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Search for Dark Matter with Present & Future Collider

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LISHEP 2015 Manaus

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Overview

- DM Overview & Experimental Scenarios
- SUSY type DM
- Mono-X & Simplified models
- Searching for the Mediator
- Conclusion

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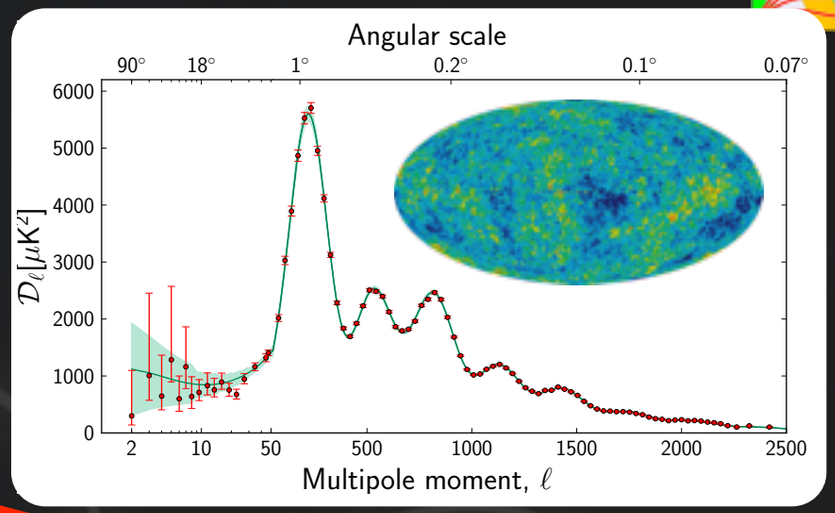
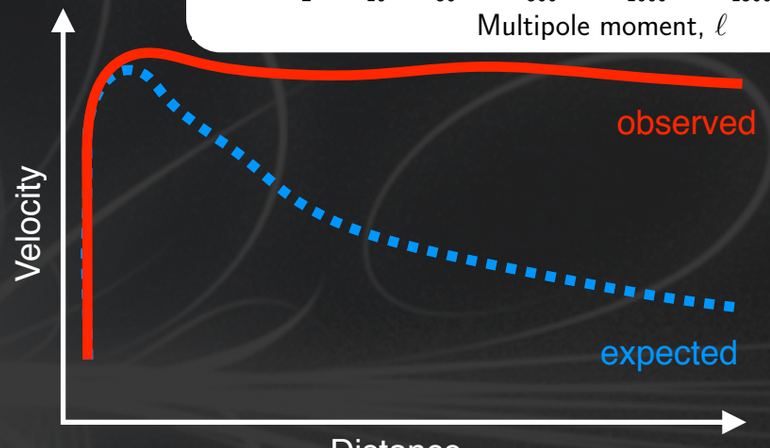
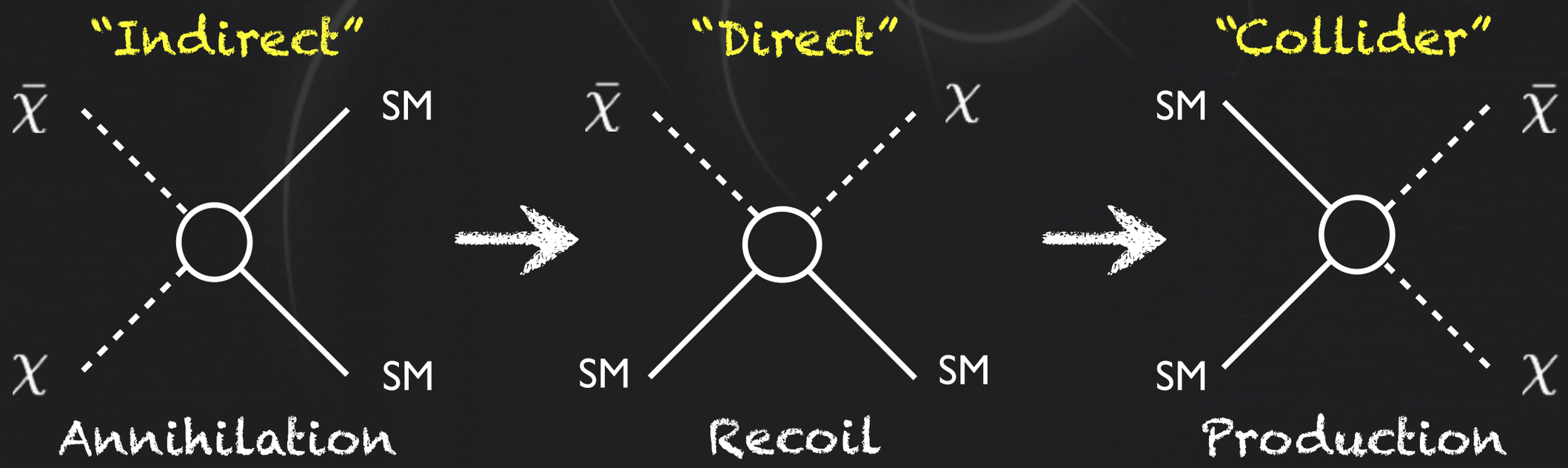
Why looking for DM

- Dark Matter (DM) **firmly established signal of new physics**
- **Many independent observations:**
  - **Rotation curves, strong lensing, Anisotropy of CMB, large-scale structure, Type Ia supernovae survey, hot gas**
- **ΛCDM: $\Omega_\Lambda \approx 0.68$, $\Omega_{DM} \approx 0.27$, $\Omega_b \approx 0.05$**





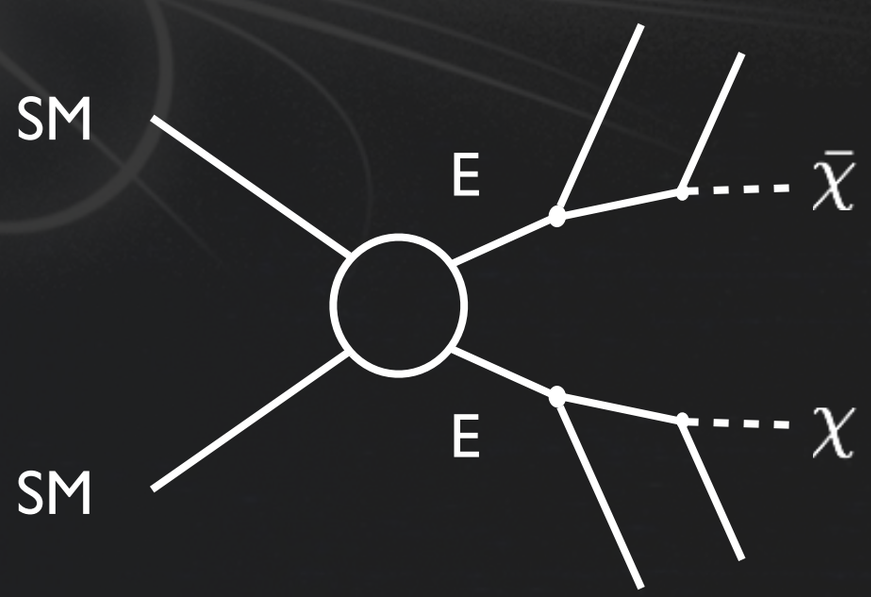
- **DM 'non-baryonic cold dark matter' → 'WIMP Miracle' → BSM physics**



Theory Landscape

- **How to create DM at collider:**
  - **SM decays to DM**: Z→xx, h→x, t→cxx
  - **Direct production**: XX+SM
  - **Associated production with heavier exotic**: x+E, E→x+SM

  - **Heavy exotics pair production**: E+E ; E→x+SM
  - **Exotic resonant decay**: E→xx
  - **Heavy metastable exotic** E→x, no decay in detector



Theory Landscape

less model dependent

- How to create DM at collider:
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Effective Field Theory

SUSY

Extra Dimensions

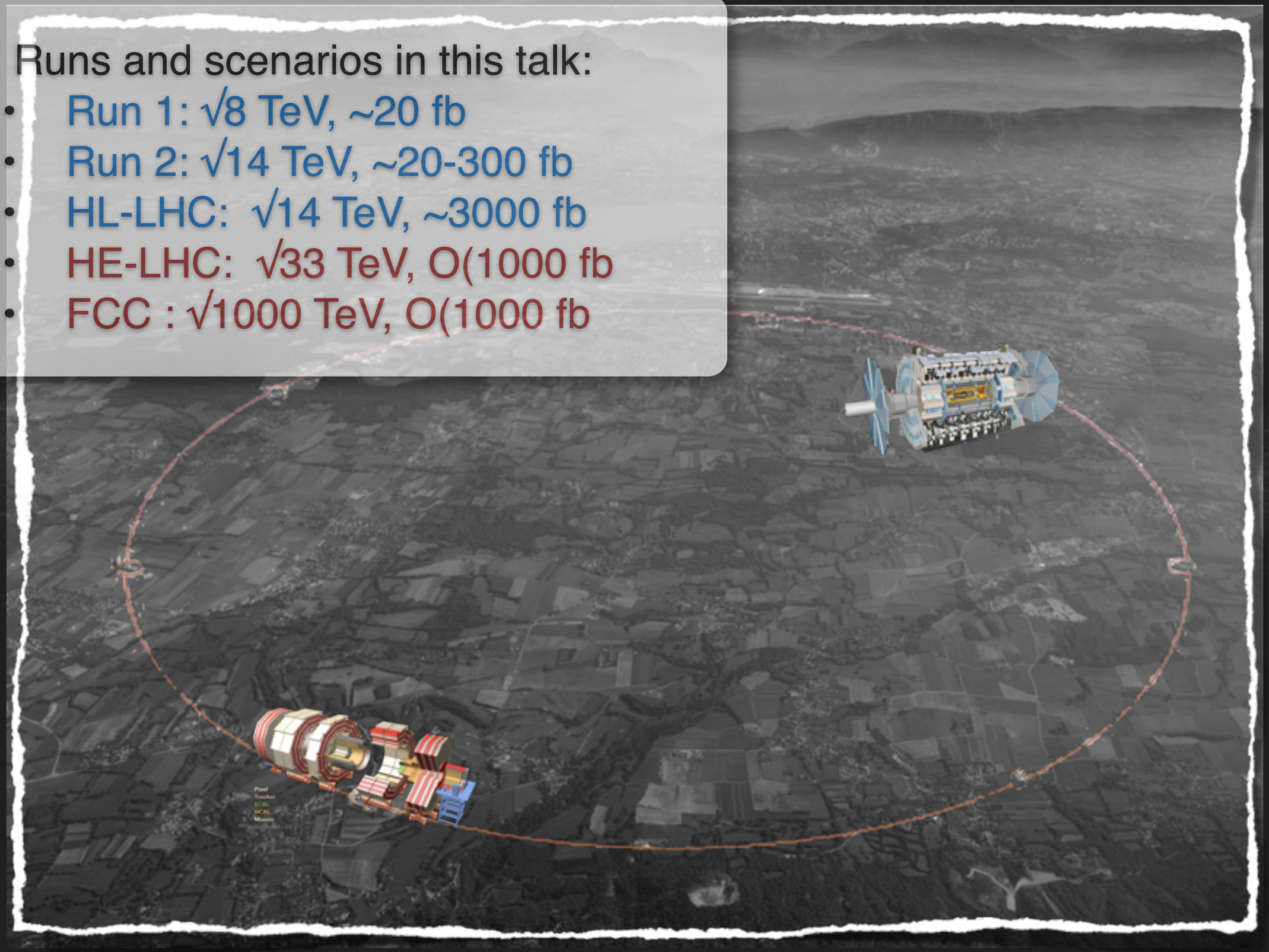
Little Higgs..

Dark Sectors

more model dependent

Experimental Environment

- Runs and scenarios in this talk:
  - Run 1: √8 TeV, ~20 fb
  - Run 2: √14 TeV, ~20-300 fb
  - HL-LHC: √14 TeV, ~3000 fb
  - HE-LHC: √33 TeV, O(1000 fb
  - FCC : √1000 TeV, O(1000 fb



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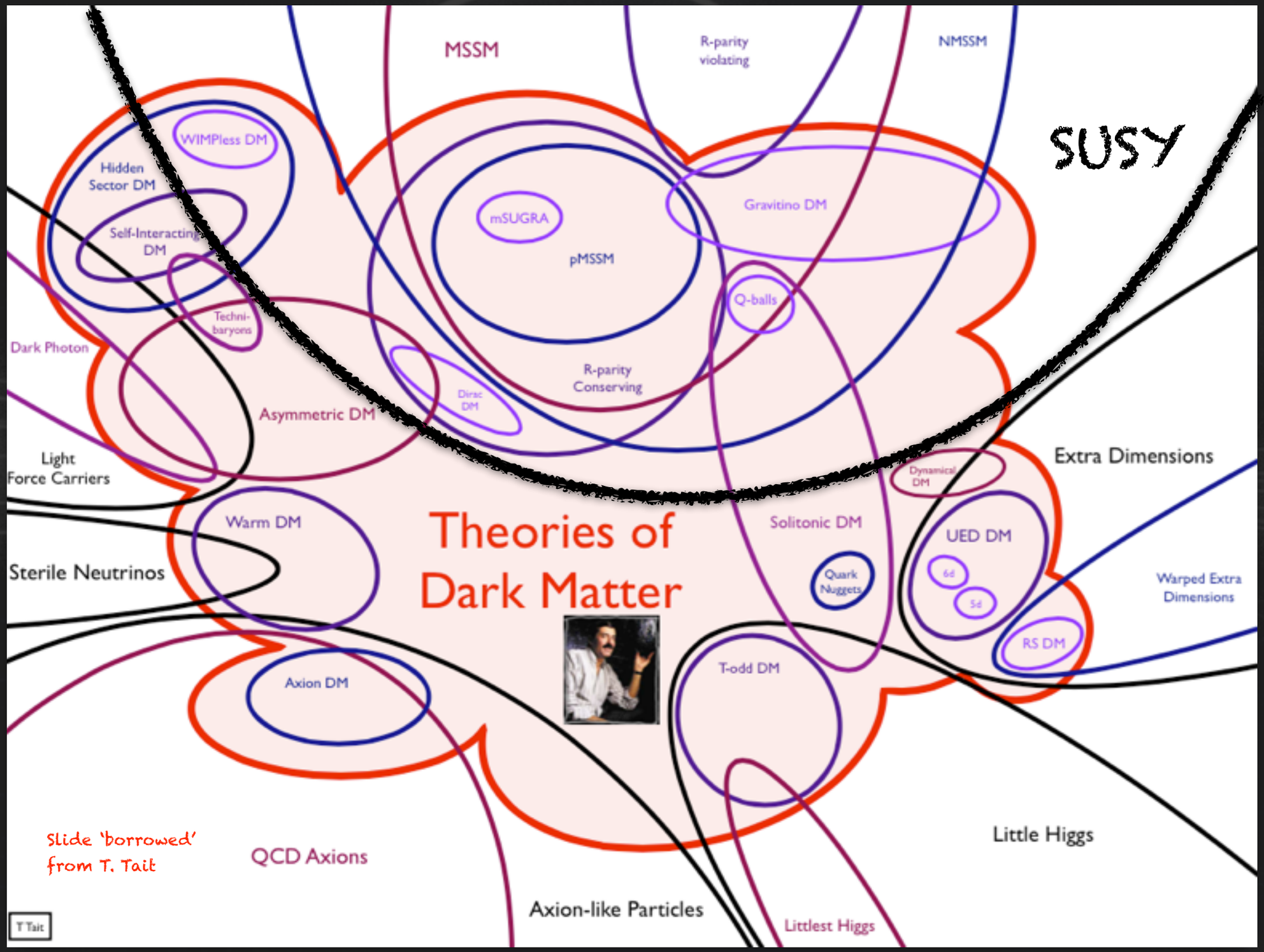
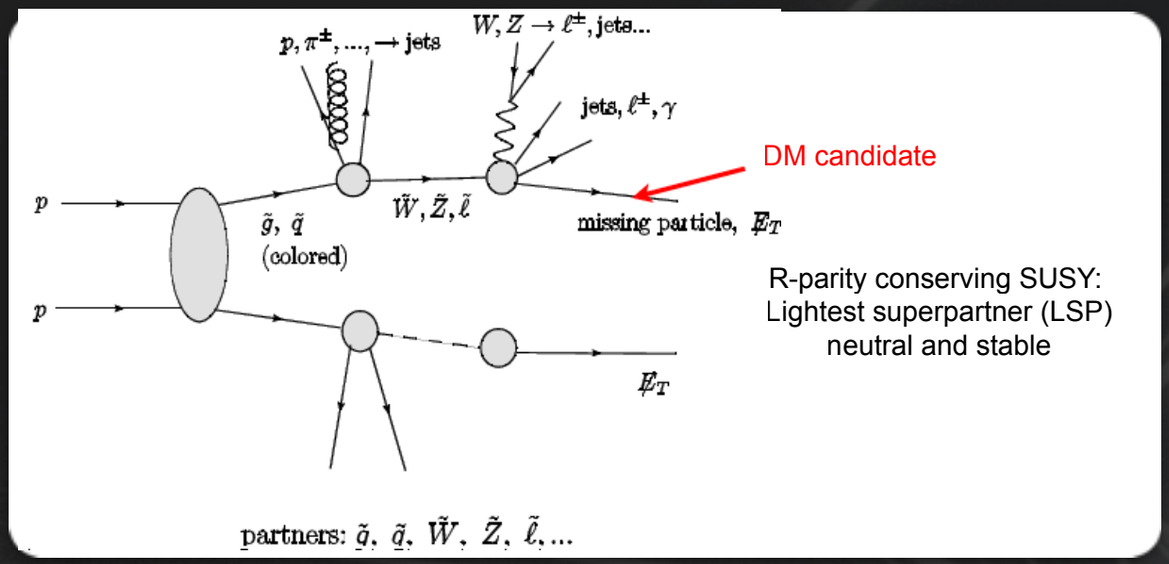
SUSY Like DM

The DM Landscape



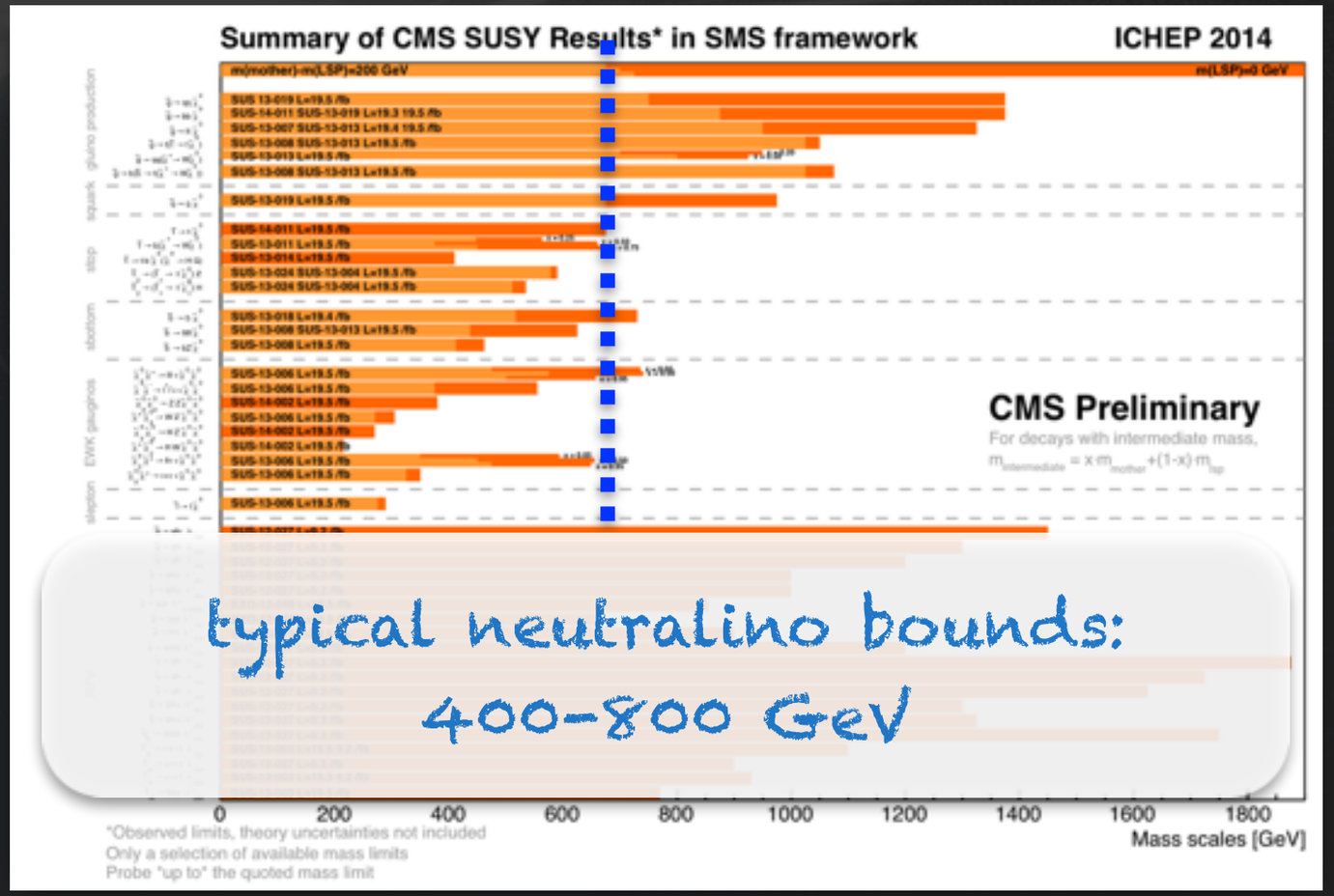
SUSY DM



R-parity conserving SUSY:
Lightest superpartner (LSP)
neutral and stable

- **DM part of extended sector** of new physics at TeV scale, searches:
  - MET + jets, MET + b, MET + 1ℓ, MET + 2ℓ, MET + j MET + j + ℓ + b, MET + j + γ...
- Results interpreted in **cMSSM, pMSSM** and **simplified models**
- Often the **neutralino** is the DM candidate (LSP)

- Details
  - **ATLAS**: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  - **CMS**: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS



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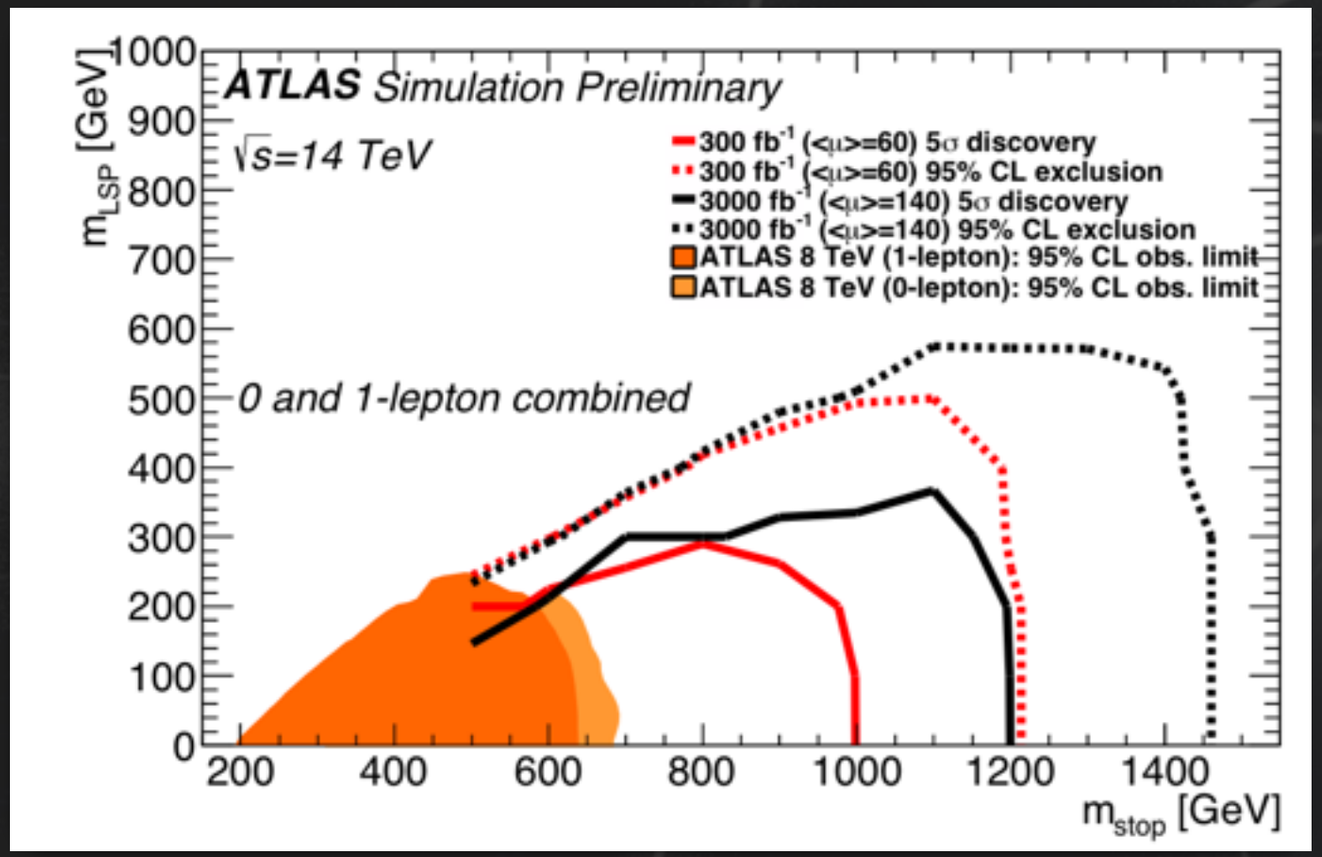
SUSY Projections

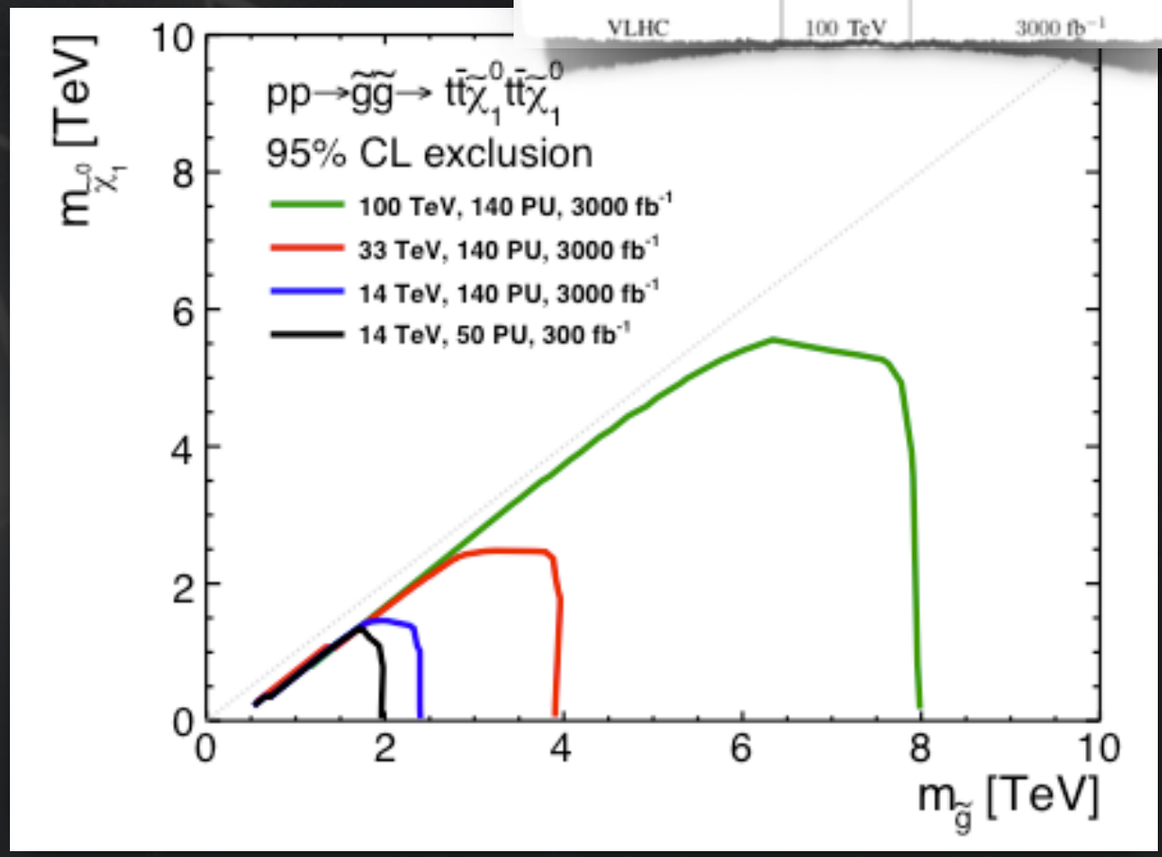
ATL-PHYS-PUB-2013-011

CMS

- **Huge improvement in sensitivity** starting now

Machine	$\sqrt{s}$	Final Integrated Luminosity
LHC Phase I	14 TeV	300 fb^{-1}
HL-LHC or LHC Phase II	14 TeV	3000 fb^{-1}
HE-LHC	33 TeV	3000 fb^{-1}
VLHC	100 TeV	3000 fb^{-1}





- Gluinos/stop **Run I sensitivities will be surpassed** with only **1-4 fb^{-1} at 13 TeV**
- **LHC mass reach will** more than **double** with 300-3000 fb^{-1}
- Huge increase in discovery potential, **cover much natural phase space**

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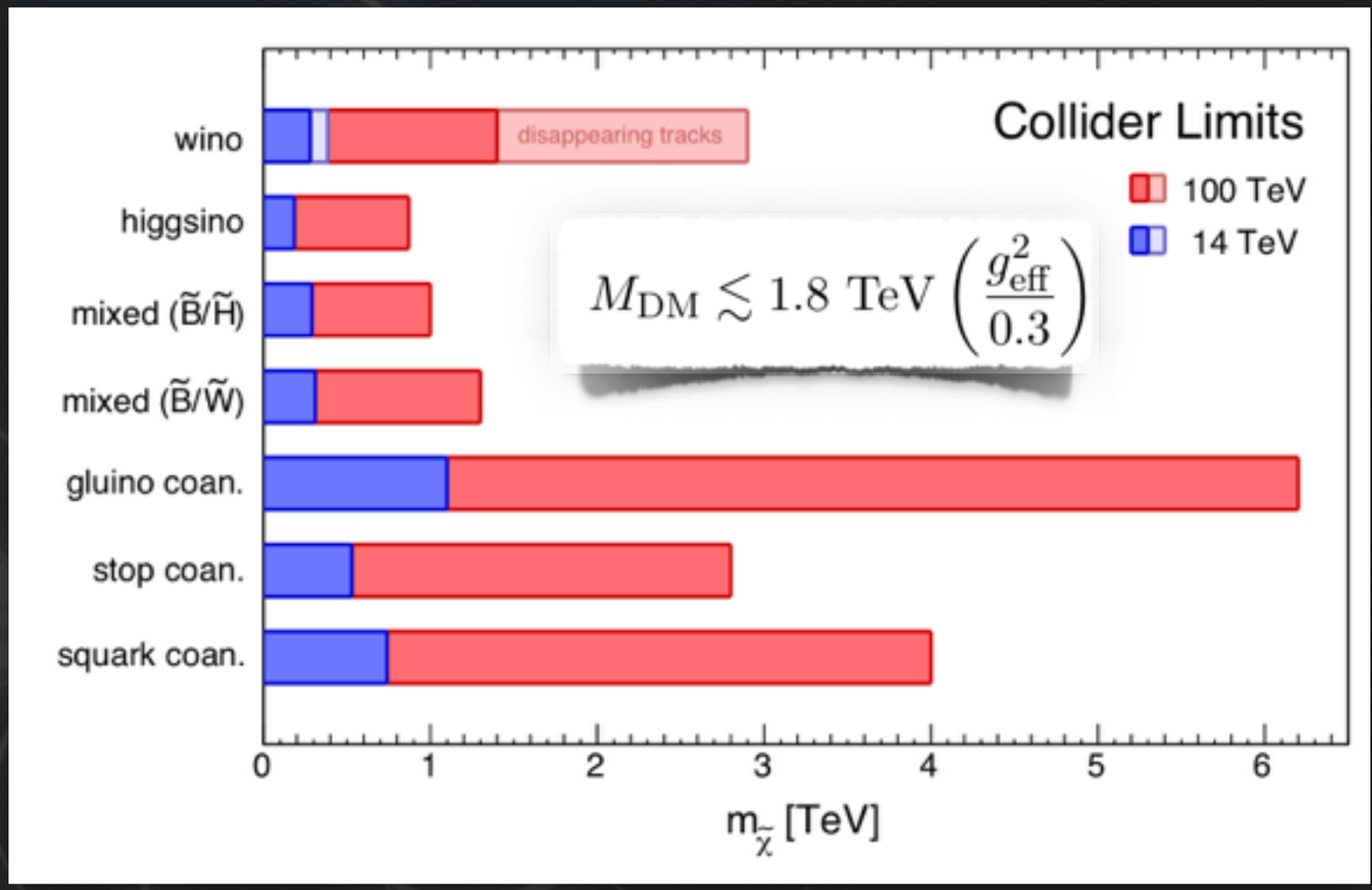
Neutralino DM

arXiv:1404.0682
M. Low; L.-T. Wang

- Studies of **Neutralino DM in several simplified models:**
  - Pure Wino (m_{DM}~3.1 TeV)
  - Pure Higgsino (m_{DM}~1 TeV)
  - Mixed Scenarios (range of m_{DM} fulfills relic density)
  - Coannil. scenarios (up to m_{DM}~7.6 TeV)
- Comparison to other searches
  - **Indirect searches**: ~2 TeV
  - **Direct searches**: TeV scale DM impeded by neutrino floor
  - **LHC**: O(100-1000) GeV



- **Many recent and interesting papers** on this subject: 1412.4789 (Bramante et al), 1410.6287 (Gori et al), 1410.1532 (Acharya et al), 1409.0005 (Curtin et al), 1407.7058 (Cirelli et al), 1406.4512 (Cohen et al)

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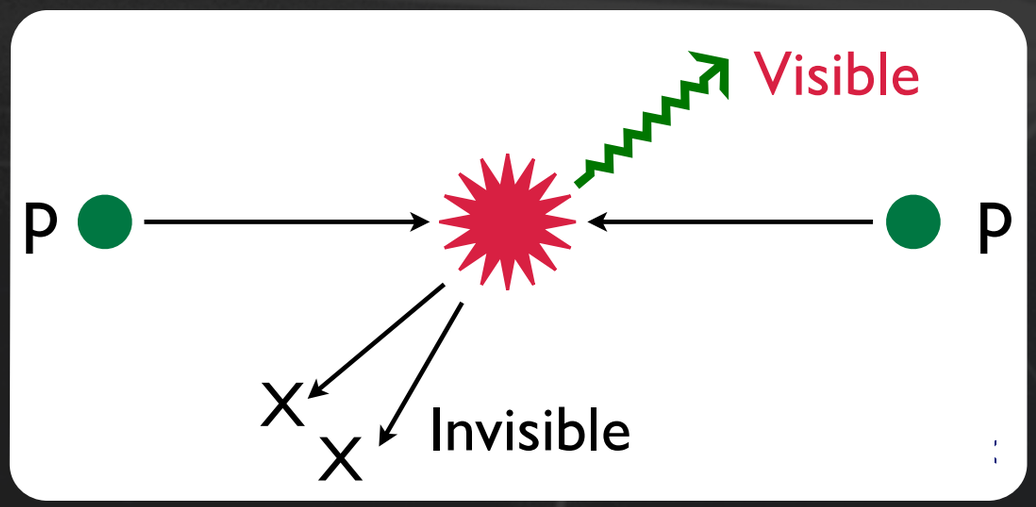
Direct Collider Searches

Mono-X

- **Properties of DM**
  - Pair produced (stable)
  - Mediating particle (M*) not directly observed → Effective Field Theory (EFT)
- **'Back 2 Back' events, recoiling SM object balanced with m(xx) (E_T^{miss}): mono-'X'**
  - (mono-madness ensued)



Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

spin-independent spin-dependent

arxiv:1008.1783v2

Mono-X

- **Properties of DM**
  - Pair produced (stable)
  - Mediating particle (M*) not directly observed → Effective Field Theory (EFT)
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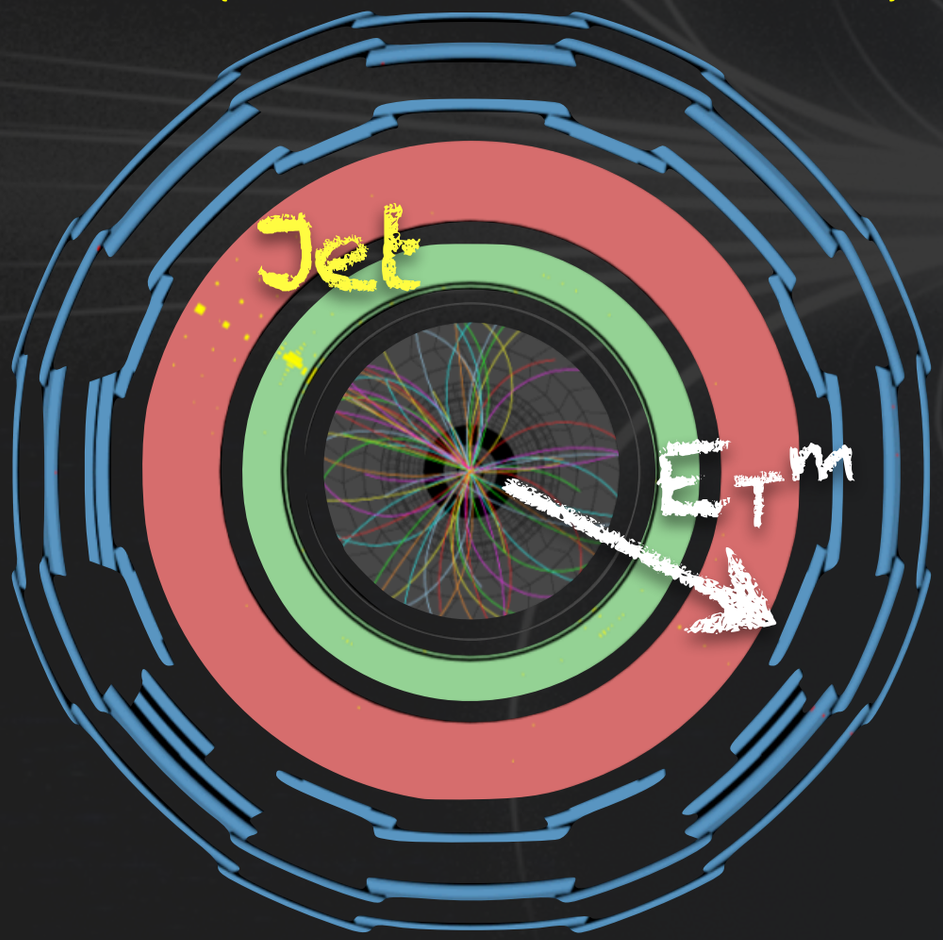
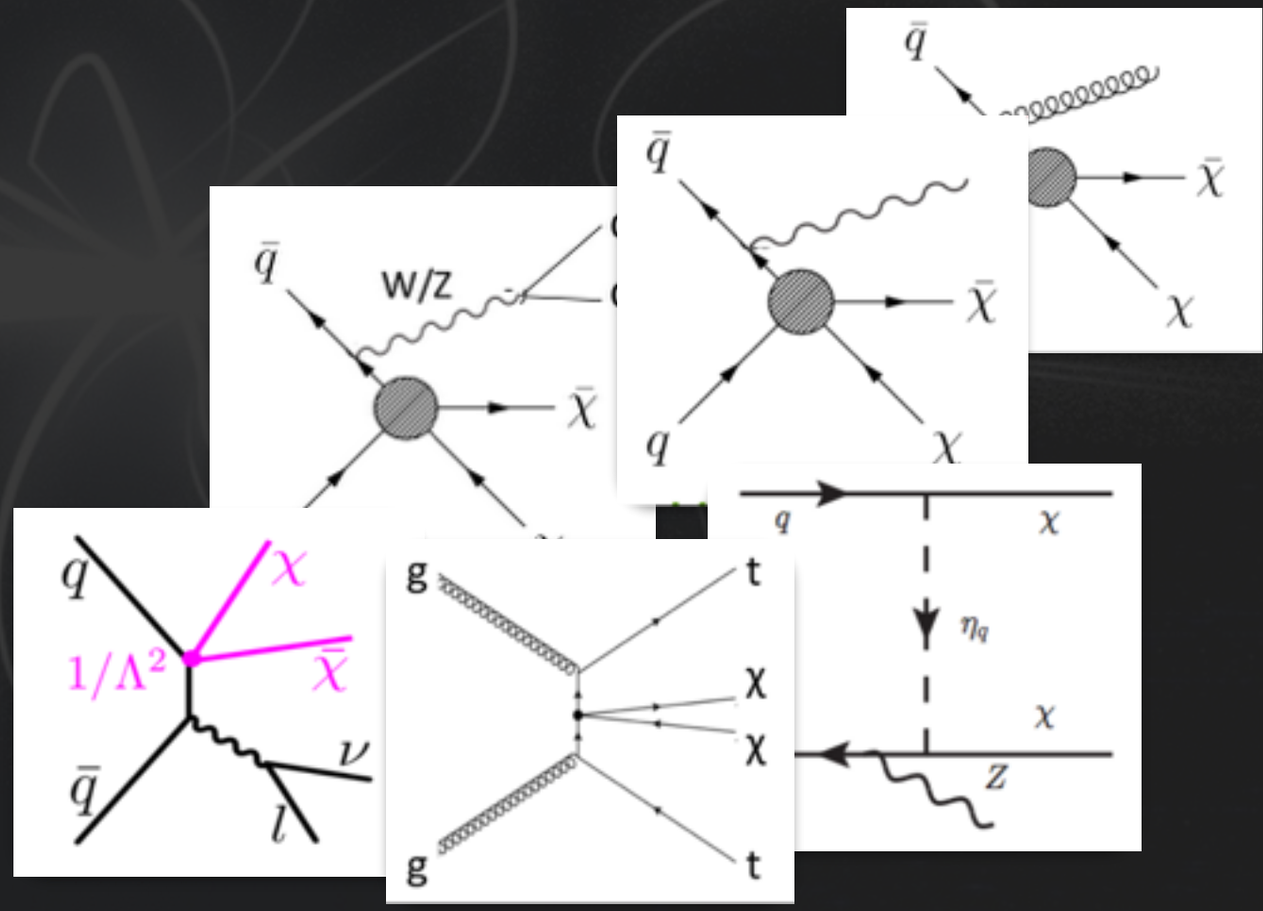
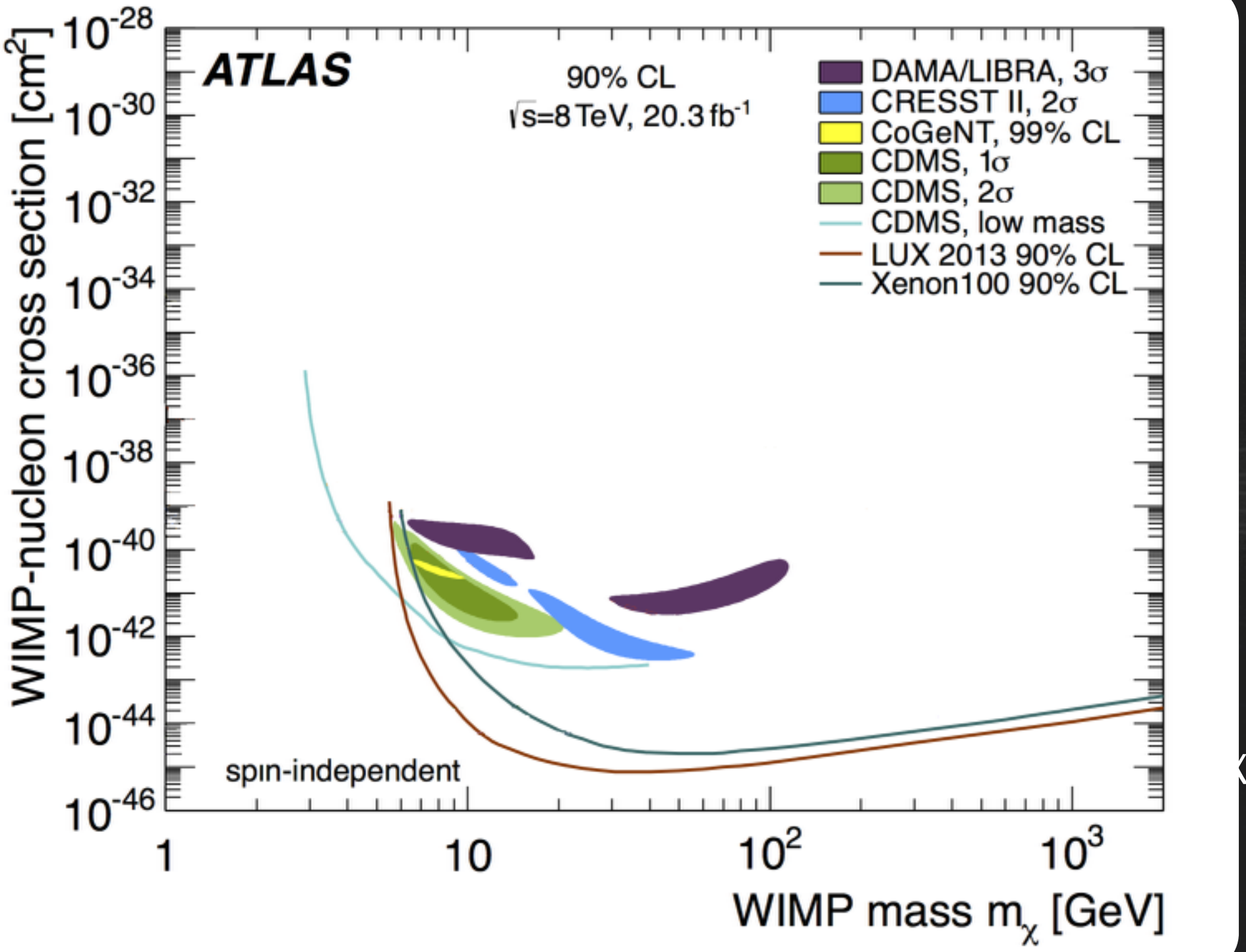




- Sensitive to **different type of couplings** to up/down type quarks, jets, photons, **spin-dependent** and **independent** couplings, **low masses**

Mono-Jet



1109.4398v1, Fox et al.

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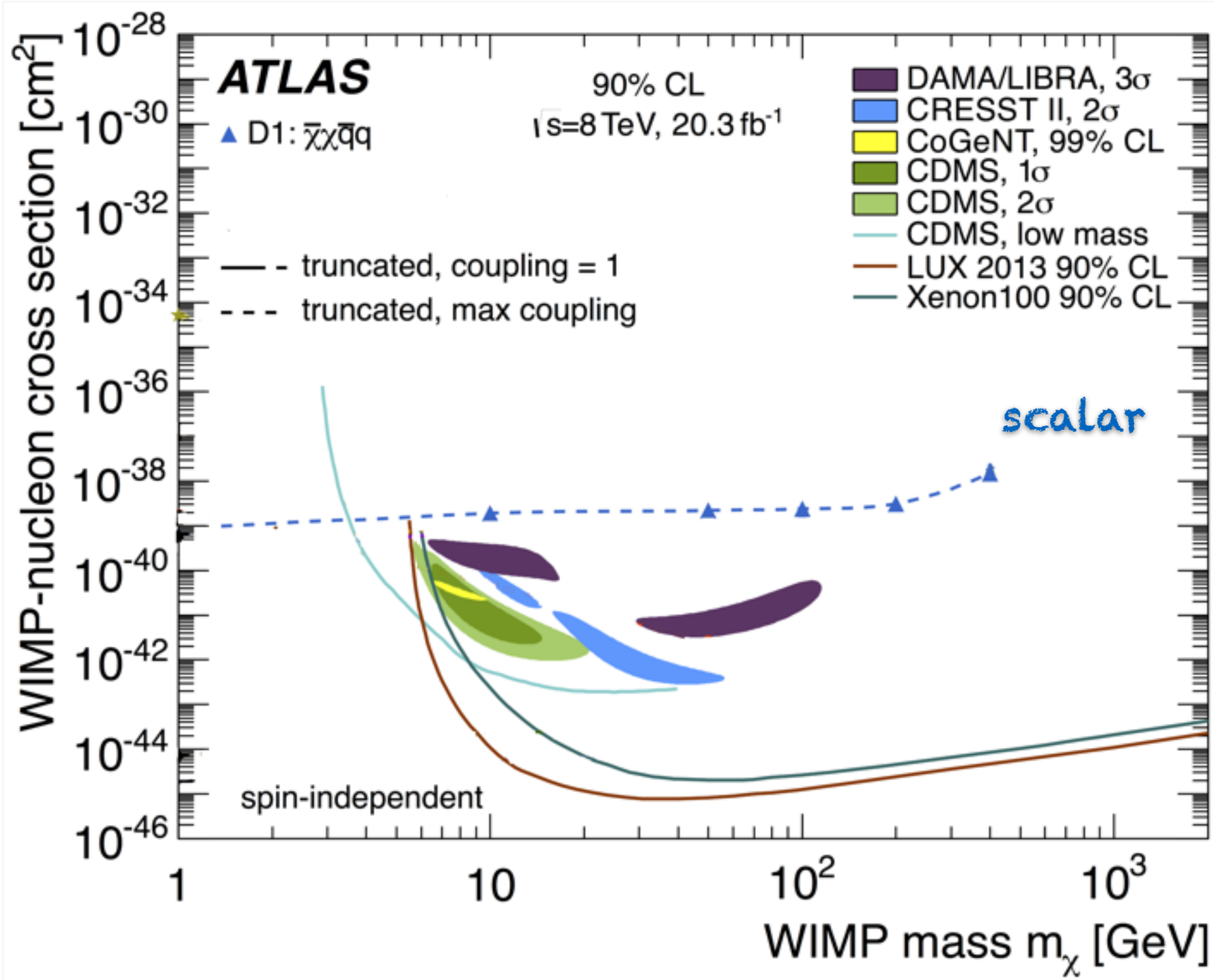
Mono-Jet



1109.4398v1, Fox et al.

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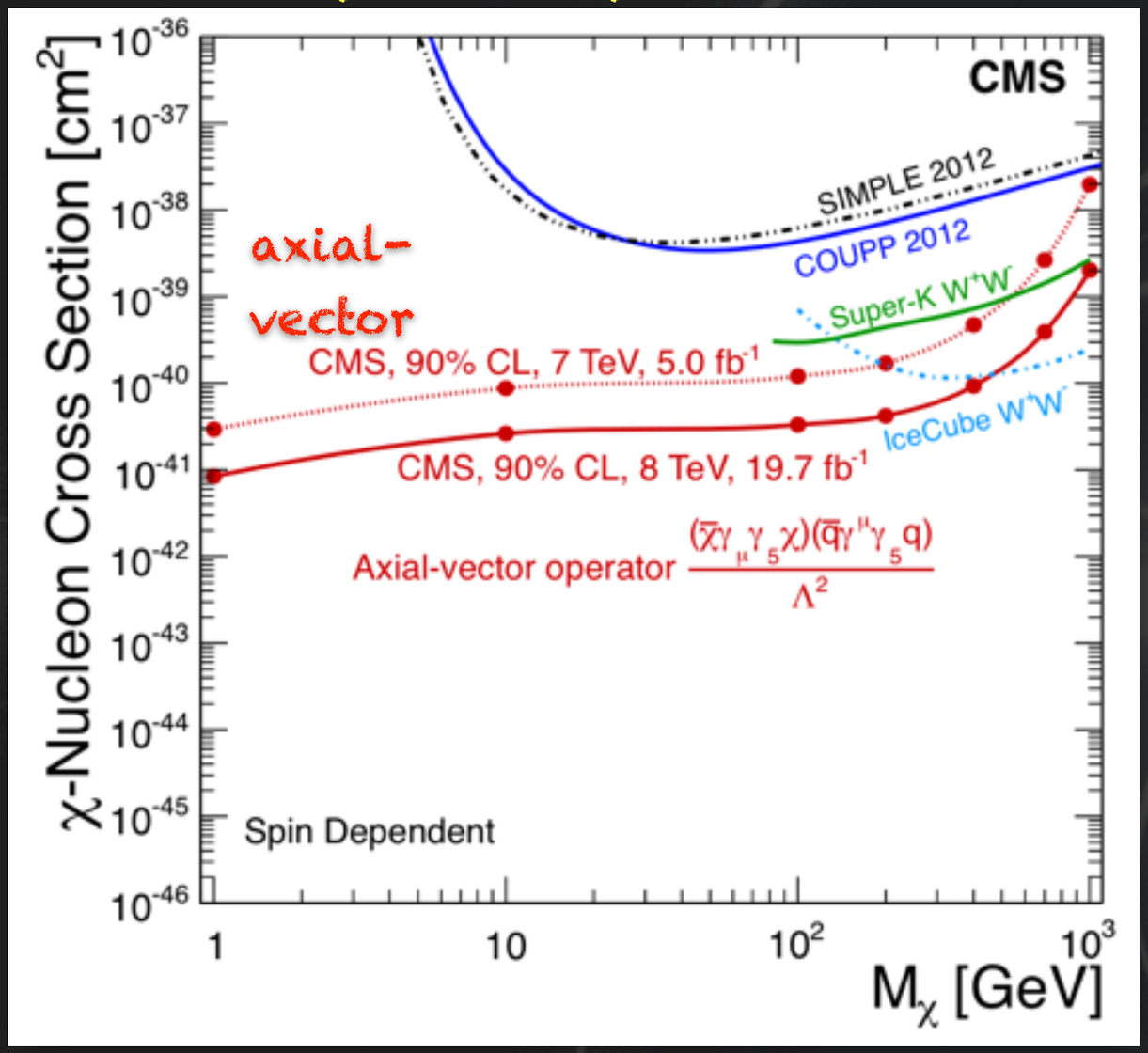
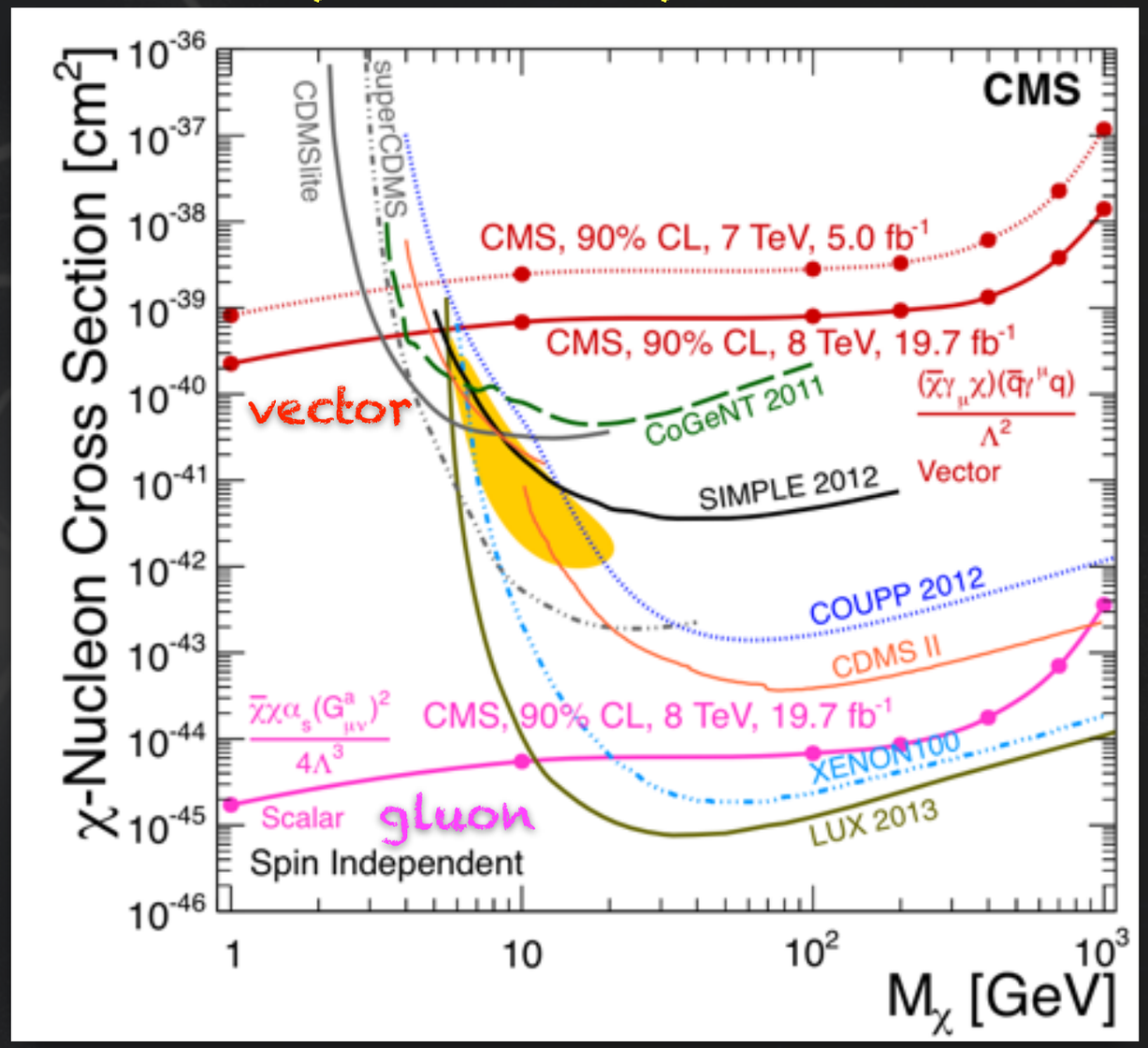
Mono-Jet

arXiv:1408.3583
Eur. Phys. J. C 75 (2015) 235

spin-dependent



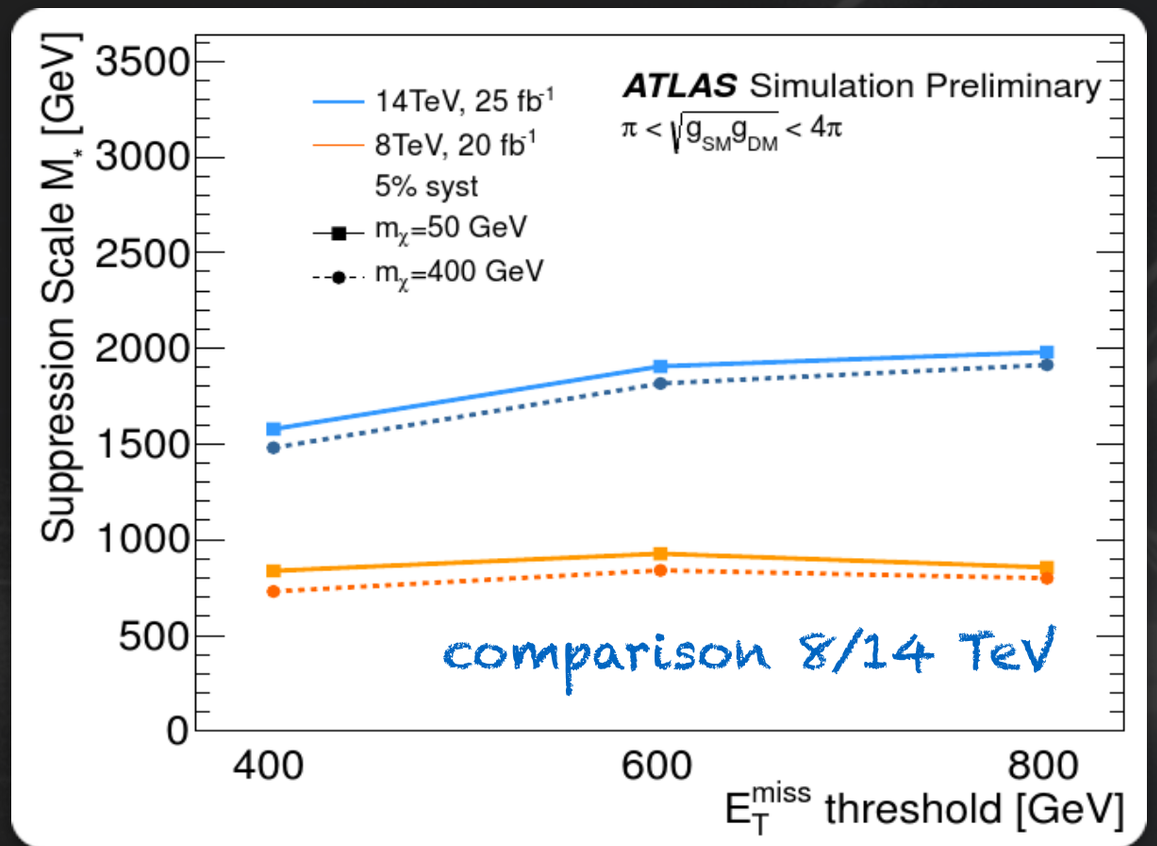
spin-independent

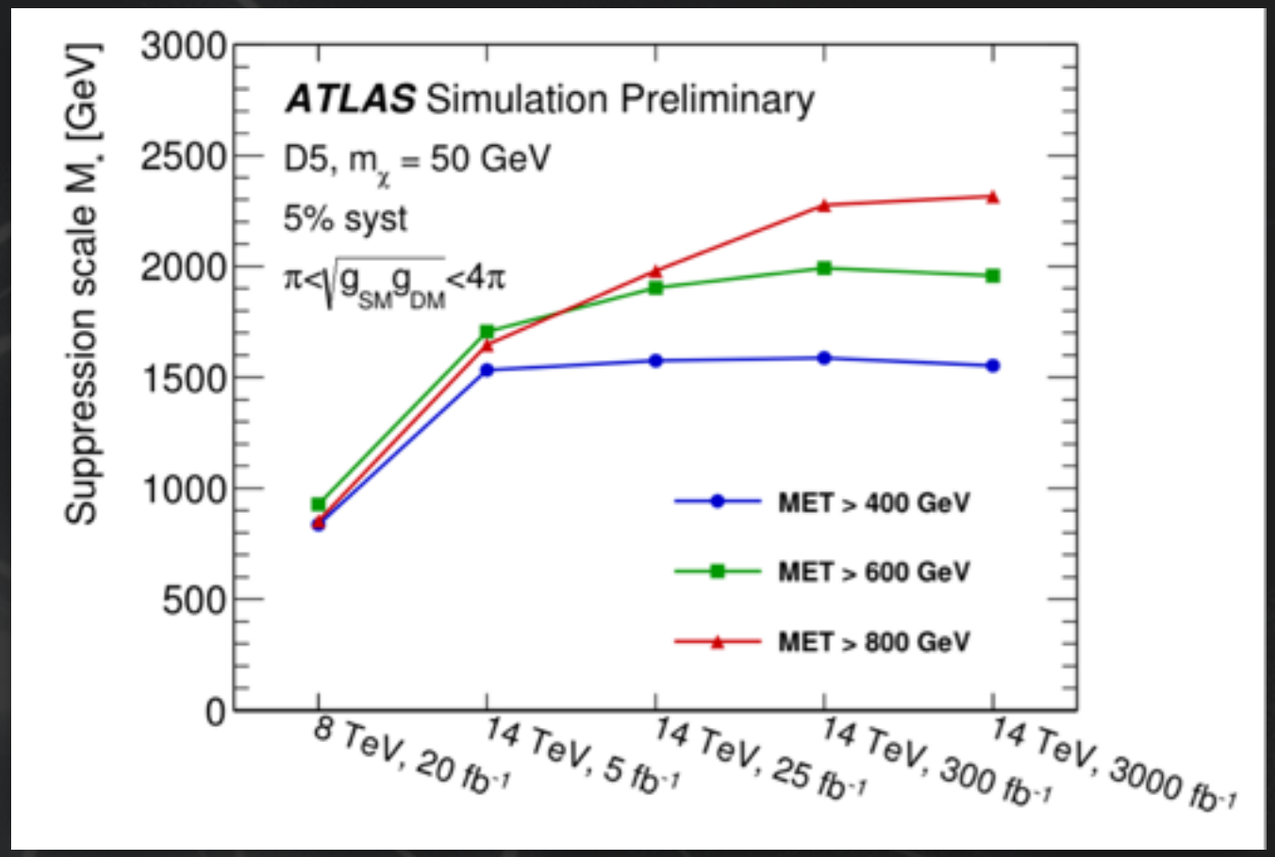


- **Spin-Dependent** (SIMPLE, Coupp, Ice-Cube)
  Collider limits stronger for axial vector and tensorcouplings
- **Spin-Independent** (Lux, Xenon, CDMSlite)
  Collider limits stronger at low masses, competitive at higher

Mono-Jet Projections

ATLAS-PHYS-PUB-2014-007

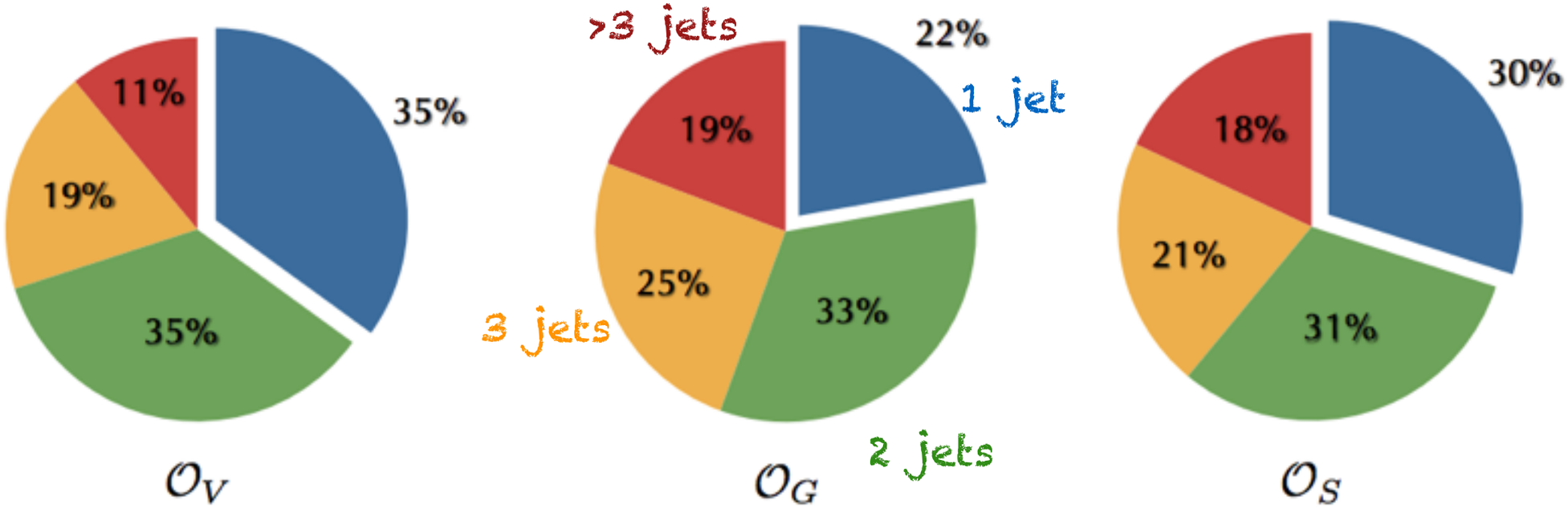




- **Lower limits on M* improve by x2 from 8→14 TeV** with about same amount of data.
- For **high luminosities** assume with **improved performance** and **systematics**
  - Again factor of two improvement
- The usual validity concerns apply but deferred here (details in reference)

Interplay among SUSY and DM

QCD effects on DM searches: 1310.4491



- Vast majority of ‘DM signals’ are **multijet events,** even 1 jet events are likely radiate soft jet
- Study **simplified models** and light/heavy jets in **all-hadronic final** states

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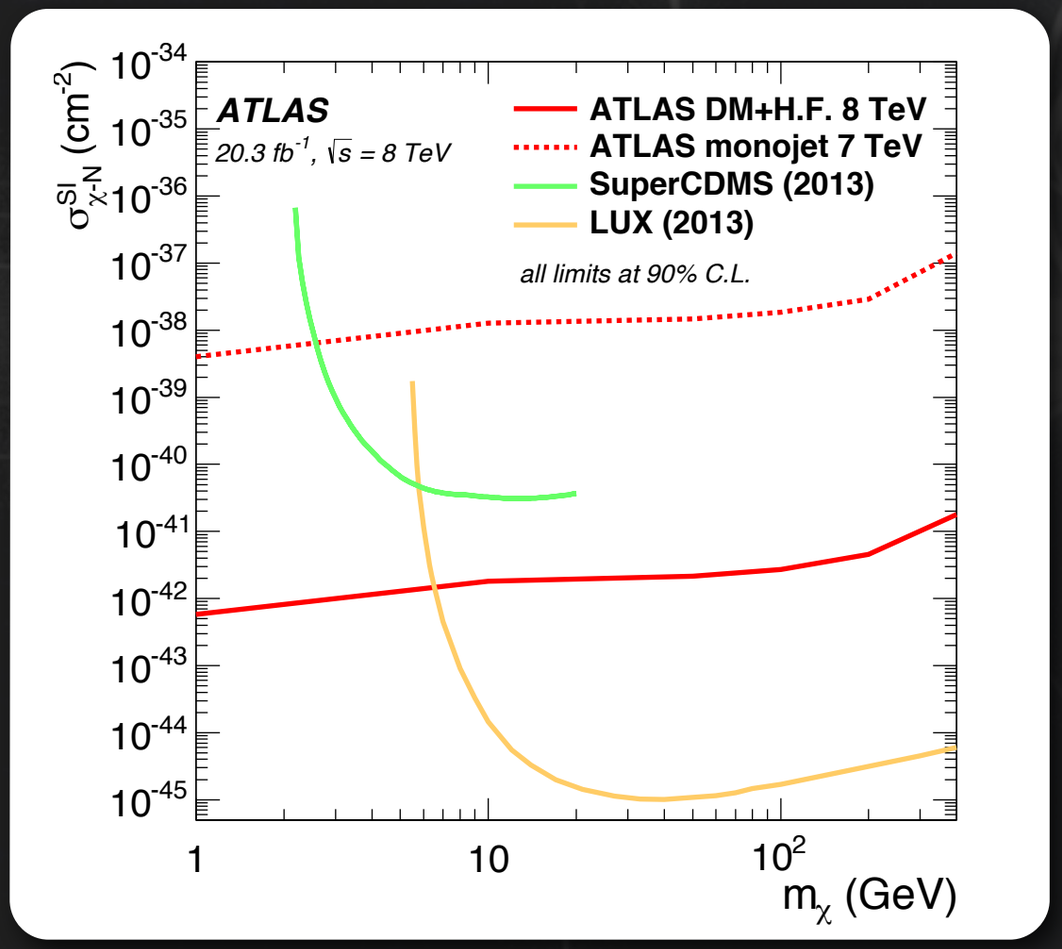
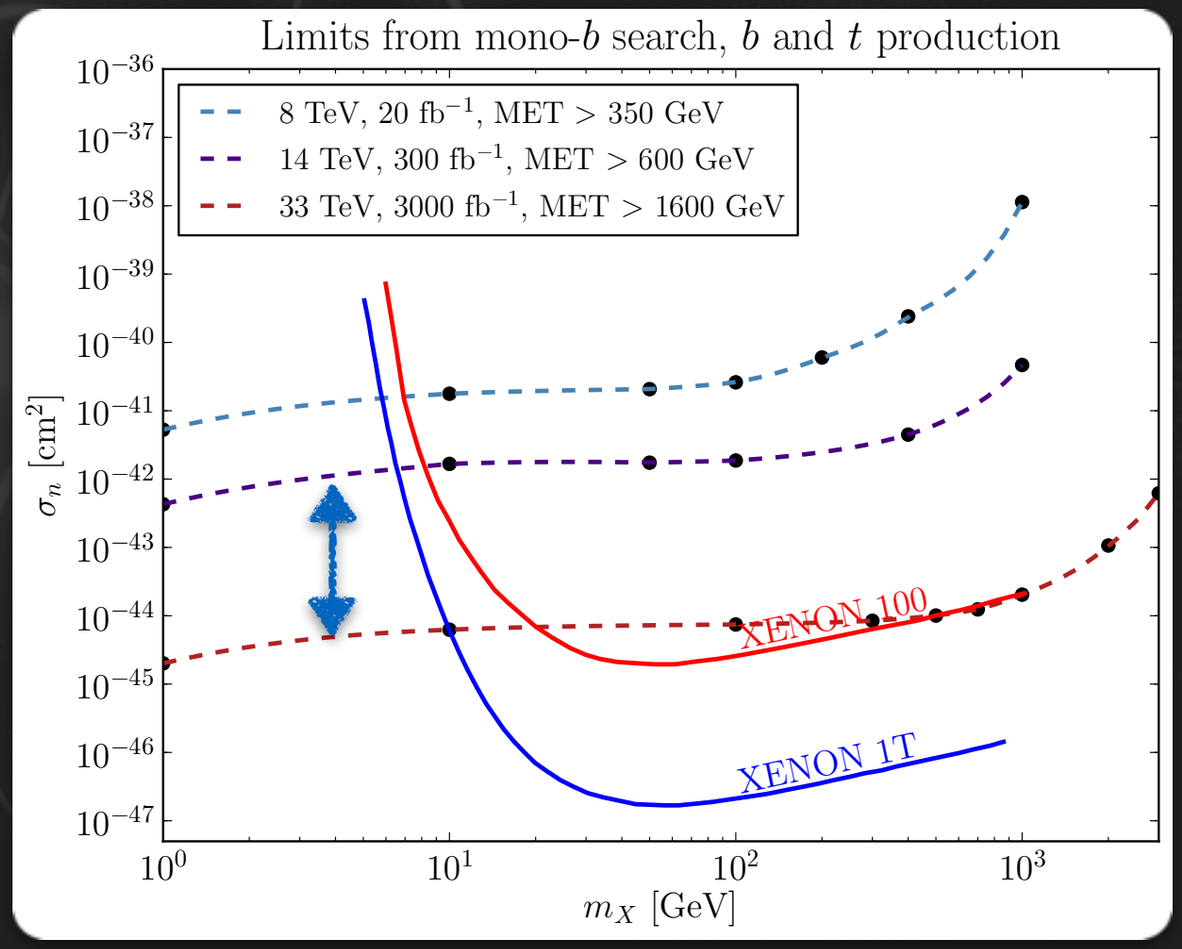
DM+b(b)/ttbar

arXiv:1410.4031

- **Monojet** provide **most powerful LHC DM limits** currently, **Mono-photon** & **mono-W/Z** probe more specific coupling $\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
- **Heavy flavor jets**: **Third generation couples enhanced,** probe **inclusive** final states, potentially sensitive to Fermi-LAT excess





- **Initial projections confirmed**, best sensitivity for scalar operators with DM+HF
- Future collider **competitive with direct searches** at high masses

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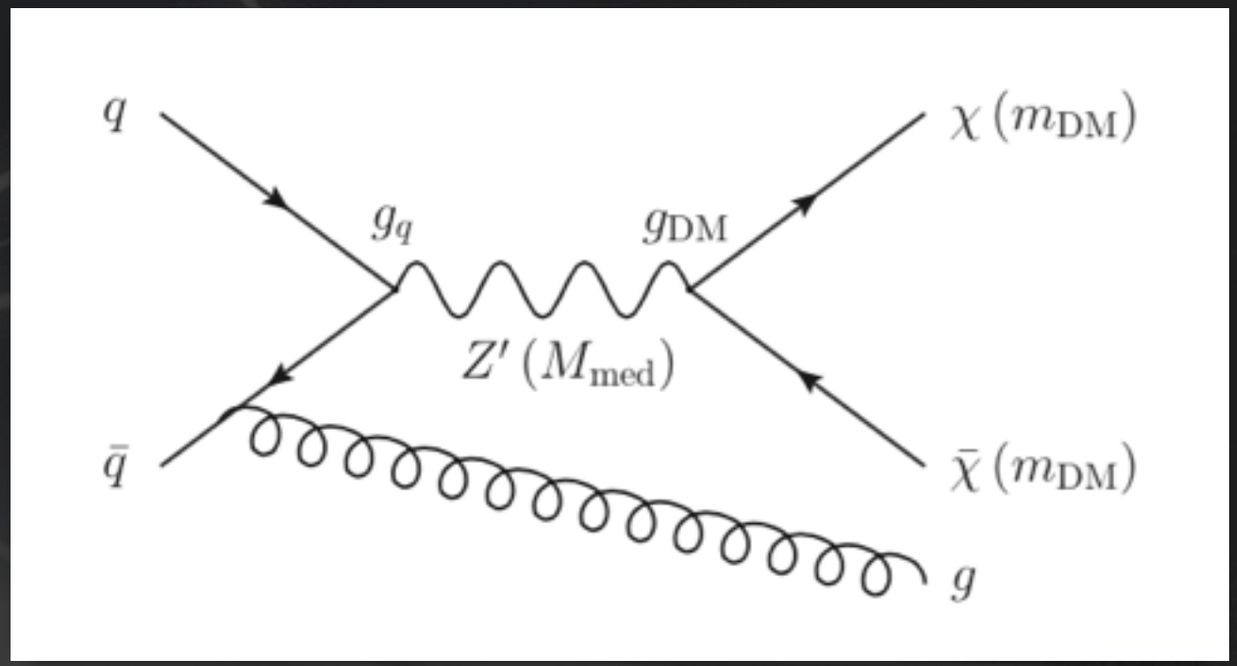
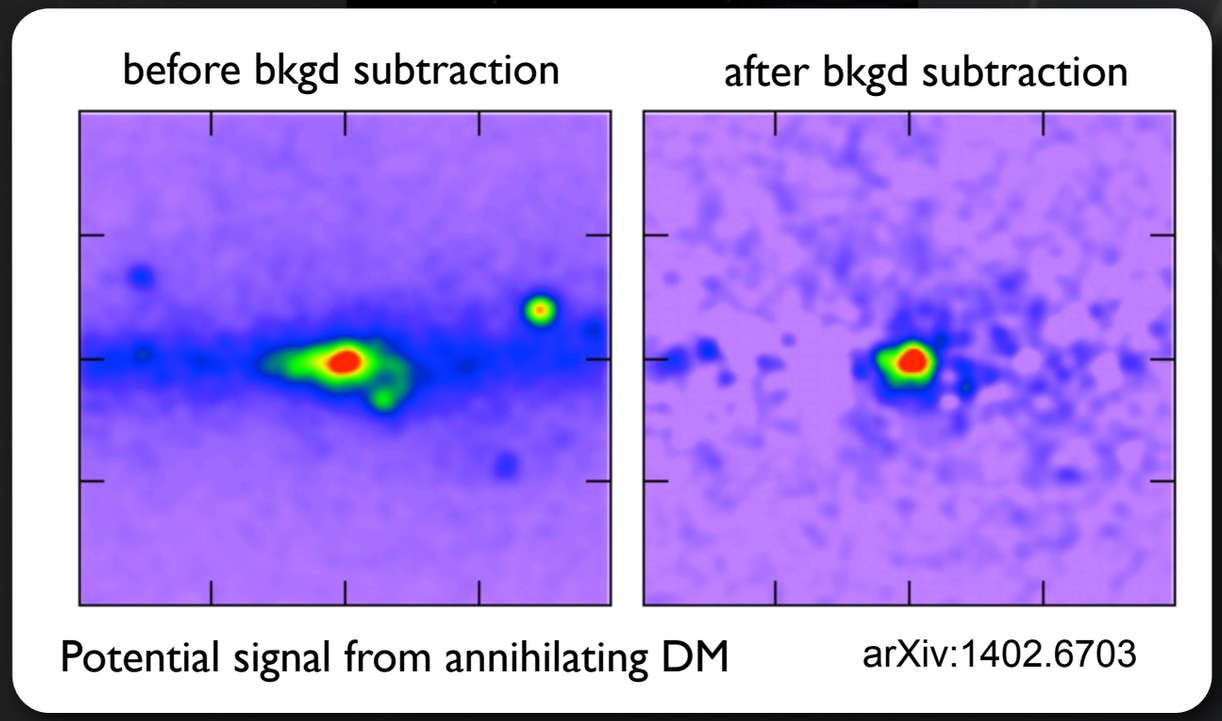
Simplified Models Analyses

arXiv:1410.4031

- **Monojet searches probe** mostly dominantly resonantly enhanced region
- **Inclusive searches** places fewer constraints on phase space
  - Simplified models allow **comparison to underground and satellite searches**





- Also allow to compare to e.g. **SUSY and dijet searches**
- Example:
  - **GC excess as pseudoscalar mediator**
  - **Spin-dependent** axial coupling

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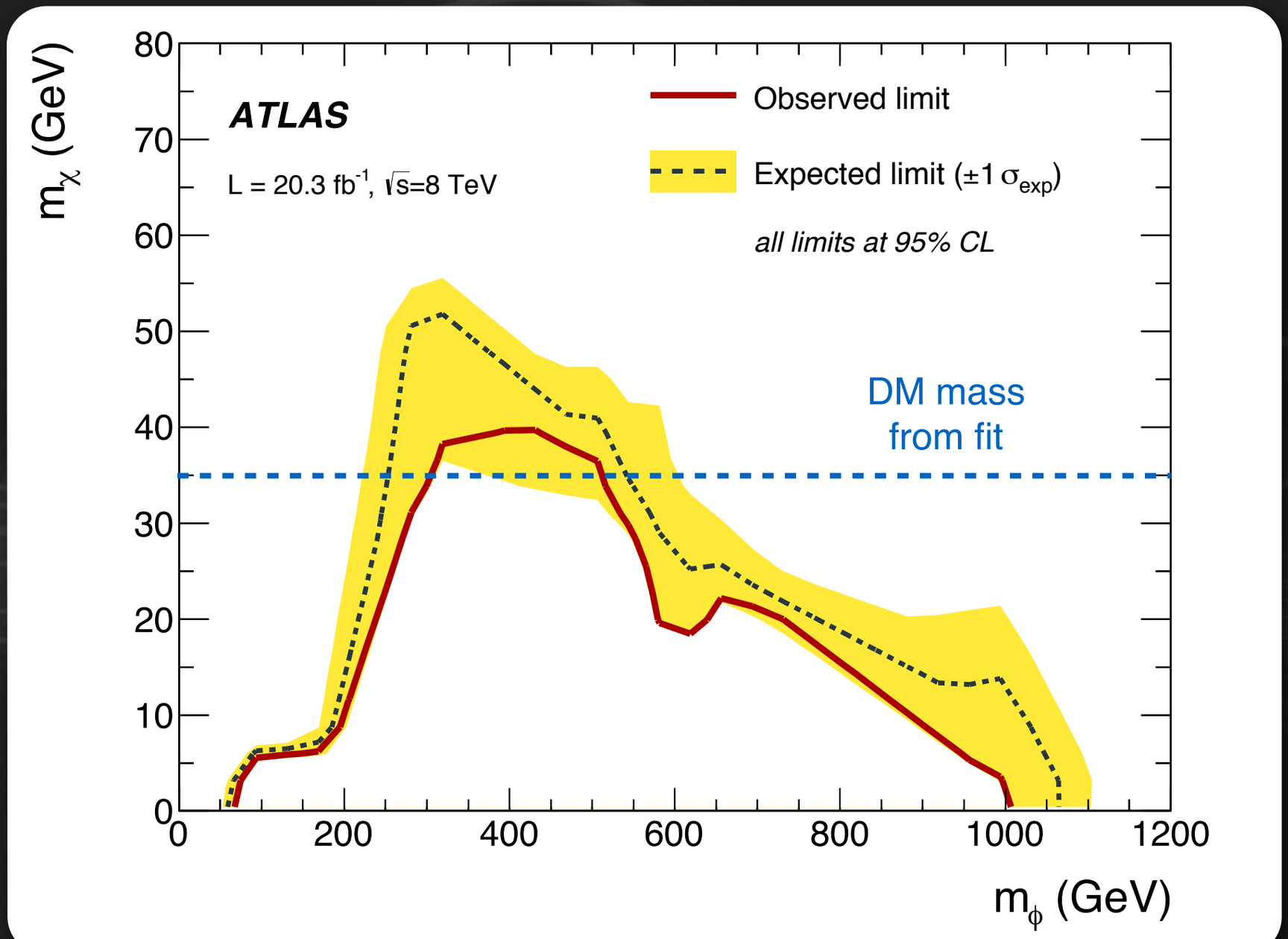
Fermi-LAT excess



- **First collider limits** on possible source of **Fermi-LAT** annihilation signal (m_{DM} ~ 35 GeV).
- Just starting to probe, **great strides expected**

Berlin, Hooper, McDermott, arXiv: 1404.0022

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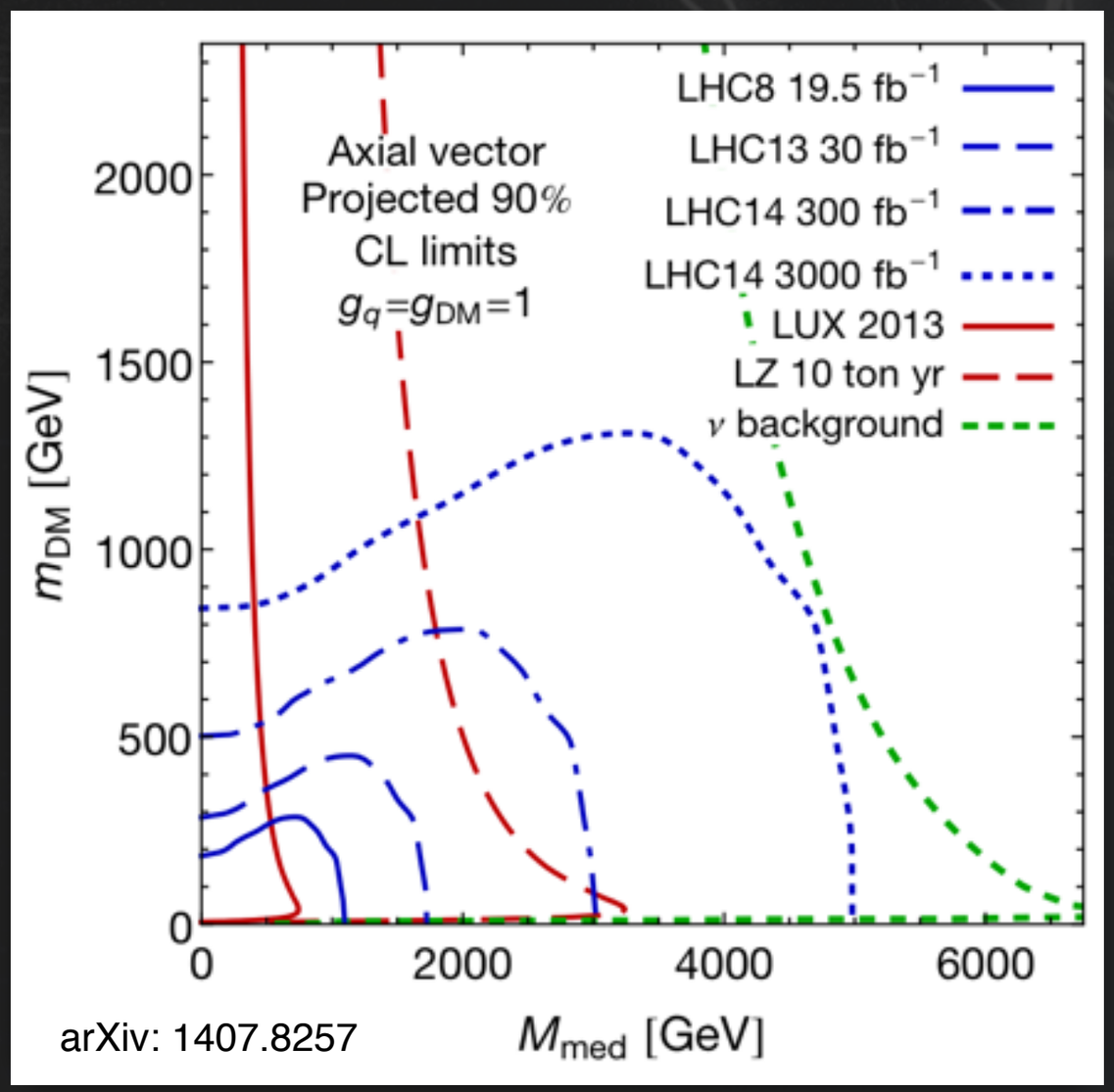
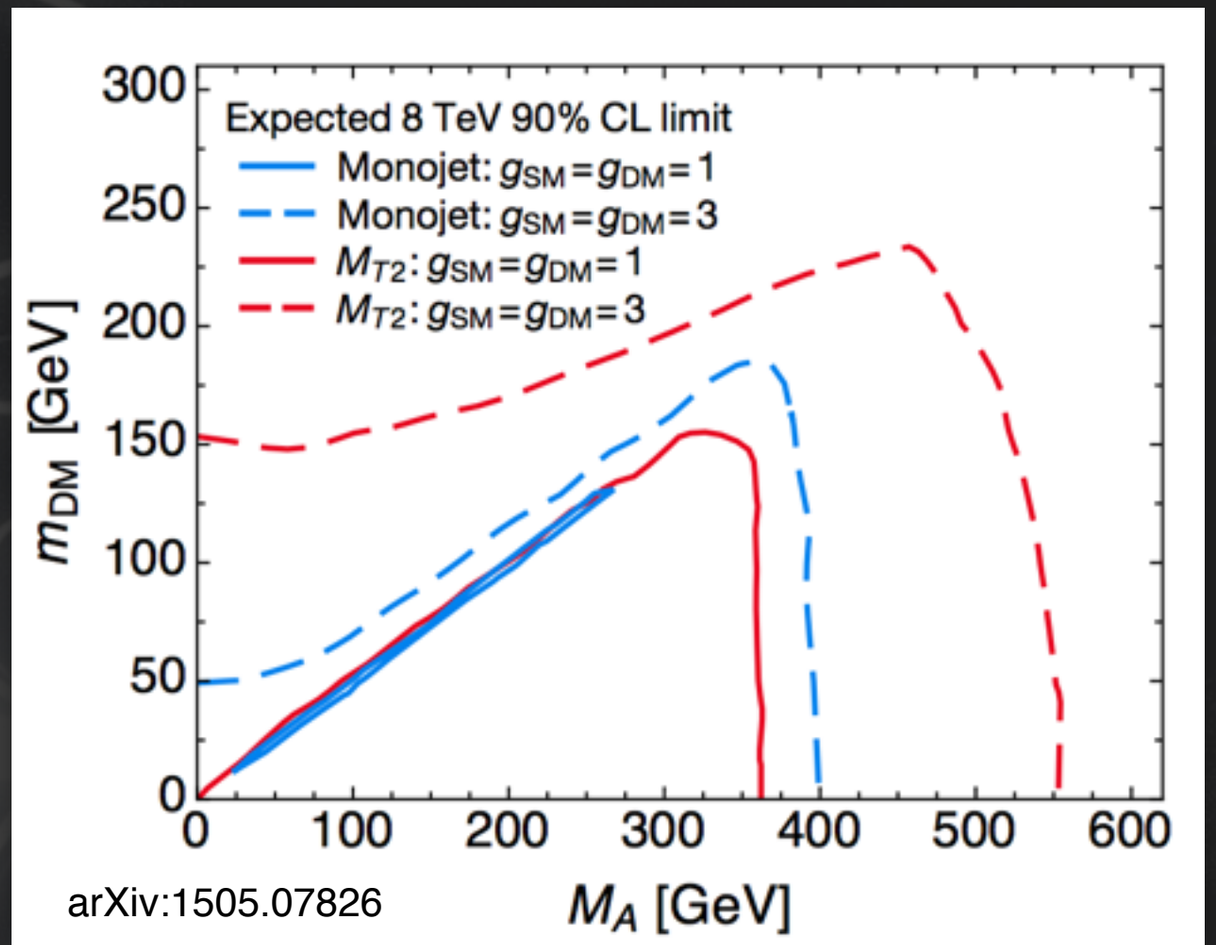
Simplified Model Reach

arXiv:1505.07826
arXiv: 1407.8257

- Using published results to study **sensitivity in simplified models** for **monojet** and **MT2** type searches
- Collider searches **powerful and complementary**



arXiv: 1407.8257



arXiv:1505.07826

- **Inclusive searches** posses **significantly better** expected sensitivity
- Collider searches can go beyond direct searches all the way to the neutrino floor.

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Searching for the Mediator

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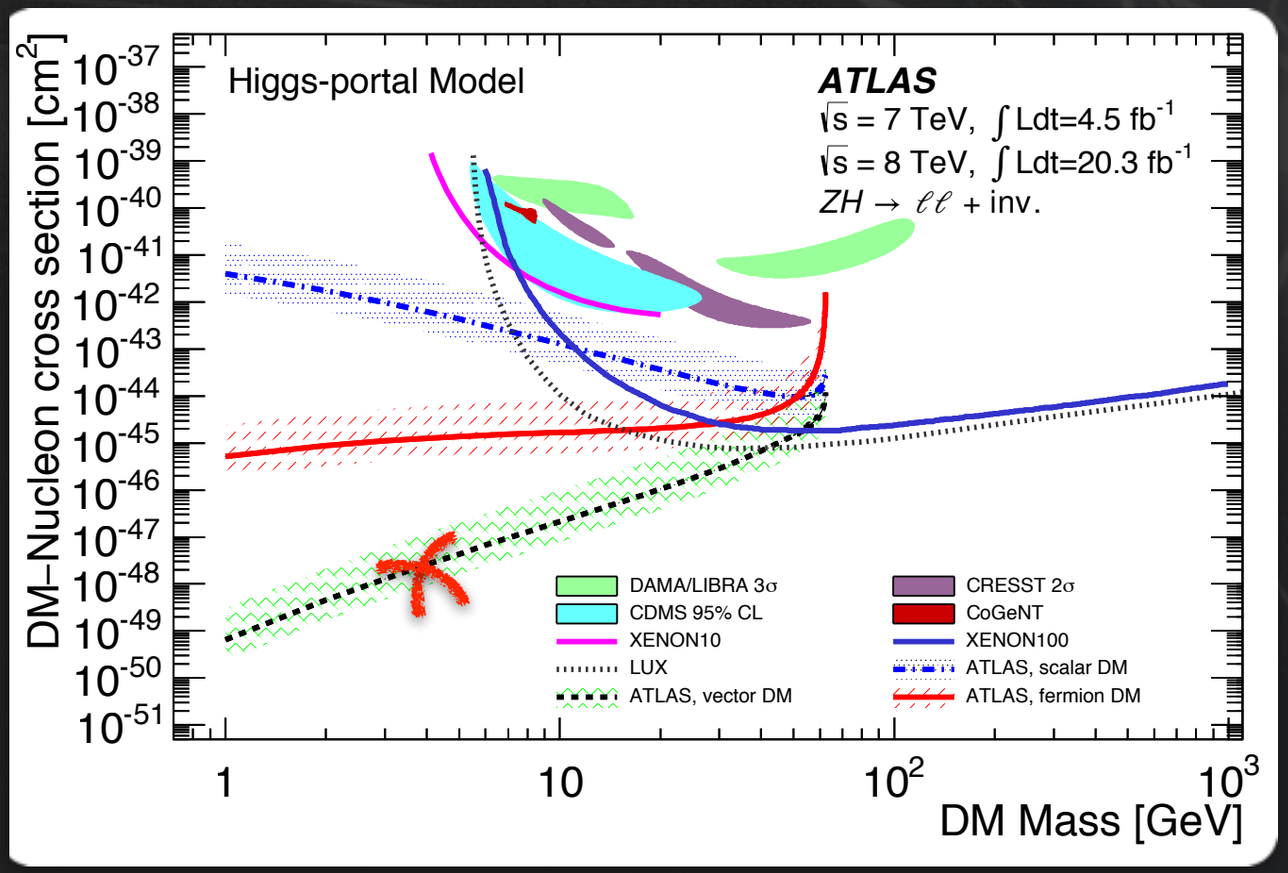
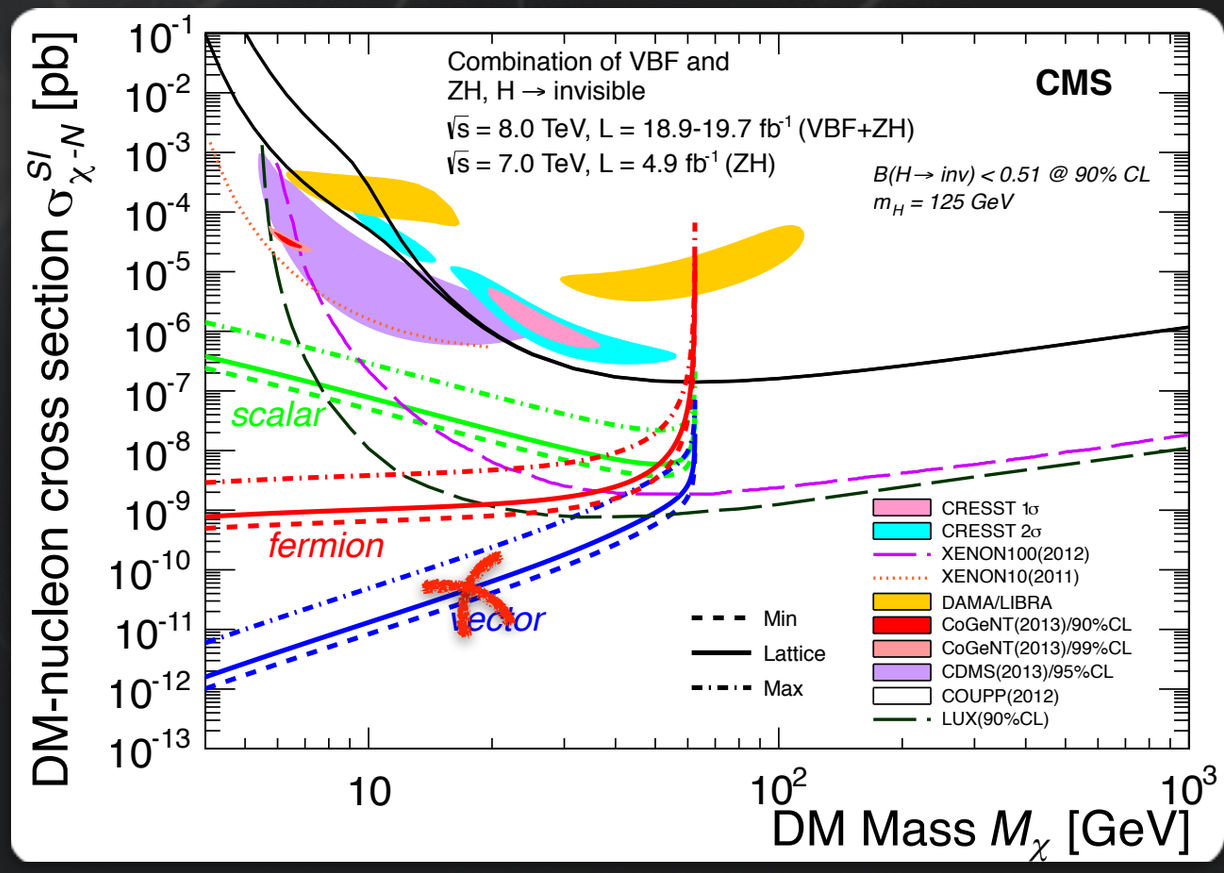
H→inv. Prospects

arXiv:1402.3244 (ATLAS)
arXiv:1404.1344 (CMS)

- Analysis based on **associated ZH** production
- **SM cross section predictions for m_H=125 GeV**
- **Upper limits** on σ x BR(H→inv) as function of m_H translated **constraints on Higgs portal DM**





Limits for scalar (fermion) DM:
~ 10^{-41} (10^{-45})cm²

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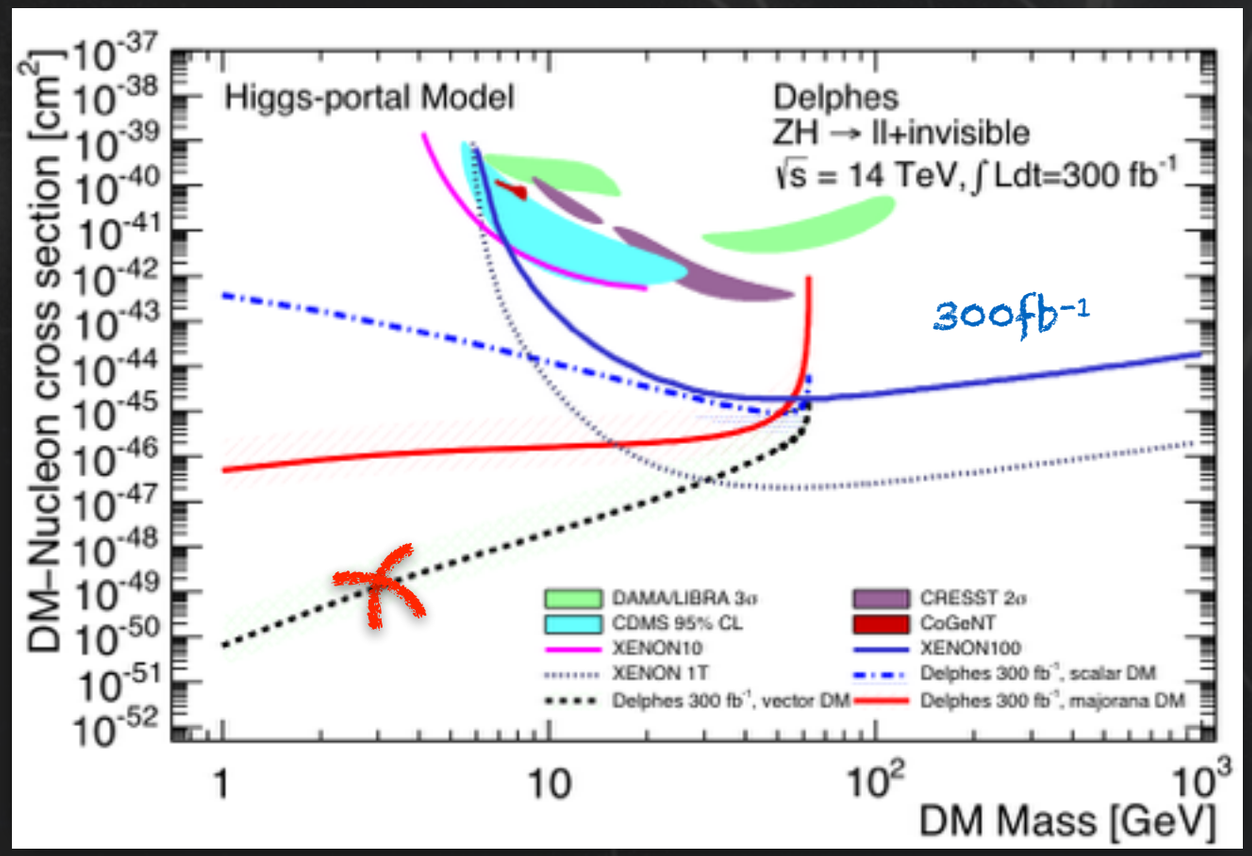
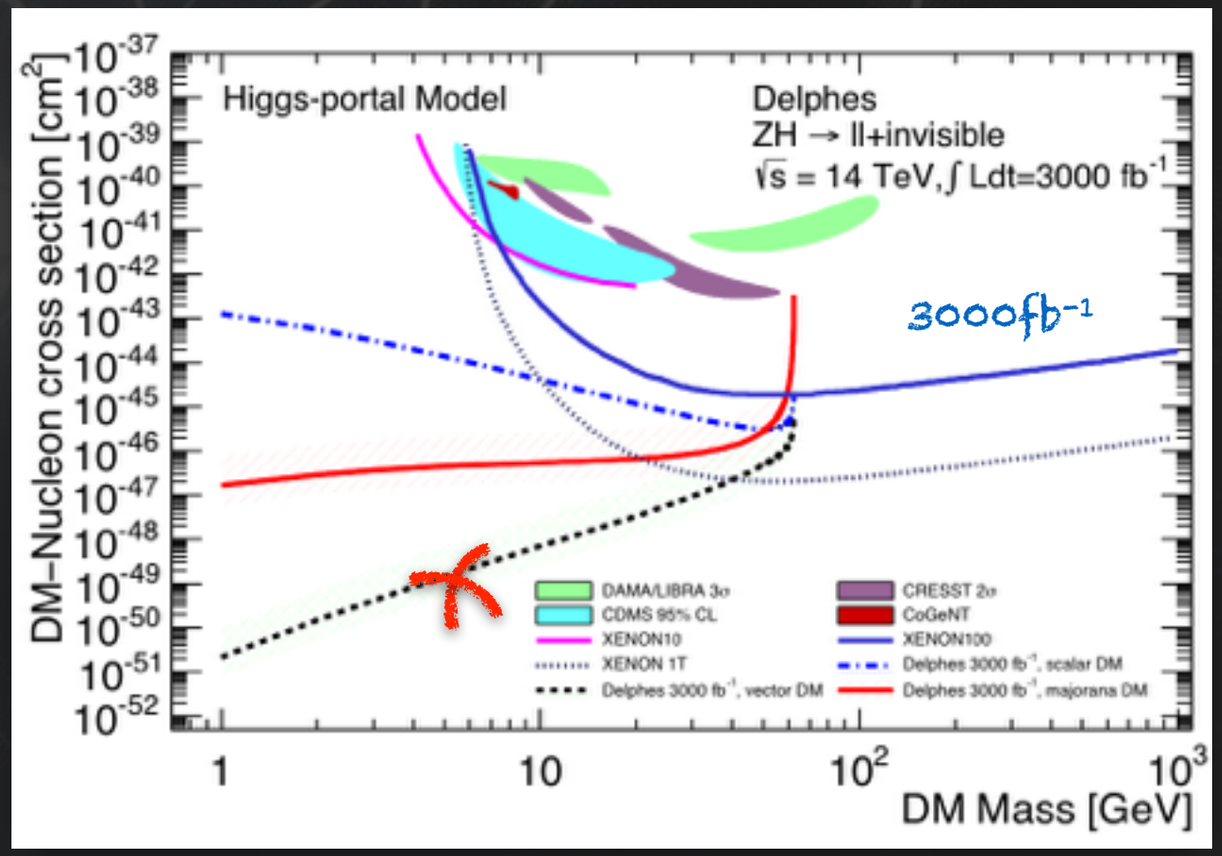
H→inv. Prospects

arXiv:1309.7925
H. Okawa, J. Kunkle, E. Lipeles

- Taking advantage of data driven methods and large data sets systematics become small: 6% (2%) for 300 (3000)fb^{-1}
- Inv. BR of ~20% (10%) may be excluded with 300 fb^{-1} (3000 fb-^{1})
- Translate into constraints on Higgs portal DM





Improvements by two orders of magnitude!

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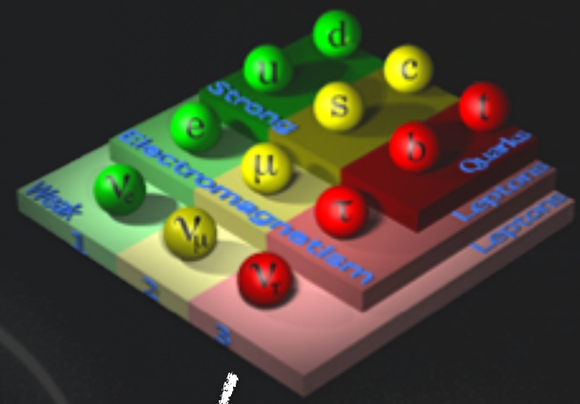
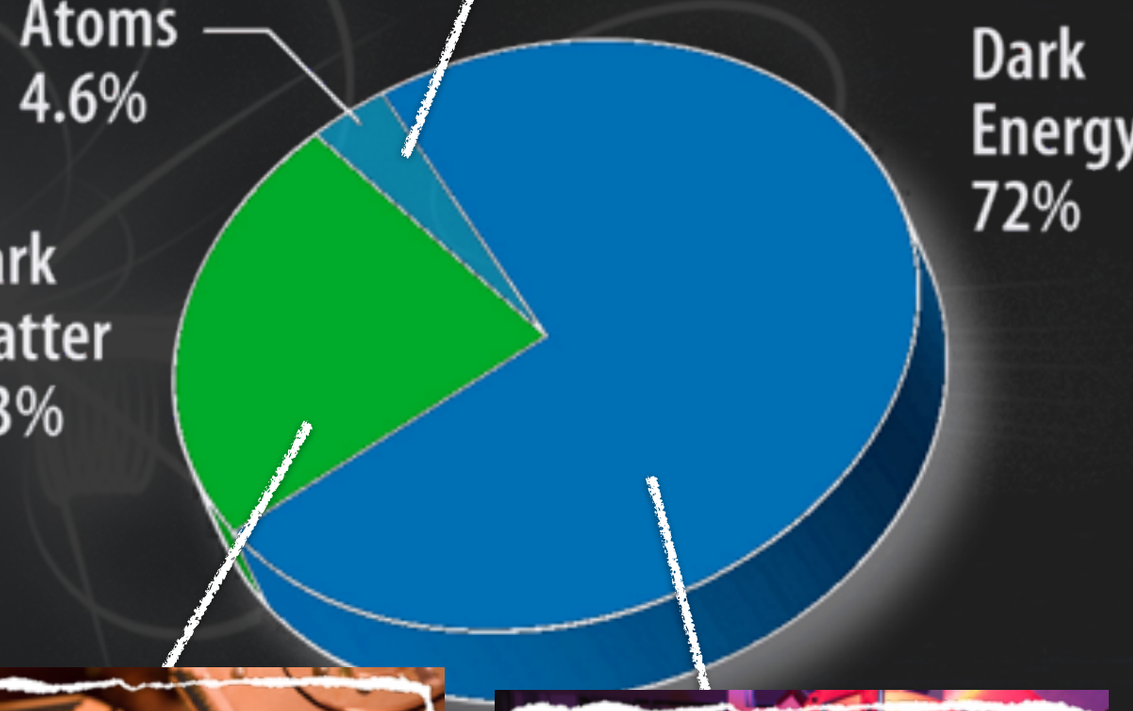
Conclusion

arXiv:1310.8621

- **DM searches at collider** are very powerful
  - **(HL-)LHC** has **great discovery** potential
  - **Multi-pronged approach**:
    - SUSY searches
    - Direct collider searches
    - Precision measurements (Higgs, Dijet, …)
- **Future collider may be needed** to probe all or largest part of allowed phase space
- **DM can only be discovered in an interdisciplinary effort**
  - Different sensitivities and uncertainties for (In-)Direct and Collider searches
  - To identify DM need to discover in more than just one way
- **DM searches** one of the **most exciting areas** these days





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Need perhaps a bit madness to conquer the river.

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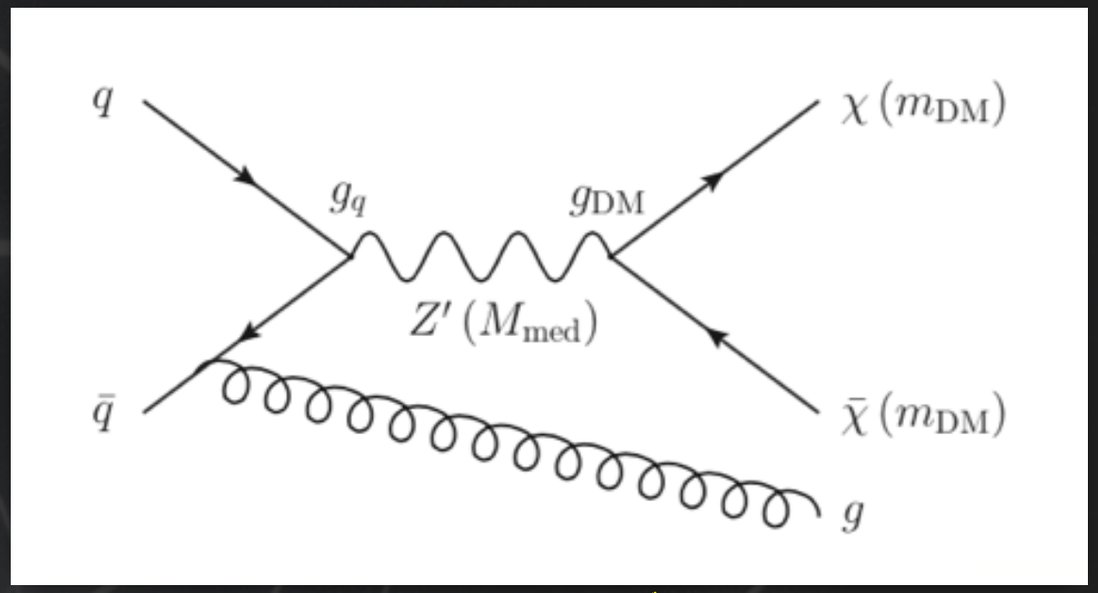
Backup

Simplified DM Models

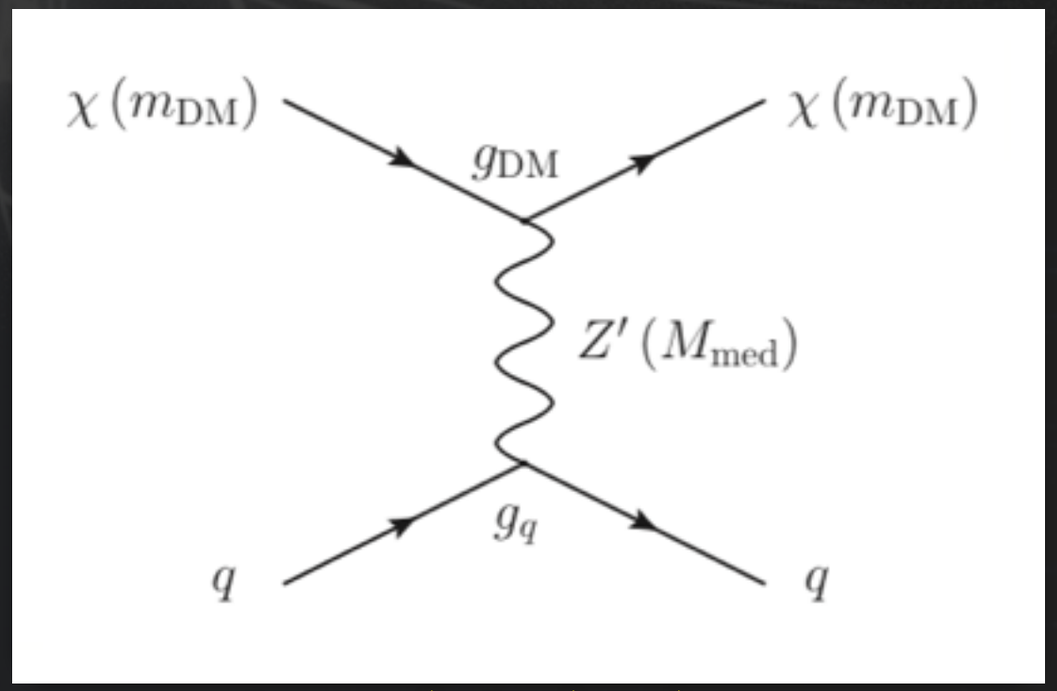
arXiv:1407.8257
Buchmueller et al

- Moving to **simplified models for more realistic picture**
- Also (vector-) axial models
- Minimal Simplified DM framework (MSDM), probe m_{DM}, m_{Med}, g_{DM}, g_q



Collider

- **Monojet searches** interpreted
  - **optimized E_T^{miss} requirement**
- Reproduce well existing collider constraints
- Compared to **direct searches**



Direct Detection

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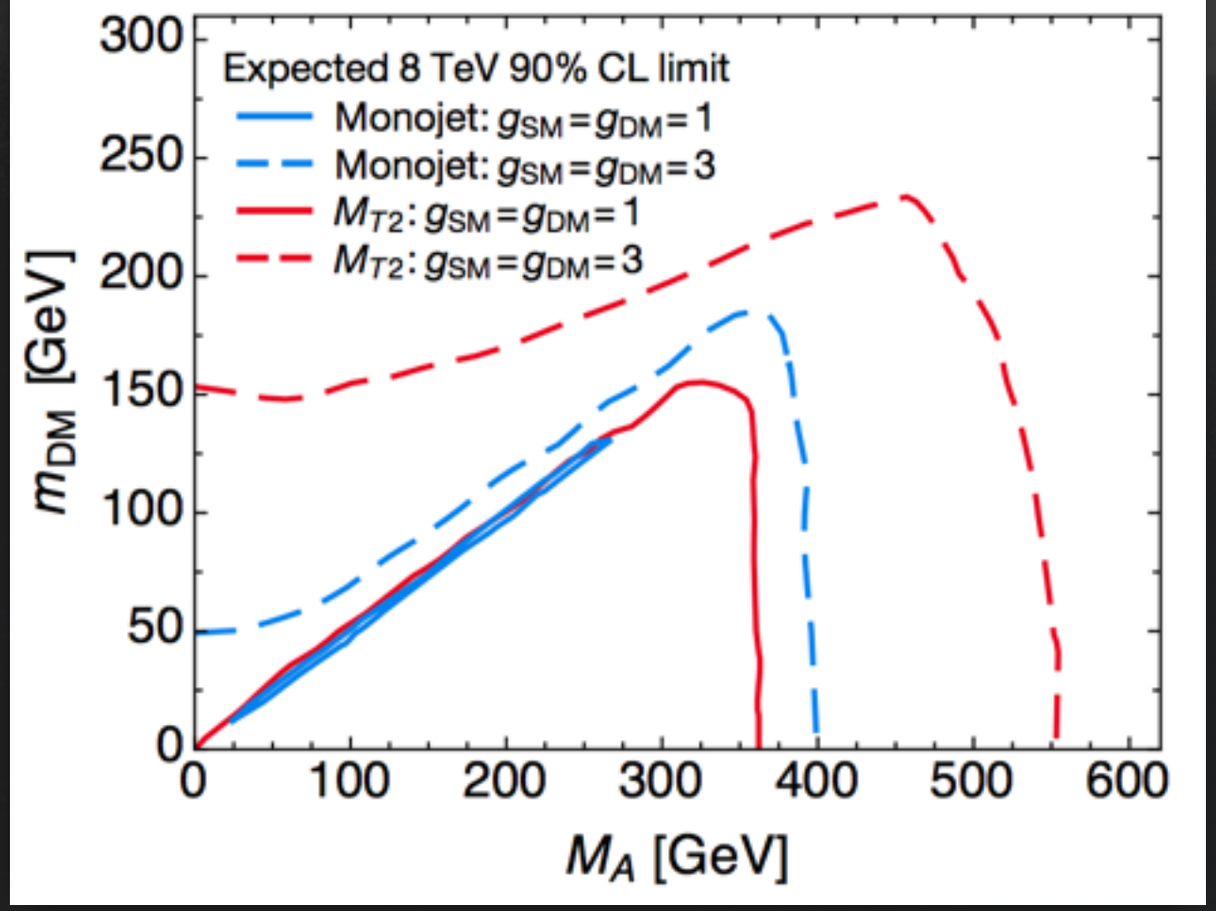
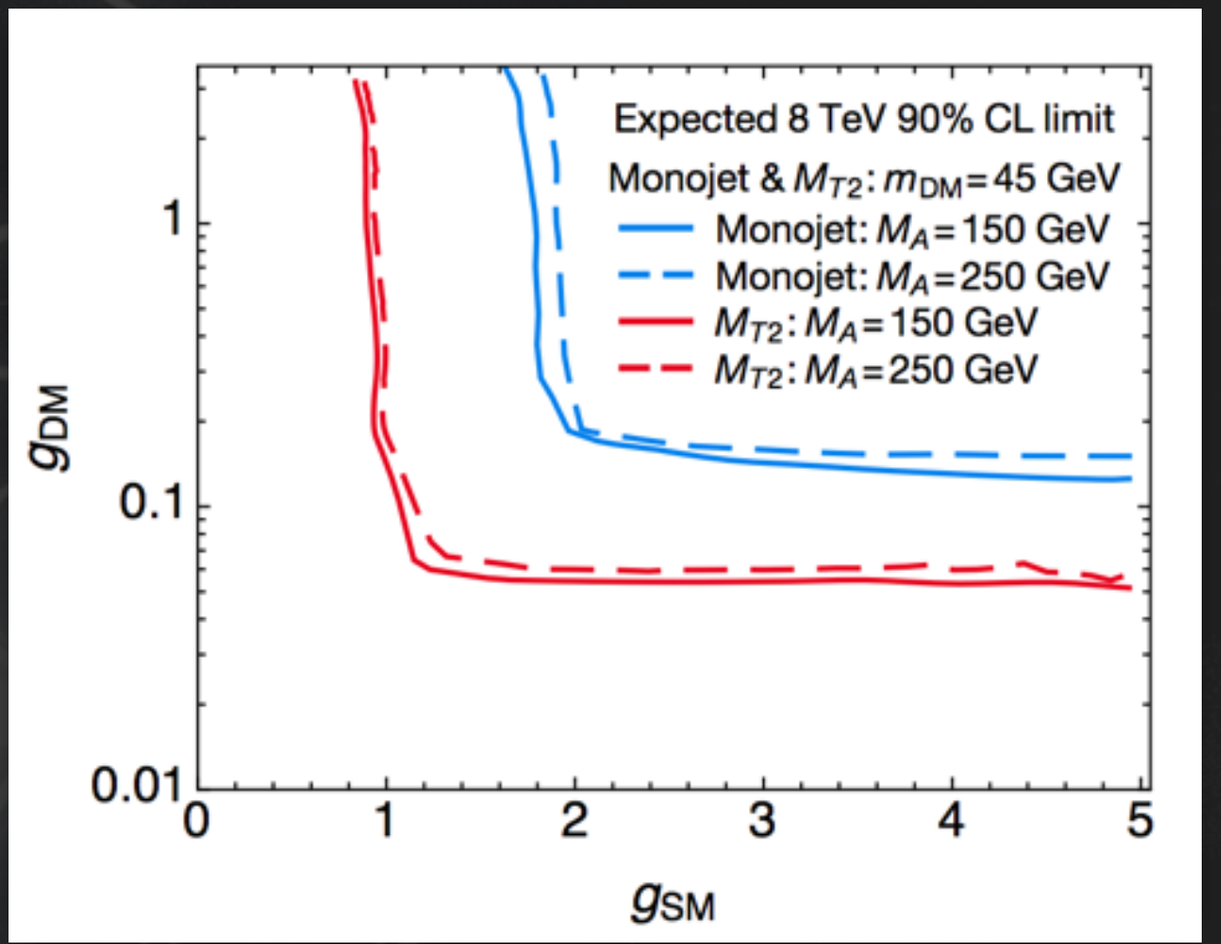
Sensitivity for GC with 8 TeV data

arXiv:1505.07826
arXiv: 1407.8257

- **Sensitivity in mediator and DM mass** and couplings compared for **monojet** and **MT2**
- Study based on **Delphes simulation** of published searches





- **MT2** possesses **significantly better** expected sensitivity
- See arXiv:1505.07826 for details
- Also see arXiv:1407.8257 for general power of MET+j for DM searches

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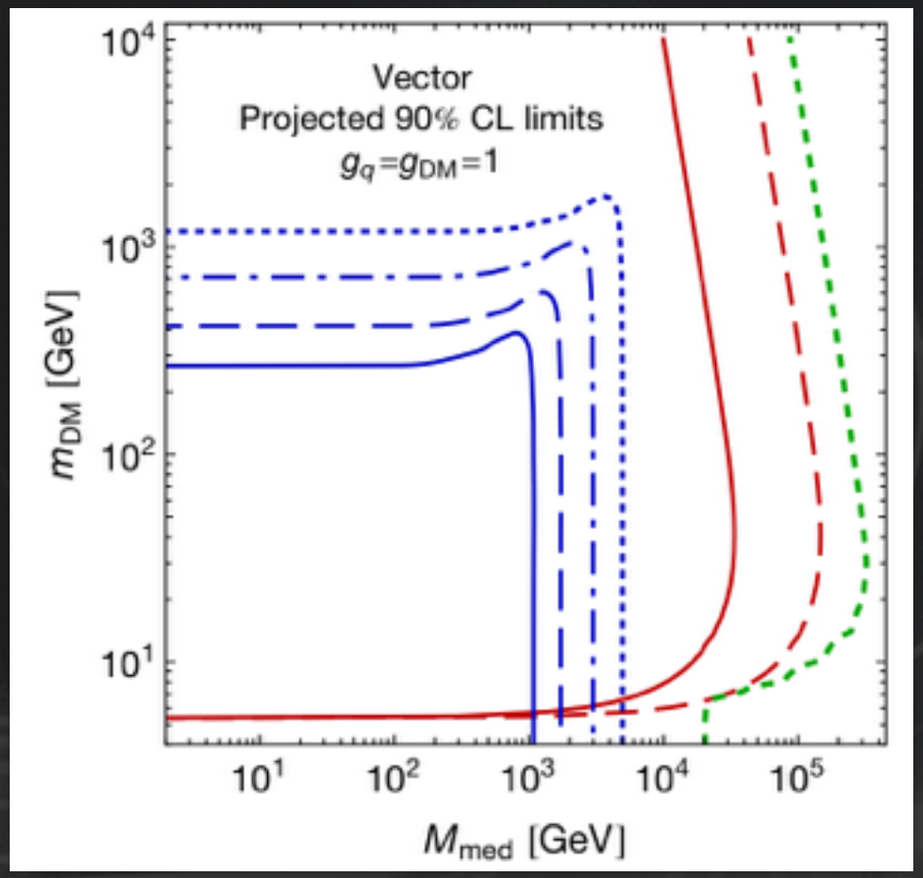
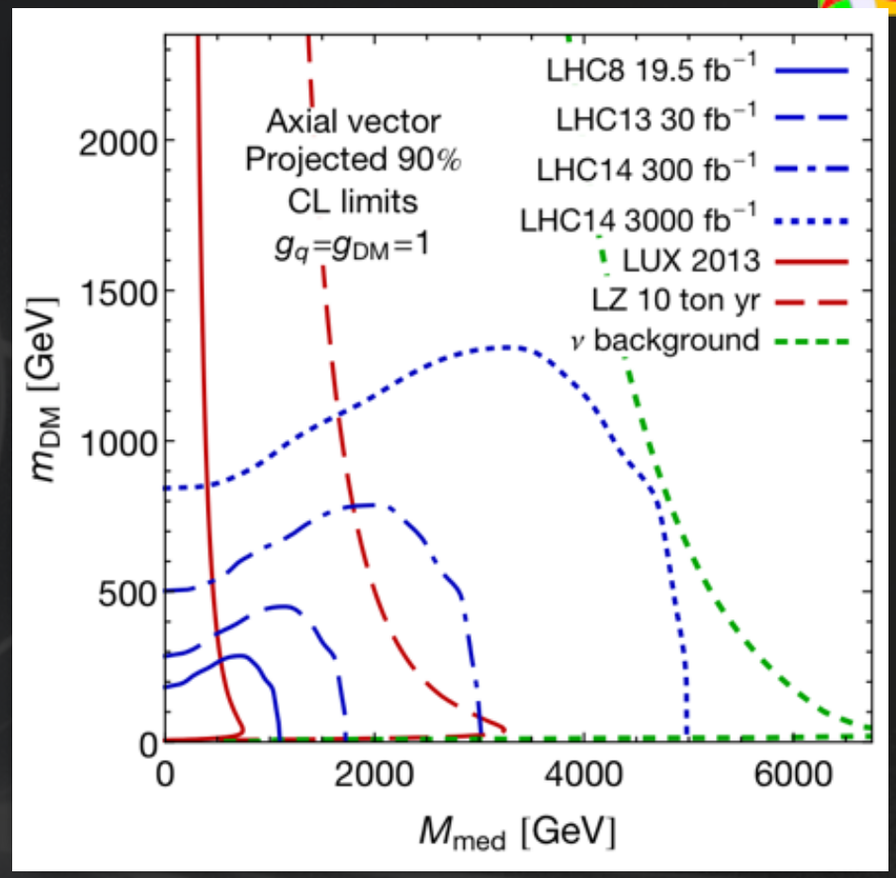
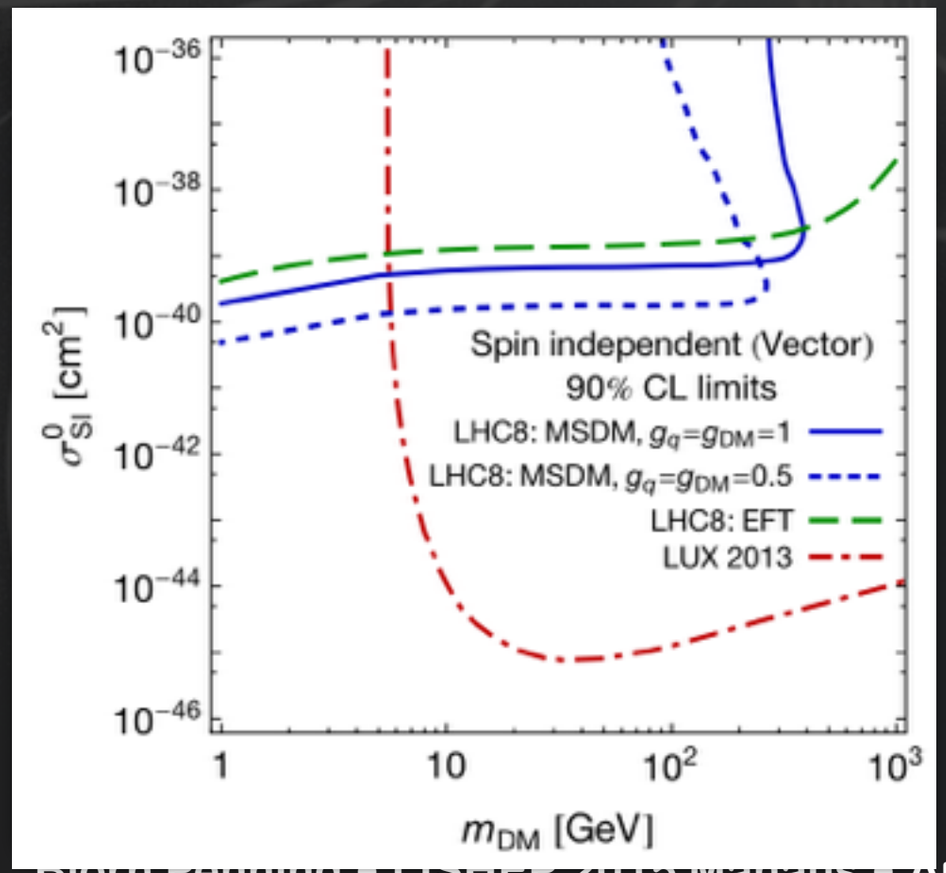
Simplified Models Monojet Projections

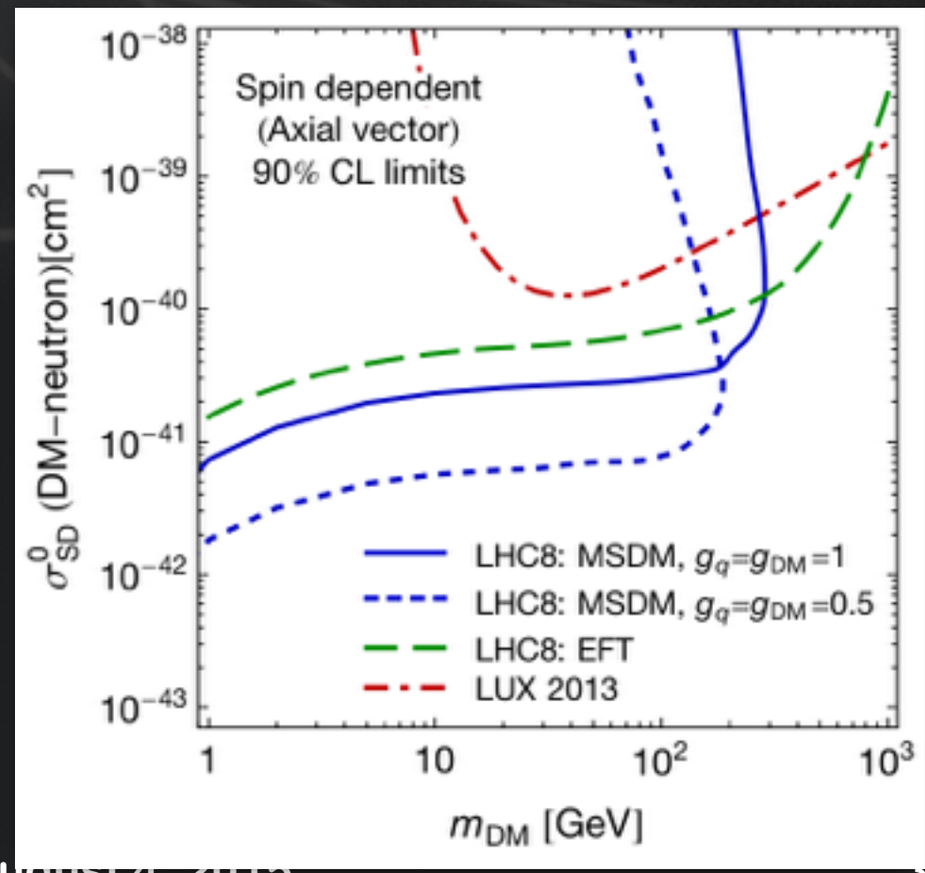
arXiv:1407.8257
Buchmueller et al

- **HL-LHC reaches impressive sensitivity**
- **Clearly future high energy collider can go beyond the neutrino floor construing direct searches**



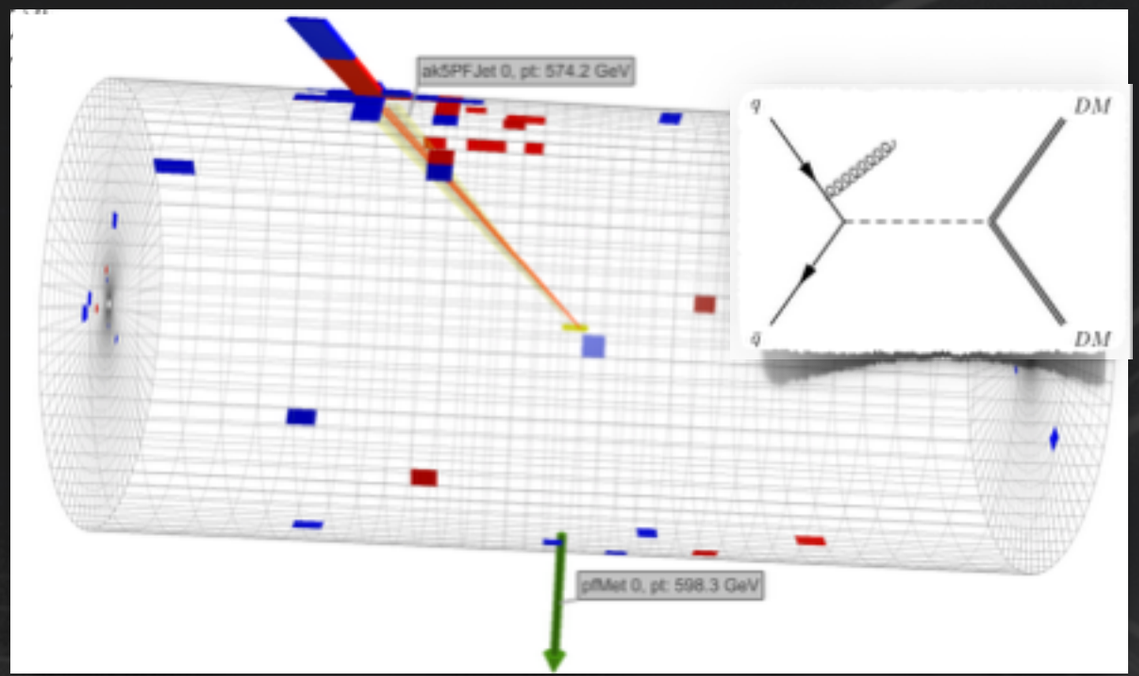






Mono-Jet

arXiv:1408.3583 (CMS)
ATLAS-CONF-2012-147

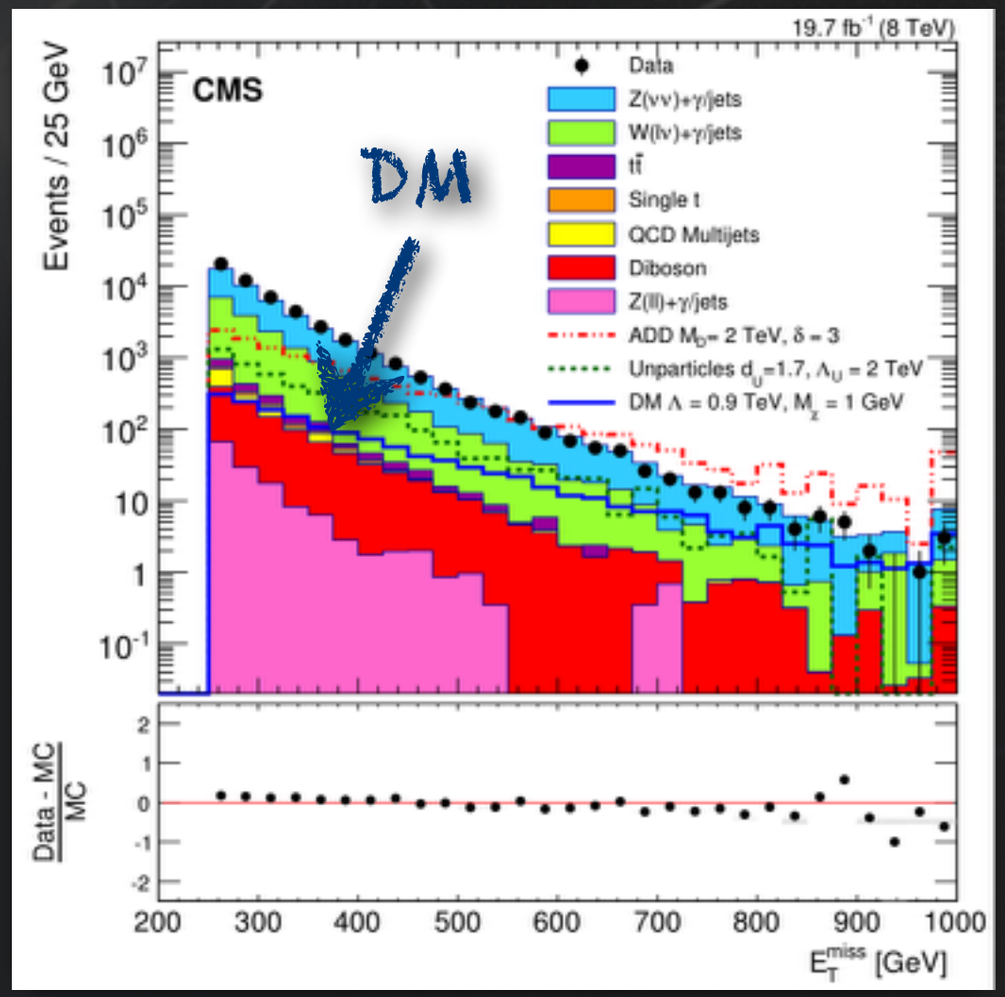


- E_T^{miss} or E_T^{miss}+jet trigger
- Require large E_T^{miss} and $p_T(jet_1)$
  - 1 or 2 jets, no leptons
  - Angular selections to remove QCD

- Main background processes:
  - $Z \rightarrow \nu\nu$, W+jets
- Typically use E_T^{miss} as discriminating variable

Yield (E_T^{miss}>500 GeV)

Exp. Bkgd	1040 +/- 100
Data	934



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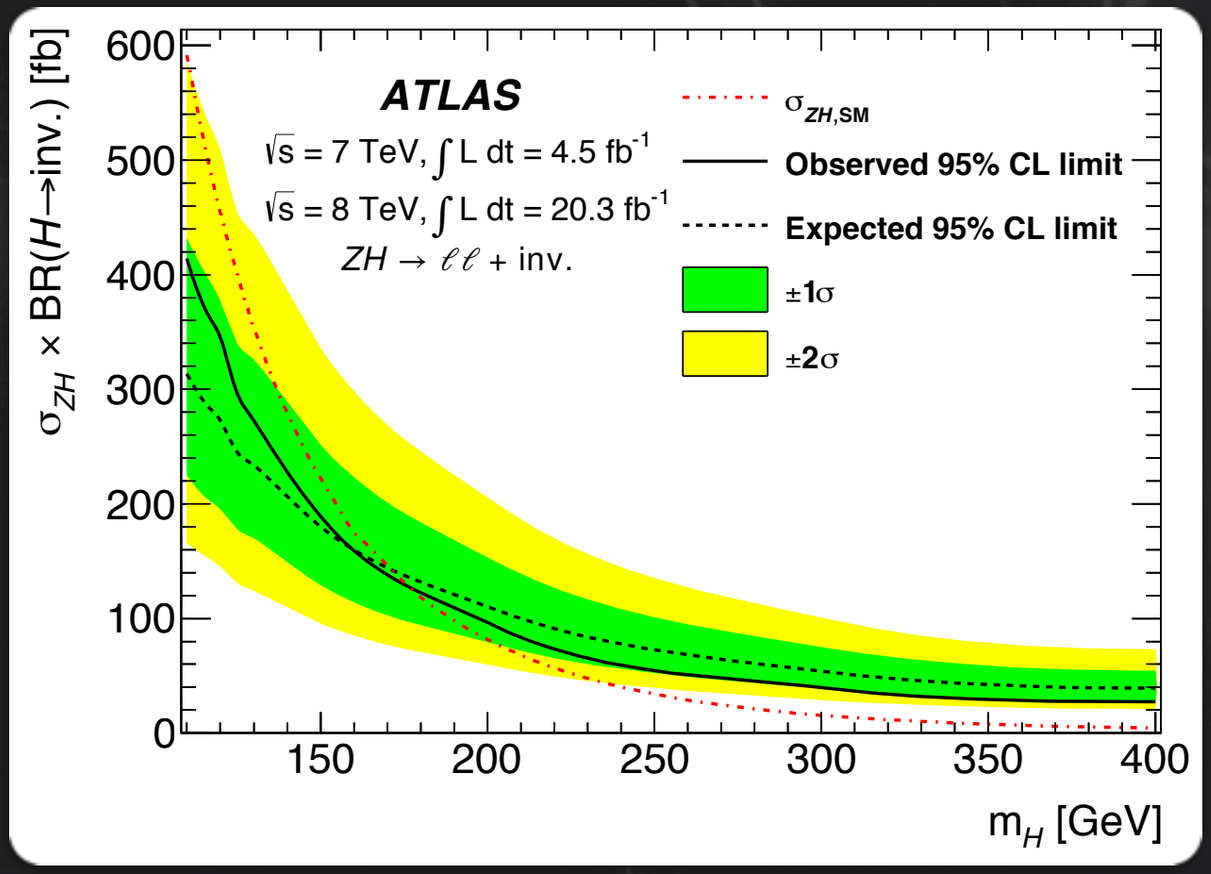
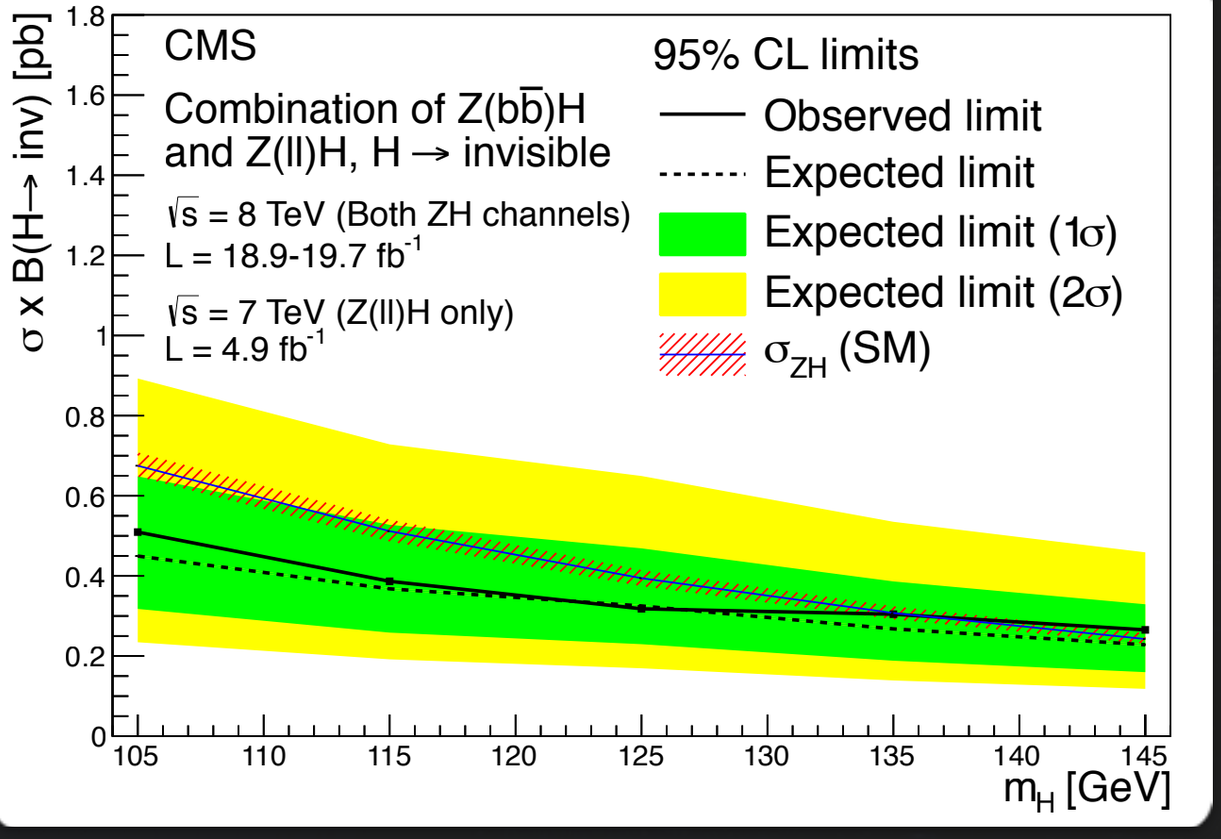
H→inv. Prospects

arXiv:1402.3244 (ATLAS)
arXiv:1404.1344 (CMS)

- Analysis based on **associated ZH** production
- **SM cross section predictions for m_H=125 GeV**
- **Upper limits** on σ x BR(H→inv) as function of m_H



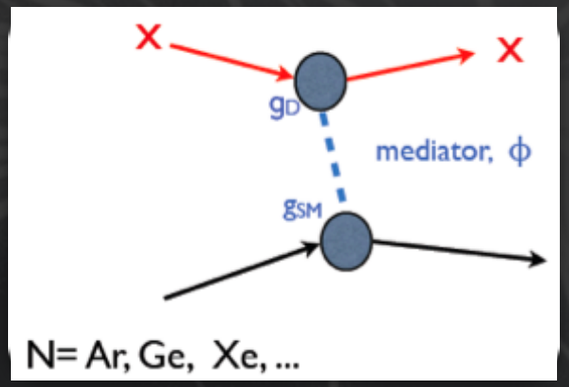
BR(H → inv) < 0.75 (0.62) obs (exp)
@m_H = 125 GeV.

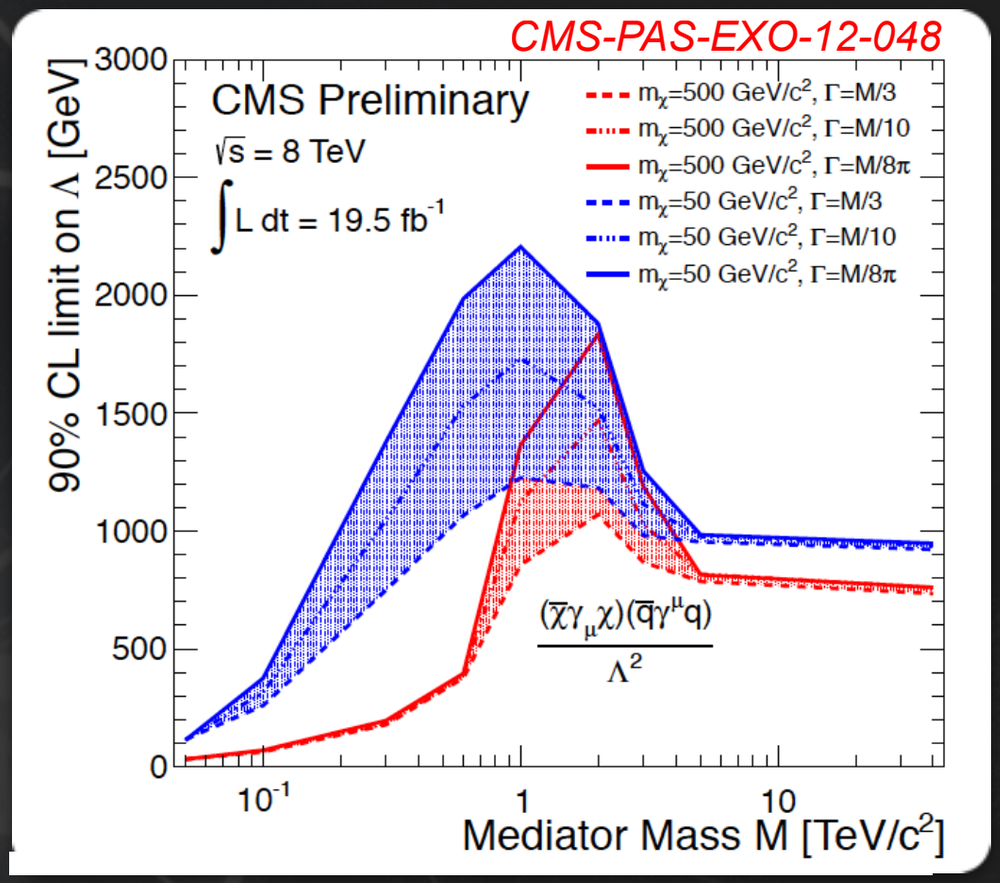


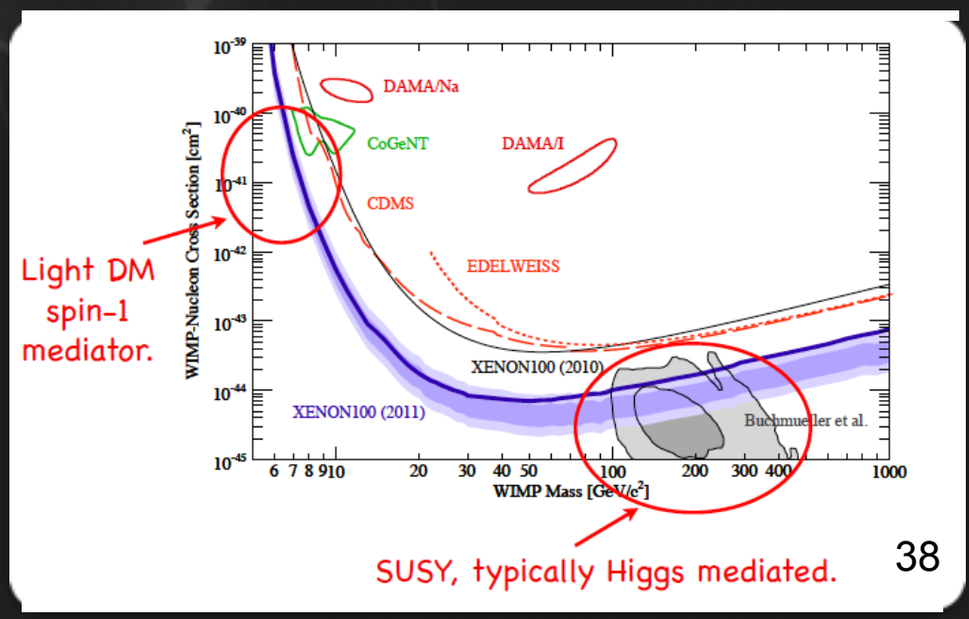
BR(H → inv) < 0.58 (0.44) obs (exp)
@m_H = 125 GeV.

Searching for the Mediator

- For energies larger than the mediator mass, probing more structure of the s-matrix
  - Depending on details for the mediator
  - Then the mediator itself can be discovered
- Typical examples of mediator Φ:
  - Φ = Higgs (spin 0)
    - M_Φ~100 GeV
    - g_{SM}~(100 MeV)/(100 GeV)
    - $\sigma n \sim 10^{-43}$-10^{-45} cm^{-2}
  - Φ = Z' (spin 1)
    - $\sigma_n \sim 10^{-36}$-10^{-39} cm^{-2}

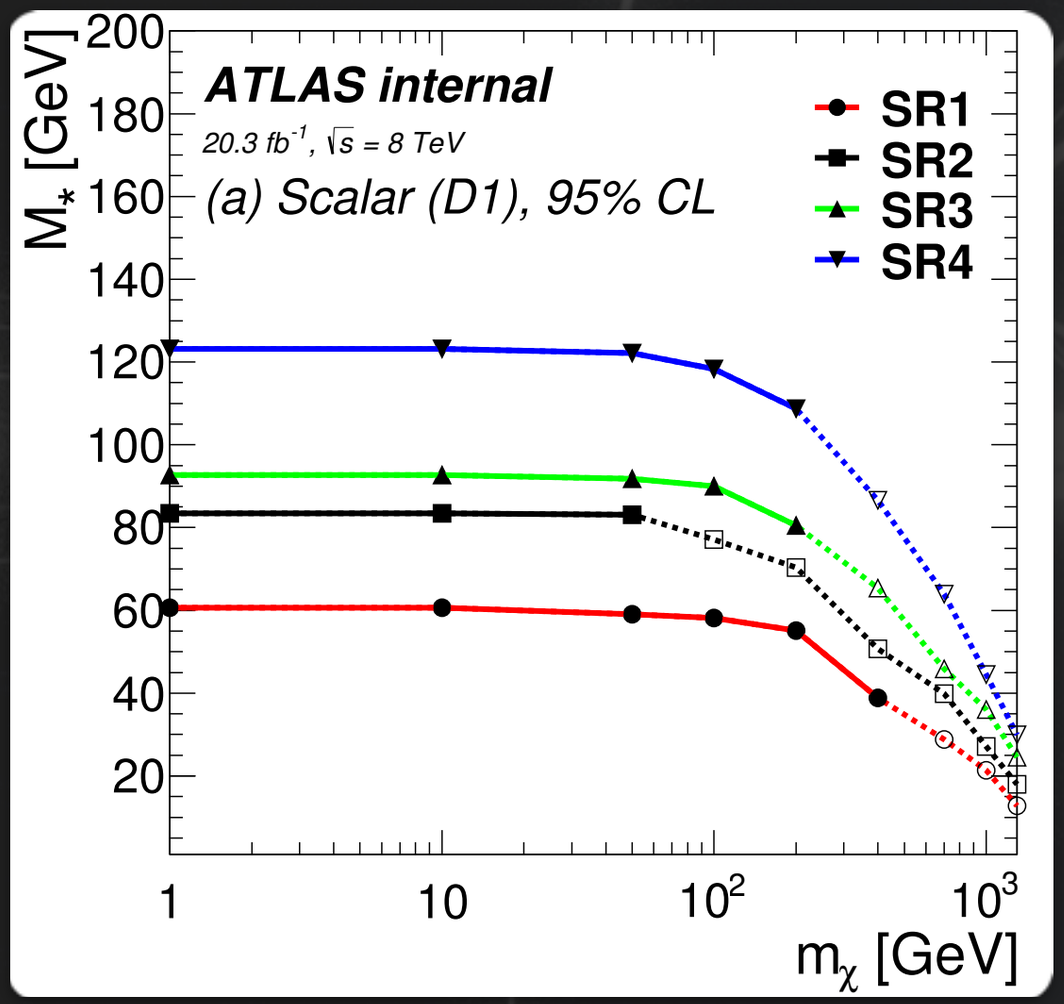






Limit Setting

- Lower limits at 95% C.L. on the suppression scale of M* set for different operators (arXiv:1008.1783v2, Goodman et al.)



coupling strength:

$$M^* \approx M/\sqrt{g_2 g_2}$$

validity requirement

$$Q_{\mathrm{tr}} < 4\pi \left(M_*^3/m_q\right)^{1/2}$$

- Determine μ → calculate g → calculate M*
- All the usual caveats of validity apply. DM+HF better validity than mono-jet.