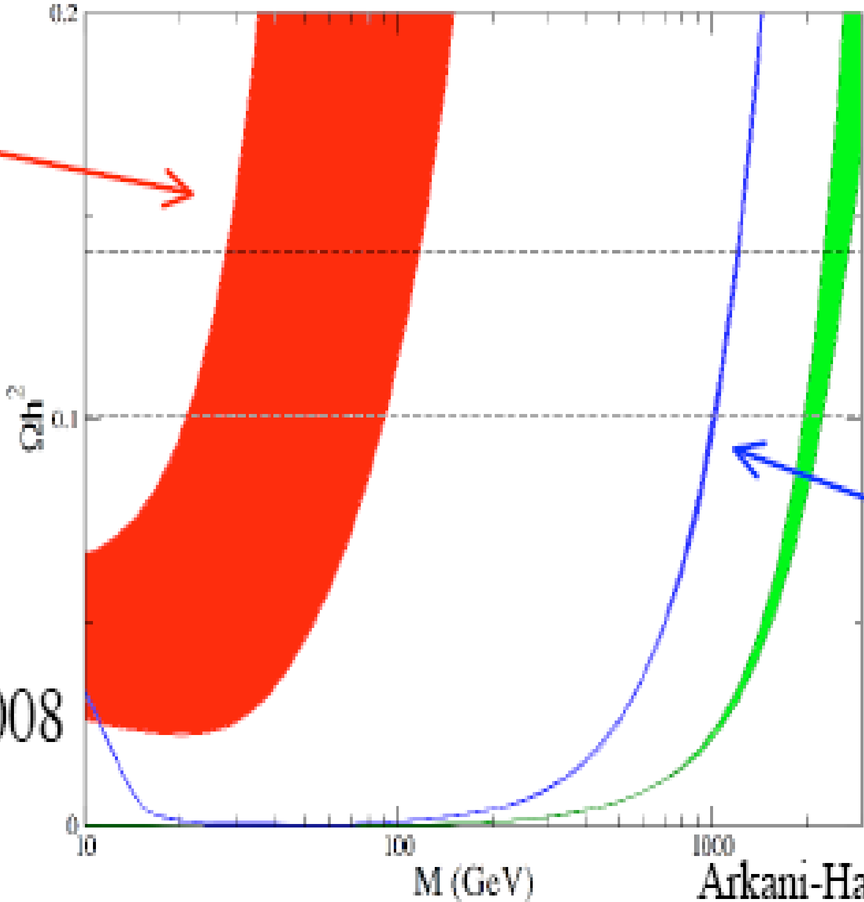
USUAL STATEMENT

Many possibilities for DM candidates, but WIMPs are really special: peculiar coincidence between particle physics and cosmology parameters to provide a VIABLE DM CANDIDATE AT THE ELW. SCALE

HOWEVER

when it comes to quantitatively reproduce the precisely determined DM density → once again the fine-tuning threat…

After LEP: tuning of the SUSY param. at the % level to correctly reproduce the DM abundance: NEED FOR A "WELL-TEMPERED" NEUTRALINO



$$1.1 < \frac{\tilde{m}_{e_R}}{M_1} < 3$$

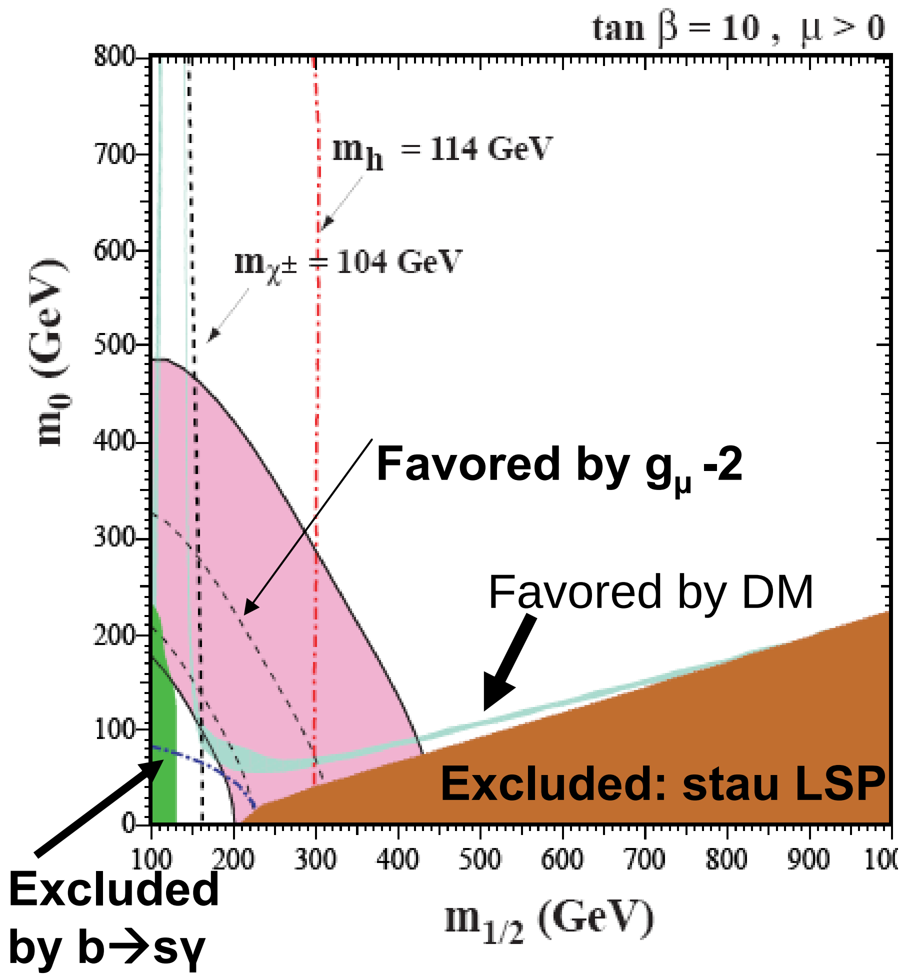
$$1.5 < \frac{\tilde{m}_{\ell_L}}{M_2} < \infty$$

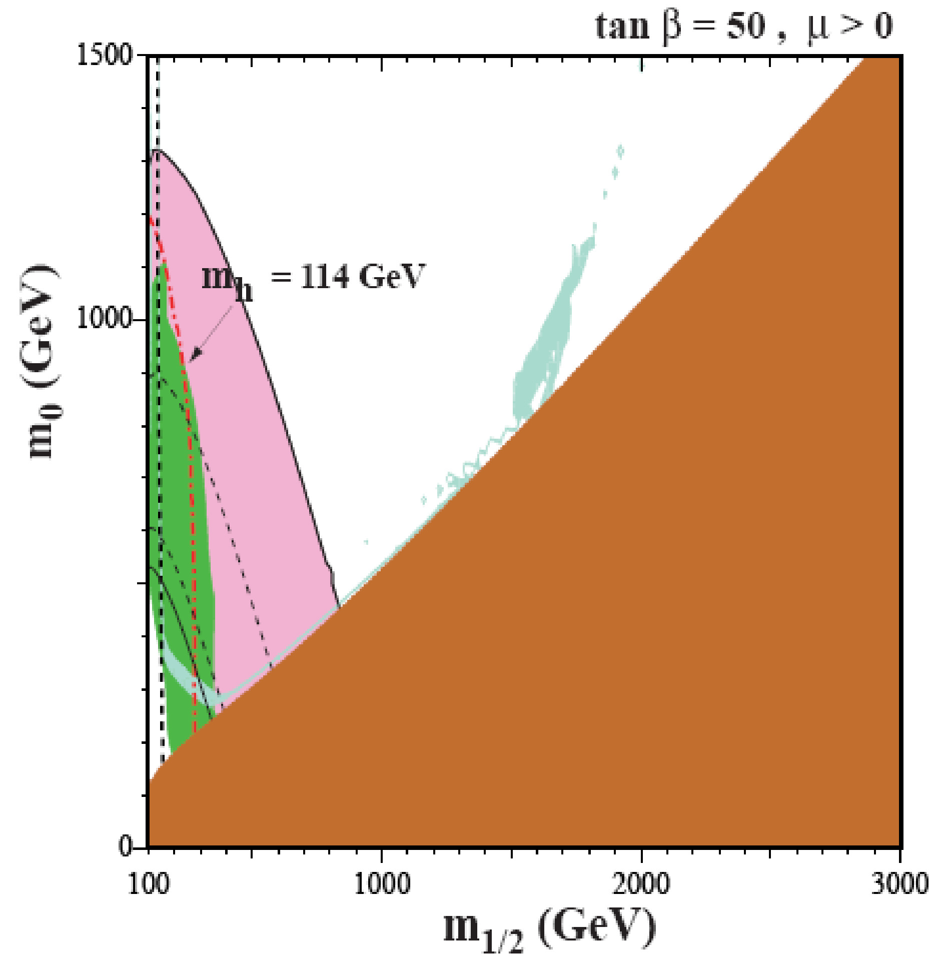
$$1.5 < \frac{\tilde{m}_t}{\mu} < \infty$$

$$\Omega_{DM} h^2 = 0.105 \pm 0.008$$

Arkani-Hamed-Delgado-Giudice

NEUTRALINO LSP IN THE CONSTRAINED MSSSM: A VERY SPECIAL SELECTION IN THE PARAMETER SPACE?





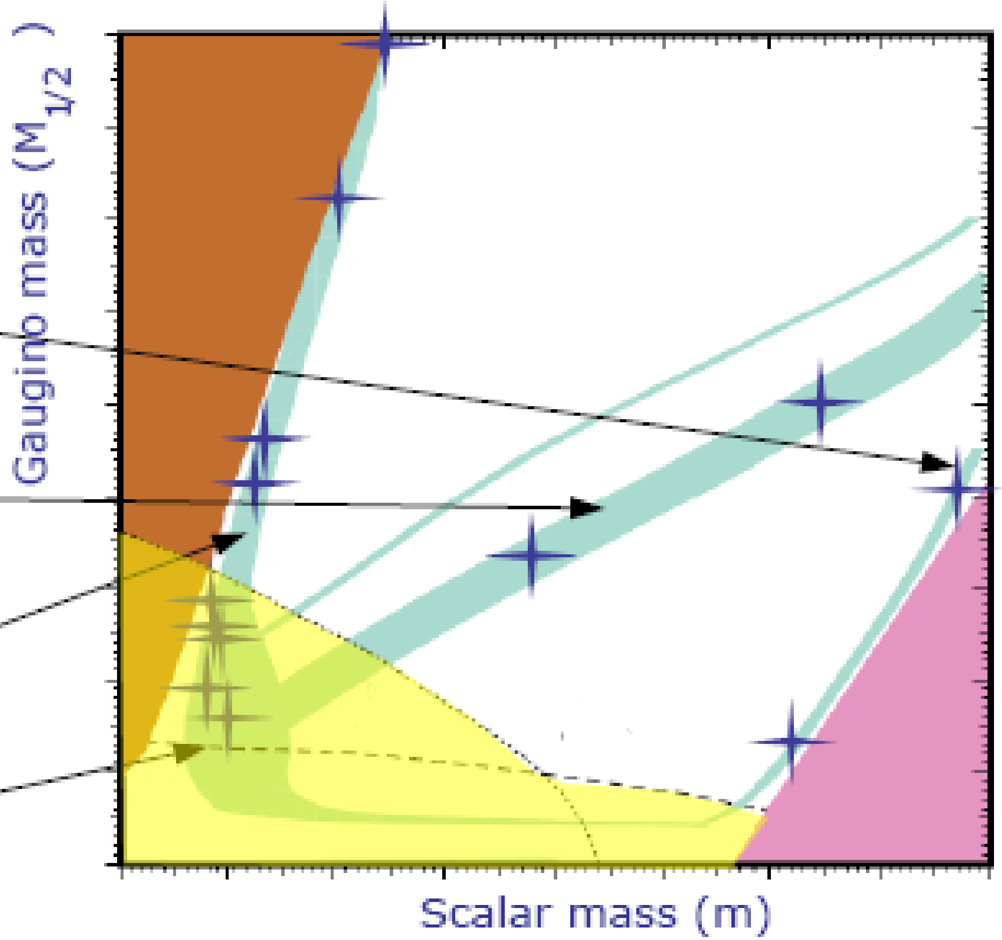
Ellis, Olive, Santoso, Spanos

LHC reach in the SUSY parameter space (example CMSSM – A, M, m, tanβ, μ)

Regions compatible with Neutralino DM (having correct relic density)

- Focus-Point region (Higgsino-Bino neutralino)
- Resonant annihilation (with pesudoscalar Higgs
- Coannihilation region (small LSP-NLSP mass difference)
- Bulk (small SUSY masses)

  Mostly excluded by LEP constraints (still available in non-minimal models)



(see e.g., Ellis, Ferstl, Olive)

DM and NON-STANDARD COSMOLOGIES BEFORE NUCLEOSYNTHESIS

- **NEUTRALINO RELIC DENSITY MAY DIFFER FROM ITS STANDARD VALUE**, i.e. the value it gets when the expansion rate of the Universe is what is expected in Standard Cosmology (EX.: **SCALAR-TENSOR THEORIES OF GRAVITY**, **KINATION**, **EXTRA-DIM. RANDALL-SUNDRUM TYPE II MODEL**, ETC.)

- **WIMPS MAY BE "COLDER",** i.e. they may have smaller typical velocities and, hence, they may lead to smaller masses for the first structures which form **GELMINI, GONDOLO**

WHY $H \neq H_{GR}$

$$H_{GR}^2 = \frac{1}{3M_p^2}\rho_{tot} \simeq 2.76\, g_* \frac{T^4}{M_p^2}$$

1. Change the number of relativistic d.o.f.'s, g_* ;

R. Catena

2. Consider a ρ_{tot} not dominated by relativistic d.o.f.'s;
   - Kination
     P. Salati, Phys. Lett. B 571 (2003) 121

3. Consider theories where the effective Planck mass is different from the constant M_p:
   - Scalar-Tensor theories
     R. C., N. Fornengo, A. Masiero, M. Pietroni and F. Rosati, Phys. Rev. D 70 (2004) 063519
   - Extradimensions
     L. Randall and R. Sundrum, Phys. Rev. Lett. 83 (1999) 4690

LARGER WIMP ANNIHILATION CROSS-SECTION IN NON-STANDARD COSMOLOGIES

- **Having a Universe expansion rate at the WIMP freeze-out larger than in Standard Cosmology→ possible to provide a DM adequate WIMP population even in the presence of a larger annihilation cross-section** (**Catena, Fornengo, A.M., Pietroni**)

- **Possible application to increase the present DM annihilation rate to account for the PAMELA results in the DM interpretation** (instead of other mechanisms like the Sommerfeld effect or a nearby resonance)

El Zant, Khalil, Okada

Scalar-Tensor Gravity (Jordan Frame)

$$S = S_G[\tilde{g}_{\mu\nu}, \Phi] + S_M[\psi_M, \tilde{g}_{\mu\nu}]$$

MASSES AND NON-GRAV. COUPL. ARE CONSTANT

$$S_g = \frac{1}{16\pi}\int d^4x\sqrt{-\tilde{g}}\left[\Phi^2\tilde{R} + \right.$$
$$\left. + 4\,\omega(\Phi)\tilde{g}^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi - 4\tilde{V}(\Phi)\right]$$

ENERGY-MOMENTUM TENSOR OF MATTER IS CONSERVED

S_M is just the (MS)SM lagrangian

– All fields feel the same metric :eq. princ. OK

– $m_\Phi^2 \sim R \sim G\, T^\mu{}_\mu \sim \Lambda_{uv}^4/M_P^2 = O(H_0^2)$: the cc fine-tuning protects m_Φ^2

Cosmology is easier in the Einstein Frame

$$\tilde{g}_{\mu\nu} \equiv A^2(\varphi) g_{\mu\nu}$$

$$\Phi^2 \equiv 8\pi M_*^2 A^{-2}(\varphi)$$

← Effective Planck Mass

$$V(\varphi) \equiv \frac{A^4(\varphi)}{4\pi} \tilde{V}(\Phi)$$

$$\alpha(\varphi) \equiv \frac{d \log A(\varphi)}{d\varphi} .$$

← Measures the distance from GR

$$S_g = \frac{M_*^2}{2} \int d^4x \sqrt{-g} \left[R + g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi - \frac{2}{M_*^2} V(\varphi) \right]$$

$$S_M = S_M[\psi_M, A^2(\varphi) g_{\mu\nu}]$$

$$\frac{\ddot{a}}{a} = -\frac{1}{6M_*^2} \left[\rho + 3\,p + 2M_*^2 \dot{\varphi}^2 - 2V(\varphi) \right]$$

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{1}{3M_*^2} \left[\rho + \frac{M_*^2}{2} \dot{\varphi}^2 + V(\varphi) \right]$$

$$\ddot{\varphi} + 3\frac{\dot{a}}{a}\dot{\varphi} = -\frac{1}{M_*^2} \left[\frac{\alpha(\varphi)}{\sqrt{2}} (\rho - 3p) + \frac{\partial V}{\partial \varphi} \right] ,$$

T^{μ}_{μ}

Masses and non-gravitational couplings are space-time dependent

The energy-momentum tensor of matter is not conserved

Free particles do not follow geodesics of the metric $g_{\mu\nu}$

PHYSICAL OBSERVABLES ARE FRAME-INDEPENDENT (Catena, Pietroni, Scarabello 06)

EXP. BOUNDS on the DEVIATION from H in GR

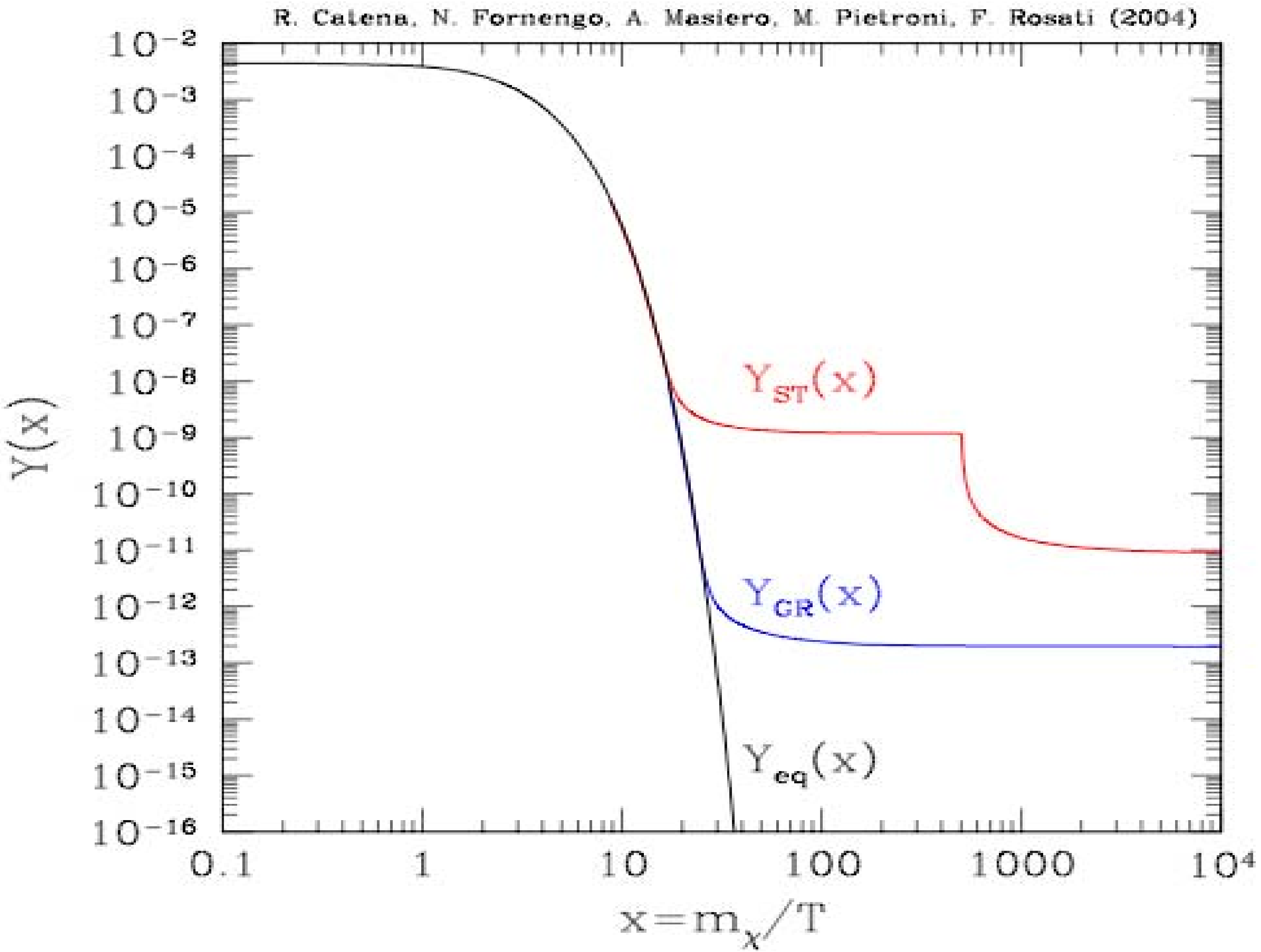
$$H_{\rm ST}^2 \simeq A^2(\varphi) \times H_{\rm GR}^2$$

$$\begin{cases} 0.1 \gtrsim \frac{\Delta H^2}{H^2} \equiv \frac{H_{\rm ST}^2 - H_{\rm GR}^2}{H_{\rm GR}^2} = A^2(\varphi_{\rm BBN}) - 1 & \text{at BBN}^1 \\ \gamma_{\rm PN} - 1 = -\frac{2\alpha^2}{1+\alpha^2} = (2.1 \pm 2.3) \times 10^{-5} & \text{Today}^2 \end{cases}$$

CATENA, FORNENGO, A.M., PIETRONI, ROSATI

BERTOTTI, IESS, TORTORA

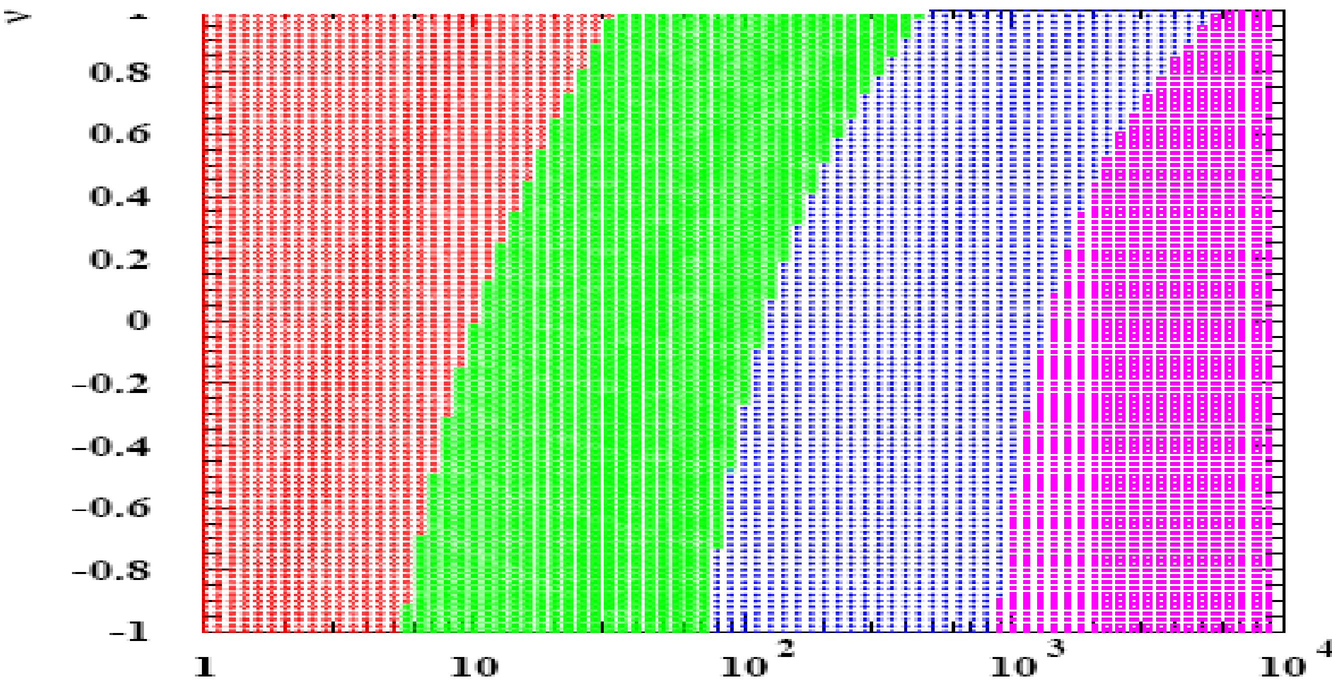
NEUTRALINO RELIC ABUNDANCE IN GR AND S-T THEORIES OF GRAVITY



$$H = A(T)H_{std} \quad \text{at early times}$$

$$H = H_{std} \quad \text{at later times}$$

$$A(T) = 1 + \eta \left(\frac{T}{T_f}\right)^{\nu} \tanh\left(\frac{T - T_{re}}{T_{re}}\right)$$



v = -1 ST cosmologies

v = +1 kination

v = +2 RS type II brane csomology

v = 0 overall boost of H

FIG. 12: Contour plot of the enhancement $R = (\Omega h^2)/(\Omega h^2)_{GR}$ of the WIMP relic abundance in a scenario with enhanced Hubble rate compared to the standard GR cosmology. The different bands refer to (from left to right): $1 \leq R \leq 10$, $10 < R \leq 100$, $100 < R \leq 1000$, $1000 < R$. The highest value of R is around $7.5 \cdot 10^3$. We have fixed $m_\chi = 500$ GeV and $T_{re} = 10^{-3}$ GeV. For all points, the WIMP relic–density, as calculated in the modified cosmology, satisfies the dark matter density constraint.

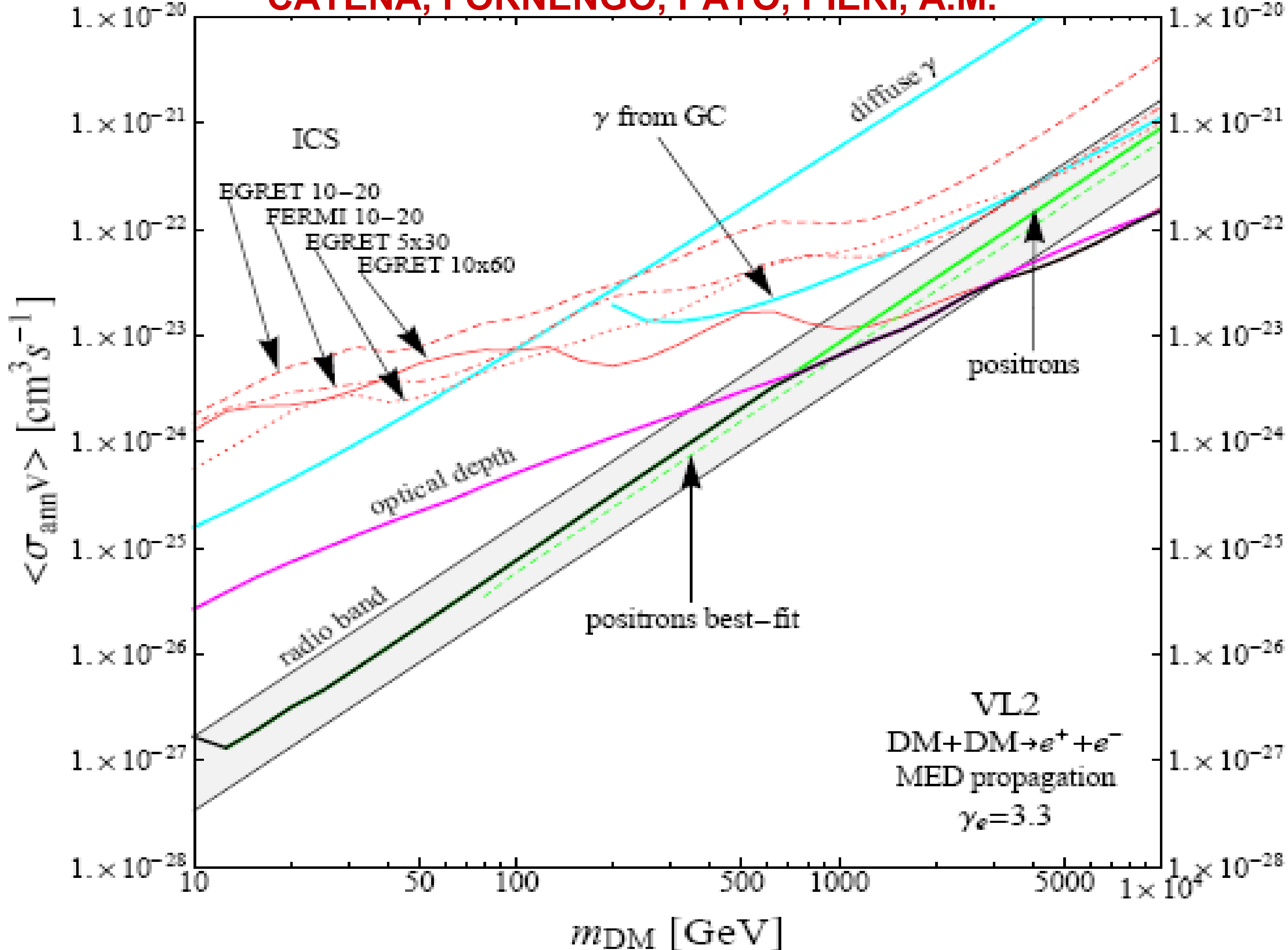
SCHELKE, CATENA, FORNENGO, A.M., PIETRONI

ST THEORIES AND DE

- Scalar-Tensor gravity is a nice environment to accommodate DE, and may lead to drastic revisions of standard DM studies

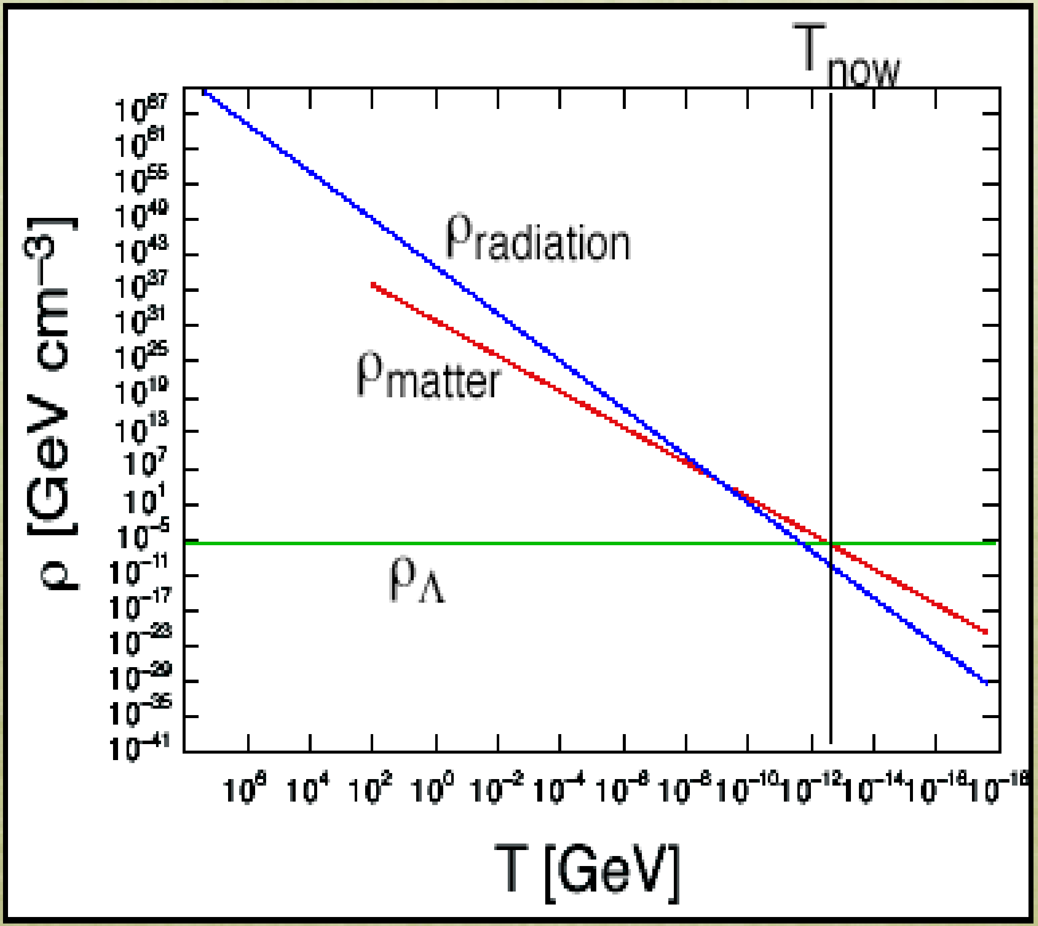
- The expansion history at T~10 GeV >>T_{BBN} may be constrained by cosmic antiprotons

CATENA, FORNENGO, PATO, PIERI, A.M.



THE "WHY NOW" PROBLEM

- *Why do we see matter and cosmological constant almost equal in amount?*
- *"Why Now" problem*
- *Actually a triple coincidence problem including the radiation*
- *If there is a deep reason for $\rho_\Lambda \sim ((\mathrm{TeV})^2/M_{Pl})^4$, coincidence natural*



Arkani-Hamed, Hall, Kolda, HM

DM ⟷ DE

DO THEY “KNOW” EACH OTHER?

- DIRECT INTERACTION ϕ (quintessence) WITH DARK MATTER

DANGER:
ϕ Very LIGHT
$m\phi \sim H_0^{-1} \sim 10^{-33}$ eV

→ Threat of violation of the equivalence principle
constancy of the fundamental “constants”,…

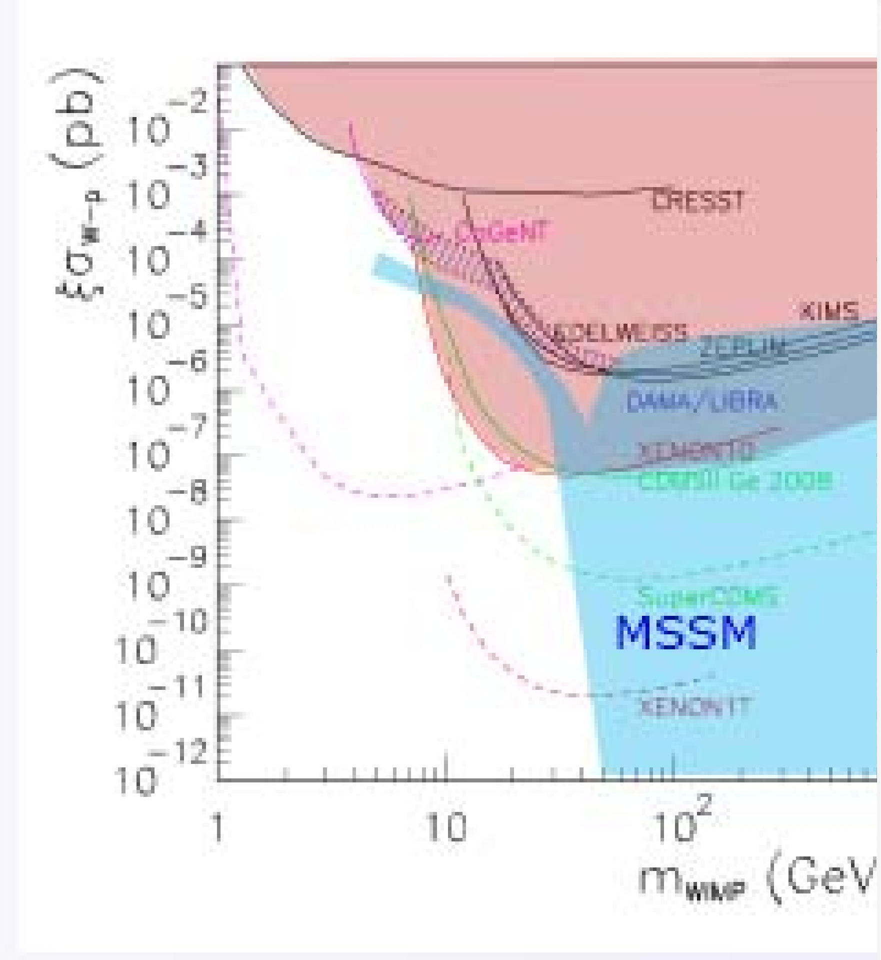
- **INFLUENCE OF ϕ ON THE NATURE AND THE ABUNDANCE OF CDM**

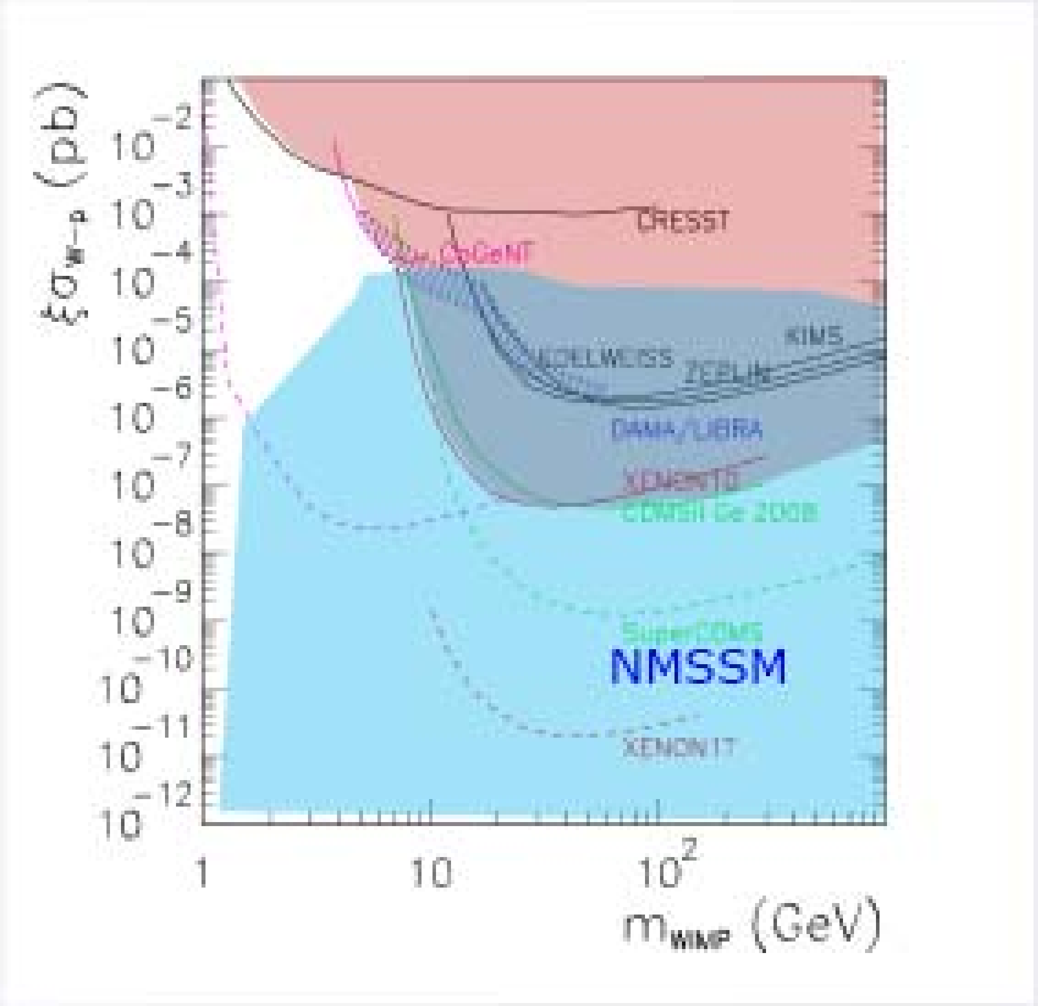
Modifications of the standard picture of
WIMPs FREEZE - OUT

CDM CANDIDATES

CATENA, FORNENGO, A.M., PIETRONI, SHELCKE

DM and the SUSY parameter space





D. Cerdeno, WONDER10

HUMAN PRODUCTION OF WIMPs

WIMPS HYPOTHESIS

DM made of particles with mass 10Gev - 1Tev

ELW scale

With WEAK INTERACT.

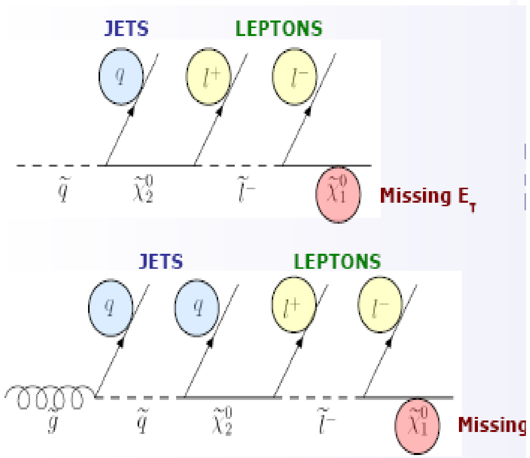
LHC, ILC may PRODUCE WIMPS

WIMPS escape the detector

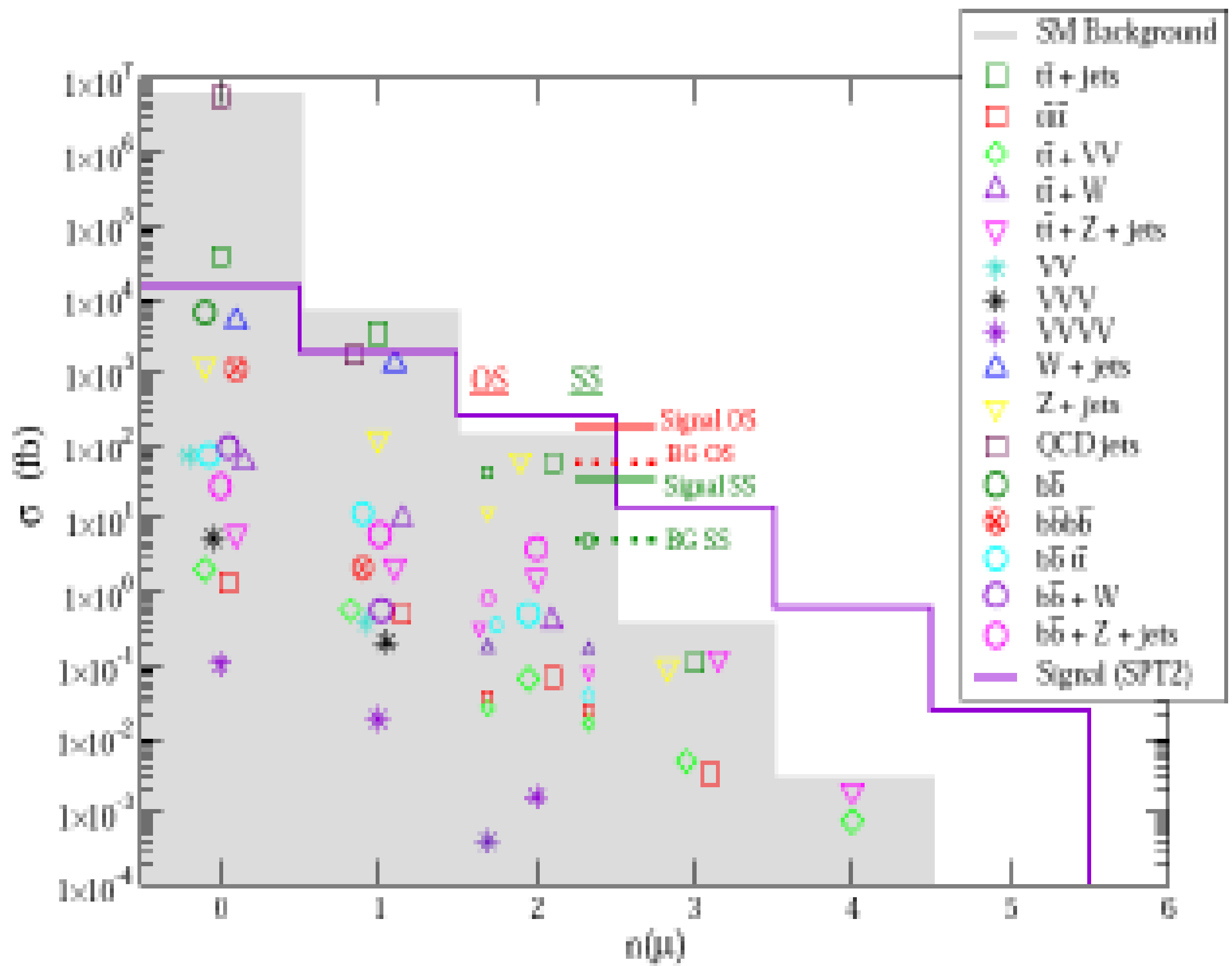
→ MISSING ENERGY SIGNATURE

POSSIBILITY TO CREATE OURSELVES IN OUR ACCELERATORS THOSE DM PARTICLES WHICH ARE PART OF THE RELICS OF THE PRIMORDIAL PLASMA AND CONSTITUTE 1/4 OF THE WHOLE ENERGY IN THE UNIVERSE

DM through the jets + missing energy signature at the LHC

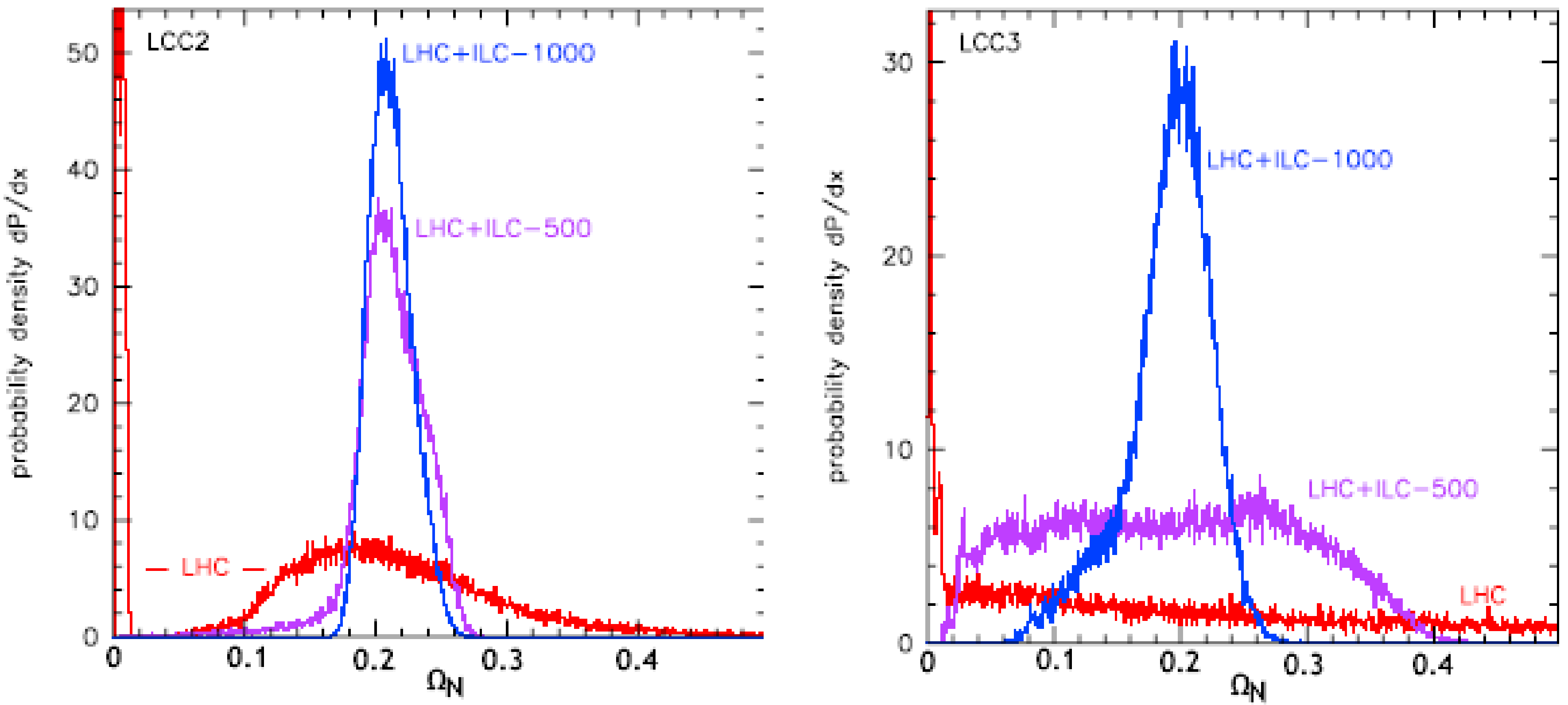


Estimation of the SM background for 4 jets + n leptons

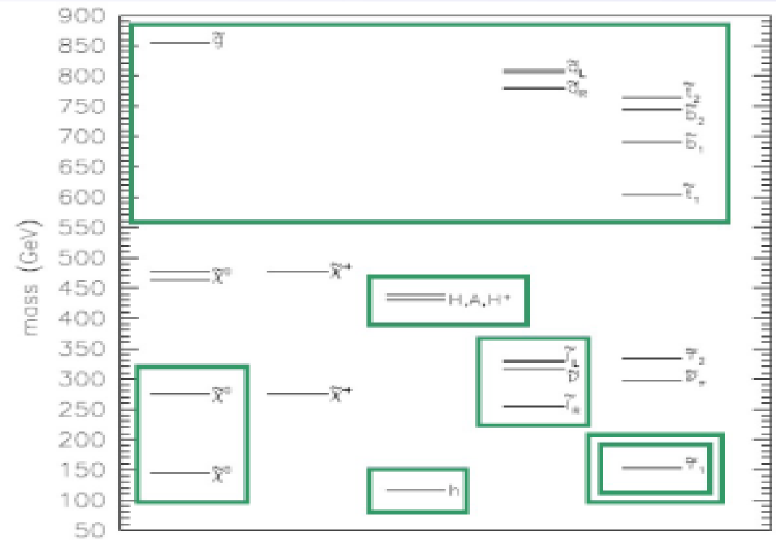


(Baer, Barger, Lessa, Tata '09)

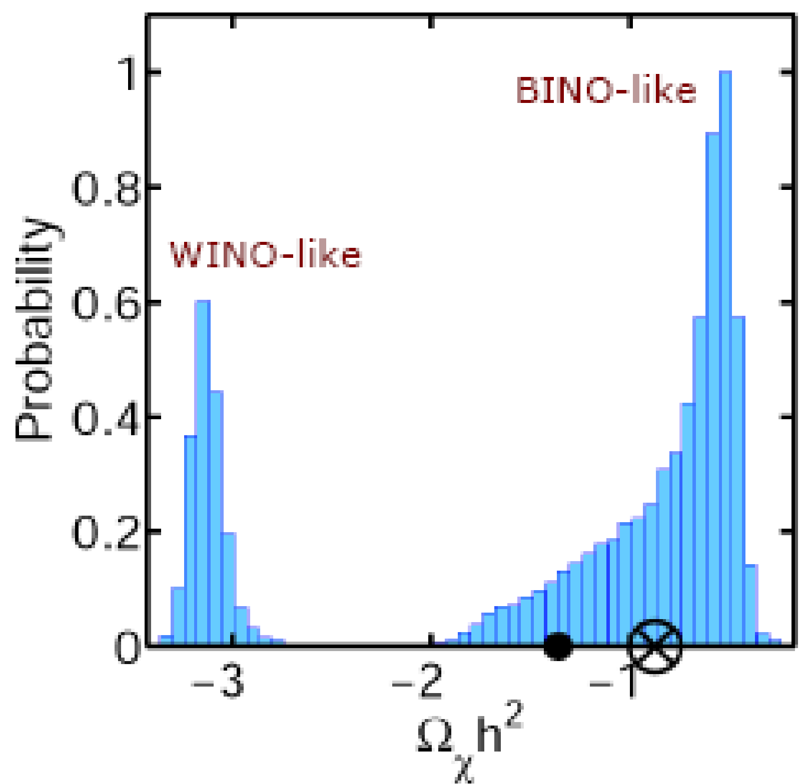
PREDICTION OF Ω DM FROM LHC AND ILC FOR TWO DIFFERENT SUSY PARAMETER SETS

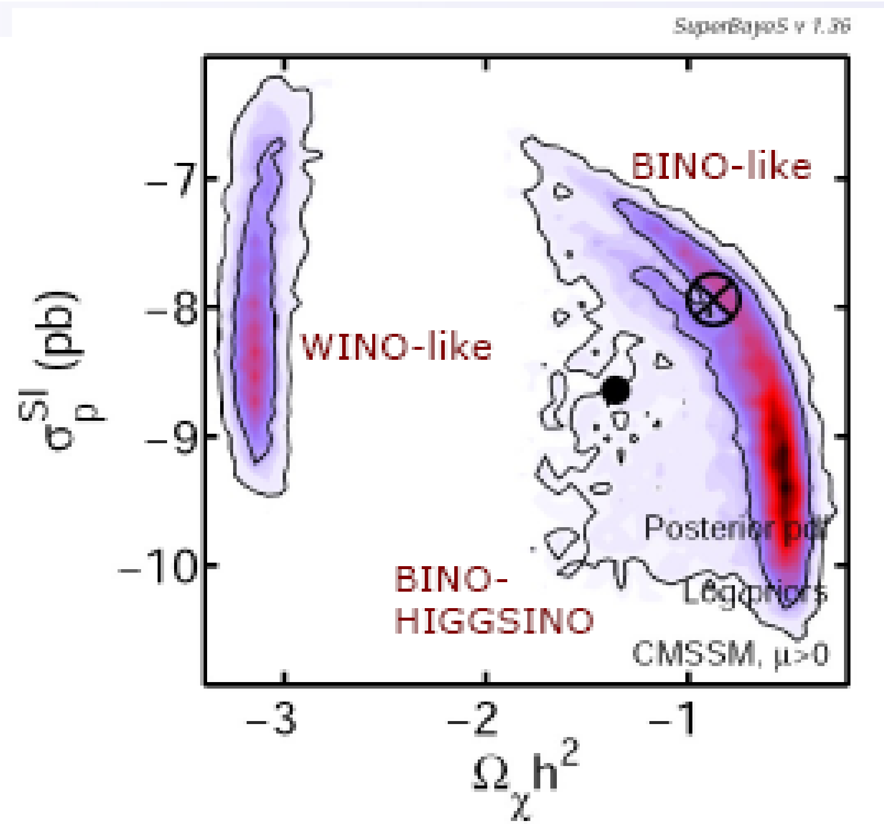


BALTZ, BATTAGLIA, PESKIN, WIZANSKY



Suppose we find some SUSY particles at LHC: will we be able to infer which s-particle is the LSP?





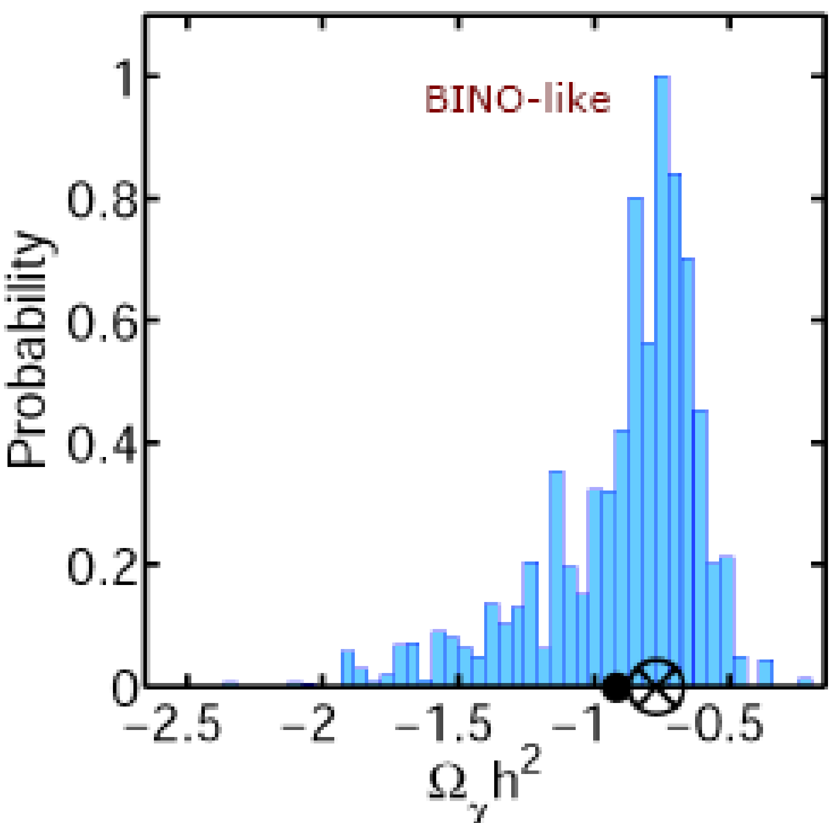
...but if at the same time we have some result from the DM searches

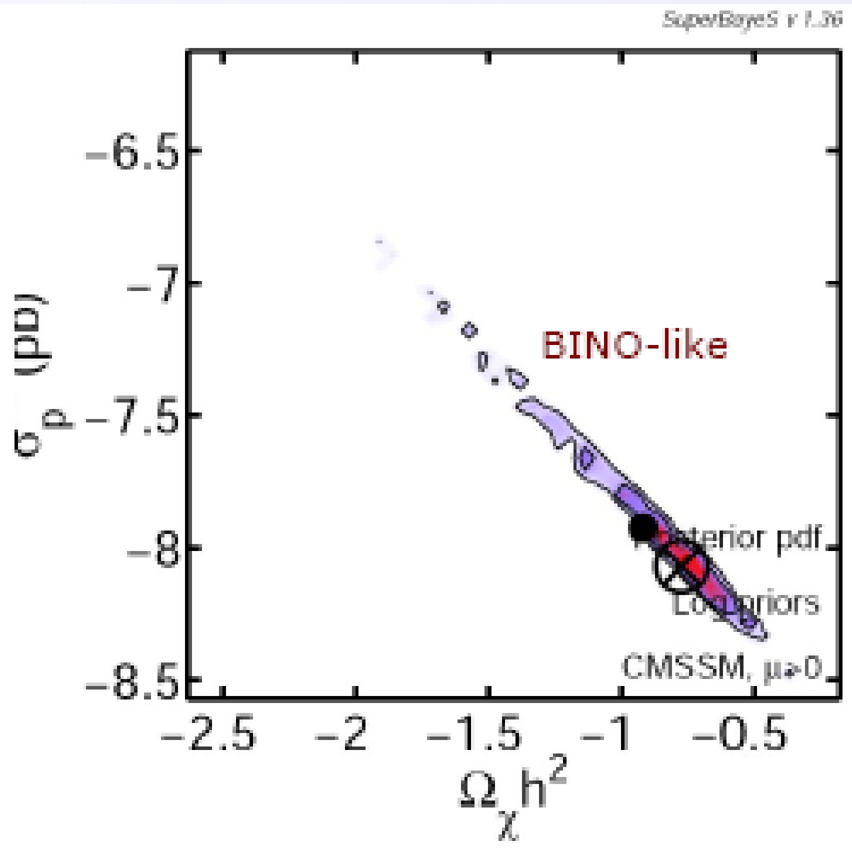
synergy LHC - DM

The combination of LHC data with Direct Detection data can resolve the degeneracy

The reconstruction of the relic abundance has a similar accuracy but spurious maxima disappear

(Bertone, Cerdeño, Fornasa, Trotta, de Austri – in preparation)





Prospects for the 2010-2011 run

$\sqrt{s}$ = 7 TeV

FABIOLA GIANOTTI, La Thuile **2010**

Machine plan:

2010: L = $\sim 10^{28} \rightarrow 10^{32}$ $cm^{-2}\,s^{-1}$
$\rightarrow$ total of 100-200 pb^{-1}
2011: L = $1 \rightarrow$ few 10^{32} $cm^{-2}\,s^{-1}$
$\rightarrow$ collect $\geq$ 100 pb^{-1} per month $\rightarrow$
total of ~ 1 fb^{-1}
2012: shut-down

Today, mid-year, already reached!!

New Physics : approximate LHC reach (one experiment) for some benchmark scenarios ($\sqrt{s}$ = 7 TeV, unless otherwise stated)

FABIOLA GIANOTTI, La Thuile 2010

Z' (SSM): Tevatron limit ~ 1 TeV (95% C.L)

50 pb^{-1} : exclusion up to ~ 1 TeV (95% C.L.)
500 pb^{-1} : discovery up to ~ 1.3 TeV
exclusion up to ~ 1.5 TeV
1 fb^{-1} : discovery up to ~ 1.5 TeV

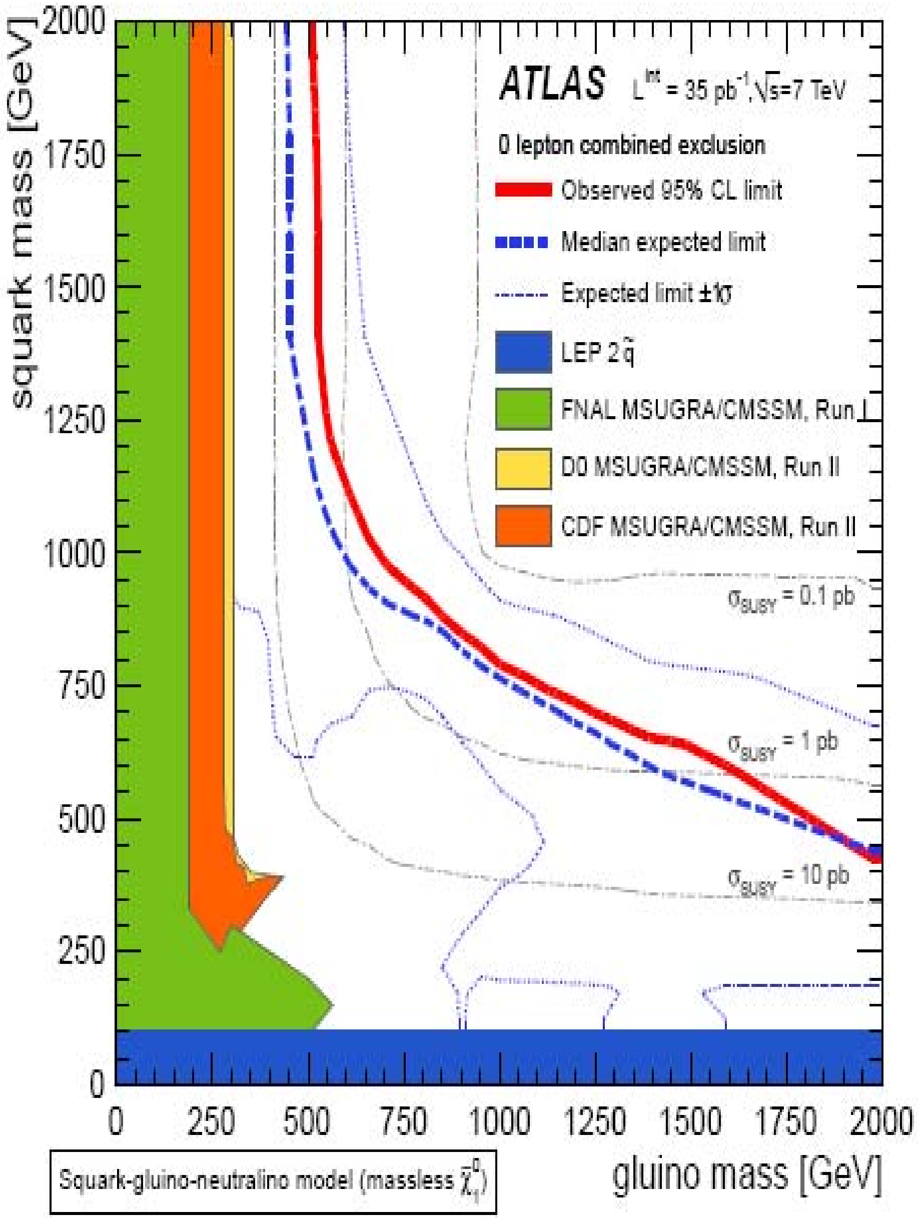
W' : Tevatron limit ~ 1 TeV (95% C.L)

10 pb^{-1} : exclusion up to 1 TeV
100 pb^{-1} : discovery up to ~ 1.3 TeV
1 fb^{-1} : discovery up to ~ 1.9 TeV
exclusion up to ~ 2.2 TeV

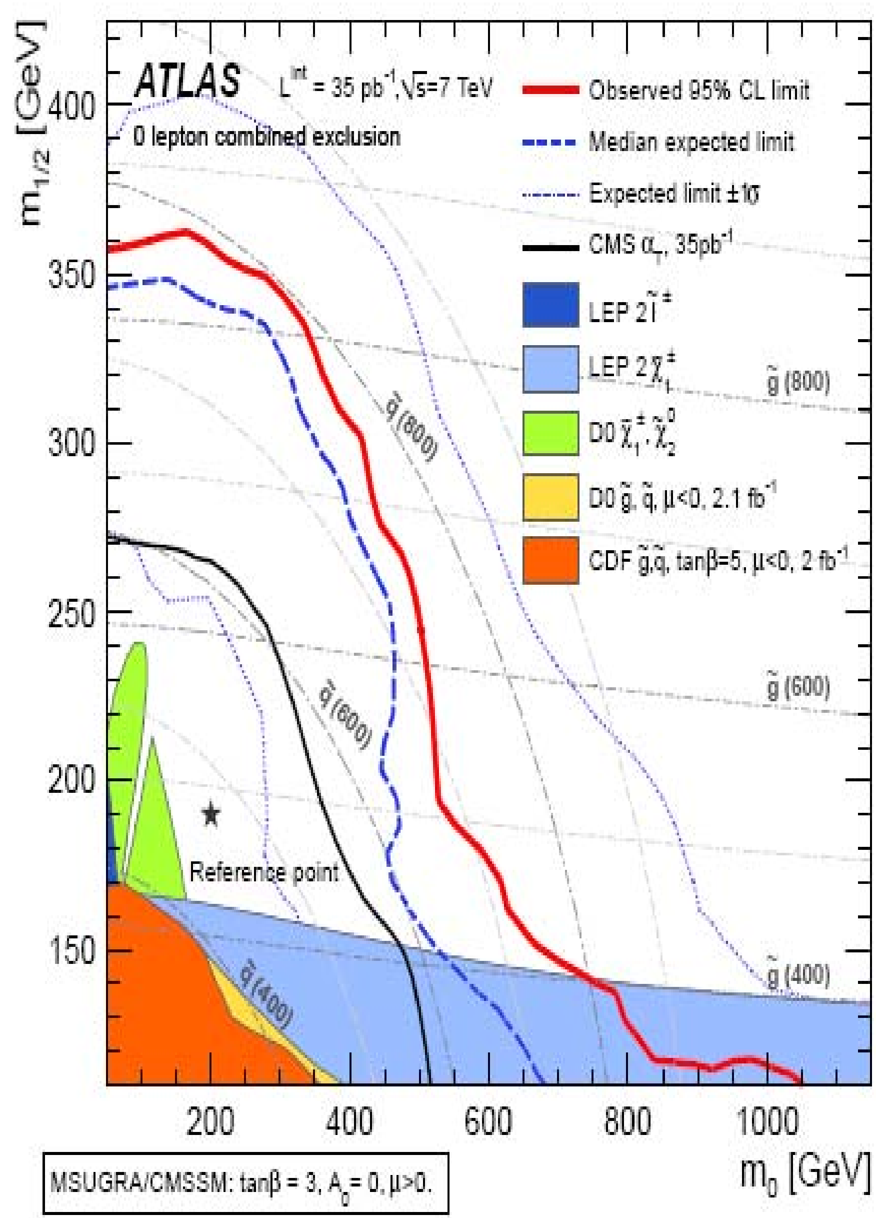
SUSY ($\tilde{q}, \tilde{g}$) : Tevatron limit ~ 400 GeV (95% C.L)

100 pb^{-1} : discovery up to ~ 400 GeV
1 fb^{-1} : discovery up to ~ 800 GeV

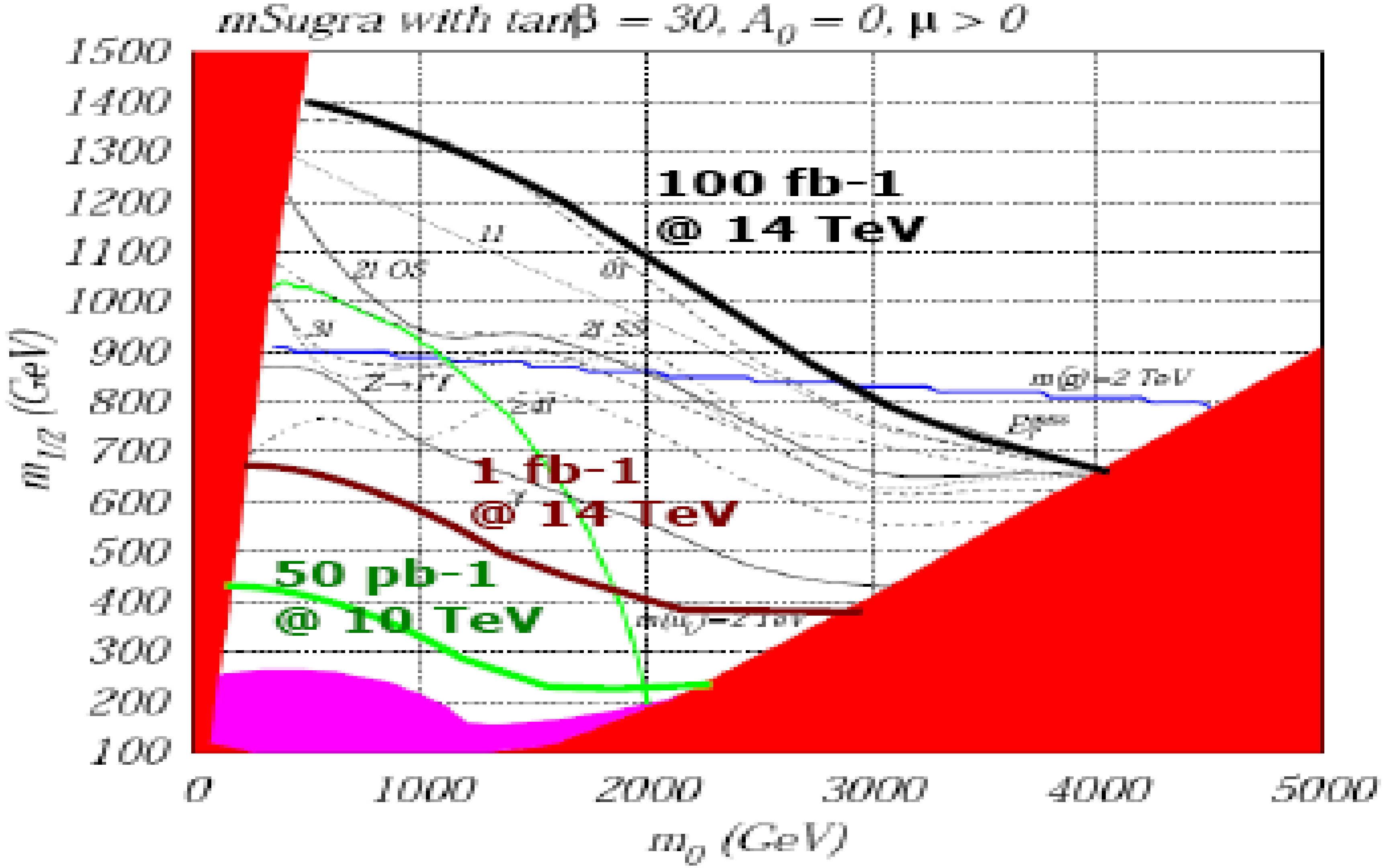
LHC will start to compete with the Tevatron in 2010, and should take over in 2011 in most cases.



ATLAS L^{int} = 35 pb^{-1}, $\sqrt{s}$=7 TeV
0 lepton combined exclusion
Observed 95% CL limit
Median expected limit
Expected limit ±1σ
LEP 2 $\tilde{q}$
FNAL MSUGRA/CMSSM, Run I
D0 MSUGRA/CMSSM, Run II
CDF MSUGRA/CMSSM, Run II
σ_{SUSY} = 0.1 pb
σ_{SUSY} = 1 pb
σ_{SUSY} = 10 pb
squark mass [GeV]
gluino mass [GeV]
0
250
500
750
1000
1250
1500
1750
2000
Squark-gluino-neutralino model (massless $\tilde{\chi}_1^0$)



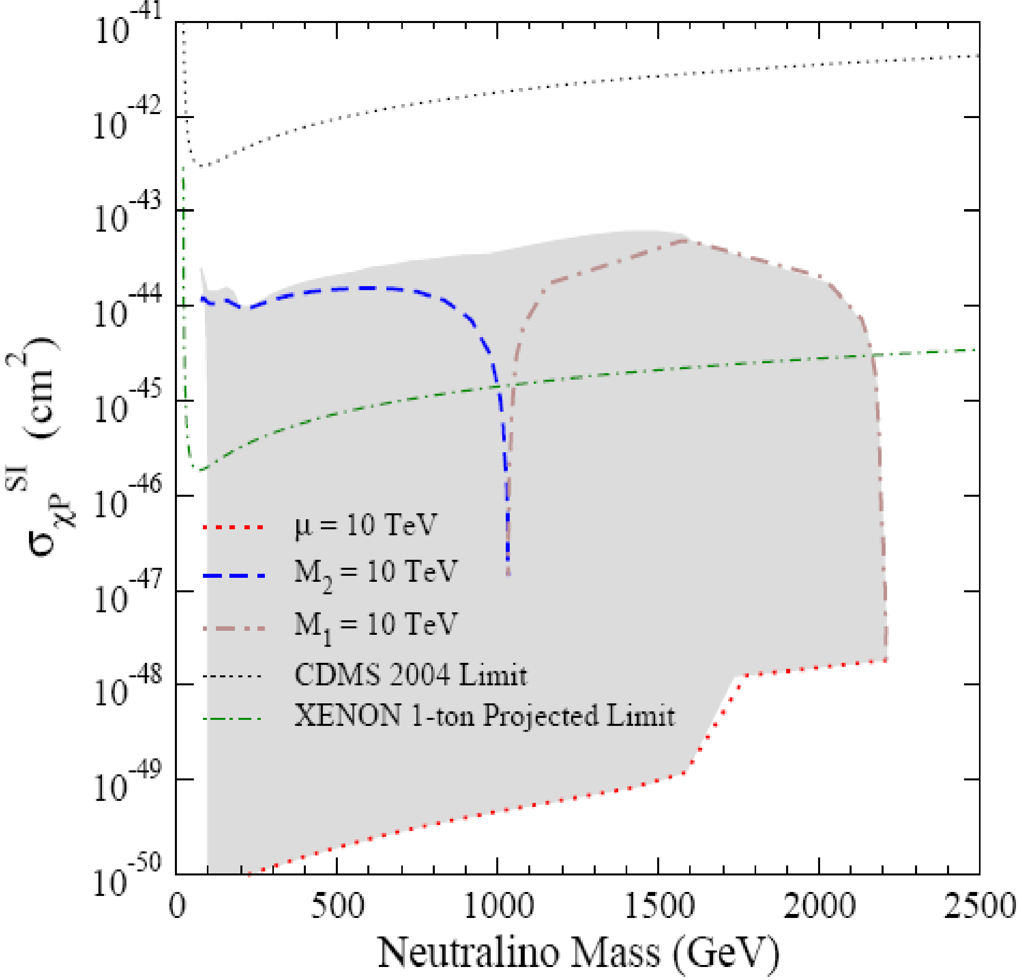
ATLAS L^{int} = 35 pb^{-1}, $\sqrt{s}$=7 TeV
0 lepton combined exclusion
Observed 95% CL limit
Median expected limit
Expected limit ±1σ
CMS α_T, 35pb^{-1}
LEP 2 $\tilde{l}^{\pm}$
LEP 2 $\tilde{\chi}_1^{\pm}$
D0 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$
D0 $\tilde{g}, \tilde{q}, \mu<0$, 2.1 fb^{-1}
CDF $\tilde{g},\tilde{q}$, tanβ=5, $\mu<0$, 2 fb^{-1}
$\tilde{g}$ (800)
$\tilde{g}$ (600)
$\tilde{g}$ (400)
$\tilde{q}$ (800)
$\tilde{q}$ (600)
$\tilde{q}$ (400)
Reference point
$m_{1/2}$ [GeV]
m_0 [GeV]
150
200
250
300
350
400
600
800
1000
MSUGRA/CMSSM: tanβ = 3, A_0 = 0, μ>0.

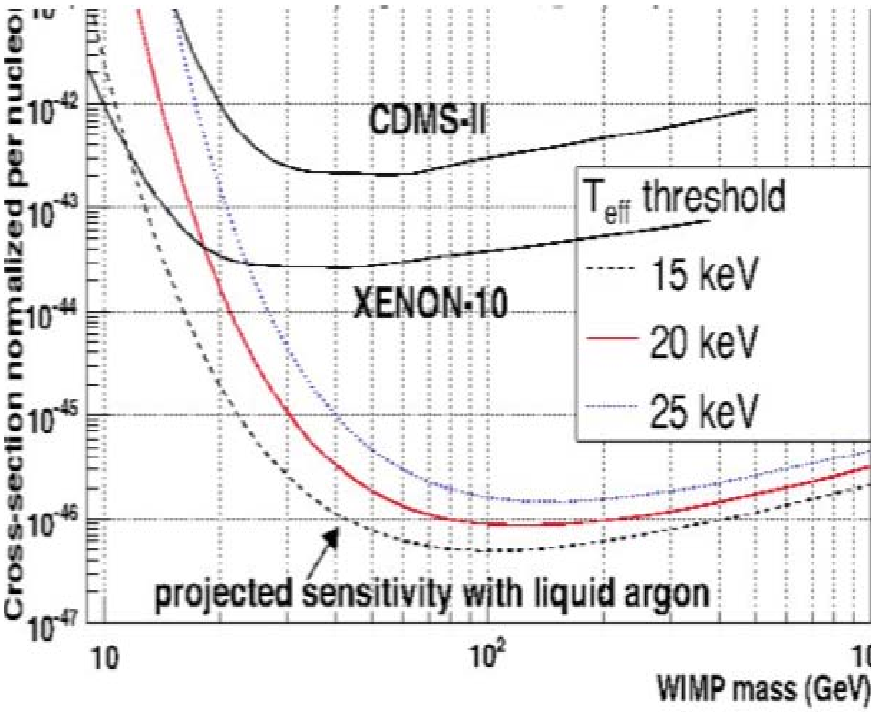


(Baer, Belyaev, Kuprovnikas, o'Farrill ' 04)

(Buchmüller et al. '08)

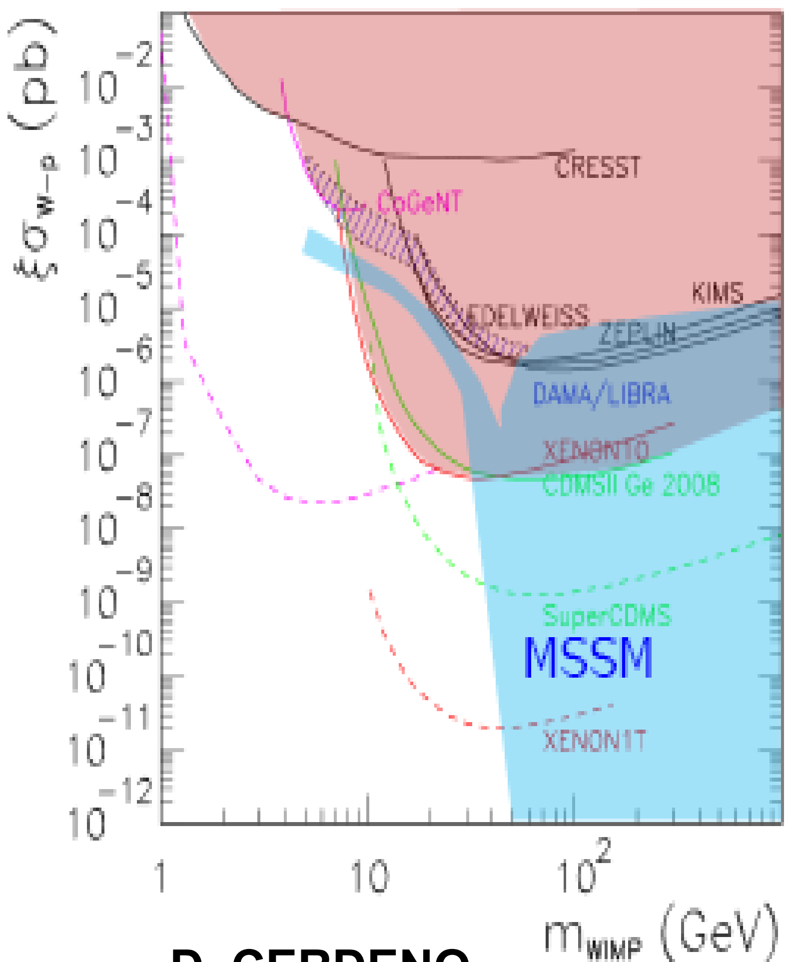
SPIN - INDEPENDENT NEUTRALINO - PROTON CROSS SECTION FOR ONE OF THE SUSY PARAM. FIXED AT 10 TEV



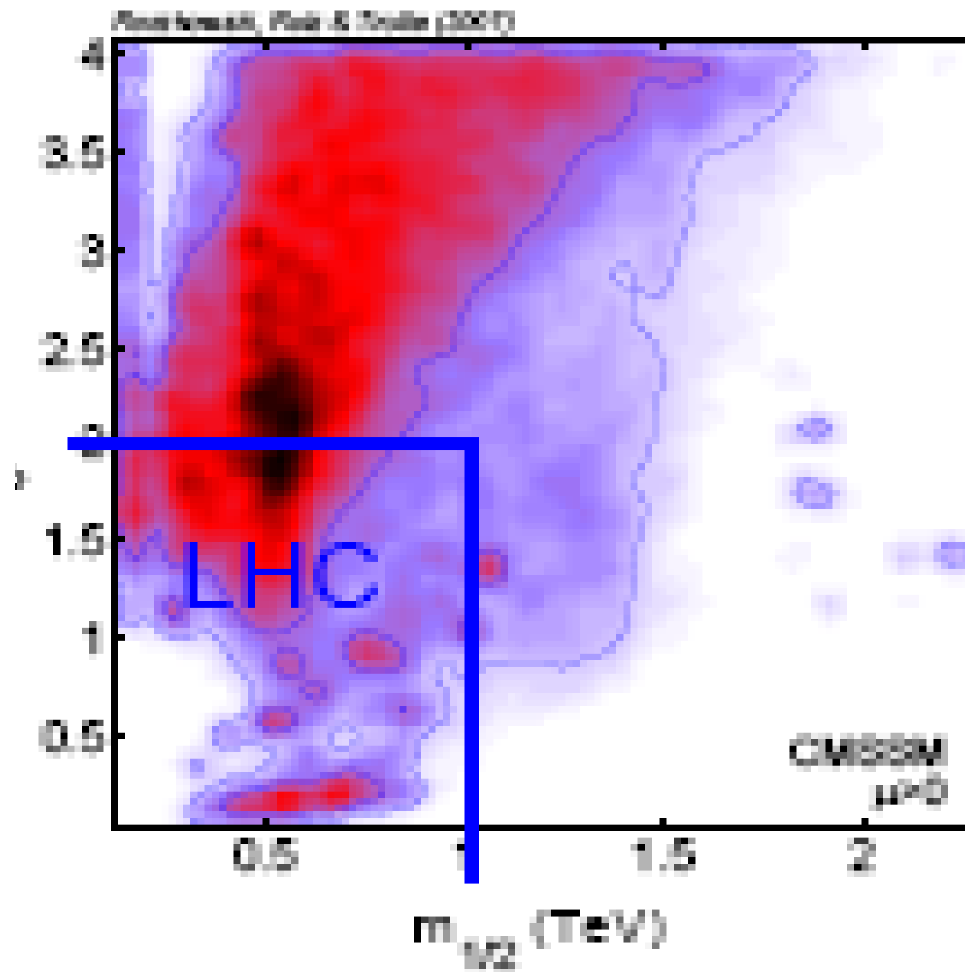


PROFUMO, A.M., ULLIO

On the LHC – Direct DM searches coverage of the MSSM parameter space

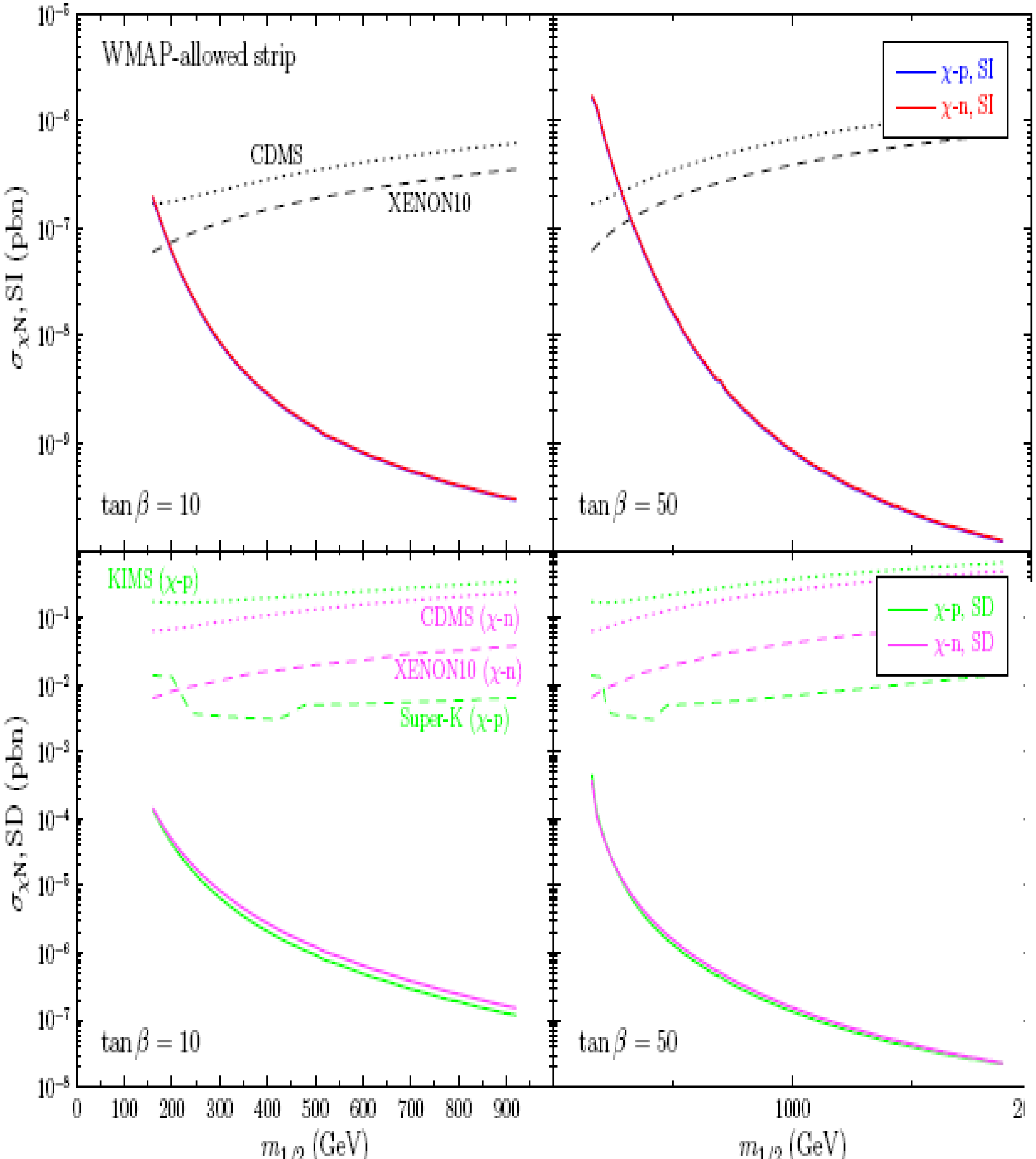


D. CERDENO
WONDER10



L. Roszkowsk et al.

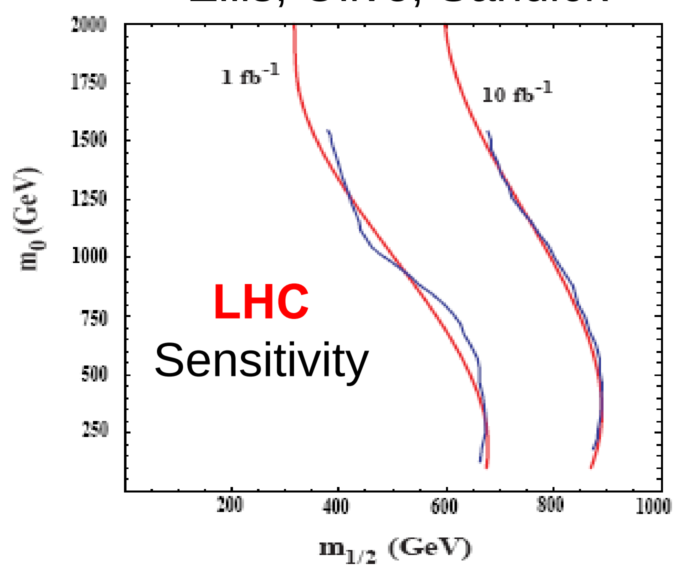
Neutralino-nucleon scattering cross sections along the WMAP-allowed coannihilation strip for tanbeta=10 and coannihilation/funnel strip for tanbeta=50 using the hadronic parameters

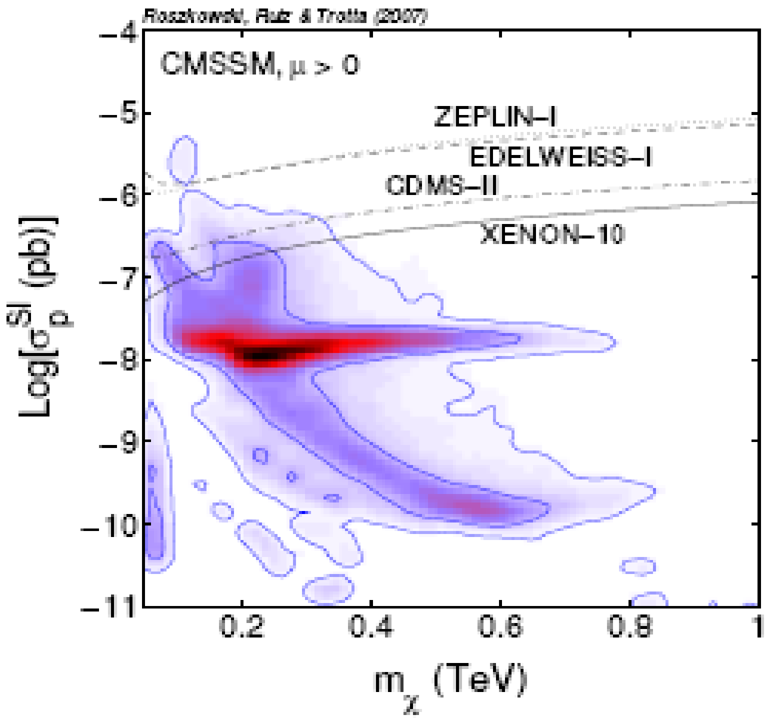


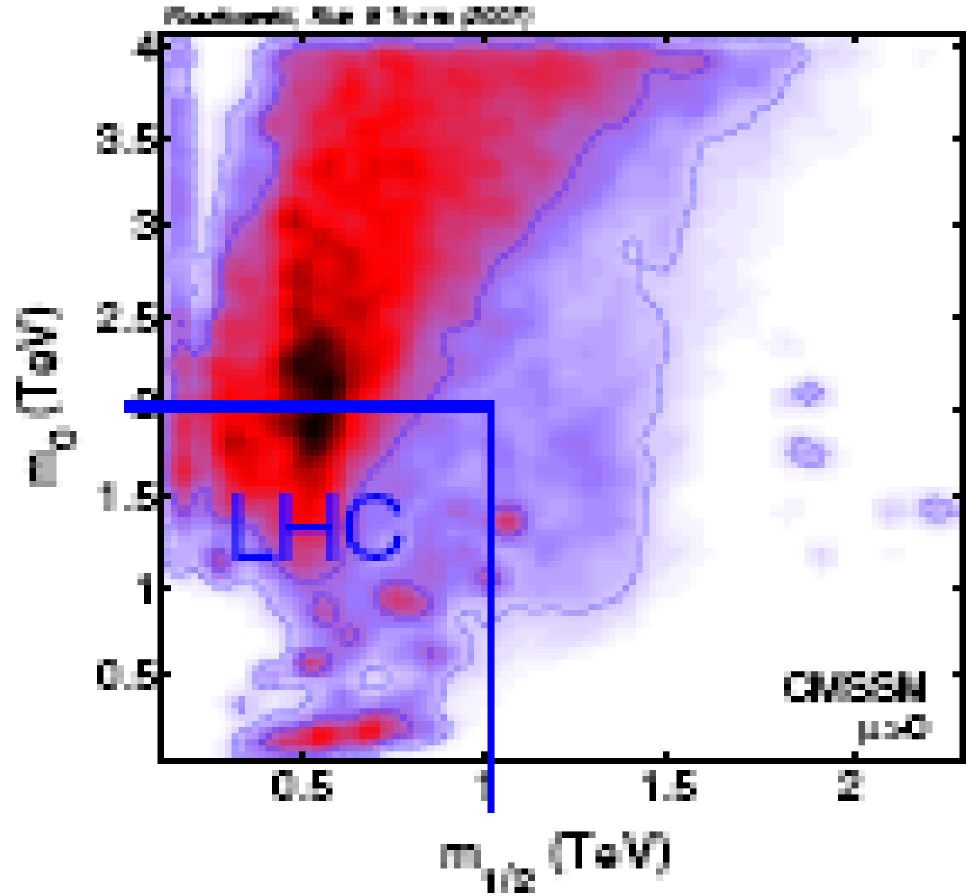
ELLIS. OLIVE. SAVAGE

m_u/m_d	0.553	±	0.043
m_d	5	±	2 MeV
m_s/m_d	18.9	±	0.8
m_c	1.25	±	0.09 GeV
m_b	4.20	±	0.07 GeV
m_t	171.4	±	2.1 GeV
σ_0	36	±	7 MeV
$\Sigma_{\pi N}$	64	±	8 MeV
$a_3^{(p)}$	1.2695	±	0.0029
$a_8^{(p)}$	0.585	±	0.025
$\Delta_s^{(p)}$	-0.09	±	0.03

Ellis, Olive, Sandick





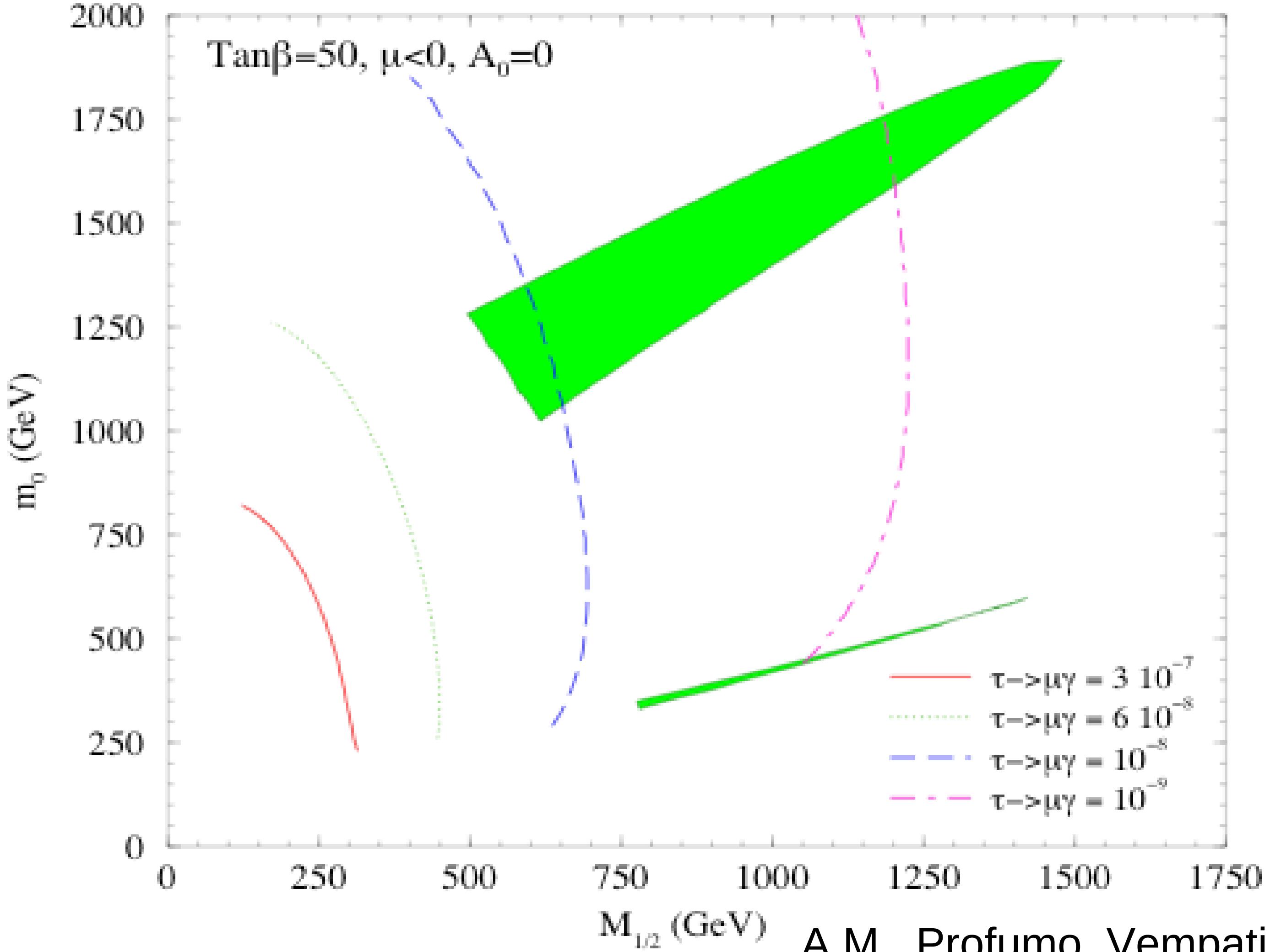


ultimately: “1 tonne” detectors:

$\sigma_p^{SI} \lesssim 10^{-10}$ pb

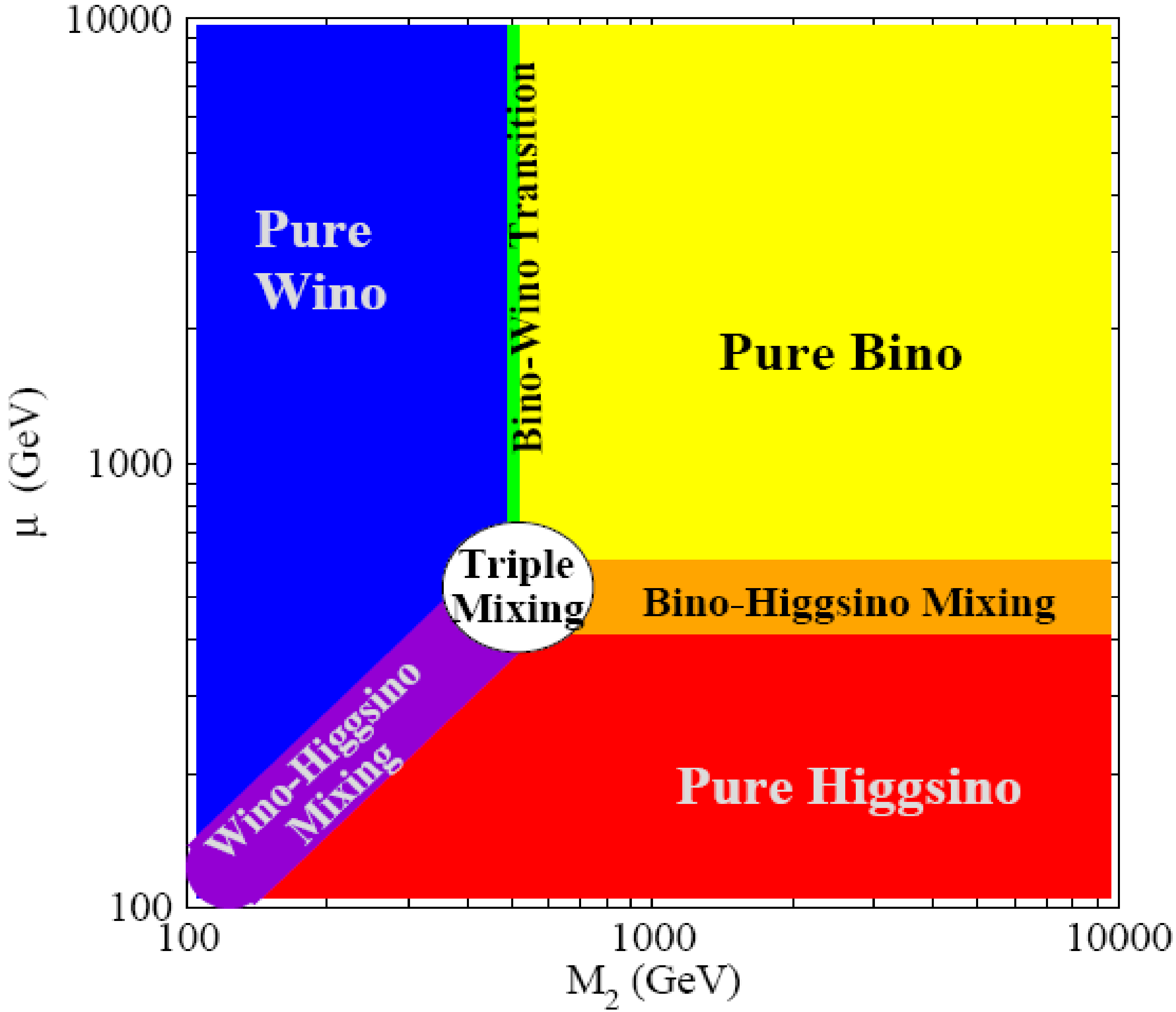
will cover all 68% region

LFV - DM CONSTRAINTS IN MINIMAL SUPERGRAVITY

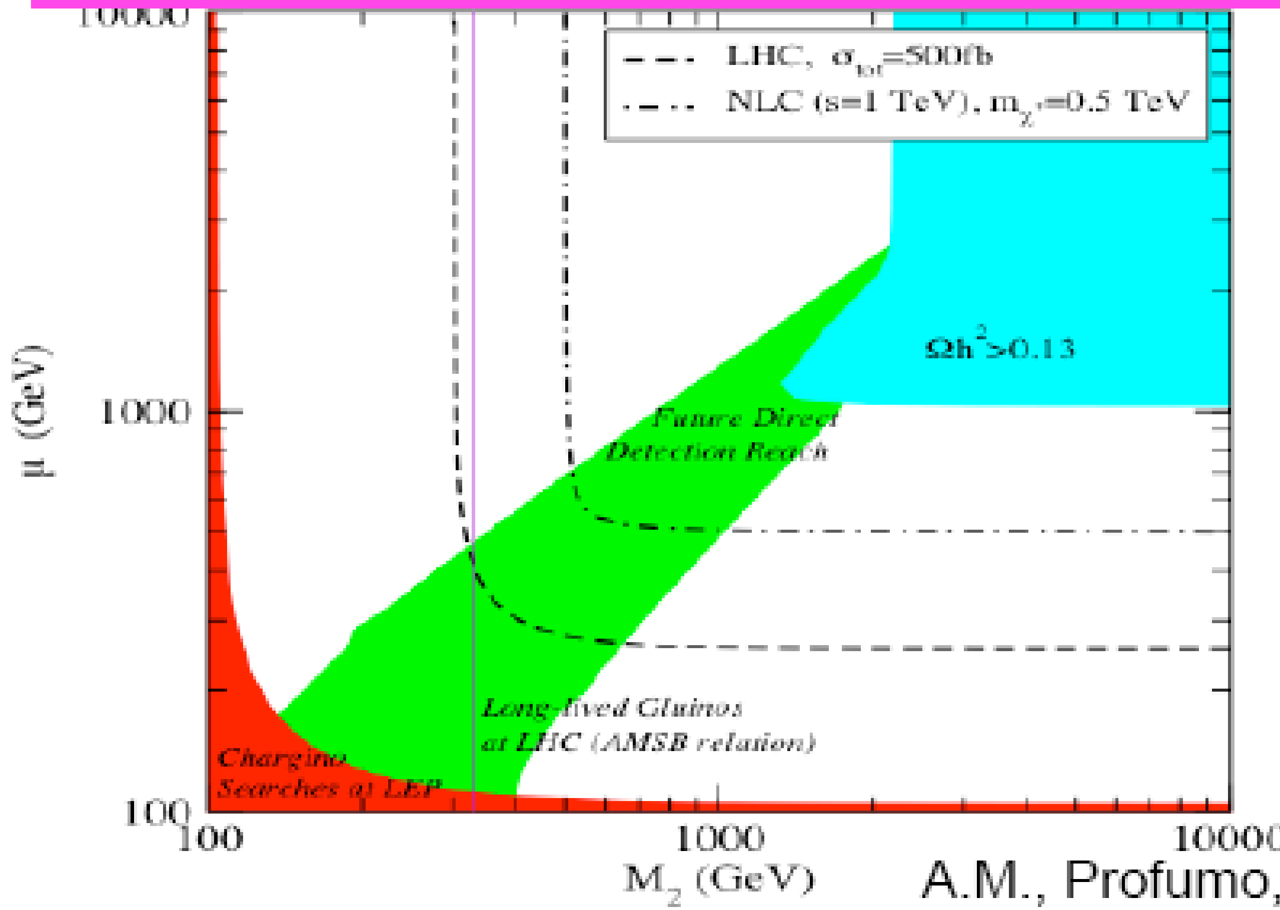


A.M., Profumo, Vempati, Yaguna

A.M., PROFUMO, ULLIO



LHC, ILC, DM SEARCHES SENSITIVITIES

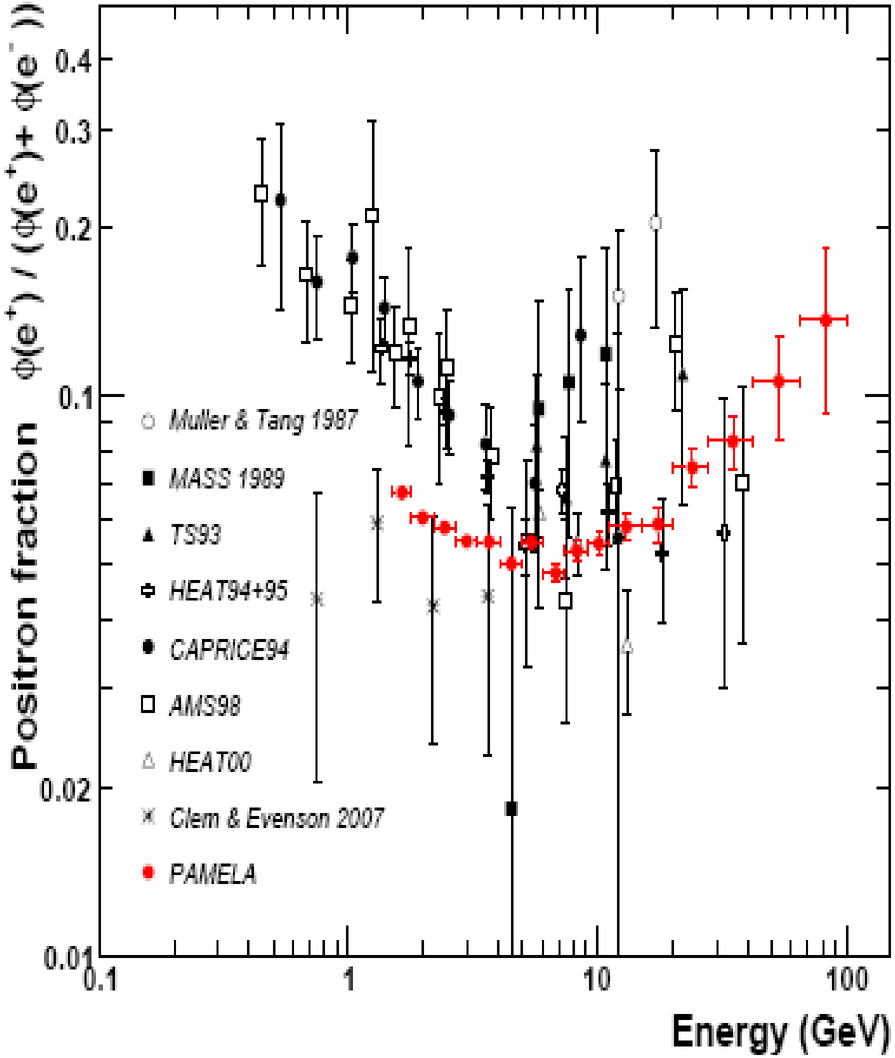


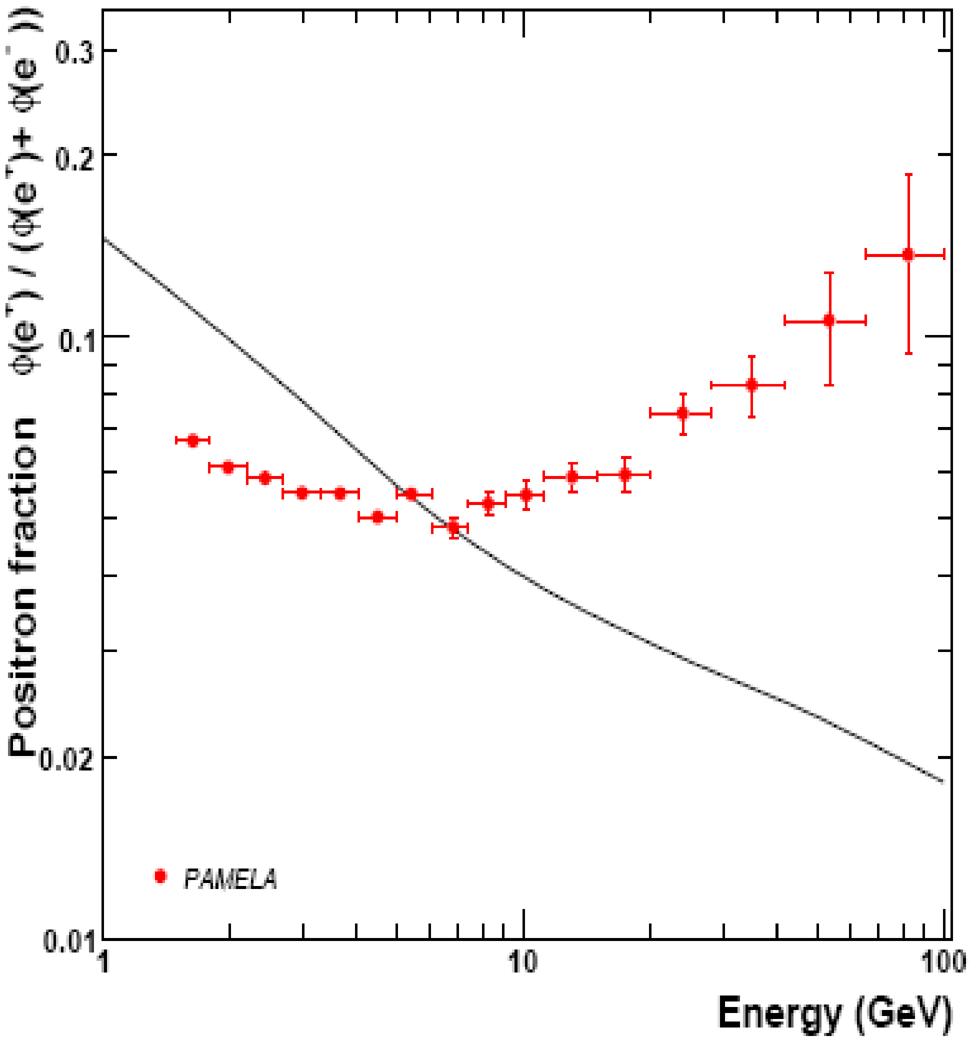
A.M., Profumo, Ullio

Has dark matter's telltale signature been spotted?

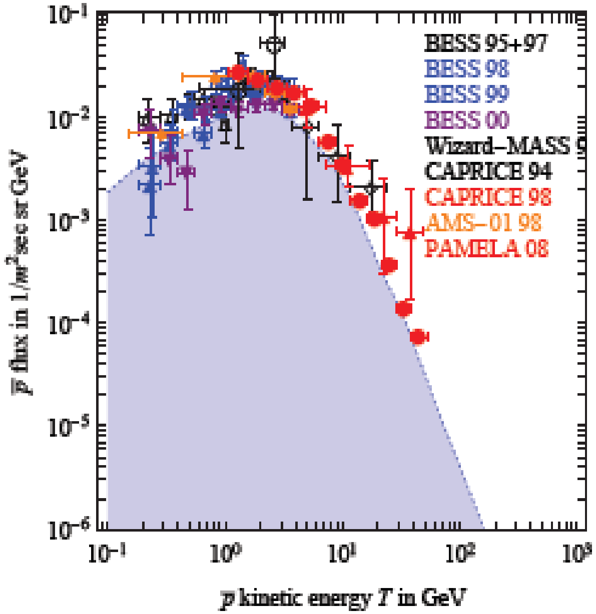
New Scientist, Aug. 2008

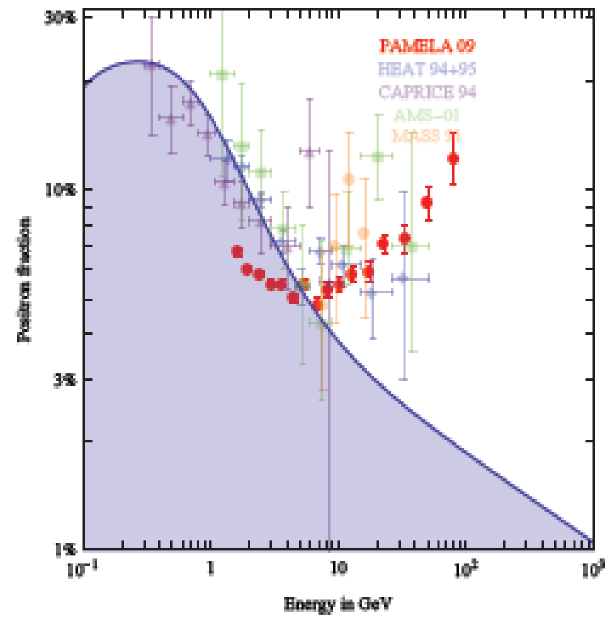
EXCESS OF ELECTRONS - POSITRONS IN PAMELA DATA?

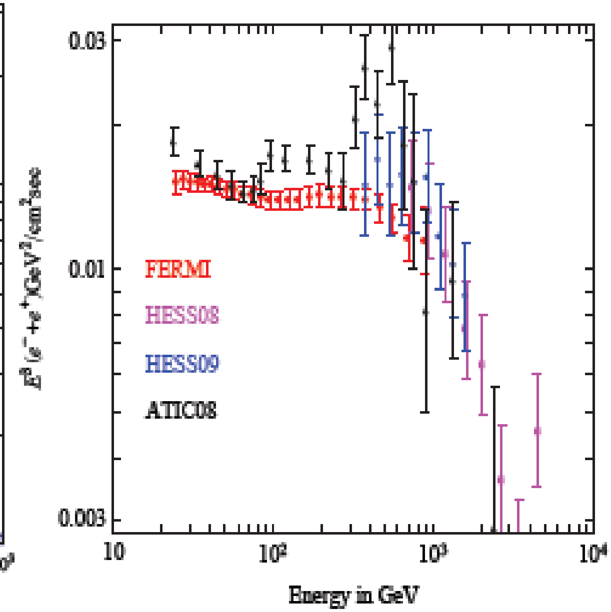




PAMELA, FERMI/ATIC, HESS







$\bar{p}$: consistent with bck

e^+/e^-: excess

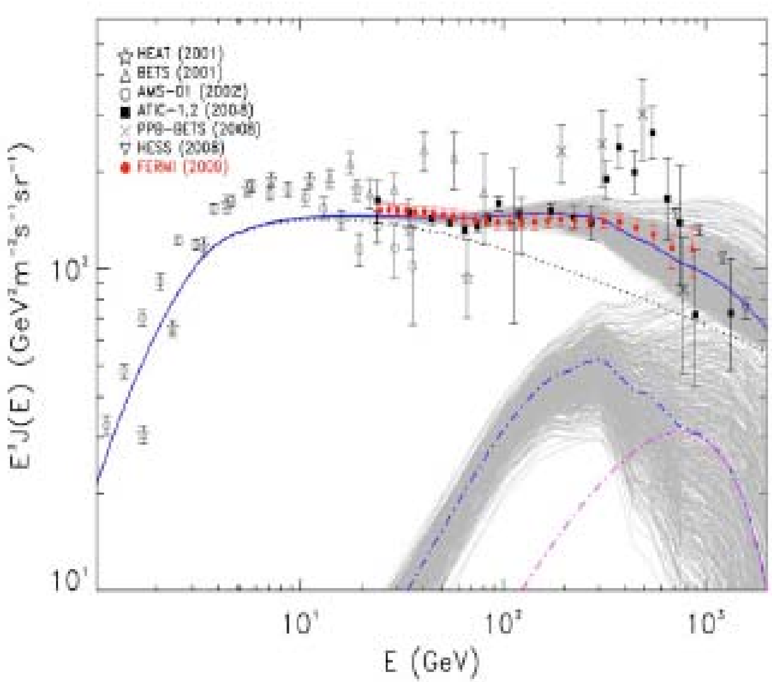
$e^- + e^+$: feature?

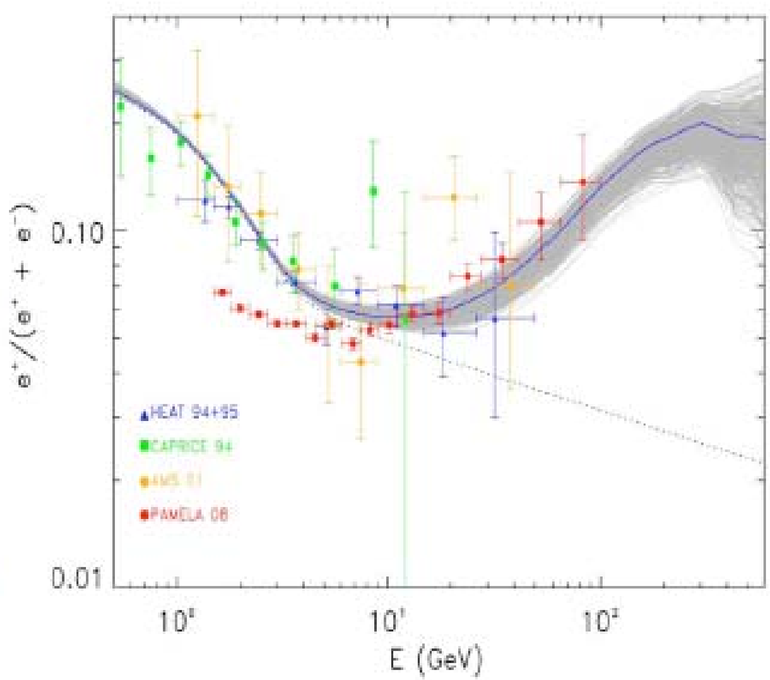
Strumia

EPS09

PAMELA excess: October 2008, stimulated enormous theoretical activity; note: statistical errors only! Fermi: feature observed by ATIC not confirmed

Pulsars: Fermi & PAMELA



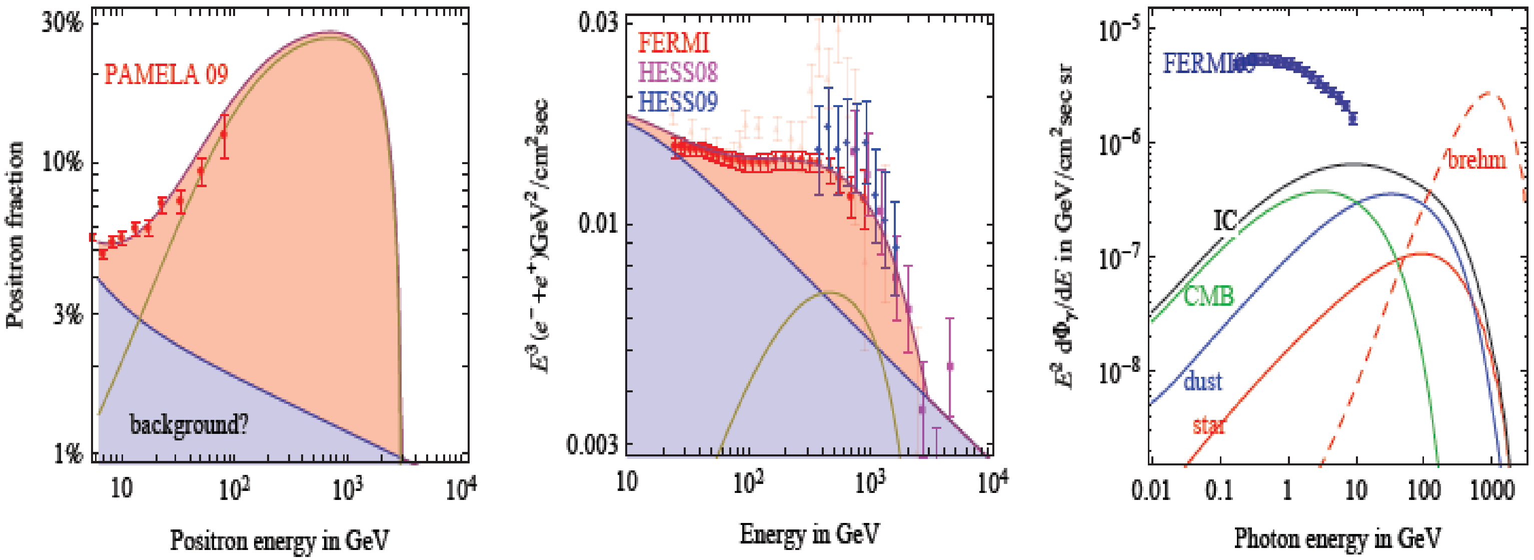


pulsar parameters “randomly” varied!

Grasso et al

Standard Dark Matter best fit

DM with $M = 3.$ TeV that annihilates into $\tau^+\tau^-$ with $\sigma v = 1.9 \times 10^{-22}$ cm^3/s



(Inverse Compton depends only on the $e^{\pm}$ spectrum)

Strumia

EPS09

Watch boost factor! DM particles too heavy for SUSY to be relevant for LHC

3 QUESTIONS

- Are we sure that there is new physics (NP) at the TeV scale? YES (barring an antropic approach)
- If yes, are we sure that LHC will see something "new", i.e. beyond the SM with its "standard higgs boson"? YES
- If there is new physics at the TeV scale, what can flavor and DM physics tell to LHC and viceversa? (or, putting it in a less politically correct fashion: if LHC starts seeing some new physics signals, are flavor and DM physics still a valuable road to NP, or are they definitely missing that train? NO, actually to catch the "right train" it is highly desirable, though maybe strictly not necessary, to make use of all the three roads at the same time

MICRO

STANDARD MODEL of PARTICLE PHYSICS

G-W-S MODEL

MACRO

STANDARD MODEL of COSMOLOGY

HOT BIG BANG

HAPPY MARRIAGE

EX: **NUCLEOSYNTHESIS**

BUT ALSO

FRICTION POINTS

DARK MATTER AND DARK ENERGY

LHC → AN EXCEPTIONAL WINDOW TO EXPLORE THE UNIVERSE AND ITS ORIGIN, BUT…

LHC and "LOW-ENERGY" NEW PHYSICS

- **LHC discovers NP**: difficult, if not impossible, to "reconstruct" the fundamental theory lying behind those signals of NP;

- **LHC does not see any signal of NP**: still a NP related to the stabilization of the elw. scale may be present, but with particles whose masses are in the multi-TeV range.

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