The Higgs - Dark Matter connection

Gabe Shaughnessy

Argonne National Laboratory

Northwestern University

Meeting of the Division of Particles and Fields of the American Physical Society

July 30, 2009

www.particlezoo.net

The Higgs portal

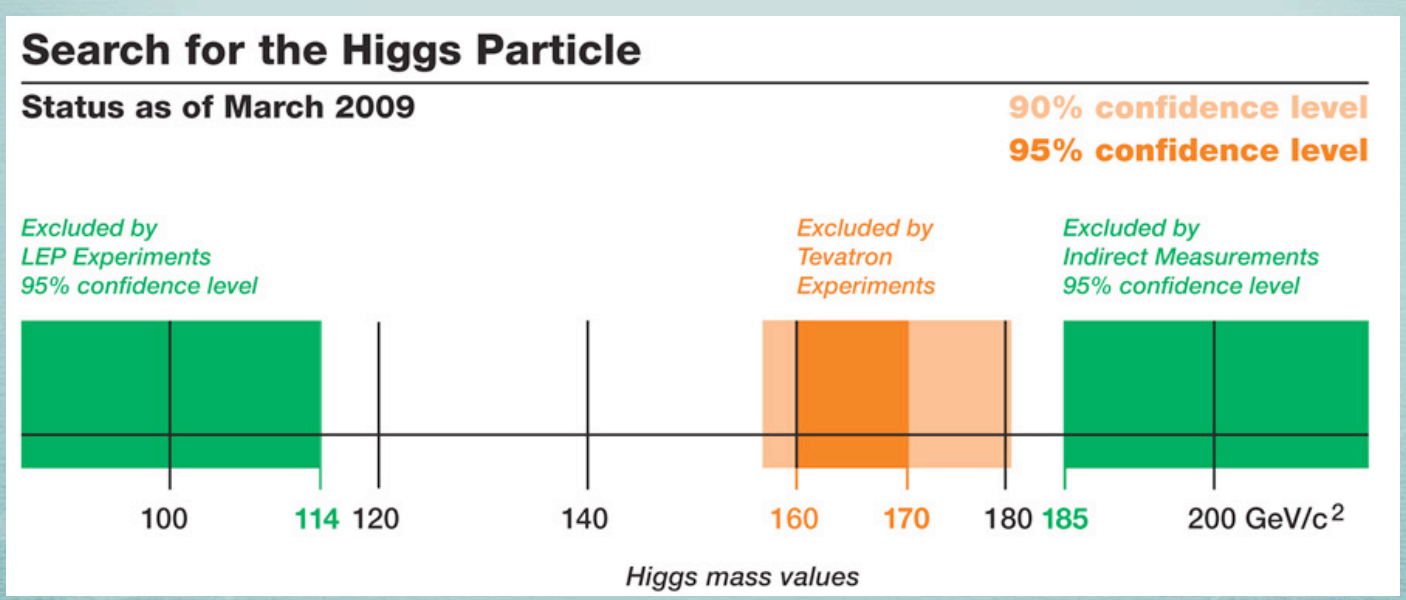
- Higgs boson is the missing piece of the SM
  - While constraints exist, it's still not yet measured
- Exciting new physics may be connected to this sector
- What can the Higgs tell us about DM?

While the higgs boson may be the missing piece of the SM, many new pieces may be found once the nature of the Higgs sector is determined

Status of the Higgs Mass

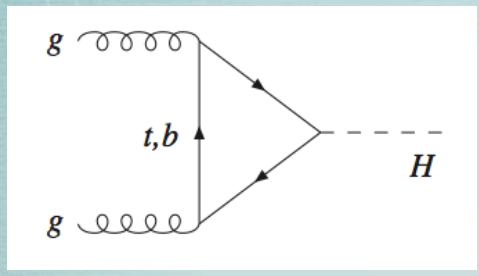
- Tevatron sensitive to intermediate SM Higgs masses
  - excluded region $160\ \text{GeV} \leq M_h \leq 170\ \text{GeV}$

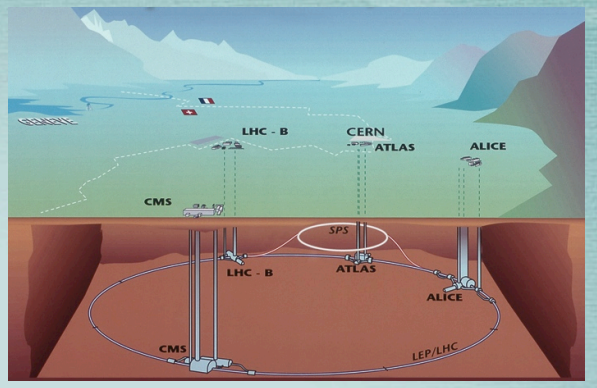
- Electroweak precision exclusion: $M_h \leq 185\ \text{GeV}$
  - New physics contributions can significantly weaken this bound!



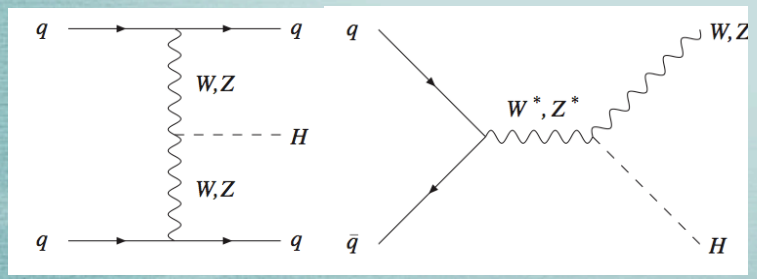
The LHC: A Higgs Factory?

Gluon fusion most dominant mode but many backgrounds present (many jets)

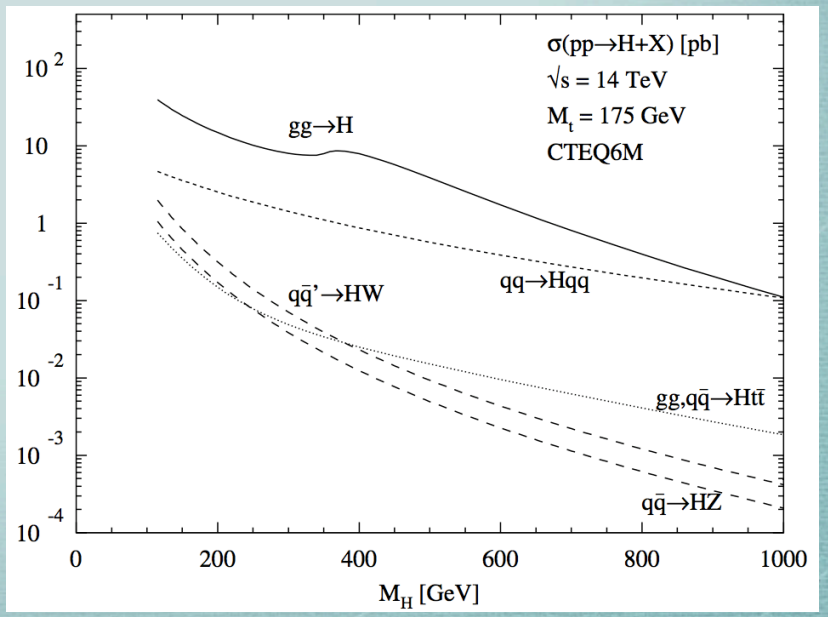




WBF and Z-Higgstrahlung weaker but may yield cleaner signals



SM Higgs production



Statistical significance of Higgs signals at the LHC

ATLAS TDR:

$gg \to H_i \to ZZ \to llvv$

~~$t\bar{t}H_i \to t\bar{t}b\bar{b}$~~

$WH_i \to 3W \to lvlvlv$

CMS TDR:

$WW \to H_i$

$H_i \to WW \to lvjj$

$H_i \to \tau\tau \to l + j$

$H_i \to \gamma\gamma$

ATLAS & CMS:

$gg \to H_i$

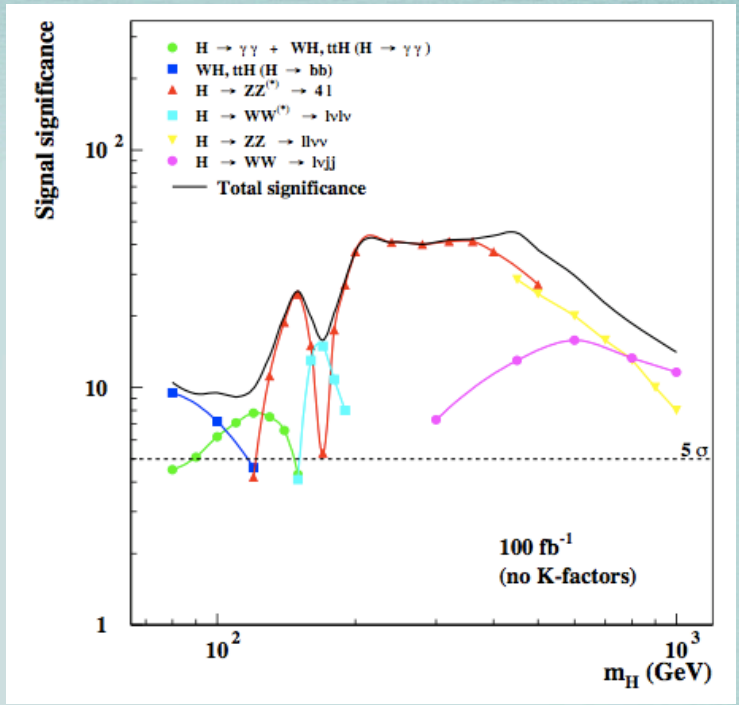
$H_i \to \gamma\gamma$

$H_i \to ZZ \to 4l$

$H_i \to WW \to lvlv$

Both ATLAS & CMS can do similar searches

SM Higgs at ATLAS 100 fb^{-1}



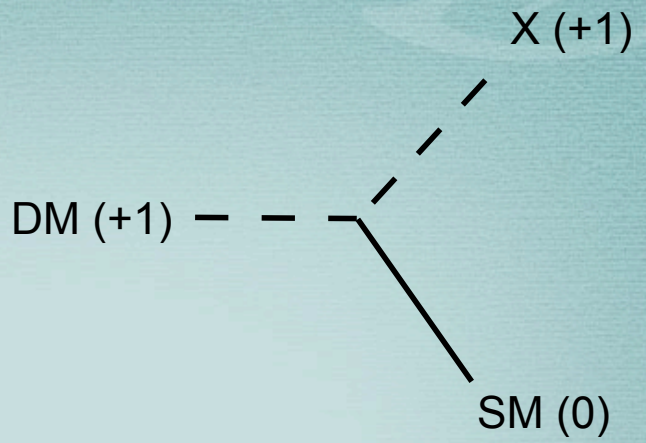
The "golden channel", $H_i \to ZZ \to 4l$, dominates most of mass range (120 GeV < M_H < 600 GeV)

High significance when combined with $H_i \to \gamma\gamma$ for M_H < 120 GeV

Lower energy running not expected to significantly reduce discovery prospects

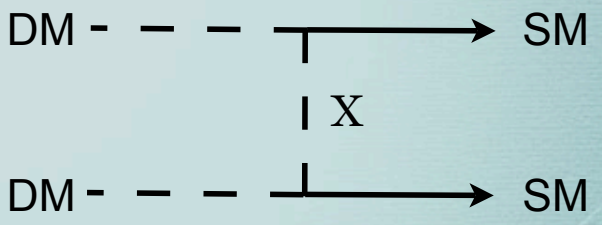
The Dark Matter portal

- DM should be approximately stable
  - Requires some parity to prevent decay
  - SM states remain uncharged

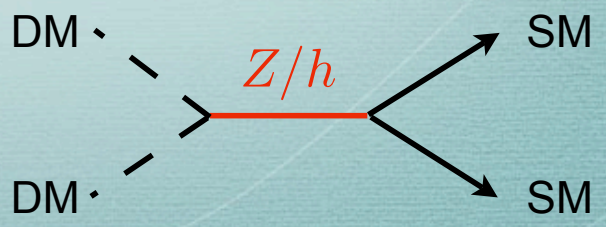


X=DM or other charged states

- Only way to deplete DM number is by pair annihilation



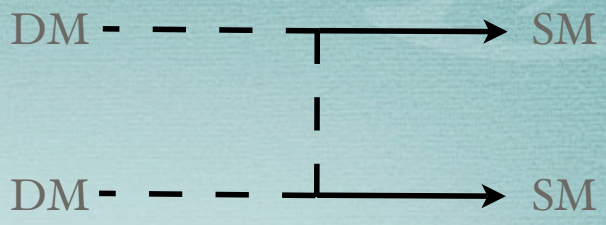
- What might DM tell us about the Higgs?



How much DM exists today?

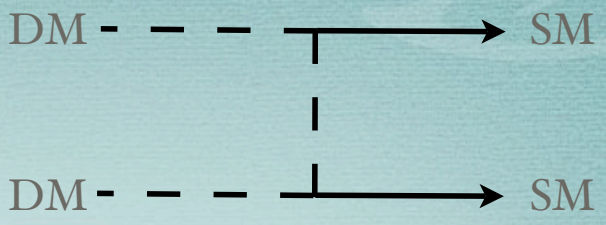
How much DM exists today?

- Remaining number of DM particles depends on annihilation rate



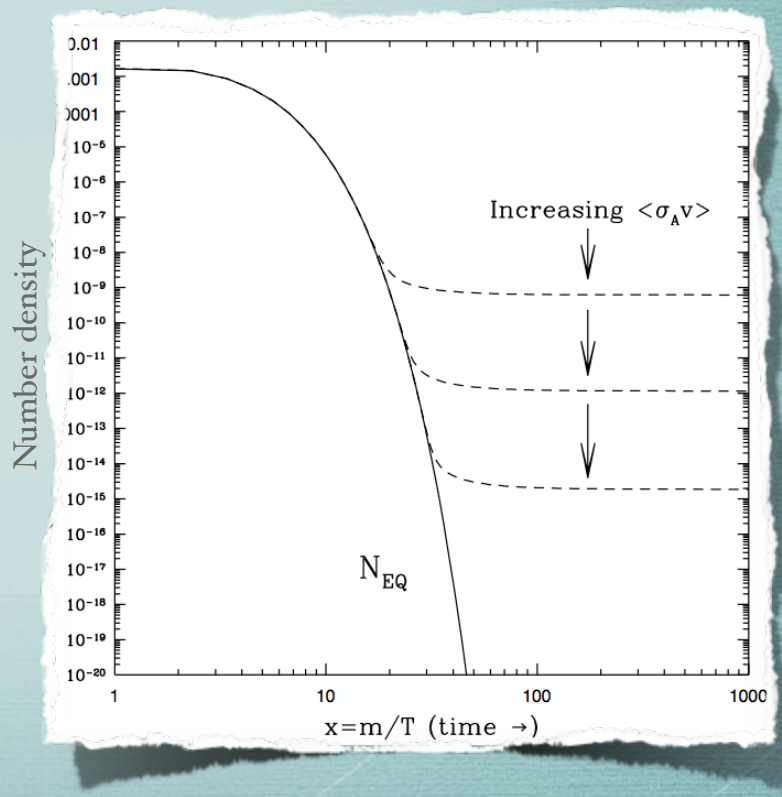
How much DM exists today?

- Remaining number of DM particles depends on annihilation rate



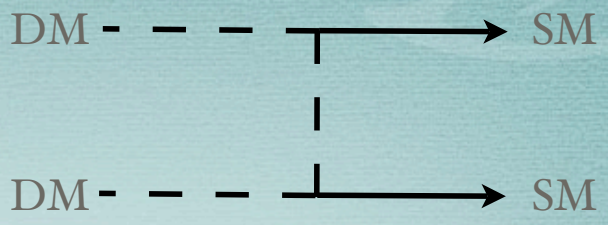
- As universe expands and cools, number density decreases until the Hubble expansion is faster than annihilation

$$\Omega_{DM} \propto \frac{H}{\langle \sigma v \rangle} \propto \frac{M_{DM}^2}{\alpha_{DM}^2}$$



How much DM exists today?

- Remaining number of DM particles depends on annihilation rate

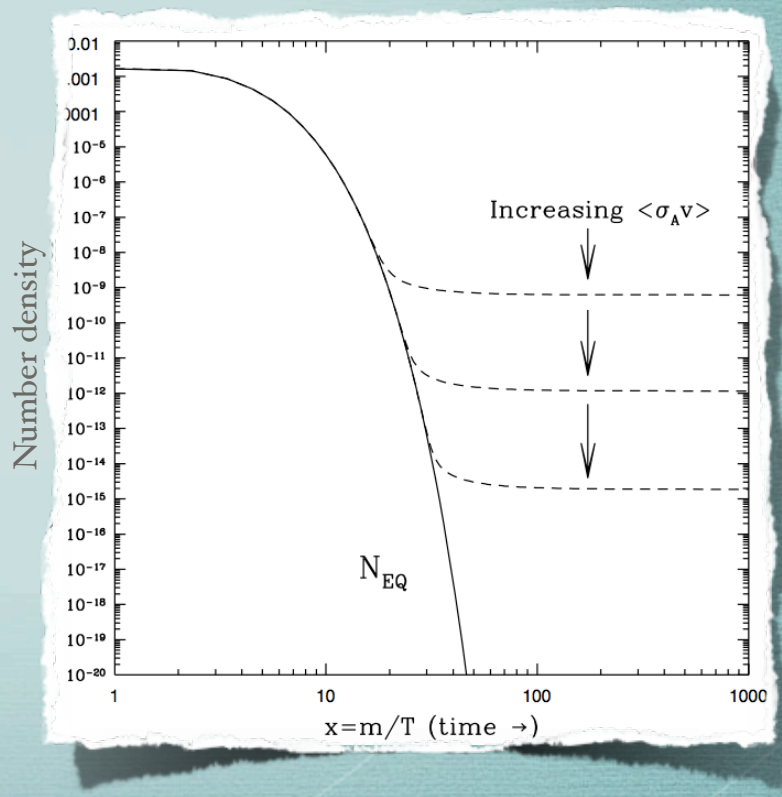


- As universe expands and cools, number density decreases until the Hubble expansion is faster than annihilation

$$\Omega_{DM} \propto \frac{H}{\langle \sigma v \rangle} \propto \frac{M_{DM}^2}{\alpha_{DM}^2}$$

- For electroweak size couplings, expect a mass about 100 GeV

- Coincidence that DM has some connection to EW scale?



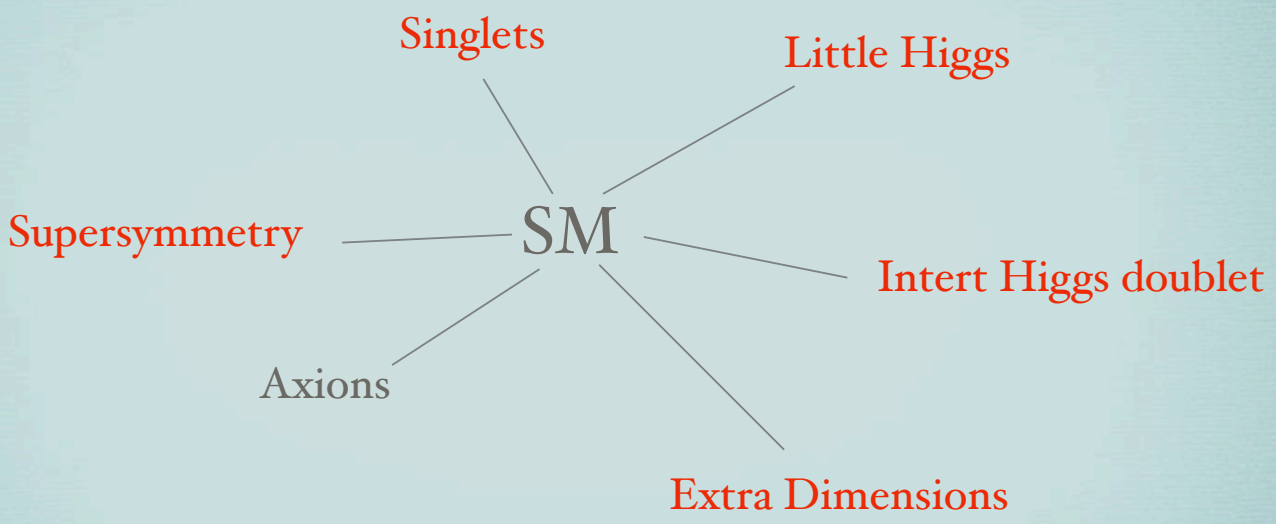
DM Models

DM Models

- Slew of models exist to solve DM problem

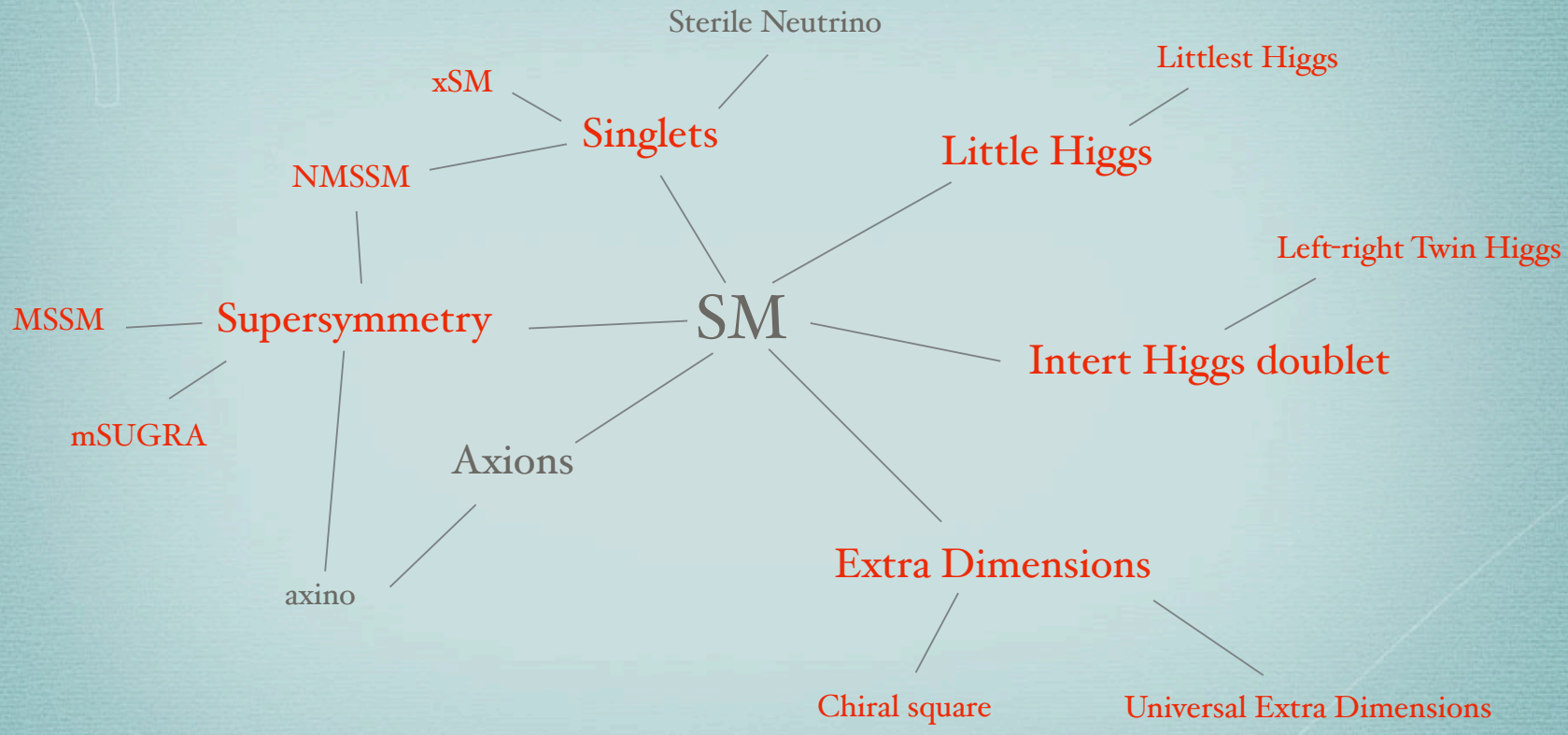
DM Models

- Slew of models exist to solve DM problem
- Many have some non-trivial connection to the Higgs sector



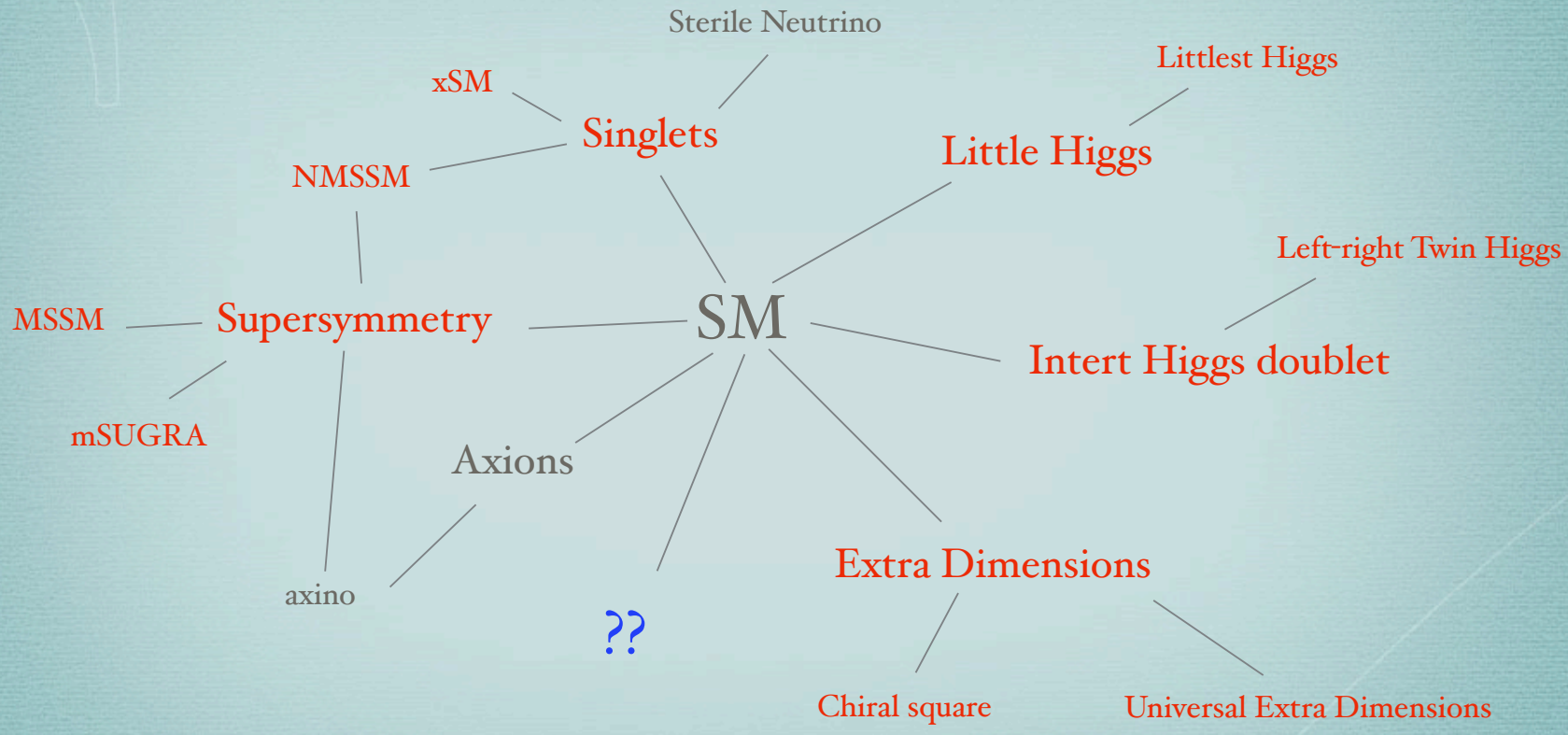
DM Models

- Slew of models exist to solve DM problem
- Many have some non-trivial connection to the Higgs sector



DM Models

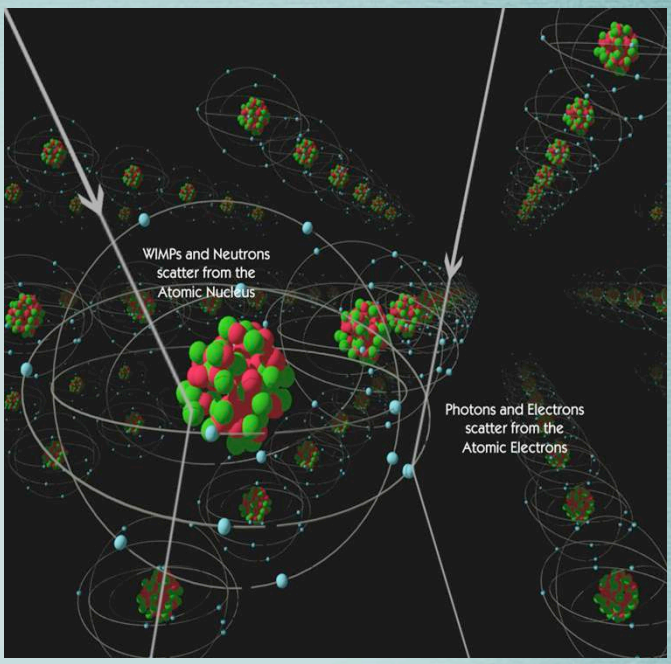
- Slew of models exist to solve DM problem
- Many have some non-trivial connection to the Higgs sector



Must be prepared for both the contemplated changes in Higgs paradigm and the unexpected!

Direct Detection of Dark Matter

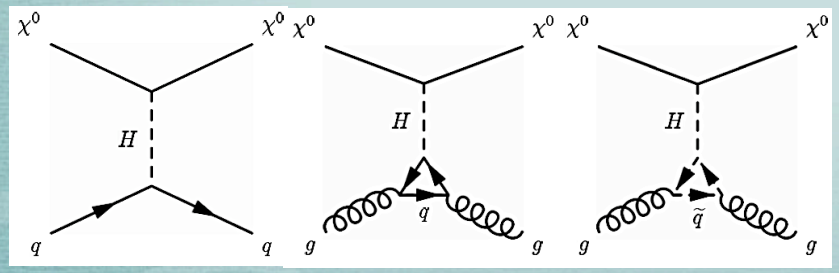
- DM particle strikes nucleus of atom
  - Large de Boglie wavelength (coherent sampling of nucleus)
  - Large A nuclei ideal
- Nuclear recoil can be seen in a variety of ways
  - Detection of phonons in lattice (Cryogenic detectors)
  - Scintillating liquid noble gasses
- Featureless differential rate
  - Very difficult to extract signal
  - Backgrounds must be known well

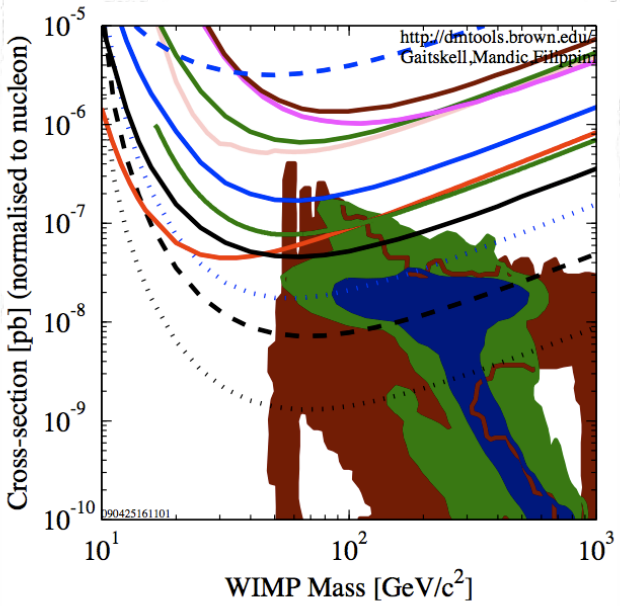


Present experimental limits

- Two kinds of scattering:
  - Spin-independent $\sigma_{DM-N} \propto A_N^2$
  - Spin-dependent $\sigma_{DM-N} \propto J_N(J_N+1)$
- Best limits on Spin-independent rate
- How might the Higgs fit in?

$$\sigma_{DM-N} \propto \frac{g_{DM-h}^2}{M_h^4}\mathcal{F}_{h-N}$$





Higgs - Dark Matter connections

- One of the simplest gauge invariant combination of Higgs: $H^\dagger H$
  - Scalar - $\mathcal{L} \supset \frac{\delta}{2} H^\dagger H \cdot DM^2$ (dim 4)
  - Fermion - $\mathcal{L} \supset \frac{\delta}{\Lambda} H^\dagger H \cdot \bar{\Psi}\Psi$ (dim 5)
  - Vector - $\mathcal{L} \supset \frac{\delta}{\Lambda^2} H^\dagger H \cdot F^{\mu\nu} F_{\mu\nu}$ (dim 6)

    $\mathcal{L} \supset \delta H^\dagger H \cdot B^\mu B_\mu$ (dim 4)

See Shepherd, Tait and Zaharijas '09
for more complete list of effective operators

- Implications for DM / Higgs searches
  - Terrestrial experiments - LHC, DM Direct detection experiments
  - Search in the Sky - Fermi, PAMELA

Scalar Dark Matter

- Gauge invariant combination of Higgs doublets: $H^\dagger H$

- Simplest interactions between scalar DM and Higgs: $\mathcal{L} \supset \frac{\delta}{2} H^\dagger H \cdot DM^2$
  - Fundamental connection? (dimension 4)

  - Singlet scalar DM: $DM^2 = \widetilde{S}^2$ or $DM^2 = \widetilde{S}^\dagger \widetilde{S}$ for complex singlets

    Silveira and Zee '84. McDonald '94. Burgess, Pospelov, ter Veldhuis '00.
    Barger, Langacker, McCaskey, Ramsey-Musolf, GS '06, '08.

  - Inert Higgs doublet: $DM^2 = \widetilde{\Phi}^\dagger \widetilde{\Phi}$

    Barbieri, Hall and Rychkov '06. Ma '07.

  - Private Higgs Model: $DM^2 = K^0 K^0$

    Porto and Zee '07. Jackson '09

- Composite DM - WIMPonium
  - DM is scalar state of bound fermions - may mix with SM Higgs boson

    Shepherd, Tait, Zaharijas '09

Singlet Scalar DM

Add one scalar singlet to SM Higgs potential

- Higgs can be indistinguishable from SM
- Singlet obtains no VEV

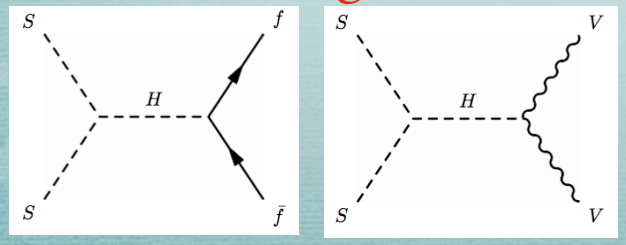
$$V = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_1}{2} H^\dagger H S + \frac{\delta_2}{2} H^\dagger H S^2 + \left(\frac{\delta_1 m^2}{2\lambda}\right) S + \frac{\kappa_2}{2} S^2 + \frac{\kappa_3}{3} S^3 + \frac{\kappa_4}{4} S^4,$$

O'Connell, Ramsey-Musolf, Wise

Singlet scenarios:

- Singlet mixes with SM Higgs (Krasnikov & O'Connell et al.)
- Reflection Symmetry $S \to -S$ (Zee et al., McDonald, Burgess et al.)

➡ DM singlet interacts only with Higgs bosons



Both cases possible if singlet is complex

Barger, Langacker, McCaskey, Ramsey-Musolf, GS

Phys.Rev.D77:035005,2008. Phys.Rev.D79:015018,2009

Fermionic Dark Matter

- SUSY models typically have neutralino LSPs.

$$\chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + \underbrace{N_{13}\tilde{H}_d + N_{14}\tilde{H}_u}_{\text{Superparters of Higgs bosons}}$$

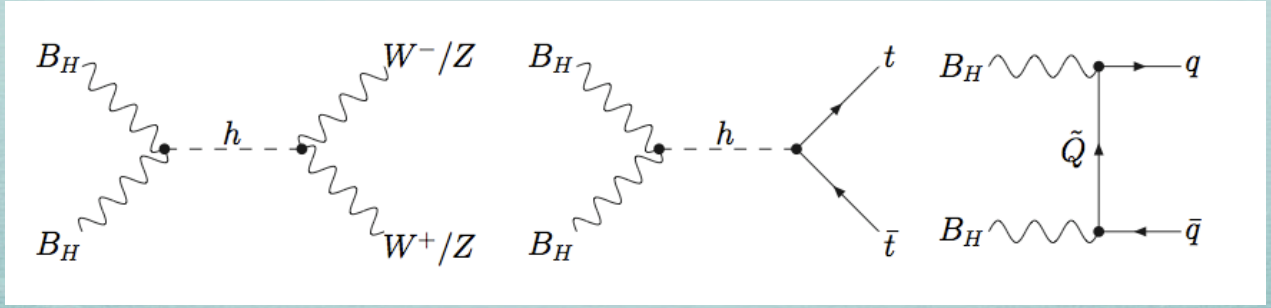
- Values of N_{13}, N_{14} dependent on Higgsino mass parameter μ and its relation to soft breaking terms
  - Dependent on Higgs masses and mixings

- Singlet extensions of SUSY add particle content to both DM sector (neutralinos) and Higgs sector
  - NMSSM, UMSSM, nMSSM

Vector Dark Matter

- Vector Dark Matter present in Universal Extra Dimensions (UED)
  - Since 5-dimensional momentum conserved, KK parity ensures stability of lightest state (LKP) Servant and Tait '02
  - Spin-1 nature of DM allows possible annihilation to $h\gamma$ (see later slides)

- Little Higgs with T-parity Cheng and Low '04
  - Higgs boson composite due to strong dynamics that break EW symmetry
  - Primary annihilation process is through the Higgs
    - Higgs mass constrains DM sector strongly

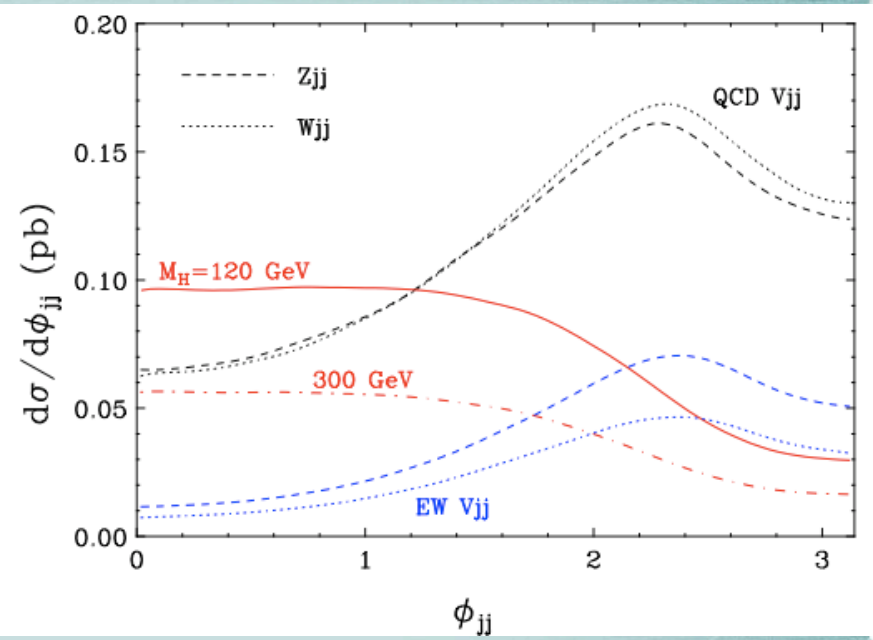


Hubisz and Meade '04
Birkedal, Noble, Perelstein, Spray '06.

The Higgs-DM connection: At the LHC

Higgs decays to DM pairs

- DM and Higgs talk to each other
  - Natural to expect Higgs decays to DM if kinematically allowed
  - May cause complications for Higgs discovery



Weak boson fusion:
Extract signal with cuts on azimuthal correlation of forward jets and large missing p_T

Eboli and Zeppenfeld

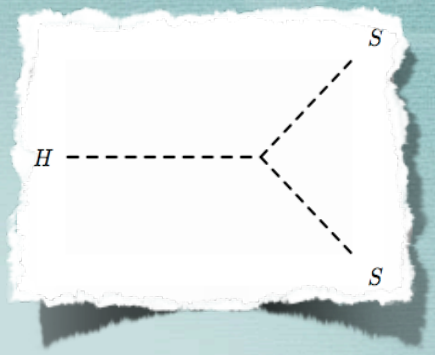
Z-Higgstrahlung:
Cuts on dilepton separation and invariant mass to extract signal

Davoudiasl, Han, Logan

Combined → model independent mass determination

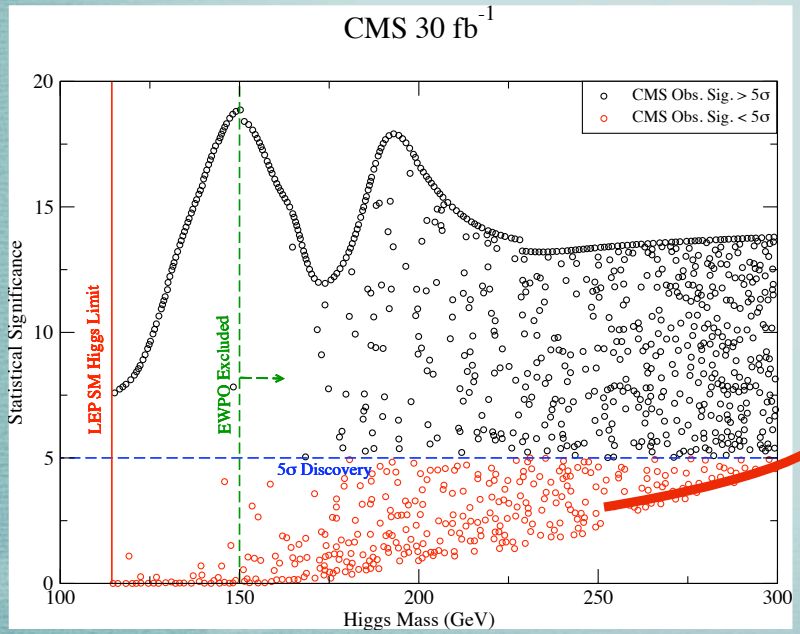
Effect on Higgs discovery in xSM

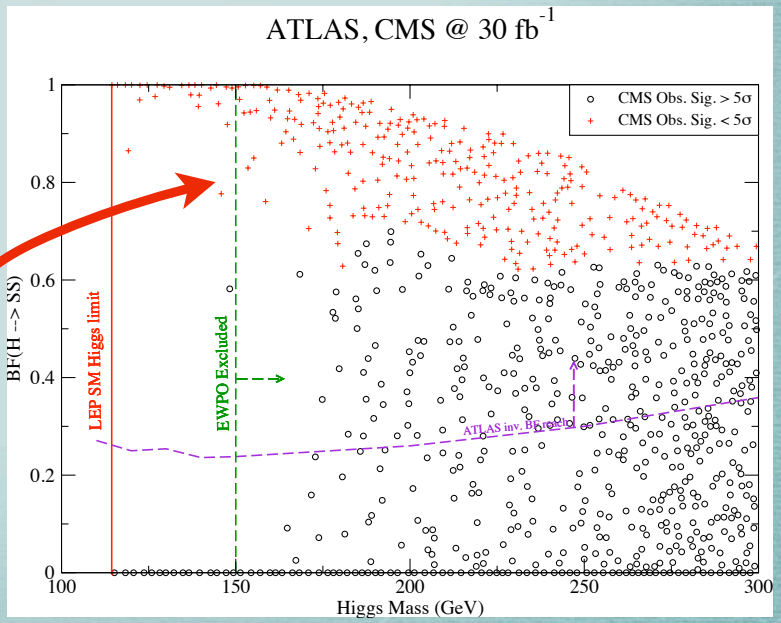
- May greatly affect Higgs discovery potential
  - Higgs decays to invisible states
  - Decrease rate of traditional Higgs modes
  - Discovery possible via dominant invisible decay



Red: not disc. with visible modes

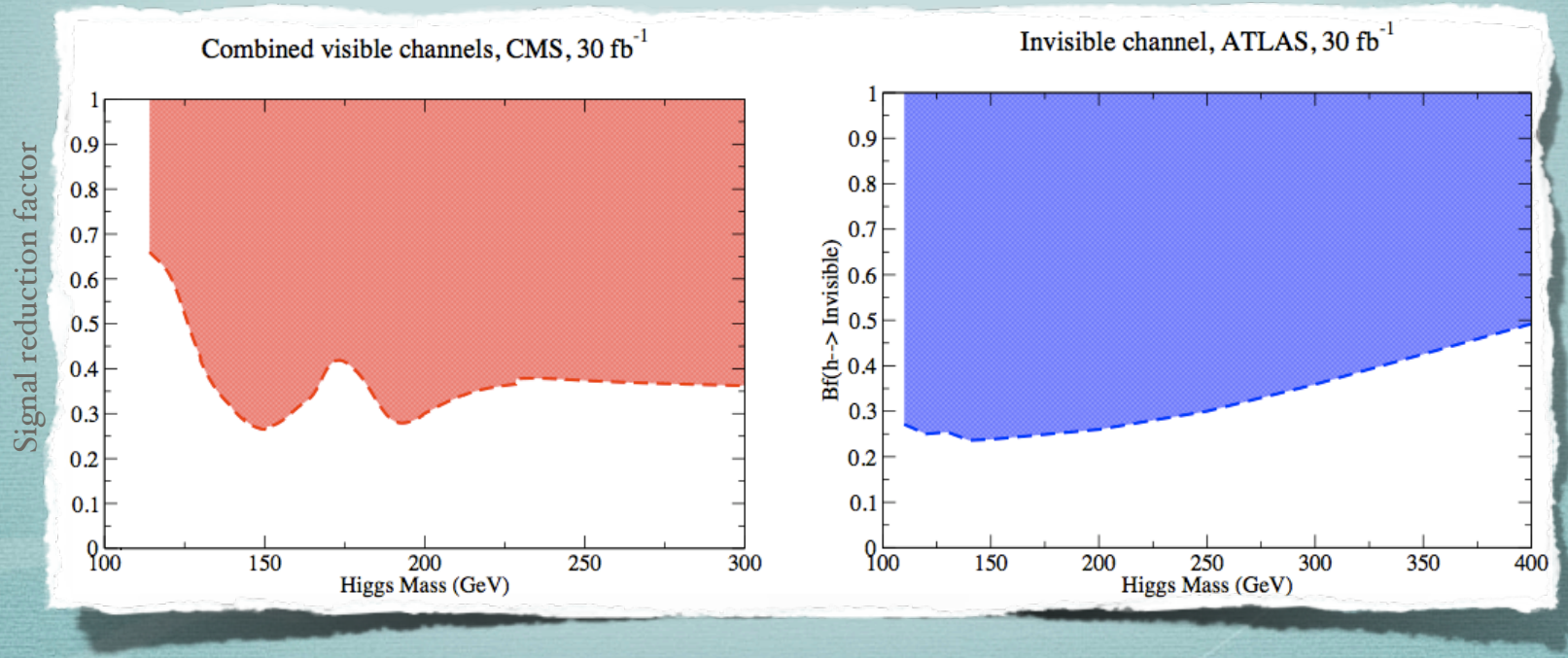
Black: disc. with visible modes





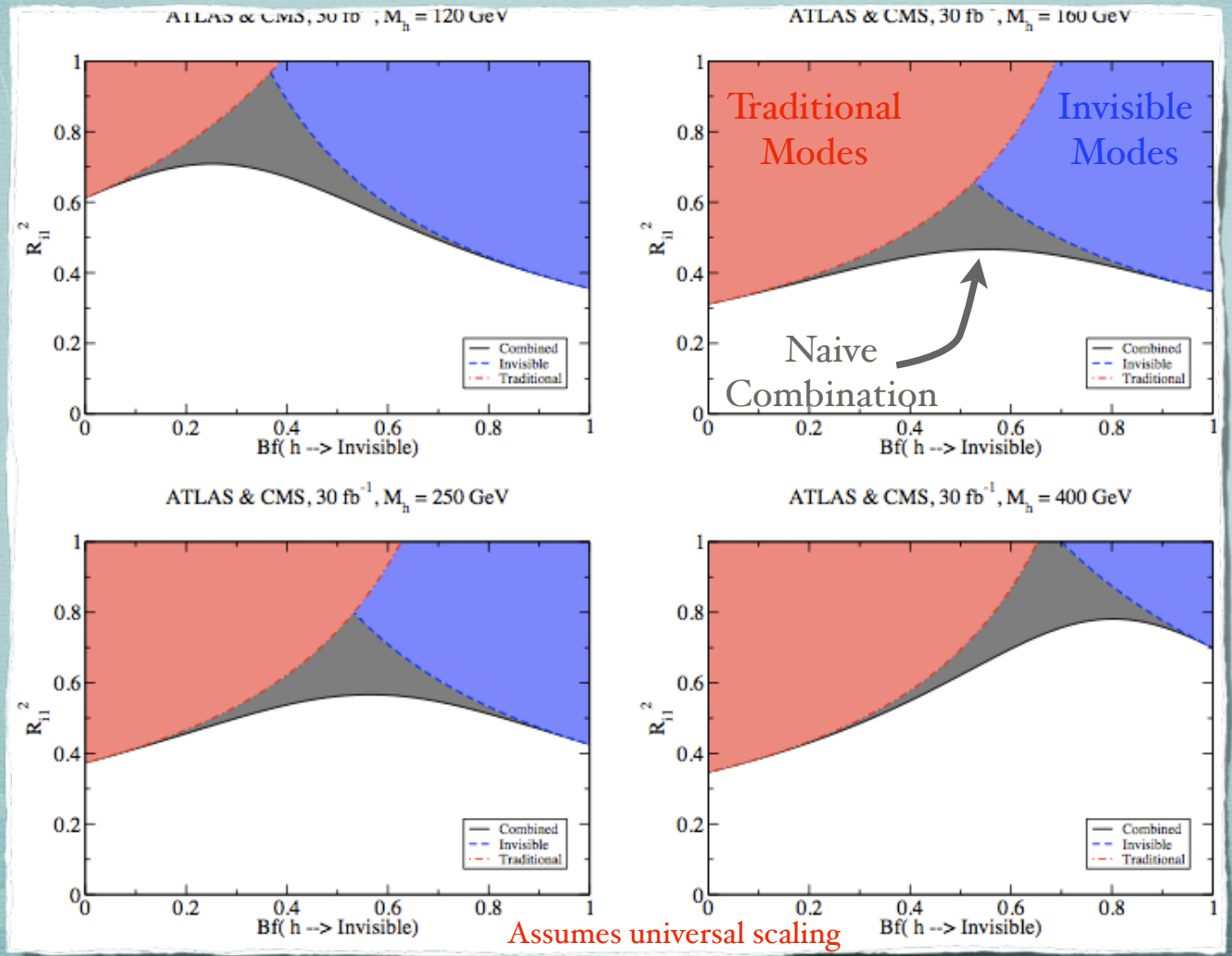
Higgs boson still discoverable even if decays to DM allowed!

- Sensitivity can be inverted to determine level of Higgs mixing can be probed at LHC



Combination

- Simple (and naive) scaling for combination paints picture of how well LHC covers space of Higgs mixing and invisible decay



Assumes universal scaling

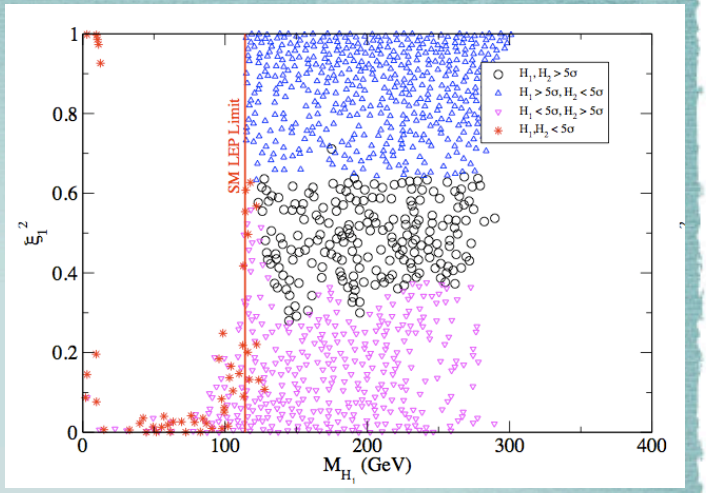
Barger, Langacker, McCaskey, Ramsey-Musolf, GS '08

Additional New Physics impact on Higgs

Additional New Physics impact on Higgs

- Reduced Higgs couplings due to mixing with scalars of model

Krasnikov '97. O'Connell et al. '06.
Barger, Langacker McCaskey, Ramsey-Musolf, GS '07 '08
Dawson, Yang '09



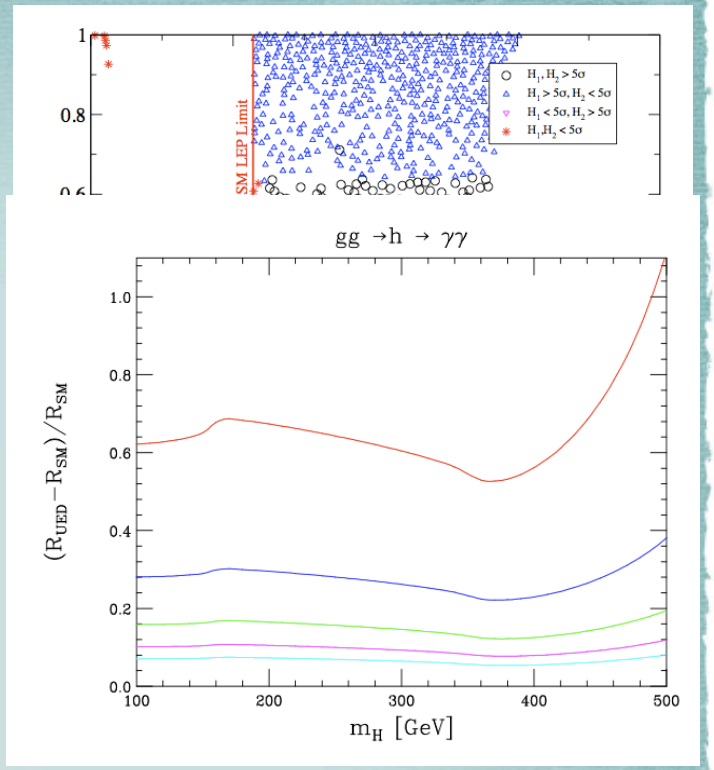
Additional New Physics impact on Higgs

- Reduced Higgs couplings due to mixing with scalars of model

  Krasnikov '97. O'Connell et al. '06.
  Barger, Langacker McCaskey, Ramsey-Musolf, GS '07 '08
  Dawson, Yang '09

- Enhanced production/decay to gg or gamma pairs
  - e.g. SUSY/UED running in loops

    Petriello '02. Hsieh, Yuan '08



Additional New Physics impact on Higgs

- Reduced Higgs couplings due to mixing with scalars of model

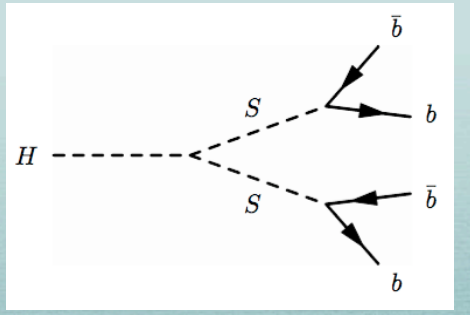
  Krasnikov '97. O'Connell et al. '06.
  Barger, Langacker McCaskey, Ramsey-Musolf, GS '07 '08
  Dawson, Yang '09

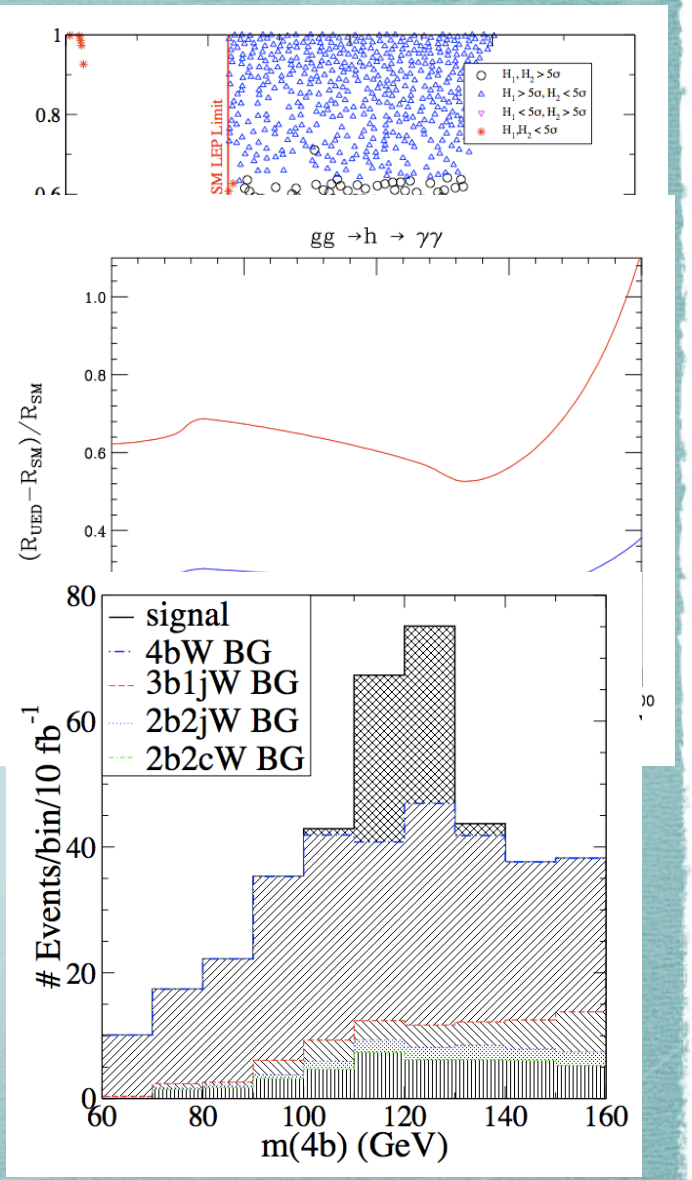
- Enhanced production/decay to gg or gamma pairs
  - e.g. SUSY/UED running in loops

    Petriello '02. Hsieh, Yuan '08

- Extended Higgs decays to >2 final states

  Gunion, Dermisek. Carena, Han, Huang, Wagner '07
  Cheng, Song, Yan '07



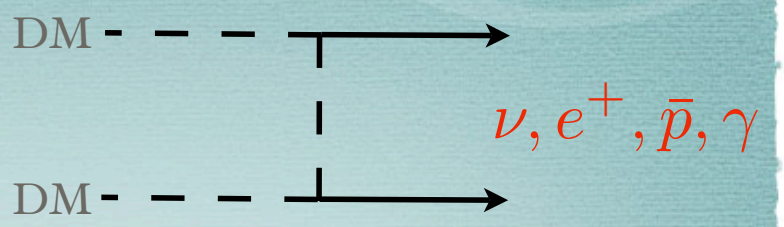


The Higgs-DM connection: Look to the Sky!

How do we find DM: Indirect Detection

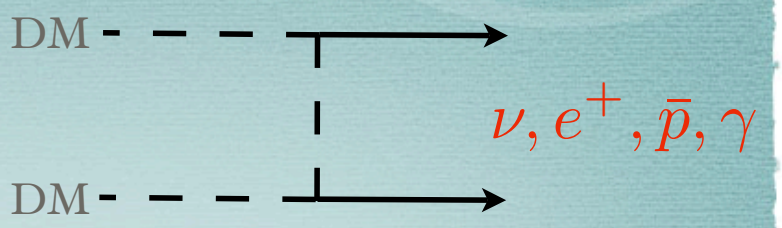
How do we find DM: Indirect Detection

- We can detect presence of DM by its annihilation products in the galactic halo

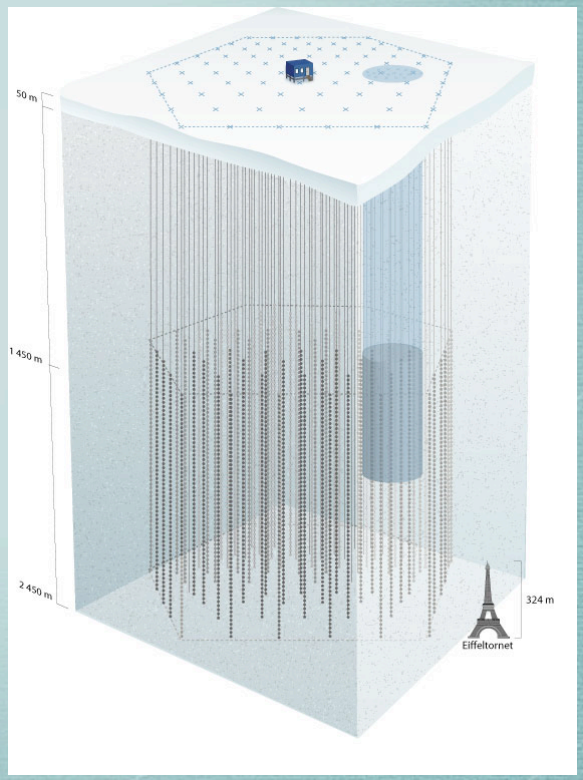


How do we find DM: Indirect Detection

- We can detect presence of DM by its annihilation products in the galactic halo

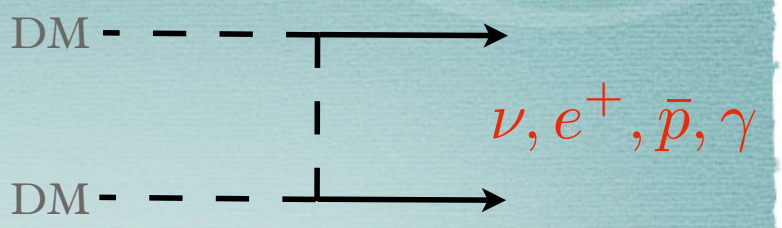


- Signatures include observation of cosmic rays
  - ν • IceCube, Antares, Super-Kamiokande (neutrino detectors/telescopes)



How do we find DM: Indirect Detection

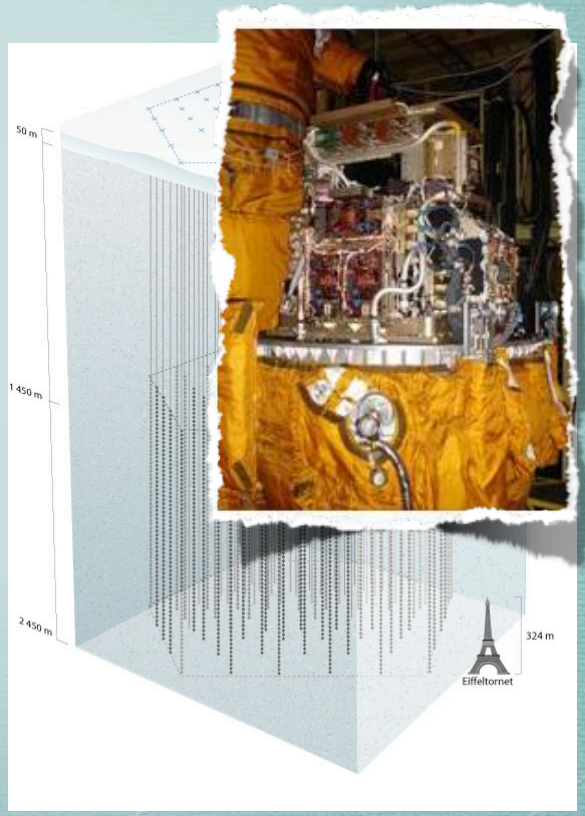
- We can detect presence of DM by its annihilation products in the galactic halo



- Signatures include observation of cosmic rays

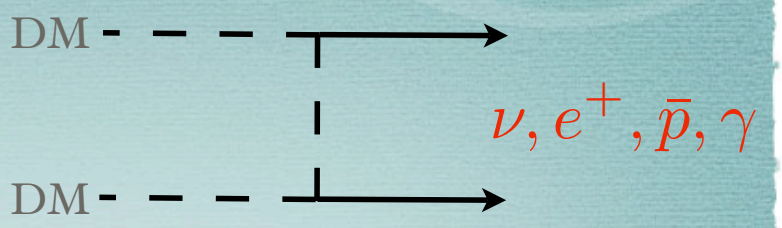
ν • IceCube, Antares, Super-Kamiokande (neutrino detectors/telescopes)

$e^+, \bar{p}$ • PAMELA (satellite)



How do we find DM: Indirect Detection

- We can detect presence of DM by its annihilation products in the galactic halo

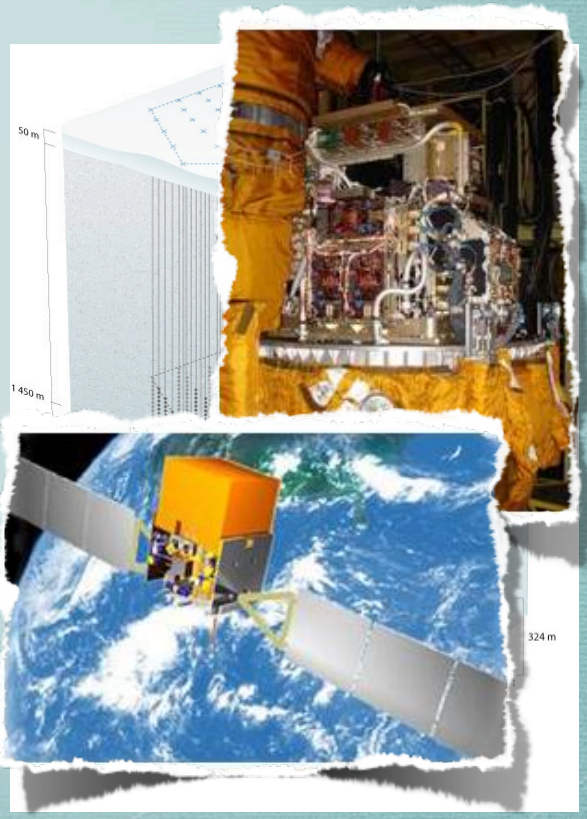


- Signatures include observation of cosmic rays

ν • IceCube, Antares, Super-Kamiokande (neutrino detectors/telescopes)

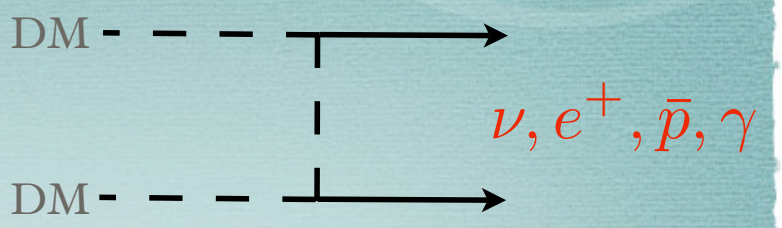
$e^+, \bar{p}$ • PAMELA (satellite)

γ, e • Fermi (satellite)



How do we find DM: Indirect Detection

- We can detect presence of DM by its annihilation products in the galactic halo

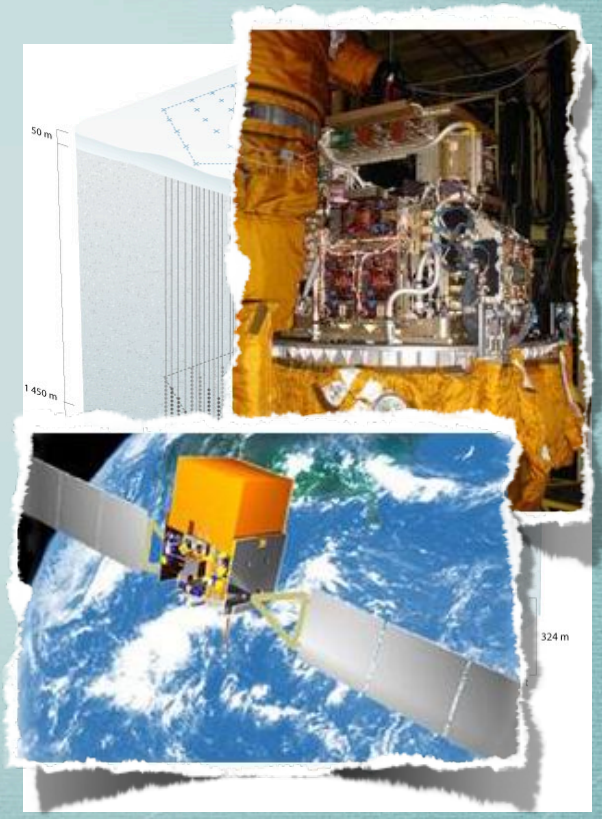


- Signatures include observation of cosmic rays

ν • IceCube, Antares, Super-Kamiokande (neutrino detectors/telescopes)

$e^+, \bar{p}$ • PAMELA (satellite)

γ, e • Fermi (satellite)

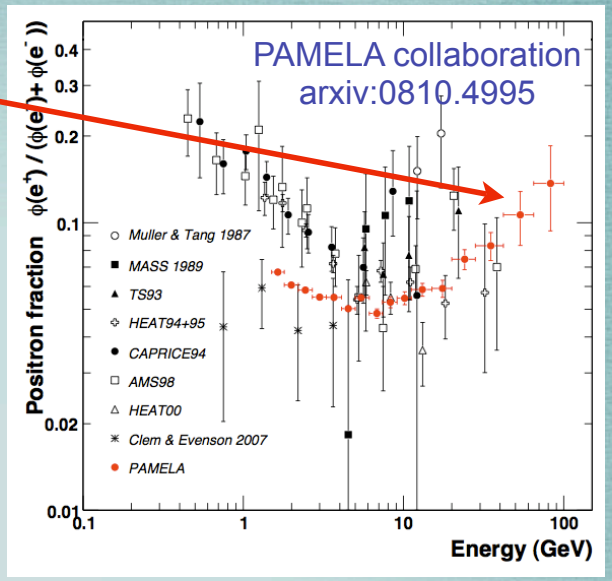


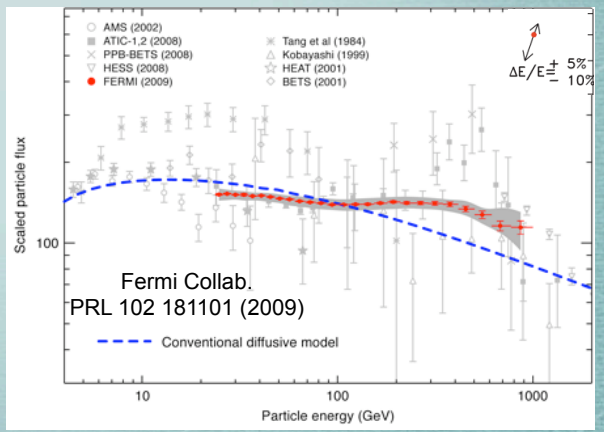
- How might these final states be connected with the Higgs?

Recent cosmic ray data

Recent cosmic ray data

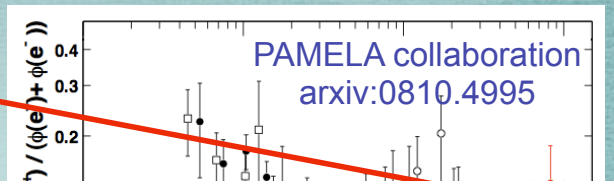
- PAMELA data point to anomalous excess of high energy positrons in galaxy
  - Injection thought to come from DM annihilations
  - Fermi sees slight excess in total electron data





Recent cosmic ray data

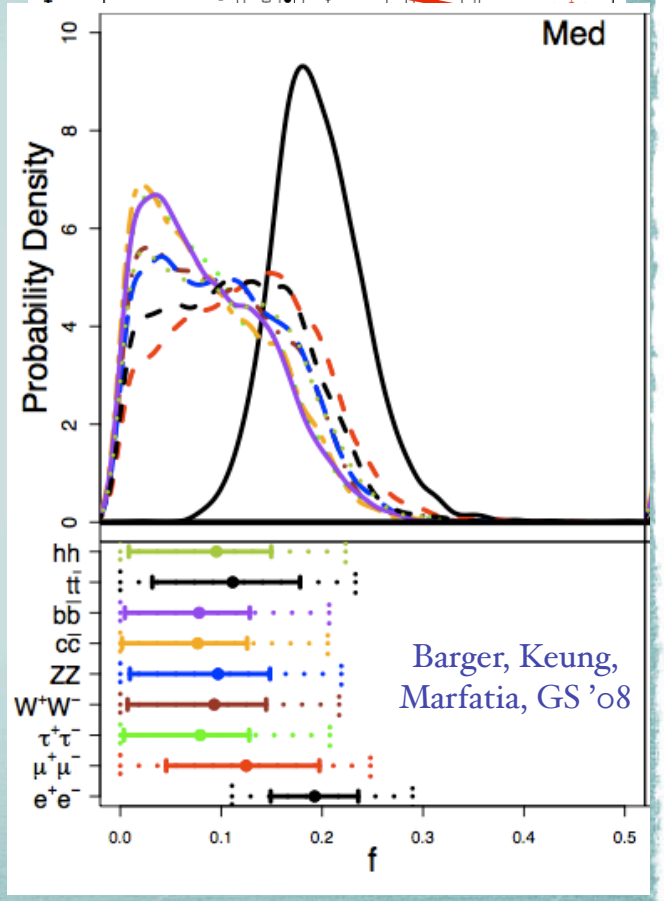
- PAMELA data point to anomalous excess of high energy positrons in galaxy
  - Injection thought to come from DM annihilations
  - Fermi sees slight excess in total electron data



- Direct annihilation to charged lepton pairs most favorable to reproduce hard spectrum

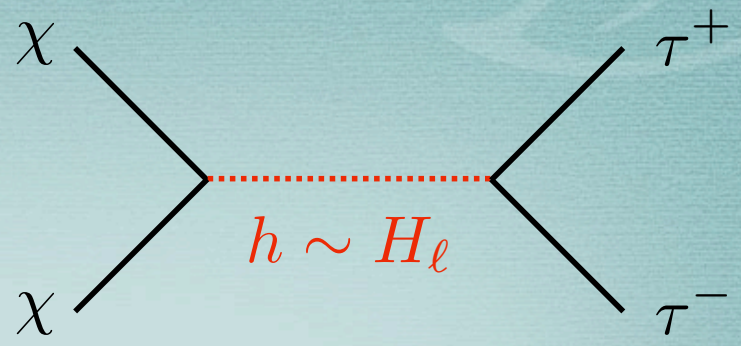
Cirelli, Kadastik, Raidal, Strumia '08
Barger, Keung, Marfatia, GS '08

- Annihilation to SM Higgs boson pairs unfavorable



Lepto-phillic Higgs mediated positron signals!

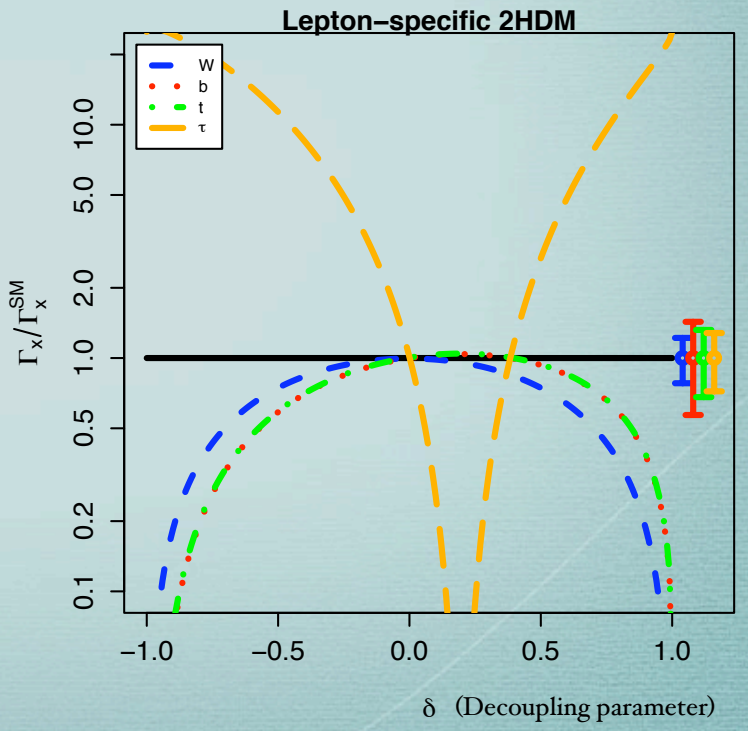
- However, leptophillic Higgs models can produce leptons prolifically Goh, Hall, Kumar '09



- Associated LHC signatures can be easy to distinguish from other Higgs sectors Barger, Logan, GS '09

- Pattern relation among couplings within Lepton-specific model:

$$P_{u\ell} = \bar{g}_W(\bar{g}_q + \bar{g}_\ell) - \bar{g}_q\bar{g}_\ell = 1$$



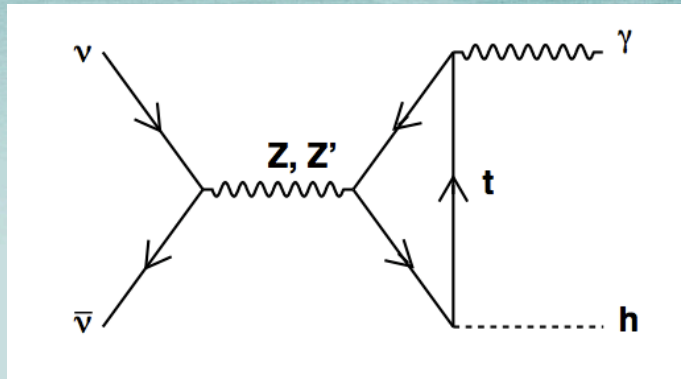
Higgs in Space!

Higgs in Space!

- Detection of DM via gamma rays can provide rich signatures

- Annihilation to $h\gamma$ can significantly displace photon line

$$E_\gamma = M\left(1 - \frac{M_X^2}{4M^2}\right)$$



Randall-Sundrum example:
Jackson, Servant, GS, Tait, Taoso (in prep)

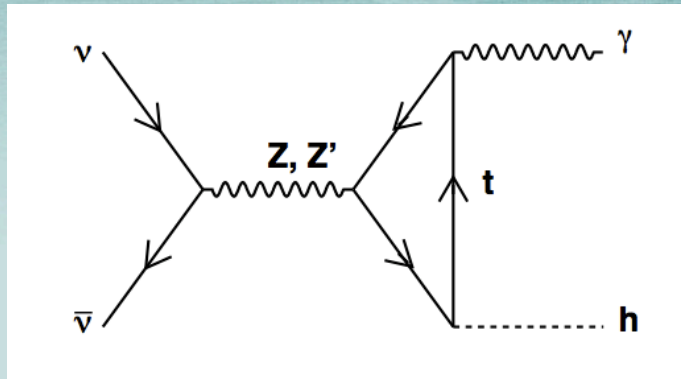
Higgs in Space!

- Detection of DM via gamma rays can provide rich signatures

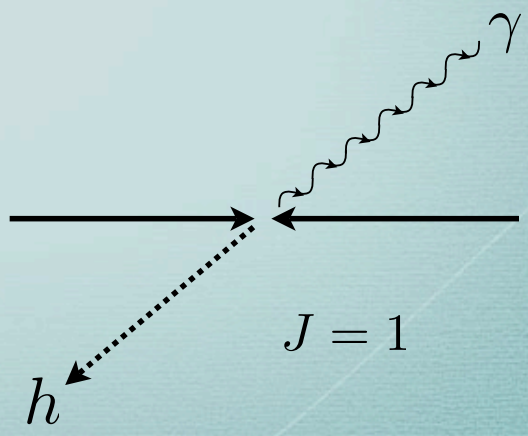
- Annihilation to $h\gamma$ can significantly displace photon line

$$E_\gamma = M\left(1 - \frac{M_X^2}{4M^2}\right)$$

- Angular momentum conservation allows Dirac Fermion or Vector Boson in initial state



Randall-Sundrum example:
Jackson, Servant, GS, Tait, Taoso (in prep)

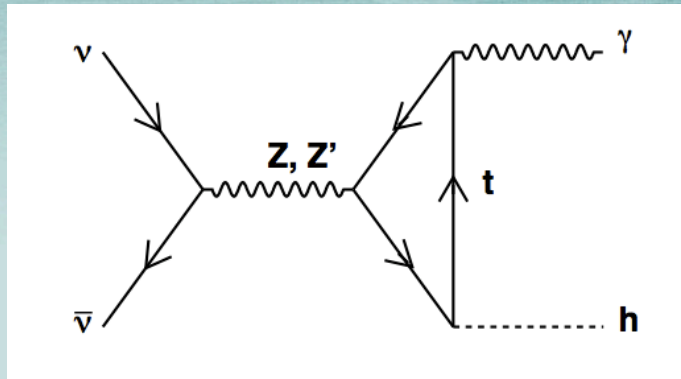


Higgs in Space!

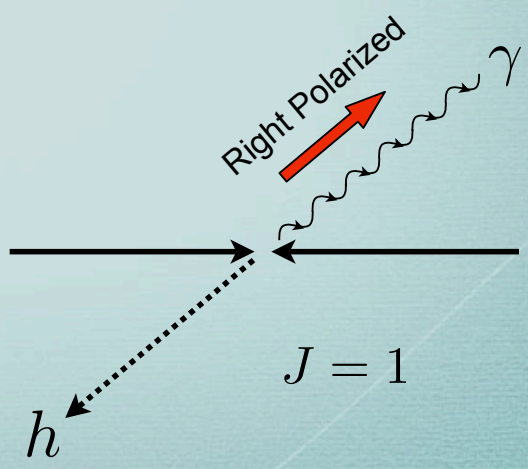
- Detection of DM via gamma rays can provide rich signatures
- Annihilation to $h\gamma$ can significantly displace photon line

$$E_\gamma = M\left(1 - \frac{M_X^2}{4M^2}\right)$$

- Angular momentum conservation allows Dirac Fermion or Vector Boson in initial state



Randall-Sundrum example:
Jackson, Servant, GS, Tait, Taoso (in prep)



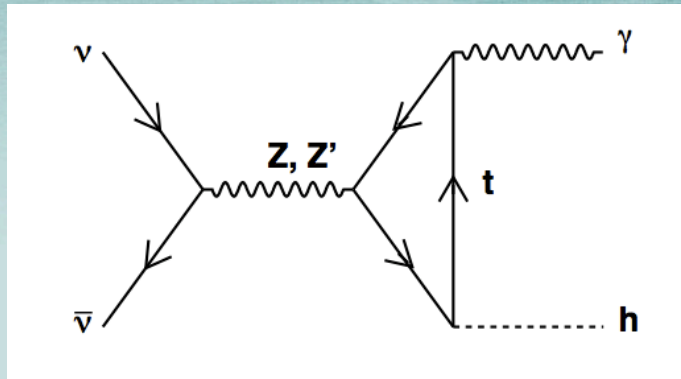
Higgs in Space!

- Detection of DM via gamma rays can provide rich signatures

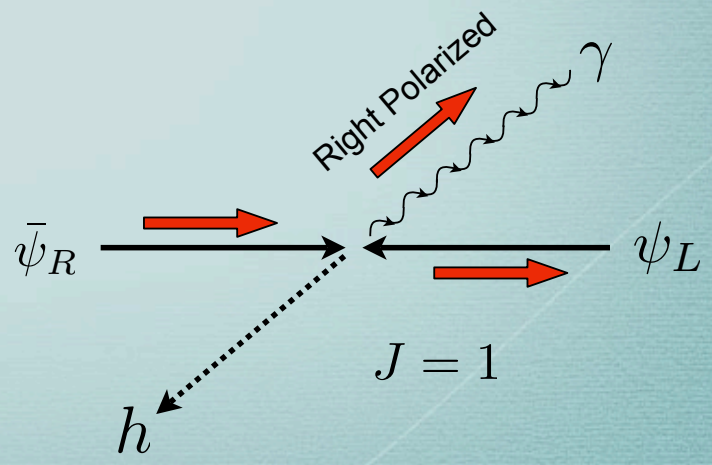
- Annihilation to $h\gamma$ can significantly displace photon line

$$E_\gamma = M\left(1 - \frac{M_X^2}{4M^2}\right)$$

- Angular momentum conservation allows Dirac Fermion or Vector Boson in initial state



Randall-Sundrum example:
Jackson, Servant, GS, Tait, Taoso (in prep)



Higgs in Space!

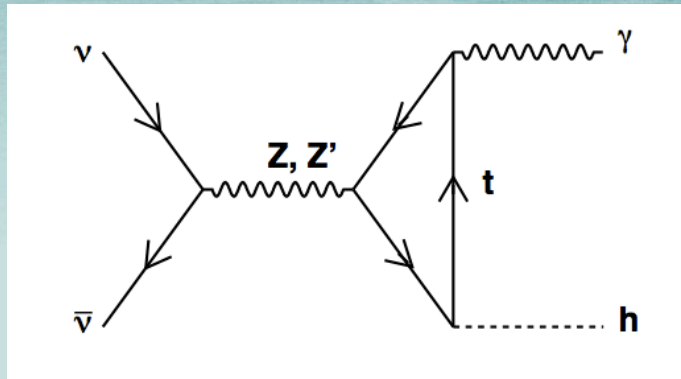
- Detection of DM via gamma rays can provide rich signatures

- Annihilation to $h\gamma$ can significantly displace photon line

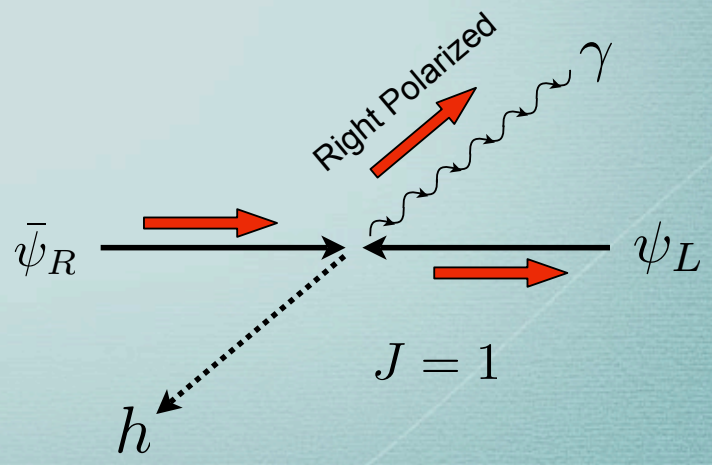
$$E_\gamma = M\left(1 - \frac{M_X^2}{4M^2}\right)$$

- Angular momentum conservation allows Dirac Fermion or Vector Boson in initial state

- Observation of Higgs line can help determine spin of DM state!



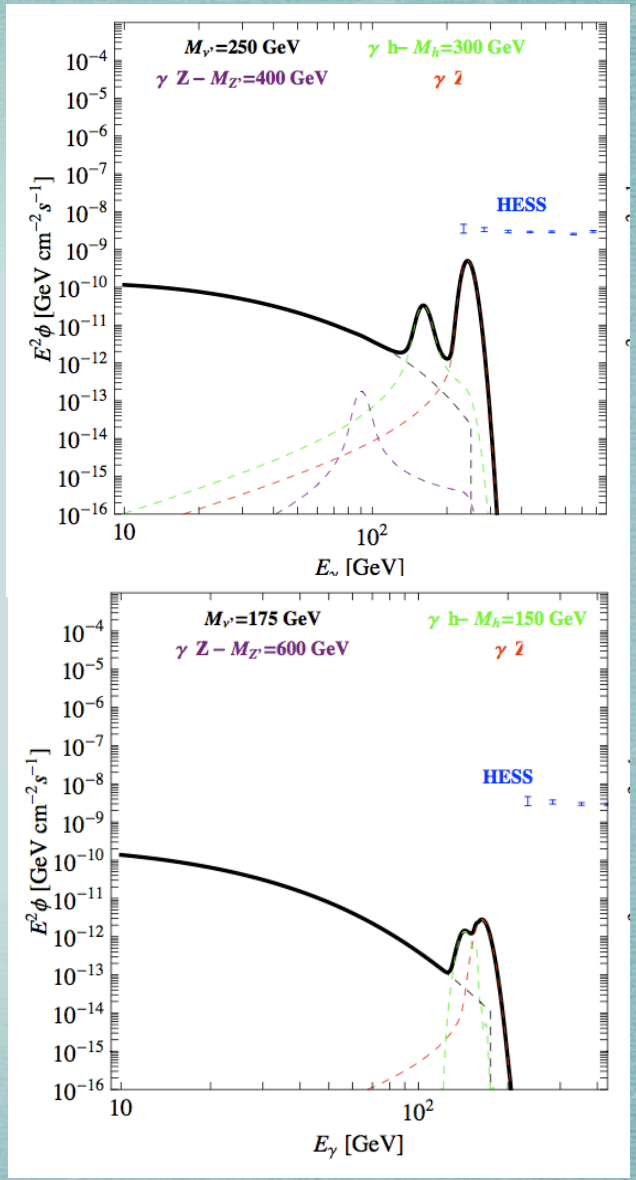
Randall-Sundrum example:
Jackson, Servant, GS, Tait, Taoso (in prep)



Higgs in Space!

- Fermi energy resolution $\frac{\delta E}{E} \sim 10\%$ smears lines
- Observation of two lines can be checked for consistency with Higgs boson
- Additional lines may appear if associated states can be produced
  - Possible "WIMP Forest"
  - New physics spectroscopy!

Bertone, Jackson, GS, Tait, Vallinoto '09



Conclusions

- Both DM and Higgs discovery may be upon us!
- Plethora of BSM models connect DM and Higgs sectors
- Terrestrial and astronomical observations may point to the nature of these sectors and how they are connected
  - DM production via Higgs decays at the LHC
  - DM annihilation to $h\gamma$ giving displaced gamma lines in galactic DM halo
  - Leptophillic Higgs connection may explain cosmic ray excess