DISCRETE '08, 11-16 DECEMBER 2008,

IFIC, VALENCIA, SPAIN

SUSY DM and LHC

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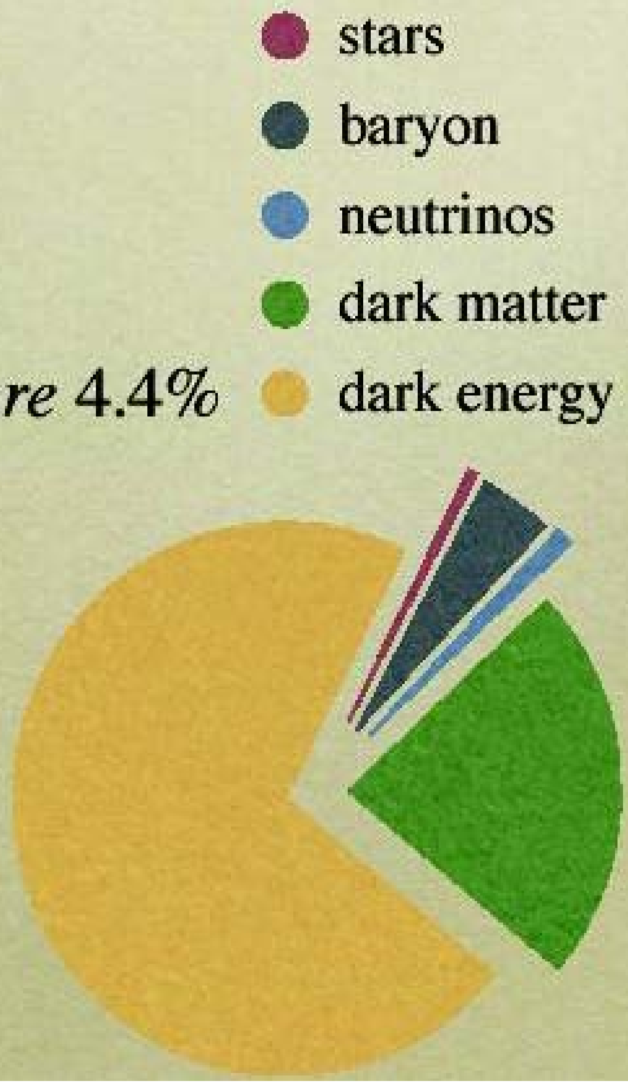
- **IS DM A CLEAR INDICATION OF NEW PHYSICS BEYOND THE SM?**
- **IS LOW-ENERGY SUSY "GENERALLY" (NATURALLY) PROVIDING A GOOD DM CANDIDATE?**
- **HOW FAR ARE WE IN DIRECT AND INDIRECT SEARCHES FOR DM TO PROBE THE SUSY PARAMETER SPACE?**
- **IF LHC DOES NOT SEE ANY SUSY PARTICLE, CAN WE HOPE THAT DM SEARCHES REVEAL A SUSY DM?**
- **OR, IF LHC FINDS SOME SUSY EVIDENCE, WHICH SENSITIVITY IN DM EXPS. SHOULD BE ACHIEVED TO BE SURE THAT WE'LL FIND SUSY DM?**
- **IN ANY CASE, IF LHC FINDS SUSY, WHAT ADDITIONAL INFORMATION COULD WE GATHER FROM THE DISCOVERY AND STUDY OF SUSY DM?**

THE ENERGY BUDGET OF THE UNIVERSE

- *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* $\sim 10^{62}\%$*??*



WMAP3 + small scale CMB exps (BOOMERang, ACBAR, CBI ans VSA)

+ **Large-Scale Structures** (SDSS,2dFCRS)

+ **SuperNova** (HST/GOODS, SNLS)

$$\Omega_b h^2 = 0.0220^{+0.0006}_{-0.0008} \quad \Omega_M h^2 = 0.131^{+0.004}_{-0.010}.$$

CONSISTENT WITH BARYON DENSITY DETERMINATION FROM BIG BANG NUCLEOSYNTHESIS

$$0.017 < \Omega_b h^2 < 0.024 \; (95\,\%\;\mathrm{CL})$$

The **BULLET CLUSTER**: **two colliding clusters of galaxies**

Stars, galaxies and putative DM behave differently during collision, allowing for them to be studied separately. In **MOND** the lensing is expected to follow the baryonic matter, i.e. the X-ray gas. However the lensing is strongest in two separated regions near the visible galaxies → **most of the mass in the cluster pair is in the form of collisionless DM**

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 ★

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 !**

The Energy Scale from the "Observational" New Physics

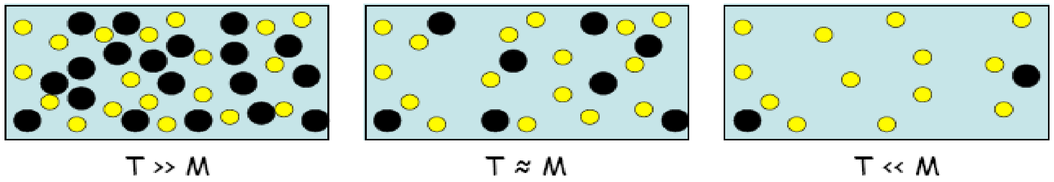
- neutrino masses
- dark matter
- baryogenesis
- inflation

→ 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



WIMPS (**Weakly Interacting Massive Particles**)

$\#\chi \sim \#\gamma$ m_χ

$\#\chi$ $\exp(-m\chi/T_\chi)$

$\#\chi$ does not change any more

$T_{decoupl.}$ typically ~ m_χ /20

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

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

$<(\sigma_{annih.}) V\chi> \sim \alpha^2 / M^2_\chi$

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) $\Omega_\chi h^2 \sim 10^{-2}$ -10^{-1} !!!

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

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).

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

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 →

M$_{\text{gravitino}}$ $\sim F/M_{Pl} \sim$

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

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

→ GAUGE INTERACTIONS

M$_{\text{gravitino}}$ $\sim F/M_{Pl} \sim$

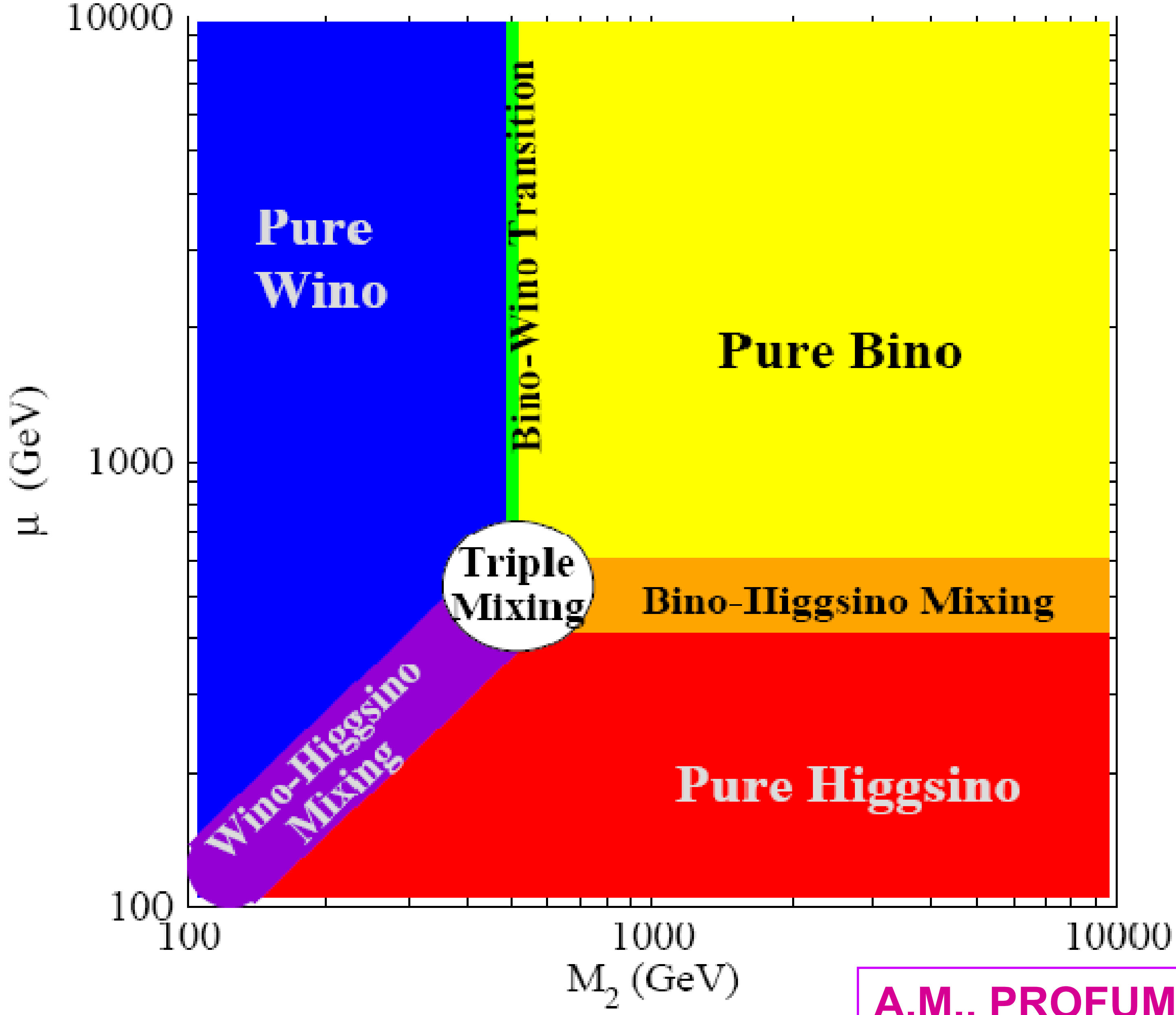
$(10^2 - 10^3)$ eV

OBSERVABLE SECTOR

SM + superpartners

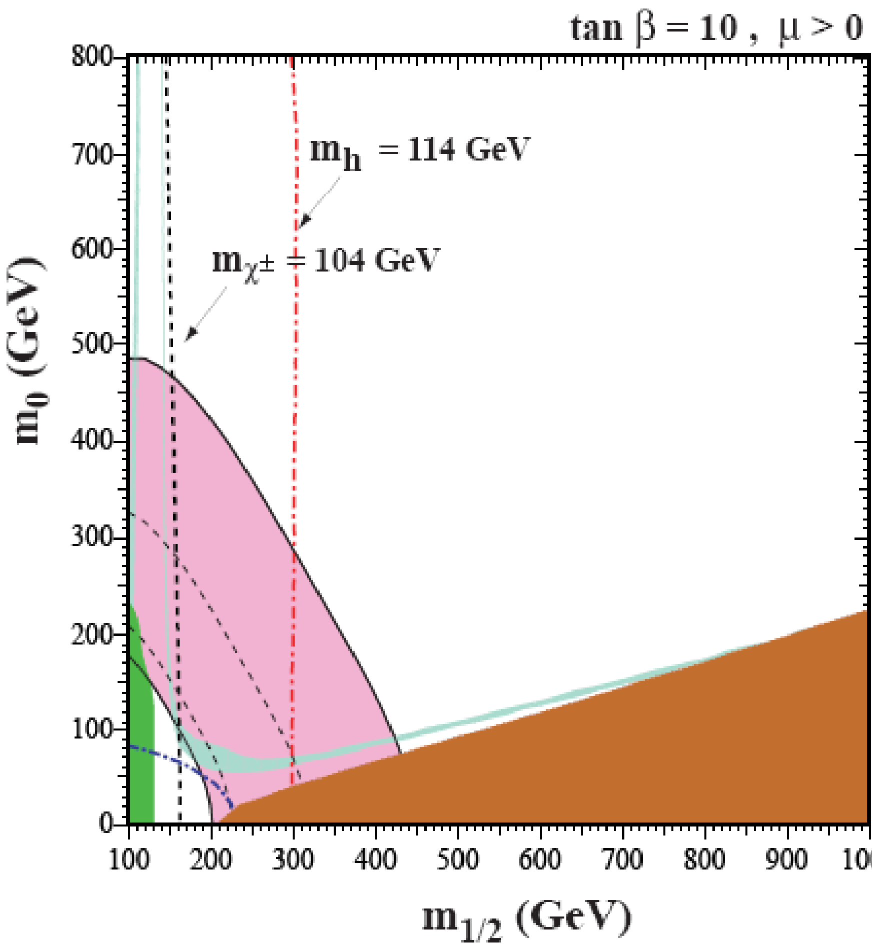
MSSM : minimal content of superfields

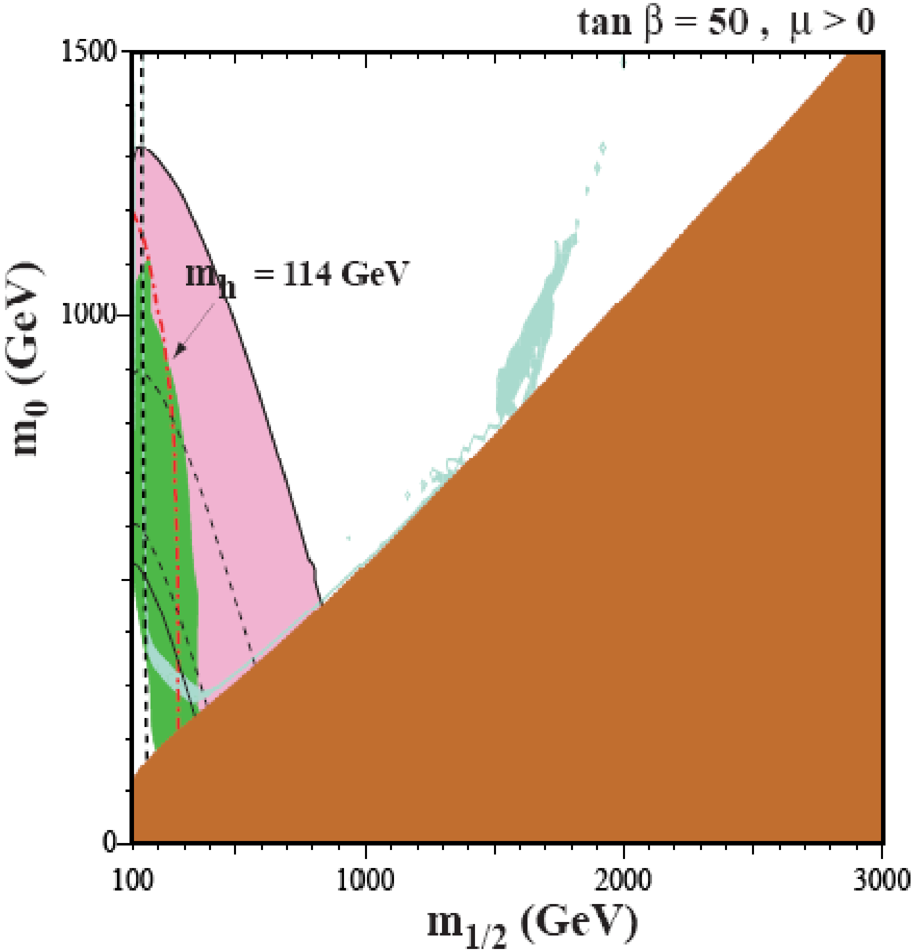
NEUTRALINO LSP IN SUPERGRAVITY



A.M., PROFUMO, ULLIO

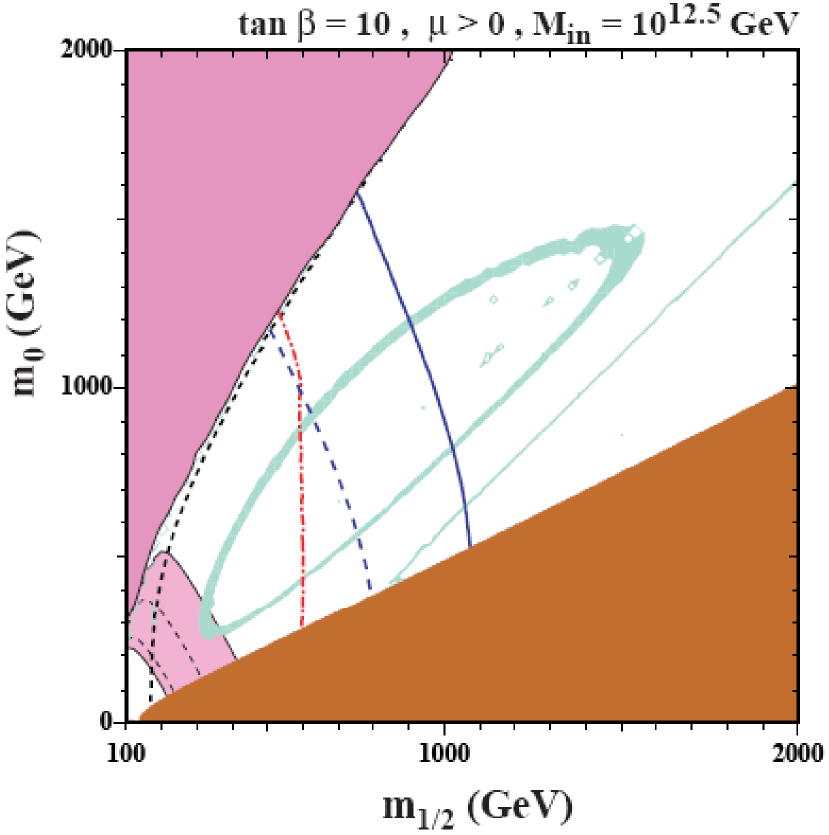
NEUTRALINO LSP IN THE CONSTRAINED MSSSM: A VERY SPECIAL SELECTION IN THE PARAMETER SPACE?



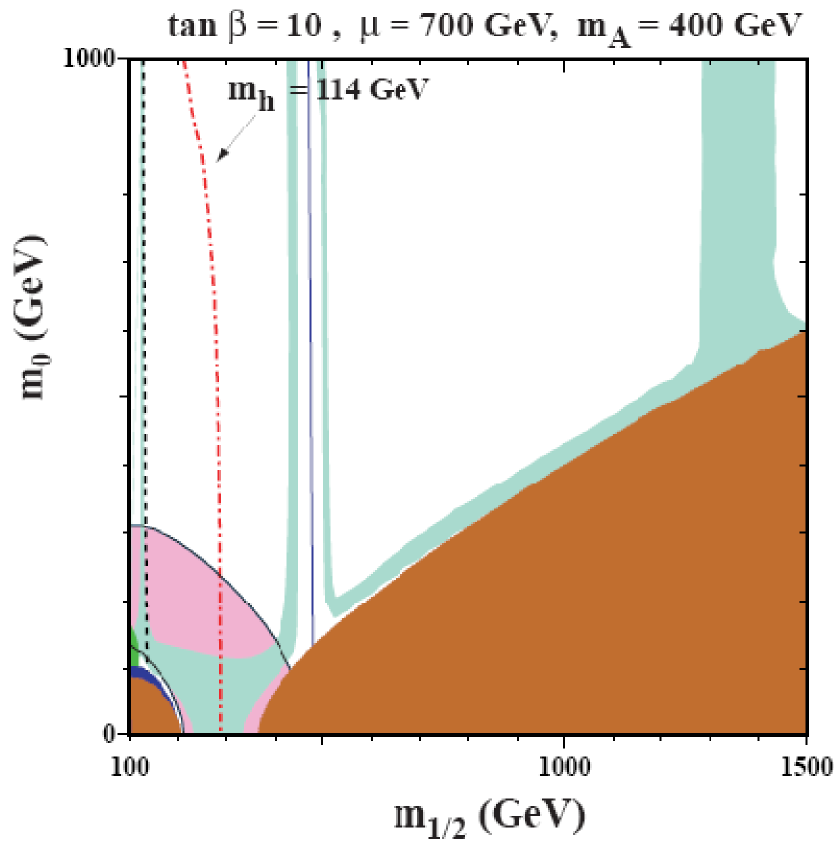


Ellis, Olive, Santoso, Spanos

LSP NEUTRALINO: THE FREEDOM IN "**UN-CONSTRAINED**" MSSM



ELLIS, OLIVE, SANDICK



ELLIS, FALK, OLIVE, SANTOSO

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

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

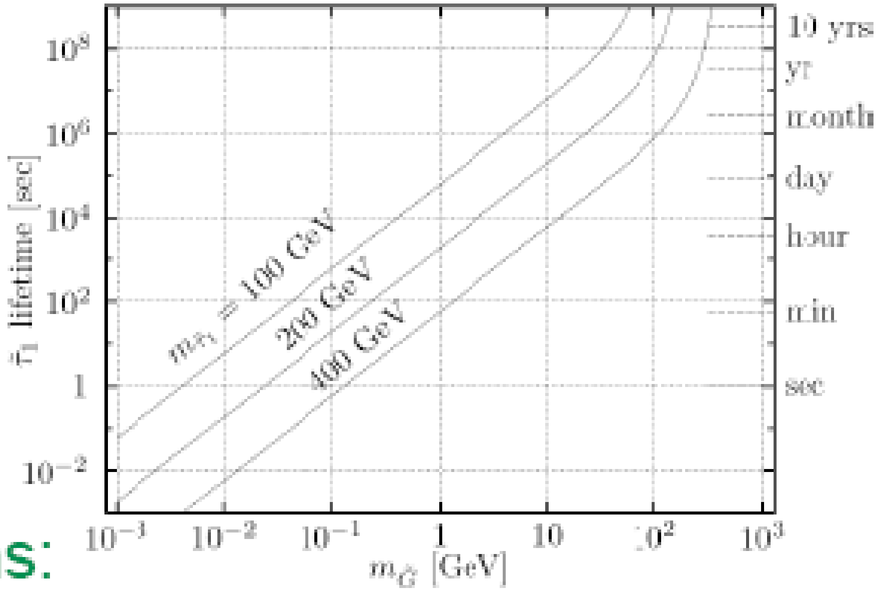
Collider experiments do not distinguish between stable ($\tau > 10^{17}$ s) and long-lived ($\tau > 10^{-7}$ s) particle

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

Gravitino

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

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



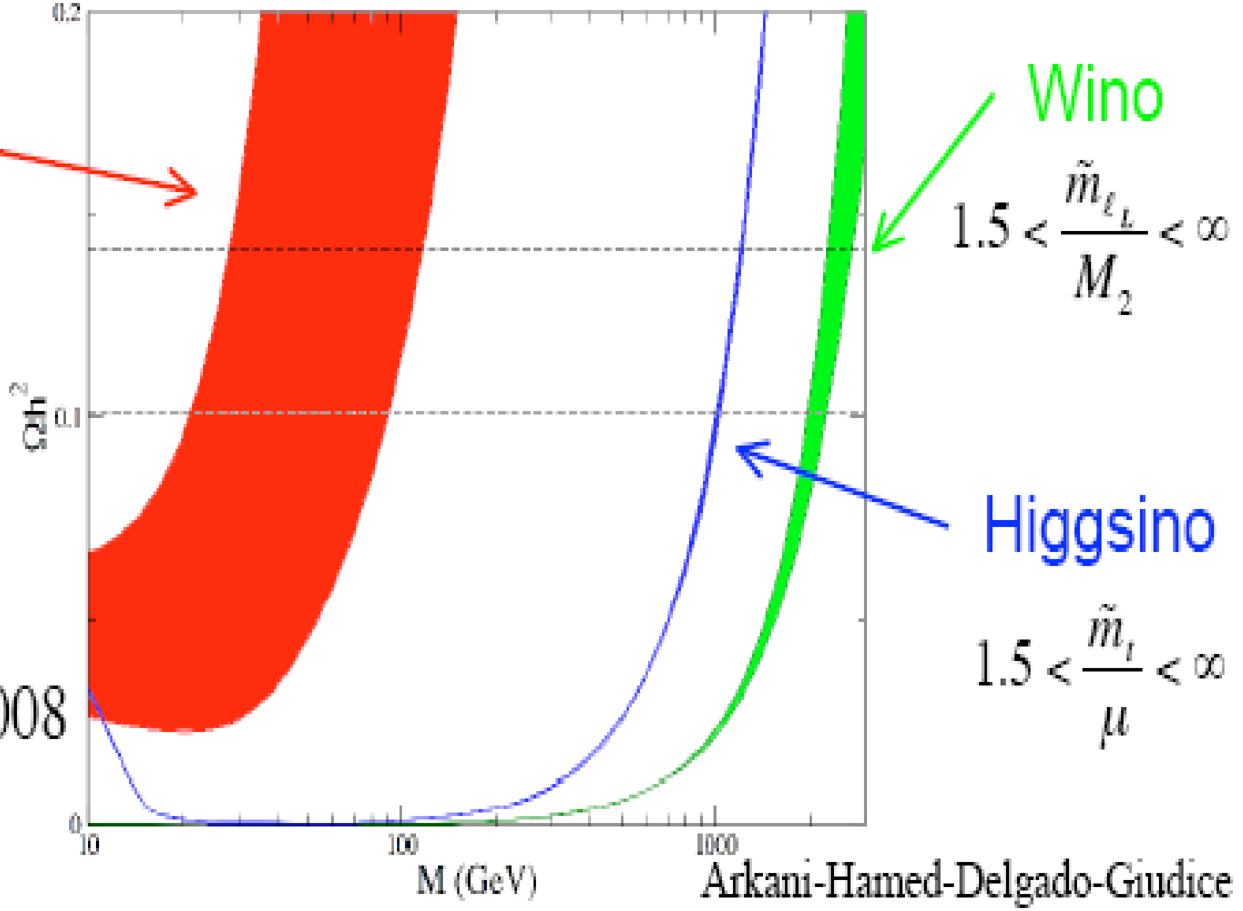
Distinctive ToF and energy loss signatures

"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

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



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

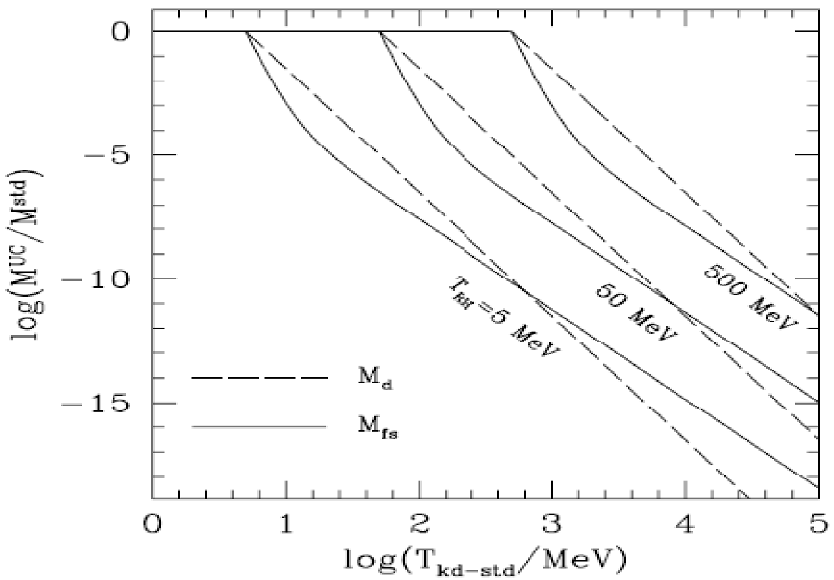
$$1.5 < \frac{\tilde{m}_{\ell_L}}{M_2} < \infty$$

$$1.5 < \frac{\tilde{m}_{t}}{\mu} < \infty$$

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

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
- **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

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",…

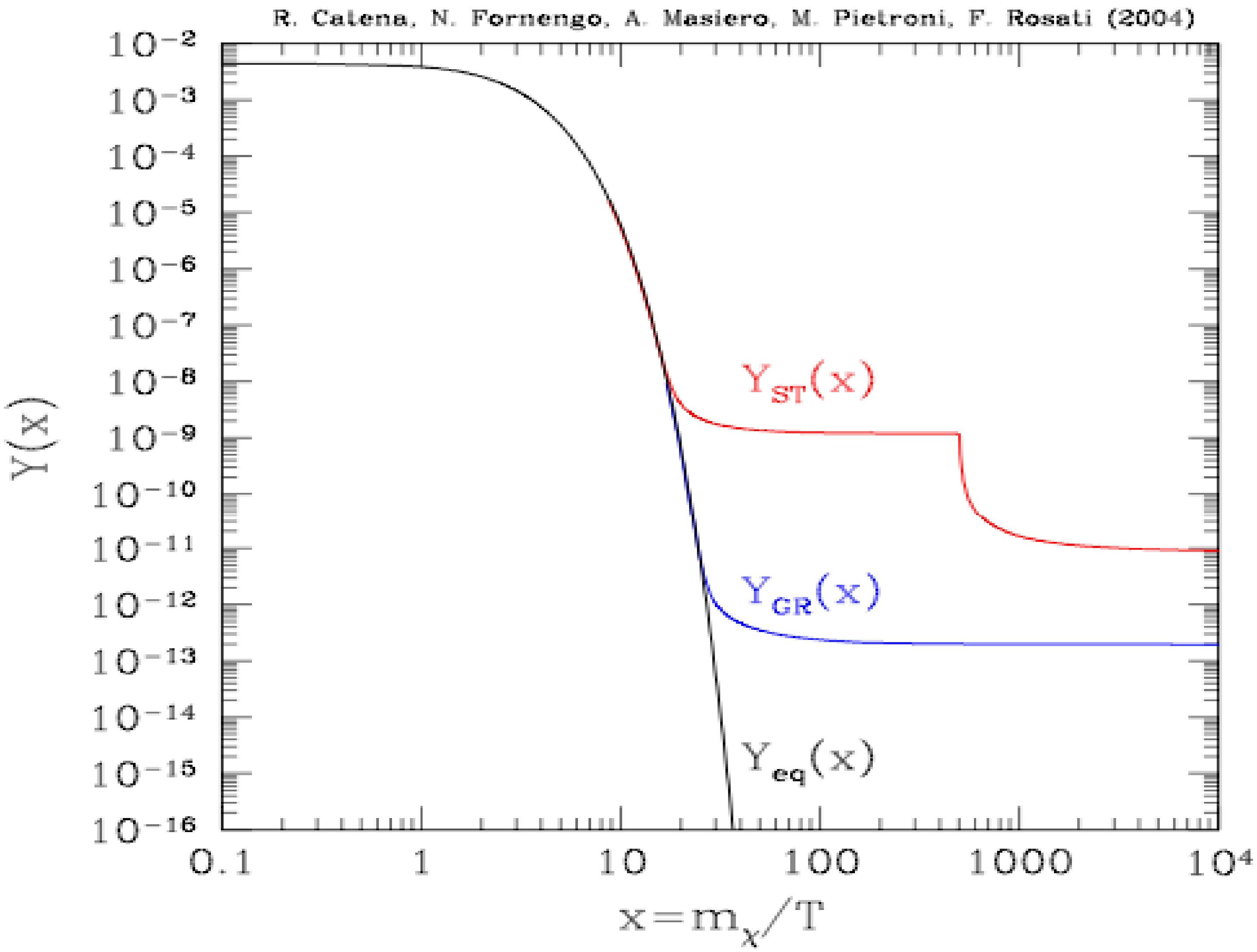
- **INFLUENCE OF ϕ ON THE NATURE AND THE ABUNDANCE OF CDM**

Modifications of the standard picture of
WIMPs FREEZE - OUT

CDM CANDIDATES

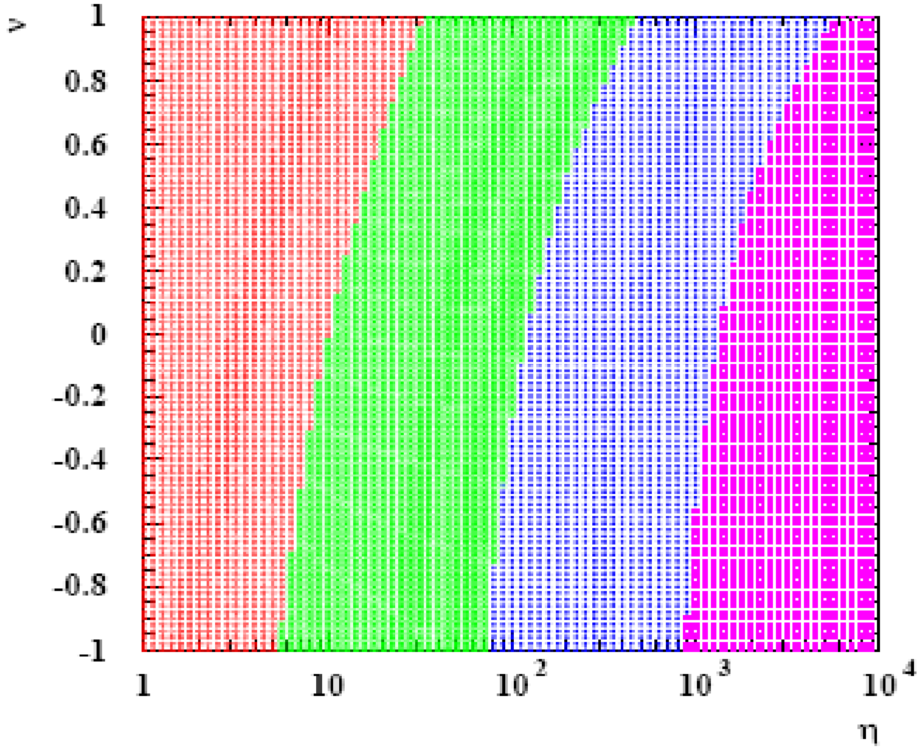
CATENA, FORNENGO, A.M., PIETRONI, SHELCKE

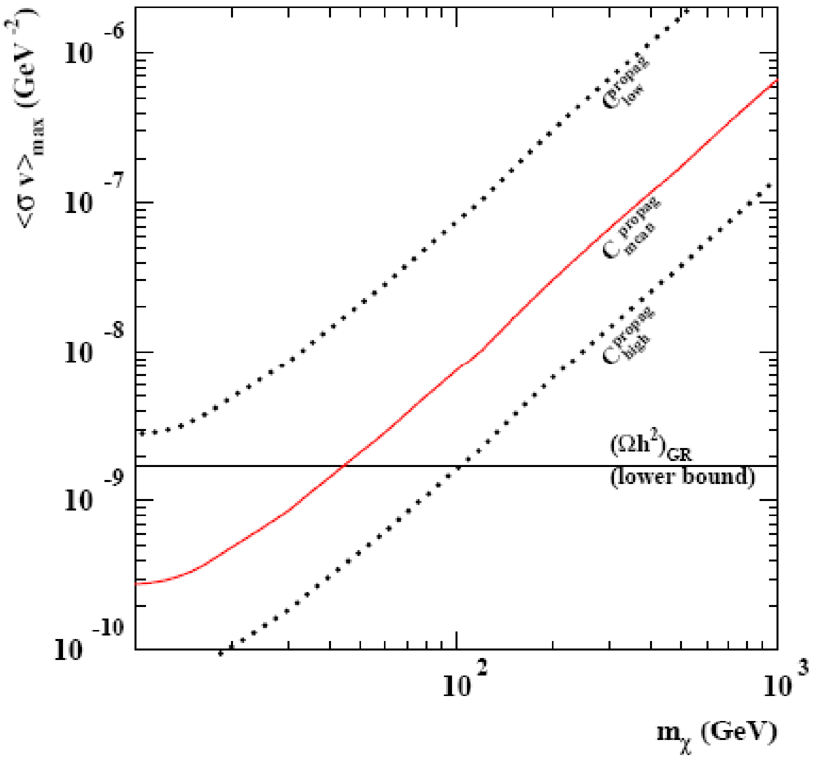
NEUTRALINO RELIC ABUNDANCE IN GR AND S-T THEORIES OF GRAVITY



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

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

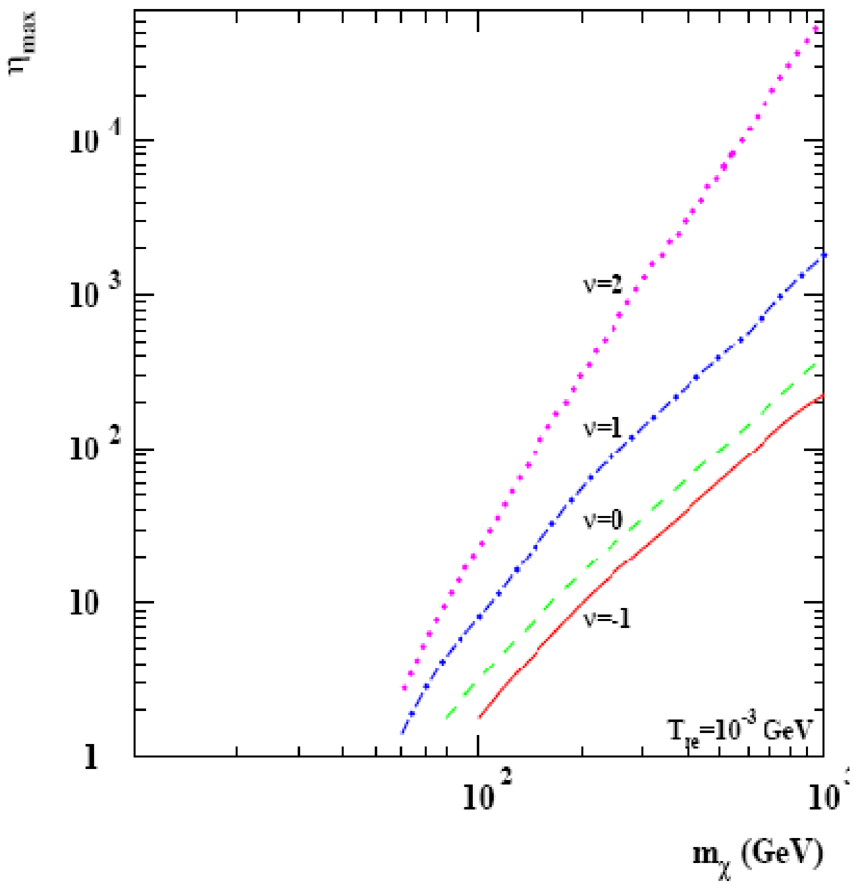


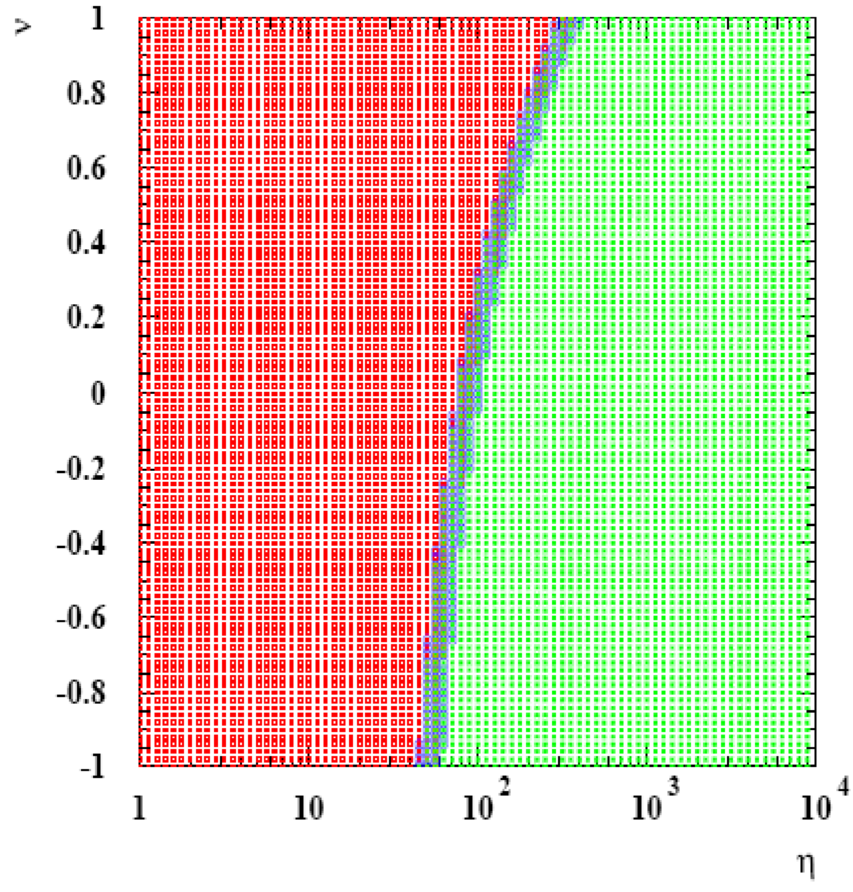


SCHELKE, CATENA, FORNENGO, A.M., PIETRONI

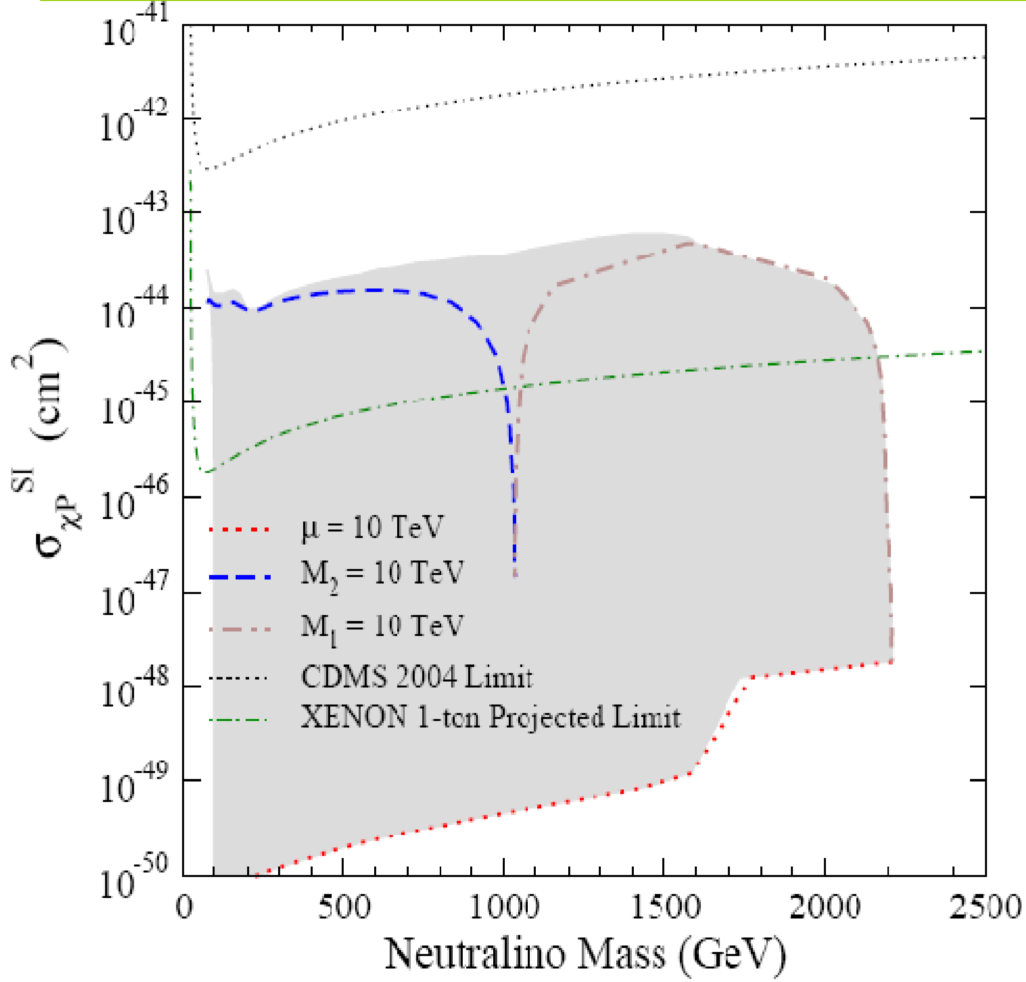
CONSTRAINTS ON THE ENHANCEMENT OF THE UNIV.EXPANSION RATE FROM THE LIMITS ON THE ANTIPROTON ABUNDANCE

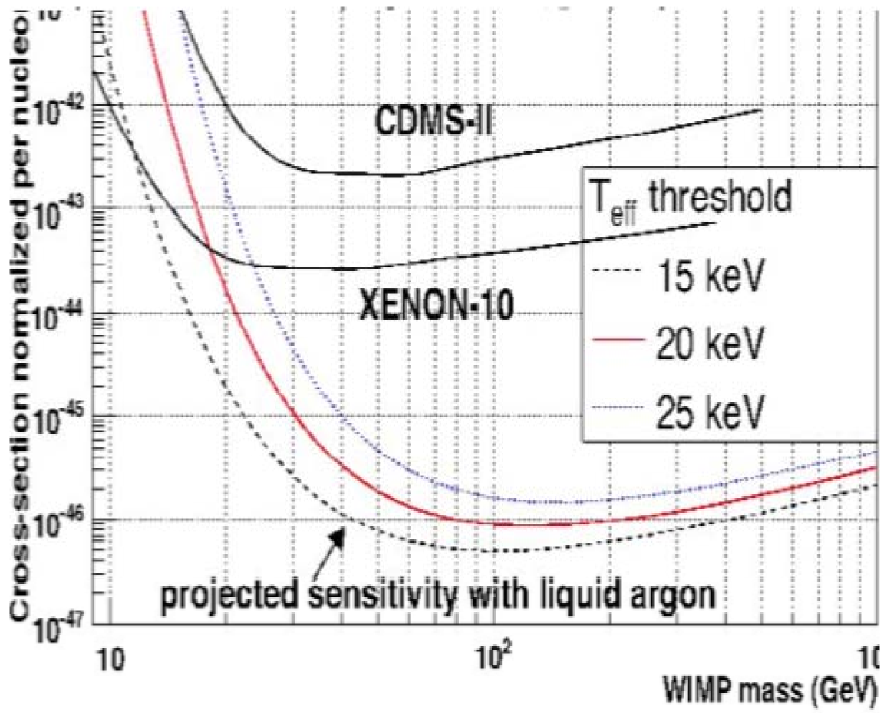
SCFMP





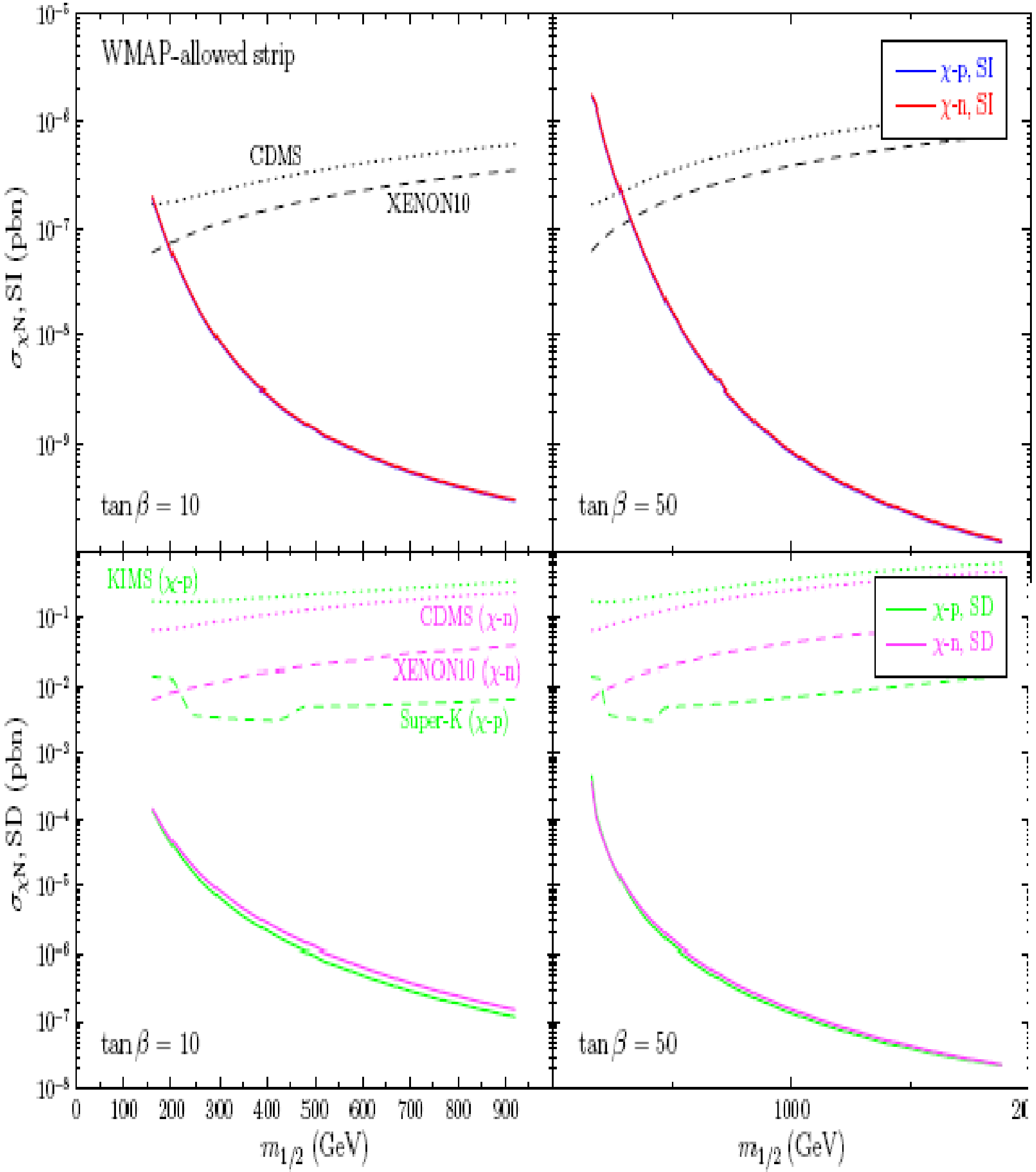
SPIN - INDEPENDENT NEUTRALINO - PROTON CROSS SECTION FOR ONE OF THE SUSY PARAM. FIXED AT 10 TEV





PROFUMO, A.M., ULLIO

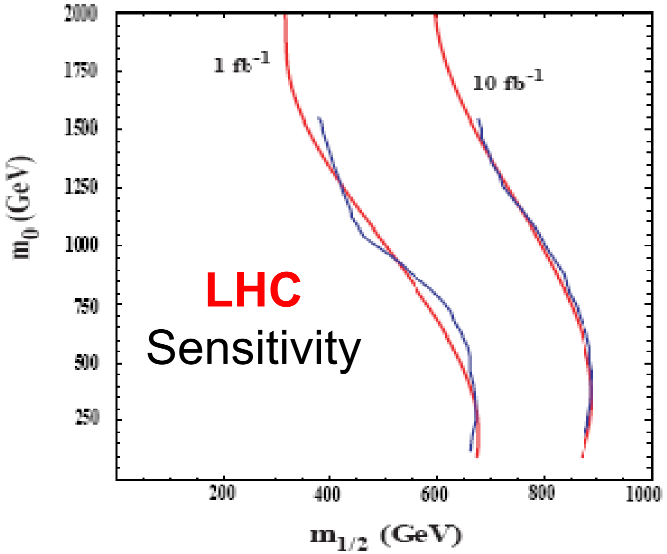
Neutralino-nucleon scattering cross sections along the WMAP-allowed coannihilation strip for tanbeta=10 and coannihilation/funnel strip for tanbeta=50 using the hadronic parameters



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

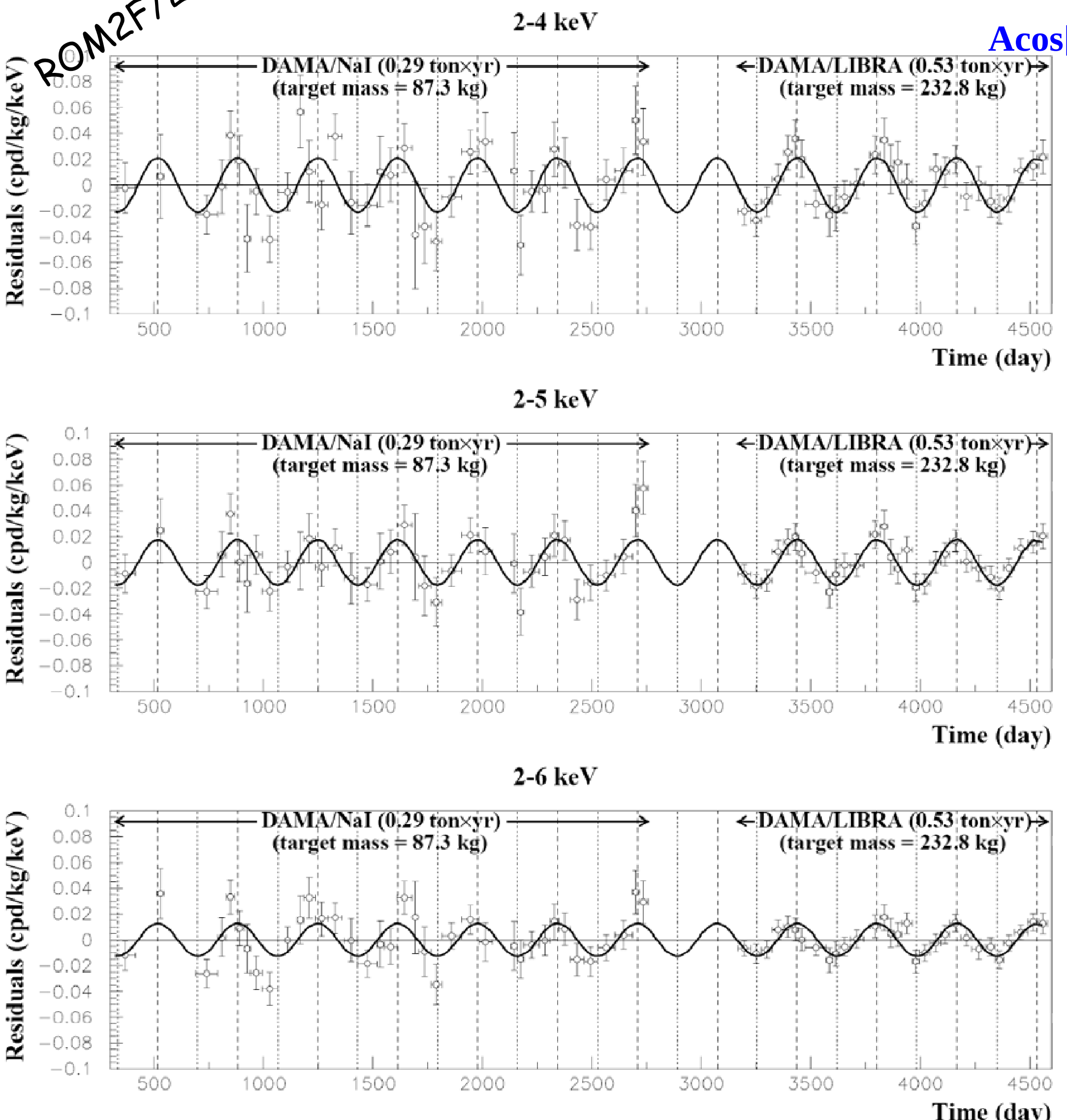


Model Independent Annual Modulation Result

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)   Total exposure: 300555 kg×day = 0.82 ton×yr

experimental single-hit residuals rate vs time and energy

$A\cos[\omega(t-t_0)]$; continuous lines: t_0 = 152.5 d, T = 1.00 y



2-4 keV

A=(0.0215±0.0026) cpd/kg/keV

χ^2/dof = 51.9/66   **8.3 σ C.L.**

Absence of modulation? No

χ^2/dof=117.7/67 ⇒ P(A=0) = 1.3×10^{-4}

2-5 keV

A=(0.0176±0.0020) cpd/kg/keV

χ^2/dof = 39.6/66   **8.8 σ C.L.**

Absence of modulation? No

χ^2/dof=116.1/67 ⇒ P(A=0) = 1.9×10^{-4}

2-6 keV

A=(0.0129±0.0016) cpd/kg/keV

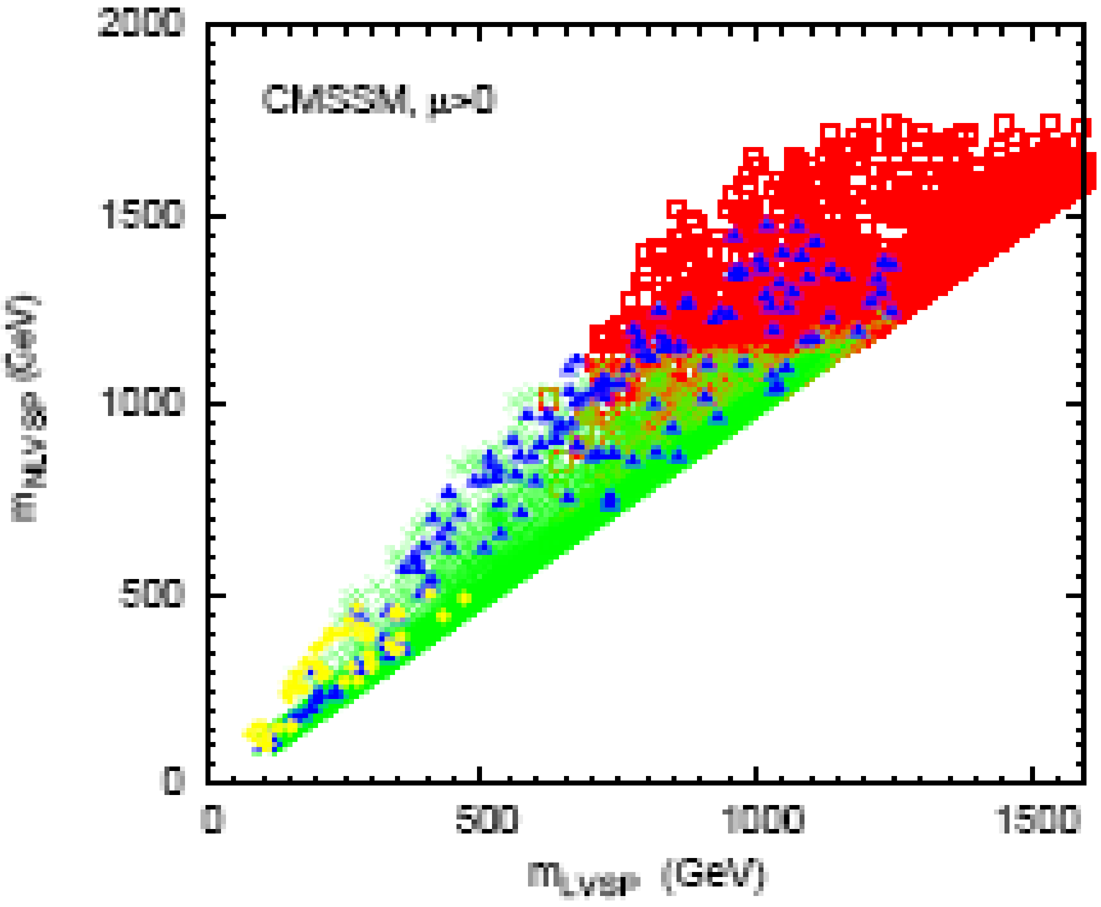
χ^2/dof = 54.3/66 **8.2 σ C.L.**

Absence of modulation? No

χ^2/dof=116.4/67 ⇒ P(A=0) = 1.8×10^{-4}

The data favor the presence of a modulated behavior with proper features at 8.2σ C.L.

PROSPECTS FOR DISCOVERING THE CMSSM AT THE LHC IN LIGHT OF WMAP



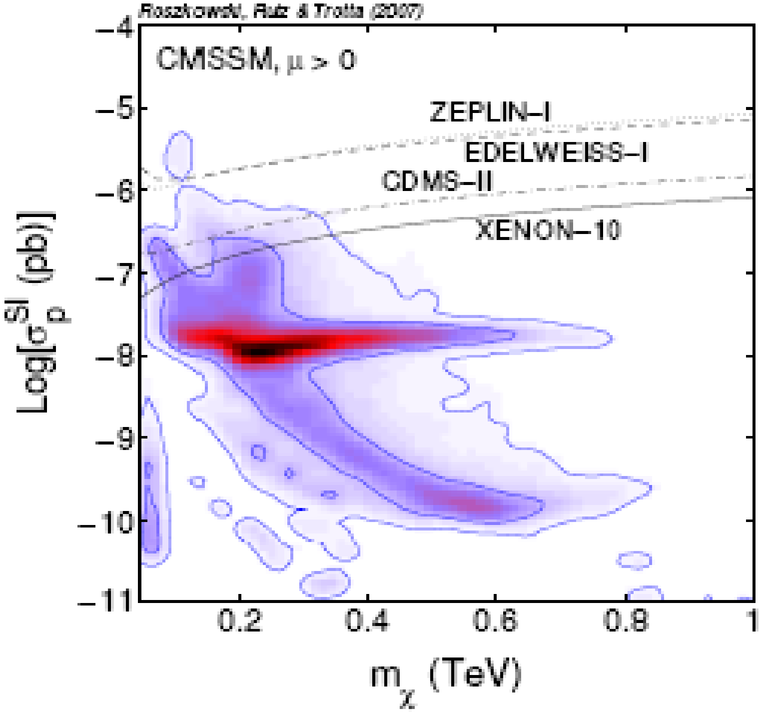
RED: FULL SAMPLE OF CMMS MODELS

BLUE: POINTS COMPATIBLE WITH WMAP

GREEN: POINTS ACCESSIBLE TO LHC

YELLOW: POINTS ACCESSIBLE TO PRESENT DIRECT DM SEARCHES

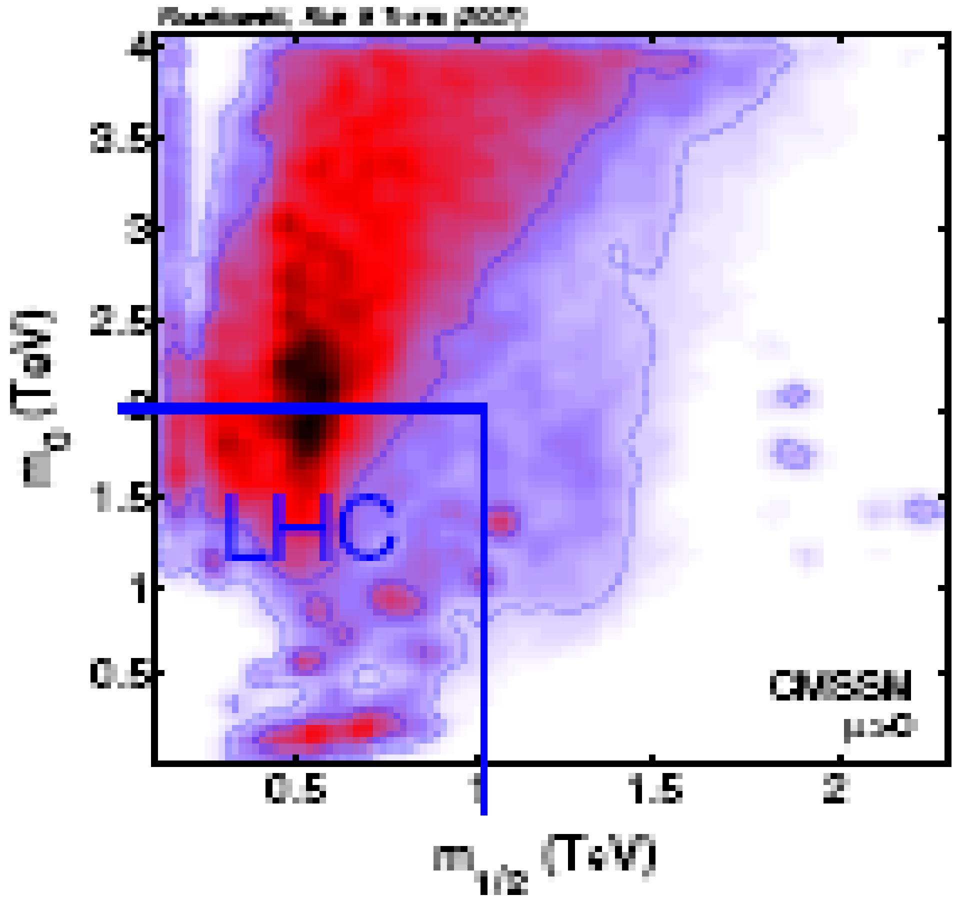
Ellis et al.



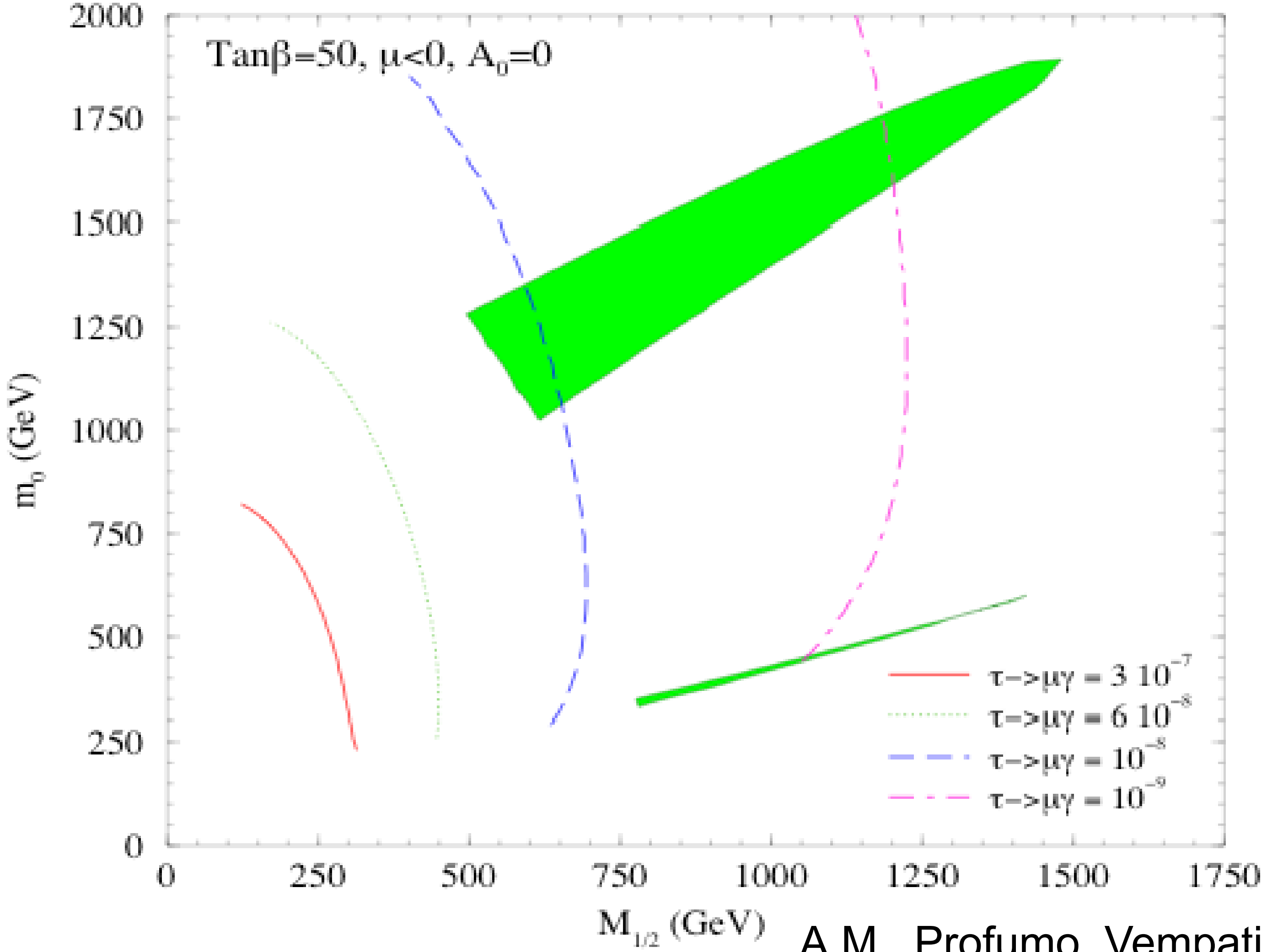
ultimately: “1 tonne” detectors:

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

will cover all 68% region



LFV - DM CONSTRAINTS IN MINIMAL SUPERGRAVITY



A.M., Profumo, Vempati, Yaguna

INDIRECT SEARCHES OF DM

- **WIMPs collected inside celestial bodies** (Earth, Sun): their annihilations produce energetic neutrinos
- **WIMPs in the DM halo**: WIMP annihilations can take place (in particular, their rate can be enhanced with there exists a CLUMPY distribution of DM as computer simulations of the DM distribution in the galaxies seem to suggest. From the WIMP annihilation:

-- **energetic neutrinos** (under-ice, under-water exps Amanda, Antares, Nemo, Antares,Nestor future IceCube, KM3 …)

--**photons in tens of GeV range** (gamma astronomy on ground Magic, Hess, future ACT , Argo… or in space Agile, Glast…)

--**antimatter:** look for an excess of antimatter w.r.t. what is expected in cosmic rays (space exps. Pamela, AMS, …)

SEARCHING FOR 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

FROM “KNOWN” COSM. ABUNDANCE OF WIMPs → PREDICTION FOR WIMP PRODUCTION AT COLLIDERS WITHOUT SPECYFING THE PART. PHYSICS MODEL OF WIMPs

BIRKEDAL, MATCHEV, PERELSTEIN ,
FENG,SU, TAKAYAMA

The muon g-2: Standard Model vs. Experiment

- Adding up all the above contribution we get the following SM predictions for a_μ and comparisons with the measured value:

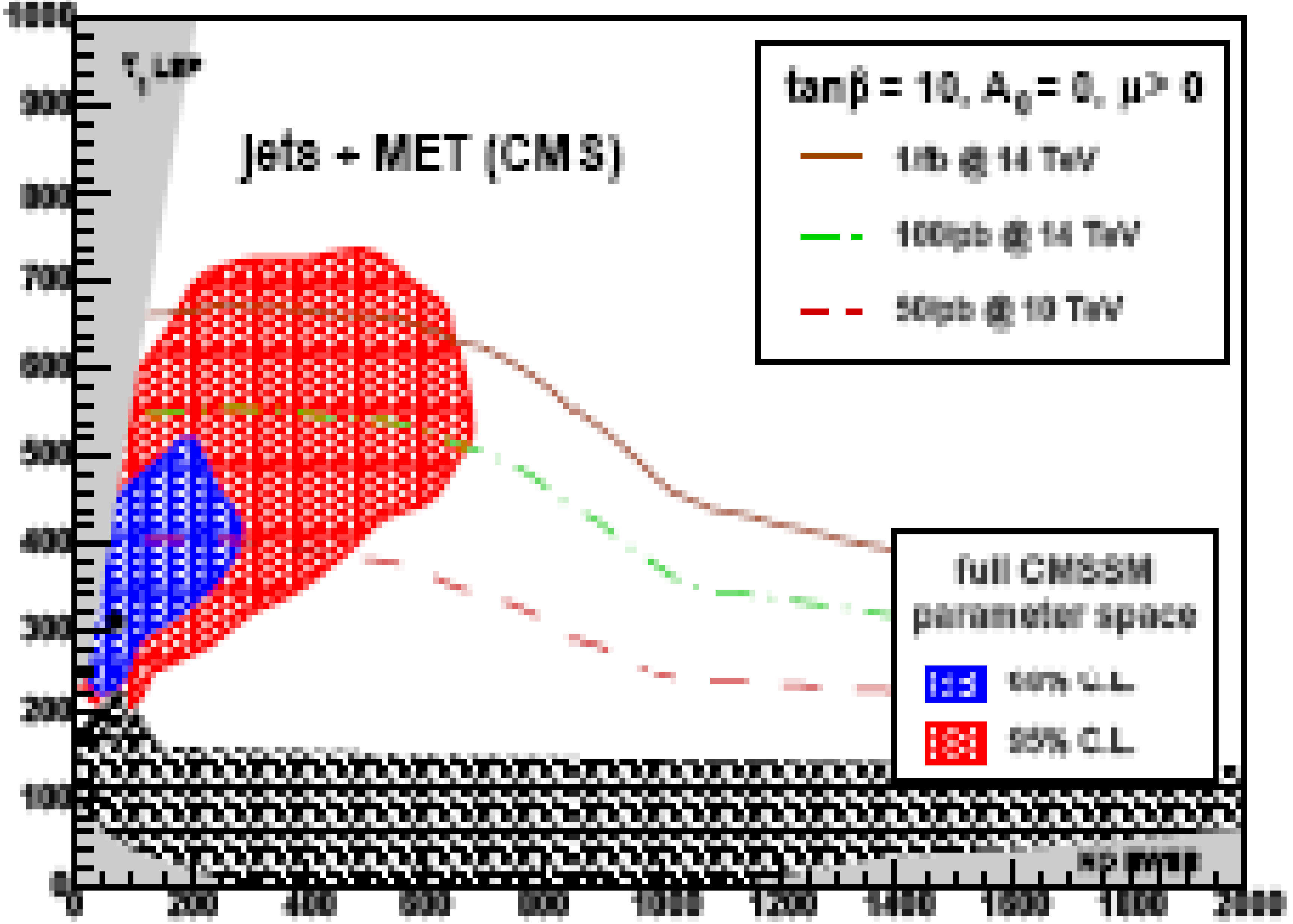
	$a_\mu^{SM} \times 10^{11}$	$\Delta a_\mu \times 10^{11}$	σ
[1]	116 591 793 (60)	287 (87)	3.3
[2]	116 591 778 (61)	302 (88)	3.4
[3]	116 591 807 (72)	273 (96)	2.8
[4]	116 591 828 (63)	252 (89)	2.8
[5]	116 591 991 (70)	89 (95)	0.9

with $a_\mu^{HHO}(lbl) = 110\ (40) \times 10^{-11}$. $\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$.

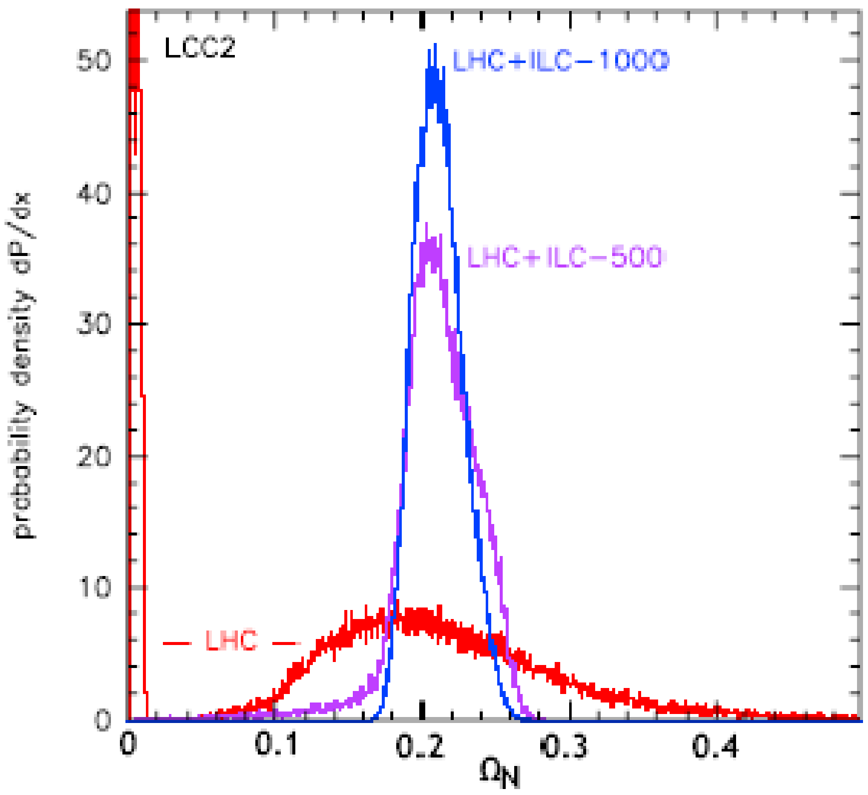
[1] Eidelman at ICHEP06 & Davier at TAU06 (update of ref. [5]).
[2] Hagiwara, Martin, Nomura, Teubner, PLB649 (2007) 173.
[3] F. Jegerlehner, PhiPsi 08, Frascati, April 2008.
[4] J.F. de Troconiz and F.J. Yndurain, PRD71 (2005) 073008.
[5] Davier, Eidelman, Hoecker and Zhang, EPJC31 (2003) 503 (τ data).

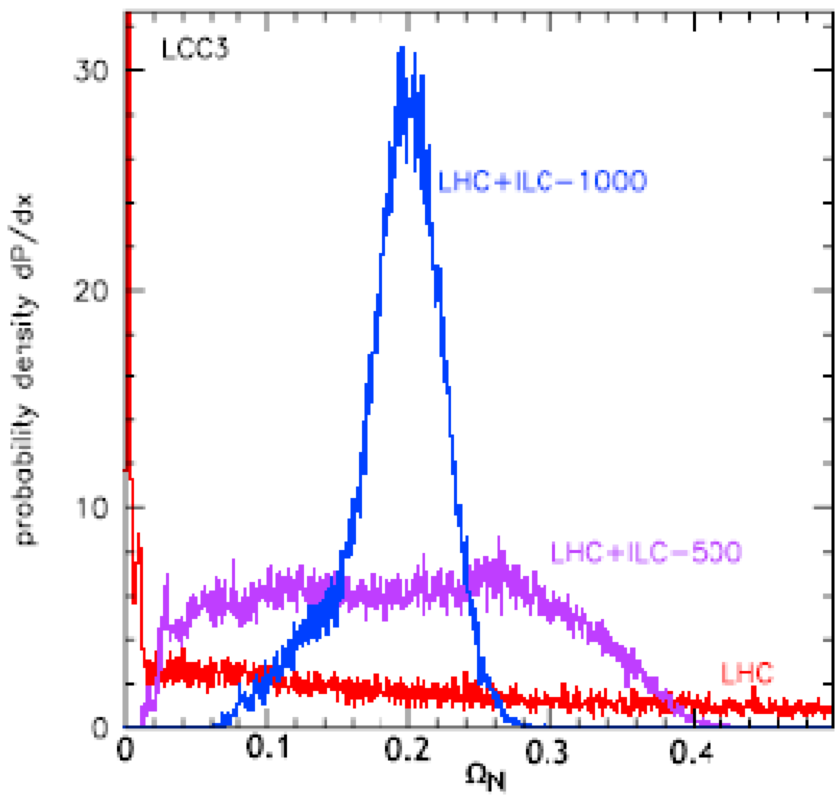
- The th error is now the same (or even smaller) as the exp. one!
- If BaBar's prelim. results are used instead, Δa_μ drops to ~1.7σ.

Courtesy of M. Passera

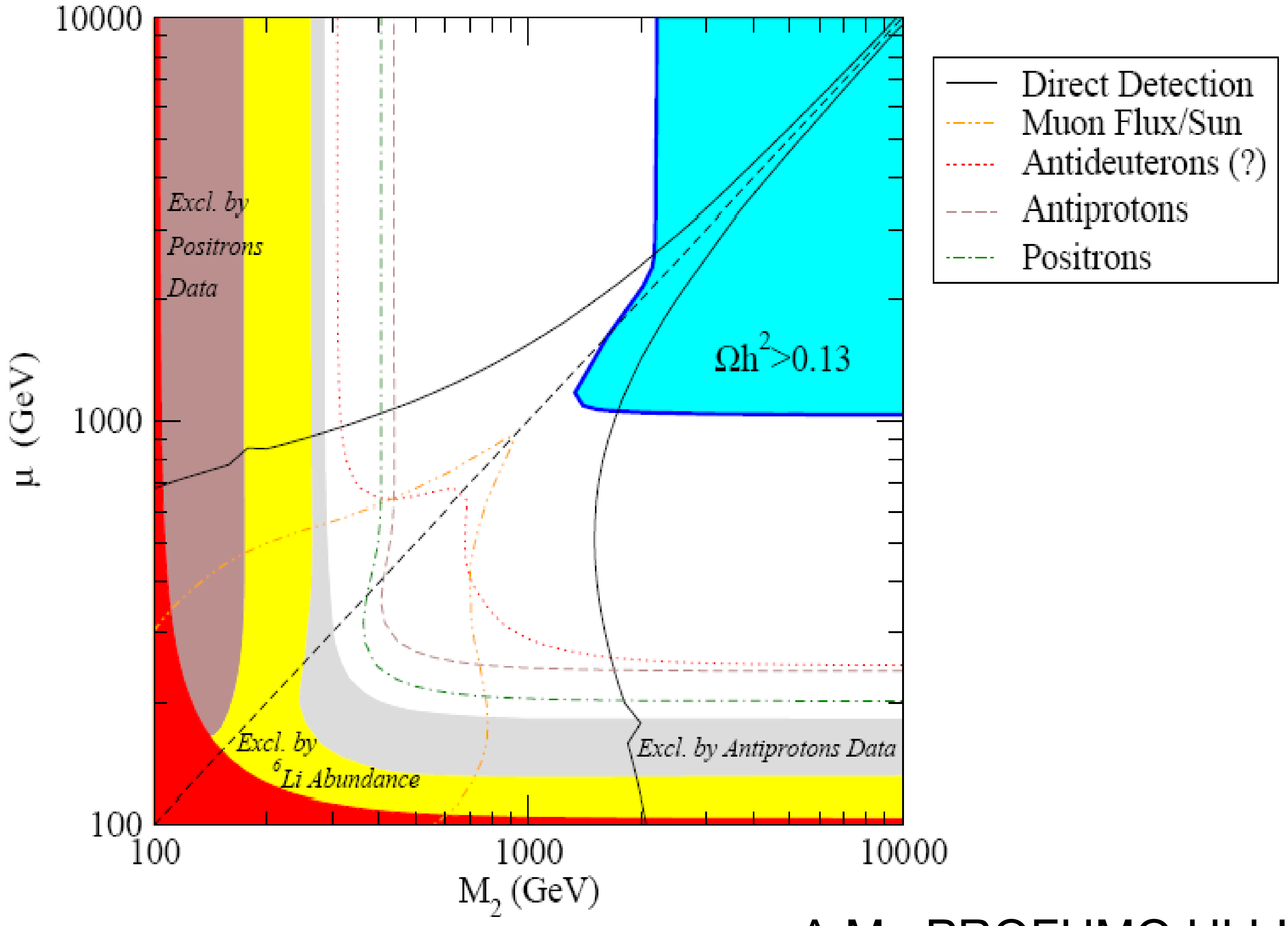

tanβ = 10, A0 = 0, μ> 0
1/fb @ 14 TeV
100/pb @ 14 TeV
50/pb @ 10 TeV
Jets + MET (CMS)
full CMSSM
parameter space
68% C.L.
95% C.L.
0
100
200
300
400
500
600
700
800
900
1000
0
200
400
600
800
1000
1200
1400
1600
1800
2000

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



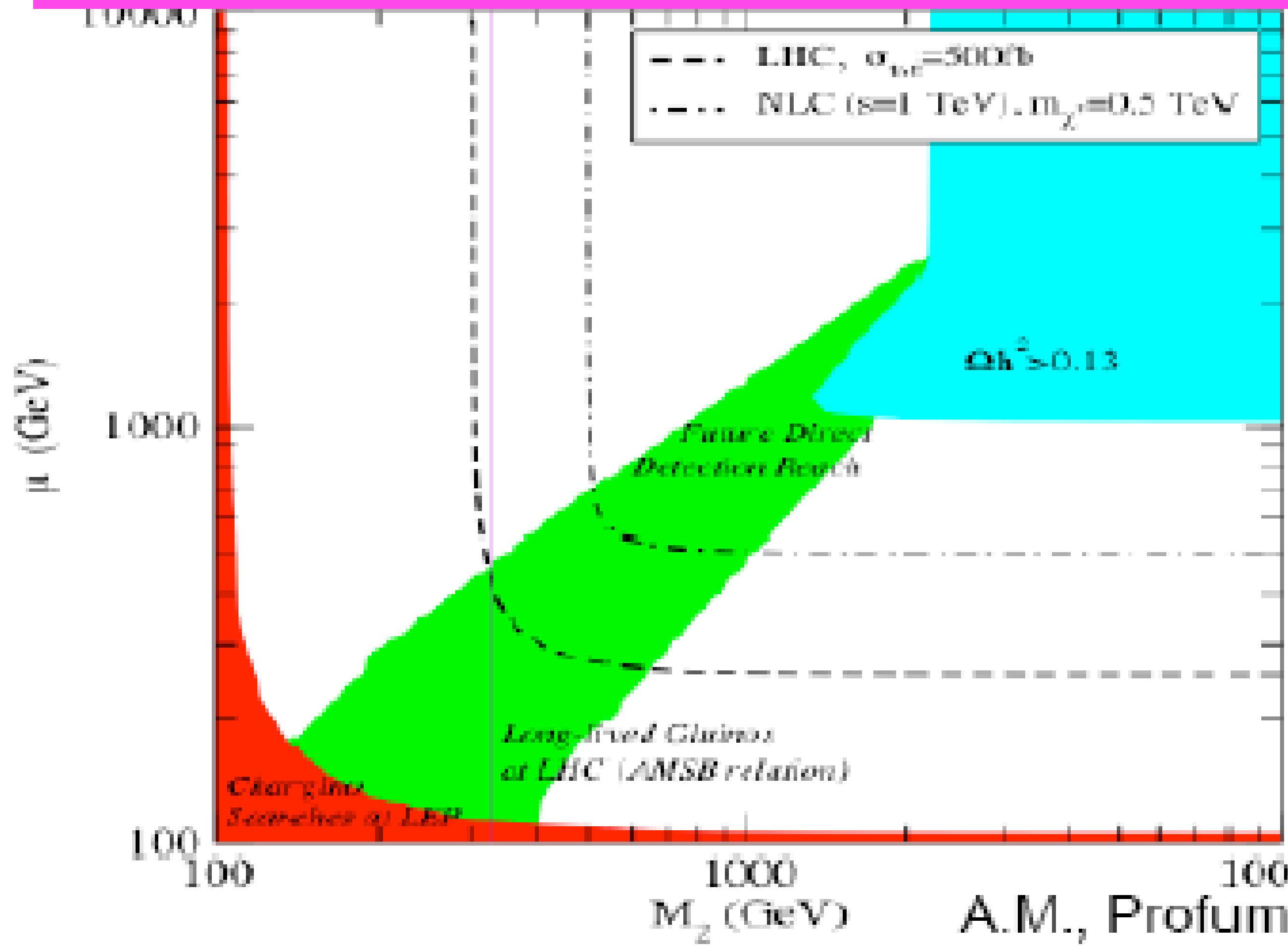


BALTZ, BATTAGLIA, PESKIN, WIZANSKY



A.M., PROFUMO,ULLIO

LHC, ILC, DM SEARCHES SENSITIVITIES



A.M., Profumo, Ullio

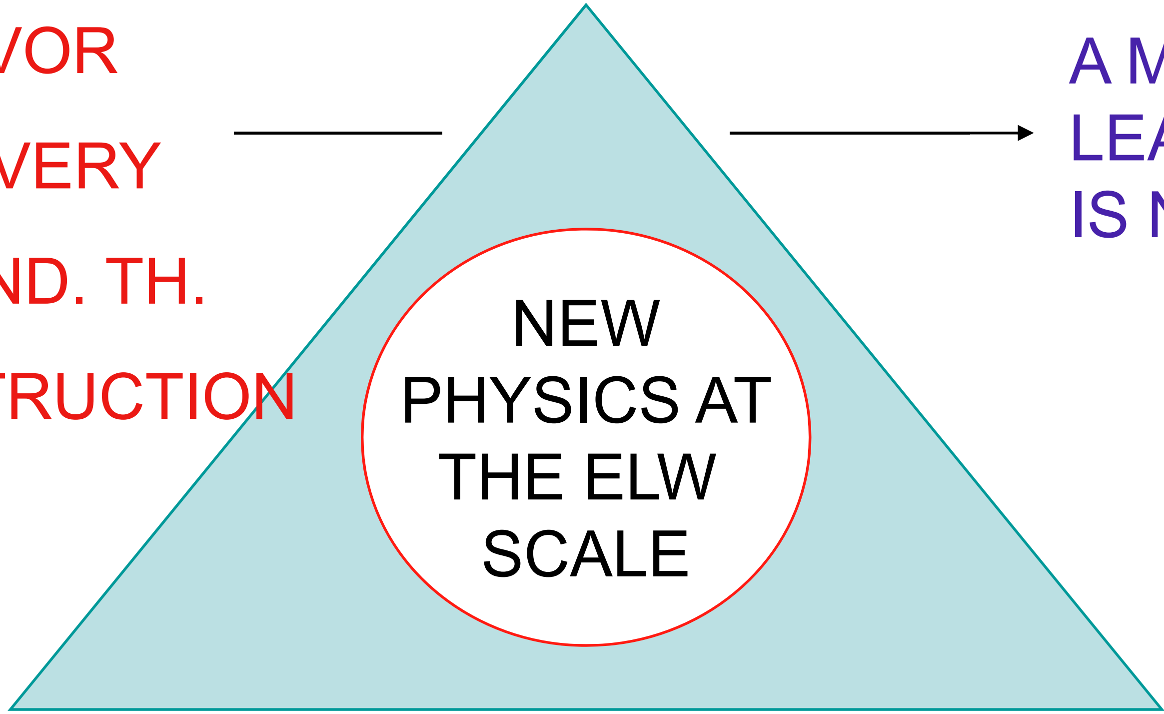
TEVATRON → LHC → I L C

DM - FLAVOR

for DISCOVERY

and/or FUND. TH.

RECONSTRUCTION



A MAJOR LEAP AHEAD IS NEEDED

DARK MATTER

m_χ n_χ σ_χ…

LINKED TO COSMOLOGICAL EVOLUTION

→ Possible interplay with dynamical DE

"LOW ENERGY" PRECISION PHYSICS

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

LFV

INFLATION

LEPTOGENESIS

NEUTRINO PHYSICS

Some final thoughts

- Very solid evidence of (a large amount of) **NON-BARYONIC COLD DM**
- In the **SM NO CANDIDATE FOR COLD DM** (ordinary neutrinos are hot DM; indeed, the best limit on neutrino masses comes from cosmology!)
- **WIMPS**: (very) appealing **COSMO (HBB SM) – PARTICLE (GWS SM) "conspiracy" in providing the (quantitatively and qualitatively) right DM**
- WIMPS can be part of the **NEW PHYSICS at the ELW** scale (link ultraviolet completion of the SM – DM constituents)
- Possibility of a **joint cosmo – and particle – exploration of the TeV New Physics**
- **If WIMP is the DM: complementary hunting for TeV New Physics at LHC and in DIRECT and INDIRECT searches of DM**