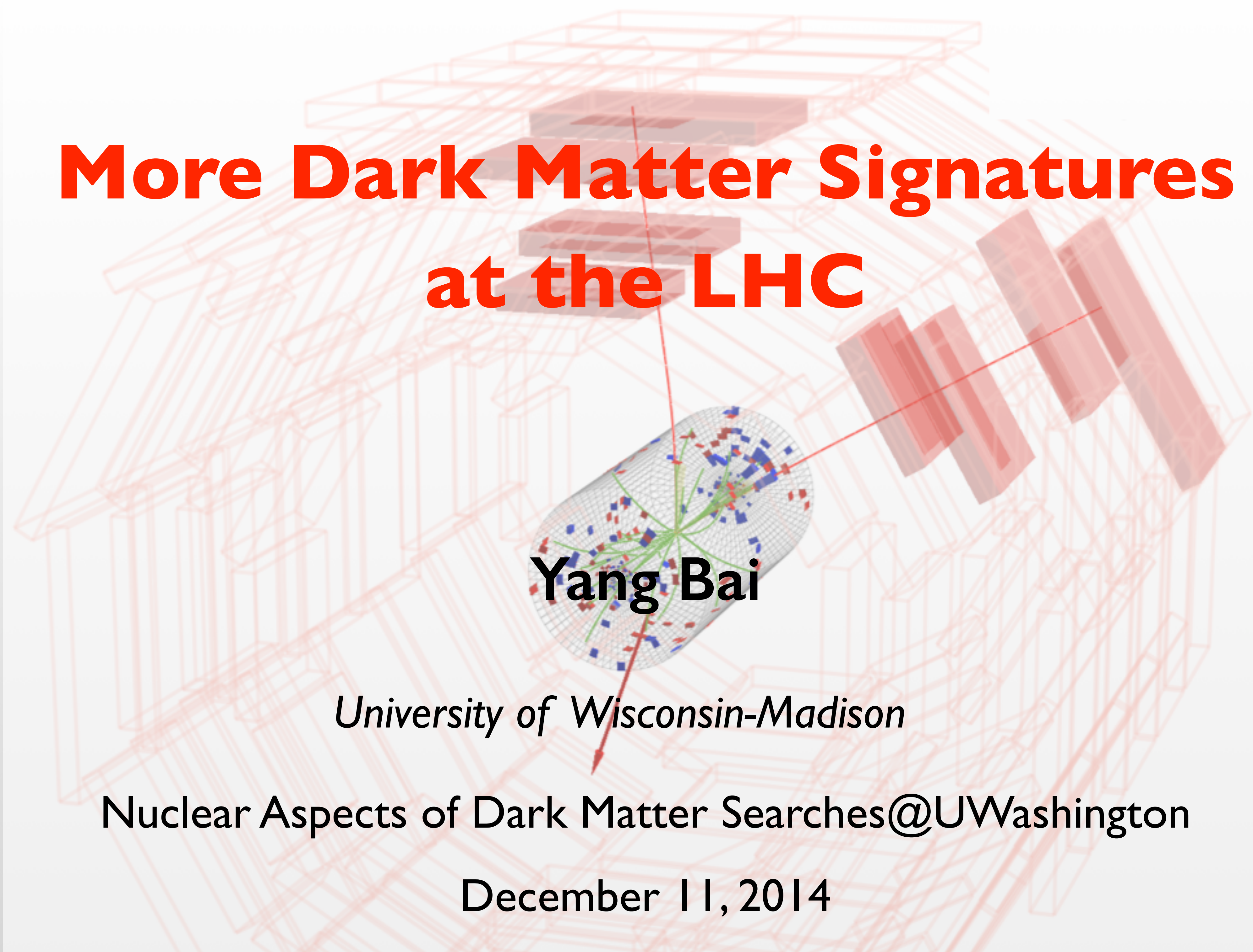


More Dark Matter Signatures at the LHC

Yang Bai

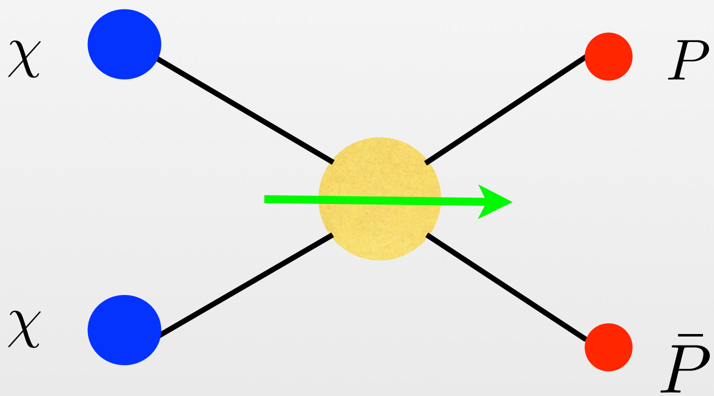
University of Wisconsin-Madison

Nuclear Aspects of Dark Matter Searches@UWashington

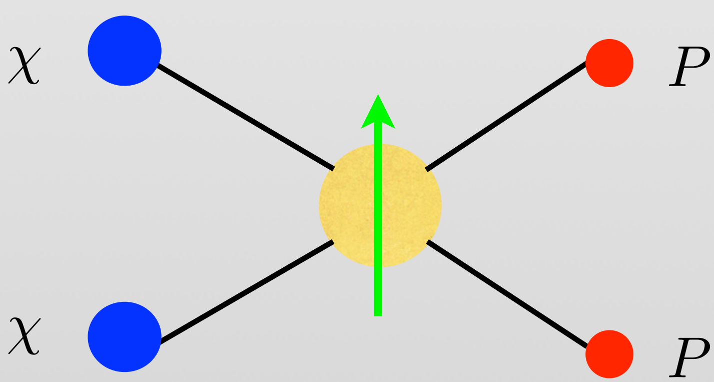
December 11, 2014

Hunt of Dark Matter

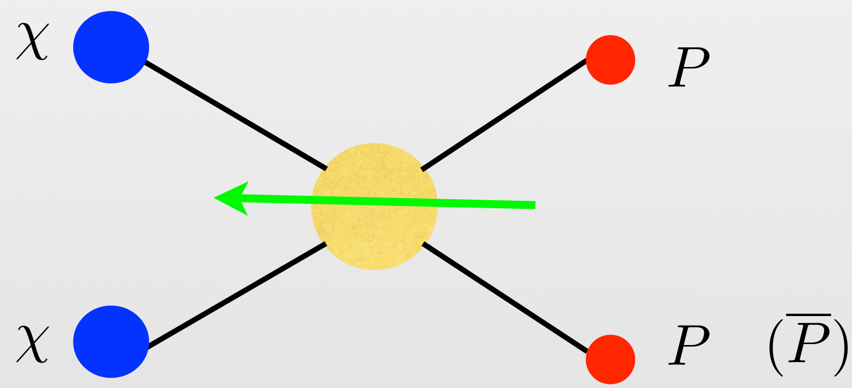
Indirect Detection



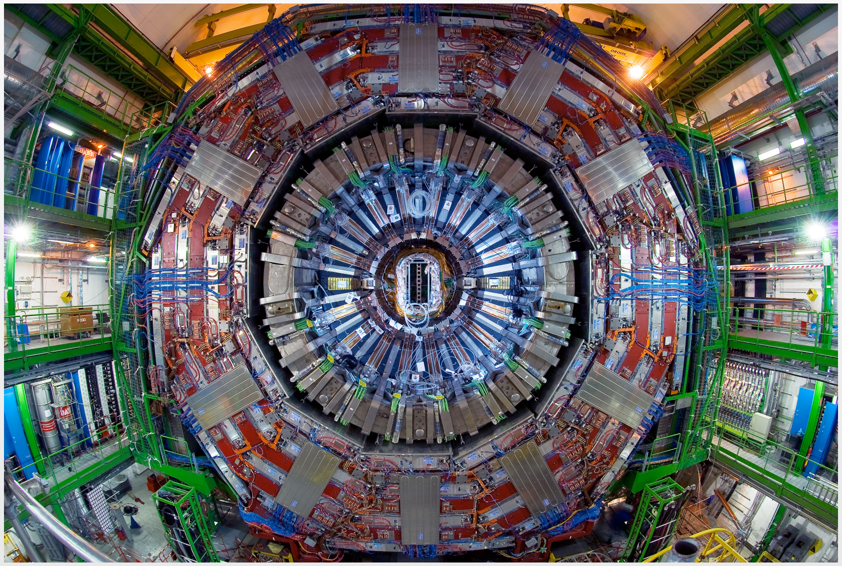
Direct Detection



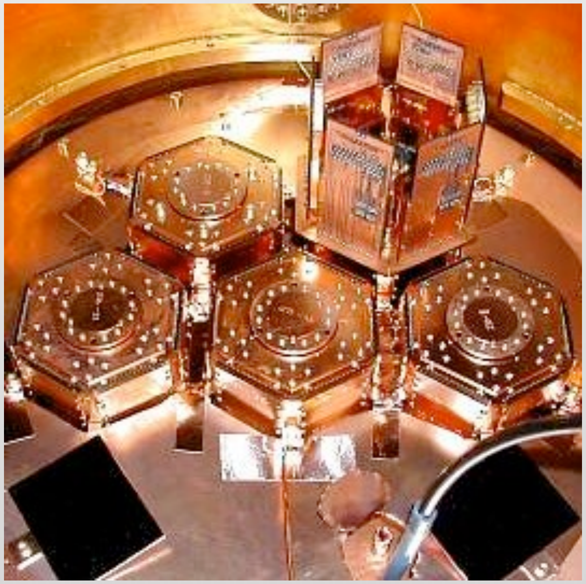
Colliders



Collider vs. Direct Detection

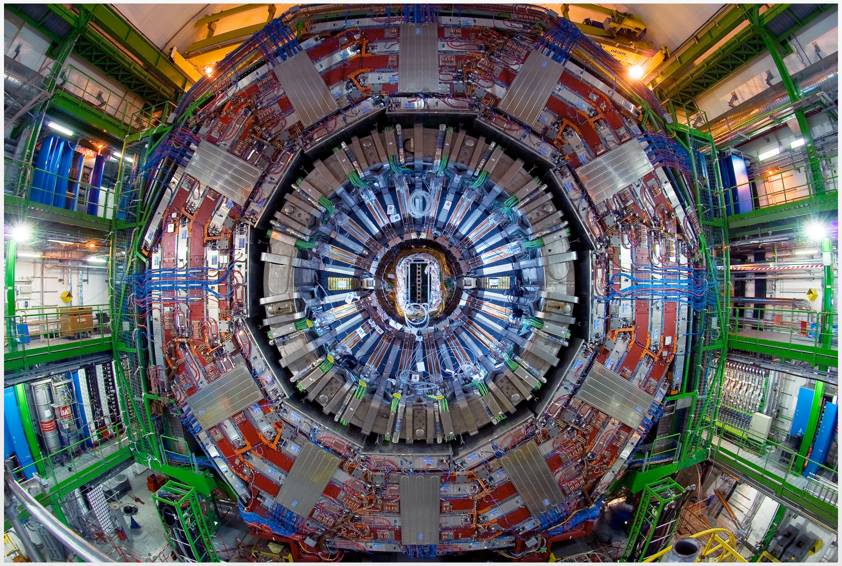


- more complicated detector
- know when to produce DM
- don't know whether it is *the* dark matter
- limited for very heavy mass

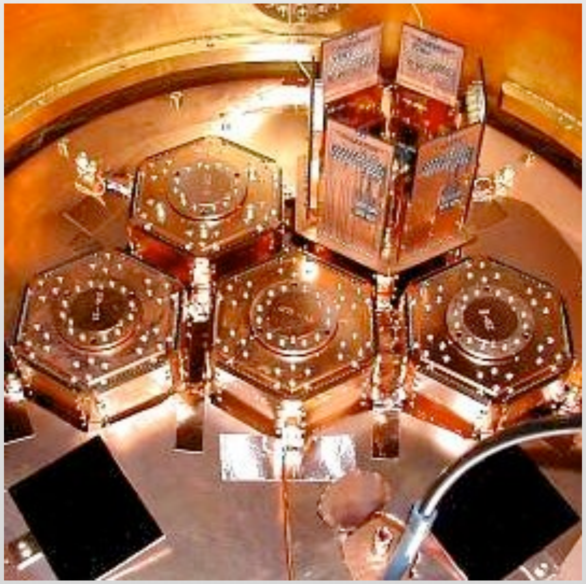


- less complicated detector
- wait for DM collision
- search for *the* dark matter
- limited for very light mass

Different Backgrounds



- Standard Model processes
- background-rich environment



- backgrounds for detectors
- cosmic rays
- small background

Different Interpretation Uncertainties

Collider	Direct Detection
• Parton distribution function	• Nuclear form factor
• Validity of the model description	• Astrophysical: density and velocity distributions

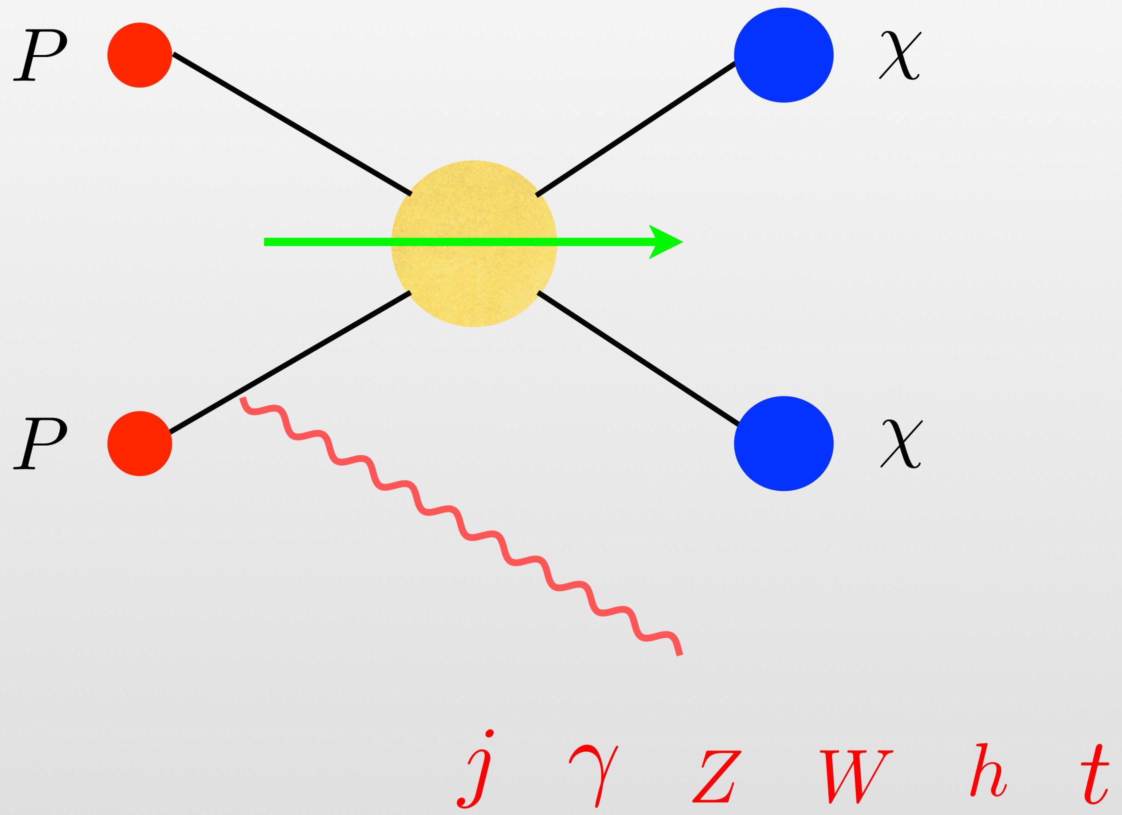
$$m_c \bar{c}\, i\gamma_5 c \to -\frac{\alpha_s}{8\pi} G\widetilde{G}$$

$$\frac{\alpha_s}{8\pi} G\widetilde{G} \to (389\ \mathrm{MeV})\, \overline{p}\, i\, \gamma_5\, p \qquad (-2\ \mathrm{MeV}) \overline{n}\, i\, \gamma_5\, n$$

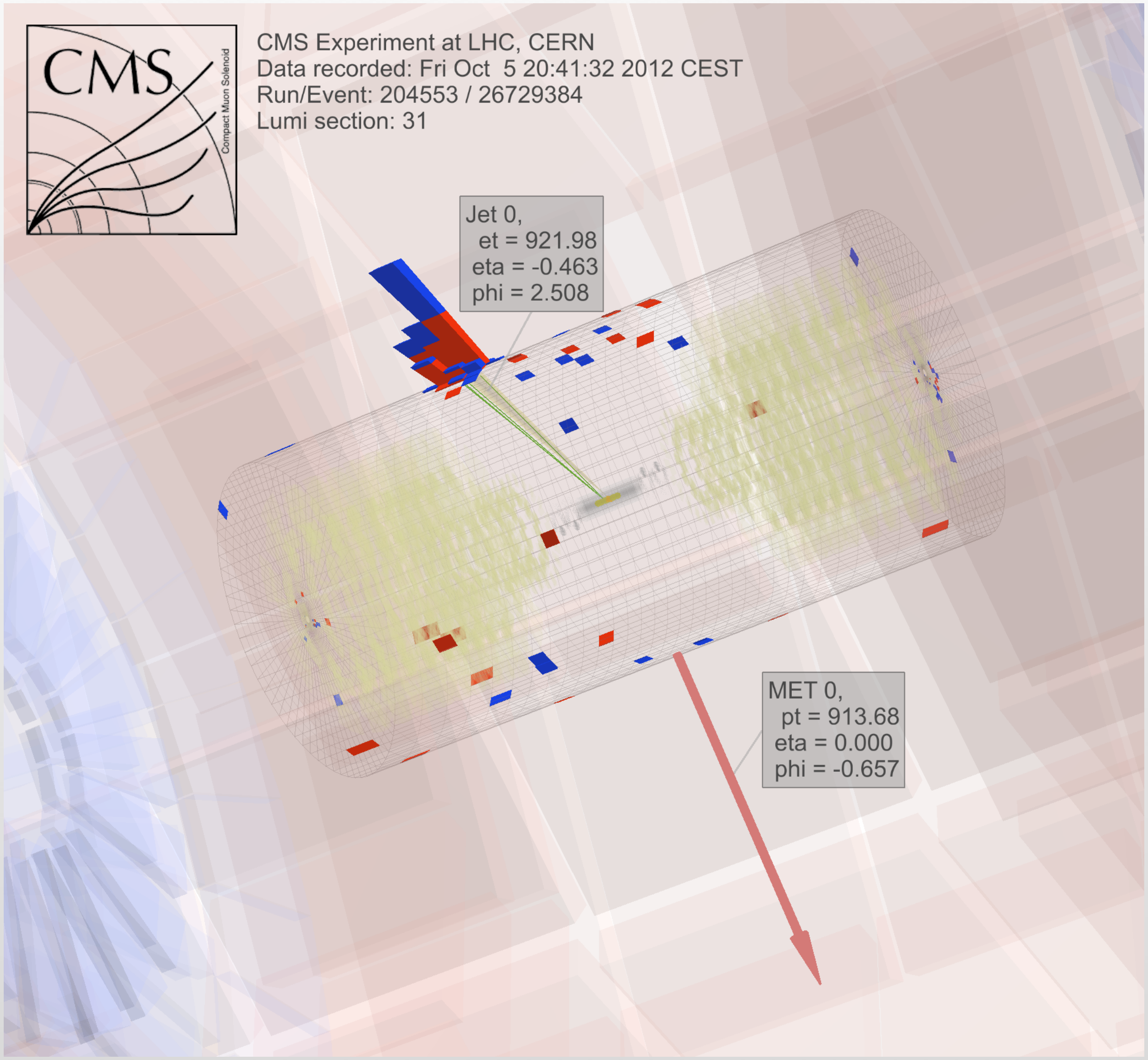
Large uncertainties

Cheng, Chiang, arxiv:1202.1292

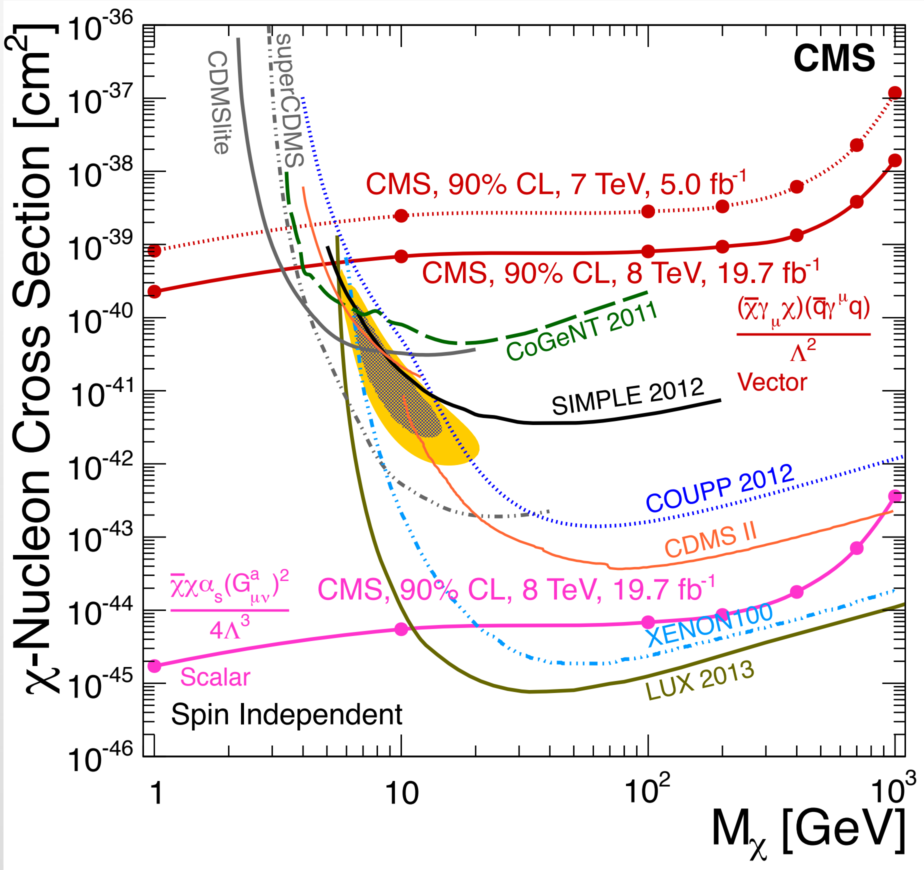
Model Independent Signature

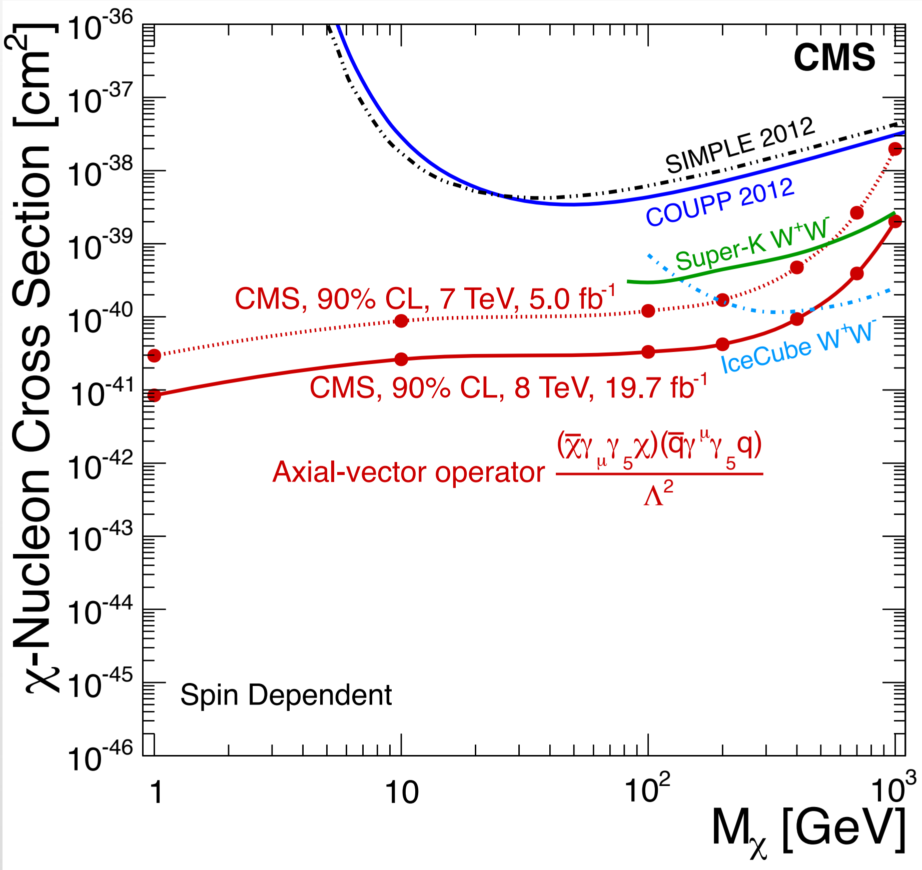


Standard Signature: monojet+MET

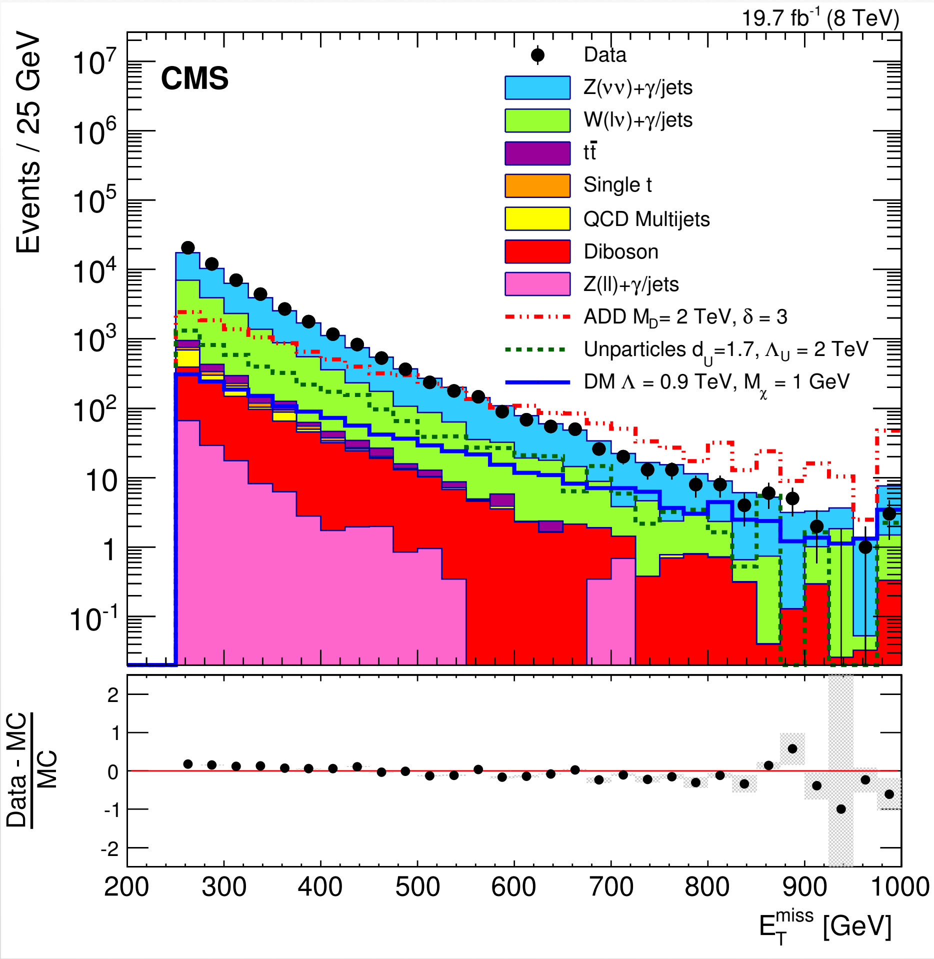


Fermi-theory for Dark Matter





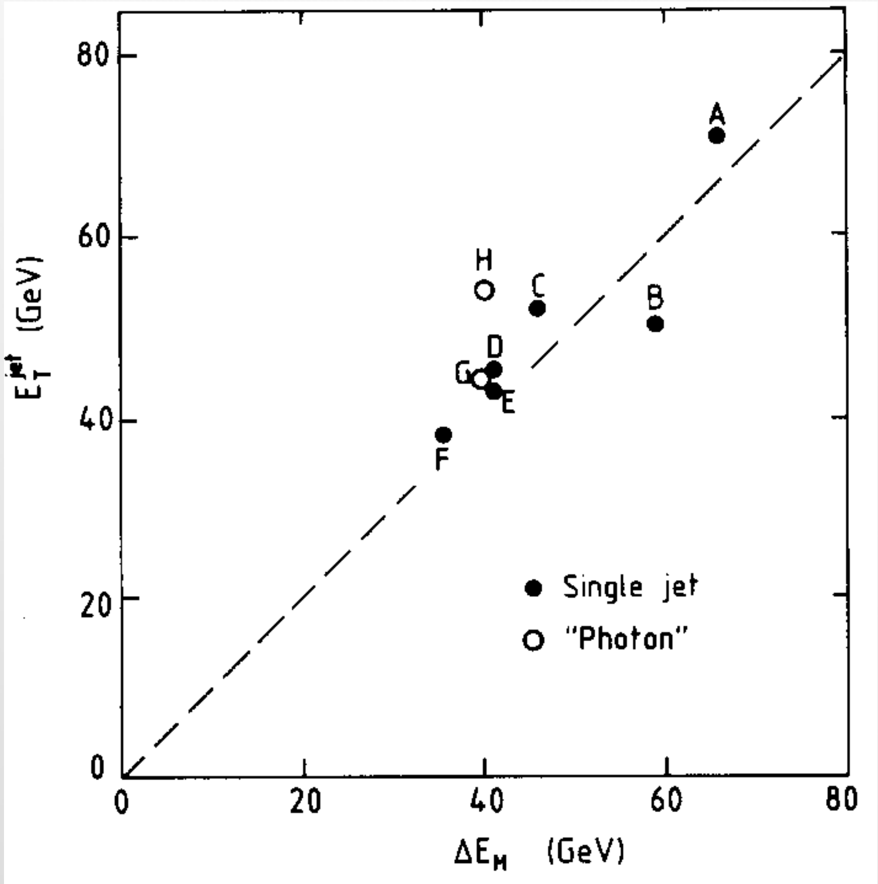
Standard Signature: monojet+MET



E_T^{miss} (GeV) $\rightarrow$	$>$500
$Z(\nu\nu)$+jets	747 ± 96
W+jets	249 ± 22
$t\bar{t}$	6.6 ± 3.3
$Z(\ell\ell)$+jets	2.3 ± 1.2
Single t	—
QCD multijets	1.0 ± 0.6
Diboson	36 ± 18
Total SM	1040 ± 100
Data	934

dominated by systematic errors

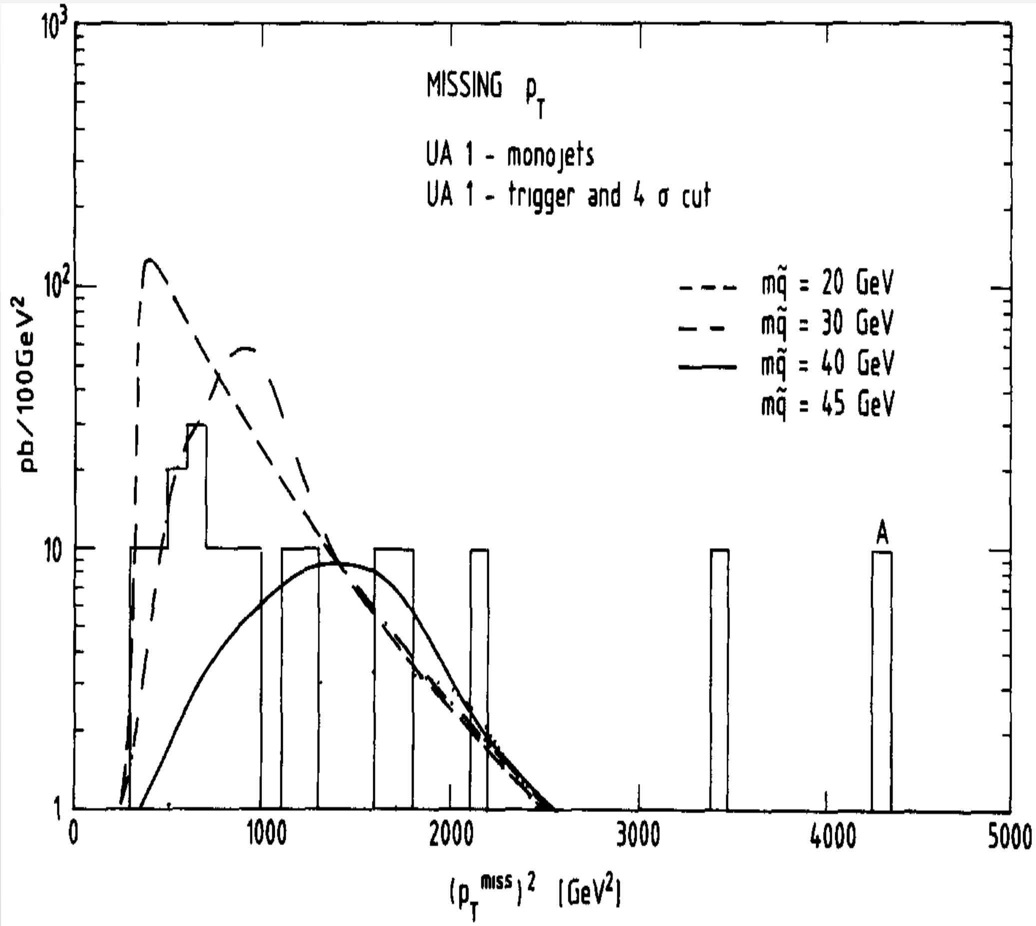
Historical "Discovery" of SUSY in Monojet



UA1, PLB, 139, 115 (1984)

Historical "Discovery" of SUSY in Monojet

SUSY



J. Ellis and H. Kowalski, NPB, 246, 189 (1984)

SM

Channel	1 Jet	2 Jets (a)	2 Jets (b)	Total
$Z \to \nu\bar{\nu}$	2.89	0.68	1.17	4.74
$W \to \not{e}$	1.34	0.21	0.29	1.84
$W \to \not{\mu}$	0.03	0.008	0.005	0.04
$W \to \tau \to \not{e}$	0.35	0.10	0.15	0.60
$W \to \tau \to \not{\mu}$	0.12	0.03	0.05	0.20
$W \to \tau \to h$	1.61	0.31	0.57	2.49
TOTAL	6.34	1.34	2.23	9.91

S. Ellis, R. Kleiss and W. Stirling, PLB, 158, 341 (1985)

Cleaner Signatures for Dark Matter

EFT Framework

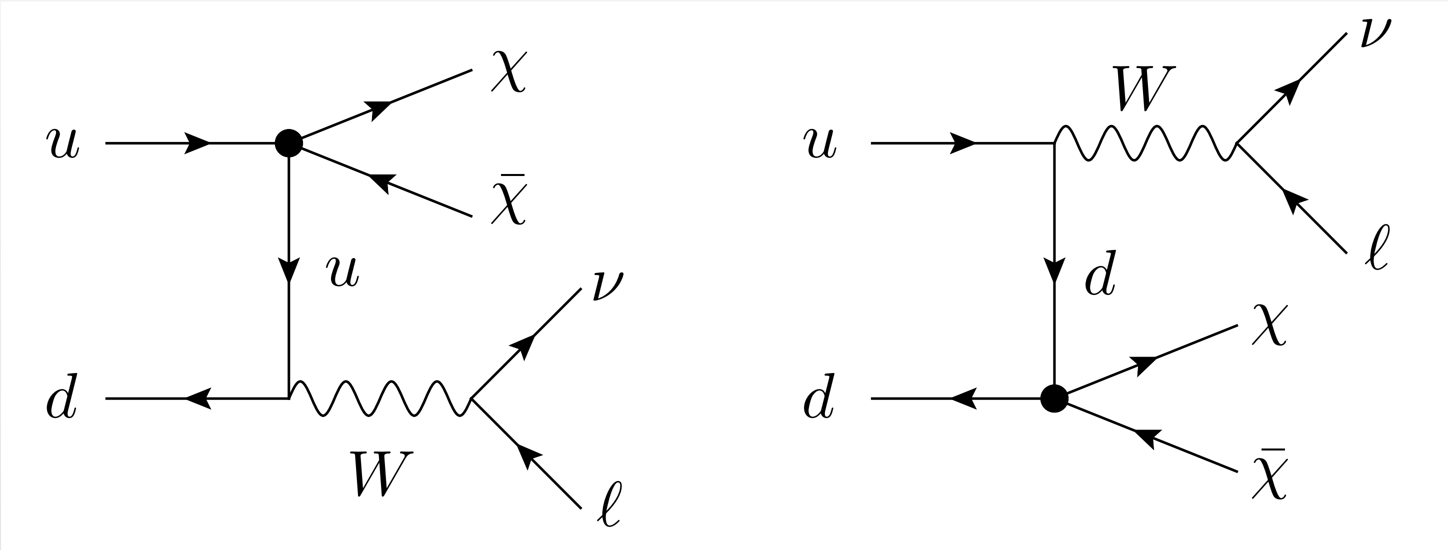
other radiated particles from proton can be better measured

Simplified Models

UV-complete the EFT operators may lead to cleaner signatures

EFT Framework

leptons are better measured: mono-lepton



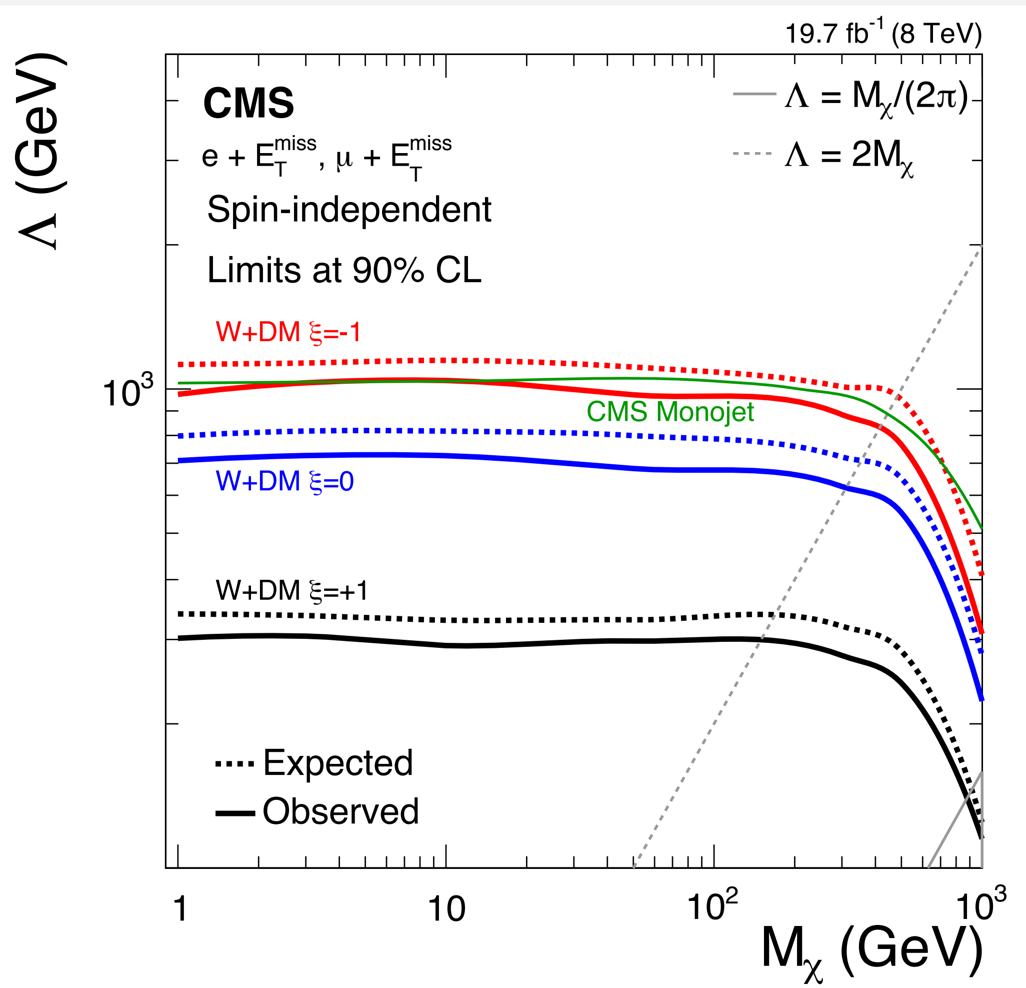
YB and Tait, 1208.4361

mono-Z (dilepton):

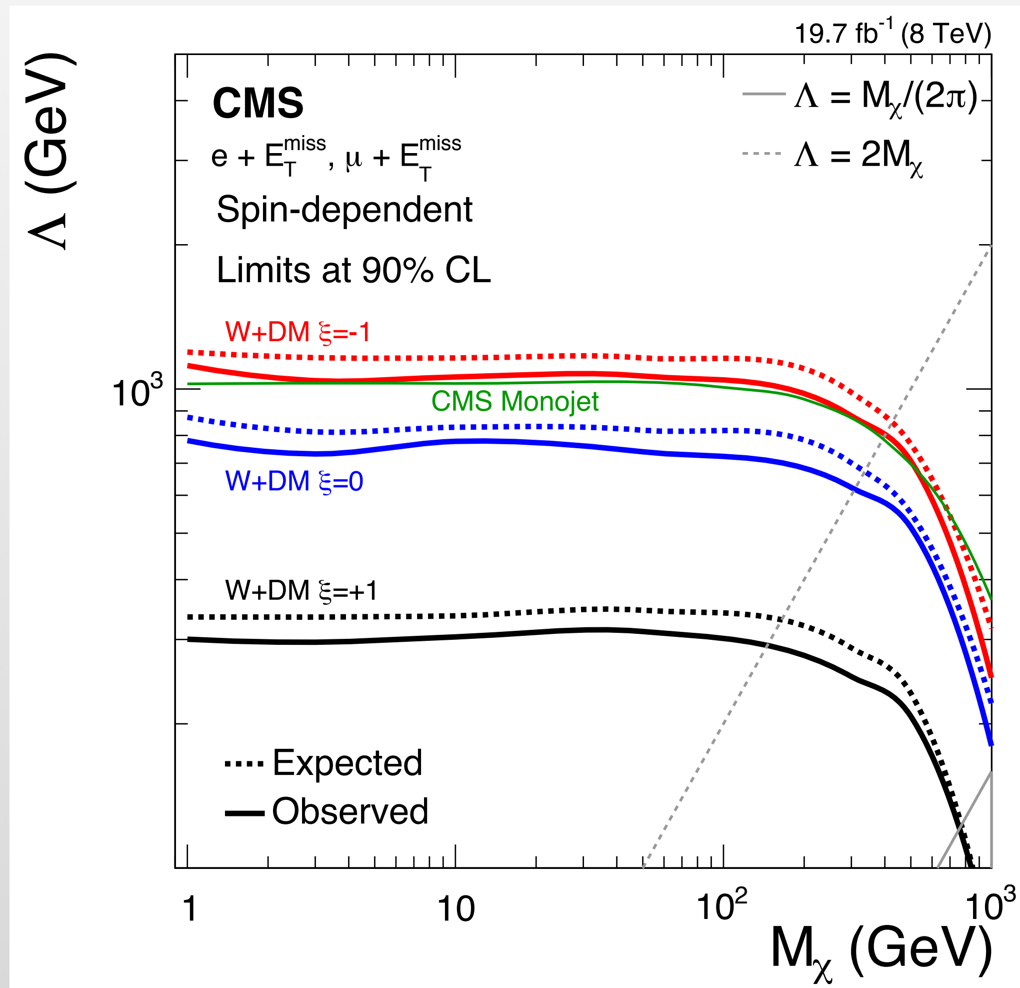
Bell et. al., 1209.0231
Carpenter: 1212.3352

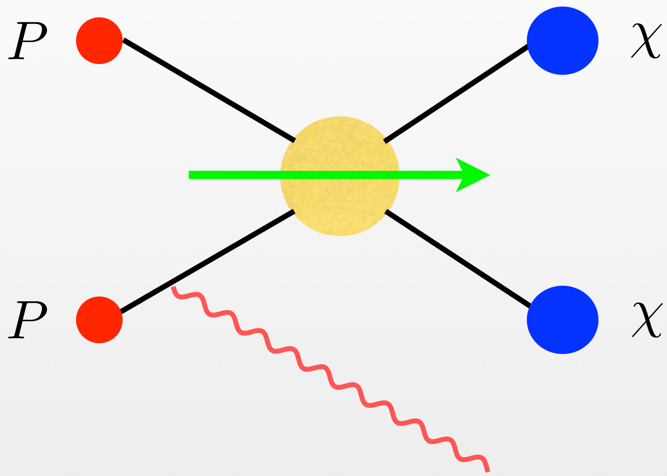
Limits from Mono-lepton

$$\frac{1}{\Lambda^2}\,\overline{\chi}\gamma_\mu\chi\ \left(\overline{u}\gamma^\mu u + \xi\ \overline{d}\gamma^\mu d\right)$$



$$\frac{1}{\Lambda^2}\,\overline{\chi}\gamma_\mu\gamma_5\chi\ \left(\overline{u}\gamma^\mu\gamma_5 u + \xi\ \overline{d}\gamma^\mu\gamma_5 d\right)$$





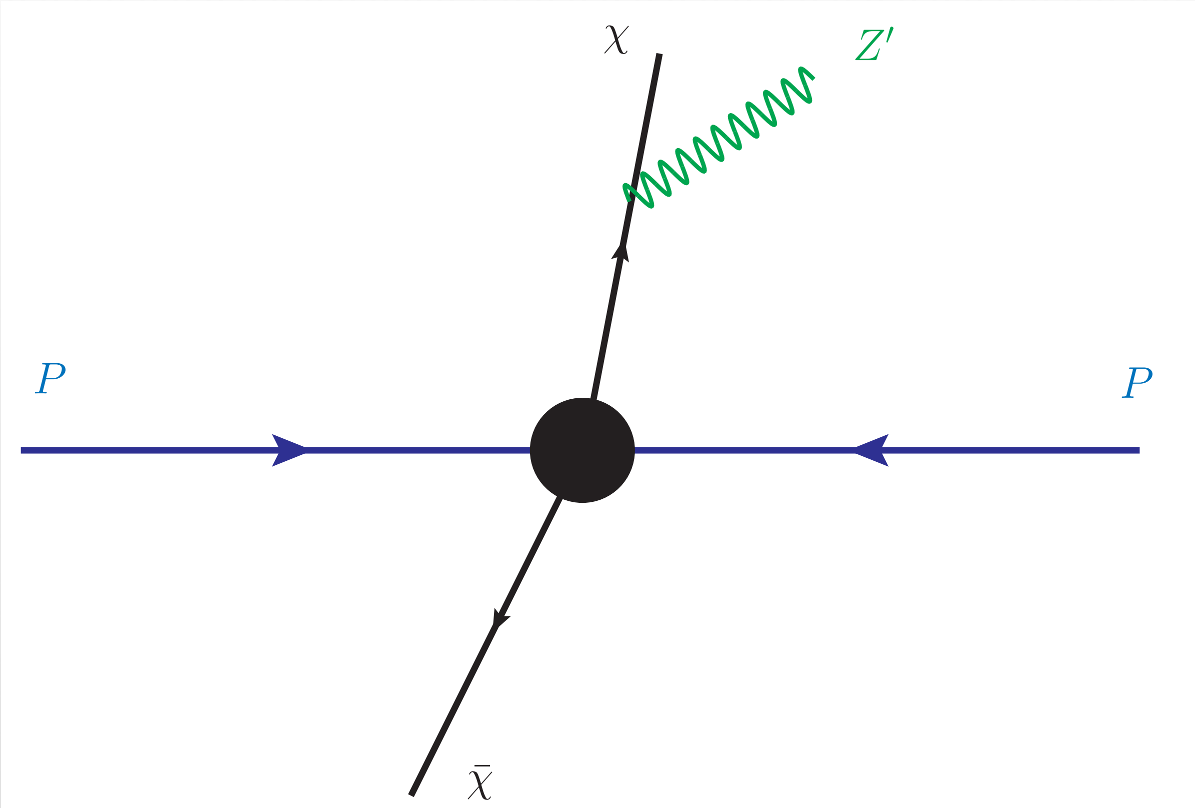
so far, we have considered only initial state radiation of visible particle

Dark sector could be more interesting:

- It may has its own dark U(1)'

- It may also have some nearby states

Probing Dark U(1)' at the LHC



$$\mathcal{O}_V = \frac{\overline{\chi}\gamma^\mu\chi\,\overline{u}\gamma_\mu u}{\Lambda^2}$$

$$g_\chi Z'_\mu \overline{\chi}\gamma^\mu\chi$$

Dark matter final state radiated a Z', the signature depends on how Z' decay

YB, James Bourbeau, Tongyan Lin; in progress

Dark Z' Decay

$$\frac{\tilde{c}}{\Lambda^2}\left(\phi'^{\dagger} D_\mu \phi' - \phi' D_\mu \phi'^{\dagger}\right)\left(\overline{u}\gamma^\mu u\right) \quad \rightarrow \quad c\,\frac{M_{Z'}^2}{\Lambda^2}\, Z'_\mu\, \overline{u}\gamma^\mu u$$

For a heavy Z', the signature is just like mono-QCD-jet + MET, except the production cross section is increased.

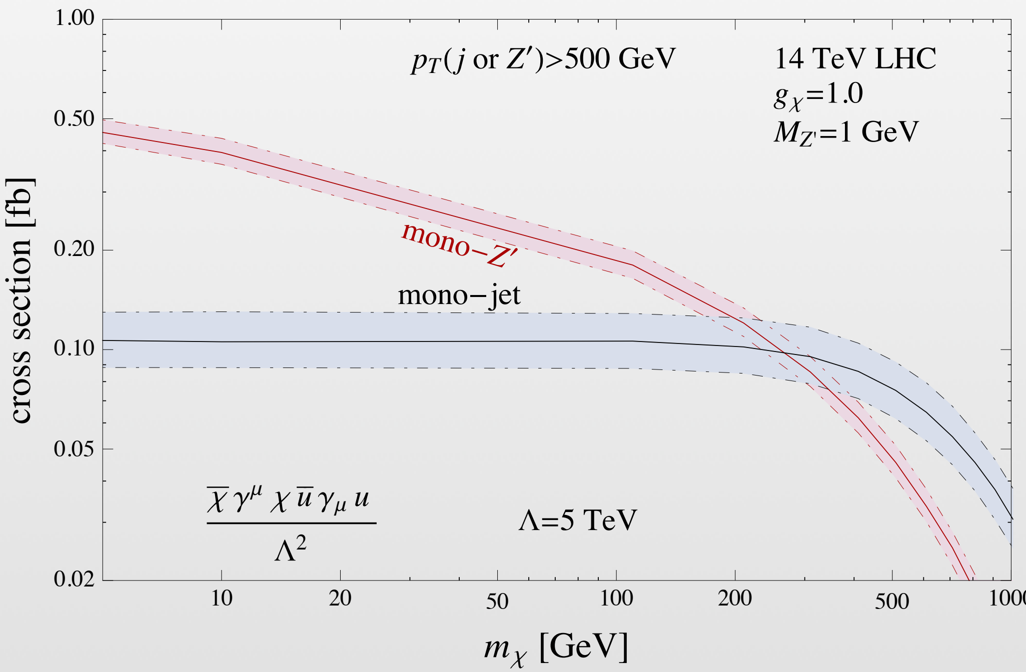
For a light Z' at O(1 GeV), the signature is more interesting $\overline{u}\gamma_\mu u \to \pi^+\partial_\mu\pi^- - \pi^-\partial_\mu\pi^+ + K^+\partial_\mu K^- - K^-\partial_\mu K^+$

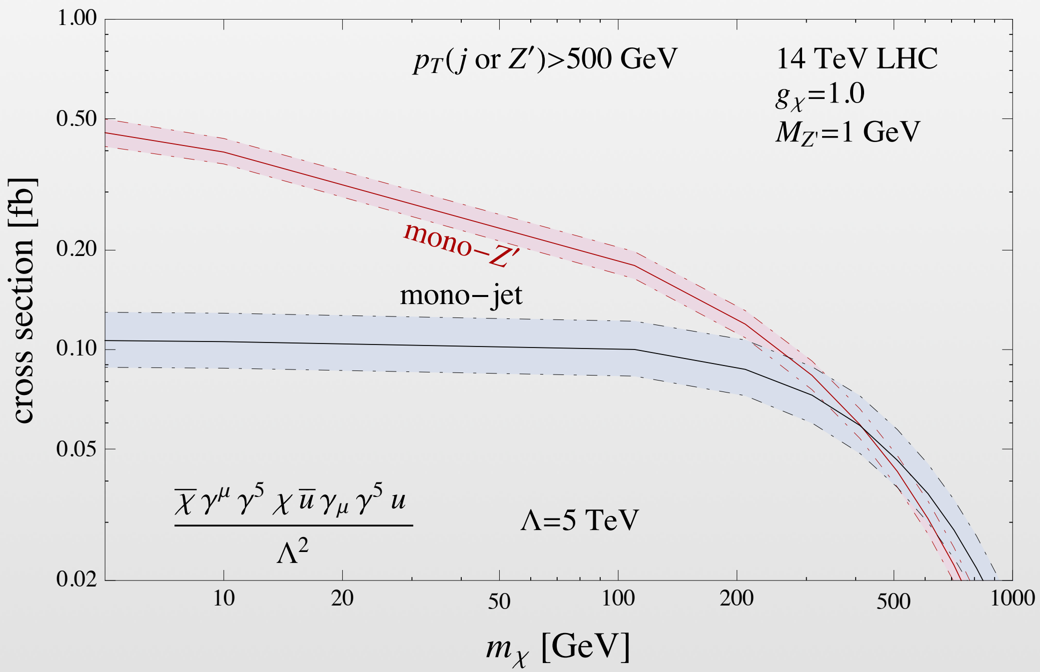
$$\Gamma(Z' \to \pi^-\pi^+) = \frac{M_{Z'}}{48\,\pi}\left(\frac{c\,M_{Z'}^2}{\Lambda^2}\right)^2\left(1 - \frac{4\,m_\pi^2}{M_{Z'}^2}\right)^{3/2}$$

$$c\tau_0 \approx 3\ \mathrm{cm} \qquad\qquad c = 1,\ M_{Z'} = 1\ \mathrm{GeV}\ \mathrm{and}\ \Lambda = 1\ \mathrm{TeV}$$

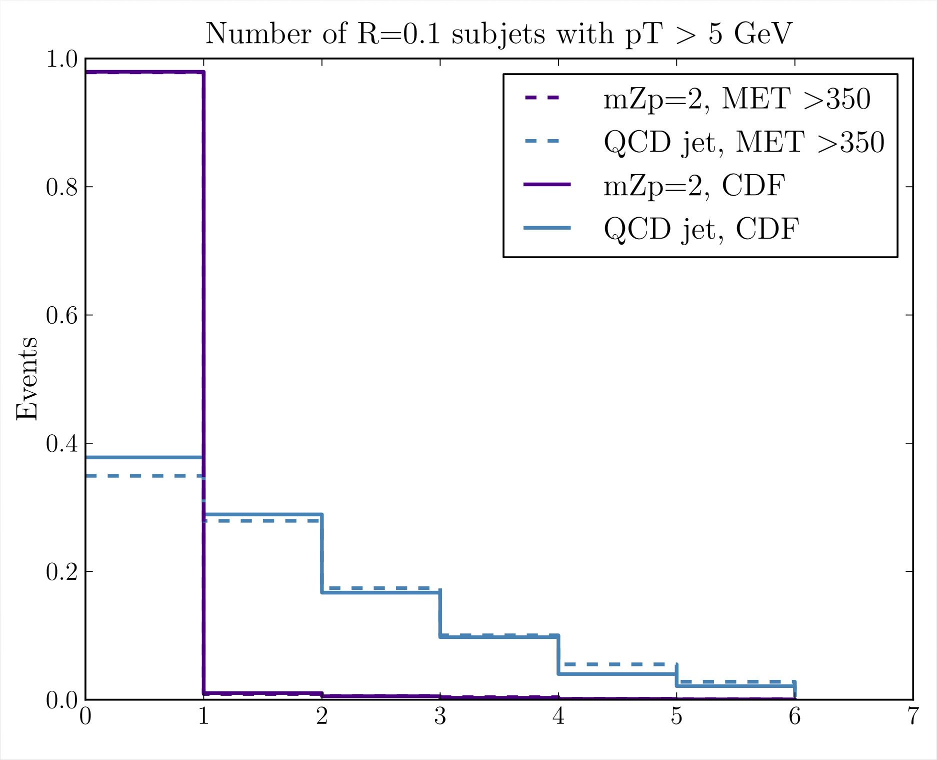
Mono-Z' jet: fewer particles and could be long-lived

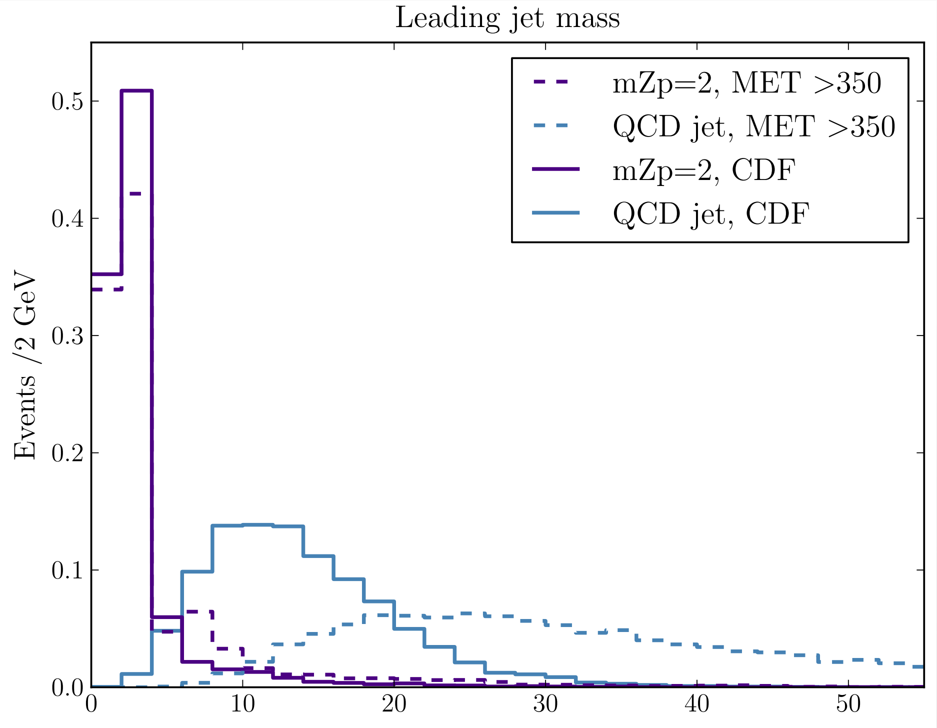
Production Cross Sections



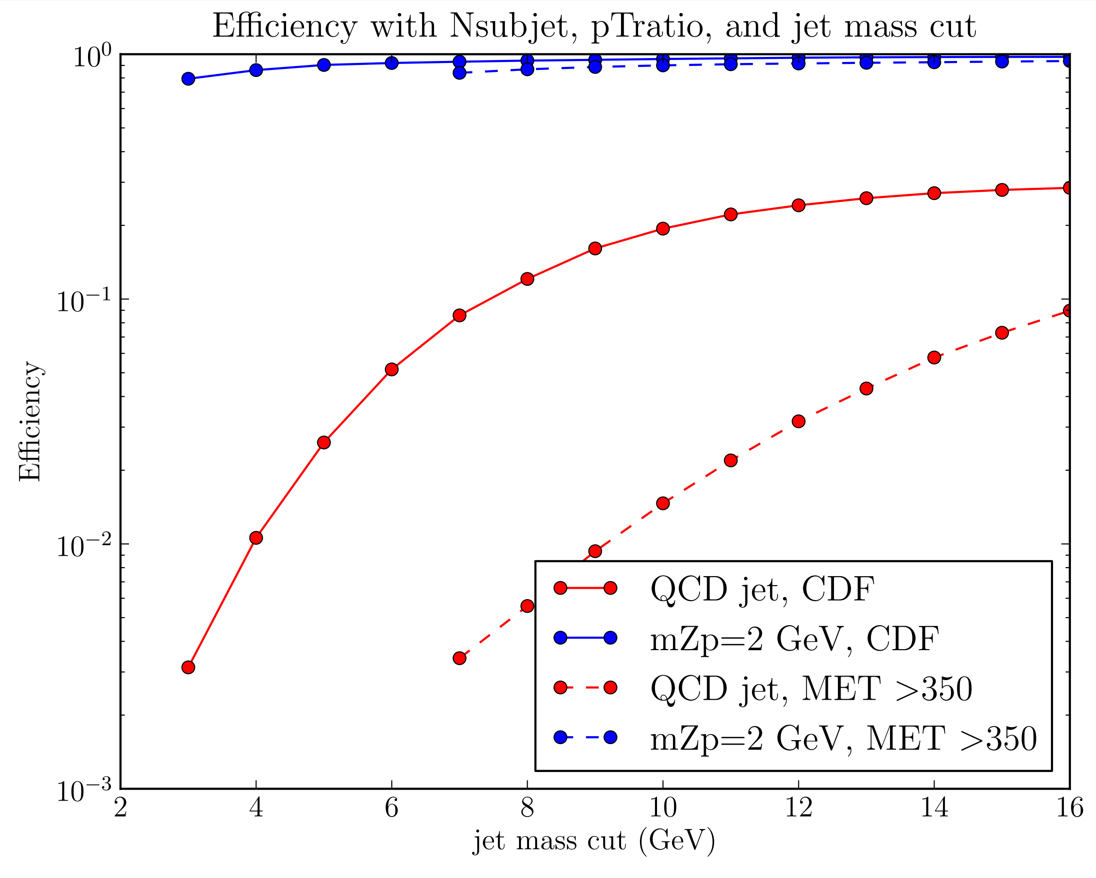


Jet Substructure Analysis





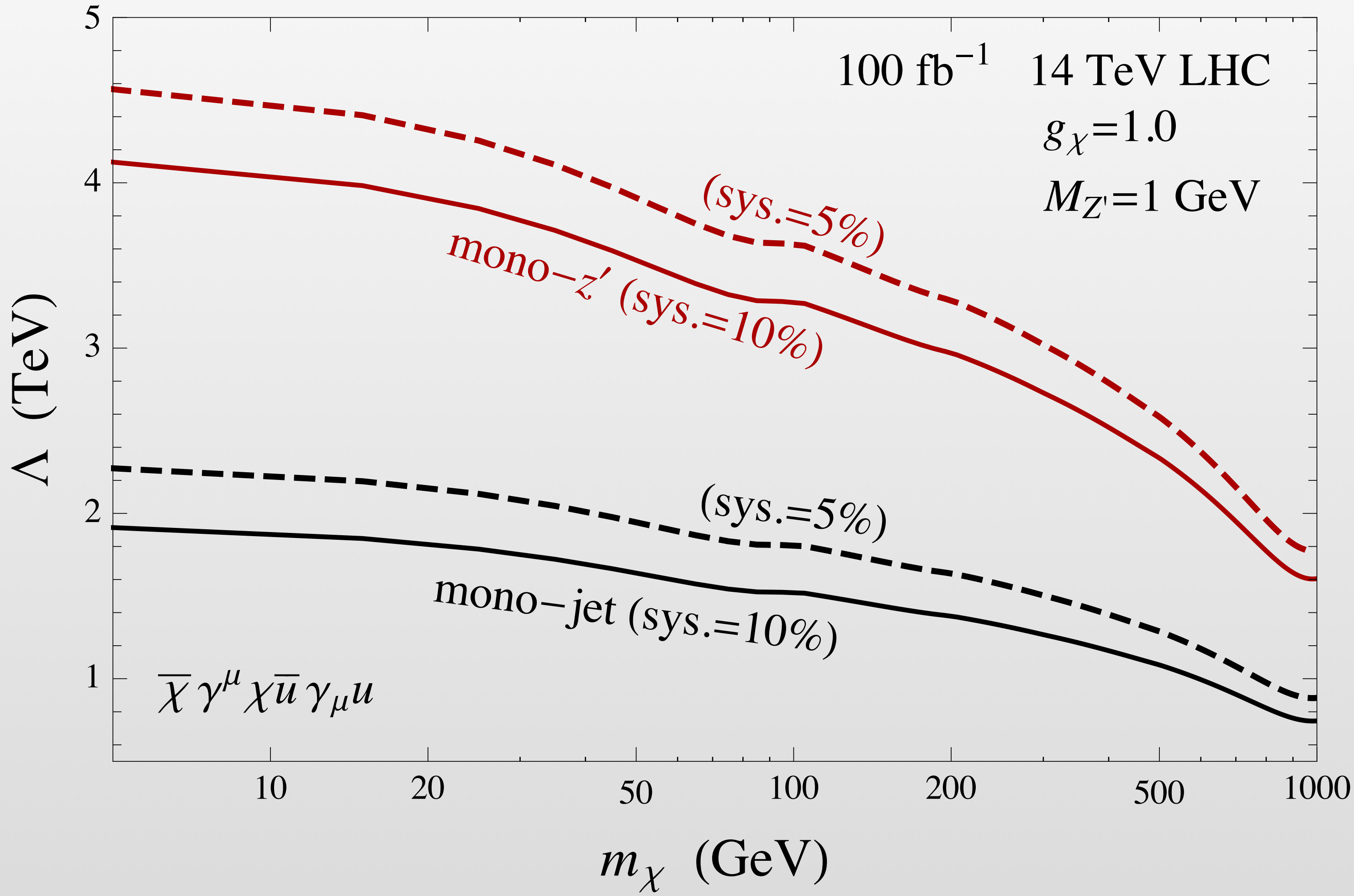
Jet Substructure Analysis



One can dramatically reduce the QCD backgrounds

Discovery Potential

YB, James Bourbeau, Tongyan Lin; in progress



Tag-efficiency: 50% for signal, 2% for QCD

Cleaner Signatures for Dark Matter

EFT Framework

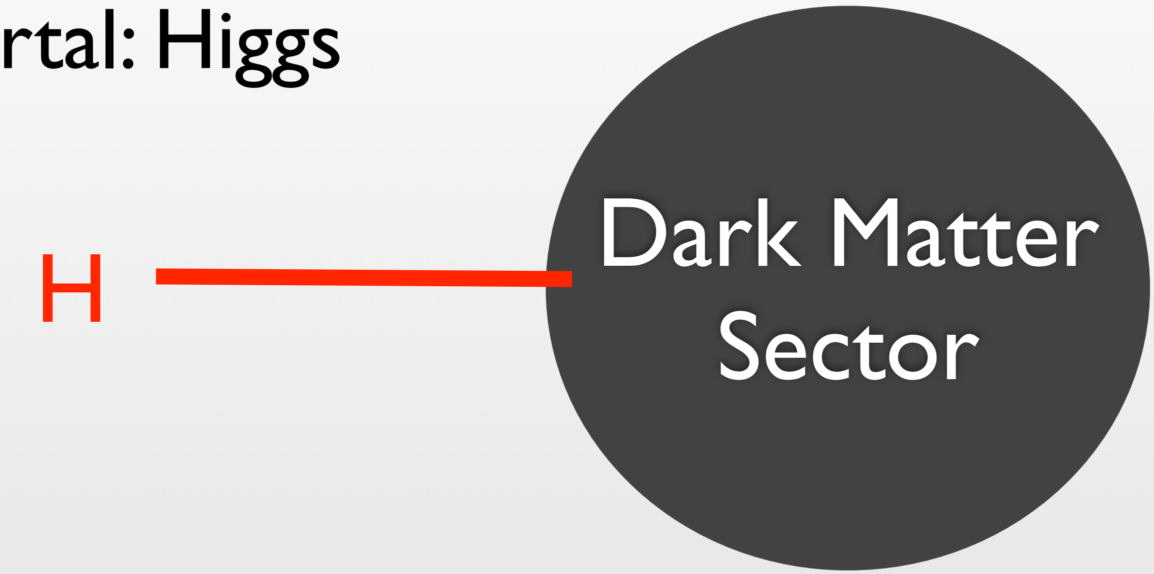
other radiated particles from proton can be better measured

Simplified Models

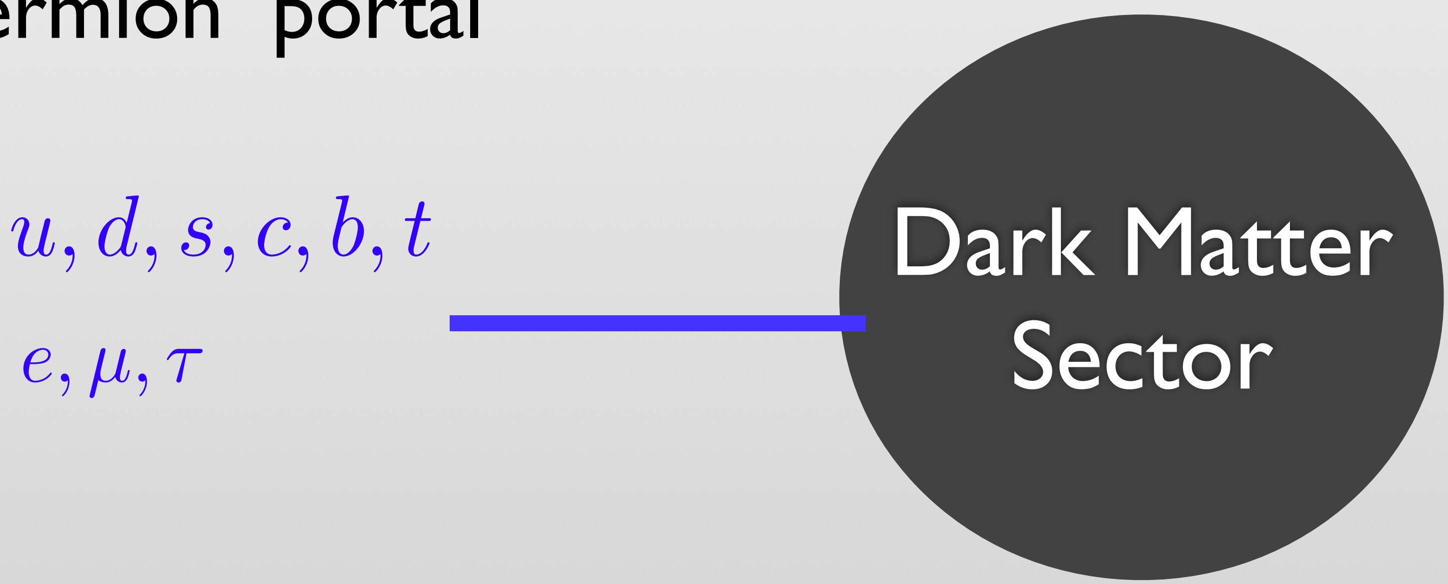
UV-complete the EFT operators may lead to cleaner signatures

Simplified Dark Matter Models

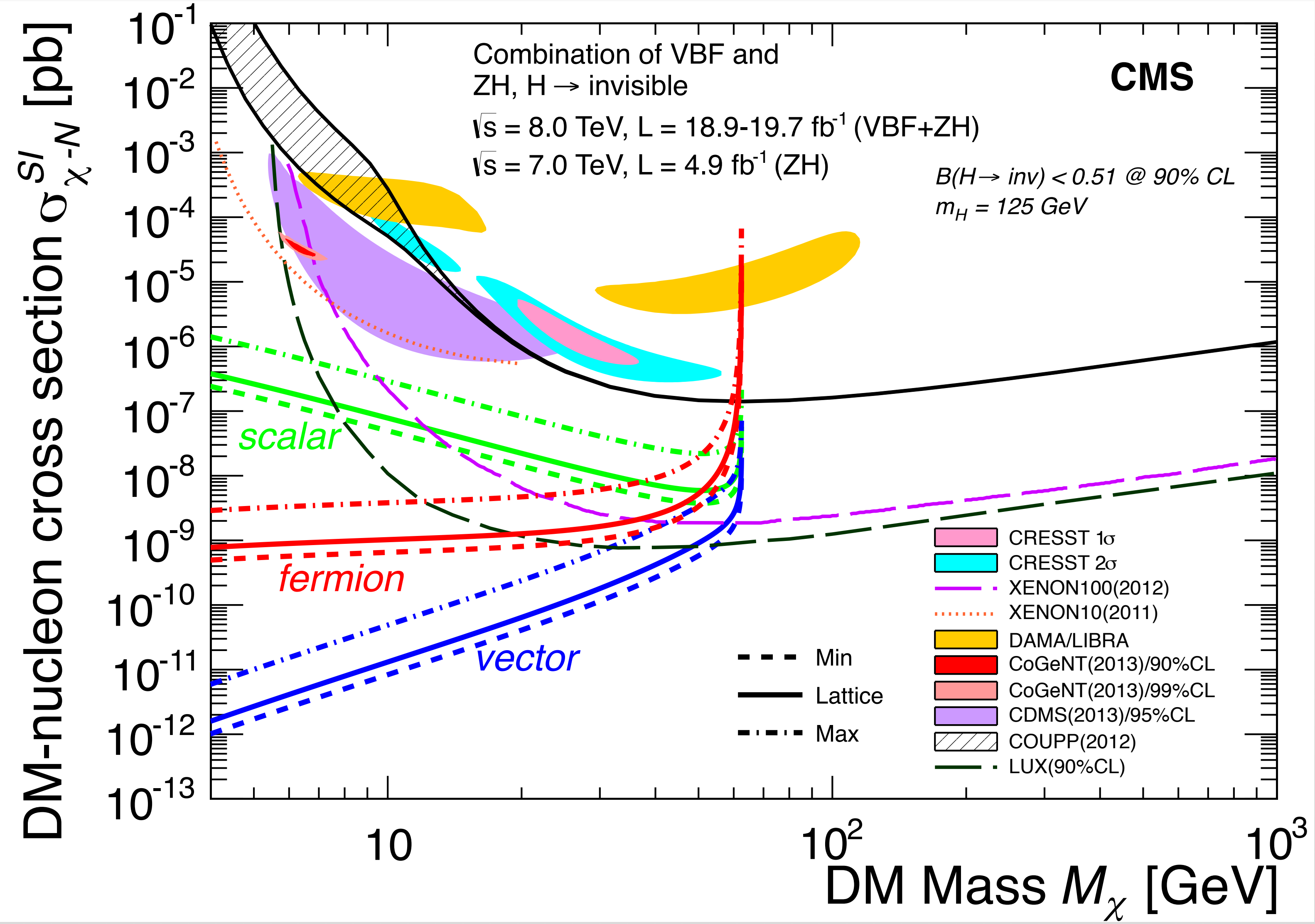
★ Boson portal: Higgs portal



★ Fermion portal



Higgs Portal Dark Matter



Fermion Portal Dark Matter

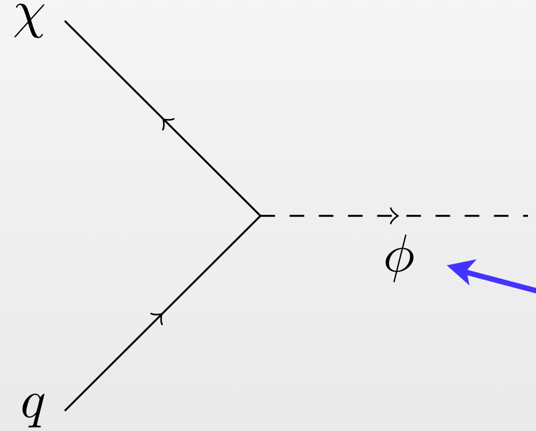
Conserving the Lorentz symmetry, at least two particles in the dark matter sector are required

one boson and one fermion

a Majorana or Dirac Fermion or a scalar dark matter

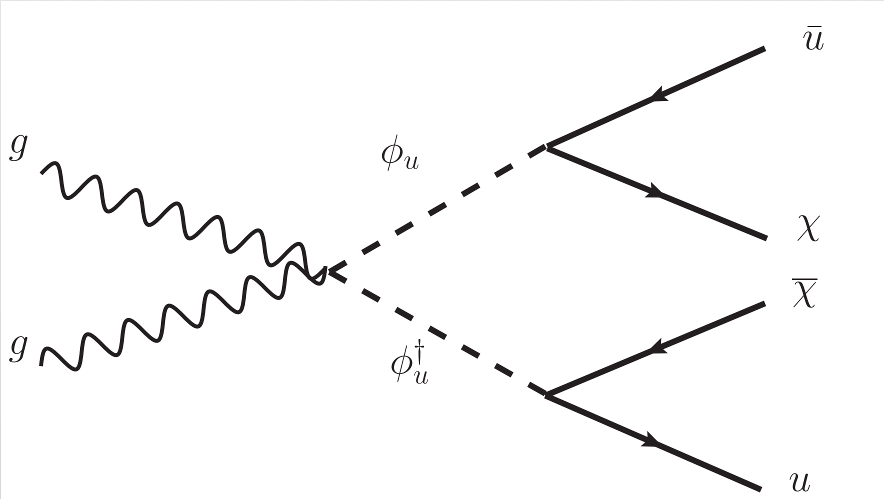
Quark Portal Dark Matter

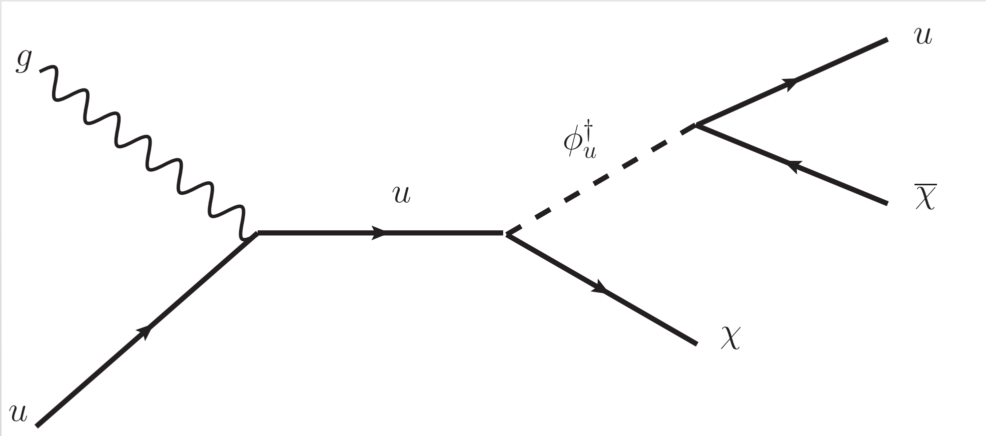
$$\mathcal{L}_{\text{fermion}} \supset \lambda_{u_i}\phi_{u_i}\overline{\chi}_L u_R^i + \lambda_{d_i}\phi_{d_i}\overline{\chi}_L d_R^i + \text{h.c.}$$



QCD triplet

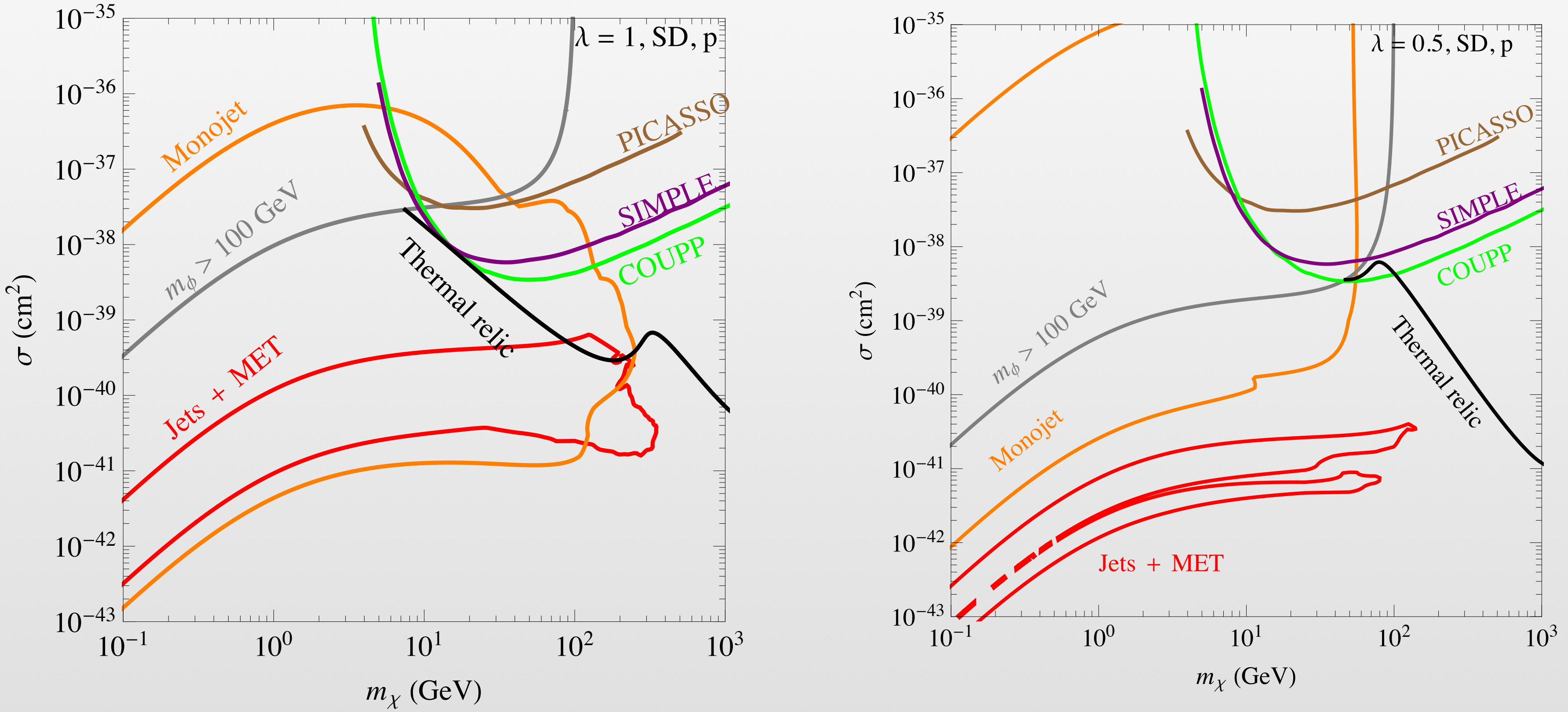
at the LHC





Quark-portal Dark Matter

YB, Joshua Berger, 1308.0612



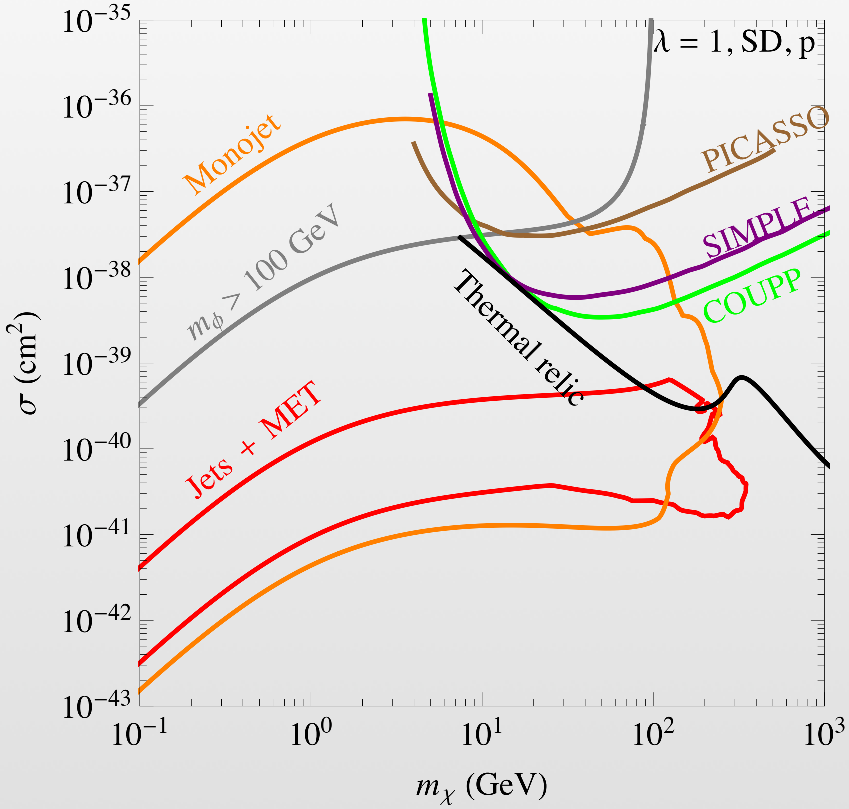
Majorana fermion dark matter up-quark

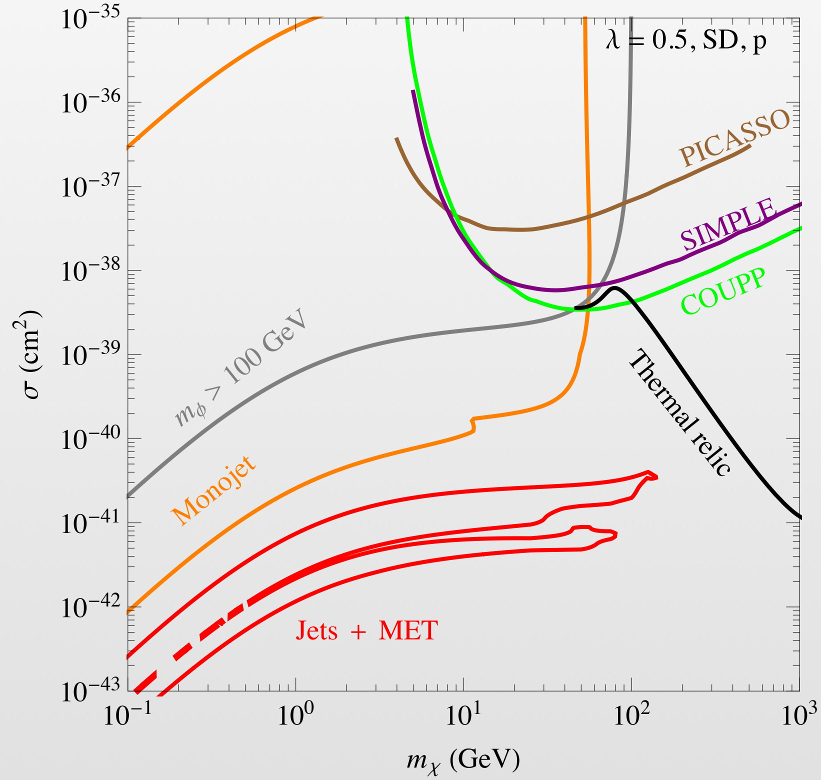
An, Wang, Zhang, 1308.0592 Chang, Edezhath, Hutchinson, Luty, 1307.8120

DiFranzo, Nagao, Rajaraman, Tait, 1308.2679 Papucci, Vichi, Zurek, 1402.2285

Quark-portal Dark Matter

YB, Joshua Berger; 1308.0612



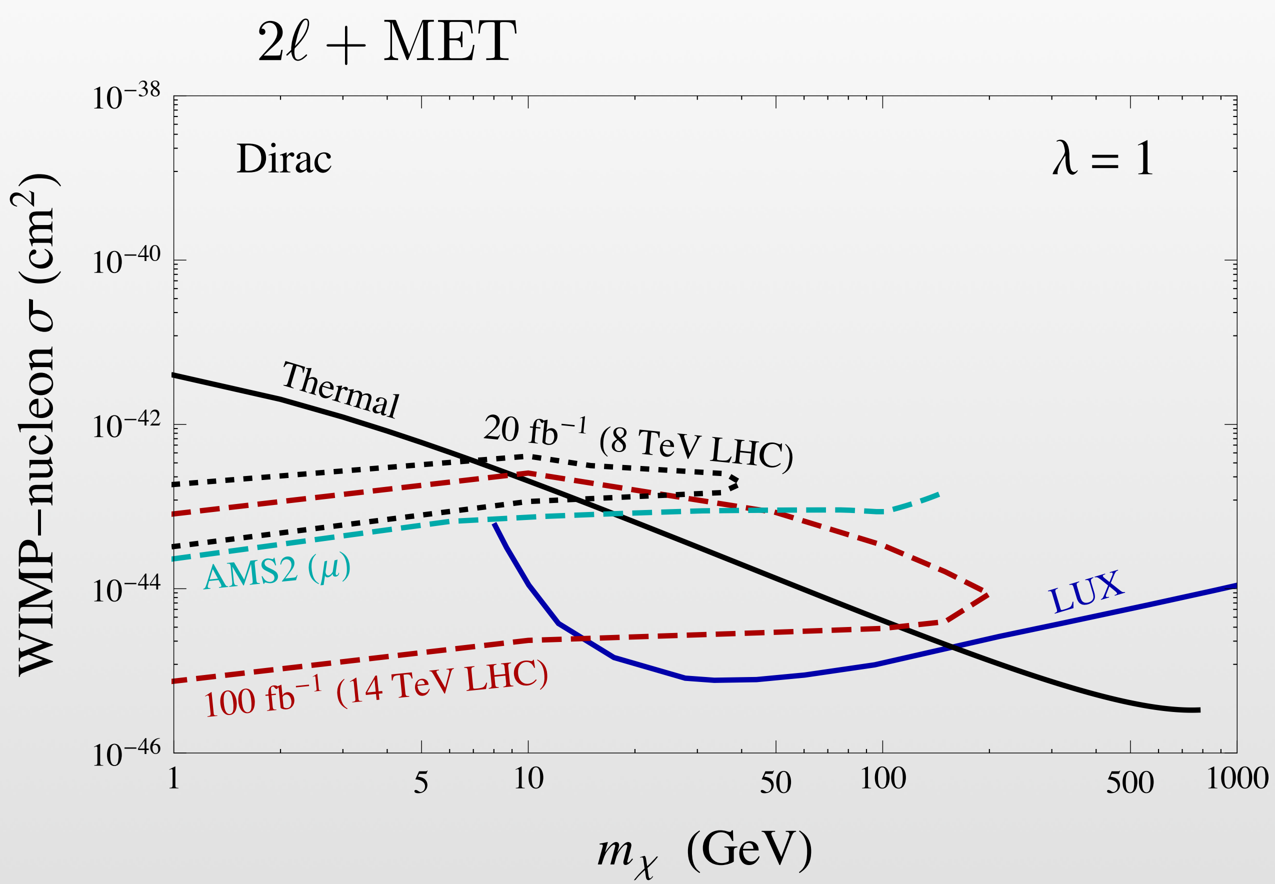


Majorana fermion dark matter up-quark

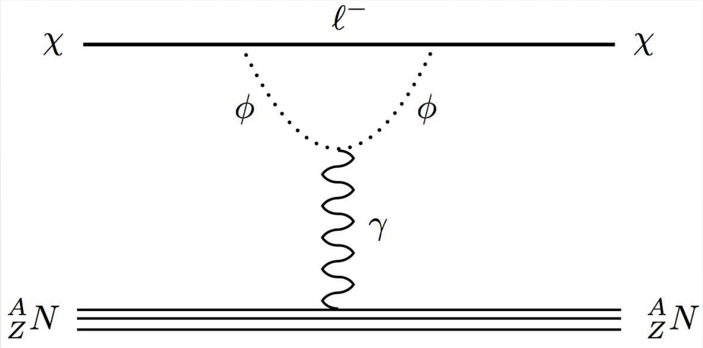
An, Wang, Zhang, 1308.0592 Chang, Edezhath, Hutchinson, Luty, 1307.8120

DiFranzo, Nagao, Rajaraman, Tait, 1308.2679 Papucci, Vichi, Zurek, 1402.2285

Lepton-portal Dark Matter



YB, Joshua Berger, 1402.6696

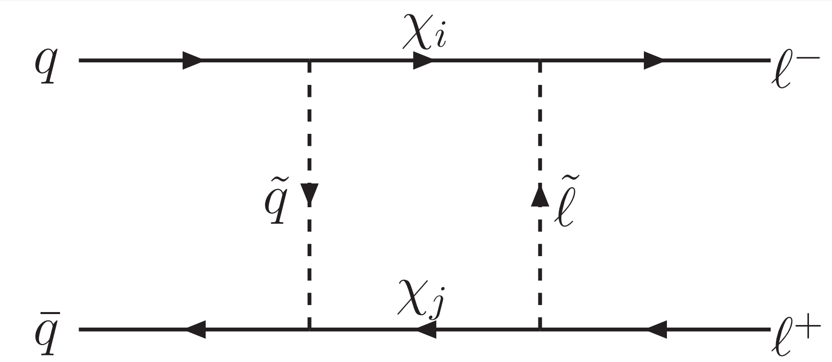


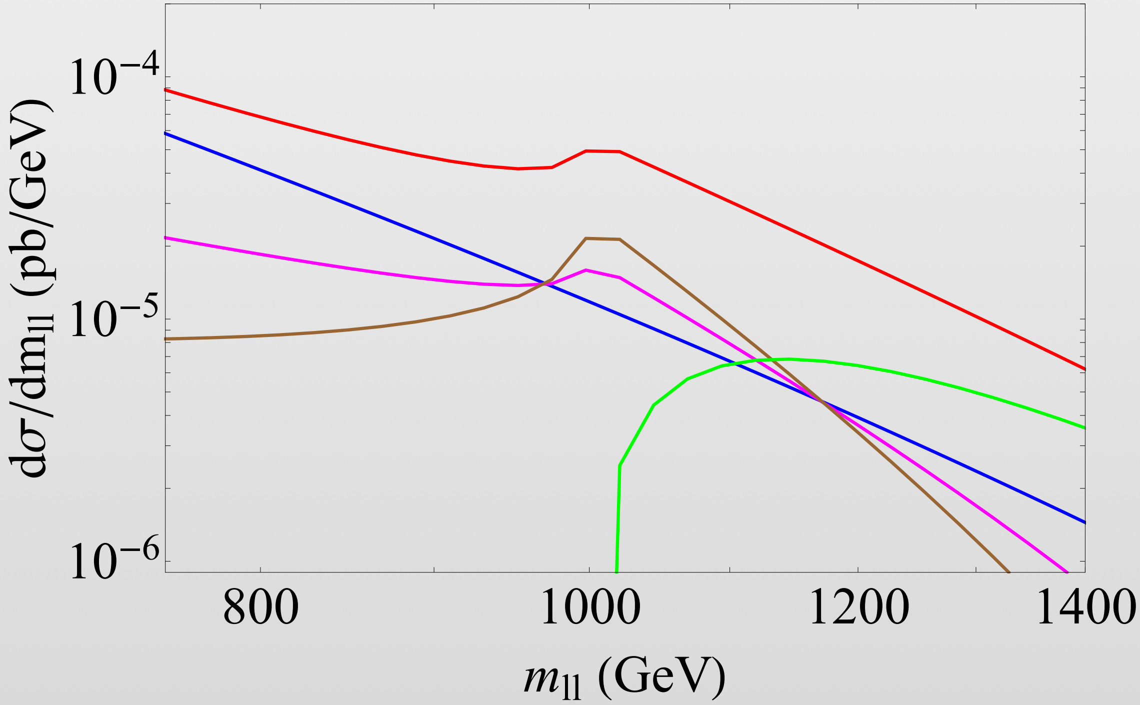
see also: Chang, Edezhath, Hutchinson, Luty, 1402.7358

Majorana fermion DM has suppressed direct detection cross sections due to the anapole moment

Del Nobile, Gelmini, Gondolo, Huh, 1401.4508

Dilepton Signature from Dark Matter



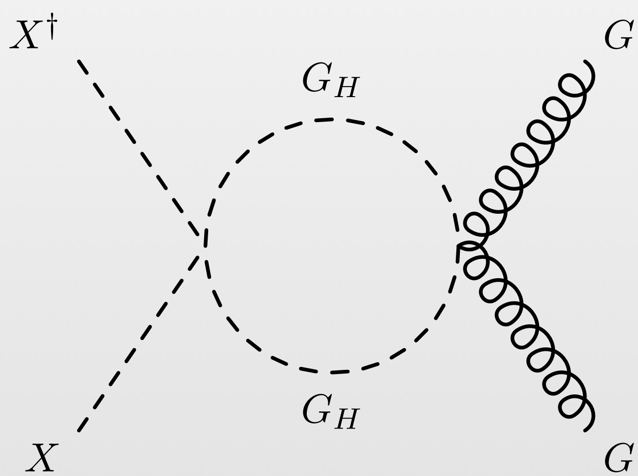


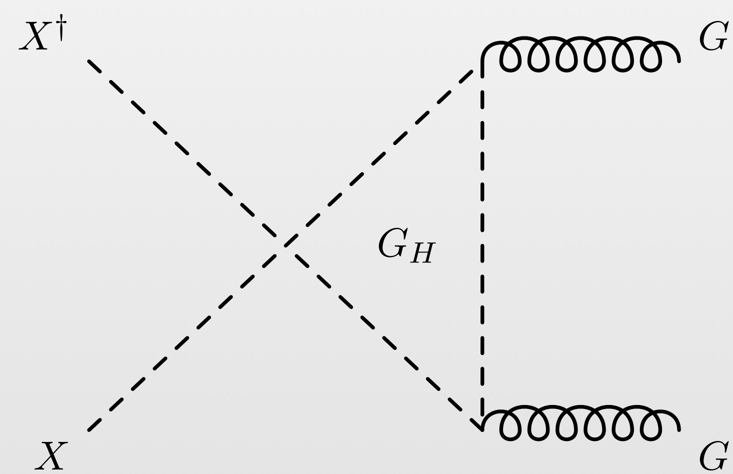
Altmannshofer, Fox, Harnik, Kribs, Raj, 1411.6743

Chromo-Rayleigh Interaction of DM

$$\frac{\alpha_s}{4\,\pi\,\Lambda_1^2} X^\dagger X G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \frac{i\,\alpha_s}{4\,\pi\,\Lambda_2^2}(XX - X^\dagger X^\dagger) G^a_{\mu\nu}\widetilde{G}^{a\,\mu\nu}$$

$$-\frac{\lambda}{2} G^a_H\, G^a_H\, X^\dagger X$$





UV-completed by adding a new QCD-charged scalar

YB, James Osborne, in progress

See also: Buckley, Feld, Goncalves: 1410.6497
for QCD-singlet UV-completion

Chromo-Rayleigh Interaction of DM

$$\frac{\alpha_s}{4\,\pi\,\Lambda_1^2} X^\dagger X G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \frac{i\,\alpha_s}{4\,\pi\,\Lambda_2^2}(XX - X^\dagger X^\dagger) G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu}$$

current collider bound from mono-jet:

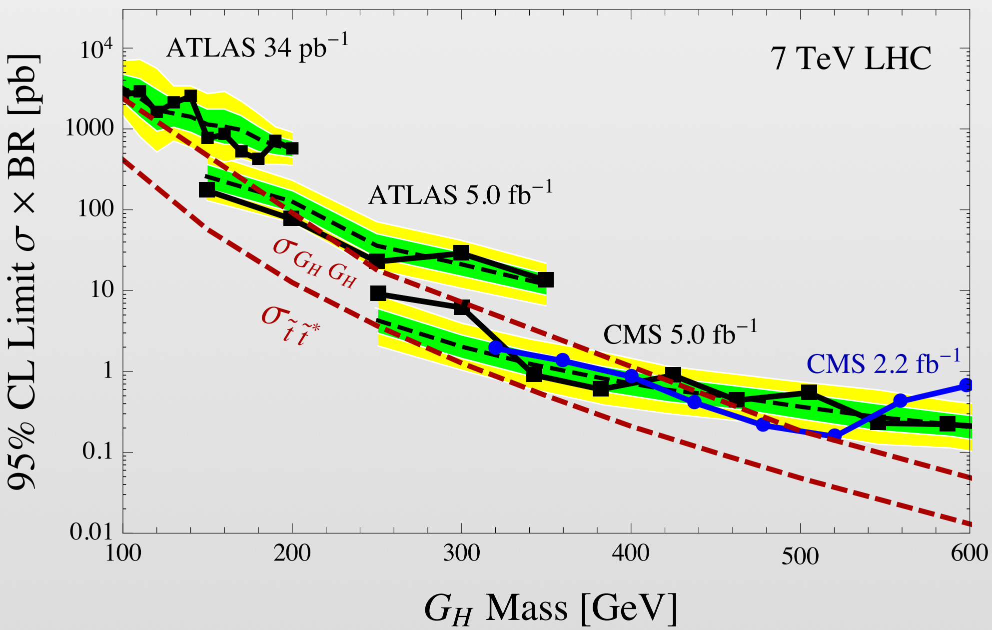
M_X (GeV)	Λ_1 (GeV)	Λ_2 (GeV)
1	130	170
10	120	180
100	120	180
200	110	160
400	90	130

The constraints are pretty weak.
The EFT description breaks down for a mass above 100 GeV.

UV Completion of the cRayleigh Interaction

$$\mu_G \, d_{abc} \, G^a_H G^b_H G^c_H \qquad \Gamma(G_H \to gg) = \frac{15\,\alpha_s^2\,\mu_G^2}{128\,\pi^3\,M_{G_H}} \left(\frac{\pi^2}{9} - 1\right)^2$$

The pair-produced dijet resonances can be used to constrain this UV model



$$M_{G_H} > 420 \text{ GeV} \qquad \Lambda > \sqrt{\frac{8}{\lambda}} \times 420 \text{ GeV}$$

Conclusions

- ★ There are more collider signatures for discovering dark matter particles
- ★ Dark matter can radiate its own charged Z' and have a mono-z' jet
- ★ One class of simplified fermion-portal dark matter models can lead to dijet+MET, dilepton+MET and even just a dilepton bump
- ★ A UV completed dark matter model can usually have a higher chance to be discovered at the LHC

Thanks