

Figure 2: Left panel: the constraints on the spin-independent DM-proton scattering cross section. Relevant experimental bounds are shown as labeled. Right panel: the same as the left panel but for the constraints on the spin-independent DM-neutron scattering cross section.

Bai-Fox-Harnik. 1005.3797

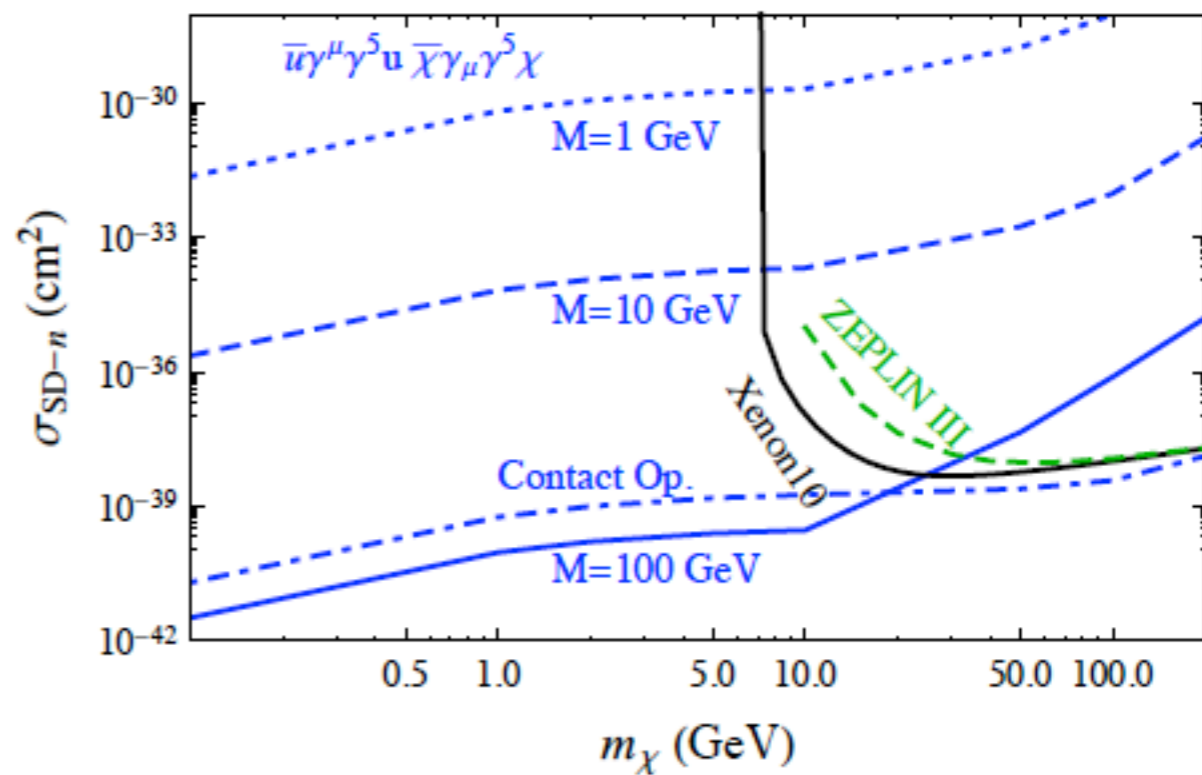
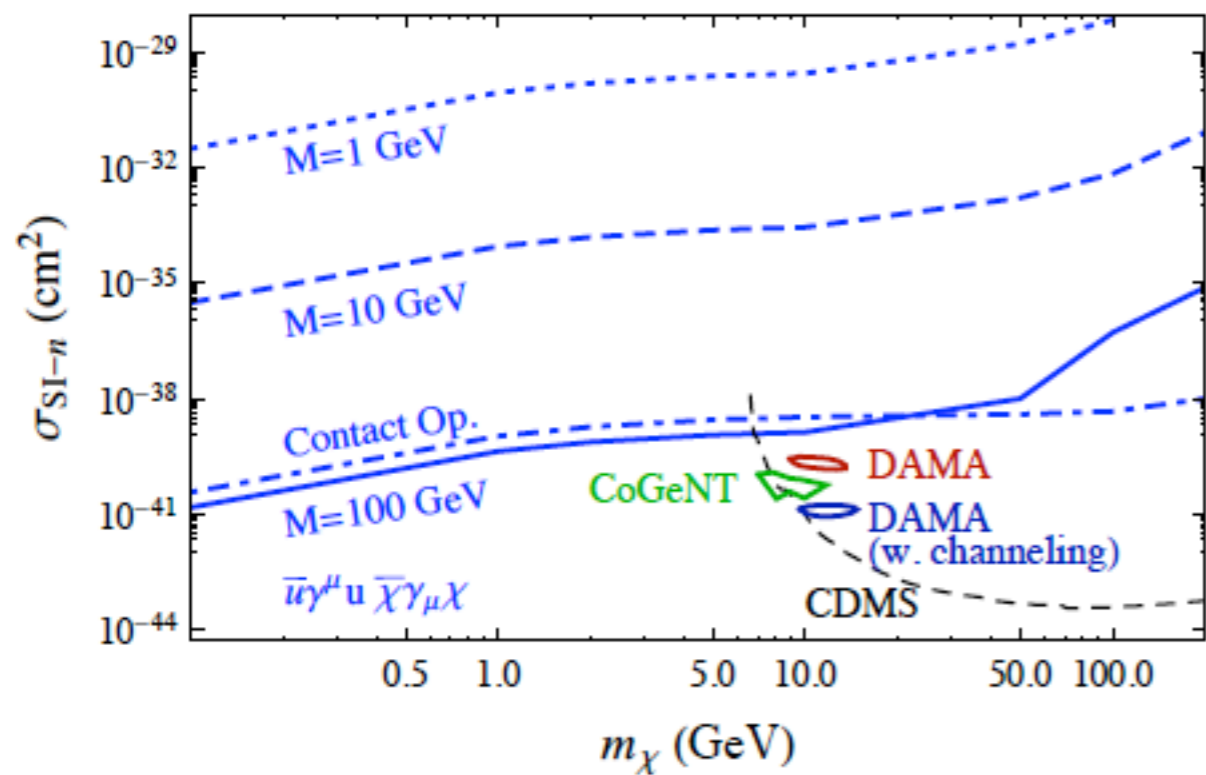


Figure 5: Left panel: constraints on the spin-independent DM-neutron scattering cross sections for different mediator masses. Right panel: the same as the left panel but for the constraints on the spin-dependent DM-neutron scattering cross section.

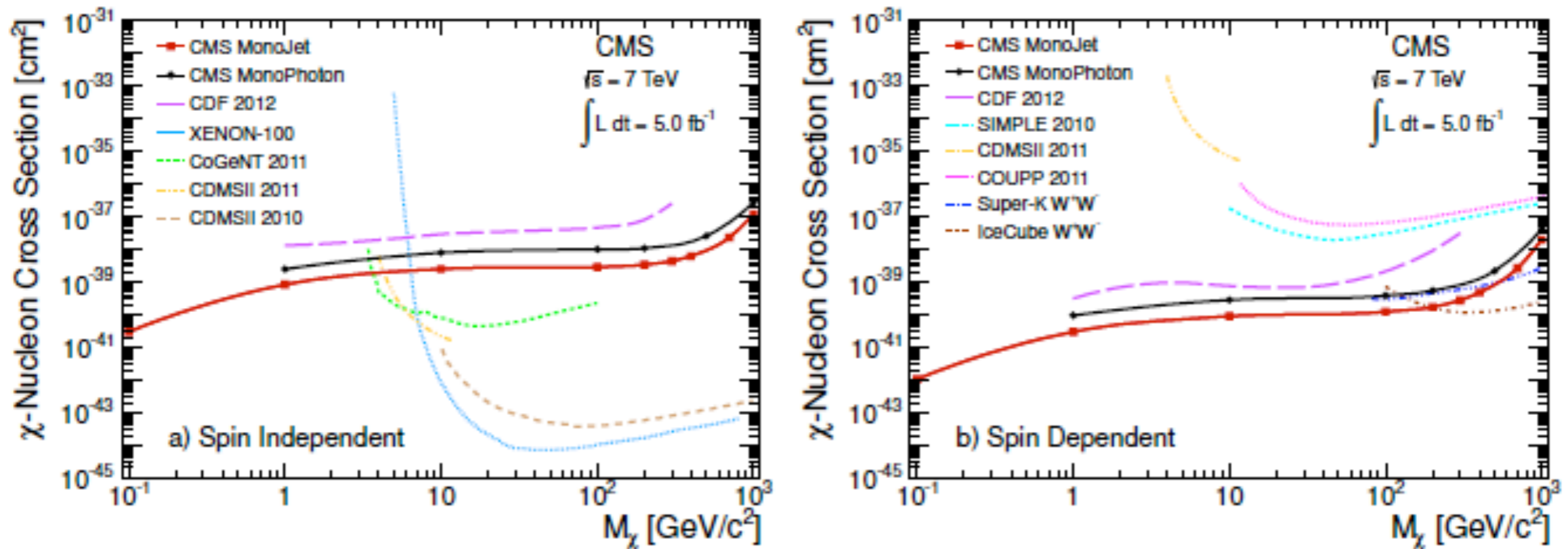
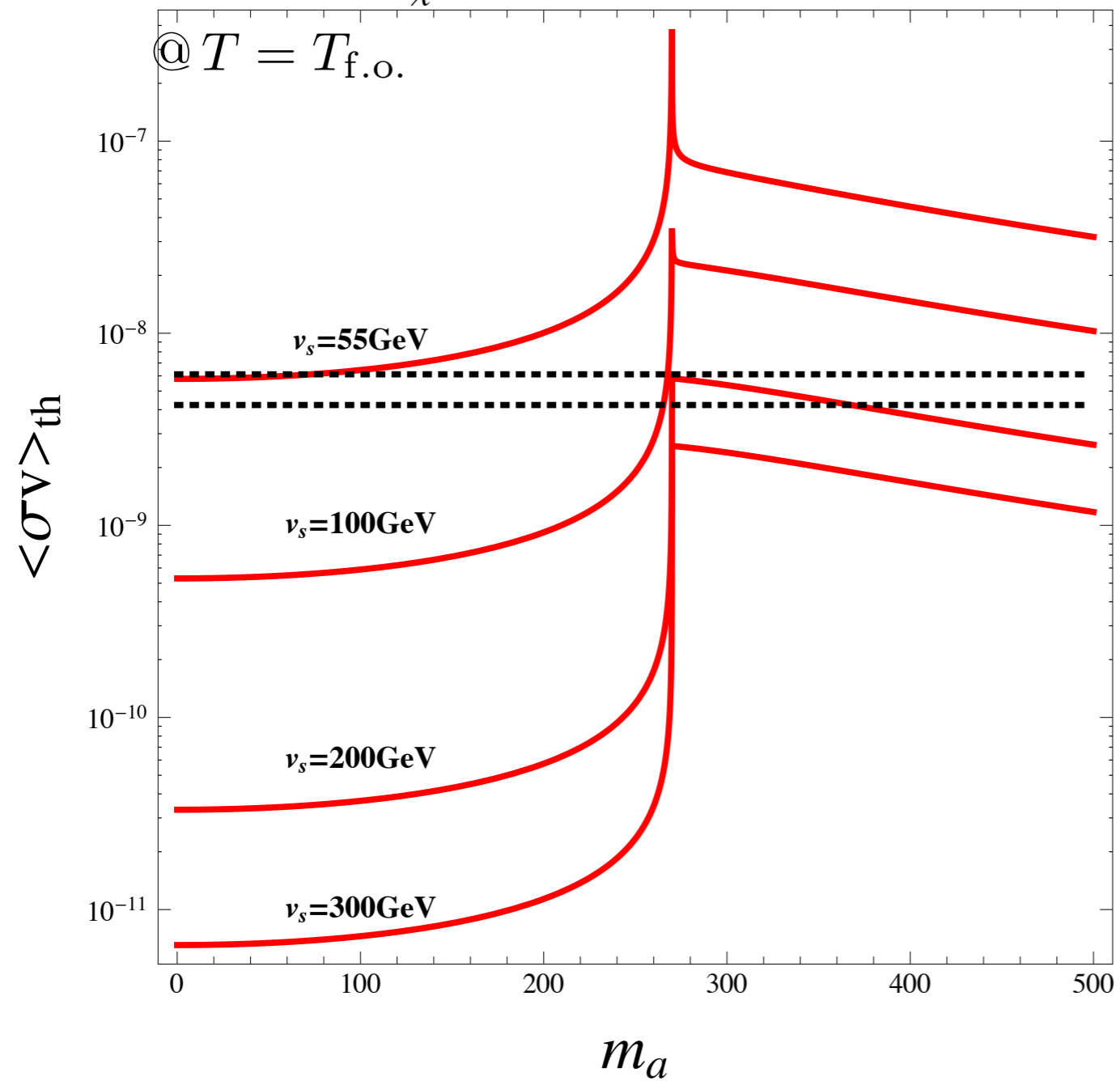
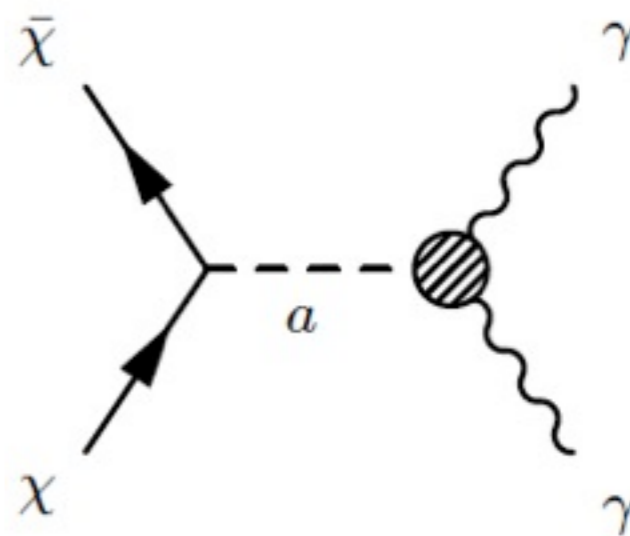


Figure 4: Comparison of the 90% CL upper limits on the dark matter-nucleon scattering cross section versus mass of dark matter particle for the (left) spin-independent and (right) spin-dependent models with results from CMS using monophoton signature [14], CDF [15], XENON100 [16], CoGeNT [17], COUPP[18], CDMS II [19, 20], Picasso [21], SIMPLE [22], Ice-Cube [23], and Super-K [24] collaborations.

$$m_\chi = 135 \text{ GeV}, c_1 = 1, c_2 = 3$$



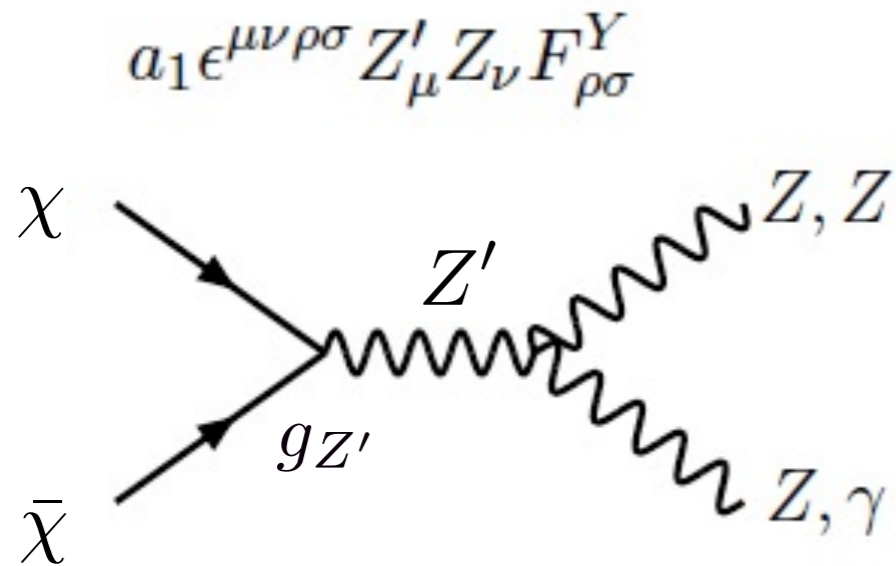
WMAP



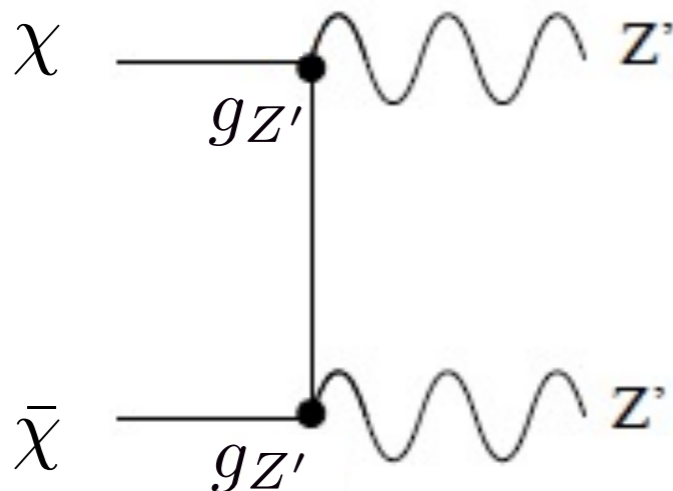
# Z'-portal

Gamma-ray line:

Chern-Simons coupling:



Relic density:



[ Jackson et al (2009,2013); Dudas et al (2012); Lee, Park, VS (2012) ]

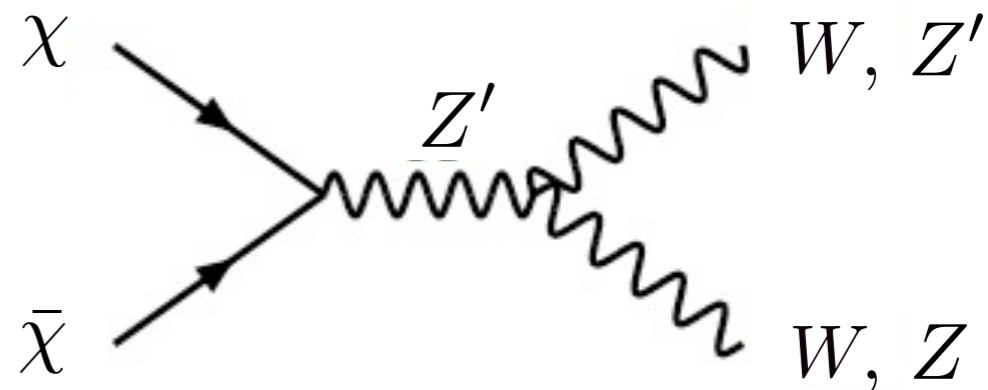
CS couplings are generated by heavy charged fermions:

$$D^\mu \theta_X \left[ i(D^\nu H)^\dagger (c_1 \tilde{F}_{\mu\nu}^Y + c_2 \tilde{F}_{\mu\nu}^W + c_3 \tilde{F}_{\mu\nu}^X) H + c.c. \right]$$

$$D_\mu \theta_X \equiv \partial_\mu \theta_X - g_X Z'_\mu$$

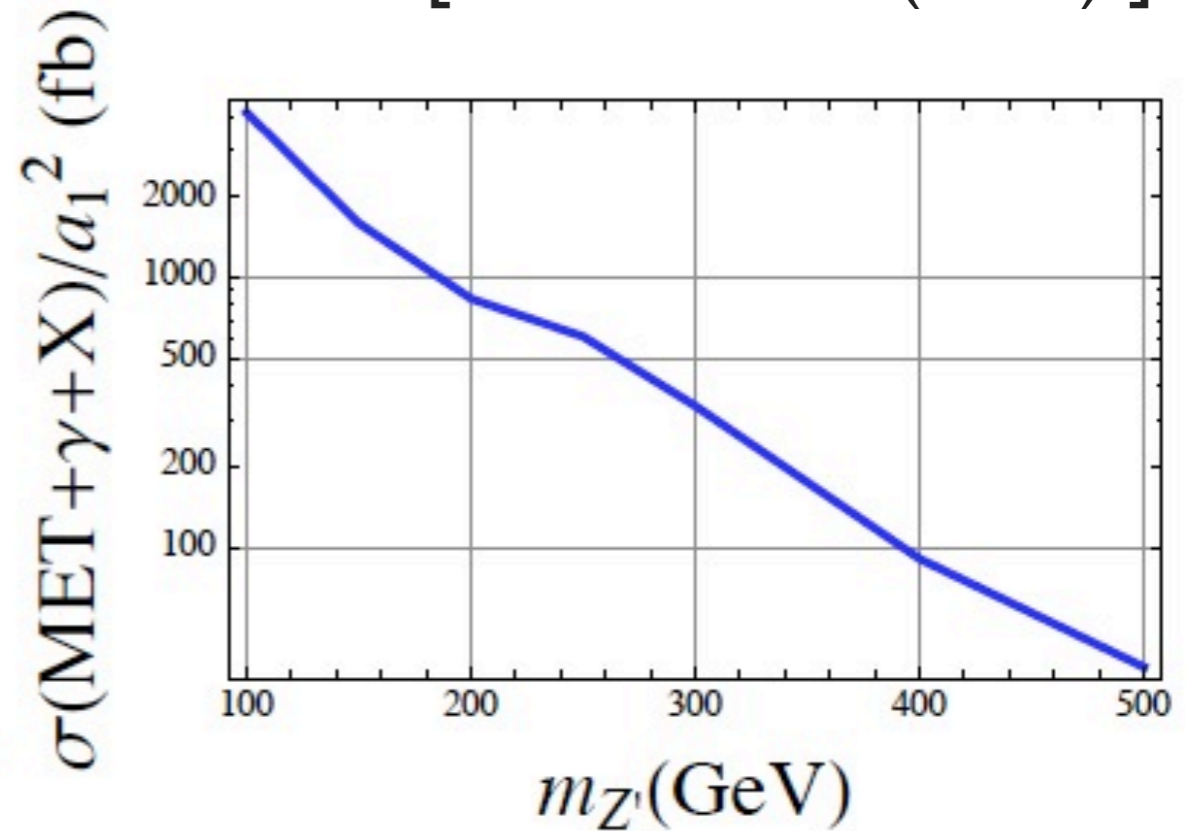
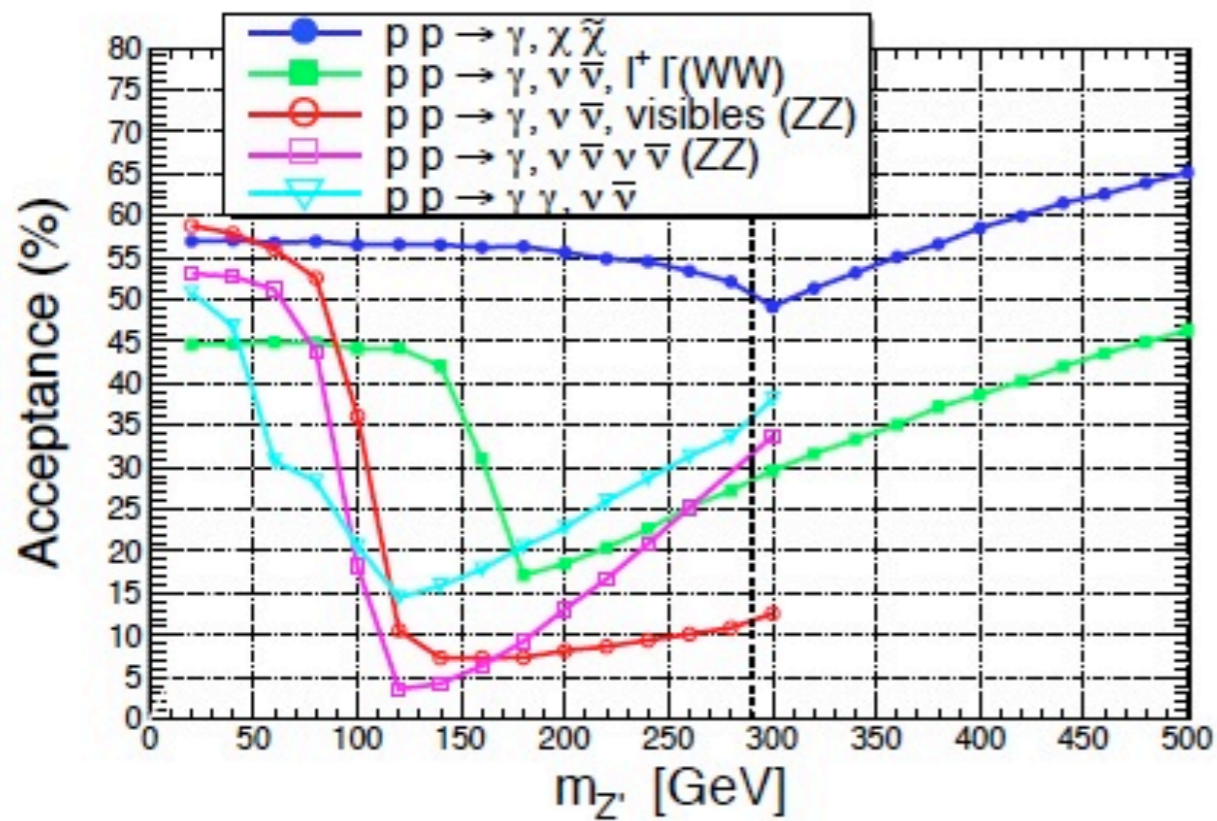
➔  $\frac{v^2}{M^2} \epsilon^{\mu\nu\rho\sigma} Z'_\mu B_\nu F_{\rho\sigma}^Y$

Landau-Yang theorem: no  $\gamma\gamma$  for on-shell vector  $Z'$ .



# Z' with monophoton

[ Lee, Park, VS (2012) ]



- Cross section:  $\sigma \sim 6.4 \text{ fb}$  for  $a_1 \sim 0.04$  @  $m_{Z'} = 100 \text{ GeV}$ .

- Efficiencies for monophoton + MET + X:

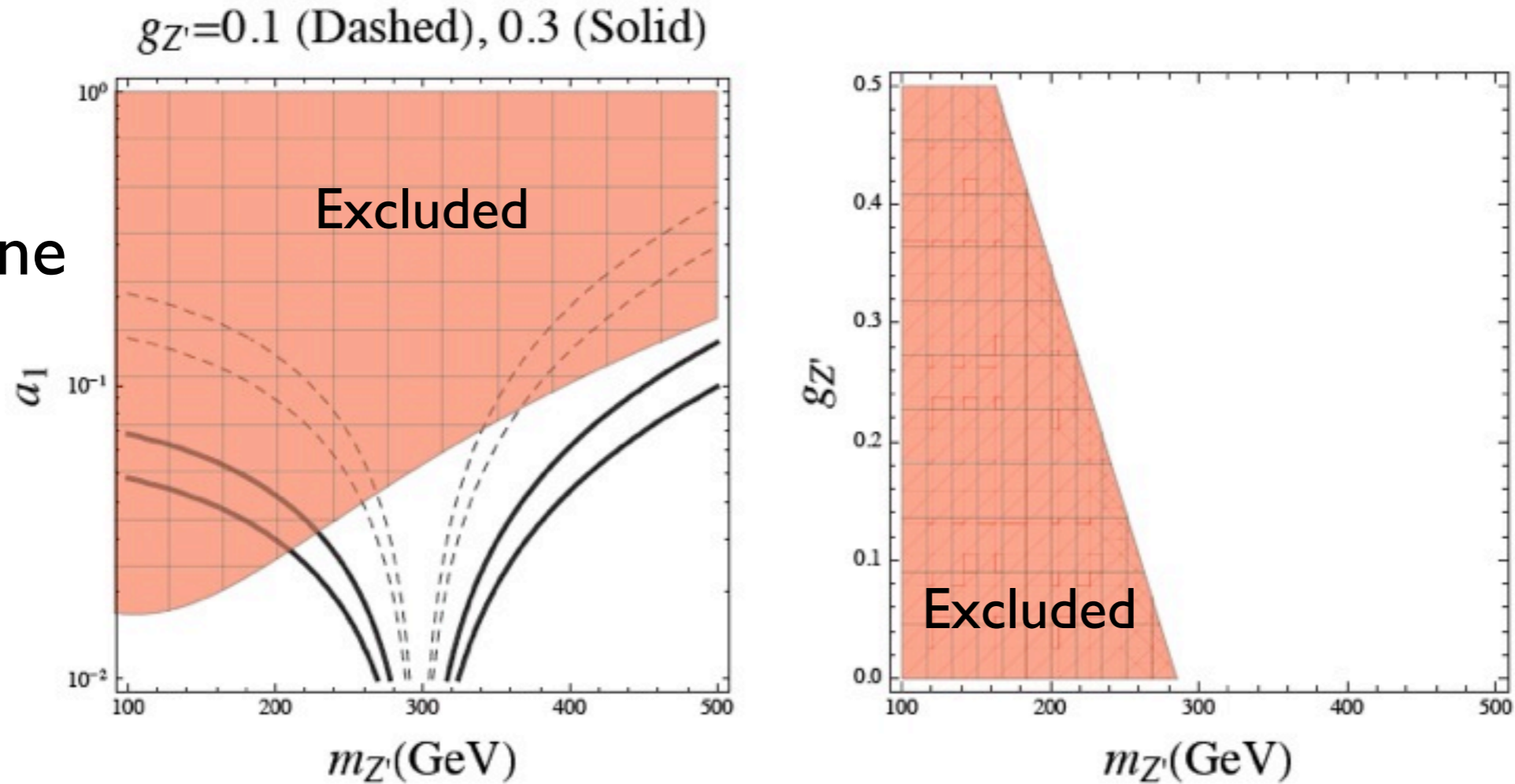
Above threshold: **50-65% (DM pair)**

Below threshold: **30-50% x Br(Z → νν) (total)**

[Feynrules + Madgraph + PHYTHIA + Delphes + ROOT(cut)]

# Bounds on $Z'$

lines:  
Fermi line



- $\text{Br}(Z' \rightarrow \chi\bar{\chi})=1$  assumed above threshold.
- Cross section limit scales up with extra channel.

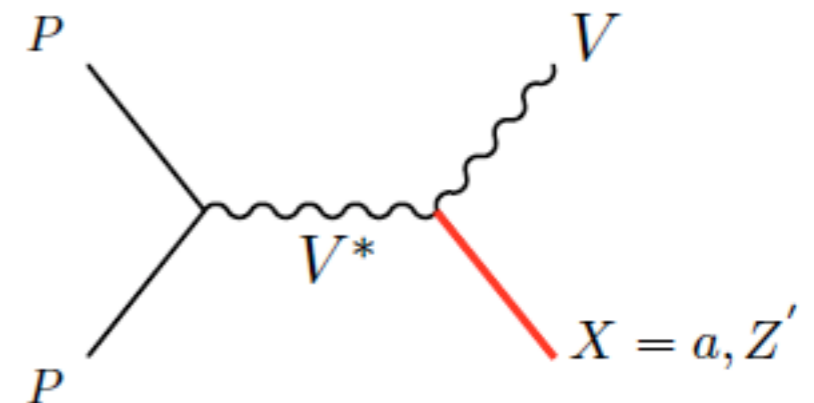
$$\sigma_{\text{eff}}(pp \rightarrow \gamma + \text{MET} + X) = \sigma(pp \rightarrow \gamma Z') \cdot \frac{\text{Acc}(\chi\bar{\chi}) + r \text{Acc}(WW)}{1 + r} \mathcal{E}$$

$$r = \frac{\Gamma_{Z'}(WW)}{\Gamma_{Z'}(\chi\bar{\chi})} \sim 1 : \mathcal{E} = 39 - 56\%$$

# DM ann. $\leftrightarrow$ Med. prod.

## Associated production

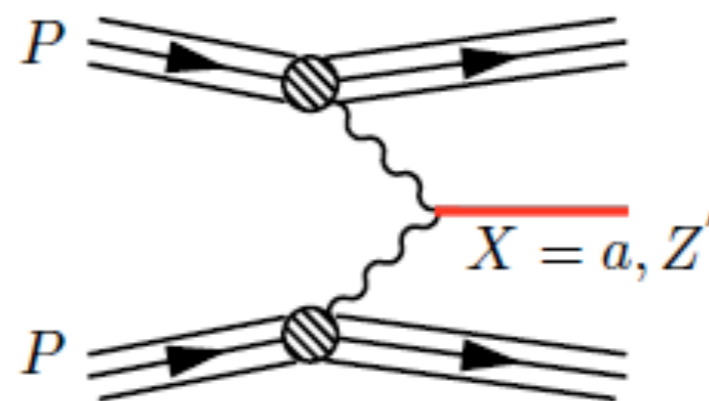
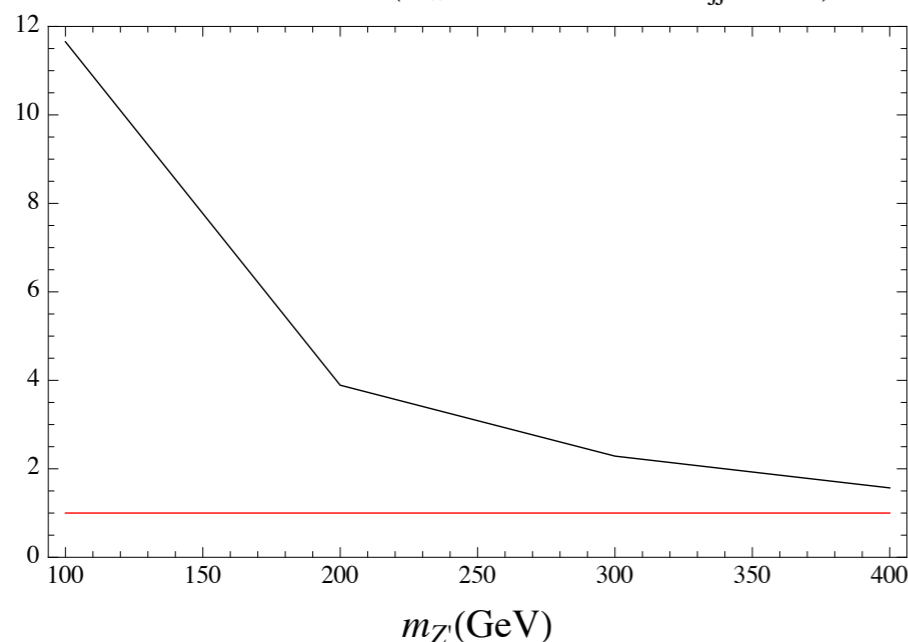
$$\langle \sigma v \rangle_{\gamma\gamma} = \frac{|\lambda_\chi|^2 |c_{\gamma\gamma}|^2}{2\pi} \cdot \frac{16m_\chi^4}{(4m_\chi^2 - m_a^2)^2 + \Gamma_a^2 m_a^2}$$



$$\leftrightarrow \sigma(q\bar{q} \rightarrow a\gamma) = \frac{2\alpha}{3N_c} \left[ 4Q_q^2 c_{\gamma\gamma}^2 + \frac{(v_q^2 + a_q^2) c_{Z\gamma}^2}{\sin^2(2\theta_W)} \frac{s^2}{(s - m_Z^2)^2 + \Gamma_Z^2 m_Z^2} + \frac{4Q_q v_q c_{\gamma\gamma} c_{Z\gamma}}{\sin(2\theta_W)} \frac{s(s - m_Z^2)}{(s - m_Z^2)^2 + \Gamma_Z^2 m_Z^2} \right] \left(1 - \frac{m_a^2}{s}\right)^3$$

## Vector-boson fusion

$$\frac{\sigma(pp \rightarrow (Z, \gamma)^* \rightarrow (\gamma, Z) Z')}{\sigma(pp \rightarrow Z' jj) (m_{jj} > 400 \text{ GeV}, \Delta y_{jj} > 2.8)}$$



- VBF production is sub-dominant. Focus on associated production.

