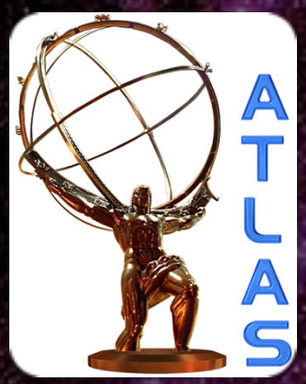
DM Searches in Run II at the LHC

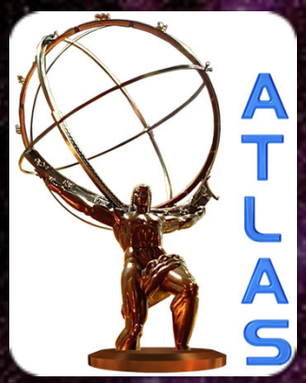
Björn Penning
Imperial College London



Imperial College London

DM Searches in Run II at the LHC

Björn Penning
Imperial College London



Imperial College London

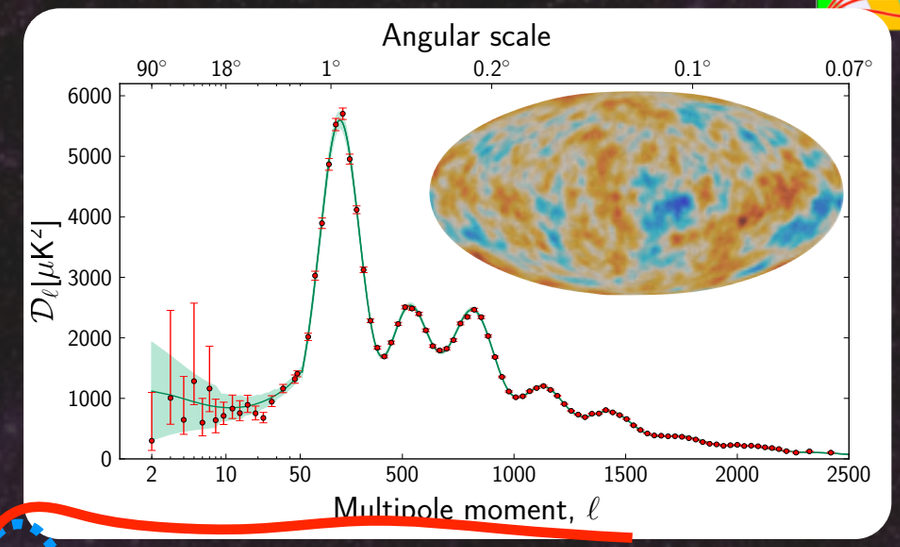
Imperial College London

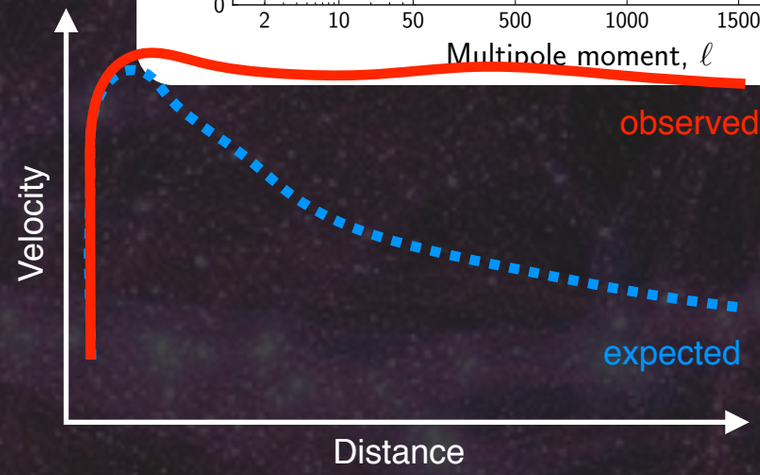
- Introduction to DM
- Run I searches at Collider
- Evolving towards more realistic searches models & projections
- Searching for the Mediator
- DM Forum
- Conclusion

Imperial College London

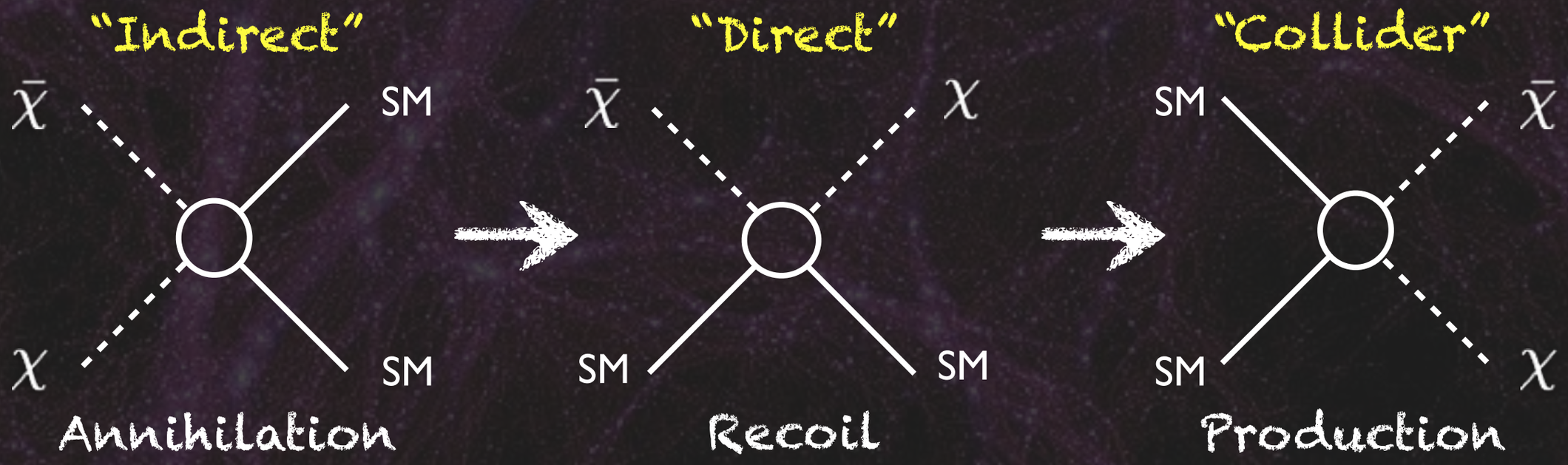
Why looking for DM

- 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: $\Omega_\Lambda \approx 0.68$, $\Omega_{DM} \approx 0.27$, $\Omega_b \approx 0.05$



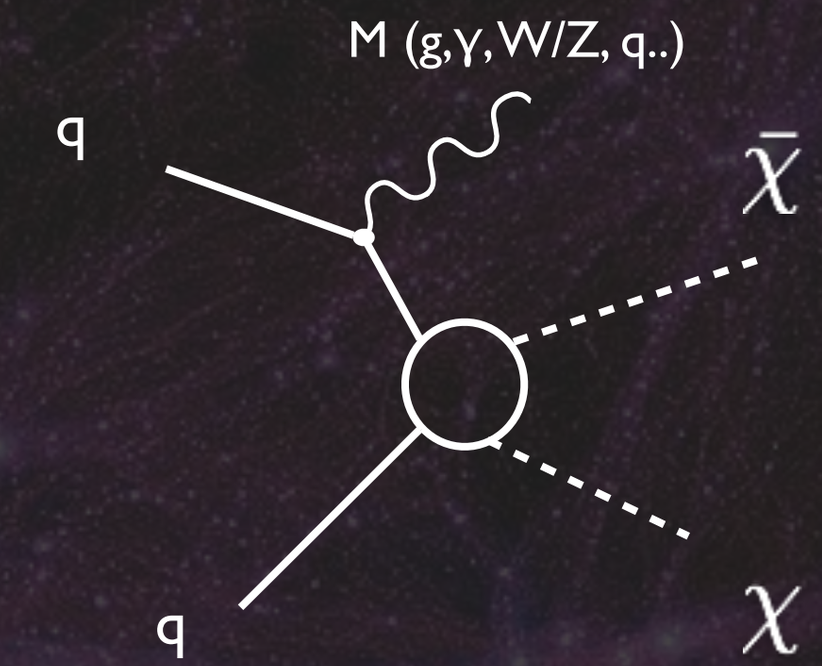


- DM 'non-baryonic cold dark matter' → 'WIMP Miracle' → BSM physics



How to look for DM

- **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



Imperial College London

How to look for DM

less model dependent

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

Effective Field Theory

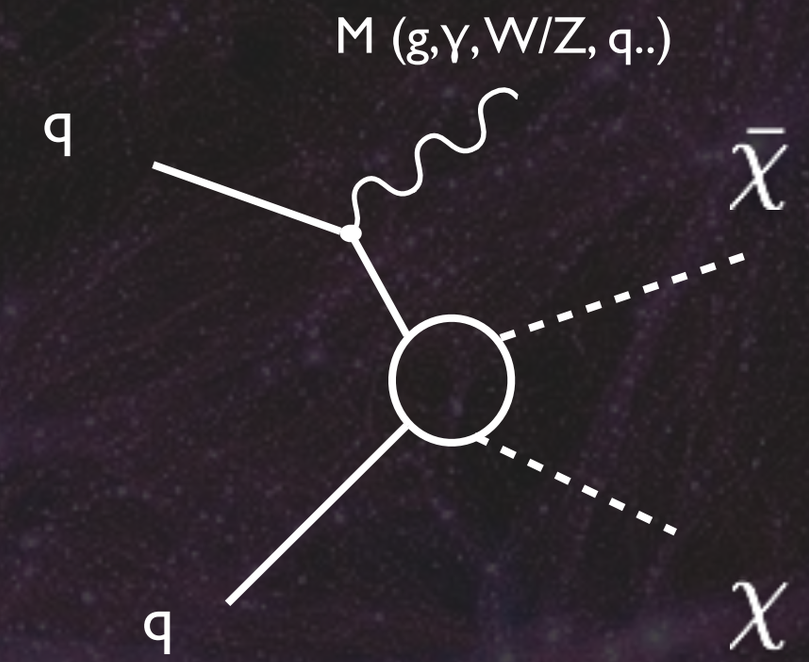
SUSY

Extra Dimensions

Little Higgs..

Dark Sectors

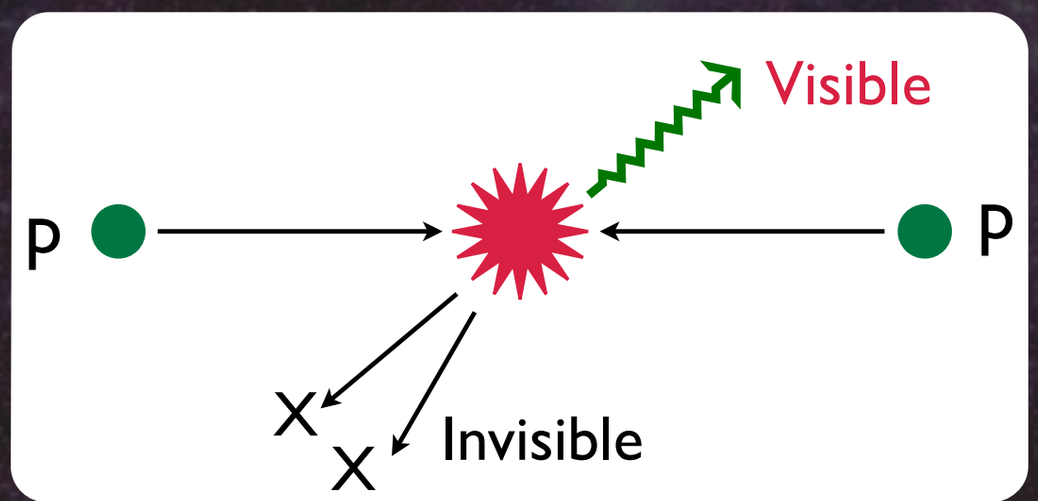
more model dependent

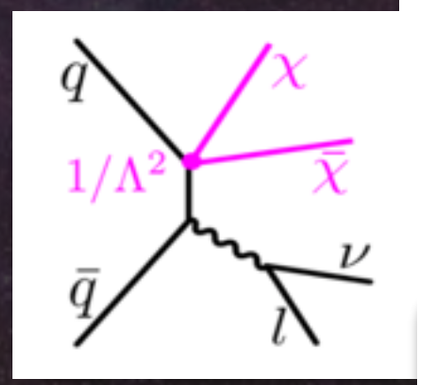


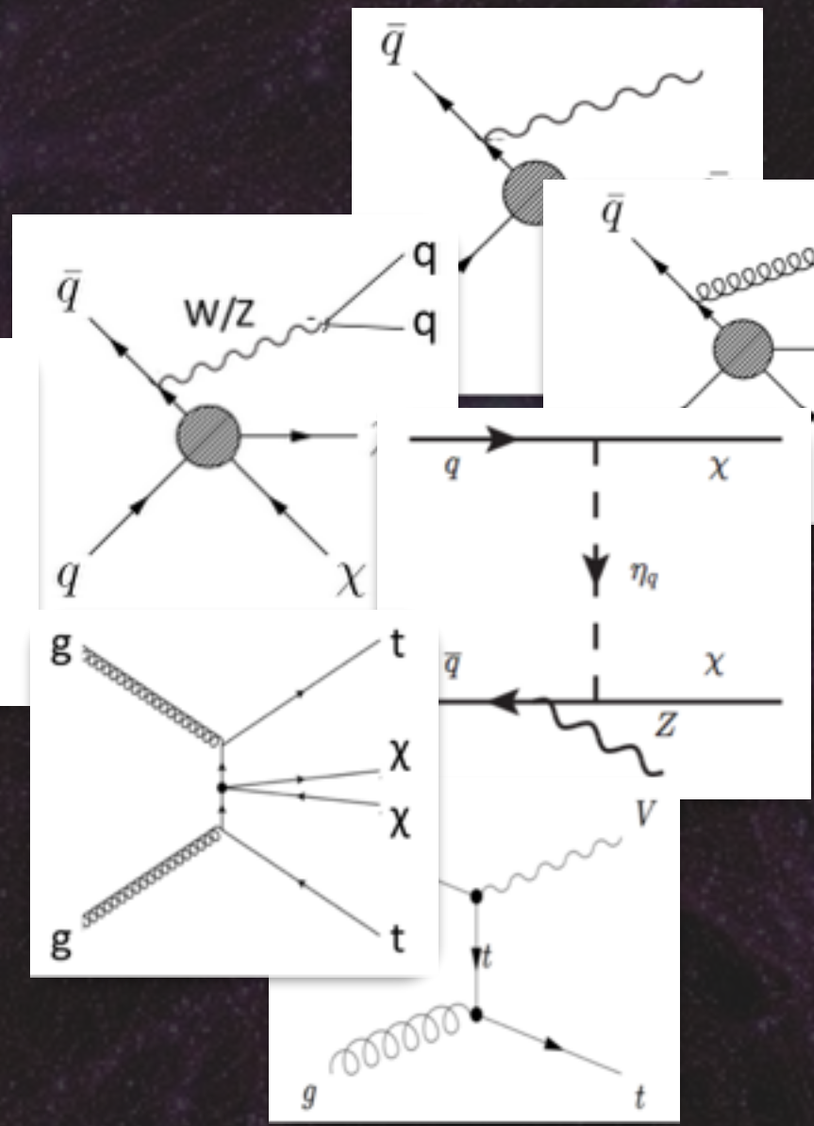
Imperial College London

Mono-X

- Dominant Run I signature: **mono-'X'** (**mono-madness ensued**)
  - '**Back 2 Back**' events, recoiling SM object balanced with m(xx) (E_T^{miss})
  - **Effective Field Theory (EFT)** approach uses **distinctive operators**







- **Operator** based approach

$$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$$

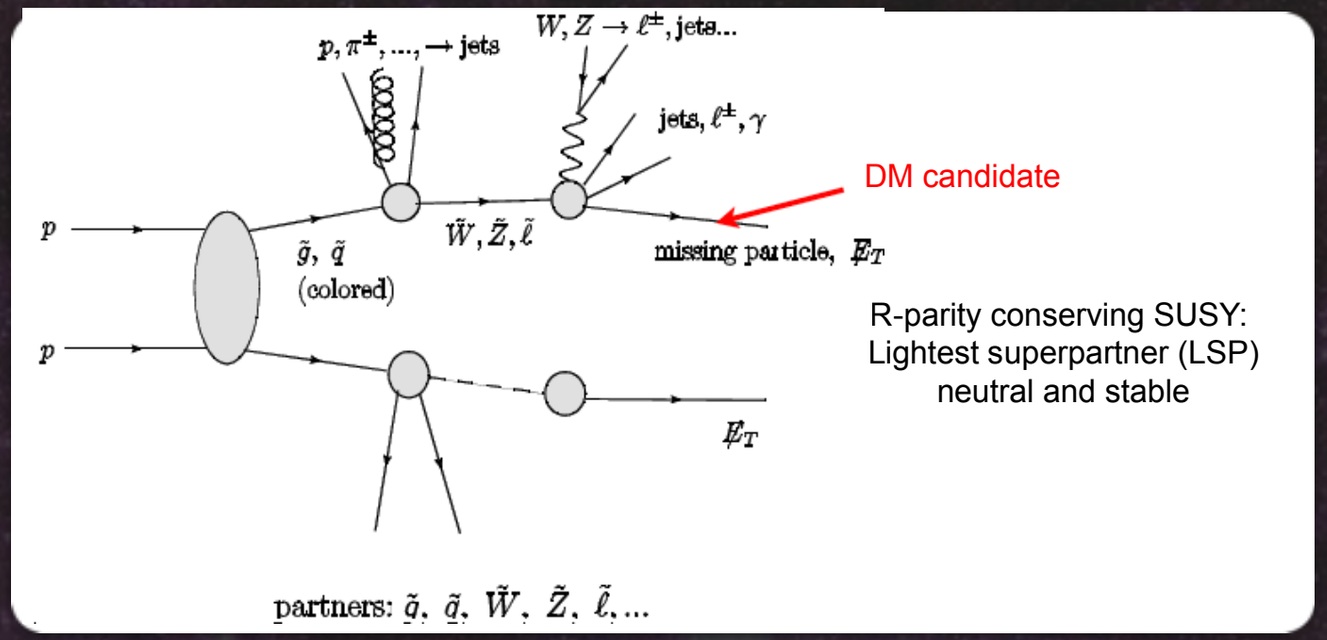
$$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

$$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$$

- Can be connected to direct searches, partially stringent validity constraints

SUSY DM

- **DM part of extended sector of new physics at TeV scale**



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

- **Discovery may be rather easy, property measurement very hard**

- **E_T^{miss} + jets**
- **E_T^{miss} + b**
- **E_T^{miss} + 1ℓ**
- **E_T^{miss} + 2ℓ (ss/os)**
- **E_T^{miss} + single jets**
- **E_T^{miss} + j + ℓ + b**
- **E_T^{miss} + j + 2ℓ + b**
- **E_T^{miss} + jets + Z-boson**
- **E_T^{miss} + 3/4 ℓ**
- **E_T^{miss} + jets + γ**
- **...**

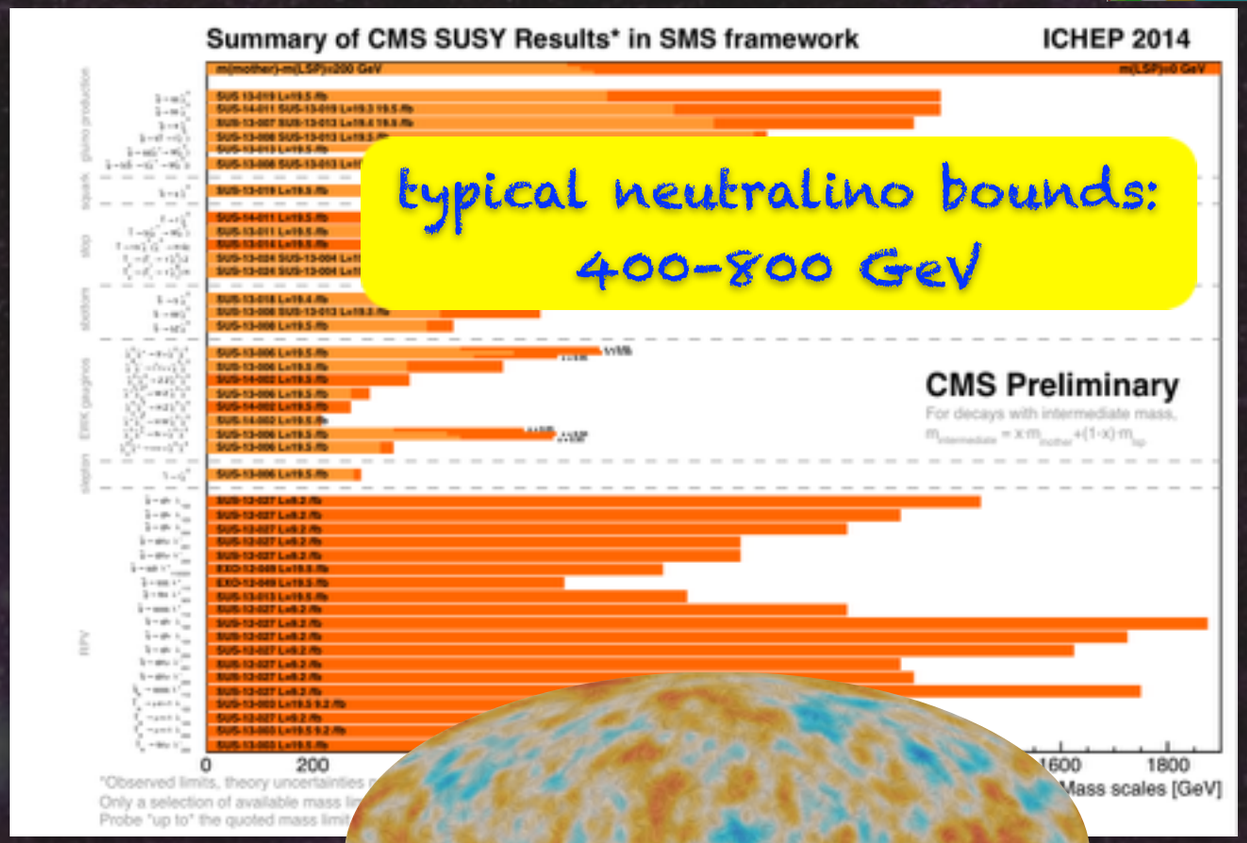
- Results interpreted in **cMSSM, pMSSM** and simplified models, **no excess yet**

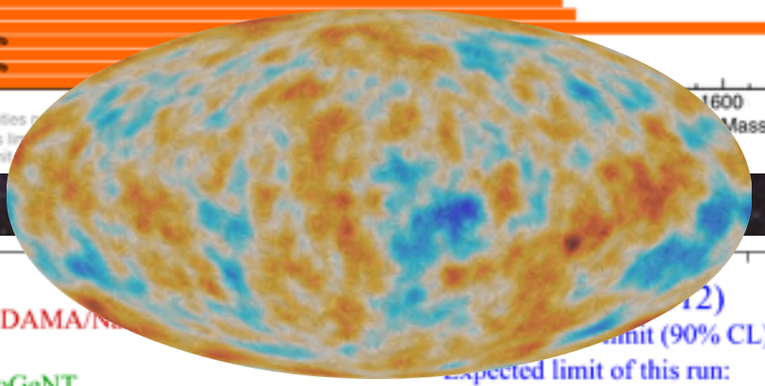
- Often stringent selection requirements

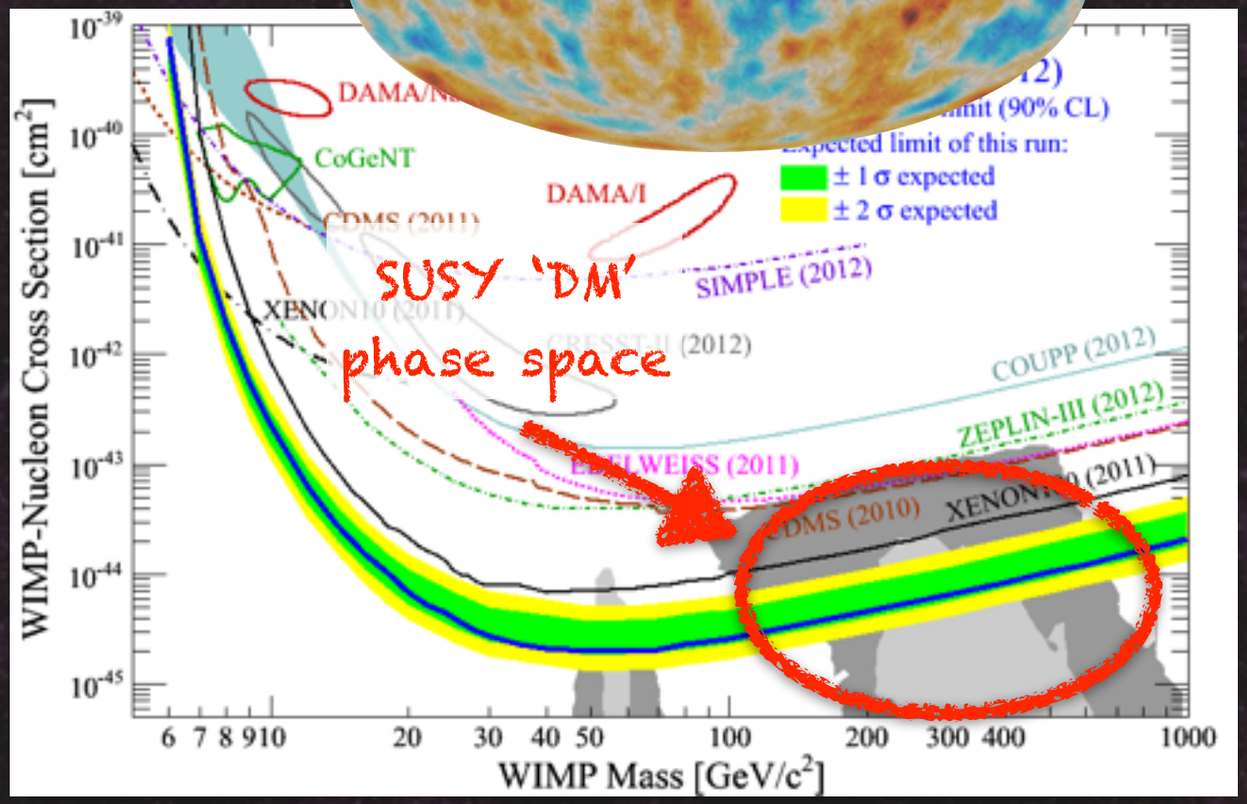
Imperial College London

Commonalities & Differences

- **SUSY**:
  - Heavily constrained
  - m_H = 126 GeV
  - Flavor observables, e.g. $b \to s\,\gamma$
  - WMAP constraints on relic density
  - Prefers g-2 (?)
  - We know a lot about it, except we don't know if it exists
- **Dark Matter**:
  - Relic density
  - Direct/Indirect DM searches
  - We know it exists, but not much more

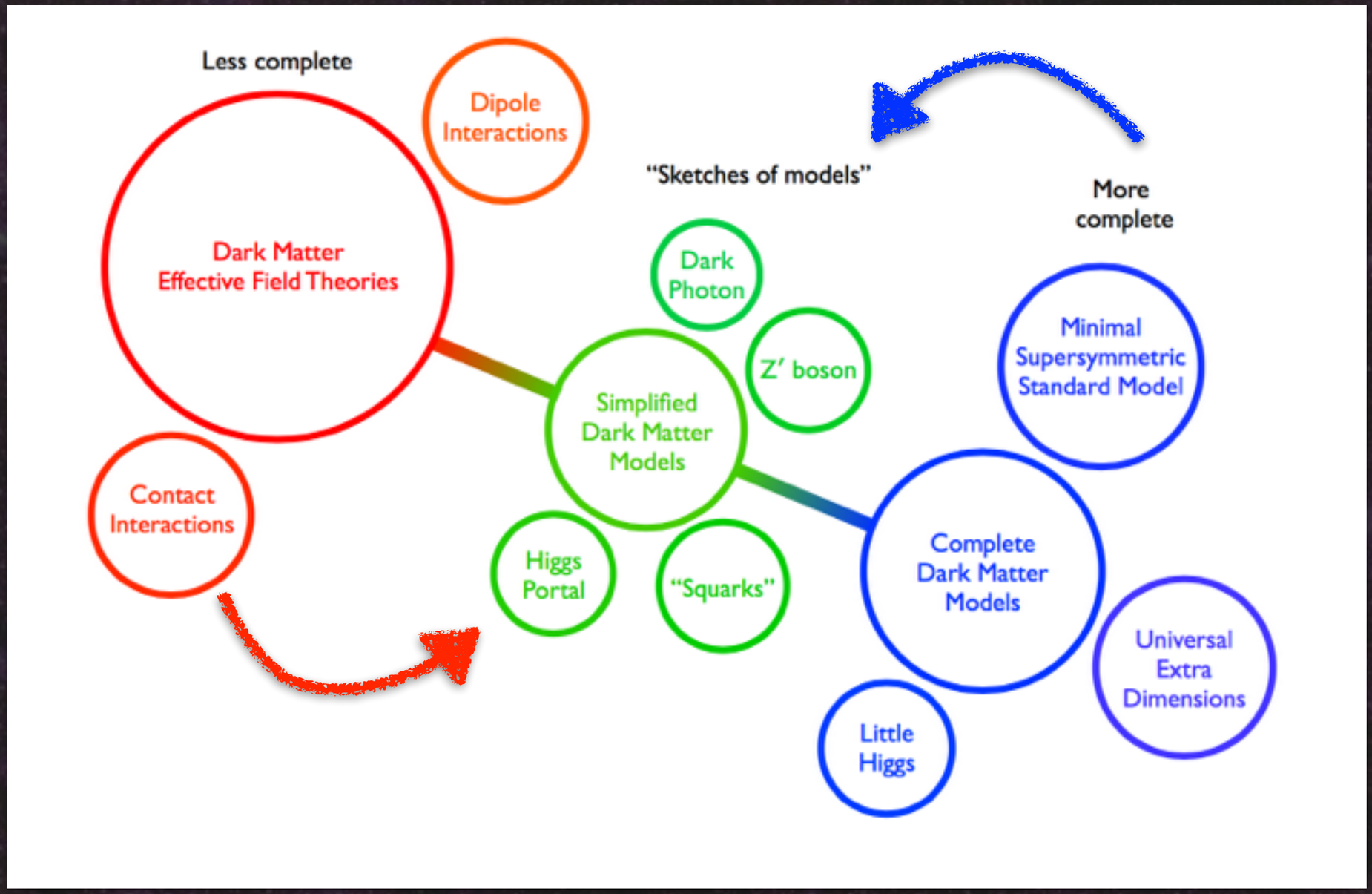






Imperial College London

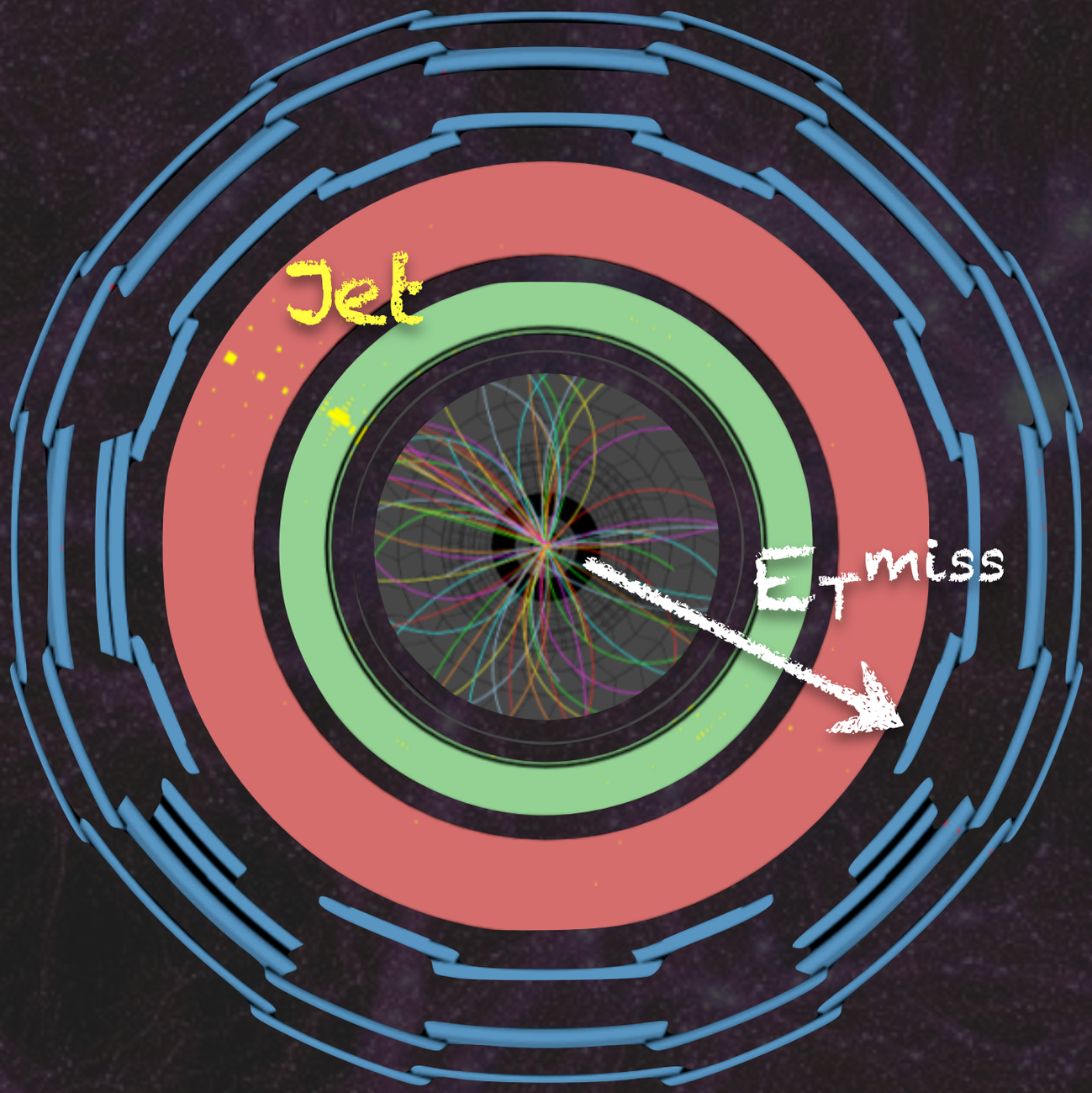
Model Landscape



- Developments in '**Exotics DM searches**' towards more predictive simplified models while **SUSY** extended full models to well understood set of simplified ones
- Clearly there are commonalities and also differences

Imperial College London

Mono-X Searches

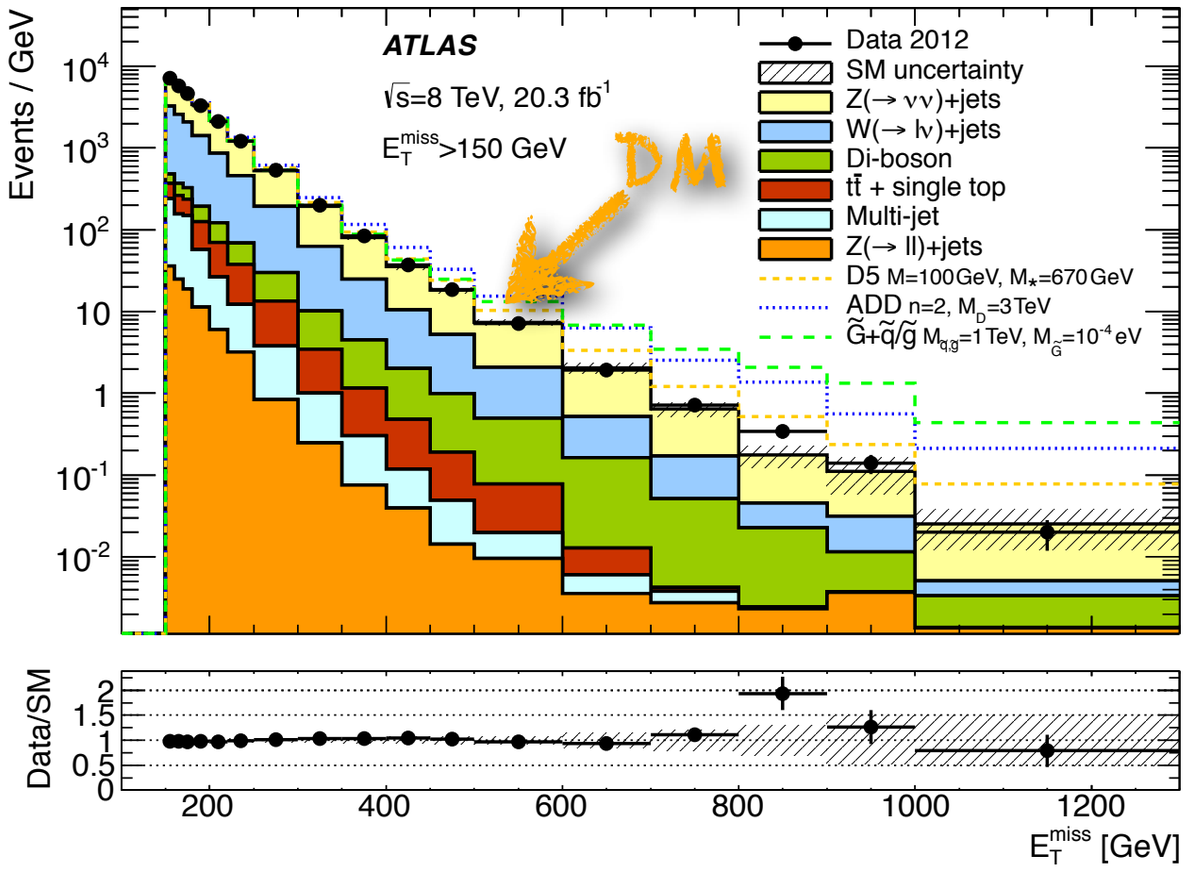


- E_T^{miss} trigger
- Monojet (8 TeV, 20.3 fb^{-1})
  - E_T^{miss} , $p_T(\gamma)$ > 150, 250,..,400,..900 GeV
  - 1 or 2 jets (anti-k_T, R=0.4, p_T>30 GeV)
  - $|\Delta\varphi(E_T^{miss}, j_2)|$>0.5
- Monophoton (8 TeV, 20.3 fb^{-1}):
  - E_T^{miss} , $p_T(\gamma)$>150 GeV,
  - N_{jet} < 2 (anti-k_T, R=0.4, p_T>30 GeV)
  - $\Delta\varphi$ (γ, E_T^{miss}) >0.4,
  - $\Delta\varphi$ (jet, E_T^{miss}) >0.4

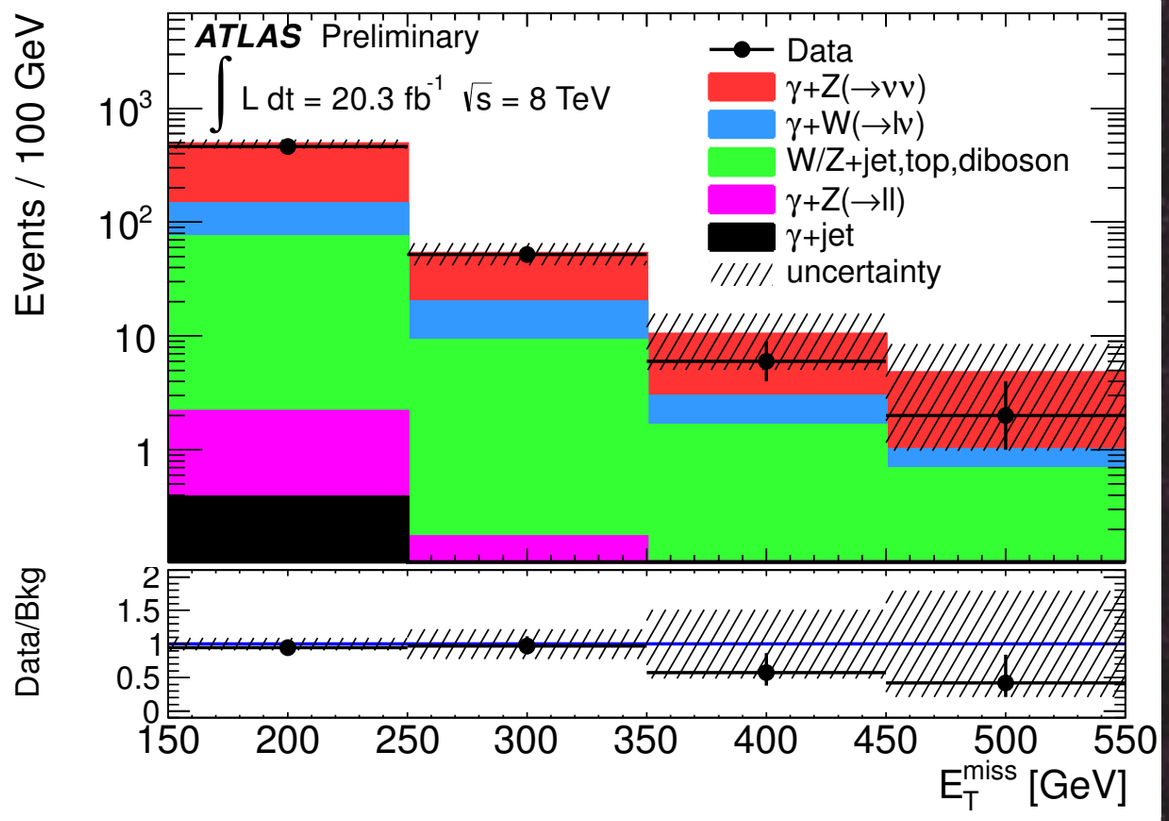
Imperial College London

Mono-X Searches

mono-jet



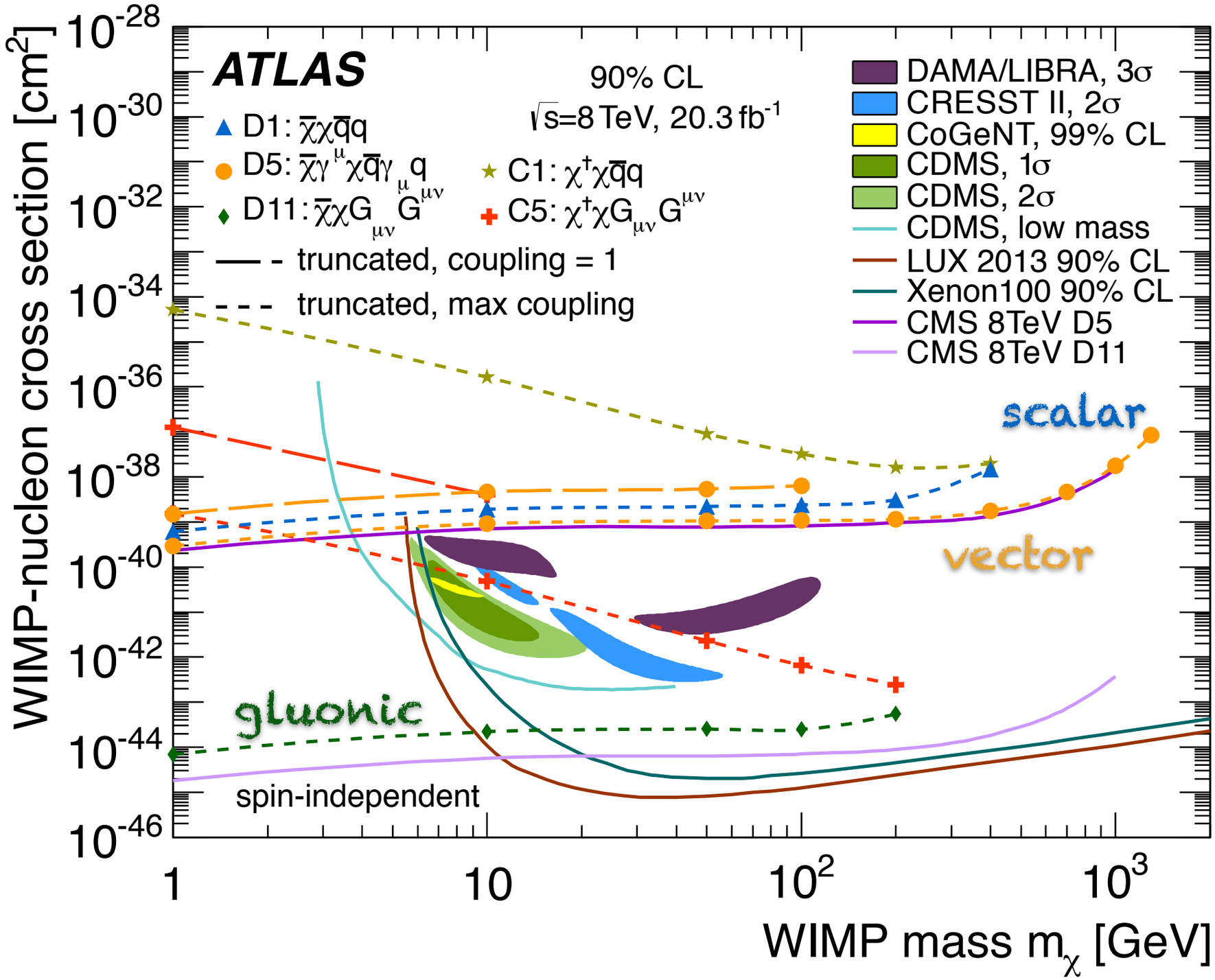
mono-photon



- Example: vector couplings in using orange
  - other limits re-interpreted but not considered in this talks
- Expected and observed number of events agree

→ Set upper limits on the visible cross section (σ×A×ε)

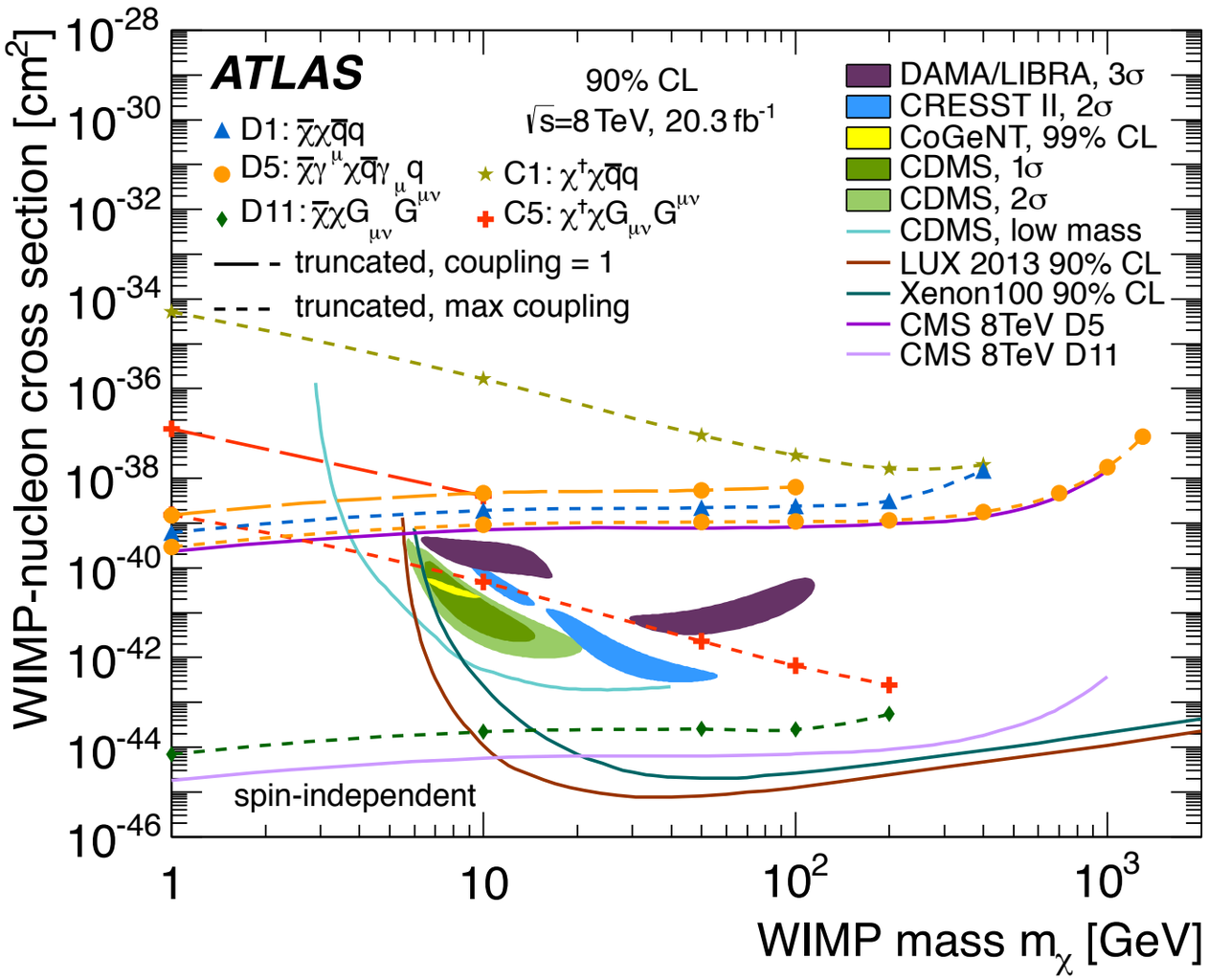
Run I Monojet



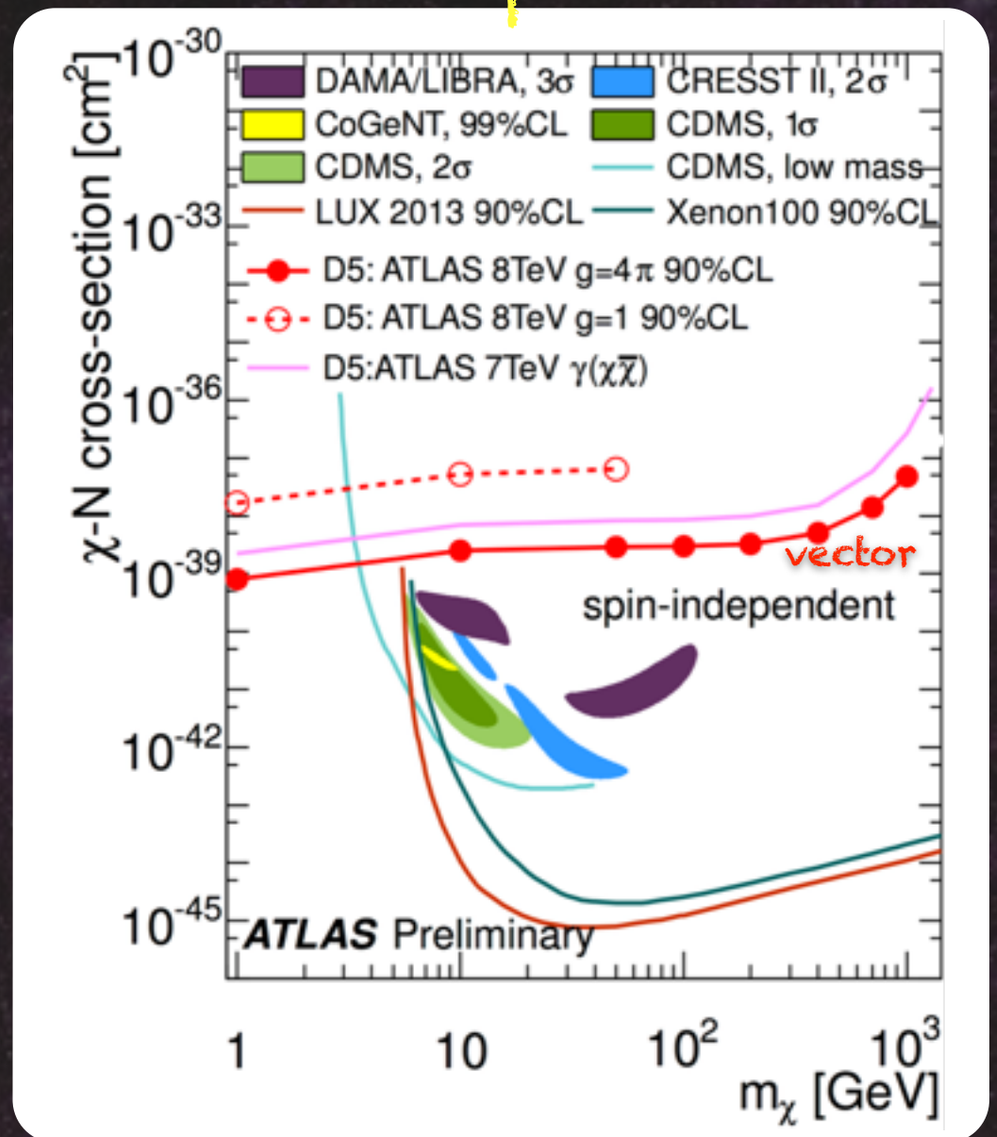
Imperial College London

Mono-X Searches

mono-jet



mono-photon

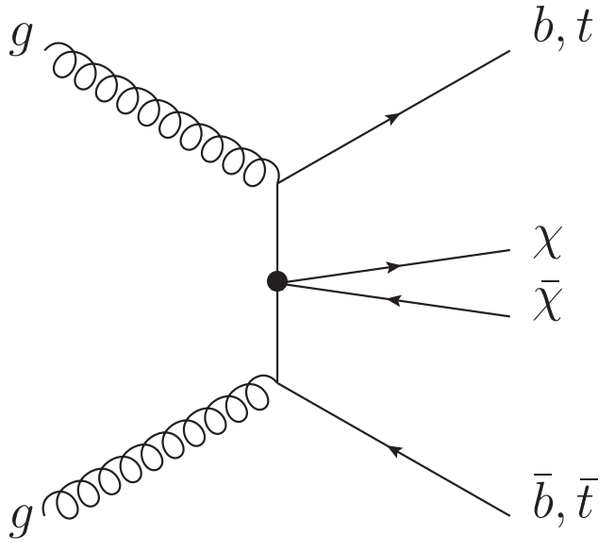


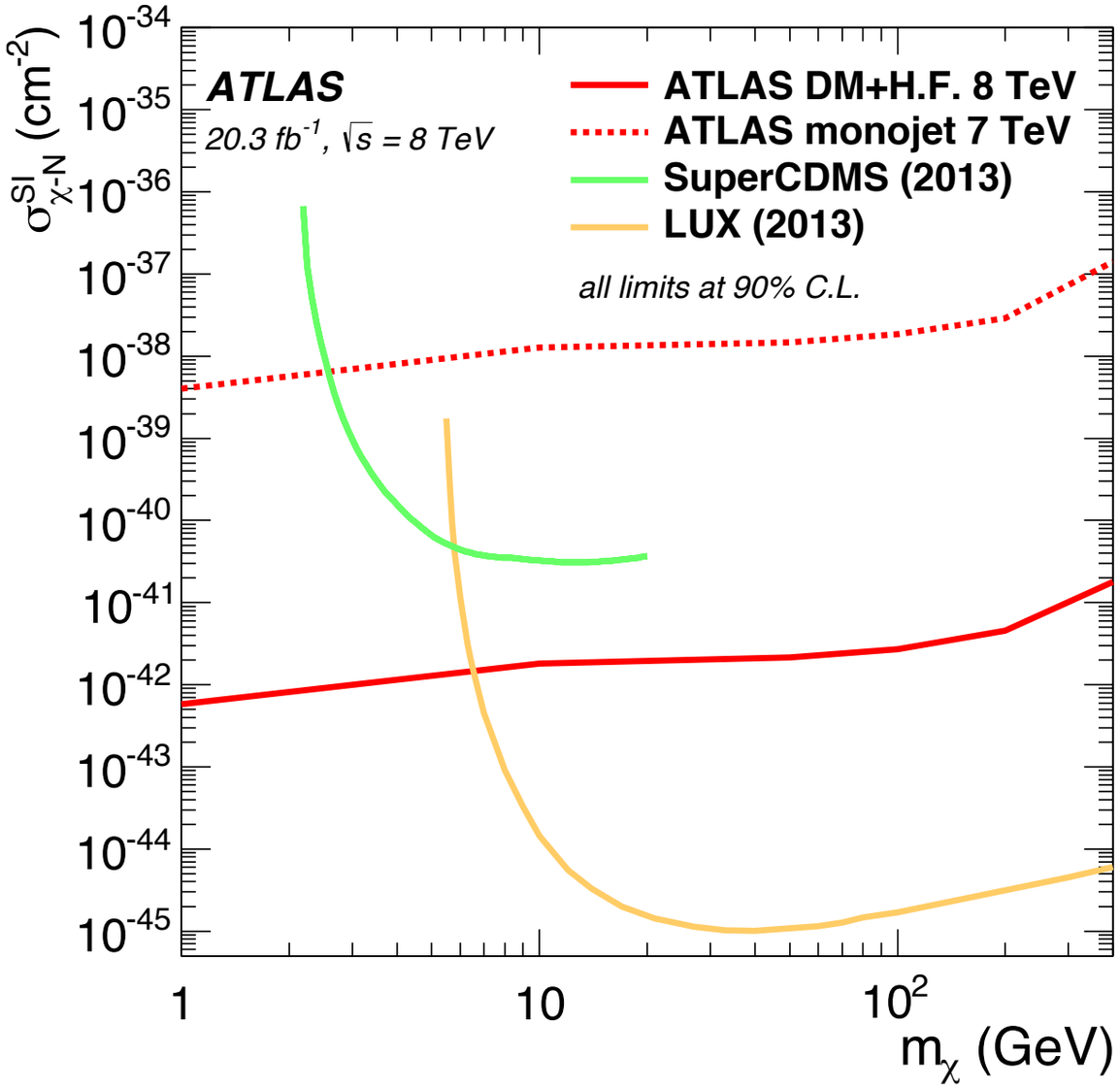
- **Cross sections for mono-photon suppressed** by ratio of strong and electromagnetic fine structure constants as well as a color factor
- **Relative size of excesses** in mono-photon vs. mono-jets is sensitive to whether the operator dominating the signal involves up or down quarks, due to their different electric charges
- Some operators (e.g. gg) **won't produce mono-photon** signals

Imperial College London

DM+HF

- **Monojet** provide **most powerful LHC DM limits** currently
  - **Mono-photon** & **mono-W/Z** probe more specific coupling



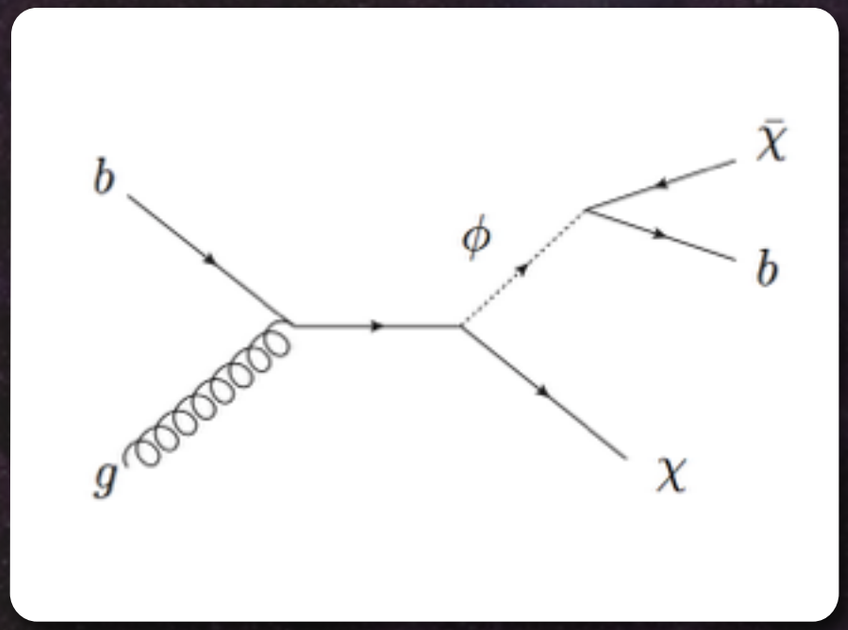


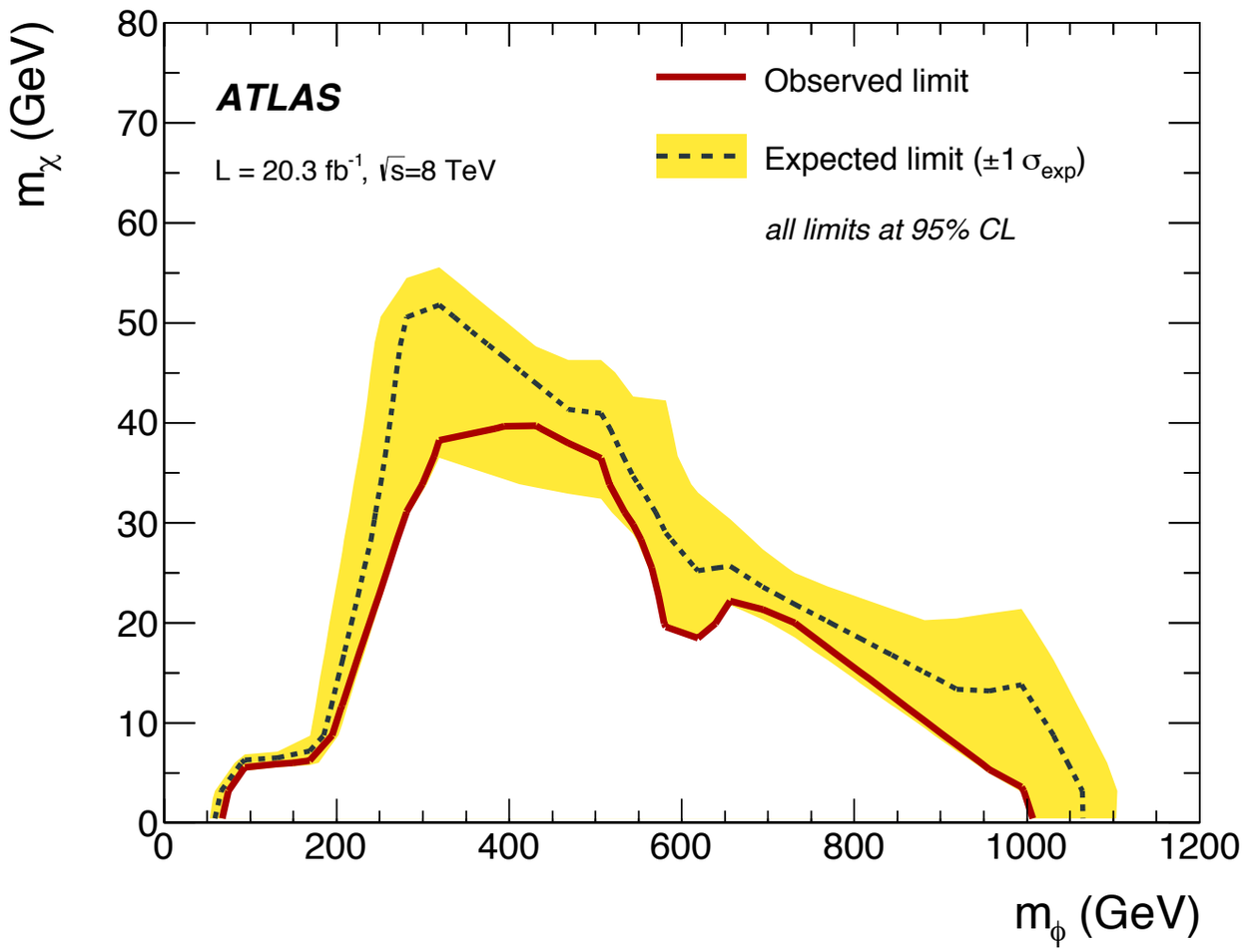
- **Heavy flavor jets**:
  - **Third generation couples enhanced** for given couplings
  - Access **more inclusive** final states, probe particular set of couplings

Imperial College London

DM+HF

- **Monojet** provide **most powerful LHC DM limits** currently
  - **Mono-photon** & **mono-W/Z** probe more specific coupling

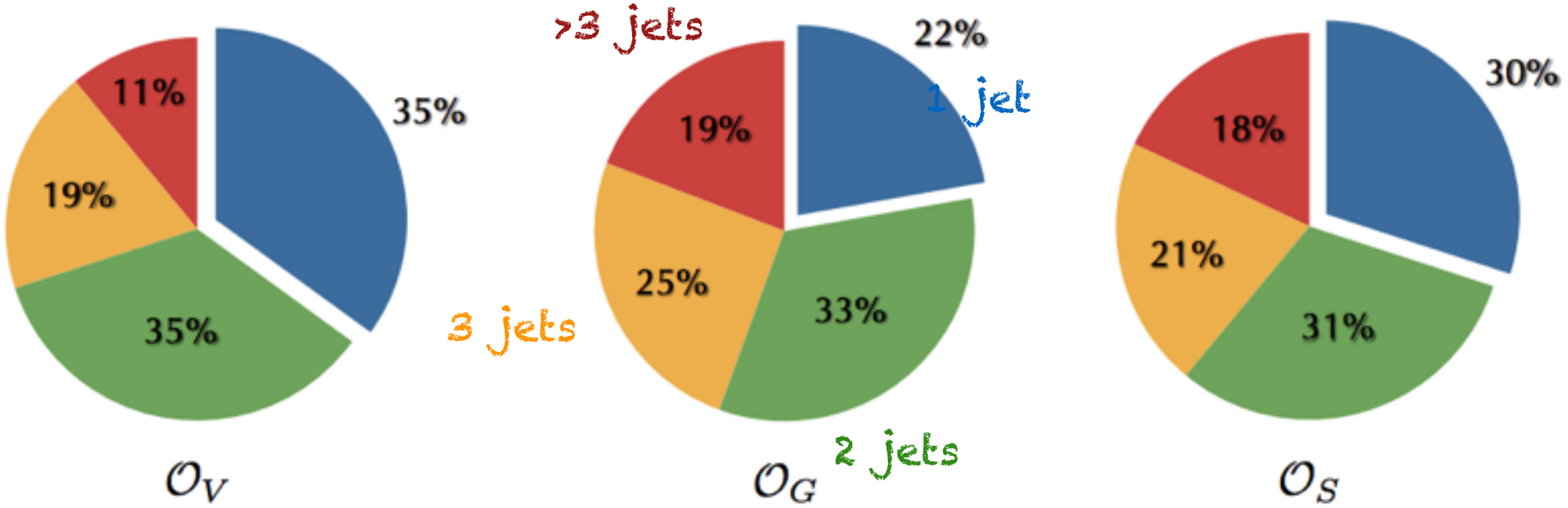




First simplified model, first search for GC excess

- **Heavy flavor jets**:
  - **Third generation couples enhanced** for given couplings
  - Access **more inclusive** final states, probe particular set of couplings

QCD effects on DM searches: 1310.4491



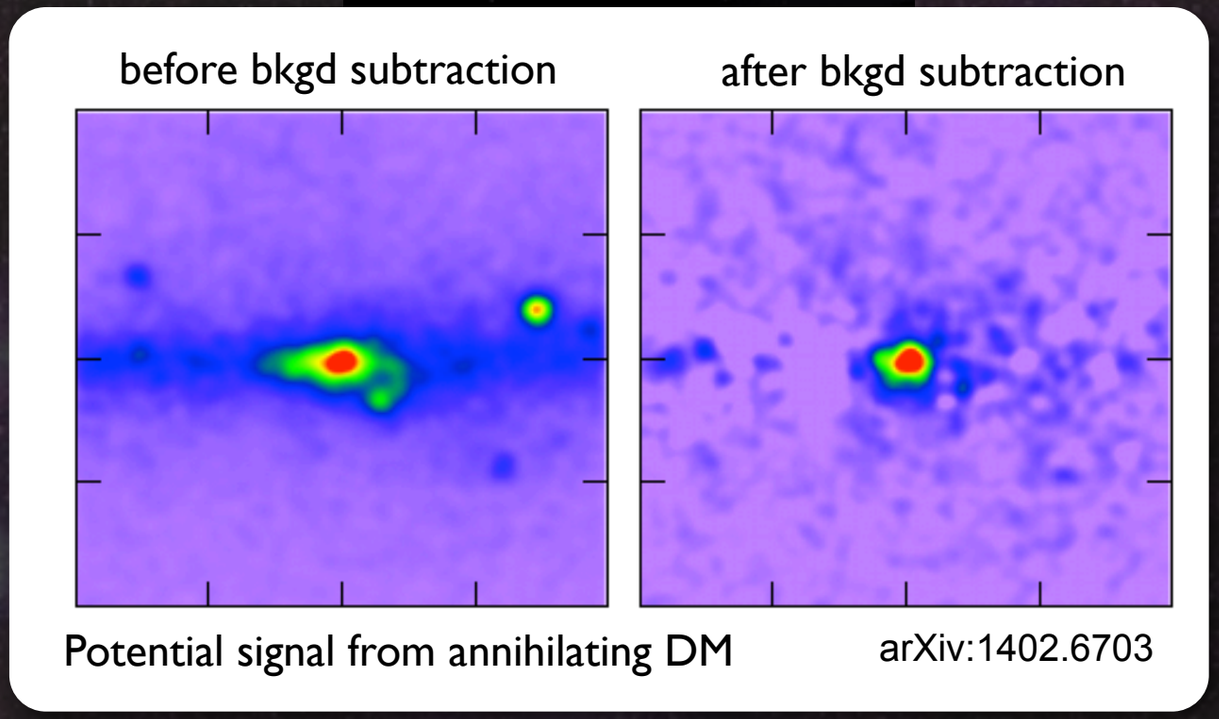
- Vast majority of ‘DM signals’ are **multijet events,** even 1 jet events are likely to radiate soft jet
- **Compare** some **inclusive SUSY analyses with their DM counterpart** for 8 and 13 TeV
- Focus on **fundamental simplified models** and light/heavy jets in **all-hadronic final** states

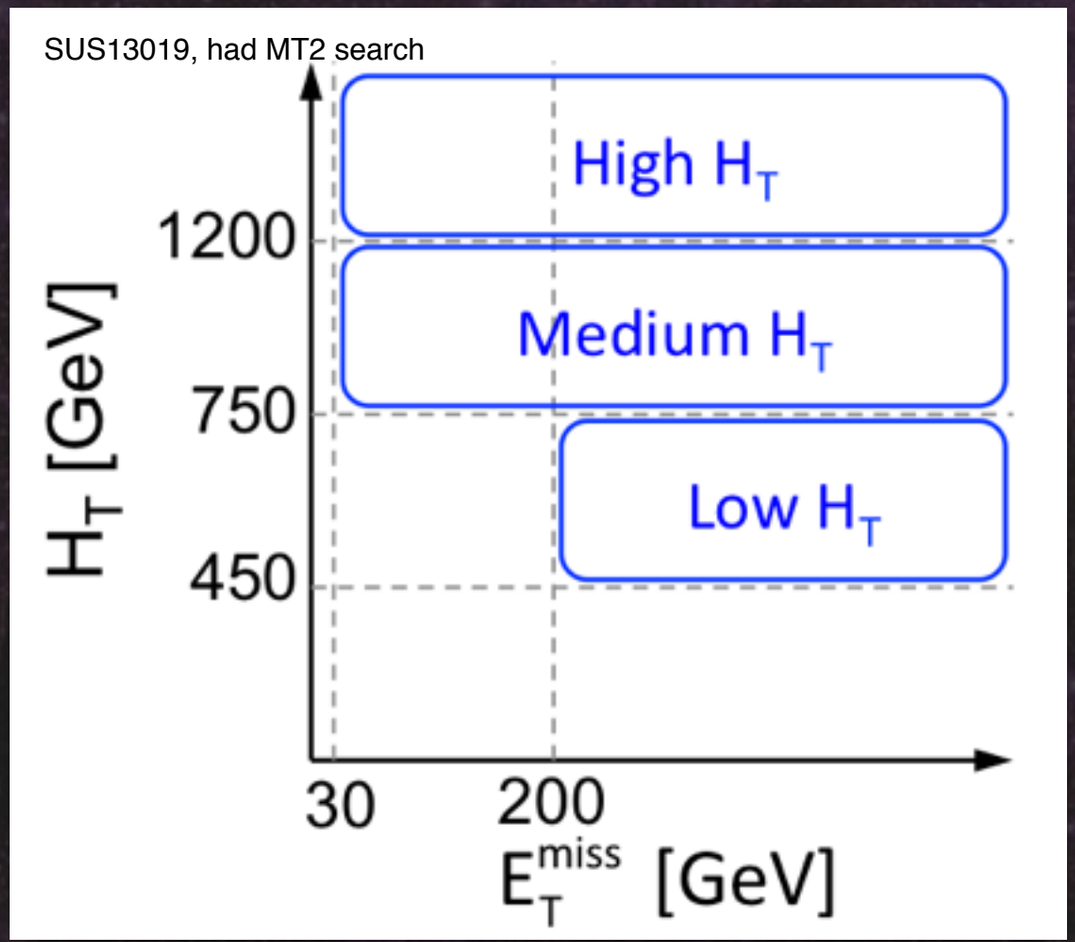
Imperial College London

8 TeV multijet example

Sensitivity for GC with 8 TeV data

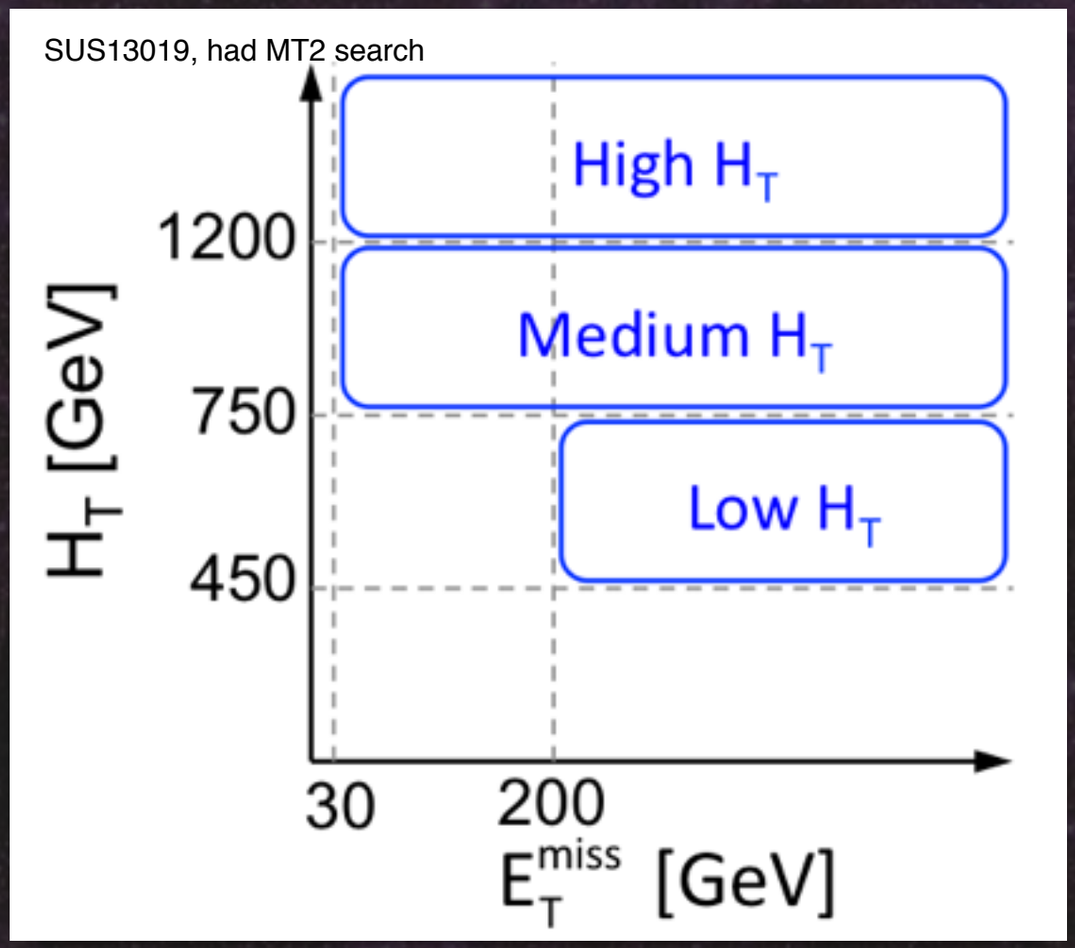
- Many models dominated by gluon fusion → large jet multiplicities
- Inclusive SUSY searches such as aT, MT2, Razor, MHT-HT place fewer constraints on phase space

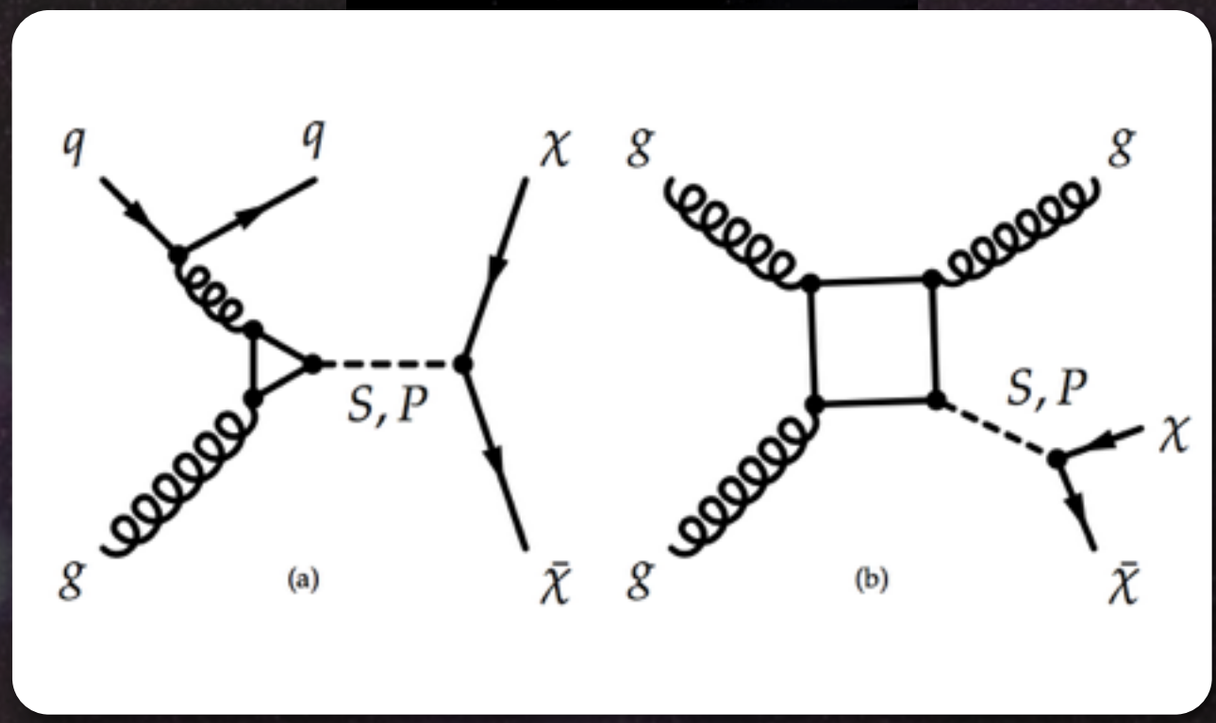




Sensitivity for GC with 8 TeV data

- Many models dominated by **gluon fusion → large jet multiplicities**
- Inclusive SUSY searches such as **aT, MT2, Razor, MHT-HT** place fewer constraints on phase space



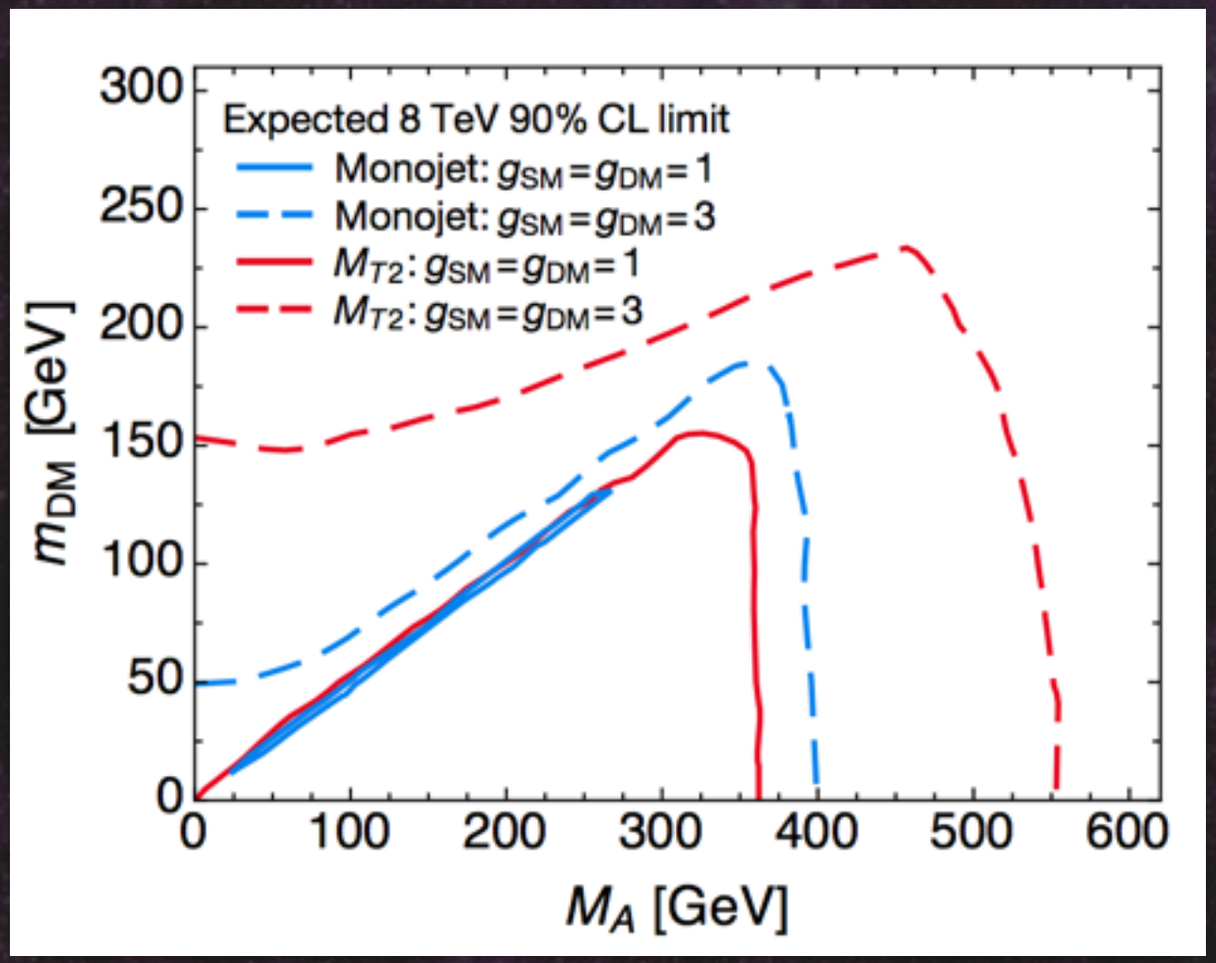


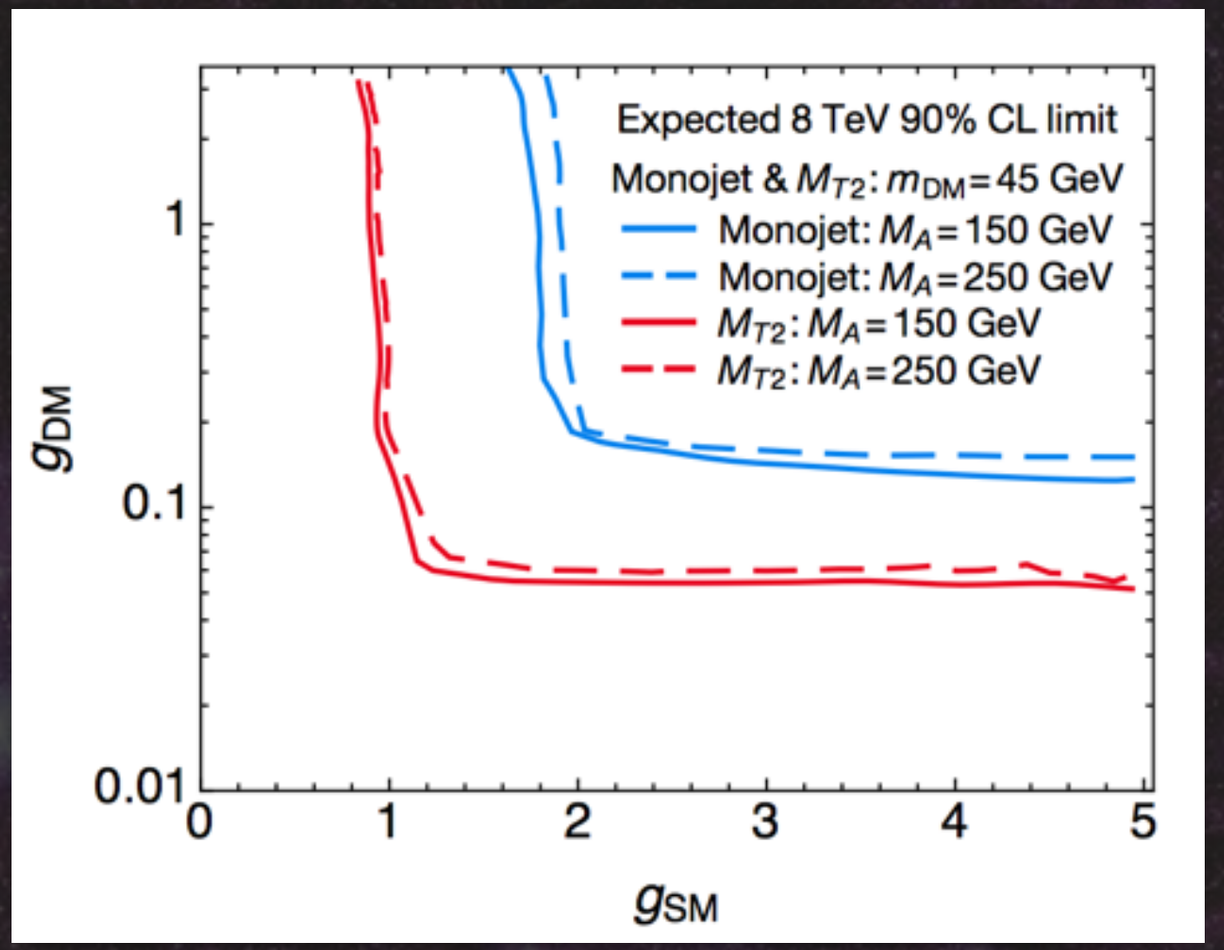
- Example: **pseudoscalar mediator** in **simplifed** model: m_{DM}, m_{Med}, g_{DM}, g_q
- **Monojet searches probe** mostly dominantly resonantly enhanced region: $m_A \sim 2m_{DM}$
- **MT2** search categories are designed so that **final states with differing jet-multiplicity have a similar sensitivity**

Imperial College London

Sensitivity for GC with 8 TeV data

- **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

Imperial College London

13 TeV projections

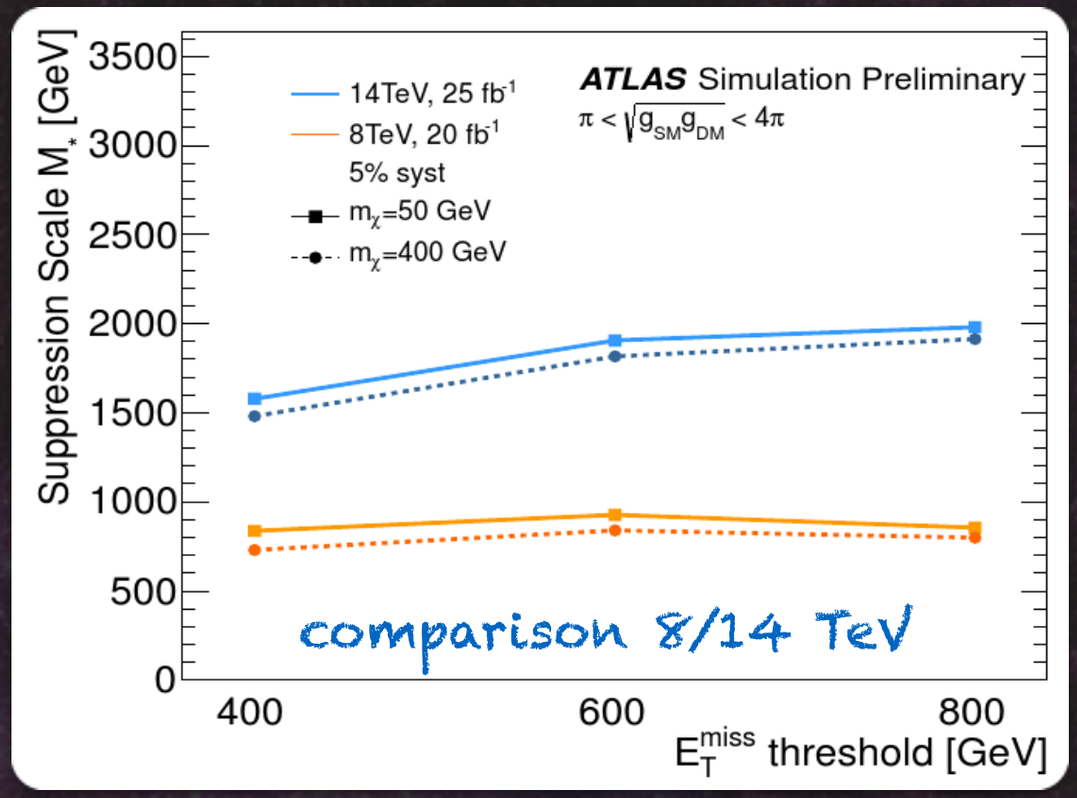
- EFT
- Multijet

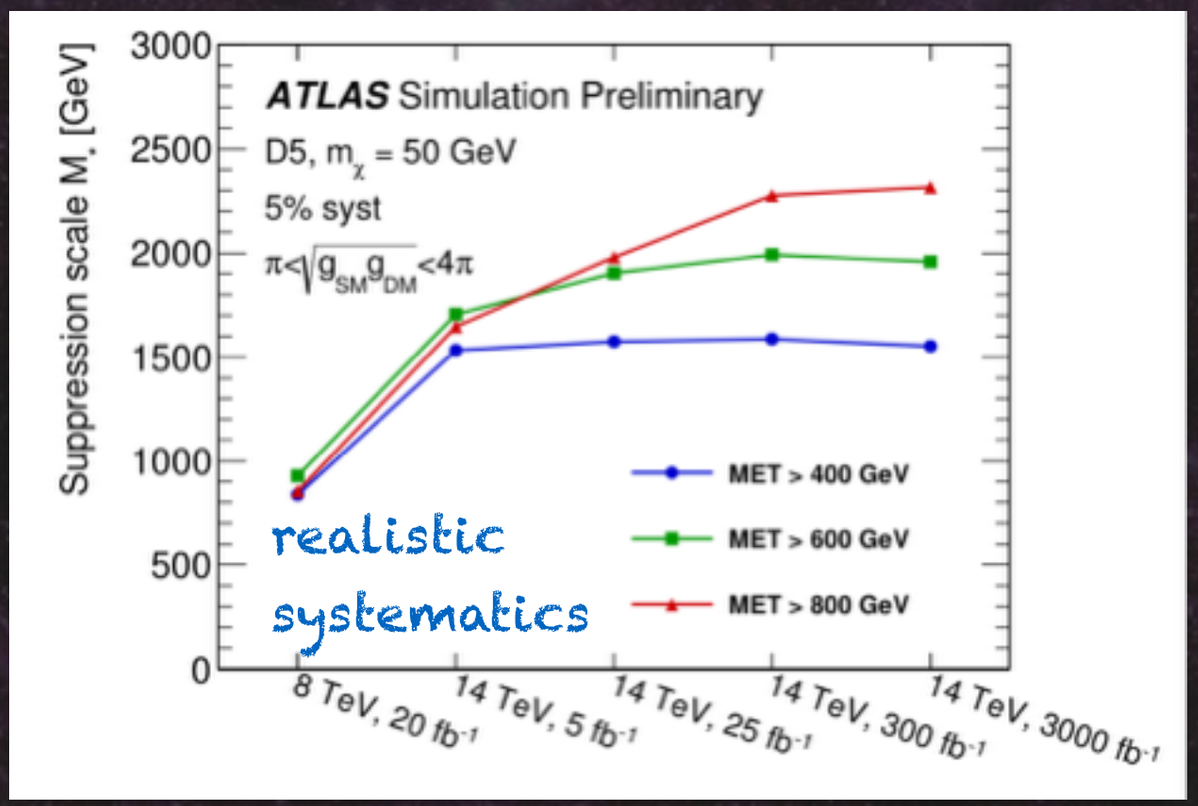
Imperial College London

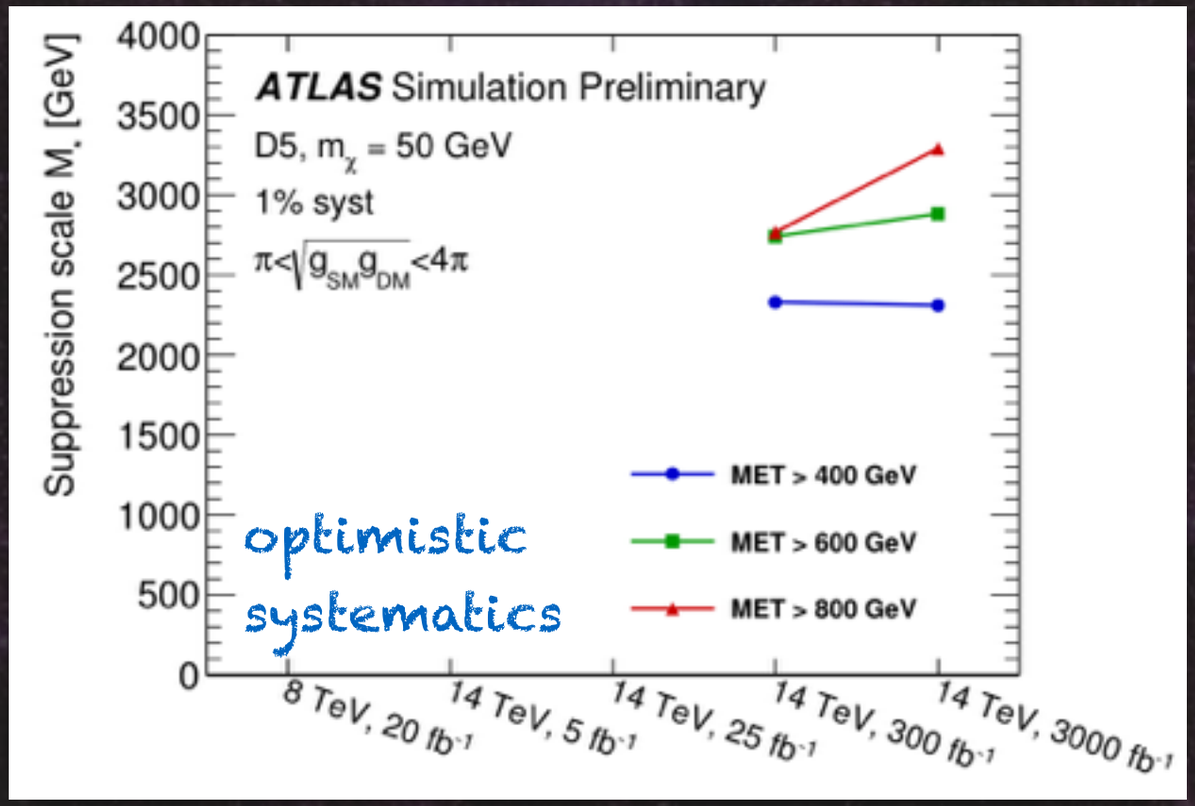
EFT projections

ATLAS-PHYS-PUB-2014-007

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





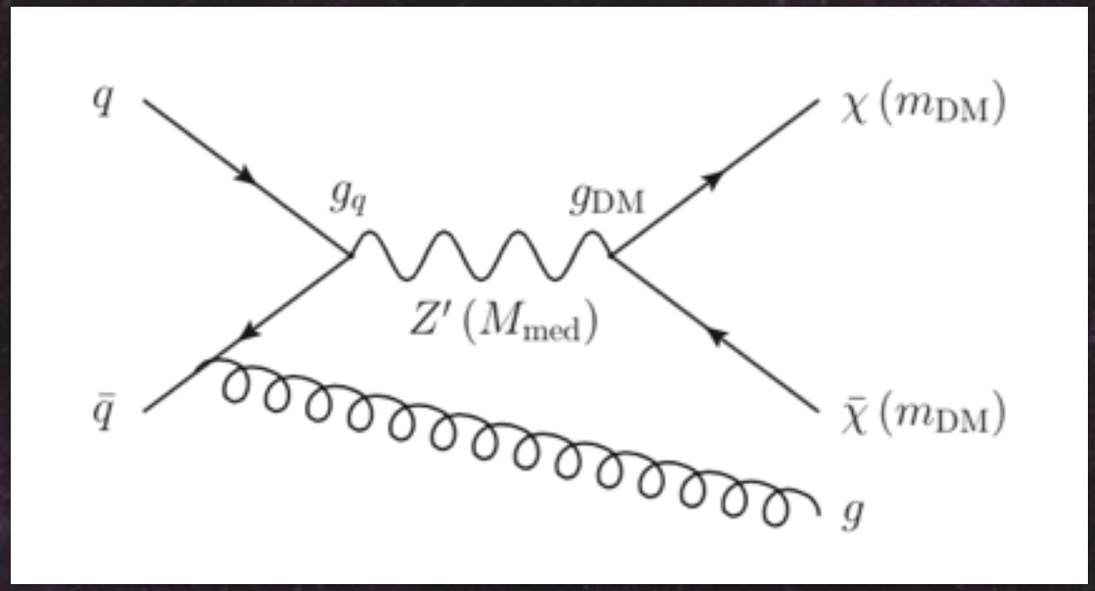


Imperial College London

Simplified Models

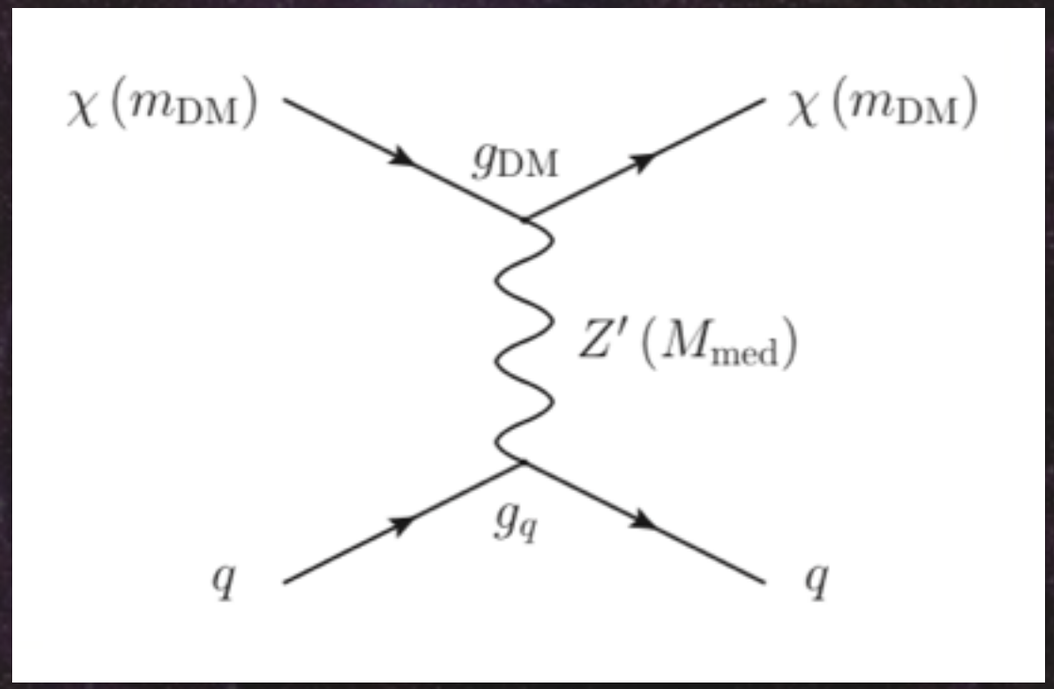
arXiv:1407.8257
Buchmueller et al

- Moving to **simplified models**
- 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**



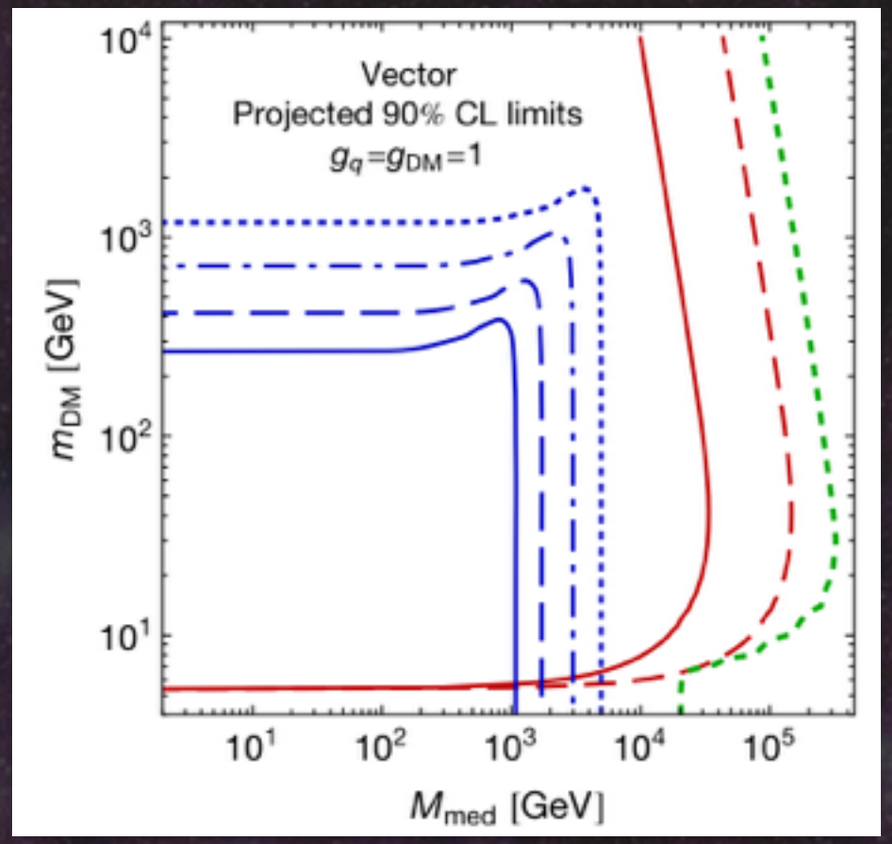
Direct Detection

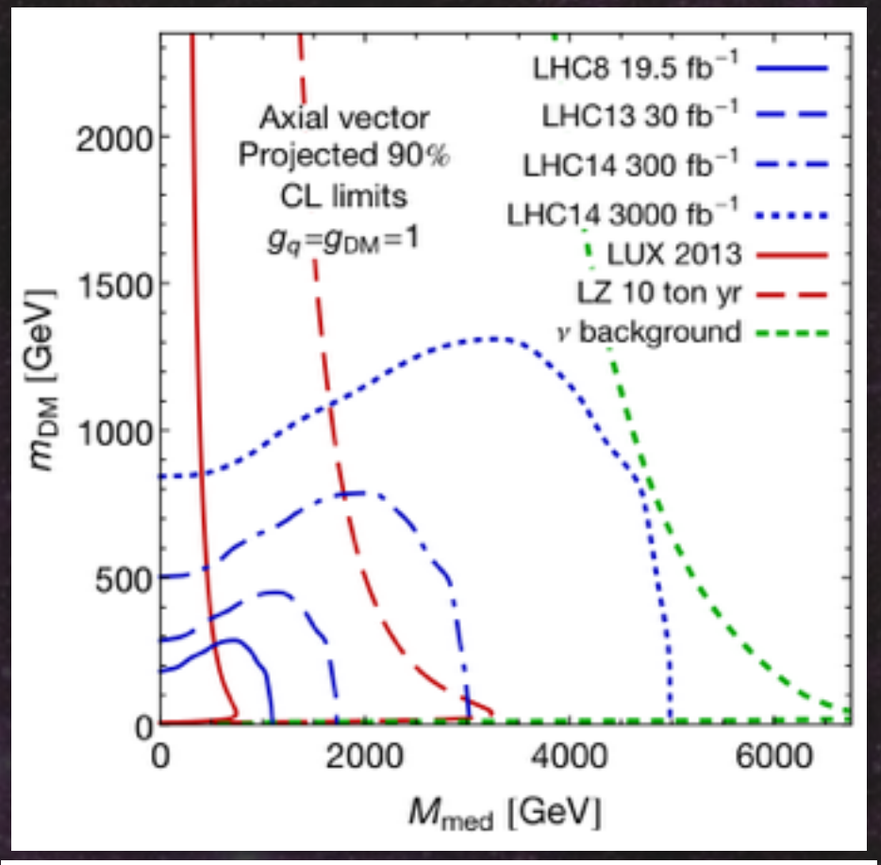
Imperial College London

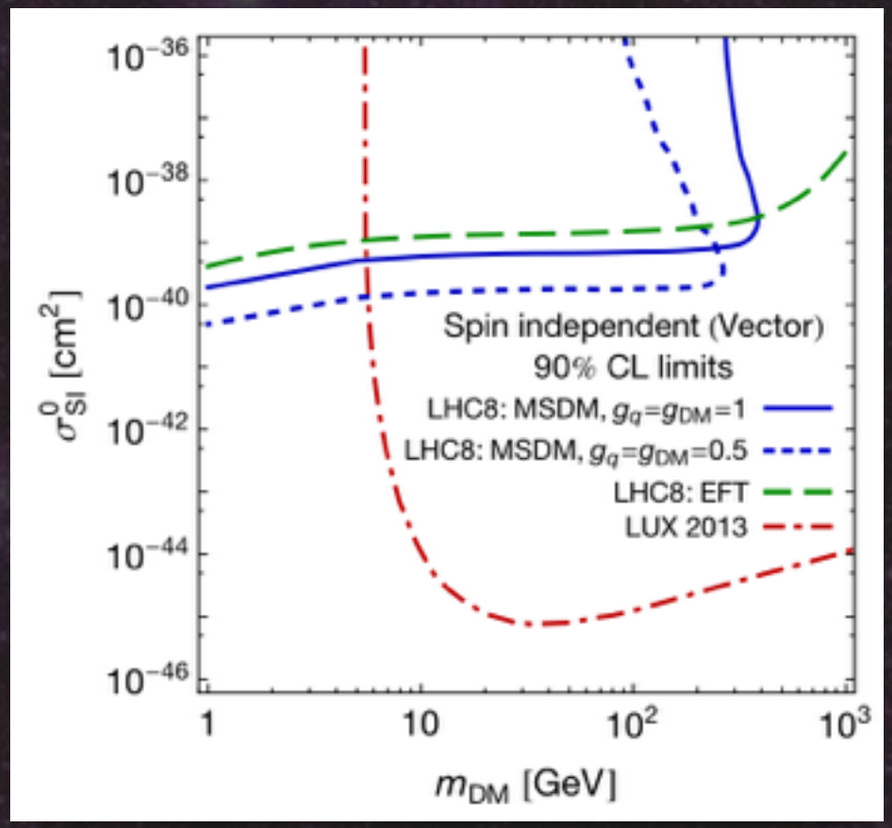
Simplified Models

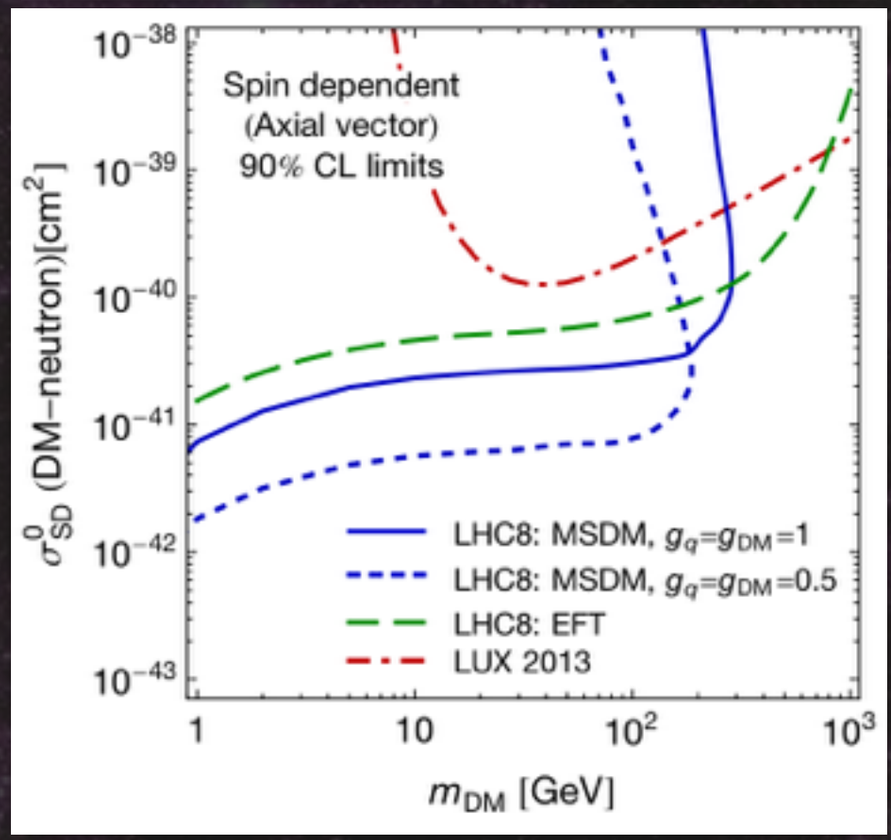
arXiv:1407.8257
Buchmueller et al

- **Run II will make large strides** in the parameter space
- **HL-LHC** reaches **impressive sensitivity**









Imperial College London

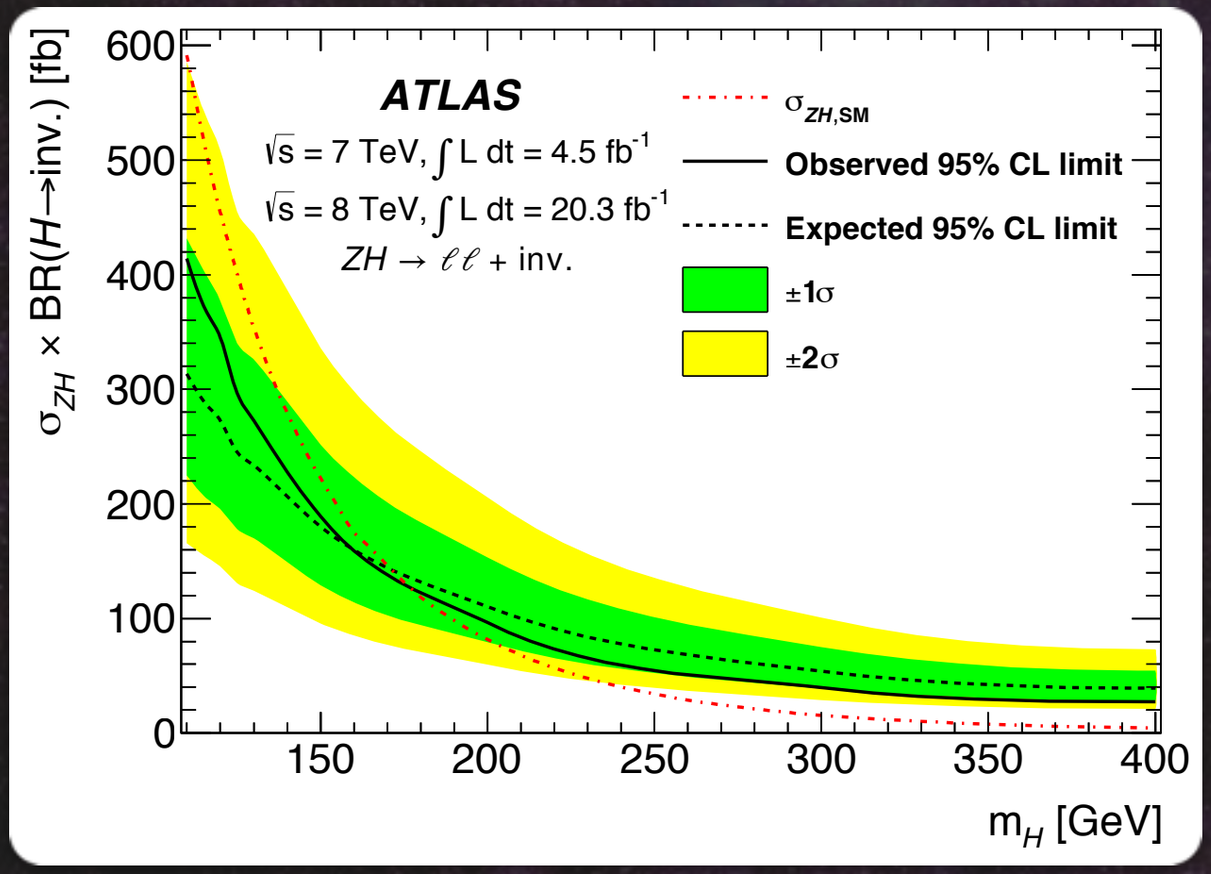
Searching for the mediator

Imperial College London

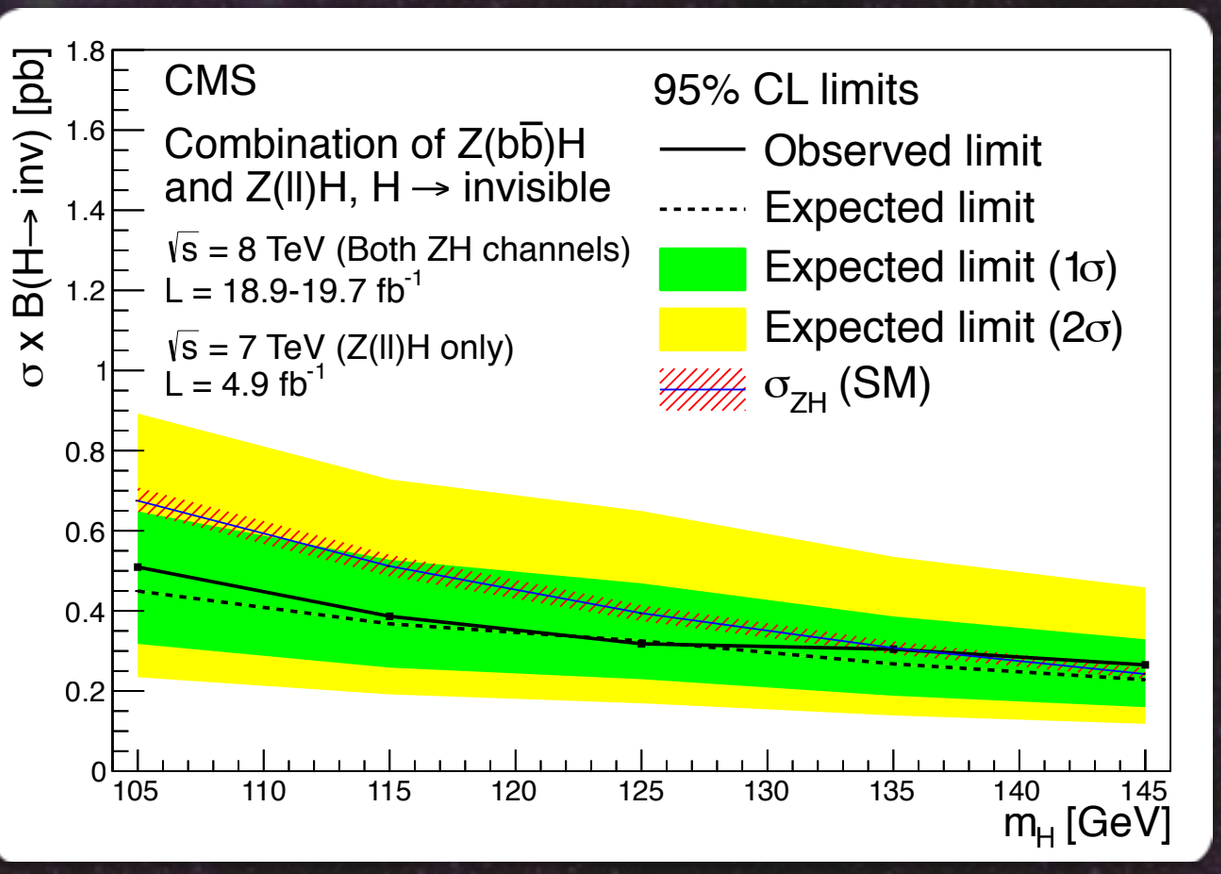
H→inv. Prospects

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.



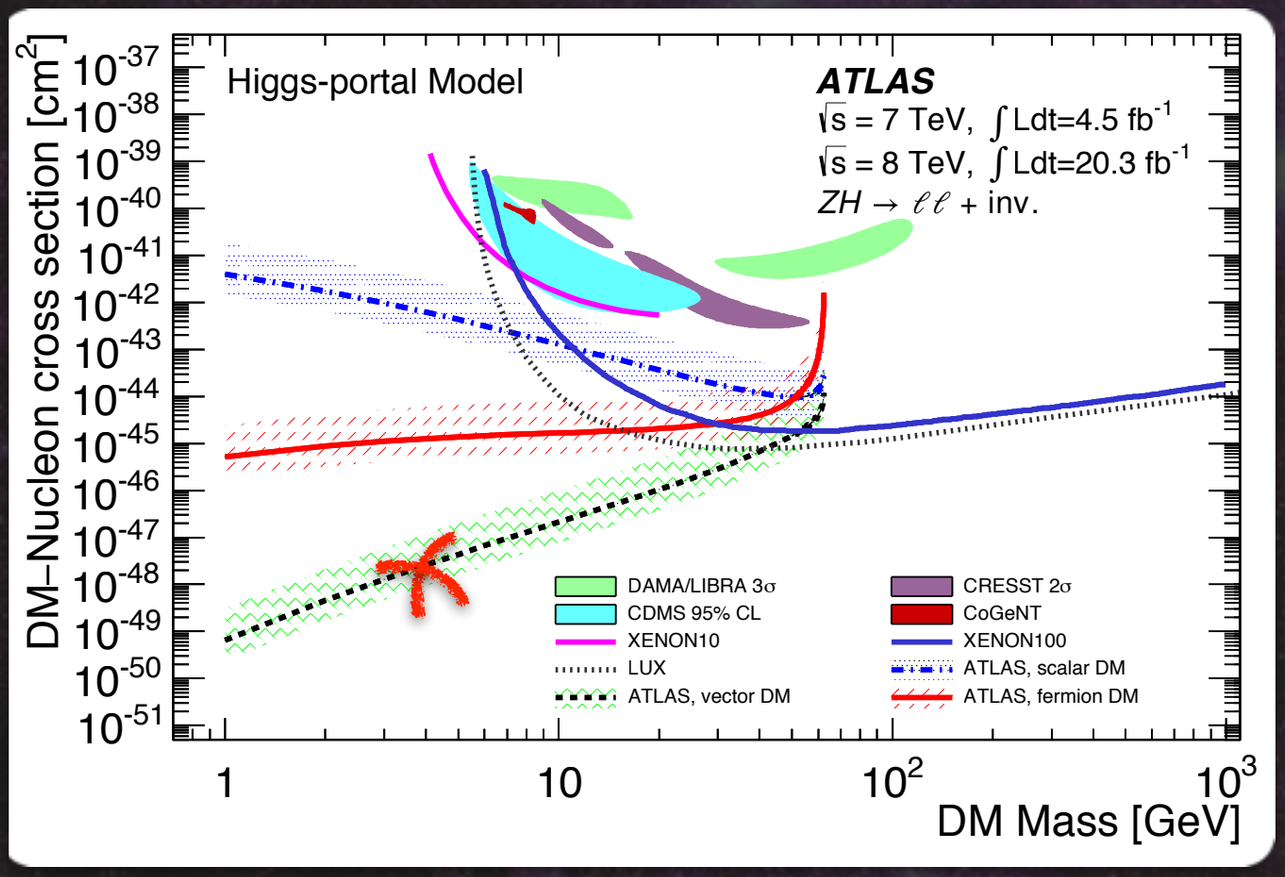
BR(H → inv) < 0.58 (0.44) obs (exp)
@m_H = 125 GeV.

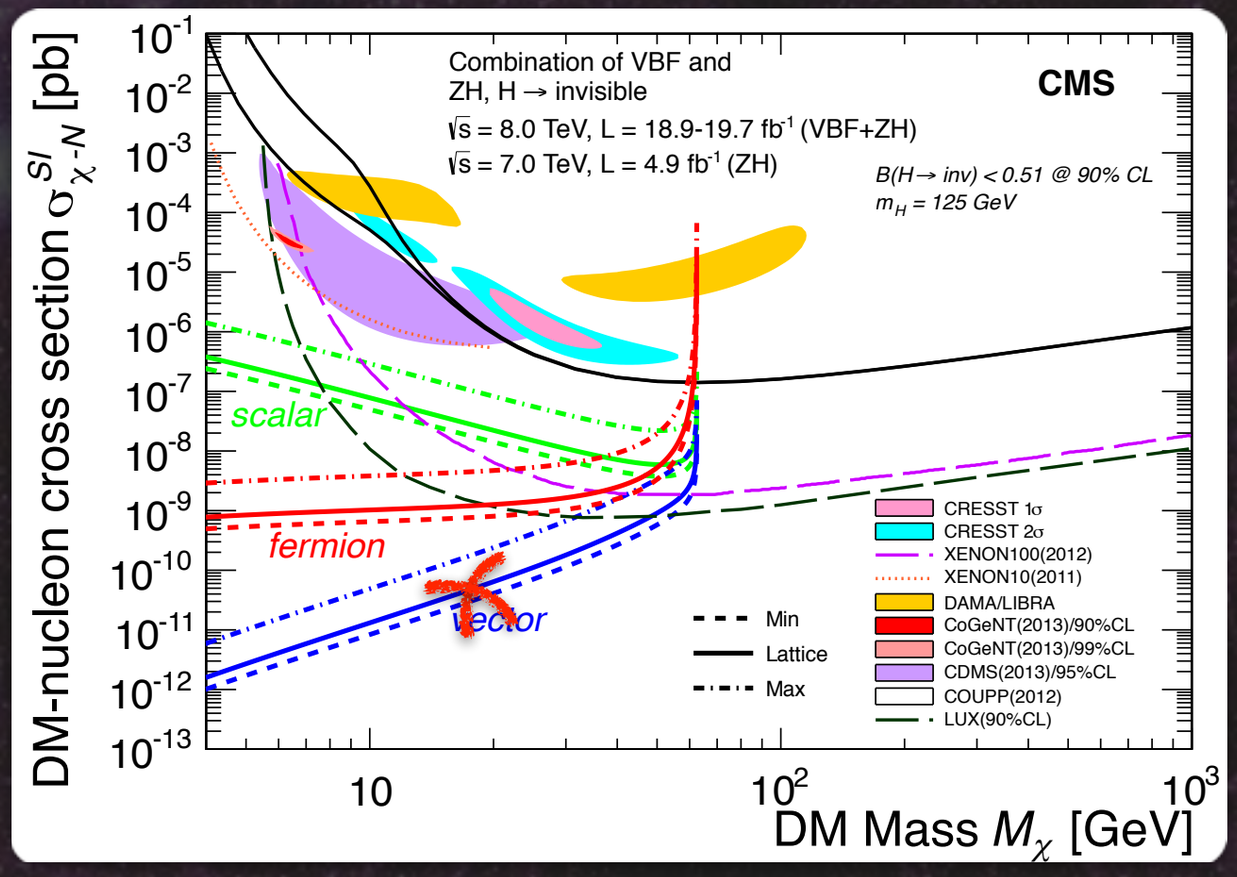
Imperial College London

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





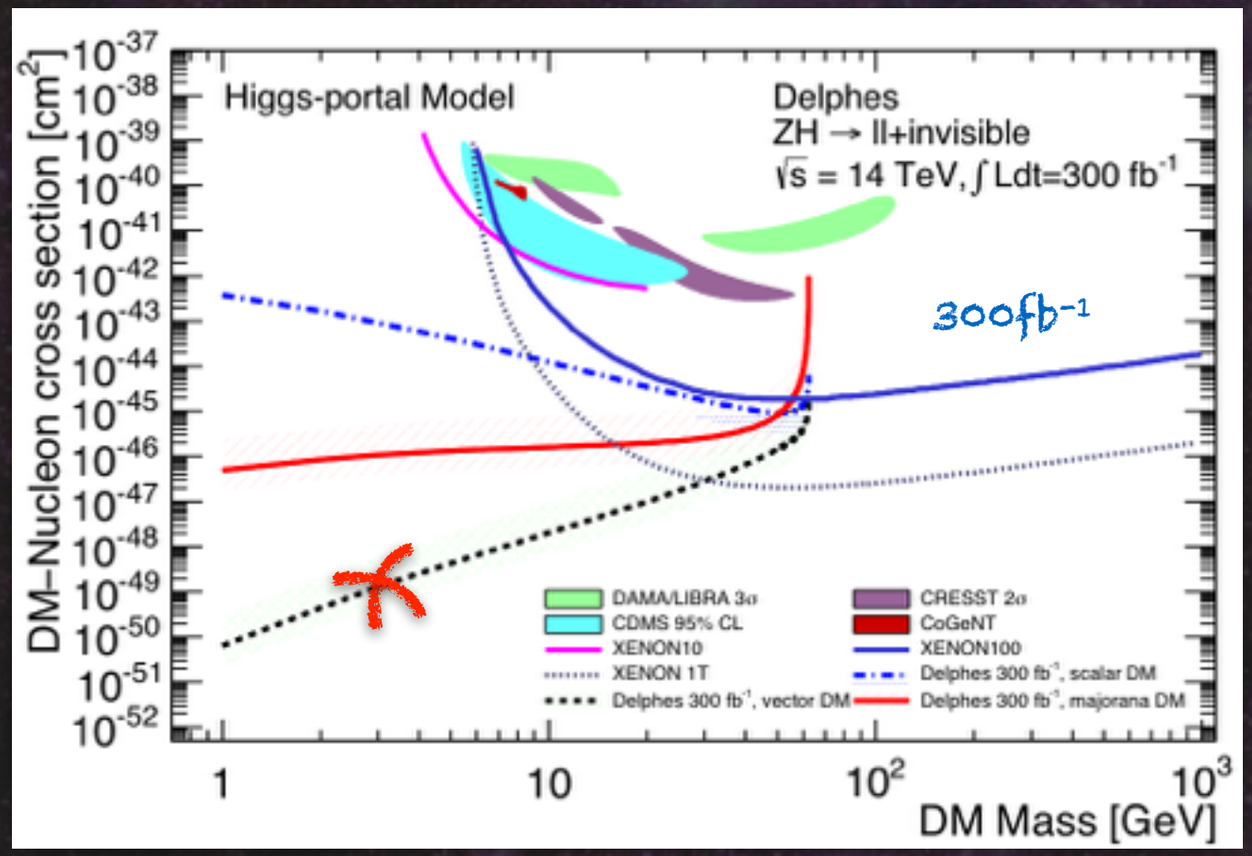
Limits for scalar (fermion) DM:
~ 10^{-41} (10^{-45})cm²

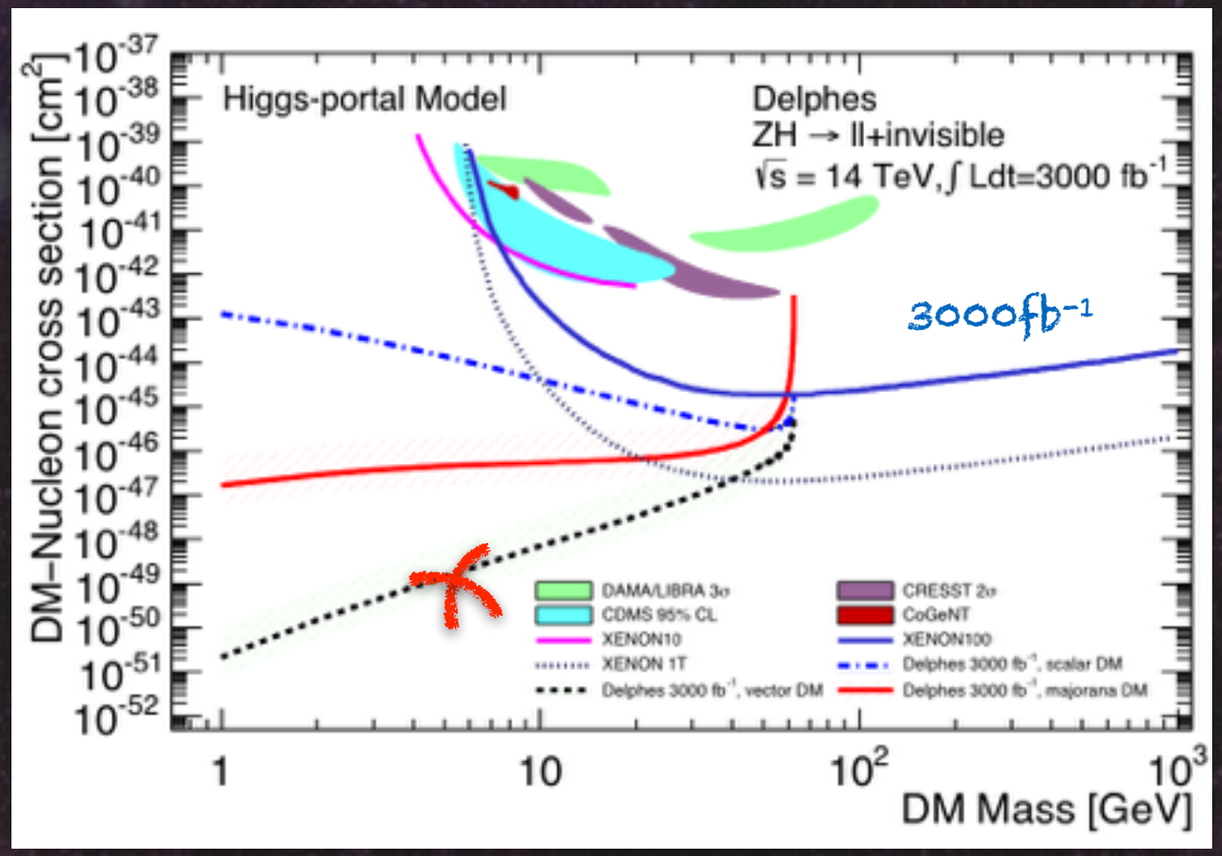
Imperial College London

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



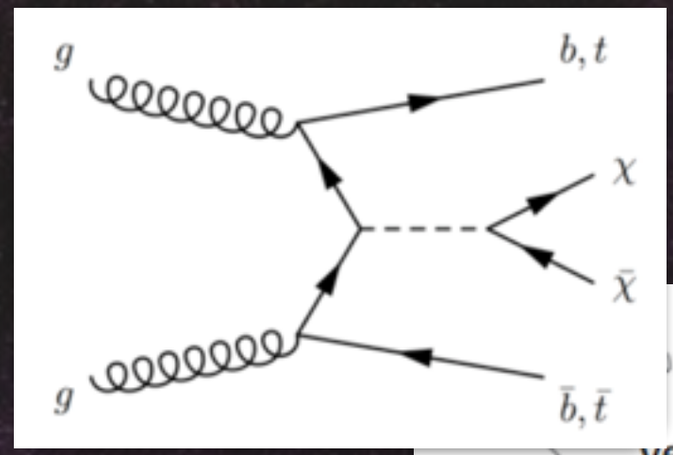


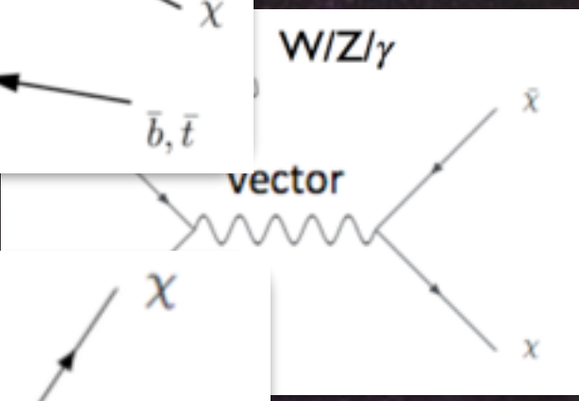
Improvements by two orders of magnitude!

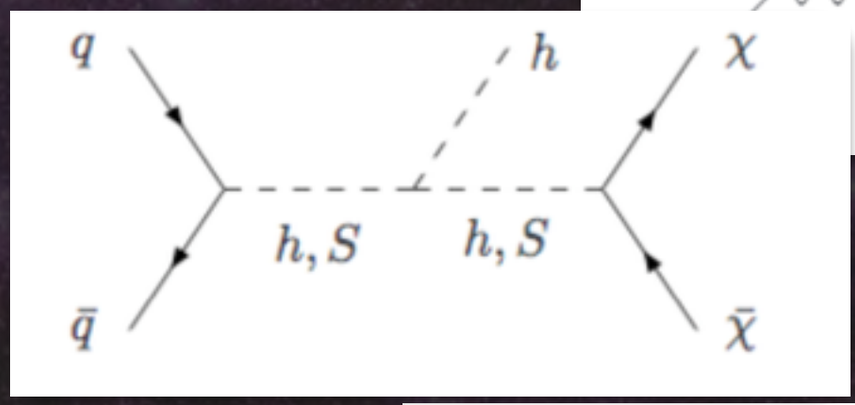
Imperial College London

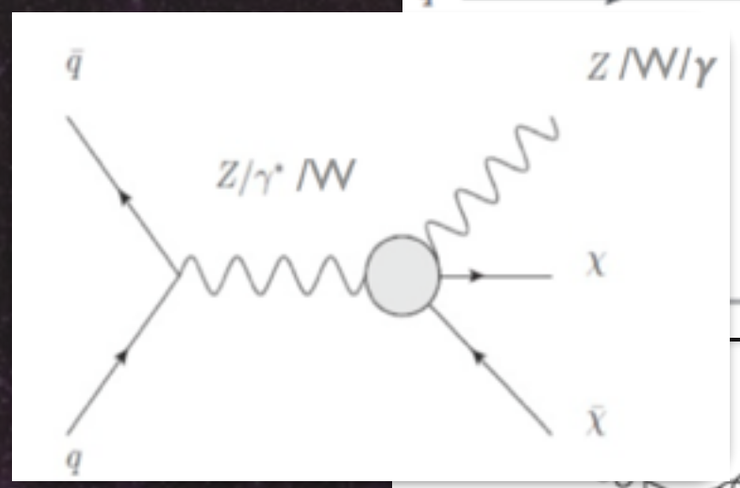
DM Forum

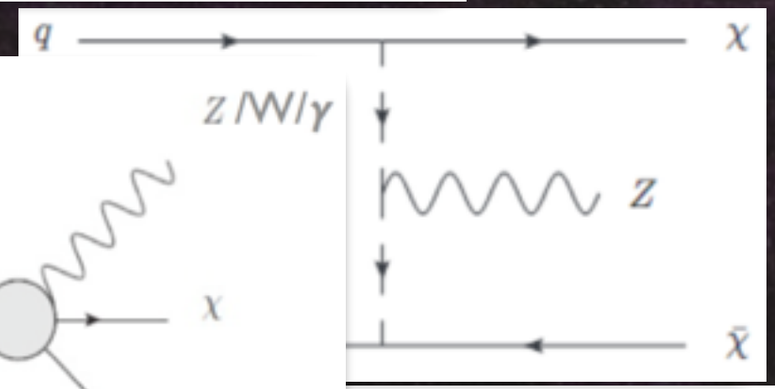
- Successful **ATLAS/CMS/Theory DM Forum** to establish Run II recommendations
- Lead by **C. Doglioni. A. Bovei, S. Mrenna, S. Malik** and active collaboration my many scientists
- Studied models, widths, couplings, astrophysical research, constrains, modeling, generators, practicality, discovery scenarios etc.
- **Final document** soon to be released
- **DM Workshop initiated in Chicago** will go into its 3rd round in Amsterdam
- Much work **still to be done in Run II**
- **Report** to be posted on **Jun 30**

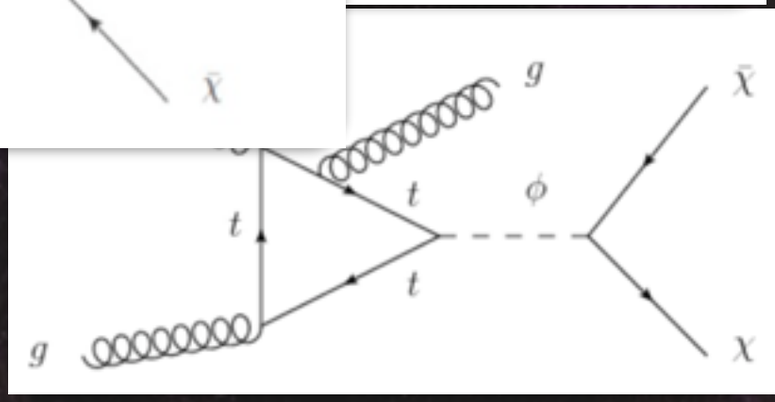








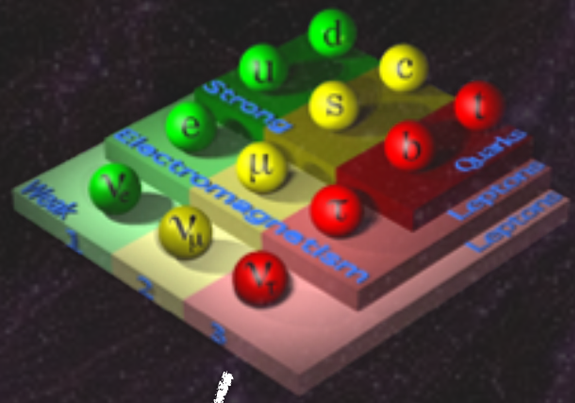


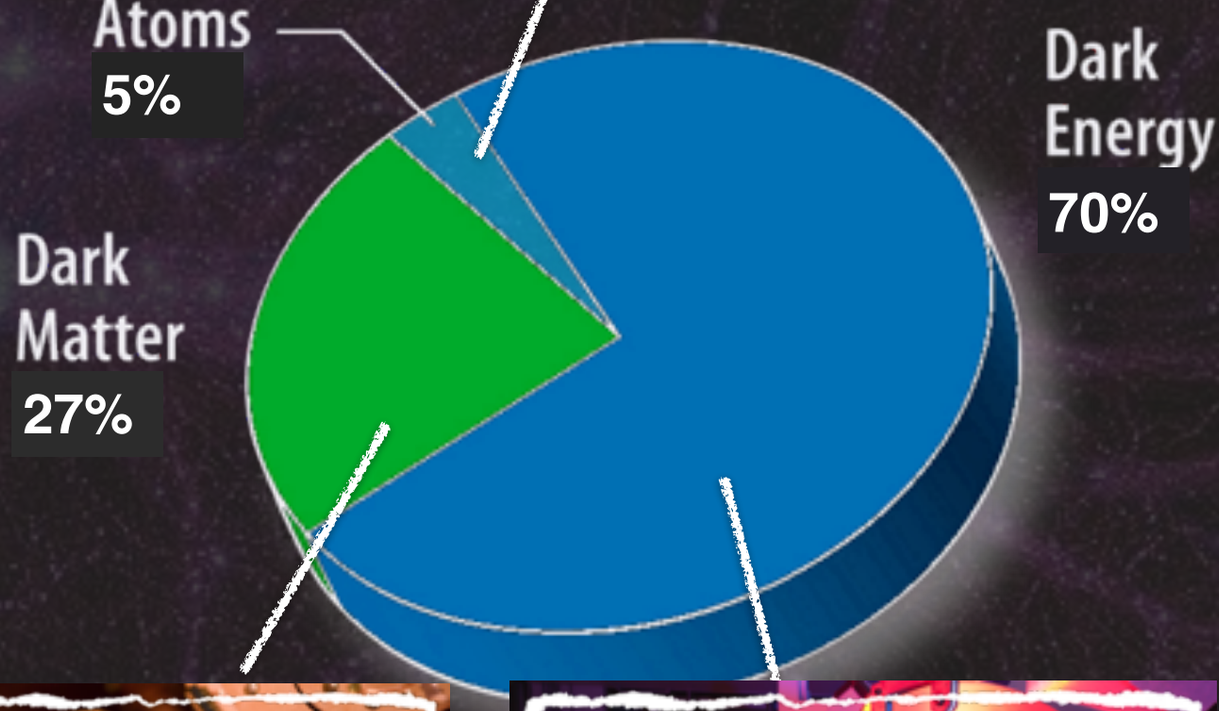


Imperial College London

Conclusion

- **DM searches at collider** are very powerful
  - **Run II** offers **great discovery** potential
  - **Multi-pronged approach**:
    - Mono-jet seraches (Mono-X)
    - Multijet searches
    - Precision measurements (Higgs, Dijet,…)
- **DM can only be discovered in an interdisciplinary effort**
- **Collider provided complementary and unique sensitivity** to direct and indirect searches
- **Exciting and increasingly important developing field**



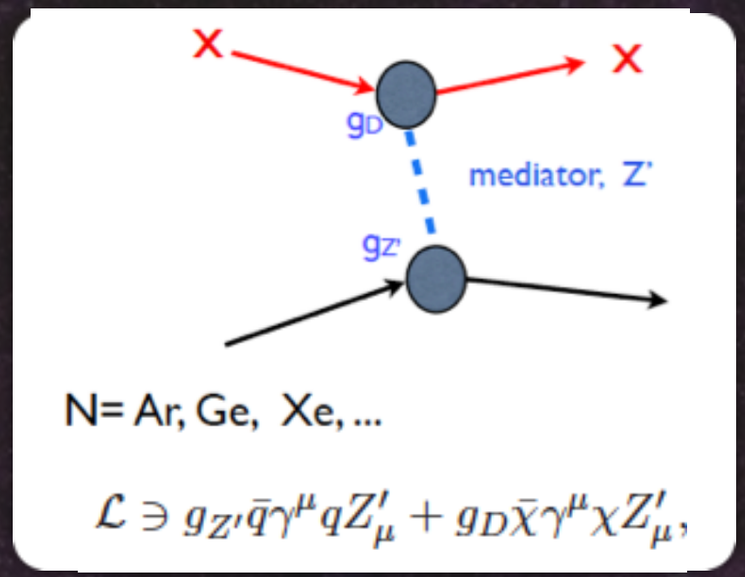
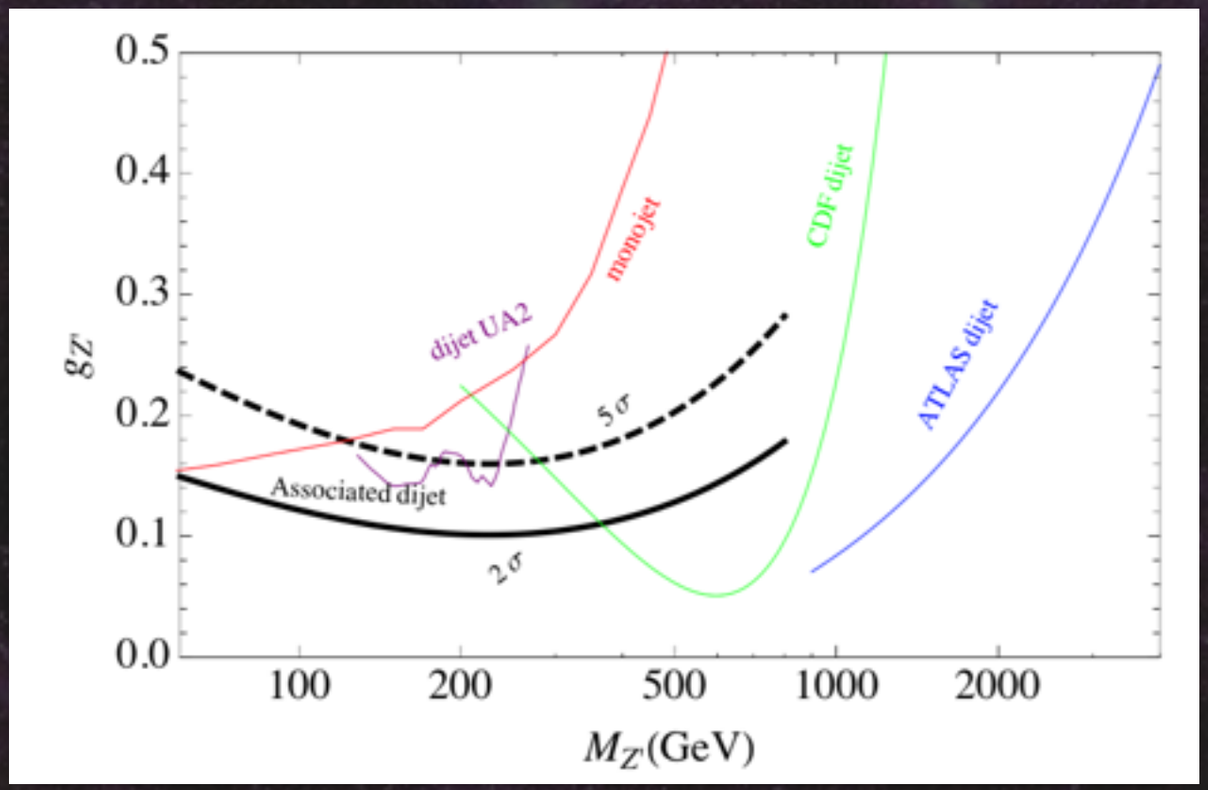
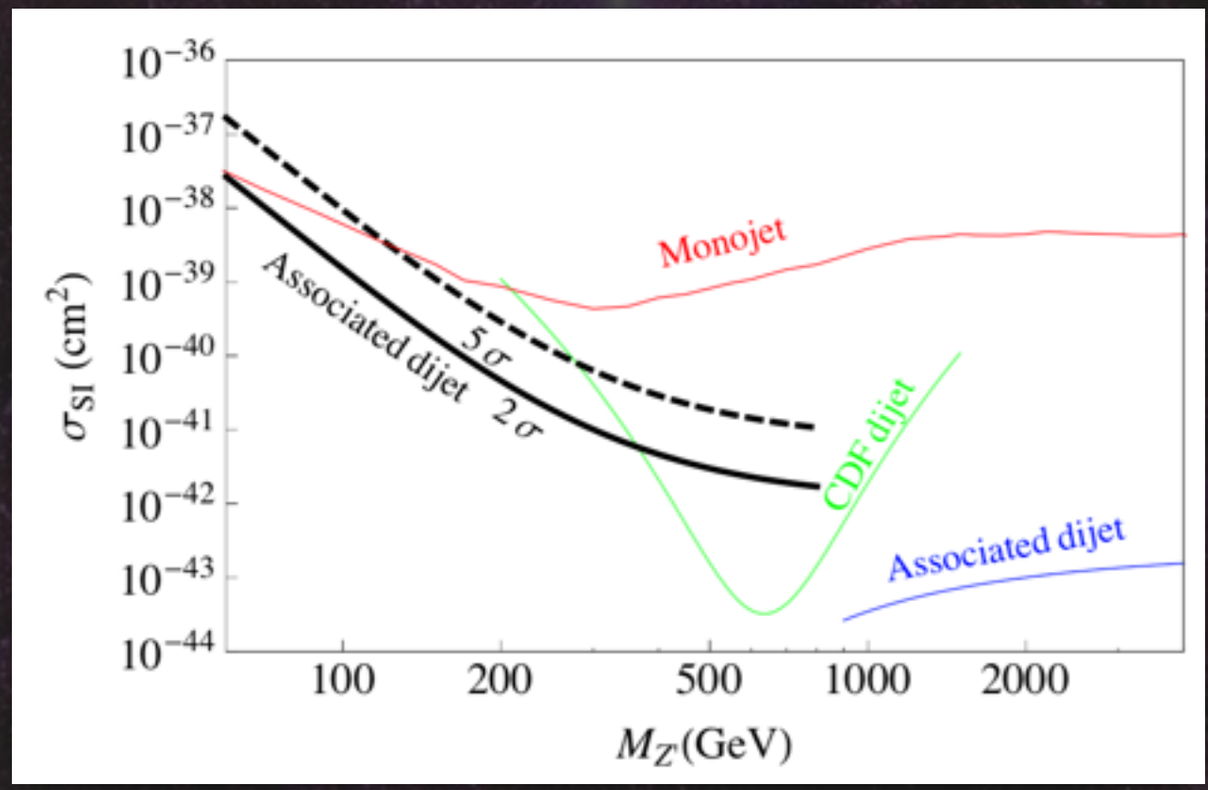


Imperial College London

Backup

Imperial College London

Low Mass Mediators

arXiv:1212.2221
Han et al, L.T.

- Consider **leptophobic Z'** to evade searches for dilepton resonances and obey relic density.
- Dijet mass resonance searches challenging at low M(Z'). **Improve sensitivity by considering associated production modes**: Z'+X (X=jet, γ, W, Z).
- **Monojet and dijet searches complementary**, probing high and low $g_D/g_{Z'}$ respectively.
- Paper assumes 15 fb^{-1} at 8 TeV, **significant potential with LHC Run 2 datasets!**