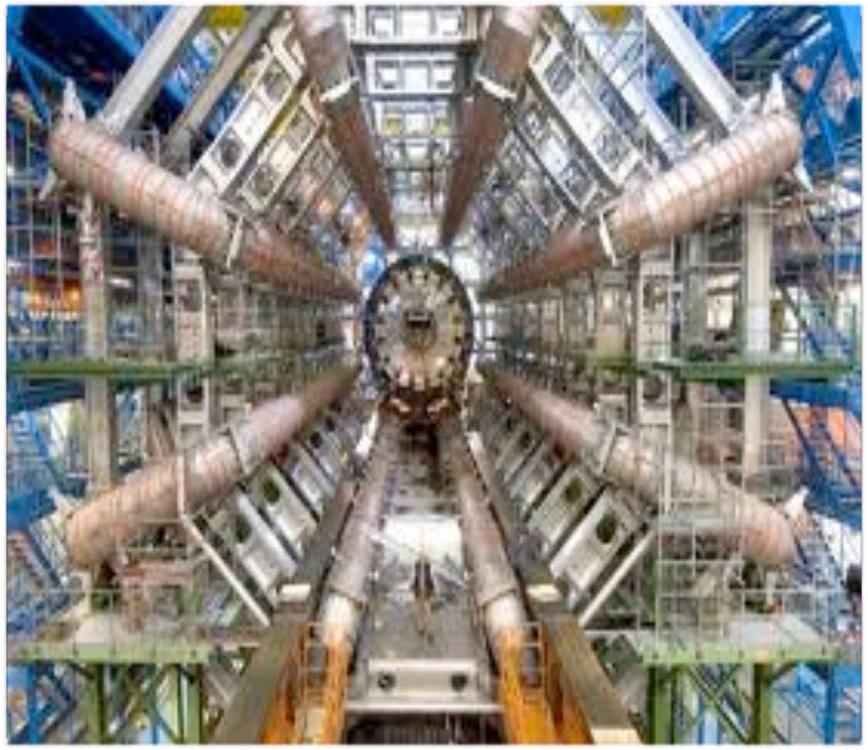
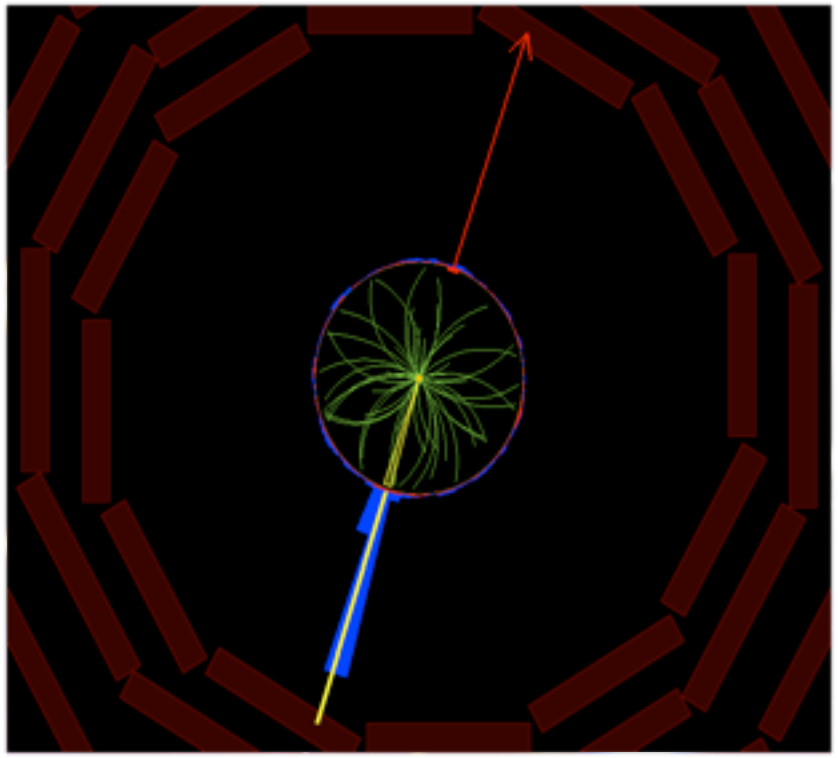
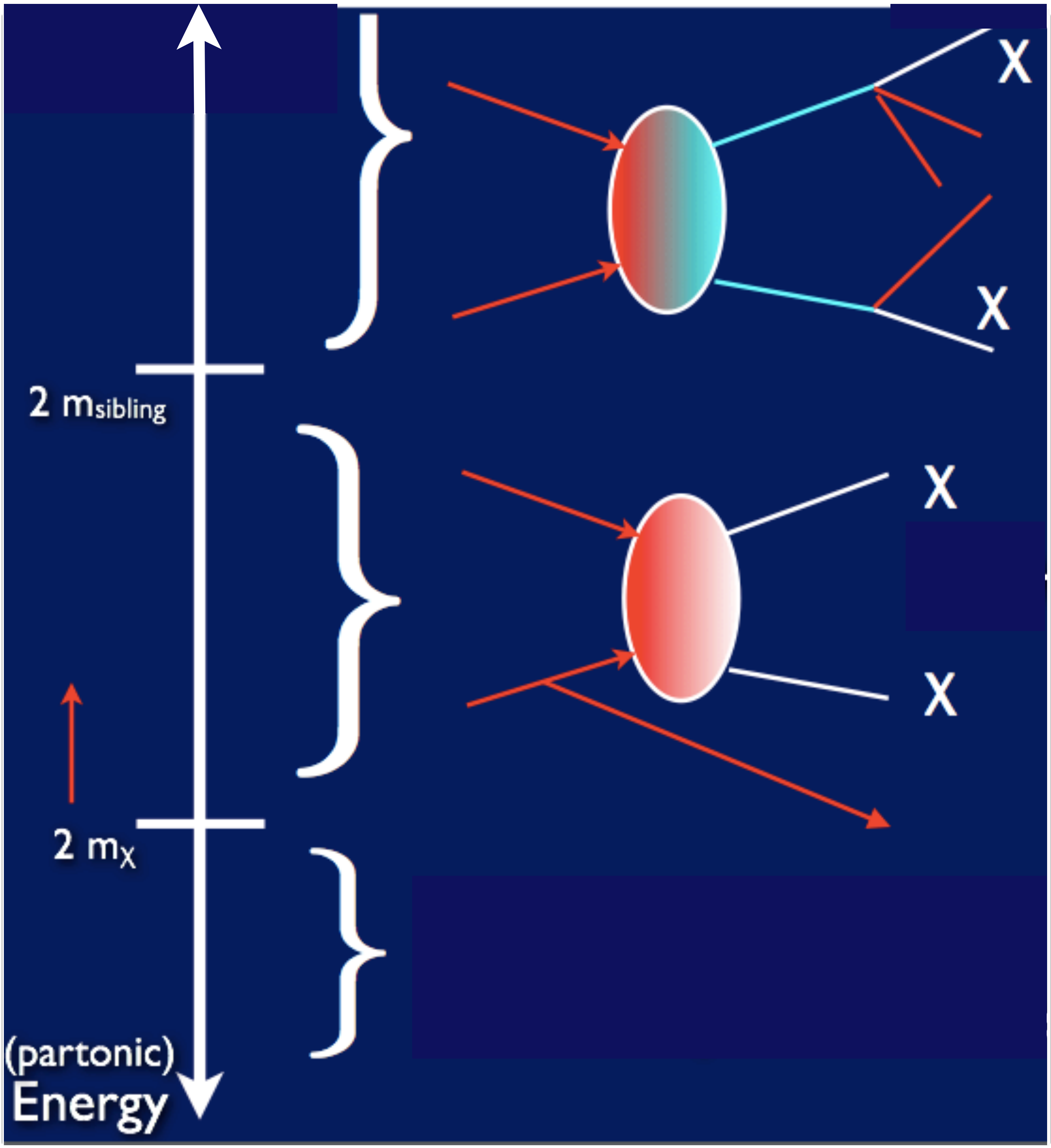




DM searches at the LHC

Sarah Alam Malik
Imperial College London

Searching for dark matter at colliders



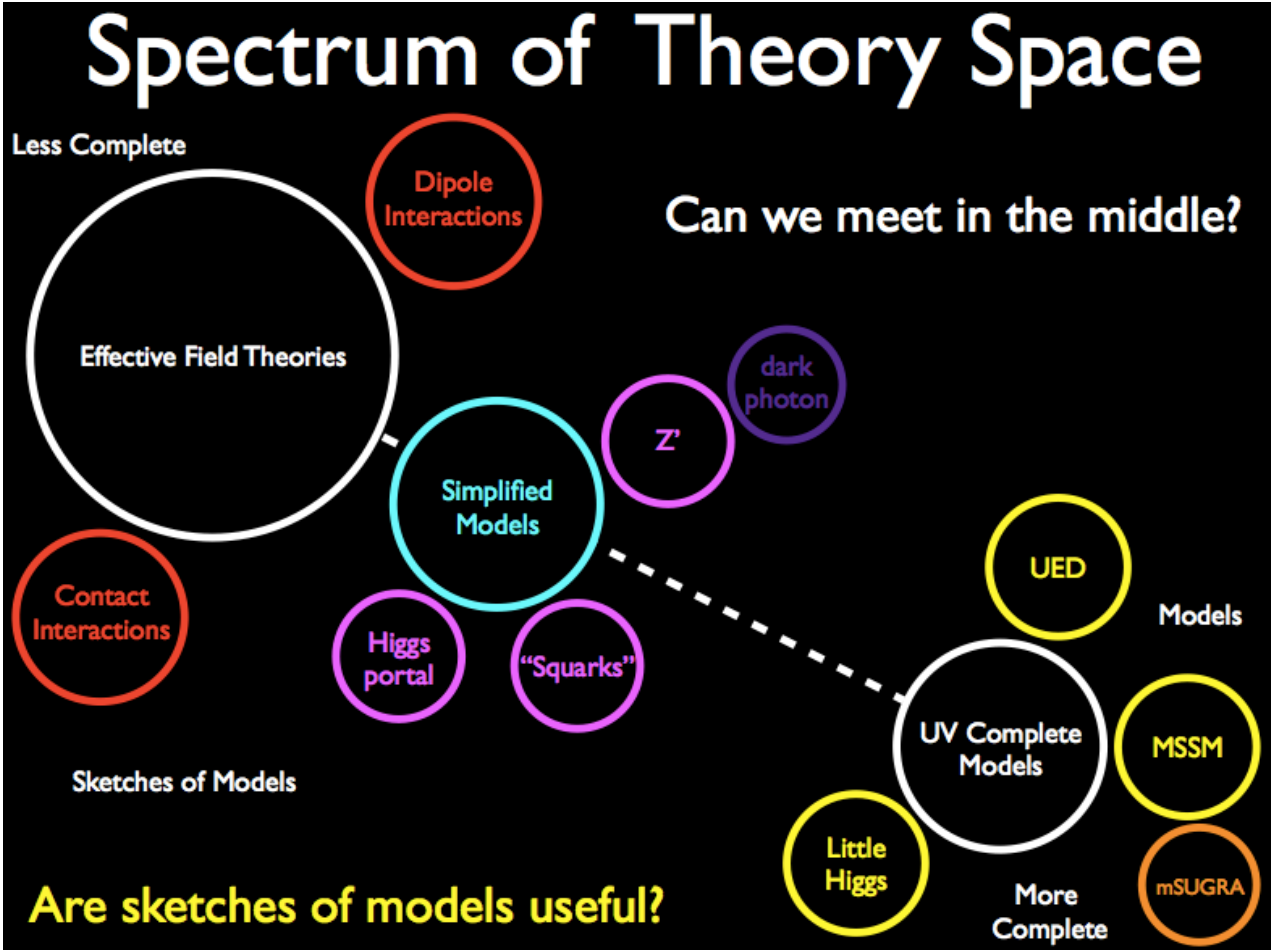
LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC can directly produce WIMP pairs

LHC cannot produce WIMPs

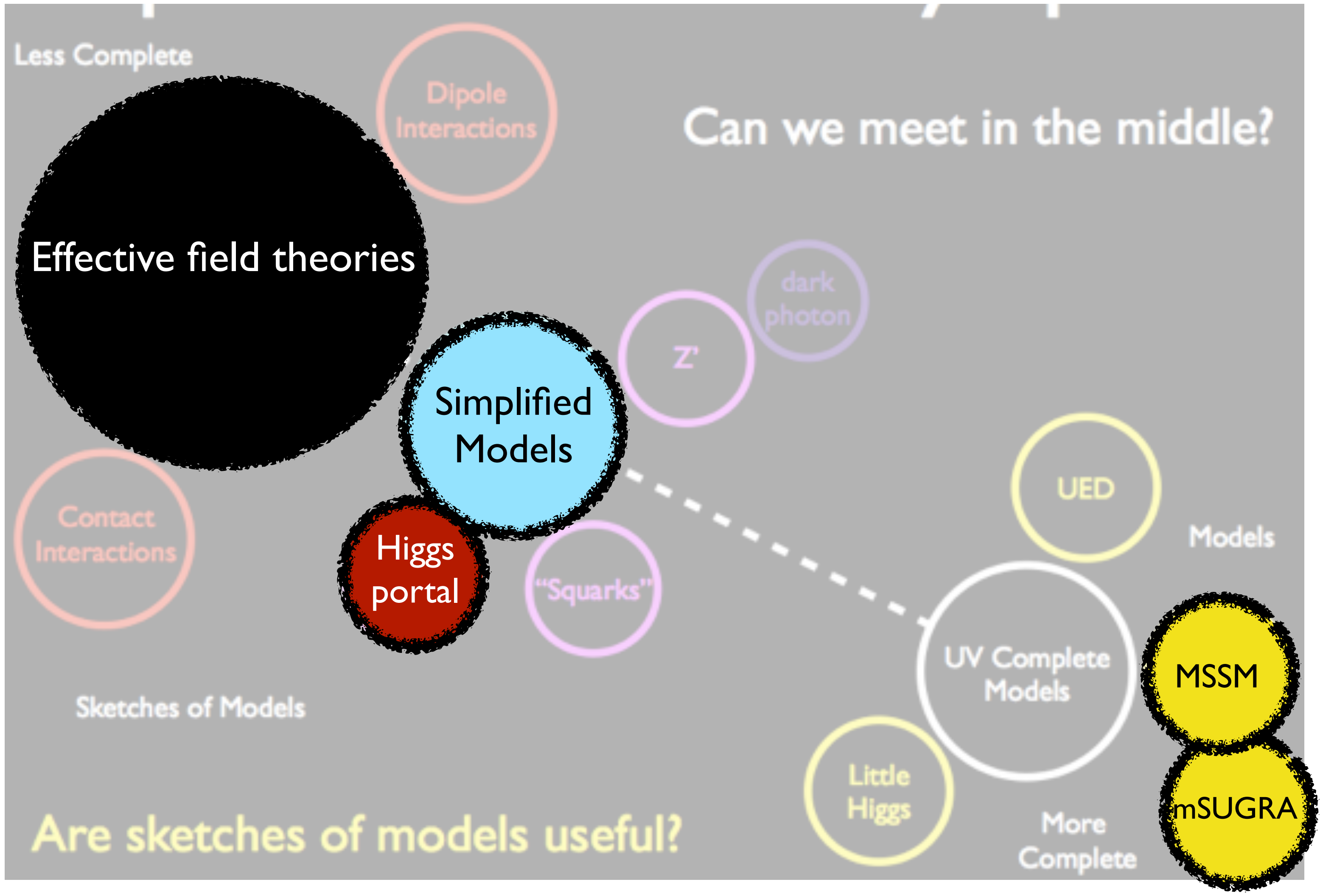
Slide taken from Tim Tait talk at Moriond

From Tim Tait



Outline of talk

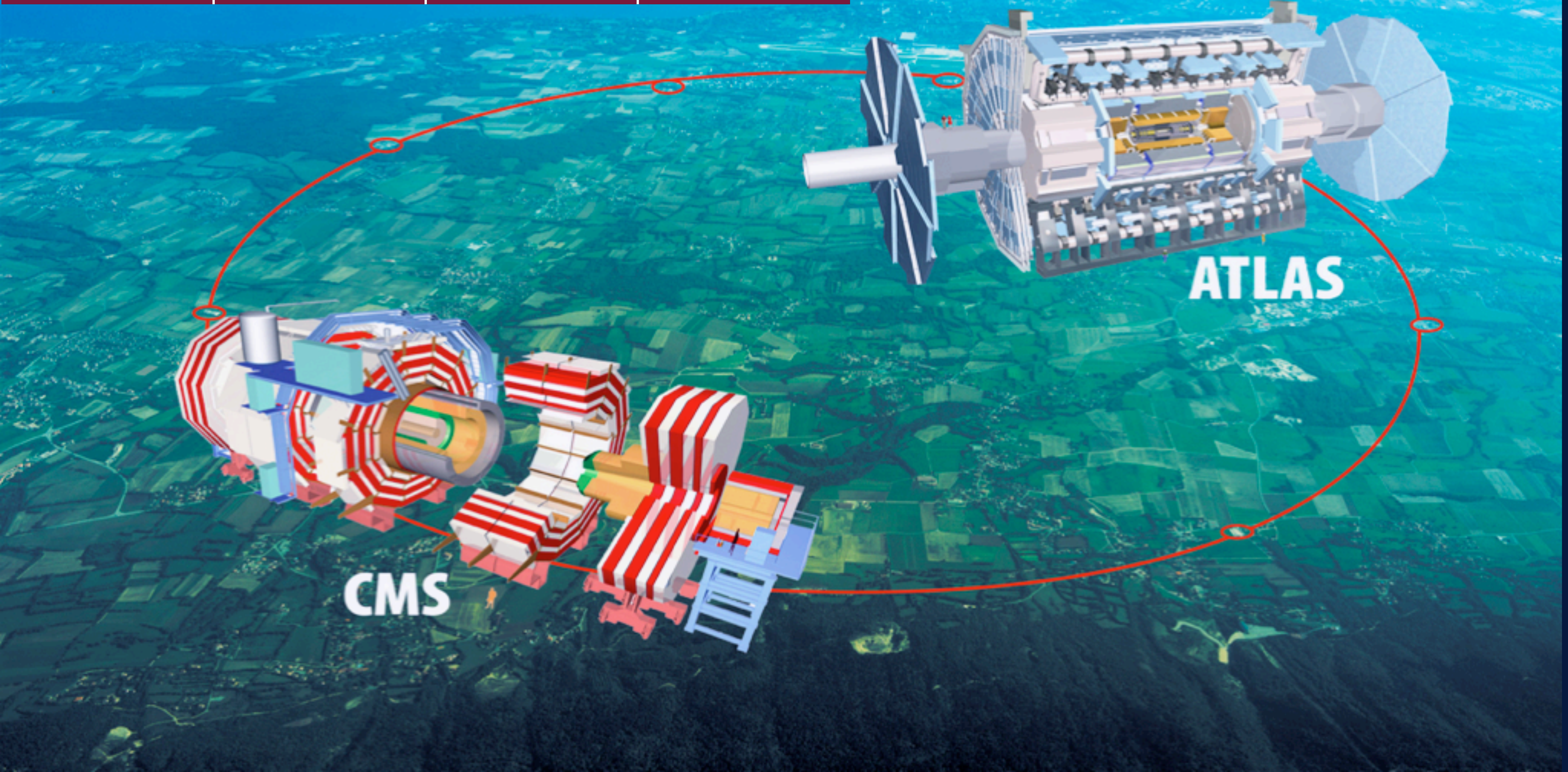
- SUSY searches
- Mono-X searches
- Invisible Higgs searches
- Interpretation of results
- Projections for 14 TeV



The Large Hadron Collider

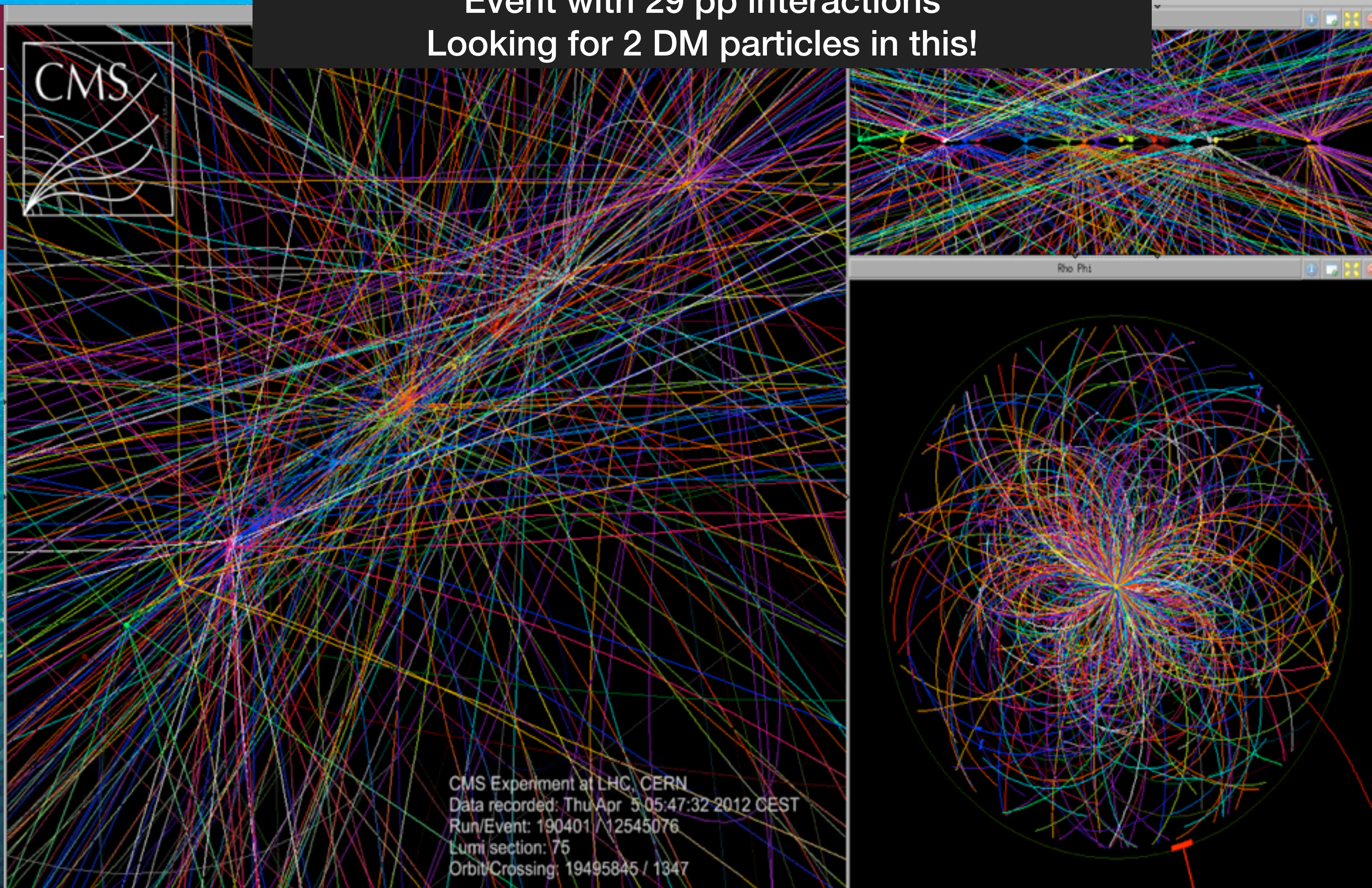
	2011	2012	2015
Energy	7 TeV	8 TeV	14 TeV
Integrated luminosity	5 fb^{-1}	20 fb^{-1}	40 fb^{-1} ?

- proton-proton collider
- two general, multi-purpose detectors
- ATLAS and CMS



The Large Hadron Collider

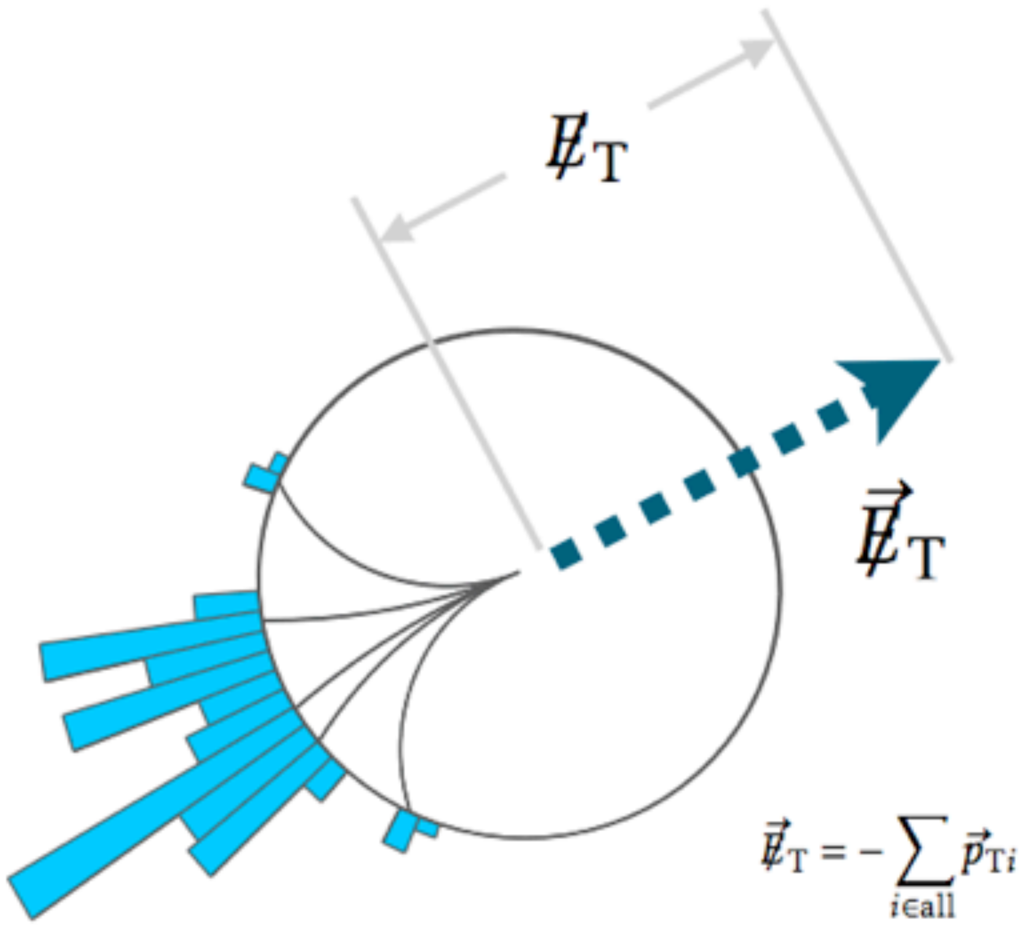
Event with 29 pp interactions
Looking for 2 DM particles in this!



Missing Transverse Energy

At the heart of all DM searches at colliders : Missing transverse energy (MET)

➡ DM neutral and weakly interacting
➡ only infer its presence in detector from imbalance in transverse momentum of all visible particles

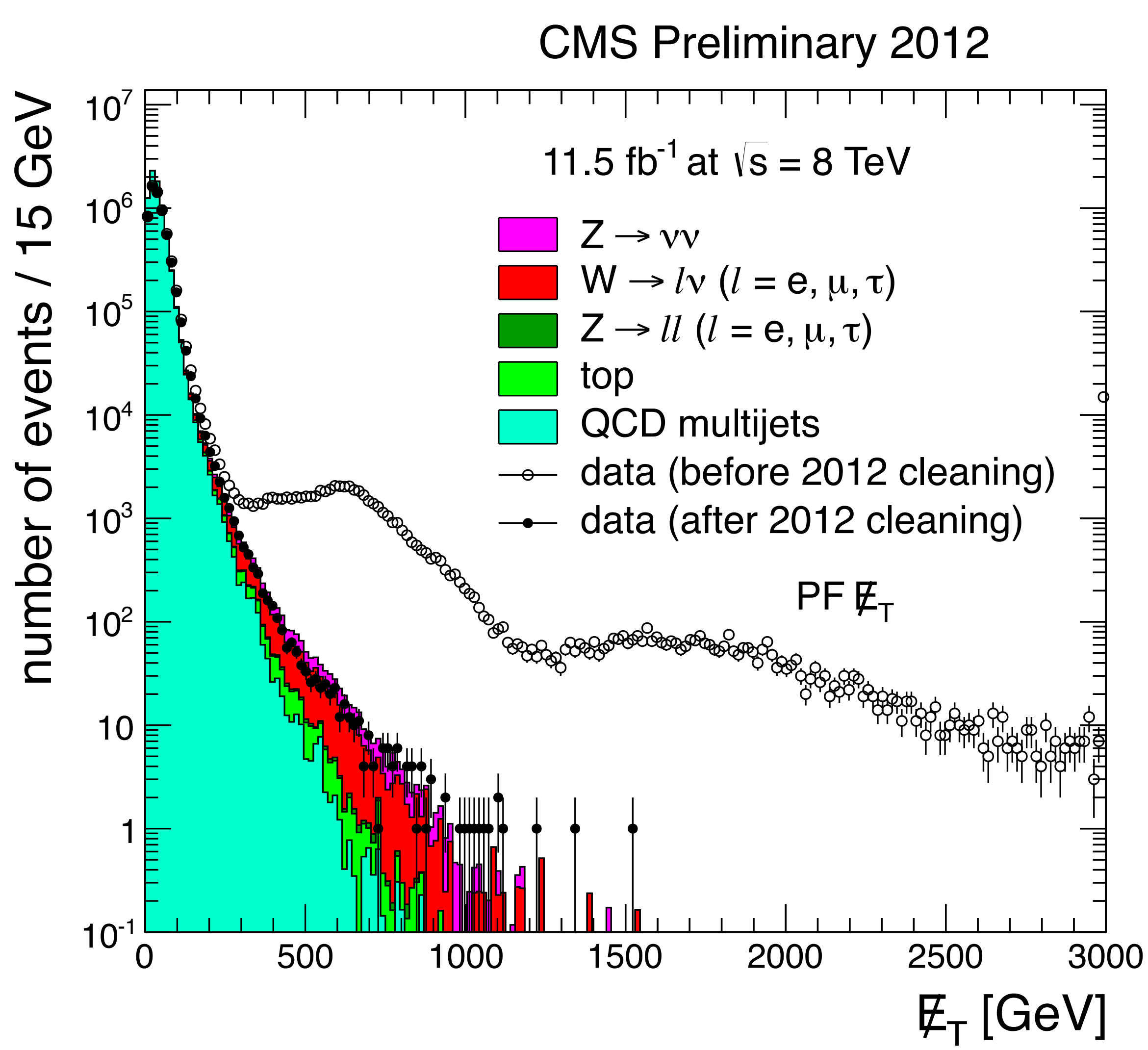


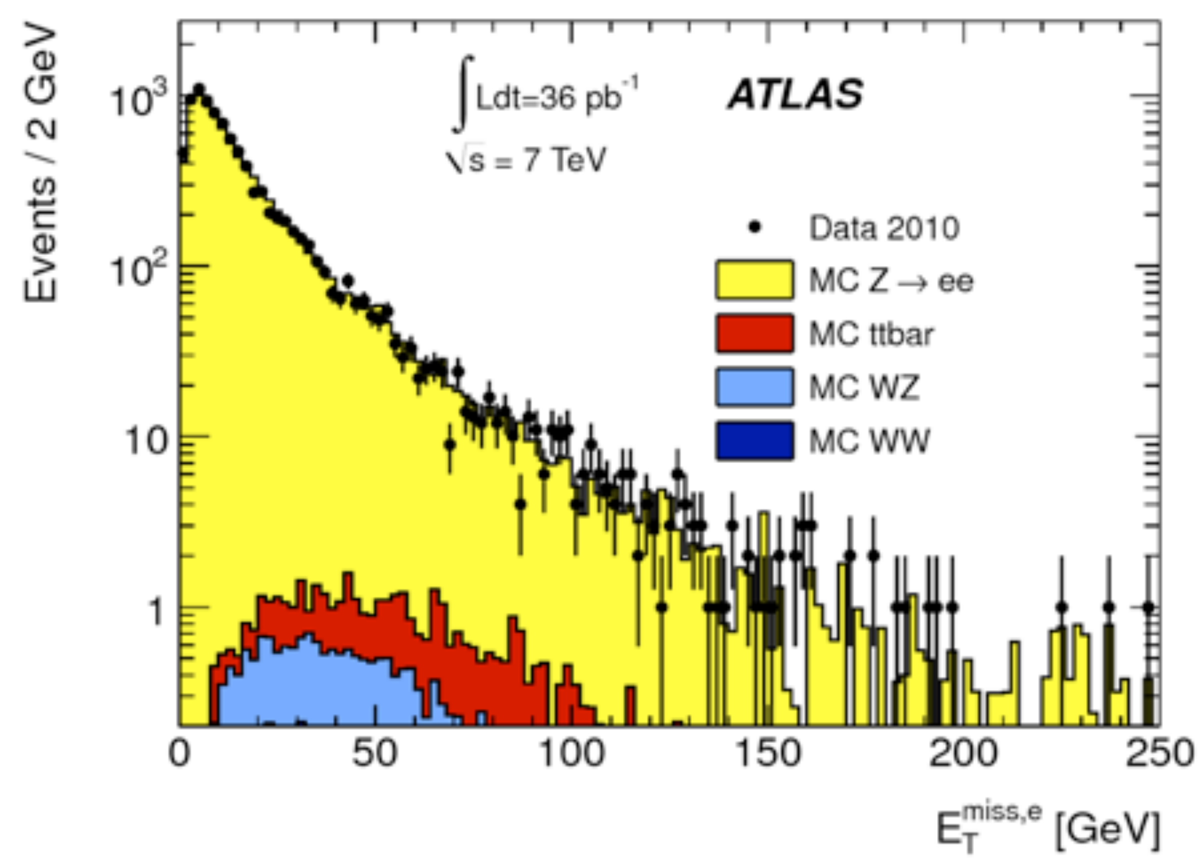
➡MET = negative of the vector sum of the transverse momenta of all particles reconstructed in the event

Missing Transverse Energy

At the heart of all DM searches at colliders : Missing transverse energy (MET)

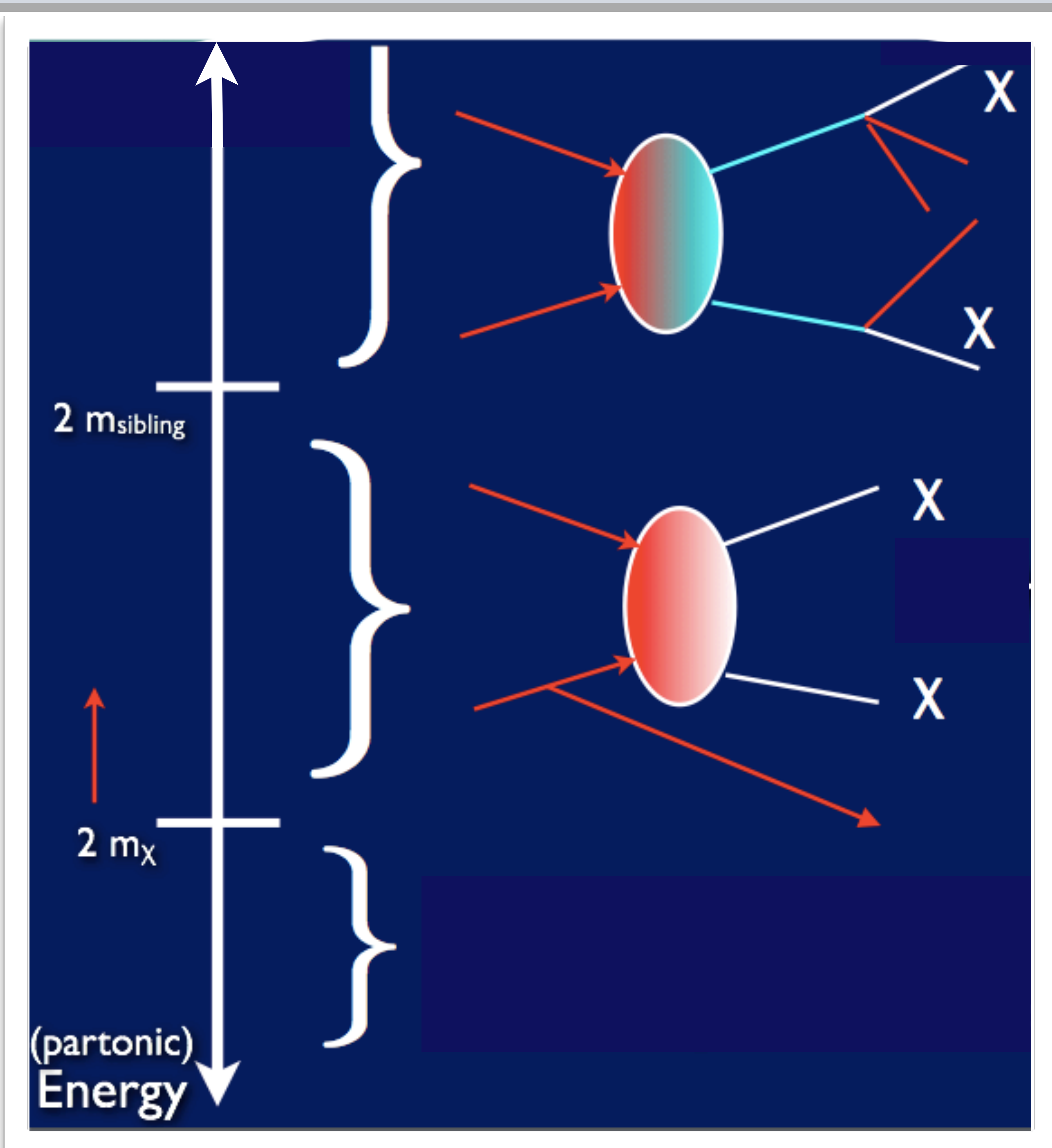
- challenging quantity to measure
- sensitive to mis-measurements, detector effects, backgrounds
- but well controlled





Searches for SUSY

Searching for dark matter at colliders



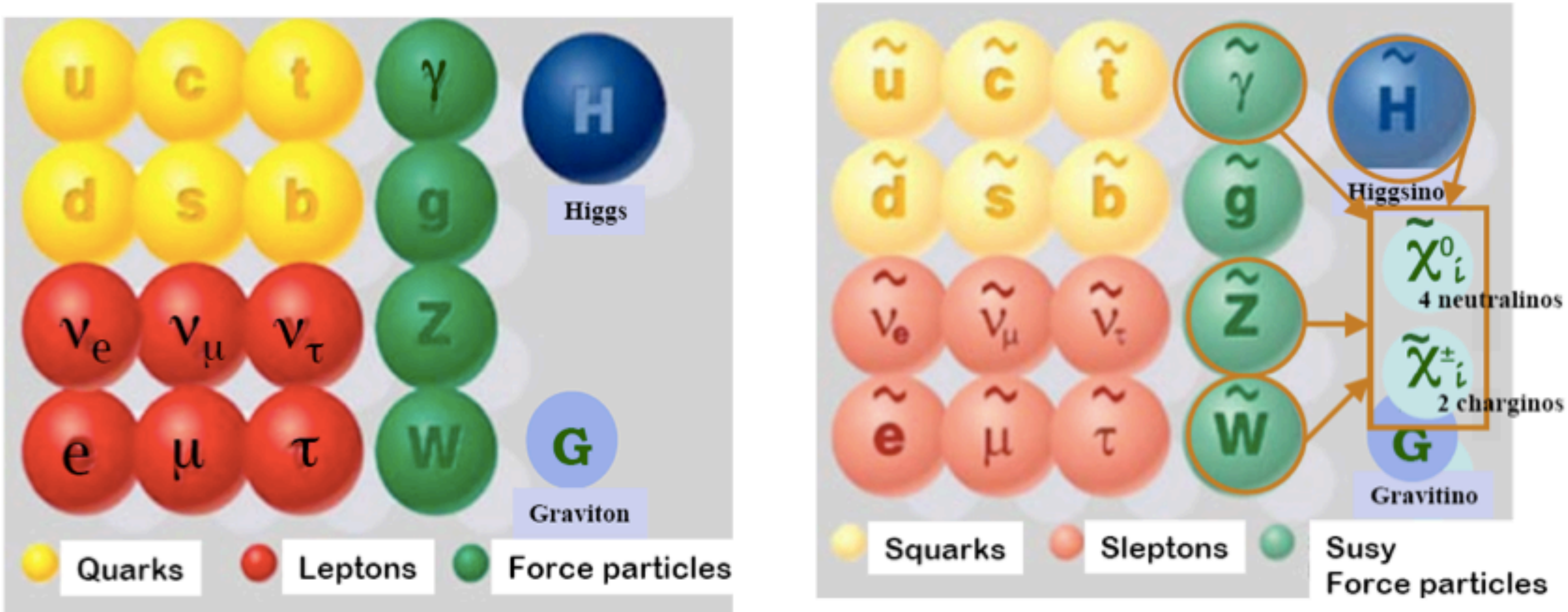
LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC can directly produce WIMP pairs

LHC cannot produce WIMPs

Supersymmetry

- symmetry between fermions and bosons
- heavy super-partners for each SM particle



R-parity : new quantum number

Requiring R-parity conservation

➡SUSY particles are produced in pairs

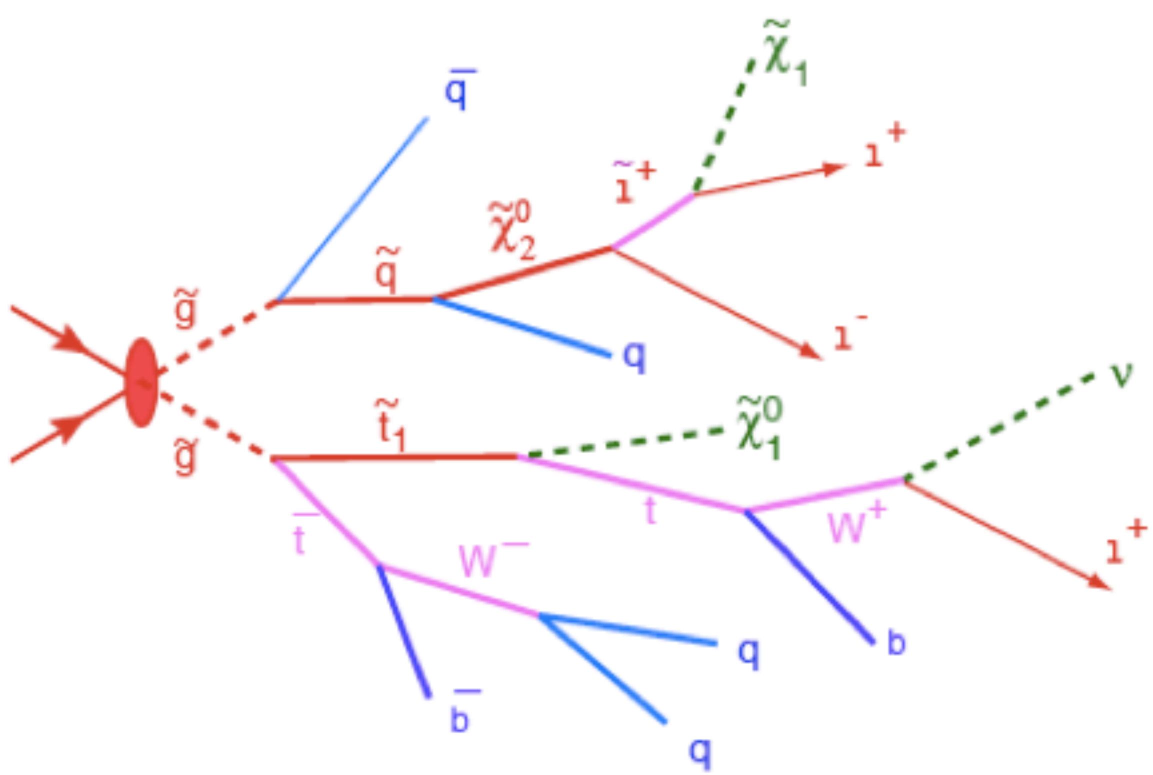
➡The lightest SUSY particle (LSP) is stable

Theories designed to address the gauge hierarchy problem naturally

- predict stable, weakly interacting particles with mass ~ weak scale
- the correct relic abundance required to be dark matter.

SUSY searches at LHC

Generic searches requiring
- missing energy,
- many jets
- possibly leptons

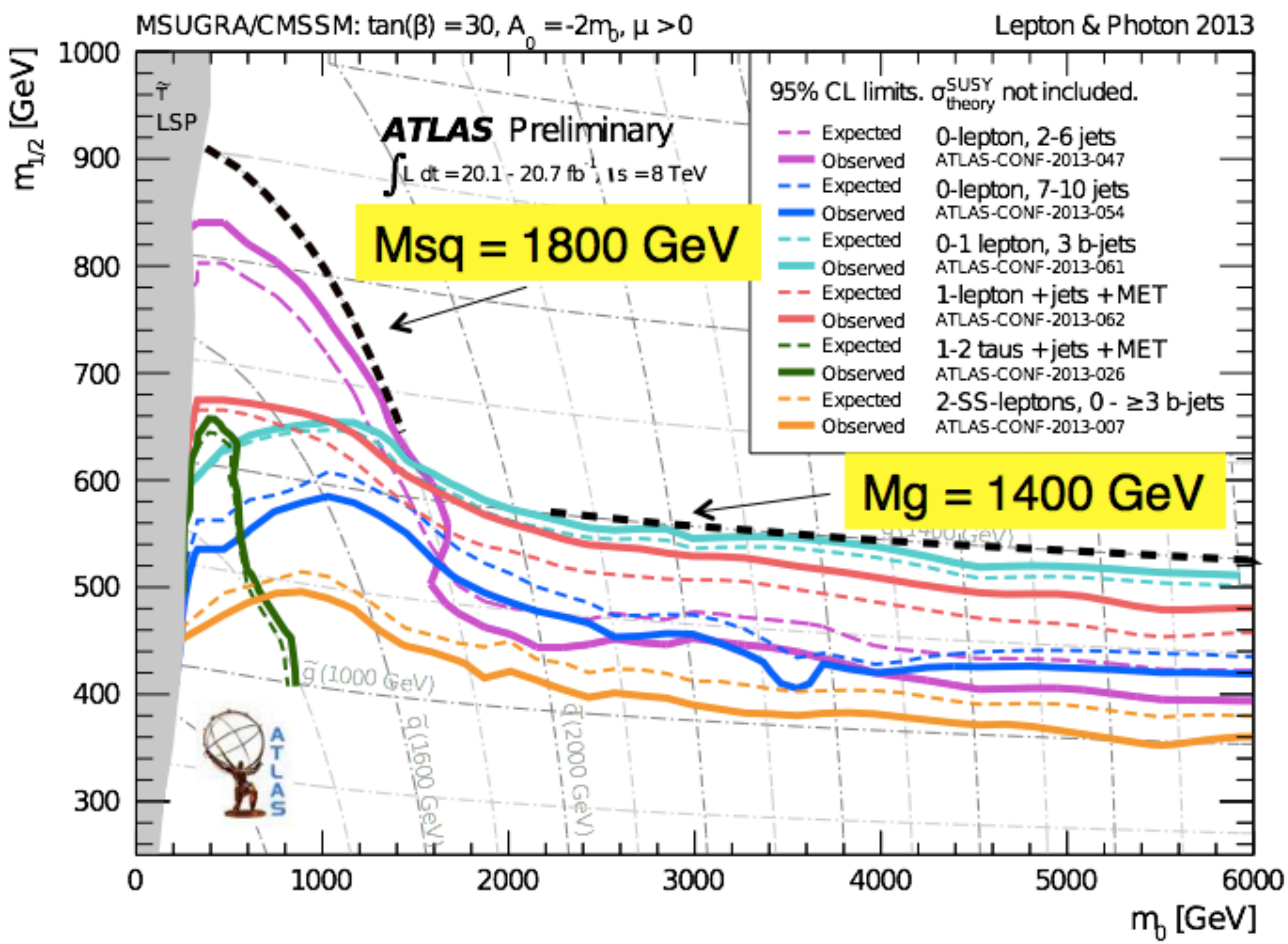


Missing Energy:
- *from LSP*

Multi-Jet:
- *from cascade decay (gaugino)*

Multi-Leptons:
- *from decay of charginos/neutralios*

SUSY searches at LHC

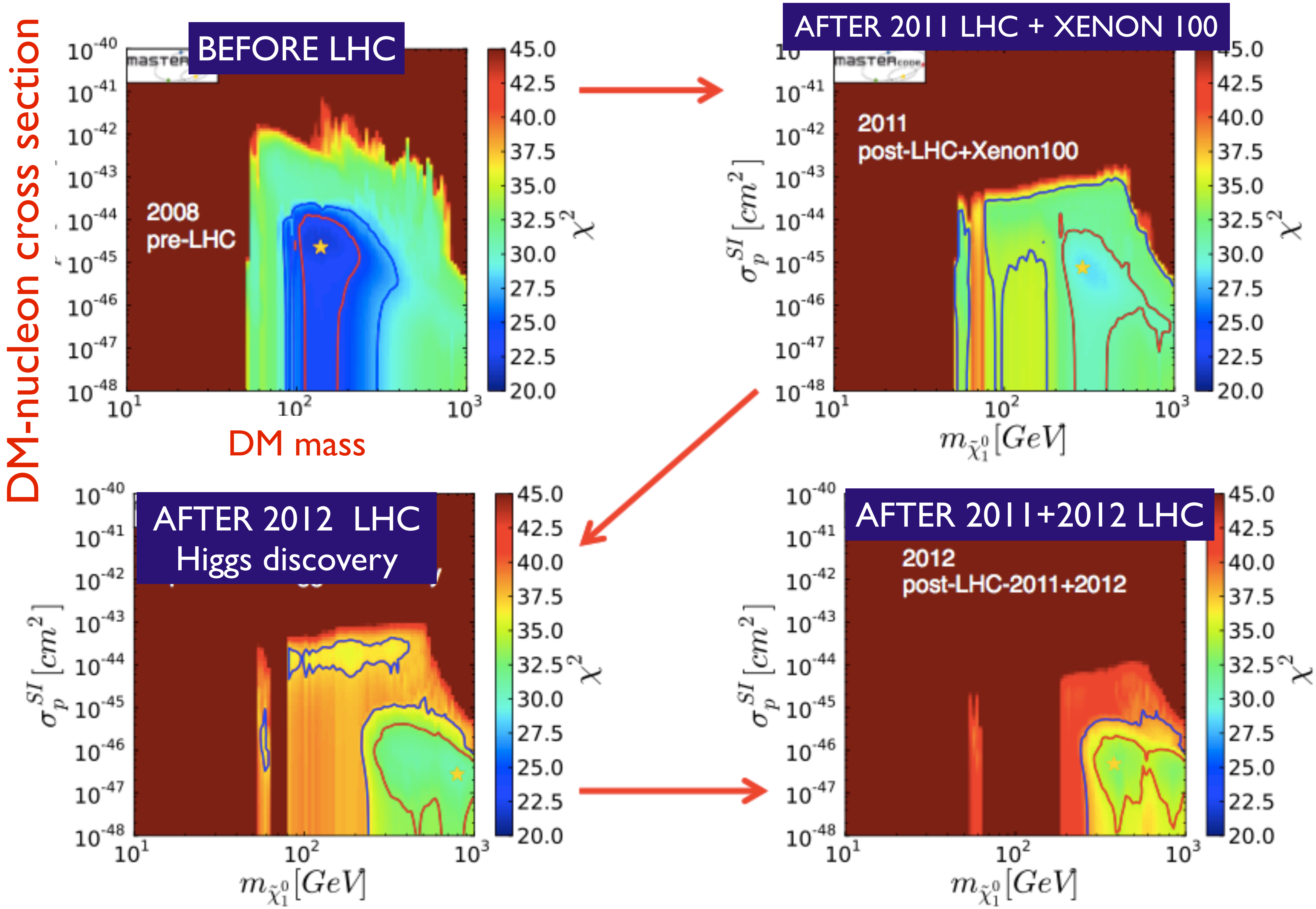


LHC pushing mass scales in constrained SUSY models

SUSY and Dark Matter : Evolution with time

Source:
http://mastercode.web.cern.ch/mastercode

Global fit to direct and indirect constraints on SUSY

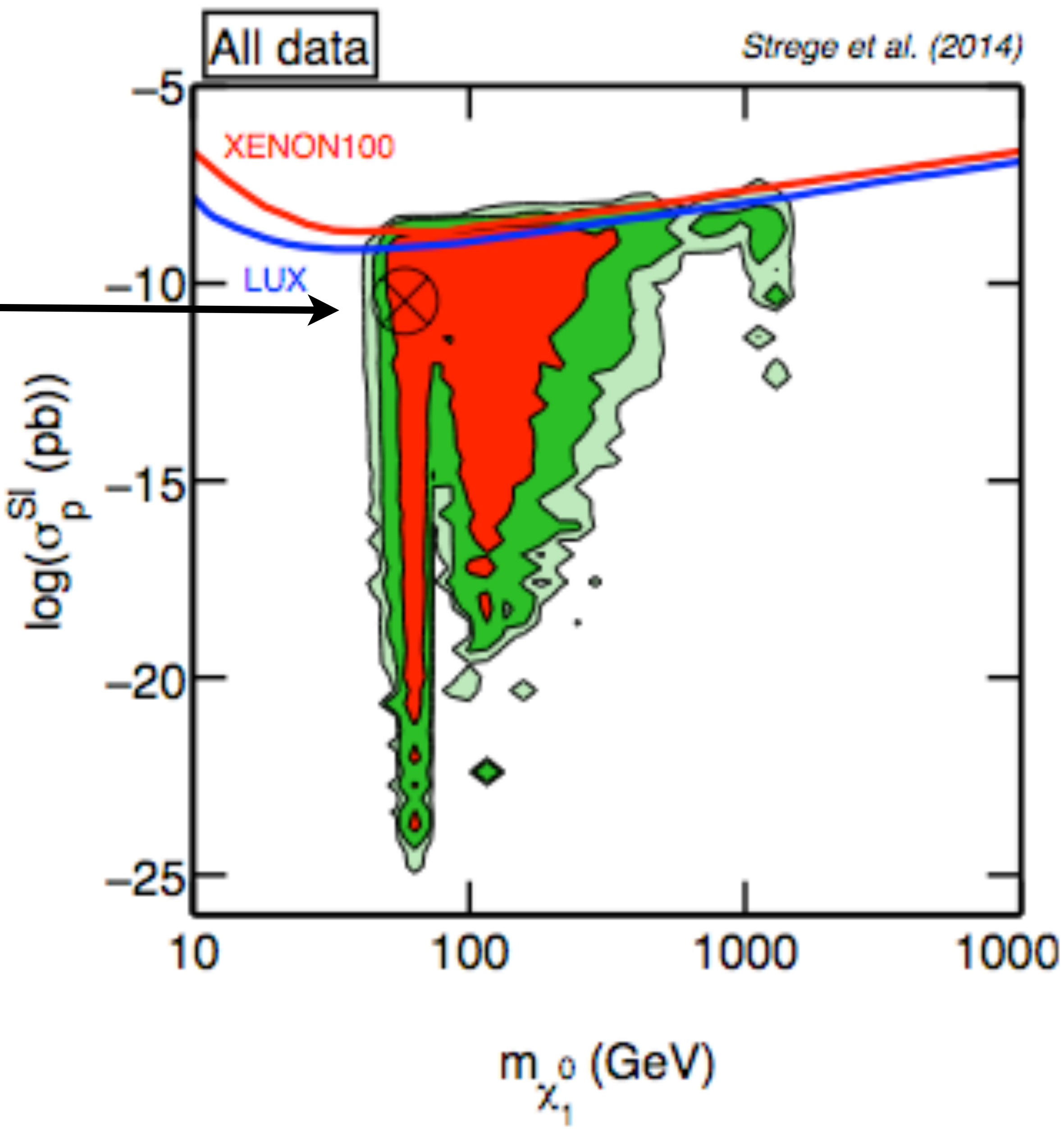


Global fits to SUSY and Dark Matter

arxiv: 1405.0622

Global fit to 15-dimensional pMSSM

Best fit point : 130 GeV neutralino mass with SI cross section of 2.4×10^{-10}pb, within reach of future nulti-ton and 14 TeV LHC

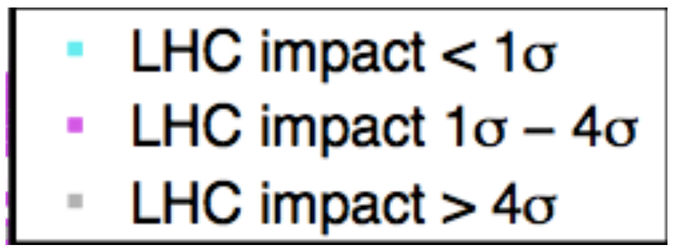


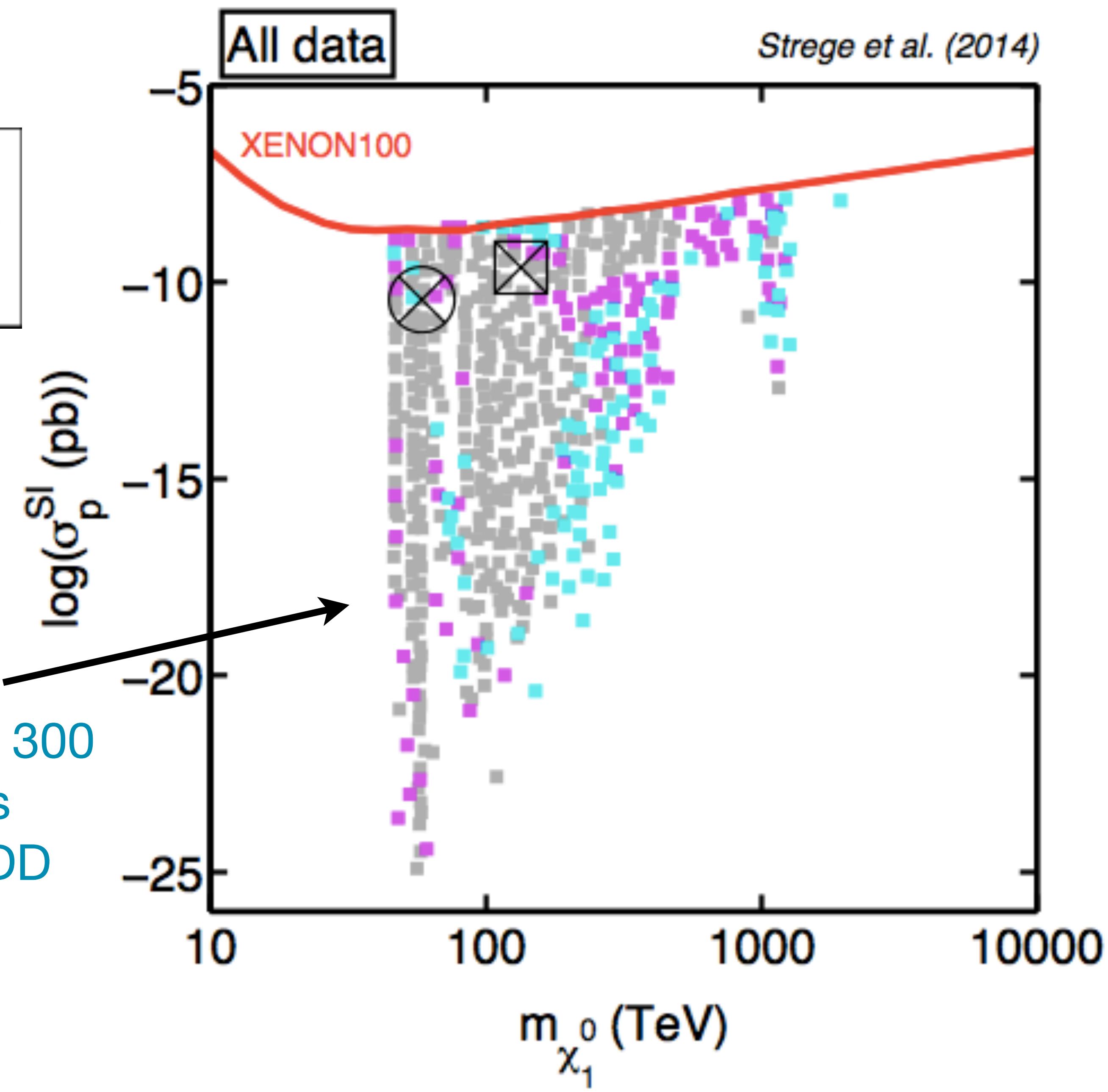
Before LHC data included

Global fits to SUSY and Dark Matter

arxiv: 1405.0622

Impact of LHC data



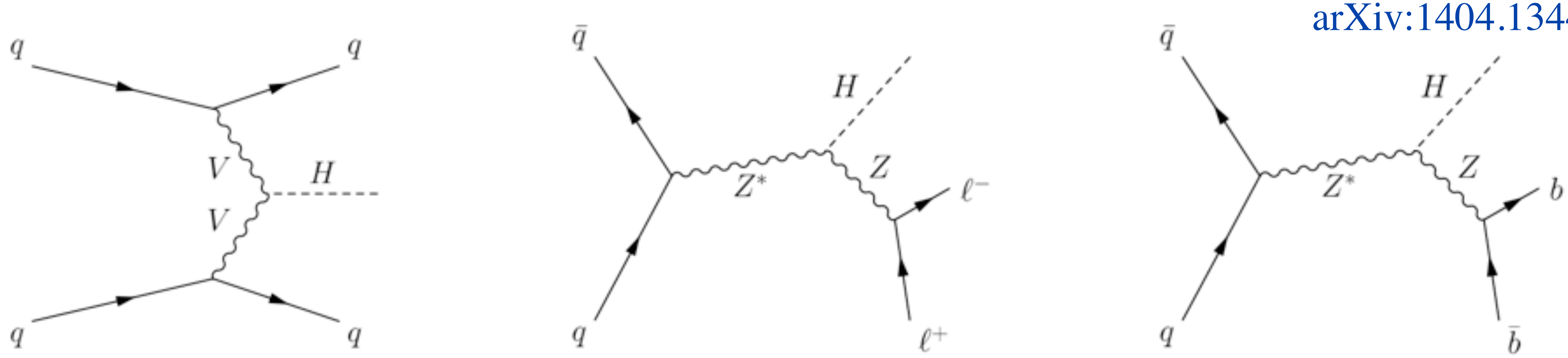


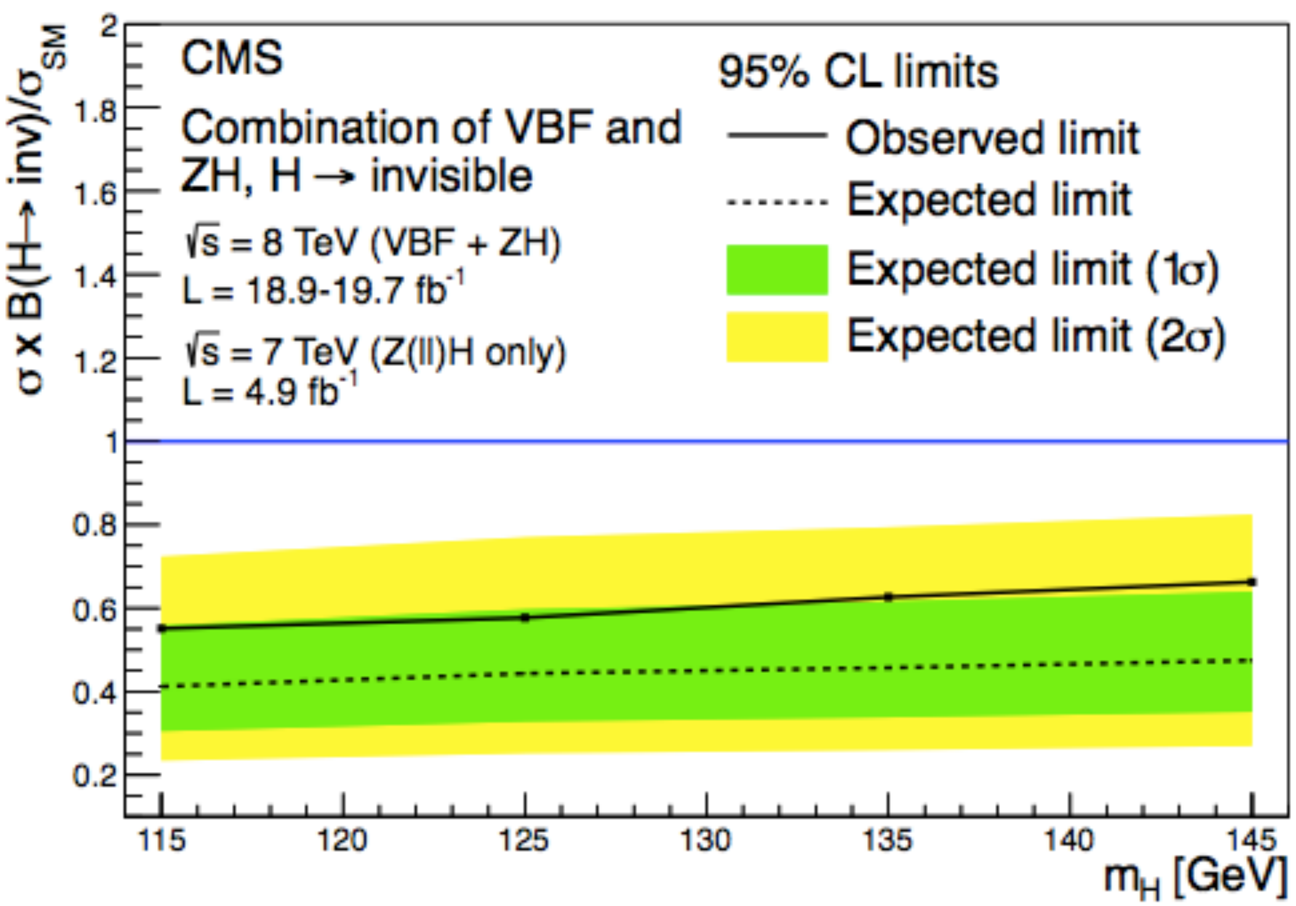
LHC powerful in region DM mass < 300 GeV or so, ruling out cross sections below reach of present and future DD expts (also below 'neutrino' floor)

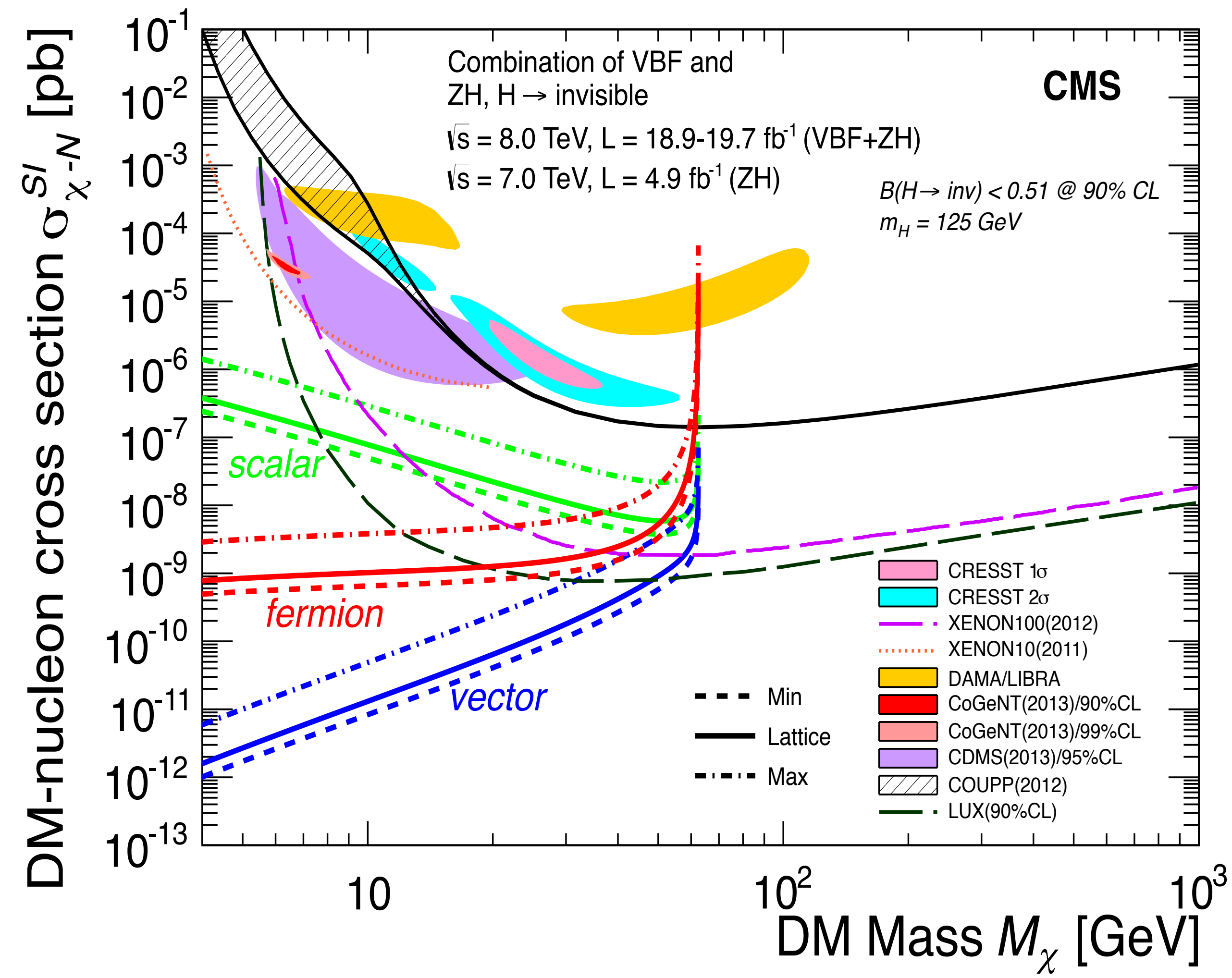
Invisible Higgs

Invisible Higgs searches

arXiv:1404.1344





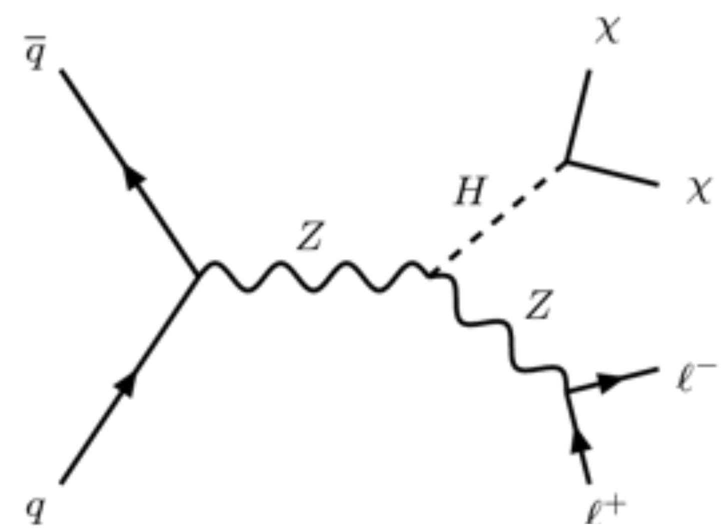


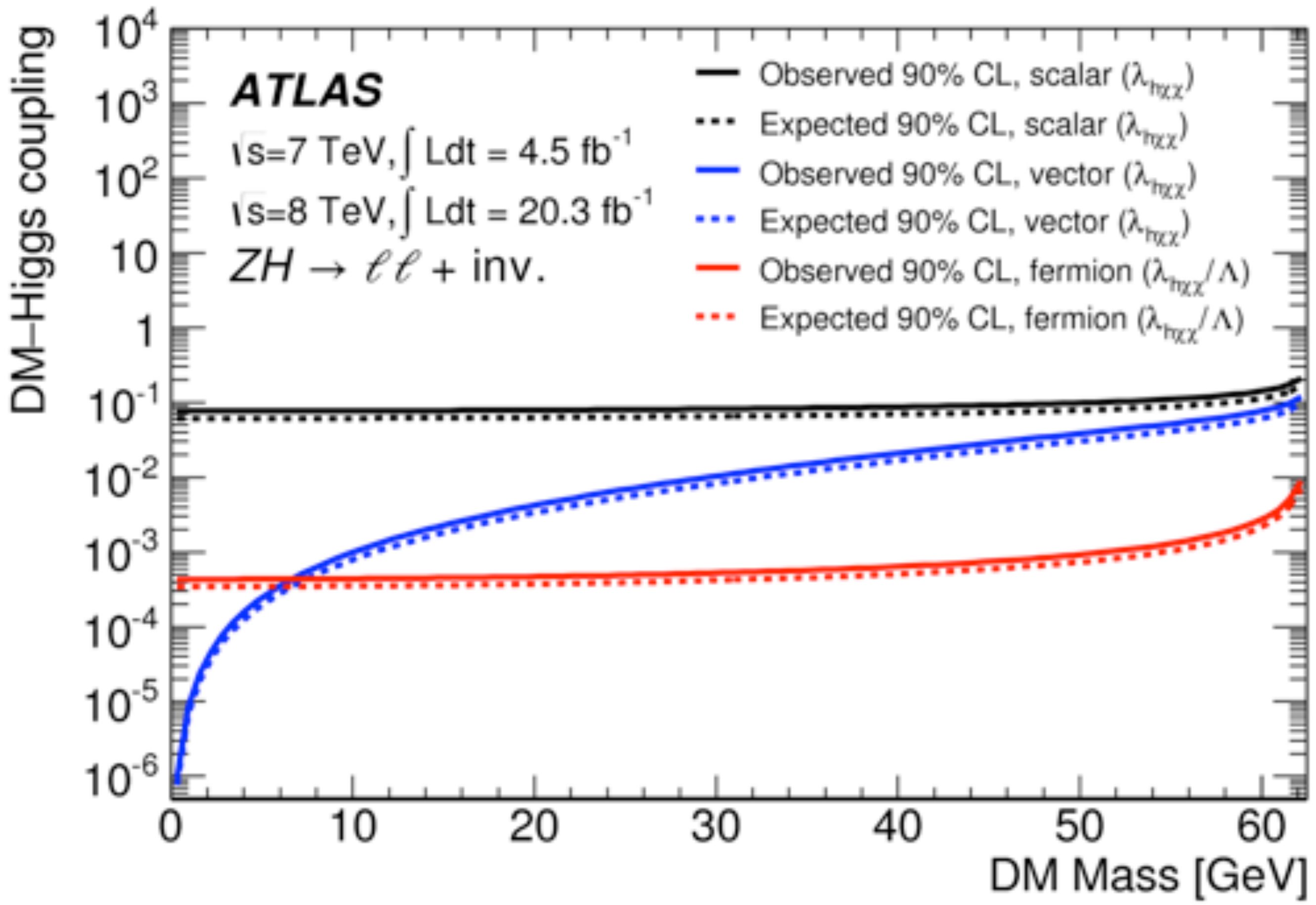
BF(H->invisible) < 0.58 @ 95%CL

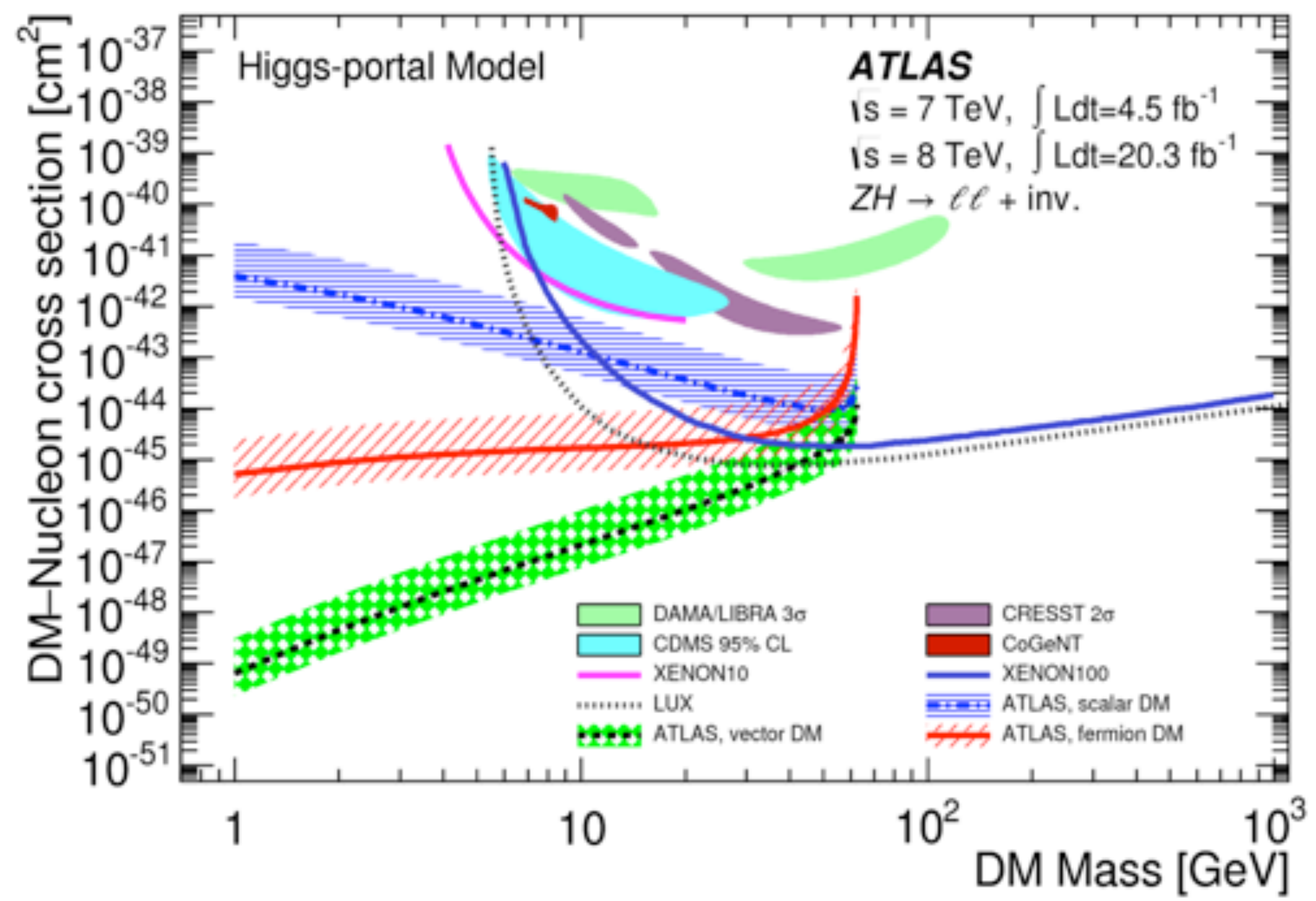
assuming SM production cross section and kinematics

Invisible Higgs searches

Phys. Rev. Lett. 112, 201802

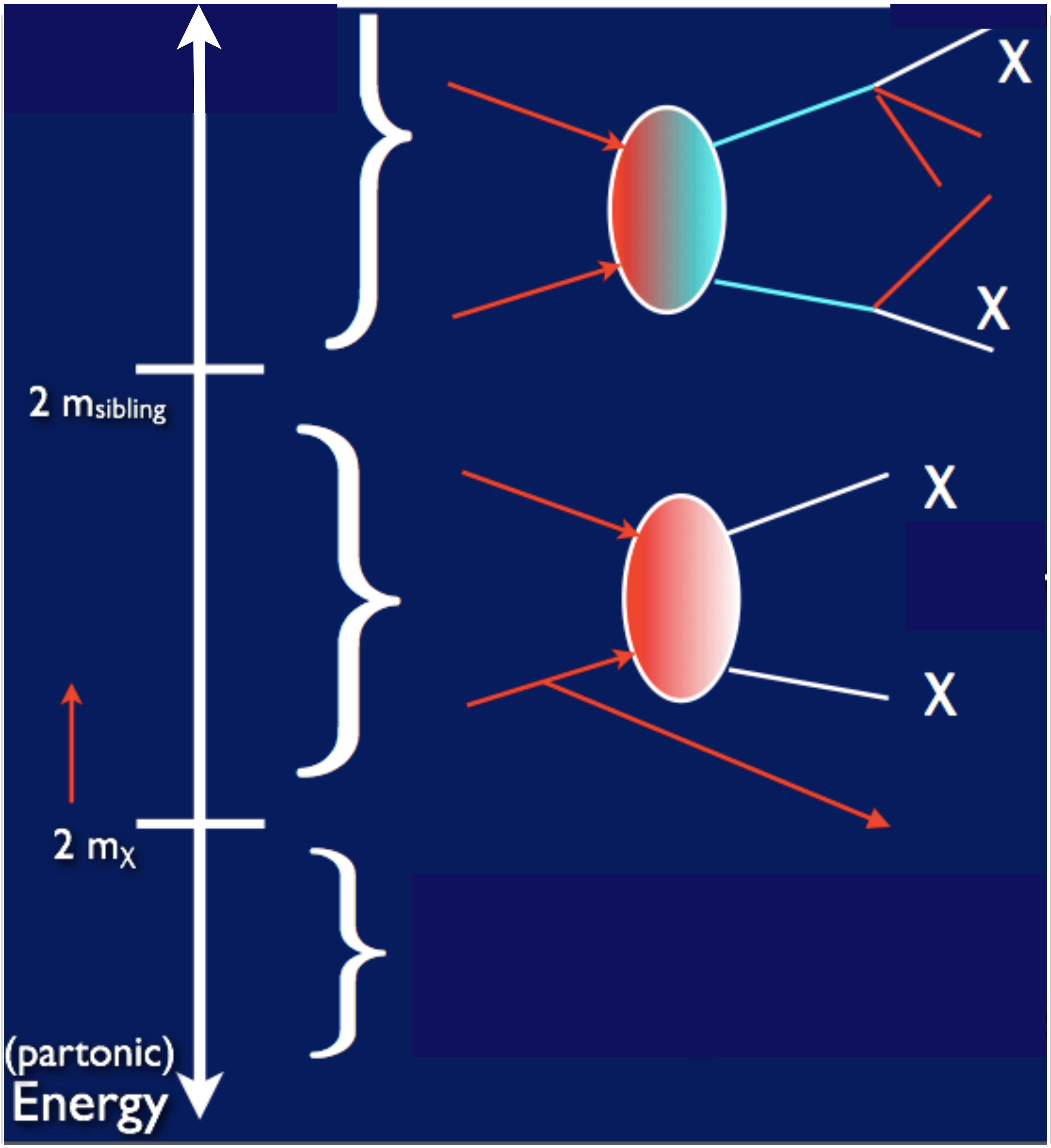






Mono-X searches

Searching for dark matter at colliders



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

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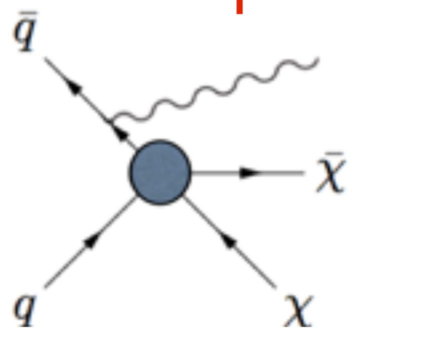
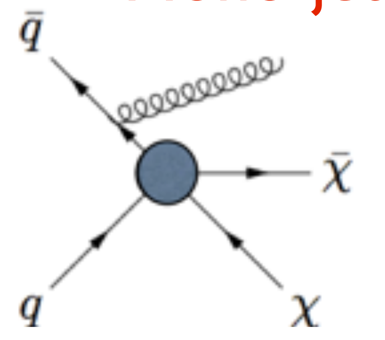
LHC cannot produce WIMPs

Mono-X

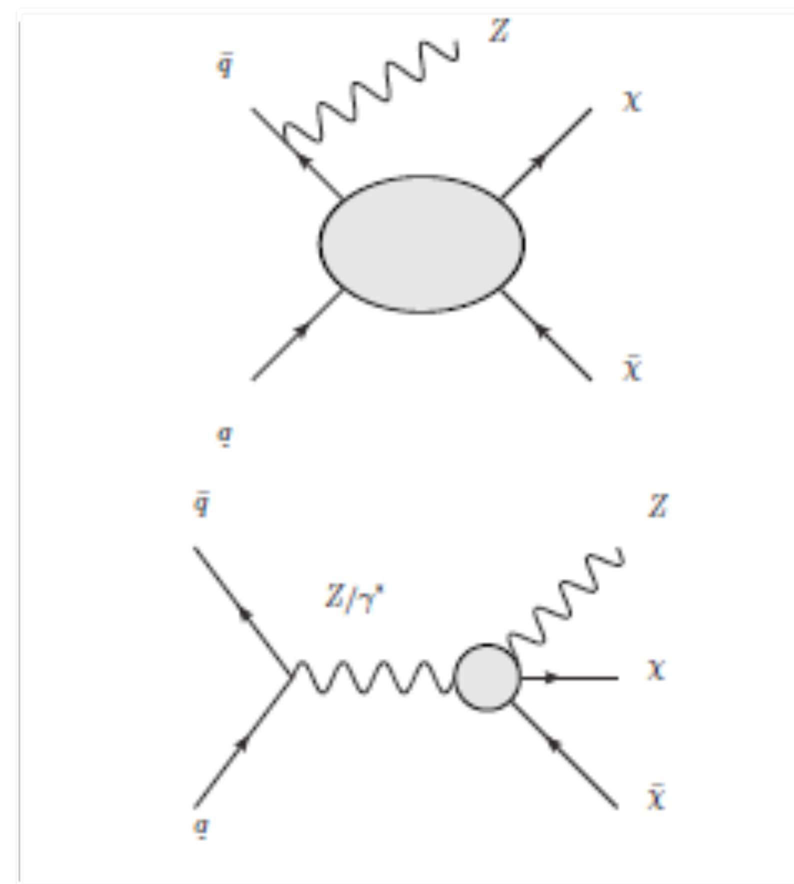
Mono-photon



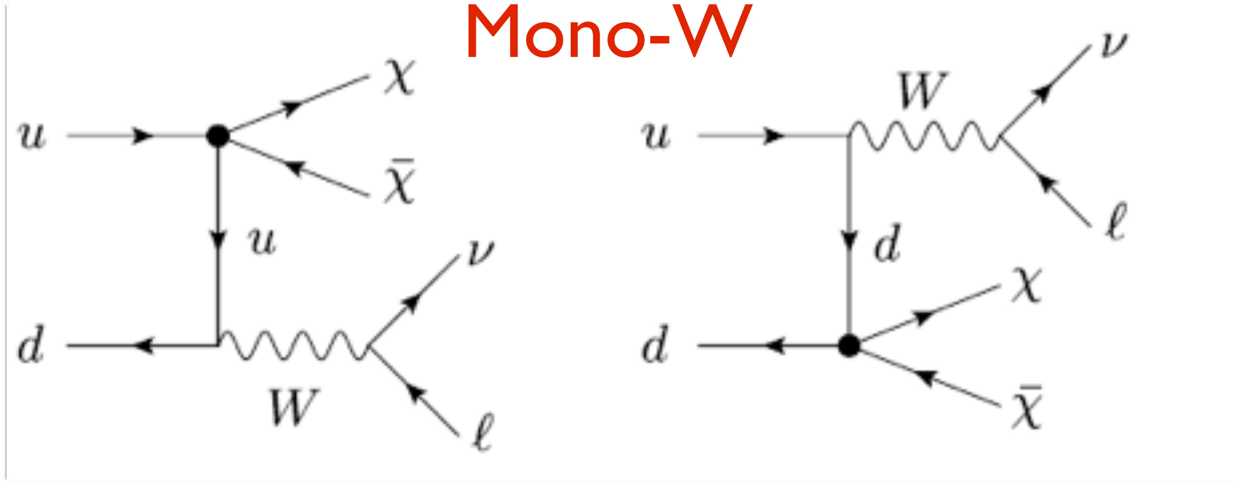
Mono-jet



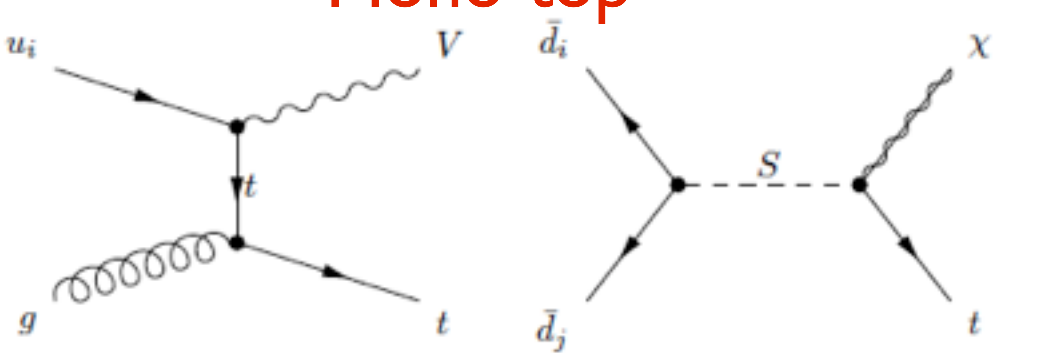
Mono-Z



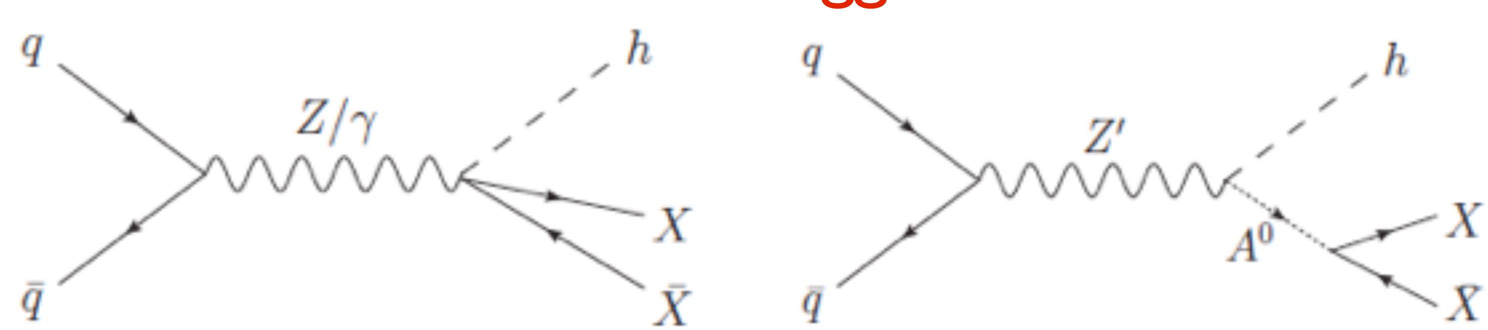
Mono-W



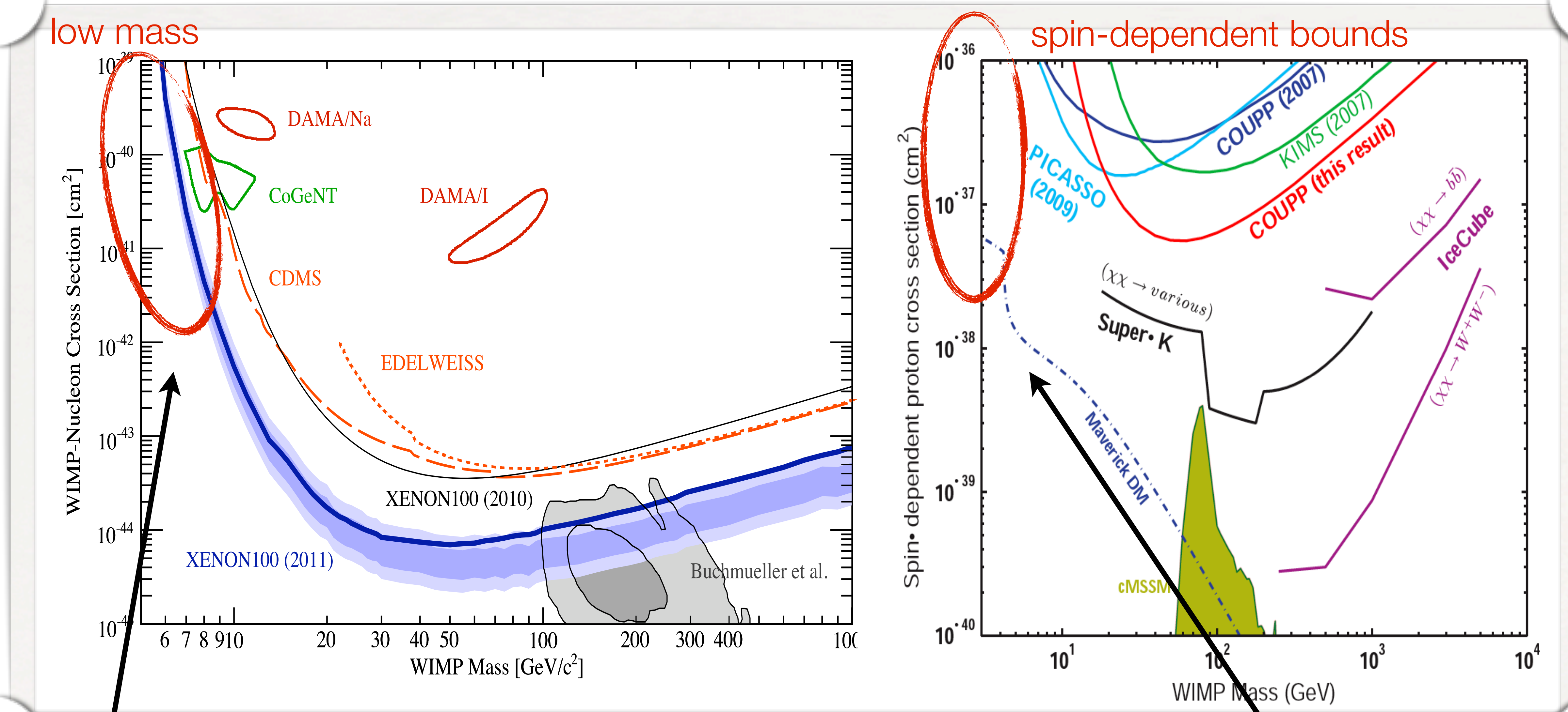
Mono-top



Mono-Higgs



Complementarity with direct detection



Collider does not have low energy threshold

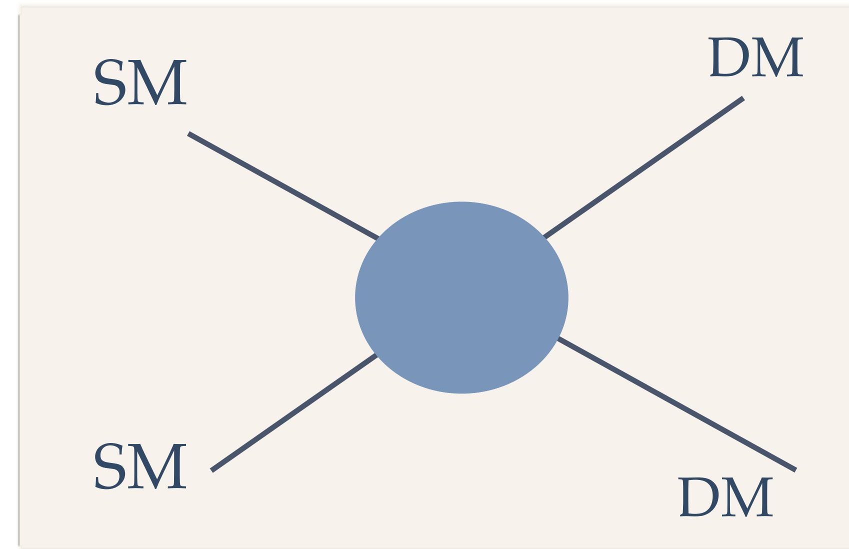
Challenges for direct detection experiments:

- low mass region not accessible
- limited by threshold effects, energy scale, backgrounds
- bounds from spin-dependent couplings weak

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

Phenomenology

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

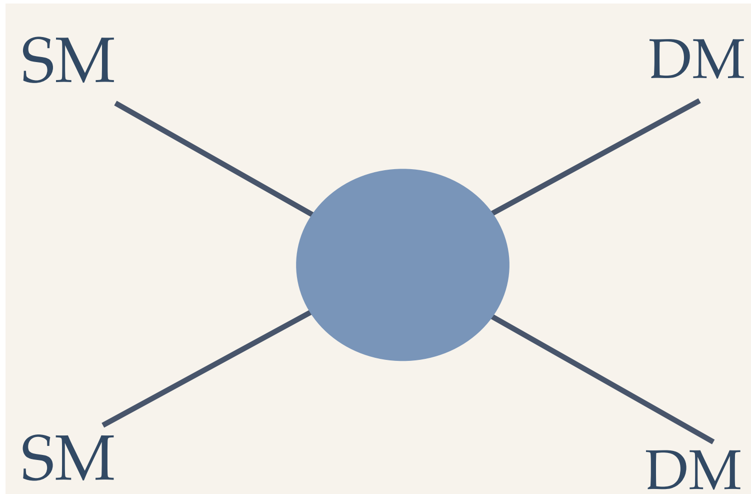
kinetic terms for DM

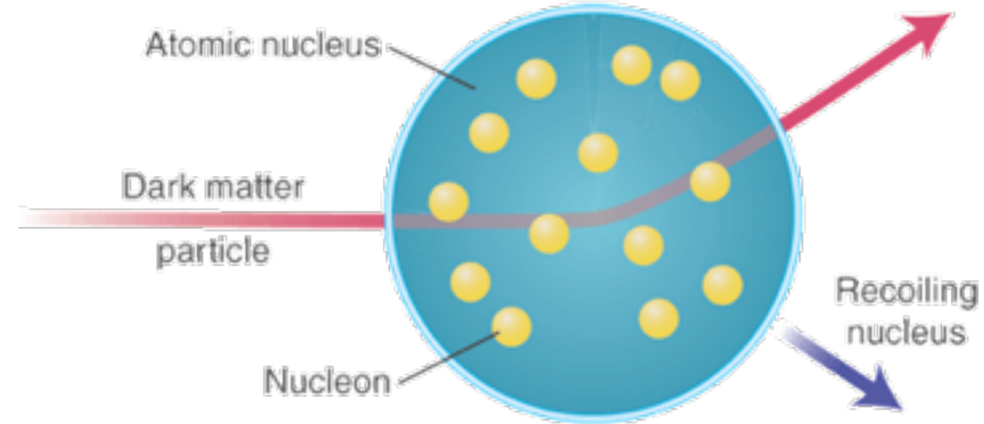
set of 4-Fermion interactions between DM and SM quarks

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

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

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

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

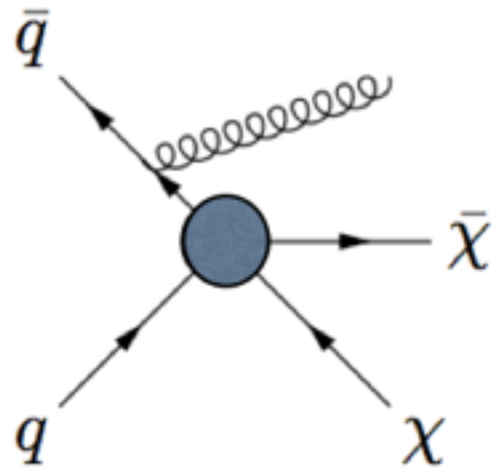
coefficient relates nucleon and quark operator

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

- 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

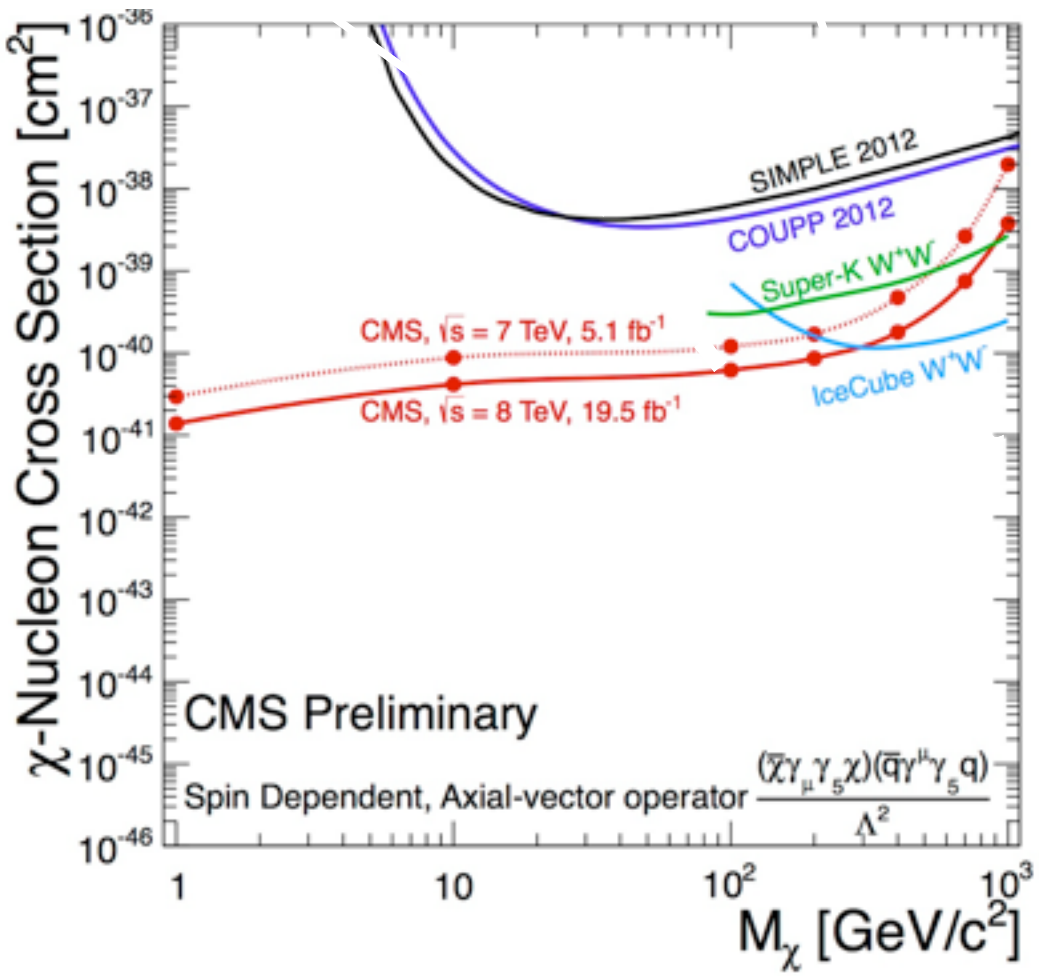
Monojet

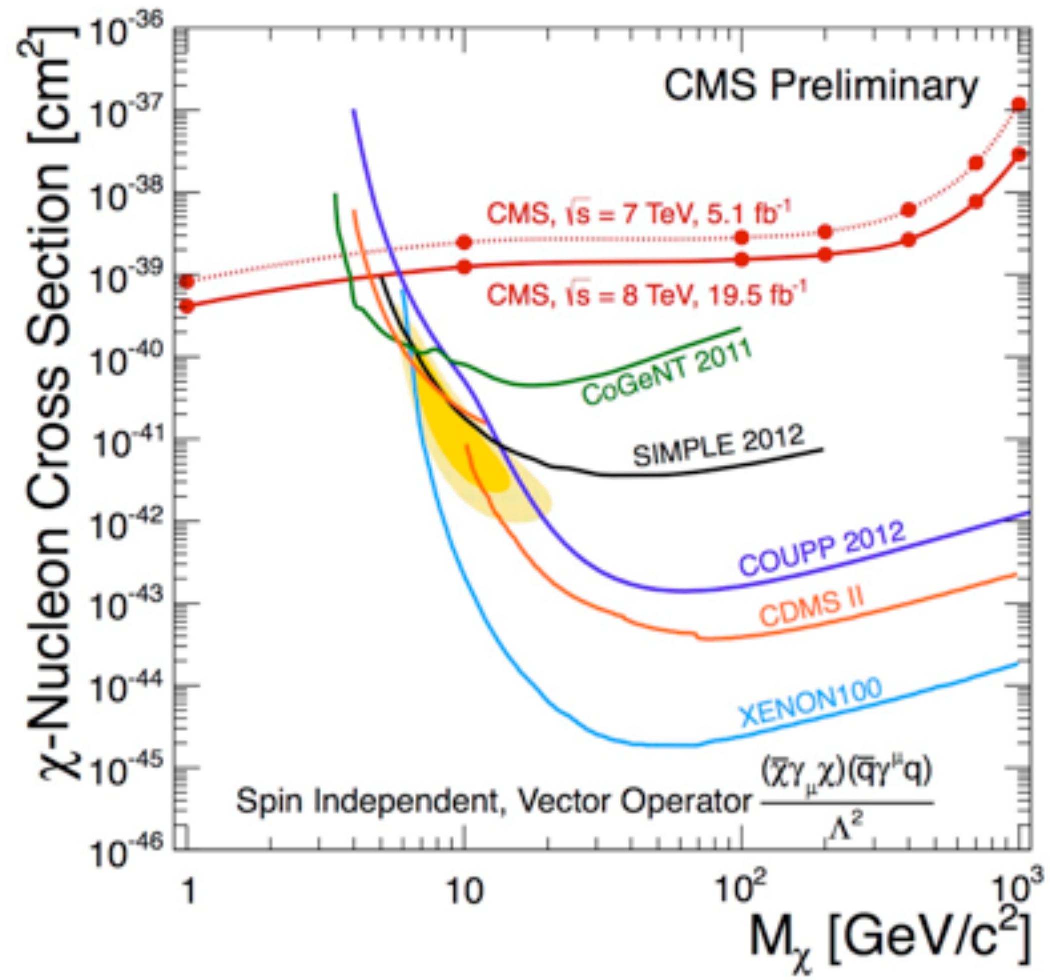
CMS PAS EXO-12-048



Assuming Effective Field theory.......

monojet +MET



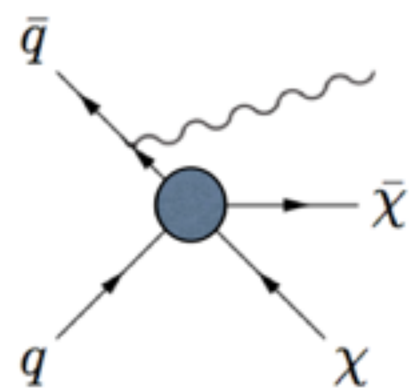


Spin-dependent interactions

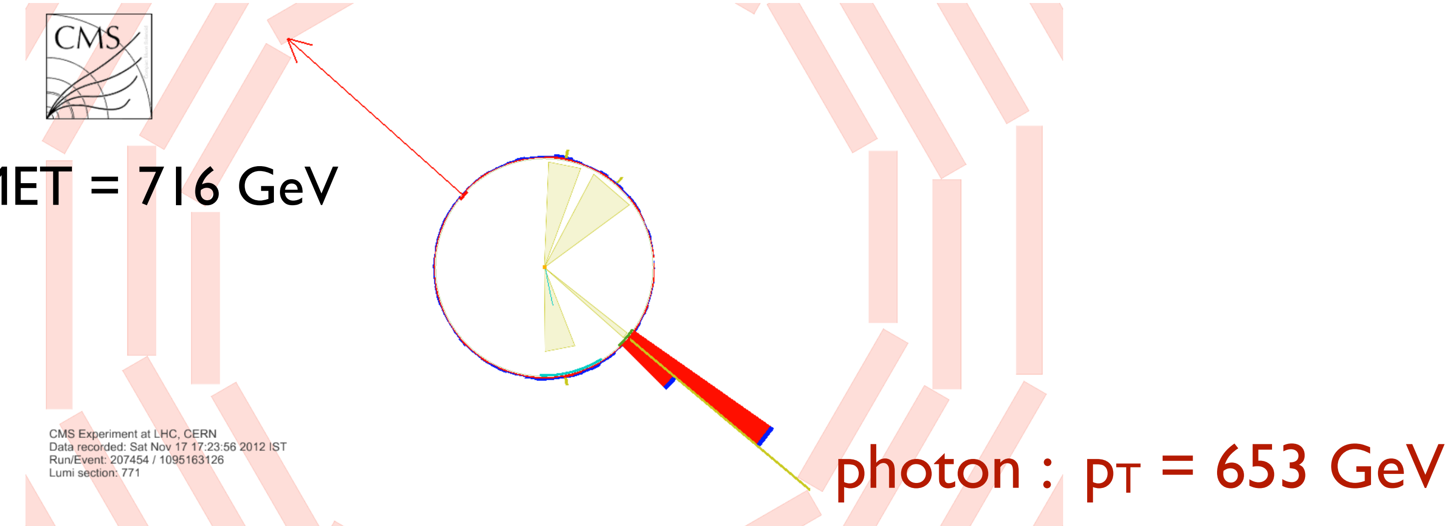
Spin-independent interactions

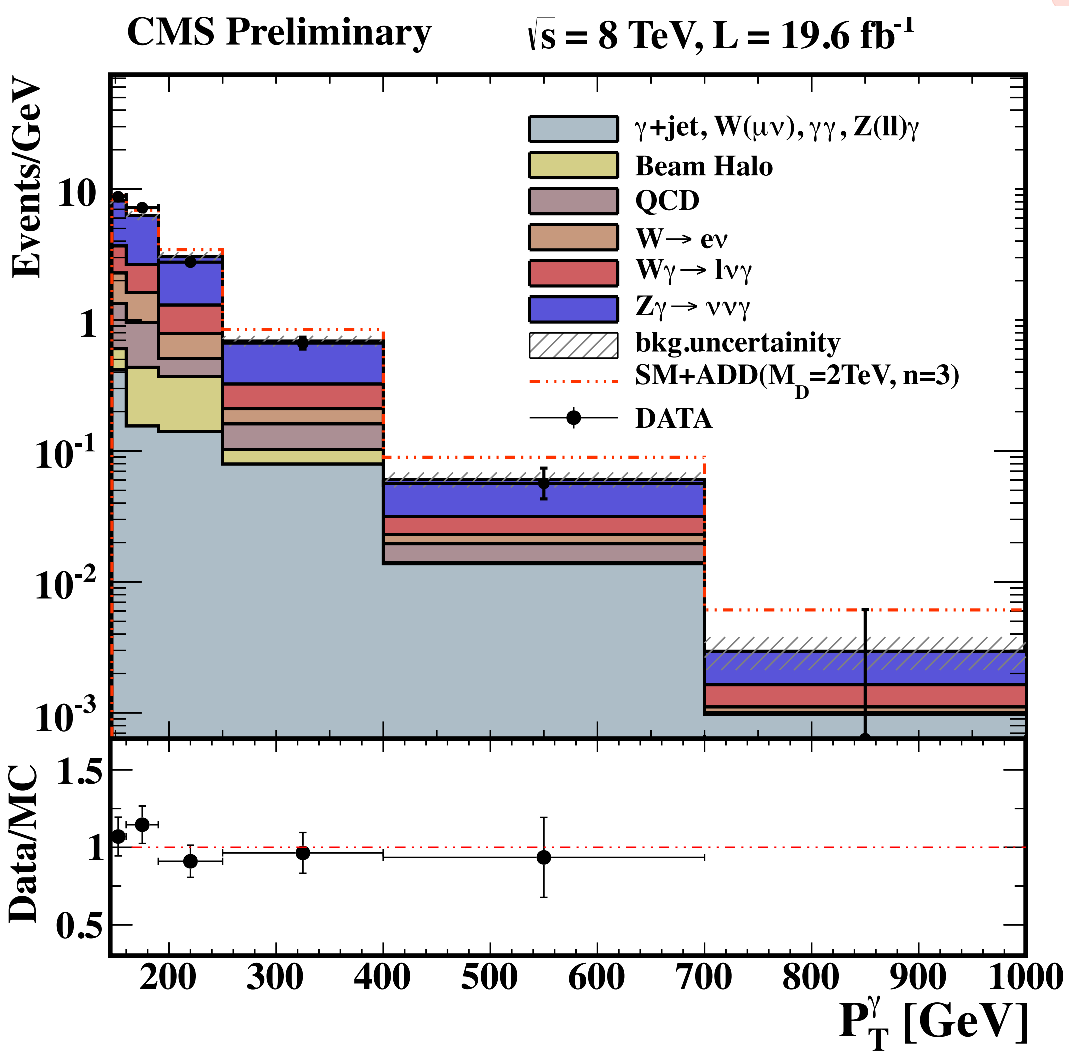
Mono-photon

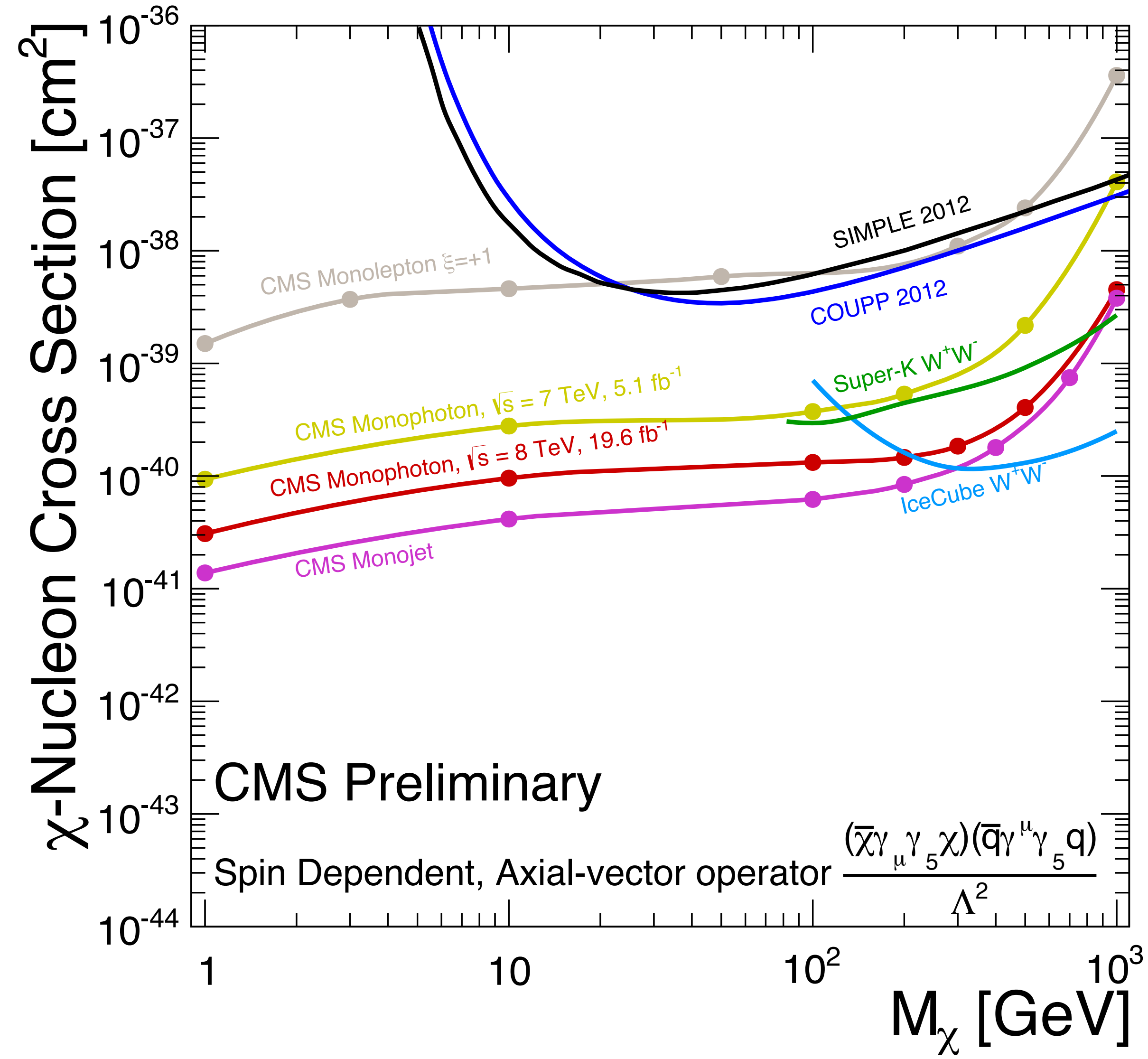
CMS-EXO-12-047



monophoton +MET

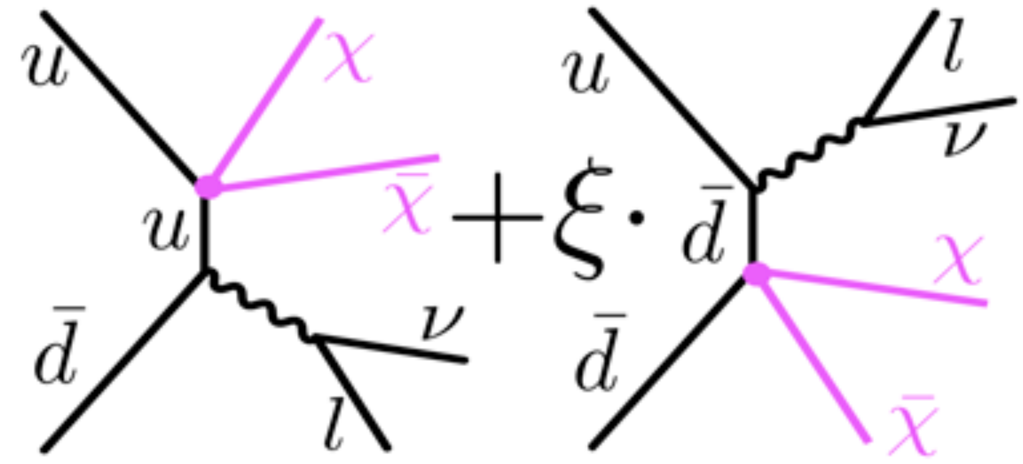


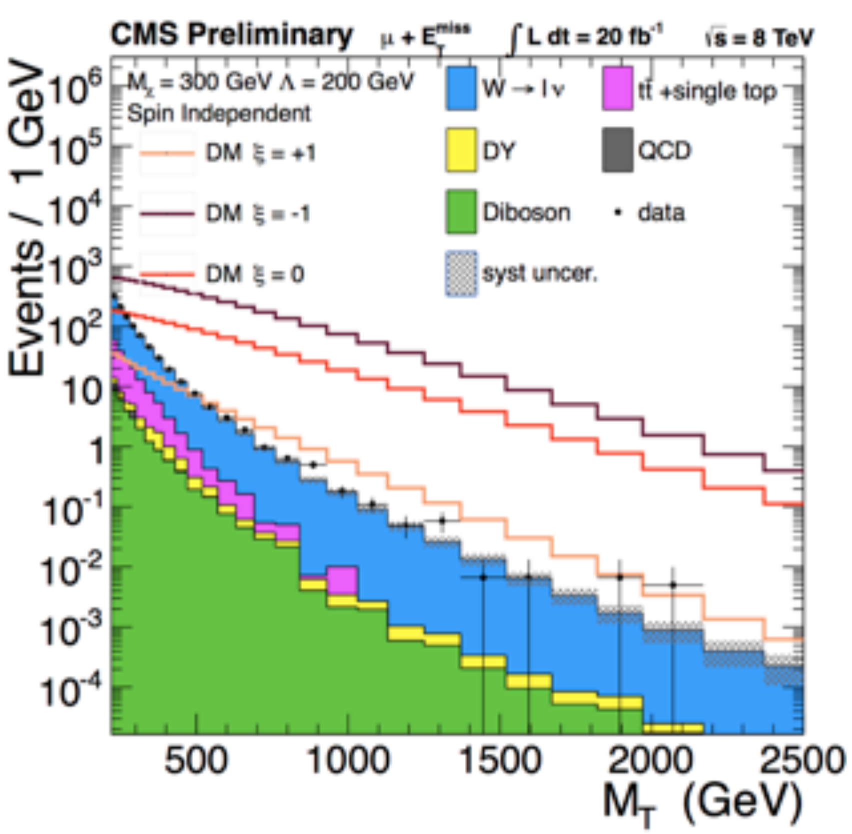


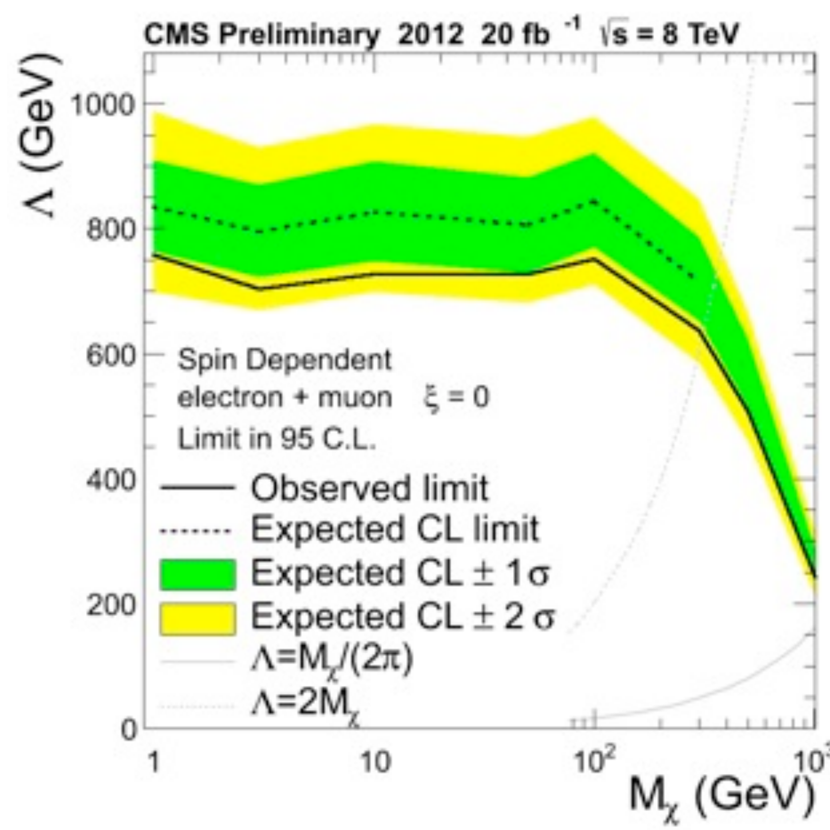


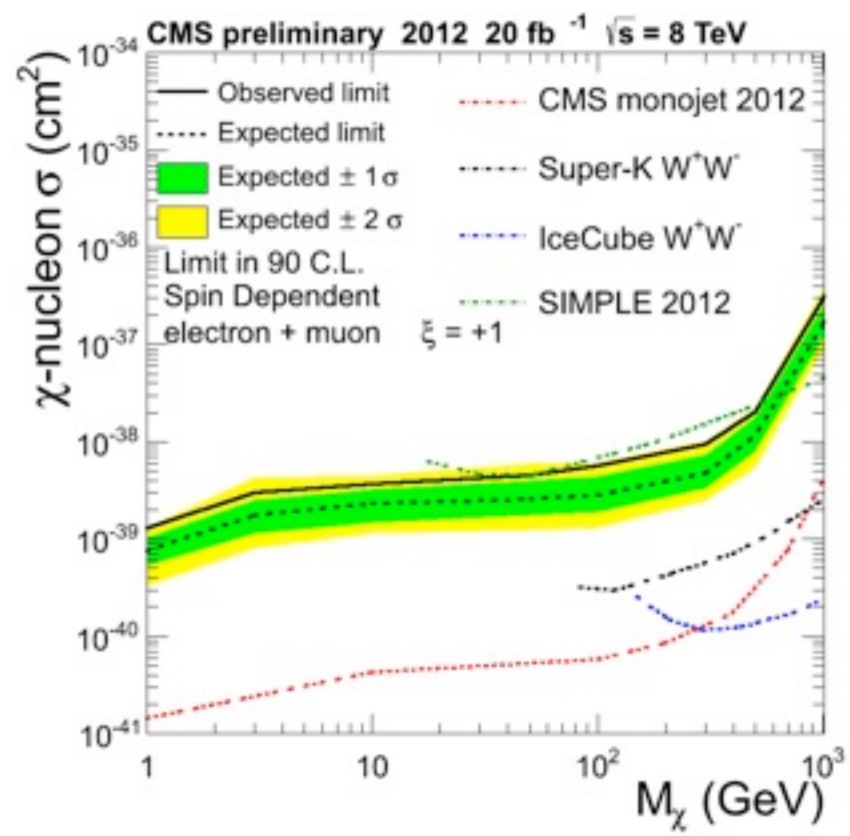
Mono-leptons

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



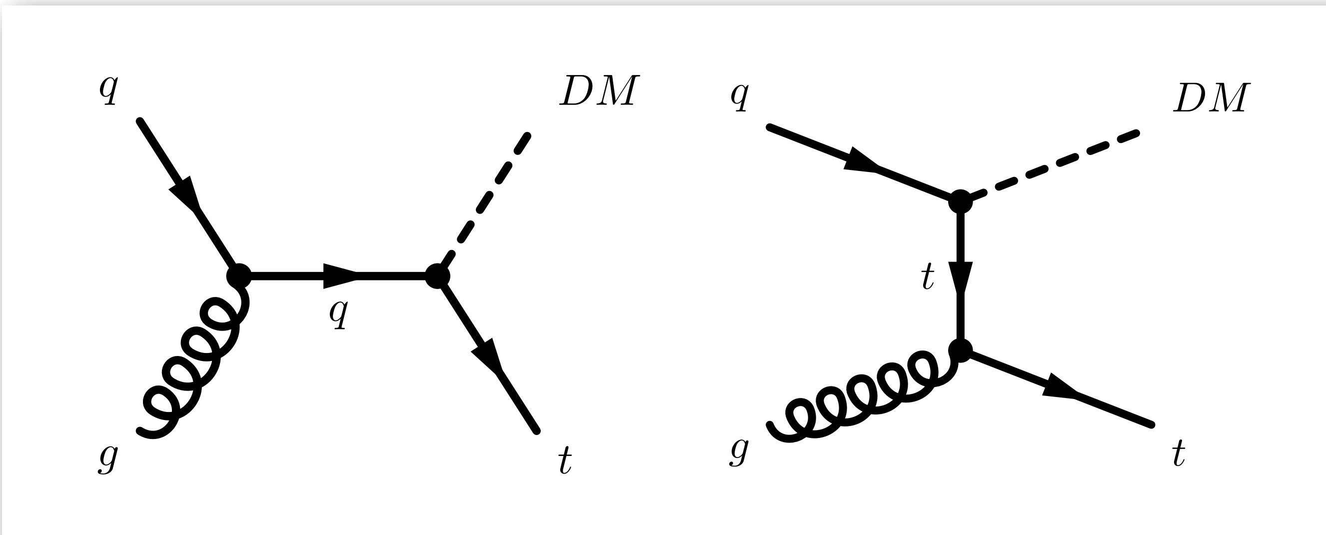


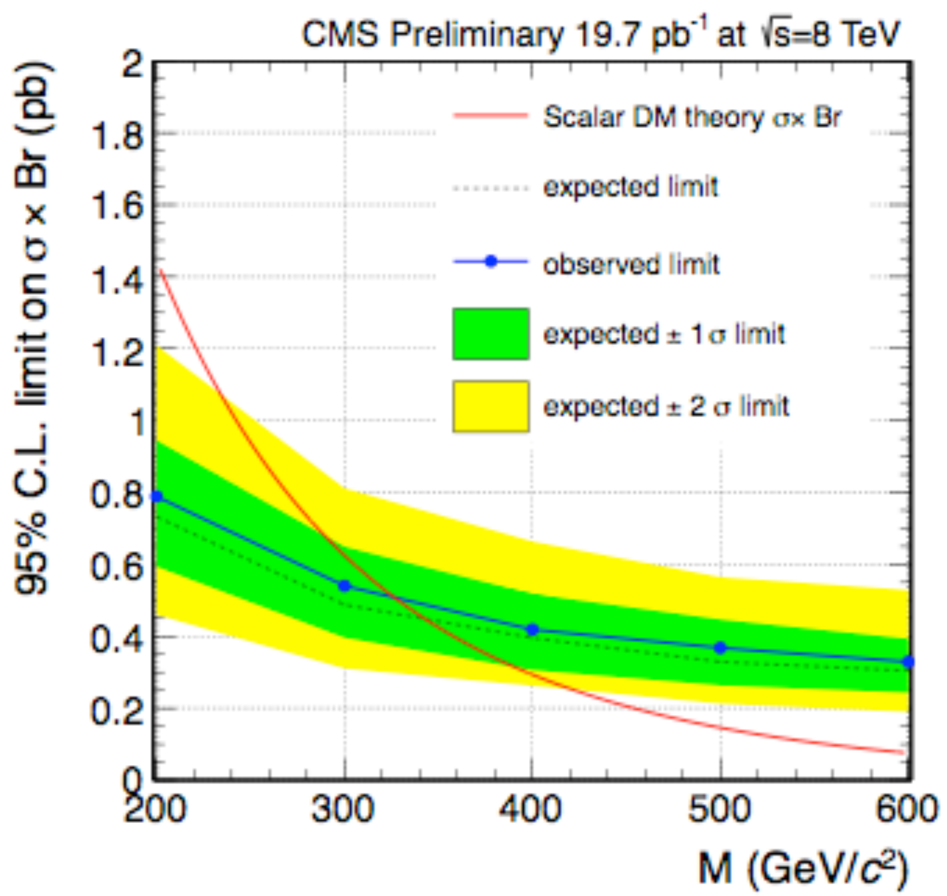




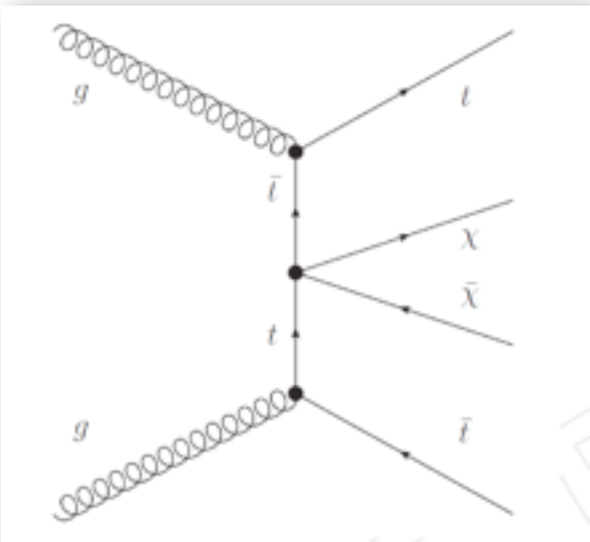
Mono-t and mono-tt

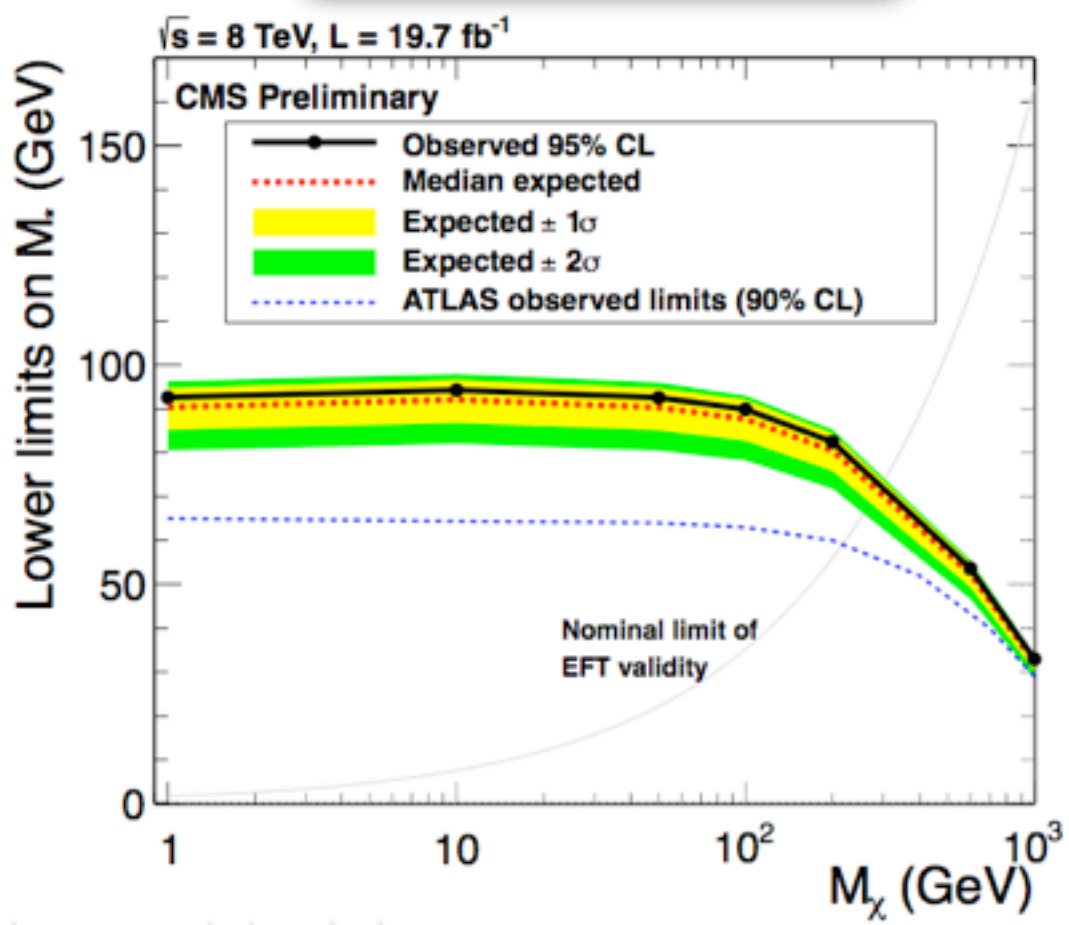
CMS-B2G-12-022





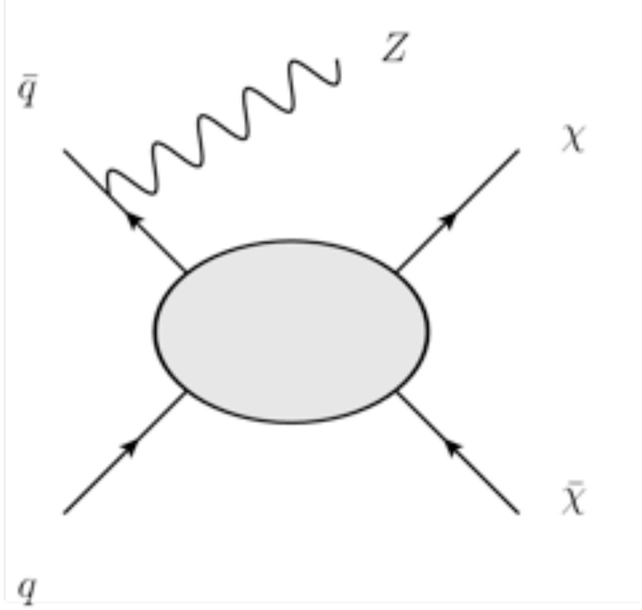
CMS-B2G-13-004

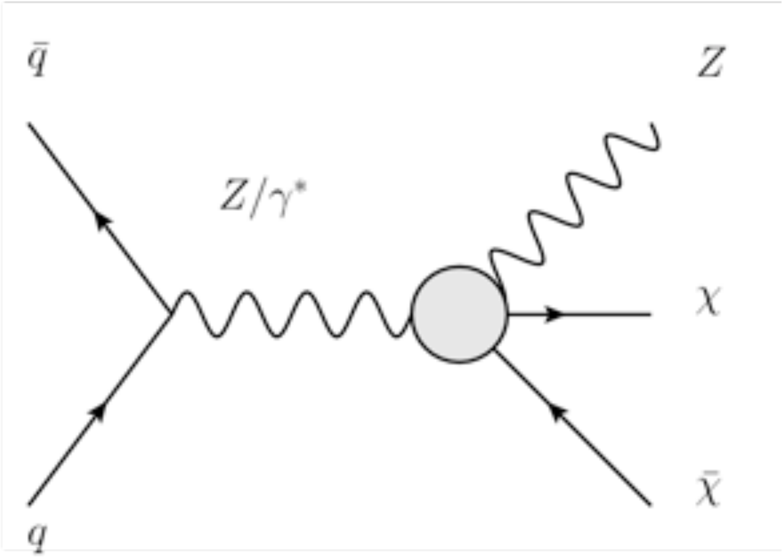




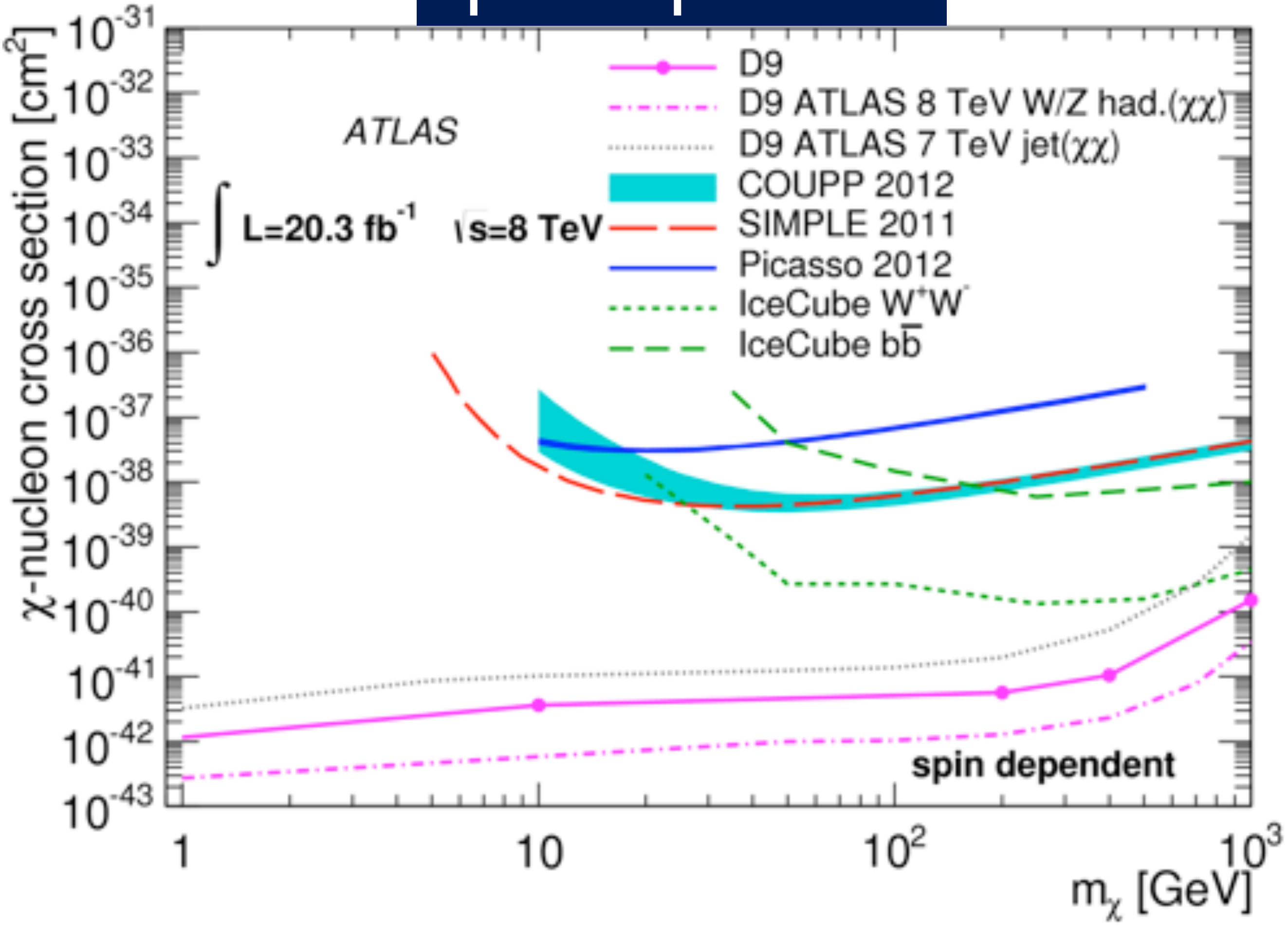
Mono-Z

arXiv:1404.0051

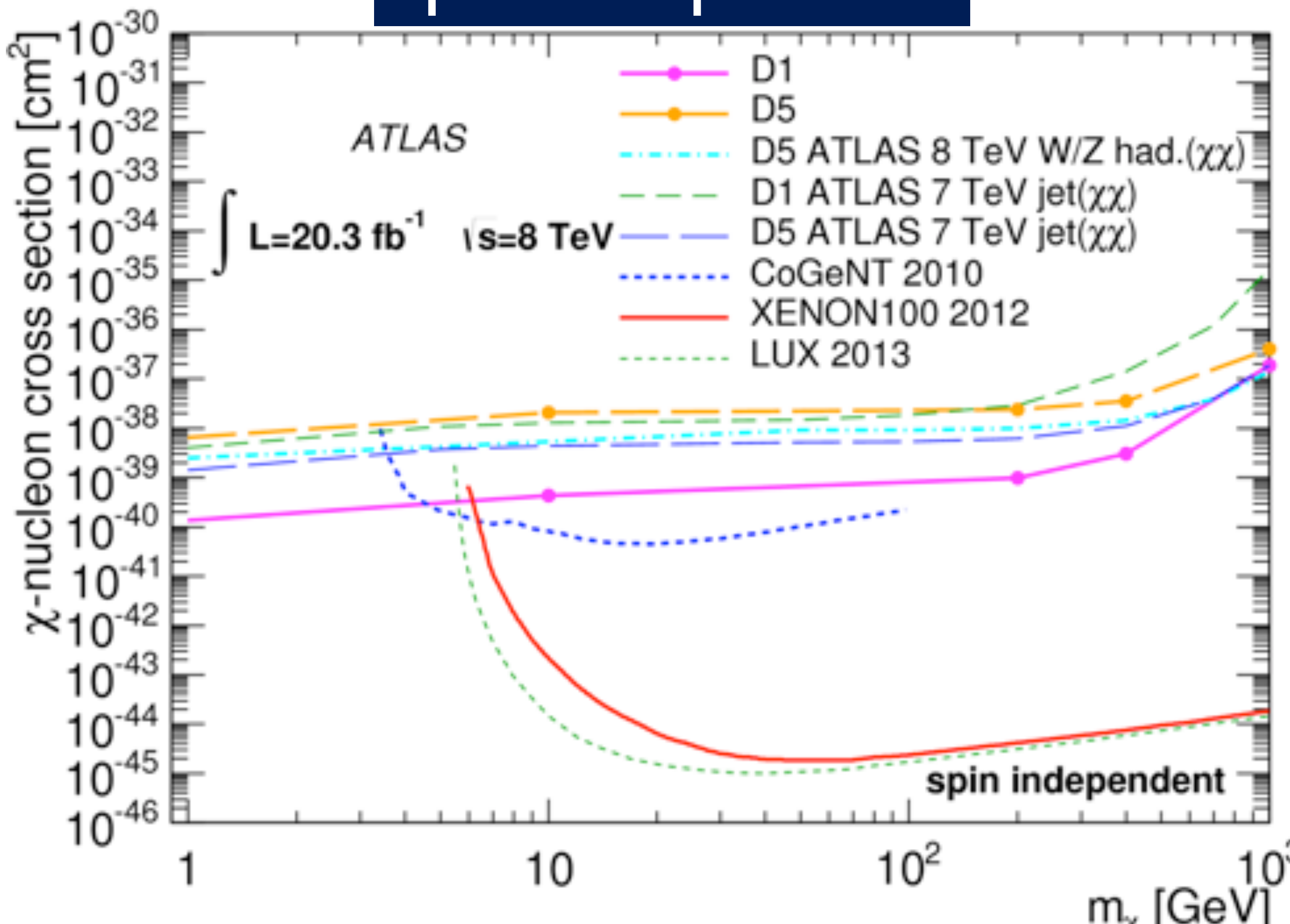




Spin-dependent

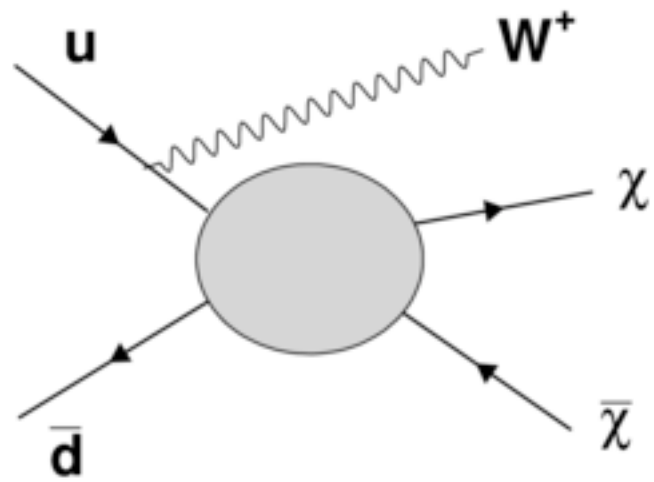


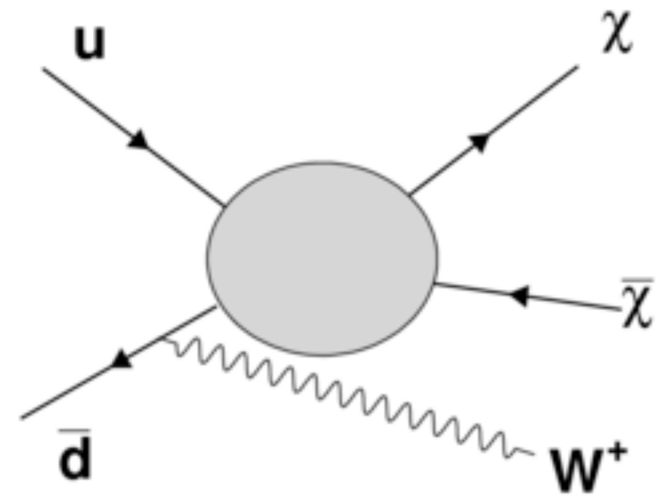
Spin-independent



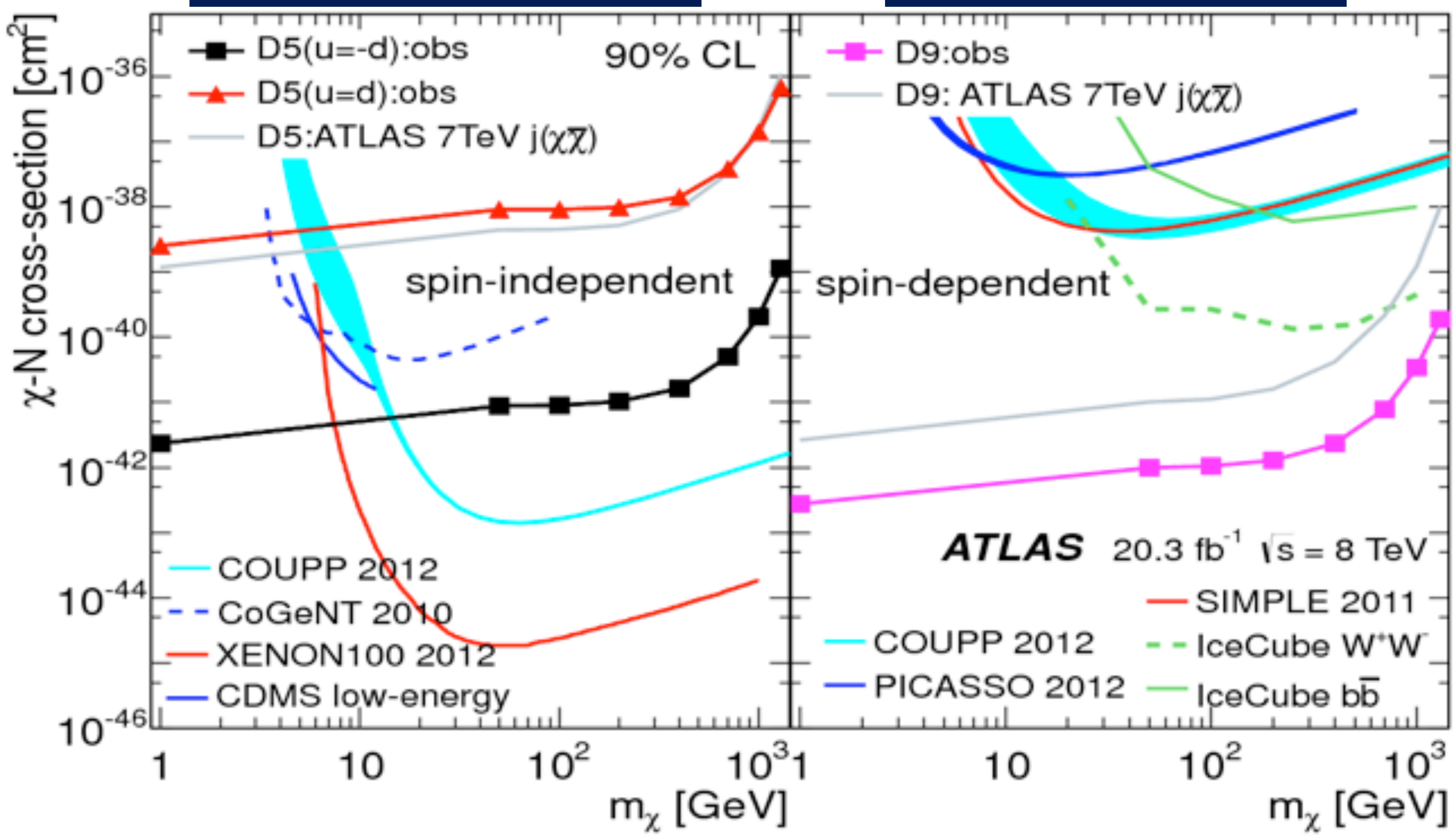
Mono-W

[Phys. Rev. Lett 112, 041802 (2014)]





Spin-independent **Spin-dependent**



Interpretation of searches

Limitations of EFT

arXiv:1308.6799

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

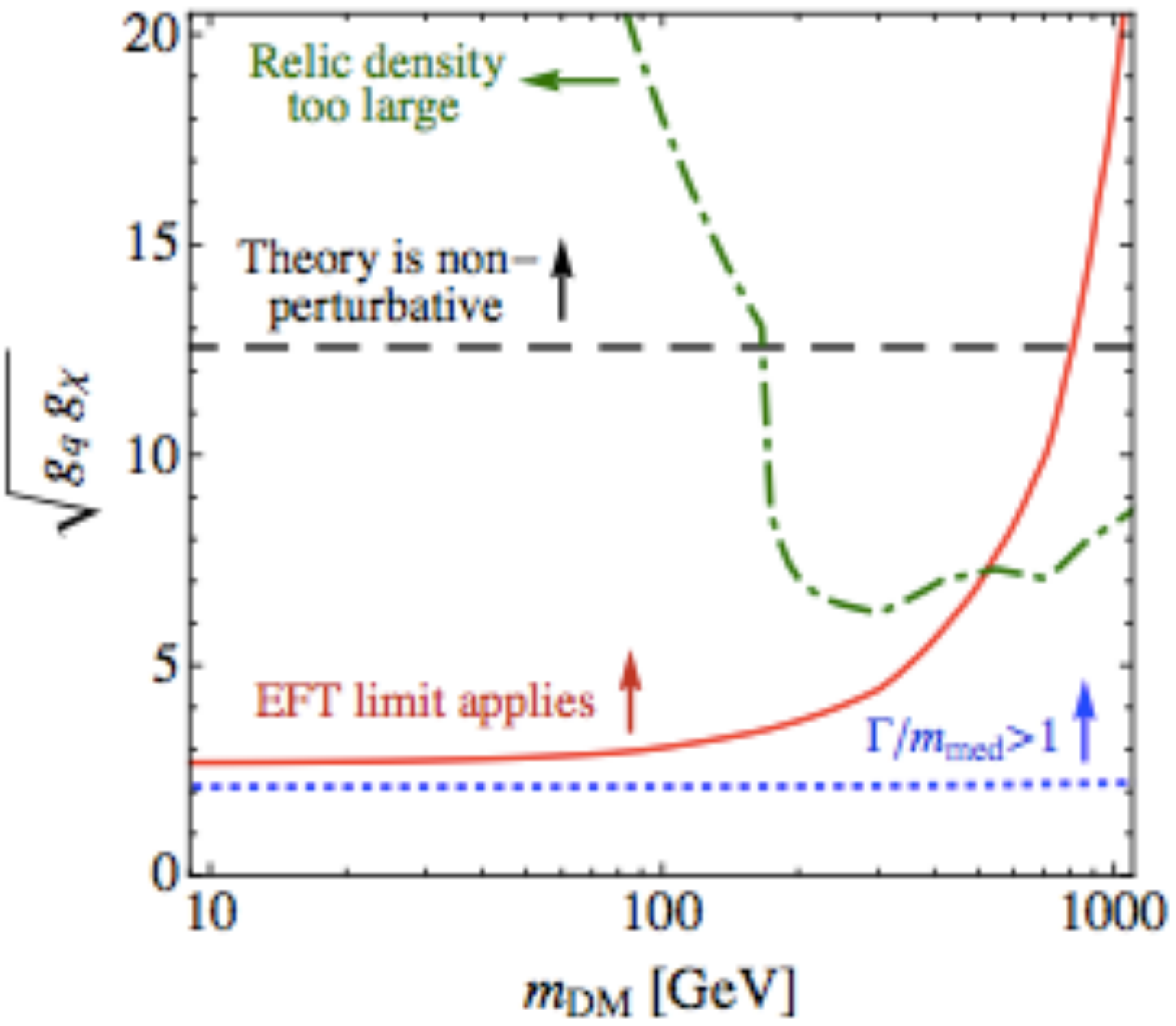
- EFT is valid when mediator mass > a few TeV
- The couplings required are large

Comparing this with known couplings:

strong interaction ~1.2

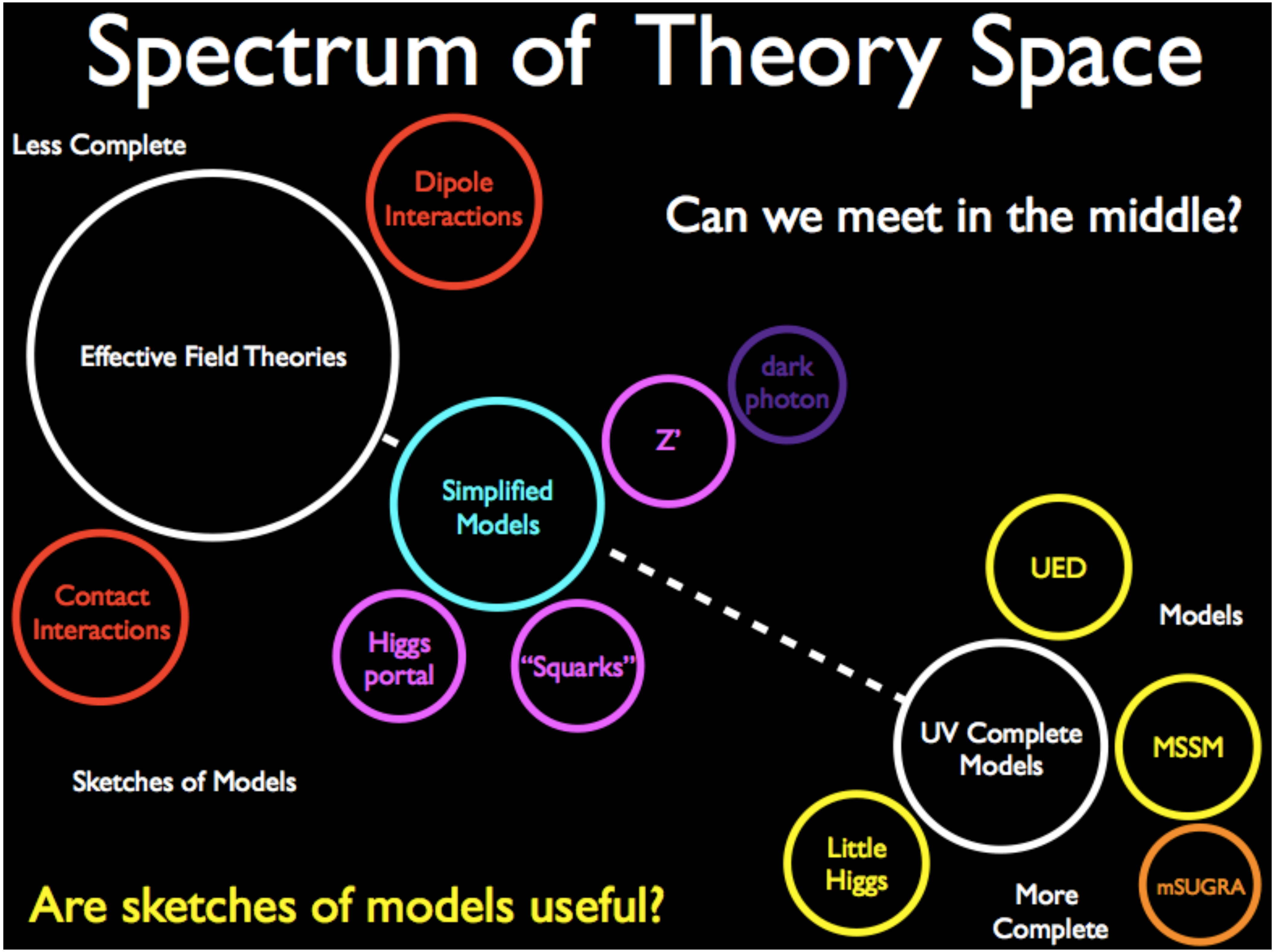
weak interaction ~0.6

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



Limits of EFT and beyond EFT

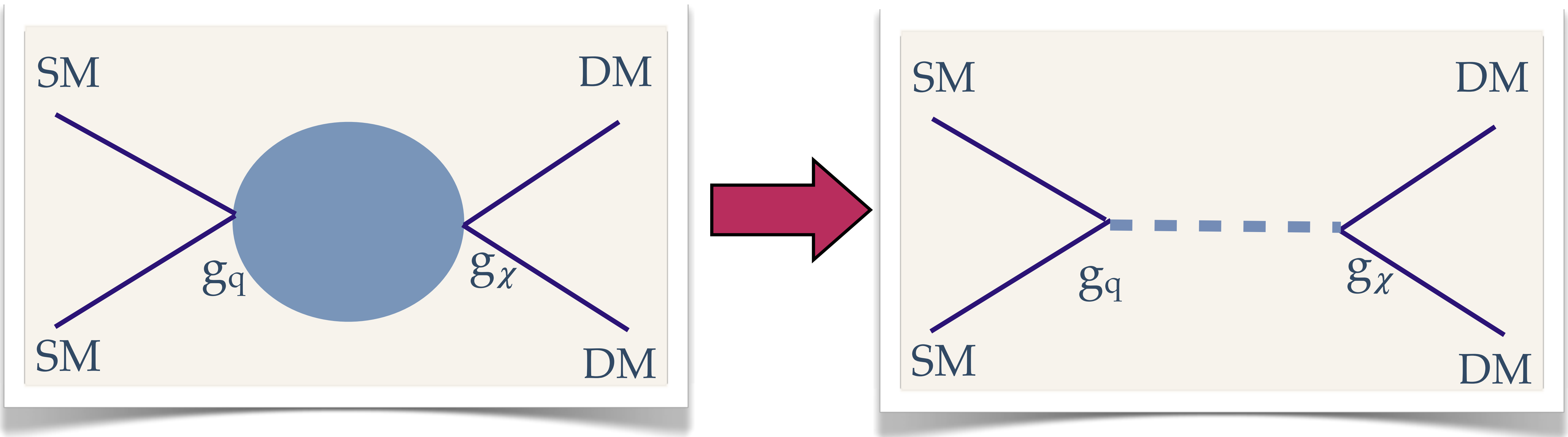
From Tim Tait



Phenomenology

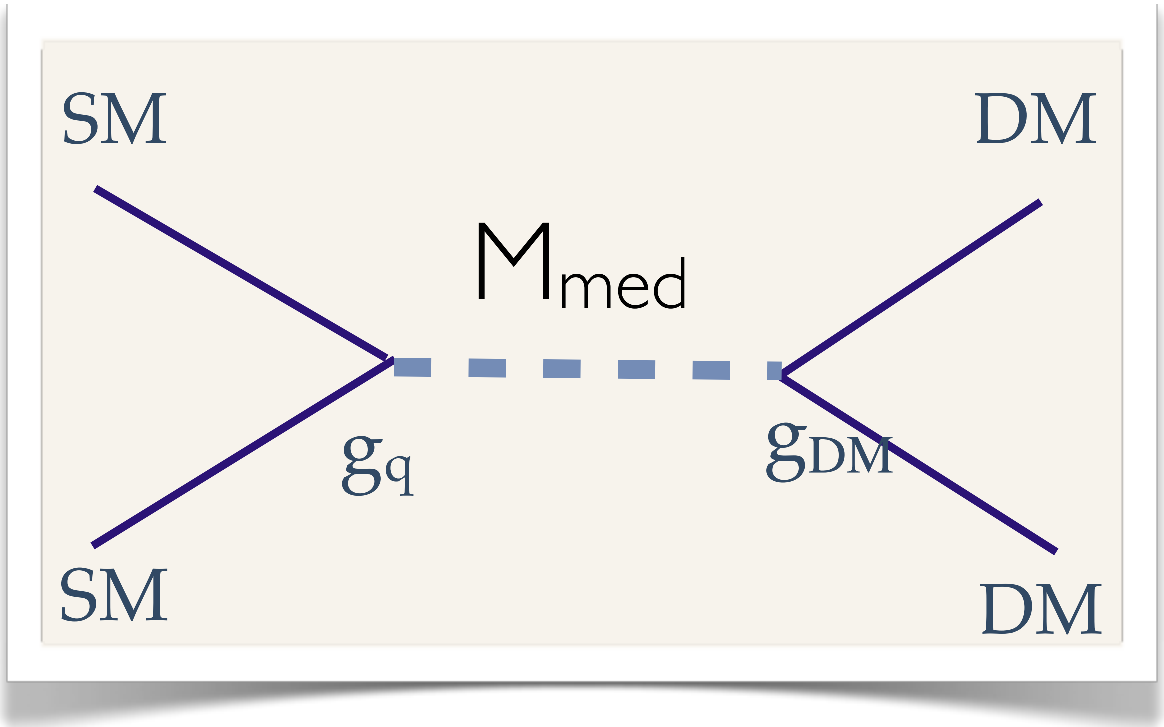
Light mediator

- Assume DM interaction is mediated by light particle
- Effective theory breaks down and explicitly have to include mediator mass.



Minimal Simplified model of dark matter

Based on work from :
O. Buchmueller, M. Dolan, S. 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

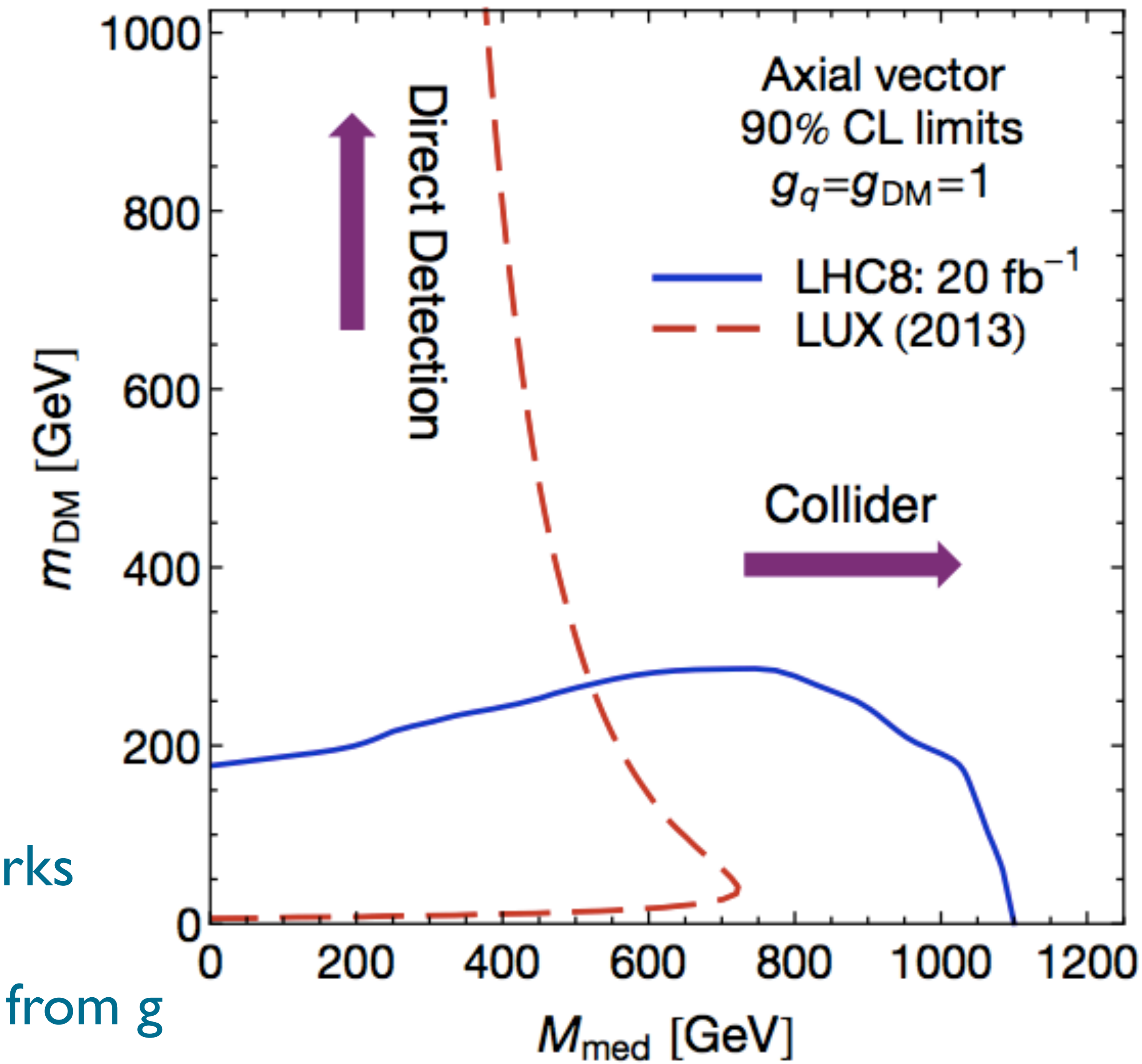
Consider comprehensive set of diagrams for mediator	
Vector	Axial-vector
Scalar	Pseudoscalar

Comparison with direct detection

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

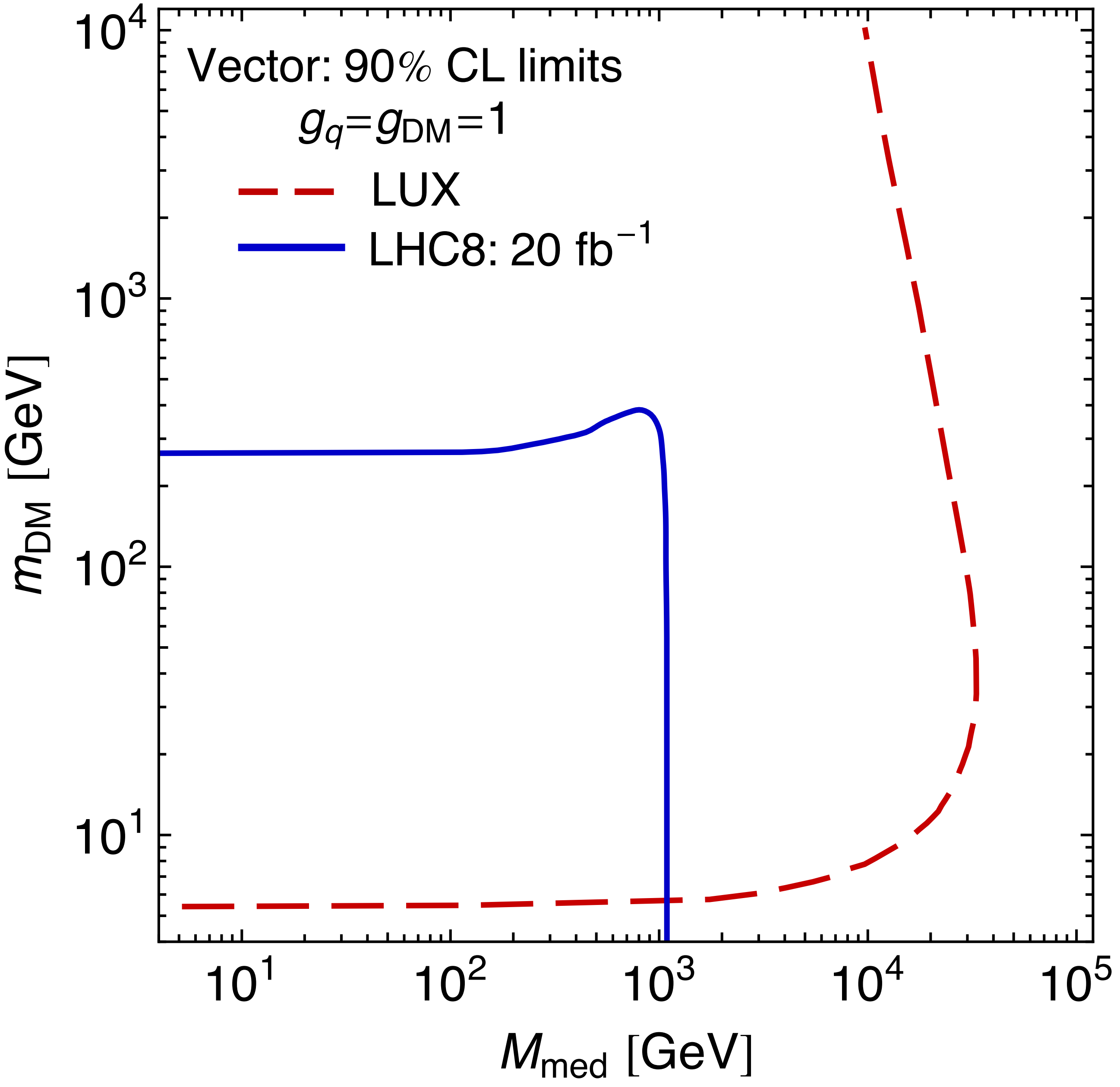
➡s-channel mediator
➡DM is Dirac fermion
➡Universal couplings to all quarks
➡$g_q = g_{DM}$
➡width of mediator calculated from g

Using CMS monojet search and LUX

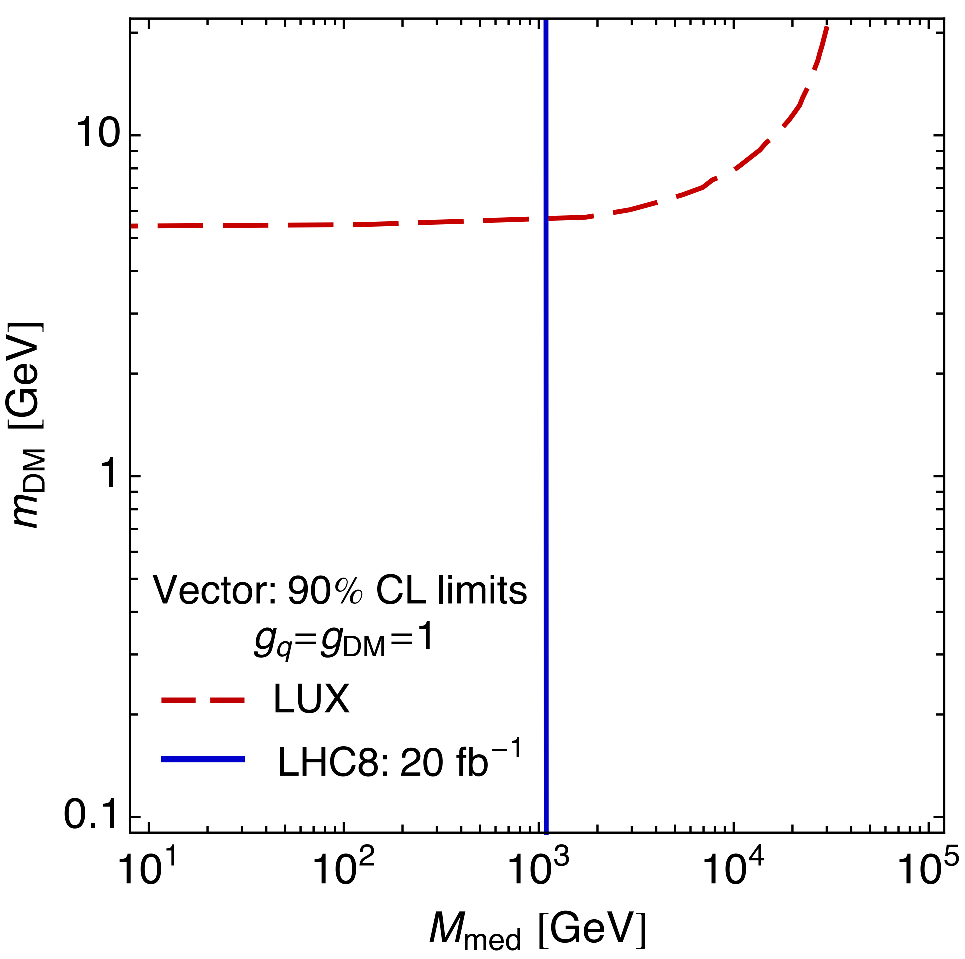


Comparison with direct detection

Vector mediator, $g_q = g_{DM} = 1$



Zooming in on low mass region........



Projections for 14 TeV

Projections for 14 TeV

Simplified Dark Matter Model

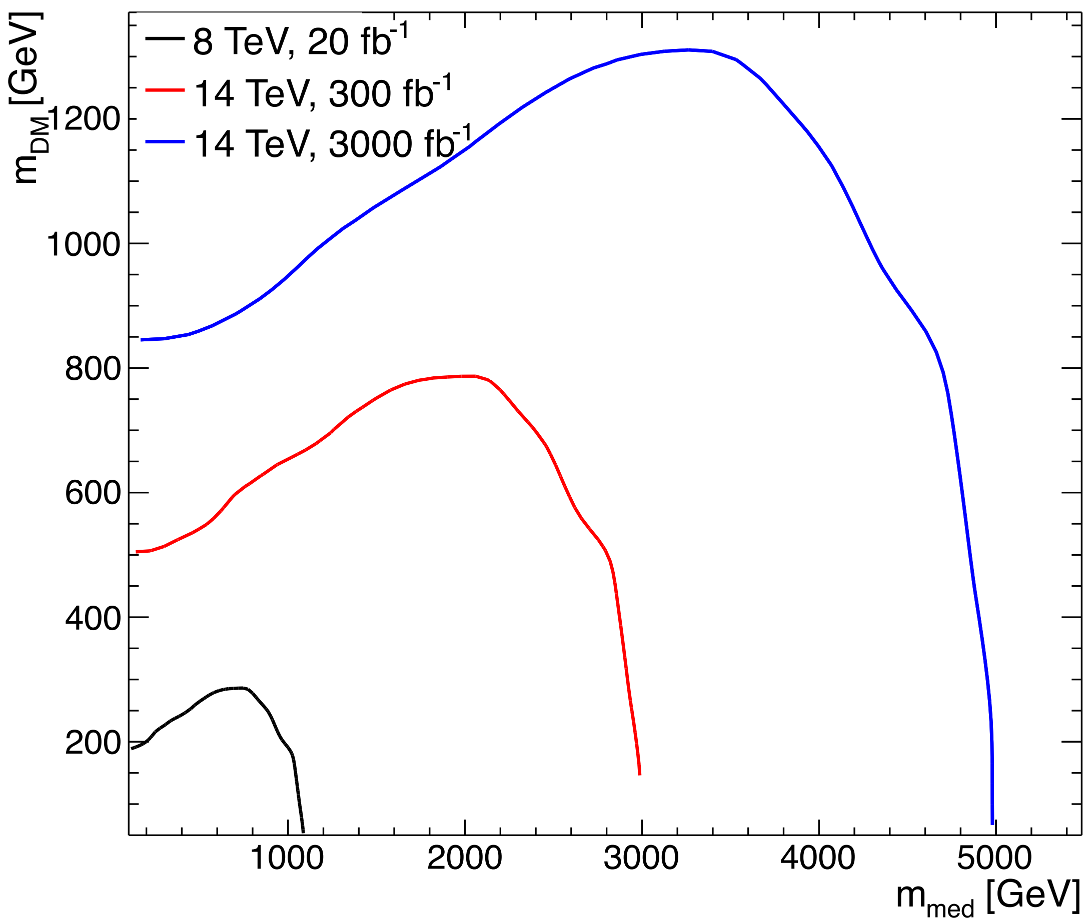
Projections for CMS monojet search:

8 TeV 20 fb^{-1}

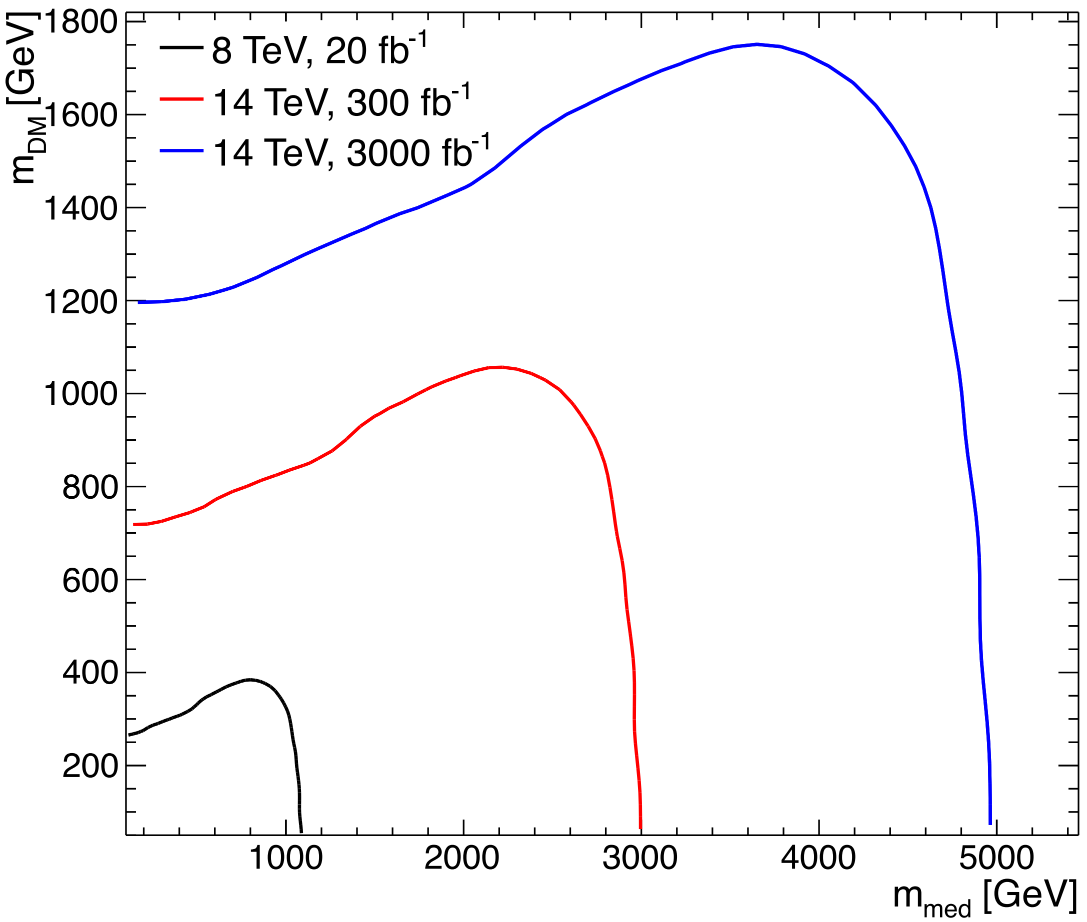
14 TeV 300 fb^{-1}

14 TeV 3000 fb^{-1}

Axial vector

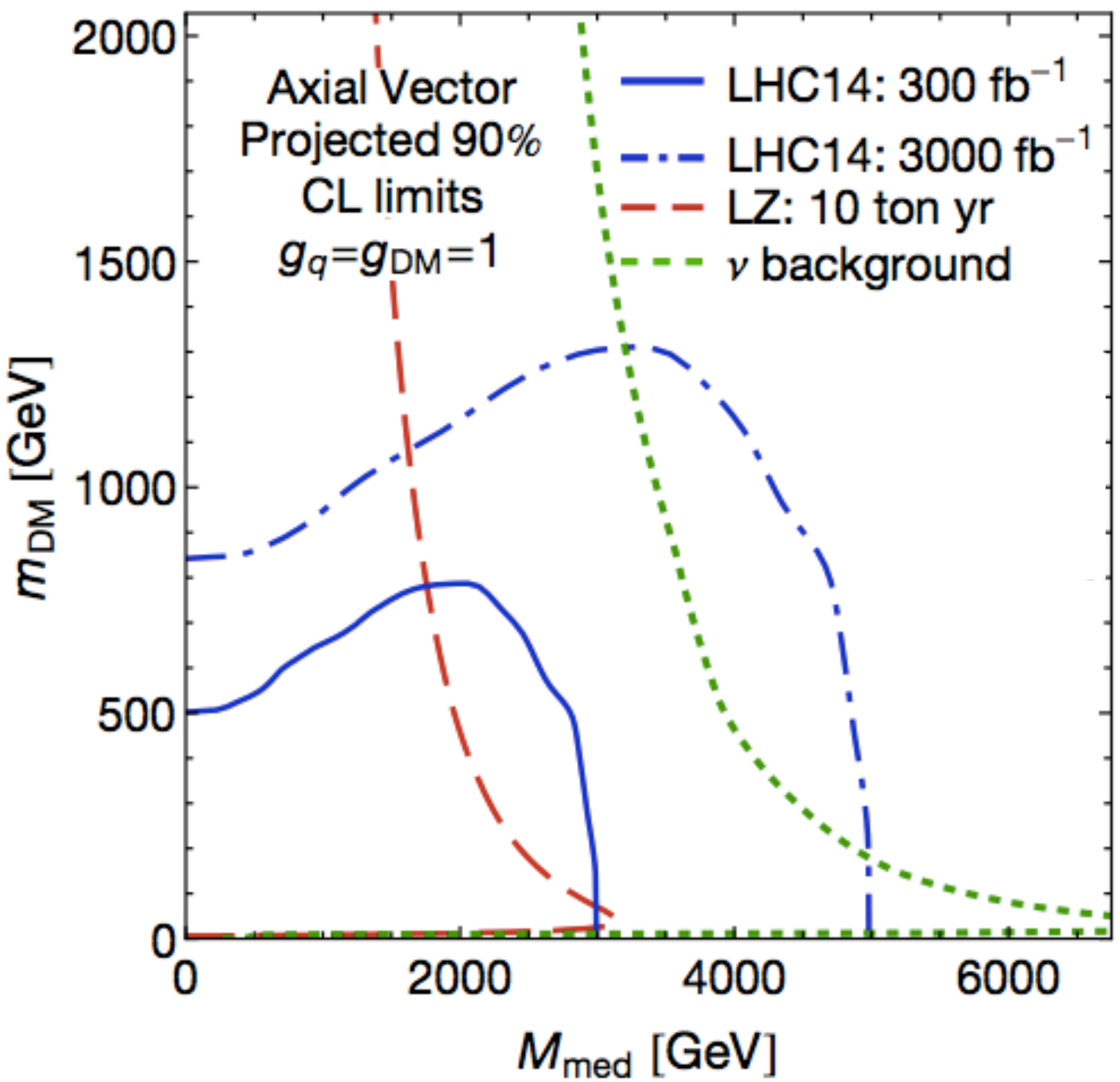


Vector

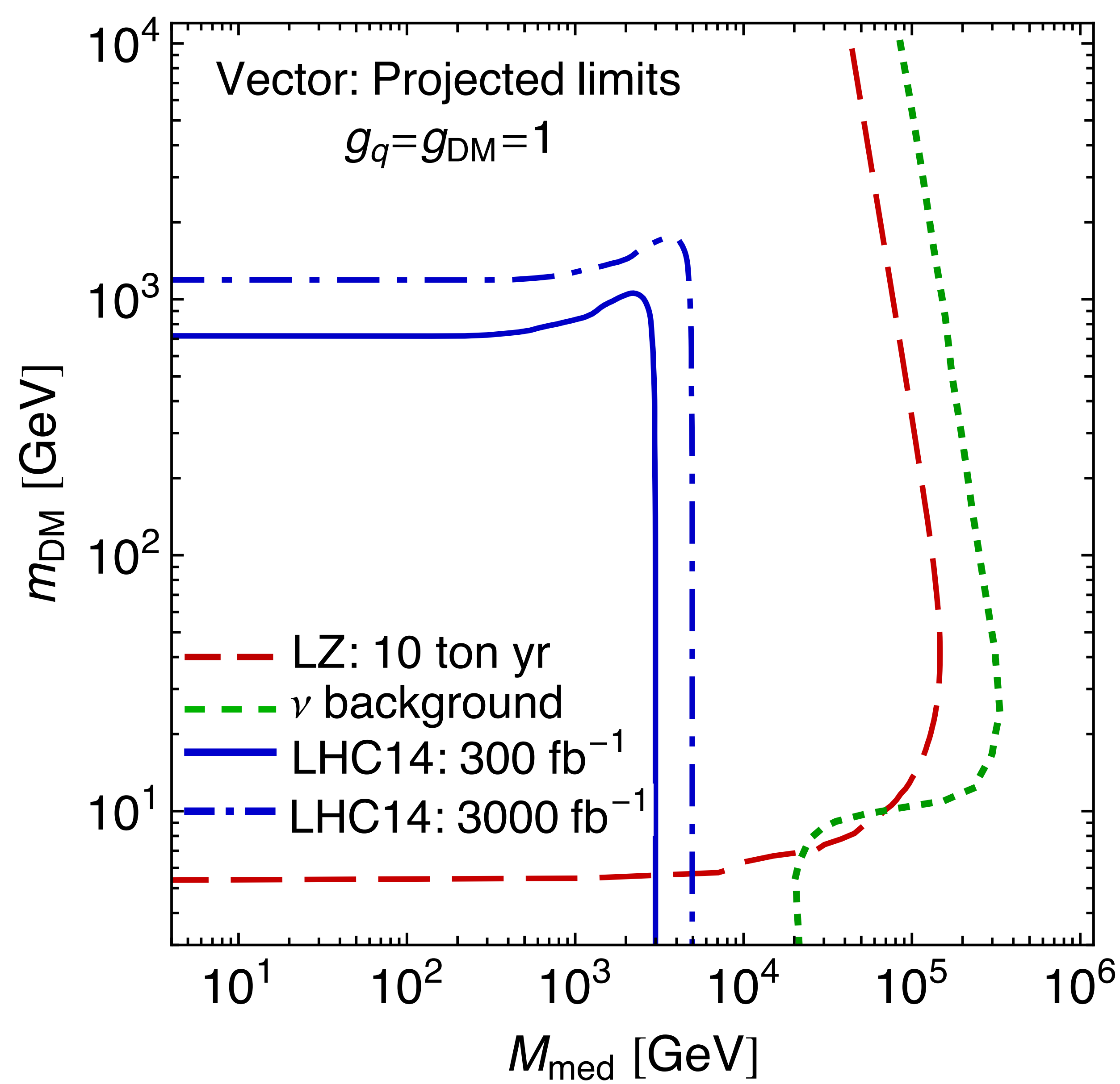


Projections

Axial vector



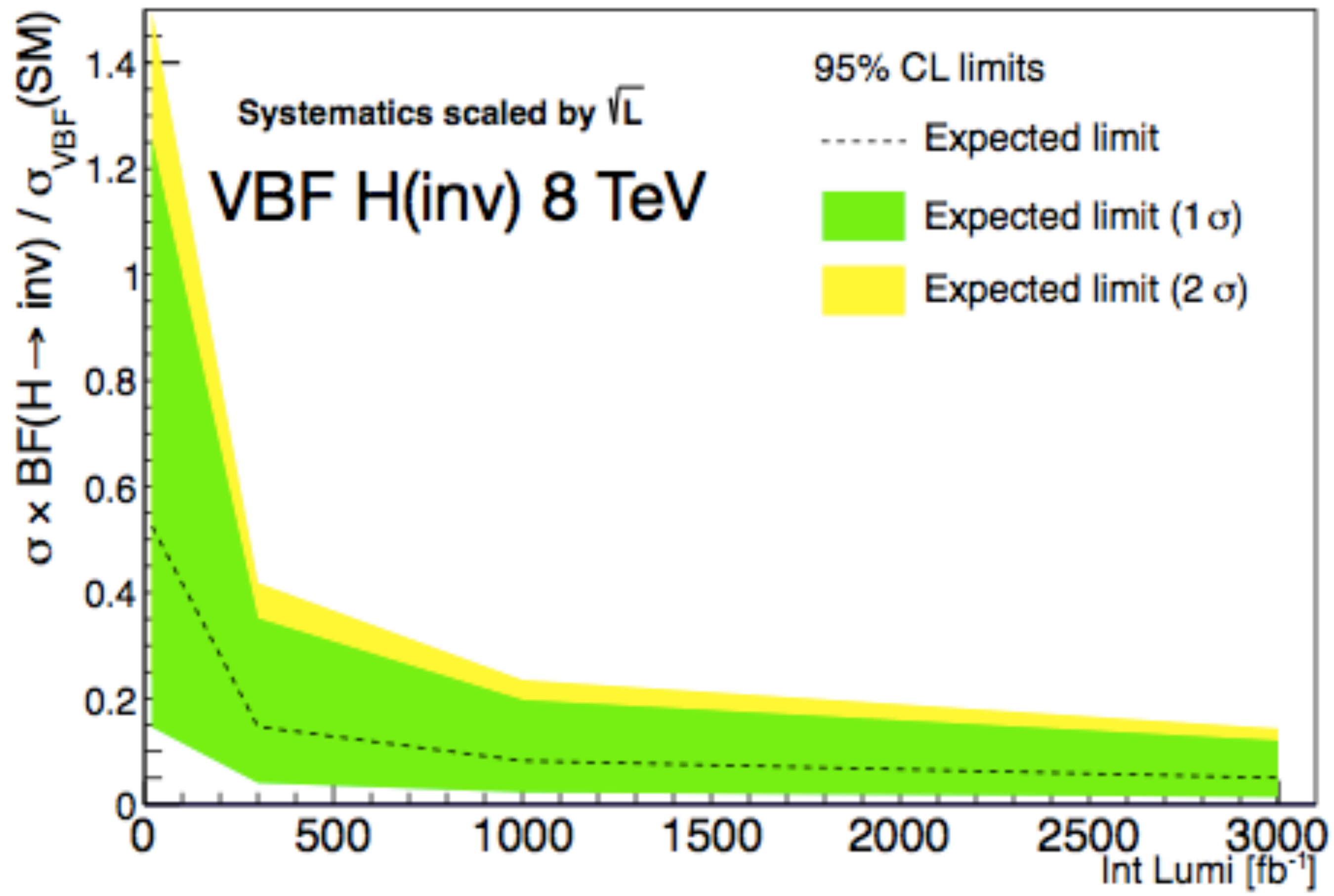
Vector



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 $1/\sqrt{L}$
  - 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

Summary

Showed limits from collider searches for dark matter

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

Lot of complementarity with direct detection experiments

- in particular, low mass DM
- spin-dependent interactions of DM

Future projections, similar complementarity going forward

Future projections for DM

Snowmass Cosmic Frontier

http://arxiv.org/abs/1401.6085