Nonstandard Dark Matter Signatures at the LHC

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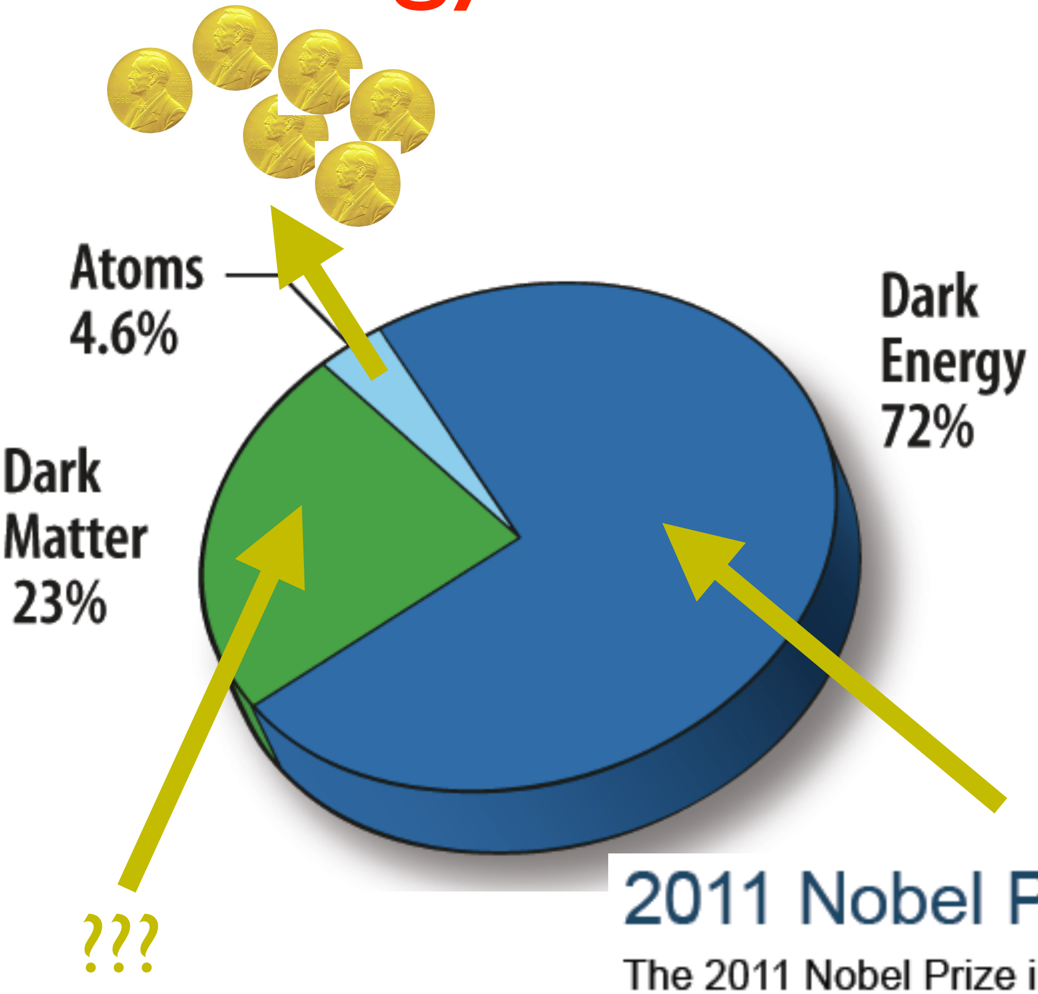
Outline

- Introduction about dark matter phenomenologies
- Effective field theory approaches to dark matter
- Inelastic dark matter models
- Strongly interacting dark matter models
- Signatures of those models at colliders
- Conclusions

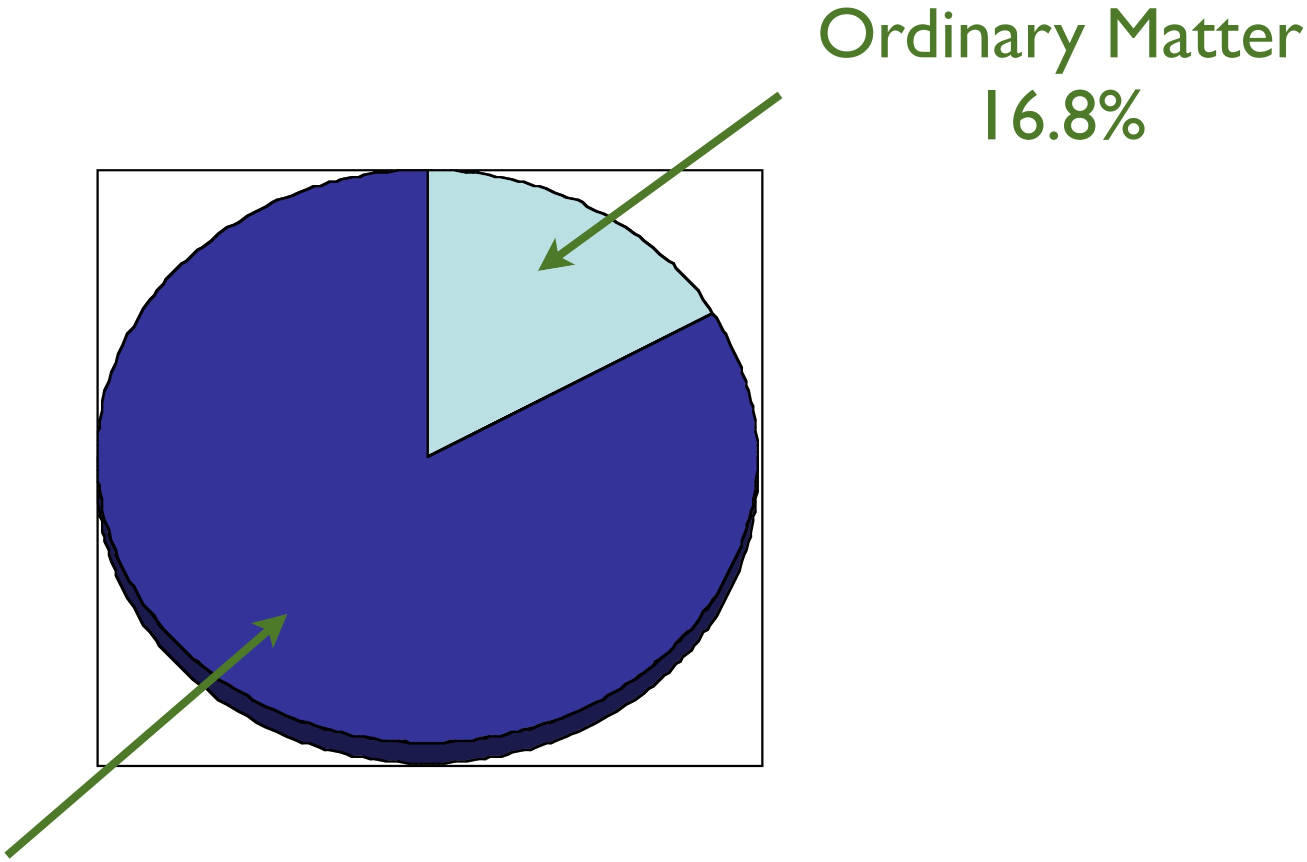
Energy Pie of Our Universe



2011 Nobel Prize in Physics

The 2011 Nobel Prize in Physics is awarded "*for the discovery of the accelerating expansion of the Universe through observations of distant supernovae*" with one half to Saul Perlmutter and the other half jointly to Brian P. Schmidt and Adam G. Riess.

Matter Pie of Our Universe

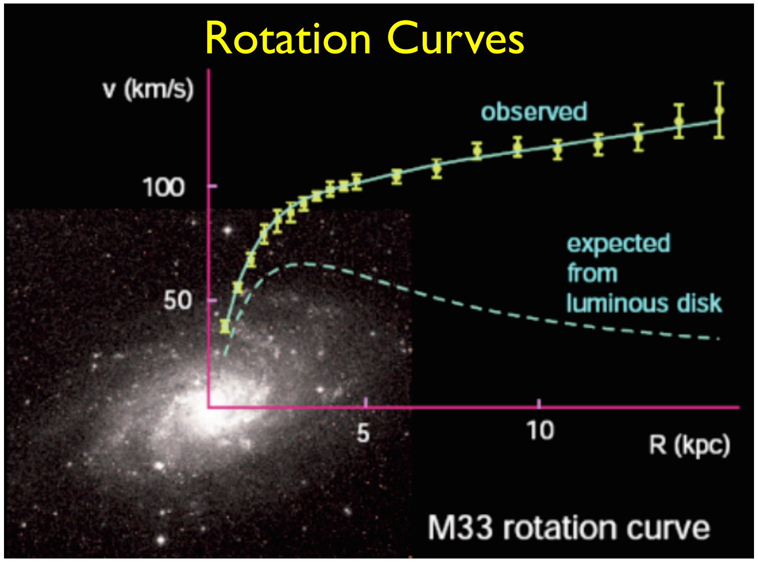


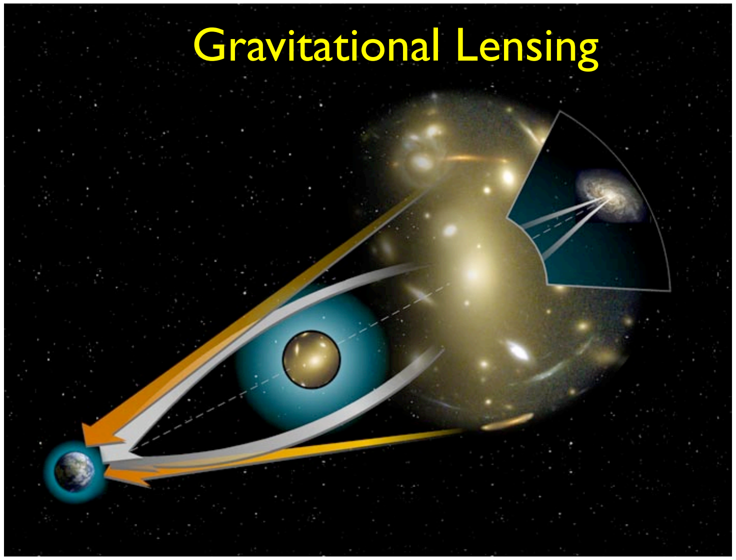
Ordinary Matter
16.8%

Dark Matter 83.2%

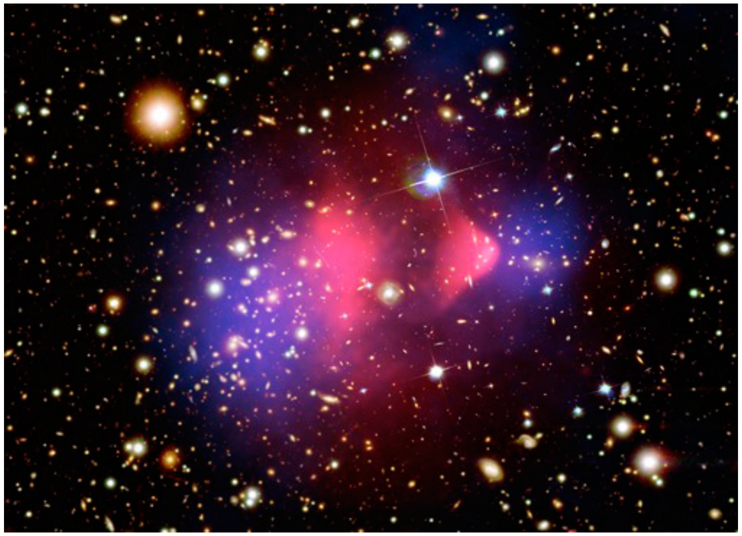
From WMAP

Evidence of Dark Matter





The Bullet Cluster

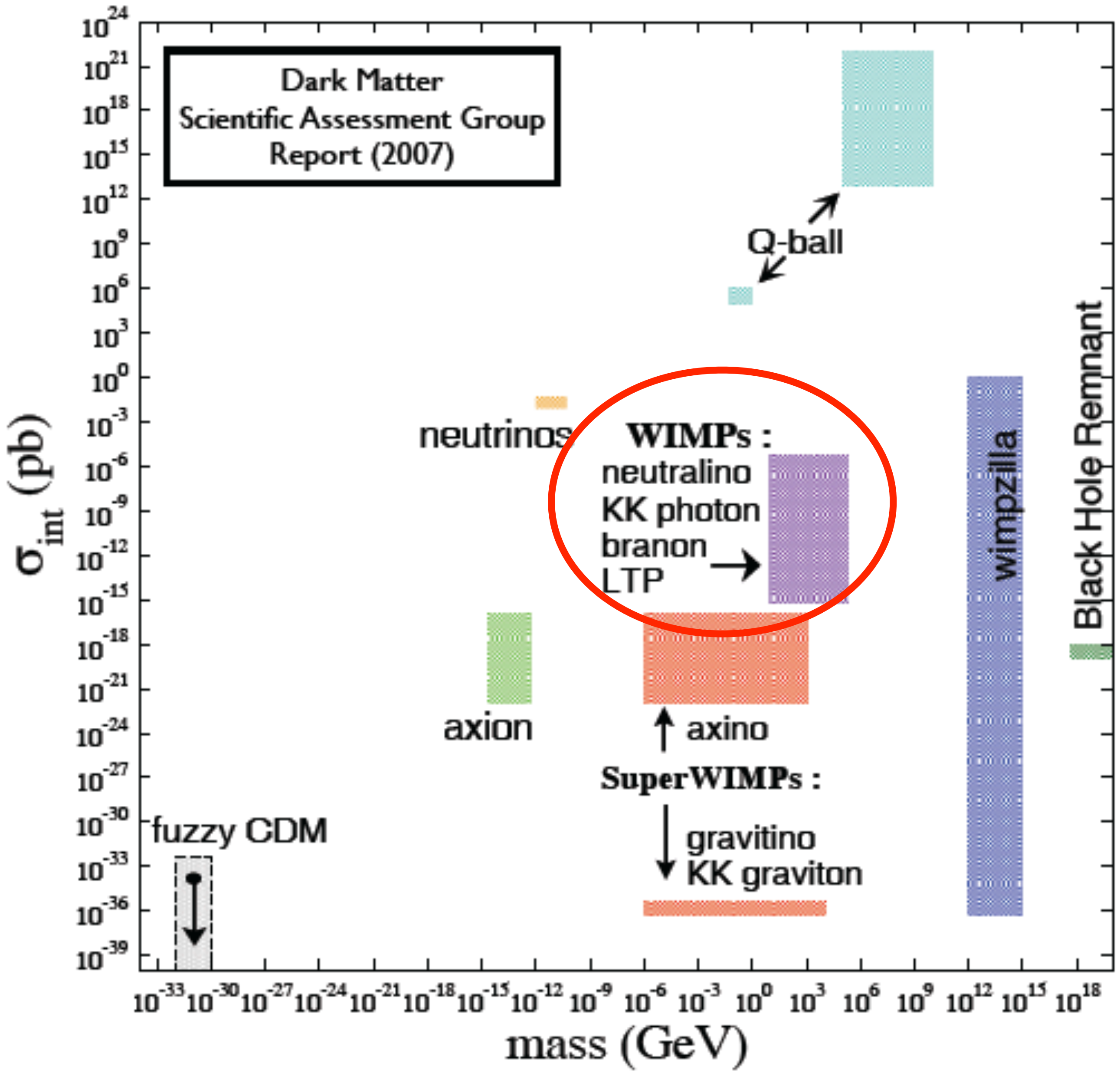


$$\frac{\sigma_{\chi\chi}}{m_\chi} \leq \frac{1200 \text{ mb}}{1 \text{ GeV}}$$

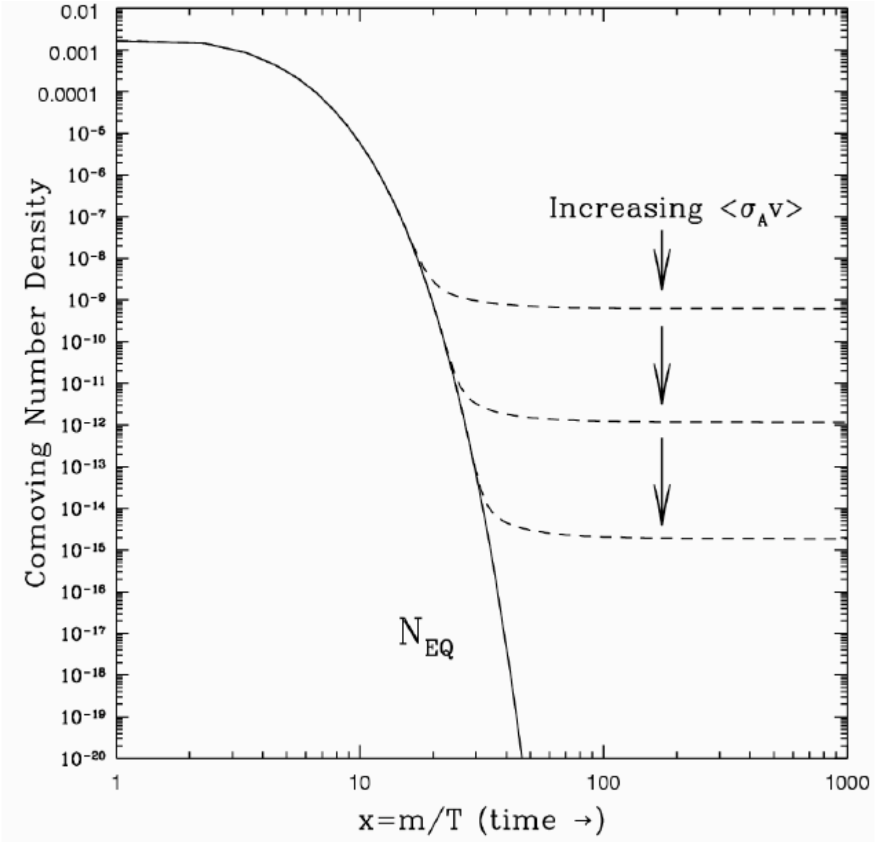
J. L. Feng, 1003.0904

$$\sigma_{pp} \sim 40 \text{ mb}$$

Candidates of Dark Matter



The WIMP “Miracle”



$$\boxed{\Omega_{\rm DM} \sim \langle \sigma_A v \rangle^{-1} \quad + \quad \langle \sigma_A v \rangle \sim \frac{\alpha^2}{m_\chi^2}}$$

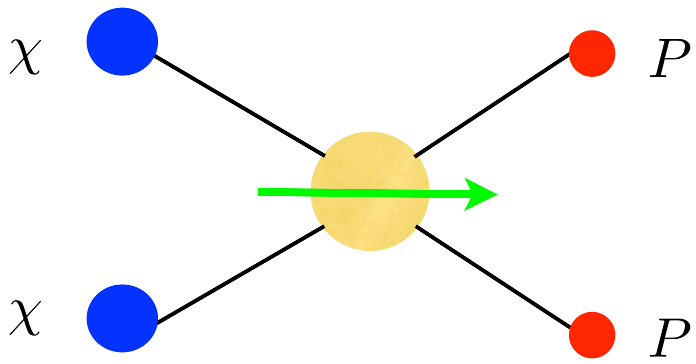
$$\Downarrow$$

$$\boxed{m_\chi \sim 100 \text{ GeV} \sim \text{W mass}}$$

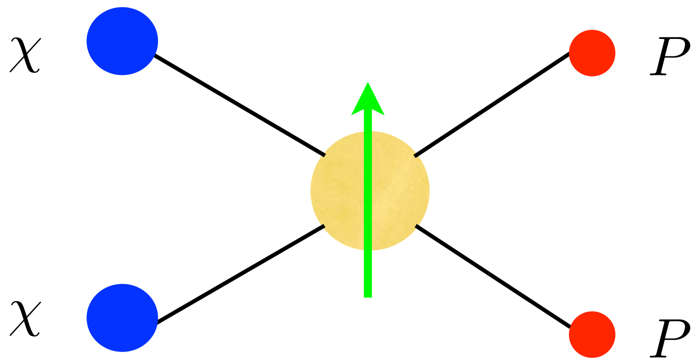
Lots of beyond-standard models predict WIMP candidates

The Hunt of Dark Matter

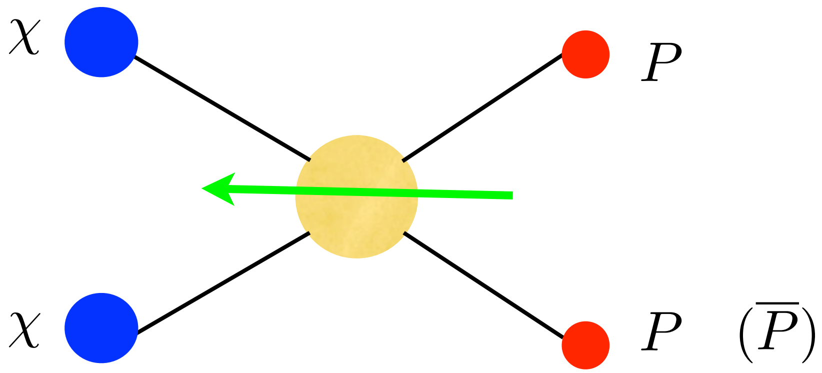
Indirect Detection



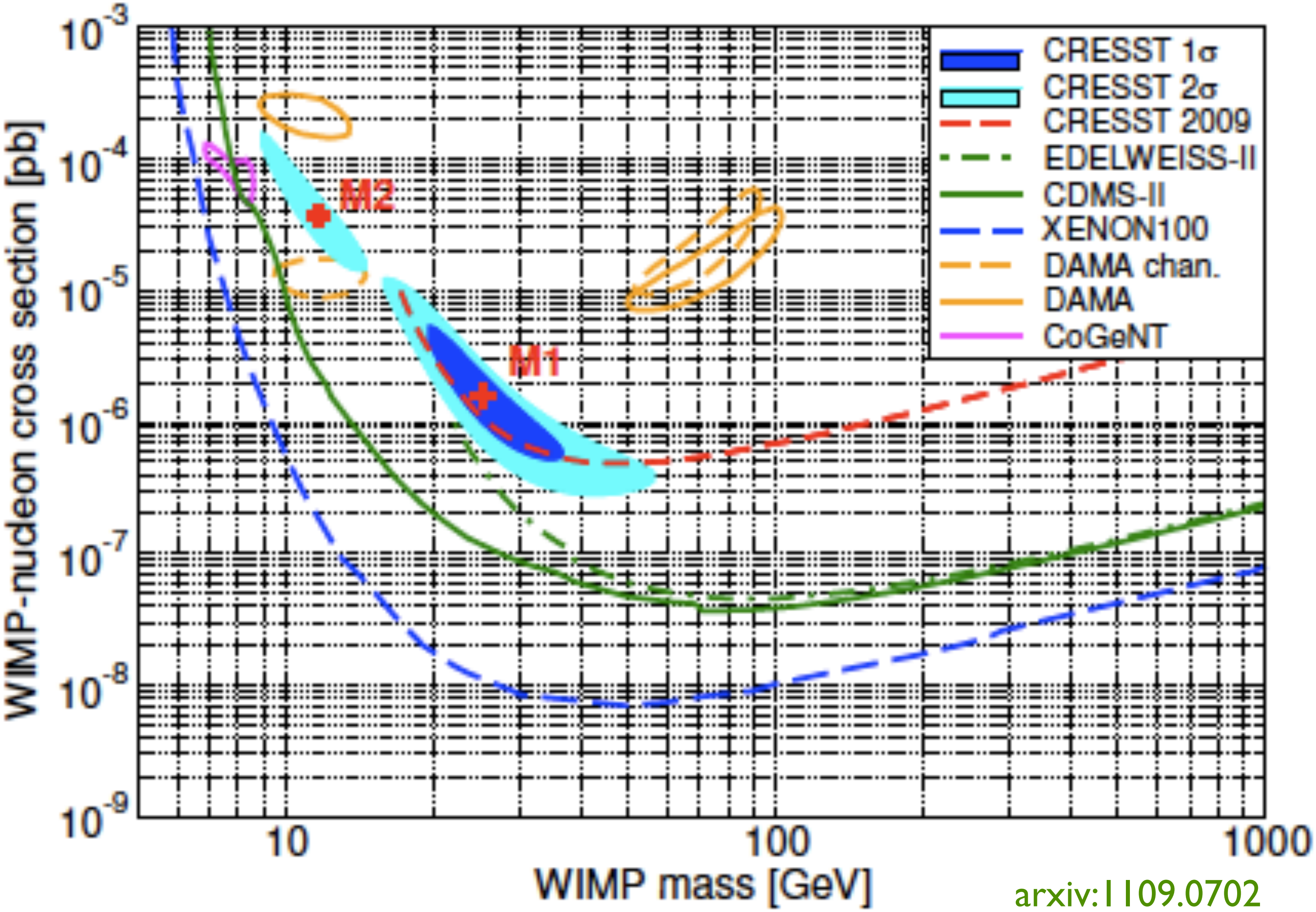
Direct Detection



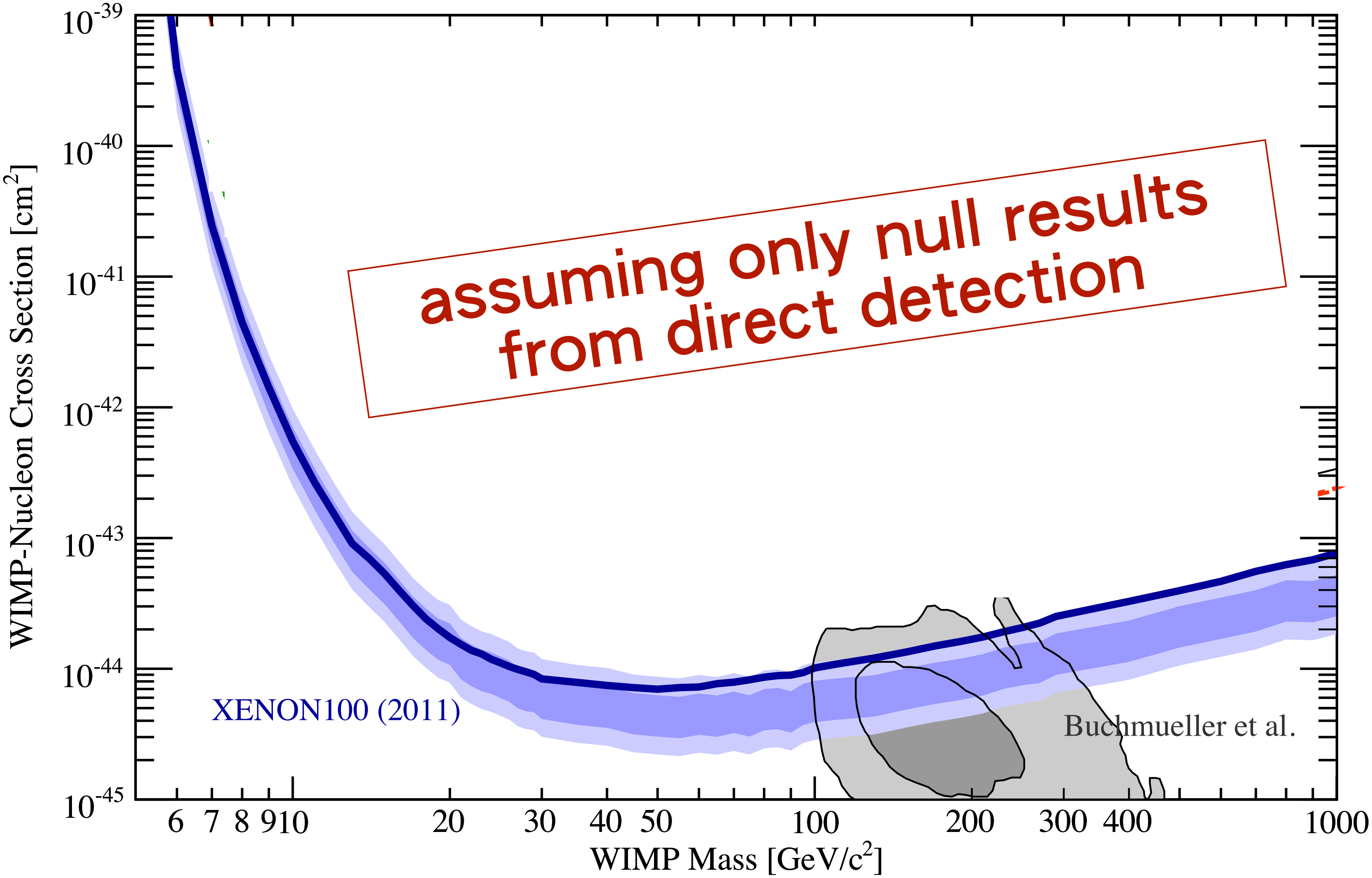
Colliders



Direct Detection of Dark Matter

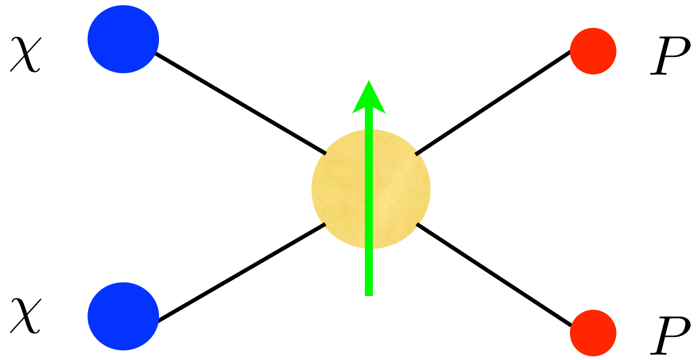


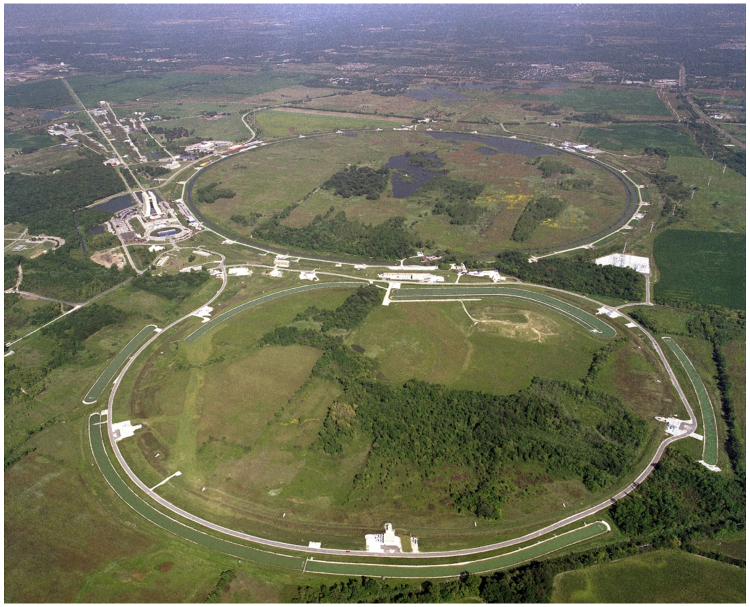
arxiv:1109.0702



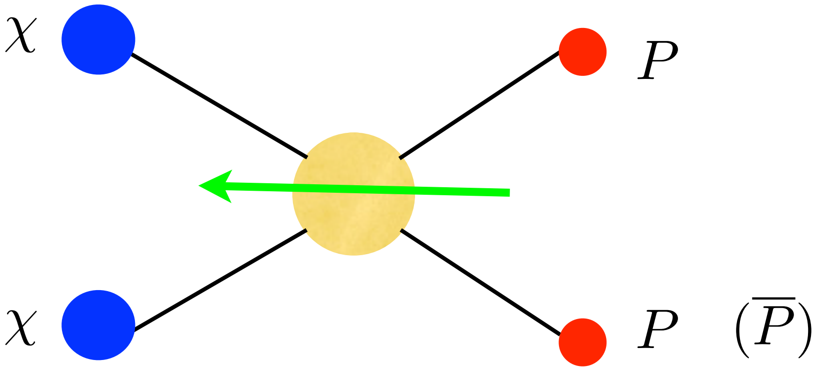
assuming only null results from direct detection

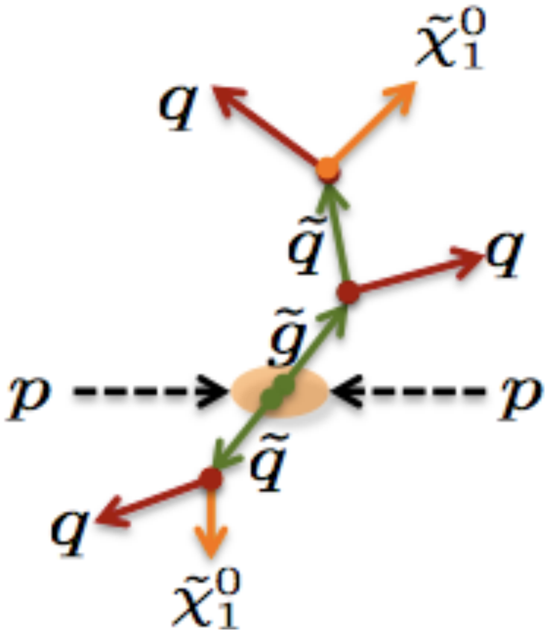
Direct Detection

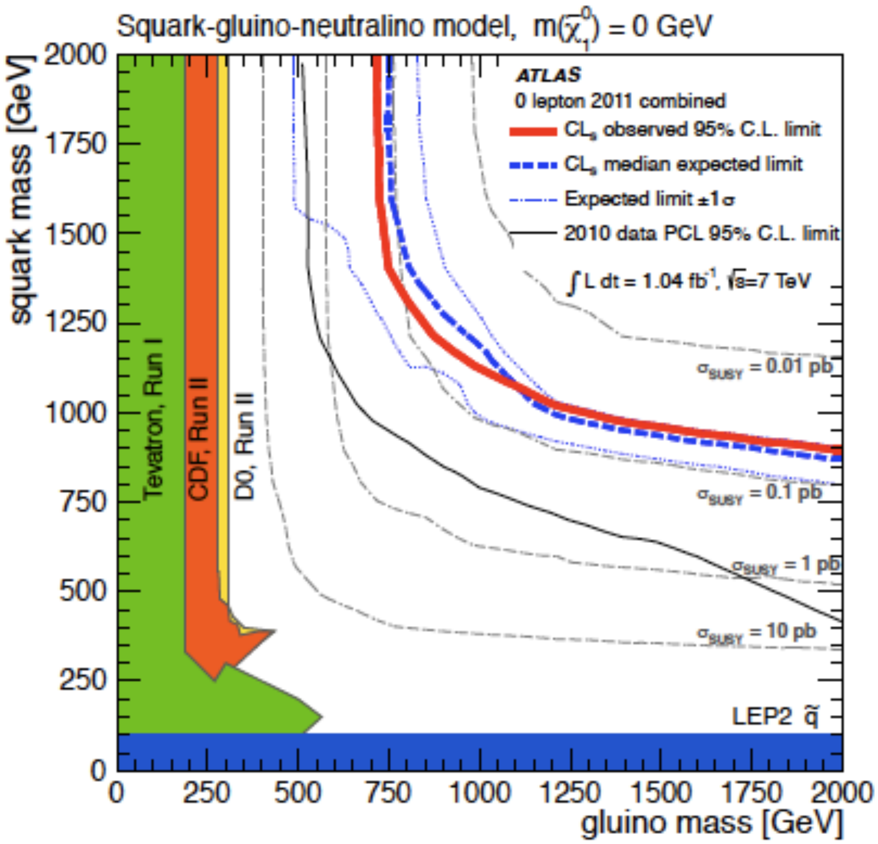


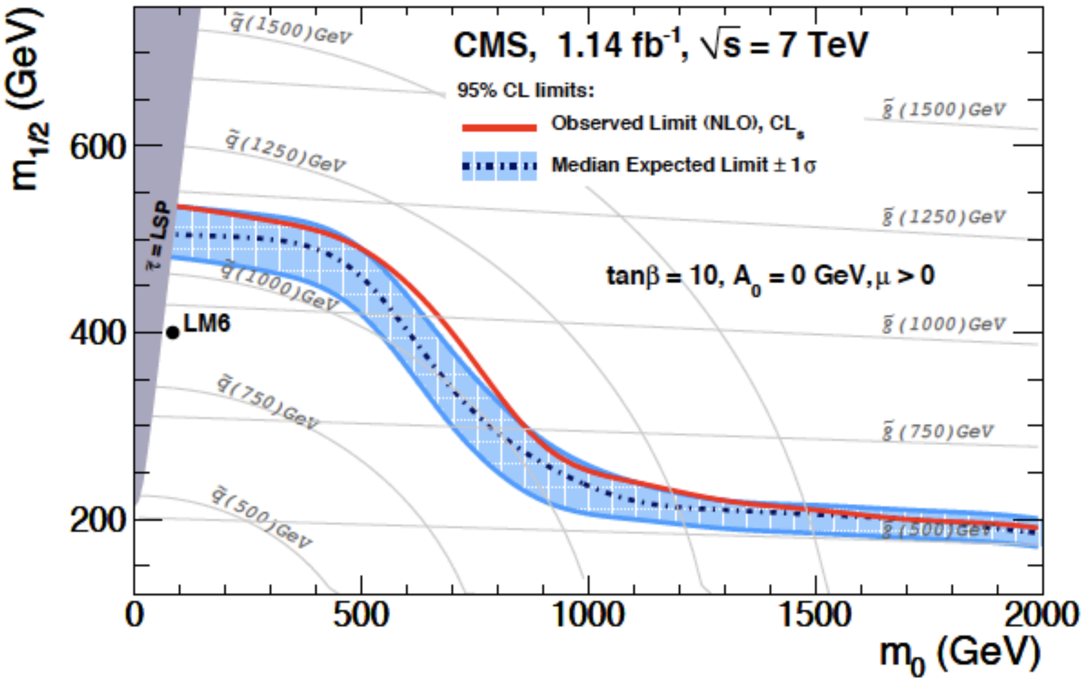


Colliders



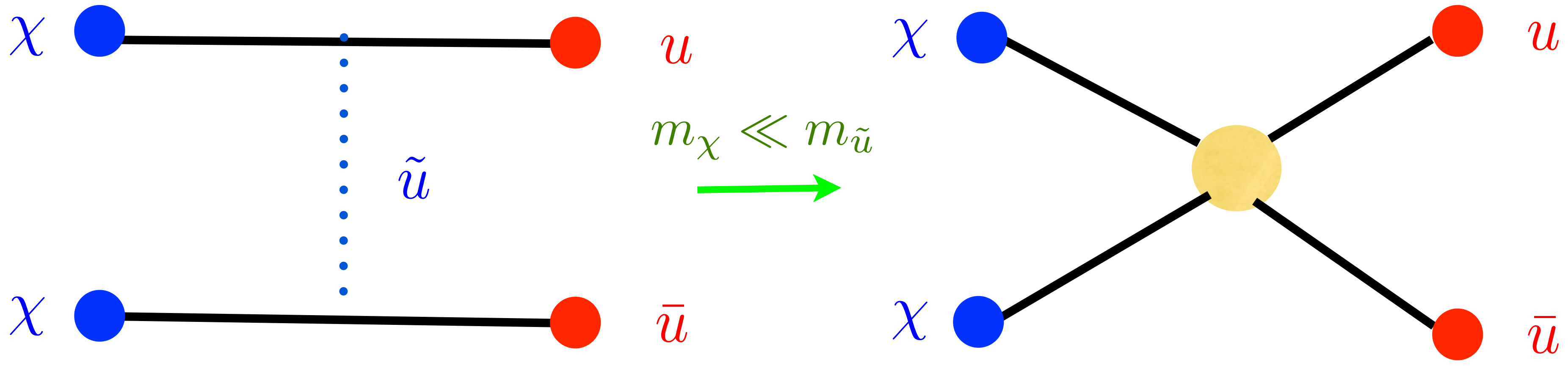






No new physics has been found associated with missing energy

Effective Approach to Dark Matter



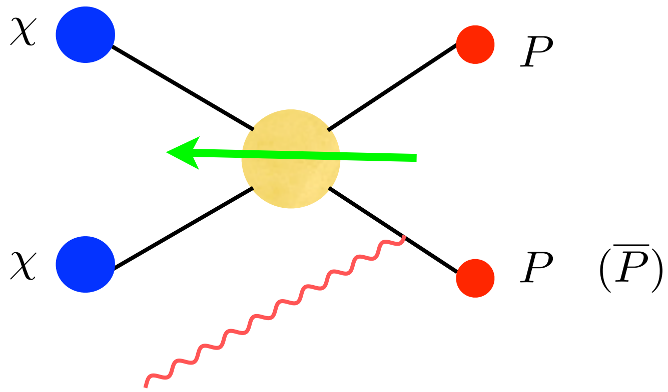
Model-independent approach to dark matter

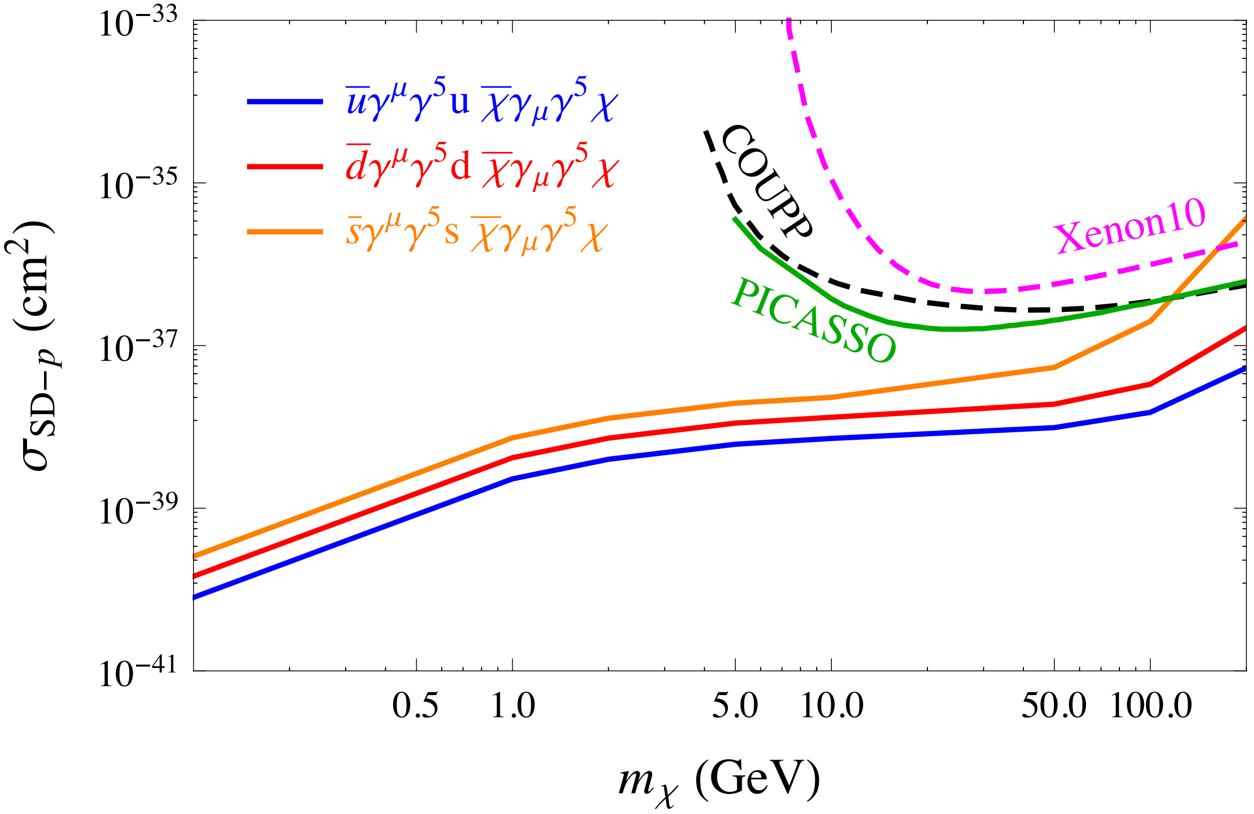
$$\frac{1}{\Lambda^2}\bar{q}q\bar{\chi}\chi \qquad \frac{1}{\Lambda^2}\bar{q}\gamma_5 q\,\bar{\chi}\gamma_5\chi$$

$$\frac{1}{\Lambda^2}\bar{q}\gamma_\mu q\,\bar{\chi}\gamma^\mu\chi \qquad \frac{1}{\Lambda^2}\bar{q}\gamma_\mu\gamma_5 q\,\bar{\chi}\gamma^\mu\gamma_5\chi$$

......

As a warmup, we can first use the Tevatron existing data to constrain the DM-nucleon interaction strength



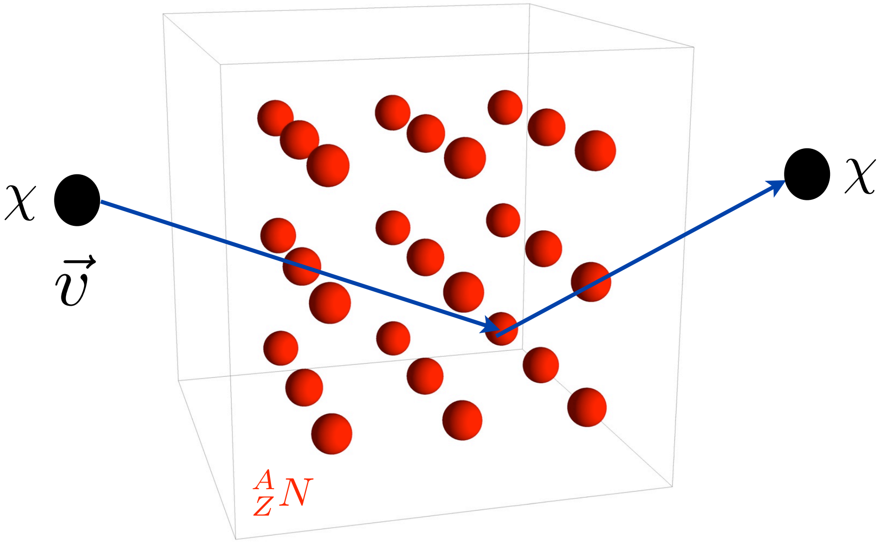


YB, Fox, Harnik,
JHEP, 1012, 048 (2010)

see also: Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu: Phys. Lett. B695 (2011)

some caveats for light mediators

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



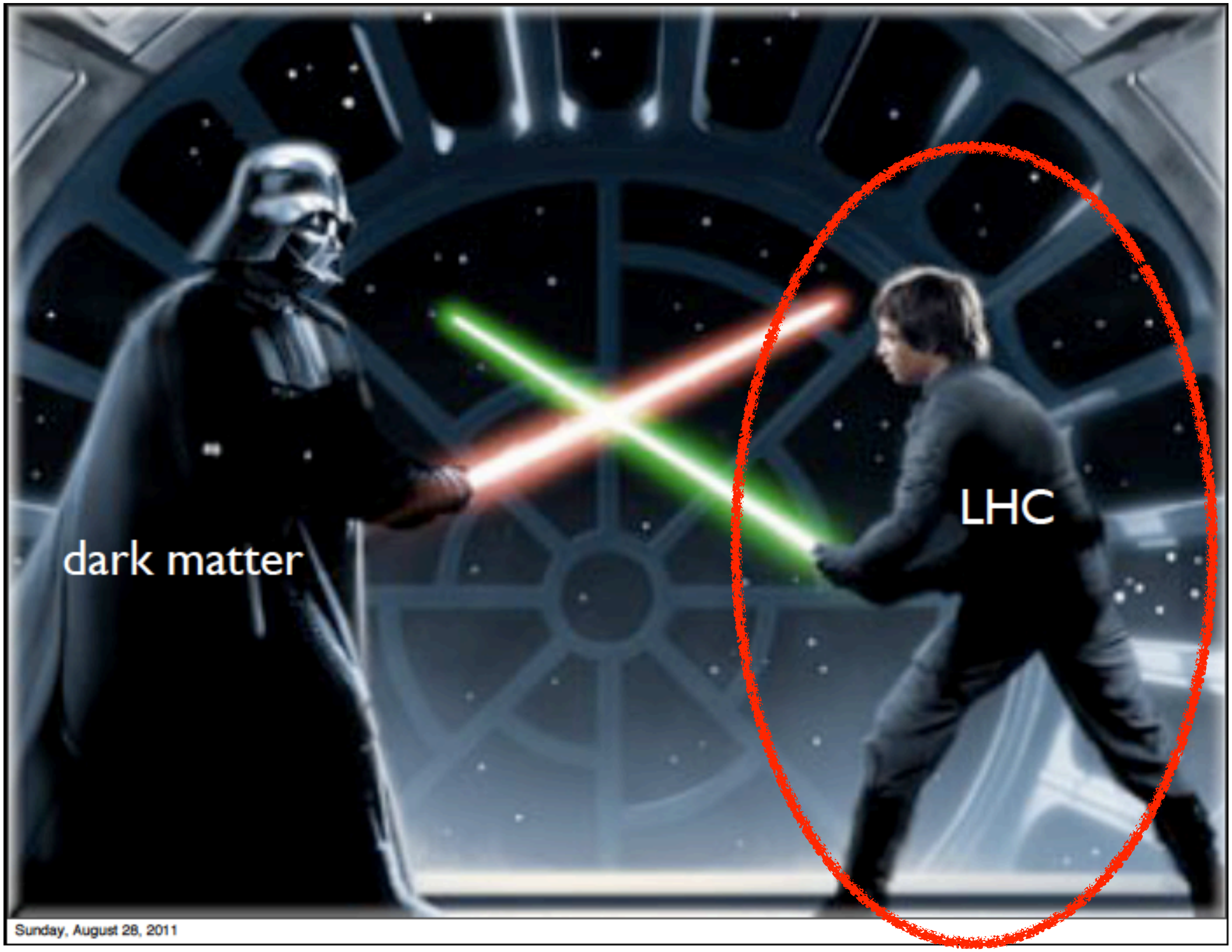
$$E_{\rm kin} = \frac{1}{2} m_\chi v^2 \sim 100 \text{ keV} \qquad m_\chi \sim 100 \text{ GeV}$$

$$\sim 1 \text{ keV} \qquad m_\chi \sim 1 \text{ GeV}$$

The typical low energy threshold at direct detection experiments is above 10 keV. Direct detection experiments are insensitive to light DM

Colliders do not have this limitation and can explore light DM region

Dark matter and collider connection or fight

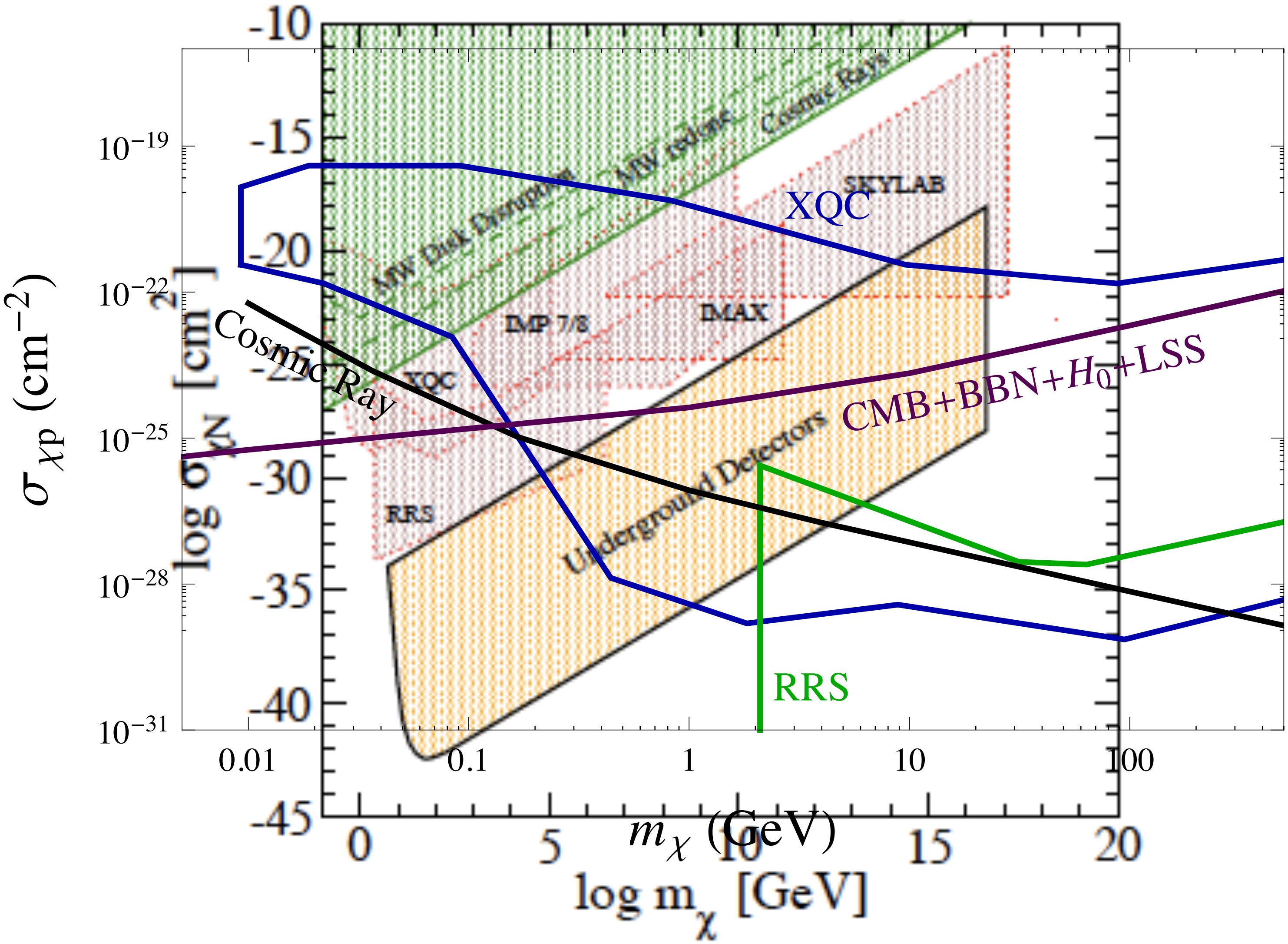


from Hitoshi Murayama's talk on SUSY2011

Let's explore other dark matter parameter space, where the LHC can definitely win over direct detection

Go Beyond WIMP

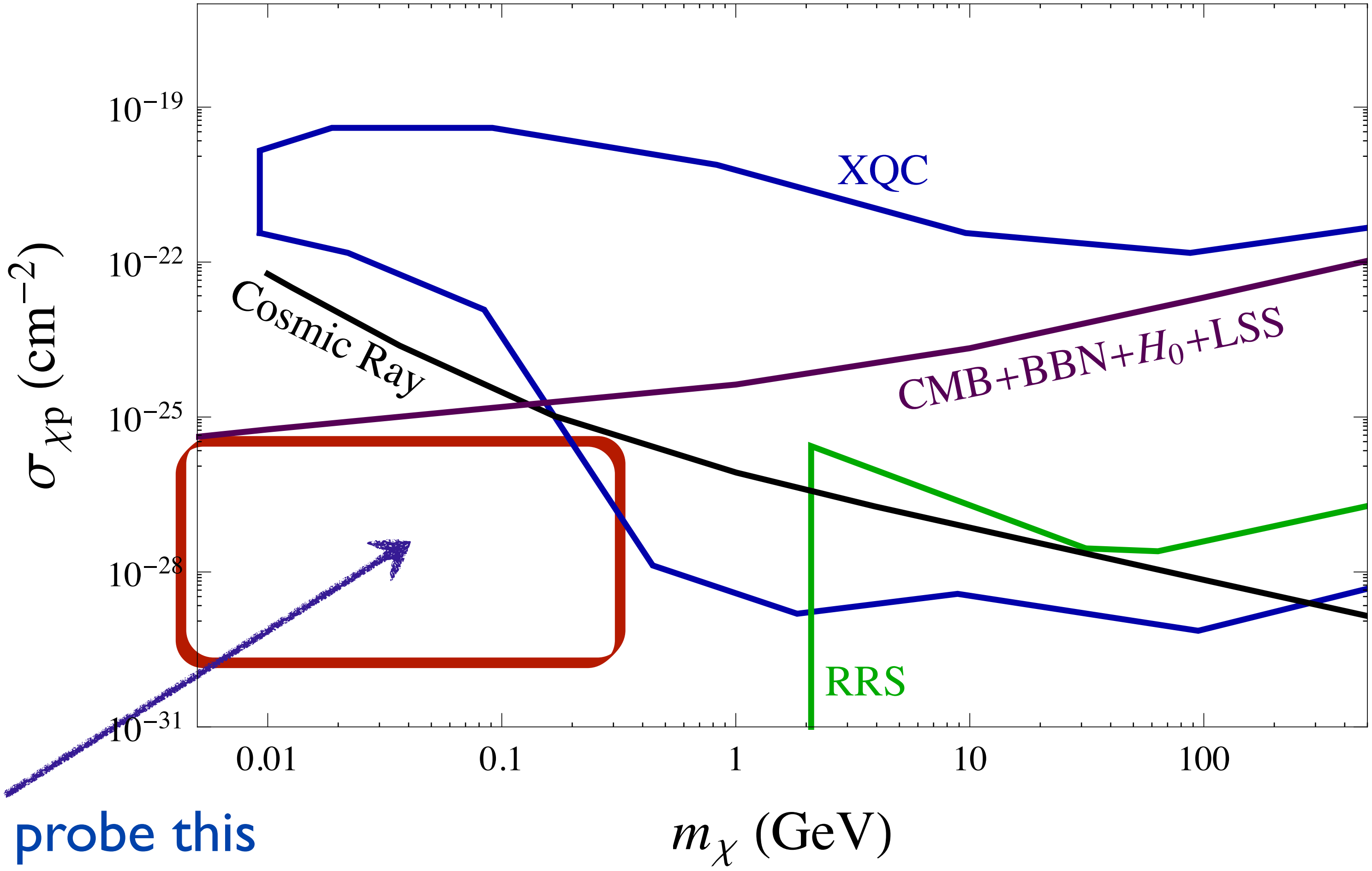
Mack, Beacom, Bertone: 0705.4298



Strongly interacting massive particle (SIMP)

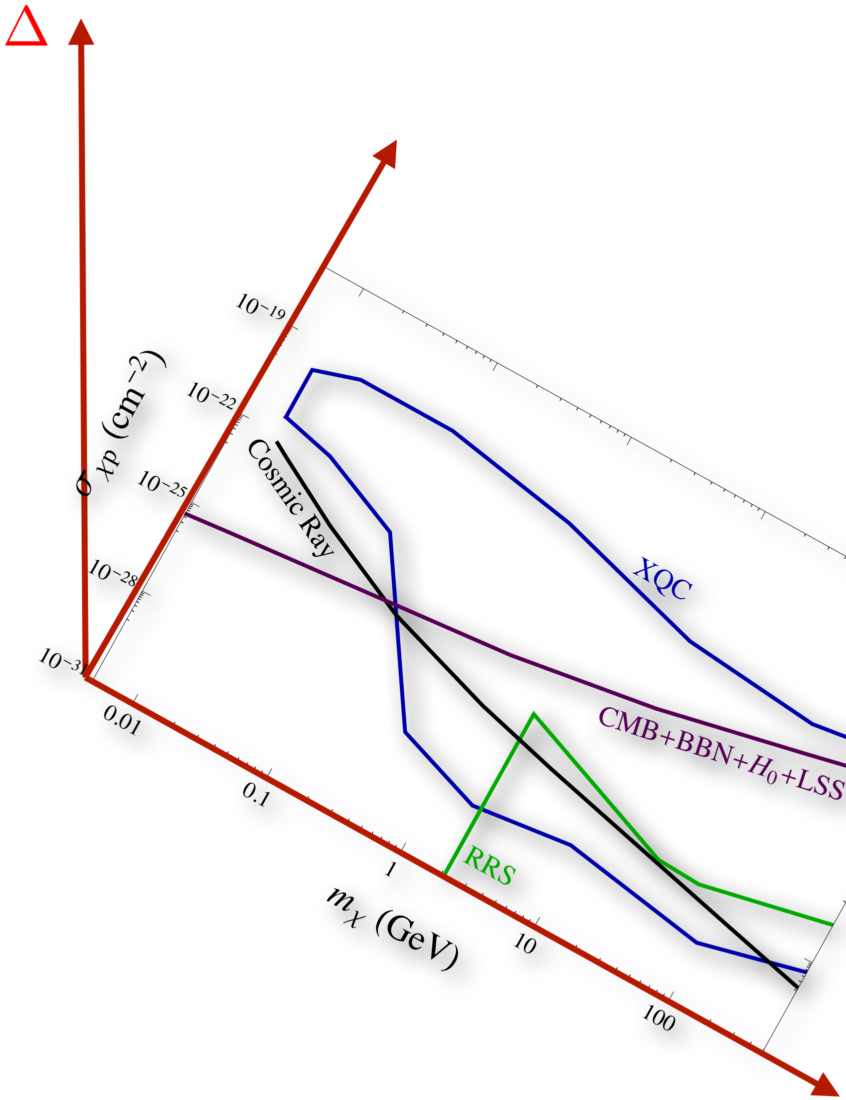
Starkman, Gould, Esmailzadeh and Dimopoulos, Phys. Rev. D 41, 3594 (1990).

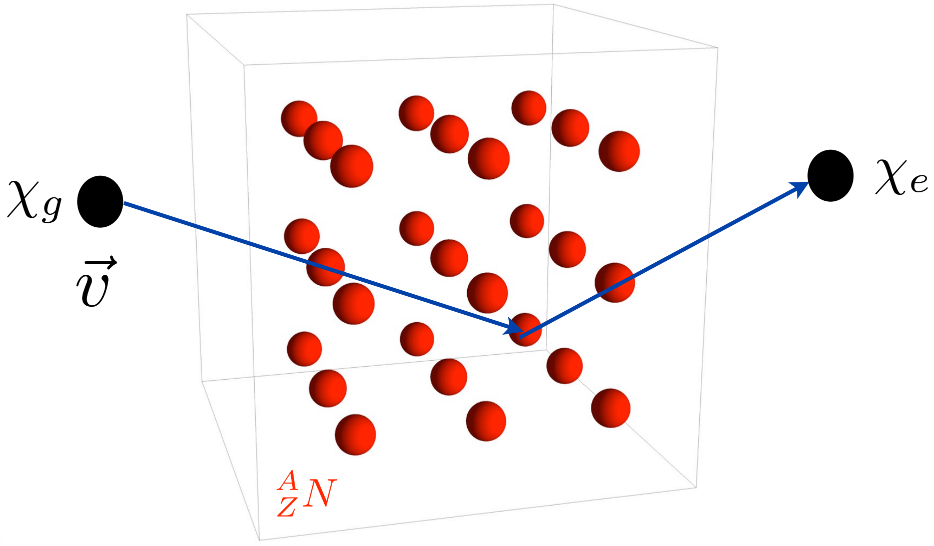
Spergel, Steinhardt: PRL 84, 3760 (2000)



Colliders can probe this range and the signature is different from monojet

An alternative way to explain the current null results at direct detection experiments is to introduce an extra-dimension (iDM)





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

no signal at direct detection

Inelastic Dark Matter

YB, Tim Tait
1109.4144

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:

T. Han, R. Hempfling, hep-ph/9708264
Hall, Moroi, Murayama, hep-ph/9712515
Tucker-Smith, Weiner, hep-ph/0101138

Perform our studies in a model-independent way:

$$\boxed{\frac{\bar{u}\,\gamma_\mu\gamma_5\,u\,\bar{\chi}_e\,\gamma^\mu\gamma_5\,\chi_g}{\Lambda_1^2}} \qquad \frac{\bar{u}\,\gamma_5\,u\,\bar{\chi}_e\,\gamma_5\,\chi_g}{\Lambda_2^2} \qquad \frac{\bar{u}\,u\,\bar{\chi}_e\,\chi_g}{\Lambda_3^2} \qquad \frac{\bar{u}\,\gamma_\mu\,u\,\bar{\chi}_e\,\gamma^\mu\,\chi_g}{\Lambda_4^2}$$

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

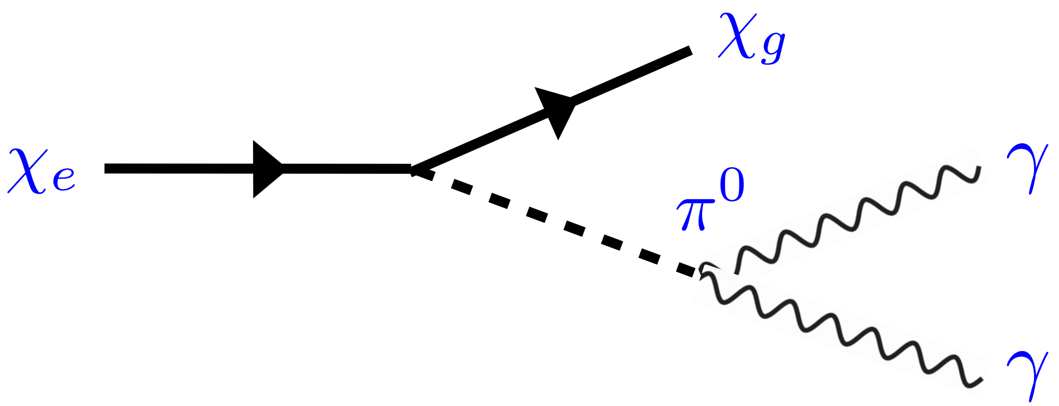
The ground state is purely stable and is the dark matter particle

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

For the mass splitting below ~ 1 GeV, using chiral Lagrangian

$$i\bar{u}\gamma^\mu\gamma_5 u \to \frac{1}{2}F_\pi\partial^\mu\pi^0 \qquad F_\pi = 184 \text{ MeV}$$

$$\begin{tikzcd}
\dfrac{\bar{u}\,\gamma_\mu\gamma_5\,u\,\bar{\chi}_e\,\gamma^\mu\gamma_5\,\chi_g}{\Lambda^2} \arrow[d] & \\
\dfrac{-i}{2}F_\pi\partial^\mu\pi^0\,\dfrac{\bar{\chi}_e\,\gamma^\mu\gamma_5\,\chi_g}{\Lambda^2} \arrow[r] & \dfrac{F_\pi\,(m_{\chi_e}+m_{\chi_g})}{2\,\Lambda^2}\,\pi^0\,\bar{\chi}_e\,\gamma_5\,\chi_g
\end{tikzcd}$$



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

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

Translation of the operators

$$\frac{\bar{u}\,\gamma_\mu\gamma_5\,u\,\bar{\chi}_e\,\gamma^\mu\gamma_5\,\chi_g}{\Lambda_1^2}$$

$$\frac{\bar{u}\,\gamma_5\,u\,\bar{\chi}_e\,\gamma_5\,\chi_g}{\Lambda_2^2}$$

$$\frac{\bar{u}\,u\,\bar{\chi}_e\,\chi_g}{\Lambda_3^2}$$

$$\frac{\bar{u}\,\gamma_\mu\,u\,\bar{\chi}_e\,\gamma^\mu\,\chi_g}{\Lambda_4^2}$$

$$\longrightarrow$$

$$\frac{F_\pi\,(m_{\chi_e}+m_{\chi_g})}{2}\,\frac{\pi^0\,\bar{\chi}_e\,\gamma_5\,\chi_g}{\Lambda_1^2}$$

$$\frac{i\,\langle\bar{u}u\rangle}{F_\pi}\,\frac{\pi^0\,\bar{\chi}_e\,\gamma_5\,\chi_g}{\Lambda_2^2}$$

$$-\frac{\langle\bar{u}u\rangle}{F_\pi^2}\,\frac{(\pi^0\pi^0+2\pi^+\pi^-)\,\bar{\chi}_e\,\chi_g}{2\,\Lambda_3^2}$$

$$\frac{(\pi^-\partial_\mu\,\pi^+-\pi^+\partial_\mu\,\pi^-)\,\bar{\chi}_e\,\gamma^\mu\,\chi_g}{\Lambda_4^2}$$

Decays of the excited state for $\Delta \lesssim 1\ \mathrm{GeV}$

$$\Gamma_1(\chi_e\to\chi_g+\pi^0)=\frac{F_\pi^2}{\Lambda_1^4}\,\frac{(\Delta^2-m_{\pi^0}^2)^{3/2}}{8\,\pi}$$

$$\Gamma_2(\chi_e\to\chi_g+\pi^0)=\frac{\langle\bar{u}u\rangle^2}{F_\pi^2\Lambda_2^4}\,\frac{(\Delta^2-m_{\pi^0}^2)^{3/2}}{8\,\pi\,\overline{m}_\chi^2}$$

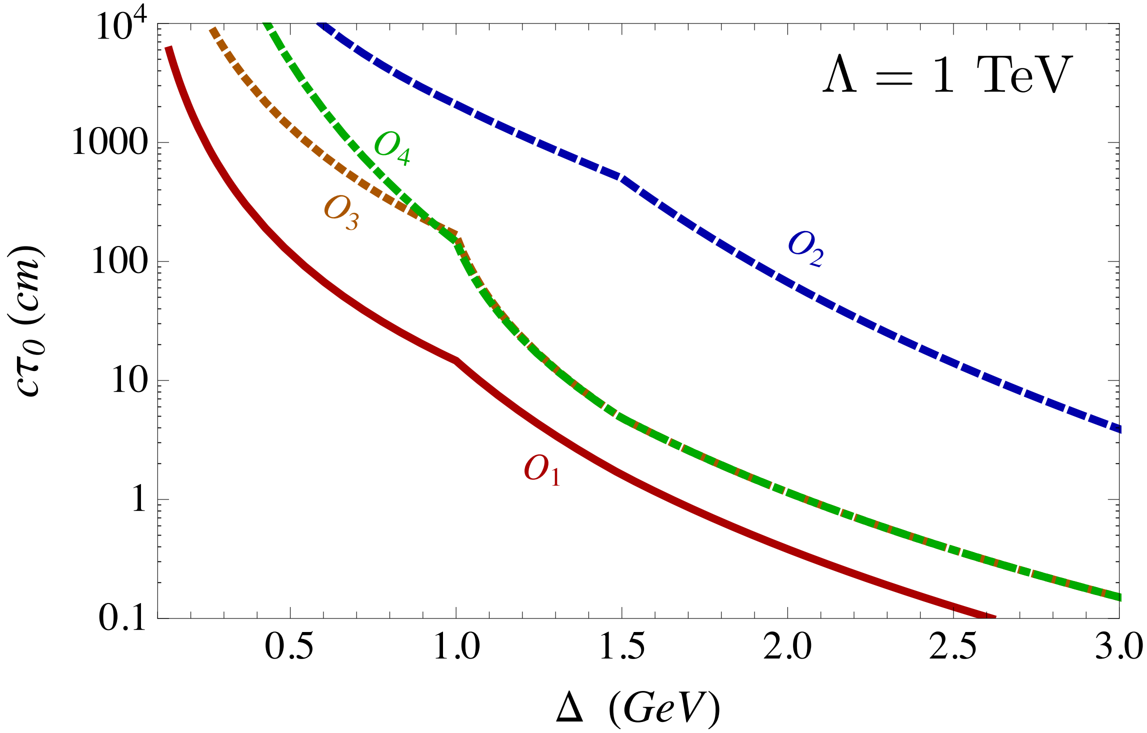
$$\Gamma_3(\chi_e\to\chi_g\pi^+\pi^-)=2\Gamma_3(\chi_e\to\chi_g2\pi^0)=\frac{\langle\bar{u}u\rangle^2\Delta^3}{48\pi^3\,F_\pi^4\Lambda_3^4}$$

$$\Gamma_4(\chi_e\to\chi_g\pi^+\pi^-)=\frac{\Delta^5}{240\pi^3\Lambda_4^4}$$

For $\Delta \gtrsim 1.5\ \mathrm{GeV}$, the chiral Lagrangian is not suitable anymore, but one can use a simple parton model to estimate the decay widths

$$\Gamma(\chi_e \to \chi_g u\bar{u}) = \frac{a_i}{\pi^3}\frac{\Delta^5}{\Lambda_i^4}$$

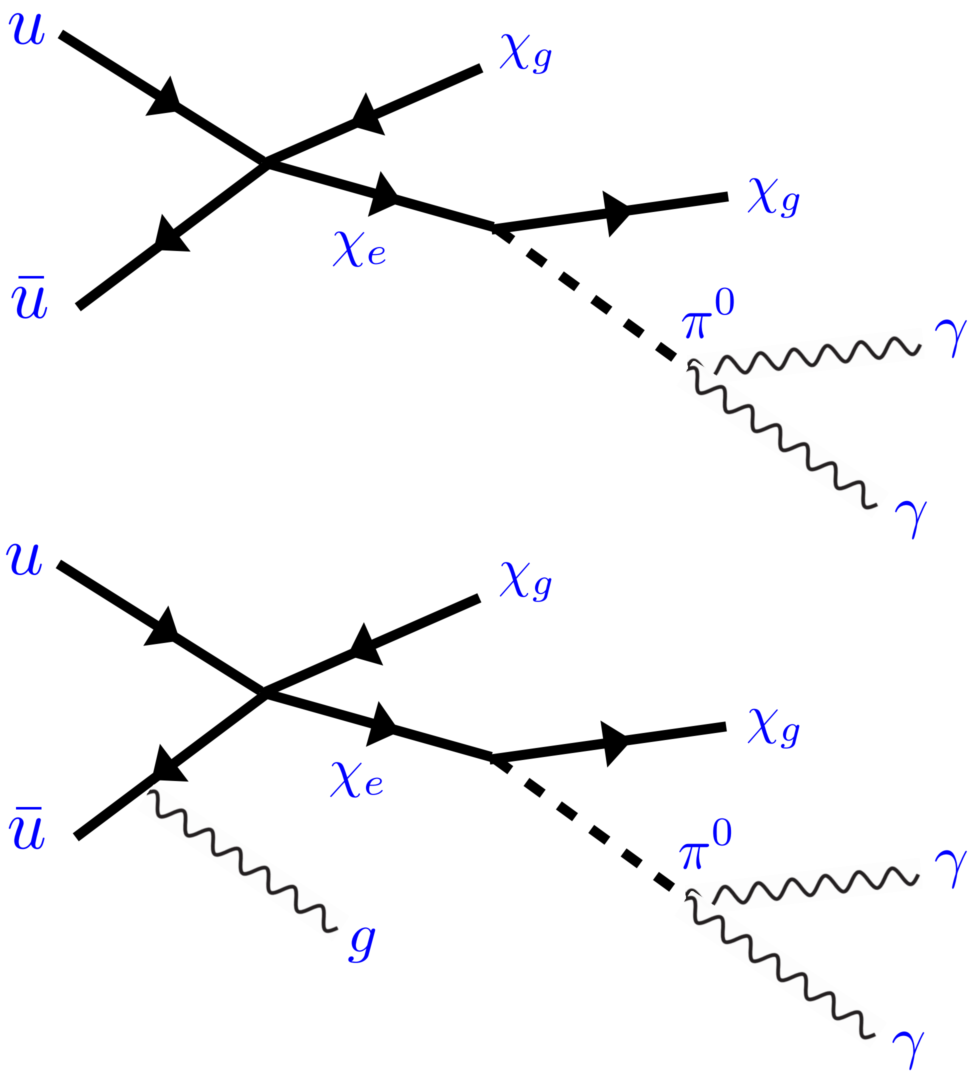
$$a_1 = 1/20,\ a_3 = a_4 = 1/60,\ \text{and}\ a_2 = \Delta^2/(560\,\overline{m}_\chi^2)$$



decay length at rest

It is generic that the excited state decays with a large displaced vertex

fast moving particle lives longer $c\tau = \gamma\, c\tau_0$



However, the photons are too soft, because their transverse momenta are related to the mass splitting, which is below 5 GeV

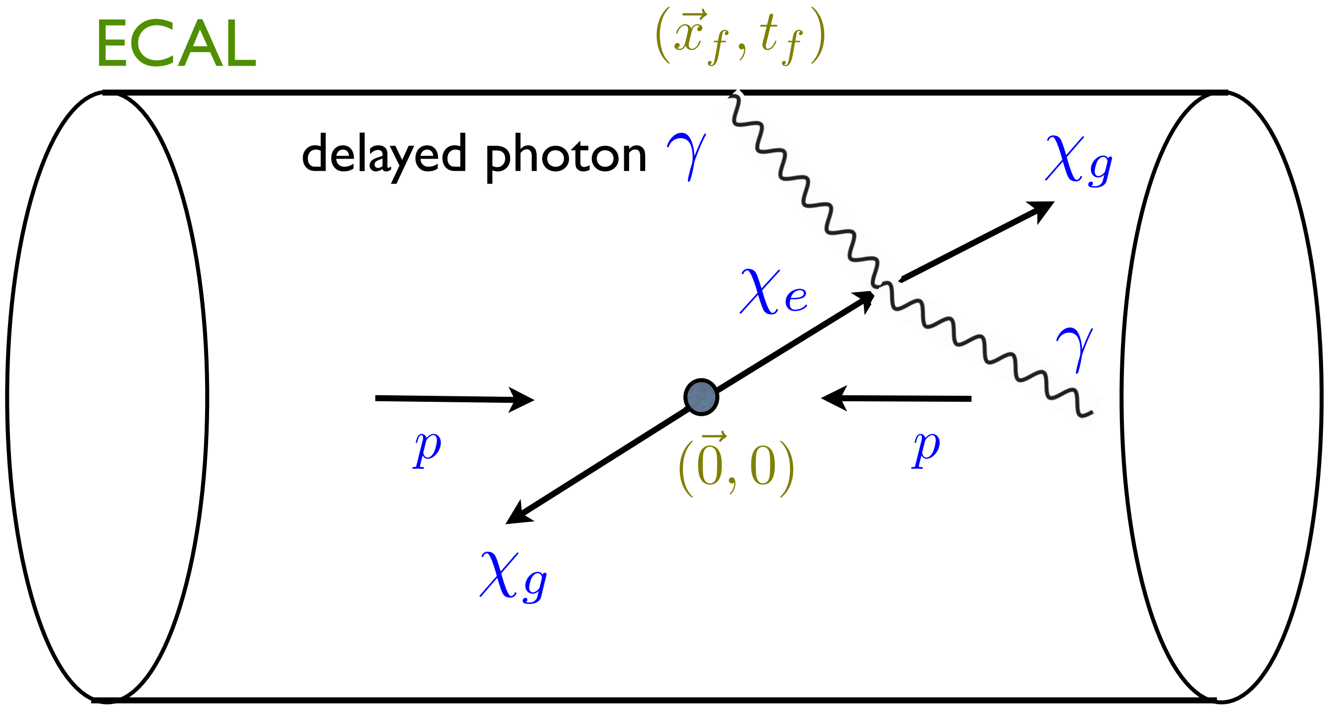
Fortunately, we can use the initial state radiation to boost final state particles

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

The signatures could be:

non-pointing photons

displaced pions or jets



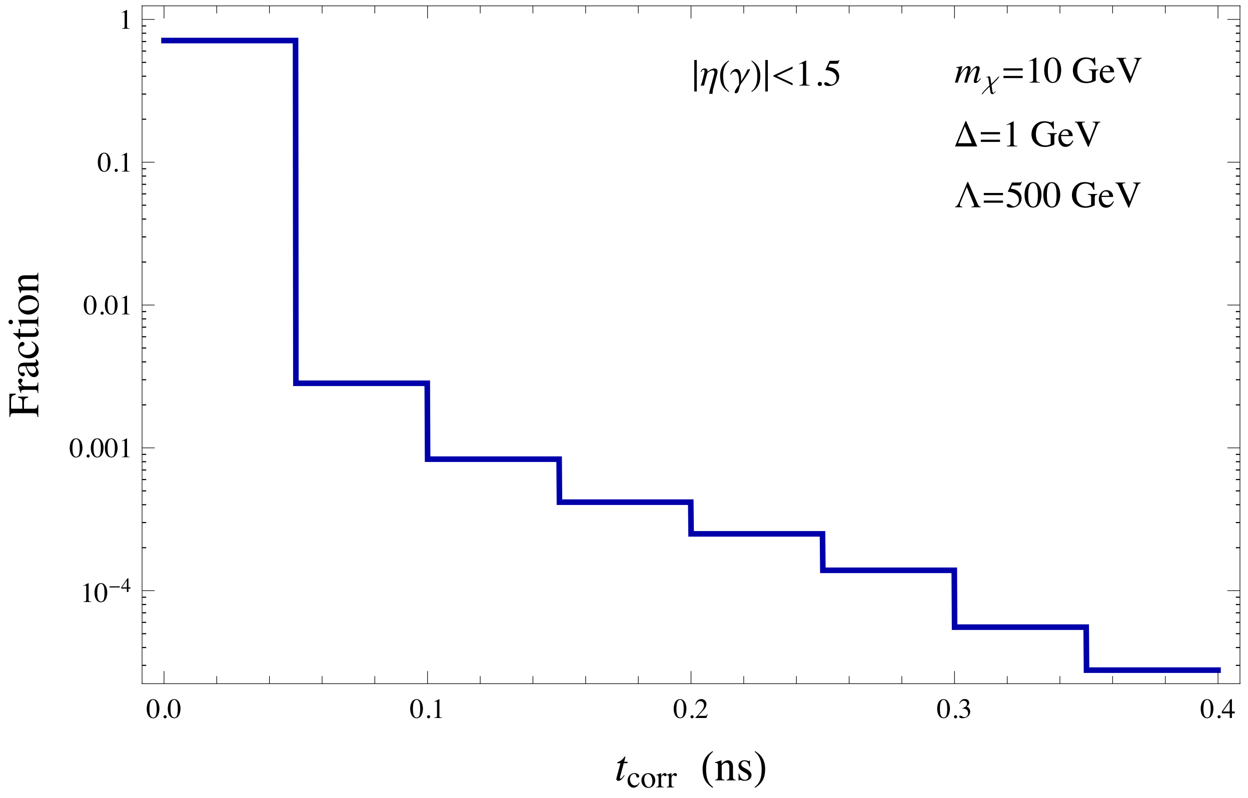
$$t_{\rm corr} \equiv t_f - \frac{\vec{x}_f}{c}$$

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: $\tilde{\chi}^0 \to \gamma\,\tilde{G}$

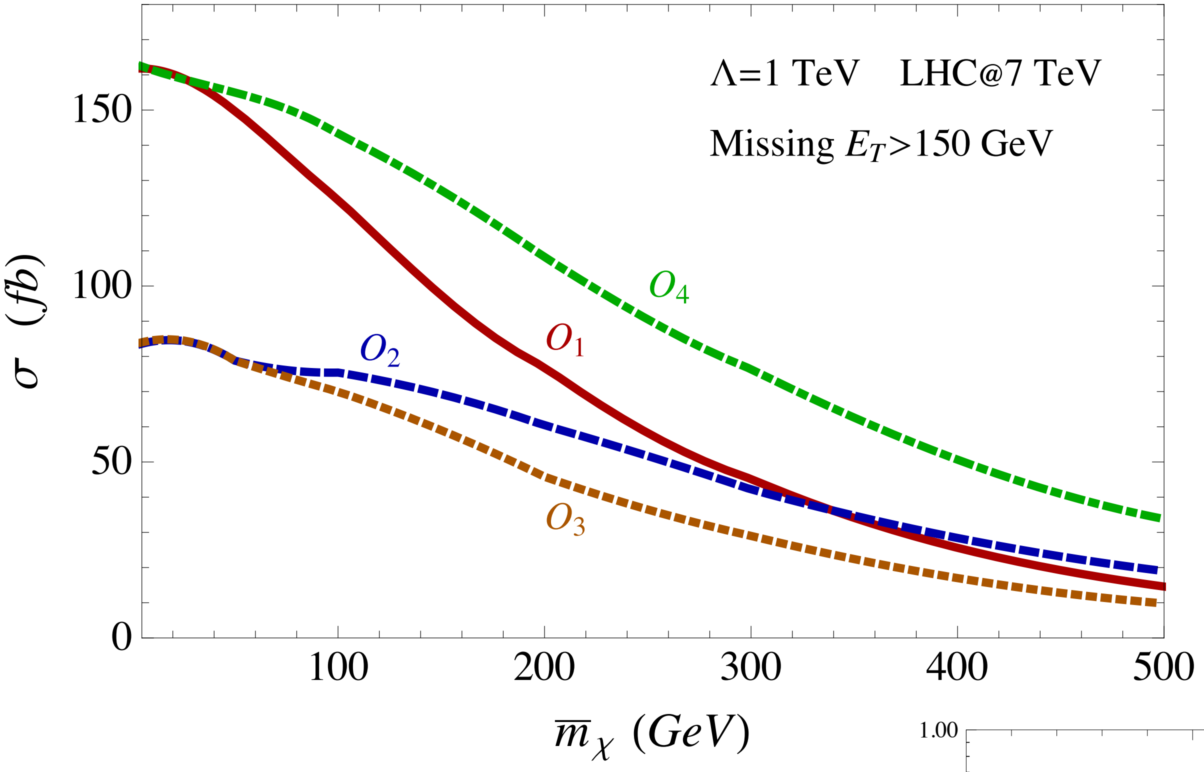


SM backgrounds can also have tcorr up to one ns

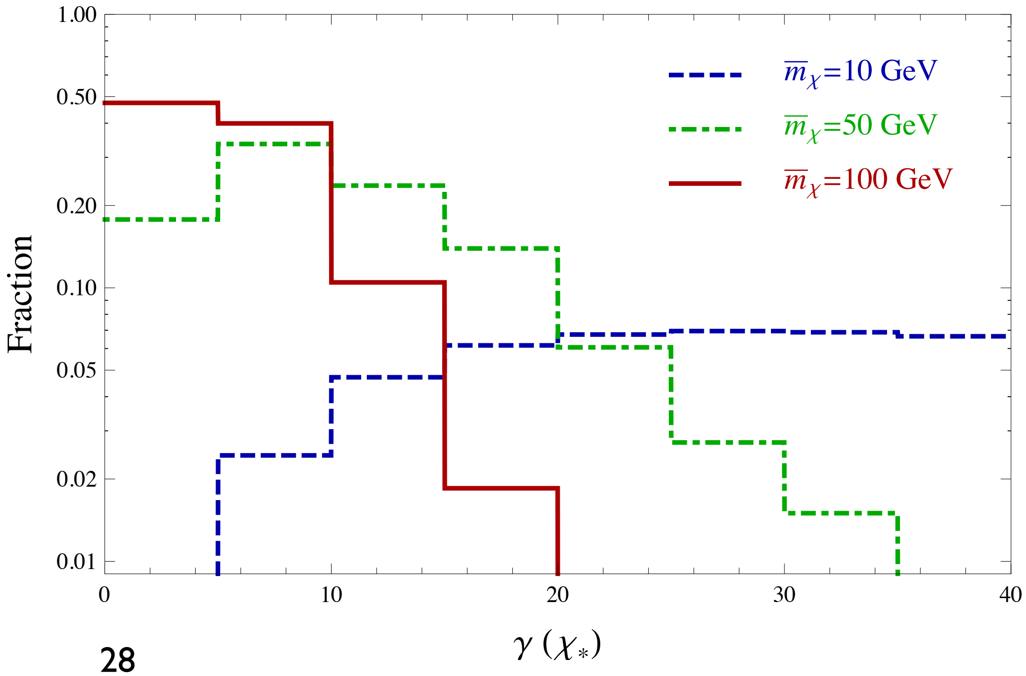
tcorr is not a good variable for the iDM model, as opposite to the GMSB model

~~non-pointing photons~~

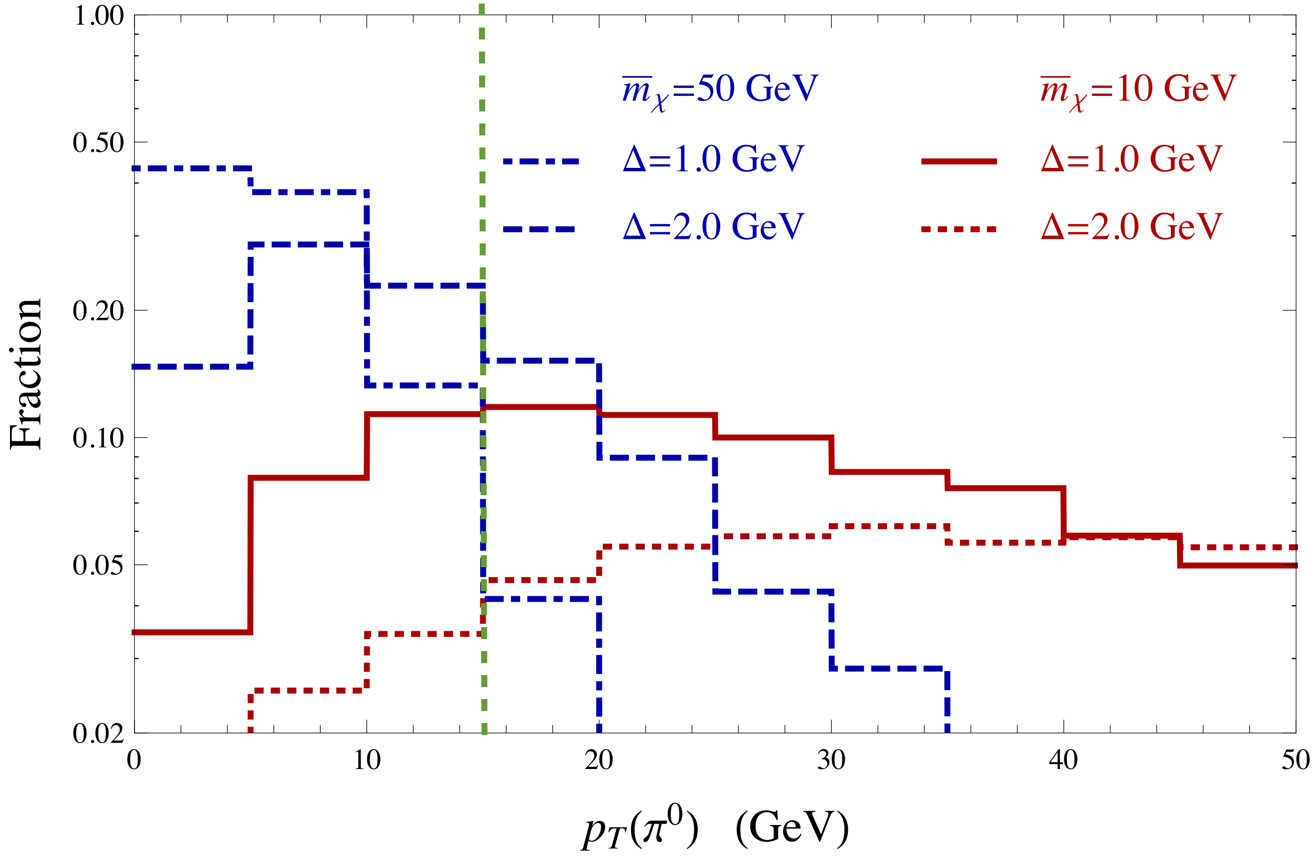
Production cross sections



Gamma factors



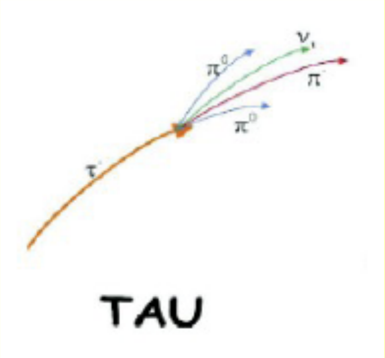
Pt distributions of the displaced pions



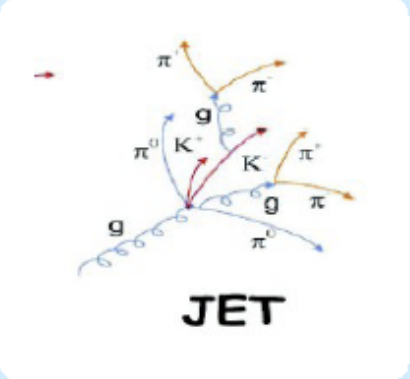
$\not{E}_T > 150$ GeV

$p_T(\pi^0) \sim \not{E}_T \Delta / \overline{m}_\chi$

Without using displaced information, the hadronic-tau tagging efficiency can provide some estimation of the discovery potential of the iDM

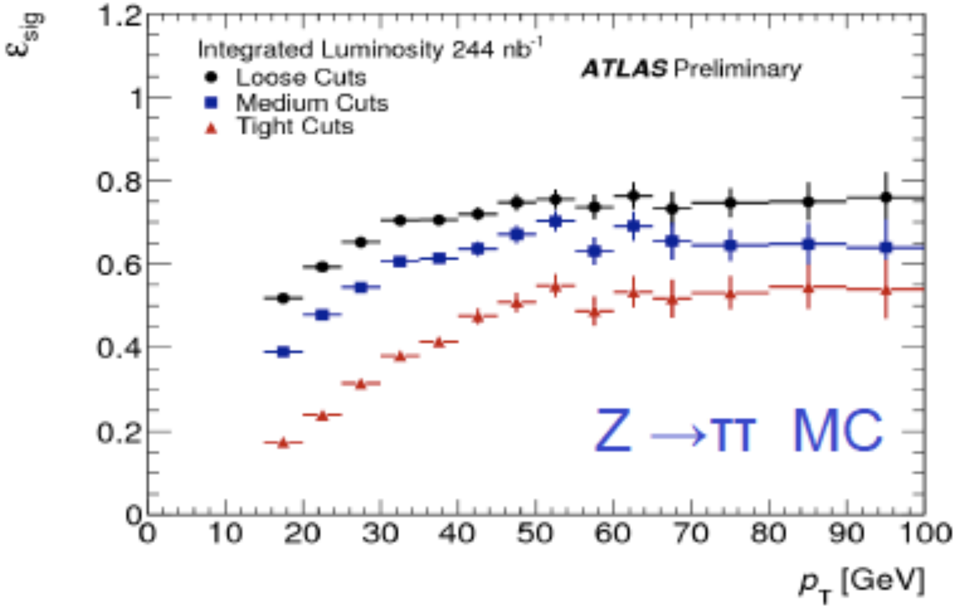


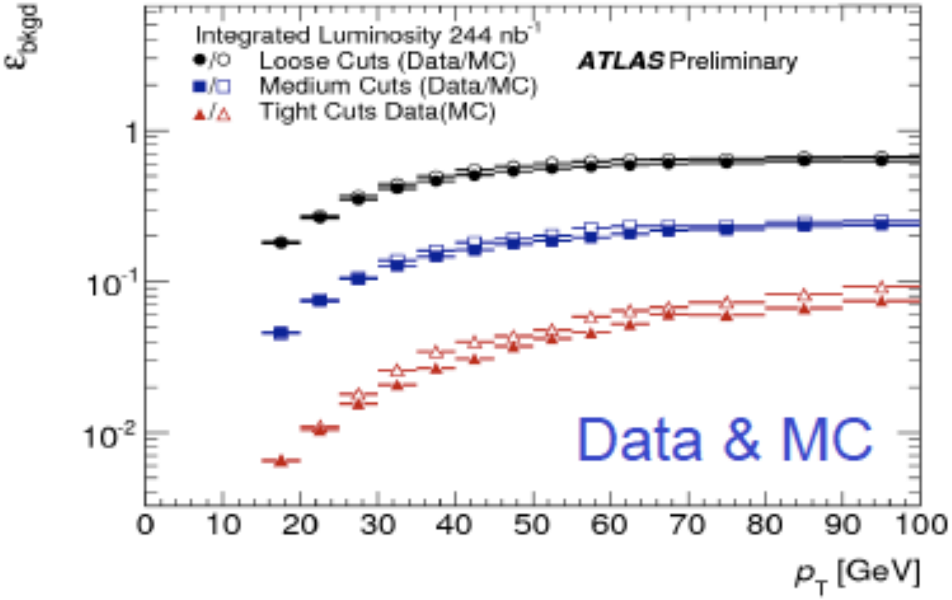
- Narrow, collimated
- 1 or 3 tracks
- Can define isolation regions with low activity
- The leading track carries significant fraction of tau momentum



- wide
- can have many tracks
- isolation regions busy
- jet momenta spread over tracks

Marcin Wolter, Atlas, talk at Cracow Epiphany Conf., January 2010

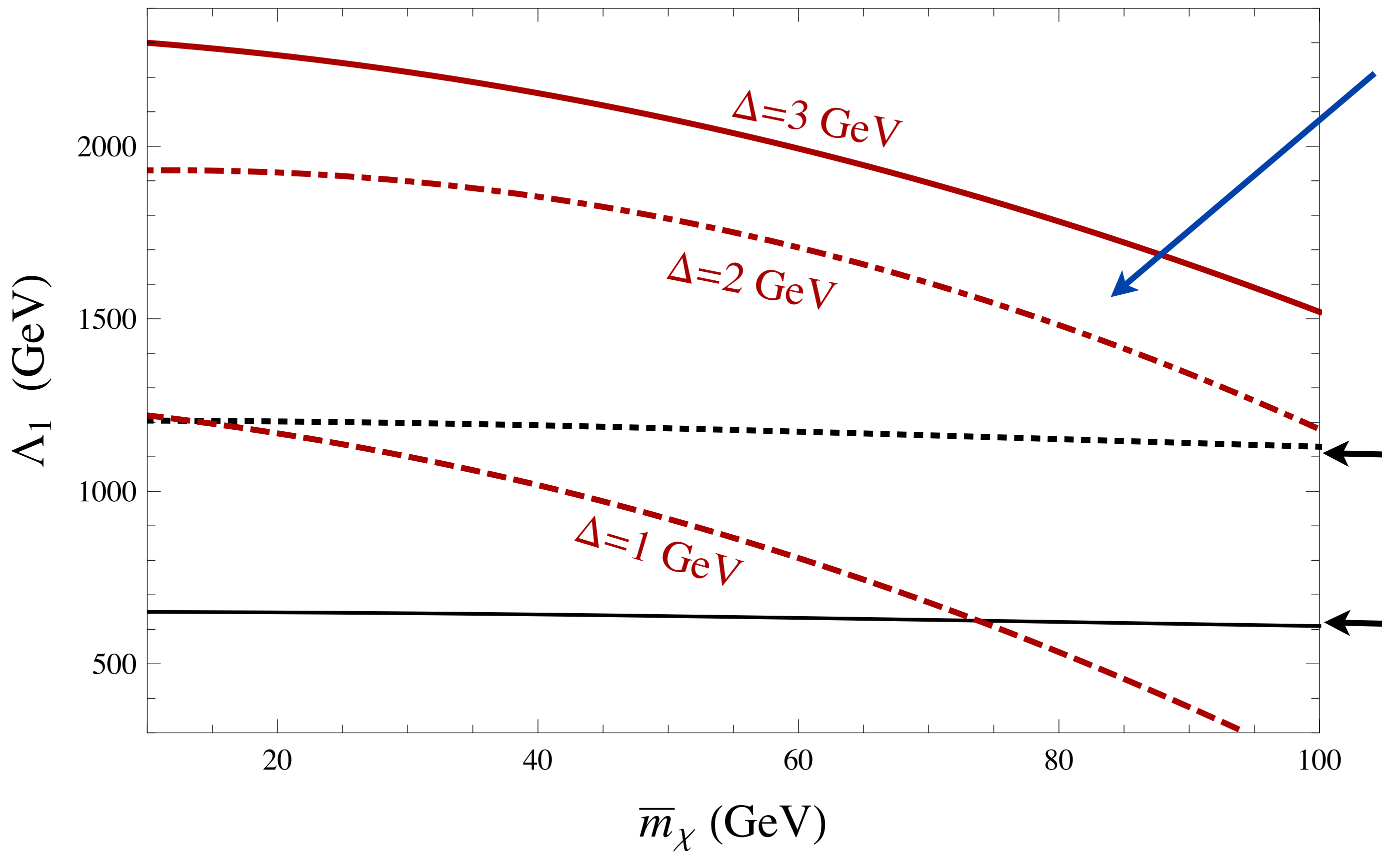




discovery (or exclusion) potential at the 7 TeV LHC

$$N_{jets} = 2 \qquad p_T(j_1) > 110\ \mathrm{GeV} \quad 15 < p_T(j_2) < 30\ \mathrm{GeV} \qquad \not{E}_T \geq 150\ \mathrm{GeV}$$

requiring the excited state to decay before HCAL (1.29 m) and using the tau-tag efficiency



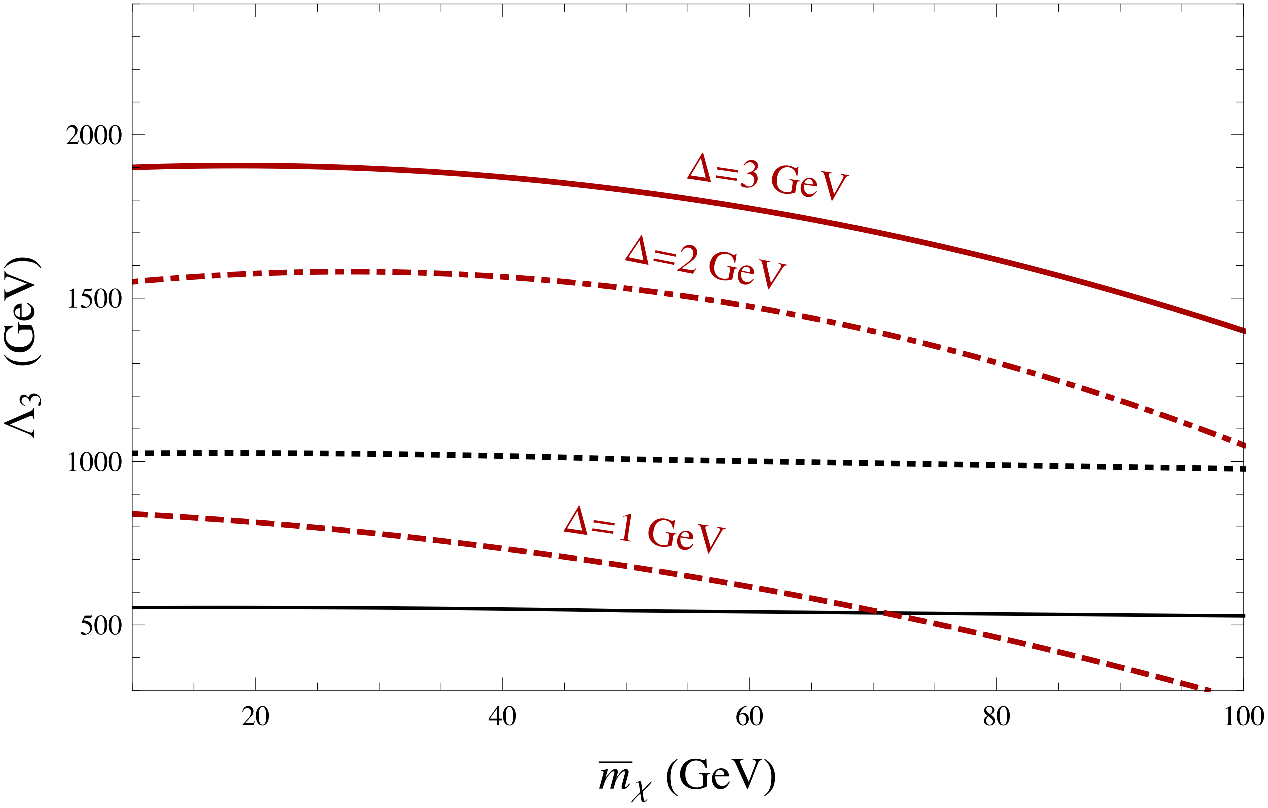
IDM signature reach at 5 fb^-1

$$\frac{\bar{u}\,\gamma_\mu\gamma_5\,u\,\bar{\chi}_e\,\gamma^\mu\gamma_5\,\chi_g}{\Lambda_1^2}$$

projected monojet reach at 5 fb^-1

current limit from 36 pb^-1 at CMS: 1106.4775

discovery (or exclusion) potential at the 7 TeV LHC for another operator



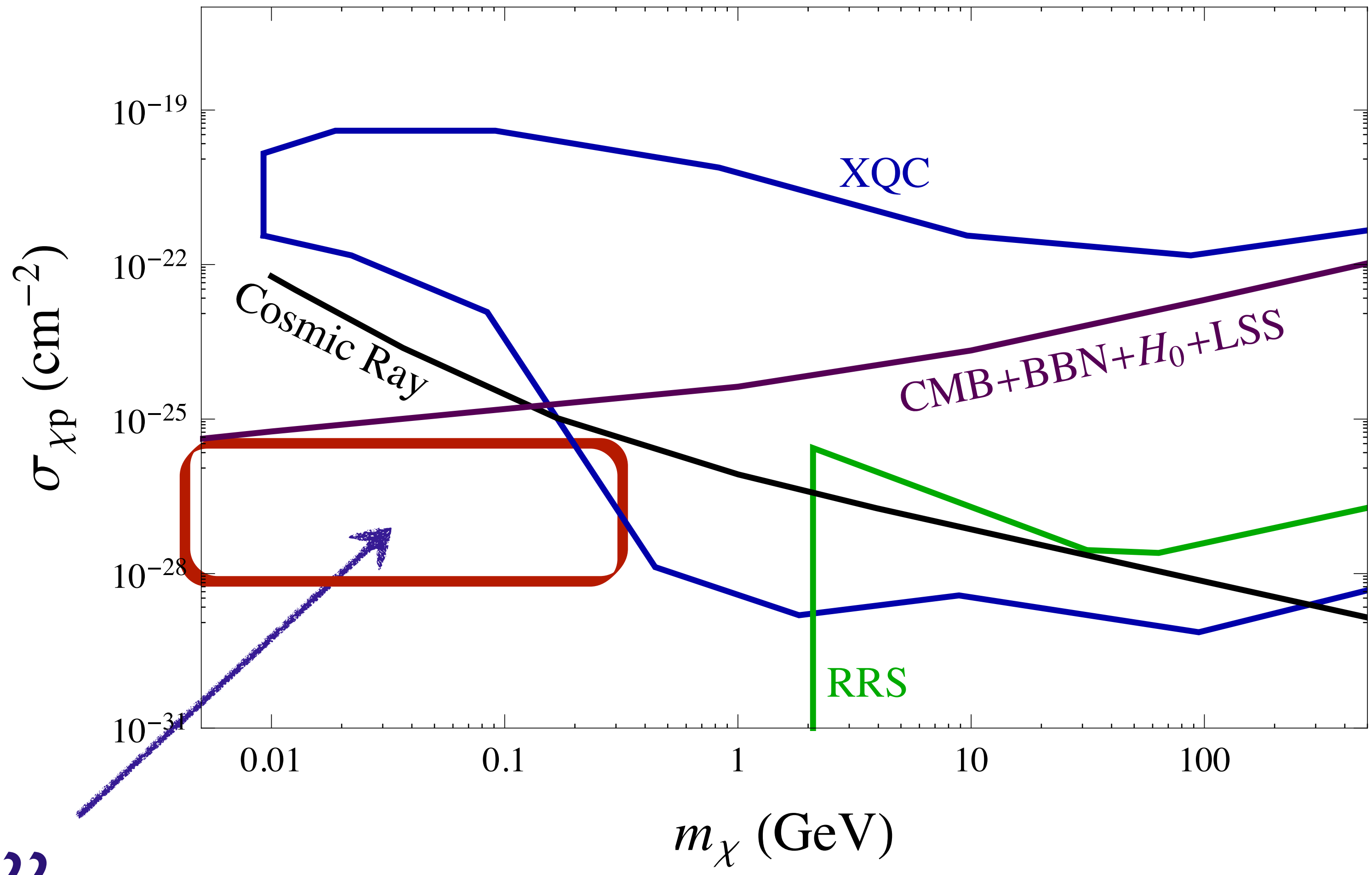
$$\frac{\bar{u}\,u\,\bar{\chi}_e\,\chi_g}{\Lambda_3^2}$$

Those limits can be improved a lot if using the displaced information

Strongly interacting massive particle (SIMP)

Starkman, Gould, Esmailzadeh and Dimopoulos, Phys. Rev. D 41, 3594 (1990).

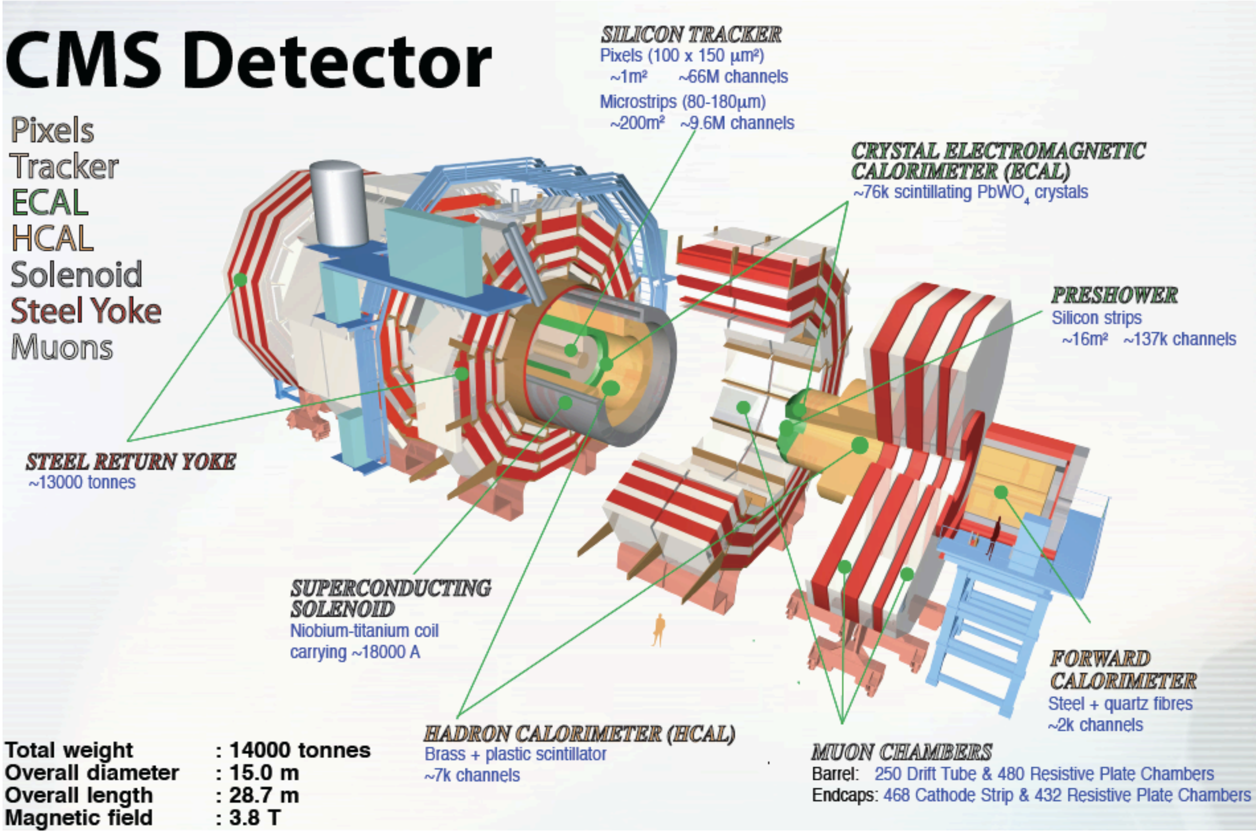
Spergel, Steinhardt: PRL 84, 3760 (2000)



???

Dark Matter Jets

YB, Arvind Rajaraman
1109.6009



$$\mathcal{O} = \frac{i\, g_\chi\, g_q\, \bar{\chi}\chi\, \bar{q}q}{q^2 - M_\phi^2}$$

$$\lambda_I = \frac{A}{N_A \cdot \rho \cdot \sigma^{inela}}$$

$$\text{For iron: } \lambda_I^n = 16.8 \text{ cm}$$

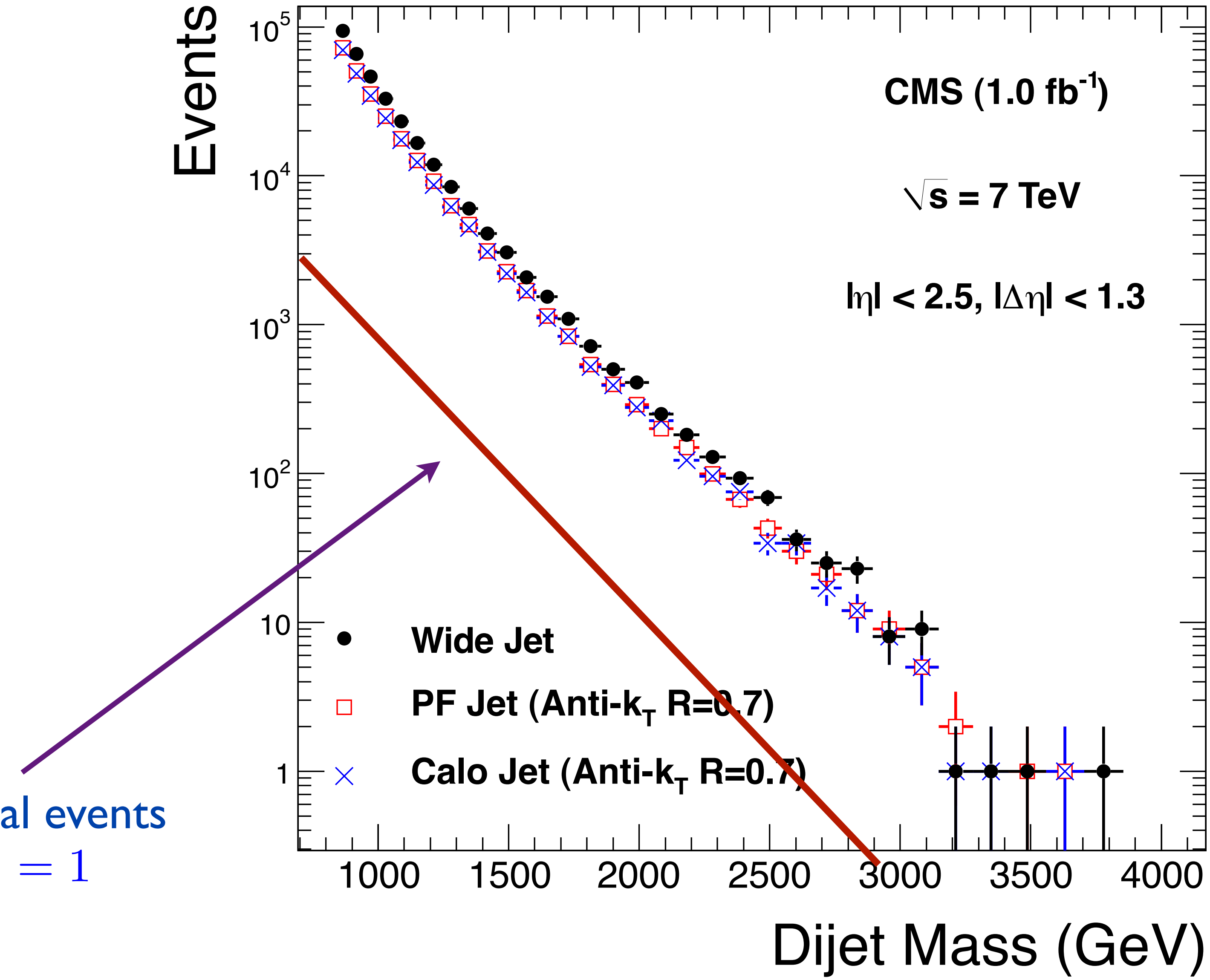
$$\text{For Copper: } \lambda_I^n = 15.2 \text{ cm}$$

$$\text{HCAL: } \sim 10\ \lambda_I$$

$$\text{ECAL: } \sim 1\ \lambda_I$$

Strongly interacting dark matter will be stopped mainly in the HCAL and behaves like a fast neutron

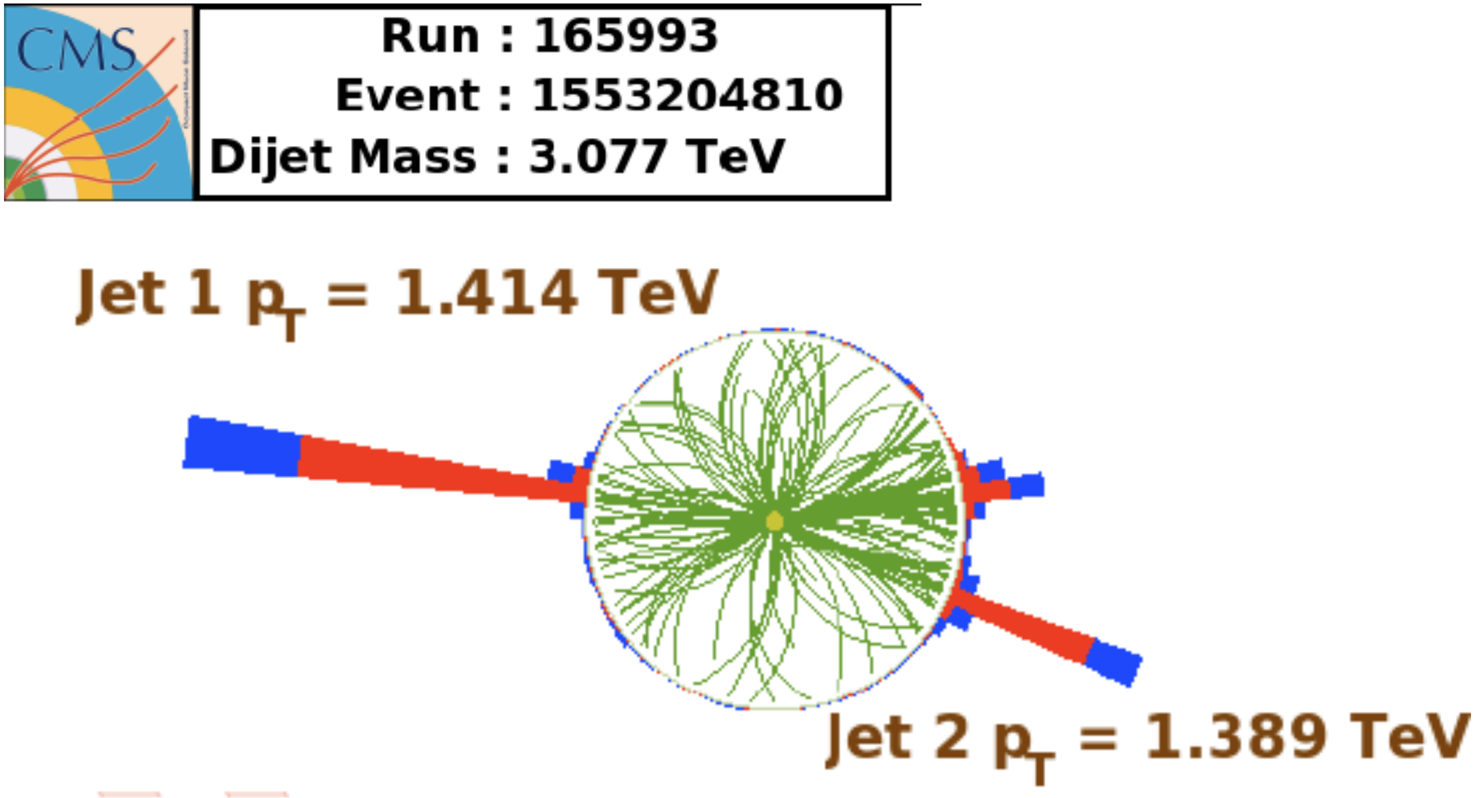
dark matter $\neq$ missing energy at the LHC



SIMP signal events

$g_\chi g_u = 1$

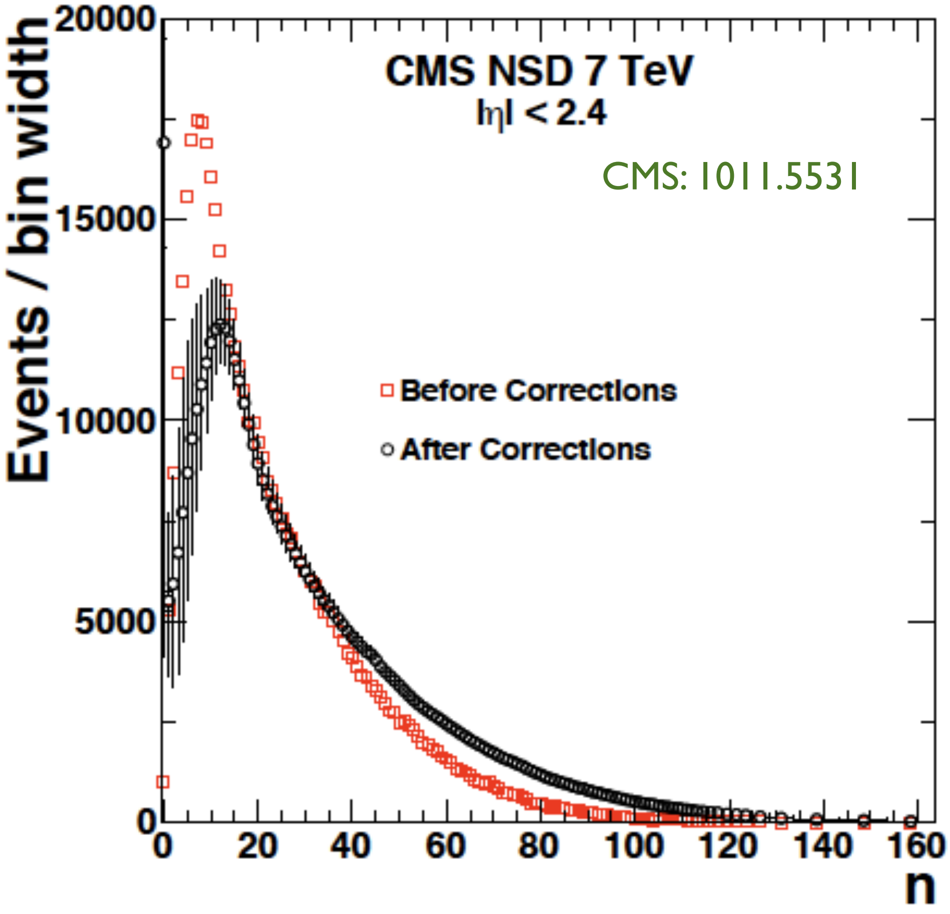
seems to be difficult to dig out the SIDM signature

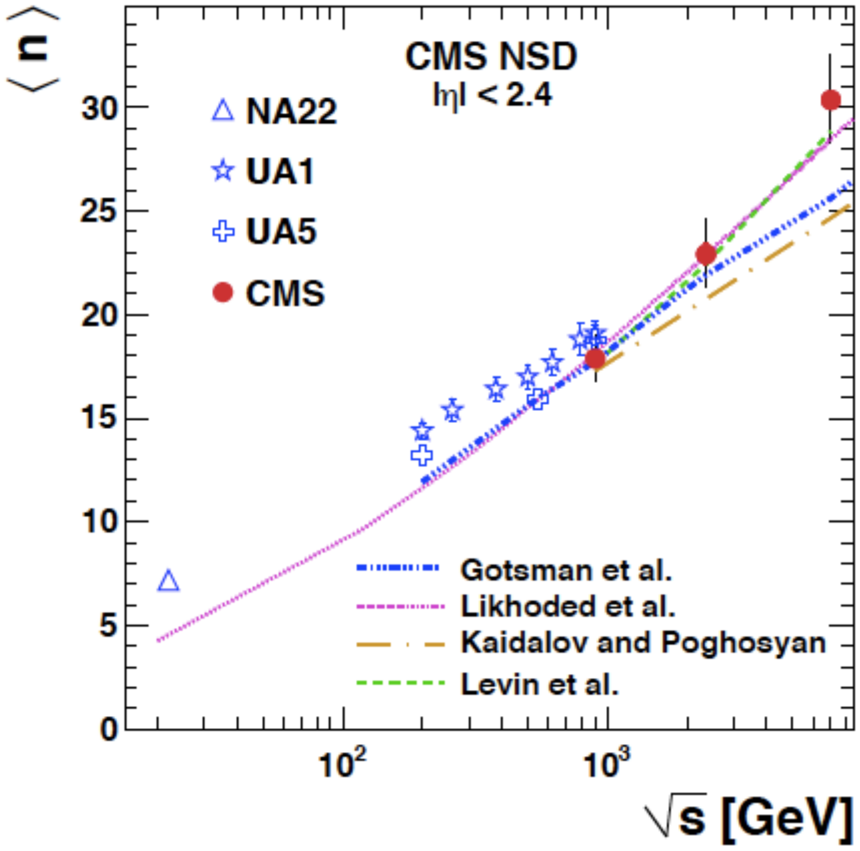


The SIMP signature is different from ordinary dijet

- No tracks: ***trackless jet***
- Less electromagnetic energy

- No tracks: ***trackless jet***


CMS: 1011.5531

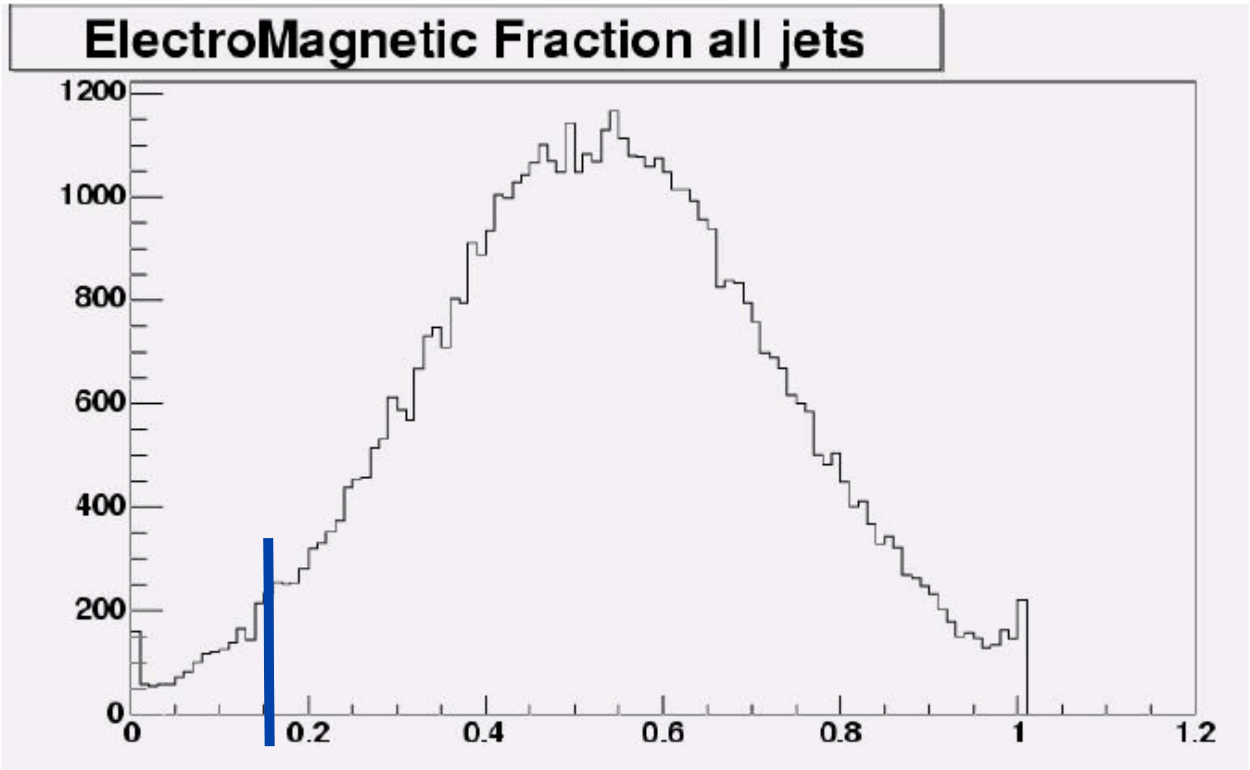


Koba-Nielsen-Olesen scaling

$$P(n) = \frac{1}{\langle n \rangle} e^{-n/\langle n \rangle}$$

using the no-track cut, one can reduce the background by ~ $\left(\frac{1}{20}\right)^2$

- Less electromagnetic energy



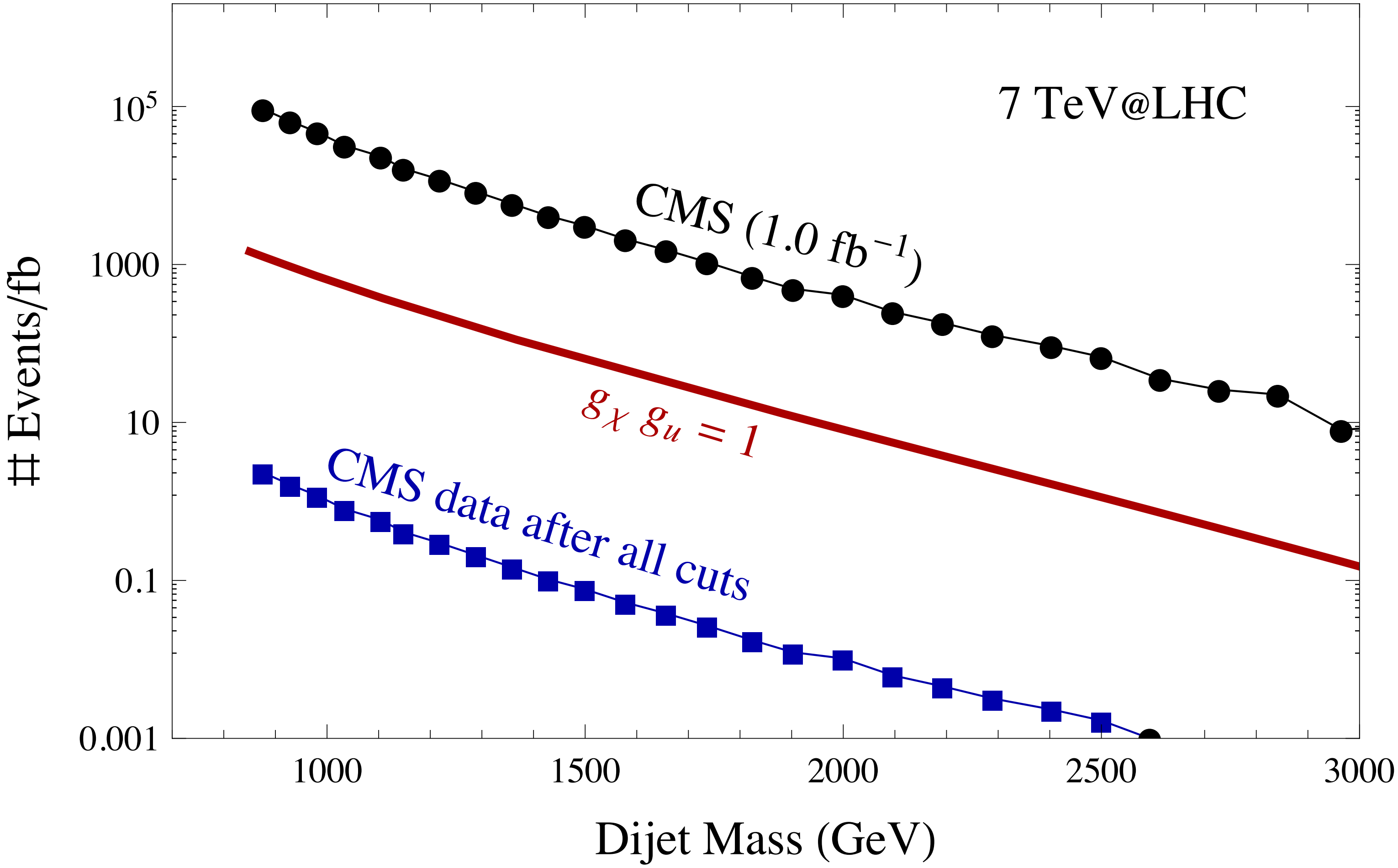
Maria Spiropulu,
talk at ISHEPAC05

EMF=Jet electromagnetic fraction= EM/(EHAD+EM) (CMS jets)

using the cut for less EM in jets, we can reduce the backgrounds by another factor of ~ 1/100

It is promising to discover SIMP at the LHC

Estimated reduction of the backgrounds



Reliable analysis requires detector simulations

Conclusion

- A lot of non-standard DM scenarios can only be explored at colliders. There could be more interesting scenarios and signatures that we have not thought about
- The generic signatures of iDM at the LHC could be one hard jet + missing energy + displaced pions
- The signature of SIMP is trackless jets
- The discovery limits are promising even for the 7 TeV LHC

Thanks