Searching for dark matter at future colliders

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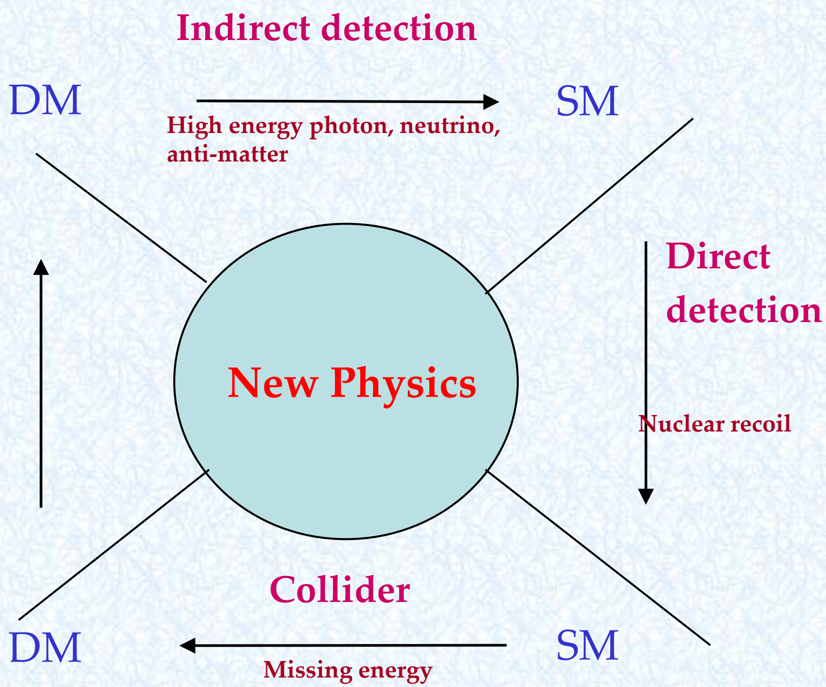
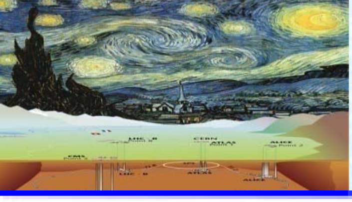
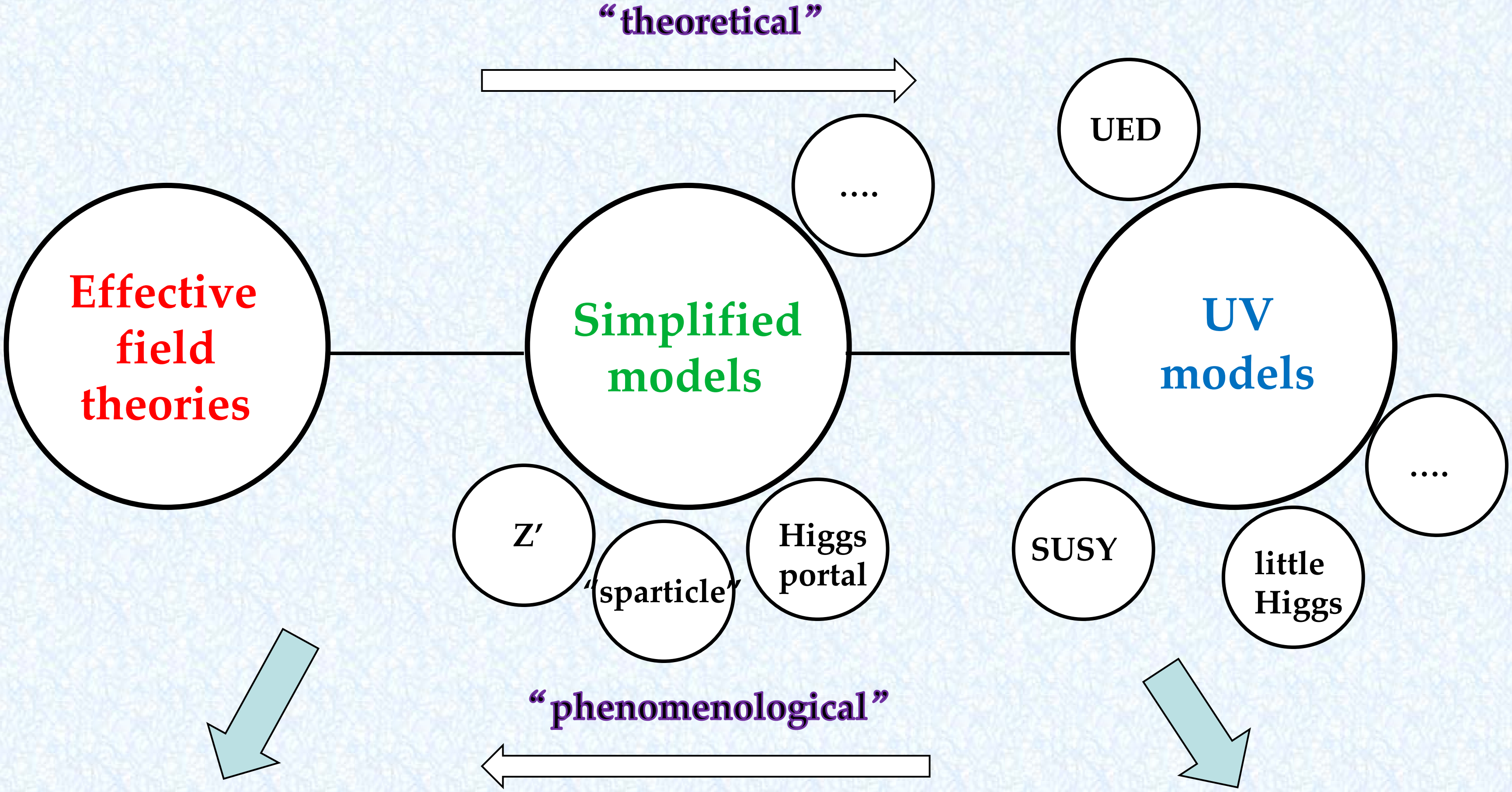
DM signatures



- We still do not know what DM is
- Neutral, stable, and weakly interacting
- $\Omega_{DM}h^2 \sim 0.12$
  thermal freeze out ? $\sigma v \sim 3X10^{-26} cm^3/s$
  $\sigma \sim g^4/m^2$, $m<1.8 TeV$ $(g^2/0.3)$
- Weakly Interacting Massive Particle !
- Missing energy at colliders
  (transverse missing energy at hadron colliders)
- Complementarity of three detections



Theoretical approaches



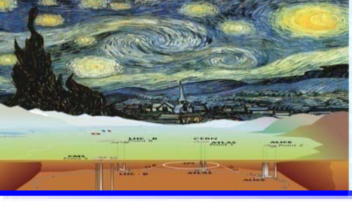
Mono-X

Direct production, "model-independent"

Multi final states +ME

Cascade decay, "model-dependent"

Other collider signatures and constraints



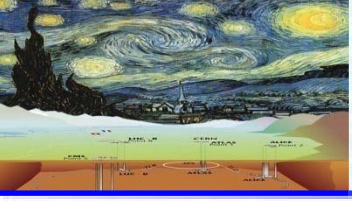
Possible studies at e^+e^- colliders

- **Disadvantage: Low CM energy;**
  Difficult to directly discover heavy new particles

- **Advantage: No large QCD background; precise beam energy; polarized beams;**
  Can accurately measure the mass, spin, and other quantum numbers
  Complementary to hadron colliders

- **Search for light DM <~100GeV**
  Search for interactions between the DM and electrons/EW gauge bosons/Higgs

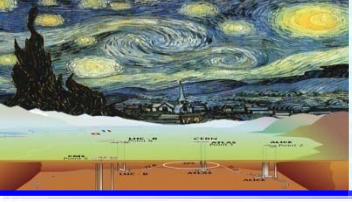
- **Probe relevant particles in new physics models? (t-channel annihilation mediator, multiplet…)**
  Indirect search through loop effects, e.g. in Higgs measurements?



Possible studies at e^+e^- colliders

- Precise measurement rather than discovery
  Can get full missing energy
  Accurately measure the mass, spin, and other quantum numbers of DM

- Even a new neutral, stable, and weakly interacting particle χ is discovered, we should answer whether it can make up all the DM in the Universe.
  Can accurately calculate the thermal relic density of this particle through the use of measured DM mass and coupling coefficients.
  Can study the DM production mechanism and cosmological effects of DM
  $\Omega_\chi h^2 = 0.12$, strong support for the discovery of DM
  $\Omega_\chi h^2 < 0.12$, multi-DM particles ? Non-thermal production?
  $\Omega_\chi h^2 > 0.12$, some other unexpected annihilation channels? Resonant annihilation? co-annihilation?

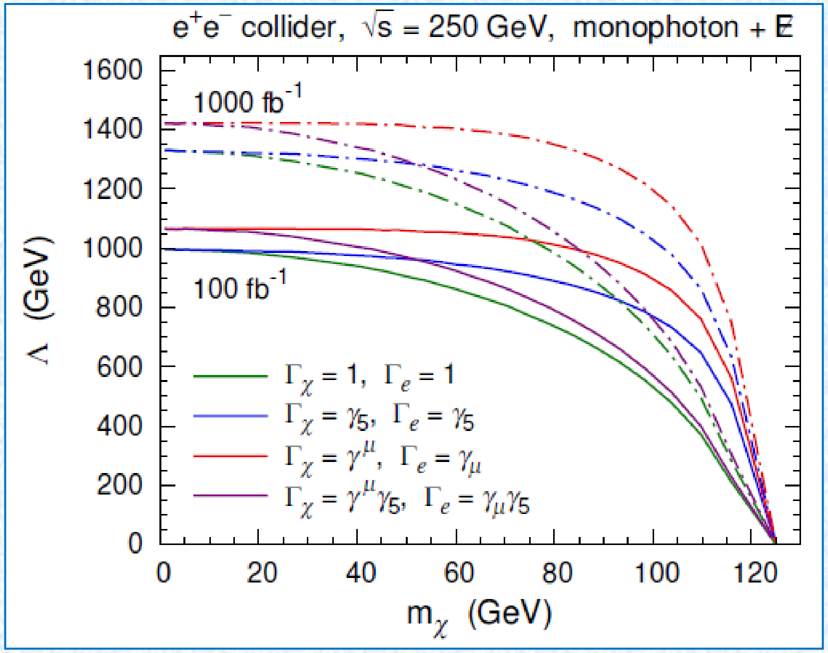


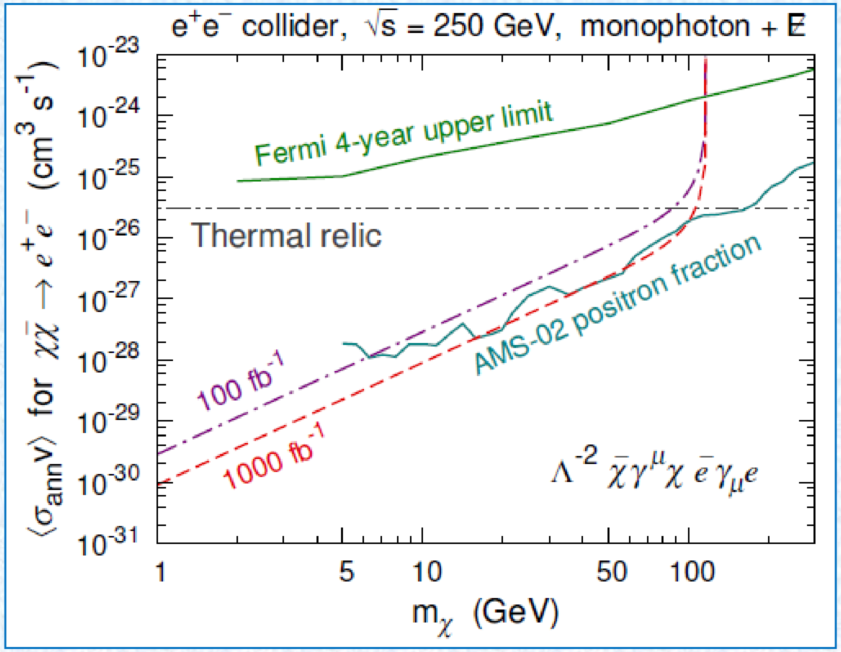
Results for DM interactions with electron/positron

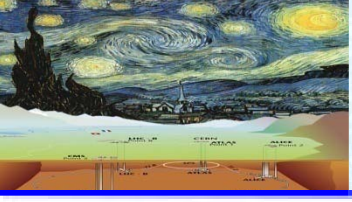
- Consider EFT

$$\mathcal{O}_e = \frac{1}{\Lambda^2}\bar{\chi}\Gamma_\chi\chi\bar{e}\Gamma_e e \qquad \Gamma_\chi, \Gamma_e \in \{1, \gamma_5, \gamma^\mu, \gamma^\mu\gamma_5, \sigma^{\mu\nu}\}$$

Search for mono-photon signals from initial state radiations

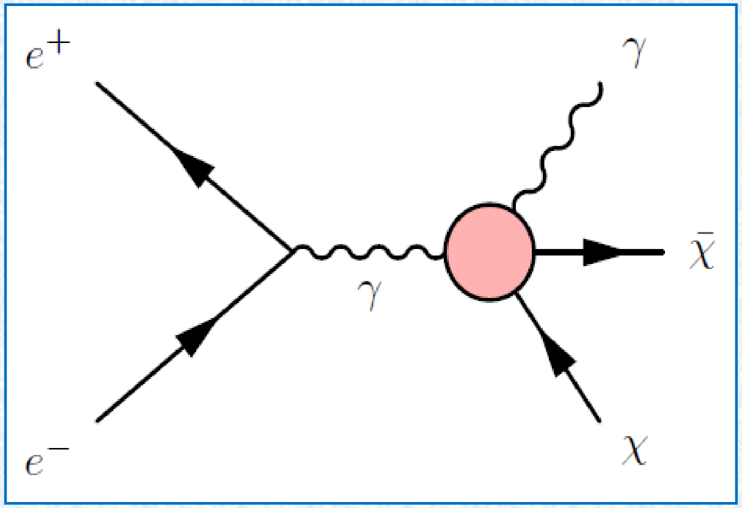


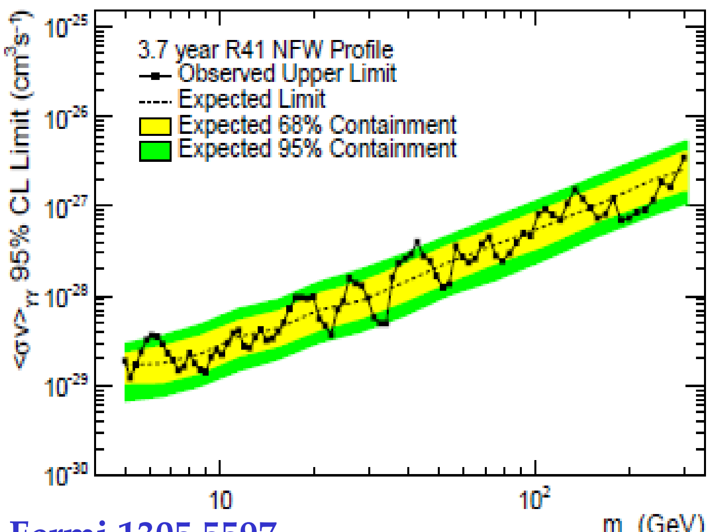




Gamma-ray line and mono-photon

- Gamma-ray line is a critical evidence of DM annihilation/decay
- ~3-4 σ signals reported by some groups but not confirmed by the Fermi-LAT collaboration.
- Search for corresponding mono-photon signals at future e^+e^- colliders





Fermi 1305.5597

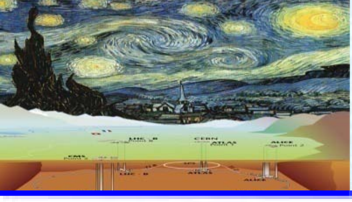
- Effective operator

Yu, Yan, Yin, 1307.5740

$$\mathcal{O}_F = \frac{1}{\Lambda^3}\bar{\chi}\, i\gamma_5 \chi\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

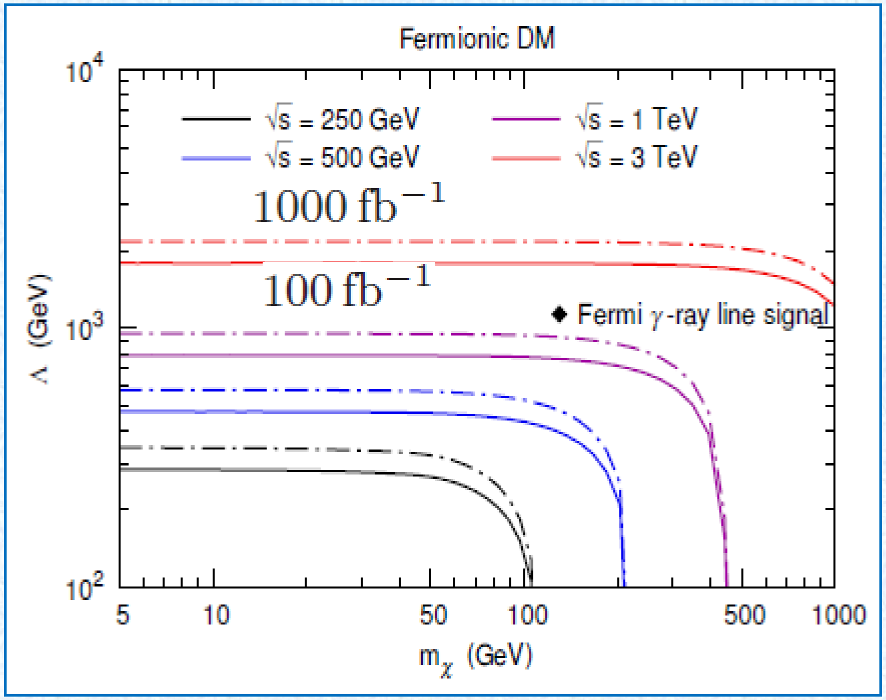
Cut scale for a ~100 GeV DM and a detectable cross section is ~TeV

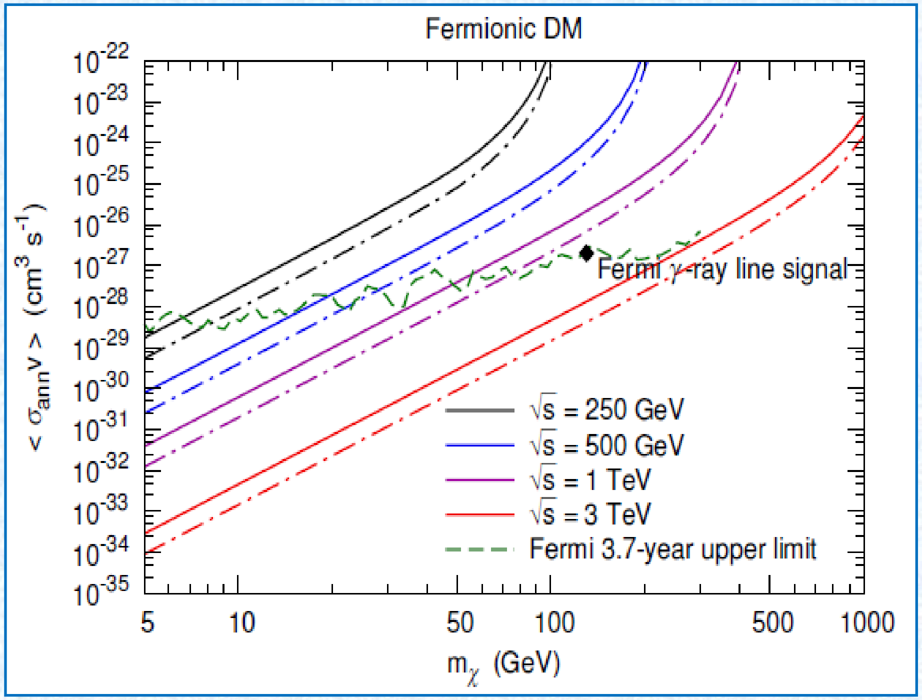
$$\langle \sigma_{\rm ann} v \rangle_{\chi\bar{\chi}\to 2\gamma} \simeq \frac{4m_\chi^4}{\pi\Lambda^6} = 10^{-27}\ {\rm cm}^3\ {\rm s}^{-1} \left(\frac{m_\chi}{130\ {\rm GeV}}\right)^4 \left(\frac{1272\ {\rm GeV}}{\Lambda}\right)^6$$

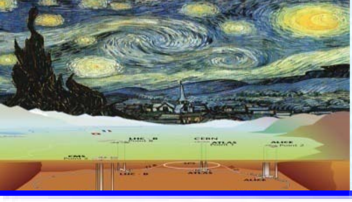


Reaches

- Consider possible e^+e^- colliders with CM energies of 250, 500, 1000 and 3000 GeV
- 3 σ reaches for mass scale and annihilation cross section
- Require large luminosities



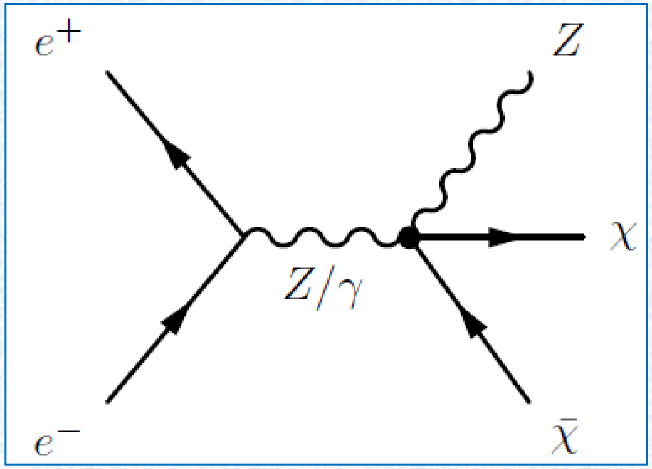




Mono-Z signals

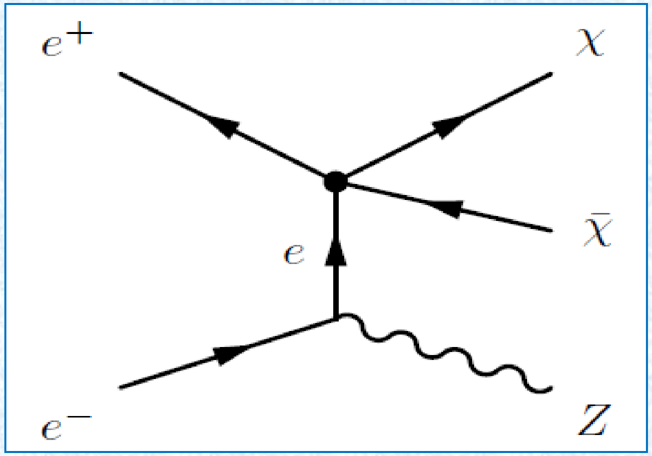
- DM can interact with both the photon and Z boson
- Consider effective operators

$$\mathcal{O}_{\mathrm{F1}} = \frac{1}{\Lambda_1^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu} + \frac{1}{\Lambda_2^3}\bar{\chi}\chi W^a_{\mu\nu}W^{a\mu\nu}$$
$$\supset \bar{\chi}\chi\left(G_{ZZ}Z_{\mu\nu}Z^{\mu\nu} + G_{AZ}A_{\mu\nu}Z^{\mu\nu}\right)$$
$$\mathcal{O}_{\mathrm{F2}} = \frac{1}{\Lambda_1^3}\bar{\chi}i\gamma_5\chi B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{1}{\Lambda_2^3}\bar{\chi}i\gamma_5\chi W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$$
$$\supset \bar{\chi}i\gamma_5\chi\left(G_{ZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + G_{AZ}A_{\mu\nu}\tilde{Z}^{\mu\nu}\right)$$
$$\mathcal{O}_{\mathrm{FH}} = \frac{1}{\Lambda^3}\bar{\chi}\chi(D_\mu H)^\dagger D_\mu H \to \frac{m_Z^2}{2\Lambda^3}\bar{\chi}\chi Z_\mu Z^\mu$$

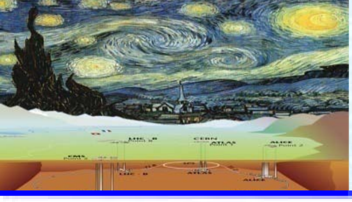


- Z boson can also com from initial state radiation

$$\mathcal{O}_{\mathrm{FP}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_5\chi\bar{e}\gamma_5 e,$$
$$\mathcal{O}_{\mathrm{FA}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma_5\chi\bar{e}\gamma_\mu\gamma_5 e$$

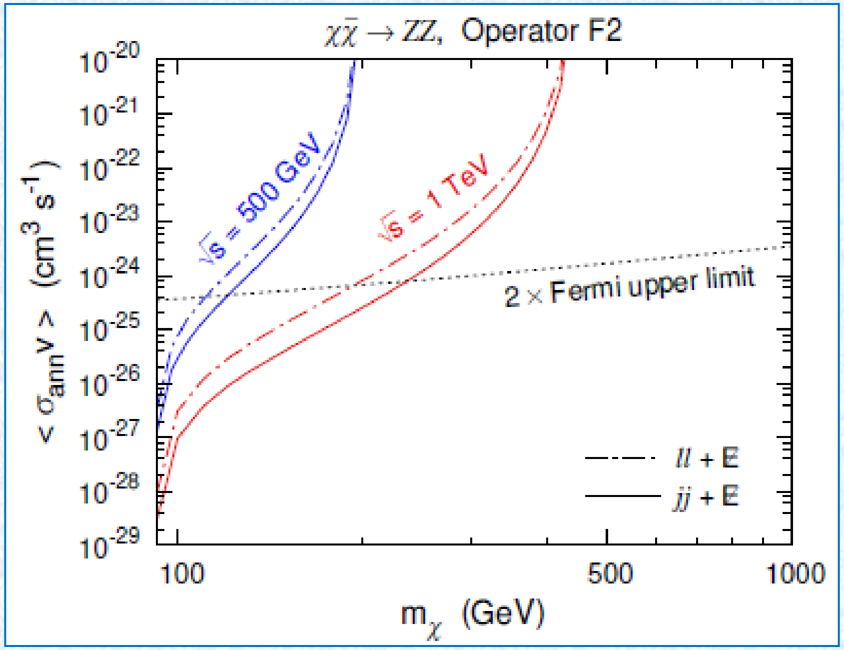


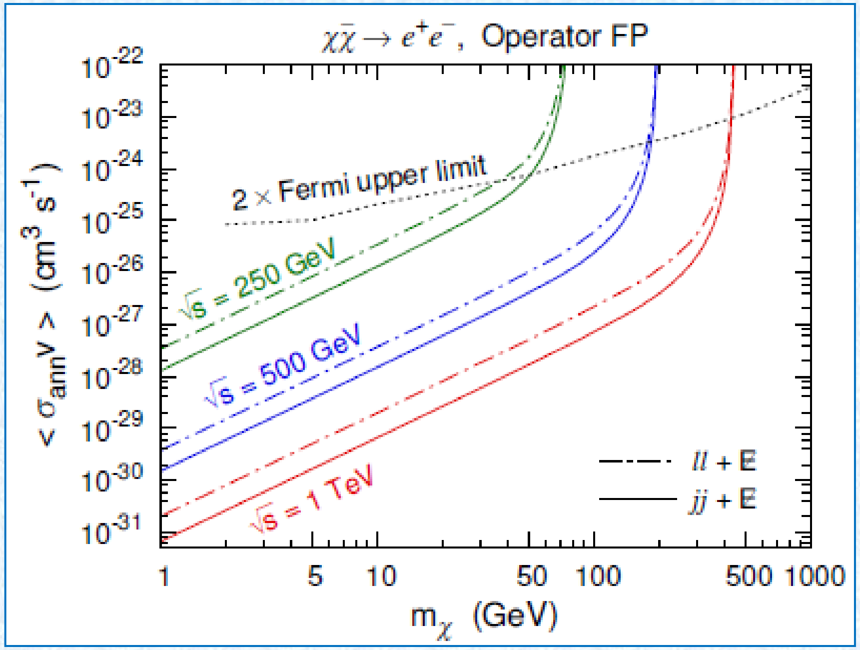
Yu, Bi, Yan, Yin, 1404.6990



Reaches

- 3 σ reaches for interactions between the DM and gauge bosons/electrons
- Assume: 1000 fb^{-1} of data; $\Lambda = \Lambda_1 = \Lambda_2$
- Compare with the limits from Fermi-LAT dwarf galaxy observations





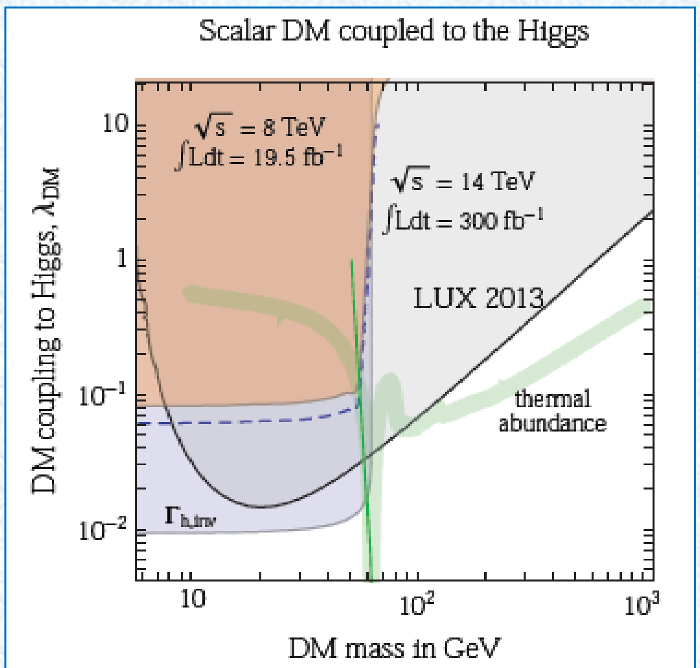
DM coupled to SM mediators

- Assume that DM couples to the SM particles through some mediators

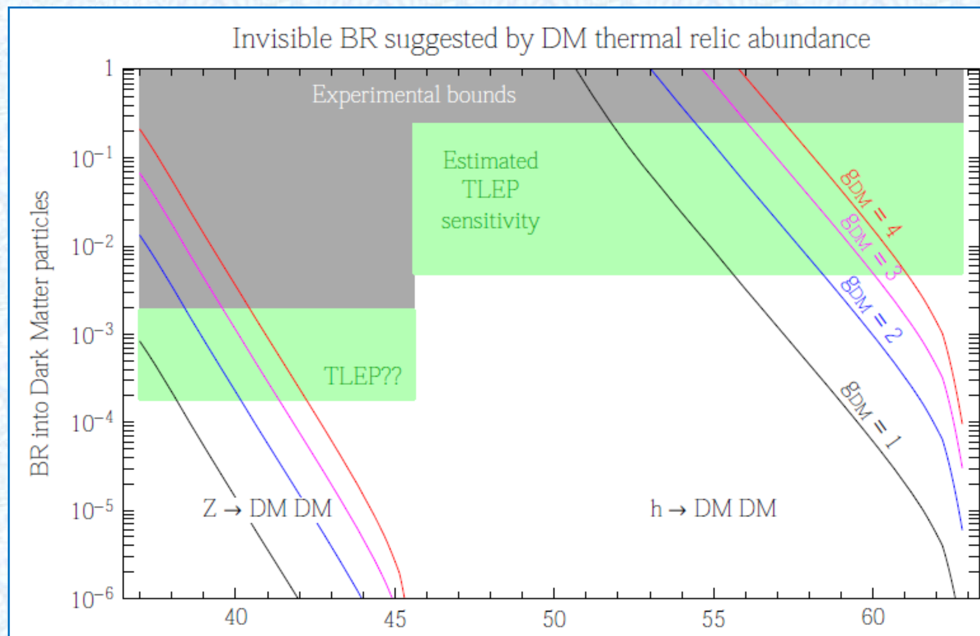
$$\mathcal{L} = -h J_h\,, \qquad J_h = \frac{1}{\sqrt{2}}\left[\sum_f y_f \bar f f + \bar\psi_{\rm DM}(y_{\rm DM} + i y^P_{\rm DM}\gamma_5)\psi_{\rm DM} + \frac{\lambda_{\rm DM} v}{2} s^2_{\rm DM}\right]$$

$$\mathcal{L} = -Z_\mu J^\mu_Z\,, \qquad J^Z_\mu = \frac{g_2}{\cos\theta_{\rm W}}\left[\sum_f [\bar f \gamma_\mu (g^f_V + \gamma_5 g^f_A) f] + \sum_s g_s [s^*(i\partial_\mu s) - (i\partial_\mu s^*) s]\right]$$

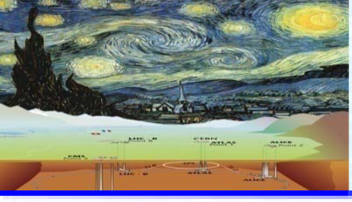
- Searches for invisible Higgs/Z decays are useful to probe DM



Simone, Giudice, Strumia, 1402.6287

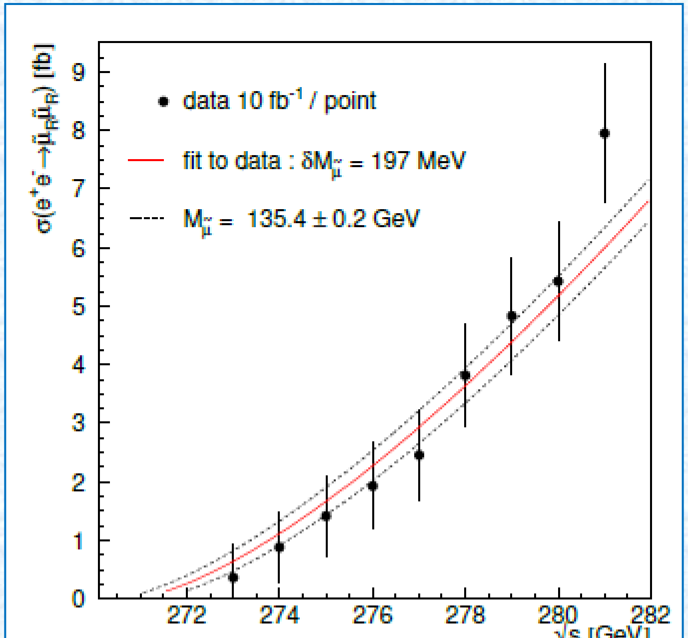


Strumia, TLEP9, 2015

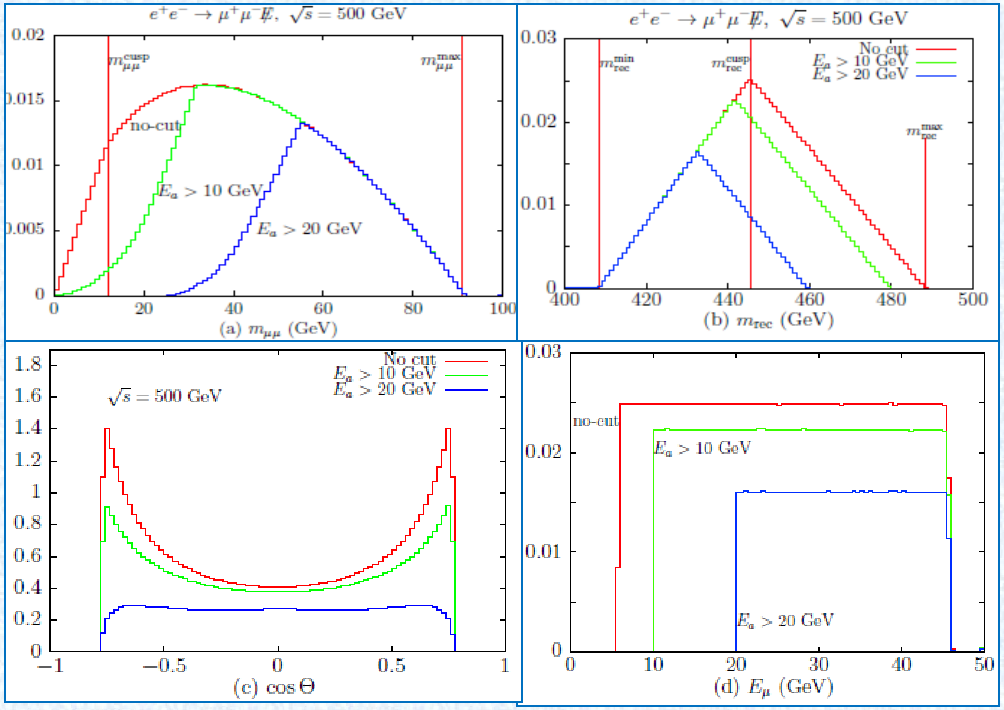


DM mass determine at e^+e^- colliders

- Consider a process $e^+ + e^- \to Y + \bar{Y}$ with $Y \to a(p_a) + N(k_1), \quad \bar{Y} \to b(p_b) + \bar{N}(k_2)$
  An example is the slepton pair production in SUSY models
- Determine the mass of Y through a threshold scan
- Use kinematic variables to determine (m_N, m_Y)
  e.g. visible particle energy endpoint, recoil mass, angle of visible particles….



Brau et.al, 1210.0202



Christensen et.al, 1404.6258

A method of DM mass determination

- Consider a process $e^+ + e^- \to Y + \bar{Y}$ with $Y \to a(p_a) + N(k_1), \quad \bar{Y} \to b(p_b) + \bar{N}(k_2)$

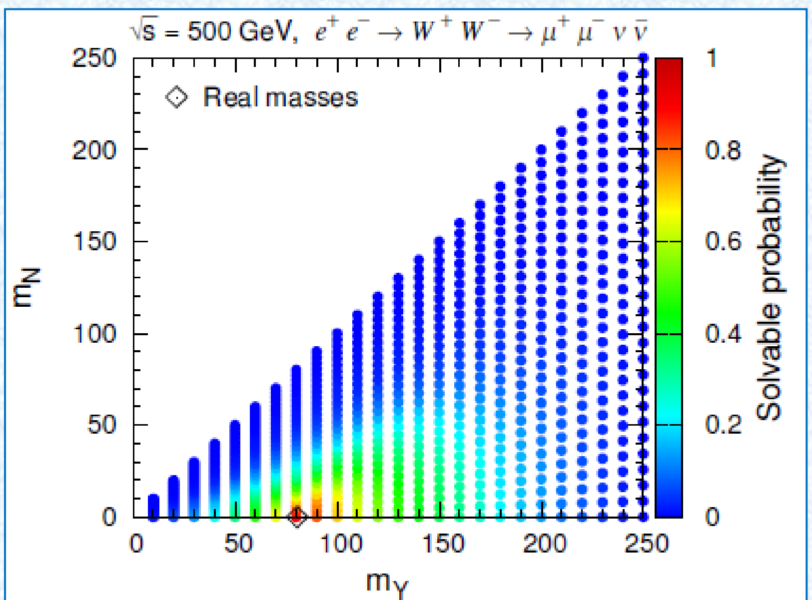
  For the known initial four-momentum and given particle masses, we have 8 Eqs and 8 variables

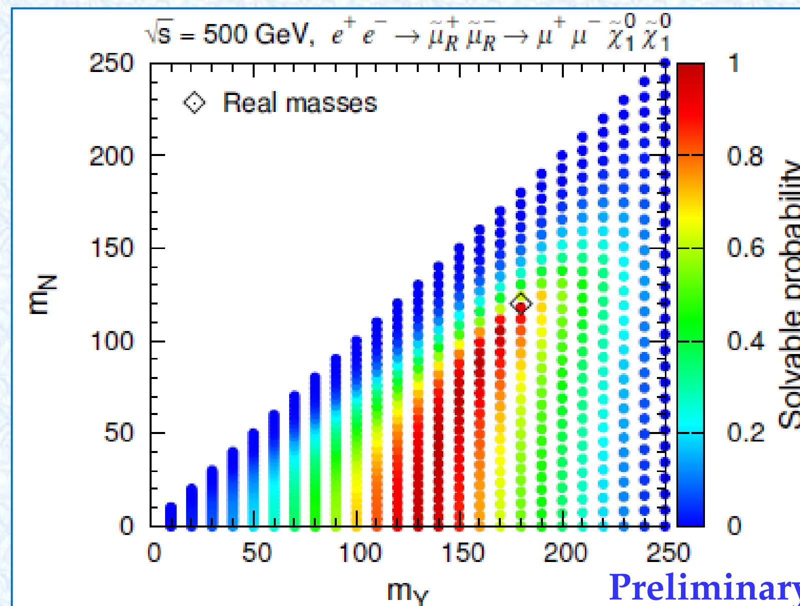
$$q^\mu = p_a^\mu + p_b^\mu + k_1^\mu + k_2^\mu, \quad k_1^2 = k_2^2 = m_N^2, \quad (p_a + k_1)^2 = (p_b + k_2)^2 = m_Y^2$$

  This is a solvable problem at the e^+e^- collider

- For a wrong set of (m_N, m_Y), the above Eqs may not have solutions

  Scan the (m_N, m_Y) plane and find realistic values by solving the Eqs





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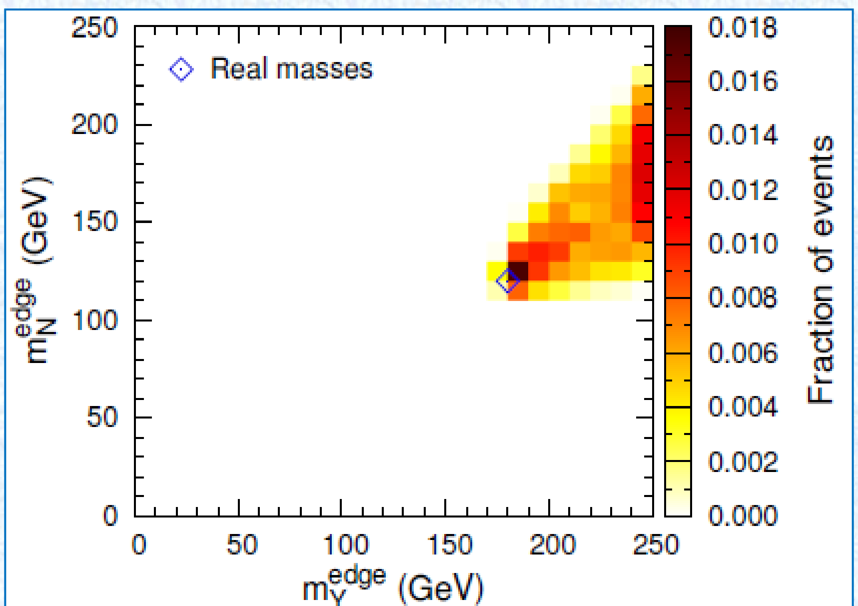
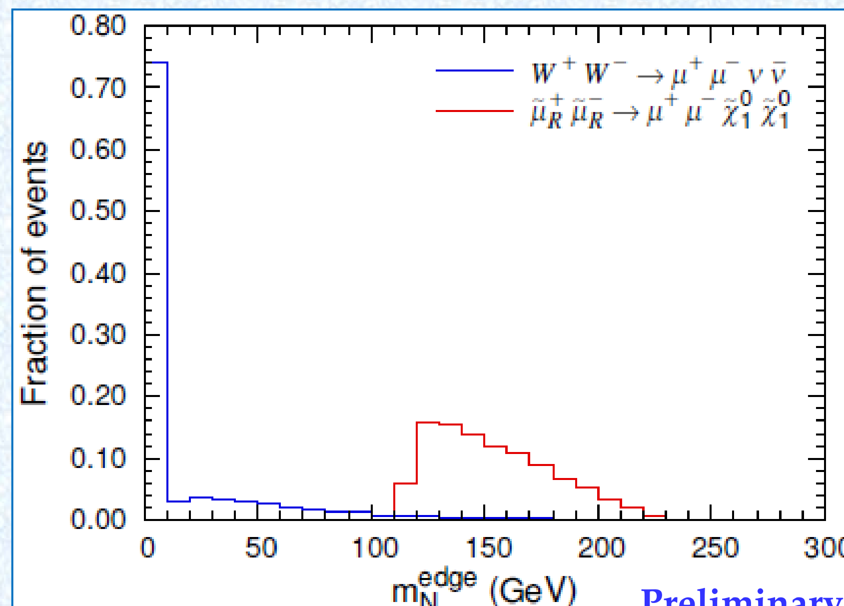
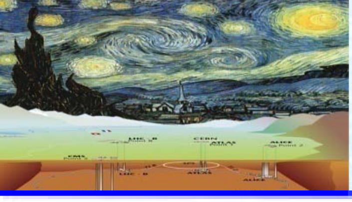
  Scan the (m_N, m_Y) plane and find the realistic values by solving the Eqs

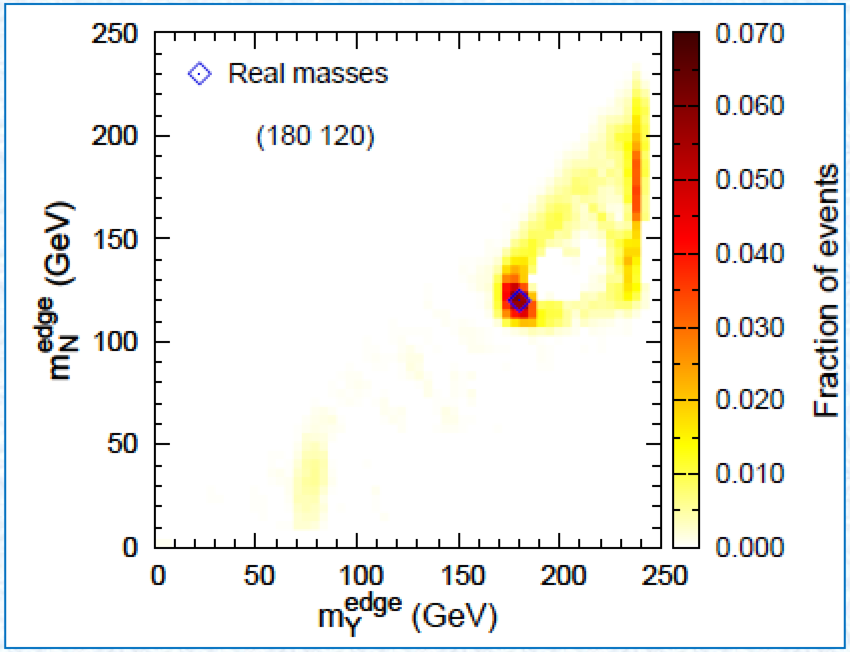


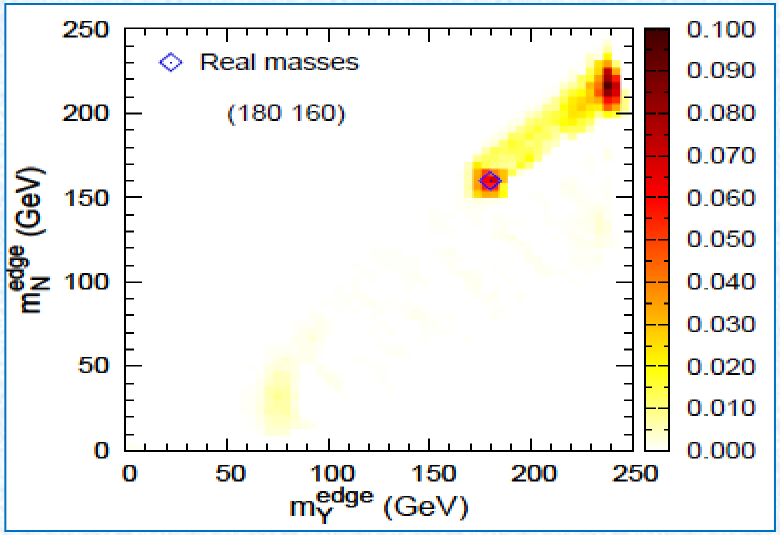


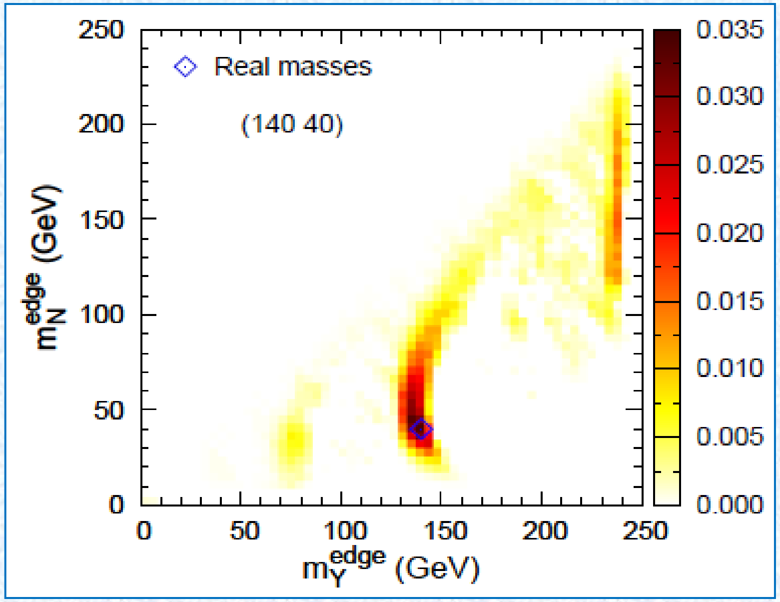


A method of DM mass determination

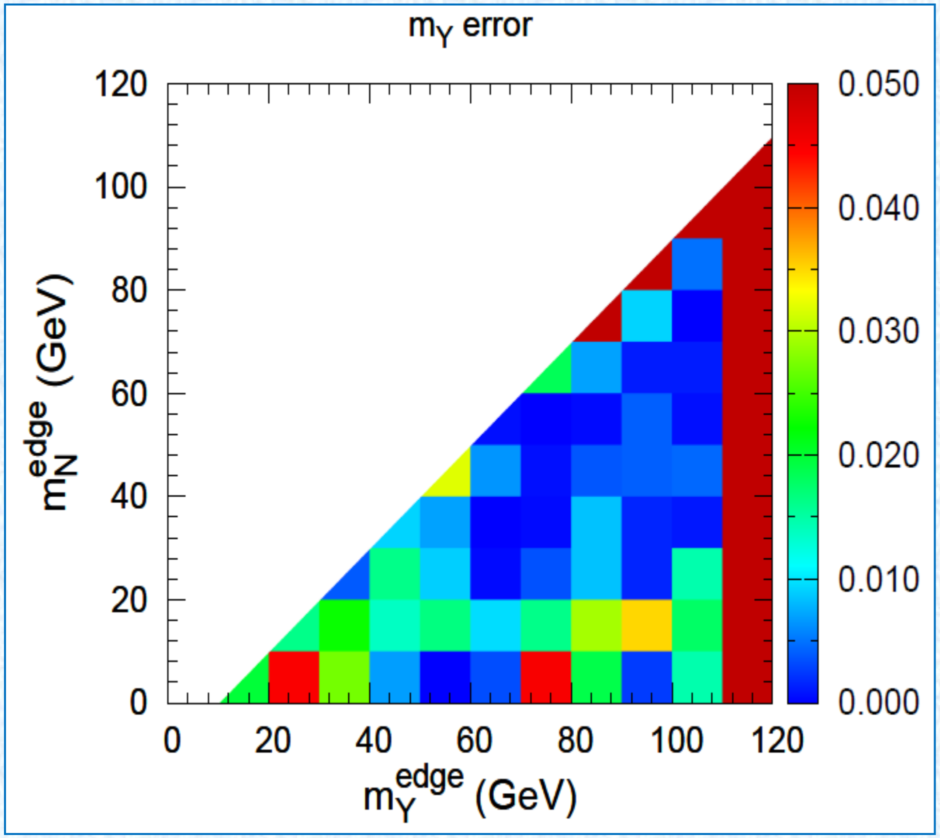
- Include detector effects in the simulation
- Consider the backgrounds
- Find realistic values of (m_N, m_Y)

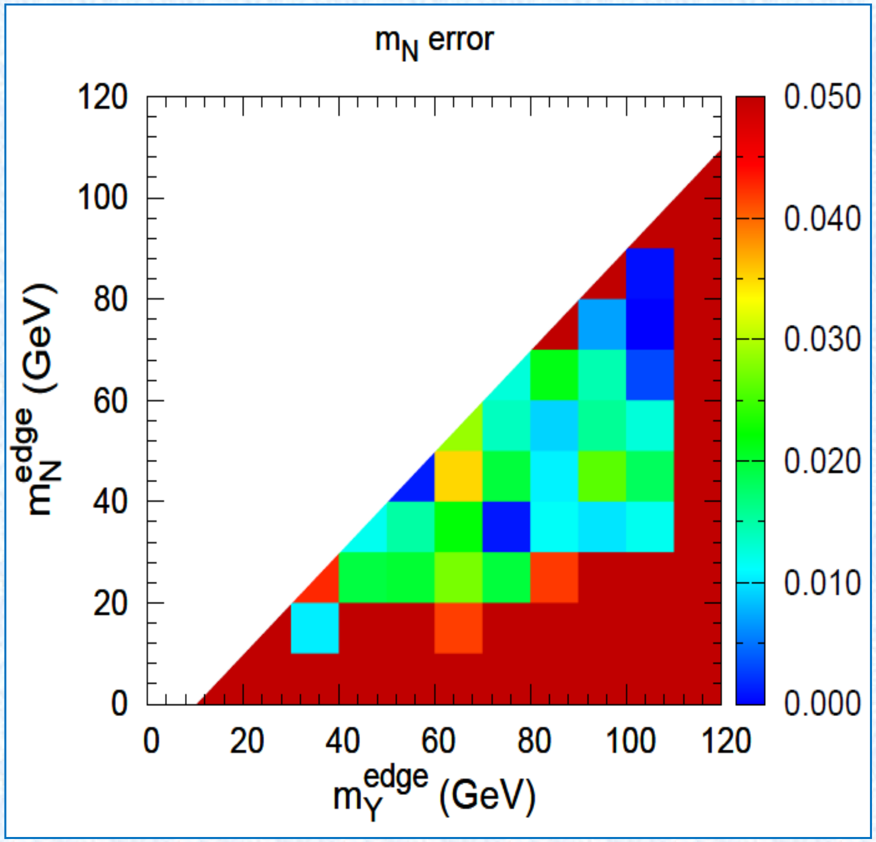




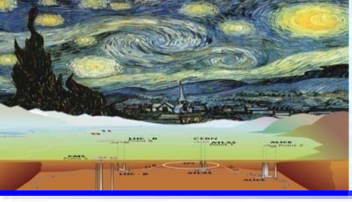


A method of DM mass determination

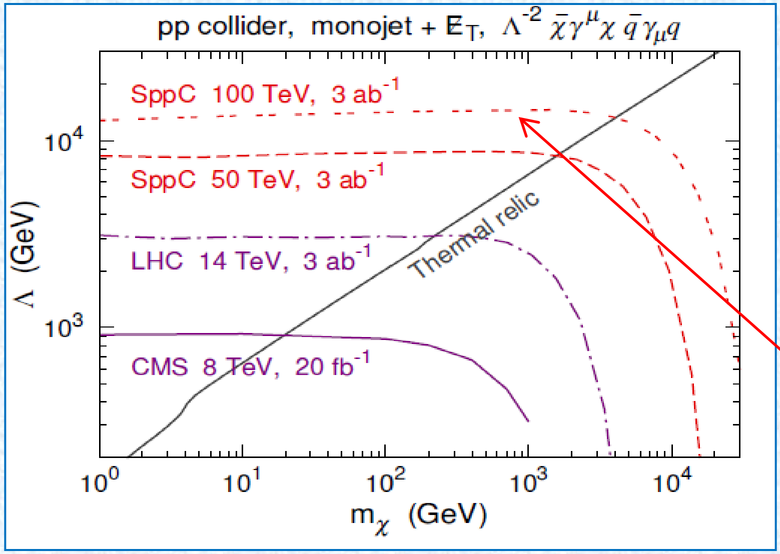




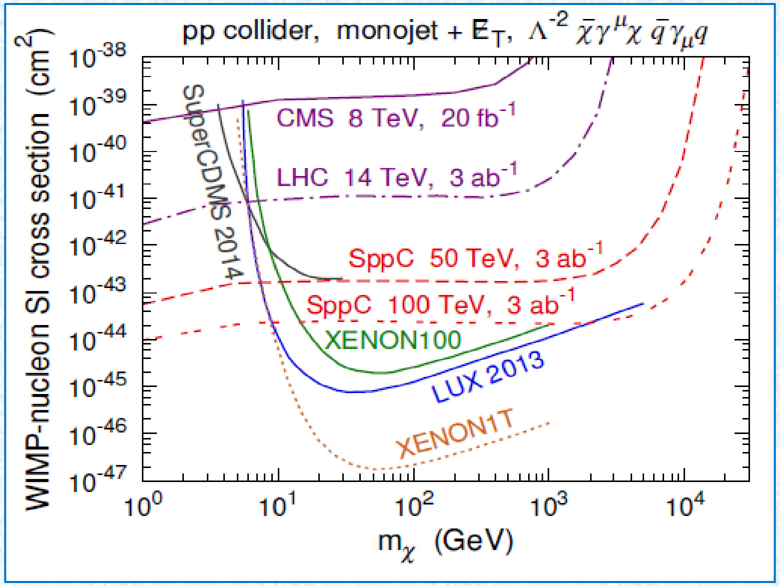
- Precision of the mass measurement

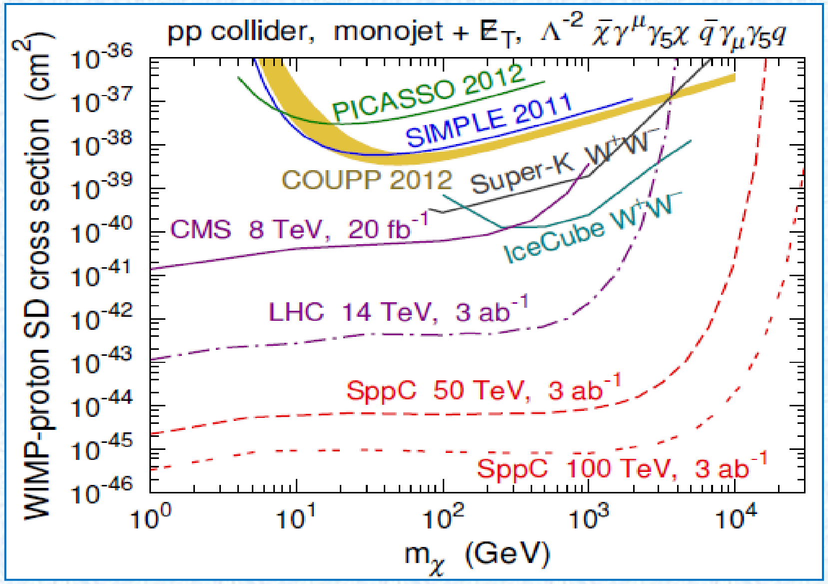


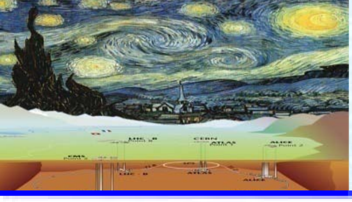
Searching for DM at the SPPC



- Advantage: large energy and luminosity for the DM production
- Disadvantage: large backgrounds
- ideal for probing light DM and spin-dependent interactions
- If Q >> m_{med} , EFT limit is not valid mediator can be directly produced







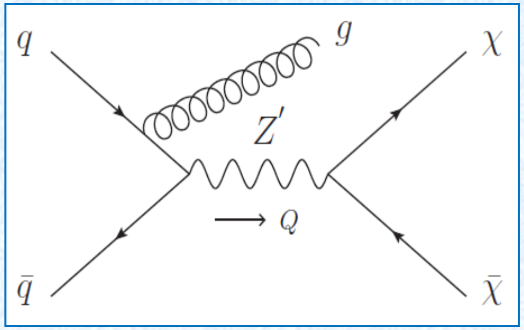
From EFT to simplified model

- (minimal) simplified models including Z′

$$\mathcal{L}_{\rm FV} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

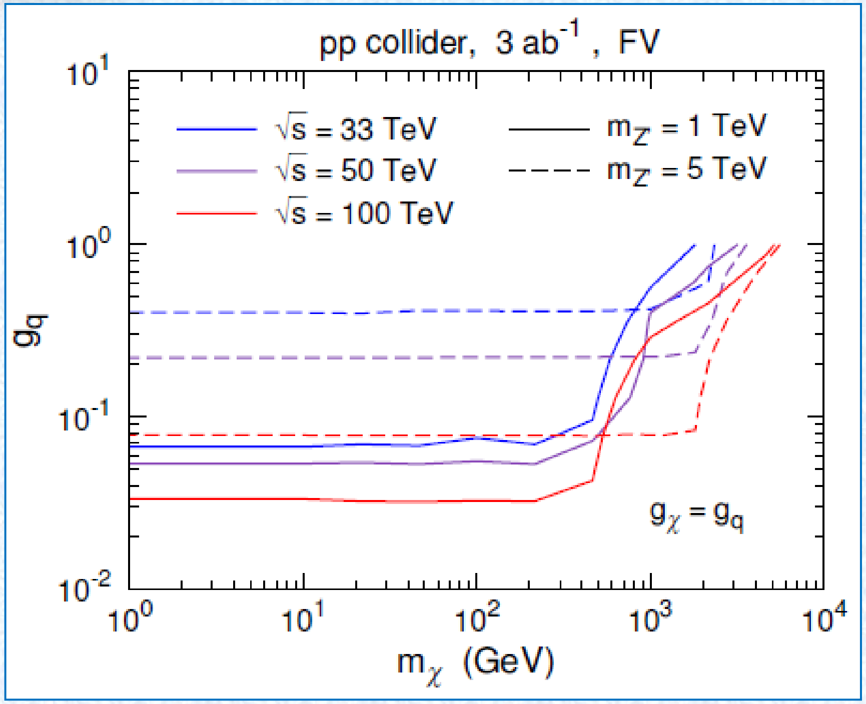
$$\mathcal{L}_{\rm FA} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu \gamma_5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi$$

$$\mathcal{L}_{\rm SV} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu q + i g_\chi Z'_\mu [\chi^* \partial^\mu \chi - (\partial^\mu \chi^*)\chi]$$

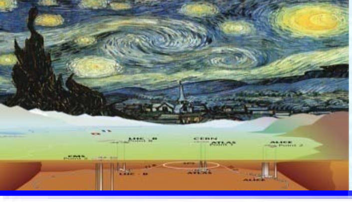


- Require $\Gamma_{Z'} < m_{Z'}$

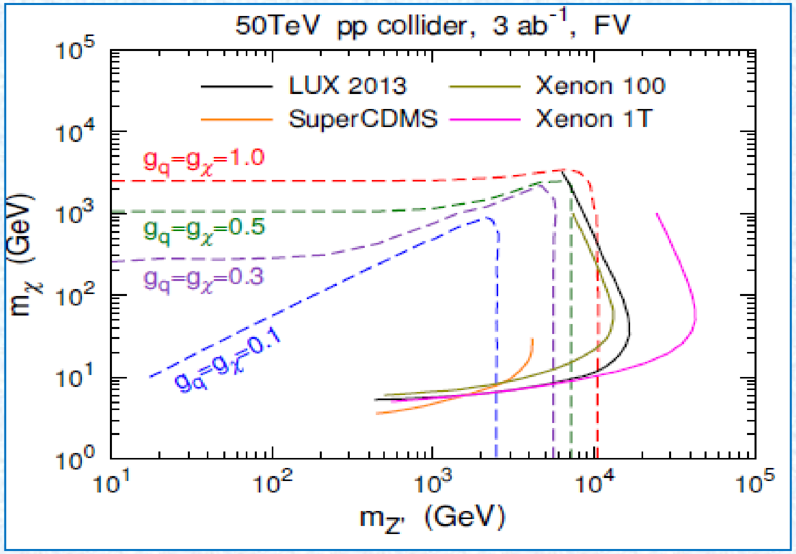
- For simplicity, assume $g_q = g_\chi$,
  Note that g_q can be limited by di-jet resonance searches.
  In the resonance region, Z′ width would affect the DM production rate

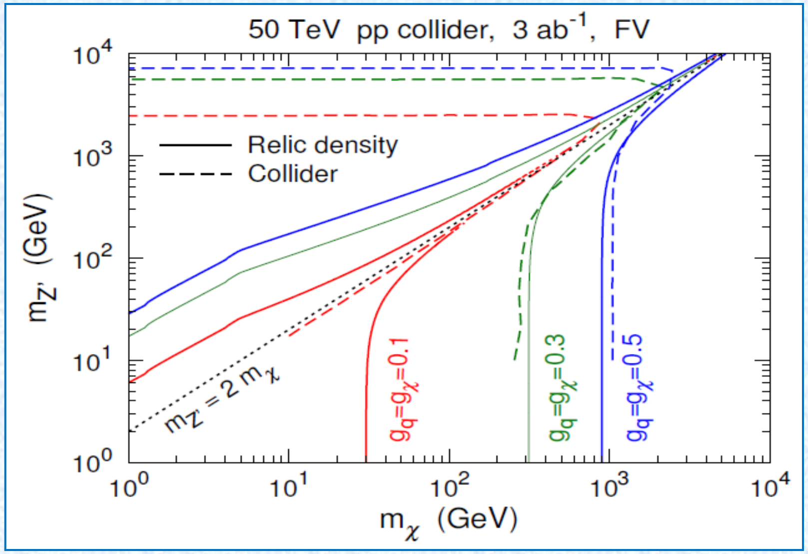


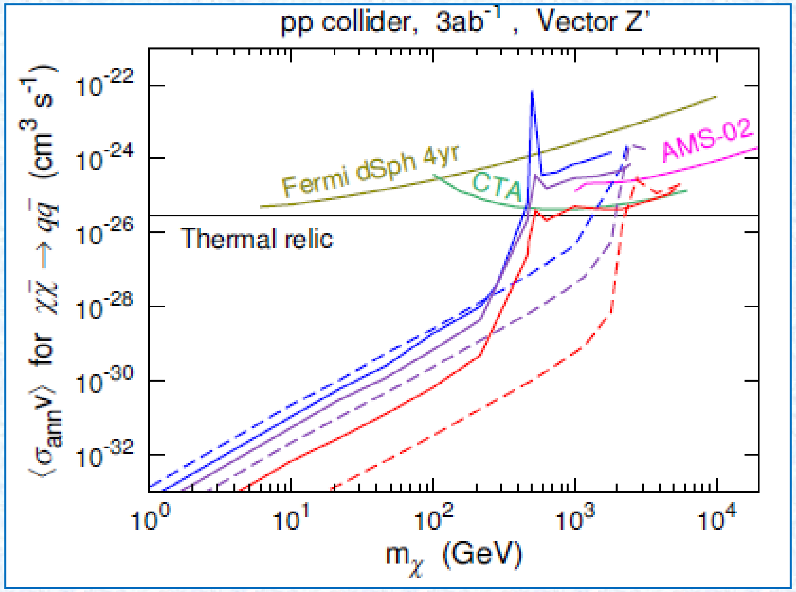
Xiang, Bi, Yin, Yu, 1503.02931



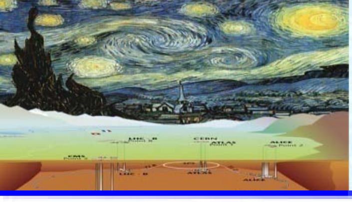
Sensitivities of SppC







- Compare with the limits from the direct detection and indirect detection
- Compare with the parameter regions for the correct thermal DM relic density
- Direct detection limits are derived for g=0.5



“Sparticle” simplified model

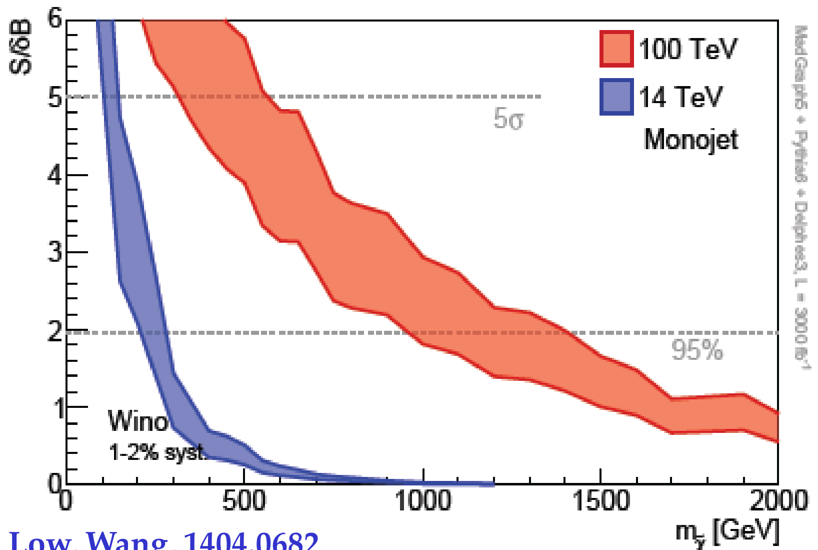
- Consider a Lagrangian similar to a SUSY model

$$\Delta L = M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + \mu \tilde{H}_u \tilde{H}_d + \sqrt{2}\kappa_1 h^\dagger \tilde{W}\tilde{H}_u + \sqrt{2}\kappa_2 h \tilde{W}\tilde{H}_d + \frac{\kappa_1'}{\sqrt{2}} h^\dagger \tilde{B}\tilde{H}_u + \frac{\kappa_2'}{\sqrt{2}} h \tilde{B}\tilde{H}_d$$

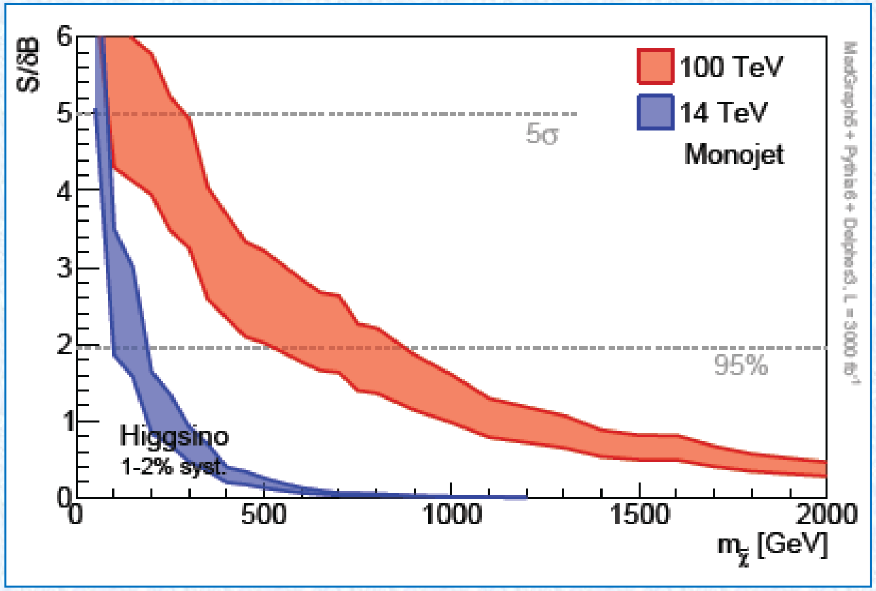
- DM may be a pure electroweak state or a mixture

Arkani et. al, 1511.06495

- Search strategies are also similar to those for the SUSY: mono-jet, soft leptons, disappearing tracks ….



Low, Wang, 1404.0682



"Sparticle" simplified model

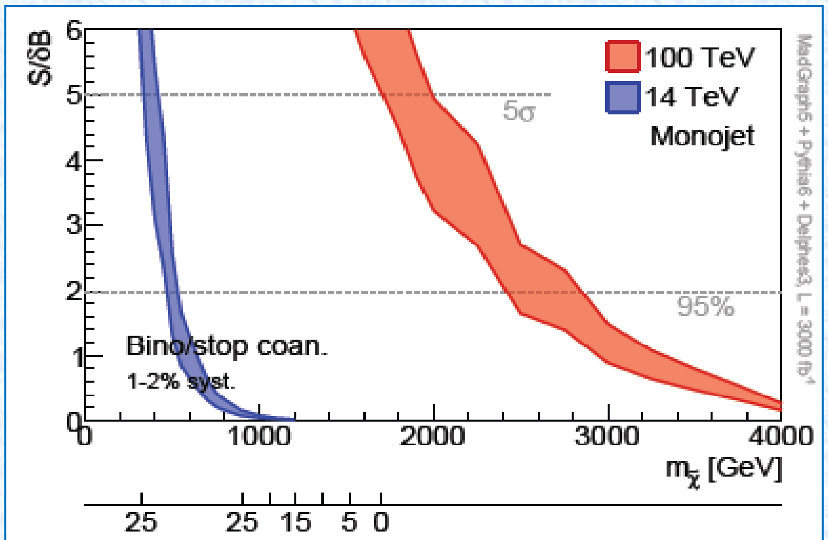
- Consider a Lagrangian similar to a SUSY model

$$\Delta L = M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + \mu \tilde{H}_u \tilde{H}_d + \sqrt{2}\kappa_1 h^\dagger \tilde{W}\tilde{H}_u + \sqrt{2}\kappa_2 h \tilde{W}\tilde{H}_d + \frac{\kappa_1'}{\sqrt{2}} h^\dagger \tilde{B}\tilde{H}_u + \frac{\kappa_2'}{\sqrt{2}} h \tilde{B}\tilde{H}_d$$

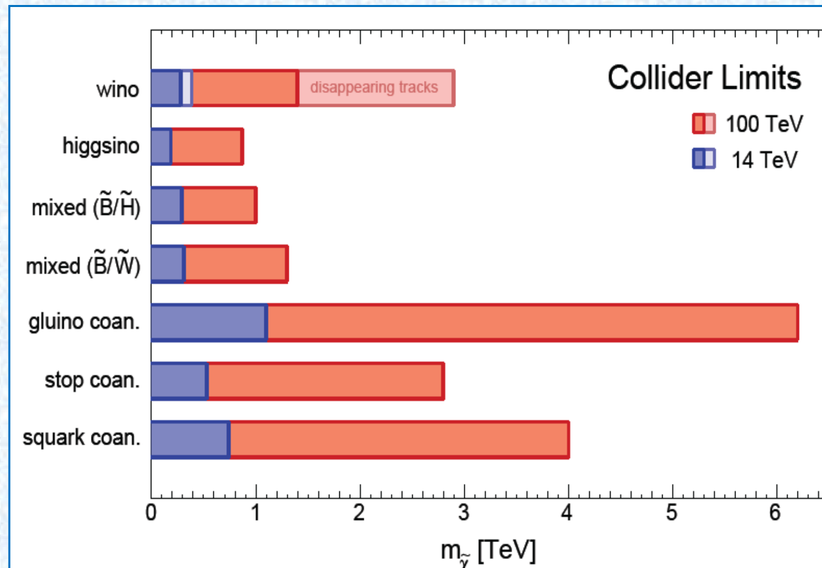
- DM may be a pure electroweak state or a mixture

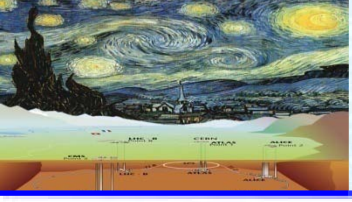
Arkani et. al, 1511.06495

- Search strategies are also similar to those for the SUSY: mono-jet, soft leptons, disappearing tracks ….



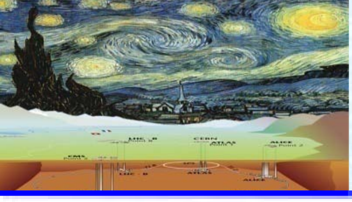
Low, Wang, 1404.0682





Summary

- Difficult to directly detect DM signals at e^+e^- colliders
- Colliders are ideal tools for probing the light DM
- e^+e^- colliders are suitable to measure the DM mass
- EFT is not valid at future hadron colliders; simplified models should be taken into account
- Complementary to direct and indirect detections



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Thank you !