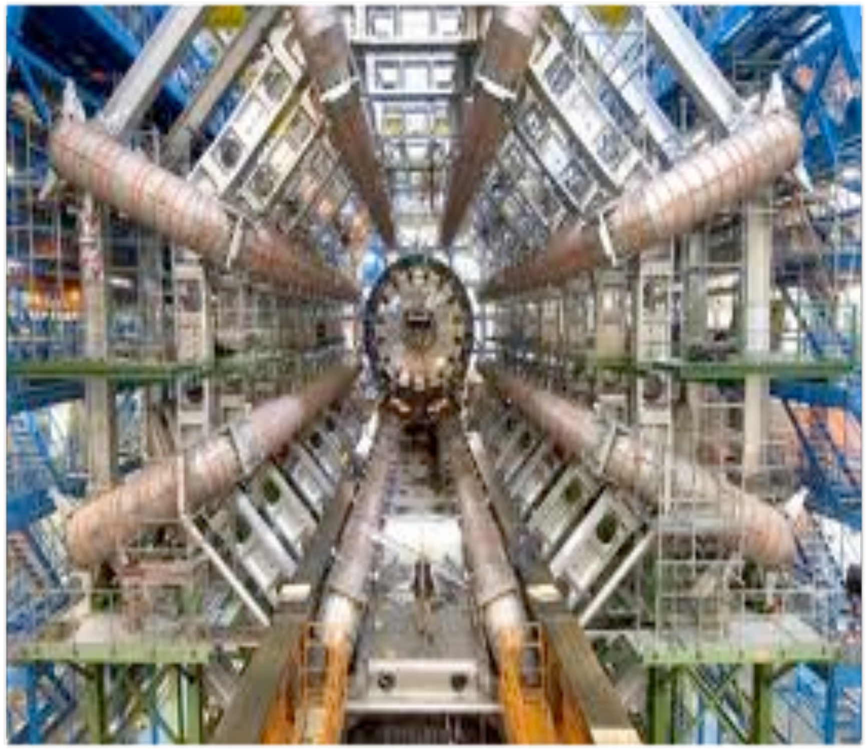
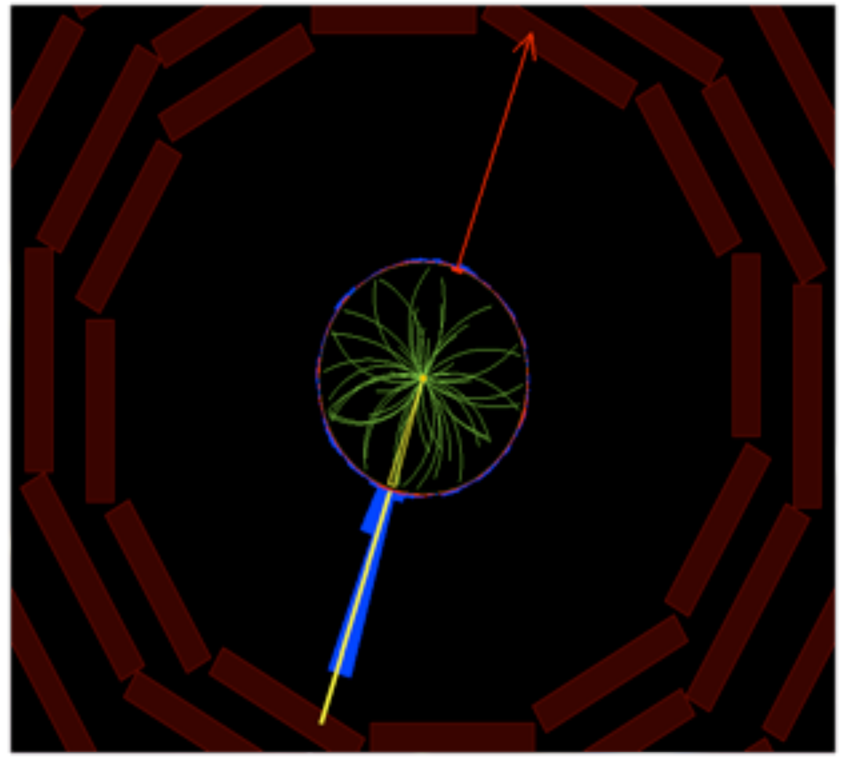
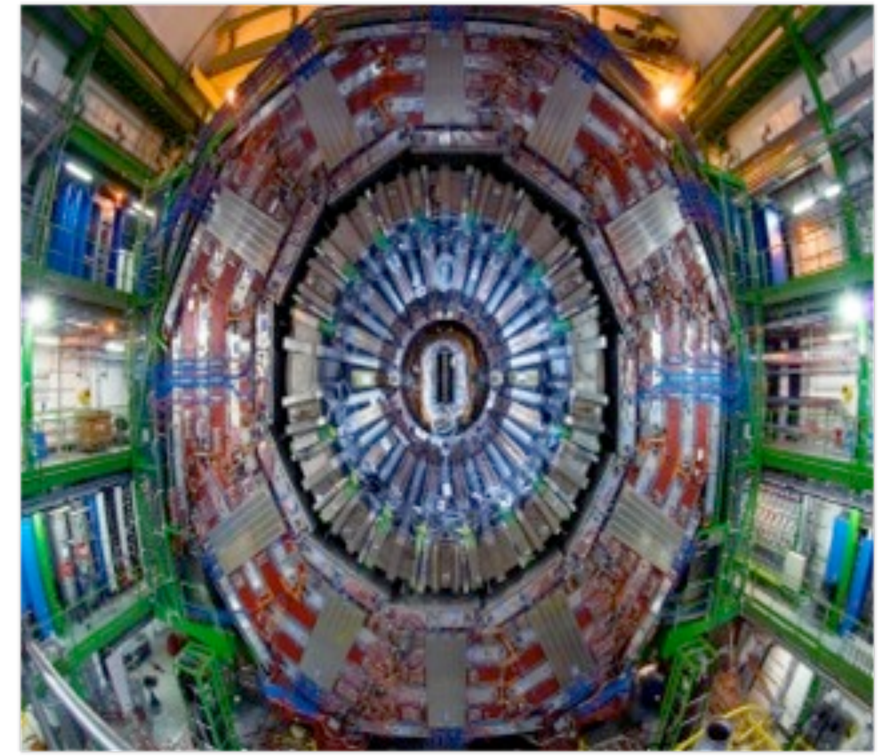
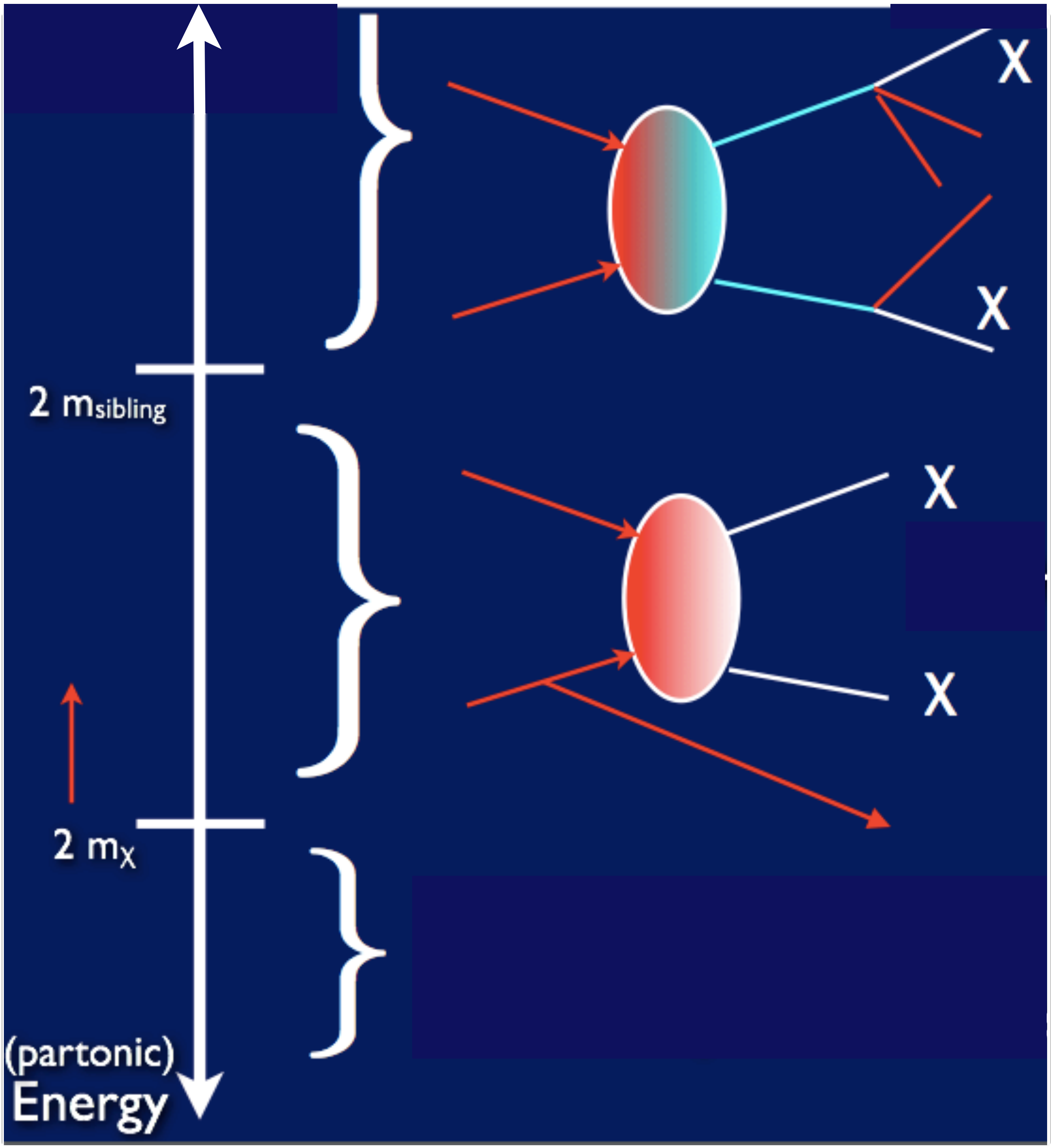




Status, prospects and interpretation of Dark Matter searches at the LHC

Sarah Alam Malik
Imperial College London

Searching for dark matter at colliders



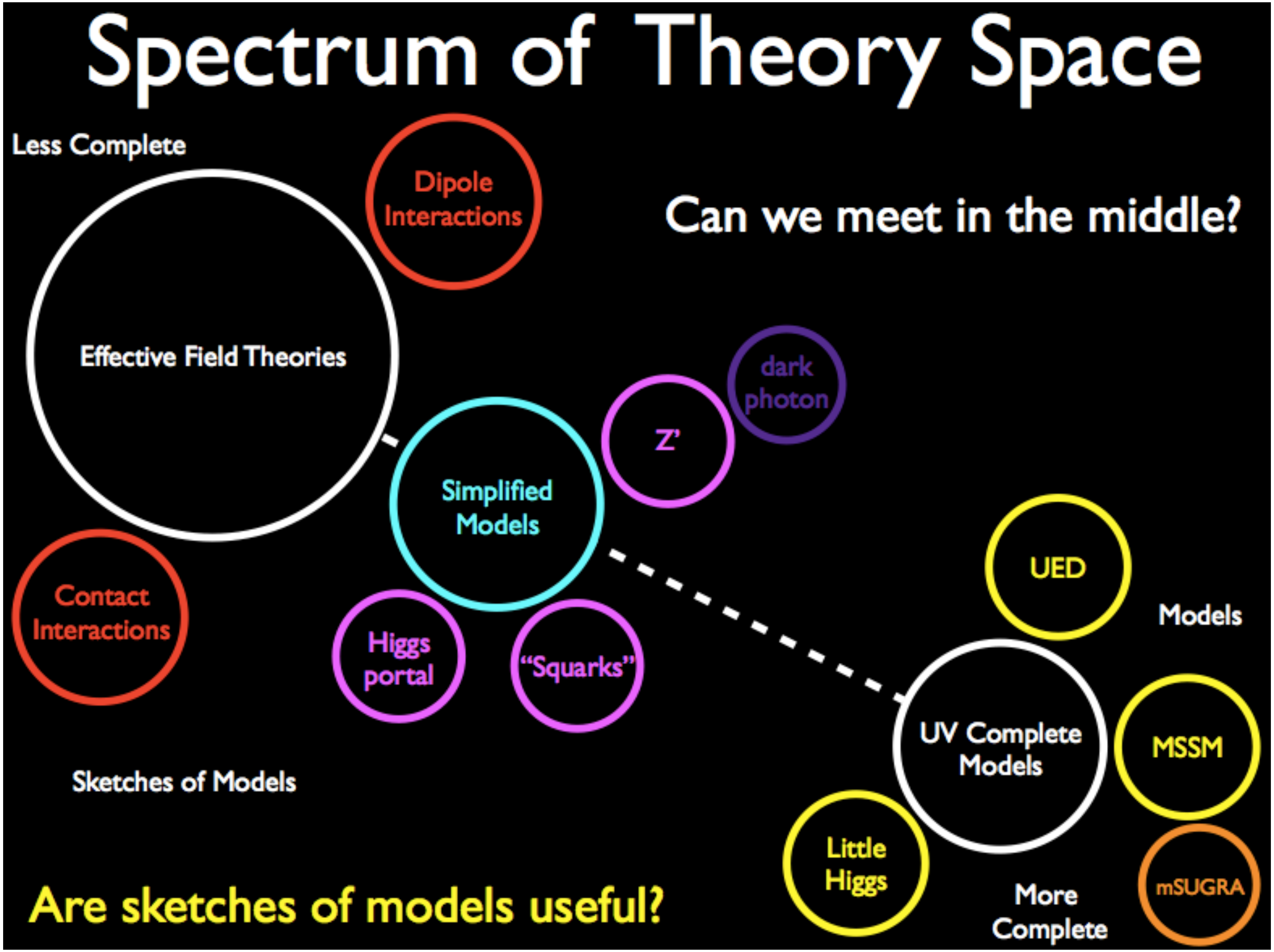
LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC can directly produce WIMP pairs

LHC cannot produce WIMPs

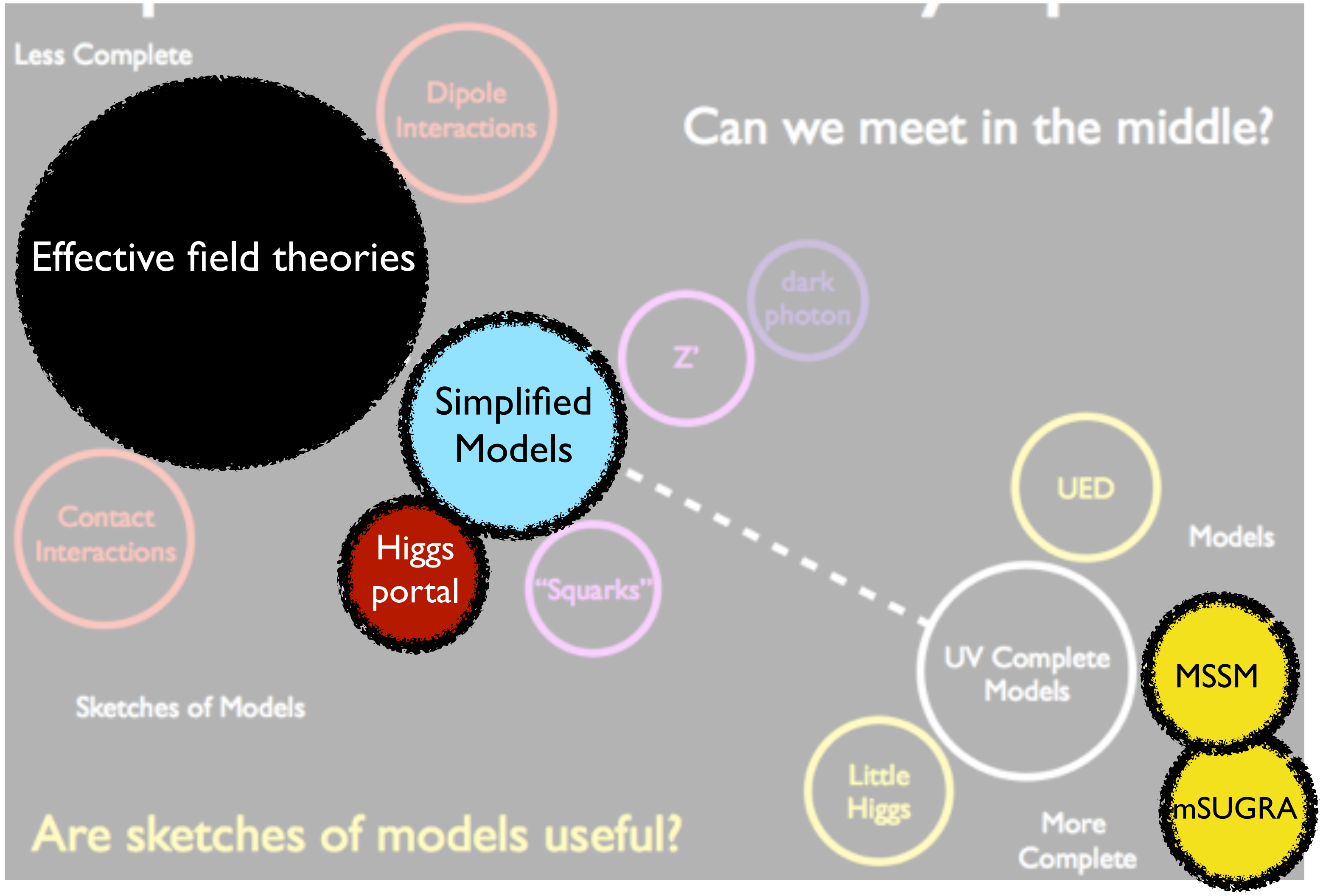
Slide taken from Tim Tait talk at Moriond

From Tim Tait

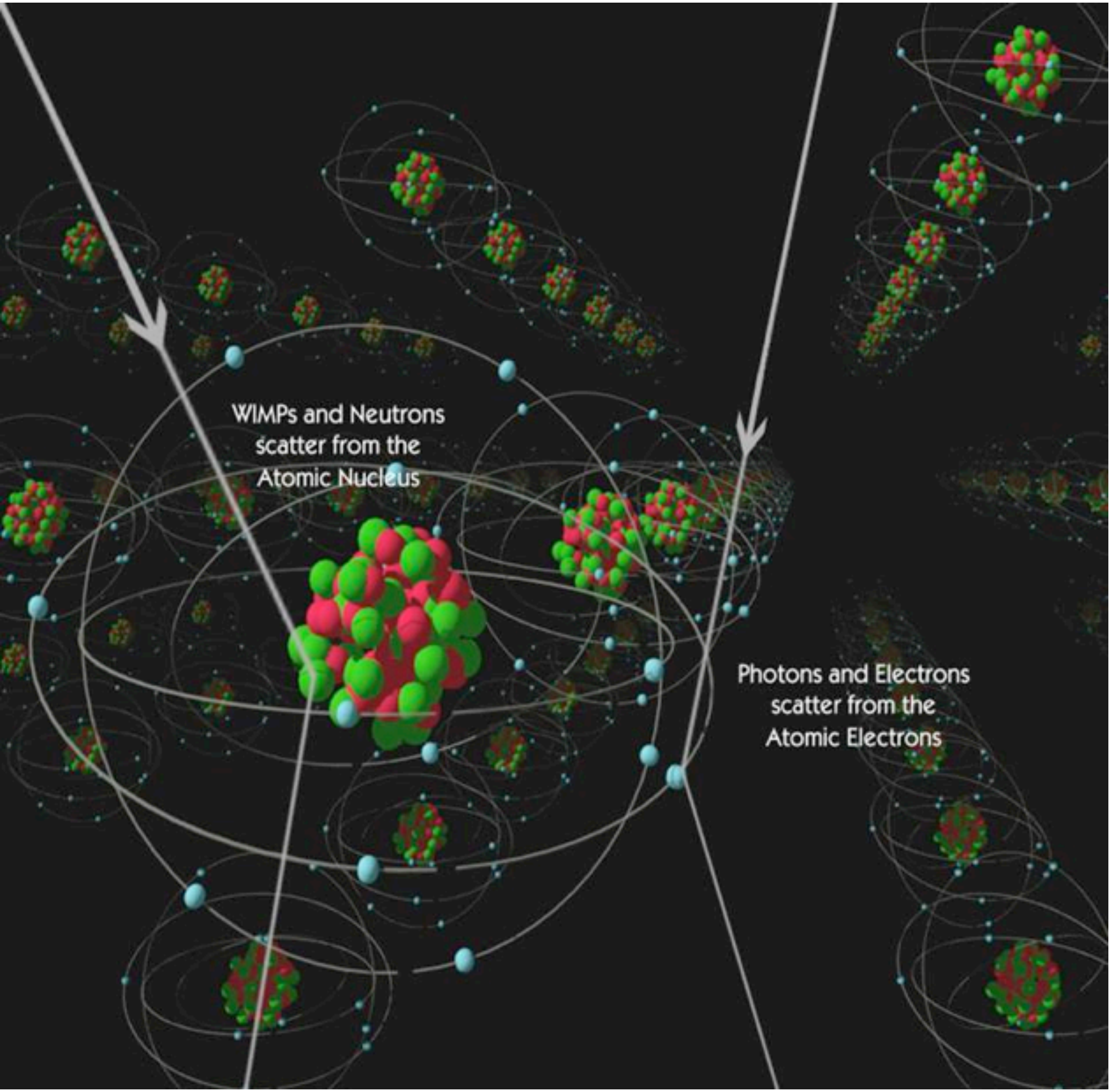


DM at colliders phenomenology

- SUSY searches
- Mono-X searches
- Invisible Higgs searches
- Interpretation of results
- Projections for 14 TeV



Direct detection search for dark matter



- Observe recoil of dark matter off nucleus, recoil energy 1- 100 keV

- Recoil detected via scintillation, ionization, phonons

- Current experiments use 10-100 kg heavy nuclei targets (Ge, Xe) located deep underground to minimize backgrounds

Backgrounds from:

- Photons and electrons scattering from atomic electrons
- Neutrons scattering from nucleus

Direct detection search for dark matter

- elastic scattering can be separated into spin-dependent and spin-independent contributions.

Spin-independent interaction

$$\sigma_A^{SI}(q \to 0) = \frac{4\mu_A^2}{\pi}[Zf_p + (A-Z)f_n]^2 \approx \frac{\mu_A^2}{\mu_p^2}\sigma_p A^2$$

Enhancement from A^2 term

Spin-dependent interaction

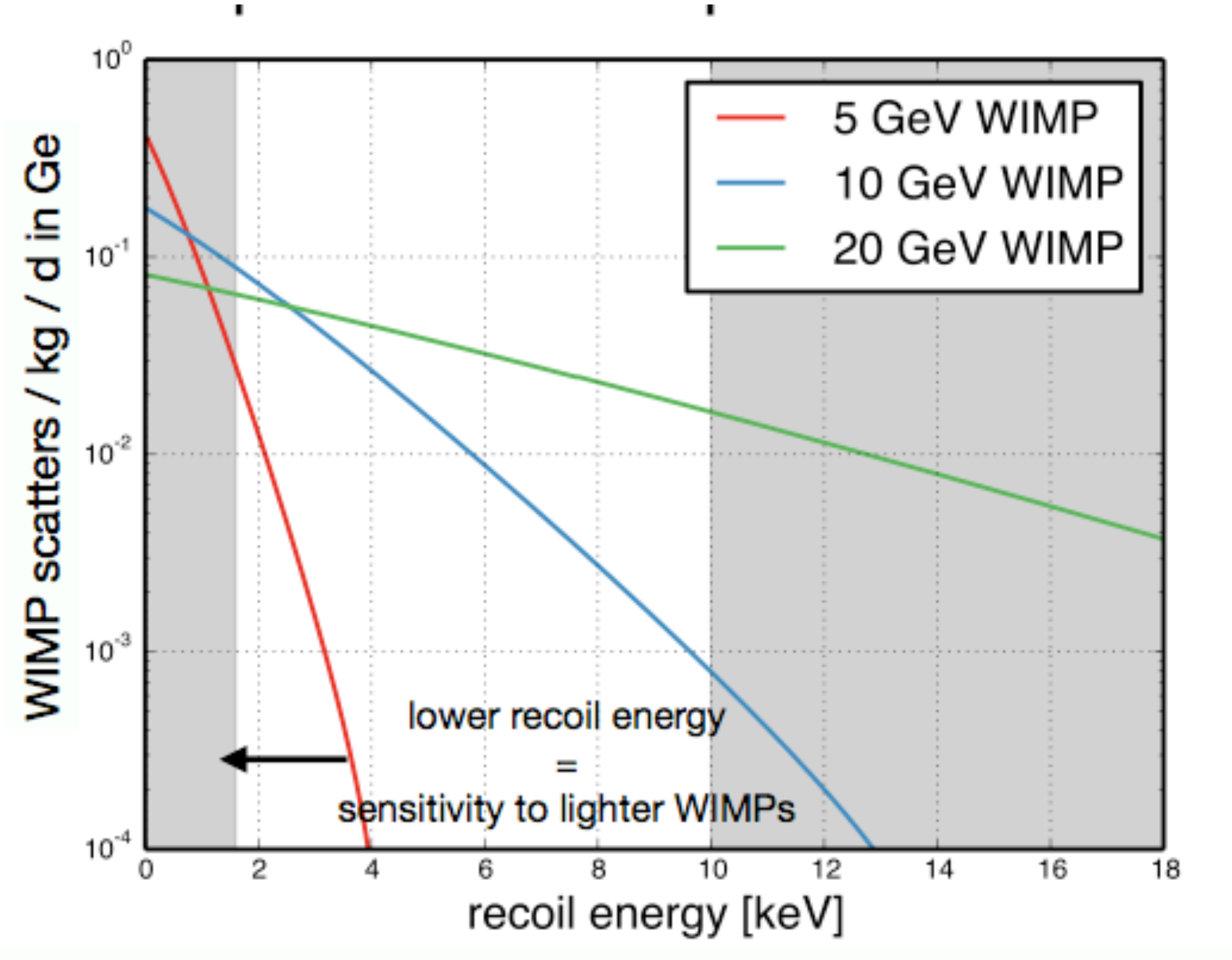
$$\sigma_A^{SD}(q \to 0) = \frac{\mu_A^2}{\mu_p^2}\sigma_{p,n}^{SD}\left[\frac{4}{3}\frac{J+1}{J}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2\right]$$

- No A^2 coherence term
- Replaced by nucleon spin (J)

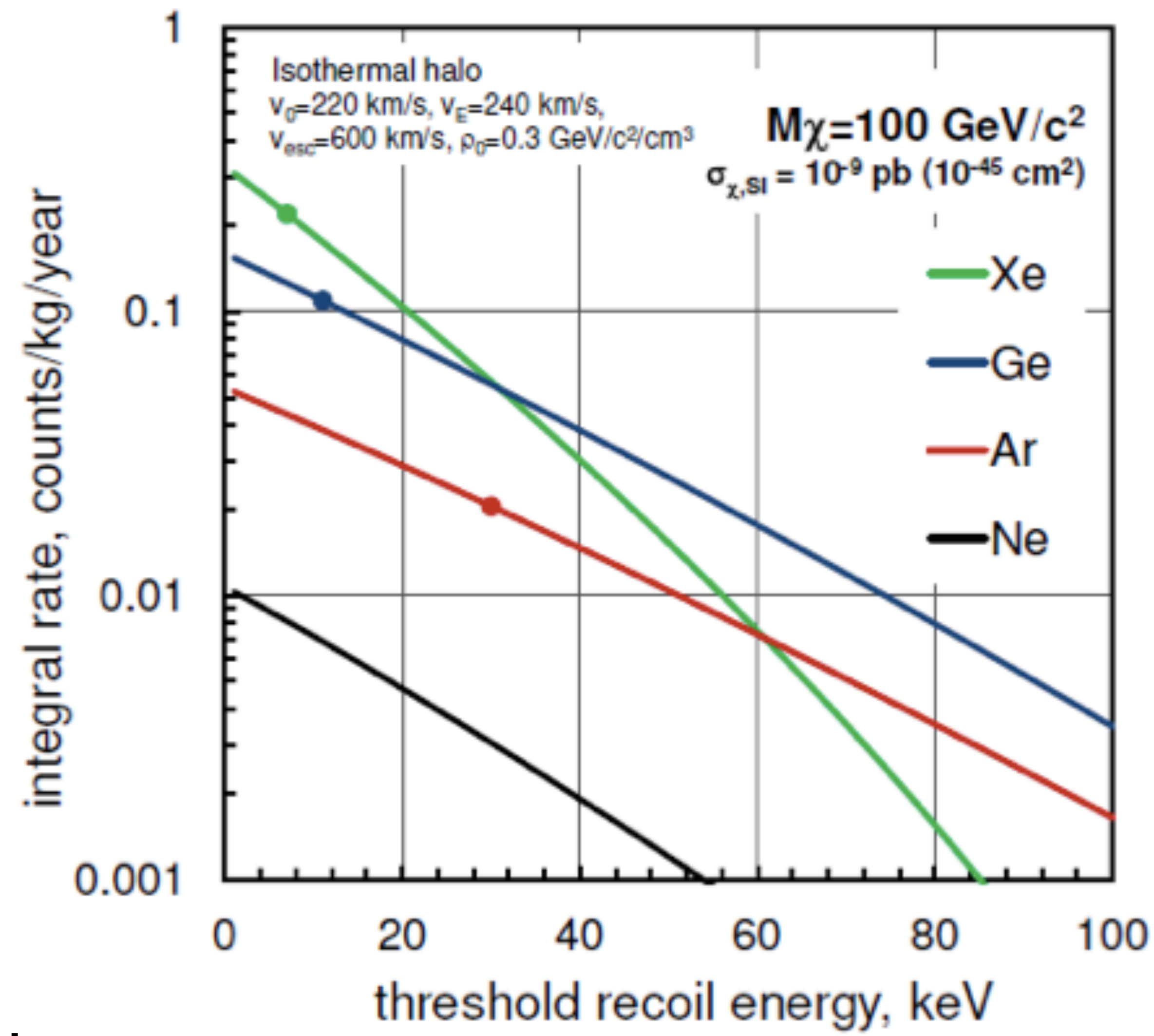
Direct detection experiments much less sensitive to spin-dependent interactions than spin-independent

Collider - similar sensitivity to spin-dependent and spin-independent interactions

Direct detection search for dark matter



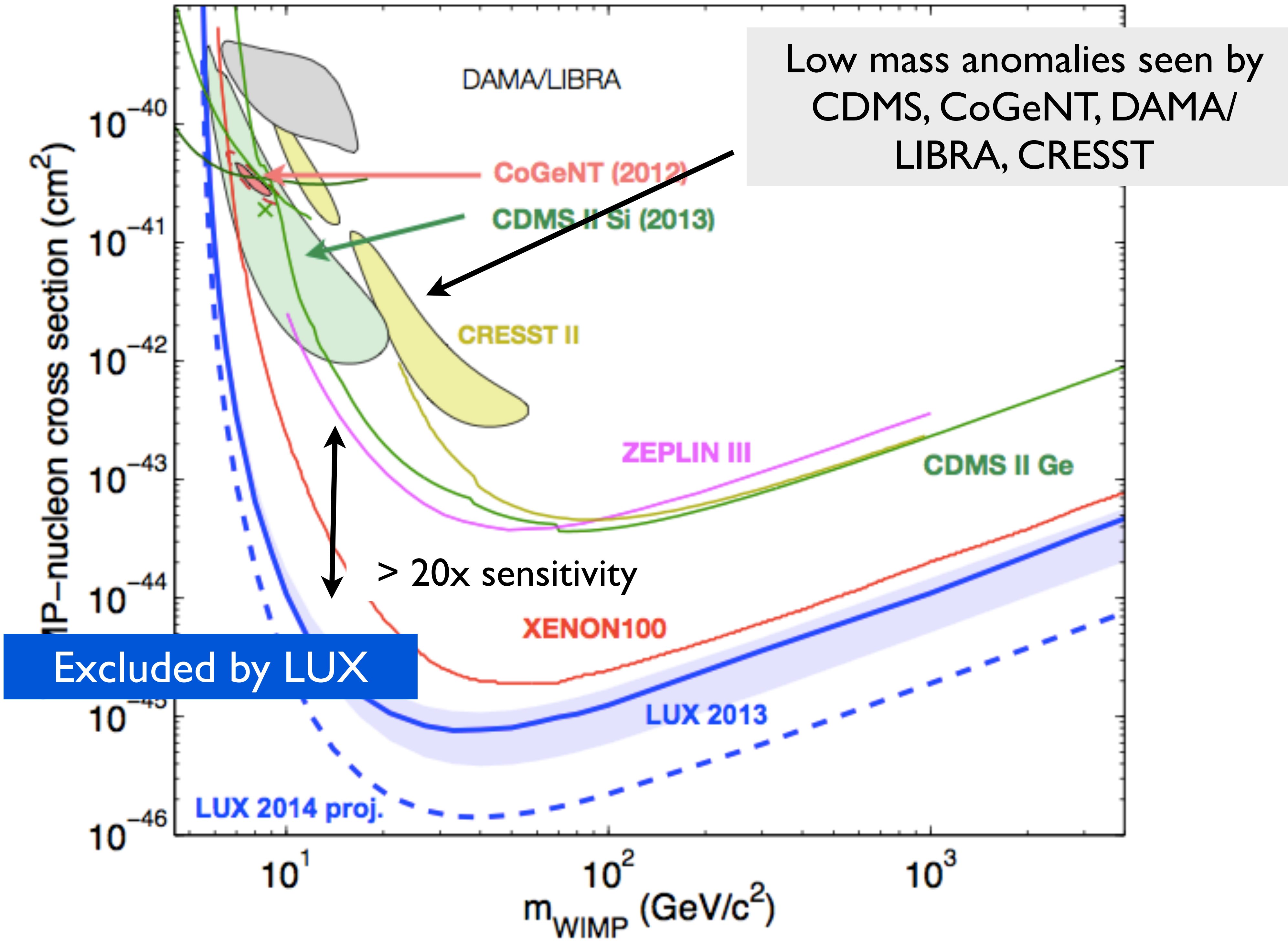
Chepel & HA, JINST 8 R04401 (2013



WIMP searches in low mass region hard
Signal expected at very low recoil energies
Not a background free region
- rare events and low energy bad combination

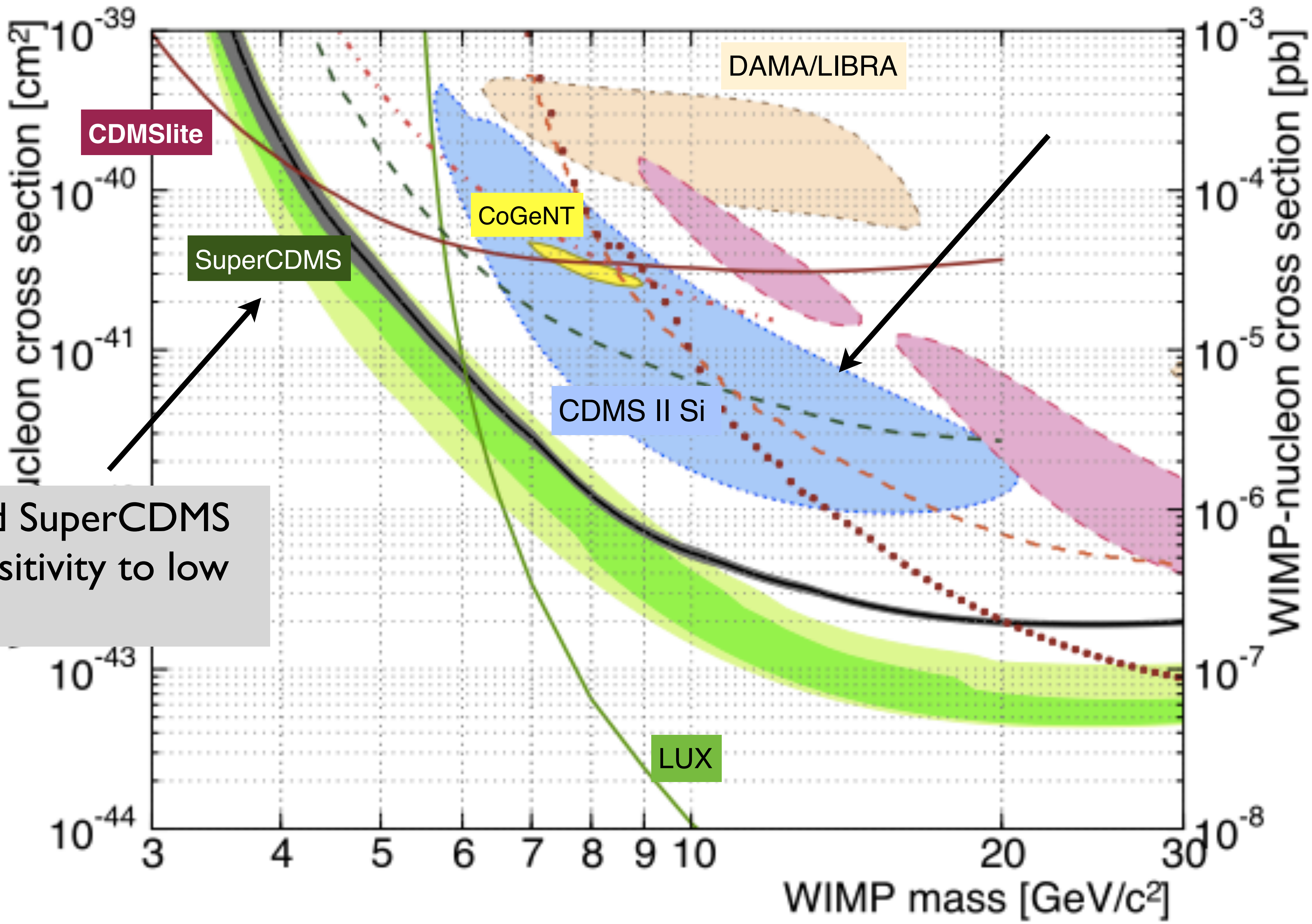
No low energy threshold for colliders

Status of direct detection searches



Independent verification from non-astrophysical experiments - colliders

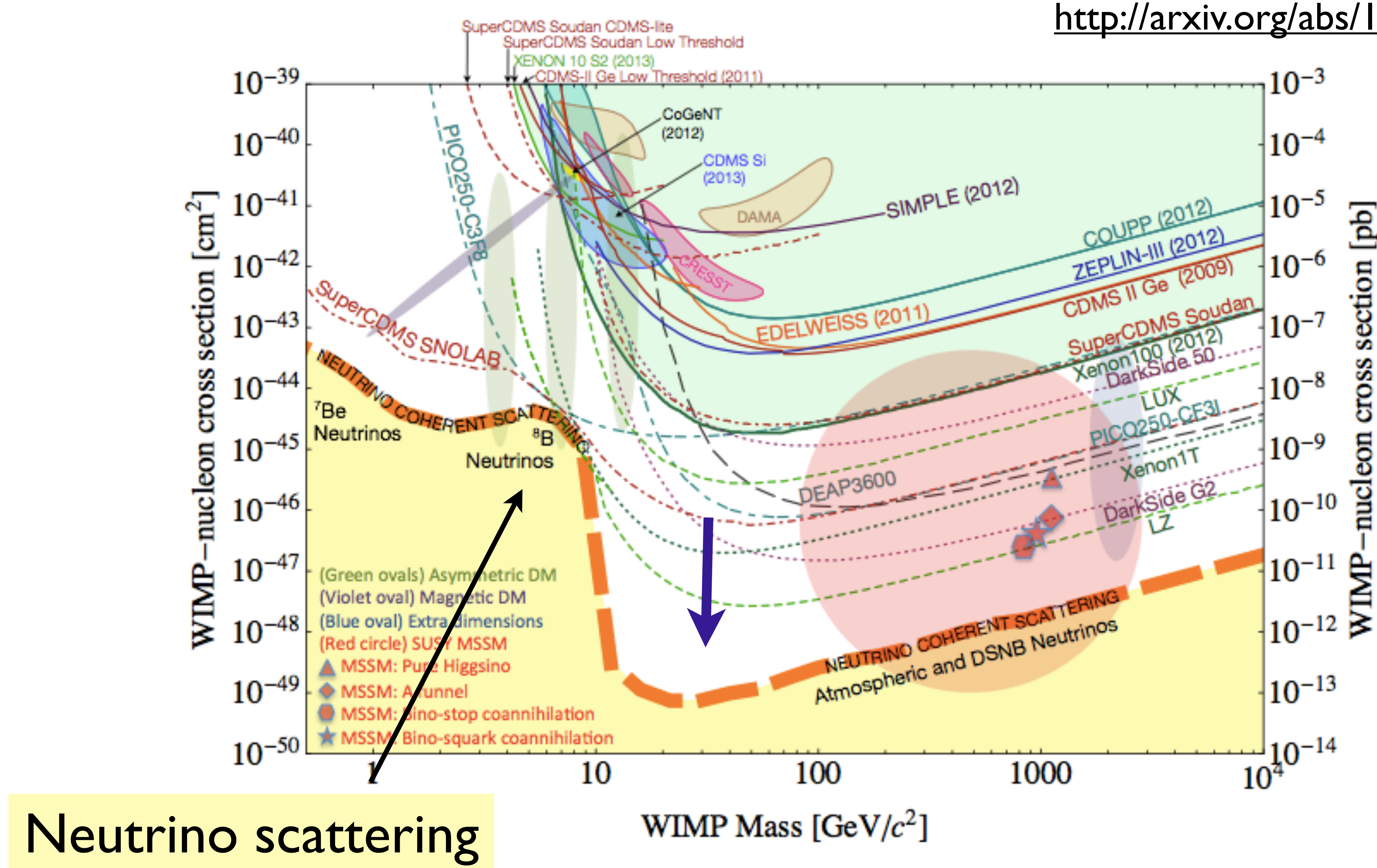
Status of direct detection searches



CDMSlite and SuperCDMS extended sensitivity to low mass region

Neutrino floor

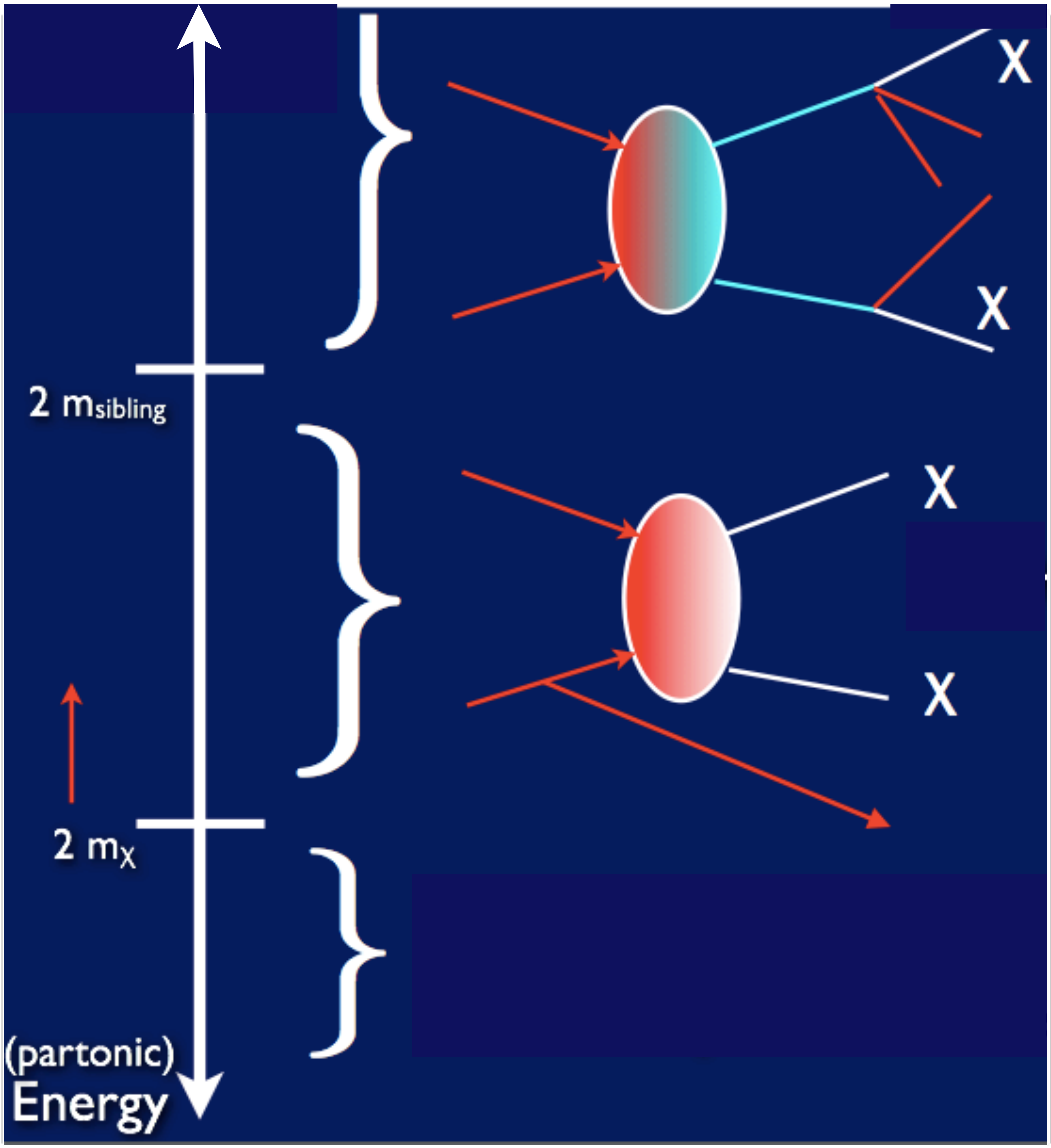
http://arxiv.org/abs/1401.6085



Can colliders complement DD push beyond neutrino floor?

LHC : Mono-X searches

Searching for dark matter at colliders



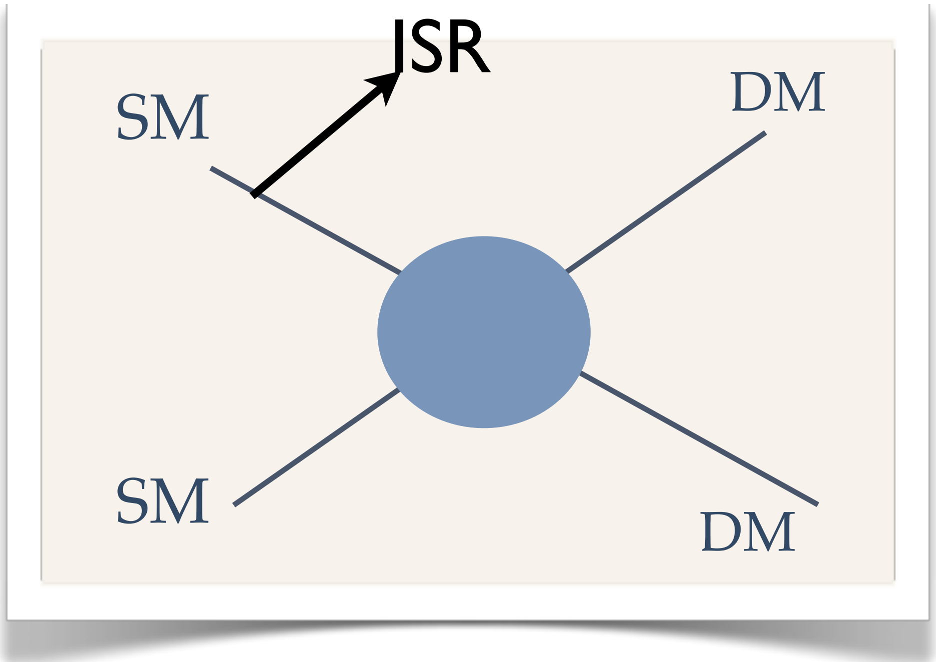
LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC can directly produce WIMP pairs

LHC cannot produce WIMPs

Phenomenology : effective field theory

Assumptions:
- DM particle is only new state accessible to the collider
- Effective field theory so interaction between DM and SM particles is contact interaction



$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{X}\gamma^\mu\partial_\mu X - M_X\bar{X}X + \sum_q \sum_{i,j} \frac{G_{qij}}{\sqrt{2}} \; [\bar{X}\Gamma_i^X X]\,[\bar{q}\Gamma_q^j q],$$

SM Lagrangian

kinetic terms for DM

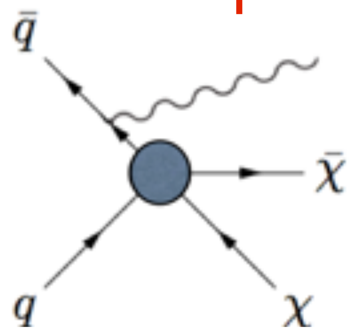
set of 4-Fermion interactions between DM and SM quarks

arXiv:1002.4137
arXiv:1005.1286,
arXiv:1007.3797
arXiv:1008.1783,
arXiv:1103.0240,
arXiv:1109.4398, etc

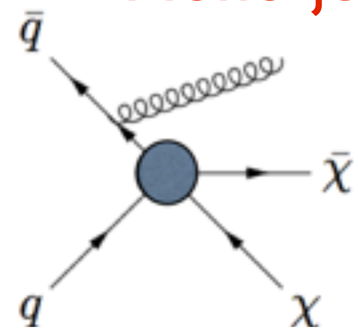
Operators **Γ** describe scalar, pseudoscalar, vector, axial vector, tensor interactions

Mono-X

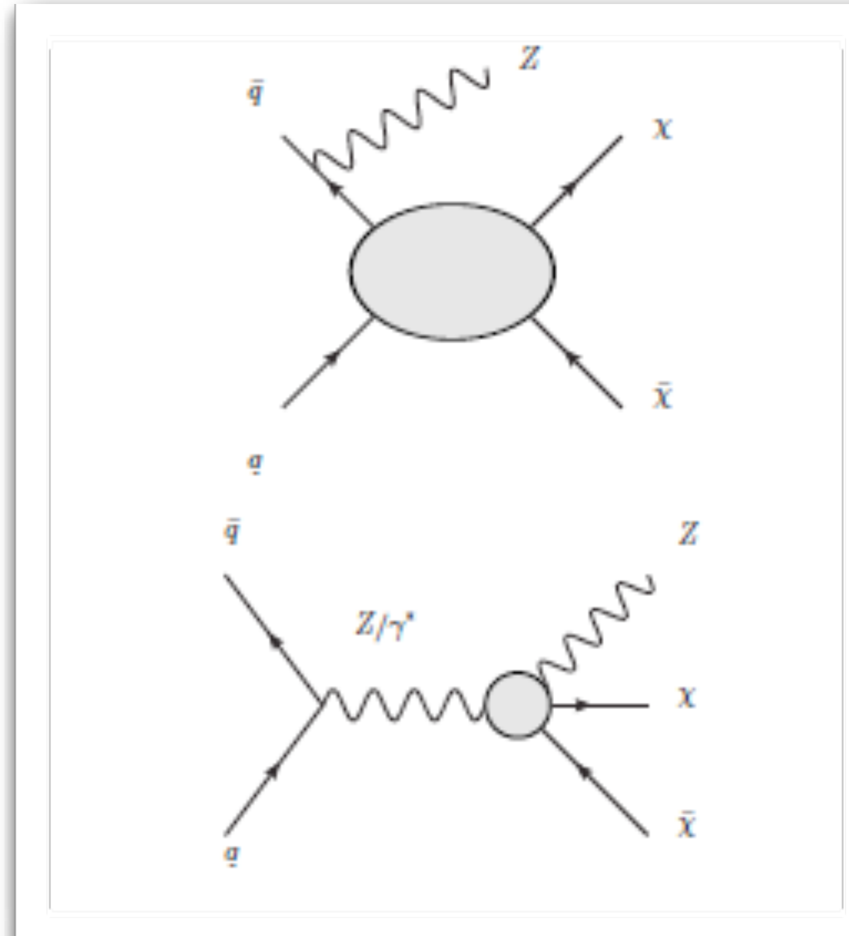
Mono-photon



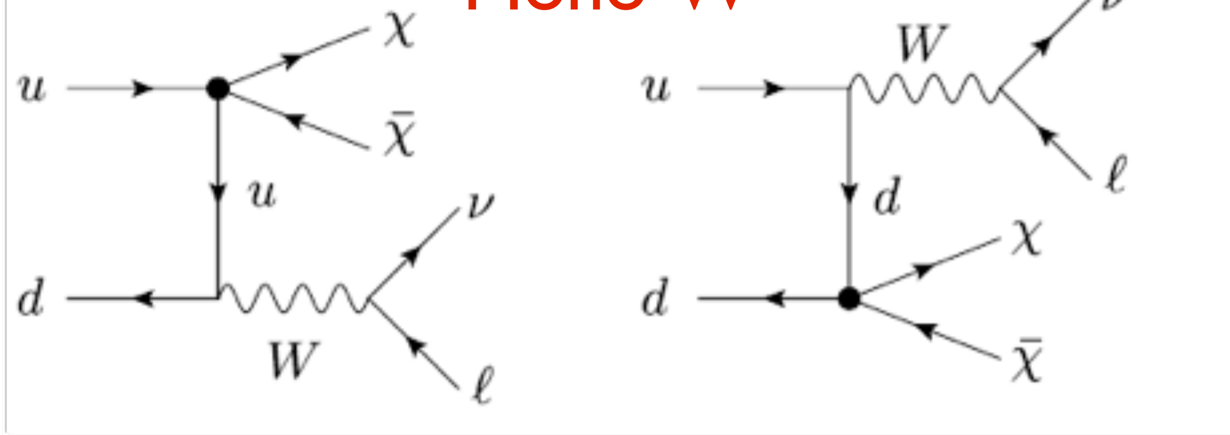
Mono-jet



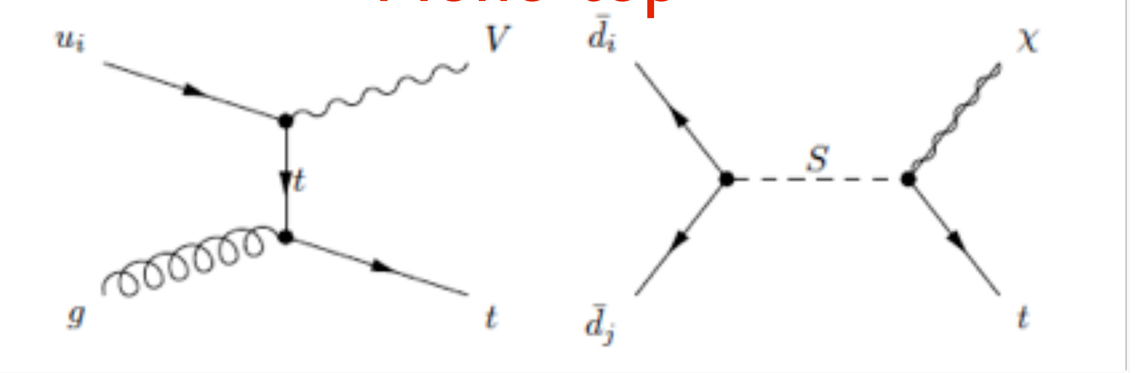
Mono-Z



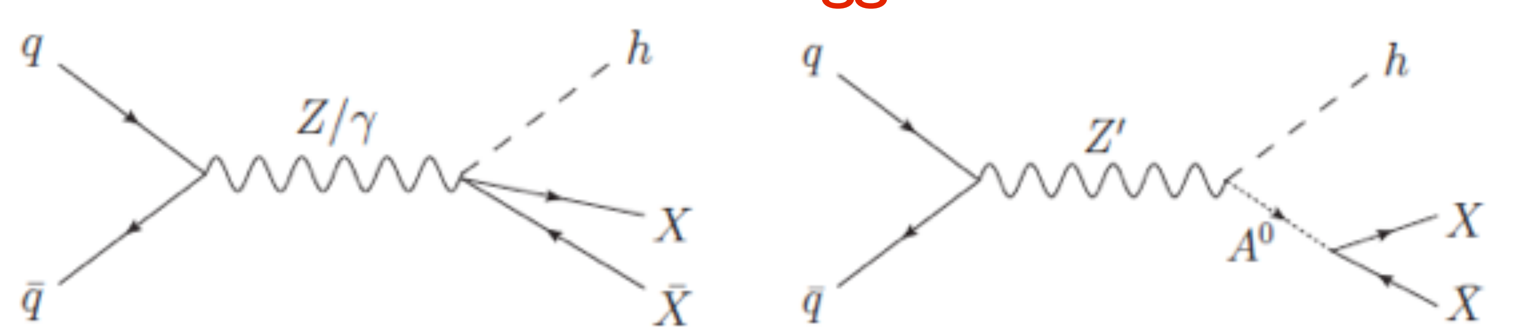
Mono-W



Mono-top

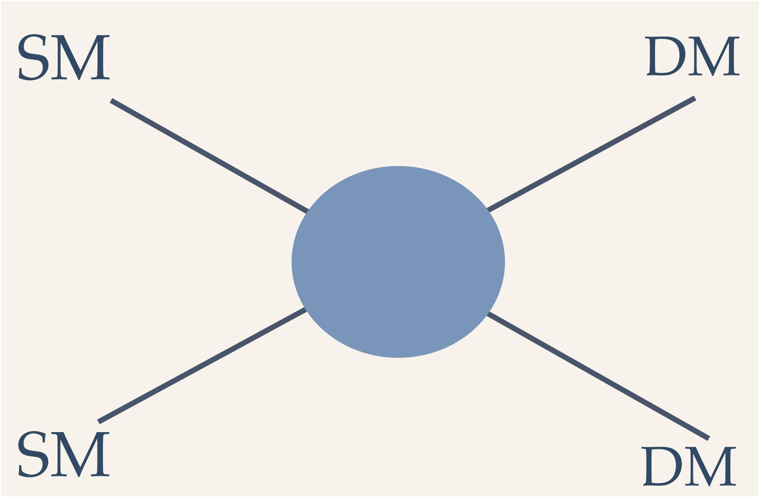


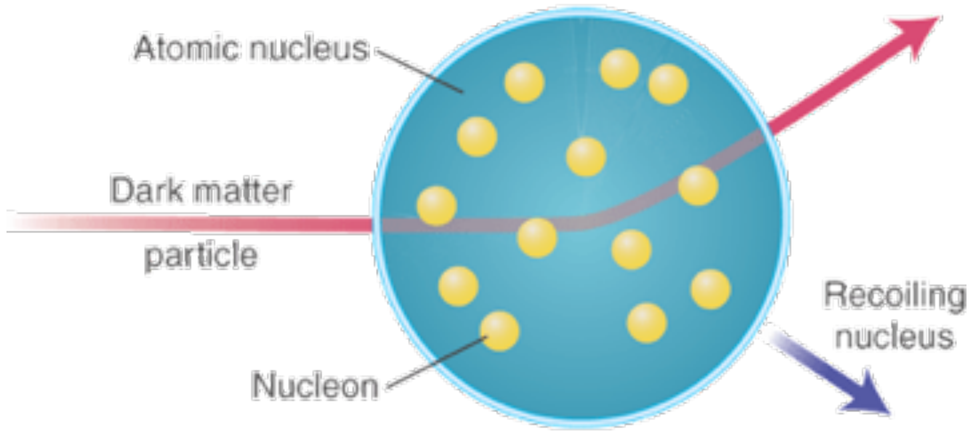
Mono-Higgs



Setting limits on DM-nucleon cross section

Translate collider limits to the same plane as direct detection experiments





$$\Lambda = M/\sqrt{g_\chi g_q}$$

For vector operator

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

$$\mathcal{O}^N = f_q^N \frac{(\bar{N}\gamma^\mu N)\,(\bar{\chi}\gamma_\mu\chi)}{\Lambda^2}$$

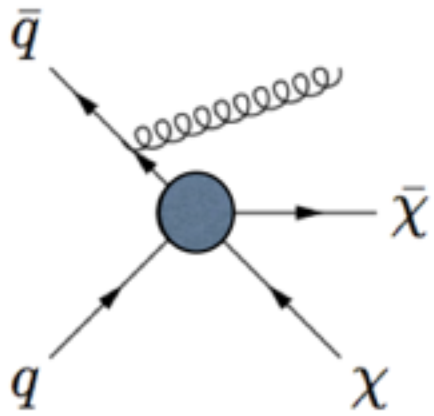
coefficient relates nucleon and quark operator

$$\sigma_{SI} = \frac{\mu^2}{\pi\Lambda^4} f_q^{N2}$$

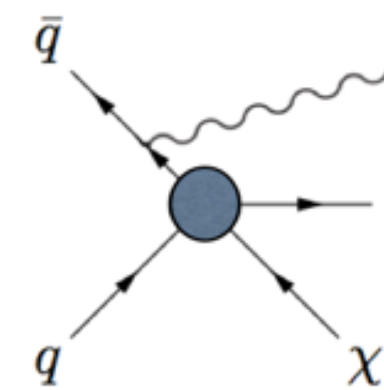
- Upper limits on mono-X cross sections converted to lower limits on Λ
- Lower limits on Λ then translated to spin-independent DM-nucleon cross-section

Monojet/monophoton

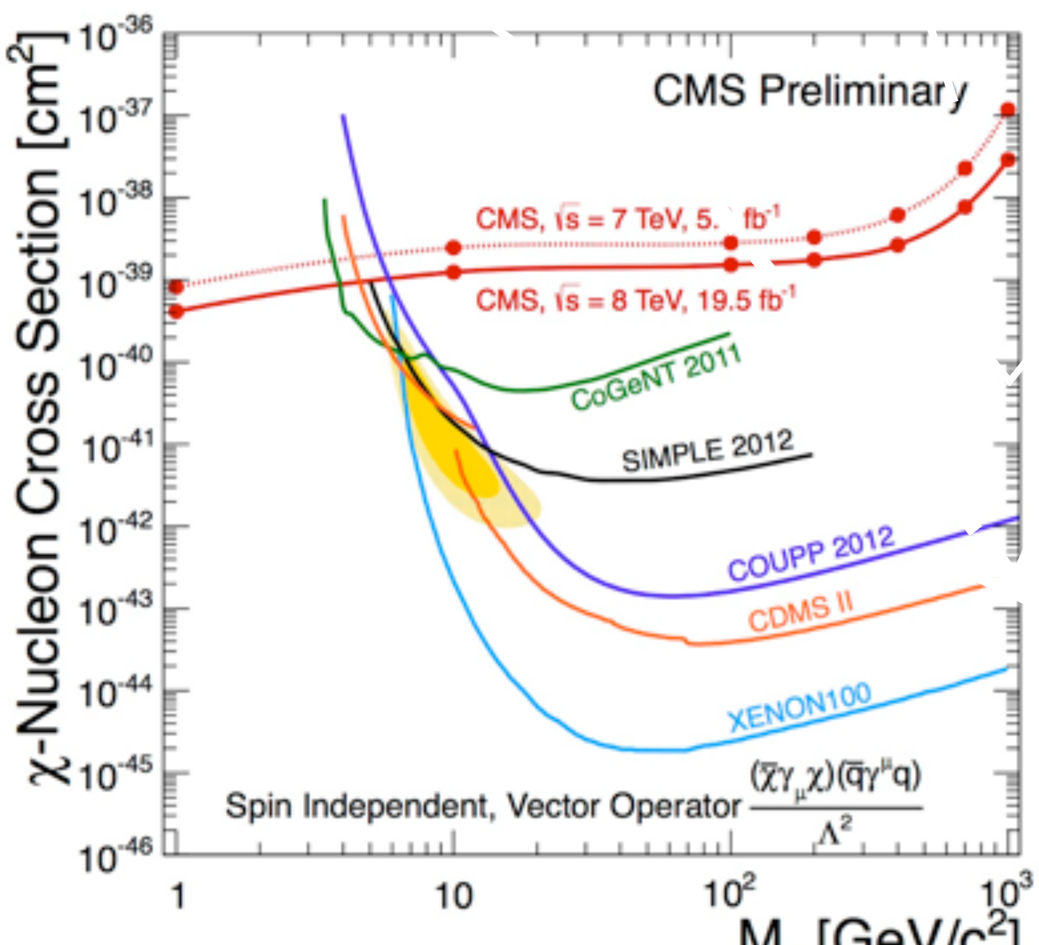
Assuming Effective Field theory.......



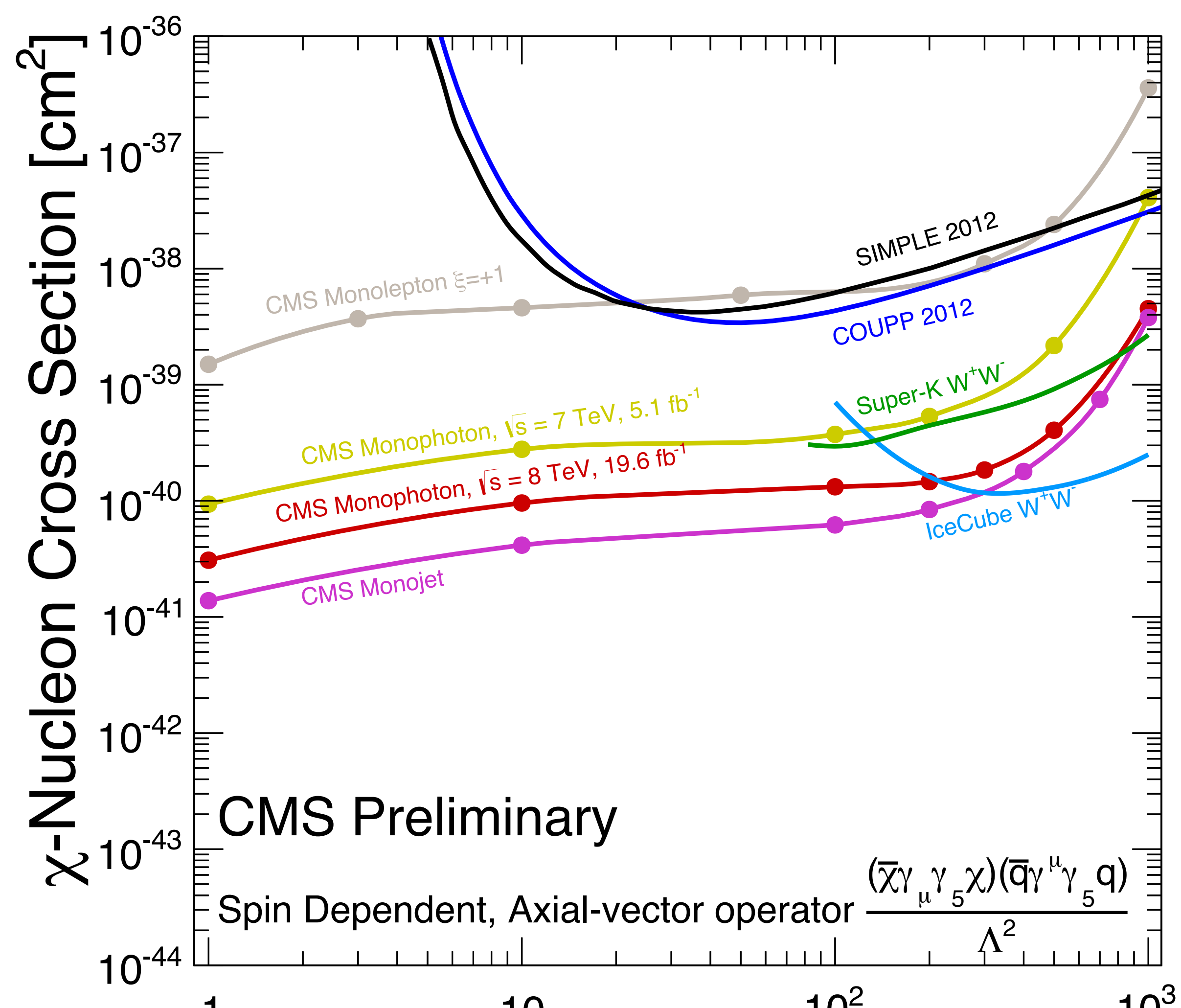
monojet +MET



monophoton +MET



Spin-independent interactions

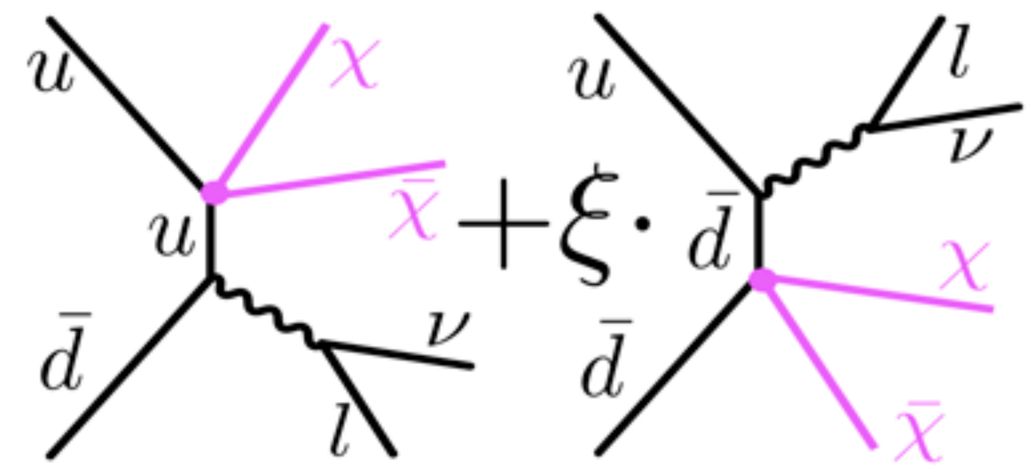


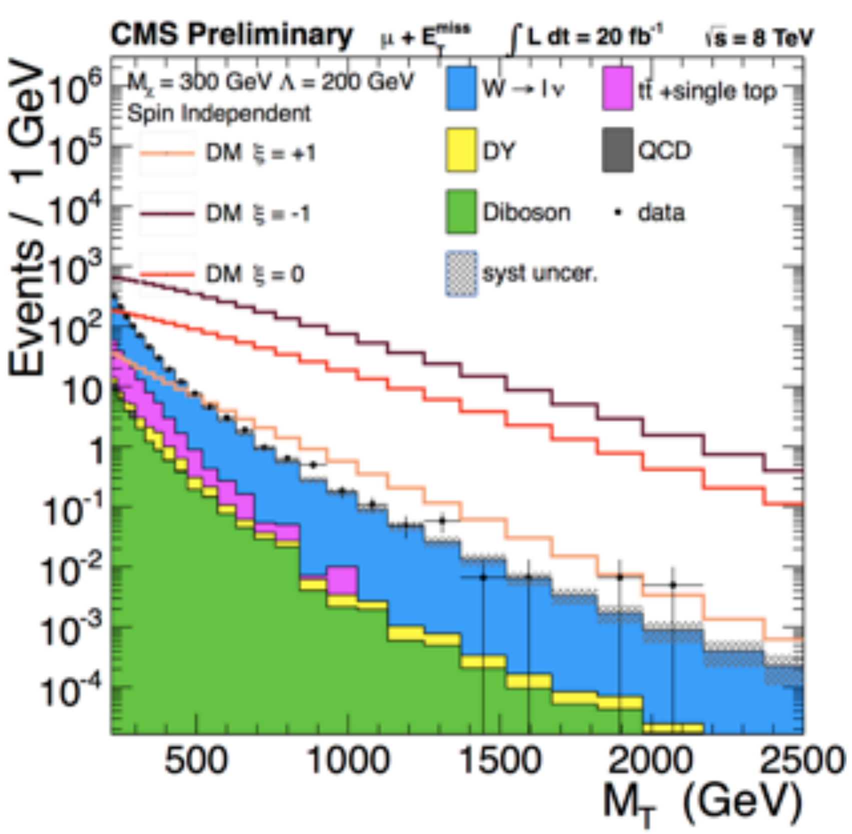
Spin-dependent interactions

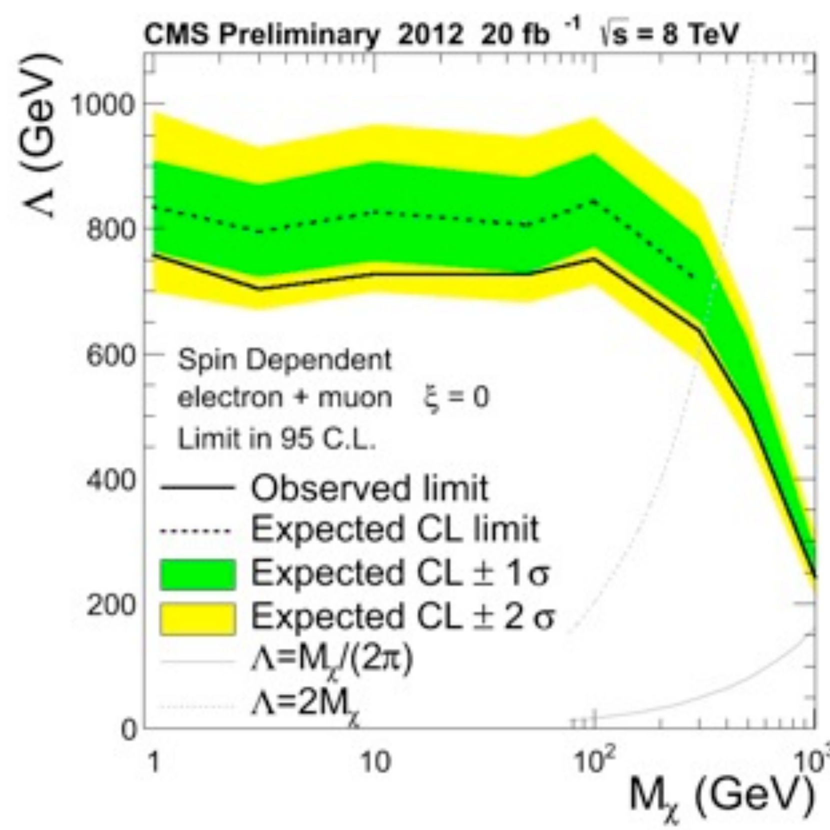
Mono-leptons

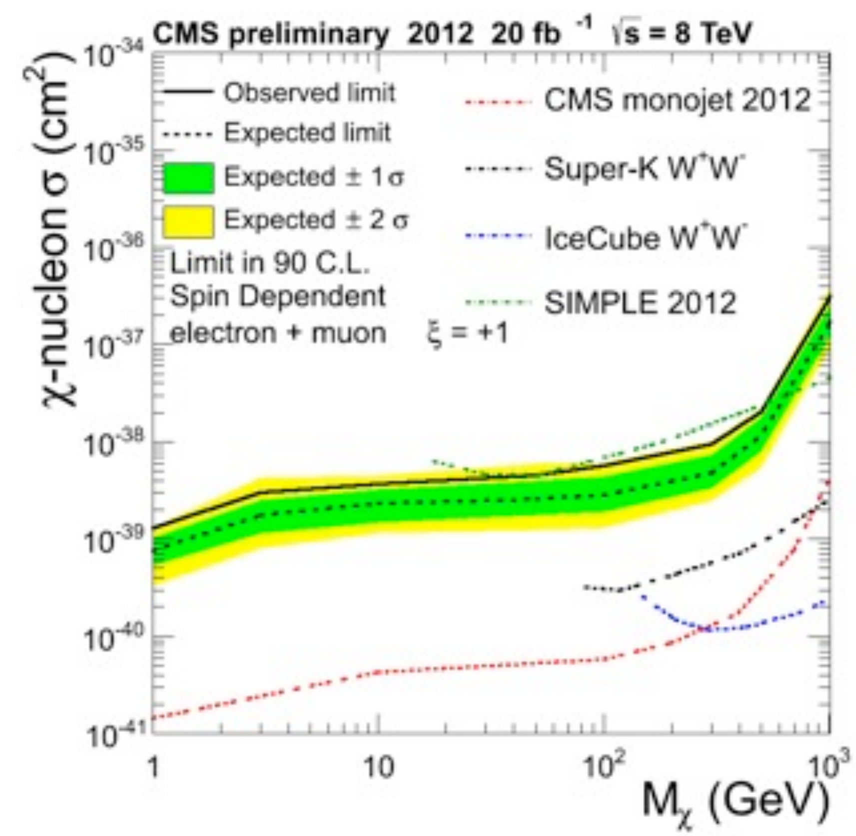
CMS-EXO-13-004

- DM produced together with W, which decays to lν
- Adapted from search for W'
- consider vector and axial-vector interactions



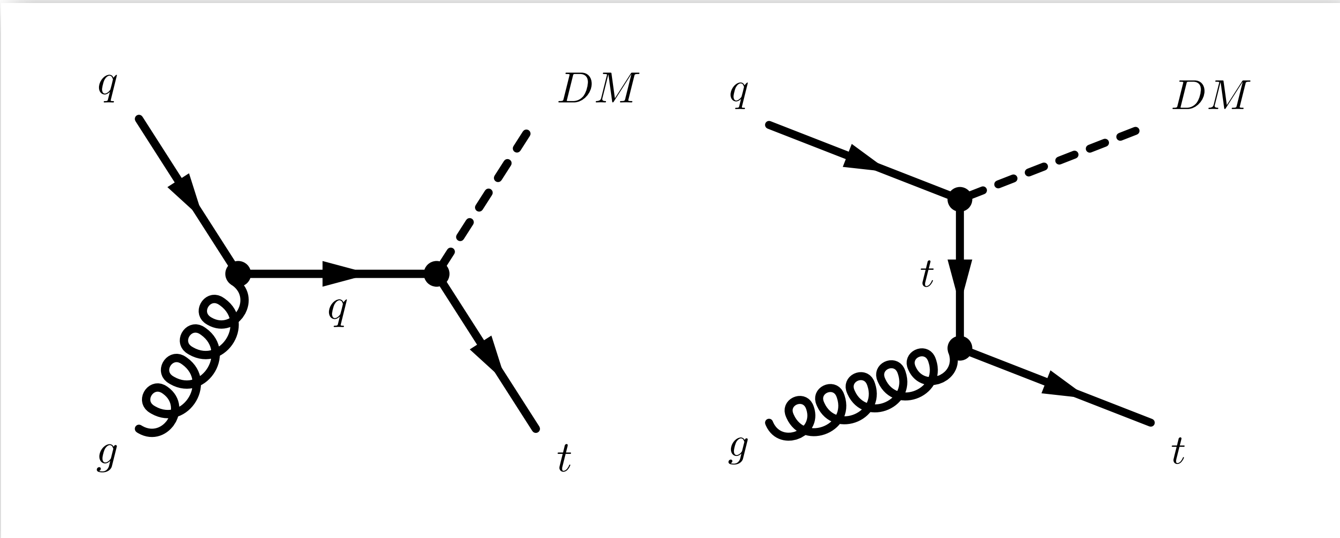


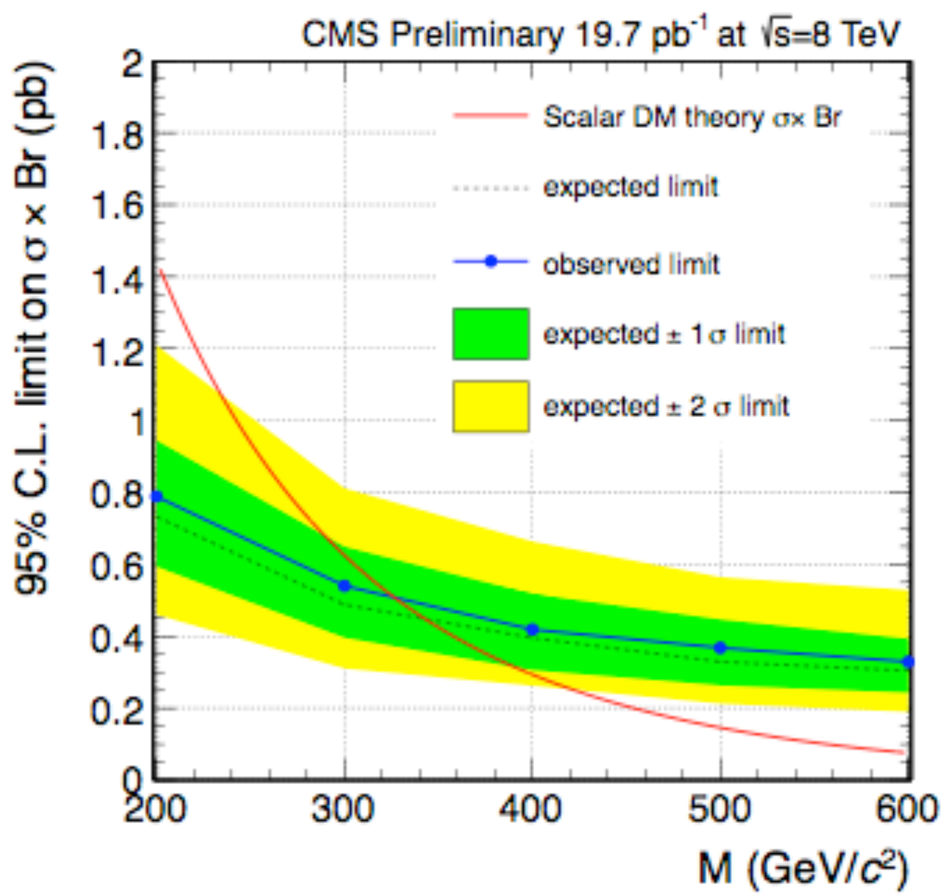




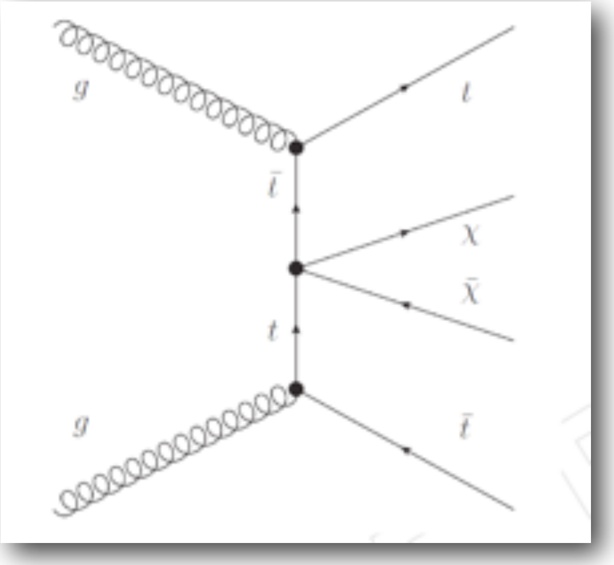
Mono-t and mono-tt

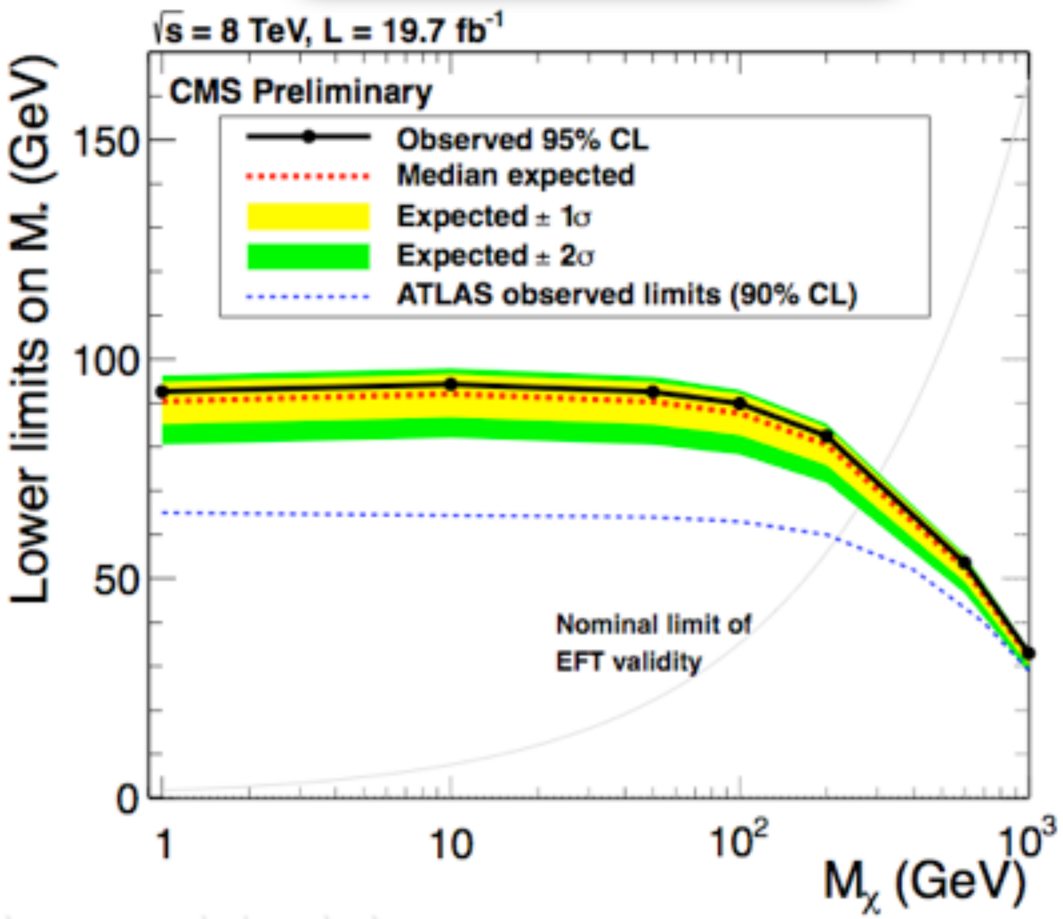
CMS-B2G-12-022





CMS-B2G-13-004

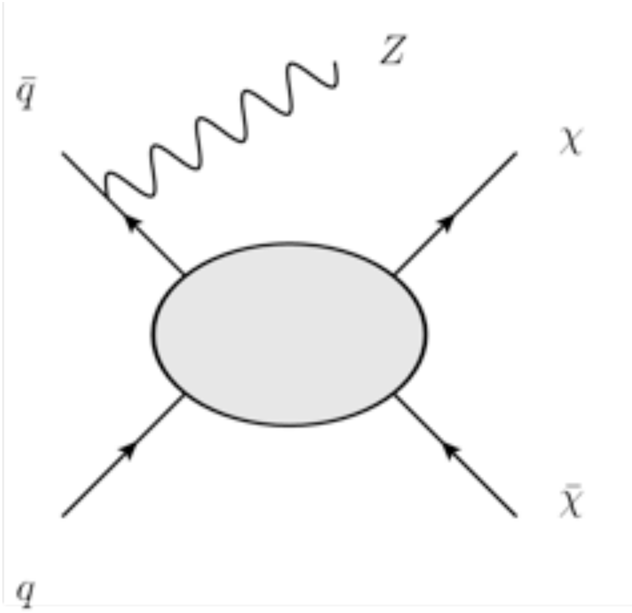


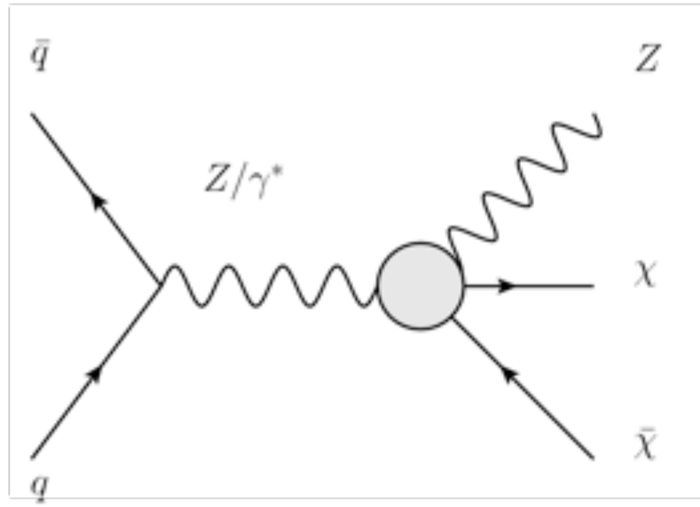


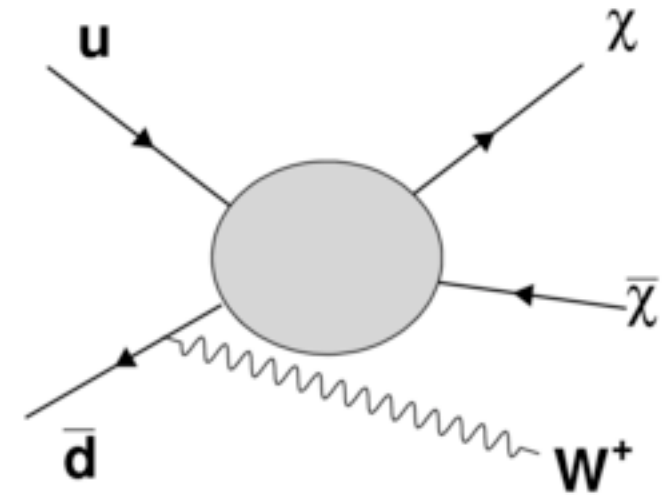
Mono-W/Mono-Z

arXiv:1404.0051

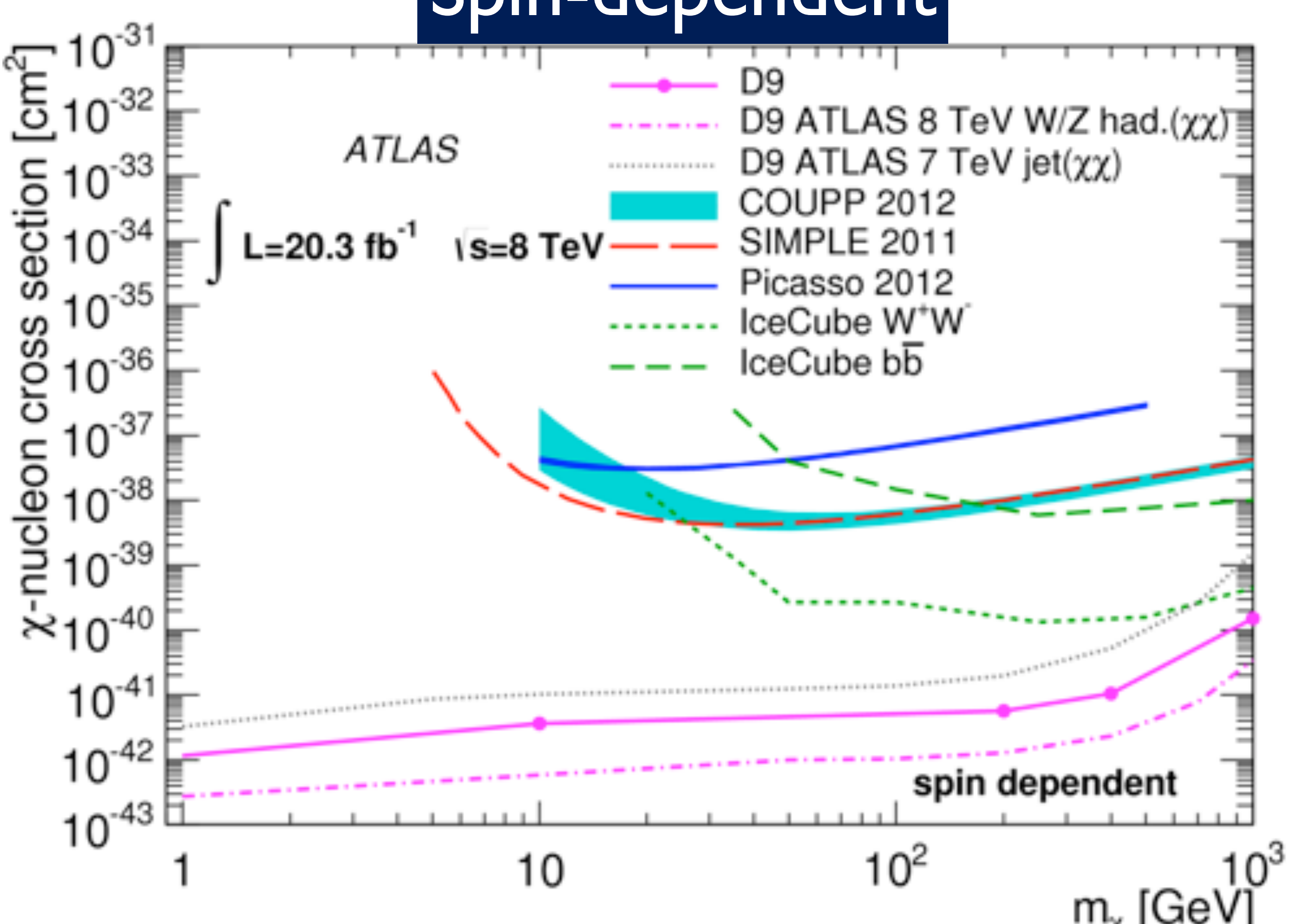
Phys. Rev. Lett 112, 041802 (2014)



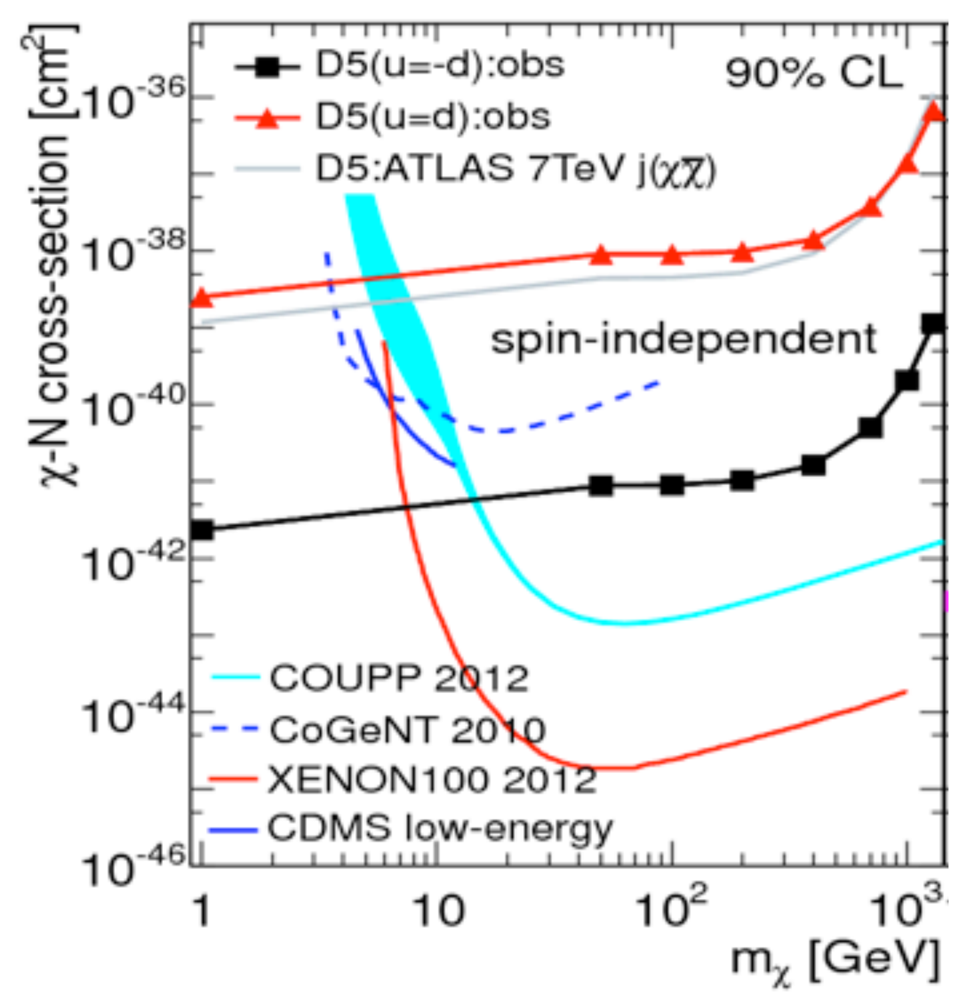




Spin-dependent



Spin-independent



Interpretation of searches

Limitations of EFT

Busoni, De Simone, Morgante, Riotto
arXiv:1307.2253

EFT valid when $q^2 << M$ and $M > m_{DM}$

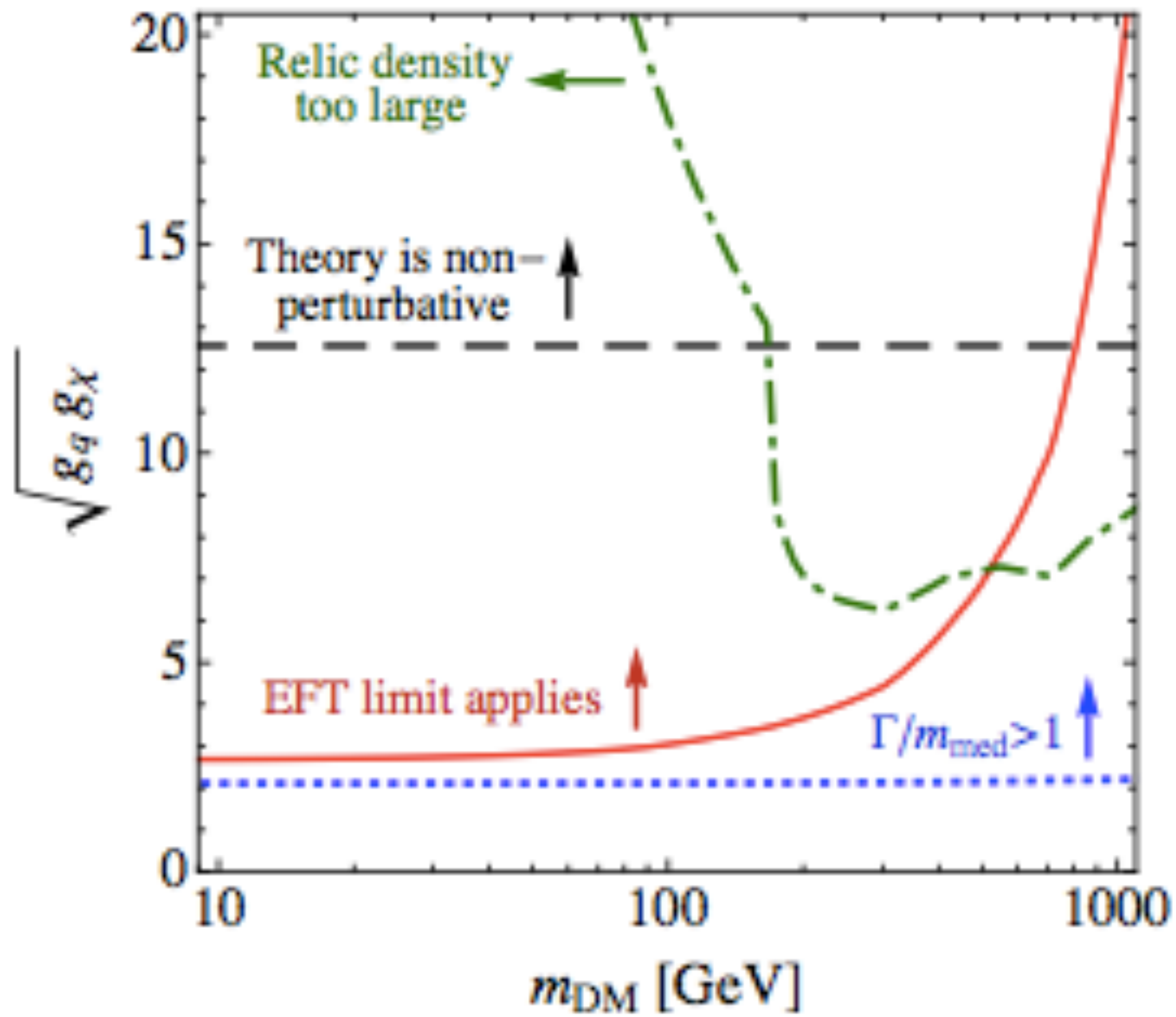
- The couplings required are large

Comparing this with known couplings:

strong interaction ~1.2

weak interaction ~0.6

- Theory is non-perturbative if $\sqrt{g_q g_{DM}} > 4\pi$
- Width larger than mass, so unlikely mediator will be identified as a particle



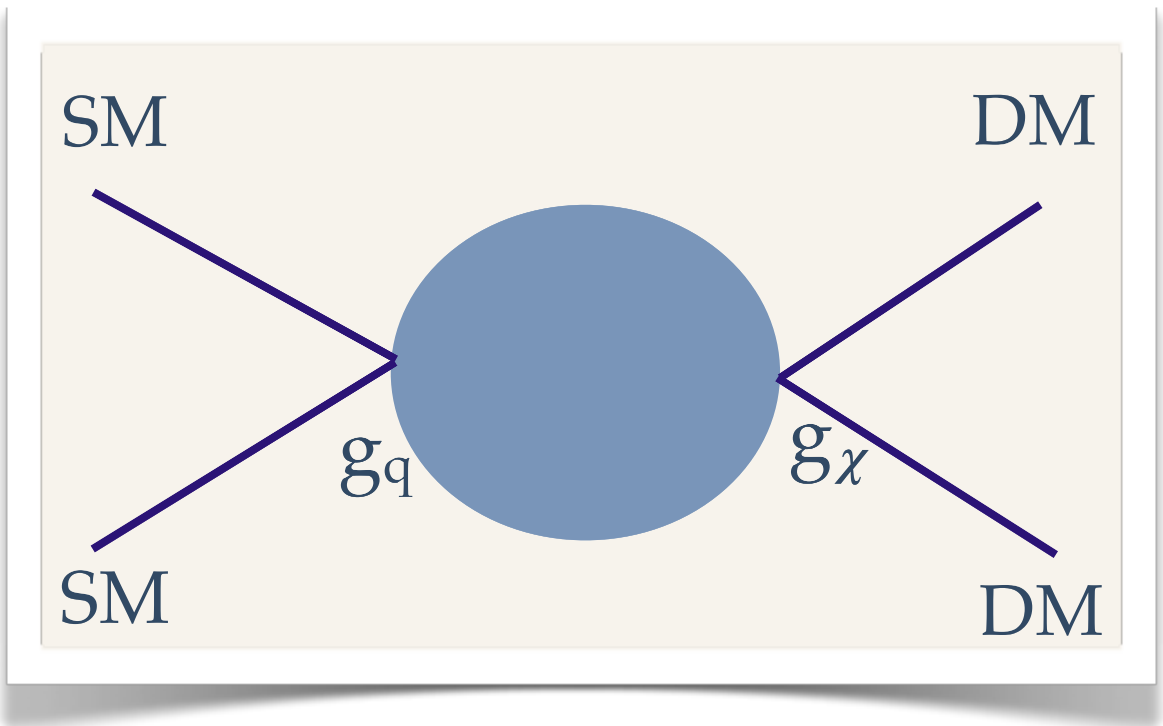
arXiv:1308.6799

O. Buchmueller,[a] Matthew J. Dolan,[b] and Christopher McCabe[b]

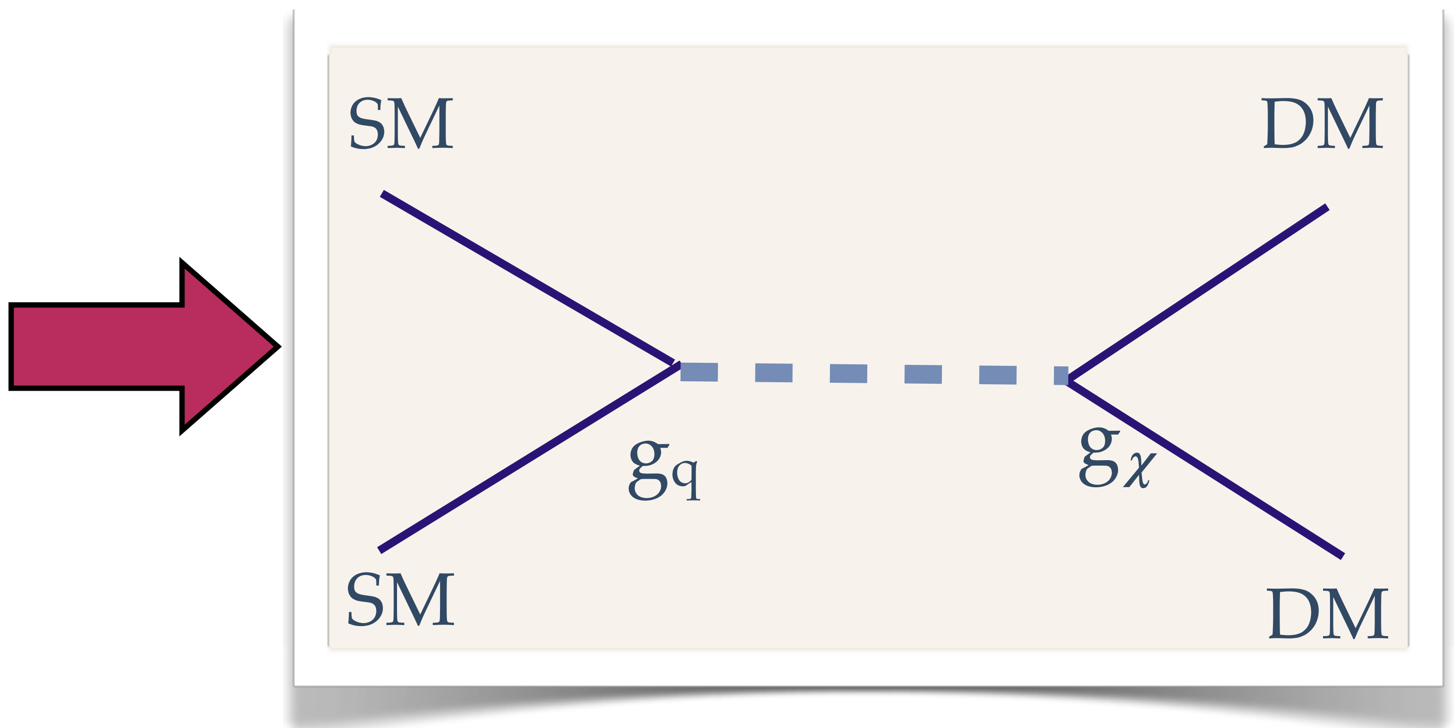
Beyond EFT : Simplified models of dark matter

Numerous papers in literature advocating simplified model approach to go beyond EFT

arXiv:1402.2285
arXiv:1308.2679
[arXiv:1308.0592
arXiv:1403.4634
[arXiv:1401.0221].
[arXiv:1312.5281
arXiv:1407.8257



Effective field theory

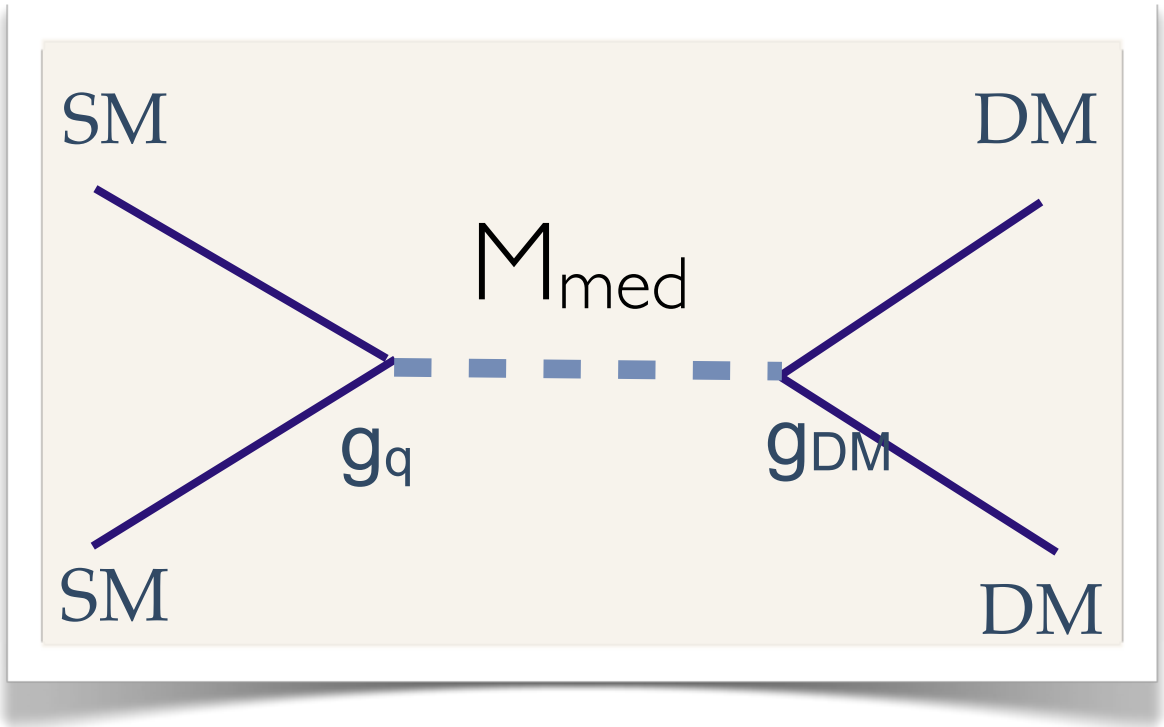


Simplified model

Minimal Simplified model of dark matter (MSDM)

arXiv:1407.8257

O. Buchmueller, M. Dolan, S.A. Malik, C. McCabe



s-channel

Define simplified model with (minimum) 4 parameters	
Mediator mass (M_{med})	DM mass (M_{DM})
g_q	g_{DM}

DM	
Dirac fermion	Scalar - real
Majorana fermion	Scalar - complex

Consider comprehensive set of diagrams for mediator	
Vector	Axial-vector
Scalar	Pseudoscalar

Simplified model of Dark Matter

M_{DM}	M_{med}
g_q	g_{DM}

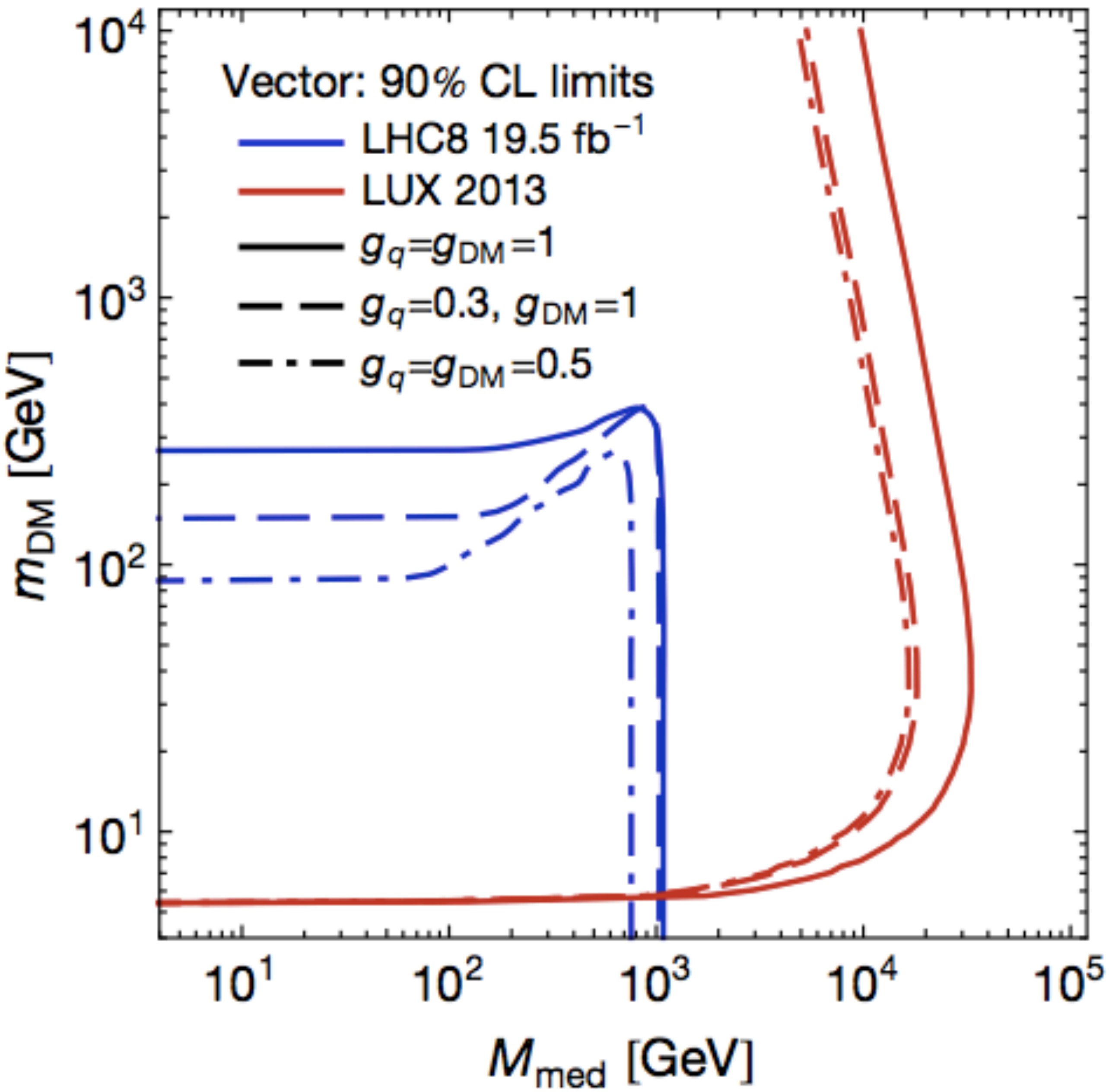
4-dimensional problem, projecting limits onto all 2-D plane:

- M_{DM} vs M_{med} assuming $g_q = g_{DM}$ and $g_q \neq g_{DM}$
- M_{med} vs g_q, g_{DM} for fixed M_{DM}
- M_{DM} vs g_q, g_{DM} for fixed M_{med}
- g_q vs g_{DM} for fixed M_{DM}, M_{med}

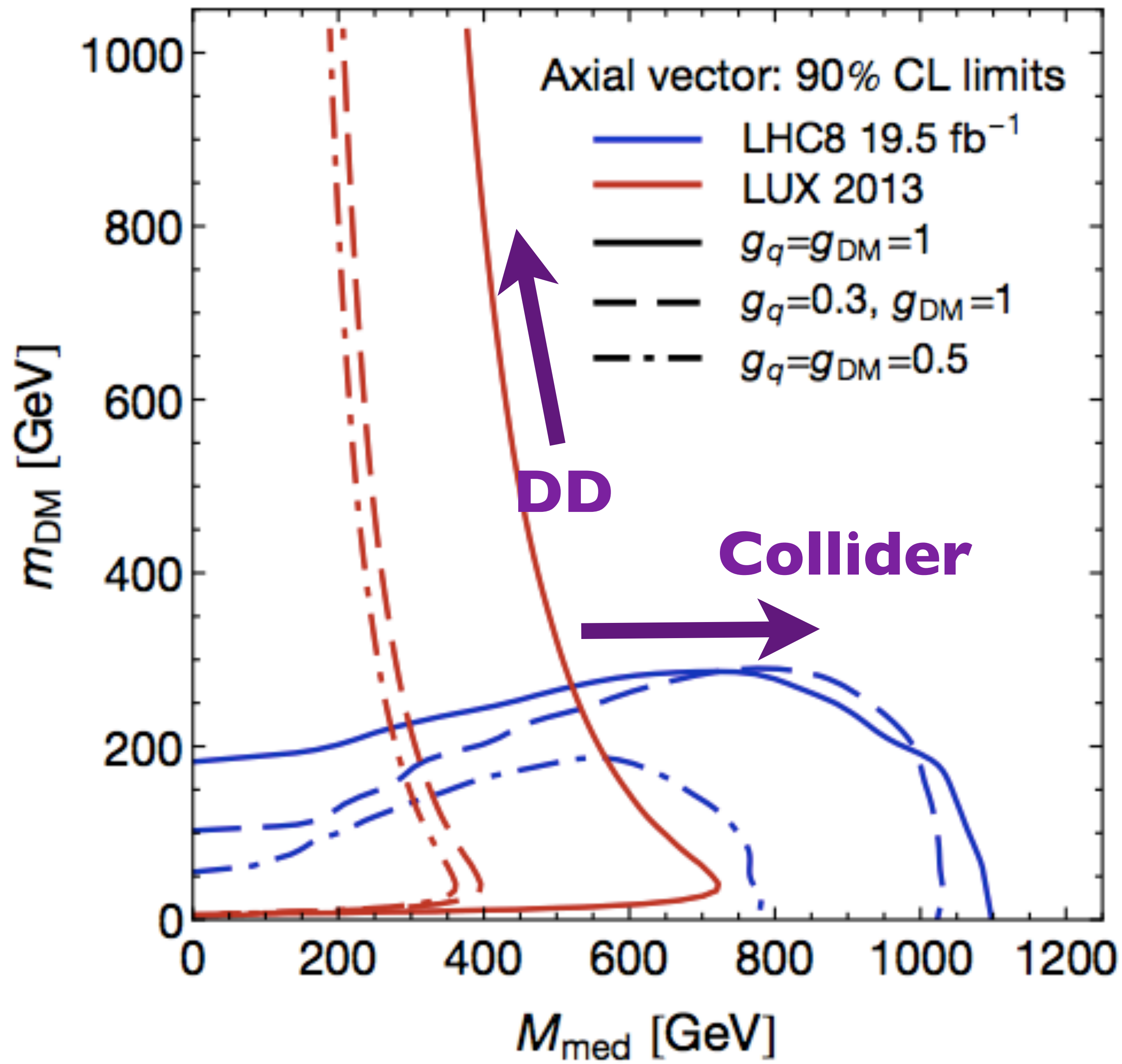
Comparison with direct detection

M_{DM}	M_{med}
g_q	g_{DM}

Vector



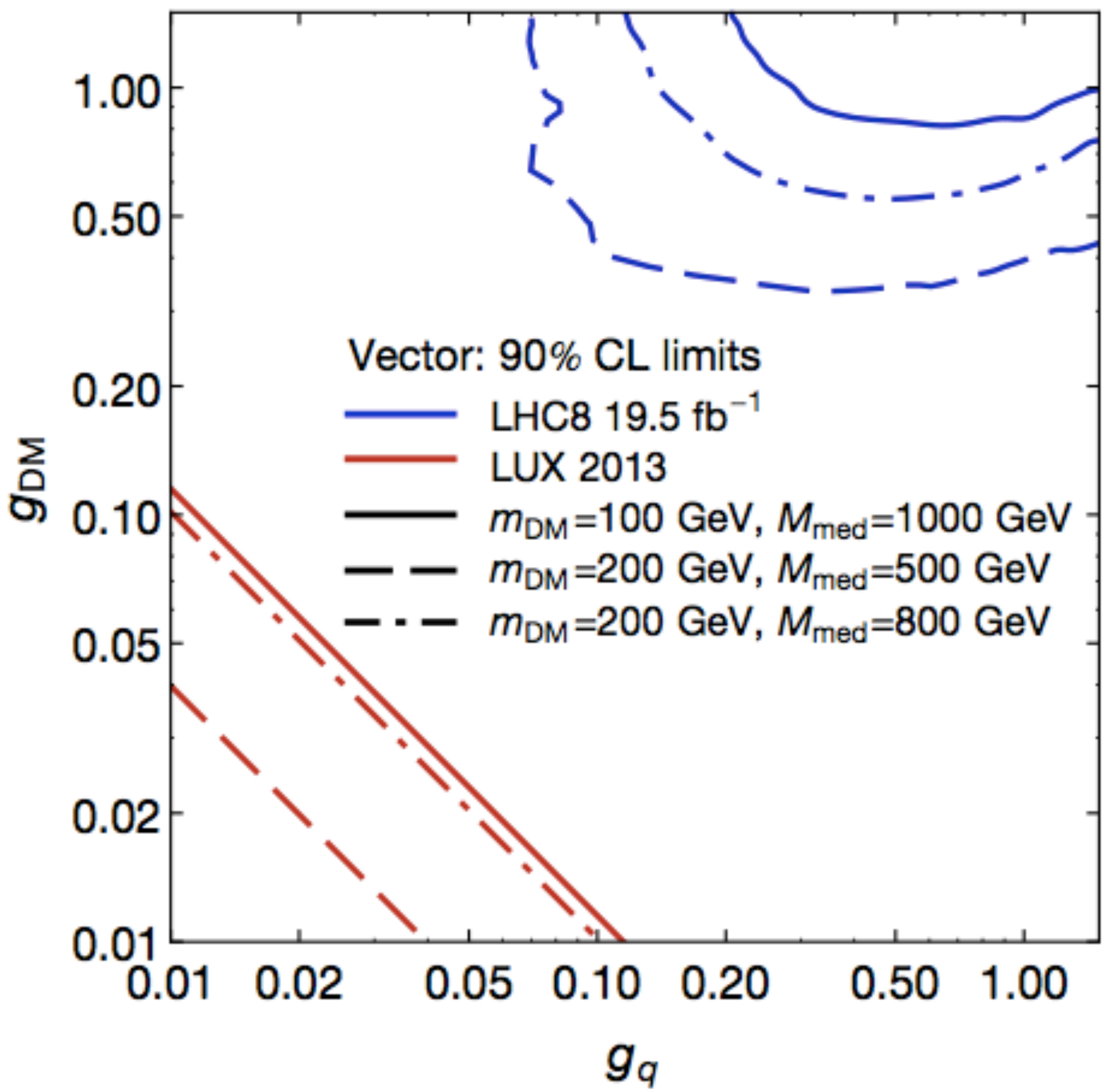
Axial vector



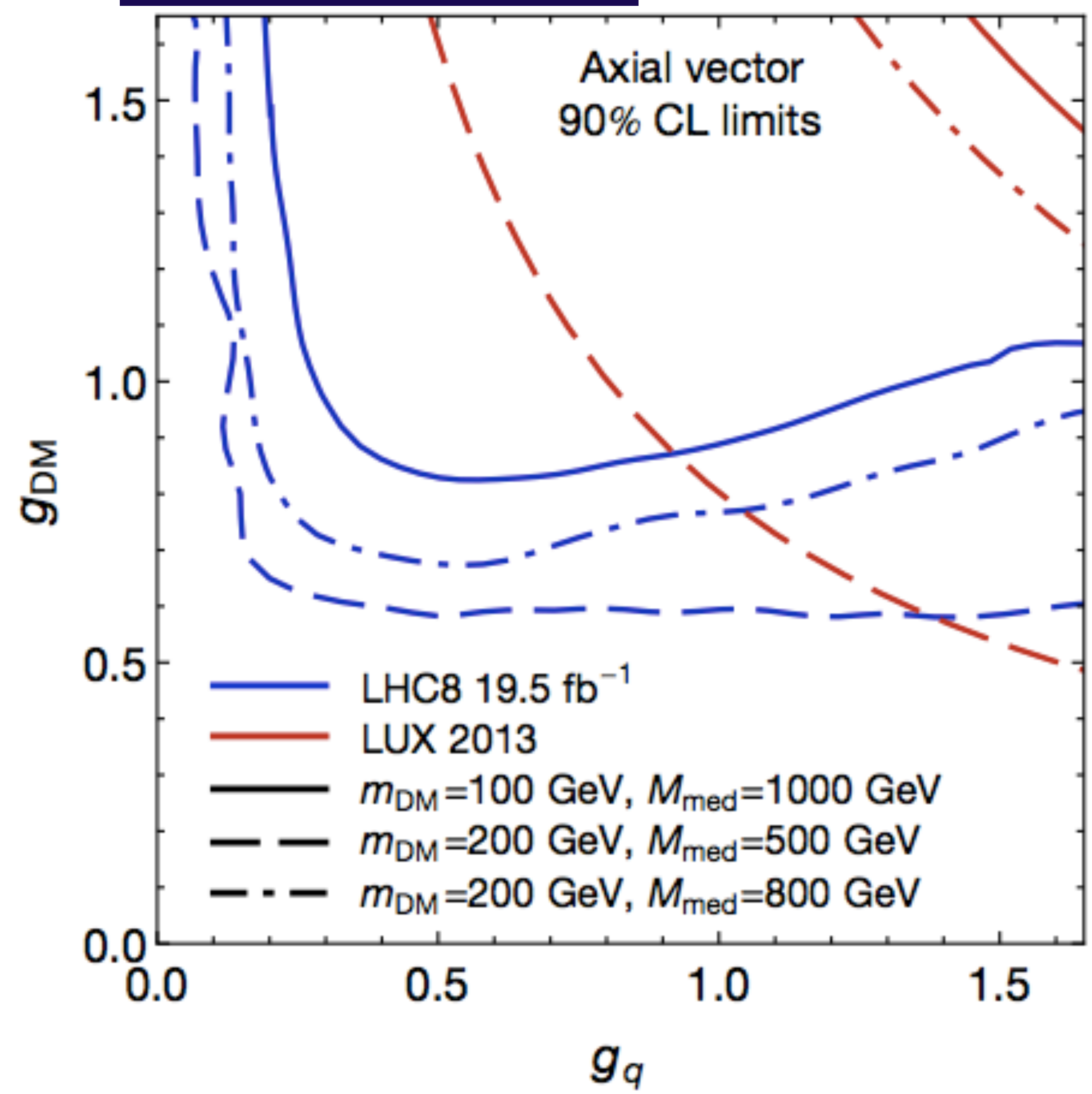
Comparison with direct detection

M_{DM}	M_{med}
g_q	g_{DM}

Vector



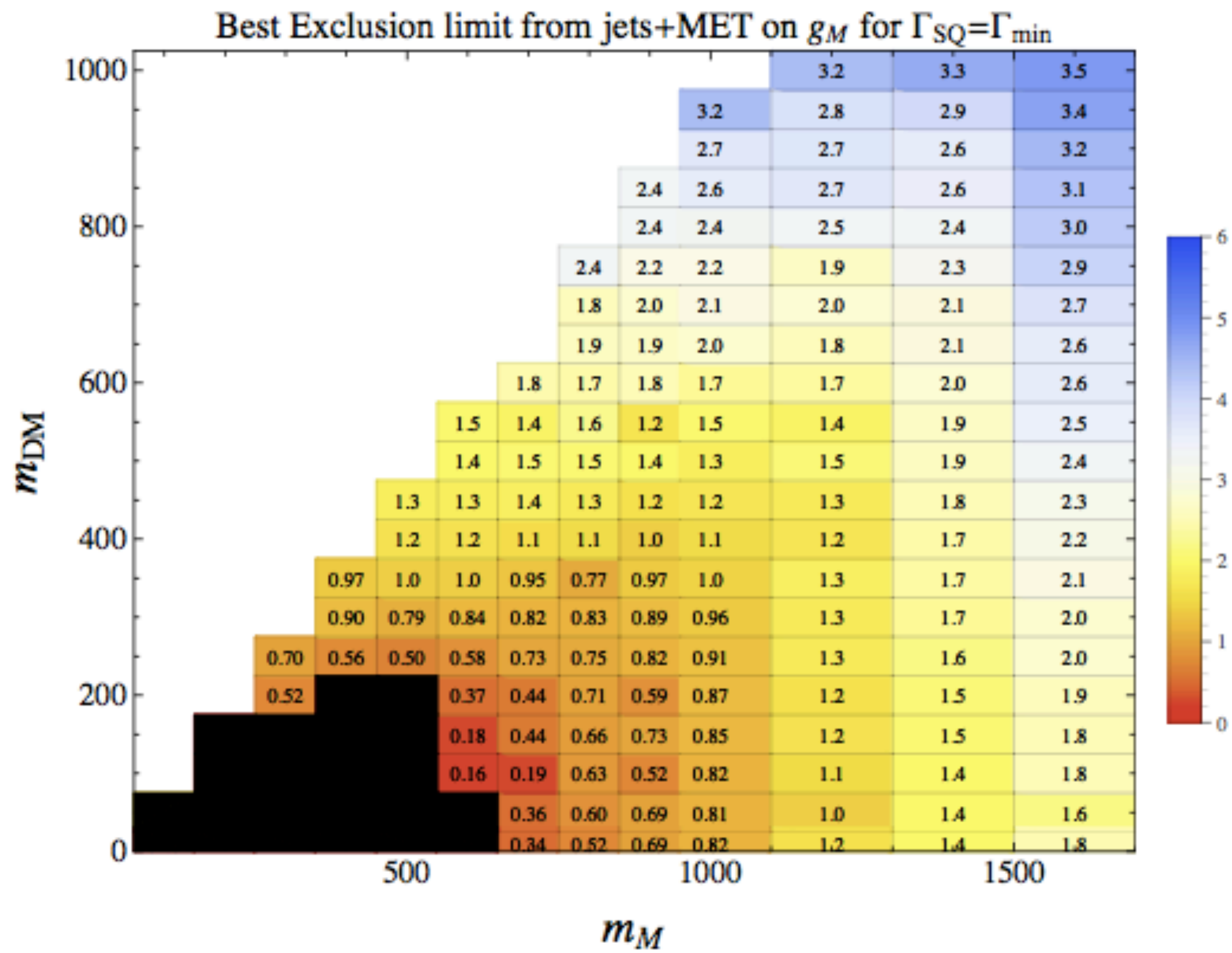
Axial vector



Simplified models of Dark Matter : t-channel mediators

Papucci, Vichi, Zurek, arXiv:1402.2285

Limits on t-channel mediator coupling to quarks



Projections for 14 TeV

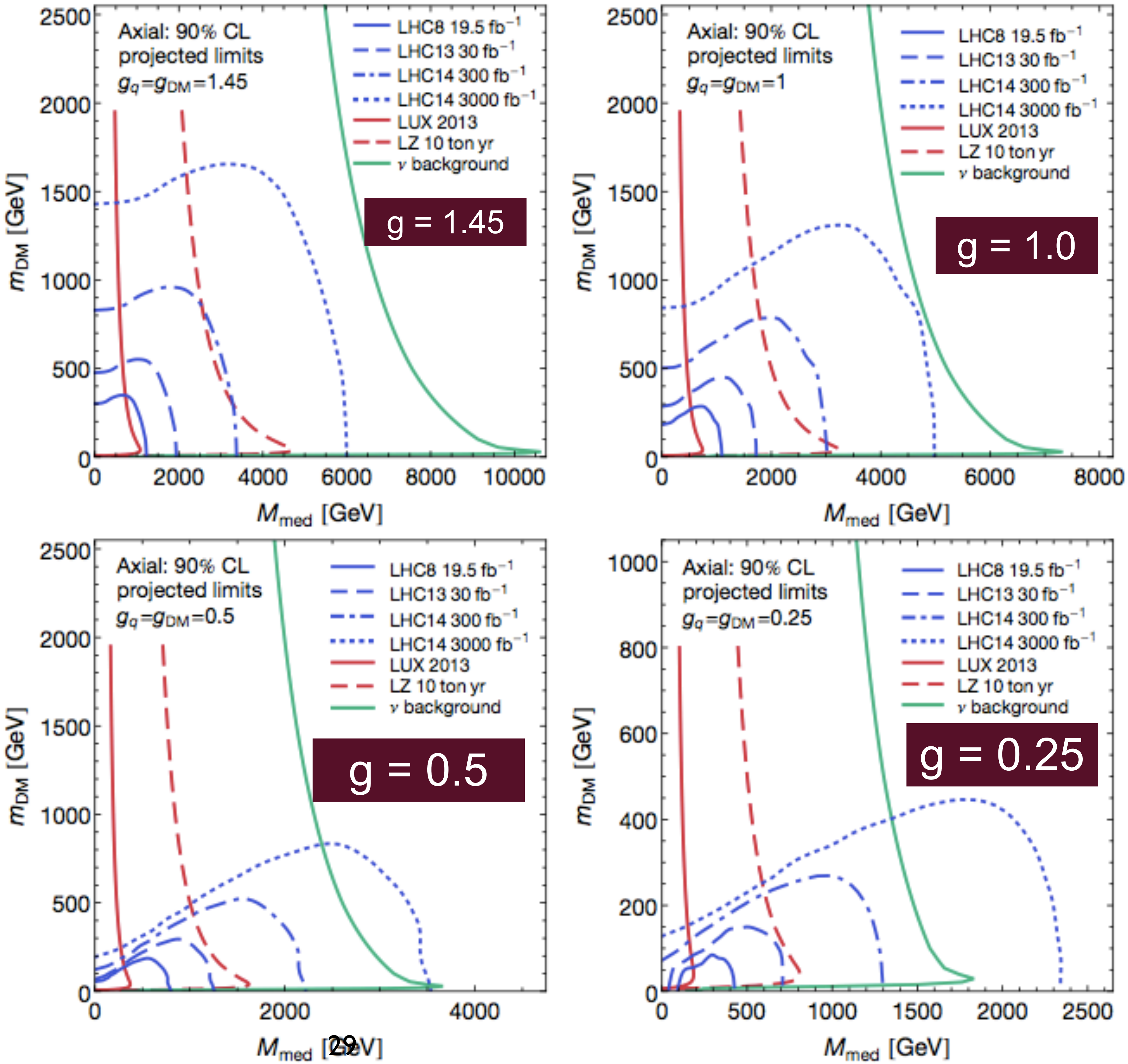
Projections

arXiv:1409.4075

Limits from 8 TeV monojet search and projected limits for 3 LHC scenarios:
- 13 TeV 30 fb^{-1}
- 14 TeV, 300 fb^{-1}
- 14 TeV, 3000 fb^{-1}

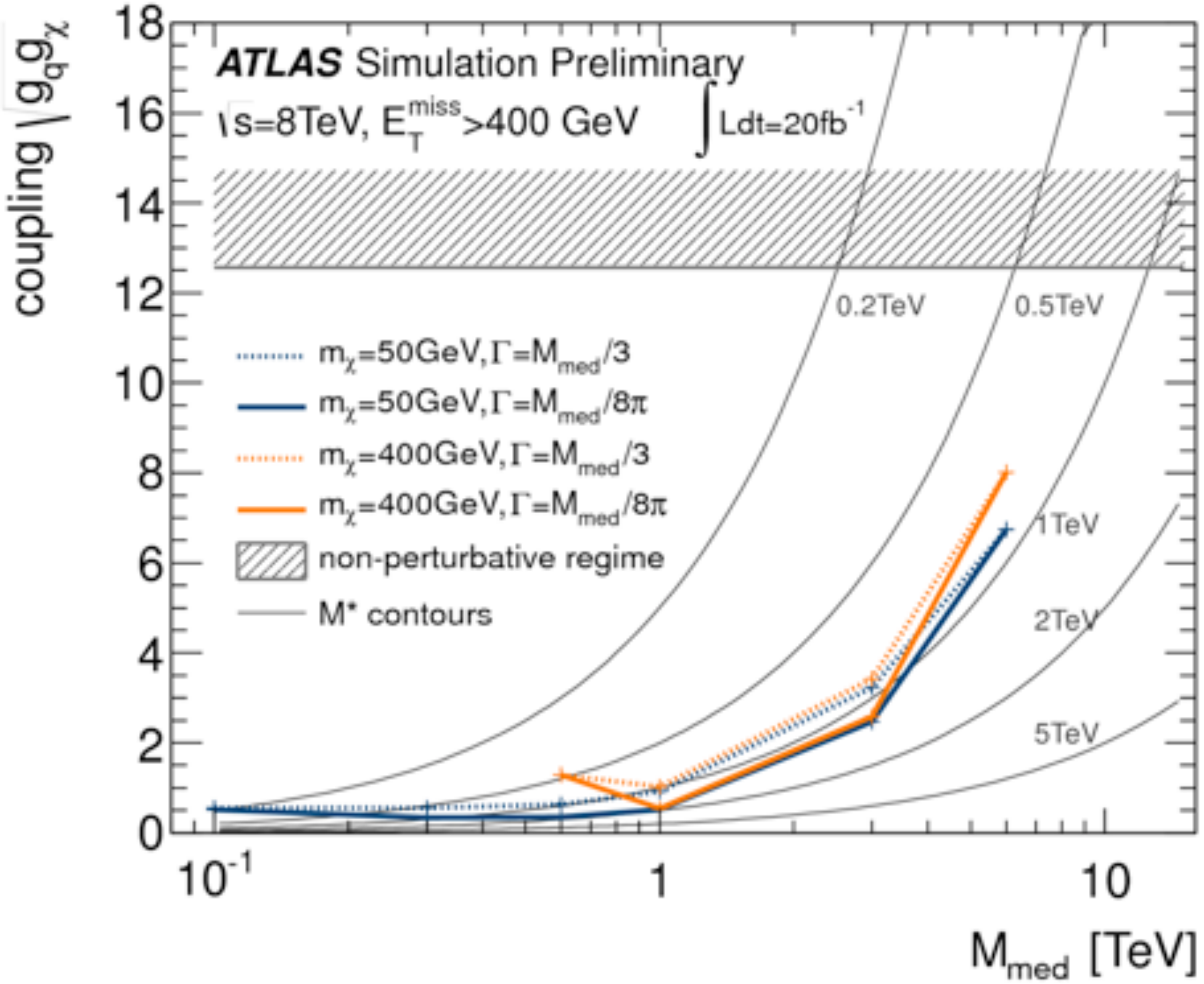
LUX 2013 limits and projected limits for LZ assuming 10 tonne-year exposure

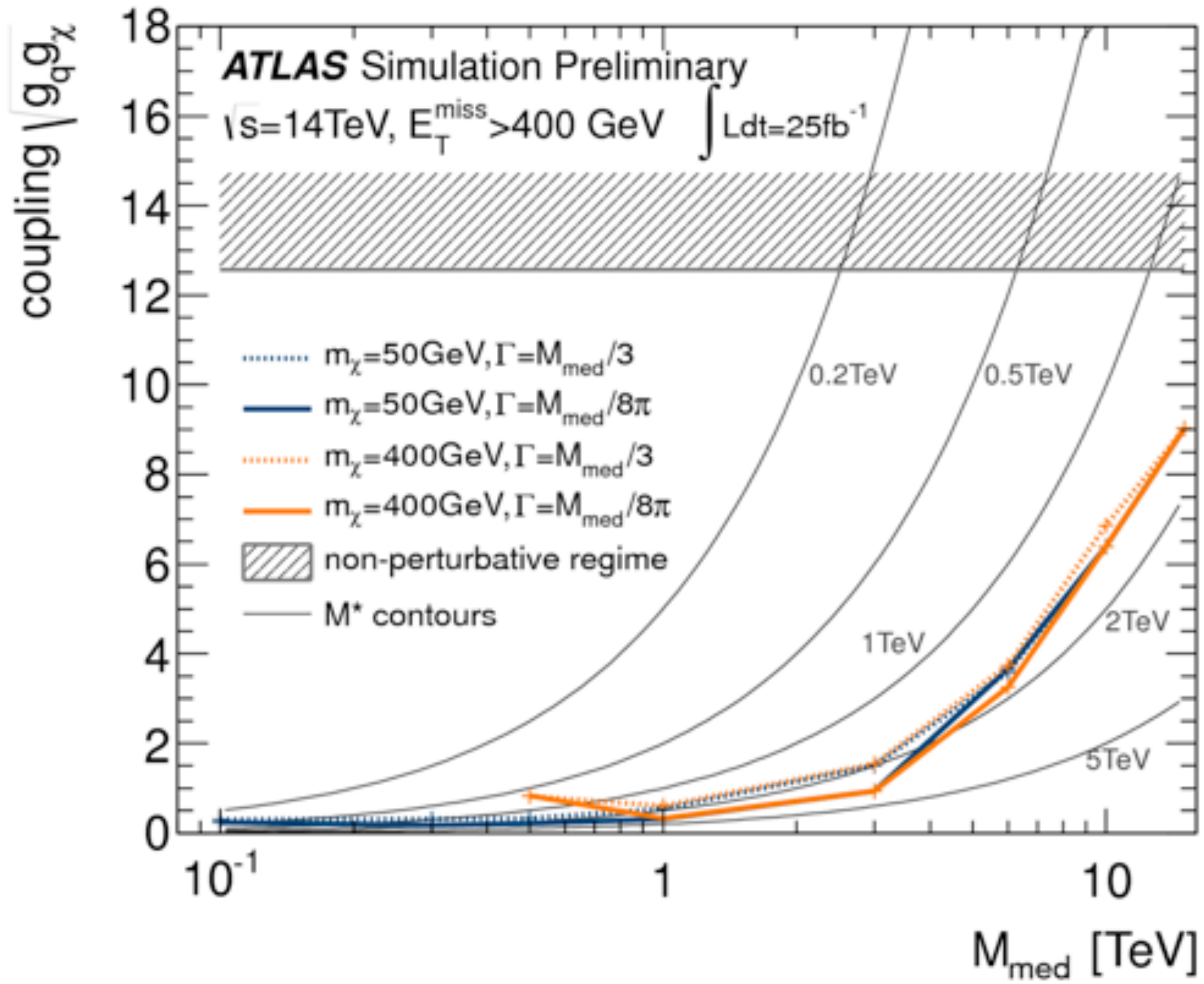
Discovery reach accounting for coherent neutrino scattering



ATL-PHYS-PUB-2014-007

ATLAS projections for monojet analysis assuming a simplified model with a Z`





Increased sensitivity by a factor of 1.5-3 when going from 8 TeV to 14 TeV

Summary

Searches for Dark matter at collider:

- via SUSY
- via generic mono-X signatures
- Higgs invisible decays

Complementarity with direct detection experiments

- low mass DM
- spin-dependent interactions of DM

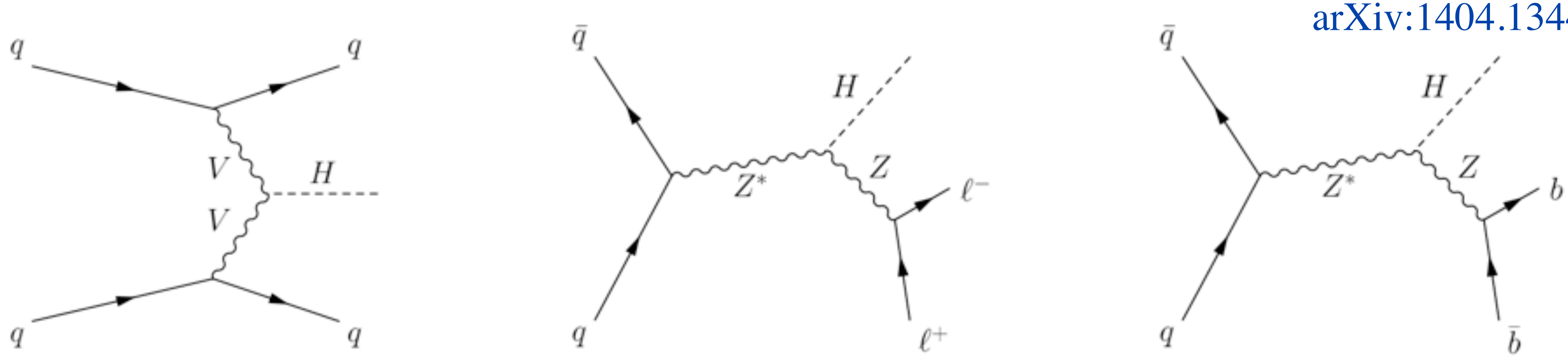
Interpretation of searches: Shift from EFT approach which has several limitations to simplified models of dark matter.

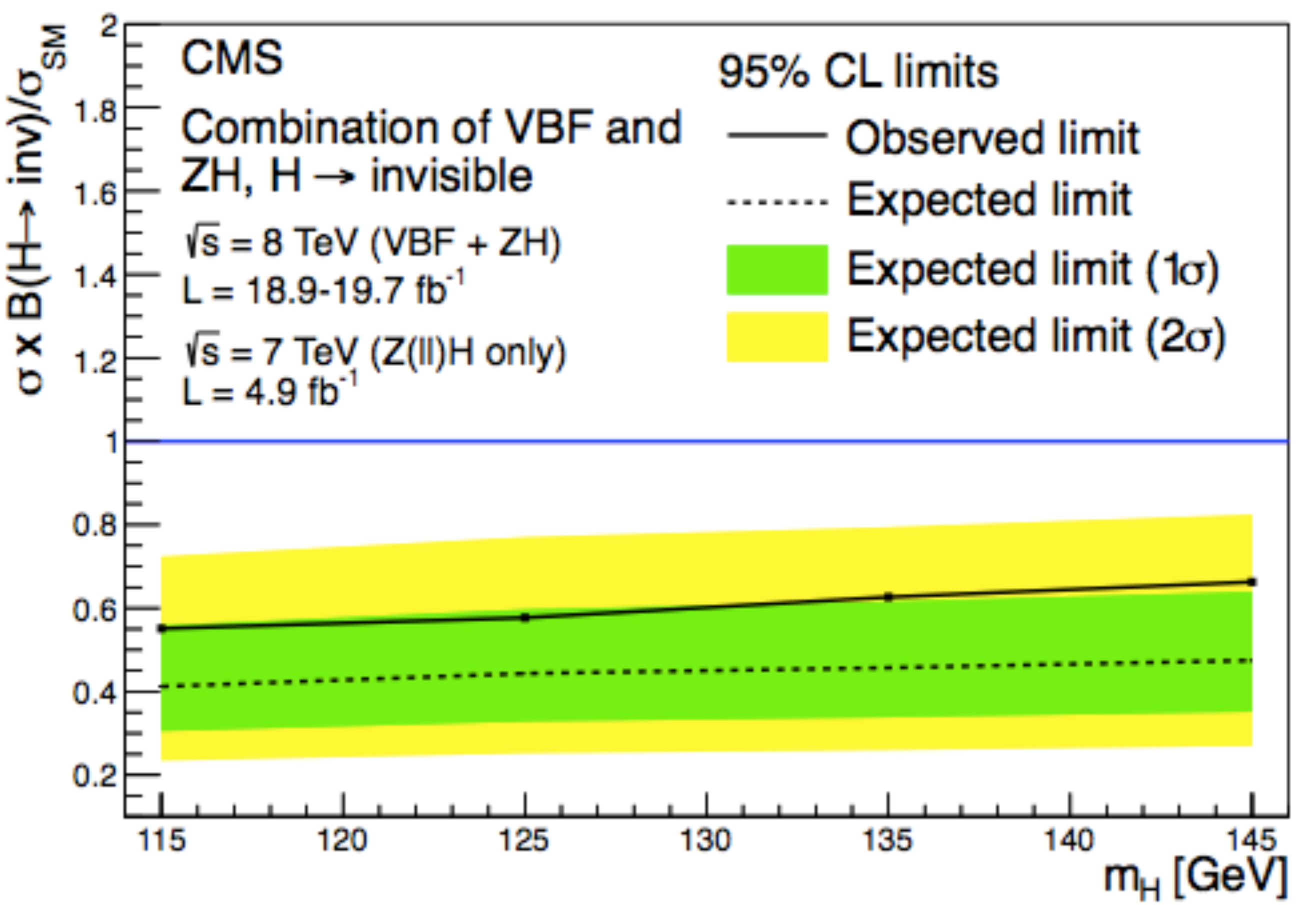
Future projections, similar complementarity between collider and DD experiments going forward.

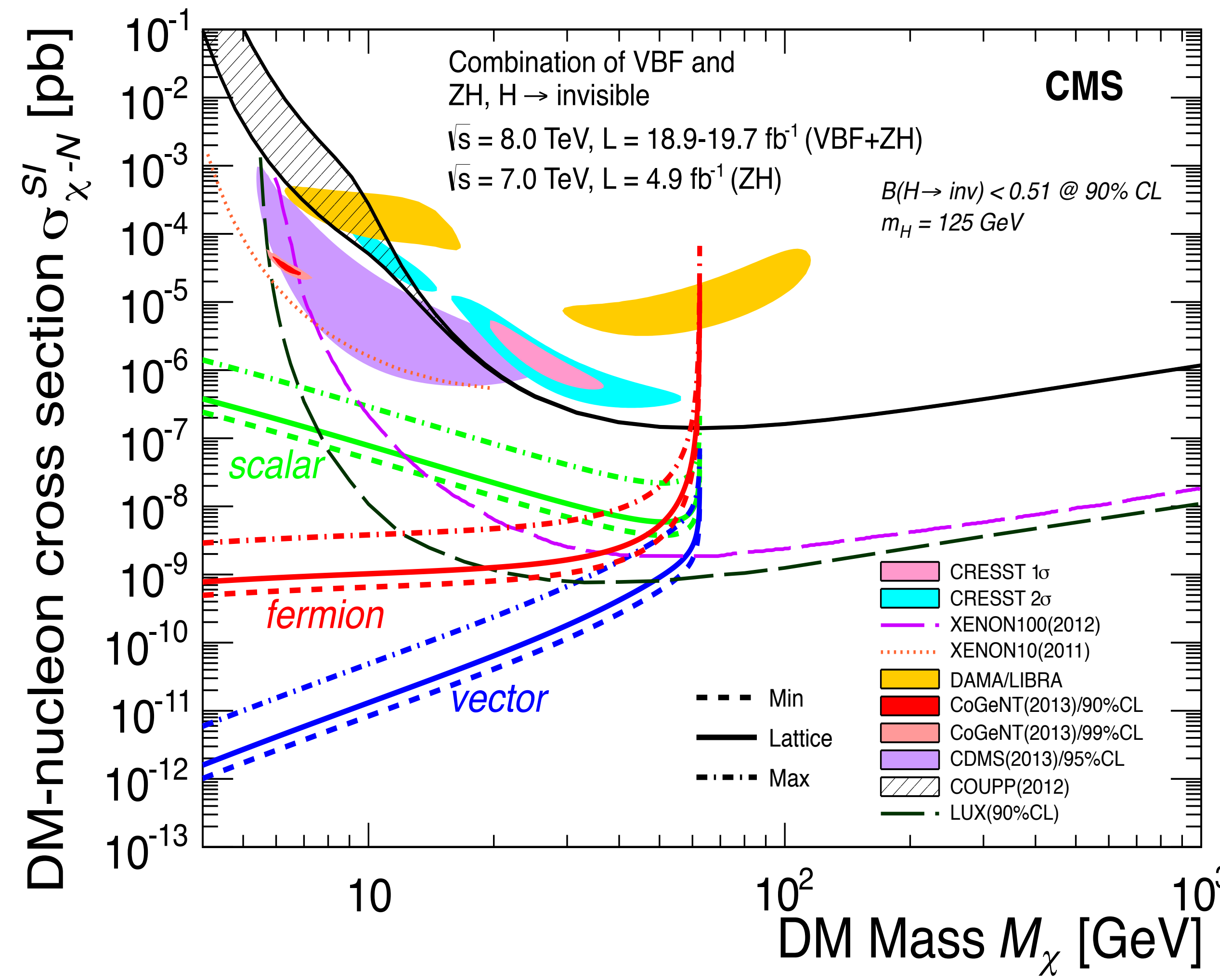
Invisible Higgs

Invisible Higgs searches

arXiv:1404.1344





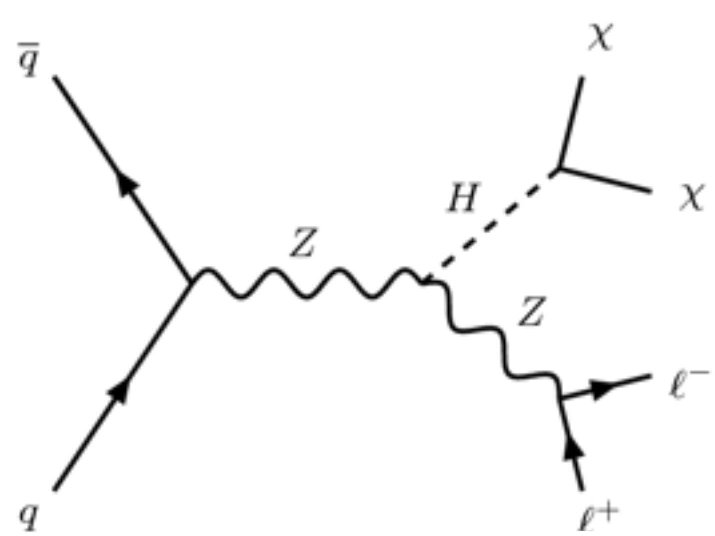


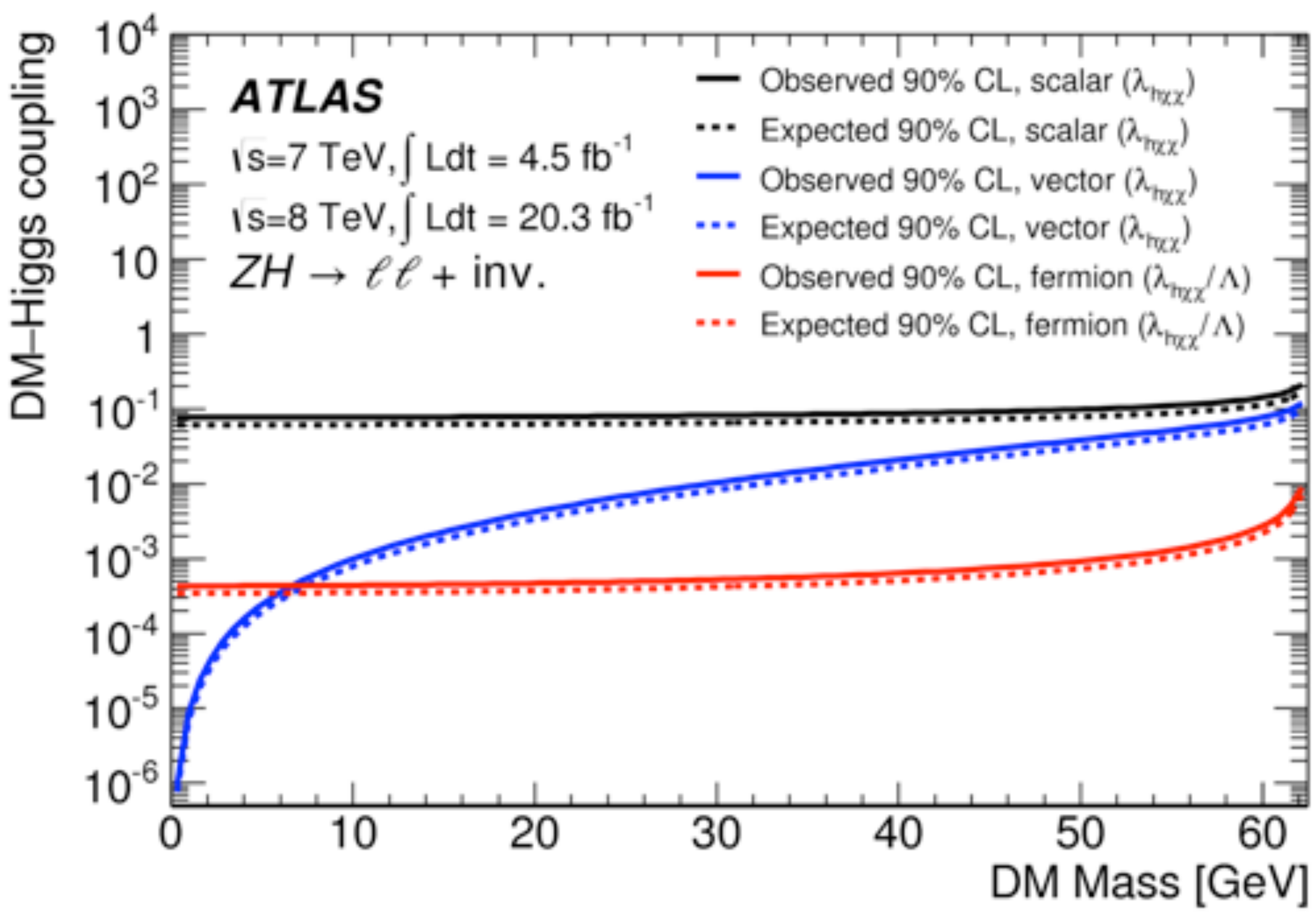
BF(H->invisible) < 0.58 @ 95%CL

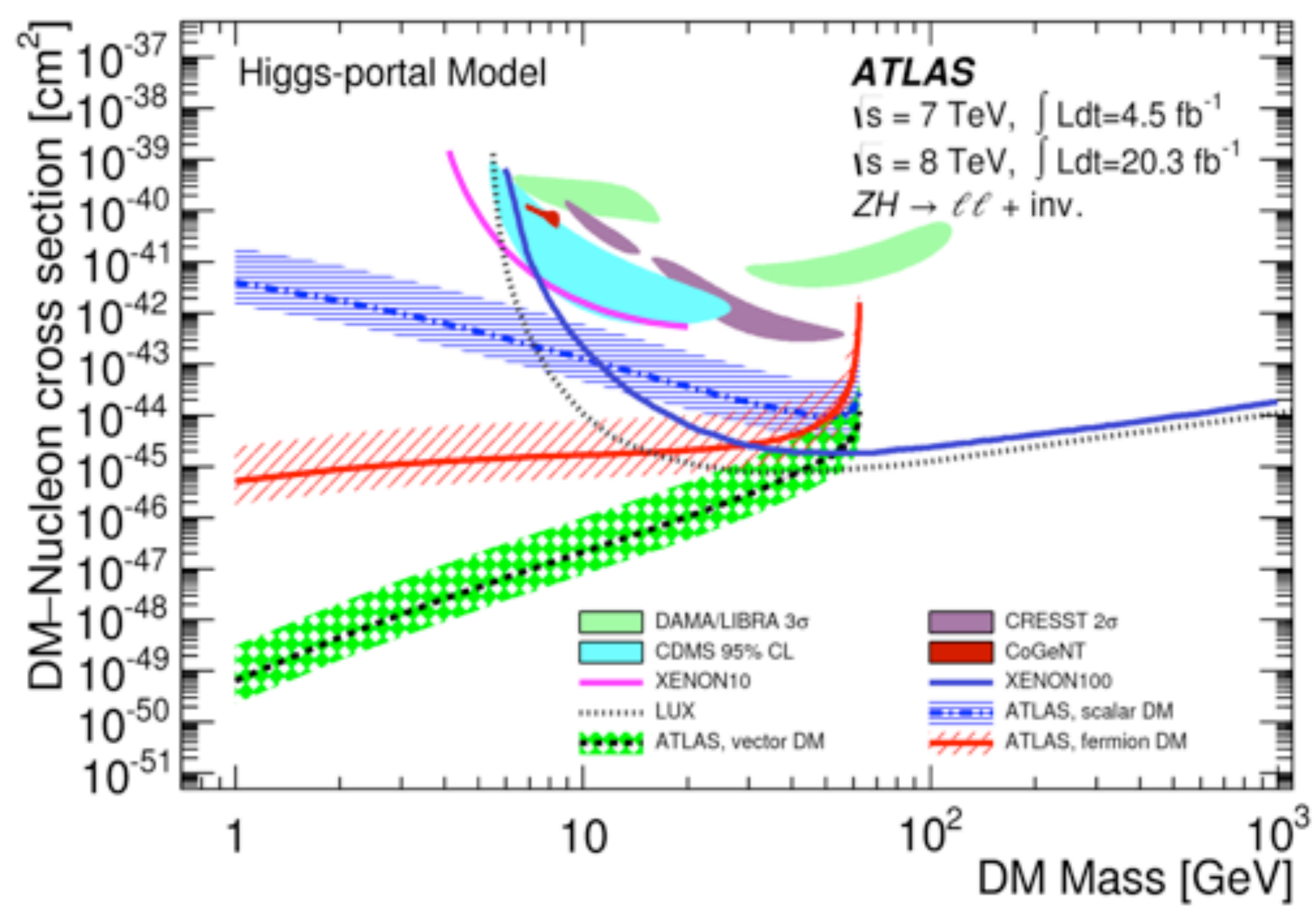
assuming SM production cross section and kinematics

Invisible Higgs searches

Phys. Rev. Lett. 112, 201802



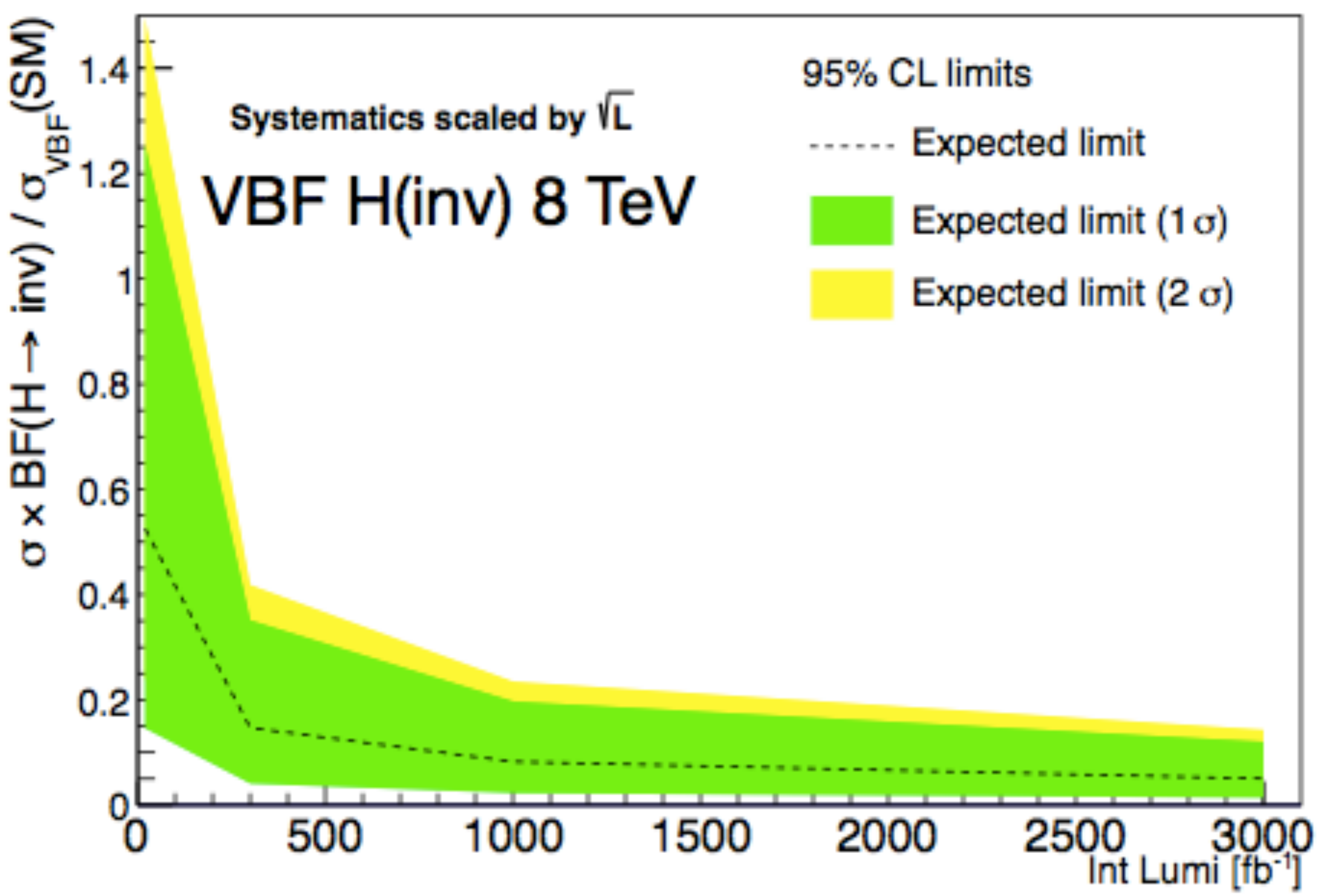




Projections for invisible Higgs

From Jim Brooke talk

- **Run 1 (8 TeV)**
  - ggH(inv) interpretation of monojet search
- **Run 2-3 (13-14 TeV 300 fb^{-1})**
  - VBF, Z(ll)H, monojet, ttH ?
  - Exp limit : BR(H→inv) ~ 10-15% ?
- **HL-LHC (14 TeV, L_{int} = 5E34)**
  - Scaling 8 TeV results to 3000 fb^{-1}
  - Assume systematics scale with 1/√L
  - Expected limits :
    - VBF : BR(H→inv) < 5% (~200 fb)
    - ZH : BR(H→inv) < 6% (~40 fb)
- Implies huge assumptions about :
  - Trigger acceptance
  - PU rejection



Limits on BF(H_{125}→invisible) at few-% level *may* be possible with HL-LHC