Searching for dark matter at future colliders

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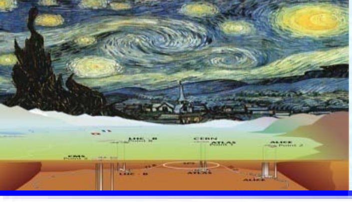
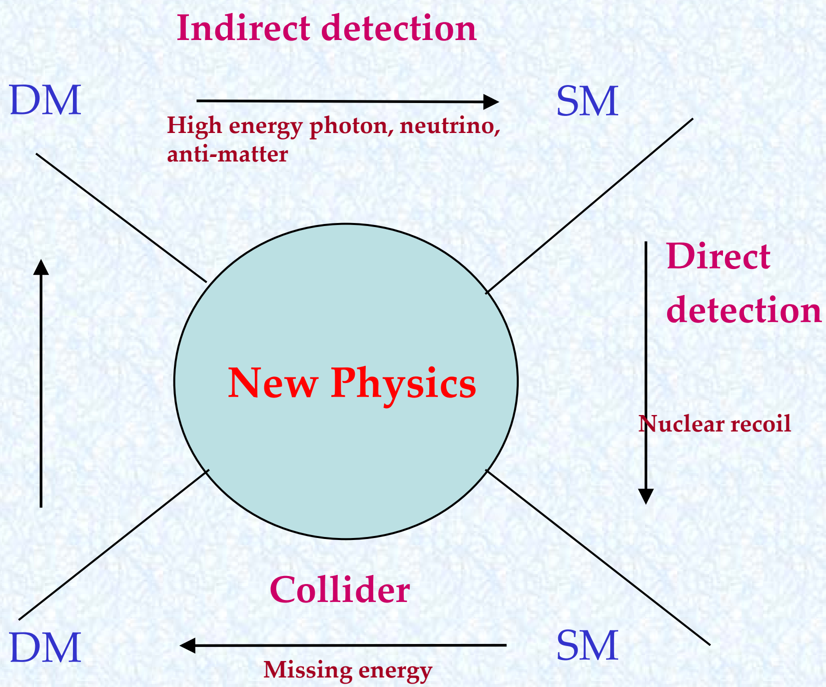
BeiHang, 2016.09.02

Outline

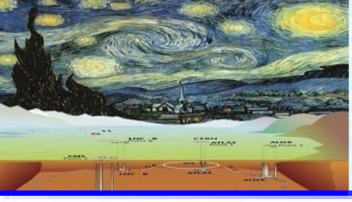
- Introduction: DM searches and DM collider searches
- Direct searches at e^+e^- colliders
- Indirect searches at e^+e^- colliders
- Mass measurements of DM
- Searches at future pp colliders



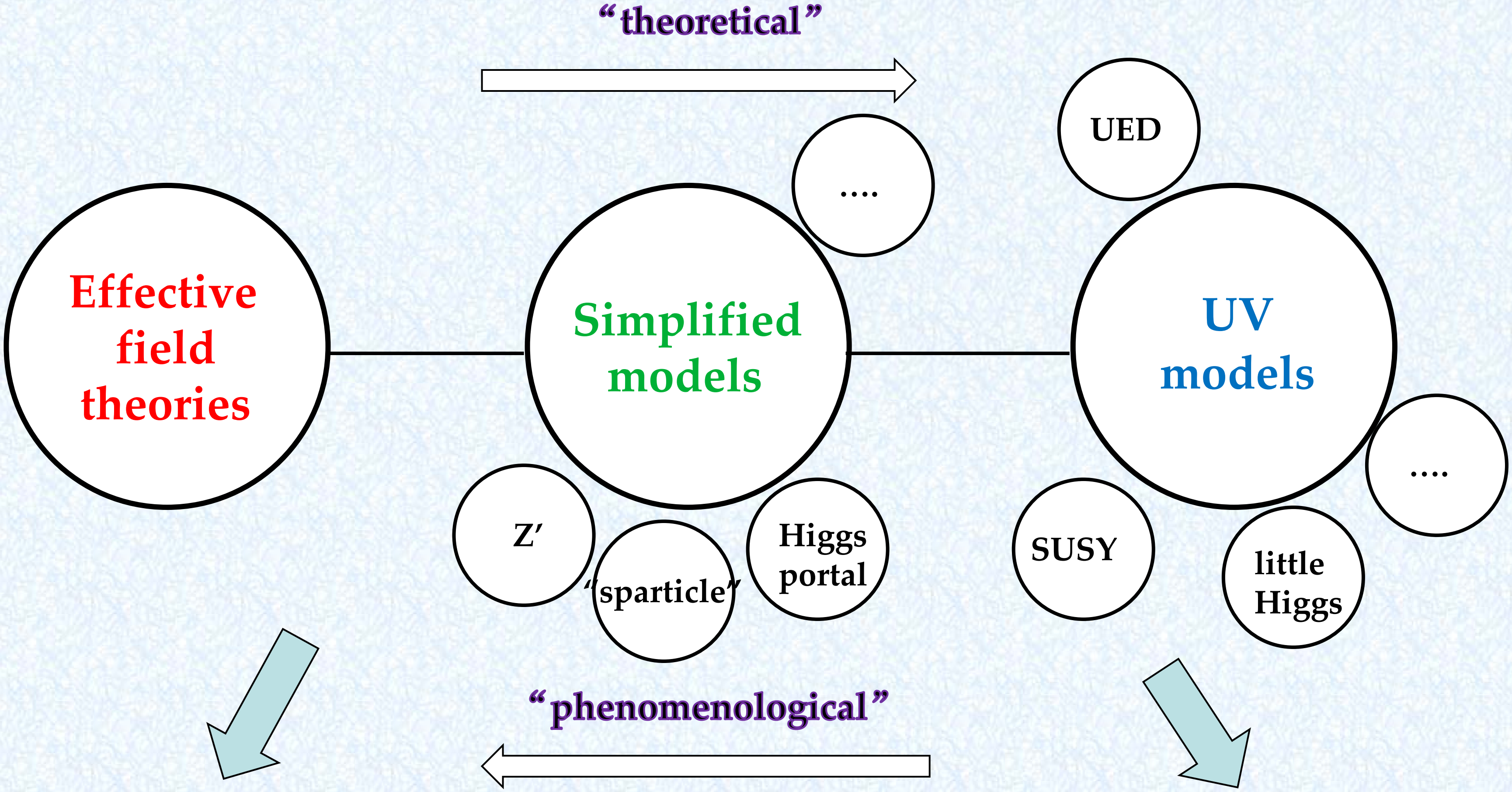
DM searches



- **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



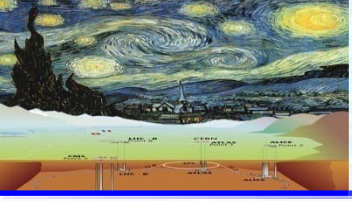
Mono-X

Direct production, "model-independent"

Multi final states +ME

Cascade decay, "model-dependent"

Other collider signatures and constraints



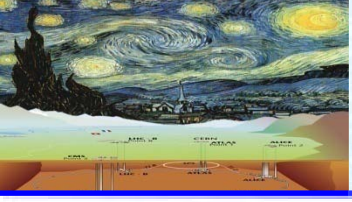
Possible studies at e^+e^- colliders

- 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, DM in the EW multiplet…)
  Indirect search through loop effects, e.g. in Higgs measurements, EW precision measurements



Possible studies at e^+e^- colliders

- Precise measurement rather than discovery
  Full missing energy can be obtained
  Accurately measure the mass, spin, and other quantum numbers of DM

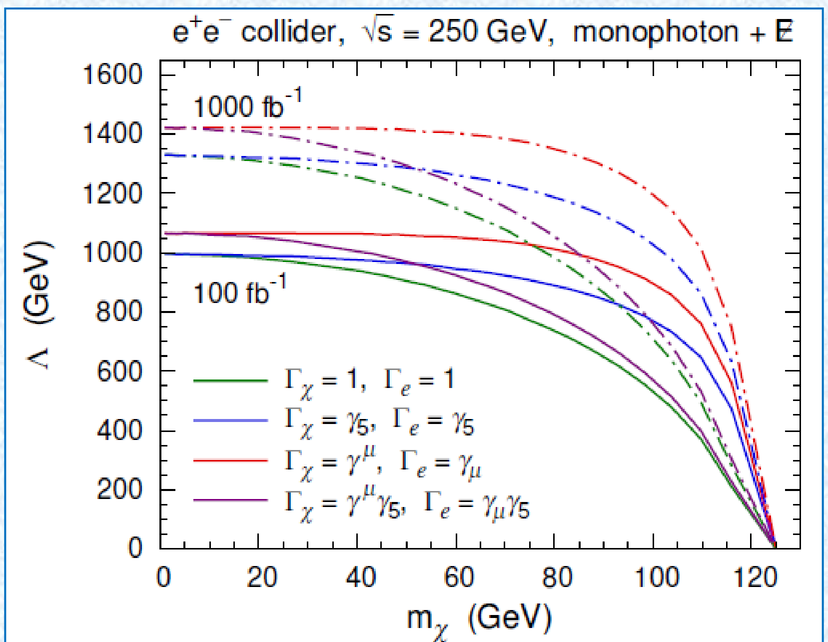
- If a missing particle χ is discovered at colliders, can it make up all the DM component in the Universe ?
  Check the thermal relic density of χ by using measured DM mass and coupling coefficients.
  Probe the DM production mechanism and cosmological effects of DM
  $\Omega_\chi h^2 = 0.12$, strong 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?

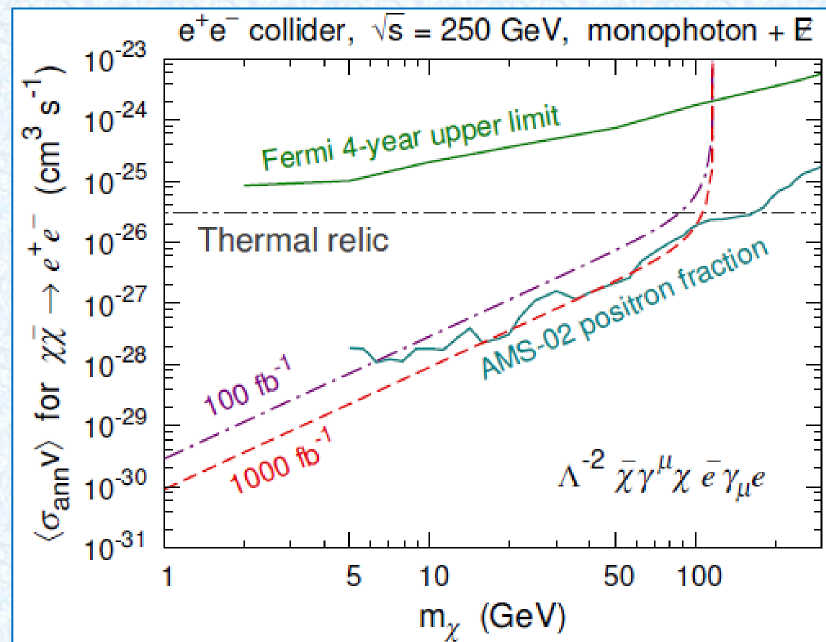
Results for DM interactions with electron/positron

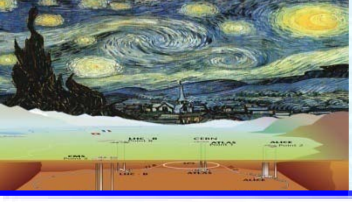
- Effective Field Theory: heavy mediator can be integrated out leaving a scale Λ

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

Search for mono-photon signals from initial state radiations

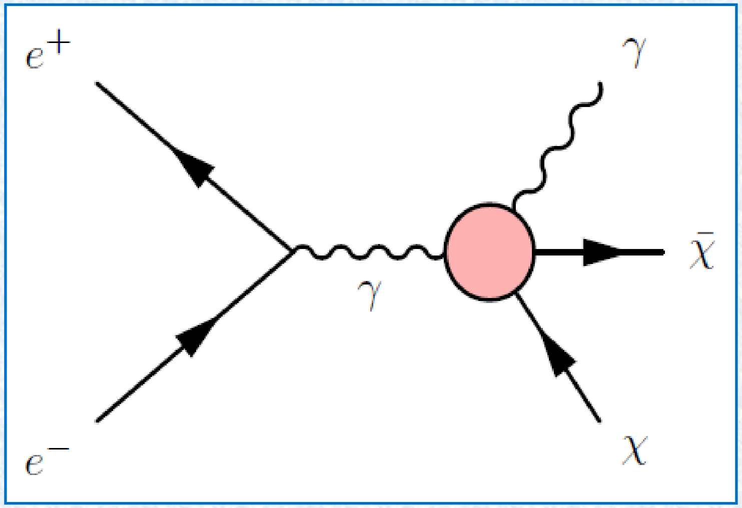


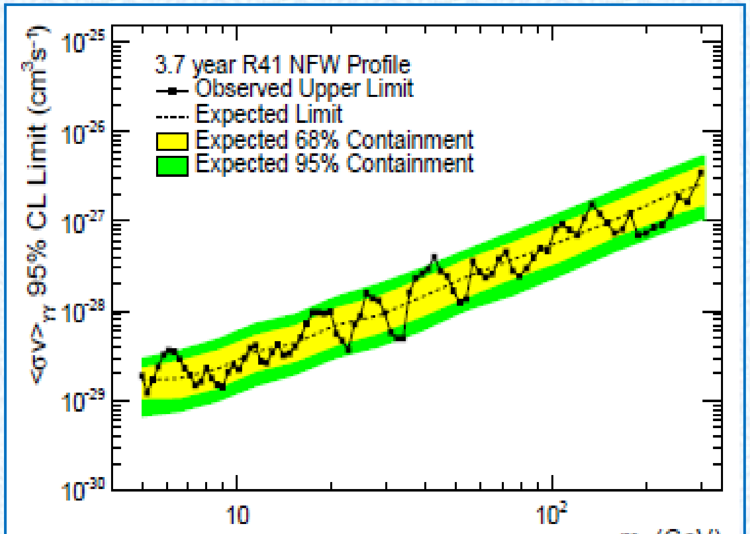




Gamma-ray line and mono-photon

- 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

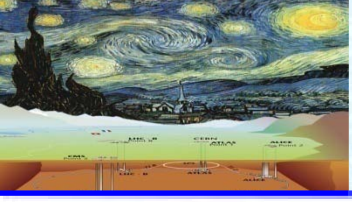
- Effective operator

Yu, Yan, PFY, 1307.5740

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

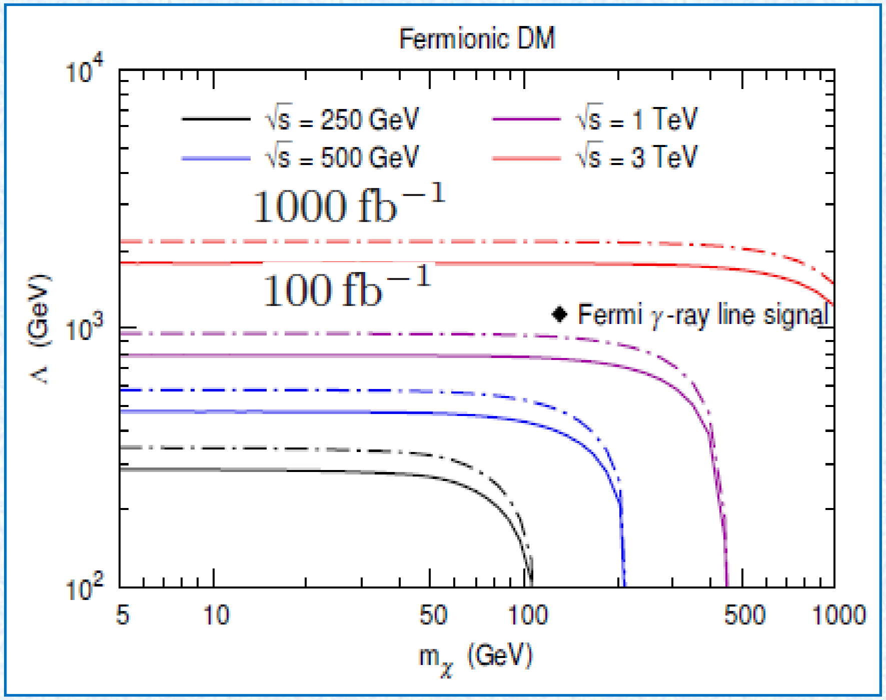
Cut scale for a ~100 GeV DM and a detectable cross section is ~TeV

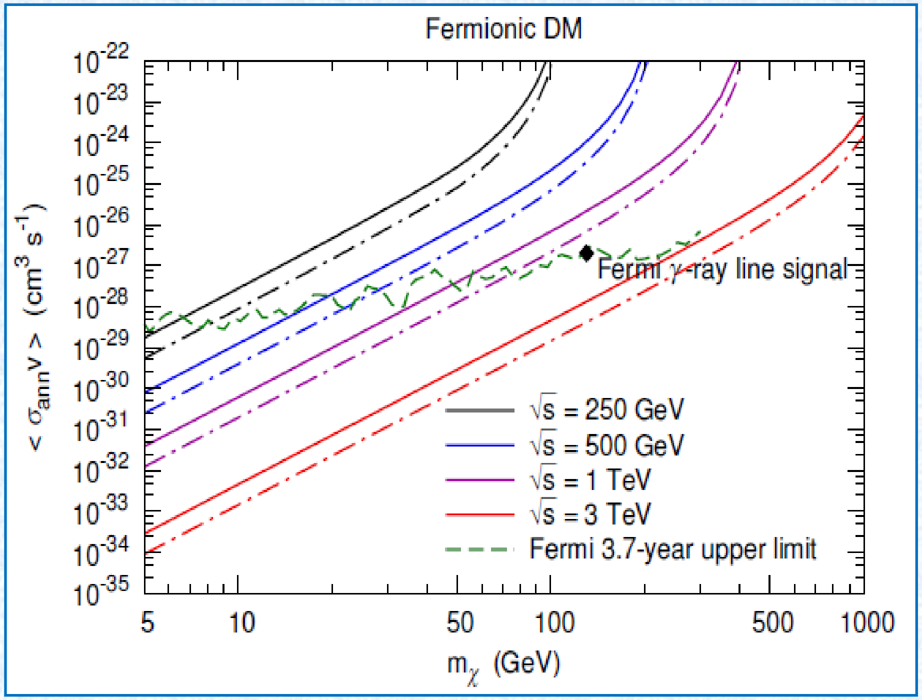
$$\langle \sigma_{\rm ann} v\rangle_{\chi\bar{\chi}\to 2\gamma} \simeq \frac{4m_\chi^4}{\pi\Lambda^6} = 10^{-27}\ {\rm cm}^3\ {\rm s}^{-1}\left(\frac{m_\chi}{130\ {\rm GeV}}\right)^4\left(\frac{1272\ {\rm GeV}}{\Lambda}\right)^6$$

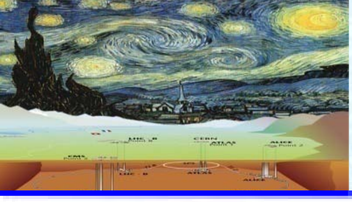


Sensitivities

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



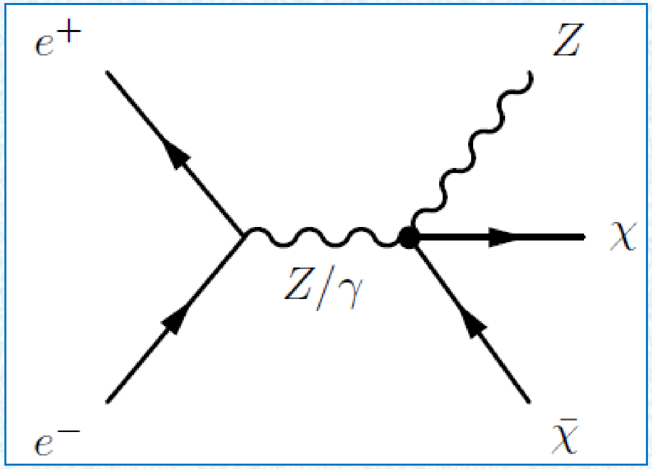




Mono-Z signals

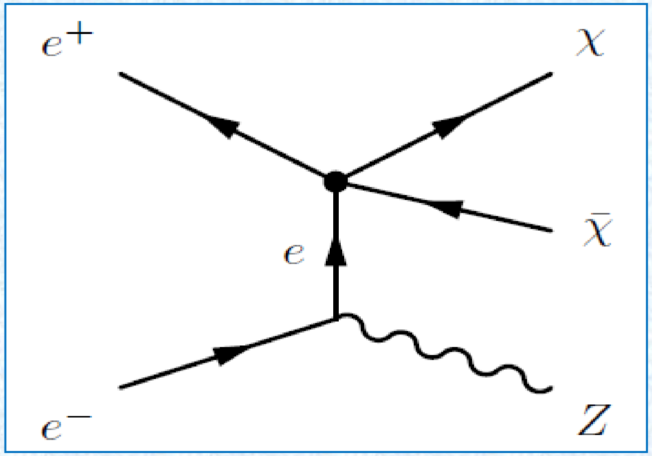
- DM can interact with both the photon and Z boson
- Consider effective operators

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

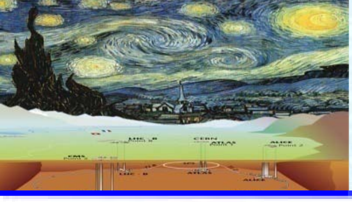


- Z boson can also com from initial state radiation

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

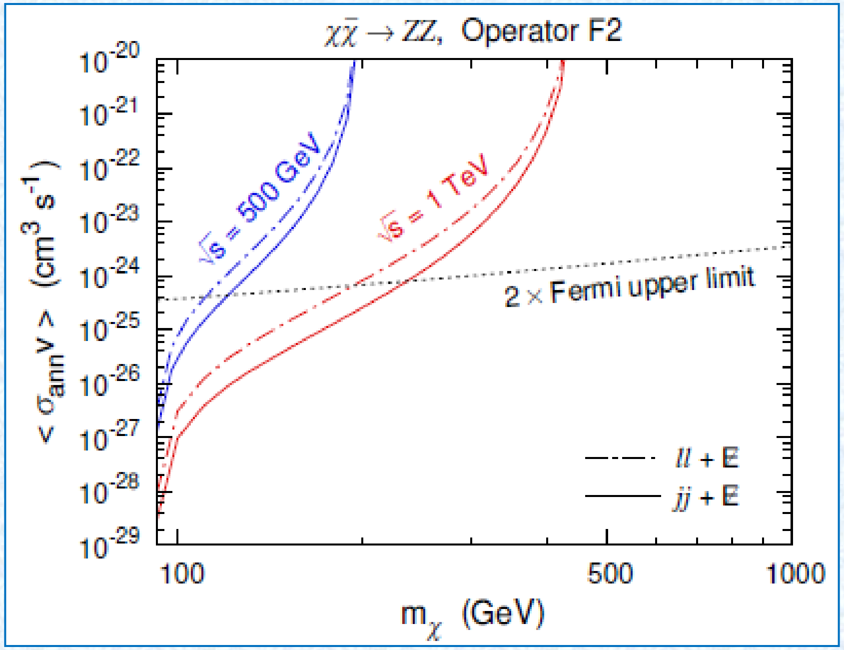


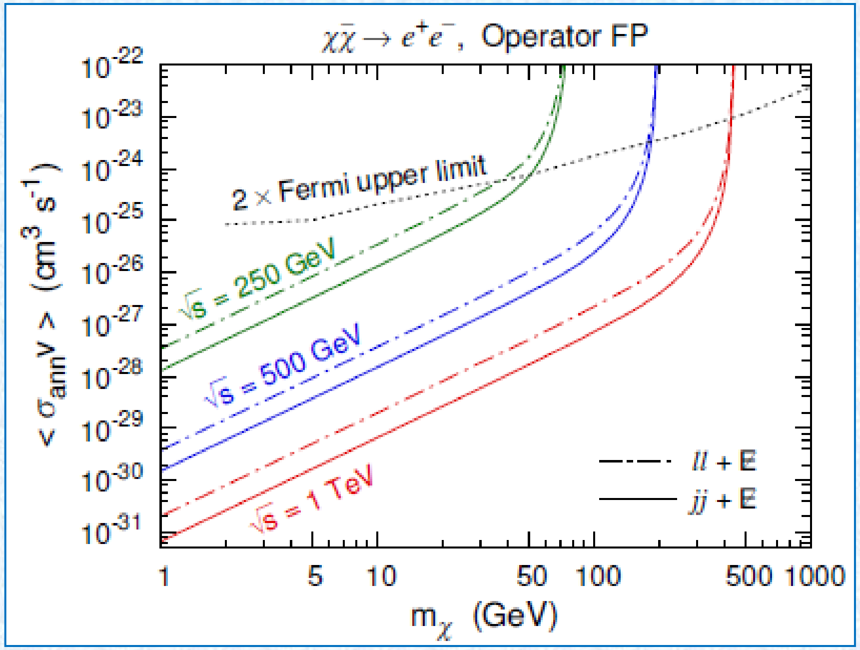
Yu, Bi, Yan, PFY,
1404.6990



Sensitivities

- 3 σ sensitivities 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





Light DM coupled to SM mediators

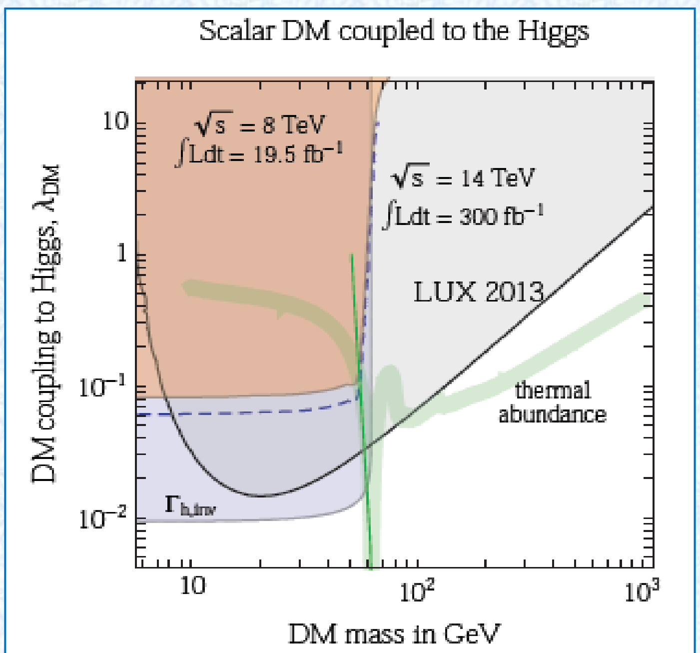
- Assume that DM couples to the SM particles through SM mediators

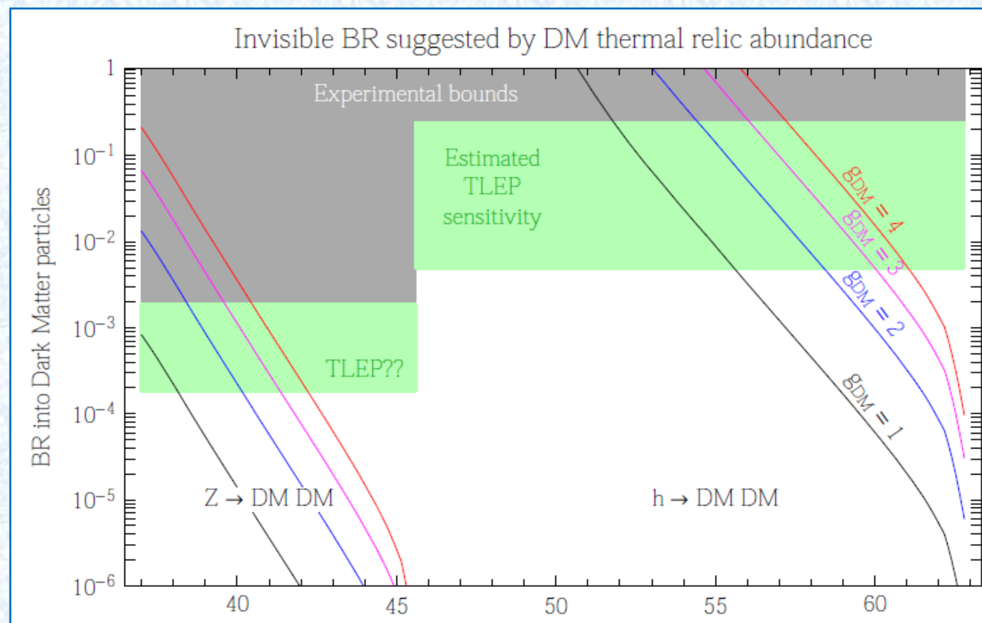
$$\mathcal{L} = -hJ_h\,,\qquad J_h = \frac{1}{\sqrt{2}}\left[\sum_f y_f \bar f f + \bar\psi_{\rm DM}(y_{\rm DM} + i y^P_{\rm DM}\gamma_5)\psi_{\rm DM} + \frac{\lambda_{\rm DM} v}{2} s^2_{\rm DM}\right]$$

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

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

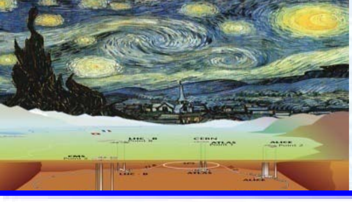
See also H.Zhang's talk on the Higgs exotic decay at CEPC





Strumia, TLEP9, 2015

Simone, Giudice, Strumia, 1402.6287

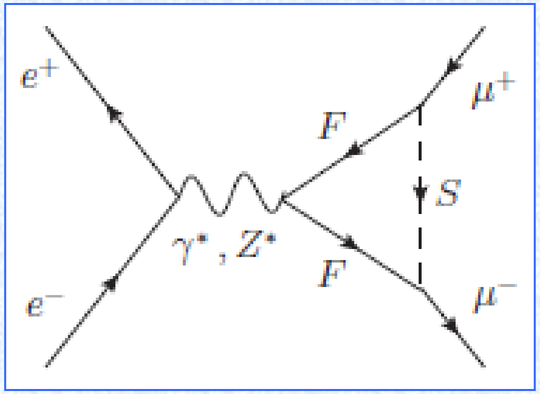


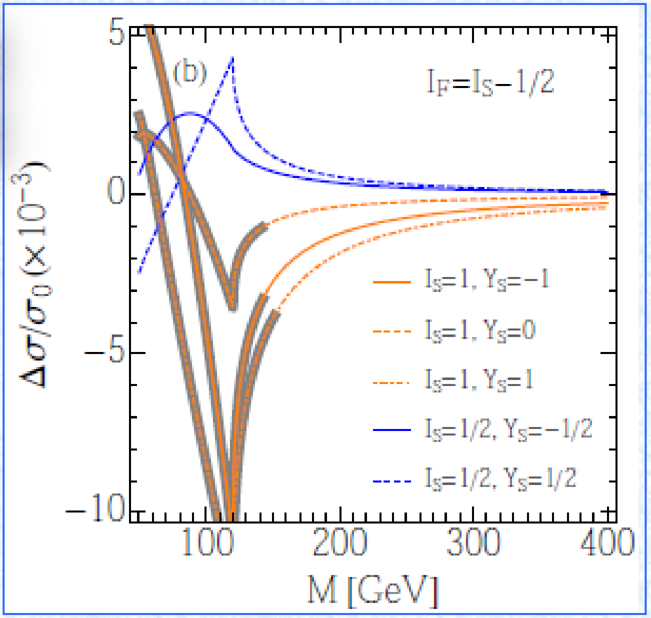
Indirect searches at colliders

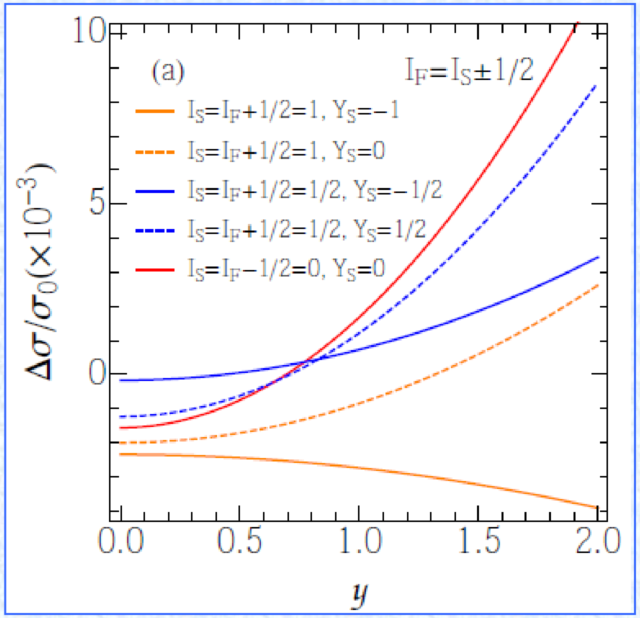
- There would be some exotic particles carrying EW charges in DM models. These particles might affect SM observations via high order effects
- May be required by the DM relic density, e.g. t-channel mediator for annihilation, coannihilation ....
- Indirect searches for new physics. Depend on detailed models
- For instance, calculate the loop correction to the $e^+e^- \to \mu^+\mu^-$ from a leptophilic DM models with a vector-like fermion F (mediator) and a scalar S (DM)

$$\mathcal{L}_{\rm Yuk} = y C_{ijk} S^i \bar{\mu}_L^k F^j + h.c.$$

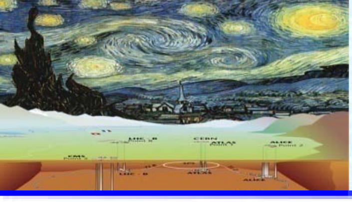
$$\mathcal{L}_{\rm Yuk} = y C_{ij} S^i \bar{\mu}_R F^j + h.c.$$







Cao et al, 1604.07536



Test from Higgs measurements

- DM embedded in EW multiplets may interact with Higgs

  For instance, a singlet-doublet Fermionic DM model

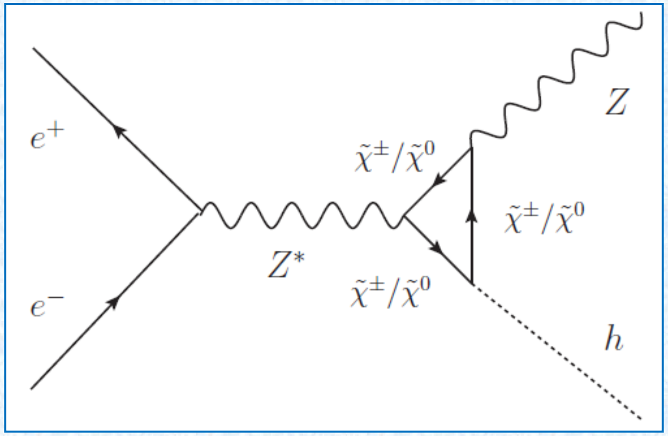
  e.g. D'Eramo, 0705.4493; Cohen et al, 1109.2604

$$\mathcal{L}_{\mathrm{S}} = iS^{\dagger}\bar{\sigma}^{\mu}\partial_{\mu}S - \frac{1}{2}(m_S SS + \mathrm{h.c.}), \quad \mathcal{L}_{\mathrm{D}} = iD_{1i}^{\dagger}\bar{\sigma}^{\mu}D_{\mu}D_1^i + iD_{2i}^{\dagger}\bar{\sigma}^{\mu}D_{\mu}D_2^i - (m_D\varepsilon_{ij}D_1^iD_2^j + \mathrm{h.c.})$$

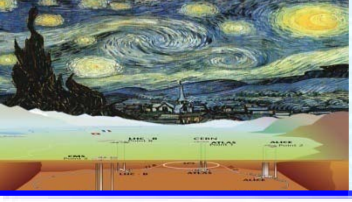
$$\mathcal{L}_{\mathrm{HSD}} = y_1 H_i S D_1^i - y_2 H_i^{\dagger} S D_2^i + \mathrm{h.c}$$

  DM could also be embedded in triplet, quadruplet ....

- Could affect the Higgs production process at e^+e^- colliders

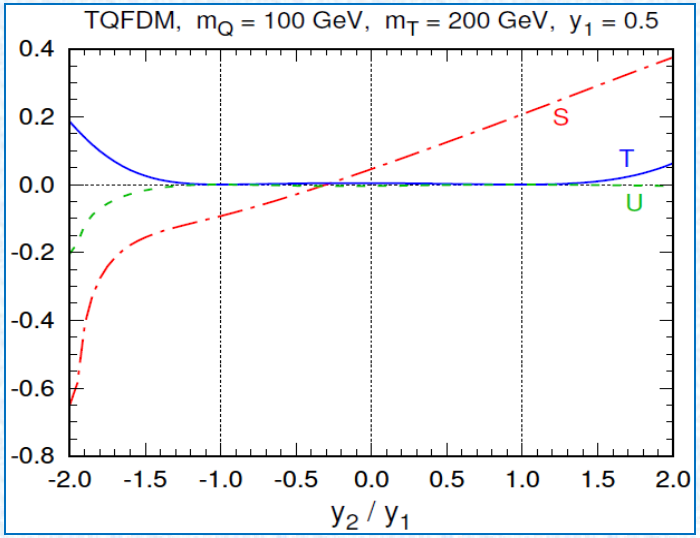


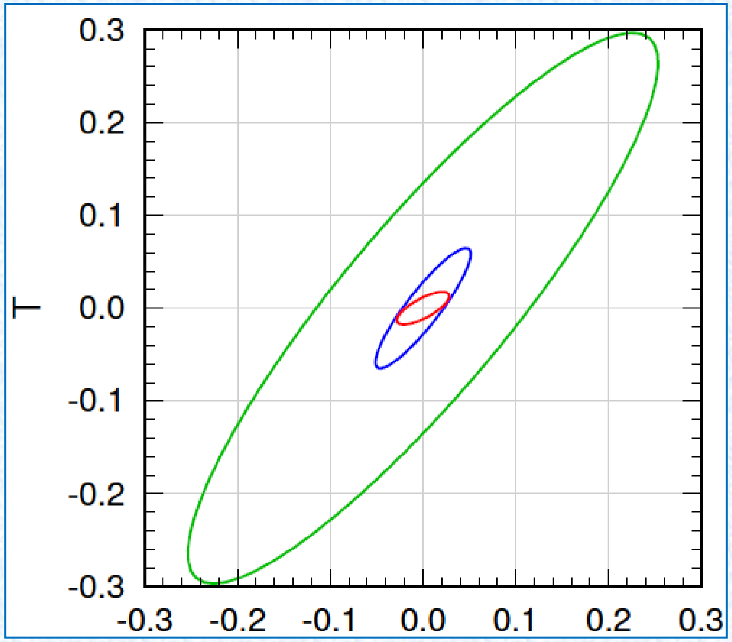
- DM and other exotic neutral/charged particles may be directly produced at hadron colliders



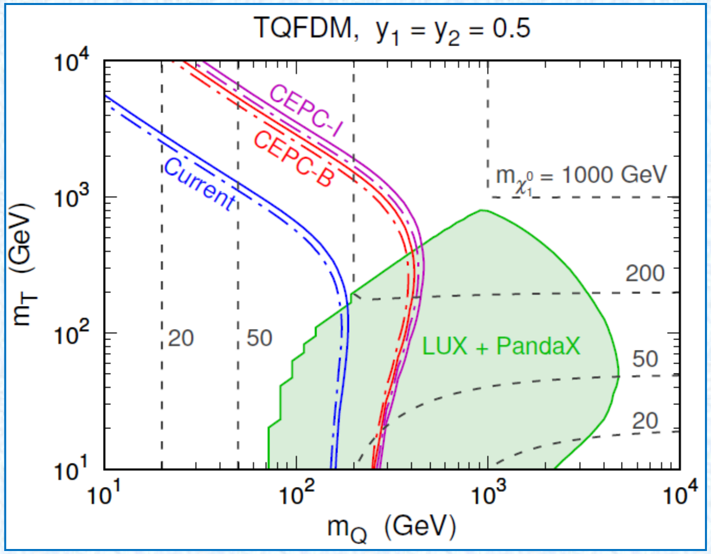
Test from EW precision measurements

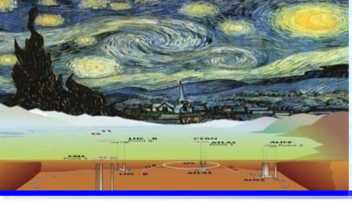
- CEPC measurements would improve the precisions of EW parameters
  See Fan, Reece, Wang, 1411.1054
- Can set constraints on DM (new physics) models





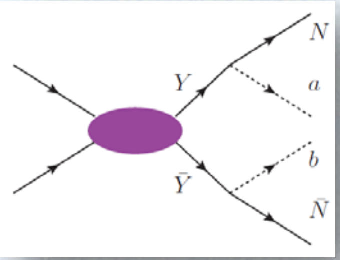
Cai, Yu, et al, in progress

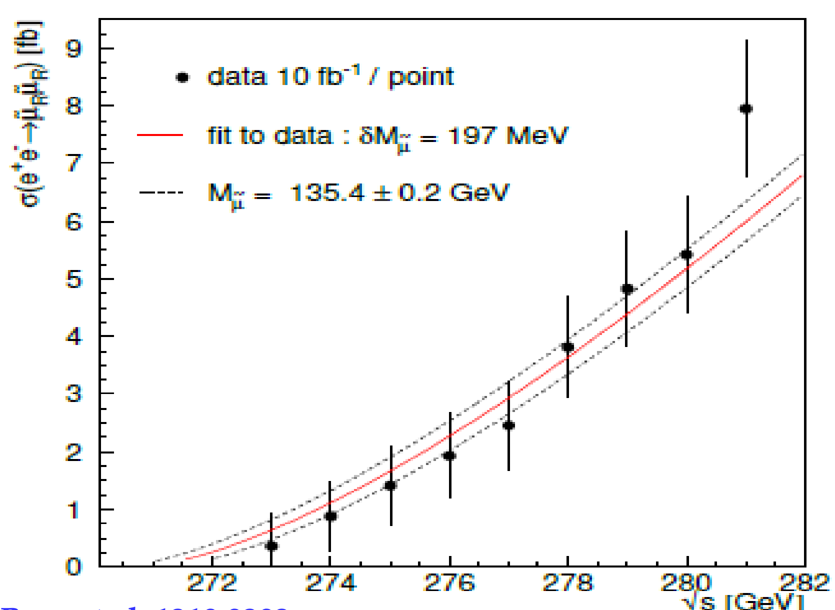




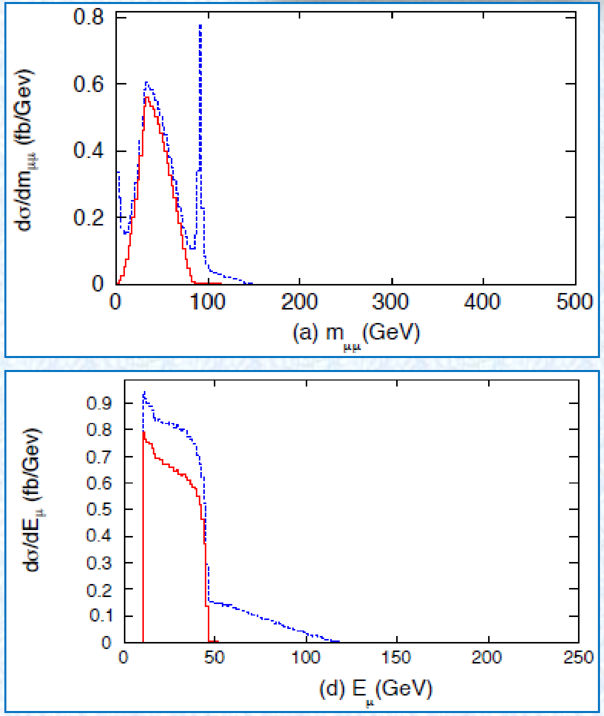
Determination of DM mass at e^+e^- colliders

- Depend on the topology of DM production process
- 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….

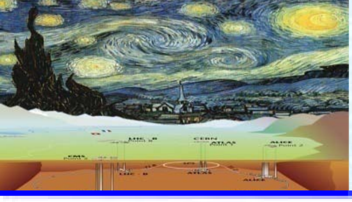




Brau et.al, 1210.0202



Christensen et.al, 1404.6258



A method of DM mass determination

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

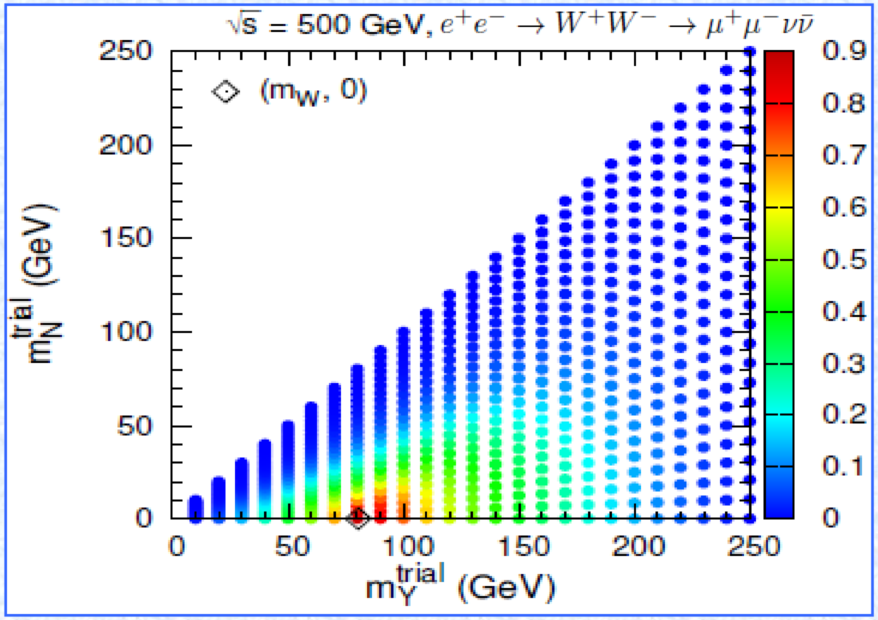
  For the known initial four-momentum and given particle masses, we have 8 Eqs and 8 variables

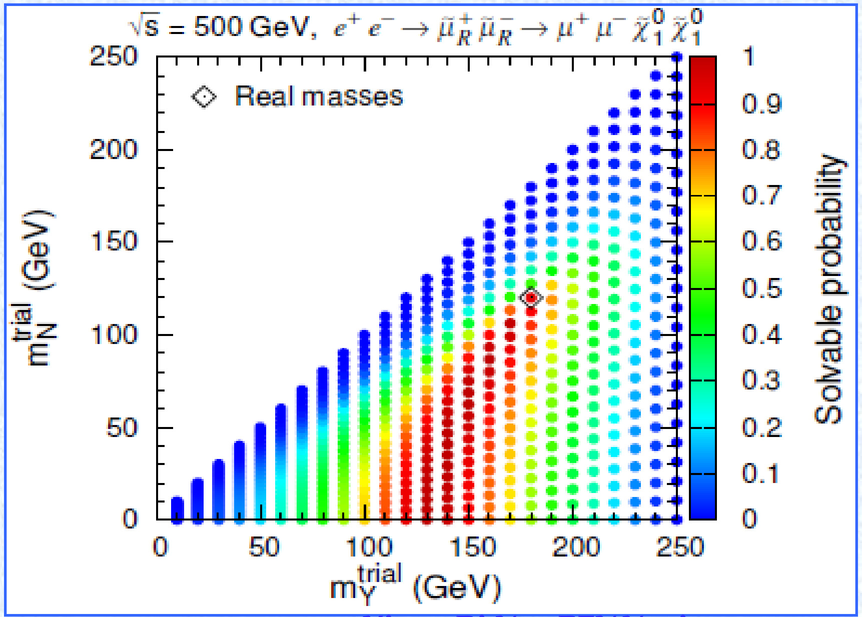
$$q^\mu = p_a^\mu + p_b^\mu + k_1^\mu + k_2^\mu, \quad k_1^2 = k_2^2 = m_N^2, \quad (p_a + k_1)^2 = (p_b + k_2)^2 = m_Y^2$$

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

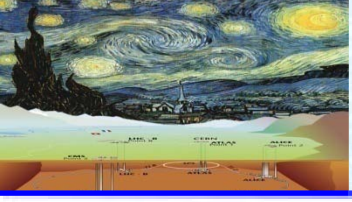
- **For a wrong set of (m_N,m_Y), above Eqs might not have solutions**

  Scan the trial m_N-m_Y plane and find realistic values by solving the Eqs



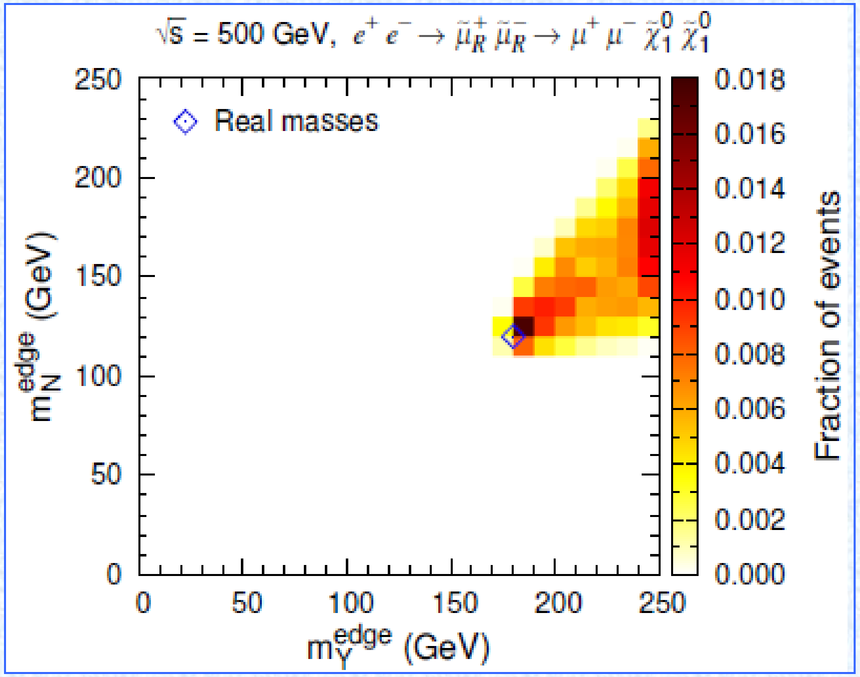


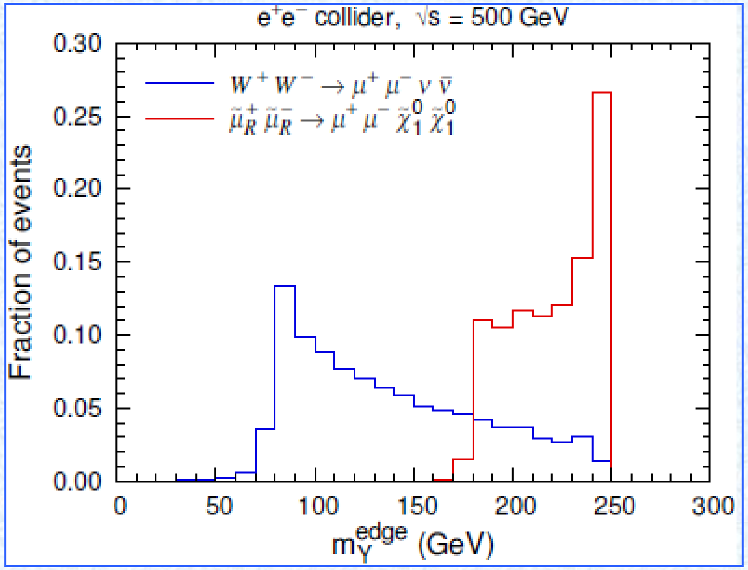
Xiang,Bi,Yan,PFY,Yu, in progress

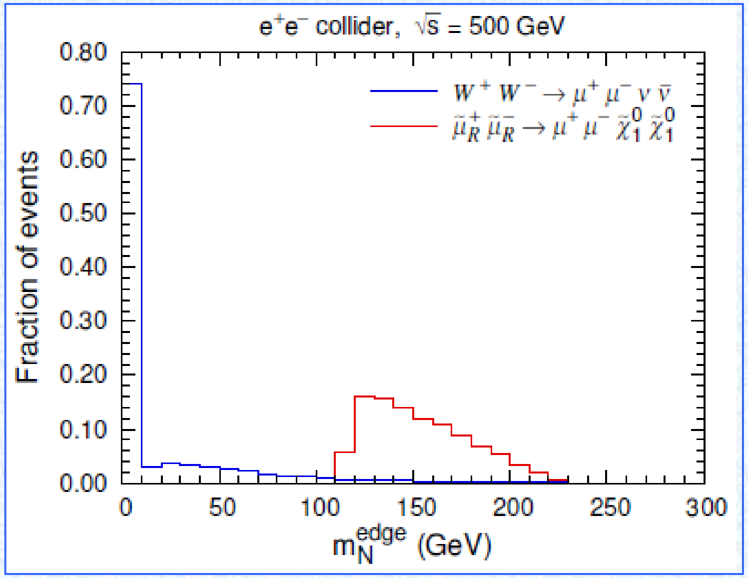


A method of DM mass determination

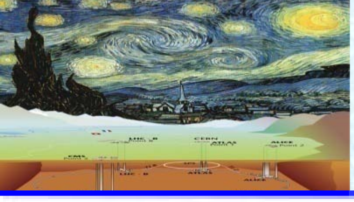
- For every event, obtain a savable point with the largest distance from the origin in the trial m_Y-m_N plane. The coordinates are defined as (m_Y^{edge}, m_N^{edge})
- Extract (m_Y, m_N) from distributions of (m_Y^{edge}, m_N^{edge})





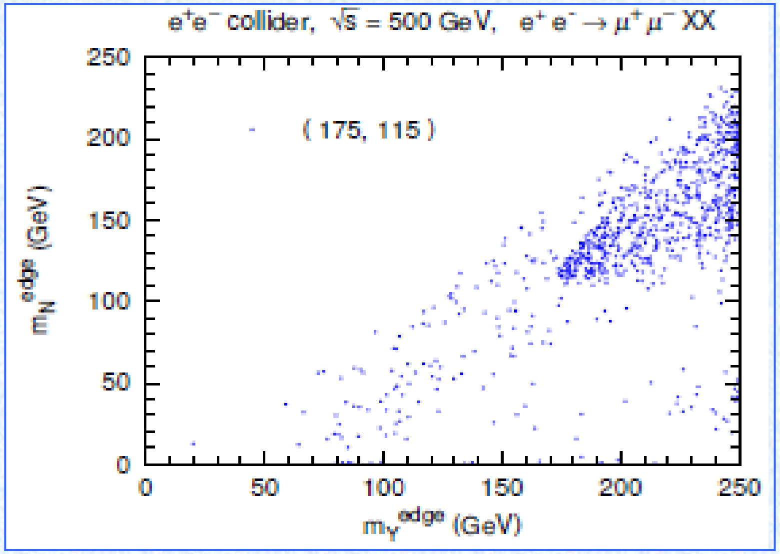


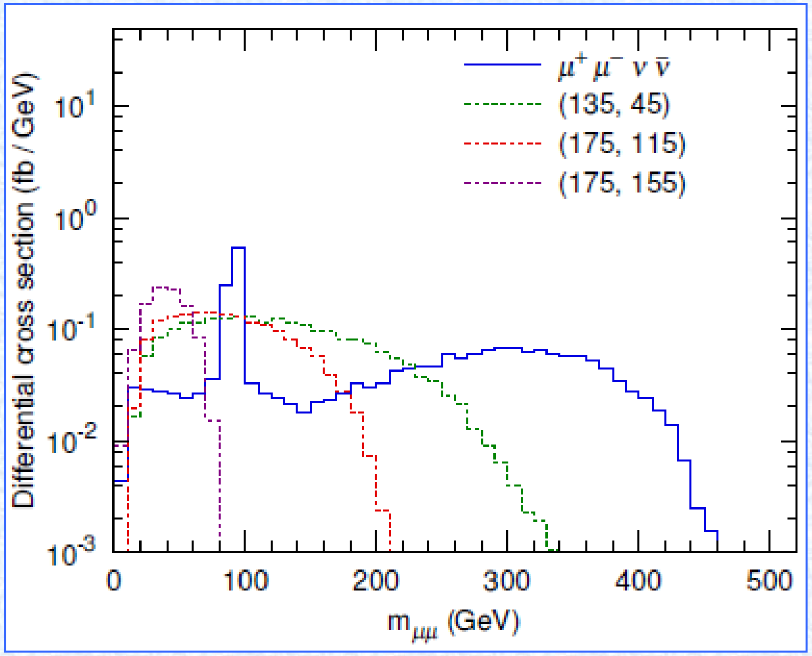
See also Harlamd-Lang et al, 1202.0047

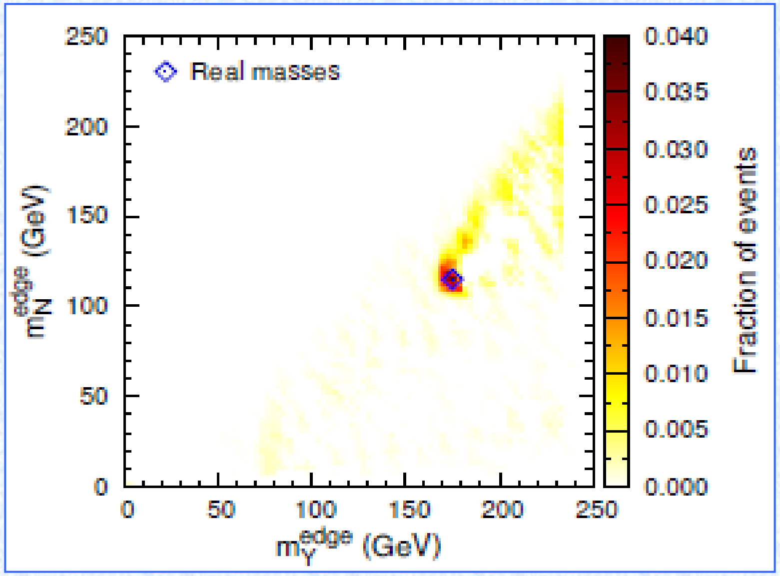


A method of DM mass determination

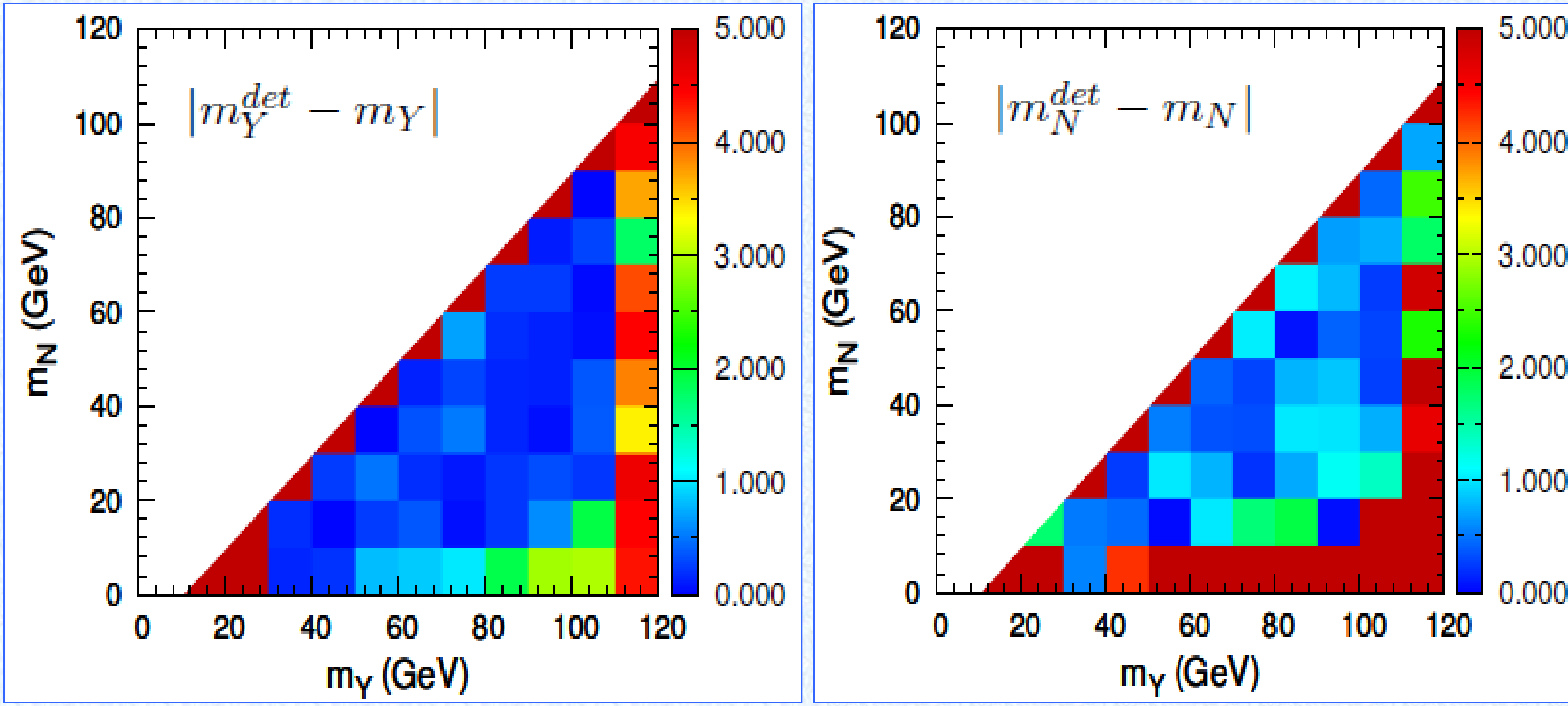
- Include detector effects in the simulation
- Consider the backgrounds from SM $\mu^+\mu^-$+MET
- Find realistic values of (m_N, m_Y)



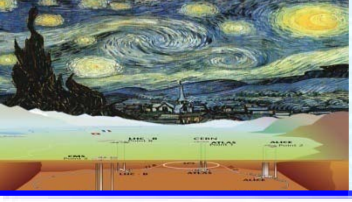




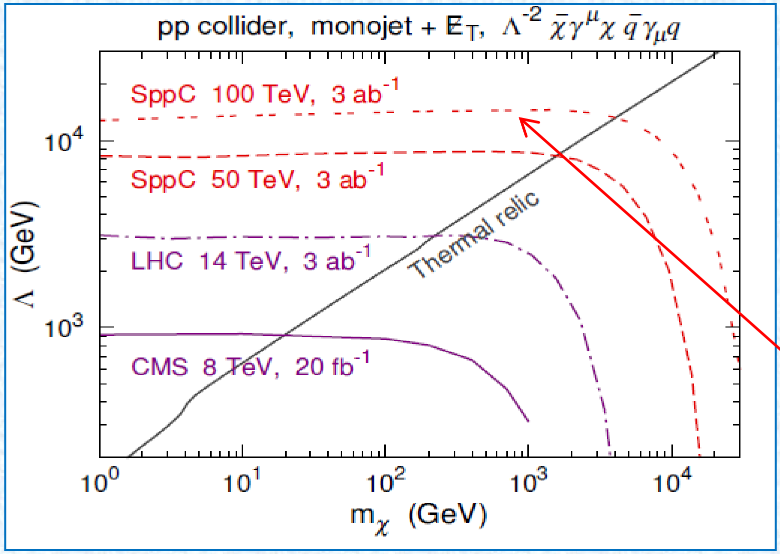
A method of DM mass determination



- **Deviations of determined masses at a CM energy of 250GeV with 200 fb^{-1} of data**

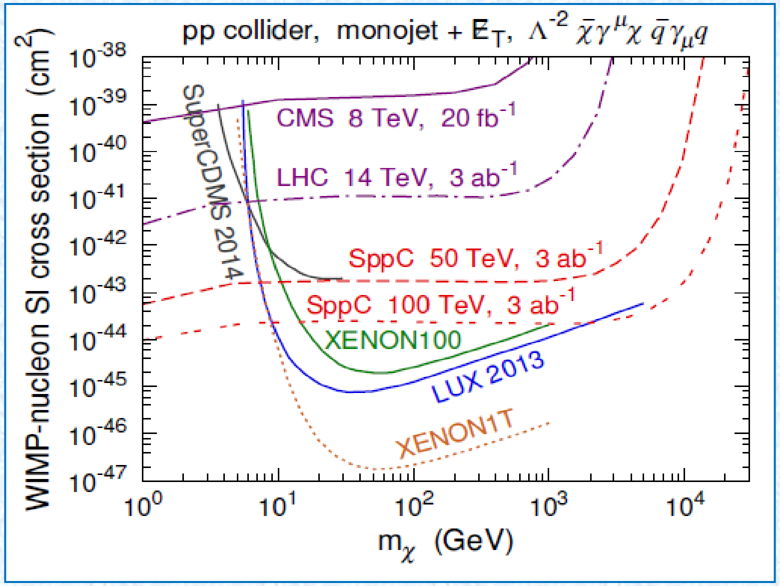


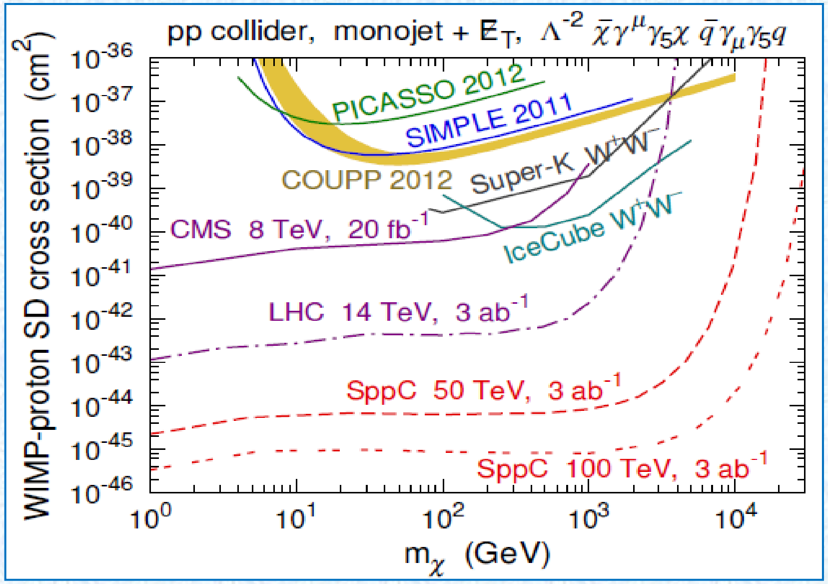
Searching for DM at the SPPC



- Advantage: large energy and luminosity for the DM production
- Disadvantage: large backgrounds
- ideal for probing light DM and spin-dependent interactions

- If $Q \gg m_{med}$, EFT limit is not valid mediator can be directly produced





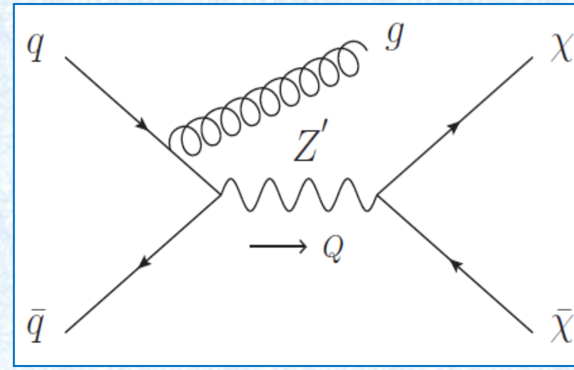
From EFT to simplified model

- (minimal) simplified models including Z′

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

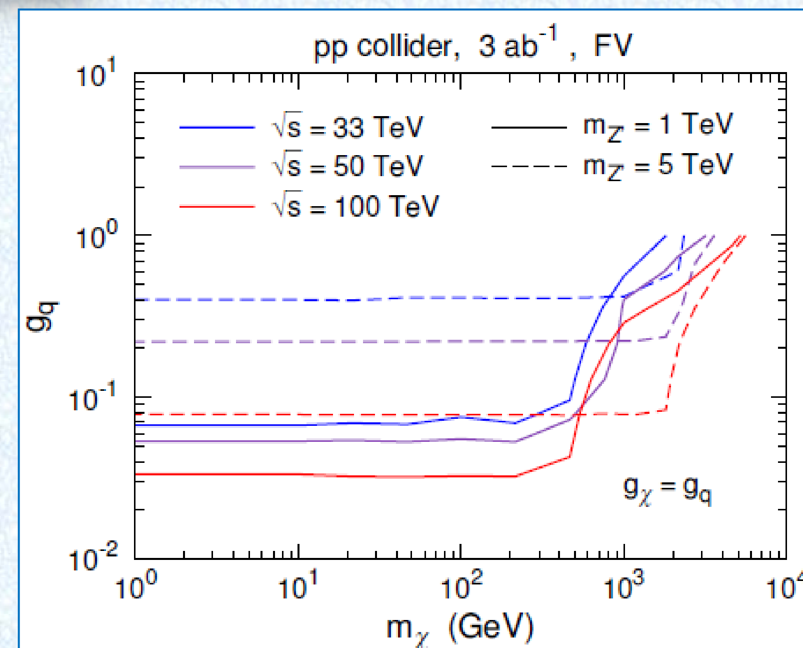
$$\mathcal{L}_{\mathrm{FA}} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu \gamma_5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi$$

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



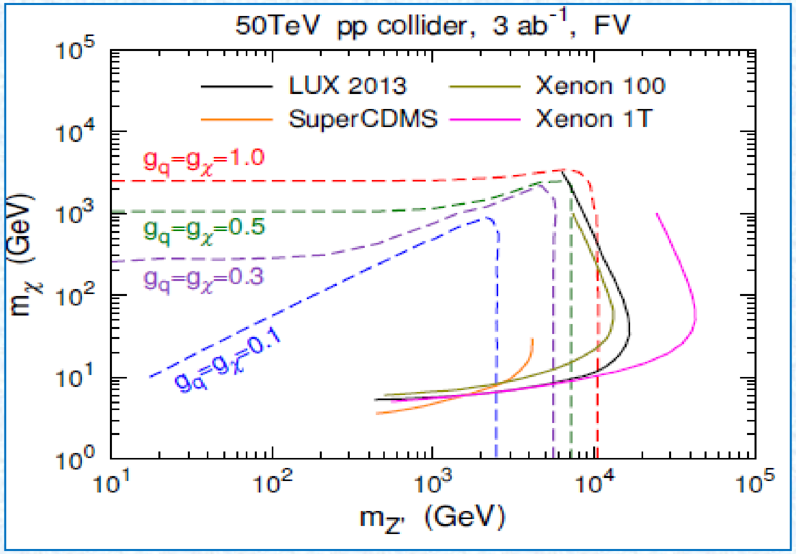
- Require $\Gamma_{Z'} < m_{Z'}$

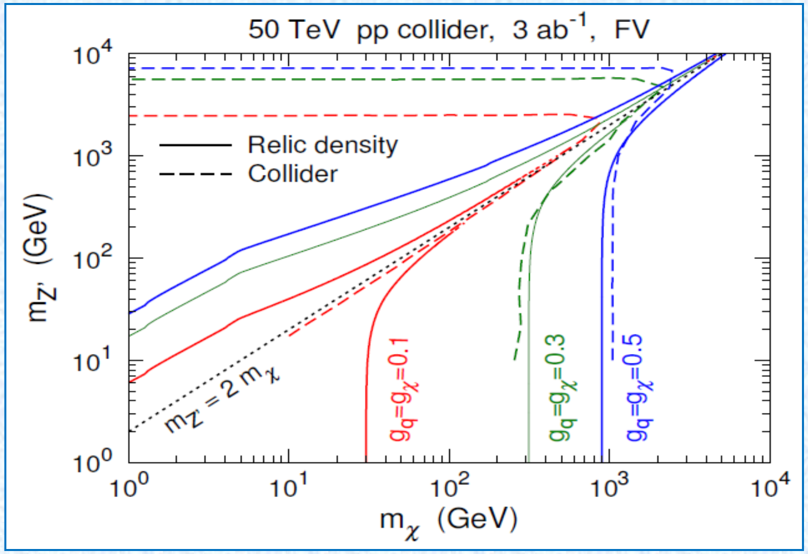
- For simplicity, assume $g_q = g_\chi$,
  g_q can be limited by di-jet resonance searches.
  In the resonance region, Z′ width would affect the DM production rate

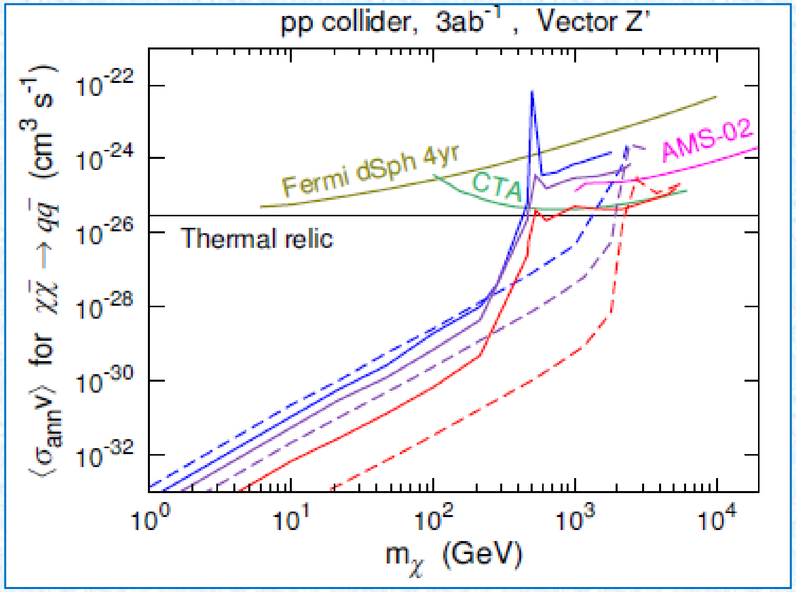


Xiang, Bi, PFY, Yu, 1503.02931

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

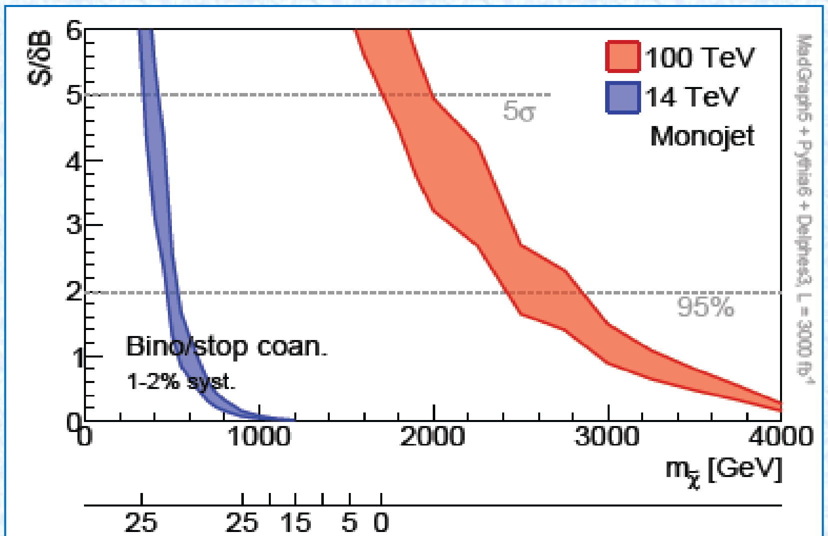
- Consider a Lagrangian similar to a SUSY model

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

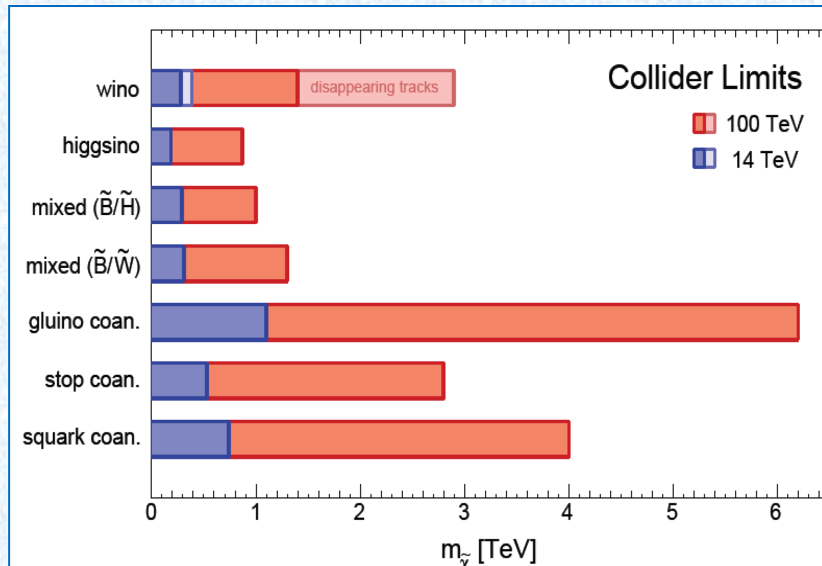
- DM may be a pure electroweak state or a mixture

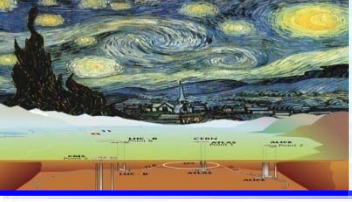
Arkani et. al, 1511.06495

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



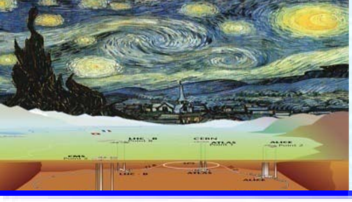
Low, Wang, 1404.0682





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
- Complementary to direct and indirect detections



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Thank you !