Inelastic Dark Matter at the LHC

Yang Bai

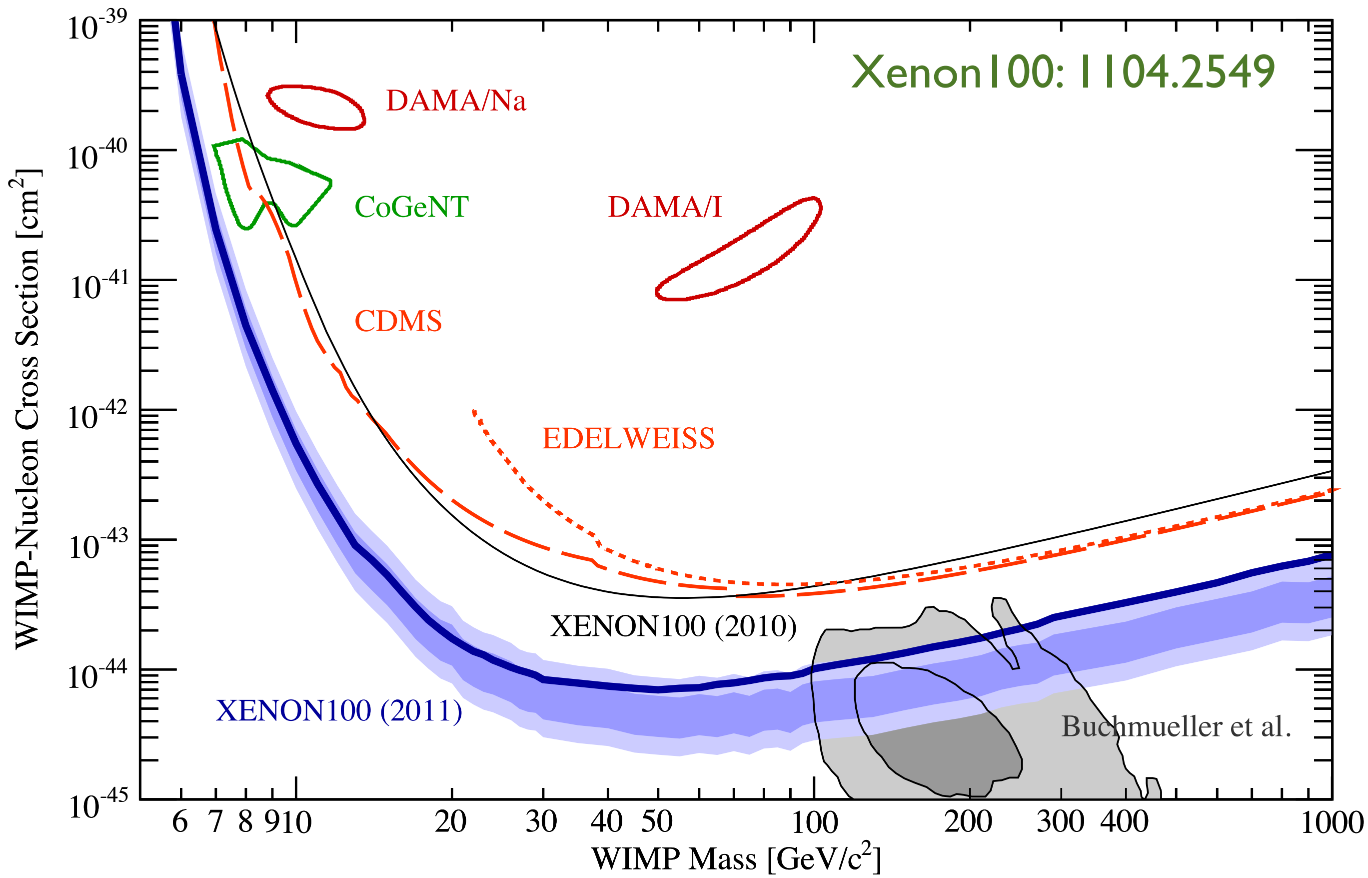
Theoretical Physics Group, SLAC

working in progress with Tim Tait

May 9, Pheno 2011 symposium

Outline

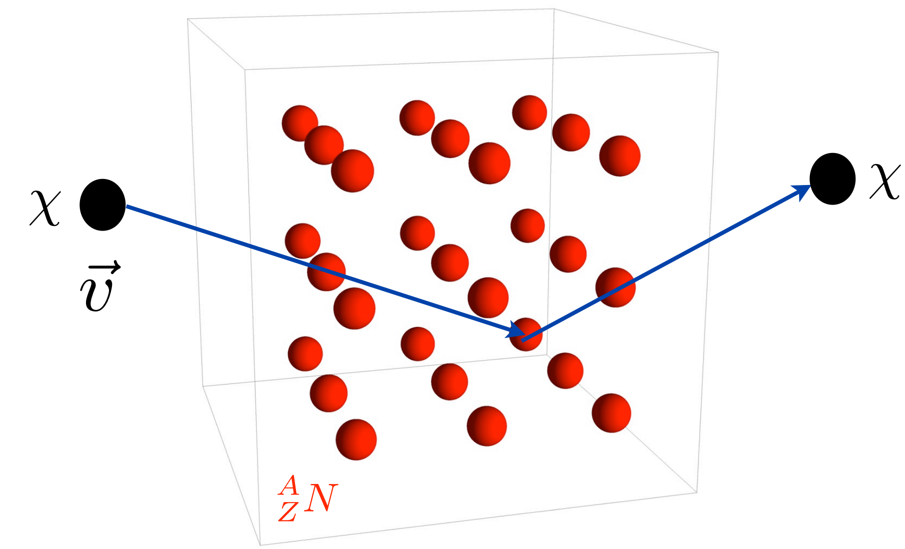
- Motivation for a general IDM model
- Signatures at the LHC
- One case study at the 7 TeV LHC
- Conclusions



Two plausible options:

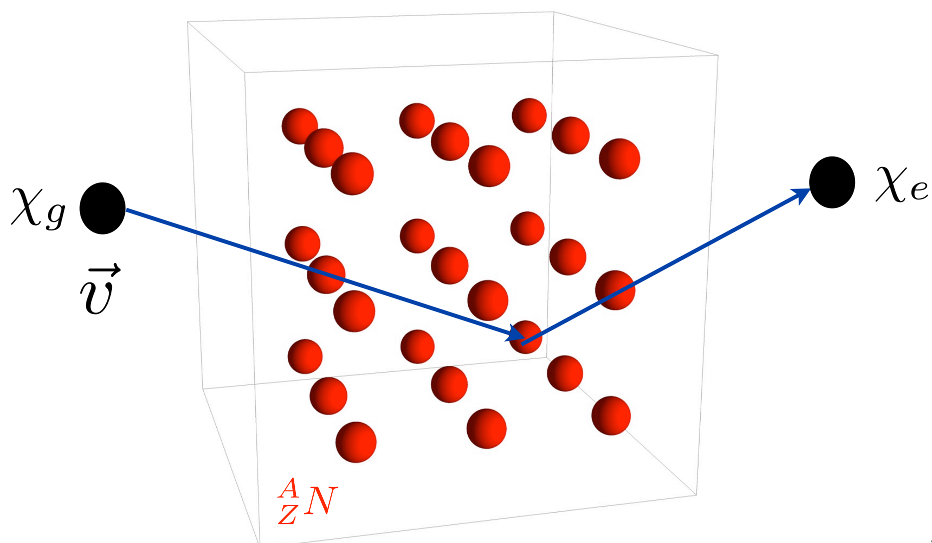
- Dark matter has a small interaction strength with SM particles
- the interaction strength is large, but kinematics forbids dark matter discovery in direction detection experiments

For elastic DM-nucleus scattering, the kinetic energy of dark matter is



$$E_{\rm kin} = \frac{1}{2} m_\chi v^2 \sim 100 \text{ keV}$$

The direct detection may have no hope, if dark matter has two states with a large mass splitting and the scattering is always inelastic



$$\Delta \equiv m_{\chi_e} - m_{\chi_g} \geq 1 \text{ MeV} > E_{\rm kin}$$

no signal at direct detection

However, the LHC may produce those two states at the same time and test a general iDM model with a large mass splitting

iDM models:

Hall, Moroi, Murayama, hep-ph/9712515

Tucker-Smith, Weiner, hep-ph/0101138

Perform our studies in a model-independent way:

$$\frac{\bar{u}\,\gamma_\mu\gamma_5\,u\,\bar{\chi}_e\,\gamma^\mu\gamma_5\,\chi_g}{\Lambda^2} \qquad \frac{\bar{u}\,\gamma_5\,u\,\bar{\chi}_e\,\gamma_5\,\chi_g}{\Lambda^2} \qquad \frac{\bar{u}\,\gamma_\mu\,u\,\bar{\chi}_e\,\gamma^\mu\,\chi_g}{\Lambda^2} \qquad \frac{\bar{u}\,u\,\bar{\chi}_e\,\chi_g}{\Lambda^2}$$

Three parameters: Λ $\quad m_{\chi_e}$ $\quad \Delta \equiv m_{\chi_e} - m_{\chi_g}$

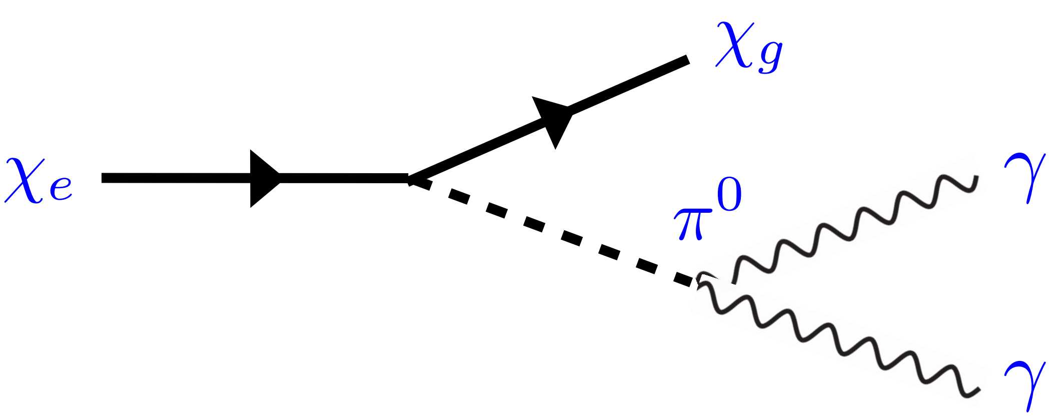
The discovery limits at the LHC depend on all of them

The ground state is purely stable and is the dark matter particle

The excited state is not stable and decays into the ground state plus other SM particles

$$\frac{\bar{u}\,\gamma_\mu\gamma_5\,u\,\bar{\chi}_e\,\gamma^\mu\gamma_5\,\chi_g}{\Lambda^2} \qquad i\bar{u}\gamma^\mu\gamma_5 u \to \frac{1}{2}F_\pi\partial^\mu\pi^0 \qquad F_\pi = 184\ \mathrm{MeV}$$

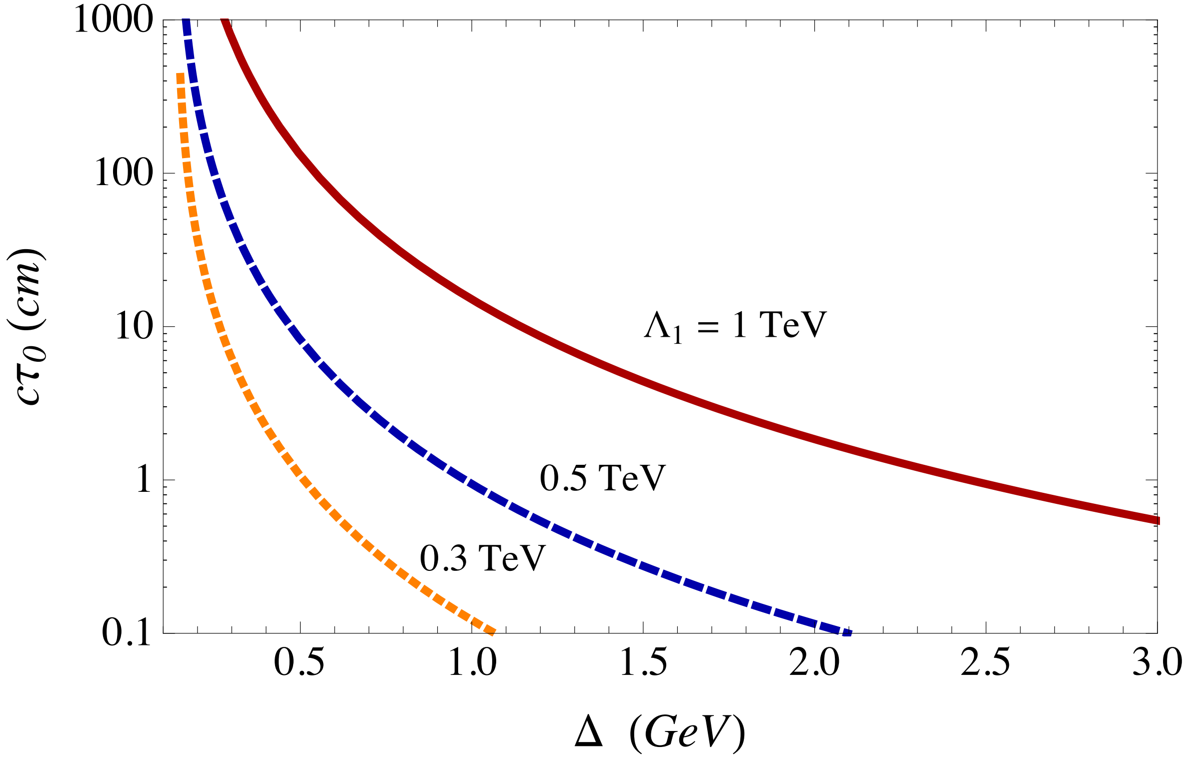
$$\frac{-i}{2}F_\pi\partial^\mu\pi^0\,\frac{\bar{\chi}_e\,\gamma^\mu\gamma_5\,\chi_g}{\Lambda^2} \longrightarrow \frac{F_\pi\,(m_{\chi_e}+m_{\chi_g})}{2\,\Lambda^2}\,\pi^0\,\bar{\chi}_e\,\gamma_5\,\chi_g$$



$$\Gamma_0(\chi_e \to \chi_g + \pi^0)$$

$$= \frac{F_\pi^2}{\Lambda^4}\,\frac{(\Delta^2 - m_{\pi^0}^2)^{3/2}}{8\,\pi}$$

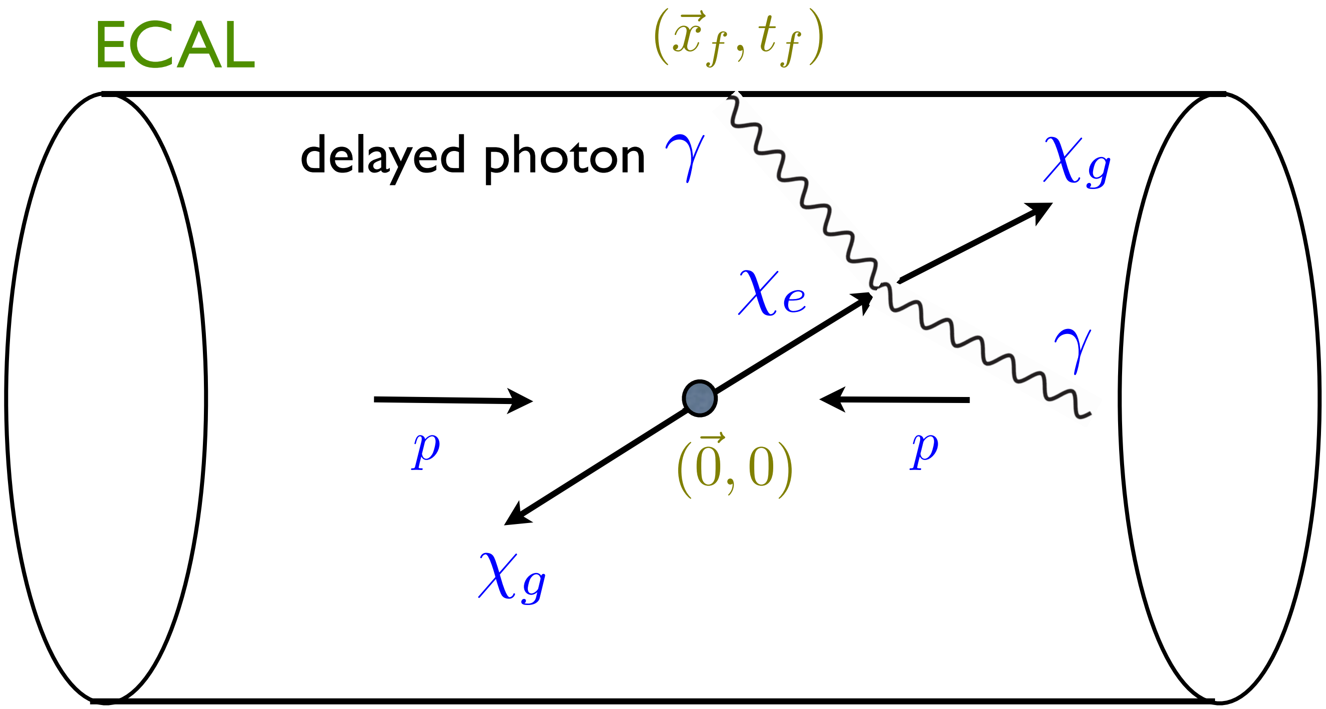
Consider the case of two-body decays for the excited state $\Delta > m_{\pi^0}$



The excited state has a long lifetime from the collider point of view

The photons from the subsequent decays should be different from the photons from the SM processes: the signatures could be

Non-pointing photons displaced neutral pions



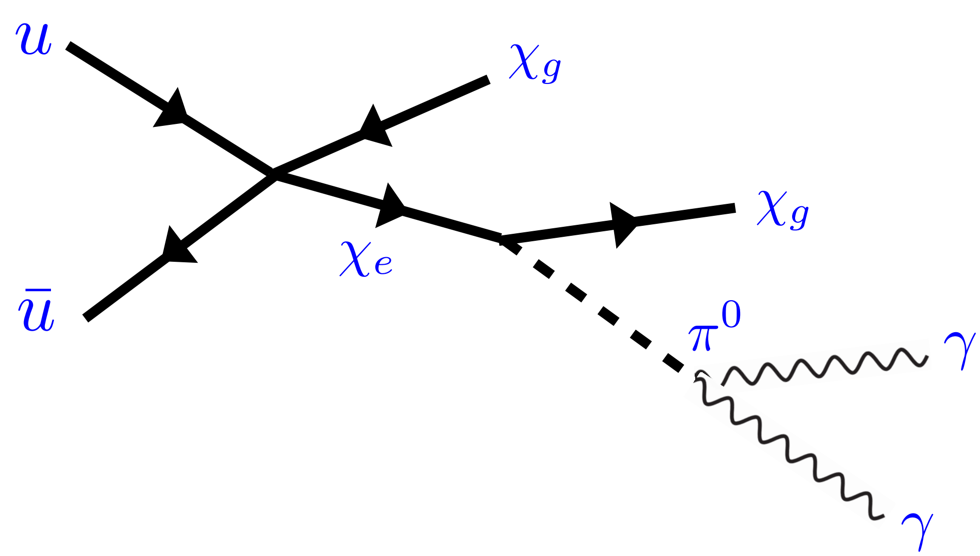
$$t_{\rm corr} \equiv t_f - \frac{\vec{x}_f}{c}$$

the photon arrival time corrected for the collision time and time-of-flight

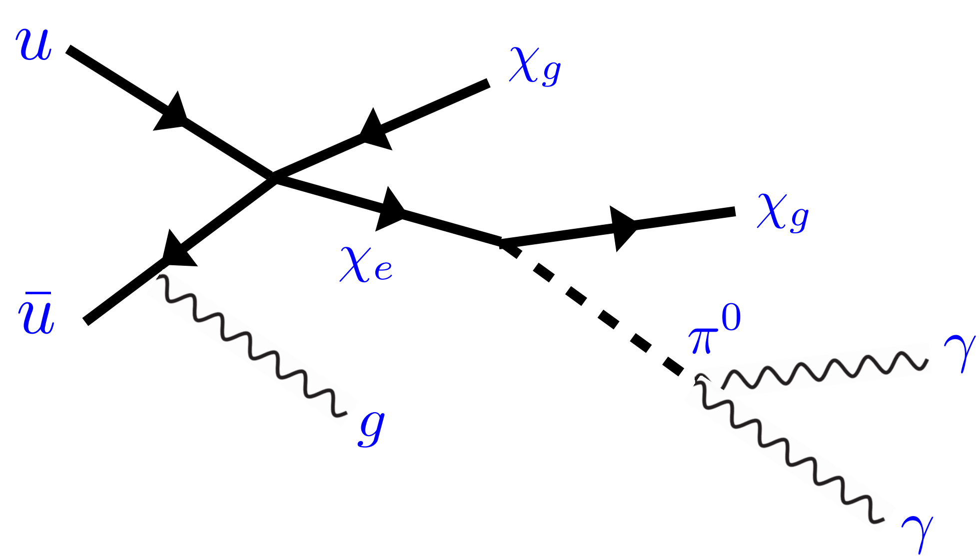
For a delayed photon: $t_{\rm corr} > 0$

For a prompt photon: $t_{\rm corr} = 0$

a similar signature exists in GMSB models: $\tilde{\chi}^0 \to \gamma\,\tilde{G}$



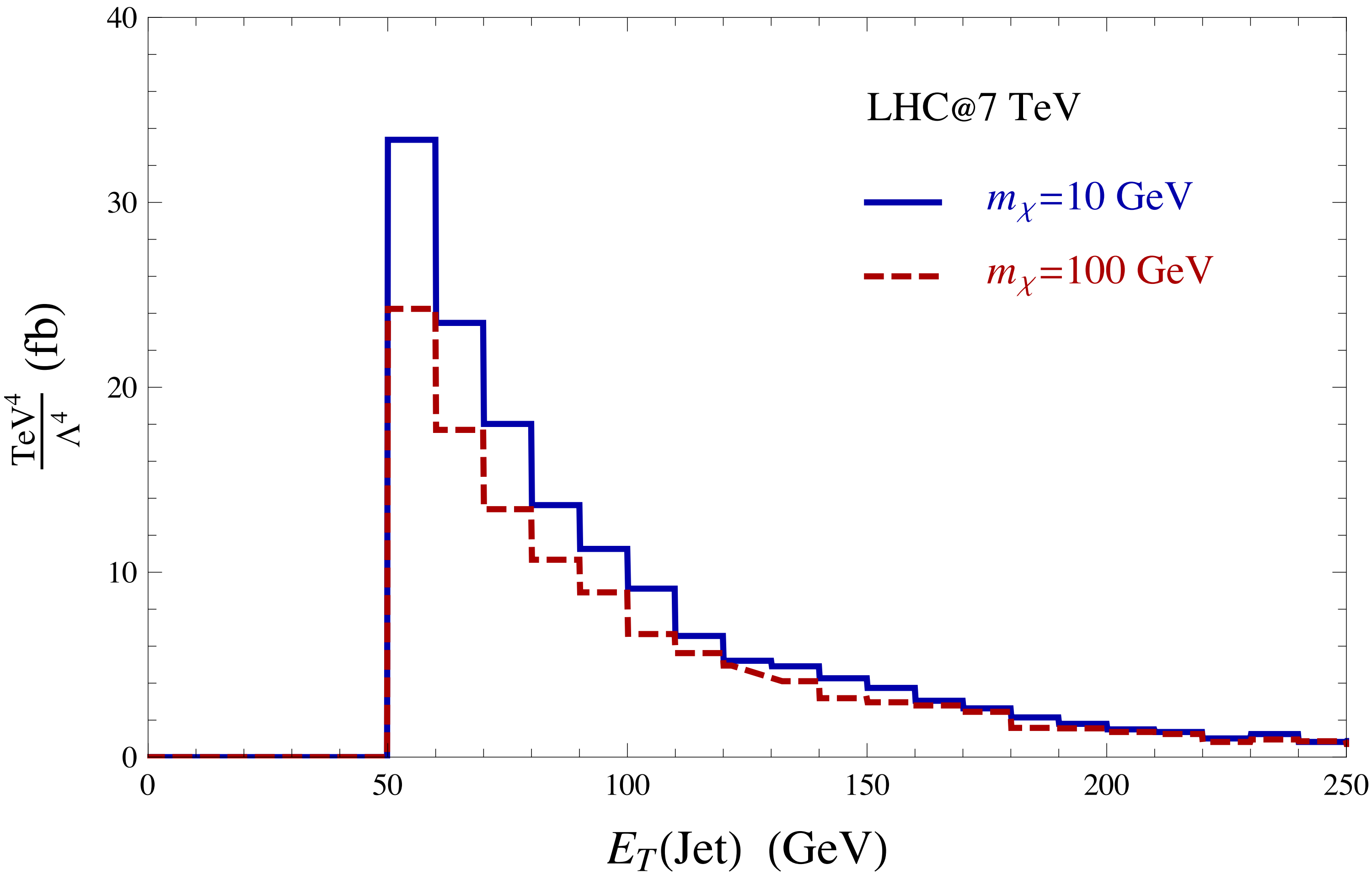
However, the photons are too soft, because their transverse momenta are related to the mass splitting, which is below 10 GeV



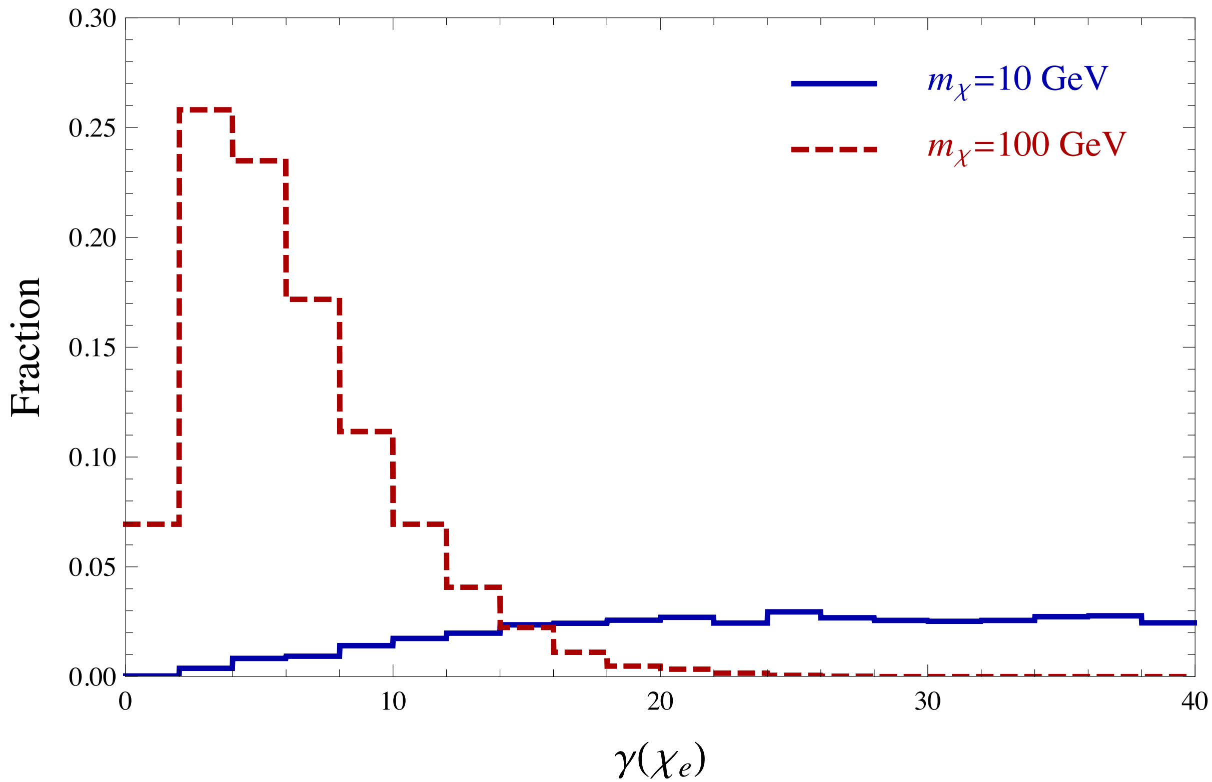
Fortunately, we can use the initial state radiation to boost final state particles

The boost can also make the excited state live longer due to time dilation

$pp \to \bar{\chi}_e \, \chi_g \, + \, g$



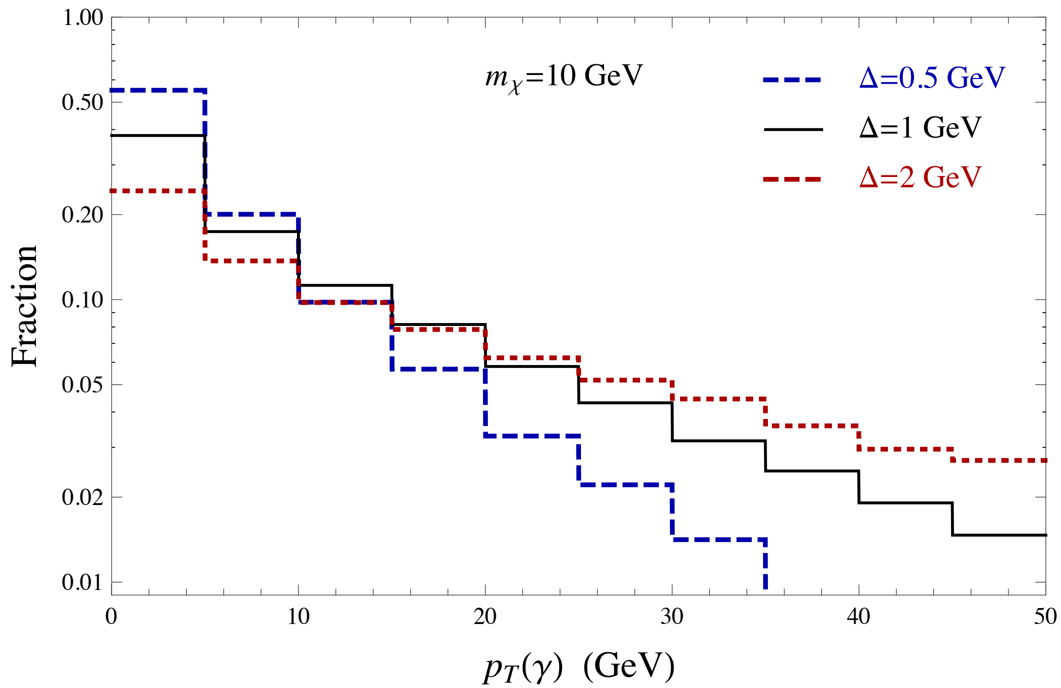
simulated at the parton level



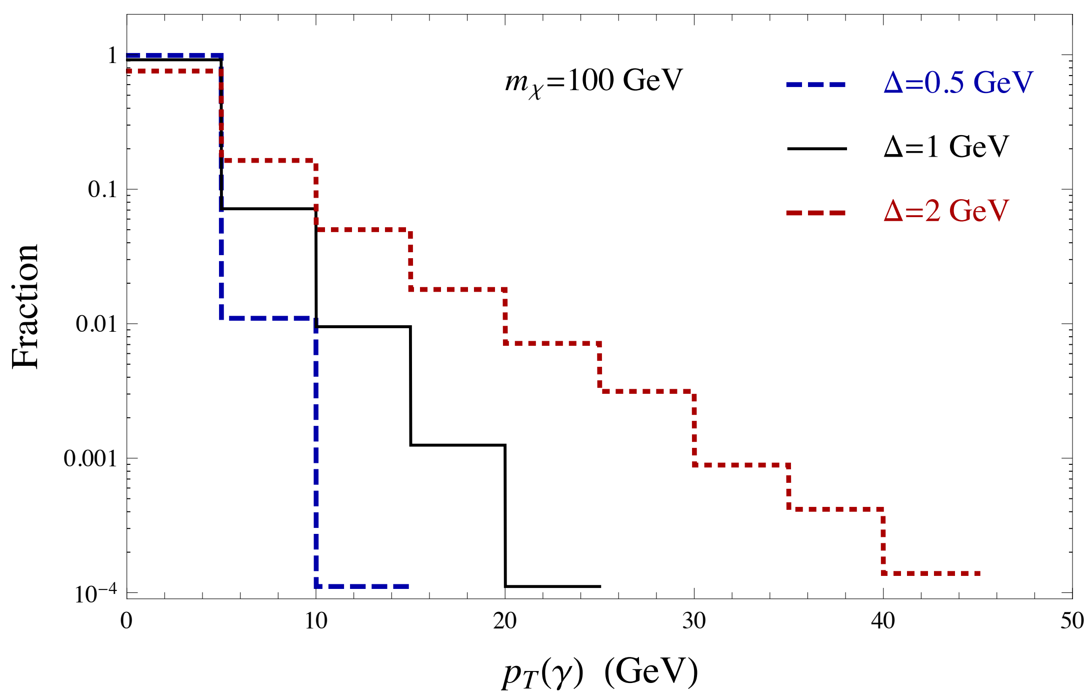
For a lighter dark matter particle below 100 GeV, its Lorentz boost can be easily a factor of 10

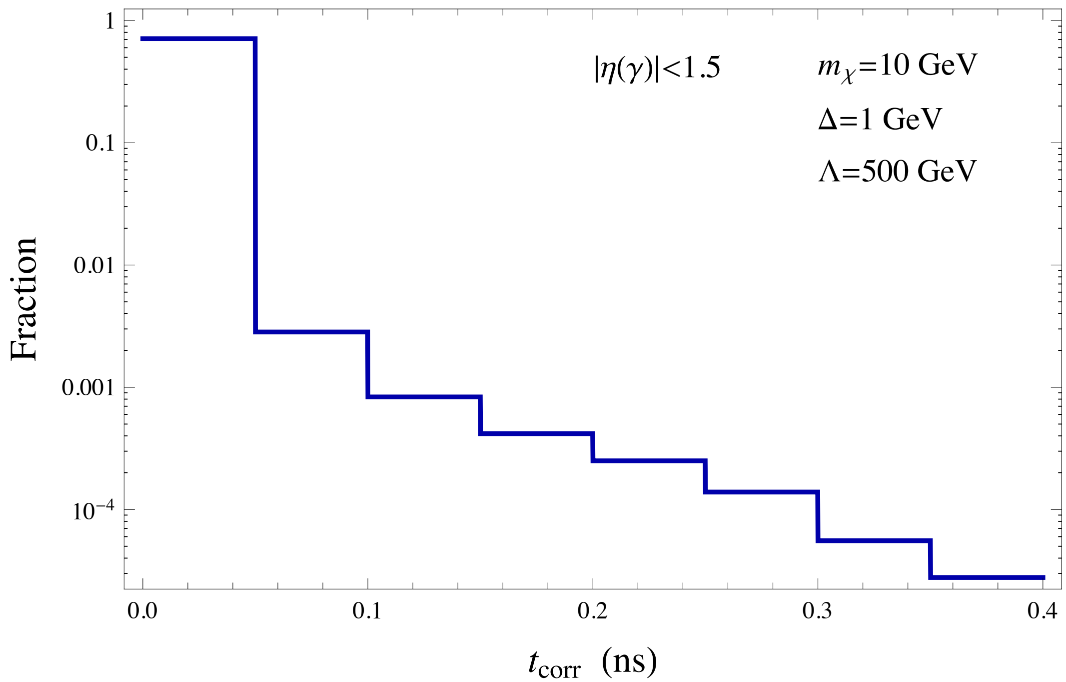
$$c\,\tau = \gamma\, c\,\tau_0$$

the excited dark matter travels even a longer distance before decay



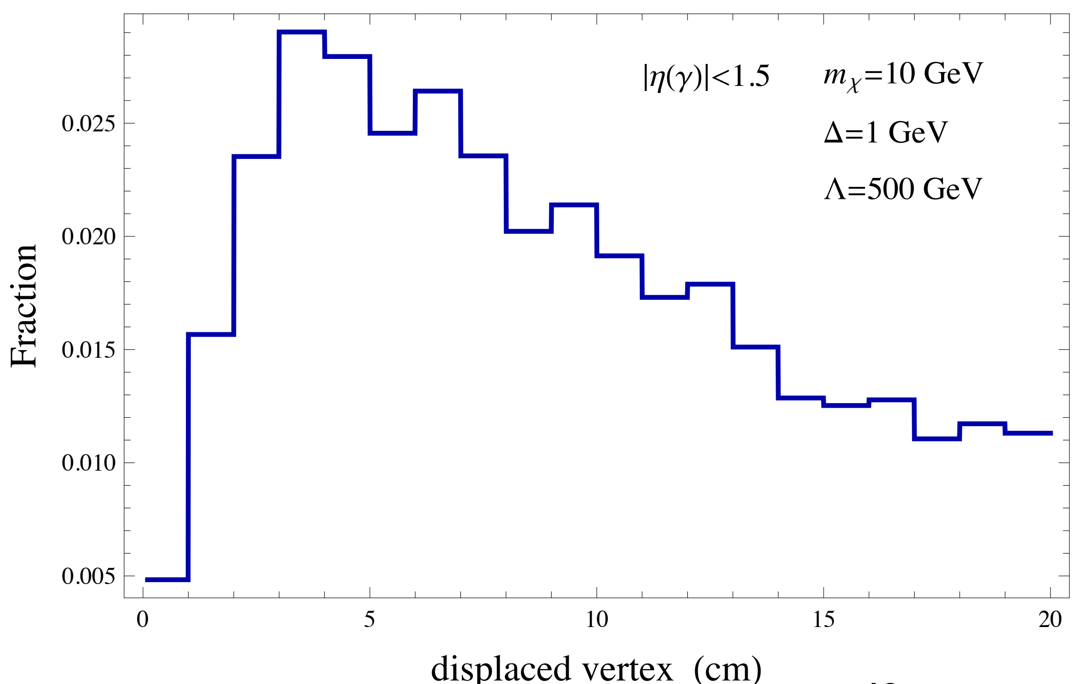
for pT(photon) > 20 GeV, the acceptance is a few percent





SM backgrounds can also have tcorr up to one ns

tcorr is not a good variable for the iDM model, as opposite to the GMSB model



requiring the displaced vertex above one cm and the photon pT above 30 GeV, one can have 5 events/fb^-1 at the 7 TeV LHC

the detailed discovery limit requires more careful studies

Conclusion

- An inelastic dark matter model with a large mass splitting above 1 MeV may only be tested at colliders.
- Its signatures at the LHC could be one jet + missing energy + displaced neutral pion.
- The traditional non-pointing photon studies for GMSB can not capture this signature.
- The discovery limit is promising even for the 7 TeV LHC.

Thanks