$SU(2)_X$ vector DM at the LHC

Takaaki Nomura (KIAS)

Based on the paper: C. H. Chen, T. N. arXiv:1507.00886

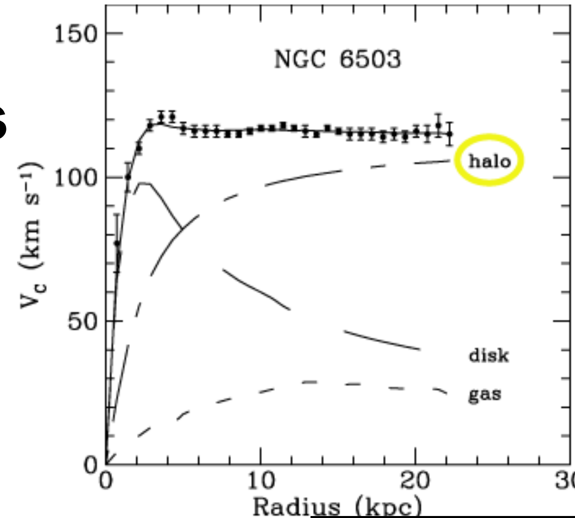
2015 9.10 Kavli-IPMU-Durham-KIAS workshop

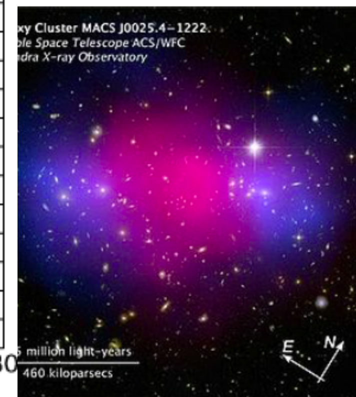
Many observation indicate the existence of dark matter

❖**Rotation of spiral galaxies**

$$v(r) \propto \sqrt{M(r)/r}$$

M(r) ∝ r in outside of visible region

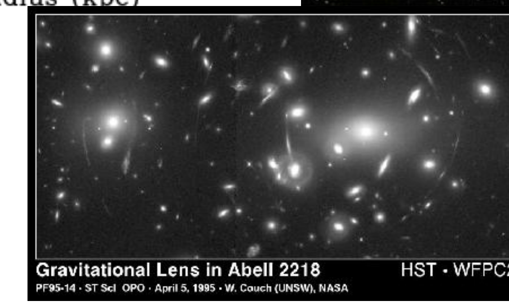




❖**Clusters of galaxies**

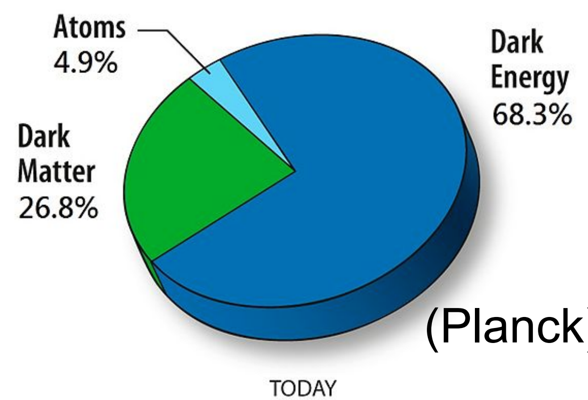
❖**Gravitational lensing**

❖**Formation of Large scale structure**



❖**Bullet Clusters**

❖**CMB anisotropy : WMAP, Planck**



Only through gravitational interaction

Vector DM from Hidden $SU(2)_X$ gauge symmetry

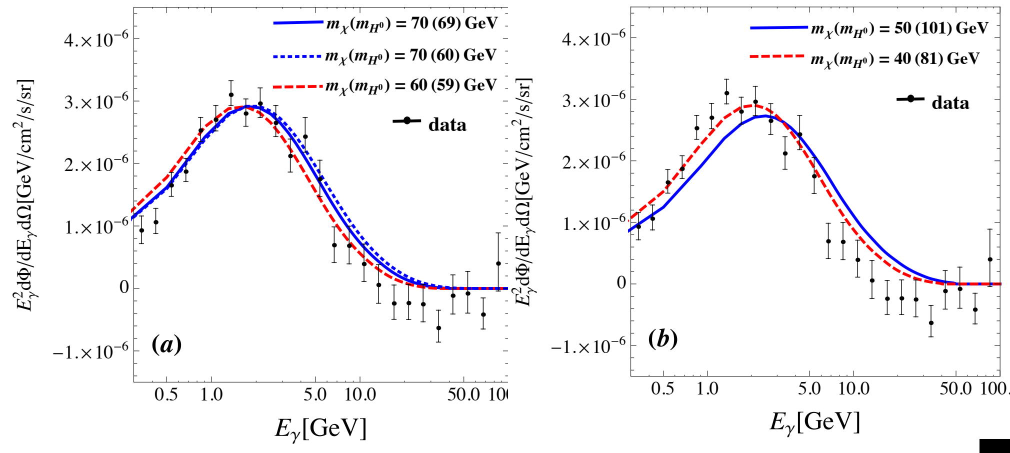
- $SU(2)_X$ model with quadraplet scalar field
  - **$SU(2)_X$ is spontaneously broken to Z_3 symmetry**
  - **Gauge boson can be Z_3 charged : DM candidate**

- $SU(2)_X$ DM phenomenology
  - **DM annihilate into SM particles via Higgs-dark Higgs mixing**
  - **Explaining galactic center gamma-ray excess**

(C.H.Chen, T.N. PLB 746 (2015) 351, 1501.07413)

$$m_{DM} = 40 \sim 100 GeV$$

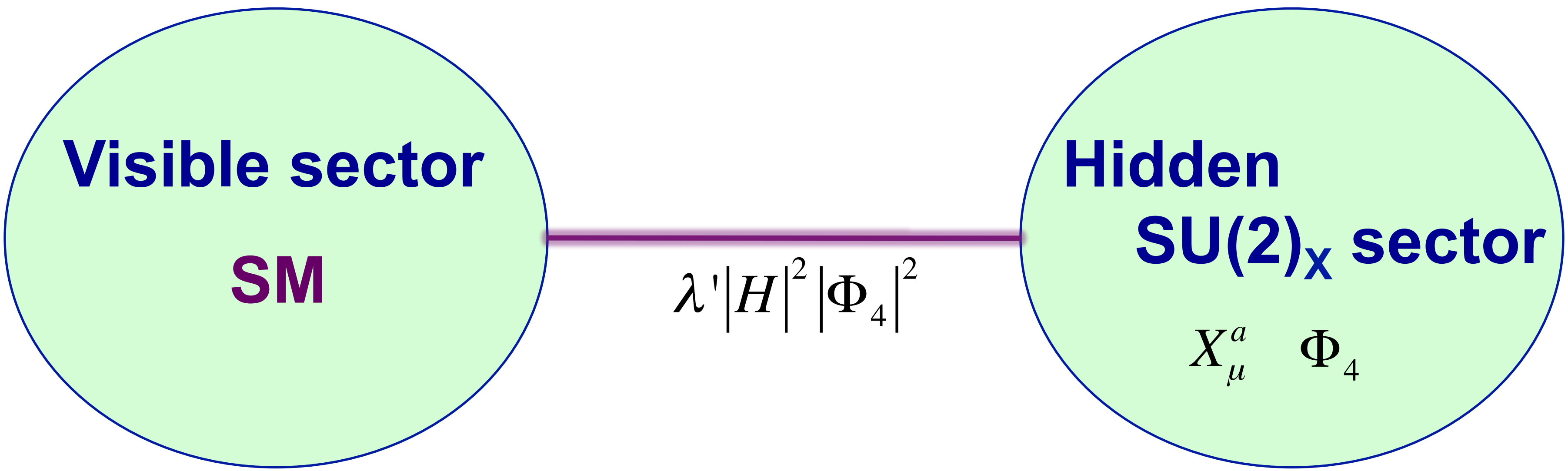
It would be produced at the LHC



Structure of the model

❖Singlet under $SU(2)_X$

❖Singlet under G_{SM}



$SU(2)_X \to Z_3$

Gauge symmetry : $G_{SM} \times SU(2)_X$

New field contents: $X_\mu^a \quad (a = 1,2,3)$ $SU(2)_X$ gauge fields

$$\Phi_4 = (\phi_{3/2}, \phi_{1/2}, -\phi_{-1/2}, \phi_{-3/2}) / \sqrt{2}$$

Scalar qadruplet for $U(2)_X$ breaking

Lagrangian of the model

$$L = L_{SM} + L_{new}$$

$$L_{new} = -\frac{1}{4} X^a_{\mu\nu} X^{a\mu\nu} + (D^\mu \Phi_4)(D_\mu \Phi_4) + V(H, \Phi_4)$$

$$X^a_{\mu\nu} = \partial_\mu X^a_\nu - \partial_\nu X^a_\mu + g_X \varepsilon_{abc} X^b_\mu X^c_\nu$$

$$D_\mu \Phi_4 = \partial_\mu \Phi_4 - i g_X X^a_\mu T^a \Phi_4$$

$$T^1 = \frac{1}{2}\begin{pmatrix} 0 & \sqrt{3} & 0 & 0 \\ \sqrt{3} & 0 & 2 & 0 \\ 0 & 2 & 0 & \sqrt{3} \\ 0 & 0 & \sqrt{3} & 0 \end{pmatrix}, T^2 = \frac{i}{2}\begin{pmatrix} 0 & -\sqrt{3} & 0 & 0 \\ \sqrt{3} & 0 & -2 & 0 \\ 0 & 2 & 0 & -\sqrt{3} \\ 0 & 0 & \sqrt{3} & 0 \end{pmatrix}, T^3 = \begin{pmatrix} 3/2 & 0 & 0 & 0 \\ 0 & 1/2 & 0 & 0 \\ 0 & 0 & -1/2 & 0 \\ 0 & 0 & 0 & -3/2 \end{pmatrix}$$

$$V(H, \Phi_4) = \mu^2 |H|^2 + \lambda |H|^4 + \mu_\Phi^2 |\Phi_4|^2 + \lambda_\Phi |\Phi_4|^4 + \lambda' |H|^2 |\Phi_4|^2$$

$$\Rightarrow \quad <\Phi_4> = (v_4, 0, 0, v_4)^T / \sqrt{2}, \quad <H> = (0, v)^T / \sqrt{2}$$

❖ Gauge bosons

- ❖ $\chi_\mu, \bar{\chi}_\mu$ ★ **Candidate of dark matter**

  From $T_3 = \pm 1$ component of $SU(2)_X$ gauge fields (Z_3 charged)

- ❖ X_μ^3

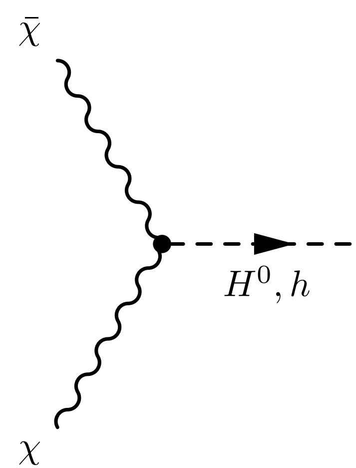
  $T_3 = 0$ component of $SU(2)_X$ gauge fields (Z_3 non-charged)

❖ Higgs bosons

$$H \supset \phi = h\cos\theta - H^0 \sin\theta \qquad \Phi_4 \supset \phi_r = h\sin\theta + H^0\cos\theta$$

❖ Gauge interaction : DM and Higgs bosons

$$\sqrt{3} g_X m_\chi \sin\theta \chi_\mu \bar{\chi}^\mu h + \sqrt{3} g_X m_\chi \cos\theta \chi_\mu \bar{\chi}^\mu H^0$$



H^0-SM particle interection

➡ **SM h coupling × sinθ**

Parameters in the model

❖ **Original parameters**

$$g_X, \mu, \mu_\Phi, \lambda, \lambda_\Phi, \lambda'$$

Gauge coupling &
parameters in the potential

after SSB

❖ **Free parameters in our analysis**

$$g_X, m_\chi, m_{H^0}, \sin\theta$$

$$(m_h = 125\, GeV, v \approx 246\, GeV)$$

Gauge coupling &
new particle masses &
and mixing angle for scalar bosons

Signal of the dark matter in our model at the LHC

DMs are produced through Higgs bosons h and H^0

We consider DM mass and H^0 mass motivated by GC γ-ray excess

$$m_\chi = 20 \sim 80 GeV \quad A: m_H \approx m_\chi \quad B: m_H \approx 2m_\chi$$

Current constraints

- **Invisible h decay**

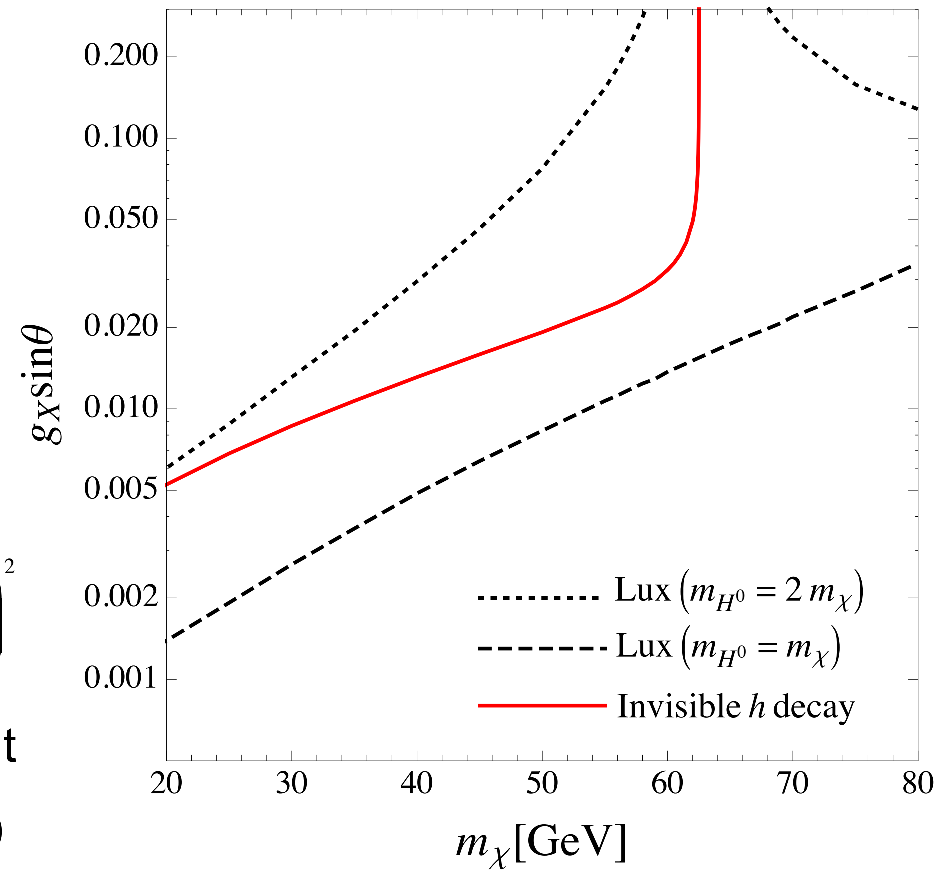
LHC 8 TeV limit from ATLAS:
ATLAS-COM-CONF-2015-004
arXiv:1509.00672

- **DM direct detection**

$$\sigma_{\chi N} \approx \frac{3g_X^2 f_N^2}{4\pi}(\sin\theta\cos\theta)^2\left(\frac{m_N}{m_\chi + m_N}\right)^2\left(\frac{m_{H^0}^2 - m_h^2}{m_h m_{H^0}}\right)^2$$

Compared with LUX constraint

(PRL 112, arXiv:1310.8214)



H and H^0 production processes

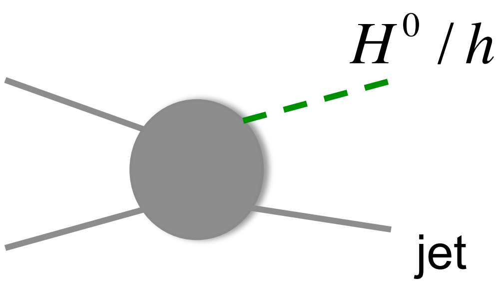
① Mono-jet production : p p > h/H^0 + jet

② Vector boson fusion (VBF) : p p > h/H^0 + 2 jets

③ Z/W associated production : p p > h/H^0 + Z/W

④ Top associated production : p p > h/H^0 + t tbar

①



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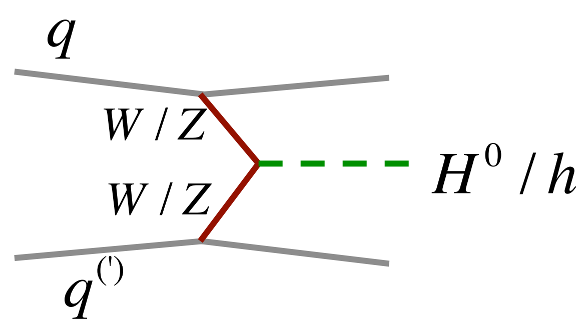

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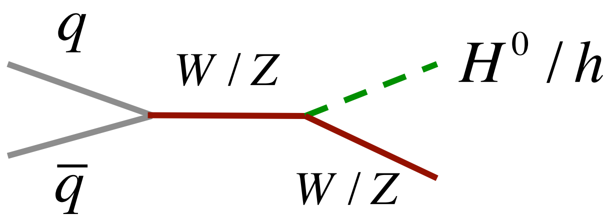

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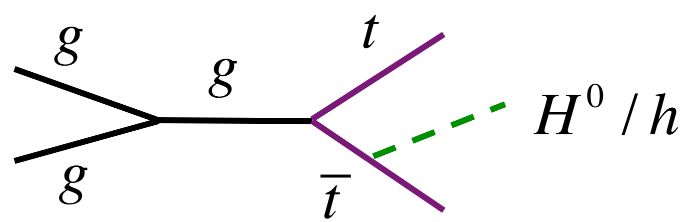
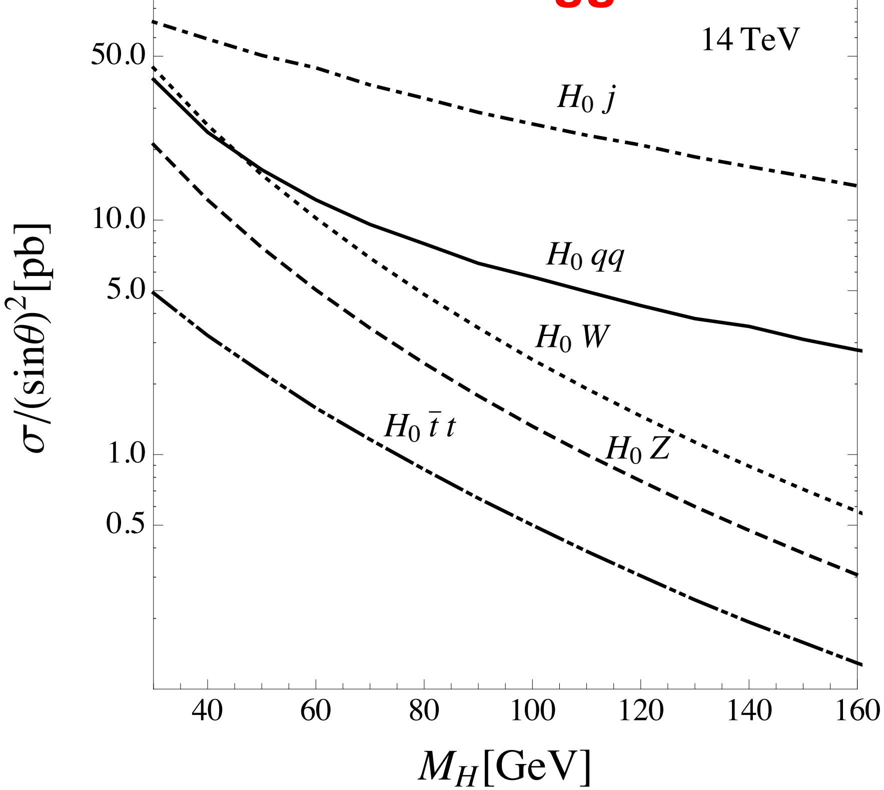
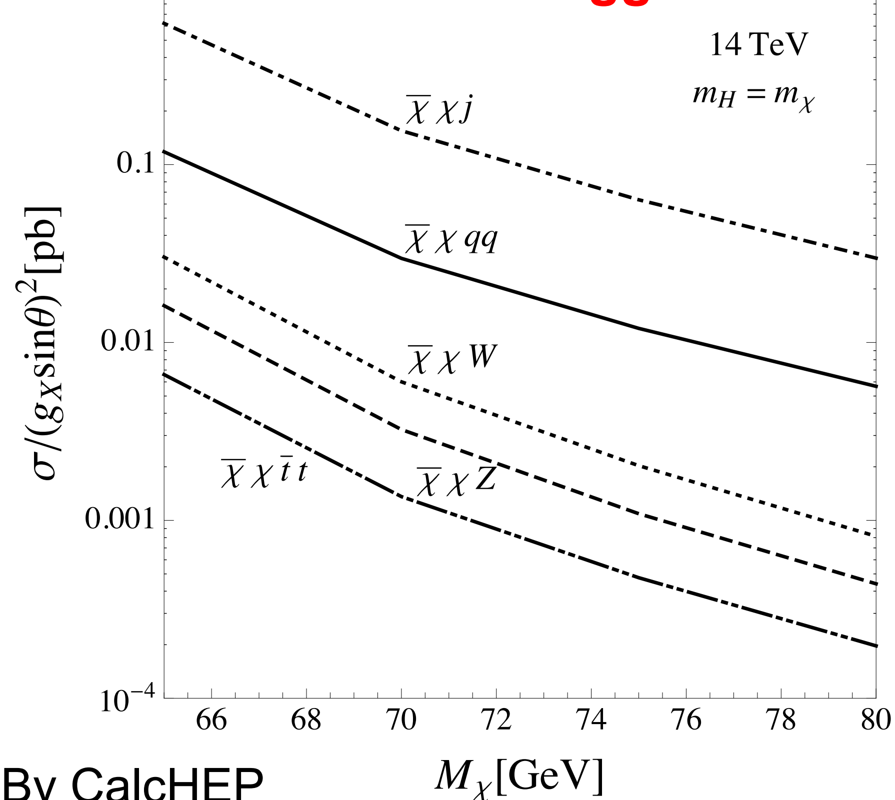


Production cross sections

On-shell Higgs



Off-shell Higgs



By CalcHEP

- H^0 production σ = SM h production σ × $\sin^2\theta$
- Mono jet production σ is largest, however background is huge
- VBF is promising; we can reduce BG with kinematical cuts

Production cross sections

On-shell Higgs

Off-shell Higgs

We consider 4 cases for VBF

	$h \to \bar{\chi}\chi$	$H^0 \to \bar{\chi}\chi$
$I_A: \quad m_h > 2m_\chi, m_{H^0} = 2m_\chi + 1\,GeV$	On-shell	On-shell
$I_B: \quad m_h > 2m_\chi, m_{H^0} = m_\chi - 1\,GeV$	On-shell	Off-shell
$II_A: \quad m_h < 2m_\chi, m_{H^0} = 2m_\chi + 1\,GeV$	Off-shell	On-shell
$II_B: \quad m_h < 2m_\chi, m_{H^0} = m_\chi - 1\,GeV$	Off-shell	Off-shell

- ❖ H^0 production σ = SM h production σ × $\sin^2\theta$
- ❖ Mono jet production σ is largest, however background is huge
- ❖ VBF is promising; we can reduce BG with kinematical cuts

Kinematical cuts

Generating events:

- **Using MADGRAPH/MADEVENT package**
- **PYTHIA6 for ISR/FSR, hadronization, decay of SM particles**
- **Detector level simulation with PGS 4**

SM backgrounds:

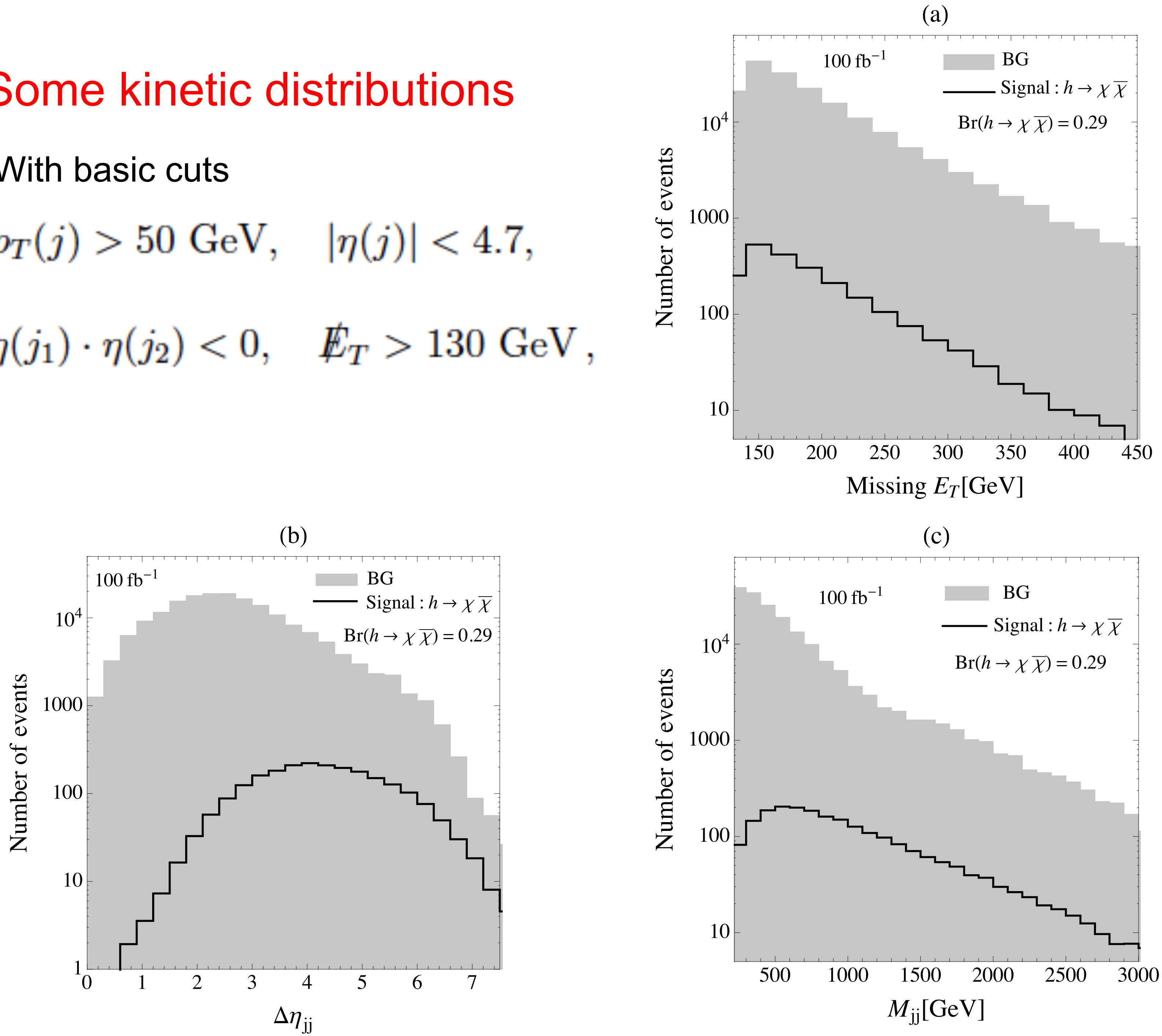
- **Z + 2jets, Z+ 3jets**
- **W+ 2jets, W+ 3jets**
- **tWb**

Some kinetic distributions

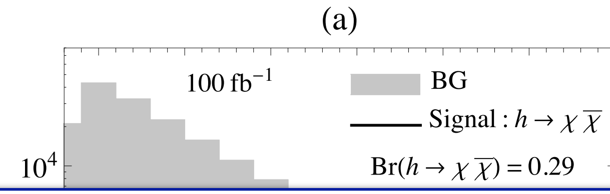
With basic cuts

$$p_T(j) > 50 \text{ GeV}, \quad |\eta(j)| < 4.7,$$

$$\eta(j_1) \cdot \eta(j_2) < 0, \quad \not{E}_T > 130 \text{ GeV},$$



Some kinetic distributions

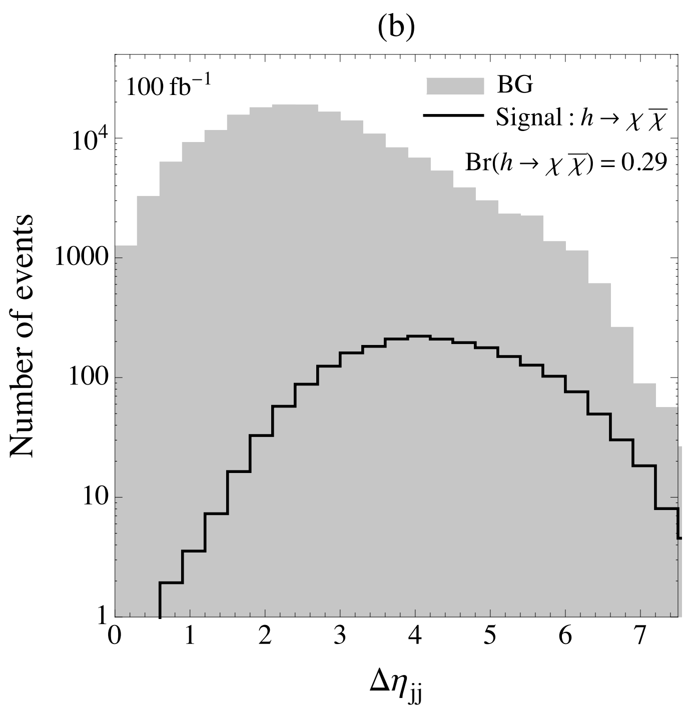


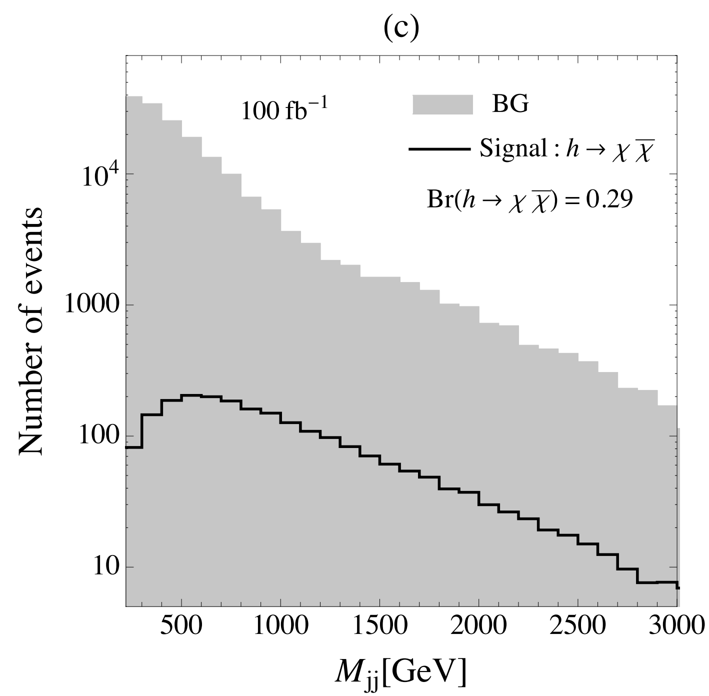
We apply kinematical cuts:

$$p_T(j) > 50 \text{ GeV}, \quad |\eta(j)| < 4.7, \quad \eta(j_1)\cdot\eta(j_2) < 0, \quad E_T^{\text{miss}} > 130 \text{ GeV},$$

$$\Delta\eta_{jj} > 4.5, \quad \Delta\phi_{jj} < 1.5, \quad M_{jj} > 1100 \text{ GeV},$$

Similar to CMS analysis : Eur. Phys. J. C 74 , 2980 (2014) [arXiv:1404.1344 [hep-ex]].





Cross sections after cuts

σ_{BG}[fb]	Zjj	Zjjj	Wjj	Wjjj
	32.9	8.54	14.2	2.20

σ_{signal}[fb]	m_χ[GeV]	40	50	60
	$\mathrm{I_A}$	$18.6\ R_{H^0} + 17.2\ R_h$	$17.5\ R_{H^0} + 17.2\ R_h$	$17.3\ R_{H^0} + 17.2\ R_h$
	$\mathrm{I_B}$	$17.2\ R_h$	$17.2\ R_h$	$17.2\ R_h$
	m_χ[GeV]	65	70	75
	$\mathrm{II_A}$	$16.3\ R_{H^0}$	$16.0\ R_{H^0}$	$15.4\ R_{H^0}$
	$\mathrm{II_B}$	$0.689\ R_{\mathrm{off}}$	$0.211\ R_{\mathrm{off}}$	$0.102\ R_{\mathrm{off}}$

$$R_{H^0} = \sin^2\theta \times Br(H^0 \to \bar{\chi}\chi)$$

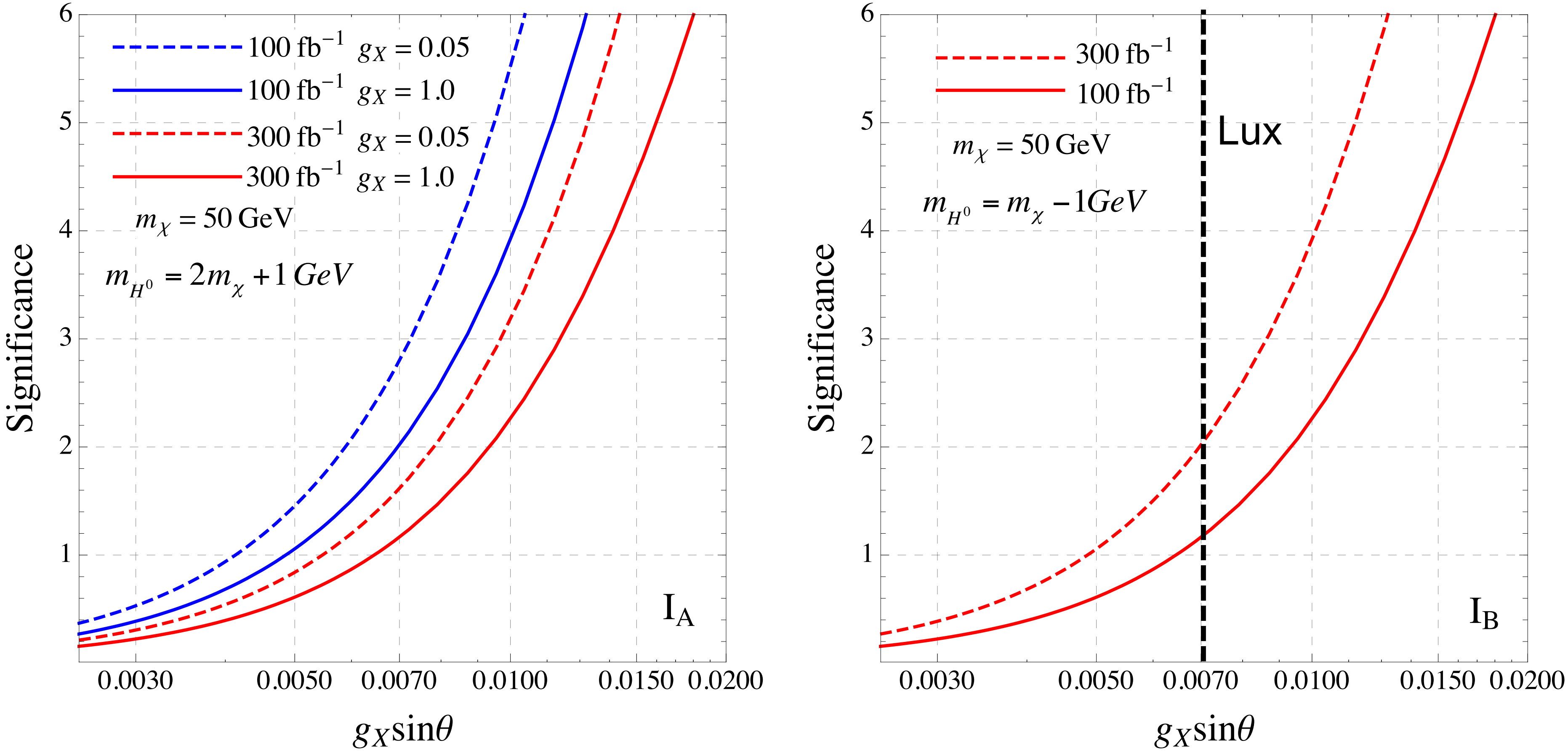
$$R_h = \cos^2\theta \times Br(h \to \bar{\chi}\chi)$$

$$R_{off} = \left(g_X \sin\theta\cos\theta\right)^2$$

Estimate significance of the signal

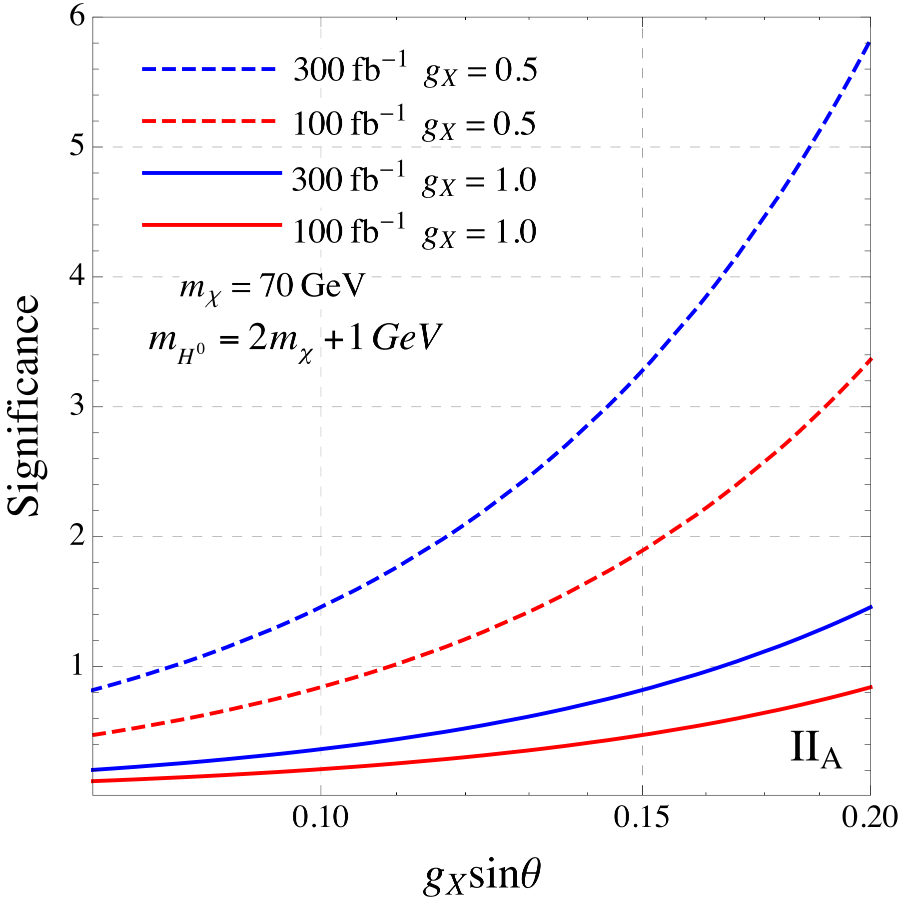
$$S = N_S / \sqrt{N_B}$$

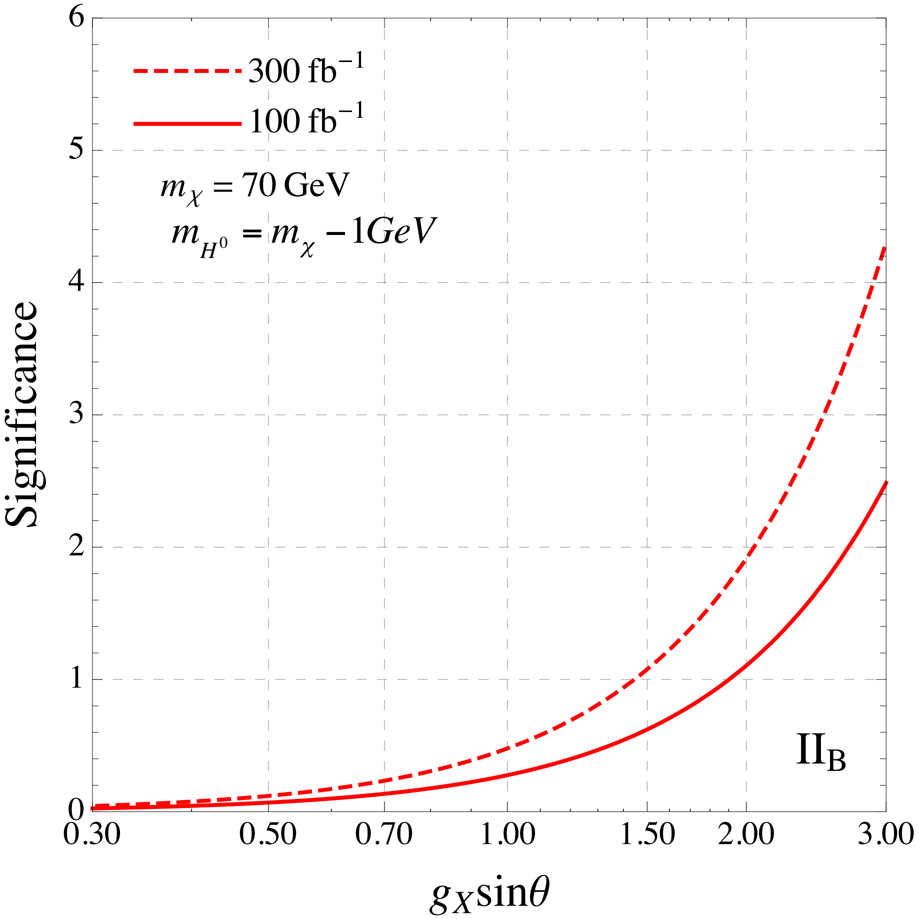
Significance VS coupling



- For simplicity, we took cosθ=1 because sinθ is small
- For I_A, sinθ is larger for smaller g_X ➔ more contribution from H^0

Significance VS coupling

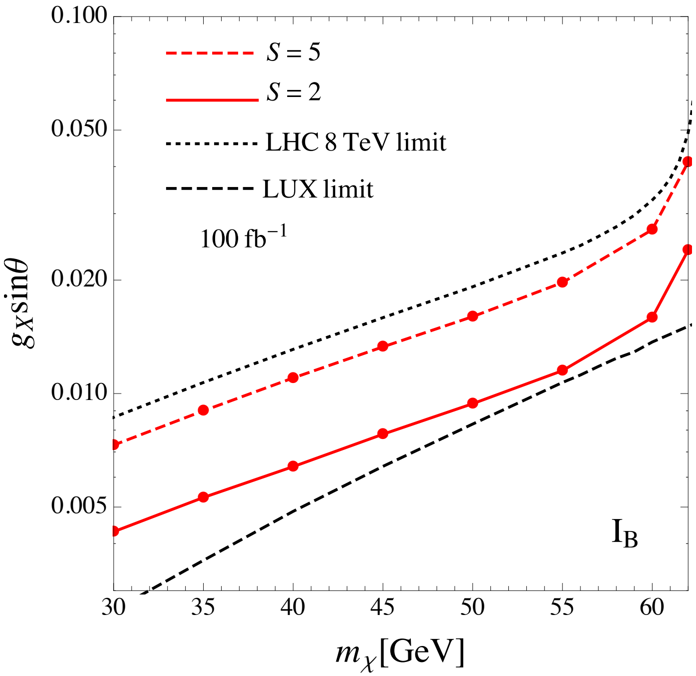




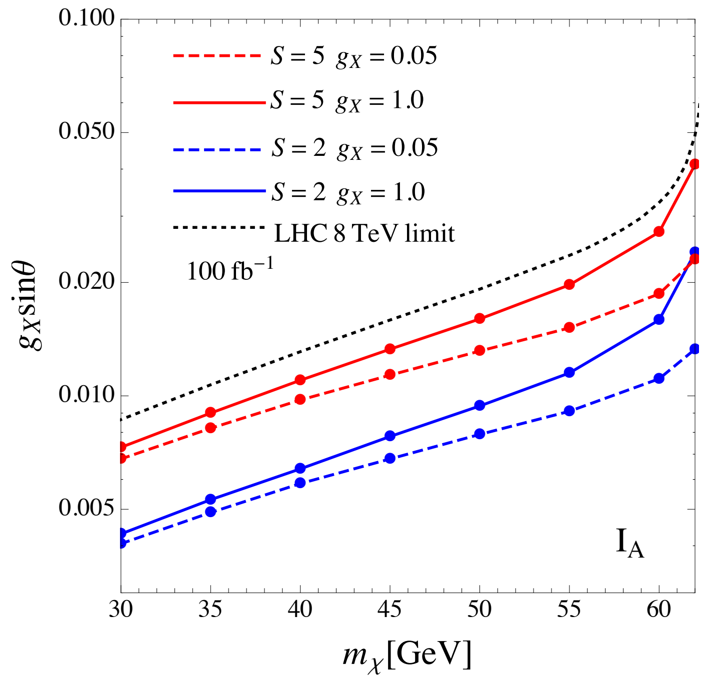
- For simplicity, we took cosθ=1 for $\mathrm{II_B}$ because we take sinθ is small
- For $\mathrm{II_A}$, sinθ is large for smaller g_X

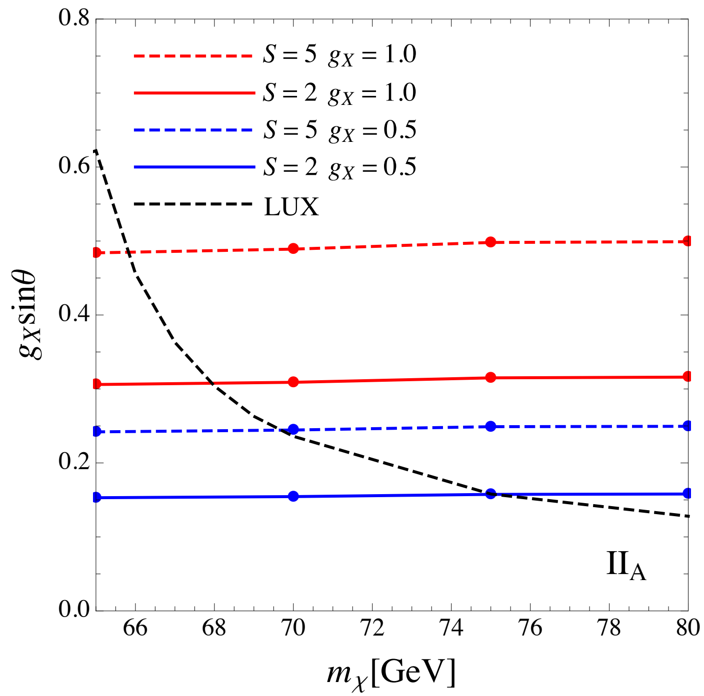
Coupling-DM mass contour for fixed significance

Luminosity = 100 fb^{-1}



LHC 8 TeV limit from ATLAS:
ATLAS-COM-CONF-2015-004





Summary

Hidden SU(2) vector DM model

- ✧Z_3 symmetry as a subgroup of SU(2)
- ✧DM candidates are massive gauge boson
- ✧DM interaction with SM through Higgs mixing
- ✧Possible explanation of galactic gamma-ray excess

Search for vector DM at the LHC

- ✧Collider signature; invisible decay of Higgs bosons
- ✧On-shell h or H^0 case is promising
- ✧We can test more parameter space by LHC-run2

Appendix

Relic density of DM

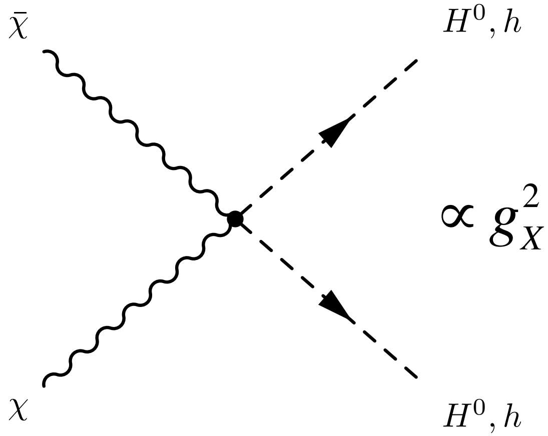
Relic density calculation

Relic density is obtained by solving Boltzmann equation :

$$\frac{dn_\chi}{dt} + 3Hn_\chi = - < \sigma v_{rel} > (n_\chi^2 - n_{\chi eq}^2)$$

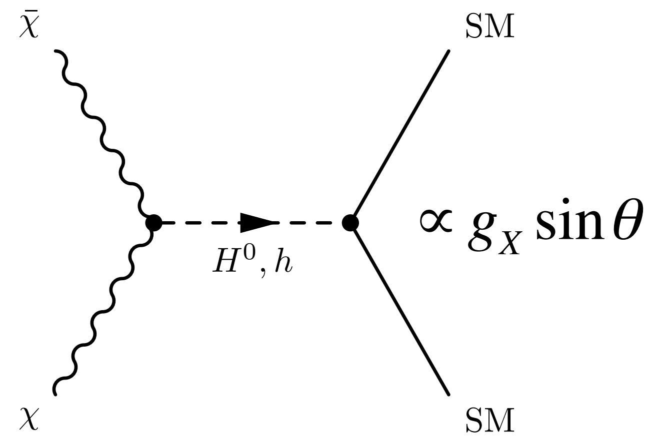
Dominant DM annihilation processes

(1) $m_\chi > m_{H^0}$



+ t(u)-channel process

(2) $m_\chi < m_{H^0}$



Suppressed by sinθ

Search for the parameter region satisfying observed relic density

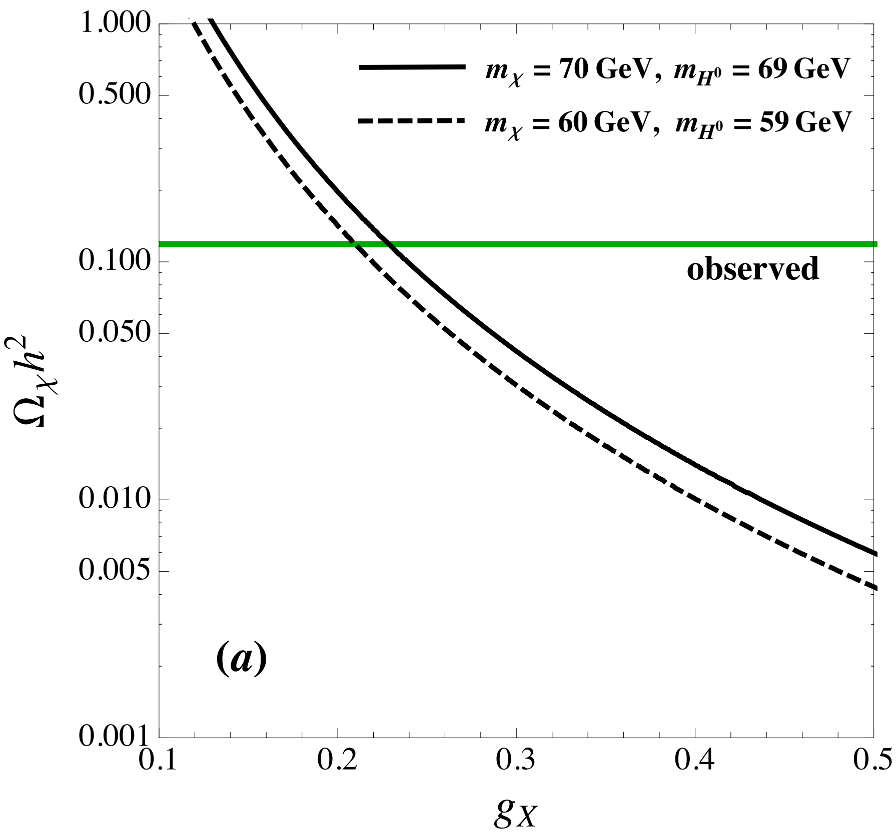
Planck data (90% C.L.) $0.1159 \le \Omega_D h^2 \le 0.1215$

P.A.R. Ade et al [Planck Collaboration] (2013)

Ω_D is Calculated with MicrOMEGAs

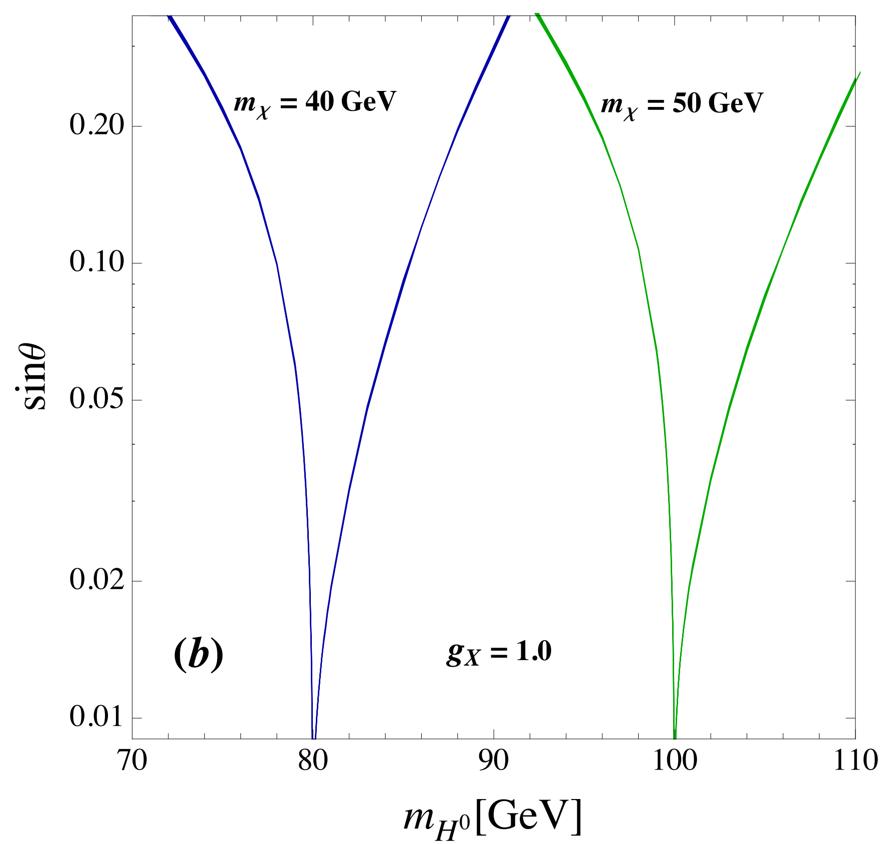
(G. Belanger, F. Boudjema, A. Pukhov and A. Semenov)

(1) $m_\chi > m_{H^0}$



Independent of sinθ

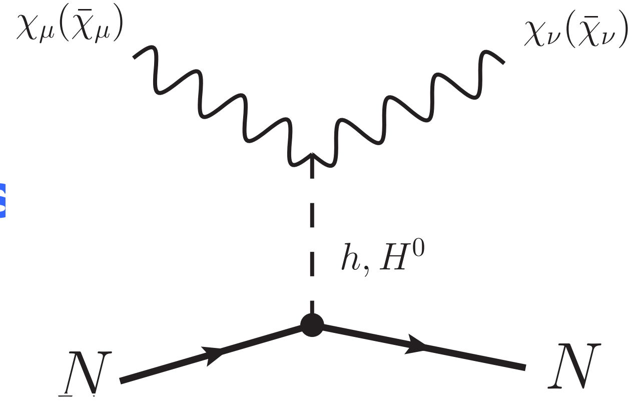
(2) $m_\chi < m_{H^0}$



$m_{H^0} \approx 2m_\chi$ **is required for small sinθ**

Constraint DM-Nucleon scattering

Scattering Process



DM-Nucleon scattering through H^0 and h exchanging processes

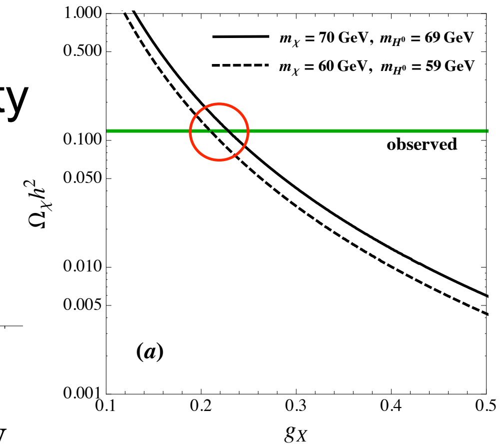
Cross section: $\sigma_{\chi N} \approx \frac{3g_X^2 f_N^2}{4\pi}(\sin\theta\cos\theta)^2\left(\frac{m_N}{m_\chi + m_N}\right)^2\left(\frac{m_{H^0}^2 - m_h^2}{m_h m_{H^0}}\right)^2$

$f_N = [1.1, 3.2] \times 10^{-3}$ **: Higgs-Nucleon coupling**

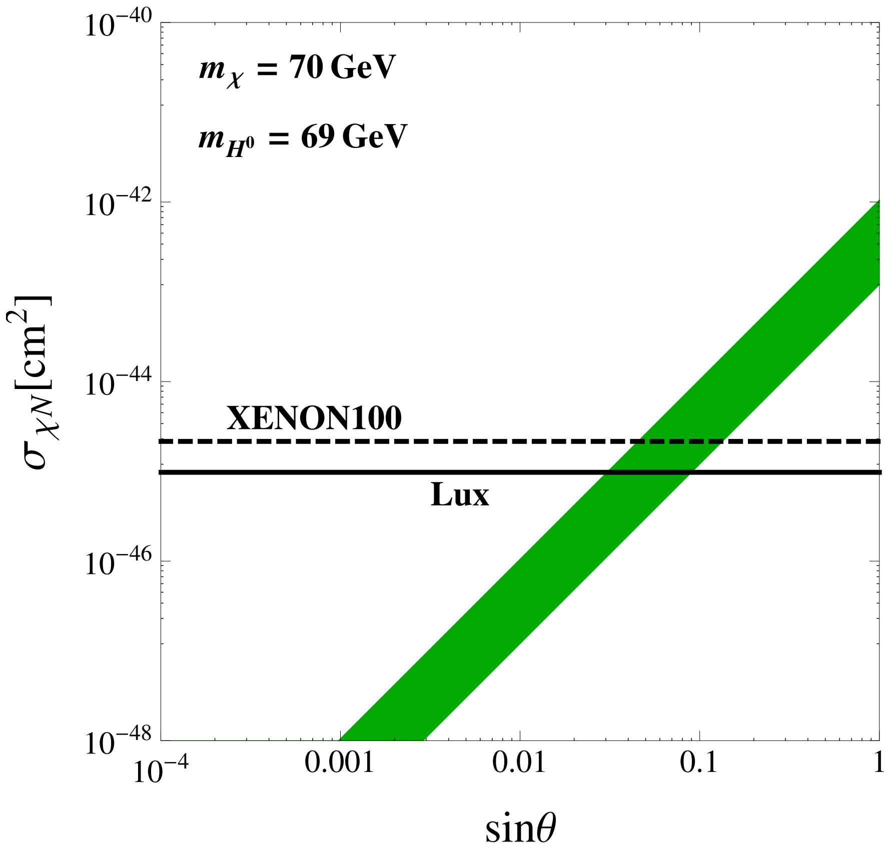
H.Y. Cheng, C.W.Chian (2012)

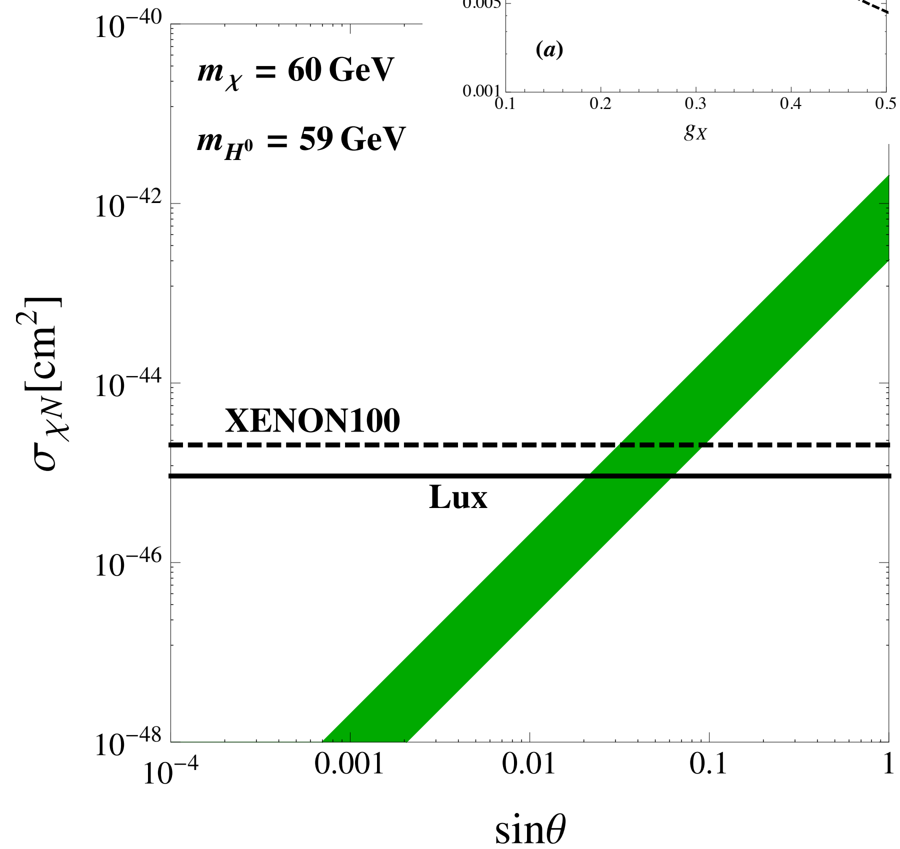
Compare the cross section with DM direct detection search

Parameter from relic density



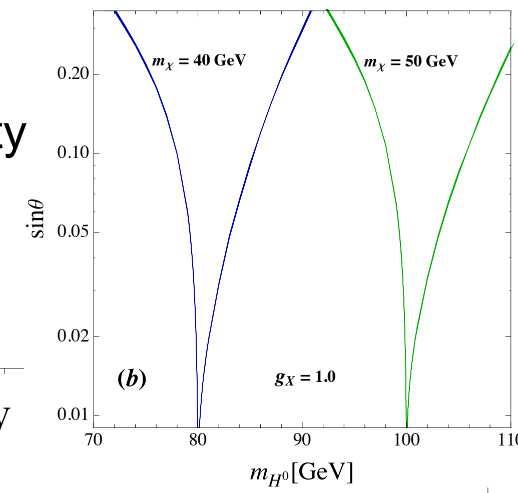
Case (1) $m_\chi > m_{H^0}$



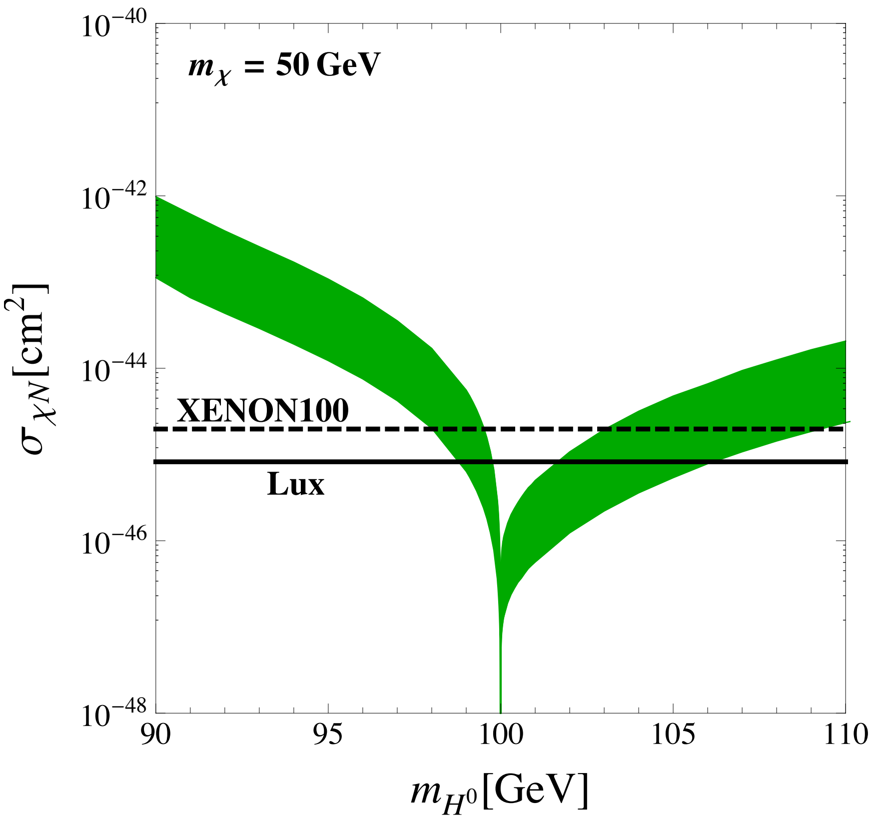


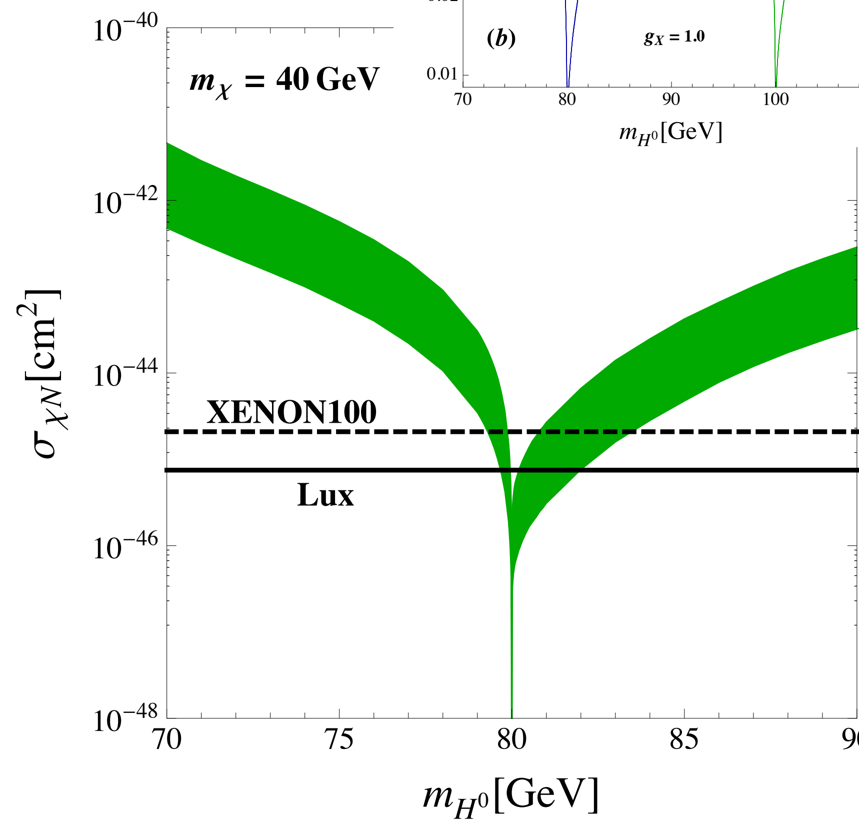
Value of sinθ is constrained to be smaller than ~ 0.1

Parameter from relic density



Case (2) $m_\chi < m_{H^0}$

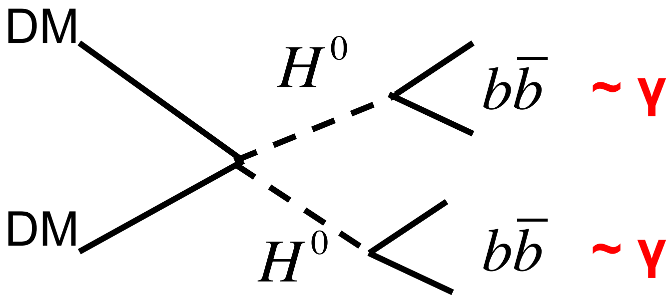




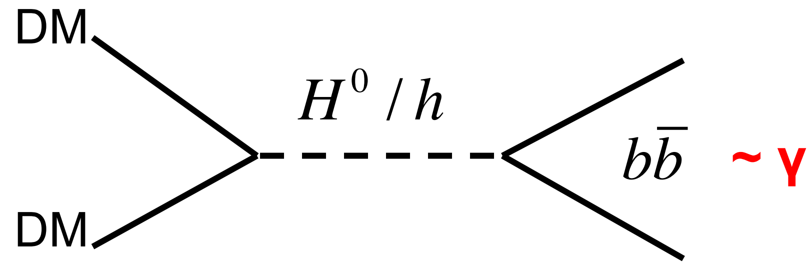
$m_{H^0} \approx 2m_\chi$ **is required to satisfy constraints from direct detection**

Galactic center Gamma-ray from DM annihilation

(1)



(2)



The flux of Gamma-ray from DM annihilation

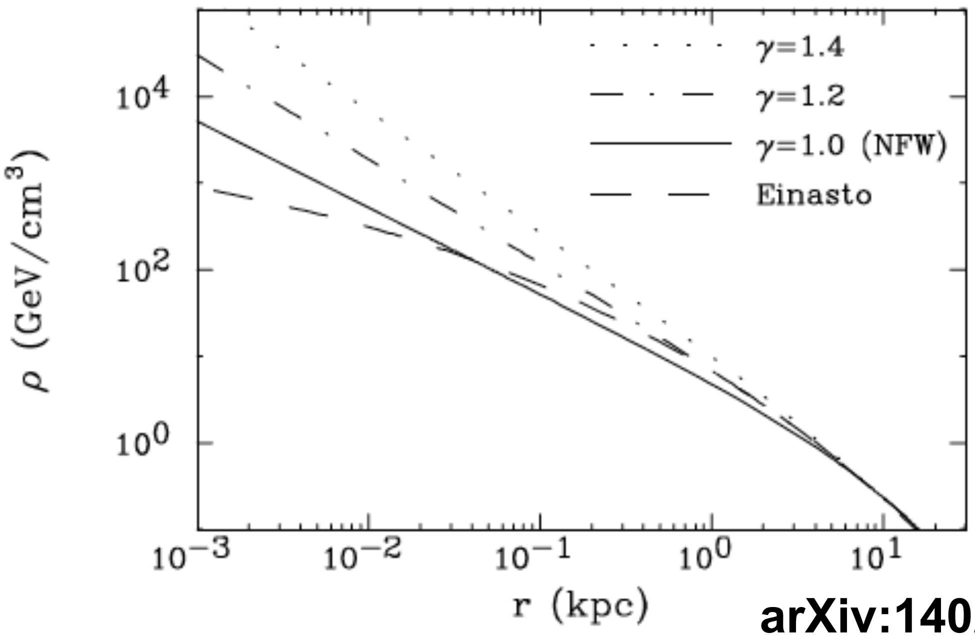
$$\frac{d\Phi(E_\gamma,\psi)}{dE_\gamma d\Omega} = \frac{<\sigma v_{rel}>}{8\pi m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\int_{los}\rho^2(r)\,dl(\psi)$$

- dN_γ / dE_γ : **Gamma-ray spectrum per annihilation**
- ψ : **Observation angle between line-of-sight and GC**
- $\rho(r)$: **Density of DM**

DM halo profile is parametrized by $\rho(r) = \rho_O \left(\frac{r_O}{r}\right)^\gamma \left(\frac{1+r_O/r_S}{1+r/r_S}\right)^{3-\gamma}$

(γ=1 is NFW profile)

Dependence of DM density on slope factor γ



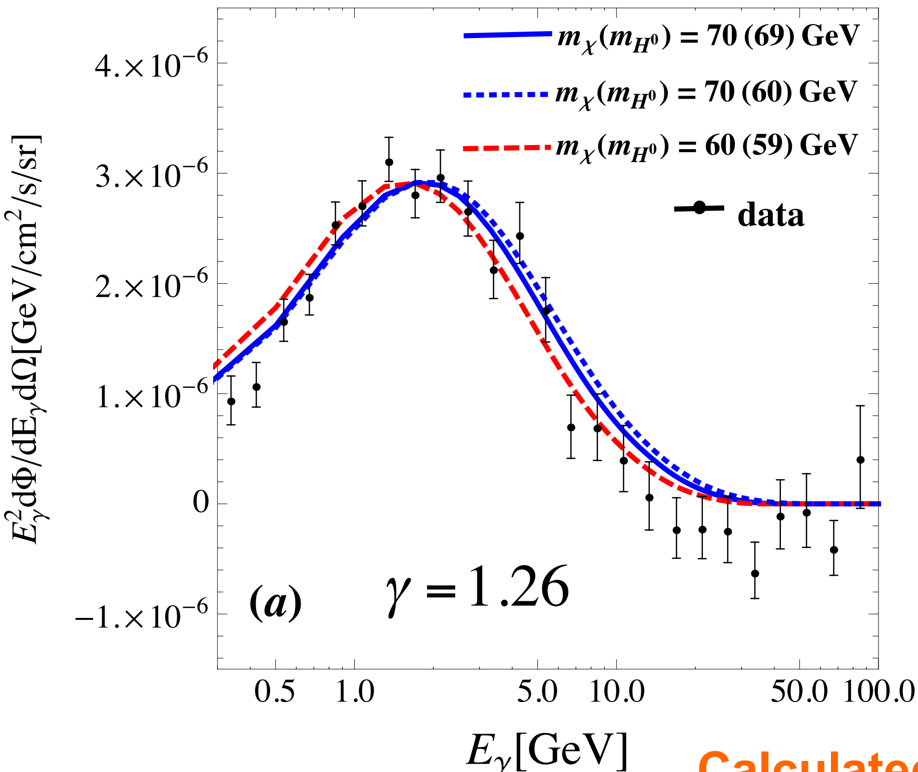
r: distance from GC

arXiv:1402.6703

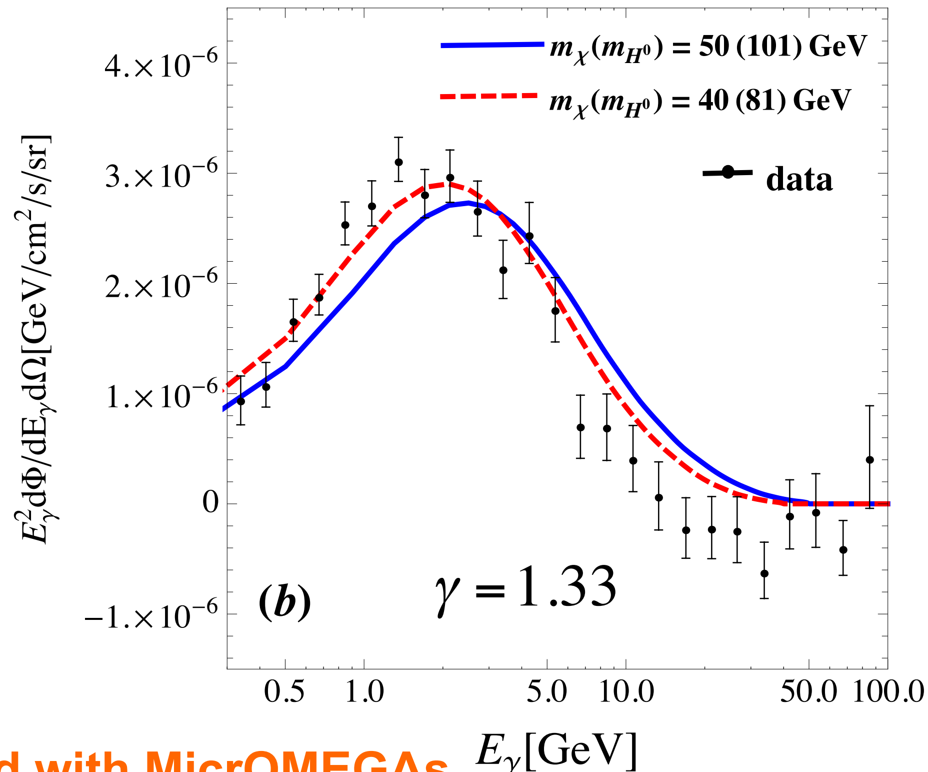
- **DM is dense at galactic center for large slope factor**
- **Gamma-ray flux depends on the factor**
- **We take γ as free parameter to fit the data**

Galactic center Gamma-ray from DM annihilation

(1) $m_\chi > m_{H^0}$



(2) $m_\chi < m_{H^0}$



Calculated with MicrOMEGAs

satisfying relic density and constraints from direct detection

Branching ratio for invisible decay of Higgs bosons

Invisible decay width

$$\Gamma_{h\to\bar{\chi}\chi} = \frac{3g_X^2\sin^2\theta}{64\pi}\frac{m_\chi^2}{m_h}\frac{m_h^4-4m_h^2m_\chi^2+12m_\chi^4}{m_\chi^4}\sqrt{1-\frac{4m_\chi^2}{m_h^2}}$$

$$\Gamma_{H^0\to\bar{\chi}\chi} = \frac{3g_X^2\cos^2\theta}{64\pi}\frac{m_\chi^2}{m_h}\frac{m_{H^0}^4-4m_{H^0}^2m_\chi^2+12m_\chi^4}{m_\chi^4}\sqrt{1-\frac{4m_\chi^2}{m_{H^0}^2}}$$

Branching ratio

$$Br(h\to\bar{\chi}\chi) = \frac{\Gamma_{h\to\bar{\chi}\chi}}{\Gamma_{h\to\bar{\chi}\chi}+\Gamma_{h\to SM}\cos^2\theta} = \frac{\Gamma_{h\to\bar{\chi}\chi}^{g_X\sin\theta=1}(g_X\tan\theta)^2}{\Gamma_{h\to\bar{\chi}\chi}^{g_X\sin\theta=1}(g_X\tan\theta)^2+\Gamma_{h\to SM}}$$

$$Br(H^0\to\bar{\chi}\chi) = \frac{\Gamma_{H^0\to\bar{\chi}\chi}}{\Gamma_{H^0\to\bar{\chi}\chi}+\Gamma_{h\to SM}^{m_{H^0}}\cos^2\theta} = \frac{\Gamma_{H^0\to\bar{\chi}\chi}^{g_X\cos\theta=1}(g_X\cot\theta)^2}{\Gamma_{H^0\to\bar{\chi}\chi}^{g_X\cos\theta=1}(g_X\cot\theta)^2+\Gamma_{h\to SM}^{m_{H^0}}}$$