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Search for Dark Matter with Future Collider

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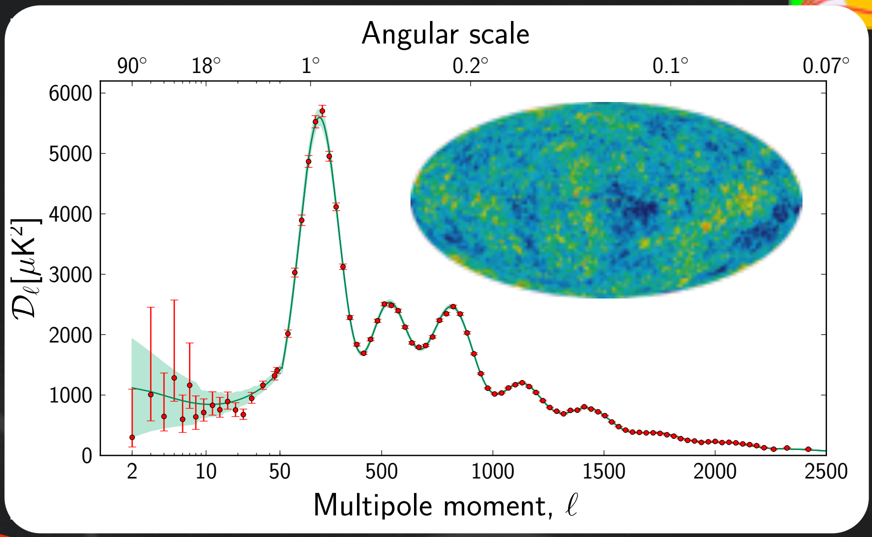
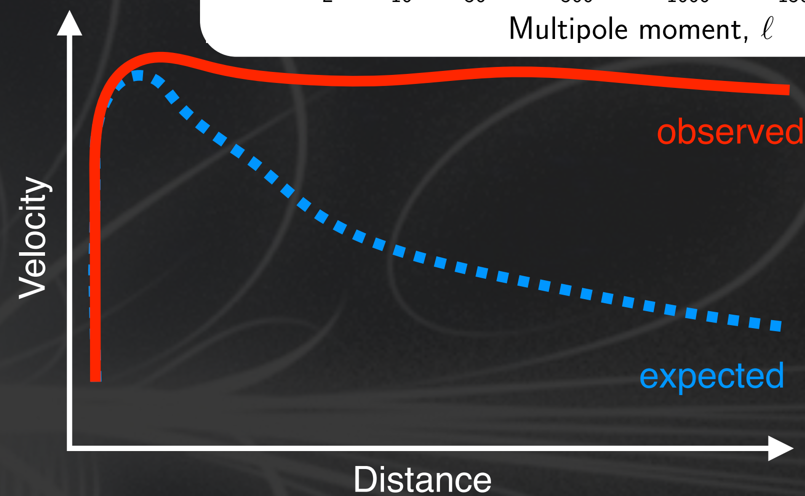
Overview

- DM Overview
- Experimental Setup
- SUSY type DM
- Mono-X & simplified models
- Searching for the Mediator
- Conclusion

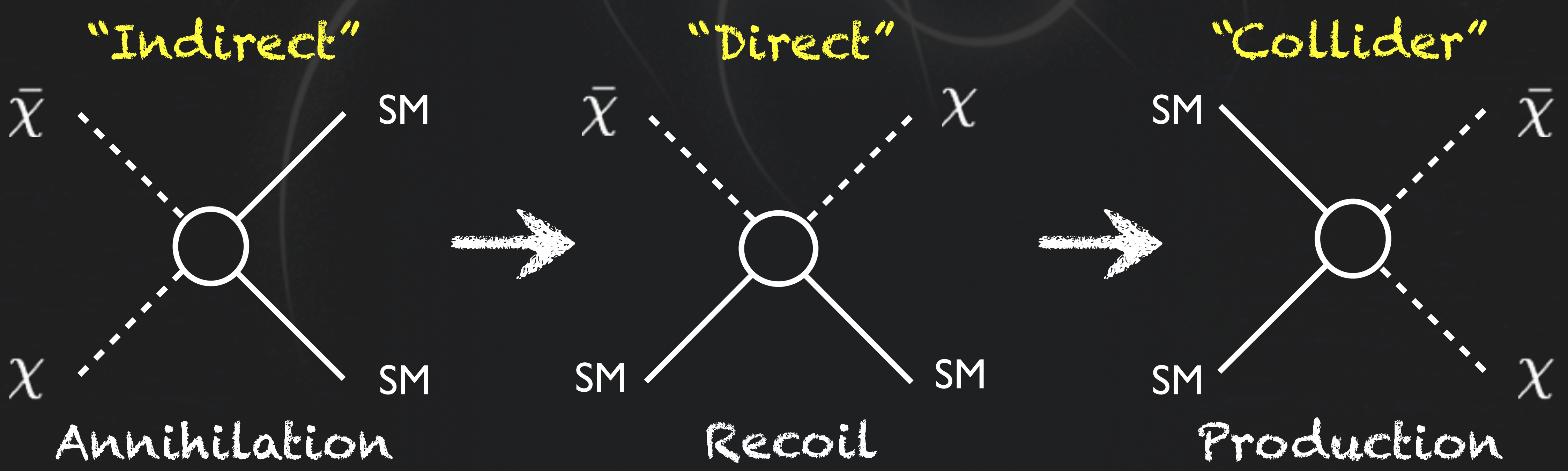
Why looking for DM

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



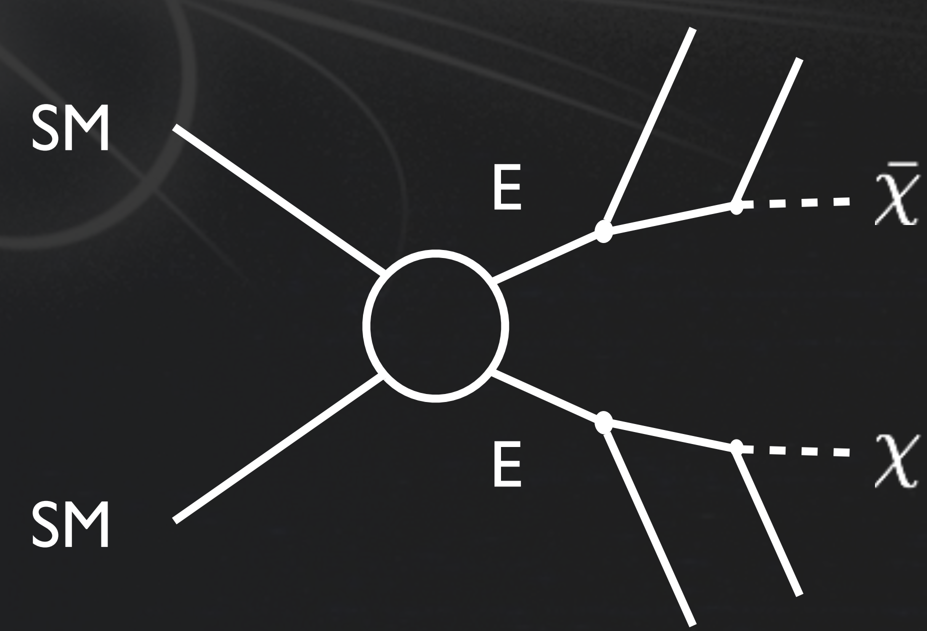


- DM **'non-baryonic cold dark matter'** → **'WIMP Miracle'** → **BSM physics**



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:
  - SM decays to DM: Z→χχ, h→χ, t→cχχ
  - Direct production: χχ+SM
  - Associated production with heavier exotic: χ+E, E→χ+SM
  - Heavy exotic pair production: E+E ; E→χ+SM
  - Exotic resonant decay: E→χχ
  - Heavy metastable exotic E→χ, no decay in detector

Effective Field Theory

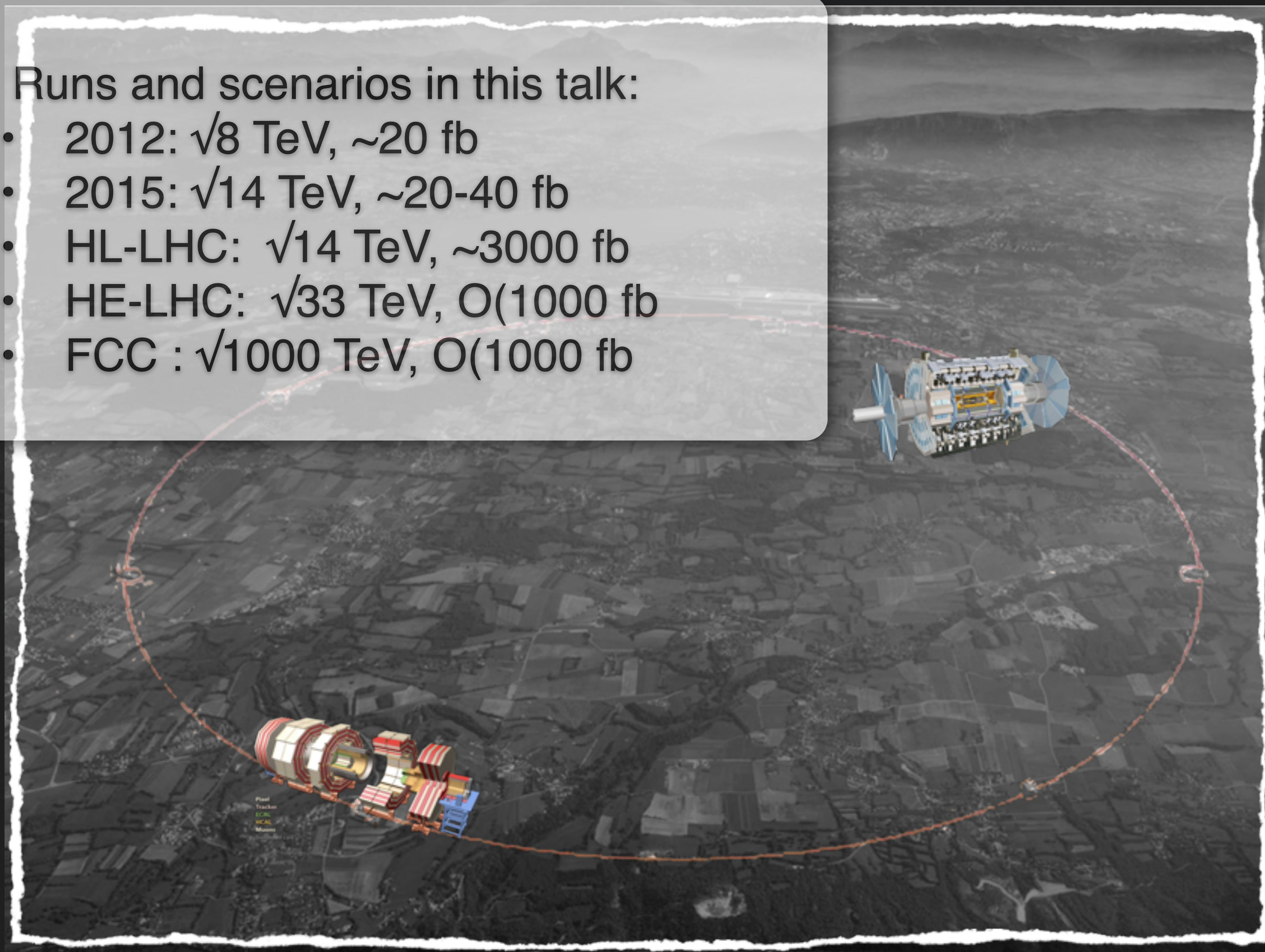
SUSY
Extra Dimensions
Little Higgs..

Dark Sectors

more model dependent

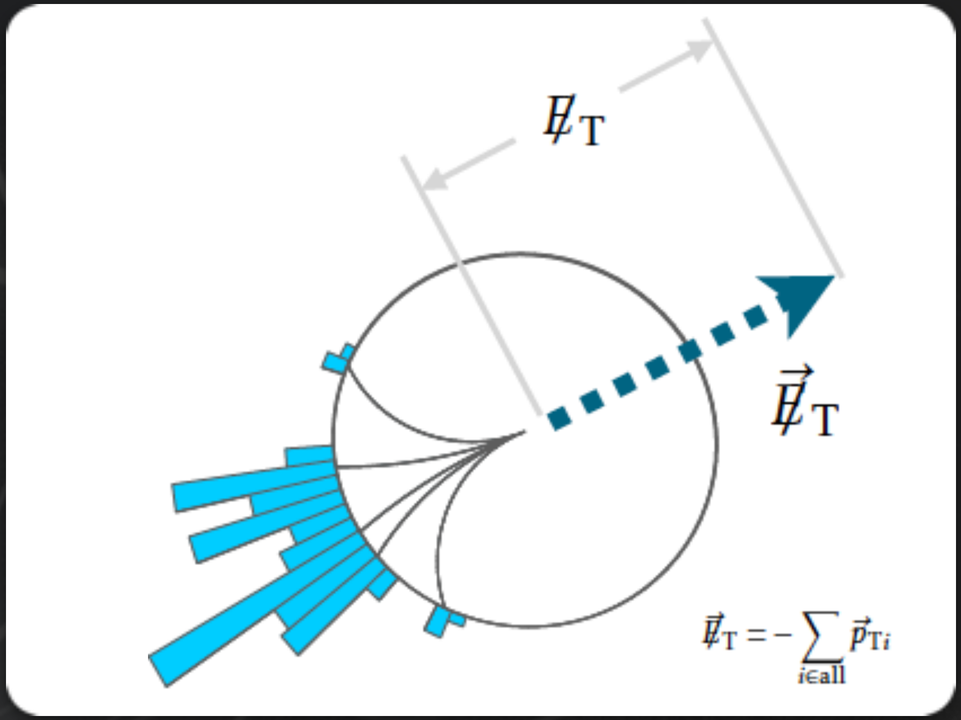
Experimental Environment

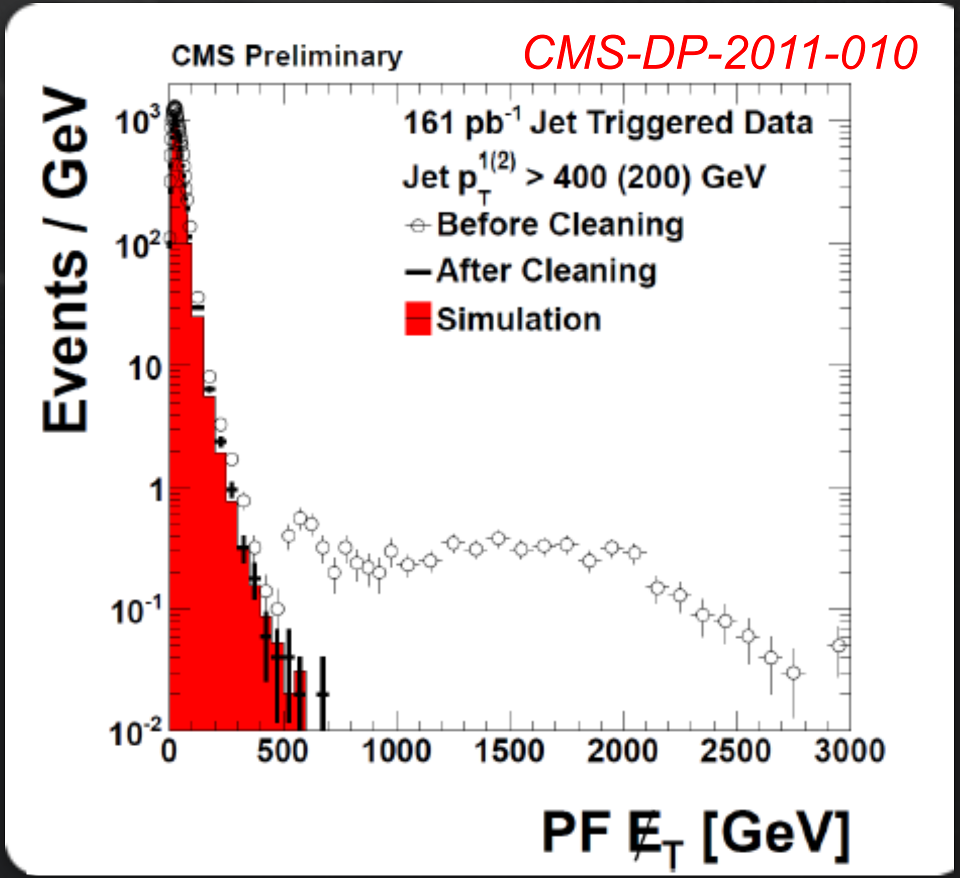
- Runs and scenarios in this talk:
  - 2012: √8 TeV, ~20 fb
  - 2015: √14 TeV, ~20-40 fb
  - HL-LHC: √14 TeV, ~3000 fb
  - HE-LHC: √33 TeV, O(1000 fb
  - FCC : √1000 TeV, O(1000 fb



Missing Transverse Momentum

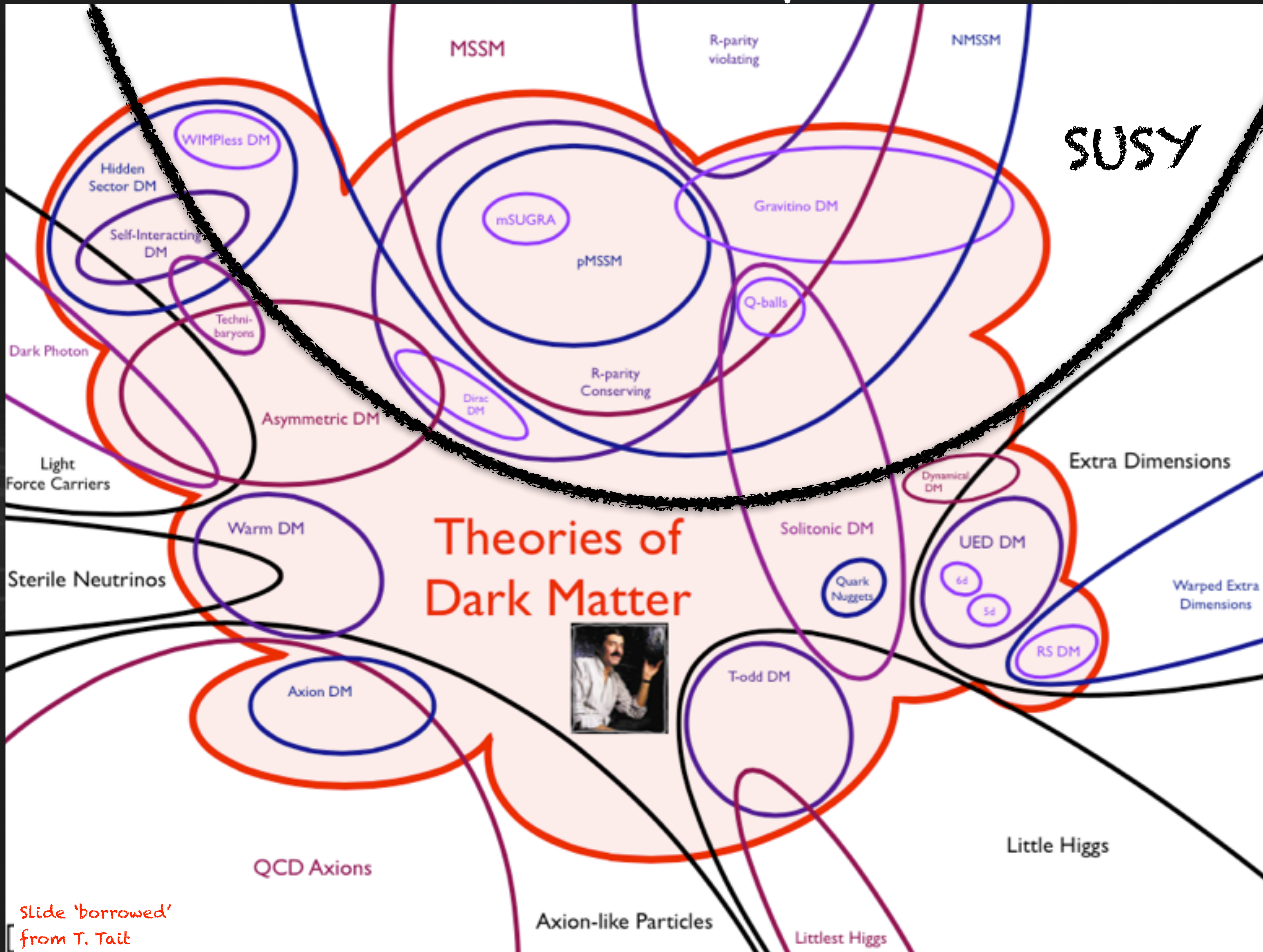
- **DM candidates** lead to imbalance in the visible vector sum of p_T (E_T^{miss})
- **Striking signature**
- **E_T^{miss} reconstruction**:
  - Hermetic detector
  - Need precise understanding of all other particles
  - Affected by instrumental effects
- **Pile up effects** will significantly effect **E_T^{miss} resolution**





SUSY Like DM

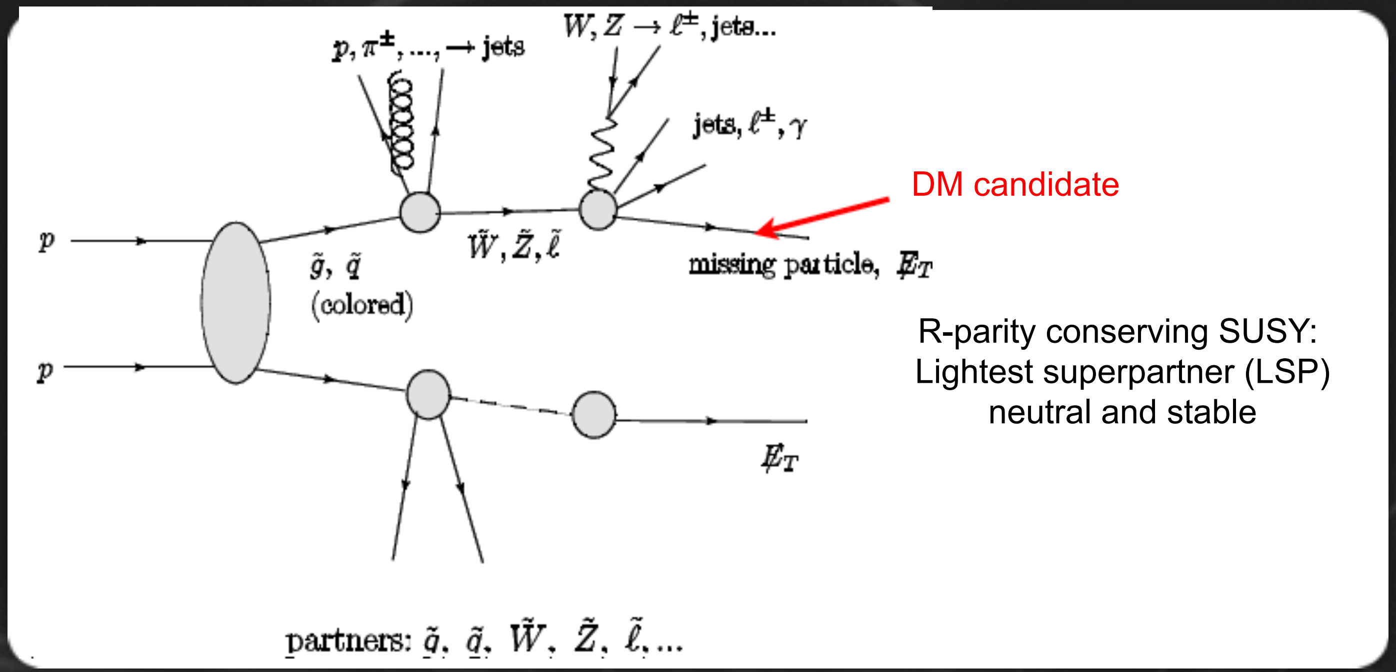
The DM Landscape



- SUSY is rather a concept than a fixed theory
- LHC searches **affect** only **comparably small parameter space**

SUSY DM

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



- 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
- E_T^{miss} + jets + γ
- ...

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

- Often the neutralino is the DM candidate (LSP)

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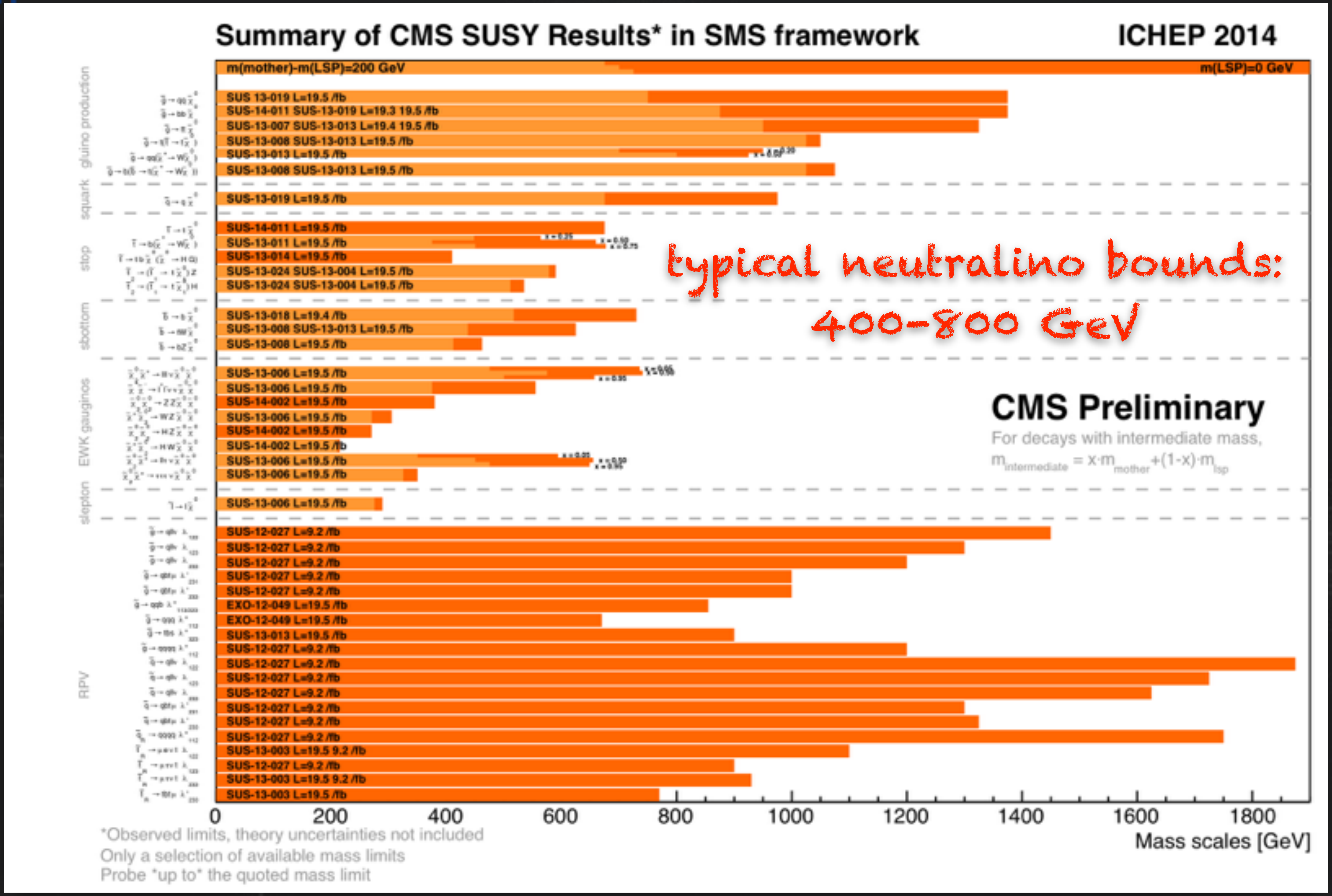
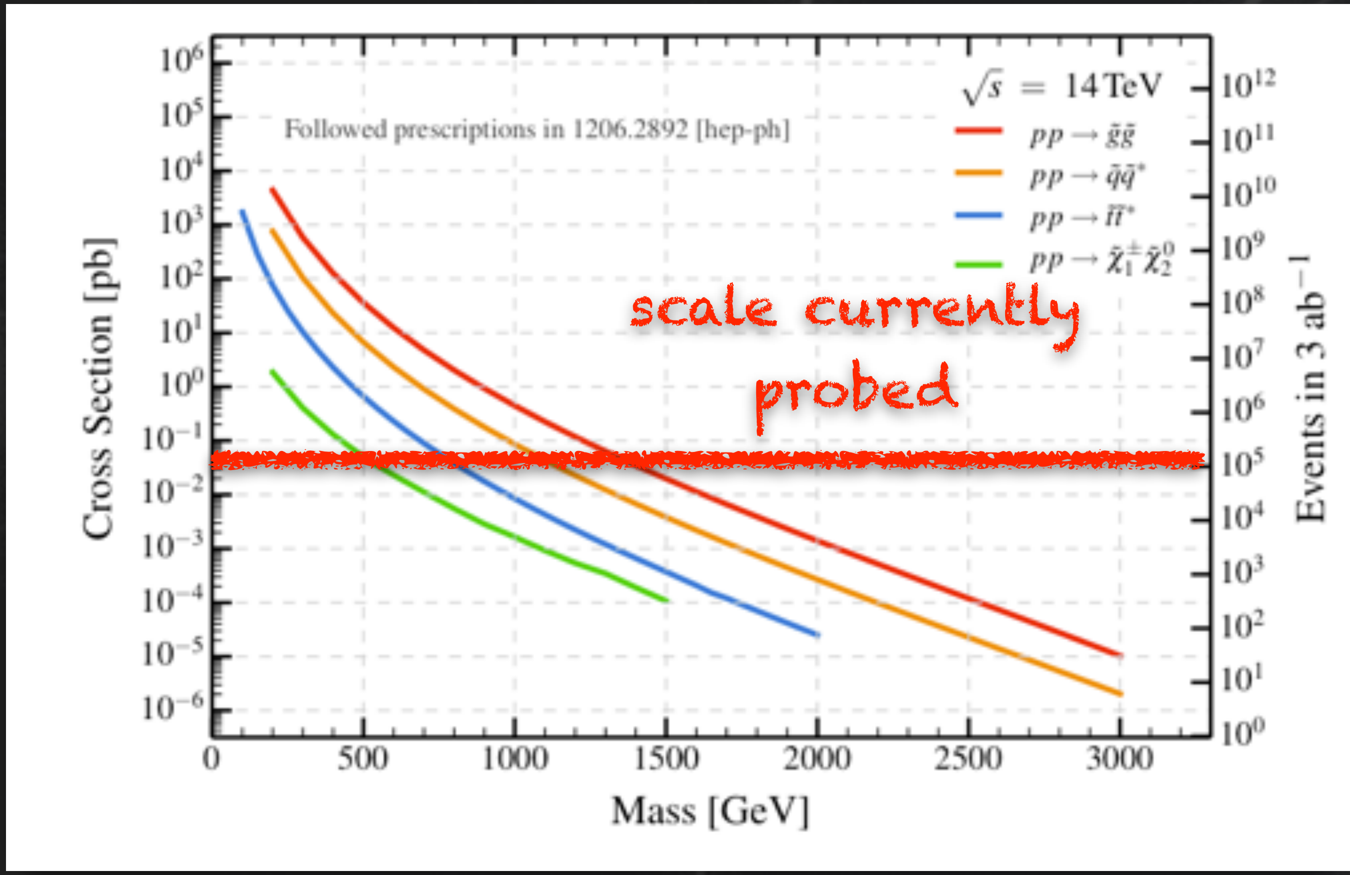
SUSY Summary

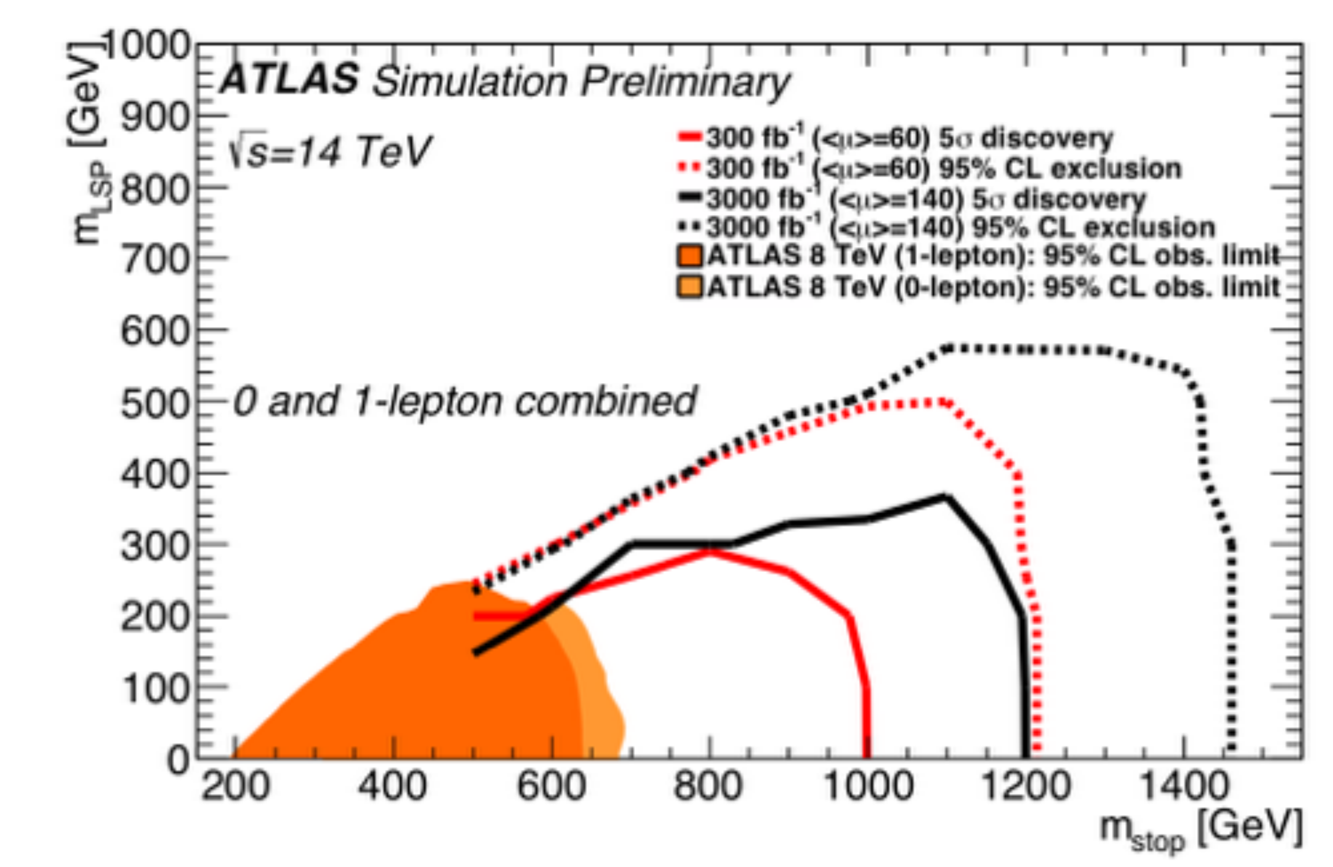


- Details
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

SUSY Projections

- Huge improvement in sensitivity during Run 2





- 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}

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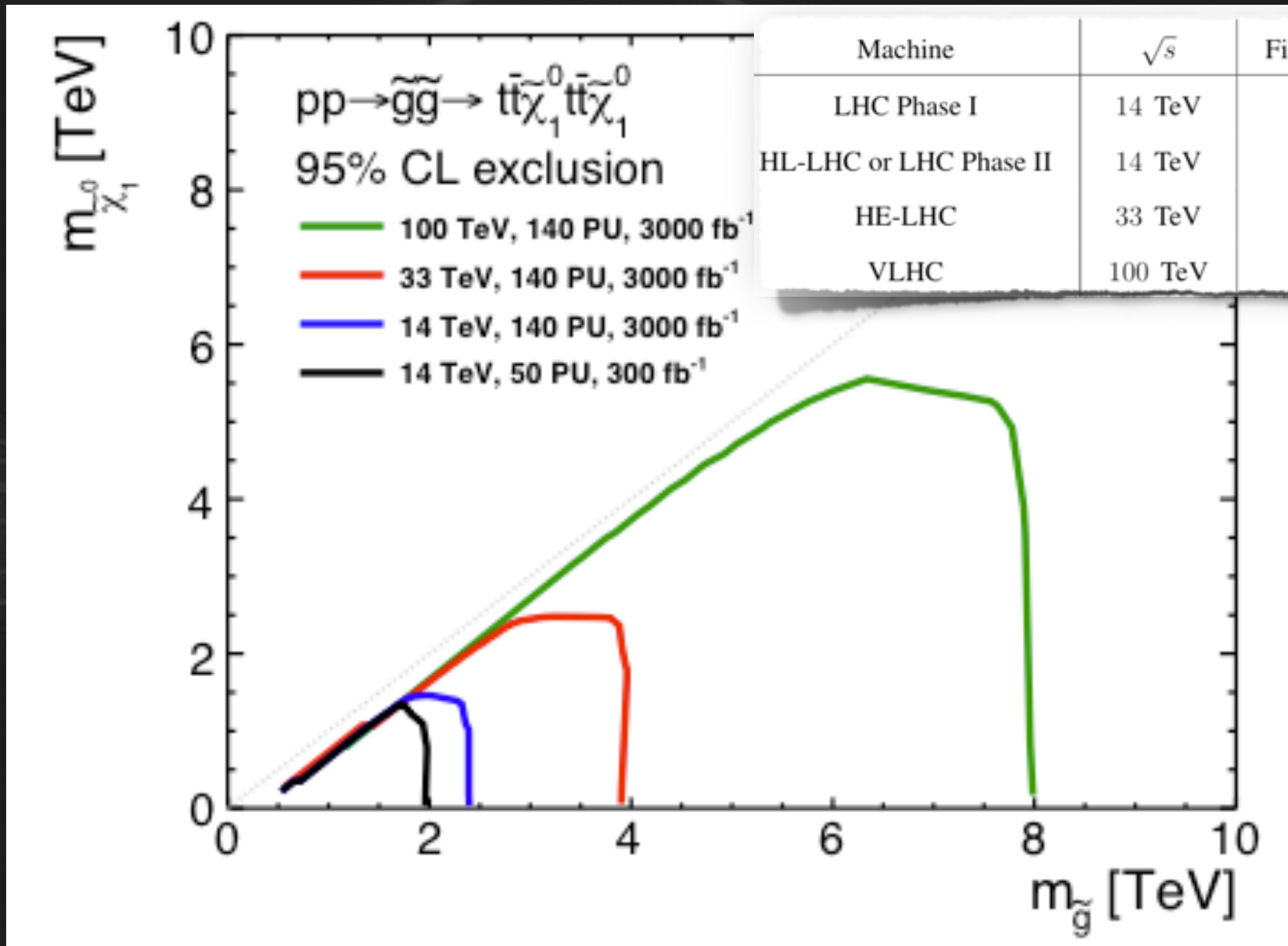
SUSY Projections

ATL-PHYS-PUB-2013-011



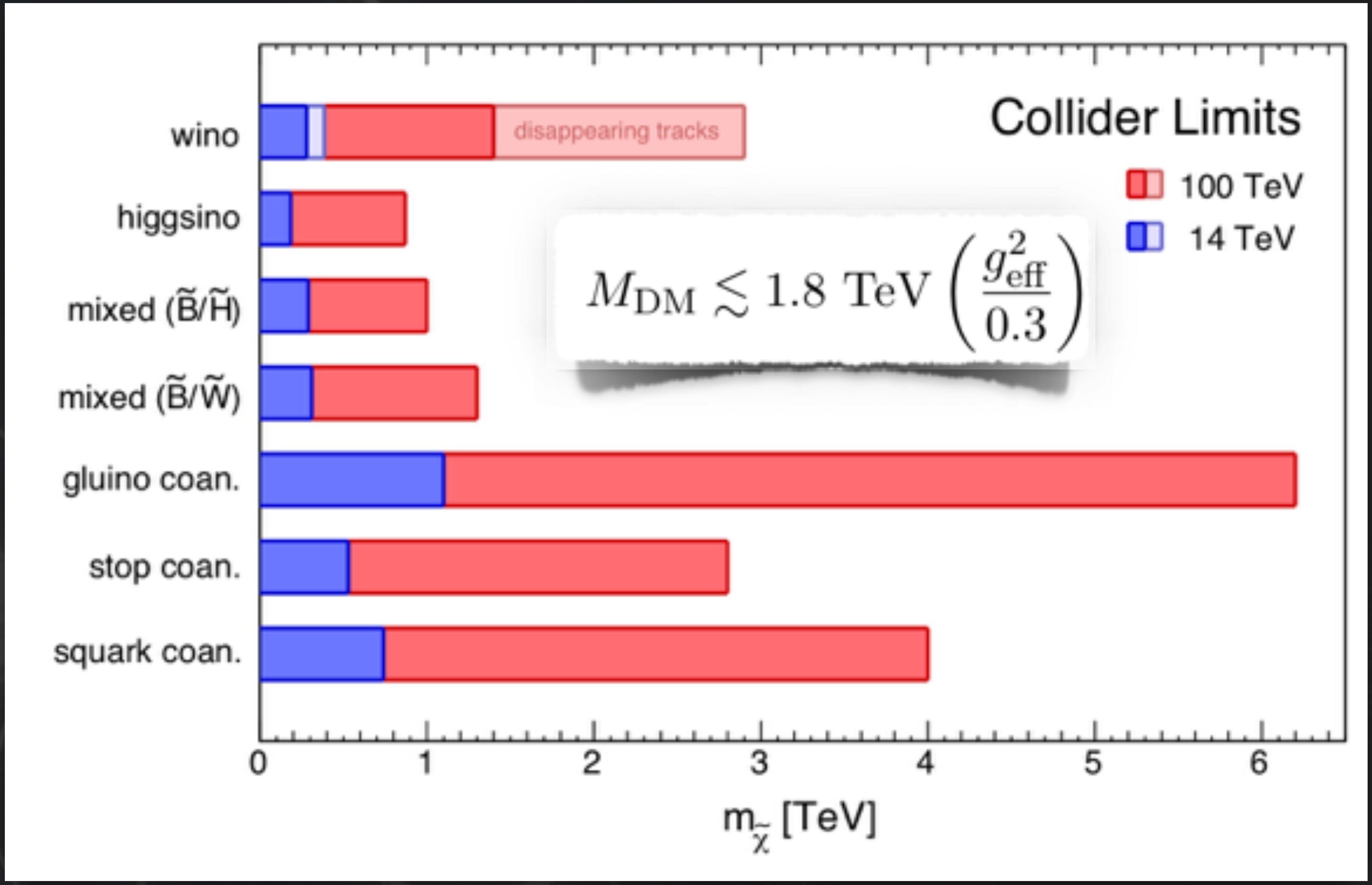
Machine	$\sqrt{s}$	Final Integrated Luminosity
LHC Phase I	14 TeV	300 fb^{-1}
HL-LHC or LHC Phase II	14 TeV	3000 fb^{-1}
HE-LHC	33 TeV	3000 fb^{-1}
VLHC	100 TeV	3000 fb^{-1}

- **Future high energy collider** will **increase physics reach** by order of **magnitude**
- Huge increase in discovery potential, **cover much of allowed phase space**

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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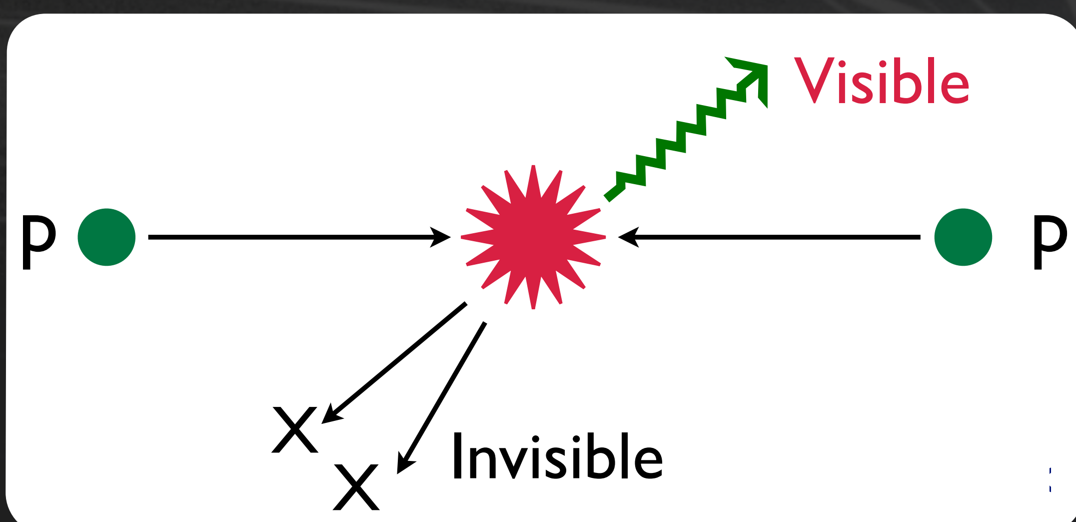
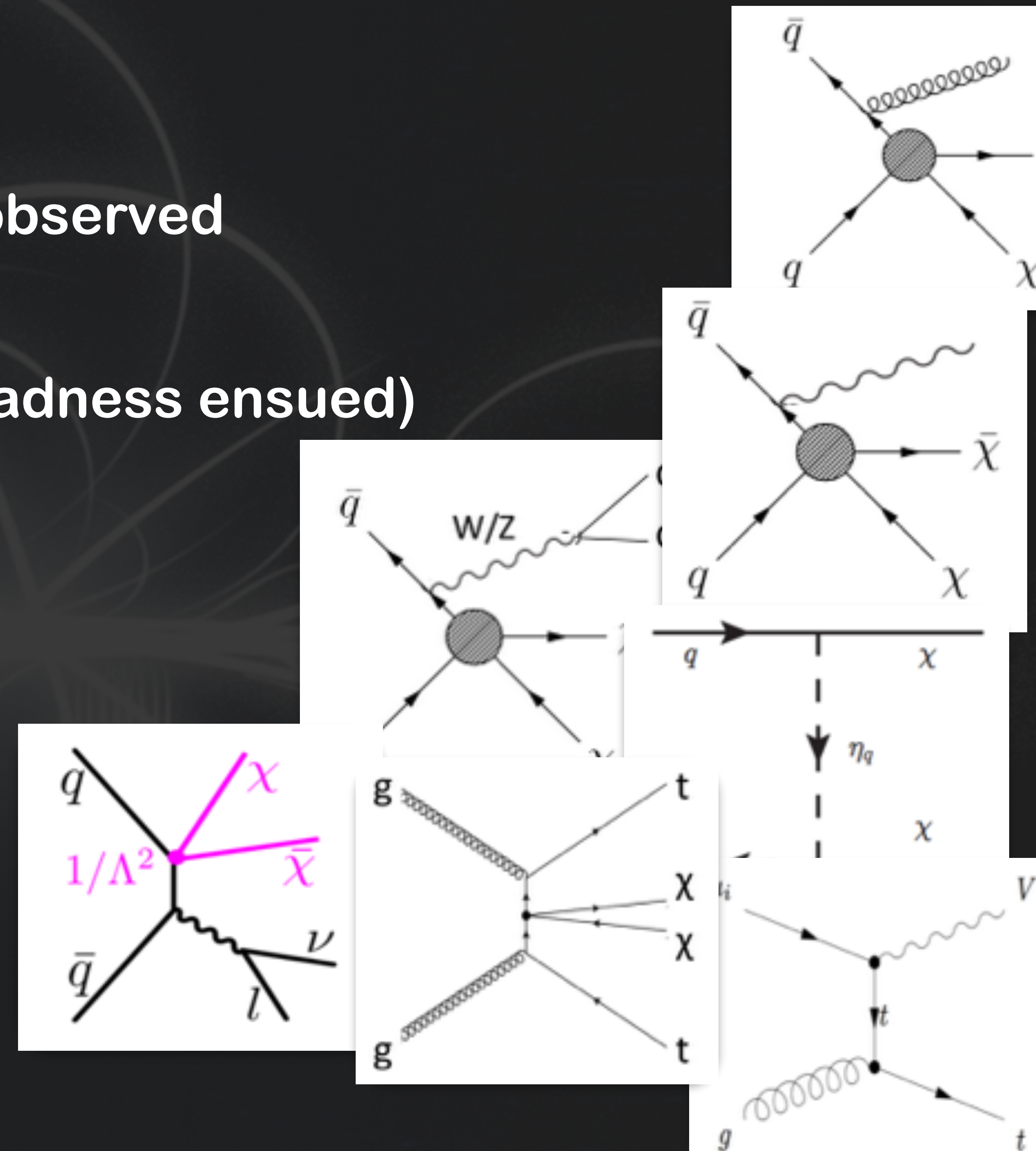
Direct Collider Searches

Mono-X

- **Properties of DM**
  - Pair produced (stable)
  - Mediating particle (M*) not directly observed
    → Effective Field Theory (EFT)
- Collider signature: mono-'X' (mono-madness ensued)

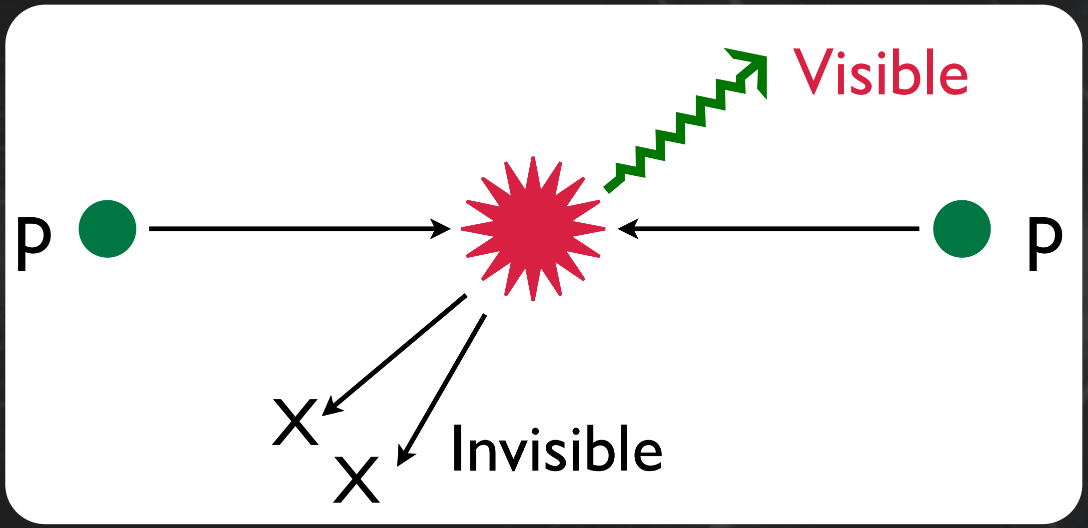




- Sensitive to different type of couplings to up/down type quarks, jets, photons
- Validity requirements not trivial

Mono-X

- **EFT** approach uses **distinctive operators**
- '**Back 2 Back**' events, recoiling SM object balanced with m(xx) (E_T^{miss})



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	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

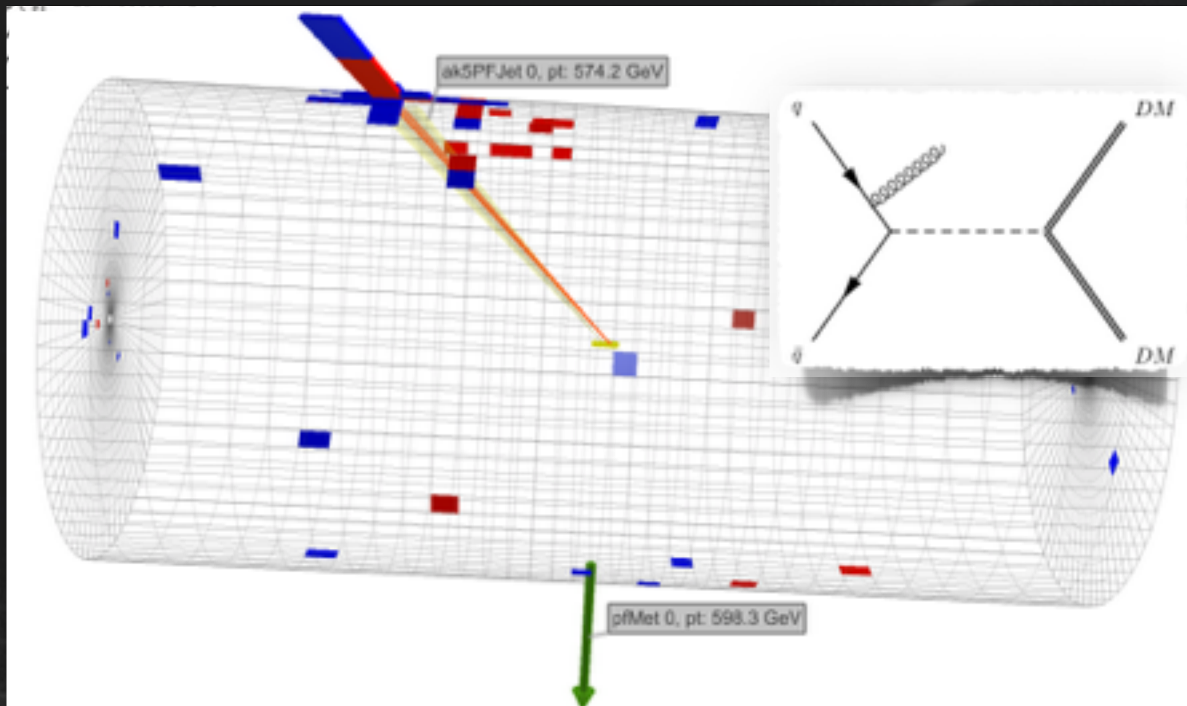
spin-independent spin-dependent

Ref: arxiv:1008.1783v2

- Sensitive to **spin-dependent** and **independent dark matter** and **low masses**
- **Monojet** channel powerful and versatile, also often **reinterpreted** in **simplified** and **SUSY scenarios**

Mono-Jet

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

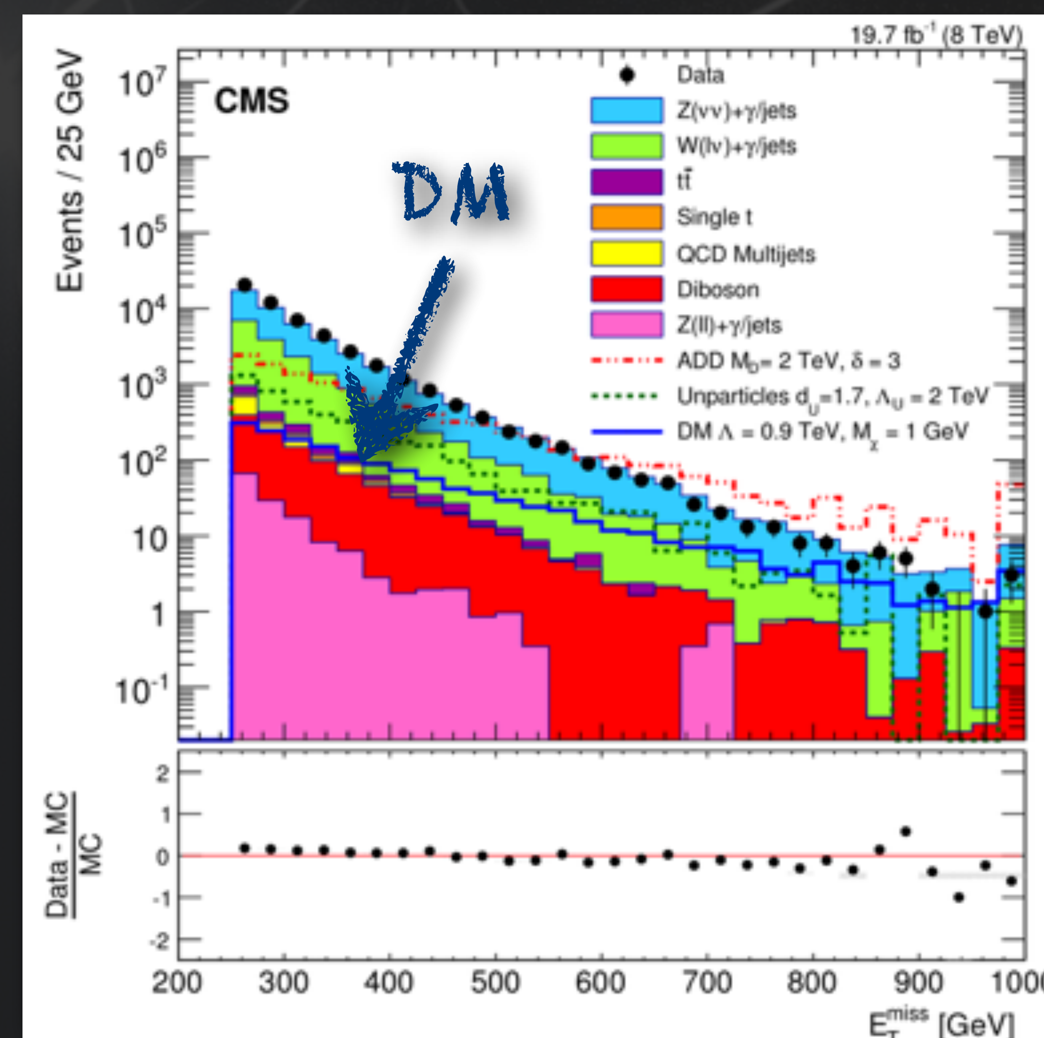


- E_T^{miss} or E_T^{miss}+jet trigger
- Require large E_T^{miss} and $p_T(jet_1)$
  - 1 or 2 jets, no leptons
  - Angular selections to remove QCD

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

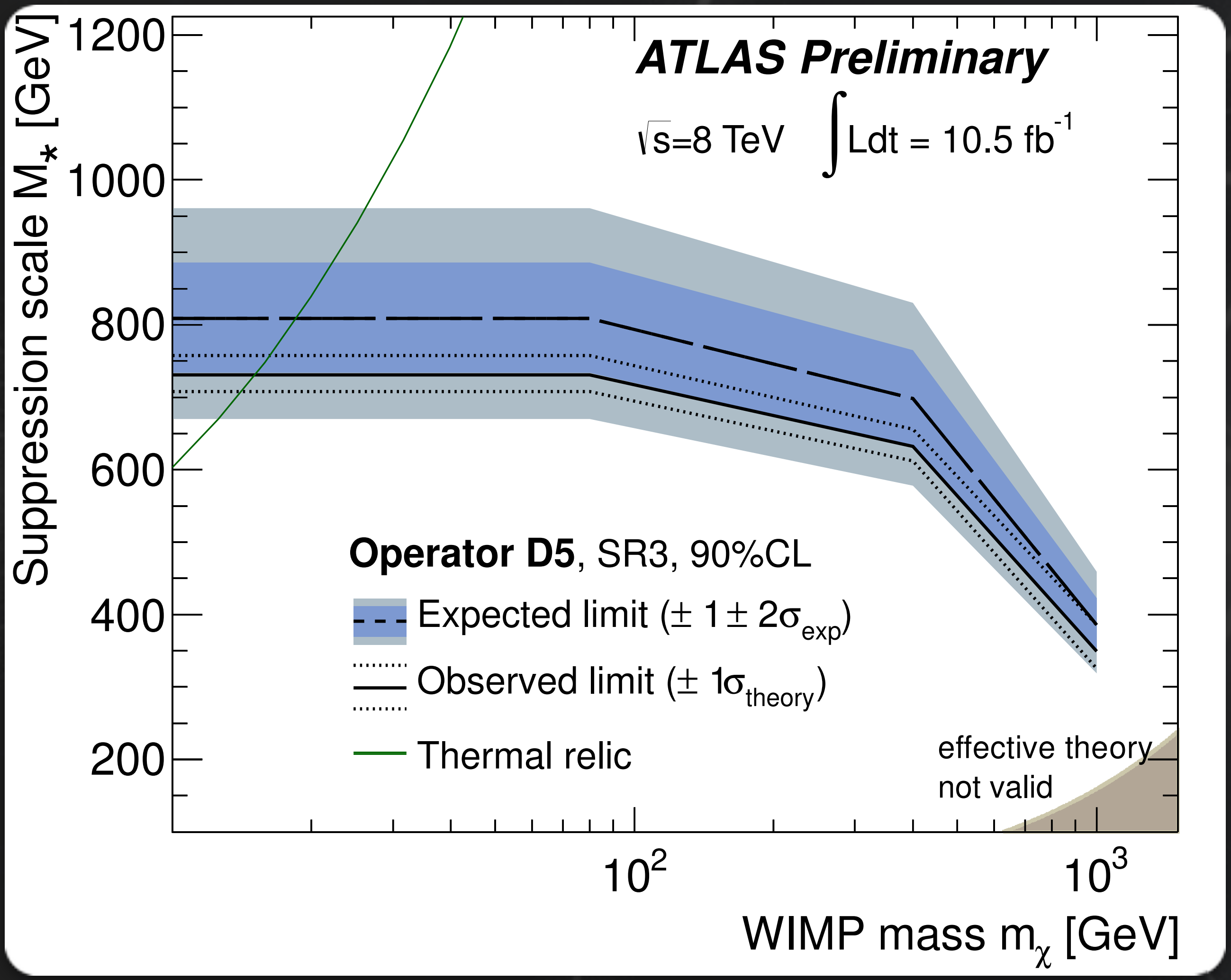
Yield (E_T^{miss}>500 GeV)

Exp. Bkgd	1040 +/- 100
Data	934



Mono-X Limit Setting

- **Lower limits** on the **reduced mass of M*** for different operators (arXiv:1008.1783v2, Goodman et al.)



characterize strength of interaction

$$M_* \sim M/\sqrt{g1g2}$$

$$M > 2m_\chi$$

- Limits on **reduced mass M*** projected on $\sigma^{SI/SD}$ using distinct conversion for each operator:

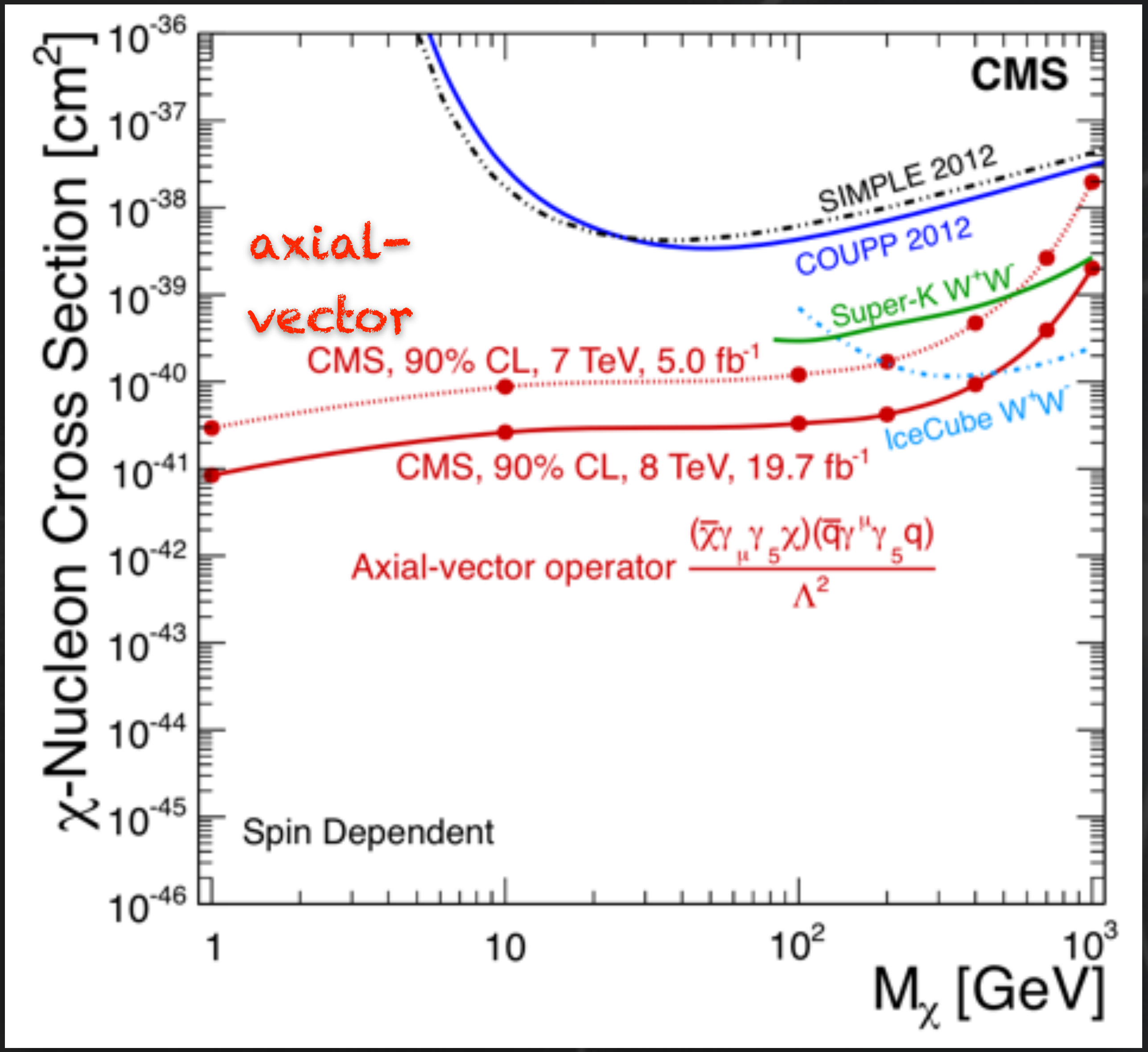
$$\sigma^{D1} = 1.6 \times 10^{-37}\mathrm{cm}^2 \left(\frac{\mu_\chi}{1\ \mathrm{GeV}}\right)^2 \left(\frac{20\ \mathrm{GeV}}{M_*}\right)^6$$

- **Constraints on relic density** may be set with some reasonable assumptions

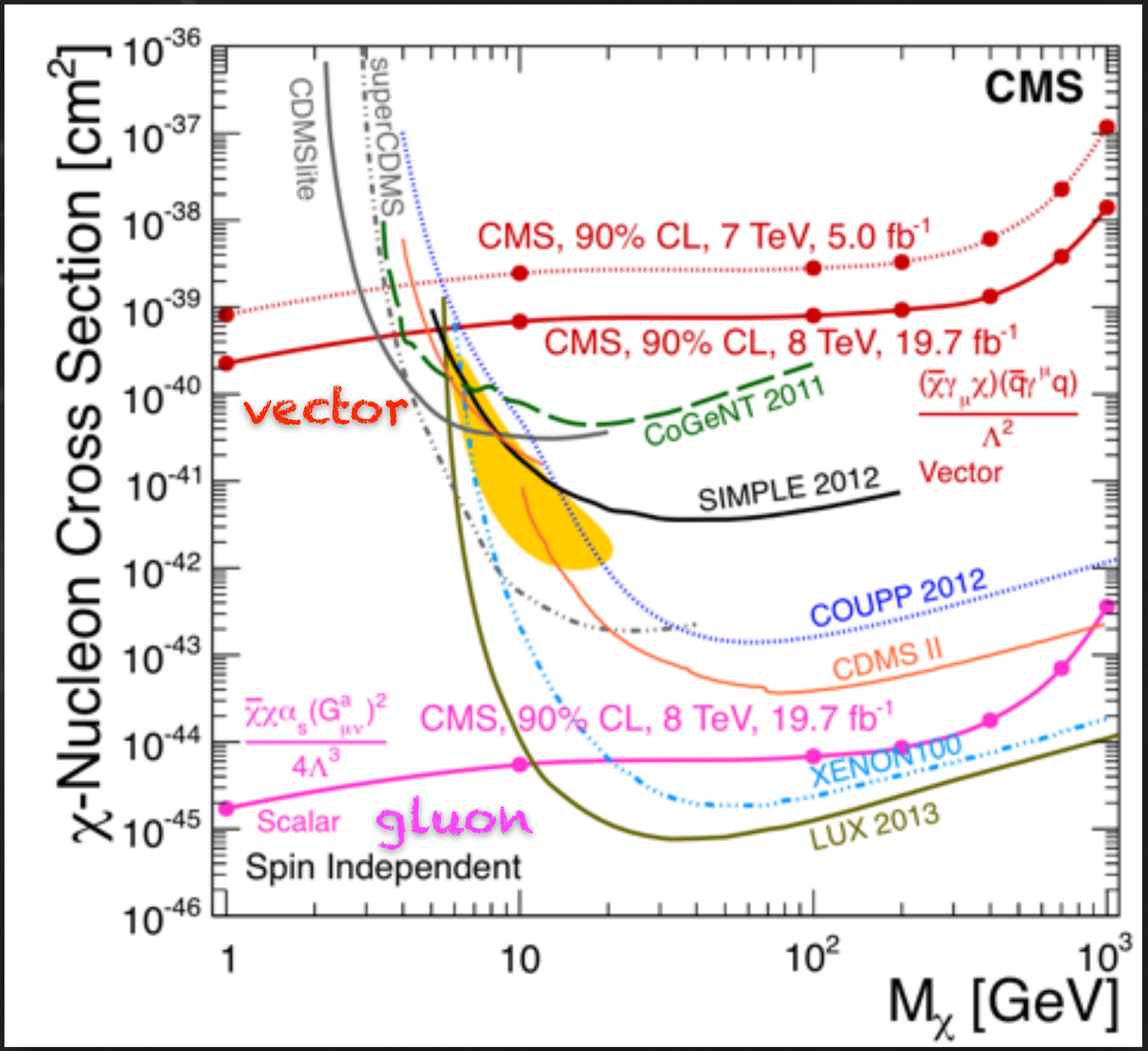
Mono-Jet

arXiv:1408.3583 (CMS)

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

- ATLAS projections following closely 8 TeV analysis
  - Realistic assumptions for future detector performance, uncertainties and pile up scenarios

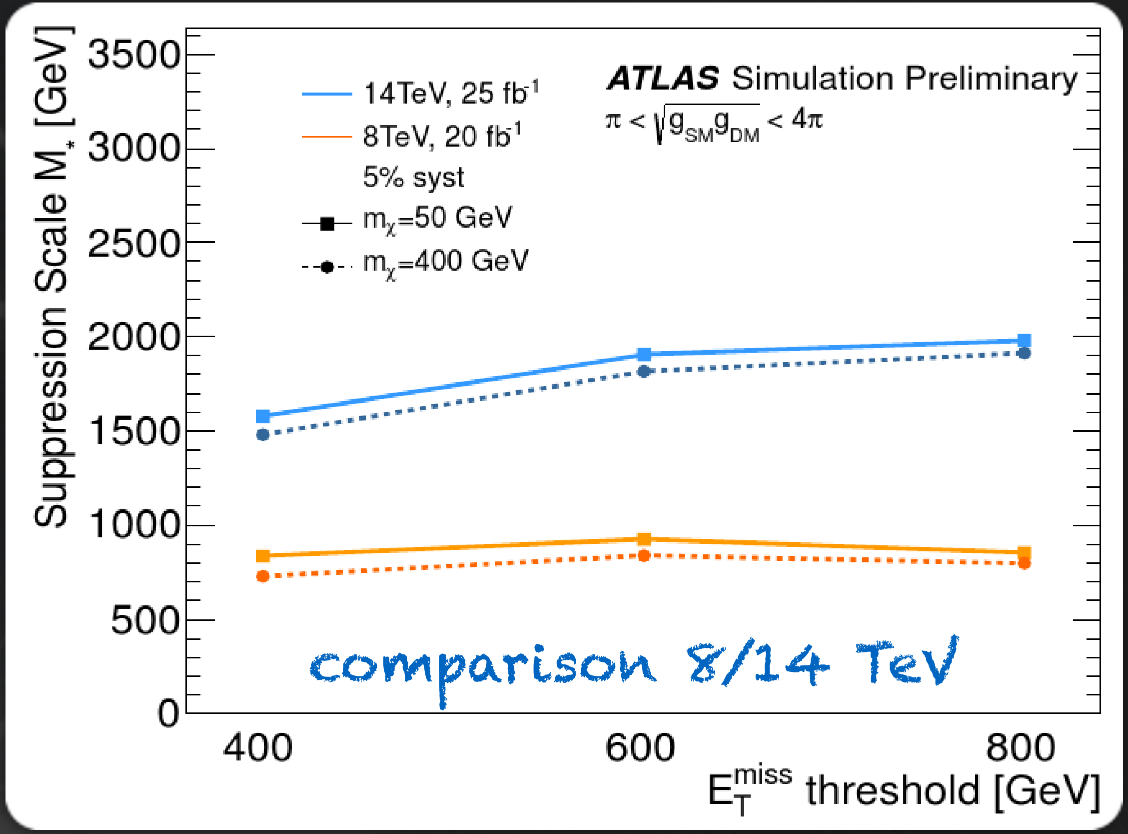
	$\sqrt{s}$ [TeV]	μ	L [fb^{-1}]
	8	20	20
Phase 0 upgrade (2014-2015)	14	60	25
Phase 1 upgrade (2018)	14	60	300
Phase 2 upgrade (2022)	14	140	3000

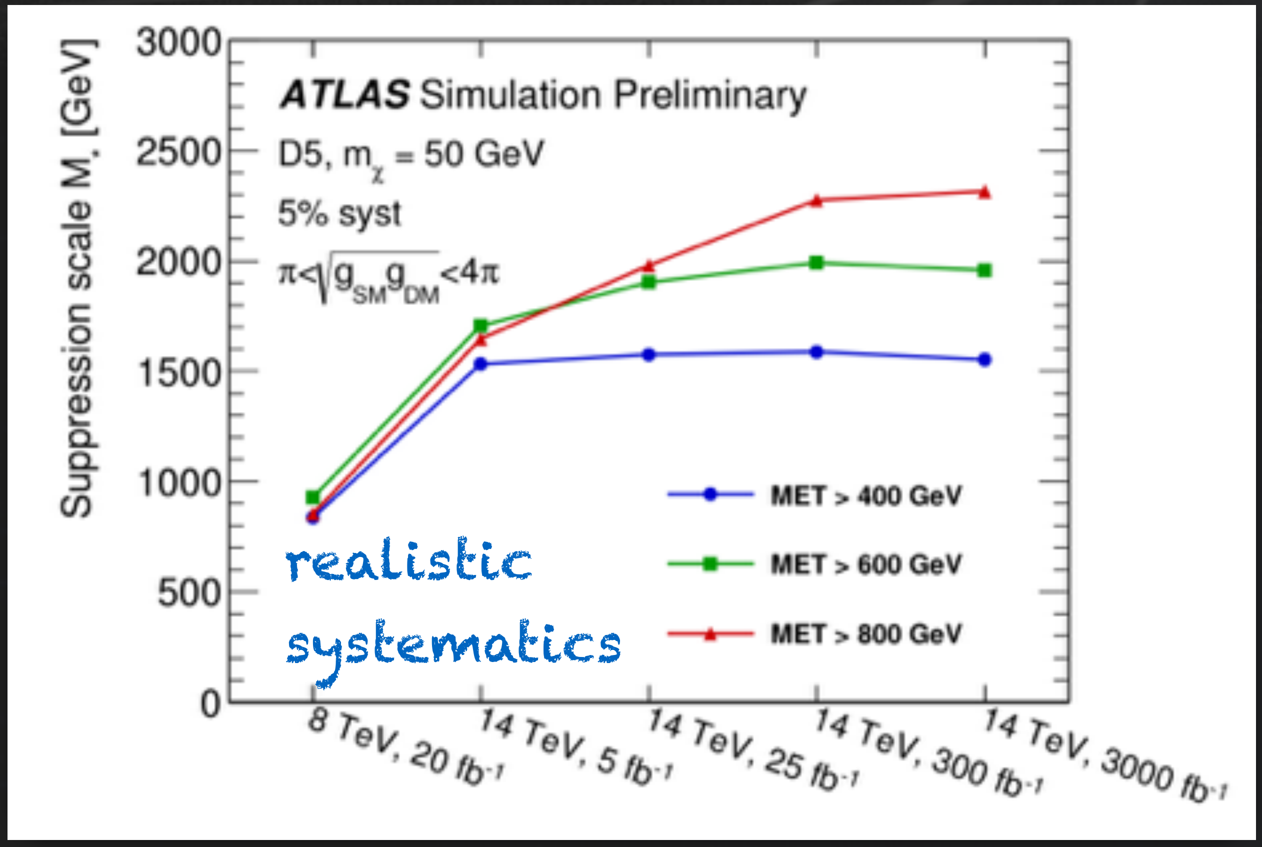
- Extended signal regions with E_T^{miss}>600, 800GeV
- (Axial-) Vector couplings considered
- Fast simulation used to reproduce existing CMS limits in simplified model

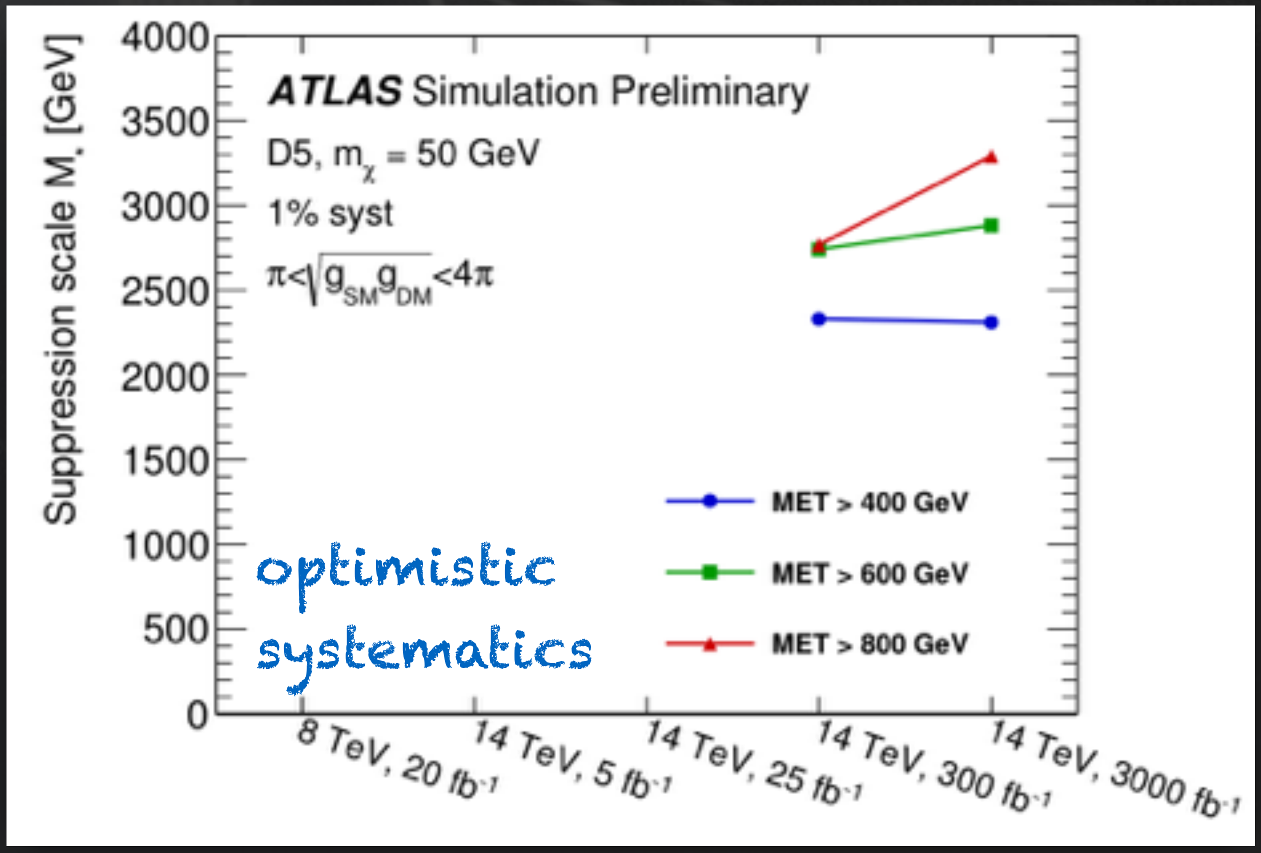
Mono-Jet Projections

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
  - Again factor of two improvement
- The usual validity concerns apply but deferred here (details in reference)



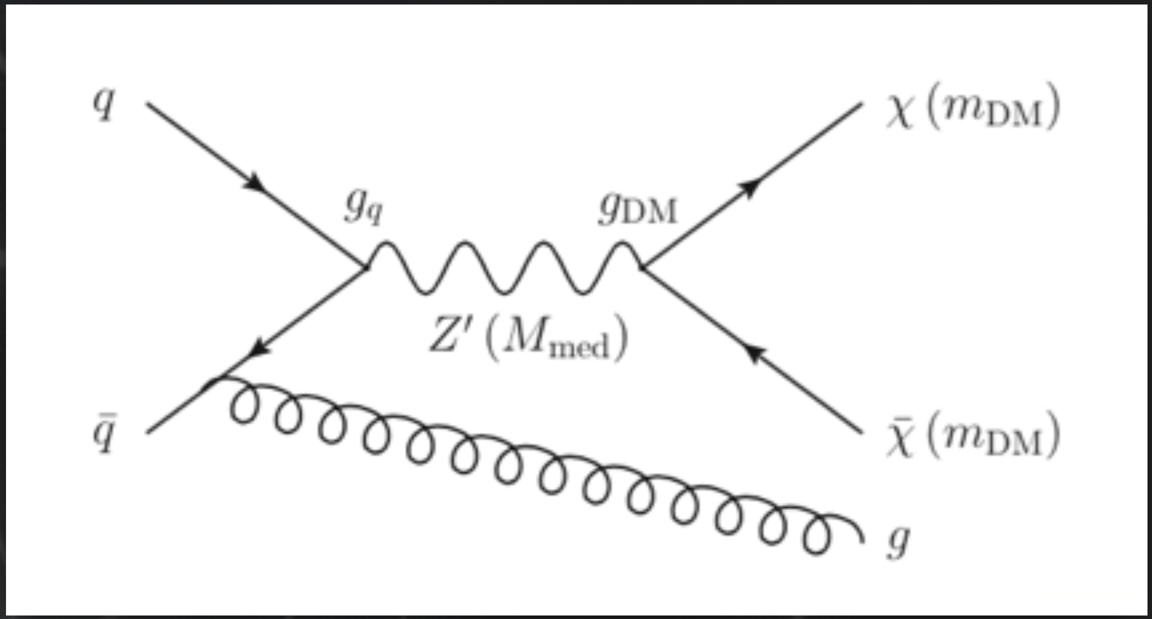




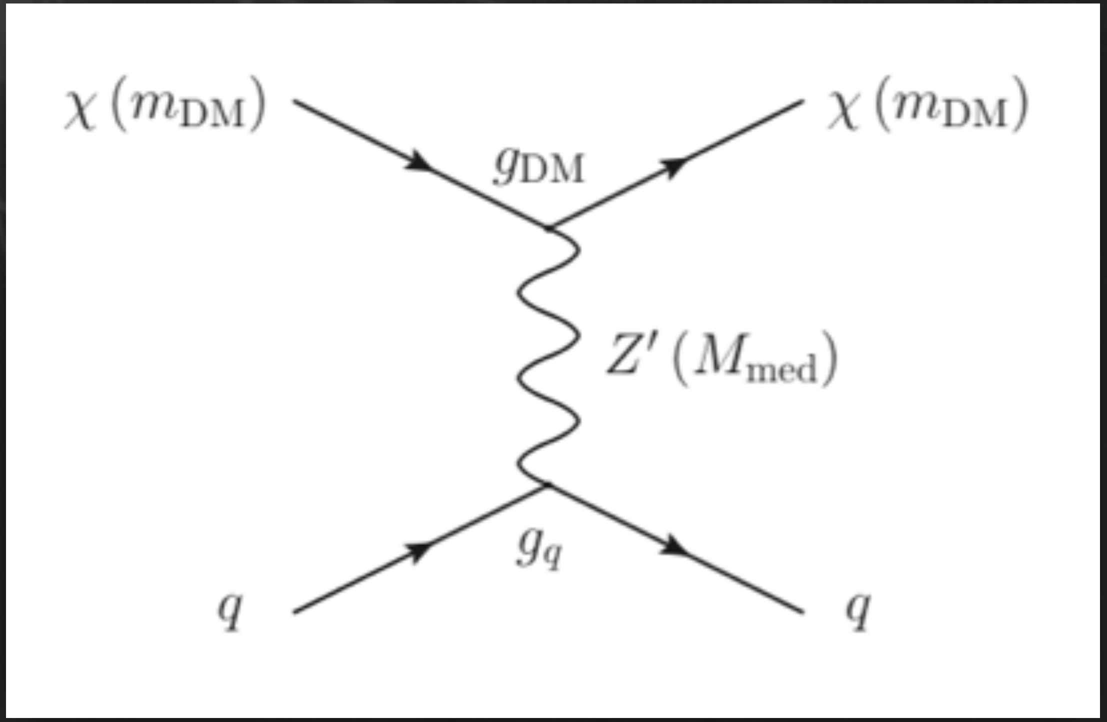
Simplified DM Models

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



Collider



Direct Detection

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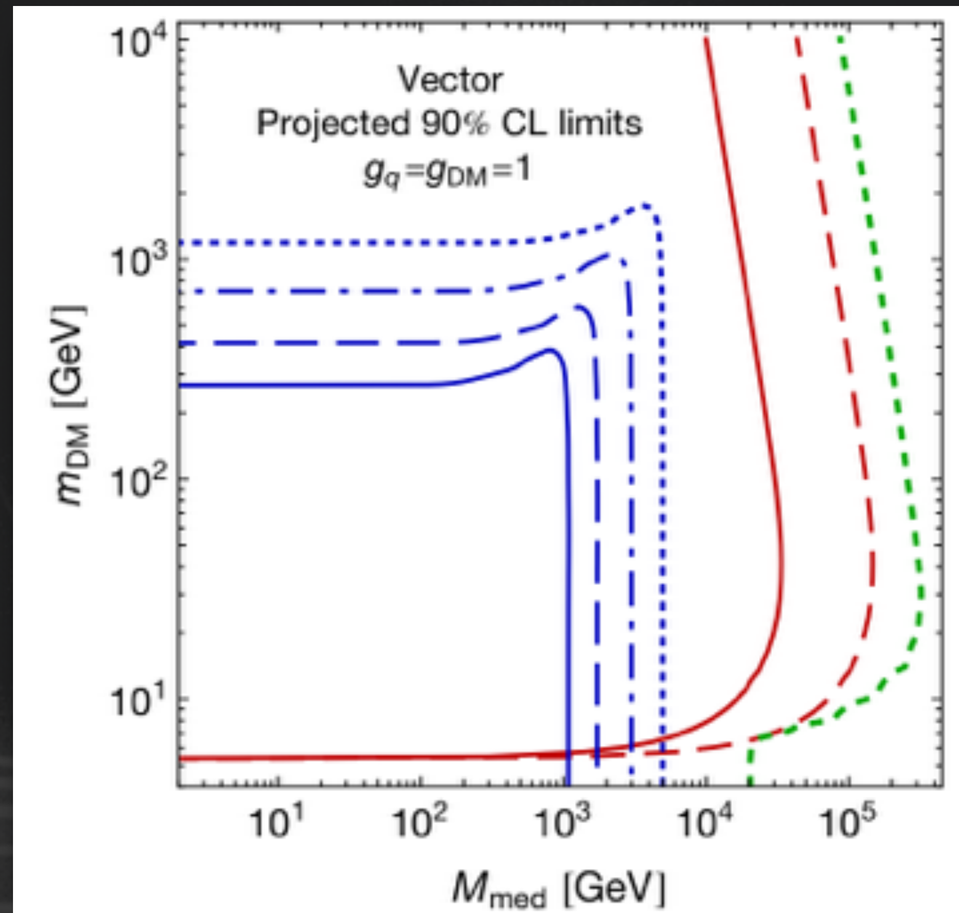
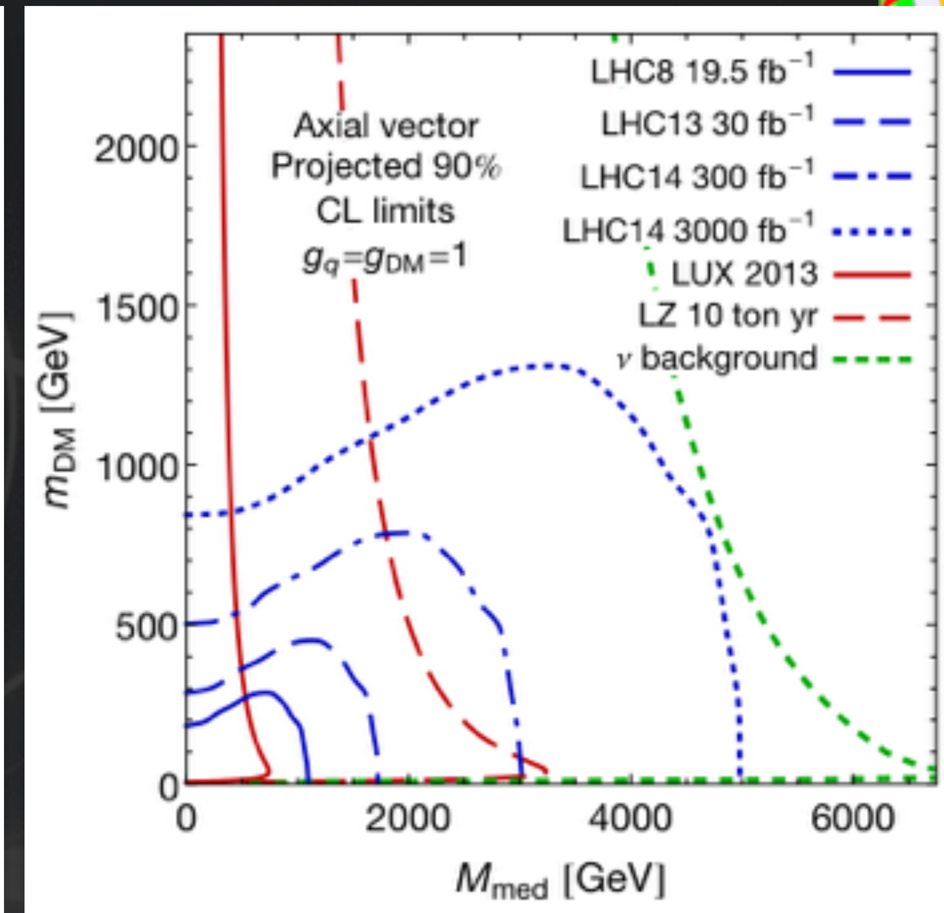
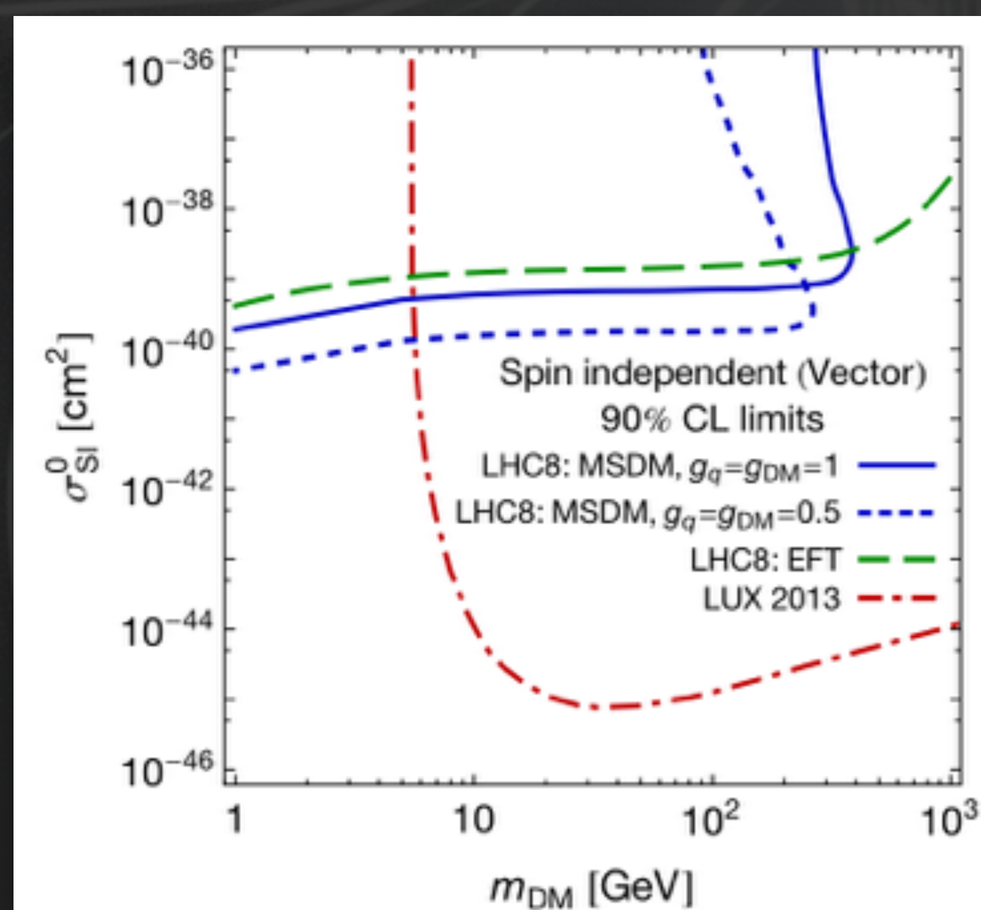
Simplified Models Monojet Projections

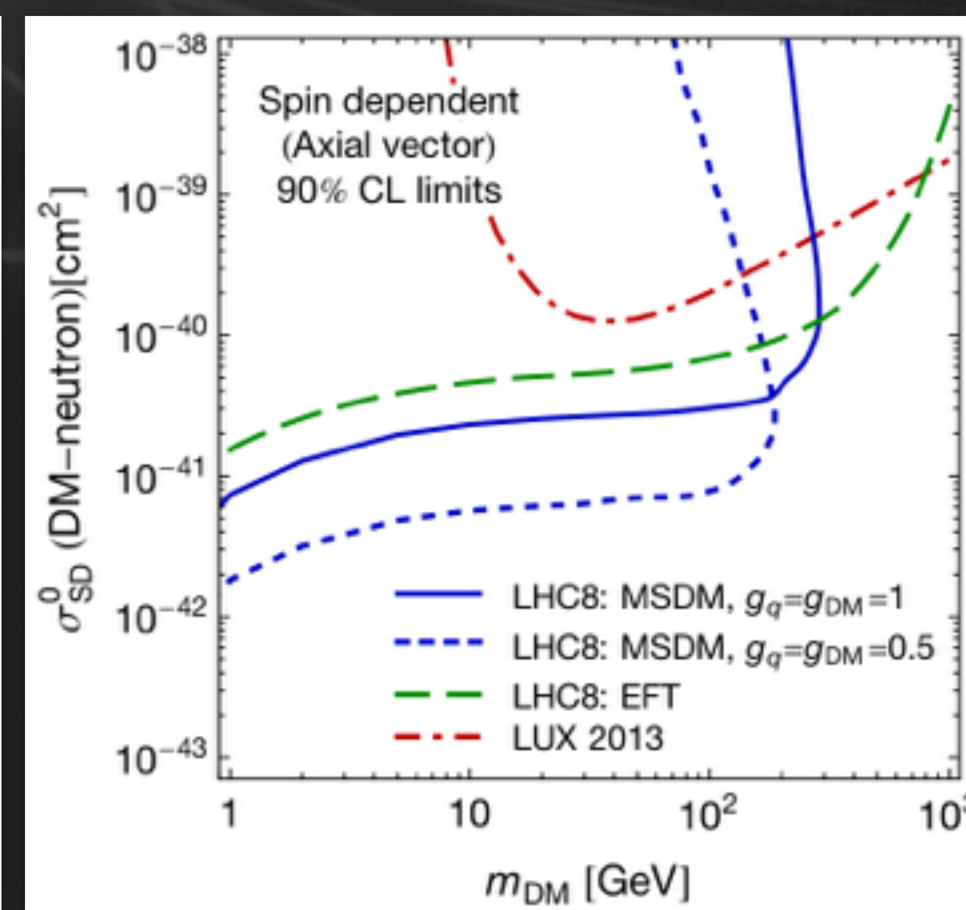
arXiv:1407.8257
Buchmueller et al

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



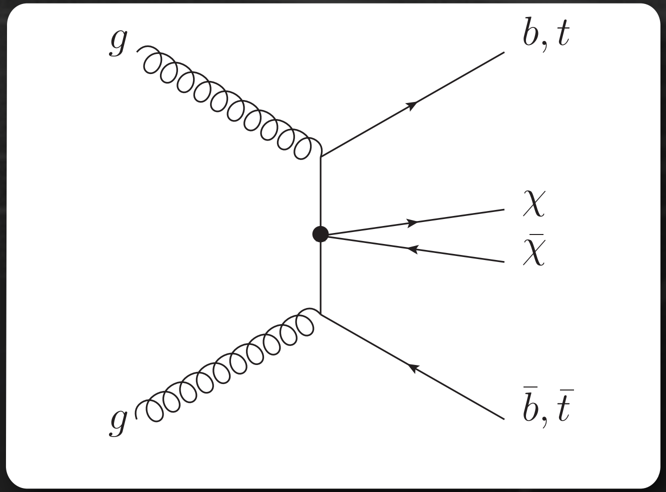


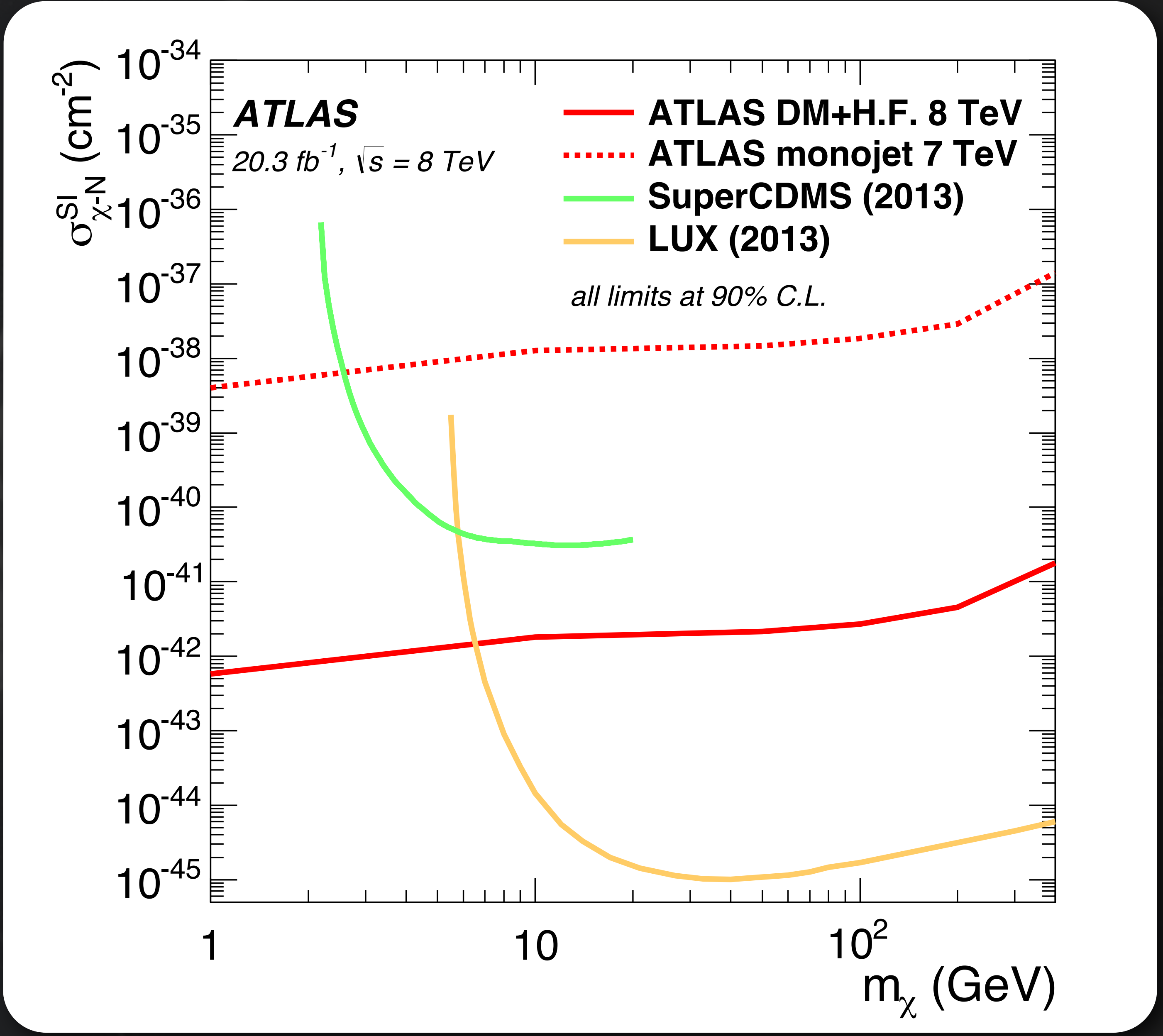




DM+b(b)/ttbar

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

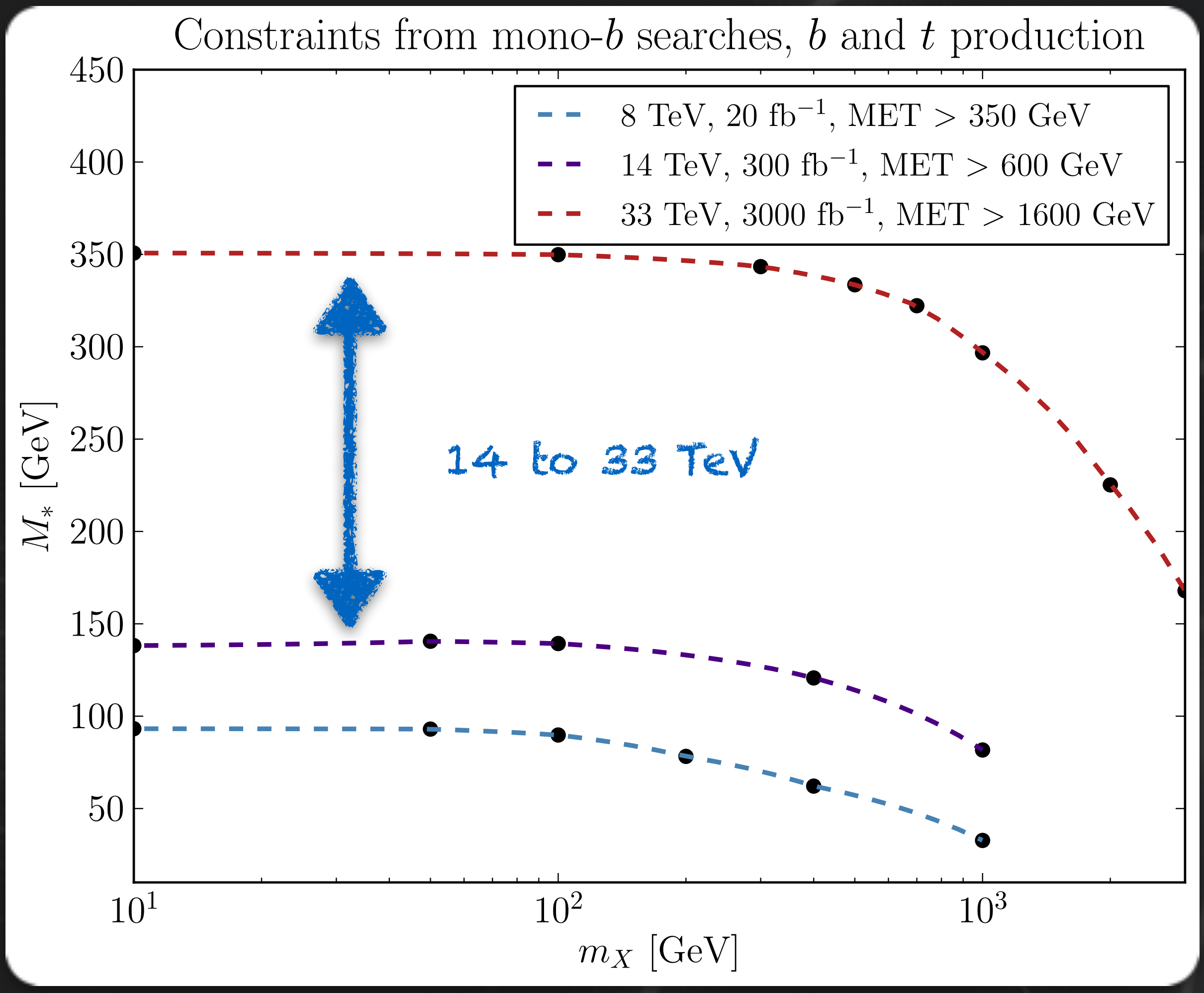


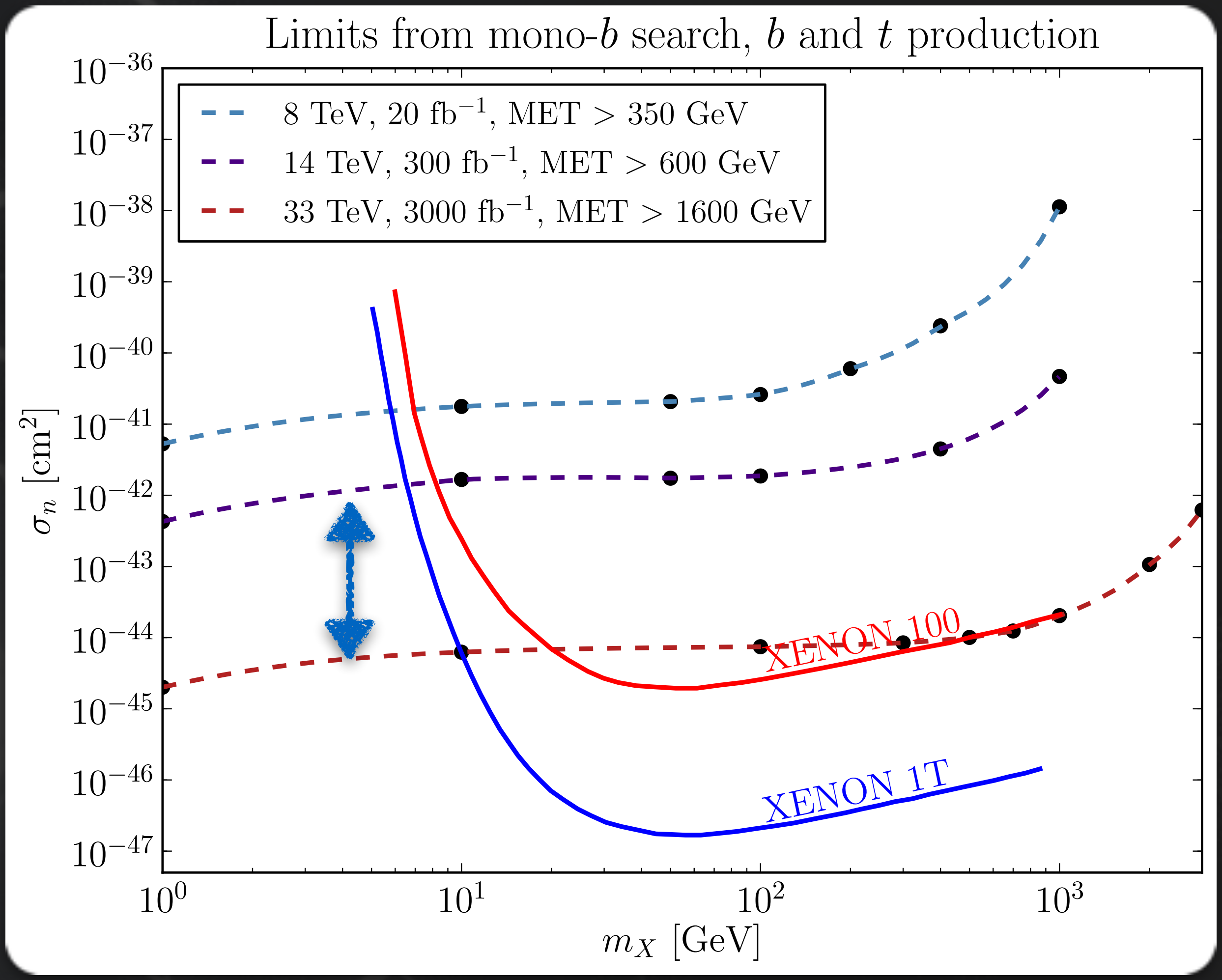


- **Heavy flavor jets**:
  - **Third generation couples enhanced** for given couplings $\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
  - Access **more inclusive** final states, probe particular set of couplings

Projections DM+b(b)/ttbar

arXiv:1307.7834
T.L.; G. S., B.P.





- Initial projections confirmed, best **sensitivity for scalar operators** with **DM +heavy quark**
- **Future collider competitive with direct searches at high masses**
- **Also sensitive to pseudo-scalar operators (Fermi-LAT)**, expect to exclude larg(est?) part of allowed phase space

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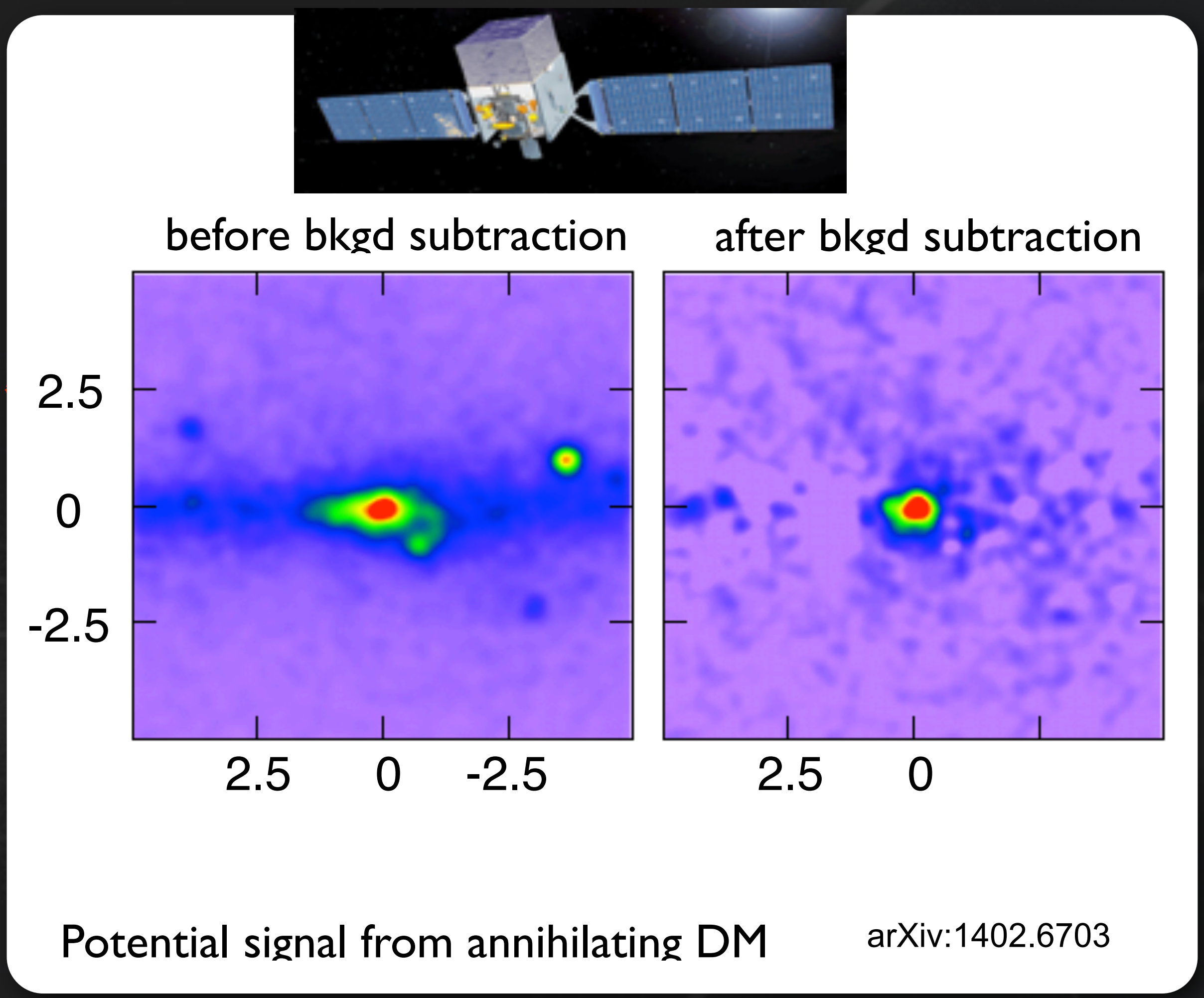
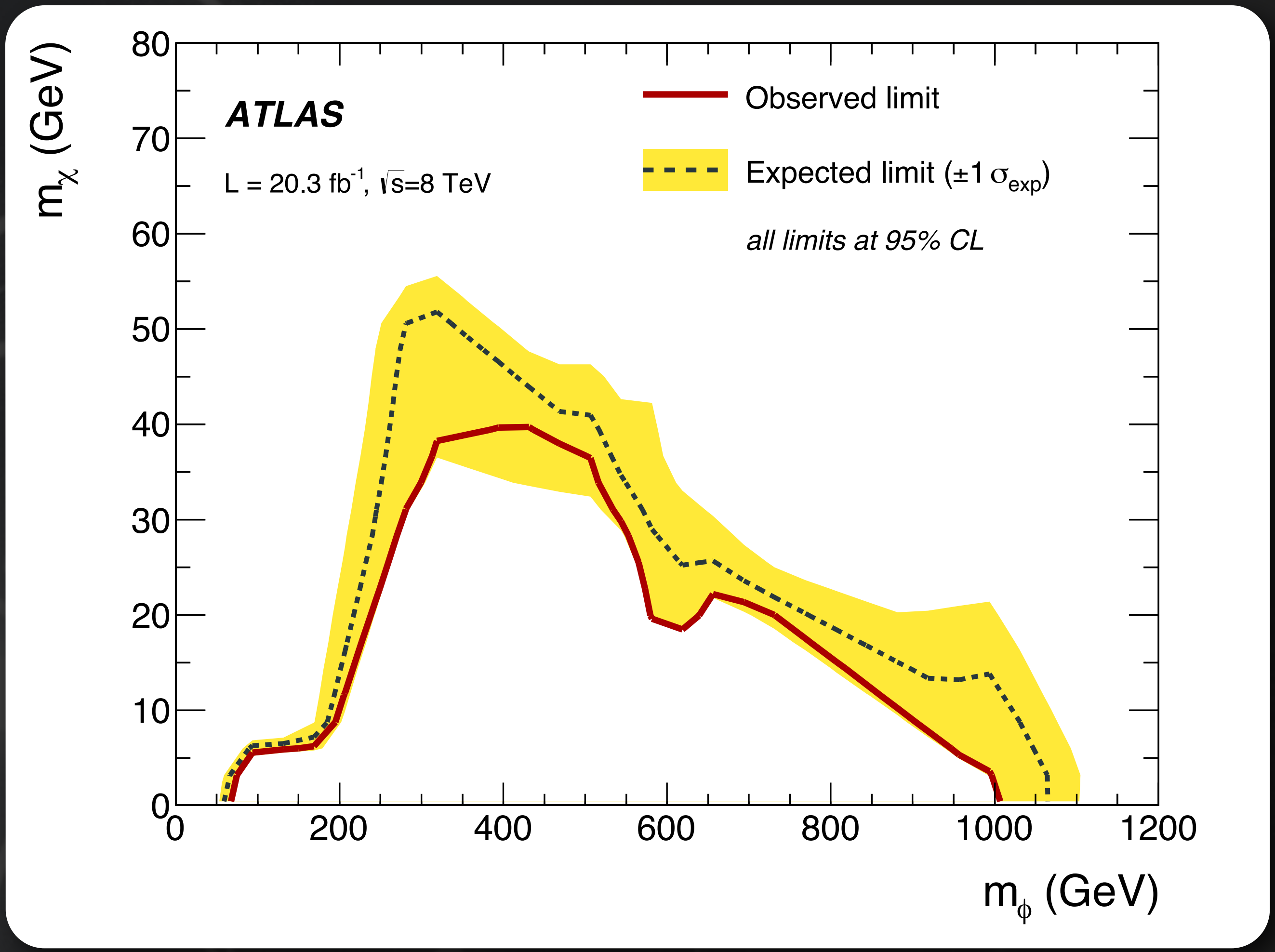




Fermi - LAT GC excess

ATLAS

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

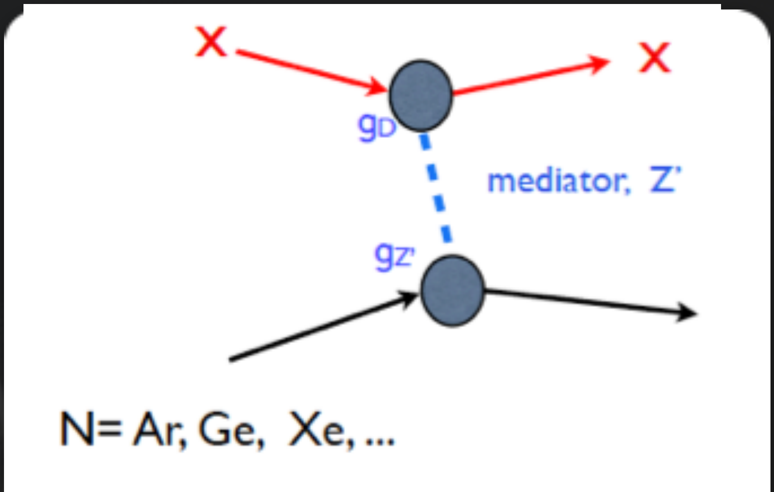
Berlin, Hooper, McDermott, arXiv: 1404.0022

Searching for the Mediator

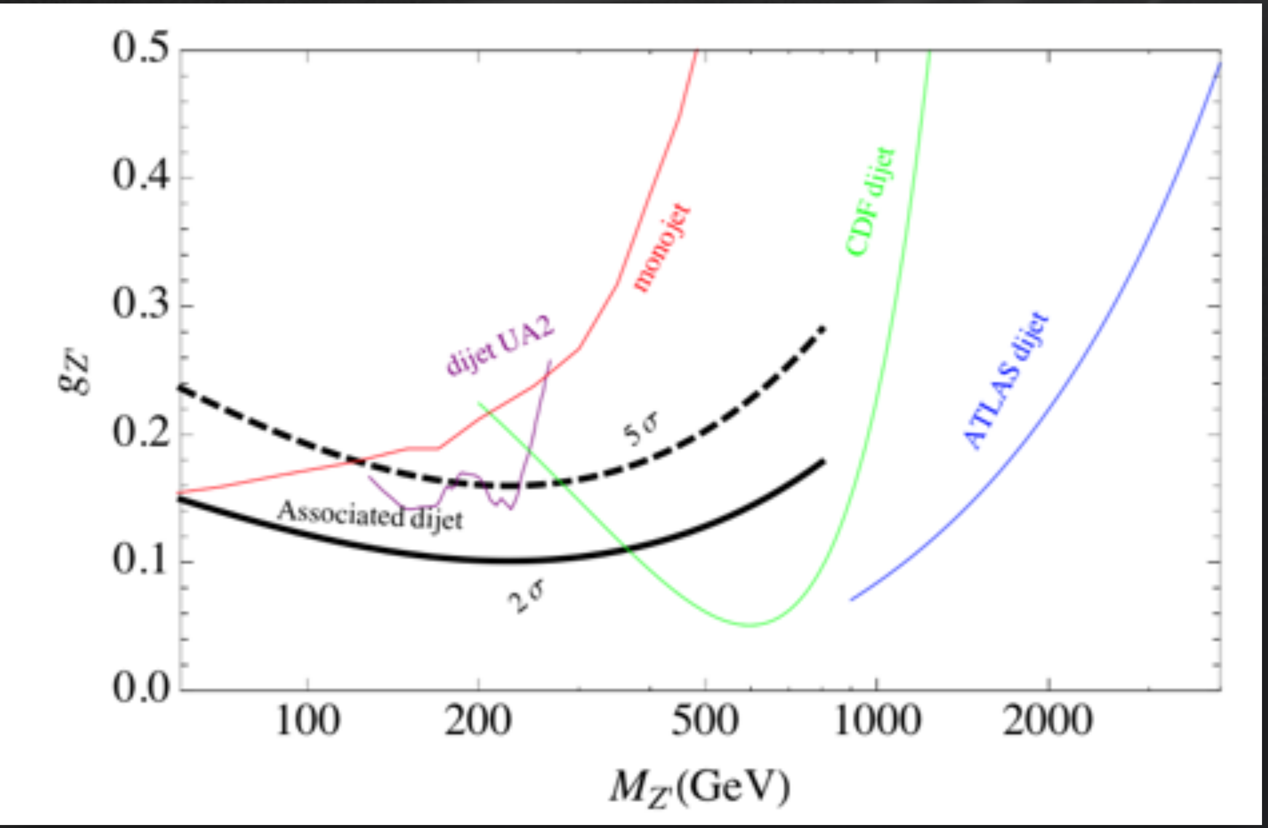
Low Mass Mediators

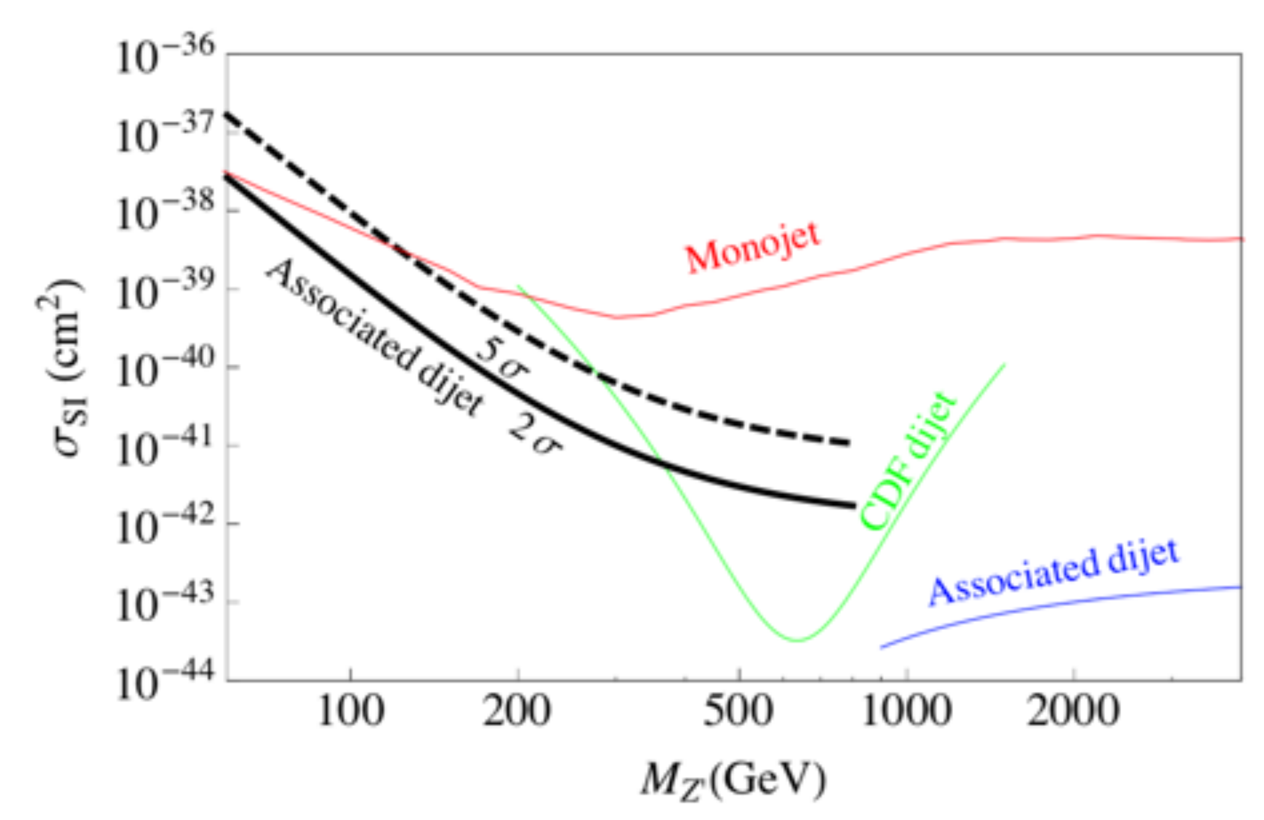
arXiv:1212.2221
Han et al, L.T.

- 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!



$$\mathcal{L} \ni g_{Z'}\bar{q}\gamma^\mu q Z'_\mu + g_D\bar{\chi}\gamma^\mu\chi Z'_\mu,$$

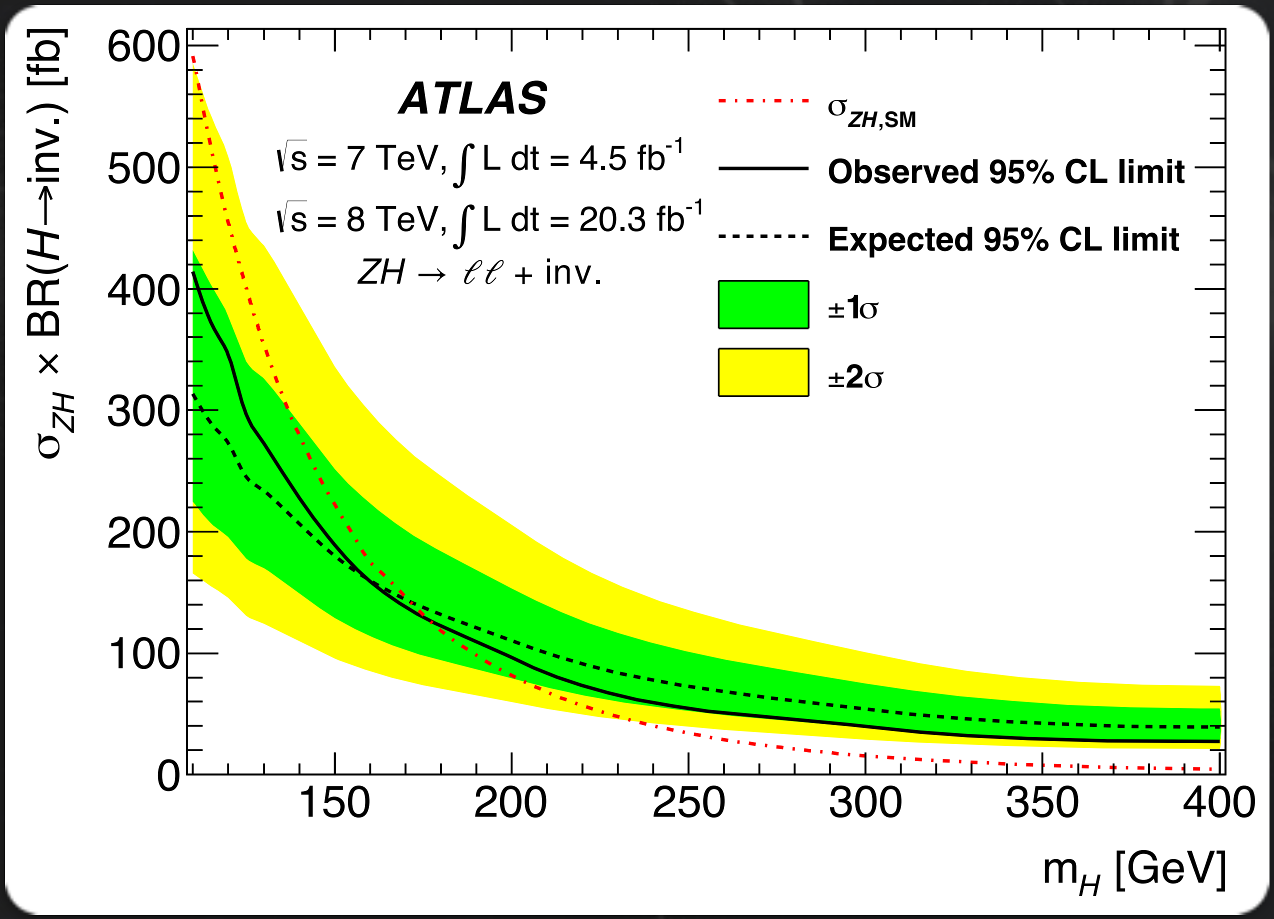


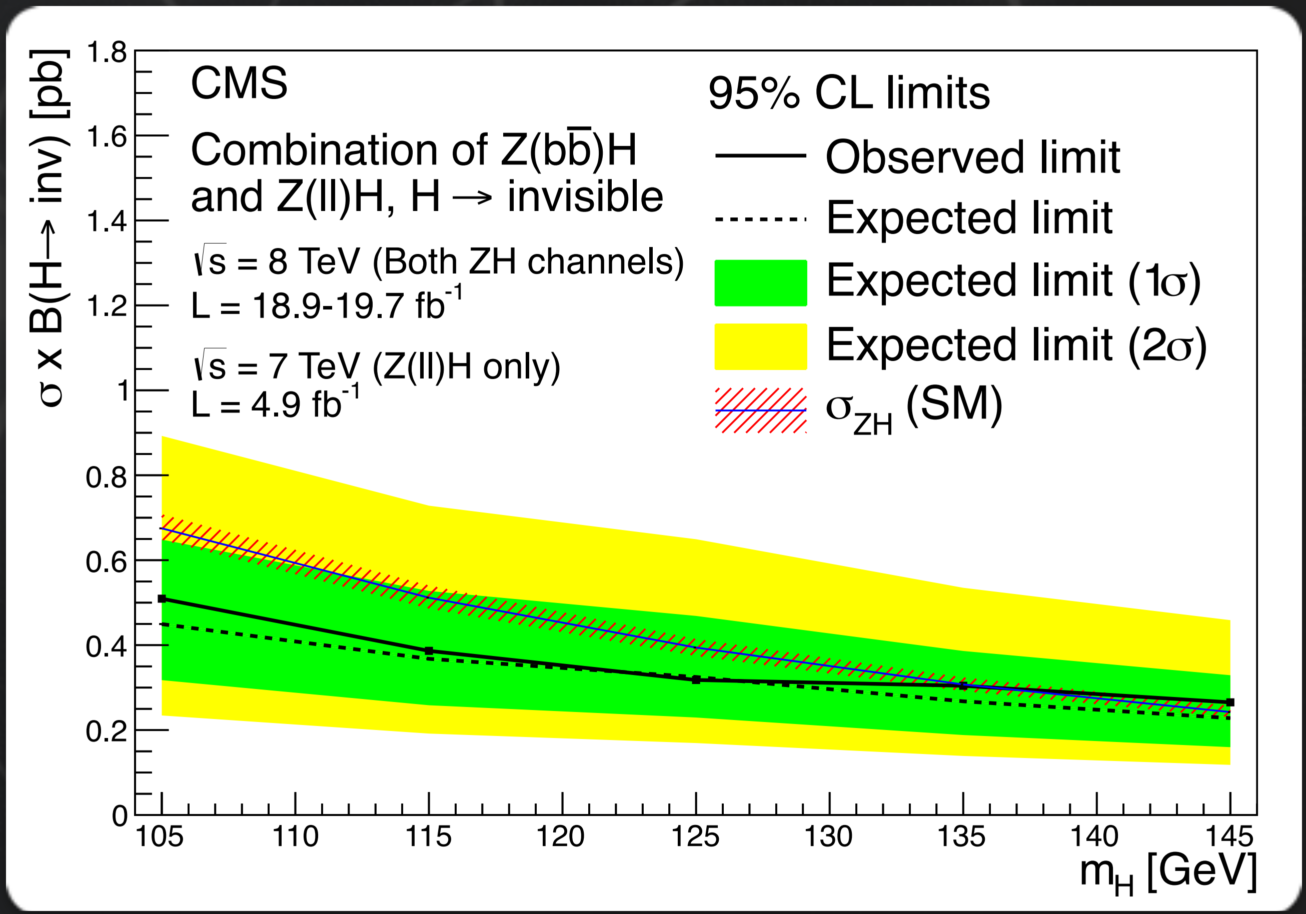


H→inv. Prospects

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.

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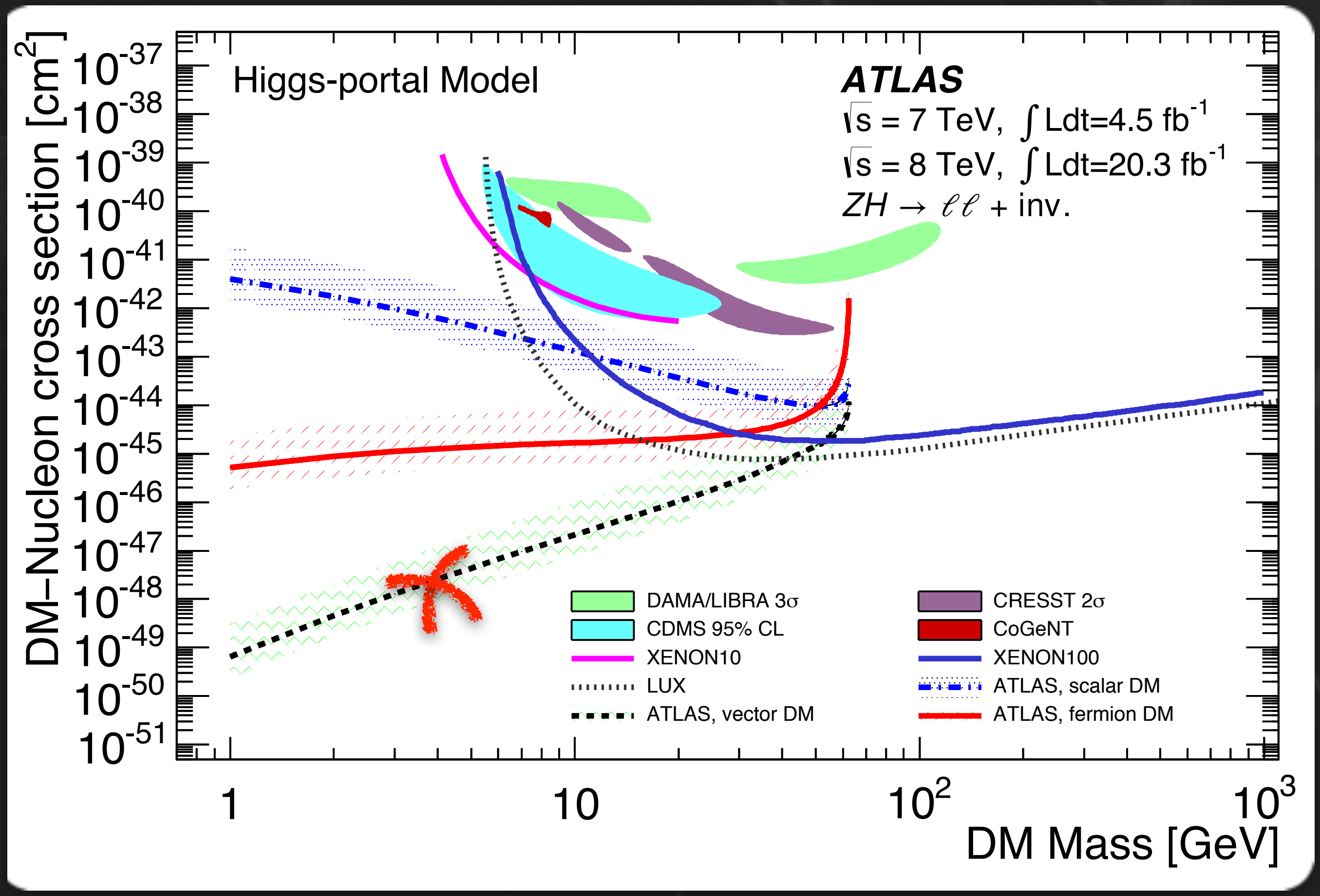
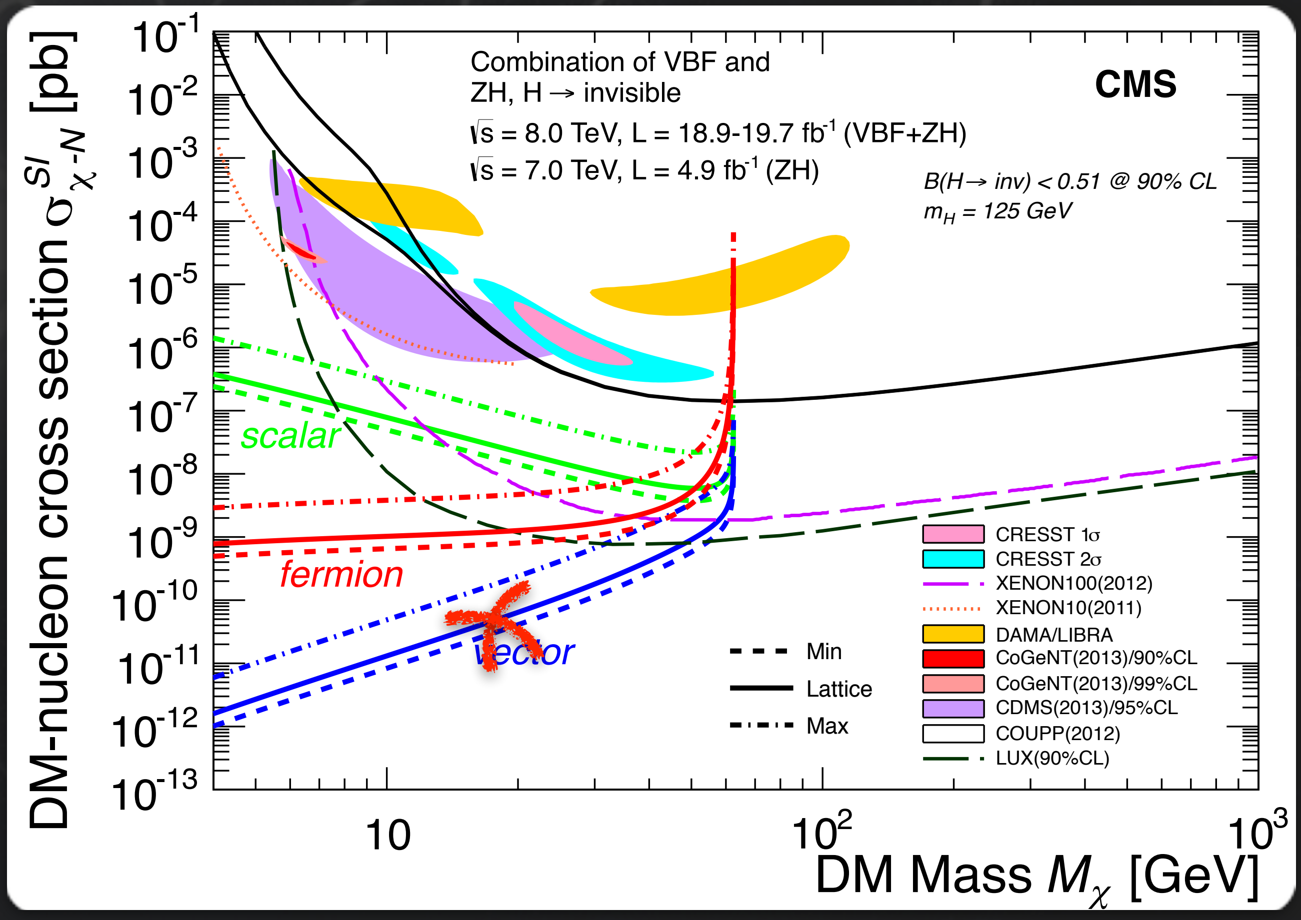


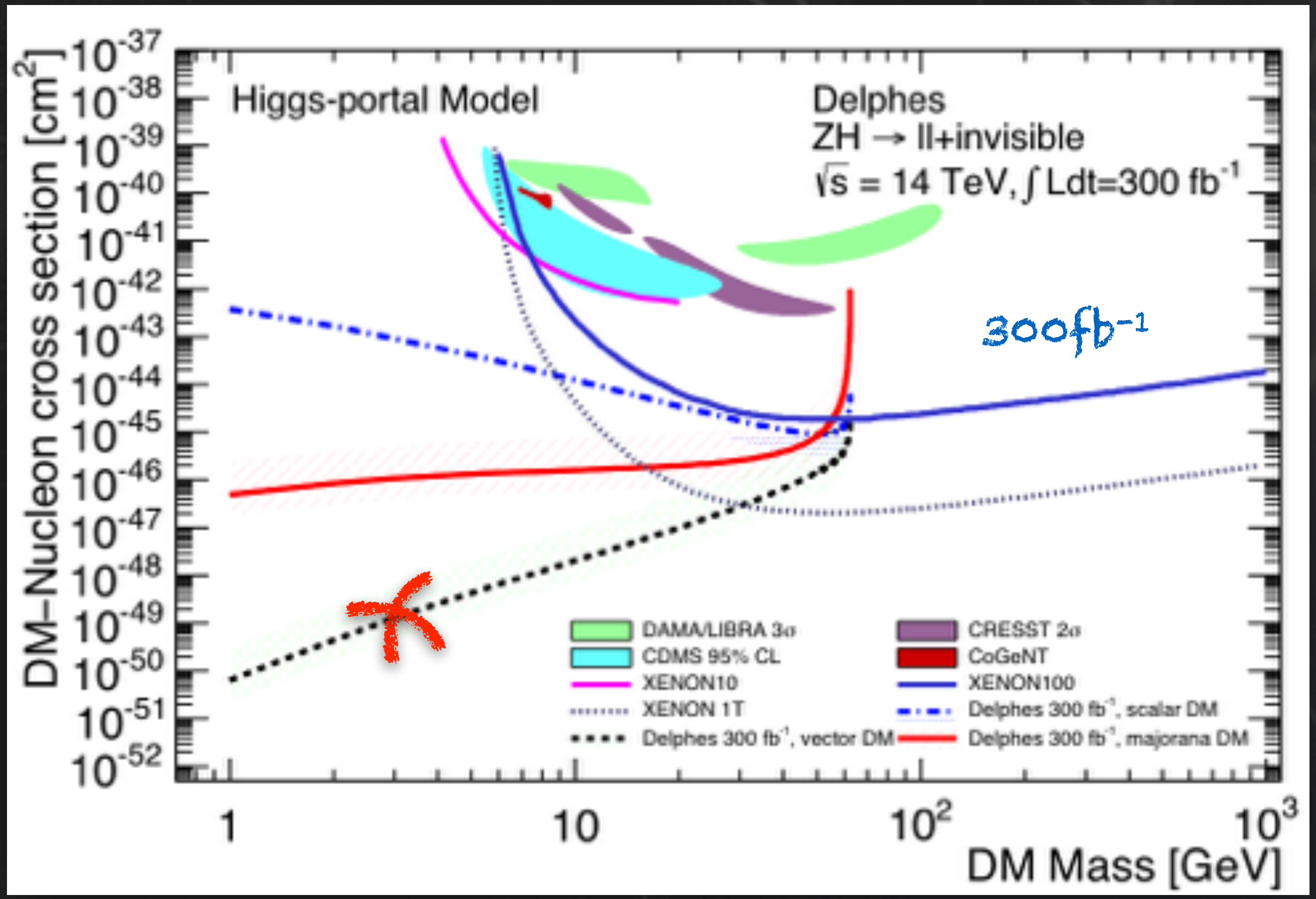


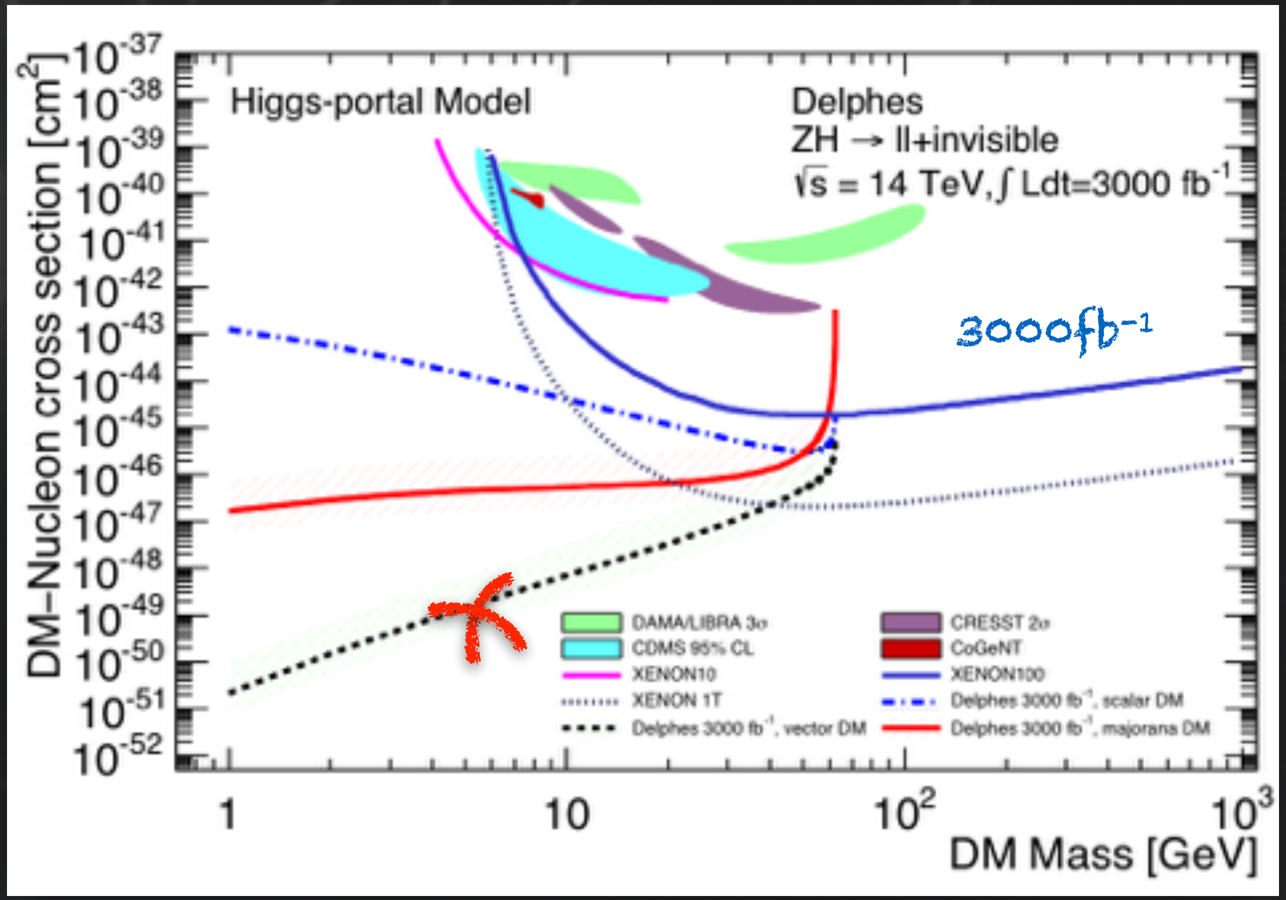
Limits for scalar (fermion) DM:
~ 10^{-41} (10^{-45})cm^2

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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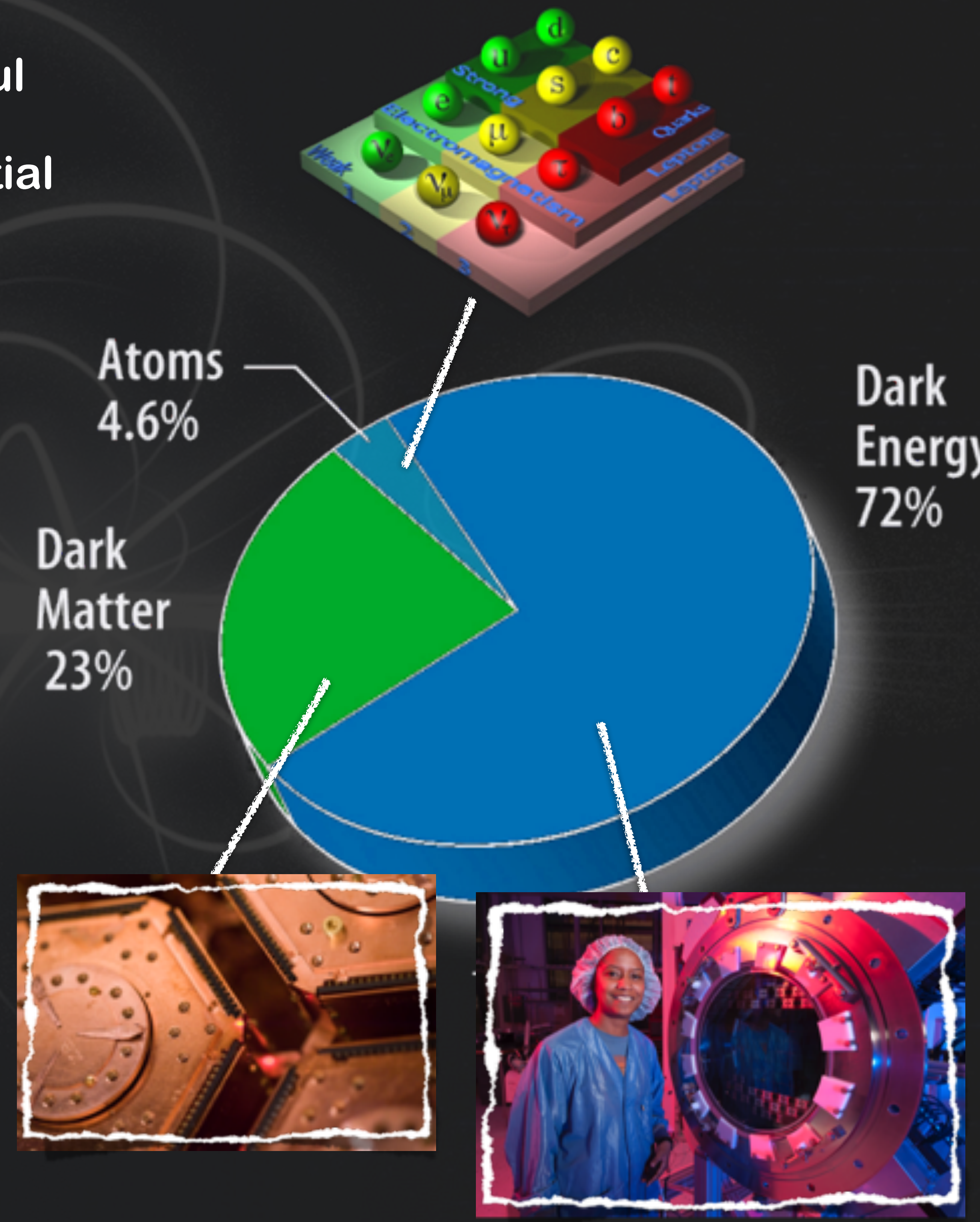
Conclusion

arXiv:1310.8621

- **DM searches at collider** are very powerful
  - **HL-LHC** offers **great discovery** potential
  - **Multi-pronged approach**:
    - SUSY searches
    - Direct collider searches (Mono-X)
    - Precision measurements (Higgs, Dijet,…)
- **Future collider needed to probe** all or largest part of **allowed phase space**
- **DM can only be discovered in an interdisciplinary effort**
- **Collider provided complementary and unique sensitivity** to direct and indirect searches
- **Exciting and quickly developing field**



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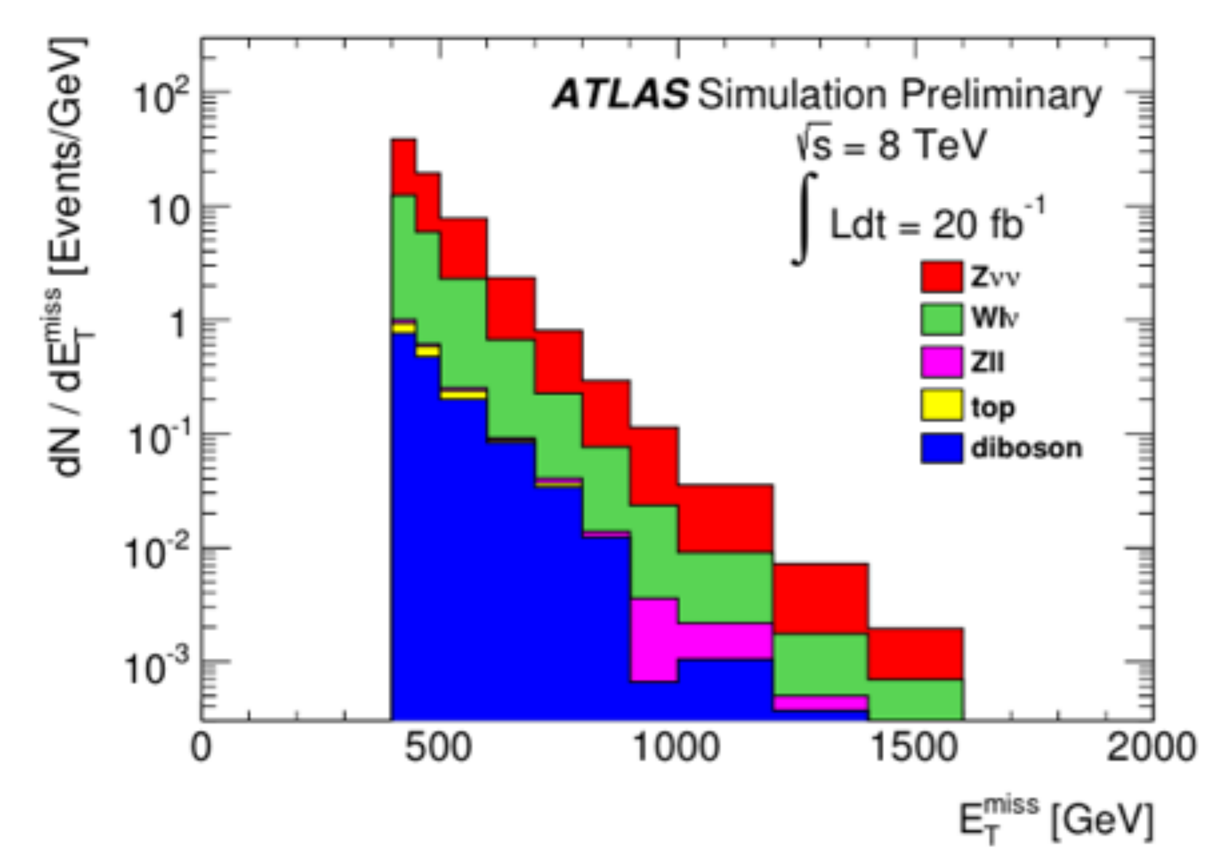
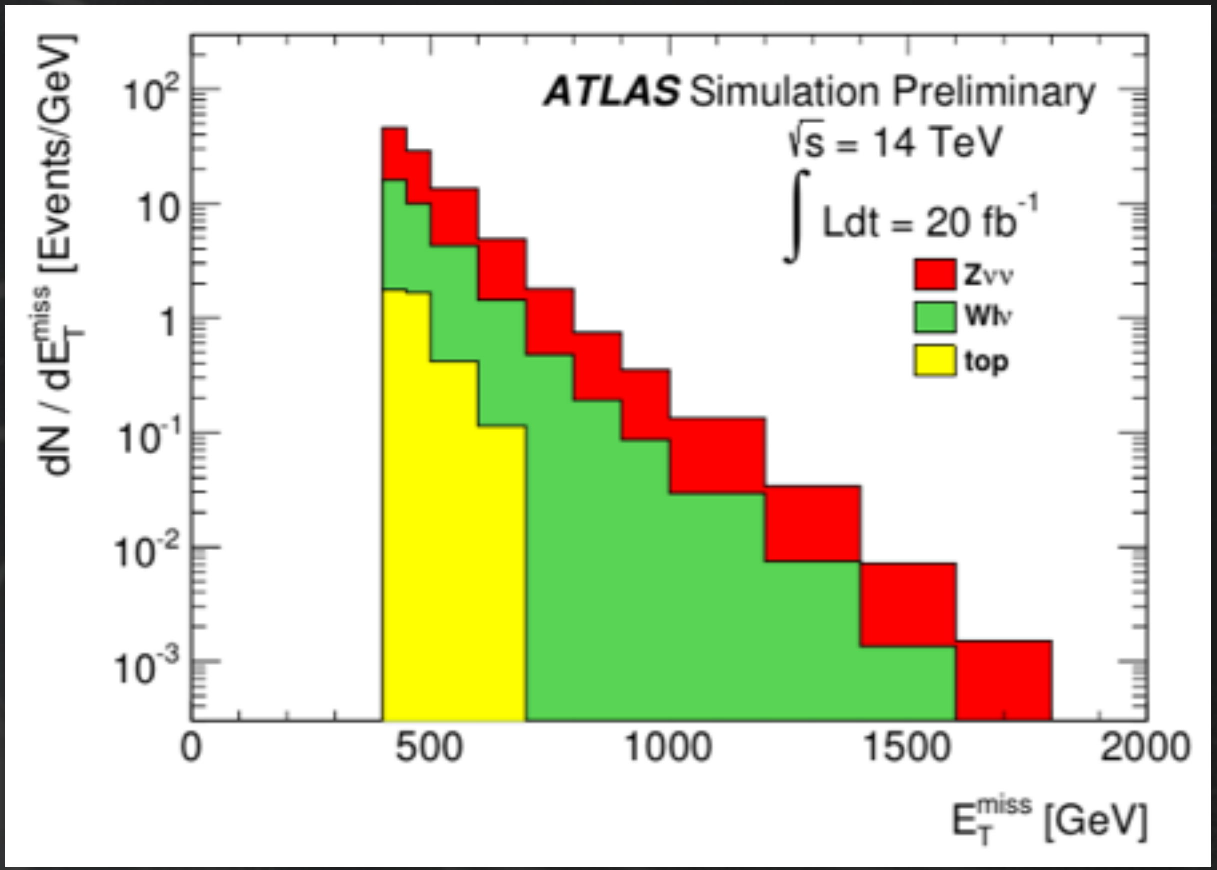
Backup

Mono-Jet Projections

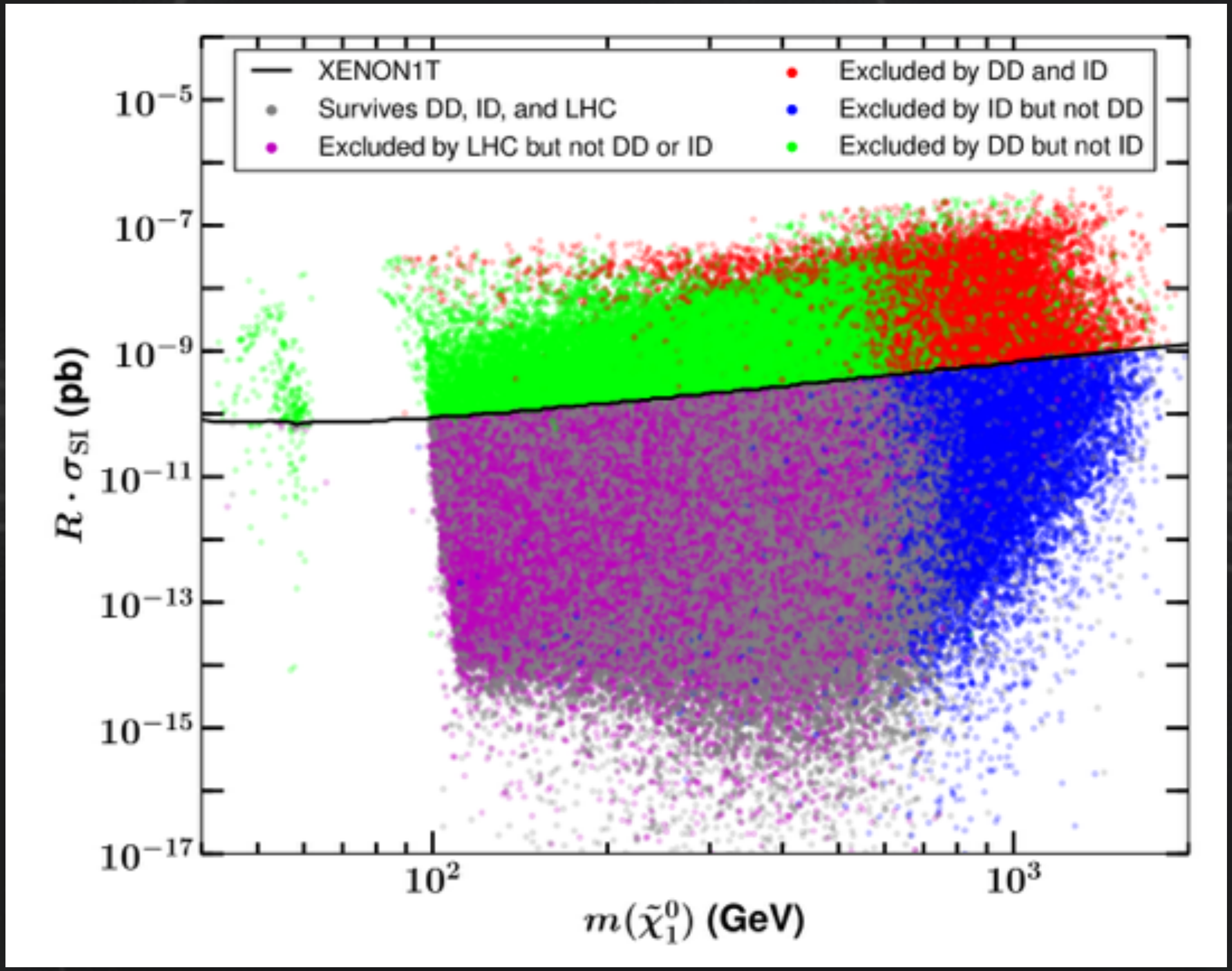
ATLAS-PHYS-PUB-2014-007





- Rather **large backgrounds**
- Dominant backgrounds remain the same

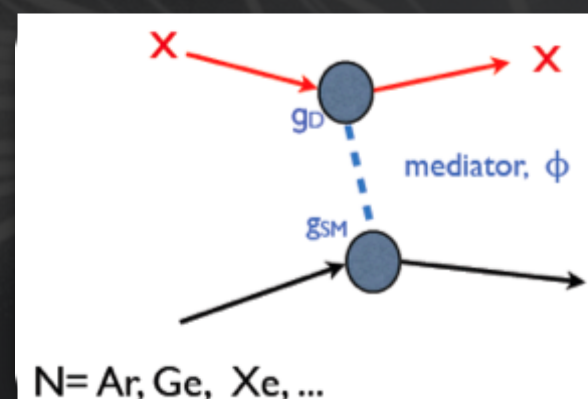
		$\sqrt{s}$ = 8 TeV L = 20 fb^{-1}	$\sqrt{s}$ = 14 TeV L = 20 fb^{-1}	
			Phase-I μ = 60	Phase-II μ = 140
$E_T^{miss} > 400$ GeV	$Z \to \nu\nu$+jets	2800	3600	3900
	D5, M_χ = 50 GeV	200	3300	3300
	D5, M_χ = 400 GeV	120	2500	2600
$E_T^{miss} > 600$ GeV	$Z \to \nu\nu$+jets	260	510	580
	D5, M_χ = 50 GeV	39	1100	1100
	D5, M_χ = 400 GeV	26	910	960
$E_T^{miss} > 800$ GeV	$Z \to \nu\nu$+jets	37	100	110
	D5, M_χ = 50 GeV	8.5	390	400
	D5, M_χ = 400 GeV	6.6	340	350

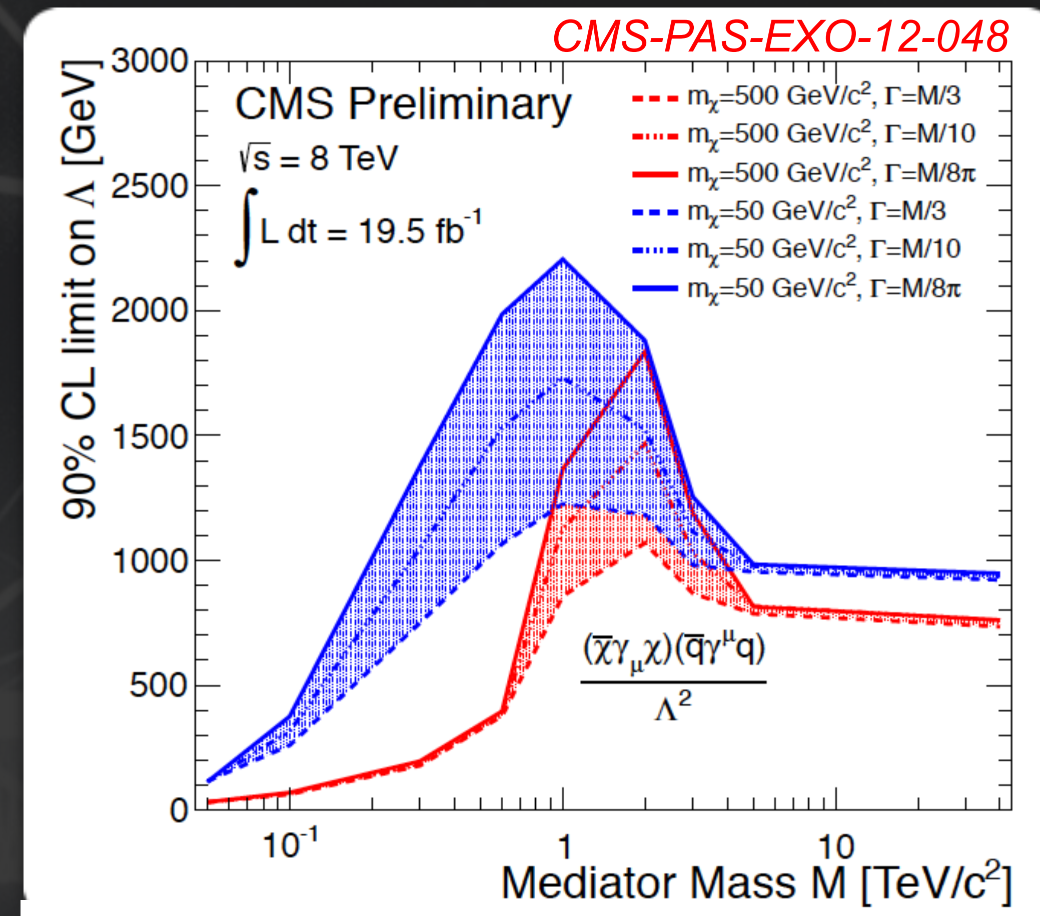


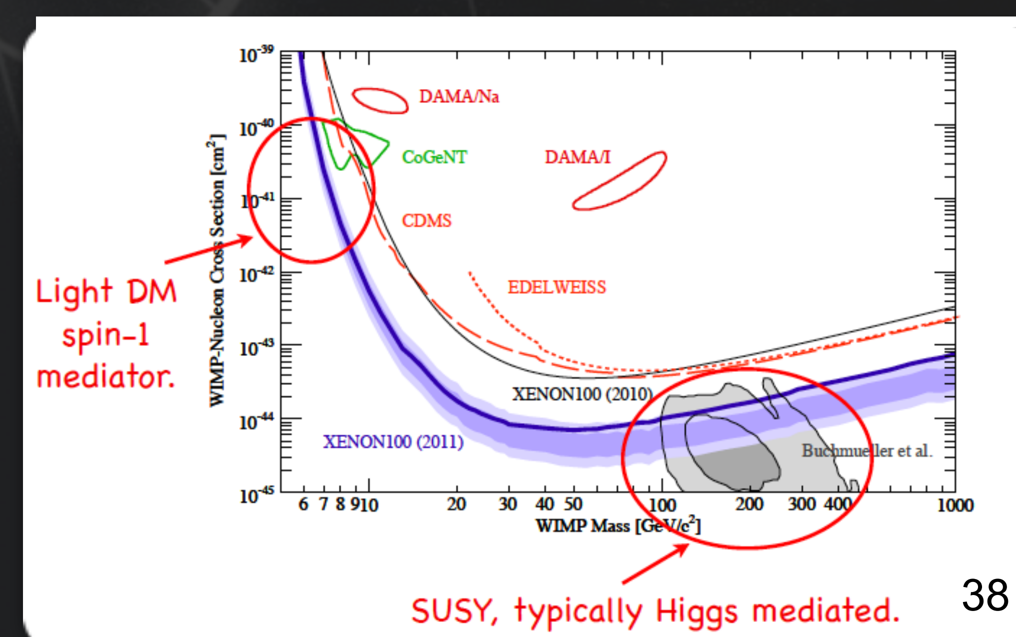
arXiv:1310.8621

Searching for the Mediator

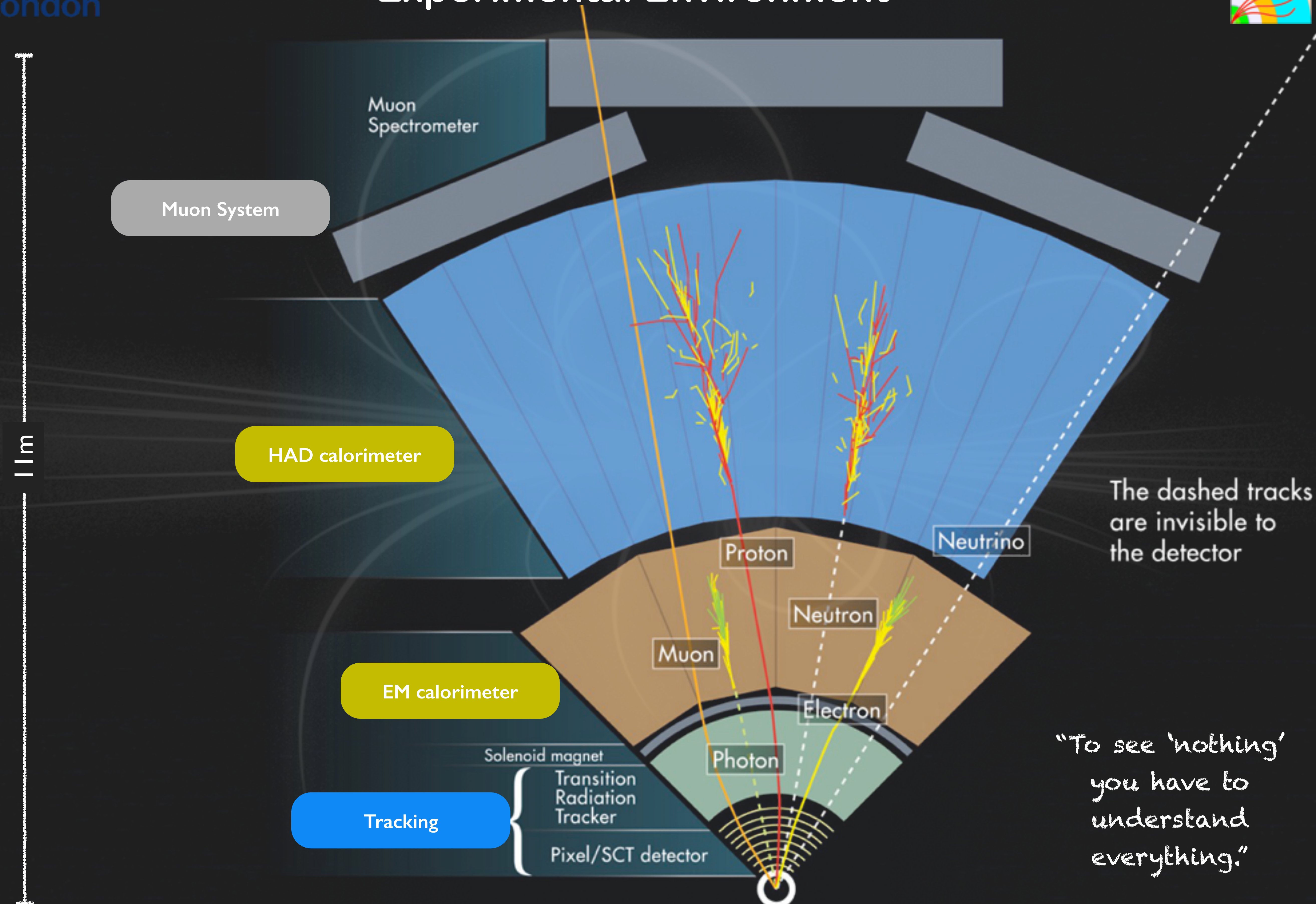
- For **energies larger than the mediator mass**, **probing** more structure of the **s-matrix**
  - Depending on details for the mediator
  - Then the mediator itself can be discovered
- Typical examples of **mediator Φ**:
  - **Φ = Higgs (spin 0)**
    - $M_\Phi \sim 100$ GeV
    - $g_{SM} \sim (100\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







Experimental Environment



The dashed tracks are invisible to the detector

"To see 'nothing' you have to understand everything."

Higgs Mediator

- Constraints on the invisible Higgs rate at the LHC can be translated into limits in the WIMP-nucleon cross section and compared with direct-detection experiments.

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \ ,$$
$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu ,$$
$$\Delta\mathcal{L}_f = -\frac{1}{2}m_f f f - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H f f + \text{h.c.} \ . \qquad (5)$$

$$\text{BR}_\chi^{\text{inv}} \equiv \frac{\Gamma(H\to\chi\chi)}{\Gamma_H^{\text{SM}} + \Gamma(H\to\chi\chi)} = \frac{\sigma_{\chi p}^{\text{SI}}}{\Gamma_H^{\text{SM}}/r_\chi + \sigma_{\chi p}^{\text{SI}}}$$

r_χ=function of M_χ and known masses and couplings (assuming M_H=125 GeV)

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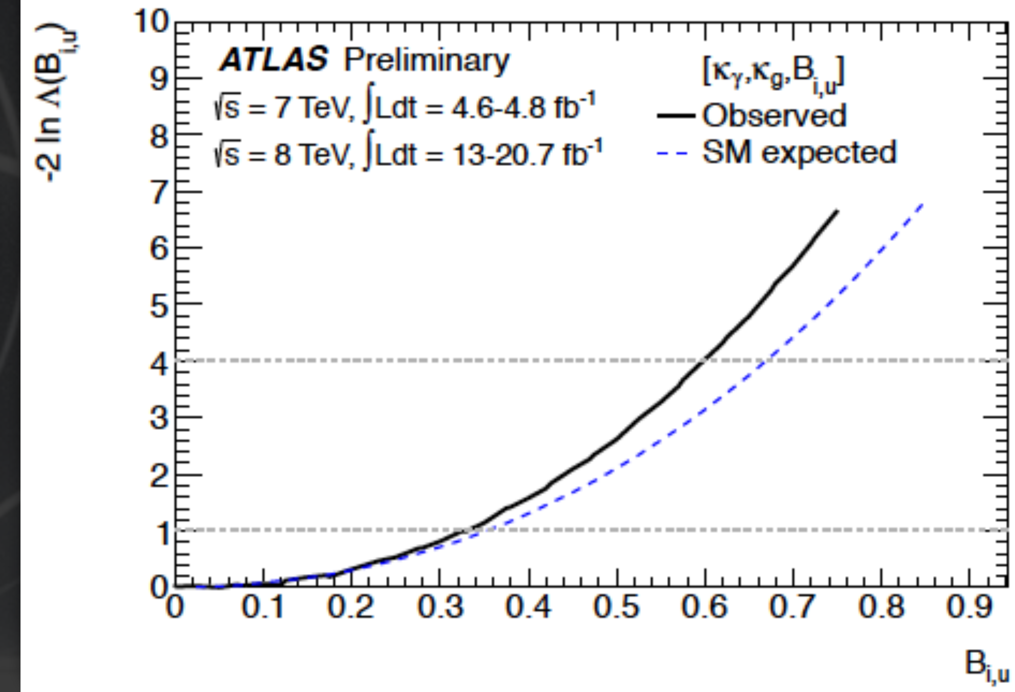
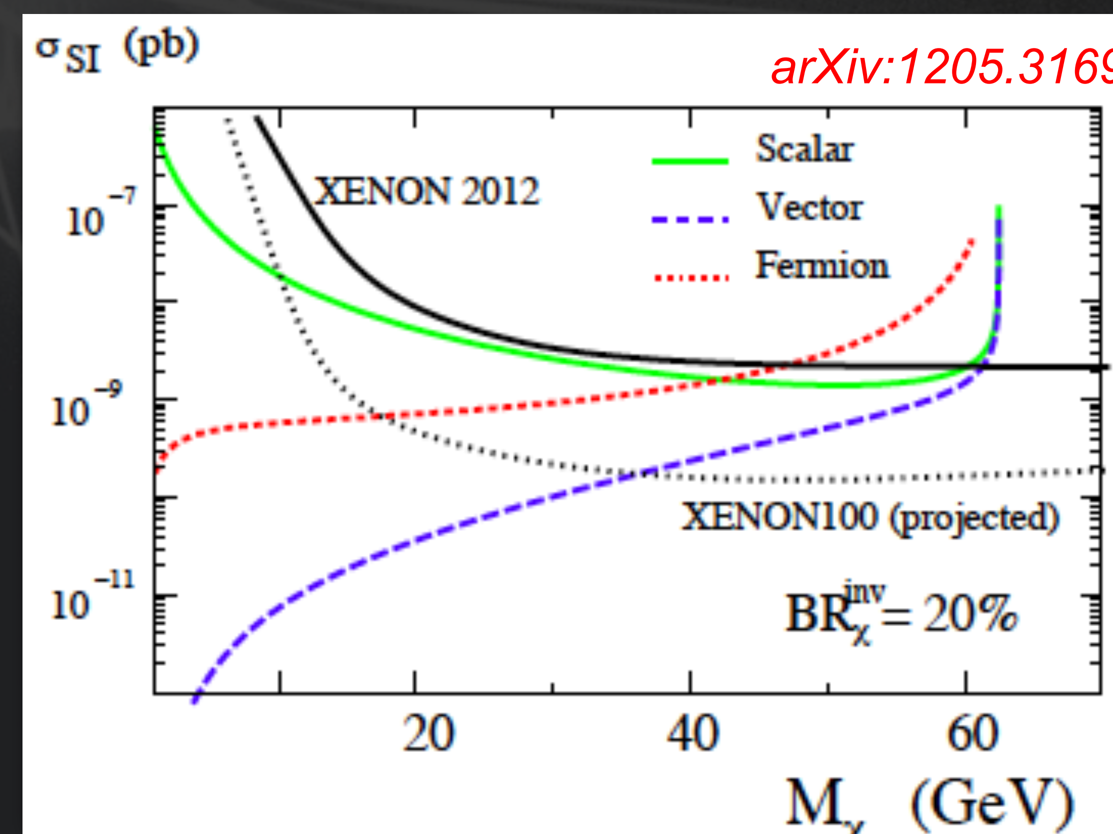
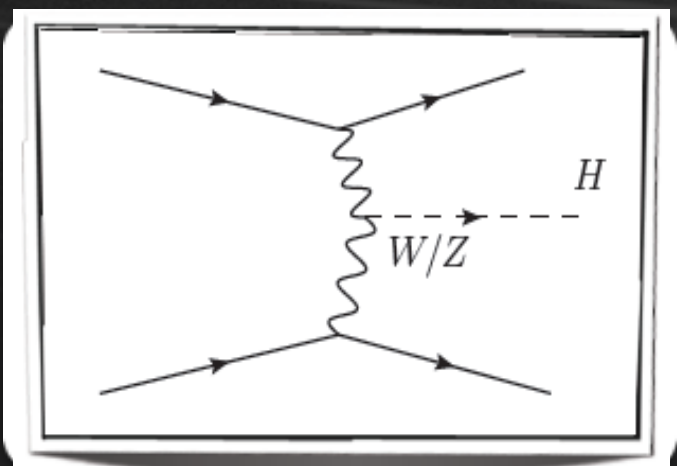


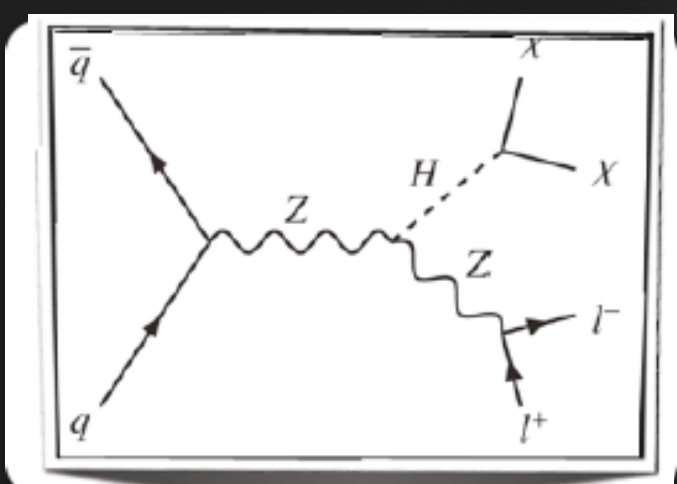
arXiv:1205.3169

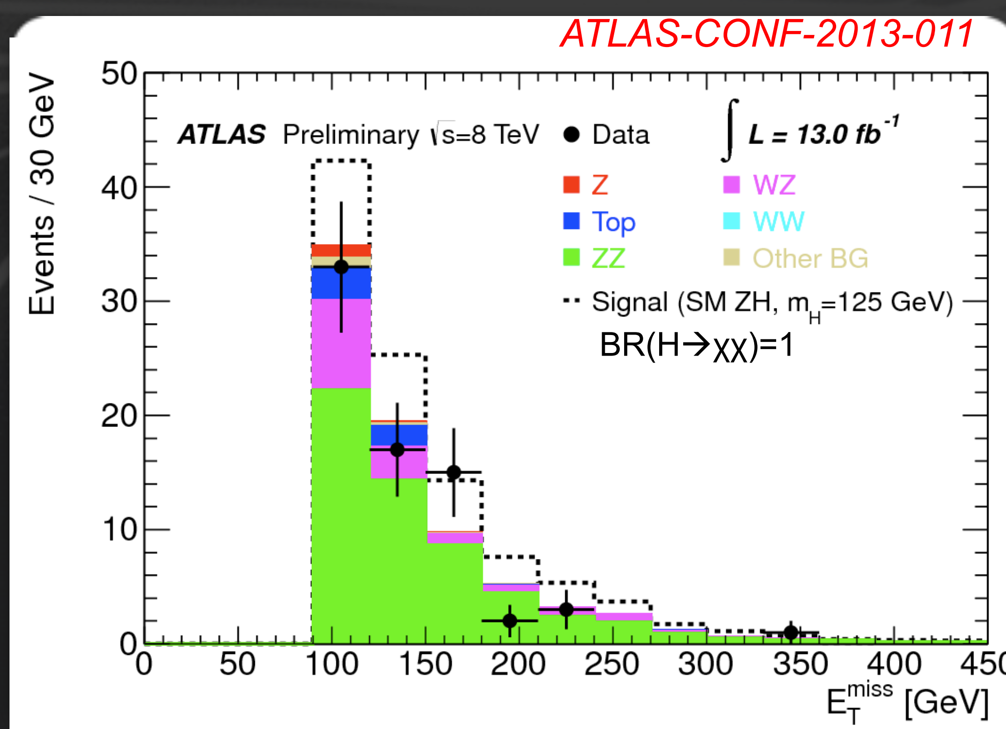


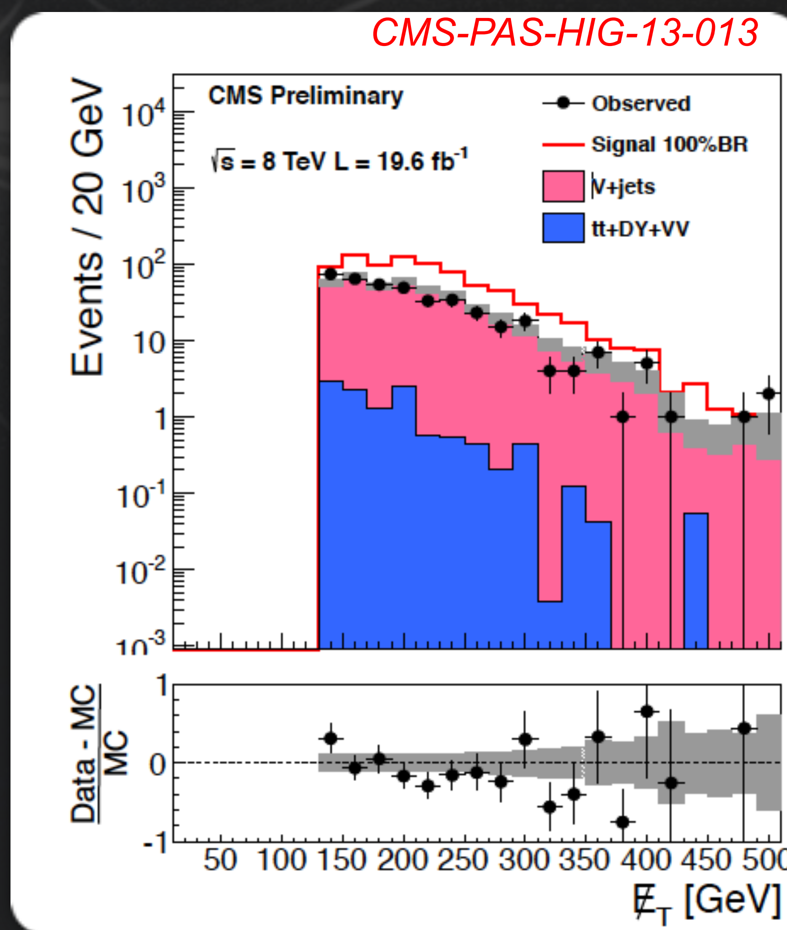
Higgs->Inv

- LEP excluded invisibly decaying Higgs boson for mH < 114.4 GeV assuming it is produced in association with Z and that it decays predominantly to invisible particles.
- At the LHC can search for a narrow scalar boson decaying to invisible particles over a mass range between 115 and 300 GeV.





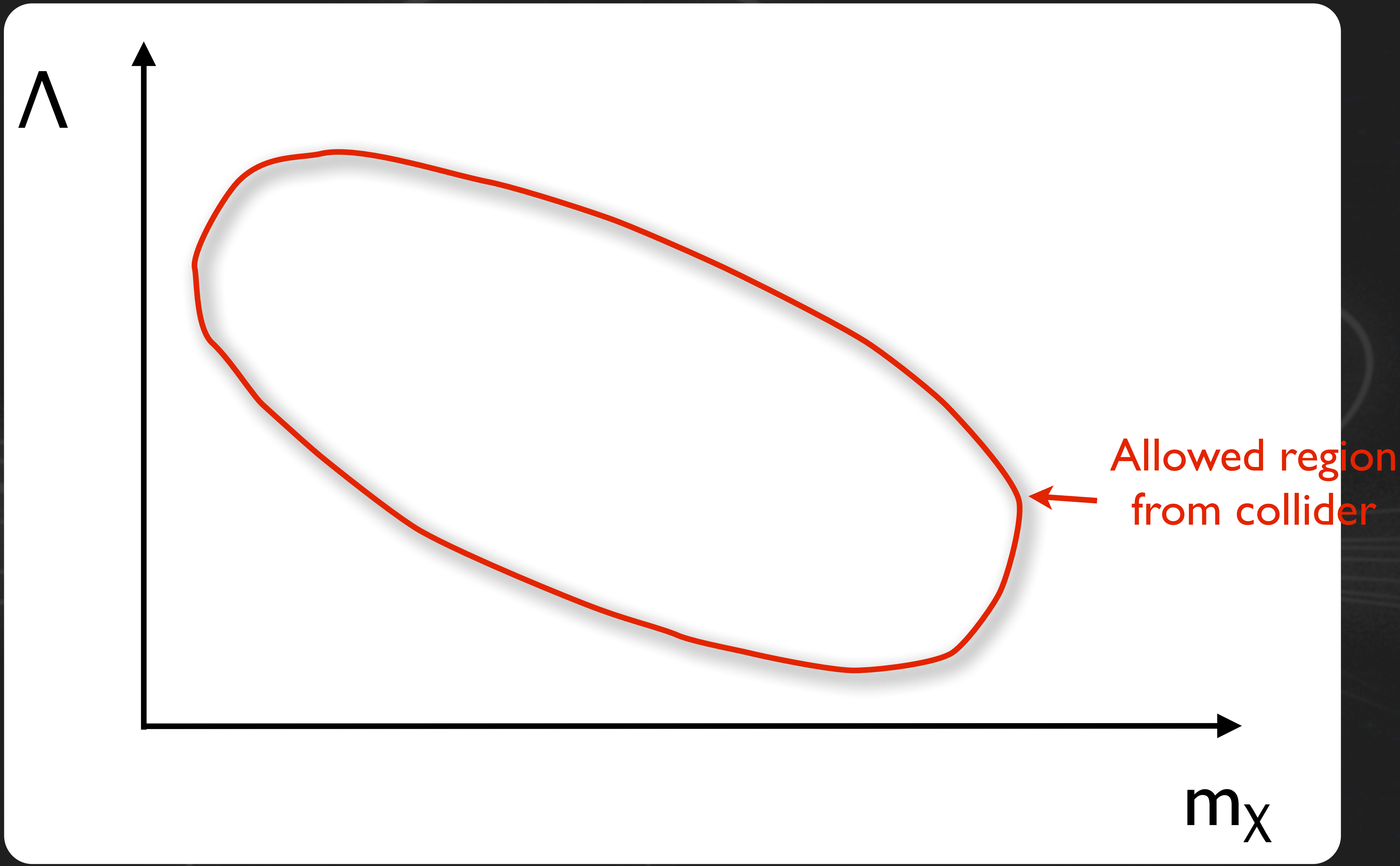




Property Measurement

- Suppose we see an excess, how to determine nature of DM candidate?

Property Measurement



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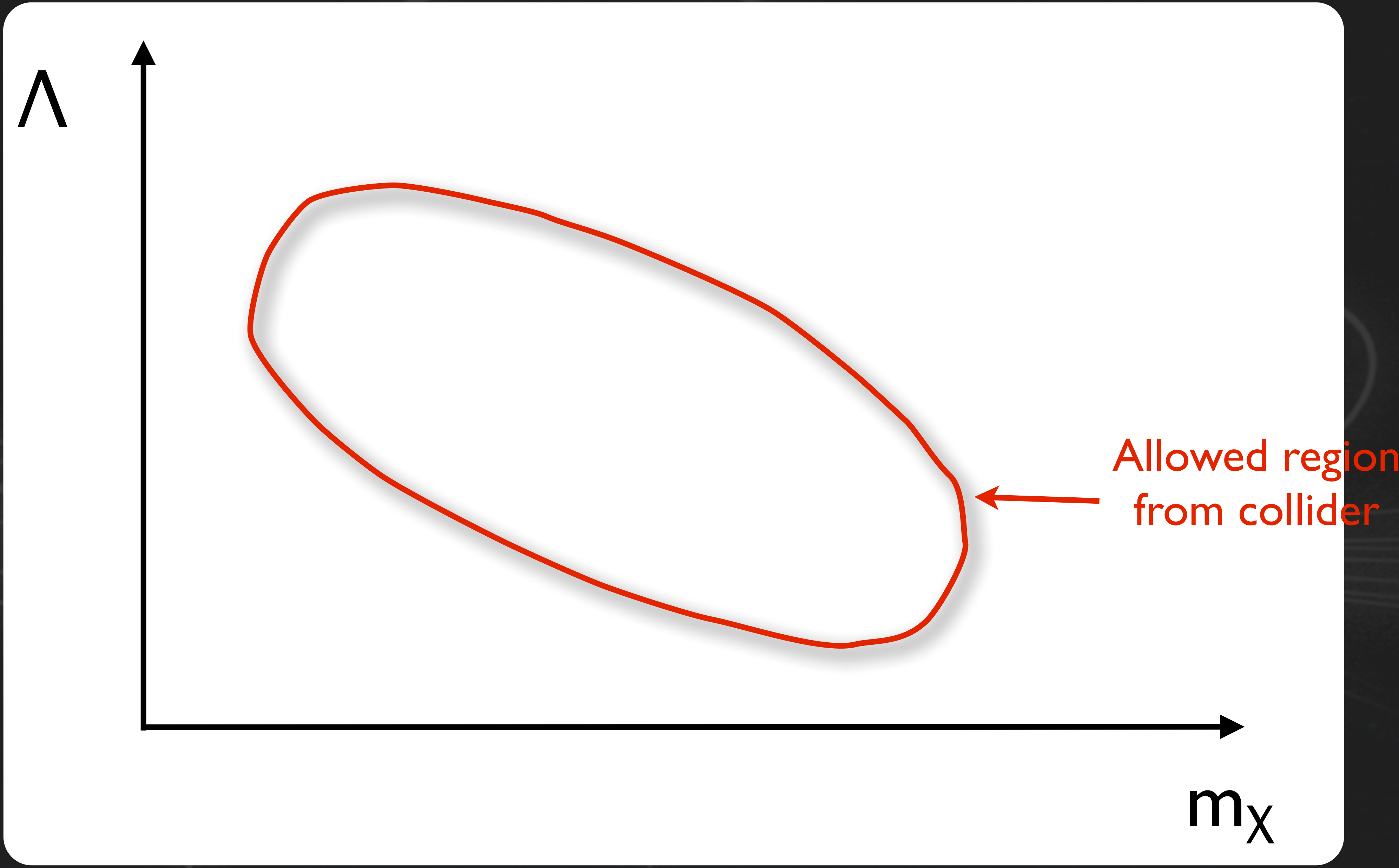
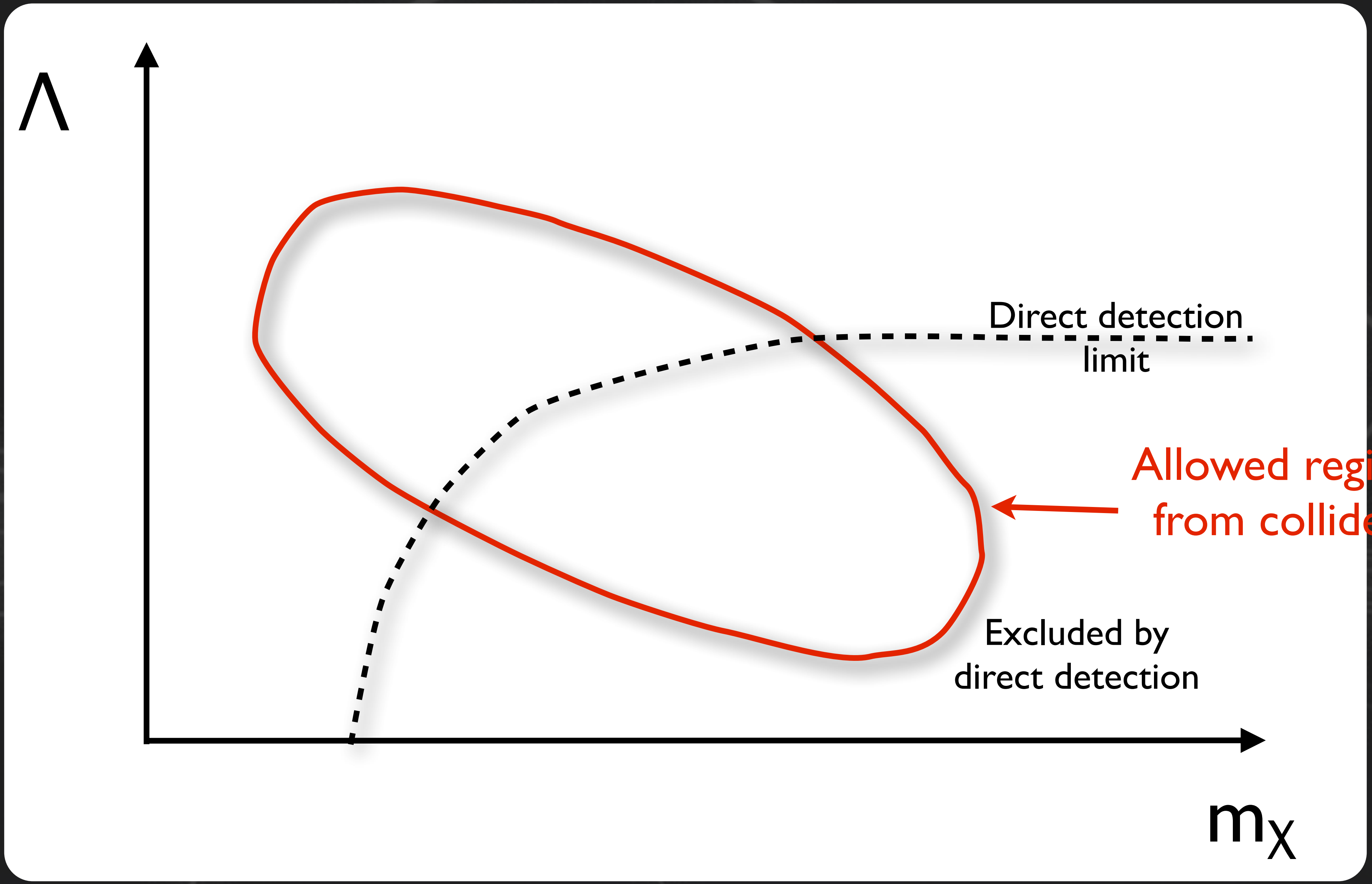
Property Measurement



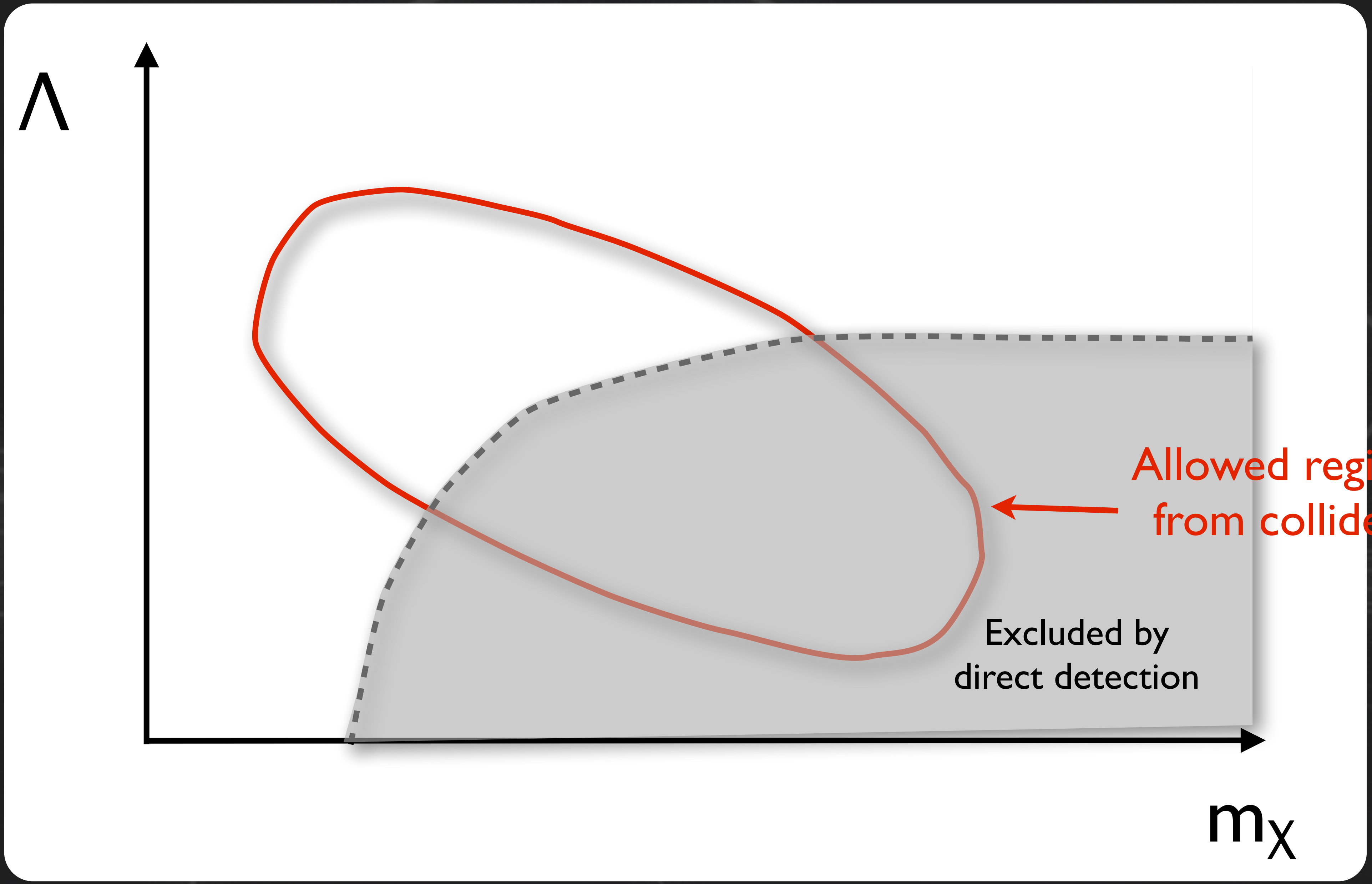
- Improve measurement and couplings to various particles
- Constrain possible interactions and/or operators

Property Measurement



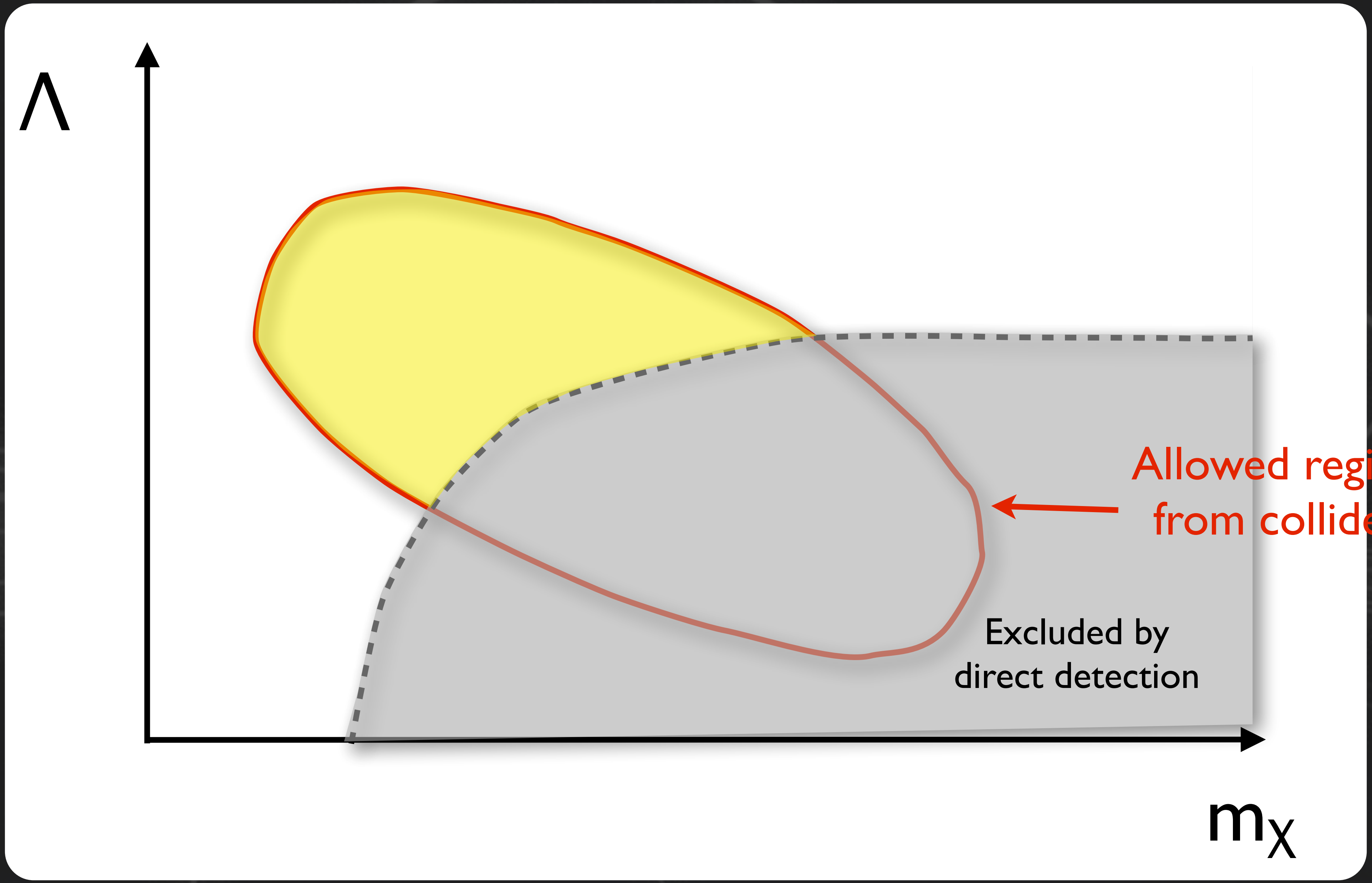
- Obtain of mass/rate by fits to kinematic variables, e.g:
  - Study operators by comparing rates up/down couplings
- Information about couplings to up and down type quarks, asymmetries

Property Measurement



- Correlate with other measurements and experiments (LEP/LHC/direct detection/relic density etc),
- Different sensitivities between direct and collider detection
  Dirav vs. Majorana DM
  Scalar vs Fermion DM
- Does ‘discovery region’ agree with relic density calculations?

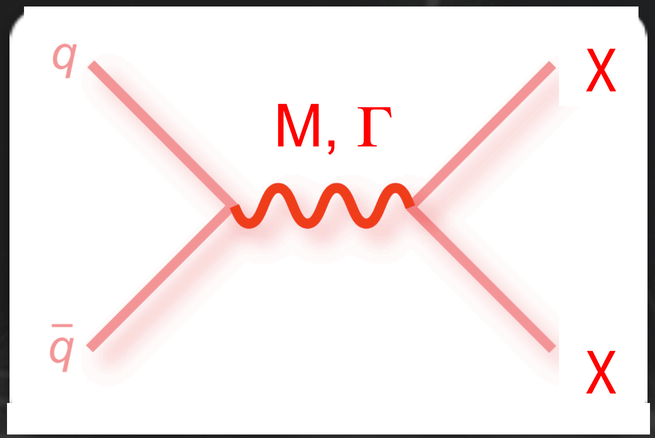
Property Measurement



- Inter-disciplinary could lead to significant information for a Dark Matter candidate

Title Text

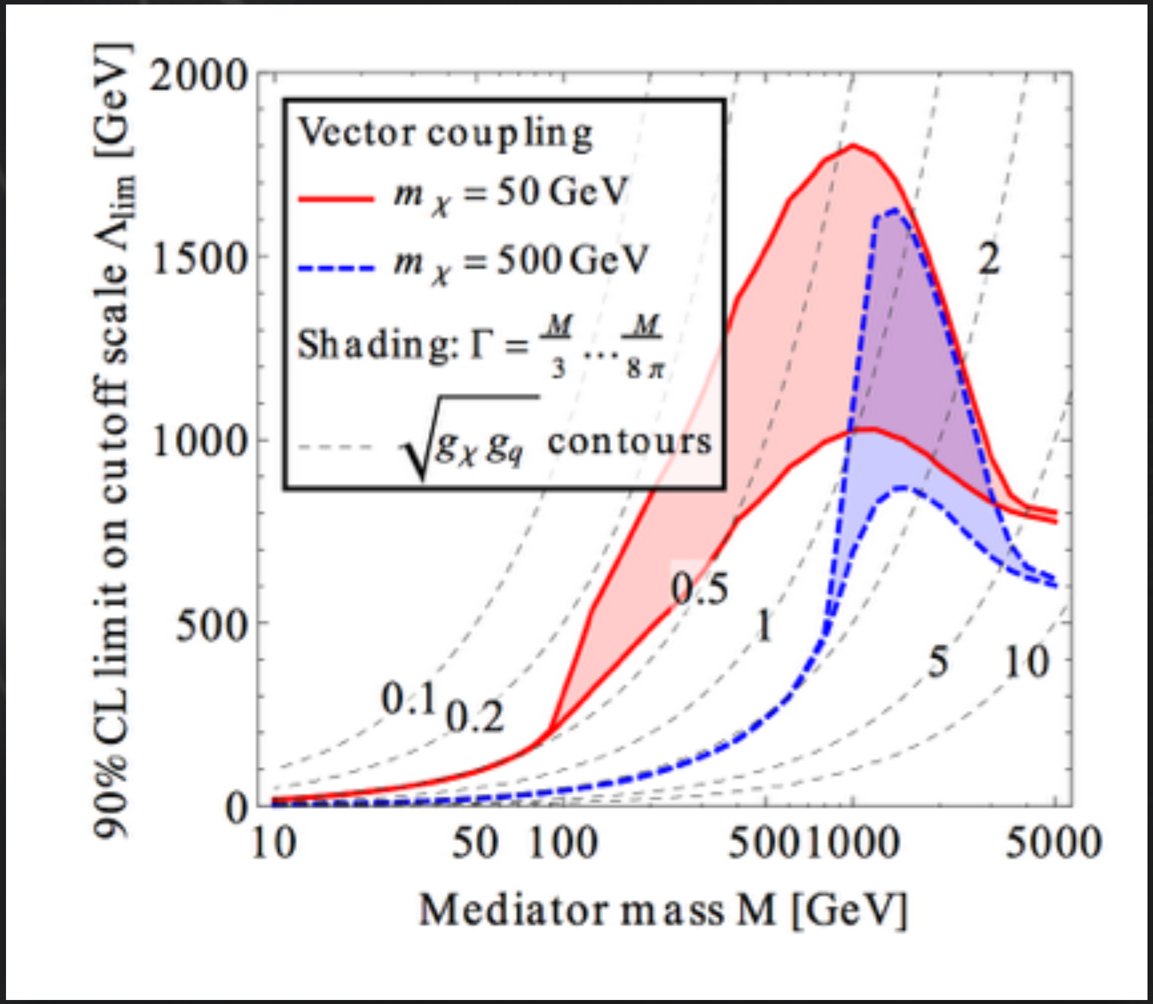
- Exploring the scenario of a vector coupling and a light mediator with mass M and with Γ:



$$\sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2$$

- For M>few x 100 GeV the EFT is adequate and somewhat conservative in the bounds on Λ* (however, note the effective couplings become large).

- For M<100 GeV the actual bounds are much weaker than claimed by the EFT approach.



Ultimate LHC reach

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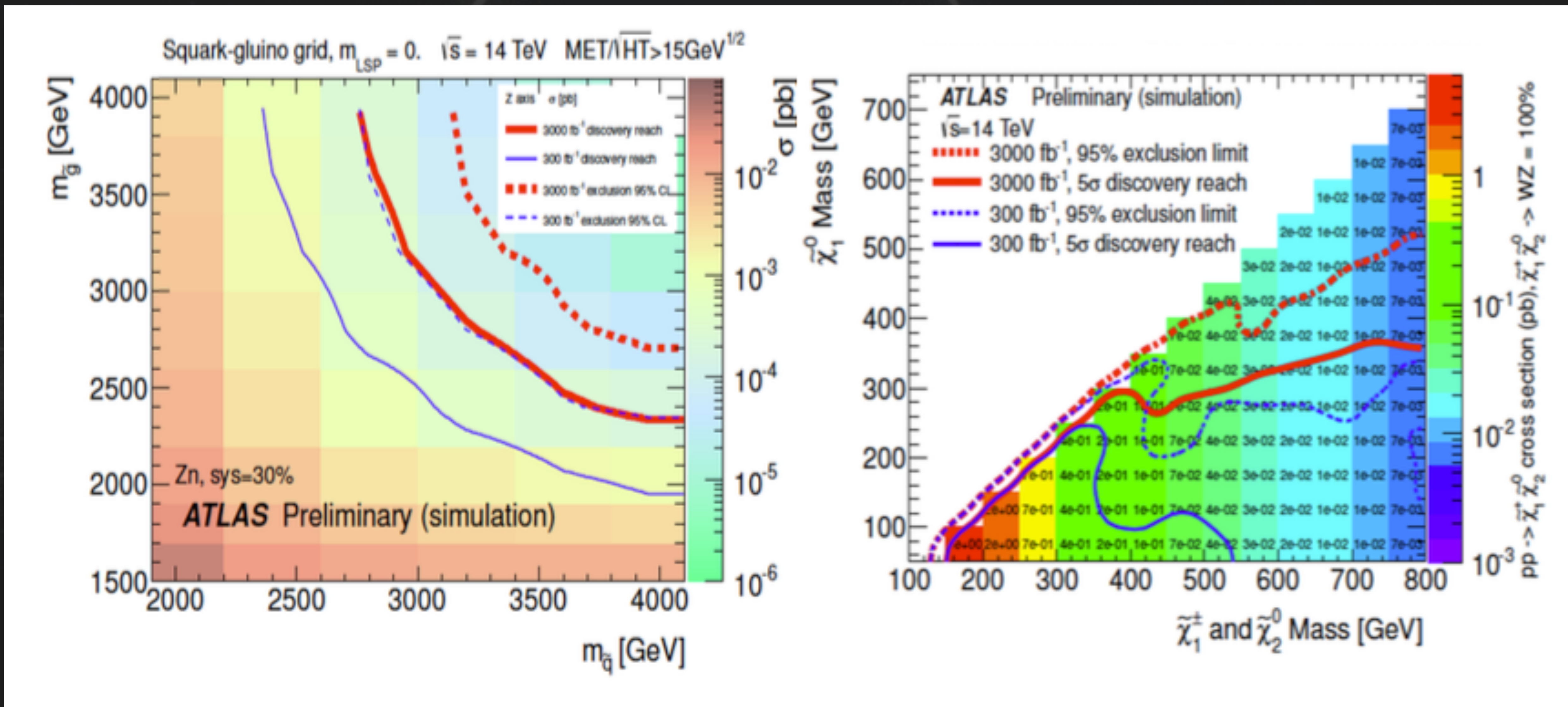
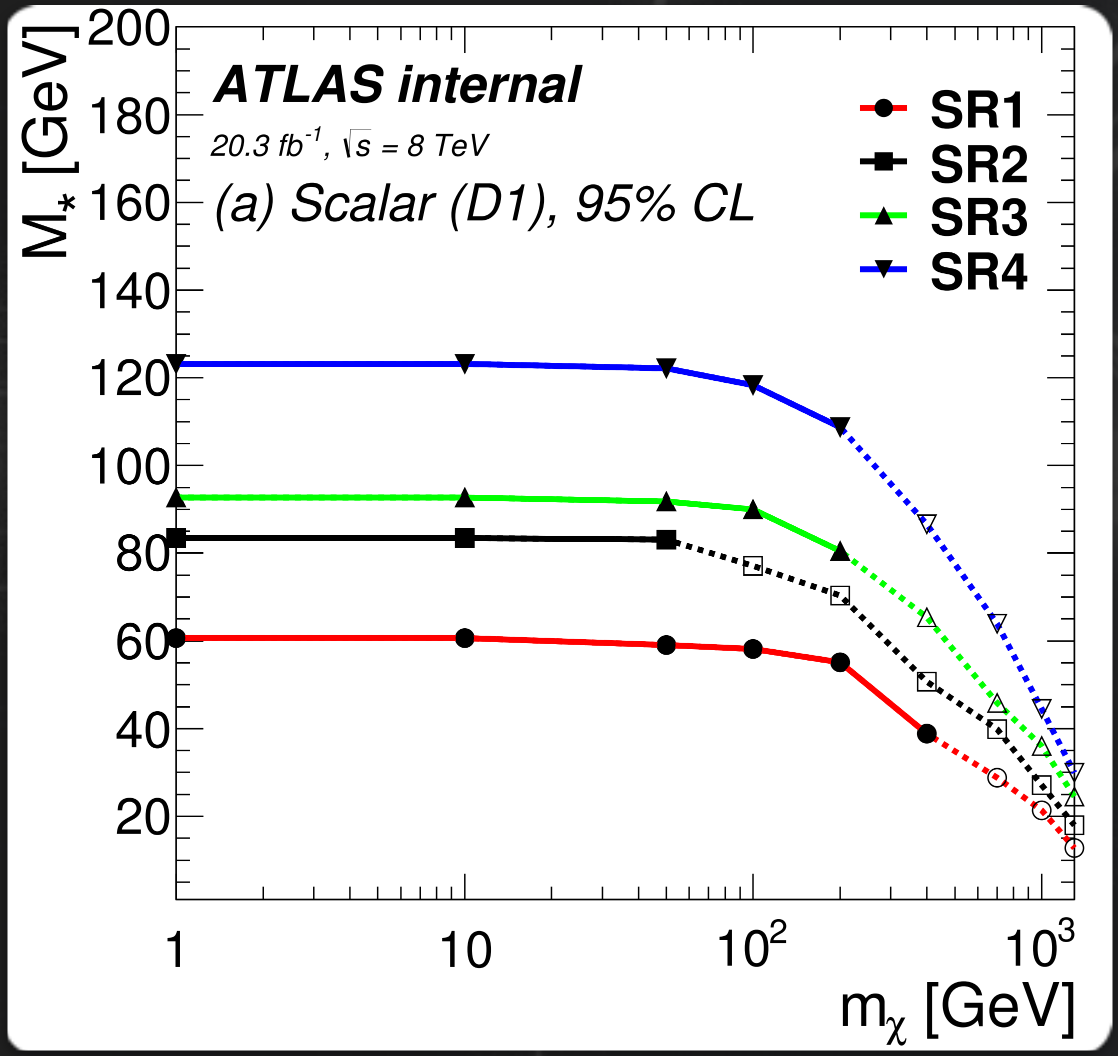


- **Difficult to make these predictions, smart people come up with smart solutions**

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

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

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

Title Text

- DM may couple to Higgs:
  - Use limits in Higgs->inv. BR to set limits on some types of DM
  - Limits only up to DM mass Mχ < MH/2
- First results from ATLAS and CMS present