Shedding light on Dark Matter from accelerator physics

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based on Y. Mambrini, B.Z., hep-ph/1106.4819
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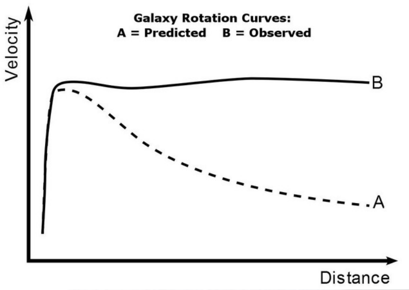
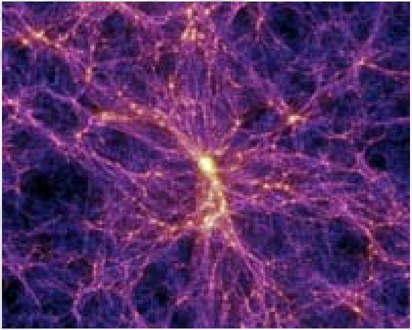
Overview

- Introduction
  - Experimental evidences
  - DM interpretations
  - Nature of couplings
  - Motivation
- Discussion & Results
  - LEP vs Tevatron
  - fermionic DM
  - scalar DM
  - combined analysis (astro+accel)
    - universal lepton coupling
    - pure electron coupling
  - words on LHC
- Conclusions

Dark Matter in a nutshell

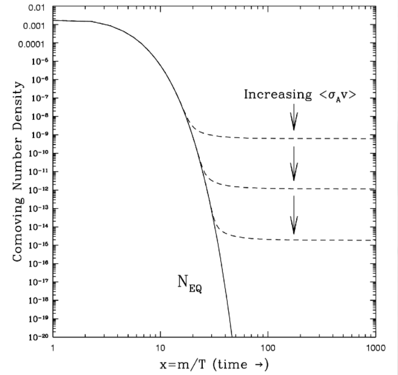




Dark Matter in a nutshell

- WMAP data: $\Omega_X h^2 = 0.1123 \pm 0.0175$
  4.7% baryonic matter, **22% dark matter**, 73% dark energy

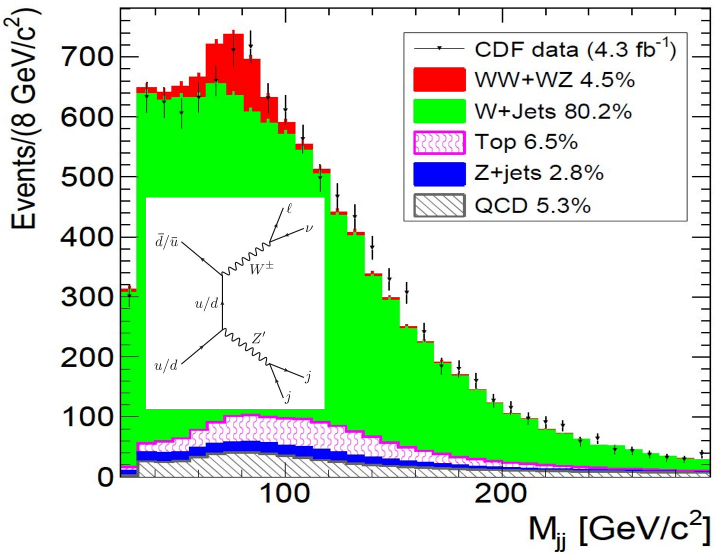
- Boltzmann equation

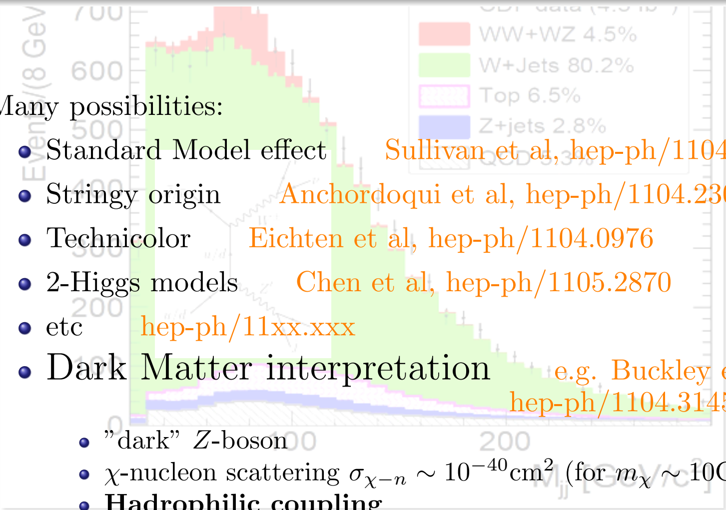


- $\Omega_X h^2 \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$
- WIMP miracle
  $m_X \sim 100$ GeV $\Rightarrow g \sim g_{\mathrm{Weak}}$
- $\langle \sigma v \rangle \approx 3 \times 10^{-26}$ cm^3/s.
- A priori requisites:
  weakly interacting, long-lived, neutral.

Dark excesses? (Acc. Exp., D.D)

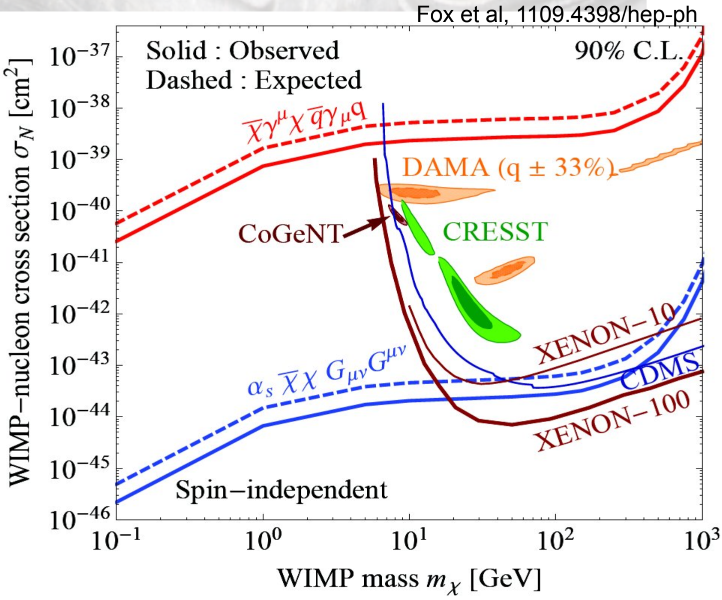
CDF Collaboration [hep-ex/1104.0699]





Many possibilities:

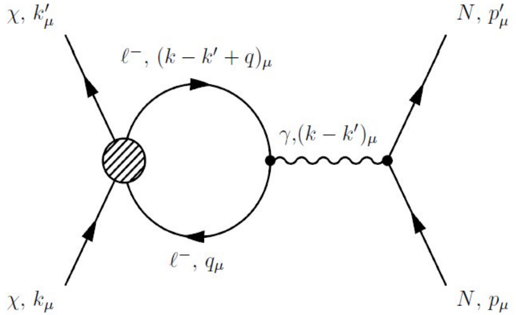
- Standard Model effect — Sullivan et al, hep-ph/1104.3790
- Stringy origin — Anchordoqui et al, hep-ph/1104.2303
- Technicolor — Eichten et al, hep-ph/1104.0976
- 2-Higgs models — Chen et al, hep-ph/1105.2870
- etc — hep-ph/11xx.xxx
- Dark Matter interpretation — e.g. Buckley et al, hep-ph/1104.3145
  - "dark" Z-boson
  - χ-nucleon scattering $\sigma_{\chi-n} \sim 10^{-40}\text{cm}^2$ (for $m_\chi \sim 10\text{GeV}$)
  - **Hadrophilic coupling**


Fox et al, 1109.4398/hep-ph
Solid : Observed
Dashed : Expected
90% C.L.
$\bar{\chi}\gamma^{\mu}\chi\,\bar{q}\gamma_{\mu}q$
DAMA (q ± 33%)
CoGeNT
CRESST
XENON−10
CDMS
XENON−100
$\alpha_s\,\bar{\chi}\chi\,G_{\mu\nu}G^{\mu\nu}$
Spin−independent
WIMP−nucleon cross section σ_N [cm^2]
WIMP mass m_χ [GeV]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

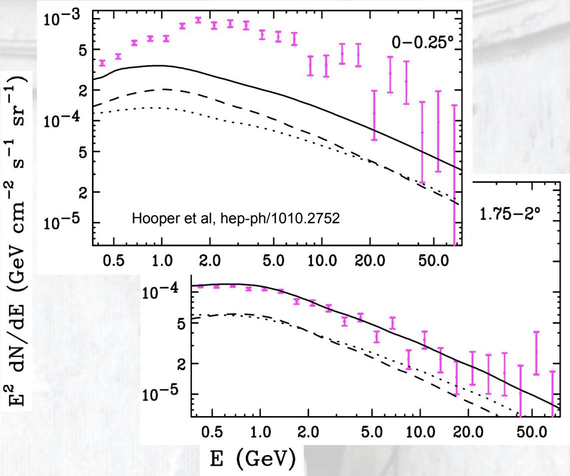
Dark excesses? (Astro. Exp., D.D.)

Tension in XENON and DAMA results

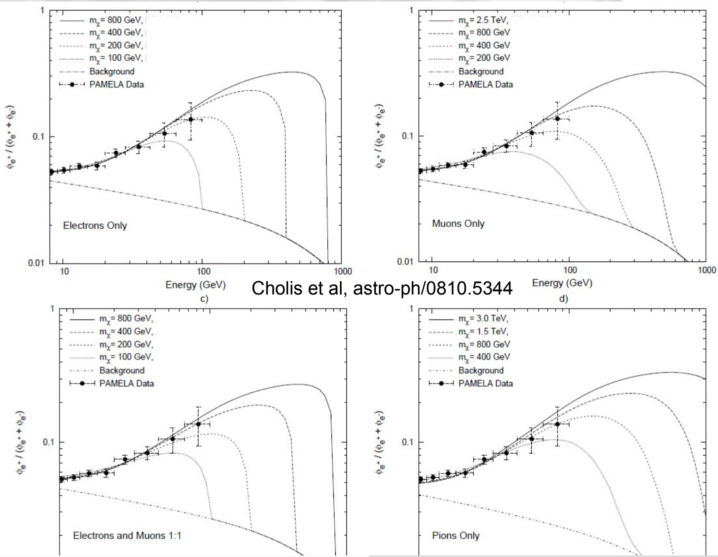
- **electrophilic** DM Bernabei et al, astro-ph/0712.0562
  DAMA sensible also to electron recoil
- **leptophilic** Fox et al, hep-ph/0811.0399
- **hadrophilic** Kopp et al, hep-ph/0907.3159



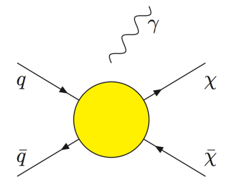
- γ-rays observed by Fermi
- inner parsecs unexplained
- **leptophilic** DM

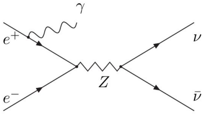


- e^+-flux, by PAMELA
- electrophilic, $\mu-$philic, $\pi-$philic, ...



Cholis et al, astro-ph/0810.5344





Fox et al, hep-ph/1103.0240

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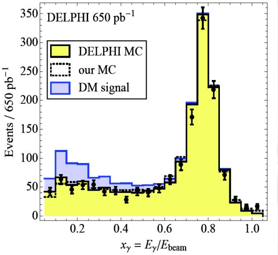
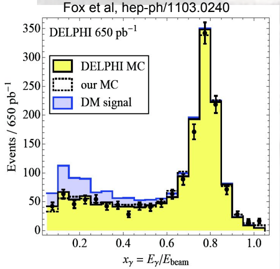


- $\mathcal{O}_V = \dfrac{(\bar{\chi}\gamma_\mu\chi)(\bar{l}\gamma^\mu l)}{\Lambda^2}$
- $\mathcal{O}_S = \dfrac{(\bar{\chi}\chi)(\bar{l}l)}{\Lambda^2}$
- $\mathcal{O}_A = \dfrac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{l}\gamma^\mu\gamma_5 l)}{\Lambda^2}$
- $\mathcal{O}_t = \dfrac{(\bar{\chi}l)(\bar{l}\chi)}{\Lambda^2}$

Motivation (LEP vs. Tevatron)



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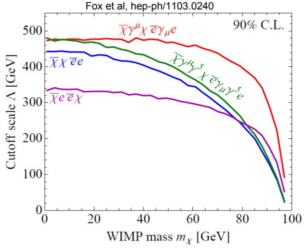

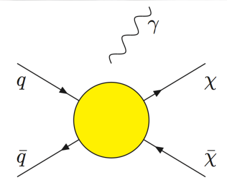

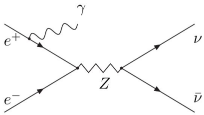

- $\mathcal{O}_V = \dfrac{(\bar\chi\gamma_\mu\chi)(\bar l\gamma^\mu l)}{\Lambda^2}$
- $\mathcal{O}_S = \dfrac{(\bar\chi\chi)(\bar l l)}{\Lambda^2}$
- $\mathcal{O}_A = \dfrac{(\bar\chi\gamma_\mu\gamma_5\chi)(\bar l\gamma^\mu\gamma_5 l)}{\Lambda^2}$
- $\mathcal{O}_t = \dfrac{(\bar\chi l)(\bar l\chi)}{\Lambda^2}$

- $\sigma_{1-\text{loop}} = \dfrac{4\alpha^2\mu_p^2}{18^2\pi^3\Lambda^4}\cdot\left[\sum_l f(q^2, m_l)\right]^2$

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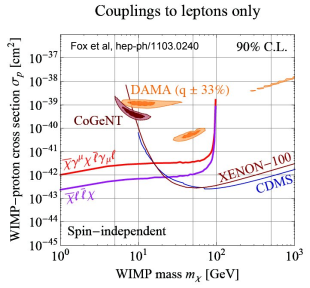
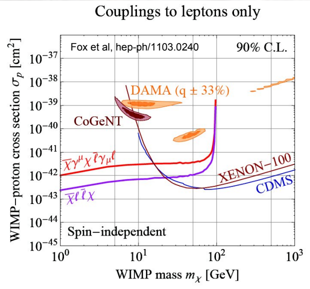


- $(\sigma v)_S =$
$$\frac{1}{8\pi\Lambda^4}\sqrt{1-\frac{m_l^2}{m_\chi^2}}(m_\chi^2 - m_l^2)v_{\text{rel}}^2$$



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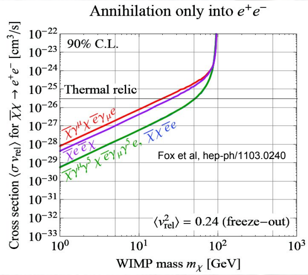
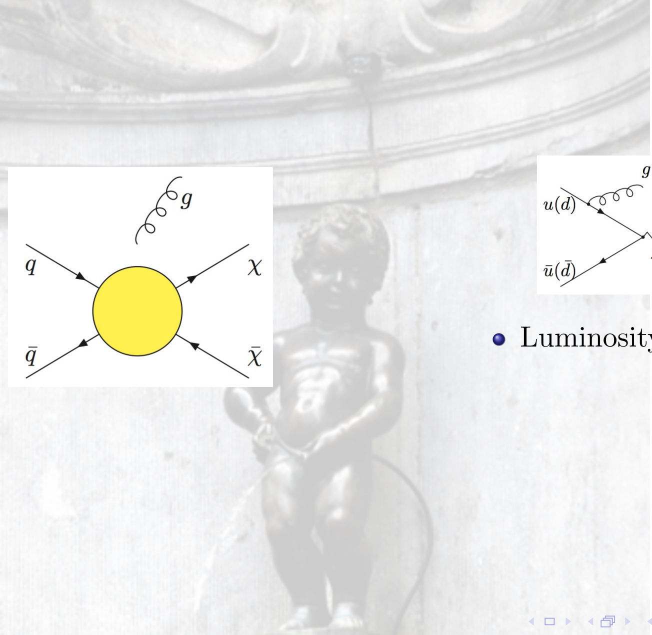


- $\sigma_{1-\mathrm{loop}} = \dfrac{4\alpha^2\mu_p^2}{18^2\pi^3\Lambda^4}\cdot\left[\sum_l f(q^2, m_l)\right]^2$

- $(\sigma v)_S =$
$$\frac{1}{8\pi\Lambda^4}\sqrt{1-\frac{m_l^2}{m_\chi^2}}\,(m_\chi^2 - m_l^2)\,v_{\rm rel}^2$$

Motivation (LEP vs. Tevatron)



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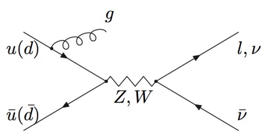
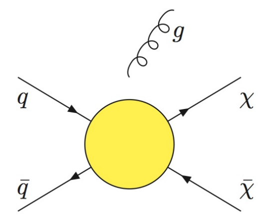
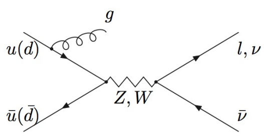


- Luminosity of 1 fb^{-1}

Motivation (LEP vs. Tevatron)





- Luminosity of 1 fb^{-1}

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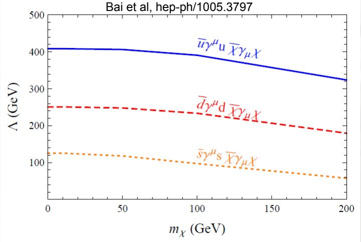
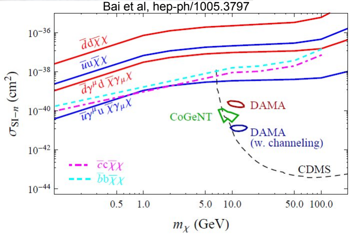
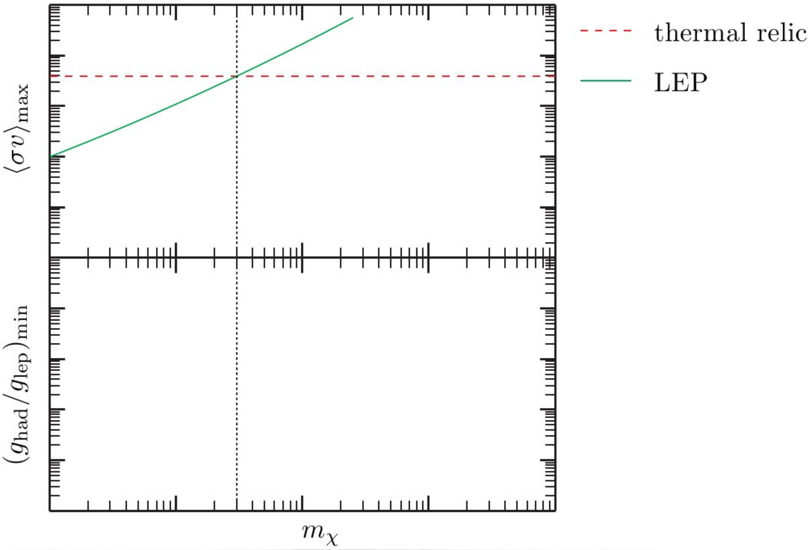
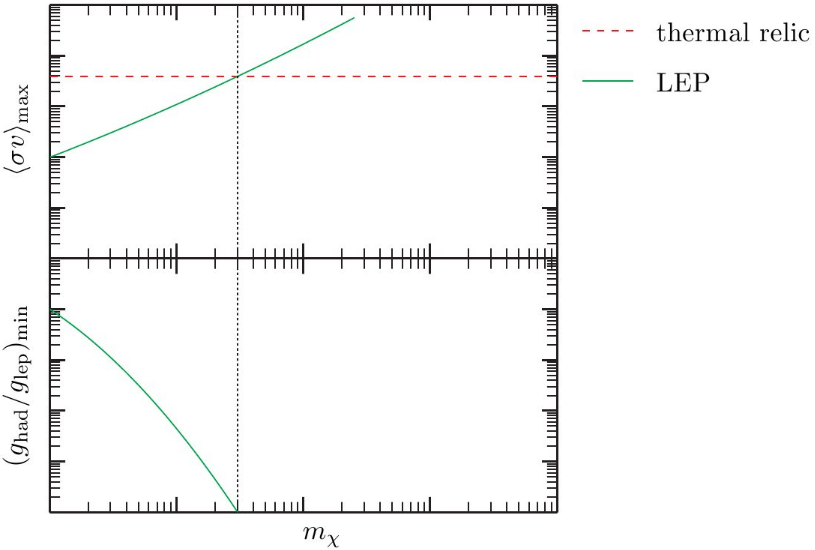




Motivation (LEP vs. Tevatron)



Motivation (LEP vs. Tevatron)



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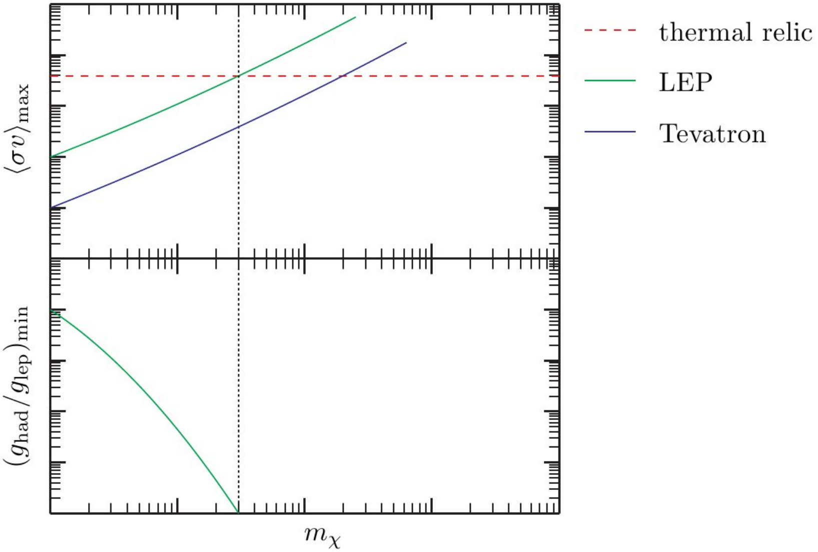
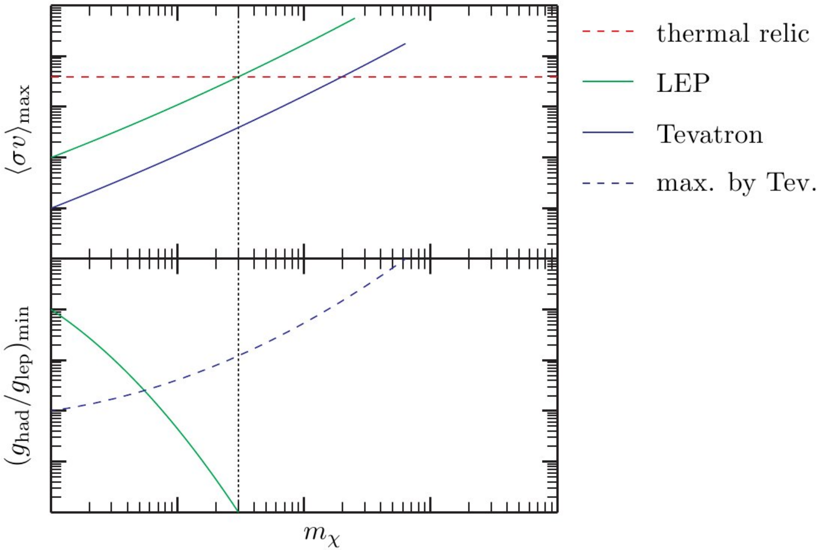
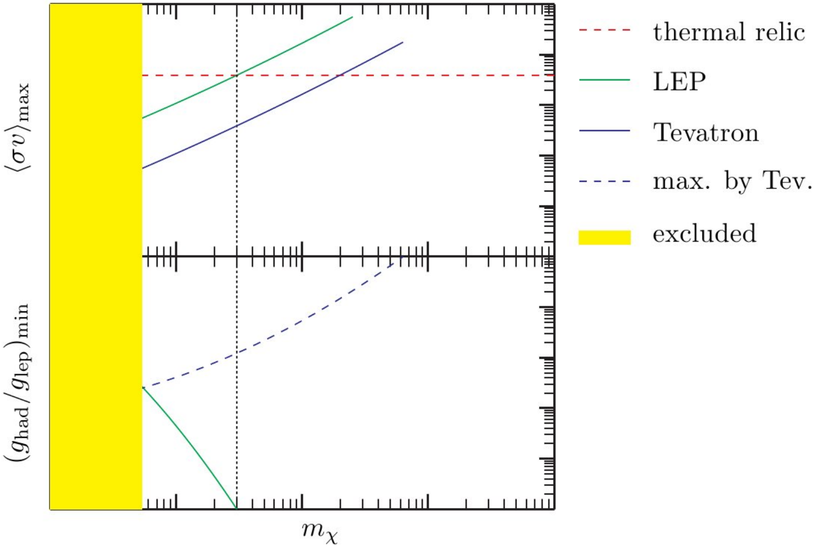


Motivation (LEP vs. Tevatron)



Motivation (LEP vs. Tevatron)



- Effective scales: $\dfrac{1}{\Lambda_l} \equiv \dfrac{\sqrt{g_l}}{\Lambda}; \qquad \dfrac{1}{\Lambda_h} \equiv \dfrac{\sqrt{g_h}}{\Lambda}$
- Operators:

$$\mathcal{L}_V = \sum_i \frac{g_l^i}{\Lambda^2}(\bar{l}^i\gamma^\mu l^i)(\bar{\chi}\gamma_\mu\chi) + \sum_i \frac{g_h^i}{\Lambda^2}(\bar{q}^i\gamma^\mu q^i)(\bar{\chi}\gamma_\mu\chi)$$

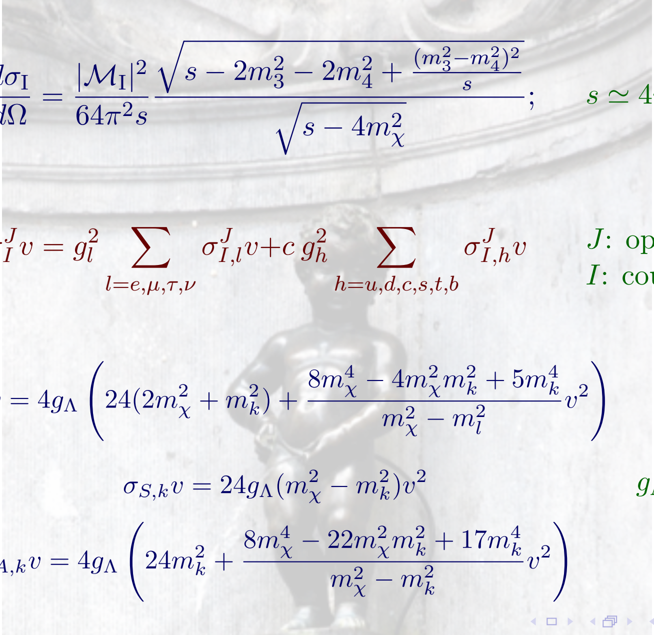
$$\mathcal{L}_S = \sum_i \frac{g_l^i}{\Lambda^2}(\bar{l}^i l^i)(\bar{\chi}\chi) + \sum_i \frac{g_h^i}{\Lambda^2}(\bar{q}^i q^i)(\bar{\chi}\chi)$$

$$\mathcal{L}_A = \sum_i \frac{g_l^i}{\Lambda^2}(\bar{l}^i\gamma^\mu\gamma^5 l^i)(\bar{\chi}\gamma_\mu\gamma^5\chi) + \sum_i \frac{g_h^i}{\Lambda^2}(\bar{q}^i\gamma^\mu\gamma^5 q^i)(\bar{\chi}\gamma_\mu\gamma^5\chi)$$

$$\mathcal{L}_t = \sum_i \frac{g_l^i}{\Lambda^2}(\bar{l}^i\chi)(\bar{\chi}l^i) + \sum_i \frac{g_h^i}{\Lambda^2}(\bar{q}^i\chi)(\bar{\chi}q^i)$$

- Models in lepton sector:
  A) Electrophilic couplings: $g_l^e = g_e,\ g_l^{i=\mu,\tau,\nu_i} = 0$
  B) Charged lepton couplings: $g_l^{i=e,\mu,\tau} = g_l,\ g_l^{i=\nu_i} = 0$
  C) Universal lepton couplings: $g_l^{i=e,\mu,\tau,\nu_i} = g_l$
- Universality in hadronic couplings: $g_h^{i=u,d,c,s,b,t} = g_h$.

Annihilation cross-sections



$$\frac{d\sigma_{\rm I}}{d\Omega} = \frac{|\mathcal{M}_{\rm I}|^2}{64\pi^2 s}\frac{\sqrt{s-2m_3^2-2m_4^2+\frac{(m_3^2-m_4^2)^2}{s}}}{\sqrt{s-4m_\chi^2}}; \qquad s \simeq 4m_\chi^4 + m_\chi^2 v^2$$

$$\sigma_I^J v = g_l^2 \sum_{l=e,\mu,\tau,\nu} \sigma_{I,l}^J v + c\, g_h^2 \sum_{h=u,d,c,s,t,b} \sigma_{I,h}^J v$$

J: operator type

I: coupling type

$$\sigma_{V,k} v = 4g_\Lambda \left(24(2m_\chi^2 + m_k^2) + \frac{8m_\chi^4 - 4m_\chi^2 m_k^2 + 5m_k^4}{m_\chi^2 - m_l^2} v^2\right)$$

$$\sigma_{S,k} v = 24 g_\Lambda (m_\chi^2 - m_k^2) v^2 \qquad g_\Lambda = \frac{\sqrt{1-m_k^2/m_\chi^2}}{192\pi\Lambda^4}$$

$$\sigma_{A,k} v = 4g_\Lambda \left(24 m_k^2 + \frac{8m_\chi^4 - 22m_\chi^2 m_k^2 + 17m_k^4}{m_\chi^2 - m_k^2} v^2\right)$$

Requiring

$$\sigma_l^{max} v + \sigma_h^{max} v \gtrsim \mathbf{3 \times 10^{-26}} \mathrm{cm}^3 \mathrm{s}^{-1} \simeq 2.5 \times 10^{-9}\ \mathrm{GeV}^{-2}$$

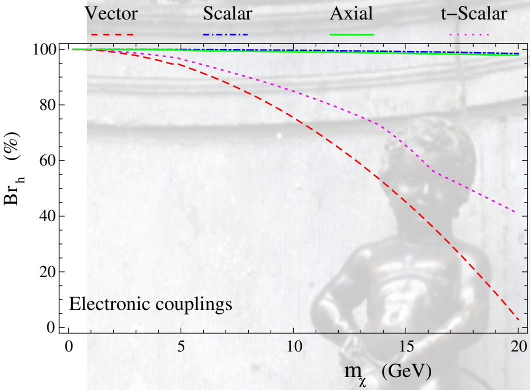
assume e.g. $m_\chi \sim 5$ GeV, in a model with only electronic coupling and vector-like interaction:

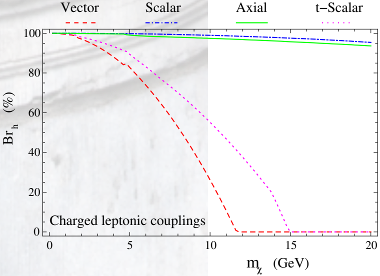
- $(\Lambda_e)_{\mathrm{min}} \simeq 480$ GeV from LEP
- $m_\chi >> m_h, m_l$
- $\sigma_V v \simeq \frac{m_\chi^2}{\pi \Lambda_e^4} + 3\frac{m_\chi^2}{\pi \Lambda_h^4} = \frac{m_\chi^2}{\pi \Lambda_e^4}(1 + 3\frac{g_h^2}{g_l^2}) \gtrsim 2.5 \times 10^{-9}$

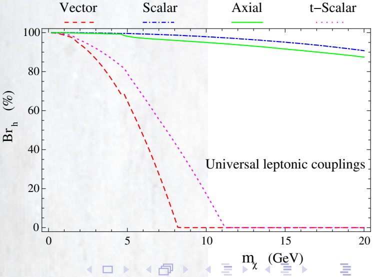
$$\Rightarrow \frac{g_h}{g_l} \simeq 16 \qquad 94\%\ \text{ann. rate to hadrons}$$

Numerical Results

- from LEP bounds:

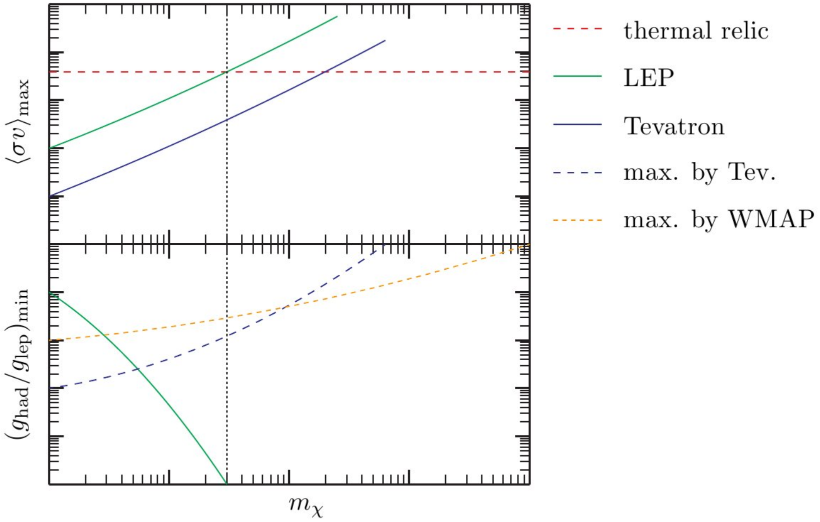




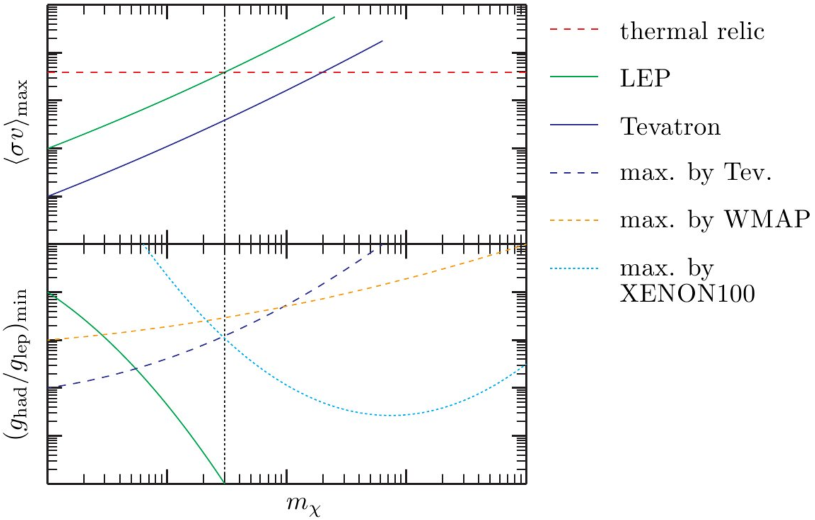


- Most-conservative:
  Universal-leptonic, vector
- Less-conservative: Electronic, scalar

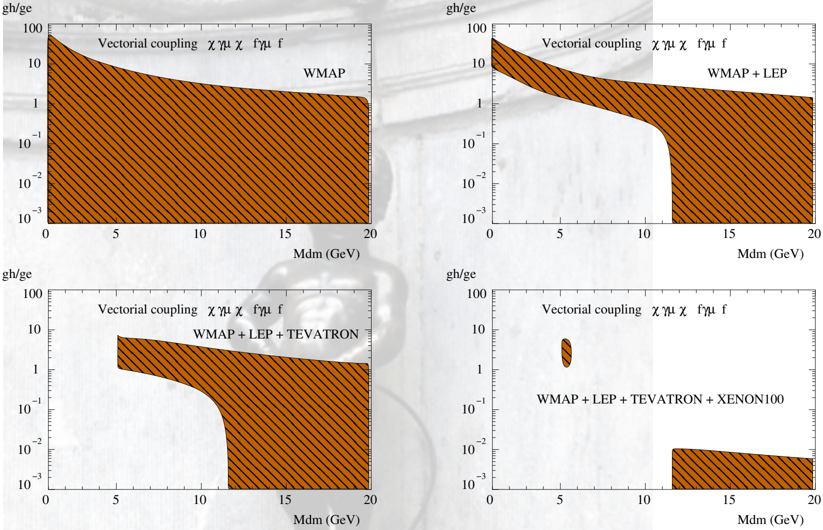
Combined analysis



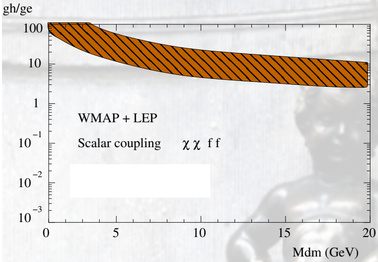
Combined analysis

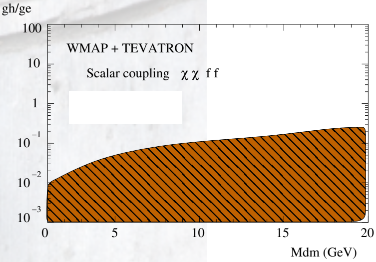


Numerical Results: universal-leptonic, vector



Numerical Results: electronic, scalar

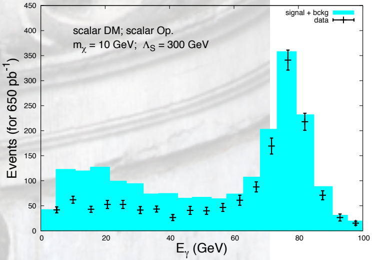




Scalar Dark Matter

- $\mathcal{L}_e = \frac{g_e}{\Lambda_S} \chi\chi\bar{e}e$
- Madgraph analysis:
  - same bckgr: $e^+e^- \to \gamma\nu\bar{\nu}$
  - χ^2-analysis
  - signal+bckgr sim.
- Infer bounds for $\langle\sigma^s_{S,e} v\rangle$:

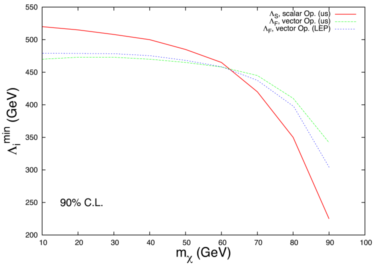
$$\sigma^s_{S,e} v \simeq \frac{g_e^2}{4\pi\Lambda_S^2}\left(1-\frac{m_e^2}{m_\chi^2}\right)^{3/2} + \frac{g_e^2}{32\pi\Lambda_S^2} v^2 \ .$$



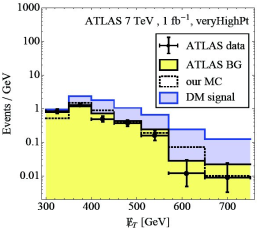
Result:

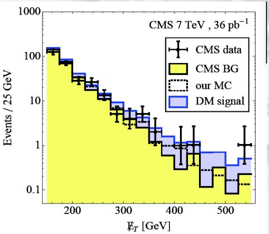
- $\sigma^s_{S,e} \simeq 10^{-24}\mathrm{cm}^3/\mathrm{s}$
- No constraints from LEP, nor Tevatron
- $\left.\frac{\Lambda_S}{g_e}\right|_{\langle\sigma v\rangle\sim 10^{-26}} \gtrsim 5\mathrm{TeV}$

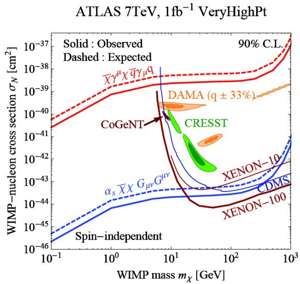
LHC?

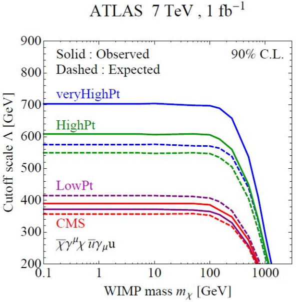


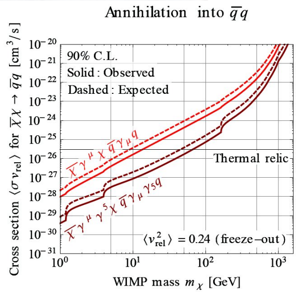
LHC (Fox et al. ph/1109.4398)











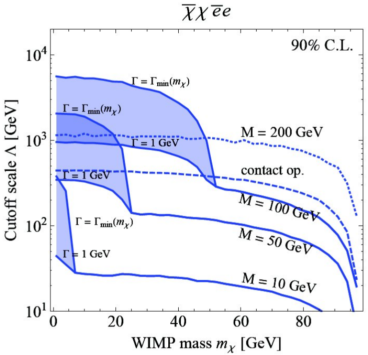
Conclusions

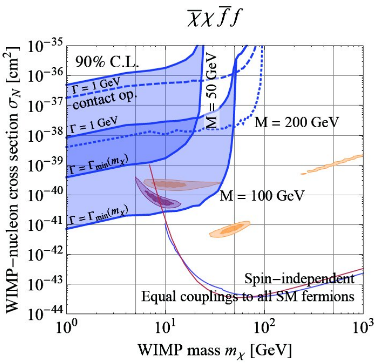
- Nature of DM coupling is crucial to fit all present data
- We computed the rate of hadronic/leptonic coupling to respect:
  1. LEP + Tevatron (mono-photon, mono-jet events)
  2. WMAP + XENON100
- A very light fermionic DM ($\lesssim$ 10 GeV) mainly excluded whatever the type of interaction
- Heavier candidates ($\gtrsim$ 10 GeV) should be largely hadrophobic (vector int.) or even excluded (scalar int.)
- Models with electrophilic couplings (motivated by INTEGRAL, or Synchrotron radiation data) are excluded by LEP/Tevatron analysis

Escaping conclusions: DM candidate not coupled to electrons (LEP bound not applicable) or hadronic coupling only to bottom or charm (Tevatron bound not applicable)

- Nothing to say for the moment for scalar DM.


merci beaucoup!


$\overline{\chi}\chi\overline{e}e$
90% C.L.
$\Gamma = \Gamma_{min}(m_\chi)$
$\Gamma = \Gamma_{min}(m_\chi)$
M = 200 GeV
Γ = 1 GeV
contact op.
Γ = 1 GeV
M = 100 GeV
$\Gamma = \Gamma_{min}(m_\chi)$
M = 50 GeV
Γ = 1 GeV
M = 10 GeV
Cutoff scale Λ [GeV]
WIMP mass m_χ [GeV]


$\overline{\chi}\chi\overline{f}f$
90% C.L.
Γ = 1 GeV
contact op.
M = 50 GeV
Γ = 1 GeV
M = 200 GeV
$\Gamma = \Gamma_{min}(m_\chi)$
M = 100 GeV
$\Gamma = \Gamma_{min}(m_\chi)$
Spin−independent
Equal couplings to all SM fermions
WIMP−nucleon cross section σ_N [cm^2]
WIMP mass m_χ [GeV]

Back-up. High-energy completions