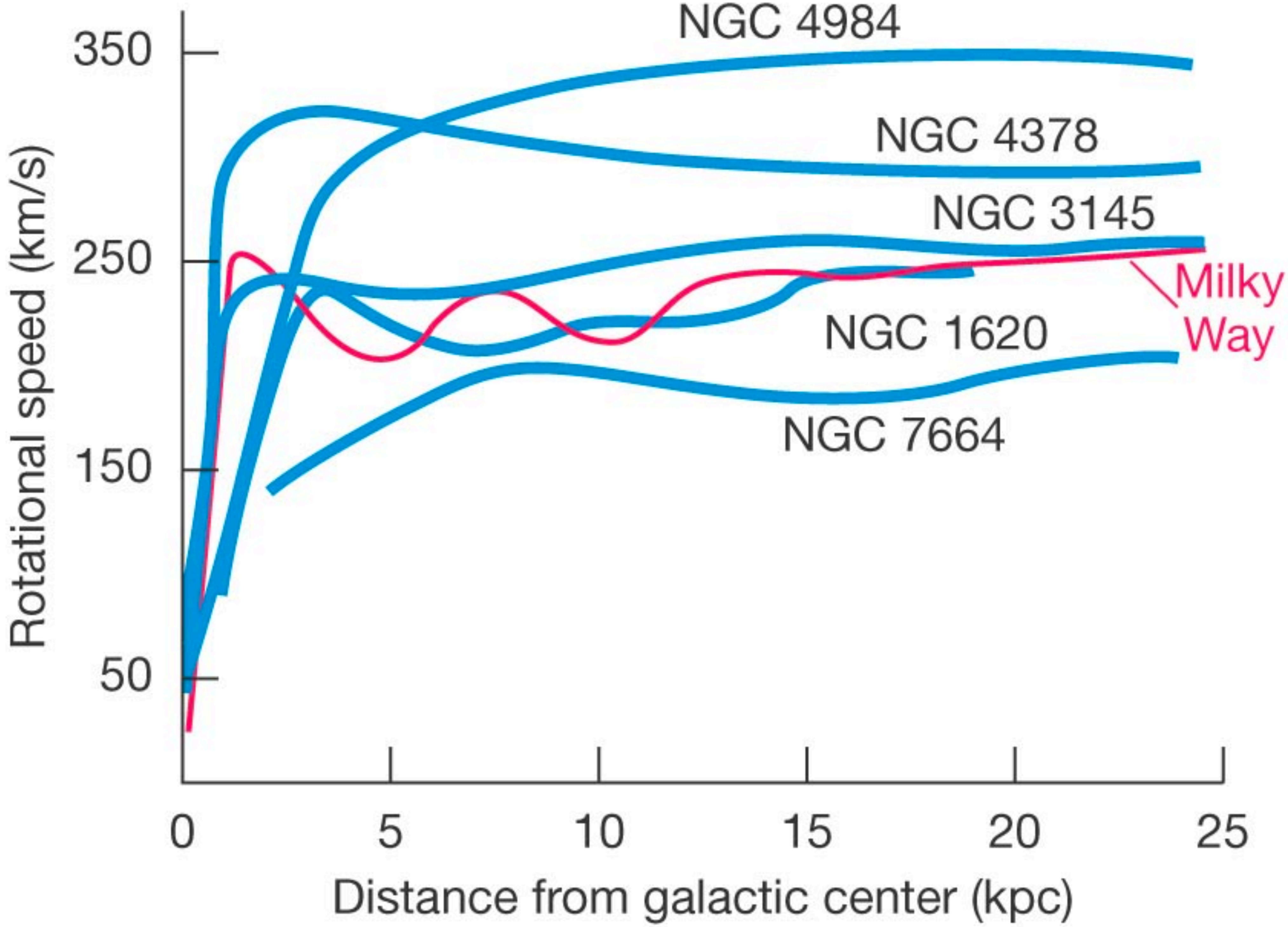
A FEW SLIDES ABOUT

DARK MATTER

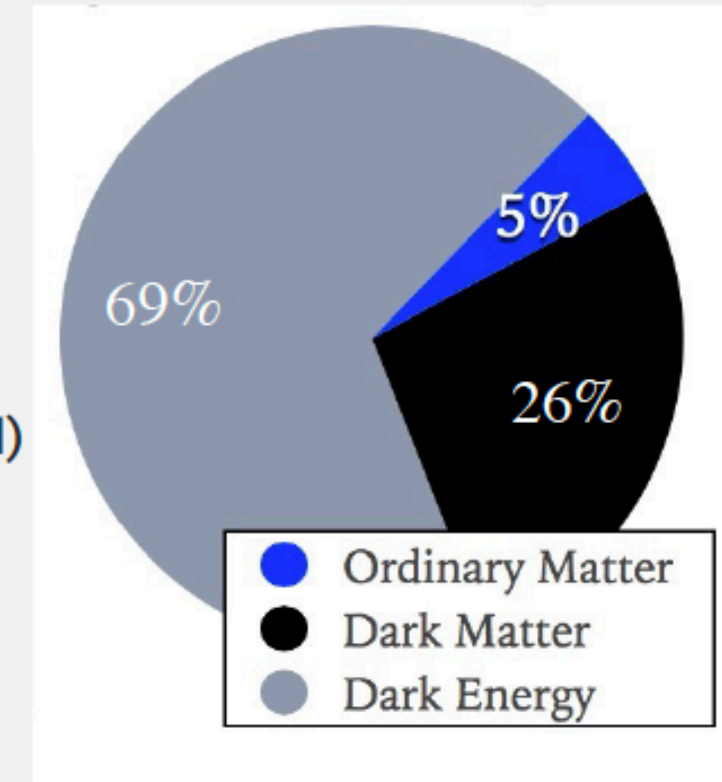

NGC 4984
NGC 4378
NGC 3145
NGC 1620
NGC 7664
Milky
Way
350
250
150
50
Rotational speed (km/s)
0
5
10
15
20
25
Distance from galactic center (kpc)

(b)

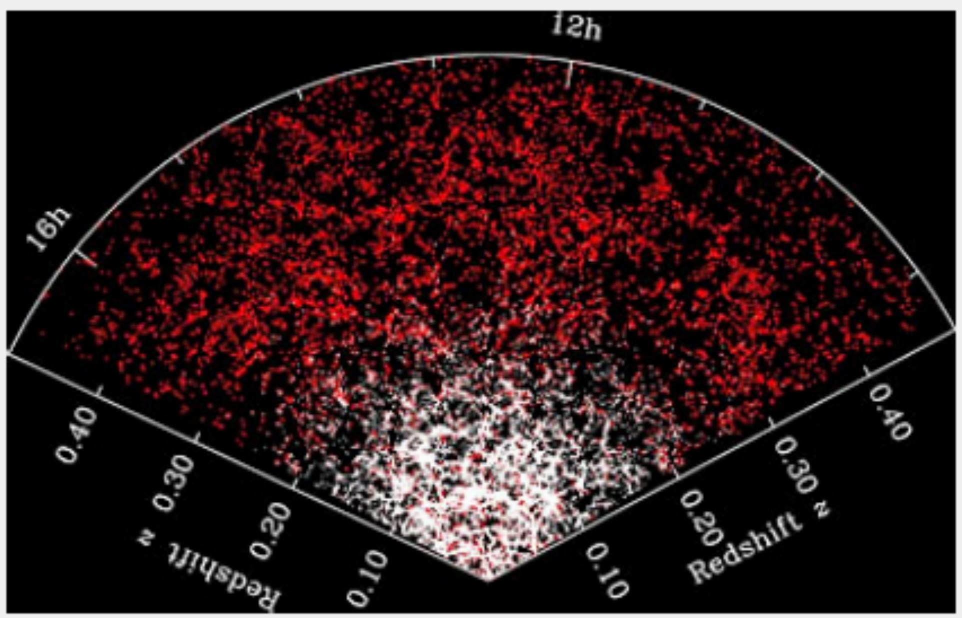
Properties of dark matter

Interacts gravitationally

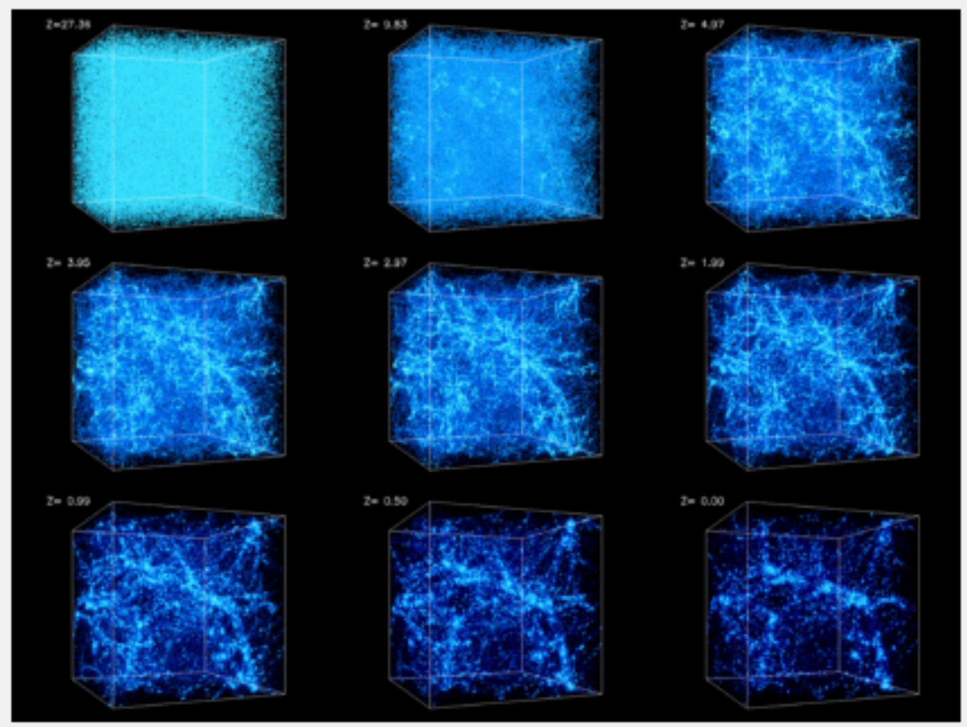
Dark
(other effective couplings to SM are zero or small)



5x as much DM as SM



Cosmologically stable



Approximately Cold / non-relativistic

Modified gravity difficult and lacks other evidence

Massive AstrophysiCal Halo Objects (MACHOs) cannot account for observed density

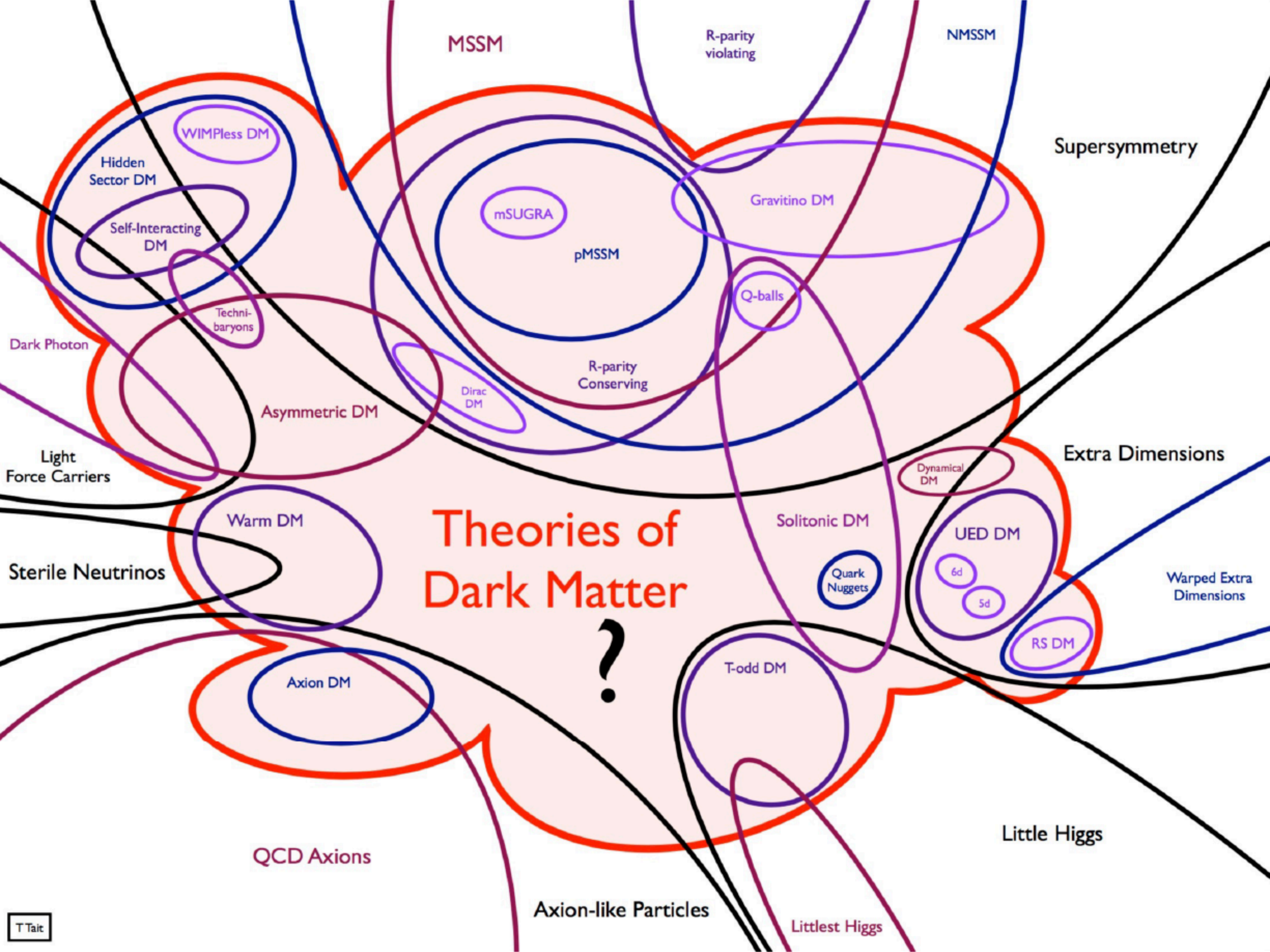
Particle dark matter: but properties inconsistent with any Standard Model particle

[Antonio Boveia (ATLAS)]

ALL WE NEED: ONE BSM PARTICLE THAT

- does NOT decay
- has the correct abundance today
- does NOT spoil BBN
- is NOT already excluded by experiments/observations

We don’t need to specify the details: **SIMPLIFIED MODELS**



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
Dirac DM
R-parity Conserving
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

WIMP PARADIGM

before the LHC

SuperSymmetry

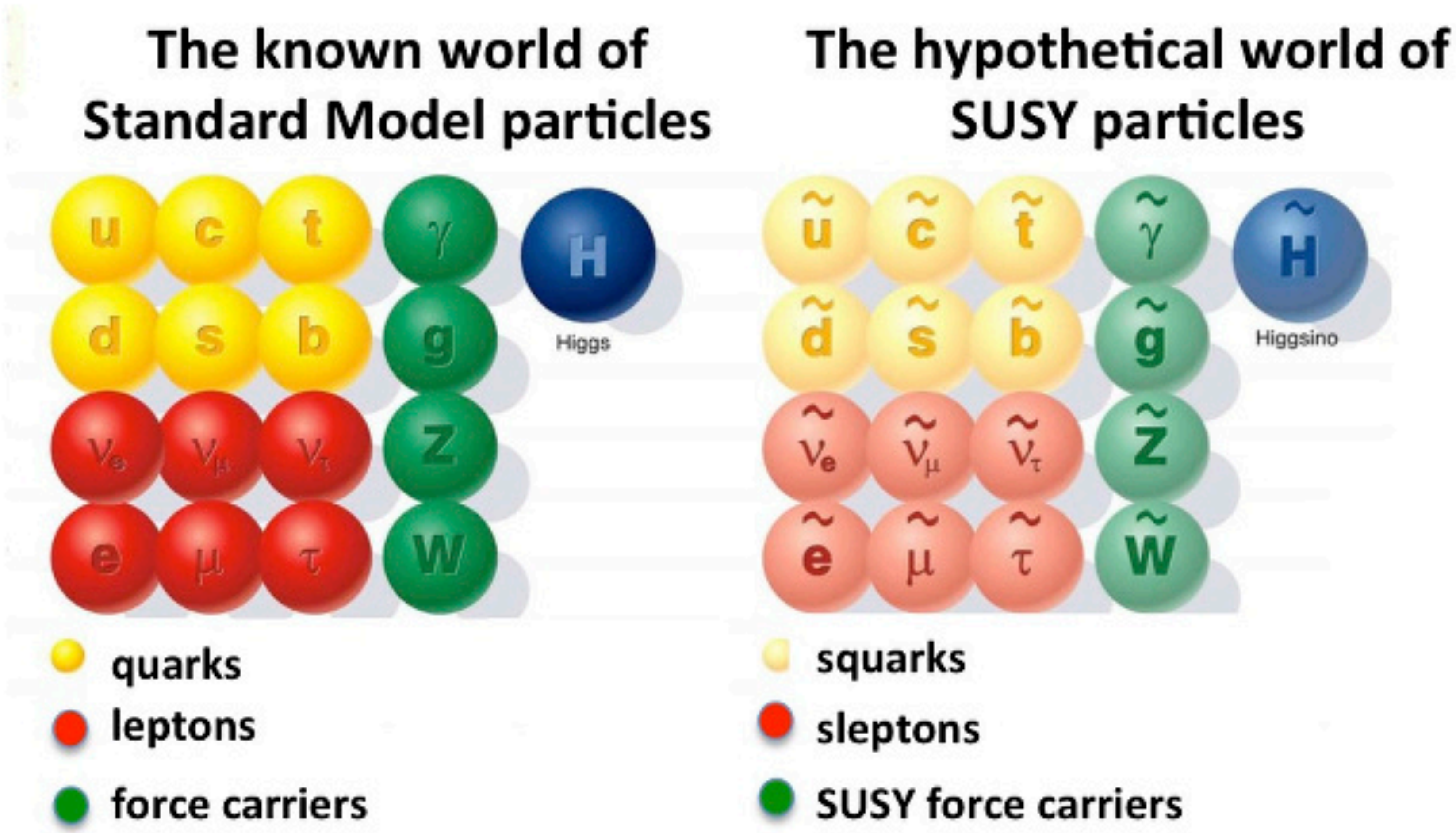
Composite Higgs

Extra Dimensions

after the LHC

Hidden sector DM, Wimpzillas, ALPs,……..

SUPERSYMMETRY (SUSY)

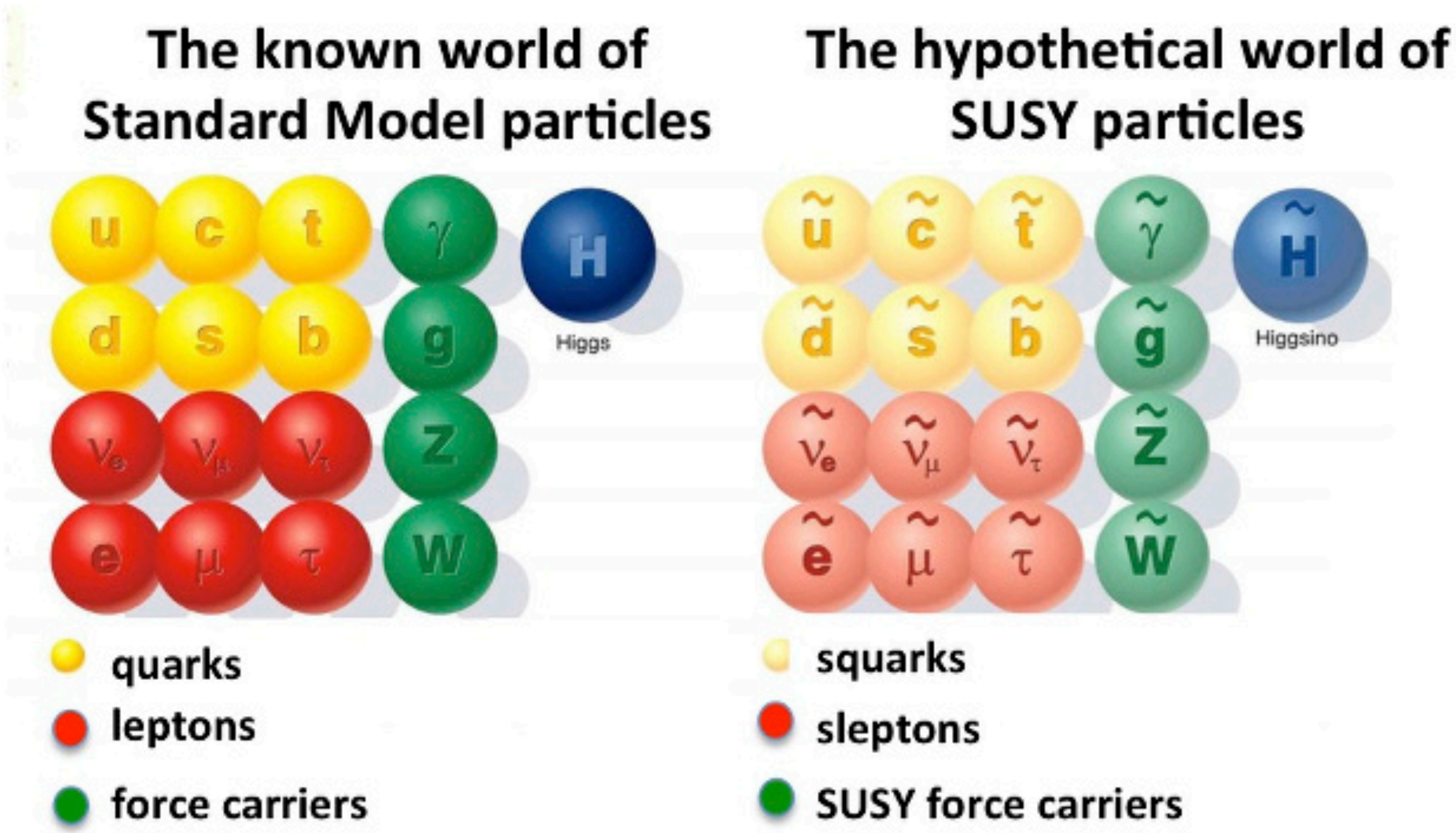


We need a different Higgs doublet to give mass to up-type fermions and down type fermions:

two Higgs doublets = 8 Higgs bosons

3 absorbed in W,Z => 5 Higgs bosons to be found

SUPERSYMMETRY (SUSY)



Supersymmetric partners interact with the **SAME** couplings as SM particles.

HIERARCHY PROBLEM

Any scalar particle (in SM we only have one) gets quadratic corrections to its mass: there is no symmetry protection mechanism for scalars.

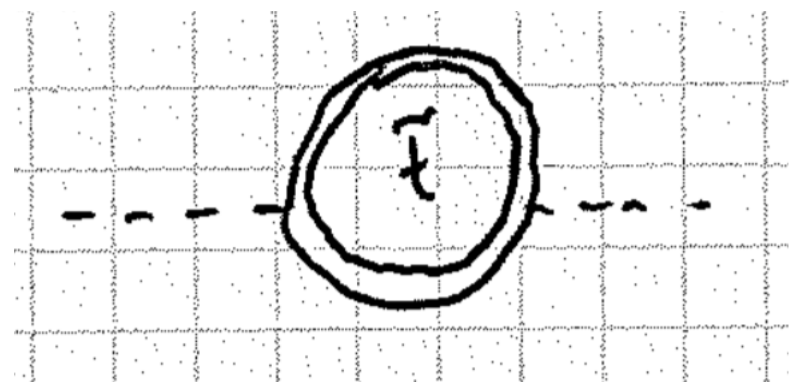
$$\Rightarrow \delta m^2 \sim \frac{\alpha}{2\pi}\left(\Lambda^2 + m_t^2\right)\cdot(-1).$$

Even in the absence of any BSM, the SM is, in fact, an effective theory at Planck scale.

$$m_H^2 = m_{H;0}^2 + \delta m_H^2 \simeq 125^2\ \text{GeV}$$

SUPERSYMMETRY'S RESPONSE

the stop quark



If SUSY was exact, the cancellation would be exact.

But SUSY is broken, so the cancellation is incomplete (little hierarchy problem)

$$\delta m_H^2 \sim m_t^2 - m_{\tilde{t}}^2$$

SUPERSYMMETRY

There are many many many supersymmetric theories, depending on how much supersymmetry is allowed (N=1, N=2, N=4), and how the supersymmetry is broken.

MSSM: Minimal Supersymmetric Standard Model: O(100) parameters (masses, Yukawas, etc)

mSUGRA: more constrained model (five parameters beyond SM)

SUPERSYMMETRY WITH R-PARITY

R-parity: a new imposed quantum number

$$R \equiv (-1)^{3B+L+2s}$$

Supersymmetric particles cannot decay to SM particles alone!

LSP: Lightest Supersymmetric Particle is stable!

LSP AS DARK MATTER CANDIDATE

- needs to be electrically neutral and color neutral
- sneutrinos
- gravitinos
- neutralinos (linear comb. of Zino, photino and neutral higgses)

Which one is the LSP depends on how SUSY is broken in each model.

COMPOSITE HIGGS / EXTRA DIMENSIONS

Composite Higgs: the Higgs boson is not a fundamental scalar, but a BOUND STATE of some new strong dynamics (like the pion or the rho meson is a bound state of QCD). In particular, the Higgs boson is supposed to be the (pseudo-)Goldstone boson of some (approximate) (global) symmetry that is spontaneously broken.

Extra dimensions: Warped with a microscopic radius. The fields propagate there, and periodic boundary conditions produce extra modes for each lower state:

Kaluza-Klein modes

The KK modes of the gluons are good DM particles

HIDDEN SECTOR DM

- Light DM candidates 1KeV - 10GeV
- Hidden sector that only interacts with SM via MEDIATOR
- abundance does not come out right by default, needs explanation
- Asymmetric DM: abundance after DM- anti-DM anihilation
- Freeze-in: interaction with SM so weak that they can never be in equilibrium. They are continuously produced, until the SM decays to them stop, which is when their abundance freezes.

HIDDEN SECTOR

Hadrophilic

Mediator interacts with hadrons

Monojets

Leptophilic

Mediator interacts with electrons

monoleptons

Dark Higgs/photons

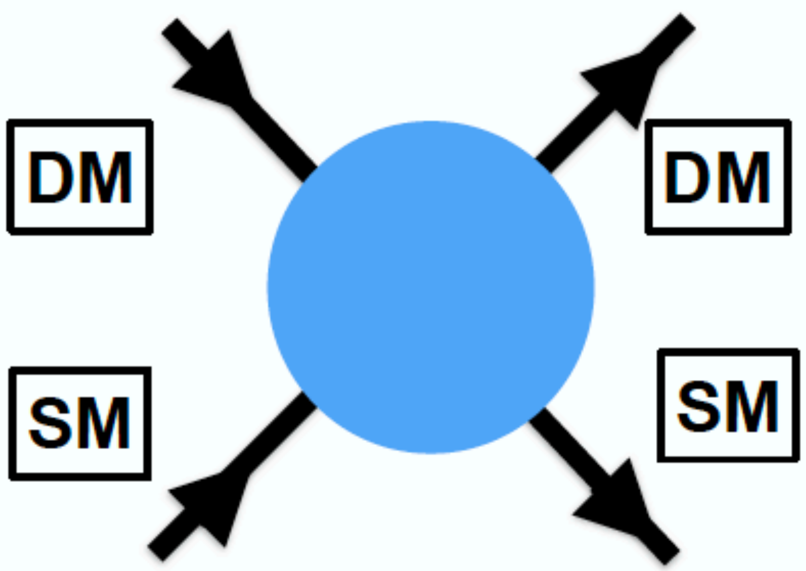
Mediator mixes with photons/higgses

Dark Matter detection

Detection of **DM** implies **its interaction** with **known matter**

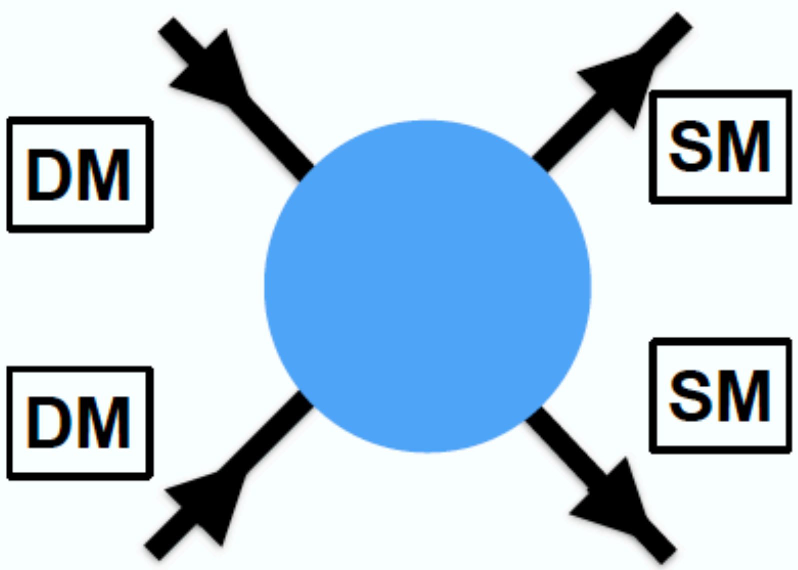
Direct Detection

DM-nucleon scattering



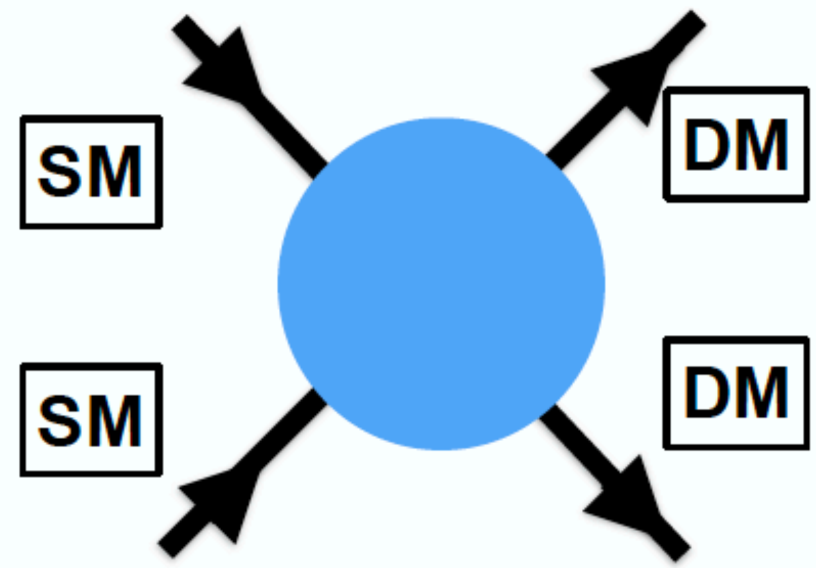
Indirect Detection

DM annihilation

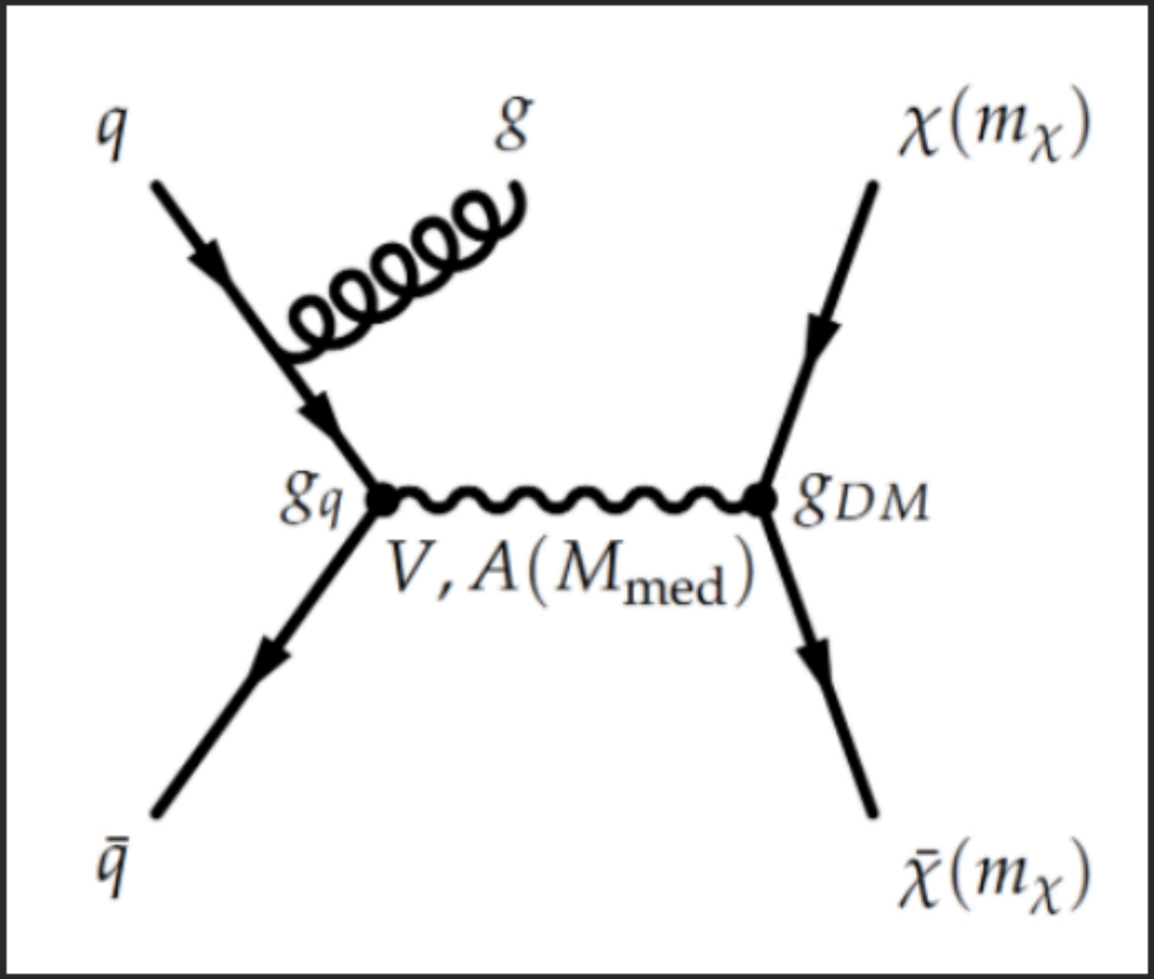


Collider experiments

Production of DM



Searching for Dark Matter Production



What do we know?

(DARK HUMOUR IN MORIOND)

Cold white matter

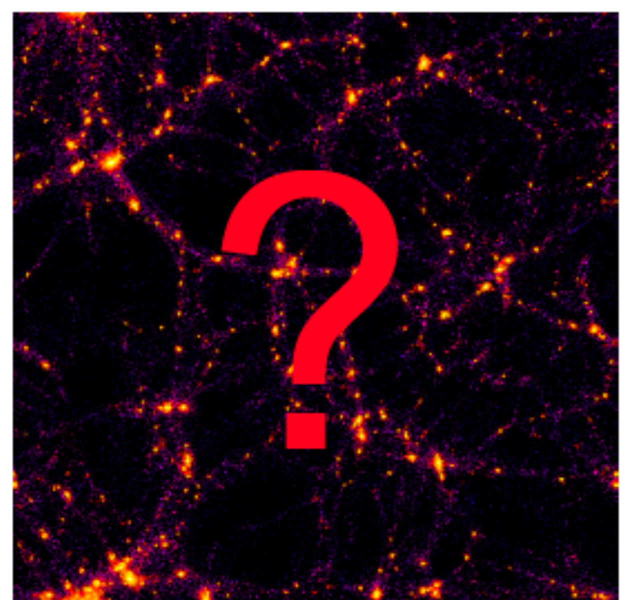
Known

Hot dark matter

DARK MATTER COFFEE

Known

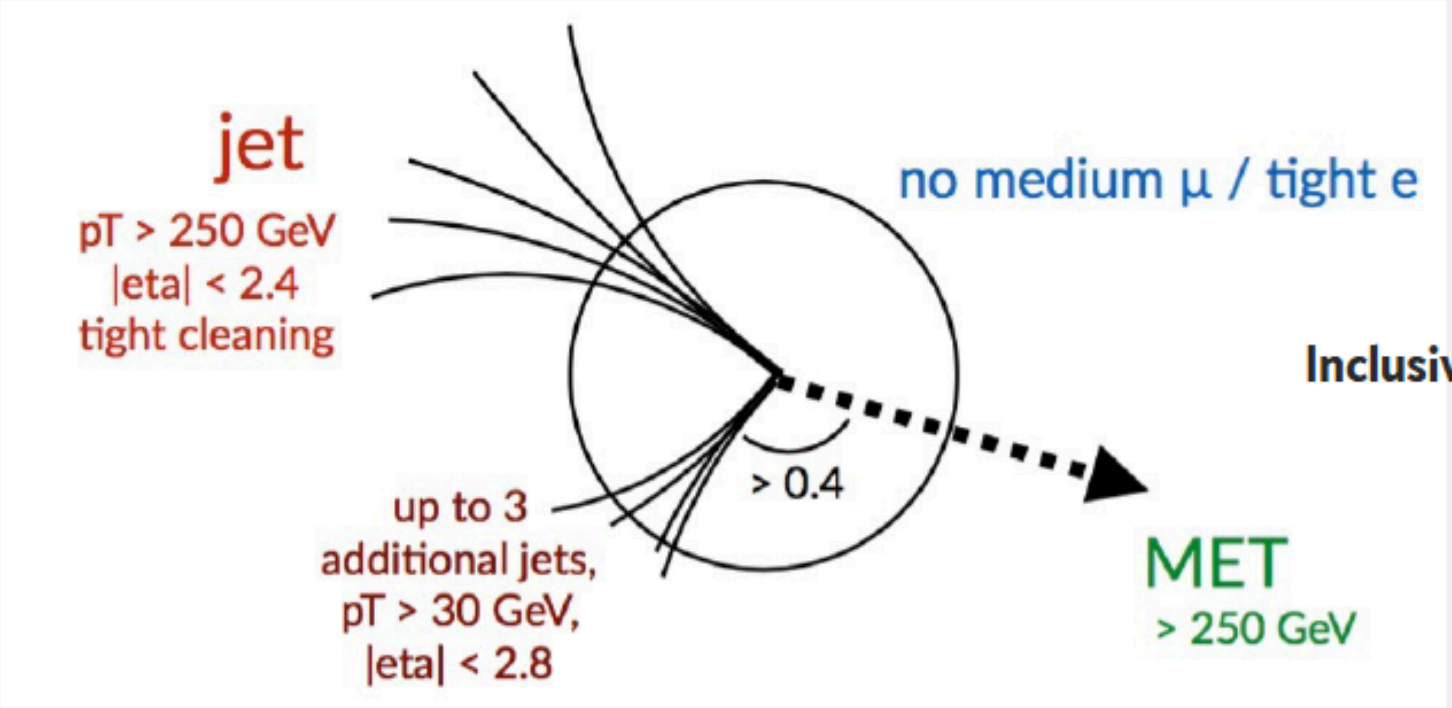
Cold dark matter



Unknown

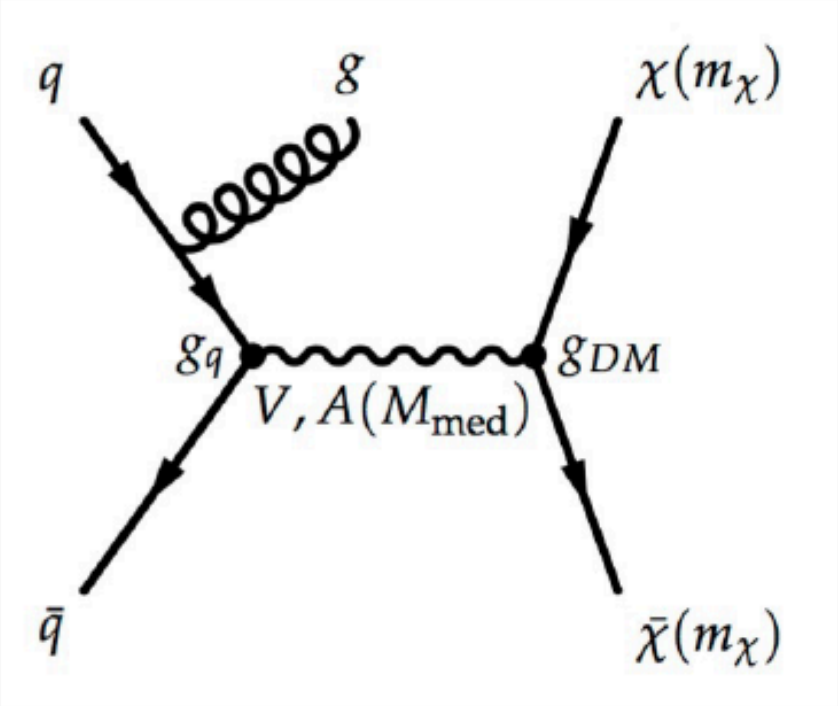
MET+X searches, or "mono-X"

New at 13 TeV: to appear

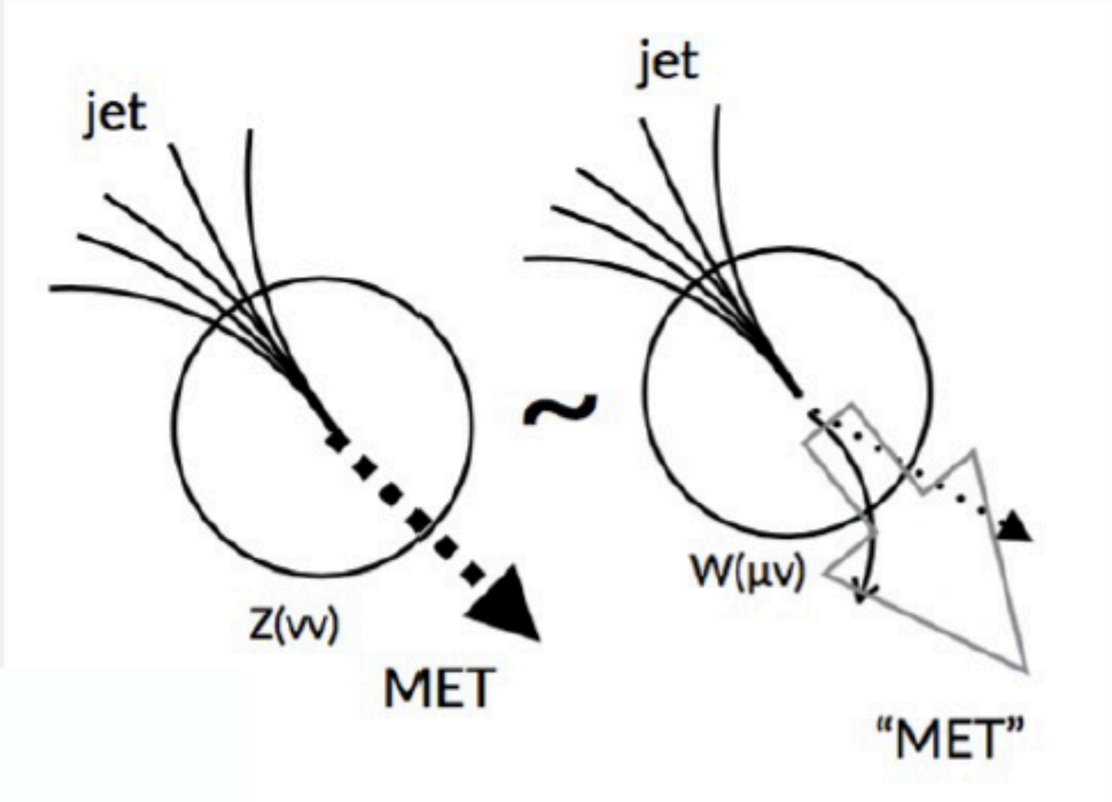


Inclusive and Exclusive signal regions with successively larger MET requirements

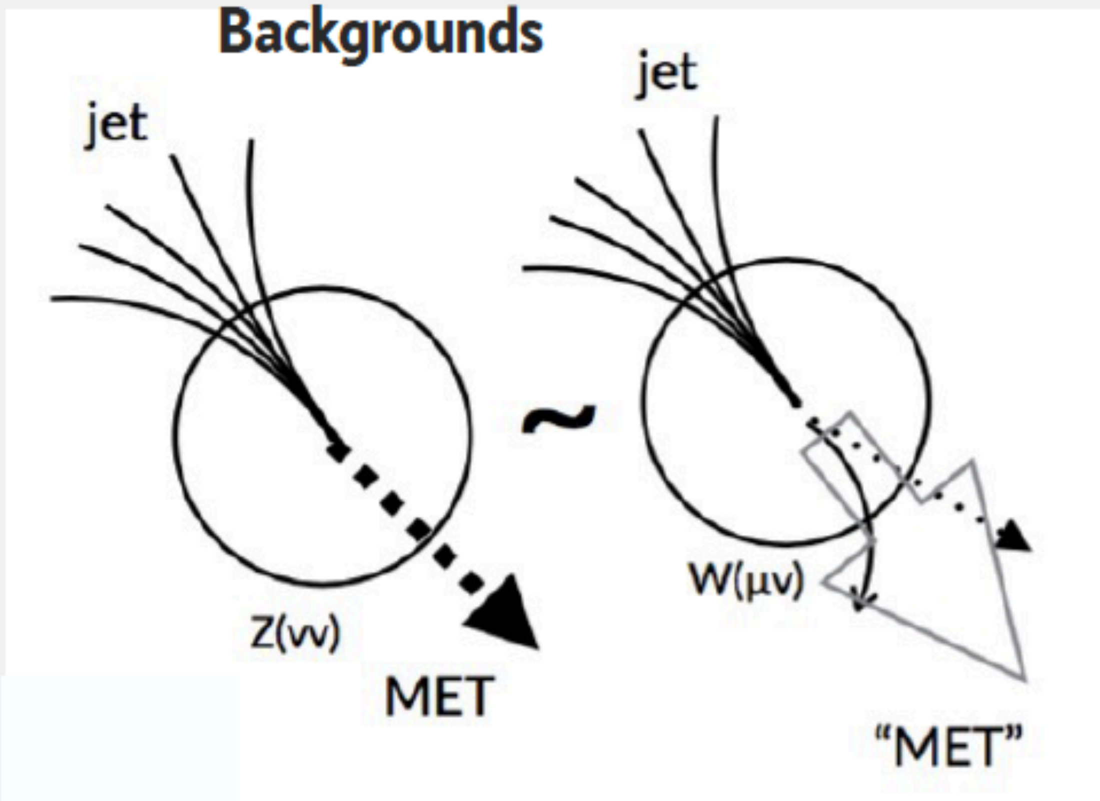
Signal



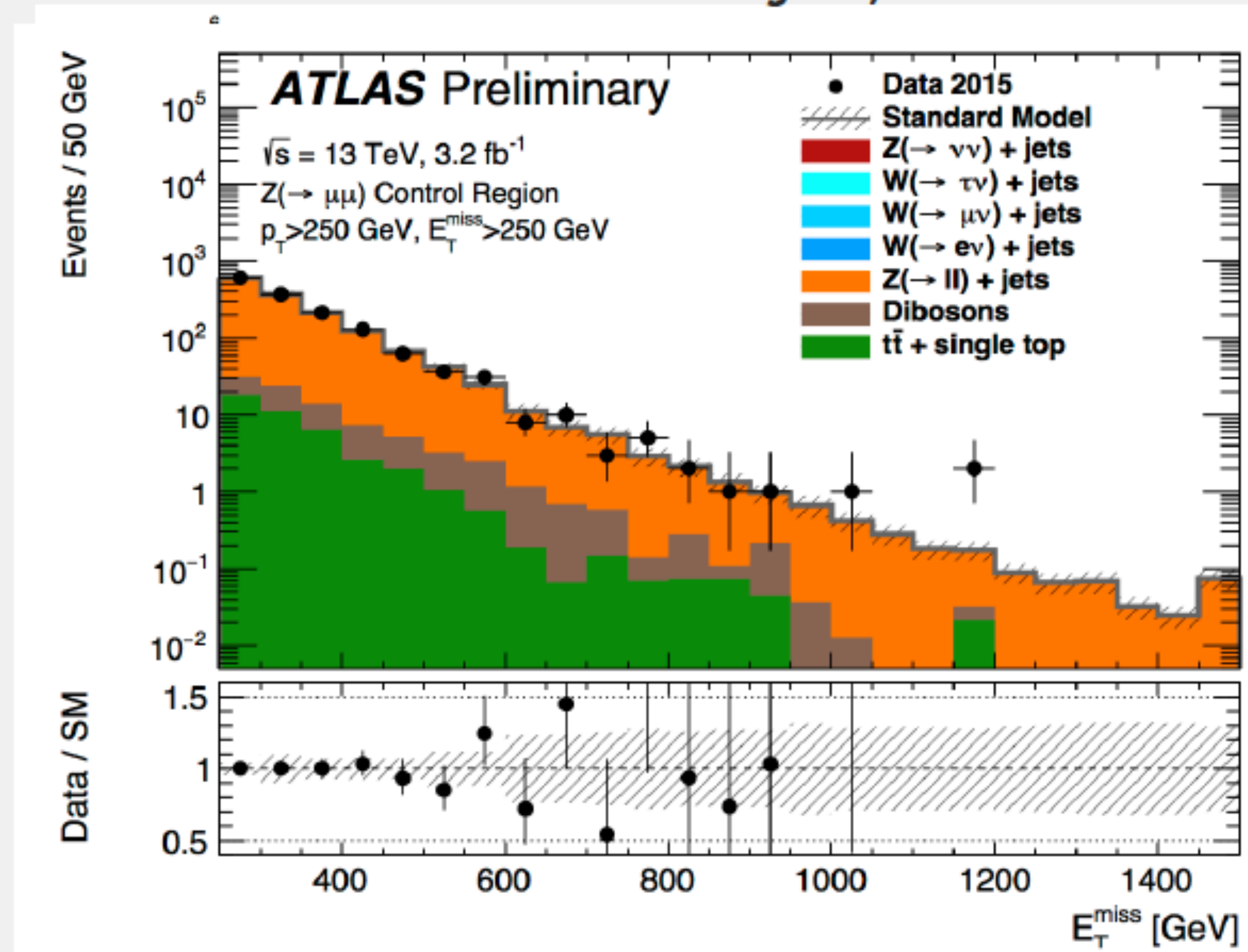
Backgrounds

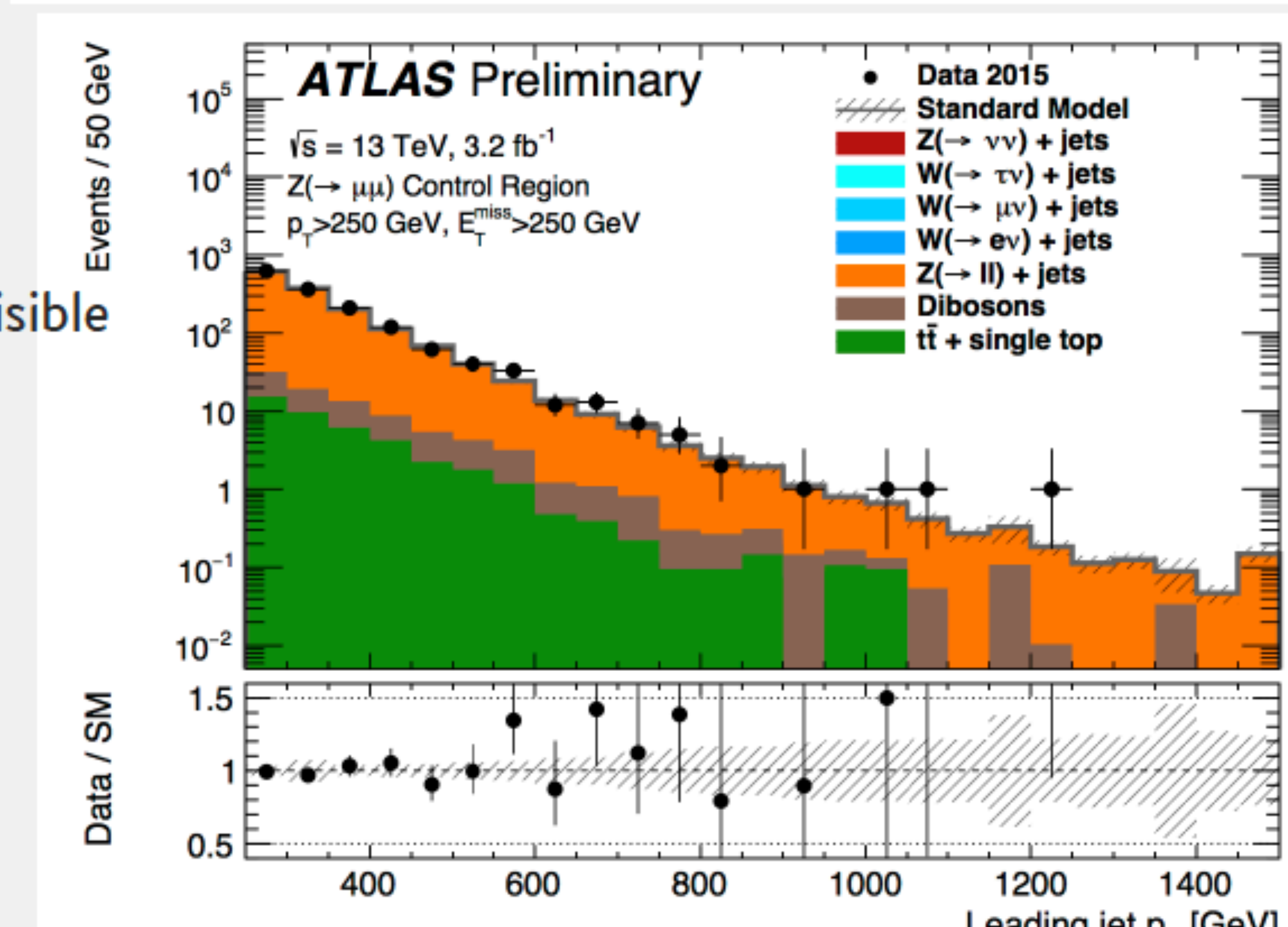


MET+X searches, or "mono-X"



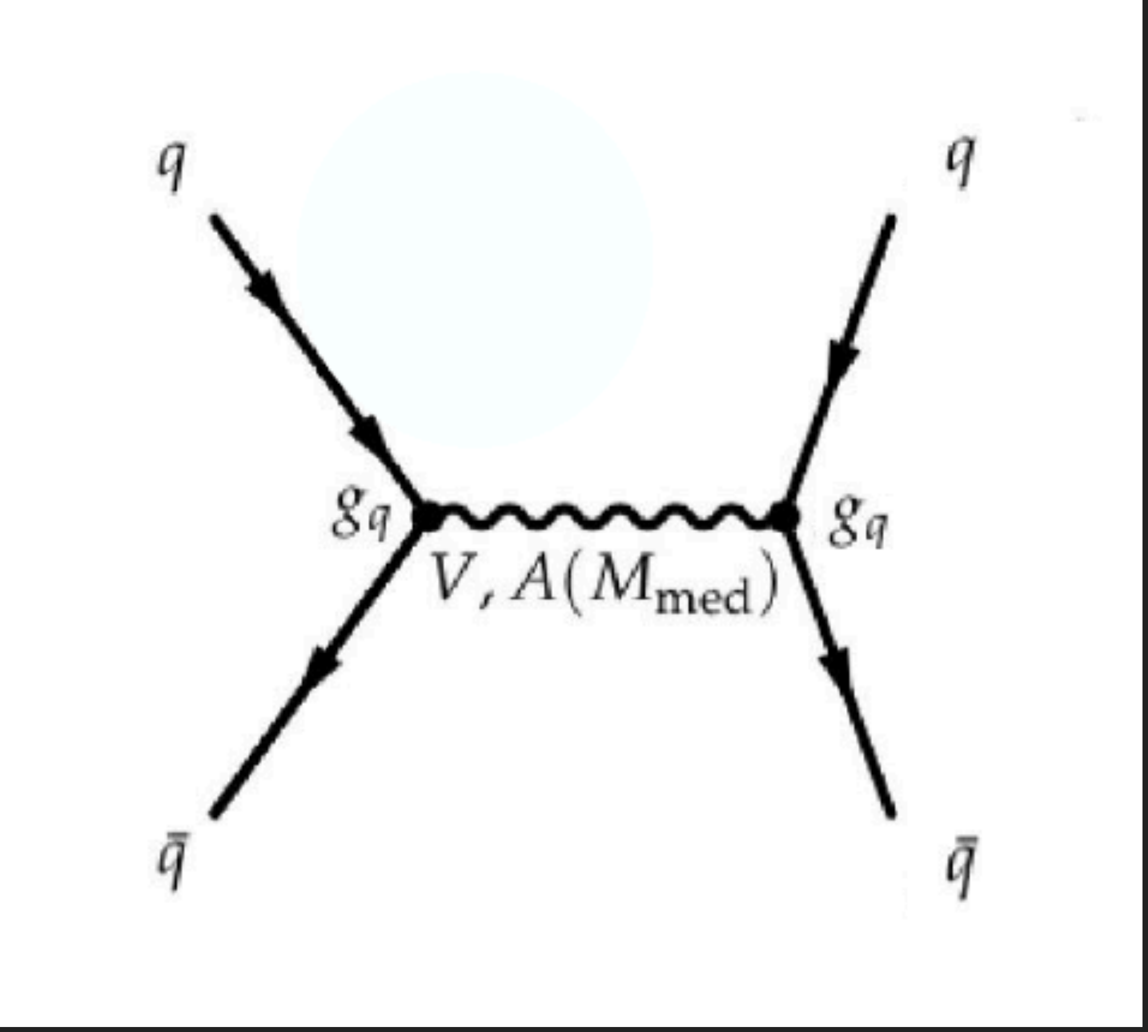
Visible Z Control Regions, Post-Fit





One key challenge of the mono-jet analysis is modeling **Z+jets and W+jets background at very high boson p_T**

- Check with visible W and Z decays, but
- invisible decays of the Z occurs 6x more often than visible



ALSO: SEARCHES FOR

DM MEDIATOR INTERACTIONS

ATLAS Dijets Searches at 13 TeV

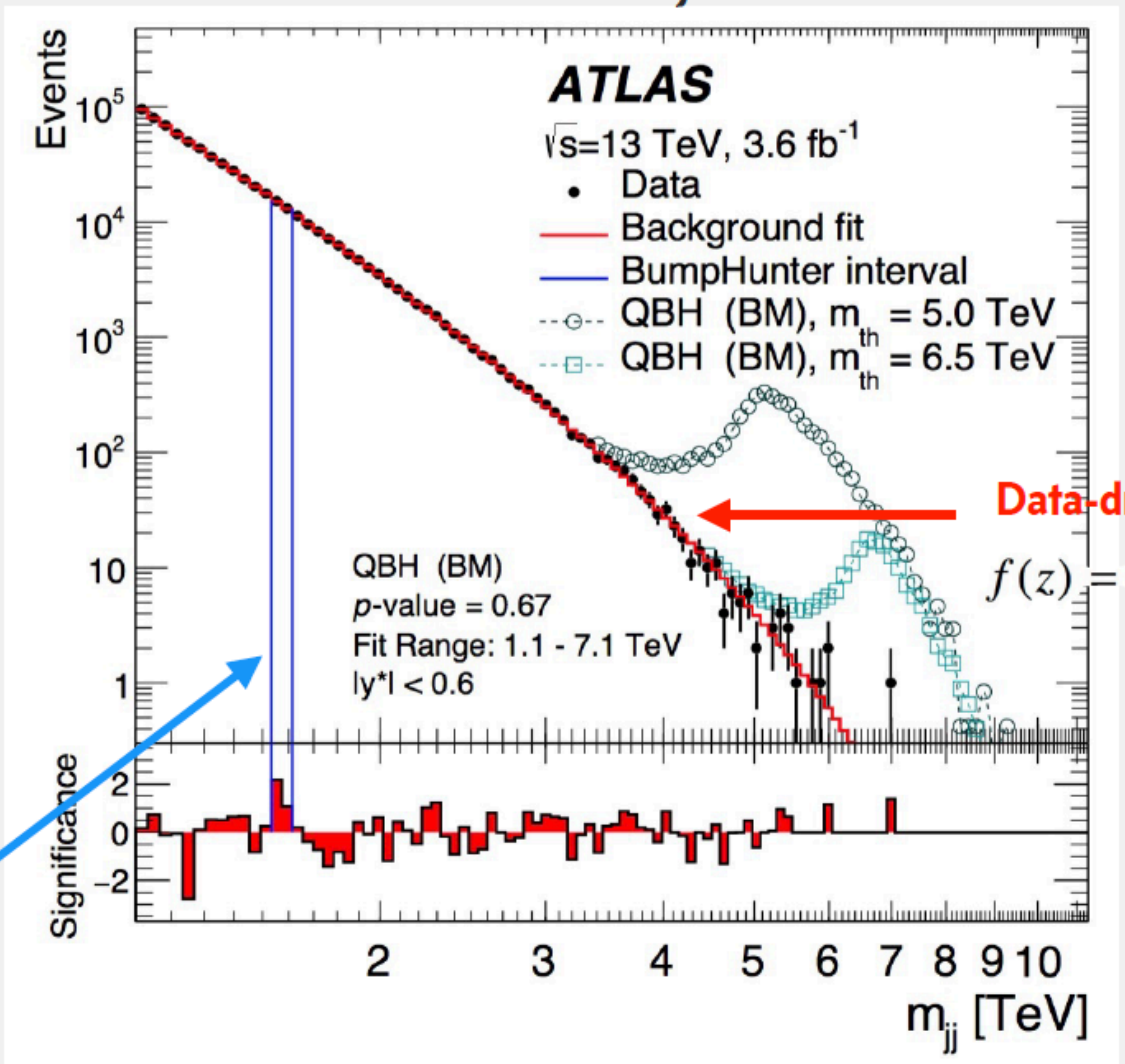
Physics Letters B 754 (2016) 302–322

Resonant analysis

Jet $p_T > 440, 50$ GeV

$|y^*| = |y_1 - y_2|/2 < 0.6$
(rejects forward-peaking t-channel QCD processes)

$m_{jj} > 1.1$ TeV



Data-driven background fit

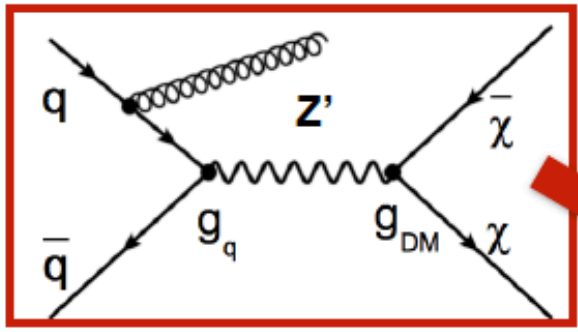
$f(z) = p_1(1-z)^{p_2} z^{p_3+p_4 \log z}$

Most discrepant region
1.53-1.61 TeV
(p-value 0.67)

DM interpretation of resonance searches

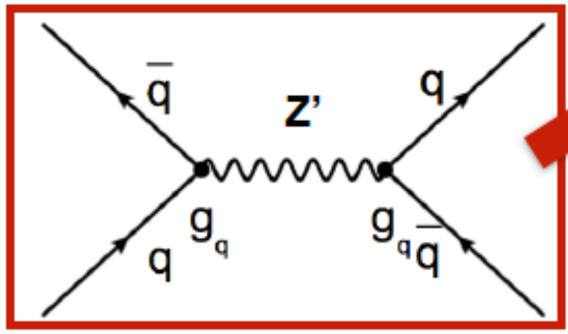
- **DM simplified model** for **spin-1 mediator** is equivalent to the **leptophobic Z'** explored in **dijet searches**
- **Difference:** the addition of a **DM candidate** modifies the **total width** of the **mediator**

Monojet production



+

Dijet production



Mediator Width

$$\Gamma^{\text{tot}}_{\text{AV}} = \Gamma^{\chi\bar{\chi}}_{\text{AV}} + 3 \times \sum_{q=u,d,s,c,b,t} \Gamma^{q\bar{q}}_{\text{AV}}$$

$$\Gamma^{q\bar{q}}_{\text{AV}} = \frac{g_q^2 M_{\text{med}}}{4\pi}\left(1 - 4\frac{m_q^2}{M_{\text{med}}^2}\right)^{3/2}$$

$$\Gamma^{\chi\bar{\chi}}_{\text{AV}} = \frac{g_{\text{DM}}^2 M_{\text{med}}}{12\pi}\left(1 - 4\frac{m_{\text{DM}}^2}{M_{\text{med}}^2}\right)^{3/2}$$

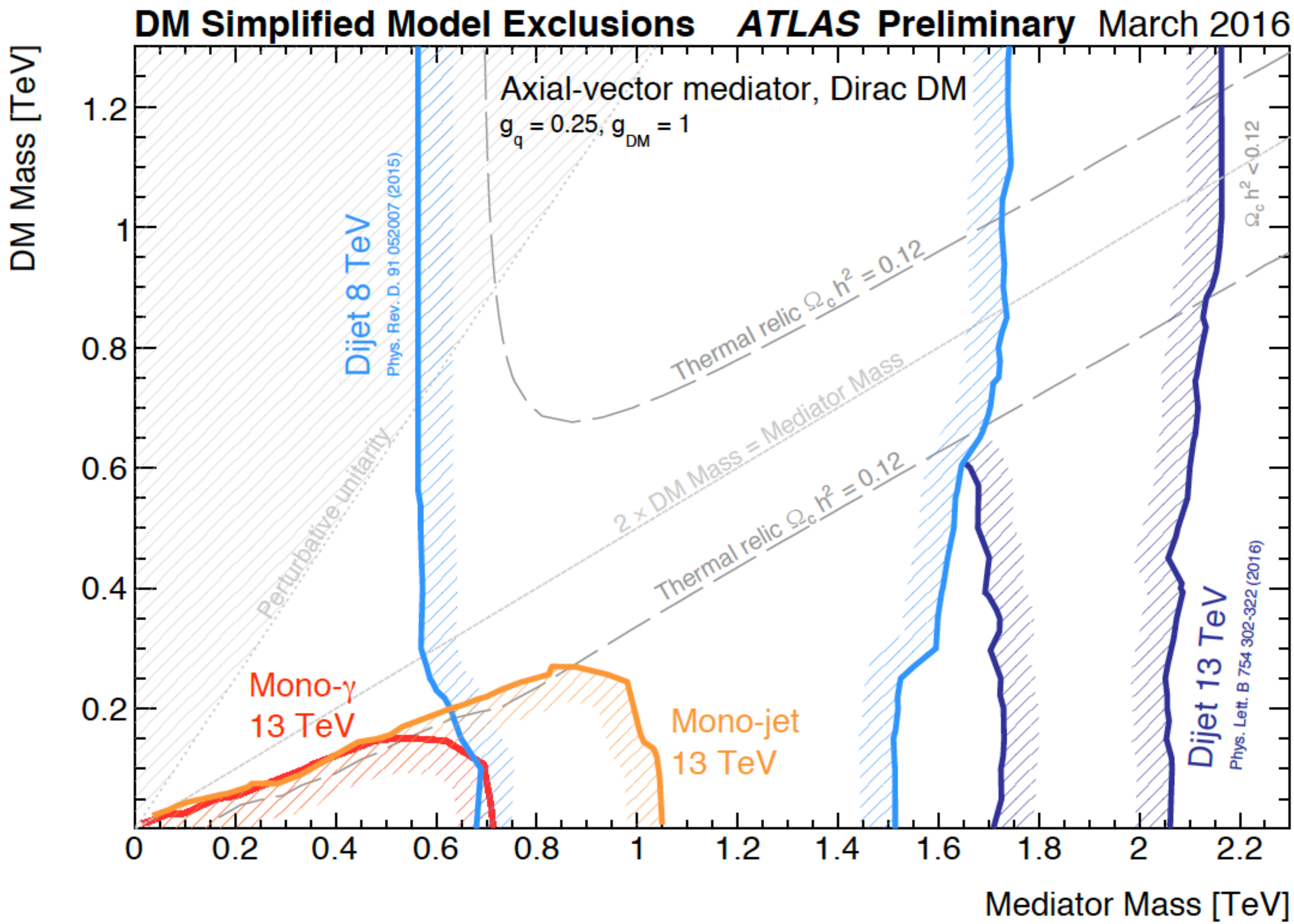
Interesting scenarios

m_{MED} >> m_{DM}: the relative branch fraction of monojet and dijet is proportional to $N_c N_q\, g_{SM}^2/g_{DM}^2$

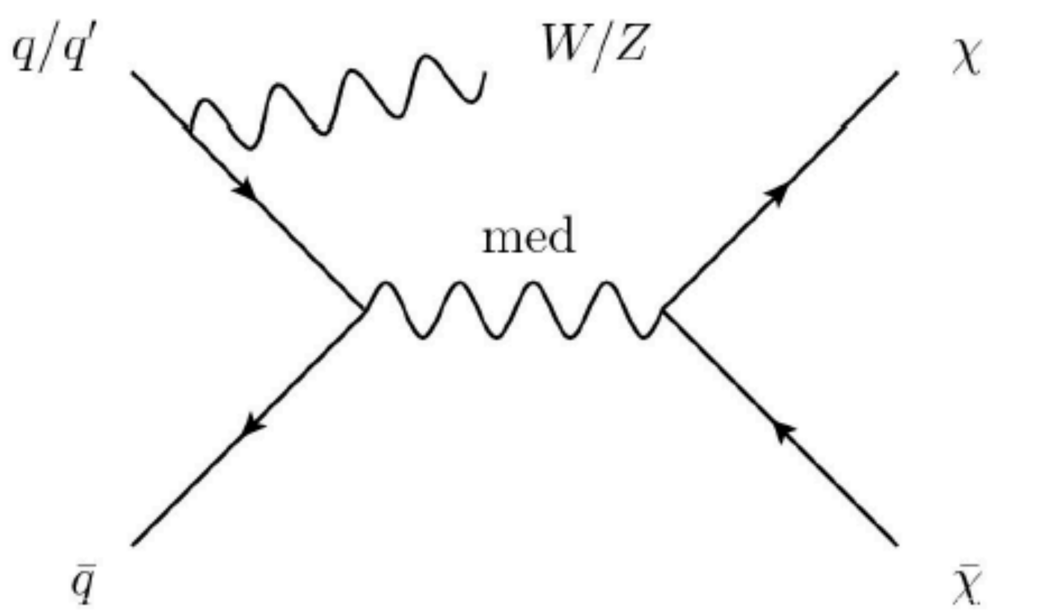
g_{SM} << g_{DM}, g_{DM} ~ 1: narrow resonance but BR monojet larger than dijet one

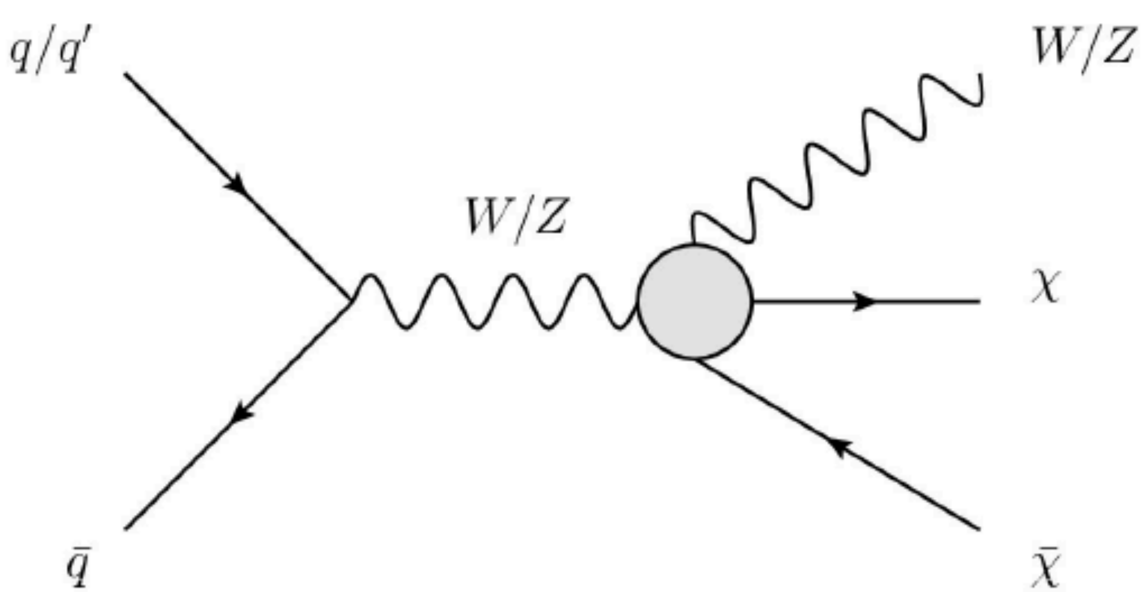
g_{DM} >> g_{SM}, g_{DM} > 1: resonance not narrow anymore BR monojet larger than dijet one

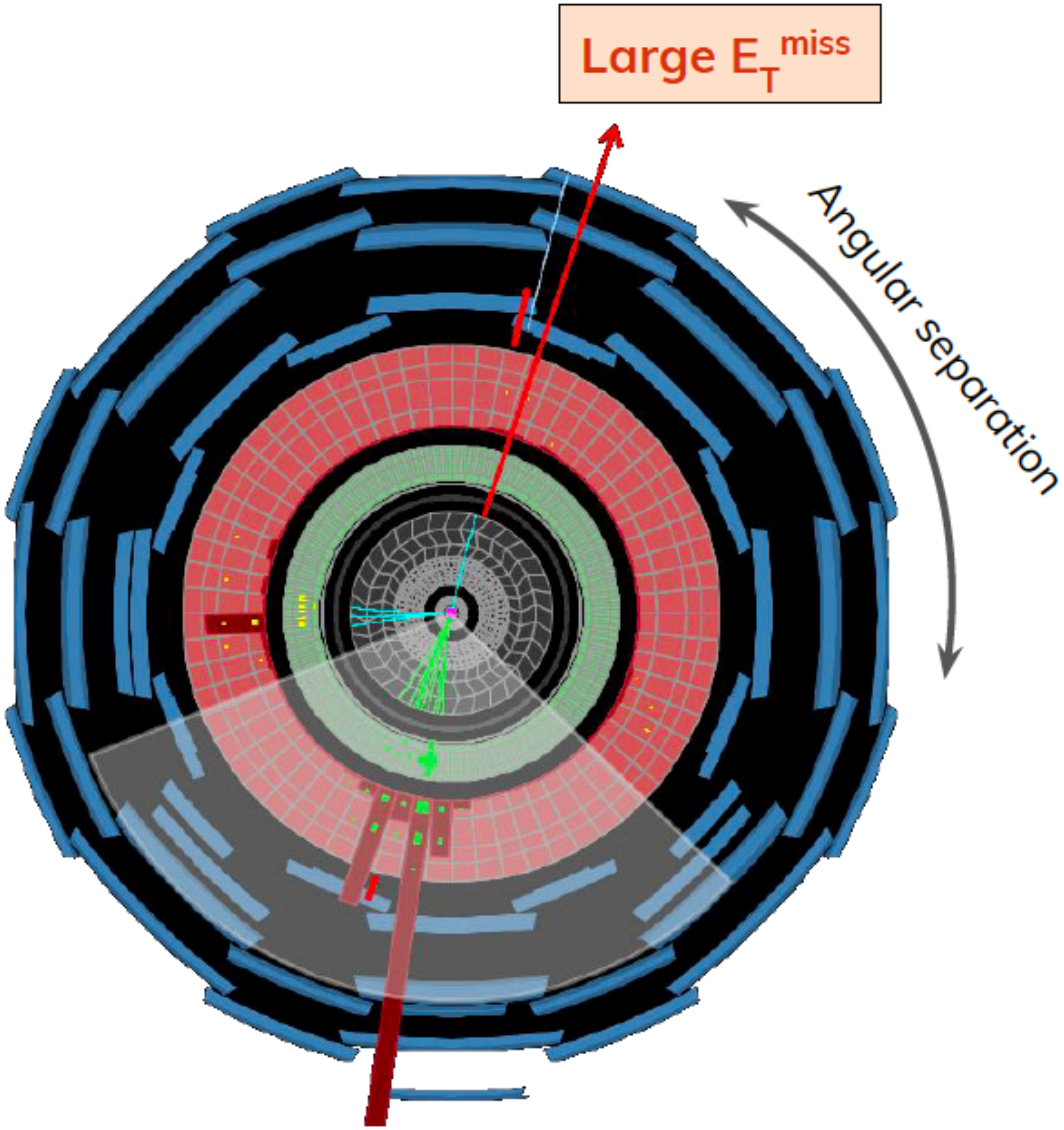
$2m_{DM}$ >> m_{MED}: no partial width into dark matter so the Z' model reduces to the standard one used in dijet searches


DM Simplified Model Exclusions ATLAS Preliminary March 2016
Axial-vector mediator, Dirac DM
g_q = 0.25, g_DM = 1
Dijet 8 TeV
Phys. Rev. D. 91 052007 (2015)
Dijet 13 TeV
Phys. Lett. B 754 302-322 (2016)
Thermal relic Ωc h² = 0.12
Ωc h² < 0.12
2 × DM Mass = Mediator Mass
Perturbative unitarity
Mono-γ
13 TeV
Mono-jet
13 TeV
DM Mass [TeV]
Mediator Mass [TeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2

Mono-W/Z (hadronic)





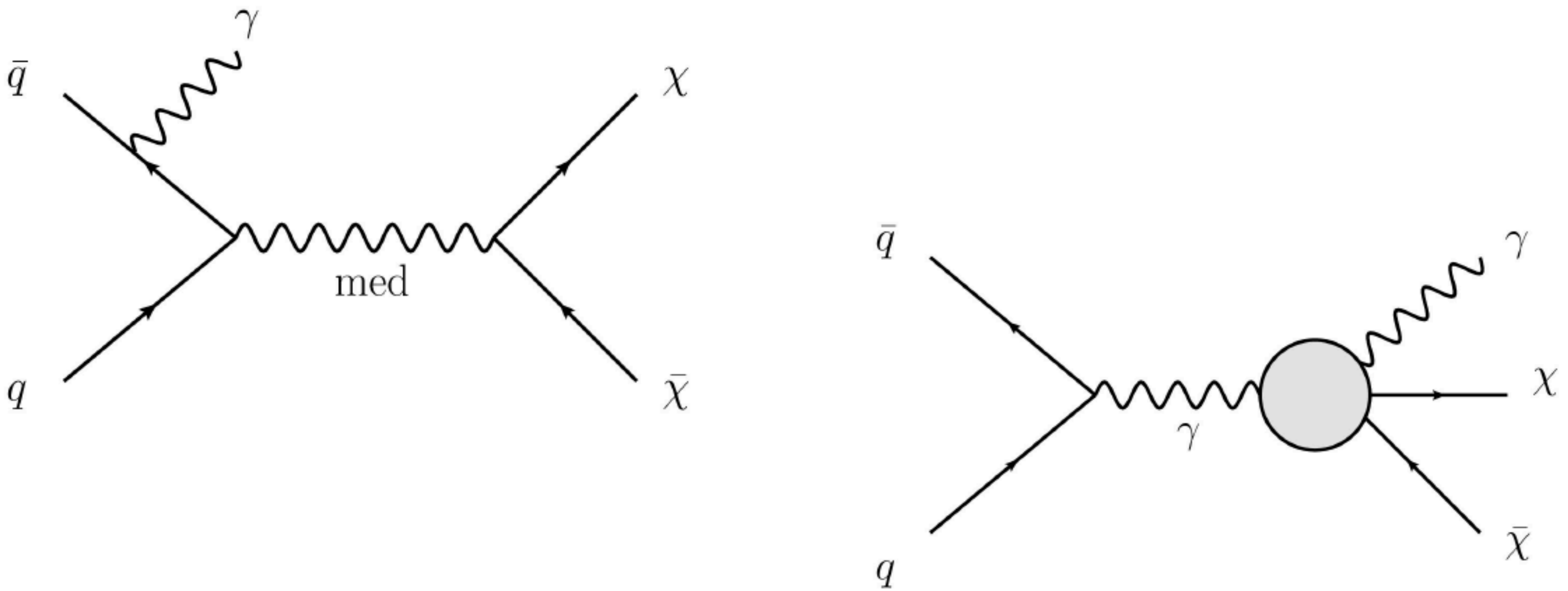


Hadronically decaying, highly boosted W or Z boson, reconstructed as a single wide-R jet.

(Mono-Z in the dilepton final state is also searched for, but not shown here.)

Mono-Photon

Mono-photon offers **clean events with low background.**
Similar to mono-Z/W, we can probe for a **γγXX contact interaction** in addition to the simplified models.

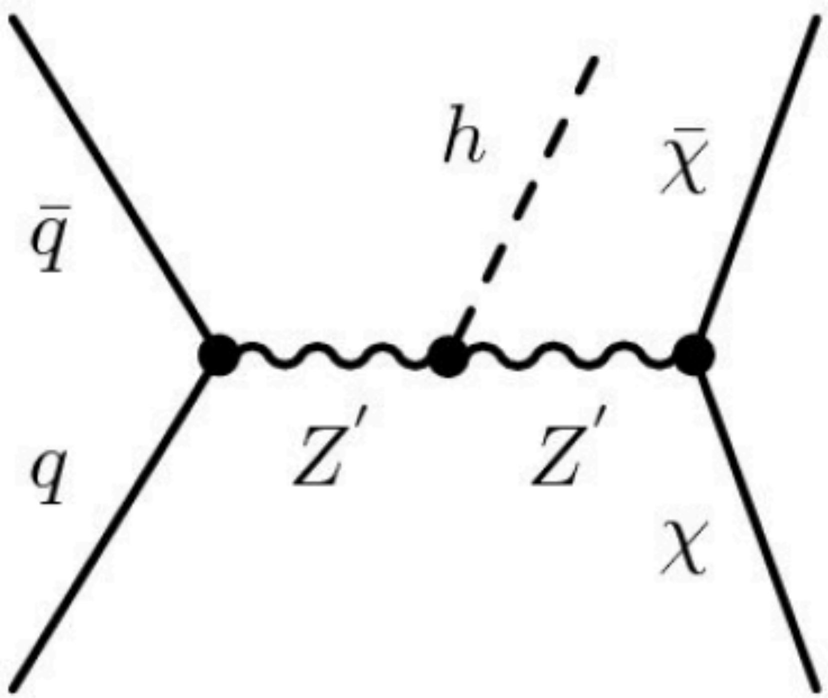


Fake photon backgrounds are estimated using data driven methods.
Z/W/jet+photon backgrounds are taken from simulations, normalized in control regions (2e and 2μ, 1μ, inverted γ/jet separation) by ATLAS.

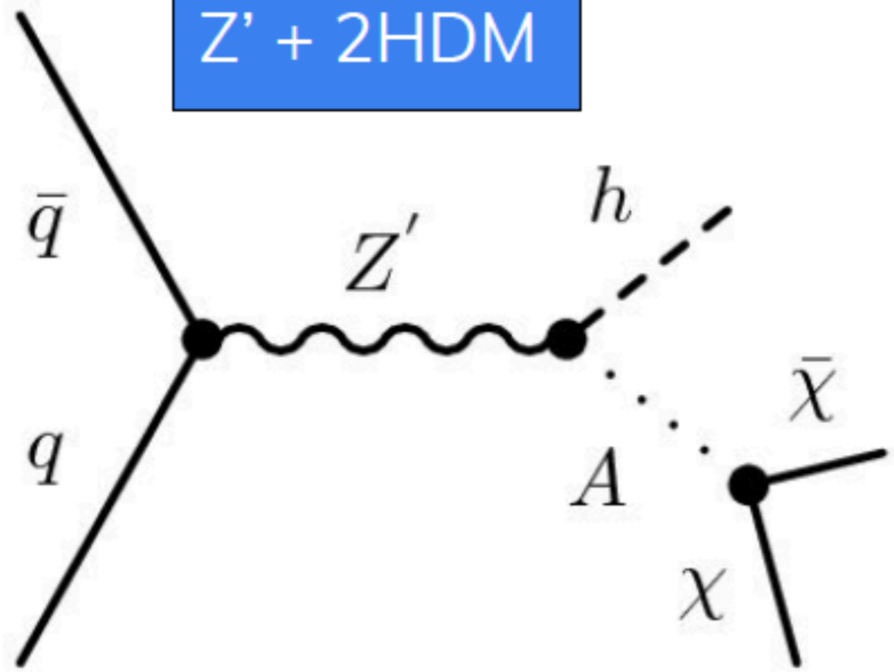
Mono-H (bb)

Higgs ISR is Yukawa suppressed, instead H can be emitted by the mediator itself - direct test of the SM-DM coupling structure.

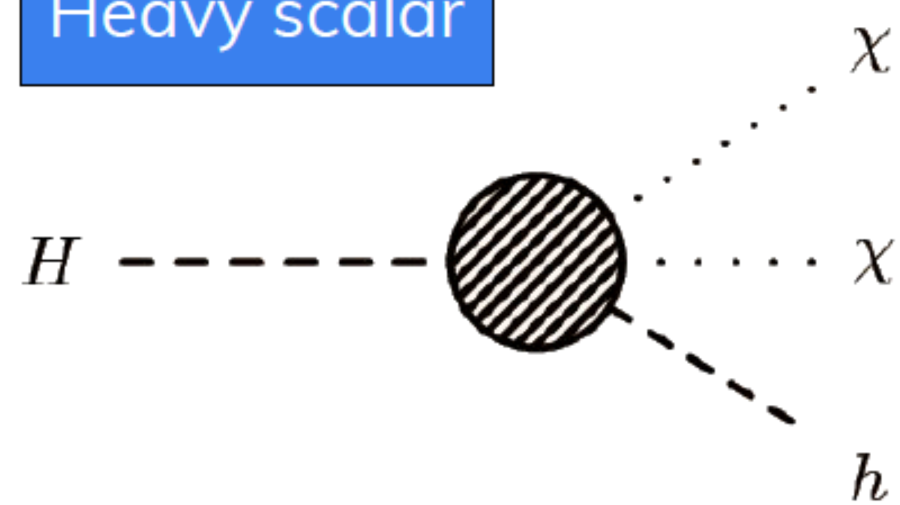
Z' with Higgs boson coupling

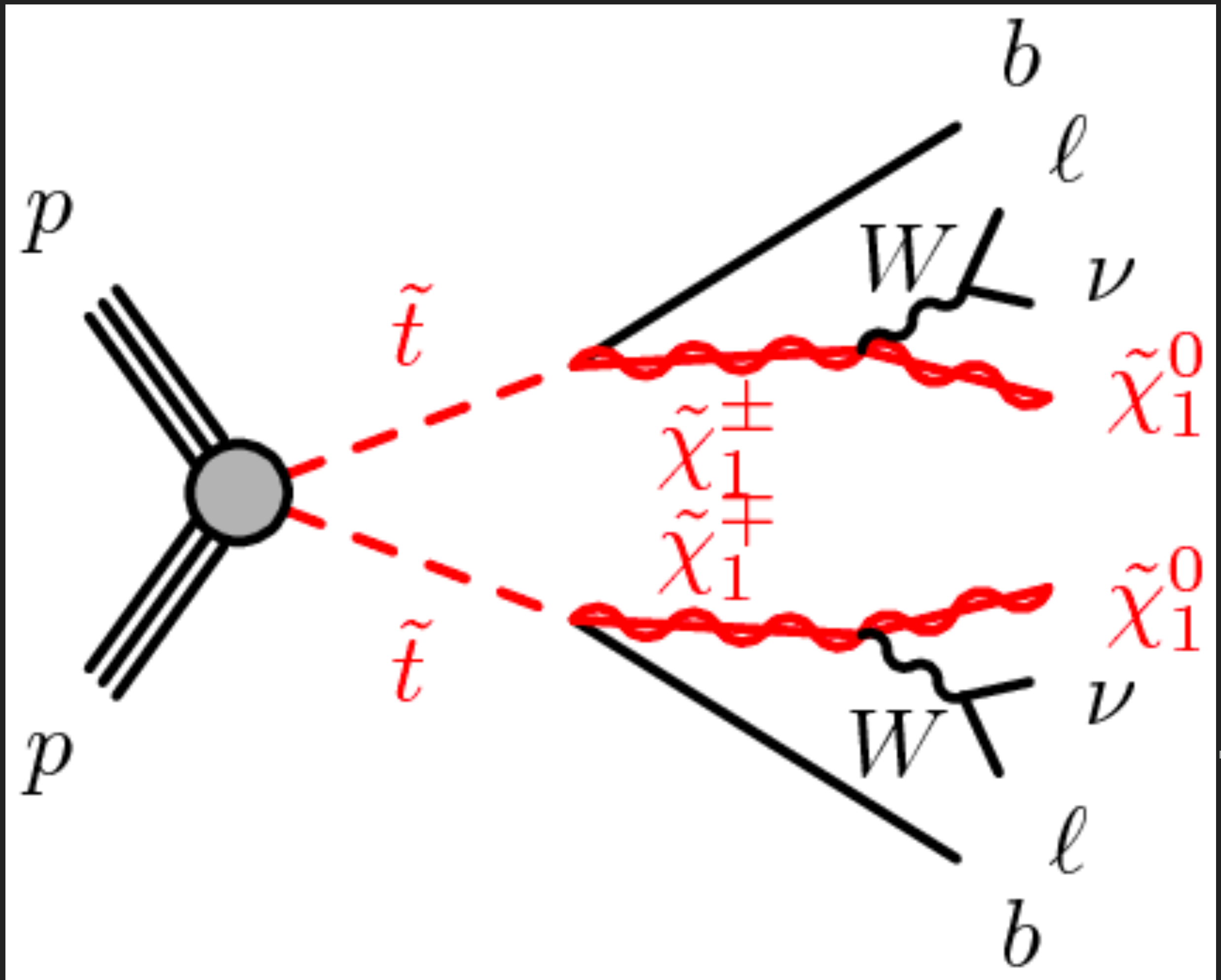


Z' + 2HDM



Heavy scalar





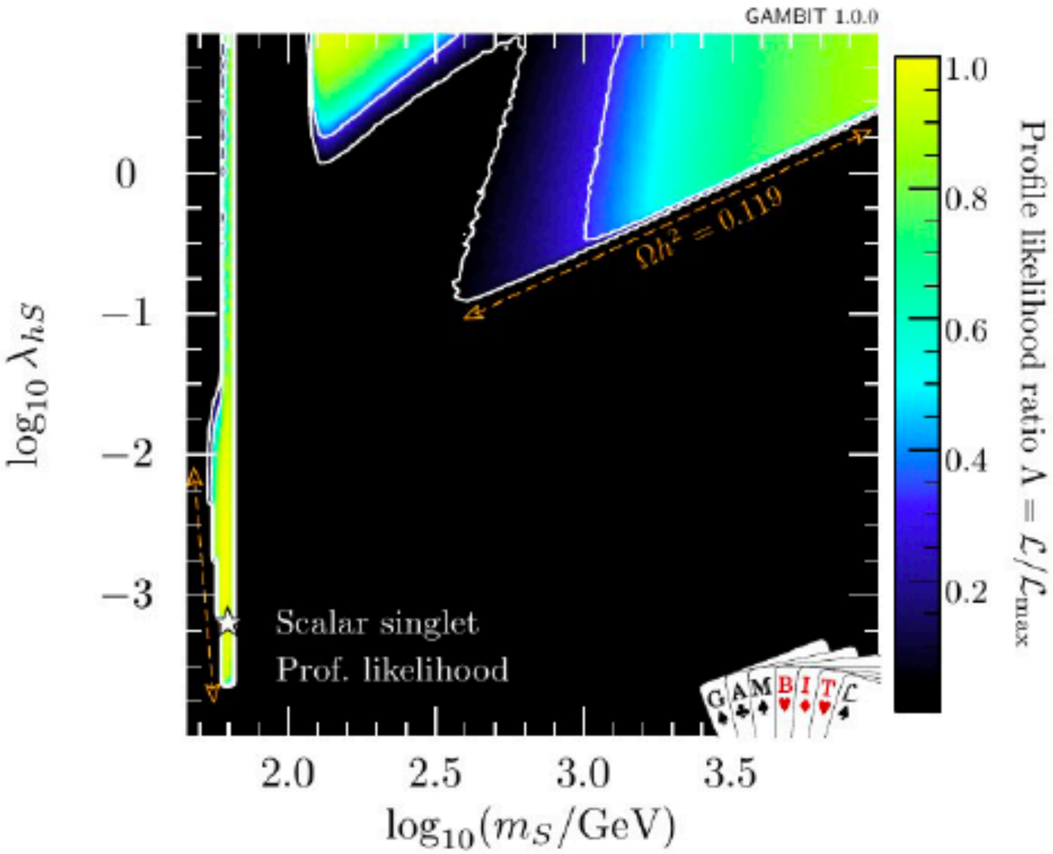
SUSY-LIKE SEARCHES

STOP SEARCHES!

How about scalar singlets?

- A real scalar singlet coupled to the SM BEH boson is arguably the simplest realization of the WIMP idea.

$$\mathcal{L} = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 |H|^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\partial_\mu S \partial^\mu S.$$



- The GAMBIT collaboration will soon publish a global analysis of this model (with constraints from direct and indirect searches and LHC).

Athron, FK et al., submitted to EPJC

- Intriguingly, the model is still viable and can account for all of the dark matter.

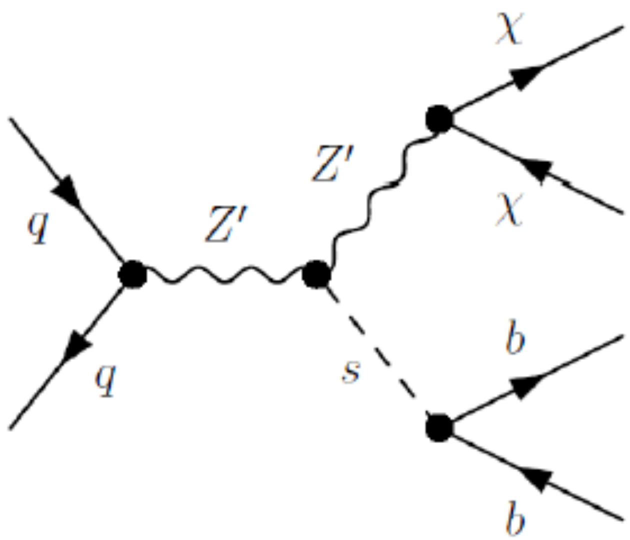
- For WIMP masses between 700 and 2000 GeV the contribution of the scalar singlet to the scalar potential stabilizes the electroweak vacuum all the way to the Planck scale.

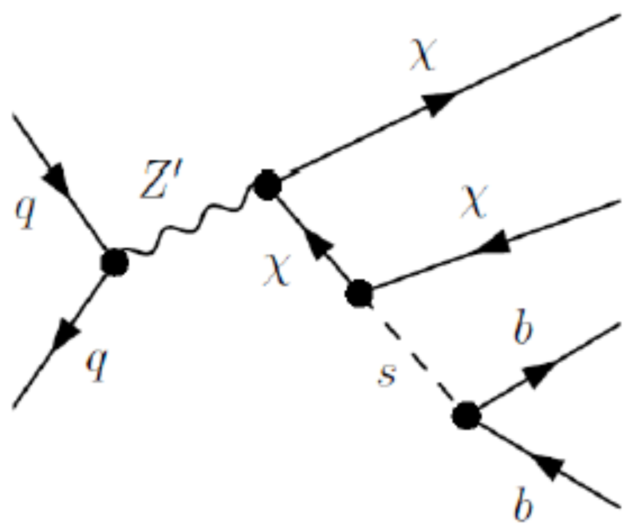
FK & McDonald, arXiv:1507.03600

- Xenon1T will be able to test this mass range within the next few years and thereby probe one of the last remaining simple WIMP models.

Experimental signatures of complex dark sectors

- Consider DM coupled to a light scalar singlet with tiny mixing with the SM BEH boson.
- Although the singlet couples weakly to the SM, couplings within the dark sector must be large!
- If any of the dark sector states are produced at the LHC, they may emit singlet-strahlung (or dark-Higgs-strahlung)!





A dark Higgs at the LHC?

Thanks to Teppei Katori for the picture!

ALPS

AXION-LIKE PARTICLES

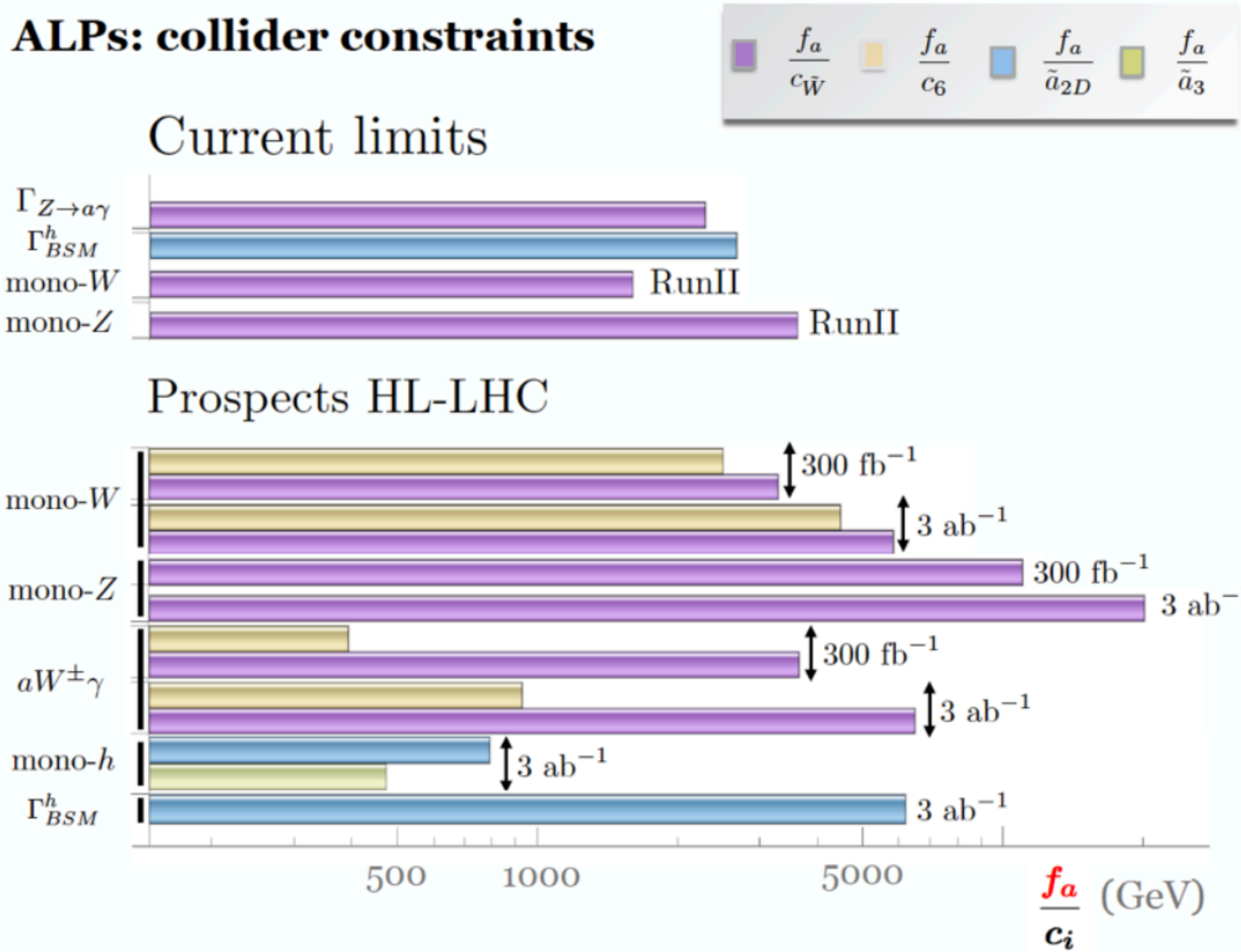
- Very light particles that are pseudo-Goldstone bosons of some global BSM symmetry

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{f_a}(\partial_\mu a) \cdot V^a$$

$$\frac{a}{f_a} \cdot F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- mono-W, mono-Z, mono-photon signatures
- a-particle goes undetected
- F_a coupling needs to be extremely small, or the mass of axions should be below 20eV, for their population not to be depleted.
- the CDM candidate is a Bose condensate of axions, i.e. a bound state of the field.

ALPs: collider constraints



95%CL

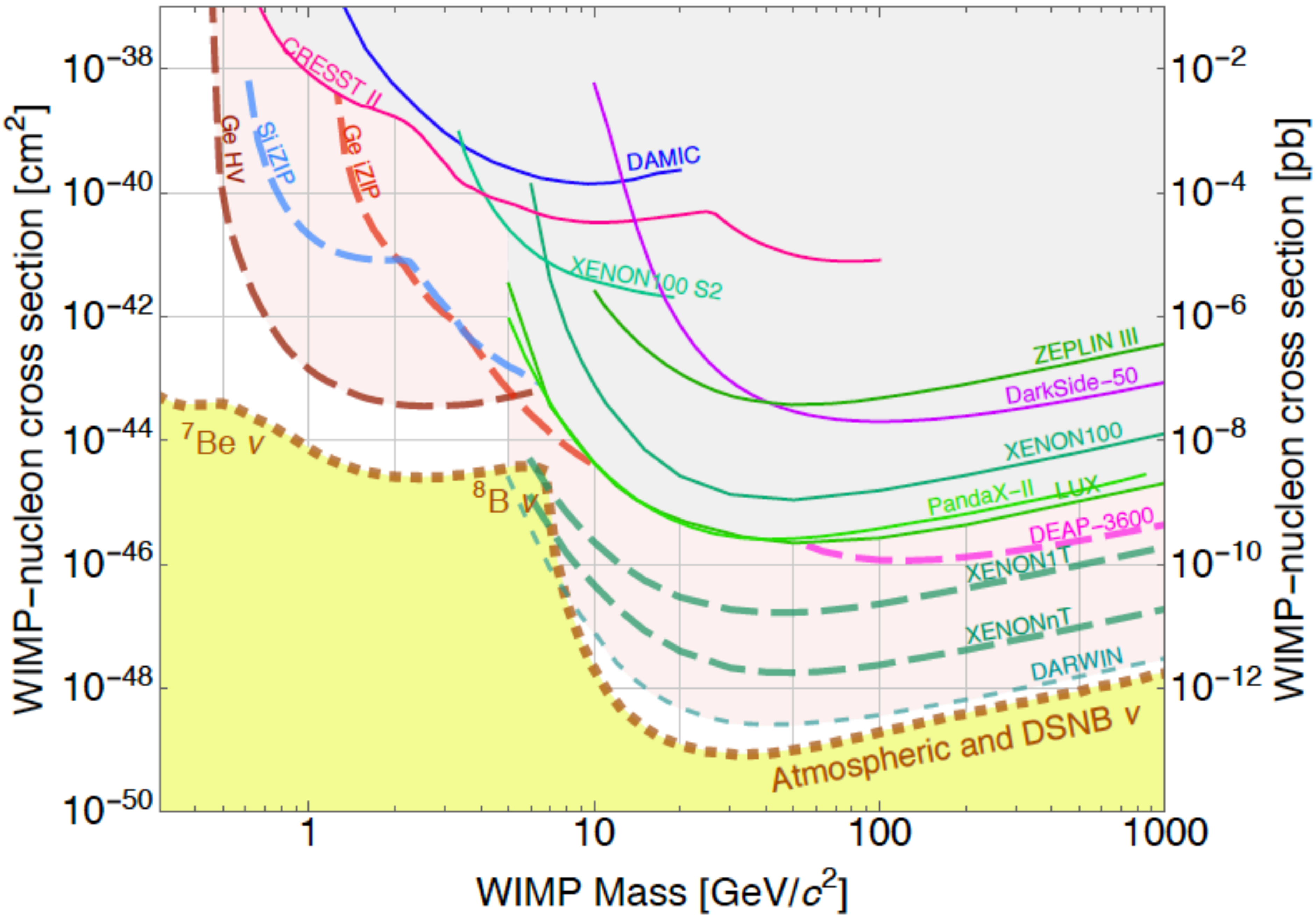
LHC 13 TeV
2σ reach

flattish MET are ALP signals

DIRECT DETECTION

Of course, “the probability of success is difficult to estimate, but if we never search, the chance of success is zero”

G. Cocconi & P. Morrison, Nature, 1959

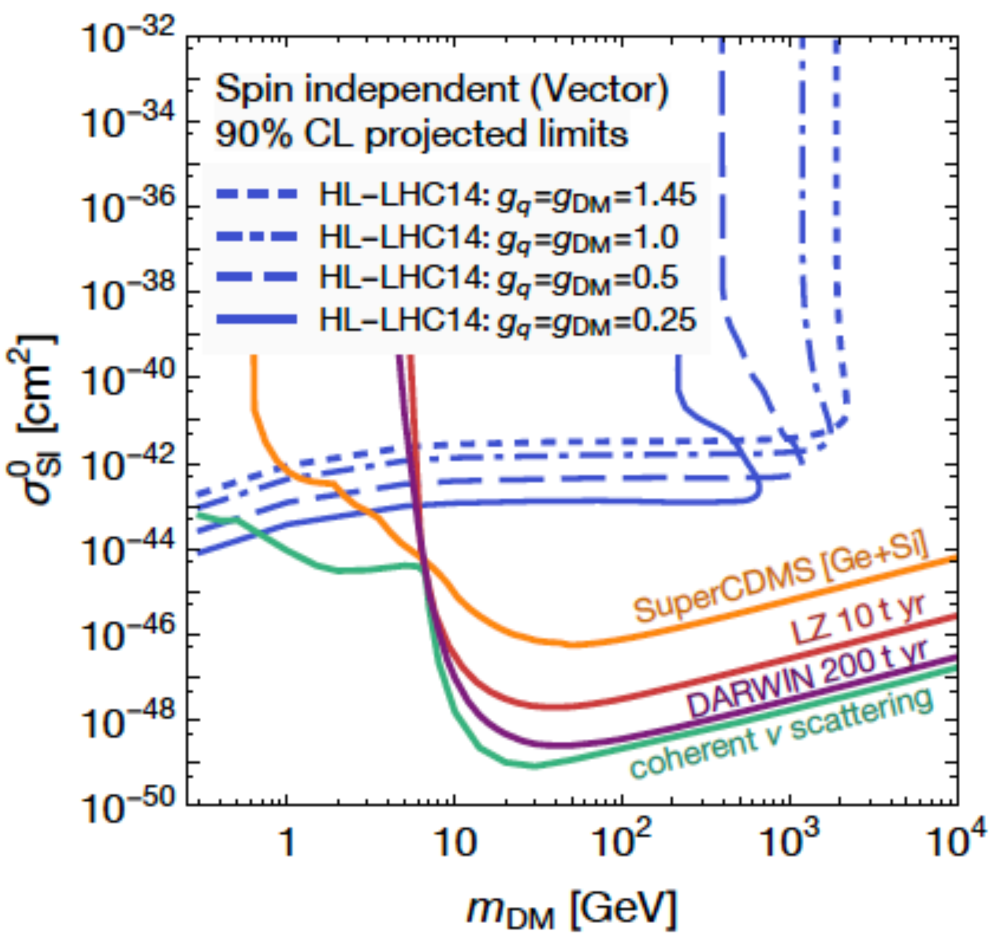


WIMP physics: complementarity with the LHC

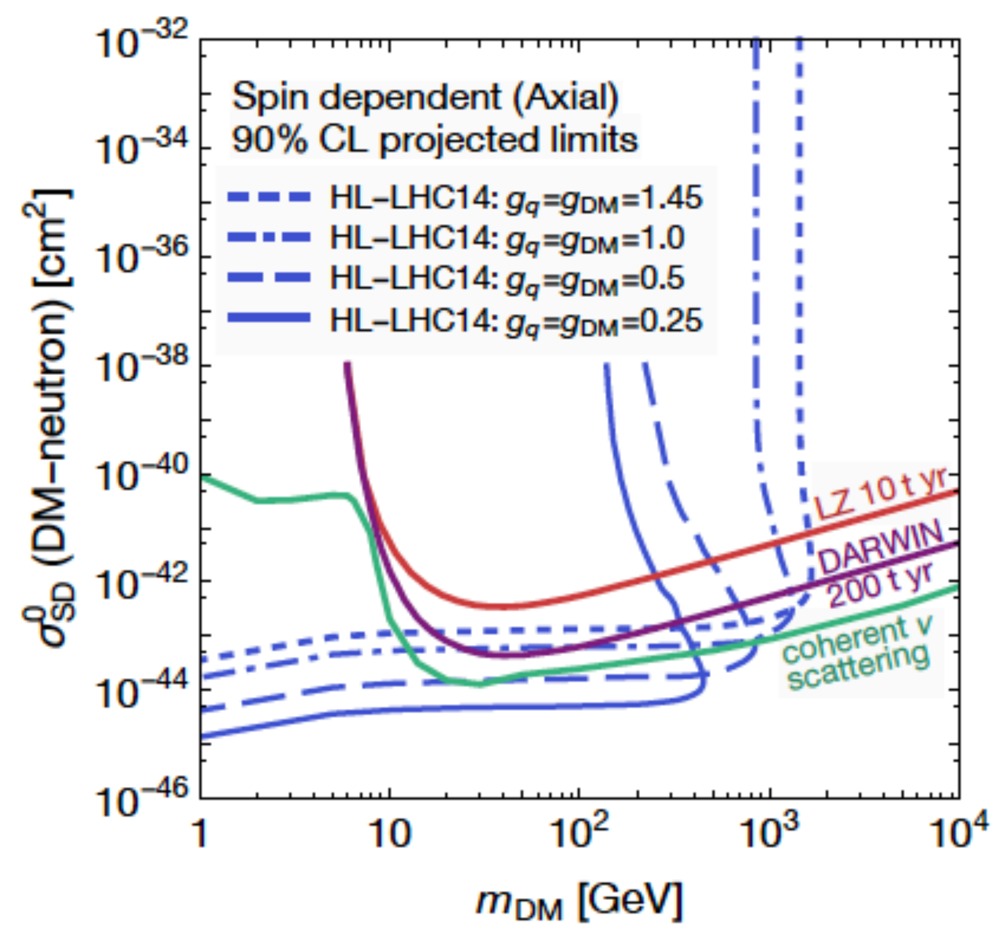
- Minimal simplified DM model with only 4 variables: m_{DM}, M_{med}, g_{DM}, g_q
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

$$\sigma_{\rm DD} \propto \frac{g_{\rm DM}^2 g_q^2 \mu^2}{M_{\rm med}^4}$$

Spin independent



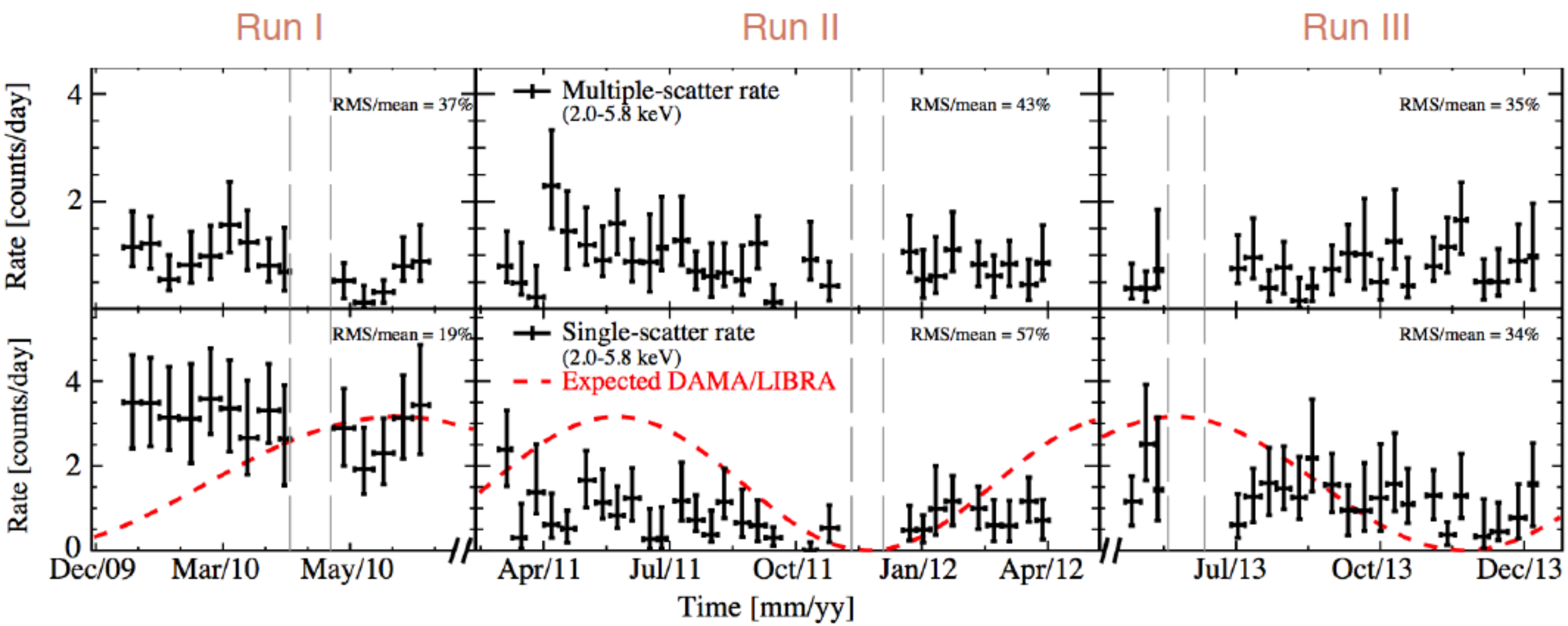
Spin dependent



S. Malik et al., Phys. Dark Univ. 9-10 (2015) 51-58

Latest XENON100 results

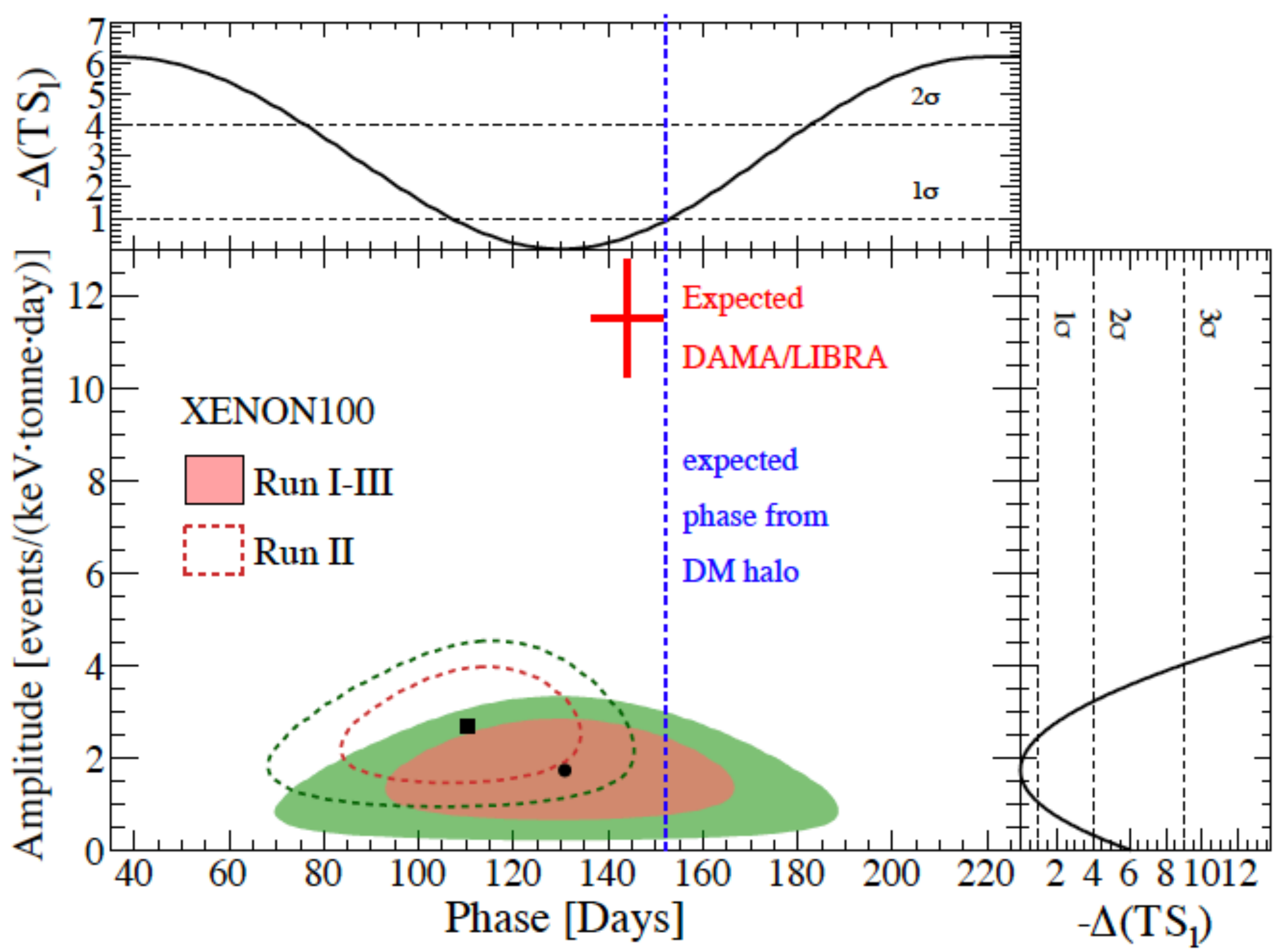
- Dark matter particles interacting with e^-
    - ➡ search for periodic variations of the ER rate in the 2-6 keV region , in 4 years of data



XENON collaboration, arXiv:1701.00769

Latest XENON100 results

- Dark matter particles interacting with e^-
  - ➡ no significant modulation is seen; exclude DAMA/LIBRA at 5.7-sigma



XENON collaboration, arXiv:1701.00769