Supersymmetric models in light of colliders and astroparticles constraints

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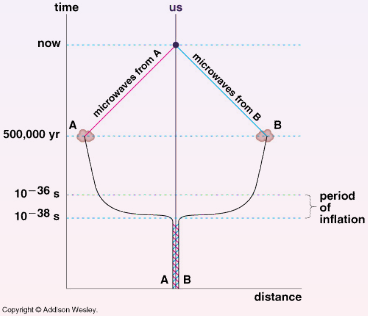
Based on :
D. A. Vasquez, G. Belanger, C. Boehm, JDS, P. Richardson and C. Wymant, Phys. Rev. D86 (2012) 035023, arXiv:1203.3446,
C. Bœhm, JDS, A. Mazumdar and E. Pukartas, JCAP submitted (2012), arXiv:1205.2815,
G. Bélanger, C. Bœhm, M. Cirelli, JDS and A. Pukhov, JCAP submitted (2012), arXiv:1208.5009

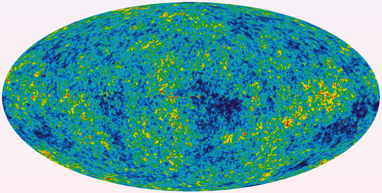
Outline

Motivations

Motivations

- **Inflation motivations**
  - Flatness problem (fine-tuning problem on Ω_k)
  - Horizon problem
  - Monopole problem (topological defect not seen)



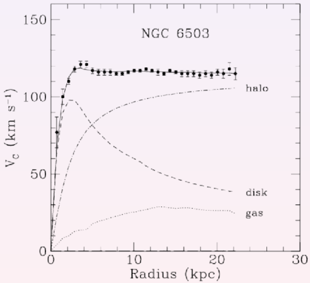


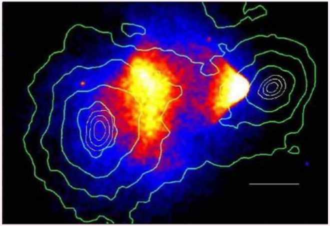
WMAP7

$\Rightarrow$ Cosmic inflation (fast expansion phase in the early universe) embedded in Grand Unified Theories (GUT)

Motivations

- **Inflation motivations**
- **Dark matter (DM) motivations**
  - Galaxy scale : rotation curves of galaxies
  - Galaxy clusters scale : example of the bullet cluster
  - Cosmological scale (CMB), large scale structures, ...



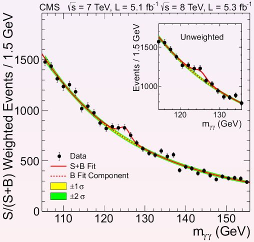


K. G. Begeman, A. H. Broeils and R. H. Sanders, 1991, MNRAS, 249, 523
A direct empirical proof of the existence of dark matter, D. Clowe et al., Astrophys. J. 648 L109-L113, 2006

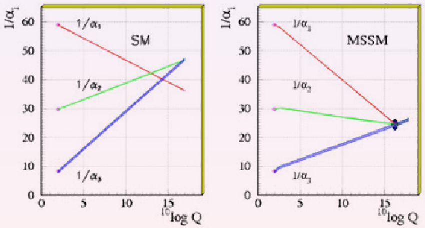
$\Rightarrow \Omega_b h^2 = 0.0226 \pm 0.0005$ and $\Omega_{DM} h^2 = 0.1123 \pm 0.0035$
DM has to be stable and weakly charged under the standard model gauge group

Motivations

- **Inflation motivations**
- **Dark matter (DM) motivations**
- **Supersymmetry (SUSY) motivations**
  - **Hierarchy problem on Higgs boson mass**
  - **Unification at GUT scale $\Rightarrow$ cosmic inflation embedded in supersymmetric models**
  - **LSP/DM (supersymmetry breaking, R-Parity)**



CMS searches on the Higgs boson



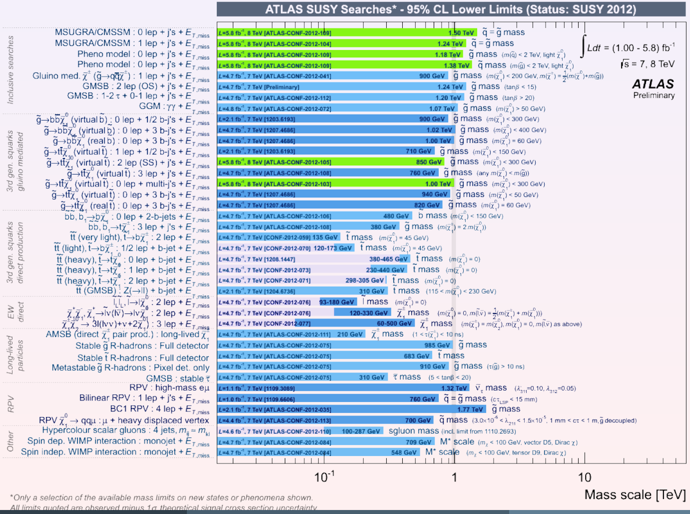
Gauge coupling unification

The lightest supersymmetric particle (LSP) is stable, at TeV scale, and can be weakly charged under the SM gauge group
$\Rightarrow$ DM candidates in supersymmetric models

Collider searches for SUSY particles

Context

Searches for exotic particles are now reaching a high level of exclusion that allow to reject a wide class of models, but limits obtained assuming simplified models of New Physics



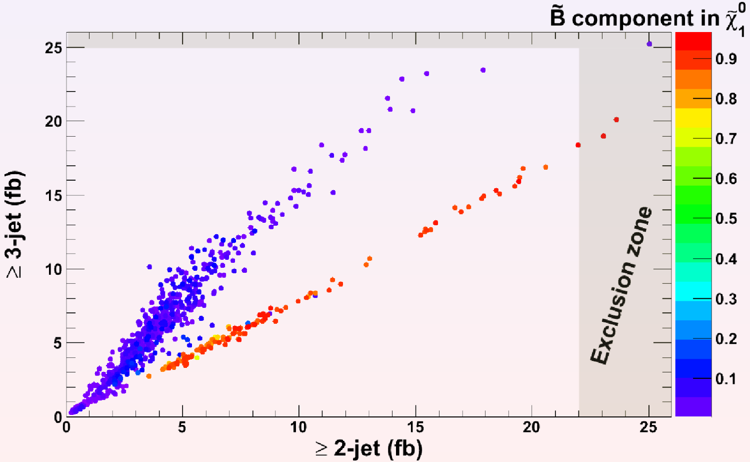
Weaken bounds in the NMSSM

Example of the exclusion limit coming from the ATLAS 1.04 fb^{-1} search for squarks and gluinos via jets and missing E_T
In general exclude squarks lighter than 0.6 - 1 TeV and gluinos below 0.5 TeV in the constrained MSSM via $\tilde{q} \to q\chi_1^0$ and $\tilde{g} \to q\bar{q}\chi_1^0$ decays
What about the NMSSM ?

- $W_{NMSSM} = W_{MSSM}(\mu = 0) + \lambda S H_u H_d + \frac{1}{3}\kappa S^3$
- $\mathcal{L}^{NMSSM}_{\text{Higgs soft}} = m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|S|^2 + (\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + \mathrm{h.c.})$
  $\Rightarrow$ less fine tuned $m_{h_1} \sim 125$ GeV
- 5 Neutralinos χ_i^0 in the basis $(\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$
- Using results of a previous work (D. Albornoz Vasquez et al., 1107.1614, 1201.6150) with constraints on DM (relic density upper bound, indirect and direct detection constraints), on B and Higgs physics to define the relevant NMSSM parameter space
- Applying SUSY searches@LHC with ATLAS's 1.04 fb^{-1} 0-lepton jets + missing E_T search using Herwig++ 2.5.1 and RIVET 1.5.2
  $\Rightarrow$ Are ATLAS limits so constraining ?

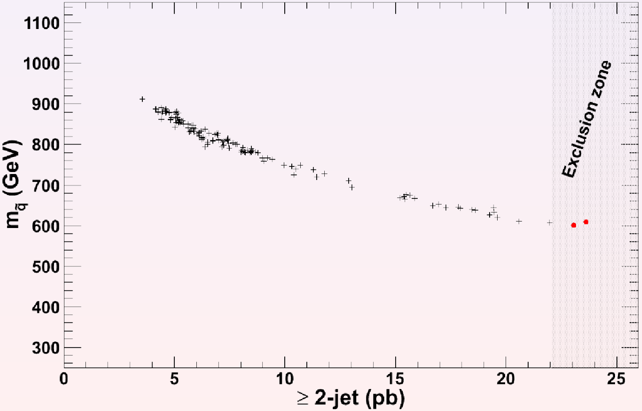
Results

- Reduced acceptance into Jets + missing E_T search channels and more jets for singlino LSP
- $\tilde{\mathbf{q}} \to \mathbf{q} + (\chi_2^0 \to \chi_1^0 + (\mathbf{f\bar{f}} \text{ or } \mathbf{A_1} \text{ or } \mathbf{h_1}))$



Results

- Reduced acceptance into Jets + missing E_T search channels and more jets for singlino LSP
- $\tilde{q} \rightarrow q + (\chi_2^0 \rightarrow \chi_1^0 + (f\bar{f} \text{ or } A_1 \text{ or } h_1))$
- Usual exclusion ($\tilde{B}$-like LSP) :



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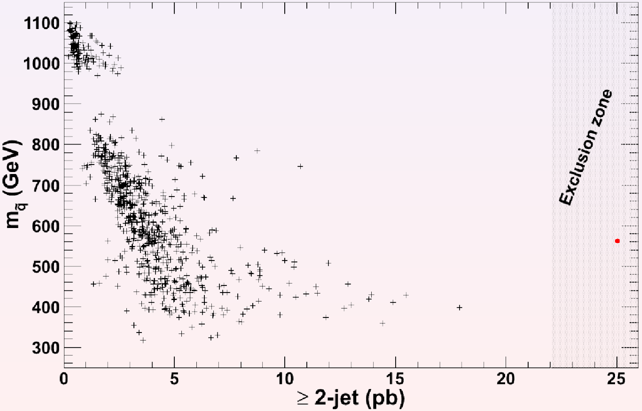
- 300 GeV squarks allowed when ($\tilde{\text{S}}$-like LSP) :



Supersymmetric inflaton

Models chosen

- **NUHM2**
  - Supersymmetric model with gravity-mediated supersymmetry breaking based on the MSSM
  - Most popular : mSUGRA/CMSSM, universal scalar masses is assumed, free parameters :

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta \text{ and } \mathrm{sign}(\mu)$$

  - Drawbacks : $m_h \sim 125$ GeV not easy, LSP mostly bino
  - We considered a non-universal scalar masses model, with $m_0^2 \neq m_{H_u}^2 \neq m_{H_d}^2$ (see H. Baer et al [hep-ph/0504001], J. R. Ellis et al [hep-ph/0210205])
  - $\Rightarrow$ Easier to reach $m_h = 125$ GeV, increase DM annihilation rates with higgsino LSP
  - NUHM2 free parameter :

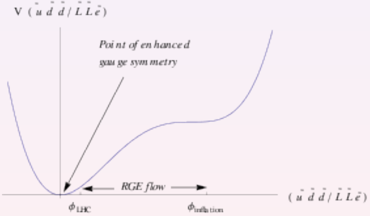
$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mu \text{ and } M_A$$

Models chosen

- **NUHM2**
- **$\widetilde{L}\widetilde{L}\widetilde{e}$ and $\widetilde{u}\widetilde{d}\widetilde{d}$**
  - Inflaton, scalar field whose flat direction potential (with a non-negligible slope) leads to the end of the inflation phase
  - Charged under the visible sector of the particle physics model considered, i.e. NUHM2
  - supersymmetric scalar potential :

$$V = \sum_i |F_i|^2 + \frac{1}{2}\sum_a g_a^2 D^a D^a,$$

$$F_i \equiv \frac{\partial W}{\partial \phi_i}, \quad D^a = \phi^\dagger T^a \phi,$$



  - $\Rightarrow$ $\widetilde{L}\widetilde{L}\widetilde{e}$ and $\widetilde{u}\widetilde{d}\widetilde{d}$ D-terms can be such candidates
  - Lifted by higher order superpotential terms $W \supset \frac{\lambda}{6}\frac{\Phi^6}{M_P^3}$, Φ scalar component : $V(\phi) = \frac{1}{2}m_\phi^2\,\phi^2 - A\frac{\lambda\phi^6}{6\,M_P^3} + \lambda^2\frac{\phi^{10}}{M_P^6}$

$$\phi = \frac{\widetilde{u}+\widetilde{d}+\widetilde{d}}{\sqrt{3}}, \quad \phi = \frac{\widetilde{L}+\widetilde{L}+\widetilde{e}}{\sqrt{3}}$$

$$\phi^4_{\text{inflation}} \simeq \frac{m_\phi M_P^3}{\lambda\sqrt{10}}, \; V''(\phi_{\text{inflation}}) = 0$$

(see R. Allahverdi et al, [hep-ph/0610134], [hep-ph/0605035])

Constraints and method

Constraints imposed on a scan made using Markov Chain Monte Carlo method :

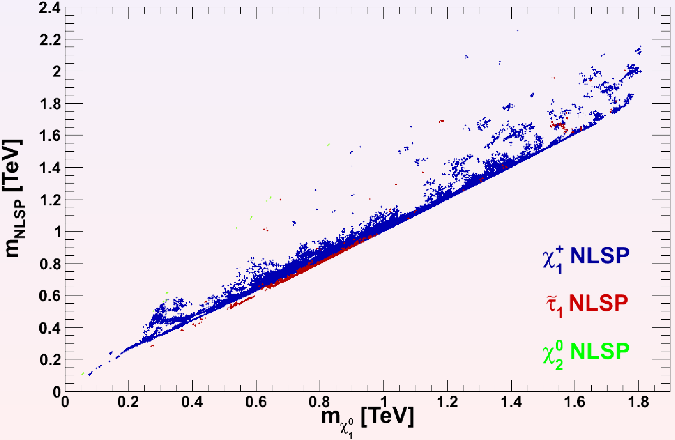
- On inflation, explain the observed temperature anisotropy in the CMB with :
  - The amplitude of density perturbations $\delta_H = \frac{8}{\sqrt{5}\pi} \frac{m_\phi M_P}{\phi_0^2} \frac{1}{\Delta^2} \sin^2[\mathcal{N}_{COBE}\sqrt{\Delta^2}]$,
    $\Delta^2 \equiv 900\alpha^2 \mathcal{N}_{COBE}^{-2} \left(\frac{M_P}{\phi_0}\right)^4$, $\quad \mathcal{N}_{COBE} \sim 50$
  - The scalar spectral index n_s of the corresponding power spectrum $n_s = 1 - 4\sqrt{\Delta^2} \cot[\mathcal{N}_{COBE}\sqrt{\Delta^2}]$,
- On the Cold DM candidate, χ_1^0 : $\Omega_{WIMP} h^2 = 0.1123 \pm 0.0035$ (WMAP7), DM-nucleon scattering cross section bounds (XENON100)
- On NUHM2 model in general :
  - $m_h \in [115.5, 127]$ GeV
  - B-physics : $BR(b \to s\gamma)$, $BR(B_s \to \mu^+\mu^-)$ and $BR(B^+ \to \tau^+\bar{\nu}_\tau)$
  - Electroweak observables : $(g_\mu - 2)$, $\Delta\rho$, $Z \to$ invisible, $\sigma_{e^+e^- \to \chi_1^0\chi_{2,3}^0} \times Br(\chi_{2,3}^0 \to Z\chi_1^0)$

In our study, SUSY contributions are not large so that both $(g_\mu - 2)$ and $BR(B^+ \to \tau^+\bar{\nu}_\tau)$ are well below the measured value

The other electroweak observables apply mainly for light LSP, not the case in this study

Results

- Hard to accommodate the correct LSP relic density with Higgs boson mass constraint for bino-like LSP (whose mass is close to $M_A/2$)
- Get mainly higgsino-like LSP, degeneracy between $\chi^0_{1,2}$ and $\chi^\pm_1$



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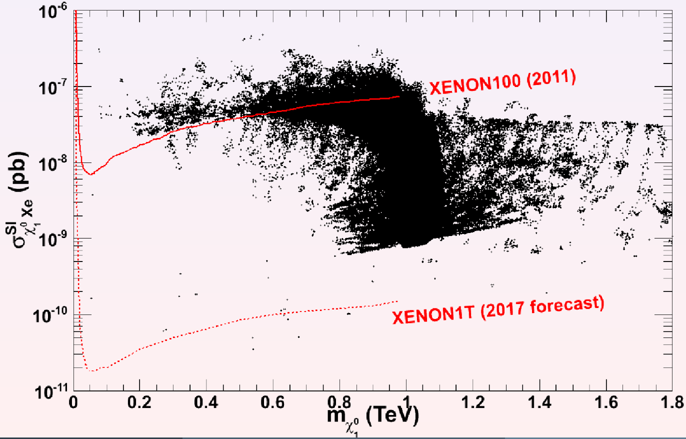
- NUHM2 scenarios within LHCb and XENON1T experiments sensitivity



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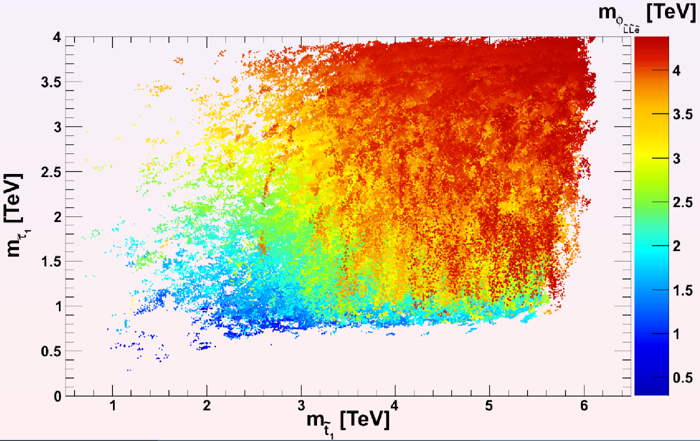
- NUHM2 scenarios within LHCb and XENON1T experiments sensitivity
- Keys on inflaton mass if we discover lightest stop/stau at LHC



DM Indirect Detection limits on the neutralino-chargino mass degeneracy

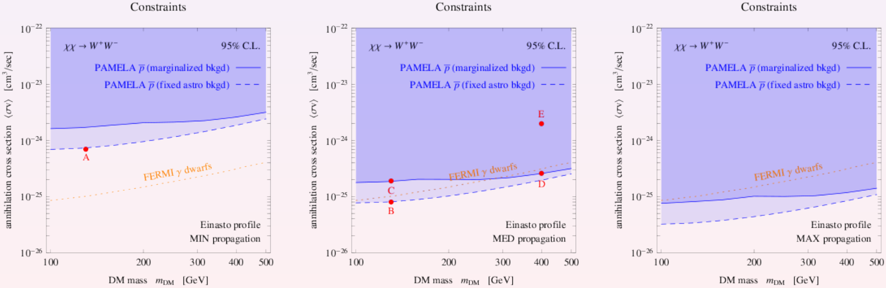
ID "state of the art"

- Indirect Detection (ID) of DM, namely search for anomalous features in cosmic rays $(\gamma, \nu, e^+, \bar{p})$ proposed at the end of the 70's to be a powerful tool to look for DM (Gunn et al., Stecker '78, Zeldovich et al. '80, ...)
- "Background drawback" : ID depends on the current knowledge of astrophysical sources
  - Remove carefully known (modelled) background
  - Clear features no mimicked by astrophysical sources
- Several claims : e^+ excess (Adriani et al. '09, Ackermann et al. '12), feature in $e^+ + e^-$ spectrum (Aharonian et al. '08, Abdo et al. '09, Ackermann et al. '10), γ-ray lines (Bringmann, Weniger, Tempel, Su, Boyarsky, ... '12), ...
- But also a huge number of data validates the modelling of astrophysical background sources in the GeV-TeV range : absence of anomalies in the $\bar{p}$ spectrum less exploited (Adriani et al., Phys. Rev. Lett. 102 (2009) 051101 and Phys. Rev. Lett. 105 (2010) 121101)

$\Rightarrow$ Possibility to set stringent constraints on DM properties by looking at DM annihilation into $W^{\pm}$, as degeneracy in the DM sector (difficult at the LHC for instance), using FERMI-LAT **AND** PAMELA data

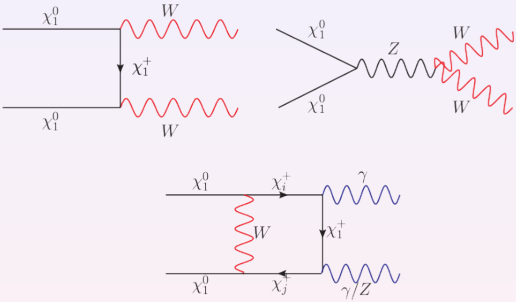
Generic bounds on DM annihilation into $W^{\pm}$

- **From γ-rays : FERMI-LAT analysis of the diffuse γ-ray emission from dwarf spheroidal galaxies (Ackermann et al, Phys. Rev. Lett. 107 (2011) 241302)**
- **From $\bar{p}$: derived bounds from PAMELA antiprotons data using an "aggressive" and a "conservative" procedure (see backup)**



A "simplified" version

Aim : dominant neutralino DM annihilation channels into gauge bosons



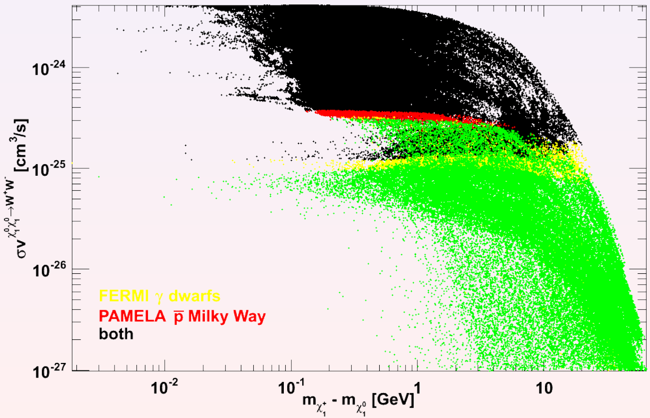
⇒ **All sfermion masses are set to 2 TeV (except for the third generation of squarks, to get $m_h \sim 125$ GeV), CP-odd Higgs at 1 TeV + light chargino/neutralino ($m_{\chi_1^0} < 500$ GeV) such that the mass splitting $\Delta m = m_{\chi_1^\pm} - m_{\chi_1^0}$ is small**

⇒ **MCMC scan**

⇒ **How powerful are the $\bar{p}$ limits on excluding parts of pMSSM parameter space and Δm values ?**

Results

- Higgsino and mainly wino DM probed
- ID constrains scenarios with $\Delta m \lesssim 20$ GeV, DM relic density being regenerated at 100%
- If $m_{\chi_1^0} < 500$ GeV and $\Delta m < 0.2$ GeV wino DM ruled out



Results

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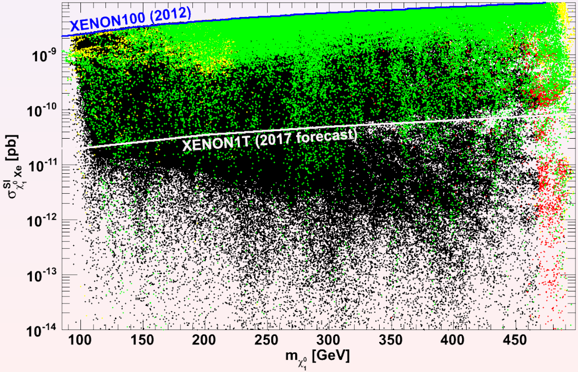
- ID constrains scenarios with $\Delta m \lesssim 20$ GeV, DM relic density being regenerated at 100%
- If $m_{\chi_1^0} < 500$ GeV and $\Delta m < 0.2$ GeV wino DM ruled out
- No explanation of the "130 GeV line" in this simplified pMSSM
- ID constraints really competitive with direct detection experiments



Conclusions

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- With the discovery of a new boson at the LHC, whose characteristics seem to match those of the Standard Model Higgs boson, the powerful limits imposed on exotic particles properties by colliders searches, the impressive sensitivity reached by DM direct detection experiments, the launch of new experiments aimed also on cosmology or DM ID constraints as PLANCK and AMS-02 satellites, etc., extensions of the SM and especially SUSY, which includes DM candidates, are now well probed
- Caveat on what assumptions the experimentalists make on the models (simplified New Physics models, astrophysical models, ...), and on uncertainties (astrophysical sources, non-perturbative QCD, ...)

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Thanks for your attention !

MORE SLIDES ! ! ! !

BACKUP

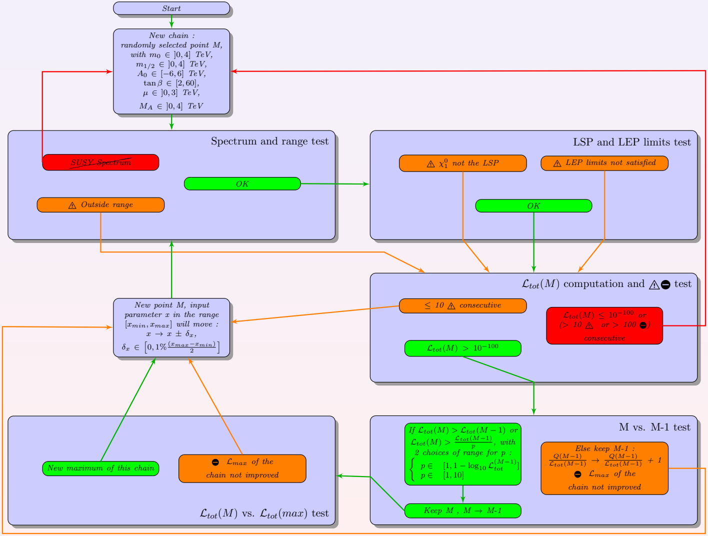
- **Scanning the NUHM2 parameter space : Markov Chain Monte Carlo method**

Constraint	Value/Range	Tolerance	Likelihood
m_h (GeV)	[115.5, 127]	1	$\mathcal{L}_1(m_h, 115.5, 127, 1)$
$\Omega_{\chi_1^0} h^2$	[0.1088, 0.1158]	0.0035	$\mathcal{L}_1(\Omega_{\chi_1^0} h^2, 0.1088, 0.1158, 0.0035)$
Relaxing constraint on $\Omega_{\chi_1^0} h^2$	[0.01123, 0.1123]	0.0035	$\mathcal{L}_1(\Omega_{\chi_1^0} h^2, 0.01123, 0.1123, 0.0035)$
$BR(b \to s\gamma) \times 10^4$	3.55	exp : 0.24, 0.09 th : 0.23	$\mathcal{L}_2(10^4 BR(b \to s\gamma), 3.55, \sqrt{0.24^2 + 0.09^2 + 0.23^2})$
$(g_\mu - 2) \times 10^{10}$	28.7	8	$\mathcal{L}_3(10^{10}(g_\mu - 2), 28.7, 8)$
$BR(B_s \to \mu^+\mu^-) \times 10^9$	4.5	0.045	$\mathcal{L}_3(10^9 BR(B_s \to \mu^+\mu^-), 4.5, 0.045)$
$\Delta\rho$	0.002	0.0001	$\mathcal{L}_3(\Delta\rho, 0.002, 0.0001)$
$R_{B^+ \to \tau^+ \bar{\nu}_\tau}(\frac{NUHM2}{SM})$	2.219	0.5	$\mathcal{L}_3(R_{B^+ \to \tau^+ \bar{\nu}_\tau}, 2.219, 0.5)$
$Z \to \chi_1^0 \chi_1^0$ (MeV)	1.7	0.3	$\mathcal{L}_3(Z \to \chi_1^0 \chi_1^0, 1.7, 0.3)$
$\sigma_{e^+e^- \to \chi_1^0 \chi_{2,3}^0} \times Br(\chi_{2,3}^0 \to Z\chi_1^0)$ (pb)	1	0.01	$\mathcal{L}_3(\sigma_{e^+e^- \to \chi_1^0 \chi_{2,3}^0} \times Br(\chi_{2,3}^0 \to Z\chi_1^0), 1, 0.01)$

Parameter	Range	Parameter	Range
m_0	]0, 4] TeV	$\tan\beta$	[2, 60]
$m_{1/2}$	]0, 4] TeV	μ	]0, 3] TeV
A_0	[-6, 6] TeV	M_A	]0, 4] TeV

BACKUP

MCMC method



BACKUP

Models

- **NUHM2**
- **$\widetilde{L}\widetilde{L}\widetilde{e}$ and $\widetilde{u}\widetilde{d}\widetilde{d}$**
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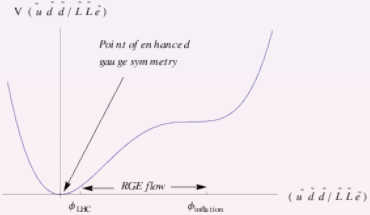


- $\phi = \frac{\widetilde{u}+\widetilde{d}+\widetilde{d}}{\sqrt{3}}, \quad \phi = \frac{\widetilde{L}+\widetilde{L}+\widetilde{e}}{\sqrt{3}}$
- $V(\phi) = \frac{1}{2} m_\phi^2\, \phi^2 - A \frac{\lambda \phi^6}{6\, M_P^3} + \lambda^2 \frac{\phi^{10}}{M_P^6}$

  $\phi^4_{\text{inflation}} \simeq \frac{m_\phi M_P^3}{\lambda\sqrt{10}}, V''(\phi_{\text{inflation}}) = 0$
- **$\widetilde{u}\widetilde{d}\widetilde{d}$ RGEs**

$$\hat{\mu}\frac{dm_\phi^2}{d\hat{\mu}} = -\frac{1}{6\pi^2}(4M_3^2 g_3^2 + \frac{2}{5}M_1^2 g_1^2),$$
$$\hat{\mu}\frac{dA}{d\hat{\mu}} = -\frac{1}{4\pi^2}(\frac{16}{3}M_3 g_3^2 + \frac{8}{5}M_1 g_1^2)$$

- **$\widetilde{L}\widetilde{L}\widetilde{e}$ RGEs**

$$\hat{\mu}\frac{dm_\phi^2}{d\hat{\mu}} = -\frac{1}{6\pi^2}(\frac{3}{2}M_2^2 g_2^2 + \frac{9}{10}M_1^2 g_1^2),$$
$$\hat{\mu}\frac{dA}{\dots} \quad \frac{1}{\dots}(\frac{3}{\dots}M\, g^2 + \frac{9}{\dots}M\, g^2)$$

BACKUP

ID constraints from $\bar{p}$

$W^{\pm}$ production leads also to abundant $\bar{p}$ production (after hadronization)

$\Rightarrow$ $\bar{p}$ flux produced by DM annihilation determined by :

- $\sigma_{\rm DM\ DM\ \to\ W^+W^-}$
- $m_{\rm DM}$
- DM halo profile (here Einasto profile)
- $\bar{p}$ propagation parameters in the galactic halo :

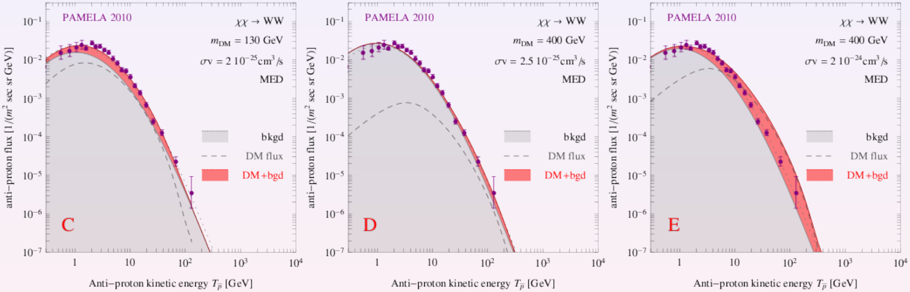
Model	δ	$\mathcal{K}_0$ [kpc^2/Myr]	$V_{\rm conv}$ [km/s]	L [kpc]
MIN	0.85	0.0016	13.5	1
MED	0.70	0.0112	12	4
MAX	0.46	0.0765	5	15

$\Rightarrow$ We compare the sum of the astrophysical background flux and predicted $\bar{p}$ flux originating from DM with the PAMELA data, 2 methods :

- "Aggressive" procedure : fixed background (standard flux from T. Bringmann and P. Salati, Phys. Rev. D 75 (2007) 083006)
- "Conservative" procedure : marginalized background, namely standard description of the background spectrum multiplied by $A\,(T/T_0)^p$ with :
  $T = \bar{p}$ kinetic energy
  $T_0 = 30$ GeV : pivot energy
  normalisation of the background spectrum : $0.6 < A < 1.4$
  spectral index : $-0.1 < p < +0.1$

BACKUP

ID constraints from $\bar{\text{p}}$



- **"Conservative" procedure approximately independent of $\mathrm{m_{DM}}$: $\bar{\text{p}}$ flux from heavy DM negligible at low energy, where PAMELA set very small error bars**
- **We consider diffuse γ-ray constraints from dwarf spheroidal galaxies and $\bar{\text{p}}$ constraints using 'MED' propagation parameters + marginalized background**