UK HEP Forum: Into the Unknown with LHC13

Interplay between collider and direct DM searches

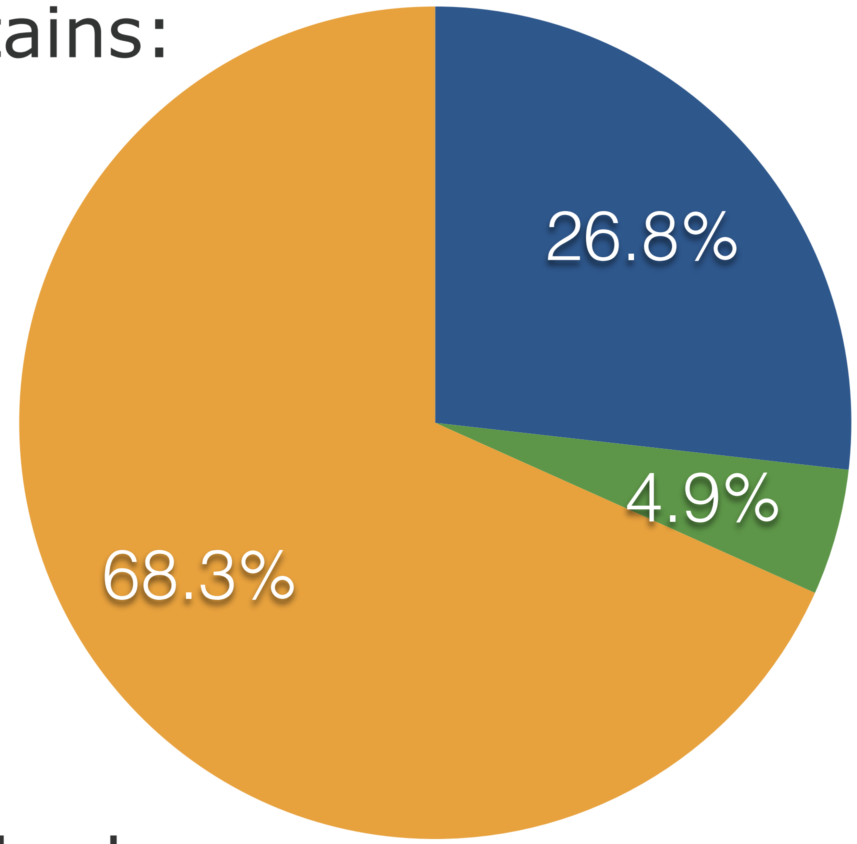
Valentin V Khoze
(IPPP Durham University)

3-4 November 2016
The Cosener's House

Dark Matter

The total mass–energy of the universe contains:

4.9% ordinary matter
26.8% dark matter
68.3% dark energy



Thus, dark matter constitutes
84.5% of total mass

while dark energy plus dark matter
constitute 95.1% of total mass–energy content.

[Most of ordinary matter in the universe is also unseen, since visible stars and gas inside galaxies and clusters account for less than 10% of the ordinary matter contribution to the mass-energy density of the universe.]

SM of Cosmology + observation: Planck Collaboration

Dark Matter

- Dark Matter: subject to gravitational interactions as ordinary matter

- DM should not carry electromagnetic charge or colour

- DM particles are massive and non-relativistic at the time when CMB forms

- Cosmological DM particle lifetime $\tau \gg \tau_{universe}$

- The current measured relic density of DM from cosmic microwave background $\Omega_{DM} h^2 = 0.1198 \pm 0.0026$

- Not too strong DM self-interactions $\sigma/M_{DM} < 100\ \mathrm{GeV}^{-3}$

- At present all evidence for the existence of DM is purely gravitational
- The particle physics nature of DM is unknown - our main challenge!
- The current measured $\boxed{\text{relic density}}$ of DM from cosmic microwave background

$$\Omega_{DM}\, h^2 = 0.1198 \pm 0.0026$$

For particles which are held in equilibrium by pair creation and annihilation processes $\chi\chi \leftrightarrow$ SM one finds:

$$\Omega_{\rm DM} h^2 \sim \frac{10^9\ {\rm GeV}^{-1}}{M_{\rm pl}} \frac{1}{\langle \sigma v \rangle}$$

$$\boxed{\Omega_{\rm DM} h^2 \sim 0.12 \times \left(\frac{M_{\rm DM}}{2\ {\rm TeV}}\right)^2 \left(\frac{0.3}{g_{\rm eff}}\right)^4}$$

$$\langle \sigma v \rangle \ \sim \ g_{\rm eff}^4 / M_{\rm DM}^2$$

WIMP miracle

Weakly inter- acting massive particles (WIMPs) can reproduce the observed relic abundance when their mass is in the 10s of GeV to few TeV range.

- At present all evidence for the existence of DM is purely gravitational

- The particle physics nature of DM is unknown - our main challenge!

- The current measured $\boxed{\text{relic density}}$ of DM from cosmic microwave background

$$\Omega_{DM}\, h^2 = 0.1198 \pm 0.0026$$

DM searches:

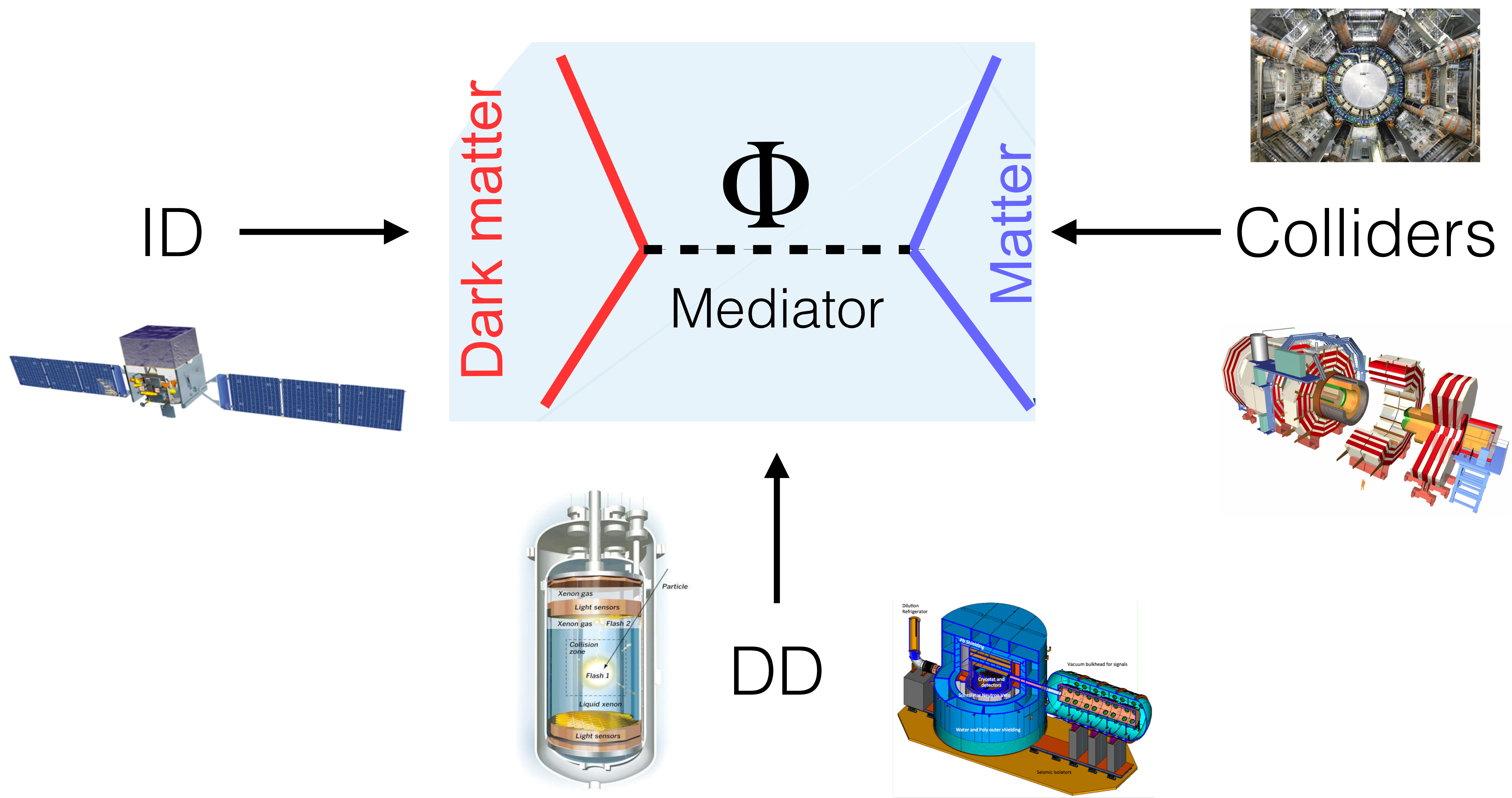
- $\boxed{\text{Direct Detection}}$ (DD) experiments

- $\boxed{\text{Indirect Detection}}$ (ID) experiments

- $\boxed{\text{Collider searches}}$ (LHC & future colls 13-100 TeV)

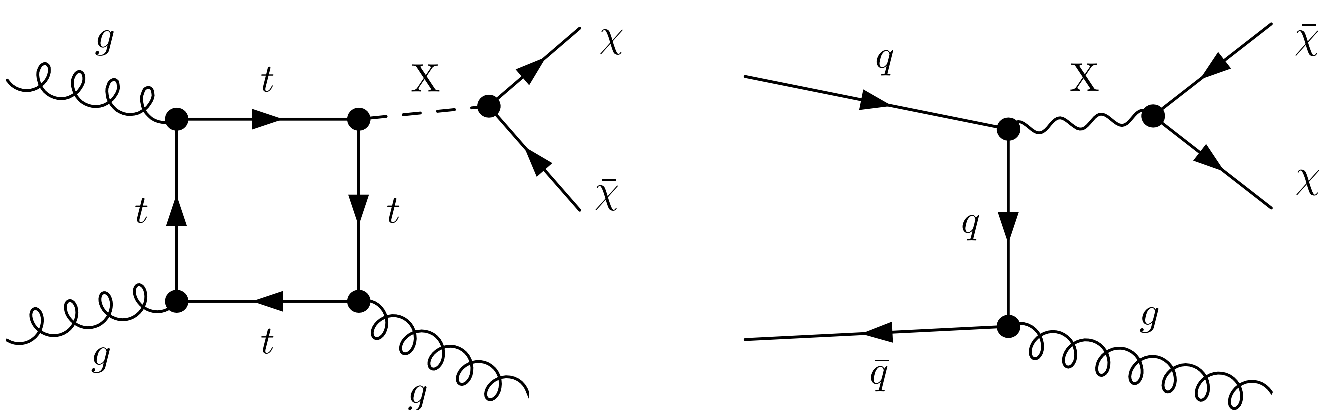
The same 2-to-2 interaction involving DM and SM particles describes the DD, ID and Collider searches (only the initial state varies).

[However note that one has to be extra careful with drawing conclusions from this in abridged theories e.g. in Simplified Models. The Dark Sector, the SM particles (and the mediators) involved in the dominant process in each case can be completely different.]



Simplified Models for Dark Matter at Colliders

- Dark Sector should contain Dark Matter (which is cosmologically stable) plus possibly other dark particles.
- At colliders dark sector particles produced in collisions would manifest themselves as missing transverse momentum (aka MET).
- Use SM jets to recoil, consider jets + MET signatures.
- Being stable on collider scales – is much less restrictive than the cosmological DM – i.e. can look for more than just DM in dark sectors.
- Dark Particles interact with the Standard Model by exchanging a *mediator* field X. Mediator particle is a key new physics d.o.f. at colliders.
- Four basic types of mediators: vectors, axial-vectors, scalars, pseudo-scalars (can be exchanged in *s*- or *t*-channel). Concentrate below on the *s*-channel models (colourless mediators):



Simplified Models for Dark Matter at Colliders

- At LHC energies mediators can be resolved and taken to be dynamical
- Four basic types of mediators to the dark sector associated with scalar S, pseudo-scalar P, vector Z' and axial-vector Z'' fields with interactions,

$$\mathcal{L}_{\mathrm{scalar}} \supset -\frac{1}{2} m_{\mathrm{MED}}^2 S^2 - g_{\mathrm{DM}} S\,\bar{\chi}\chi - \sum_q g_{SM}^q S\,\bar{q}q - m_{\mathrm{DM}}\bar{\chi}\chi$$

$$\mathcal{L}_{\mathrm{pseudo-scalar}} \supset -\frac{1}{2} m_{\mathrm{MED}}^2 P^2 - i g_{\mathrm{DM}} P\,\bar{\chi}\gamma^5\chi - \sum_q i g_{SM}^q P\,\bar{q}\gamma^5 q - m_{\mathrm{DM}}\bar{\chi}\chi$$

$$\mathcal{L}_{\mathrm{vector}} \supset \frac{1}{2} m_{\mathrm{MED}}^2 Z'_\mu Z'^\mu - g_{\mathrm{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi - \sum_q g_{SM}^q Z'_\mu \bar{q}\gamma^\mu q - m_{\mathrm{DM}}\bar{\chi}\chi$$

$$\mathcal{L}_{\mathrm{axial}} \supset \frac{1}{2} m_{\mathrm{MED}}^2 Z''_\mu Z''^\mu - g_{\mathrm{DM}} Z''_\mu \bar{\chi}\gamma^\mu\gamma^5\chi - \sum_q g_{SM}^q Z''_\mu \bar{q}\gamma^\mu\gamma^5 q - m_{\mathrm{DM}}\bar{\chi}\chi$$

Early original papers:

Vectors: S. Malik, C. McCabe, H. Araujo, *et al.*, arXiv:1409.4075

& Scalars:
- M. R. Buckley, D. Feld and D. Goncalves, arXiv:1410.6497
- P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1411.0535

Simplified Models for Dark Matter at Colliders

Jets + MET topology of the final state

P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1509.02904
updating our earlier analysis in arXiv:1411.0535 to 14-100 TeV

Our Simplified Models for Dark Particles searches at colliders are characterised by the type of the mediator plus the following free parameters:

1. mediator mass $m_{\rm MED}$
2. mediator width $\Gamma_{\rm MED}$ [ATLAS & CMS decided to use the minimal width instead
   [Can use $\Gamma_{\rm MED\,minimal}$ computed in the simplified models $\times\{1,2,5,10\}$
   and check $< m_{\rm MED}/2$] then the width is not a free parameter]
3. dark matter mass $m_{\rm DM}$
4. mediator couplings $g_{\rm DM}$ and g_q for scalar and pseudo-scalars;
   or $g_{\rm DM}$ and $g_{\rm SM}$ for axial-vector and vector mediators.

Signal generated using MadGraph for Vector and Axial mediators and a combination of MCFM and VBFNLO for the production of Scalar and Pseudoscalar mediators in association with 1 and 2 jets. Backgrounds were generated at NLO for 0,1,2 jets merged using MadGraph-aMC@NLO.

Collider Searches — Simplified DM Models [mediator types]

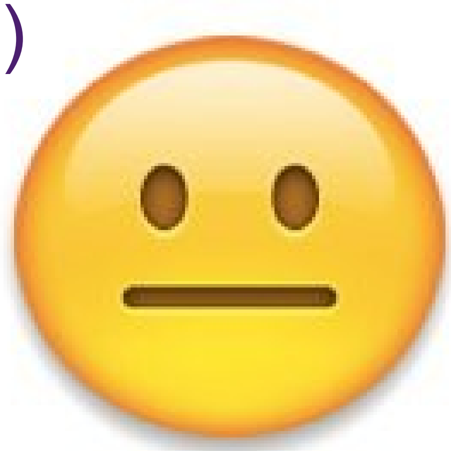
Vector(SI)

Large cross section

Axial (SD)

Same as vector

Scalar(SI)

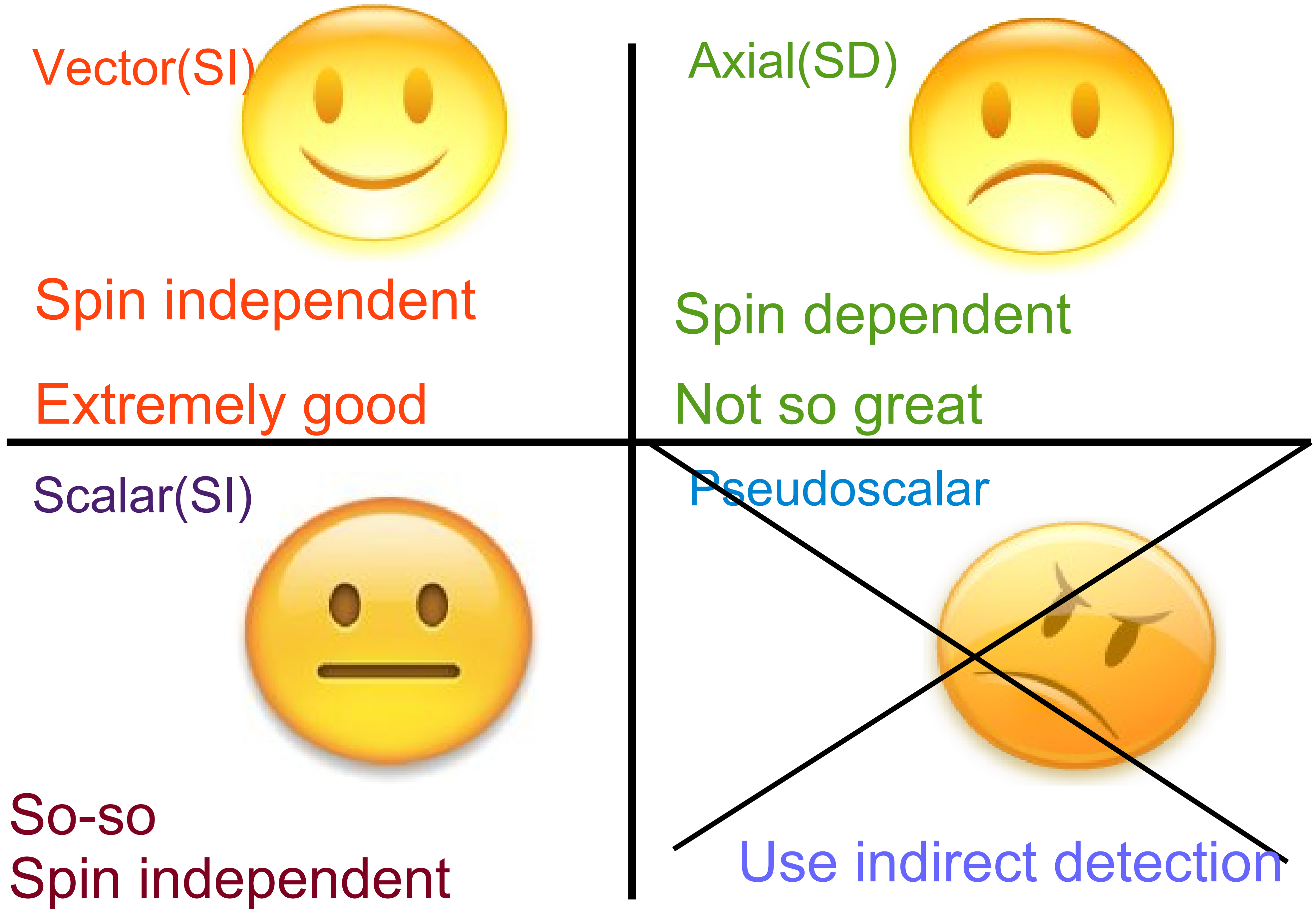


Low-ish cross section

Pseudoscalar

Better than scalar
Small cross section

Direct Detection — Simplified DM Models [mediator types]

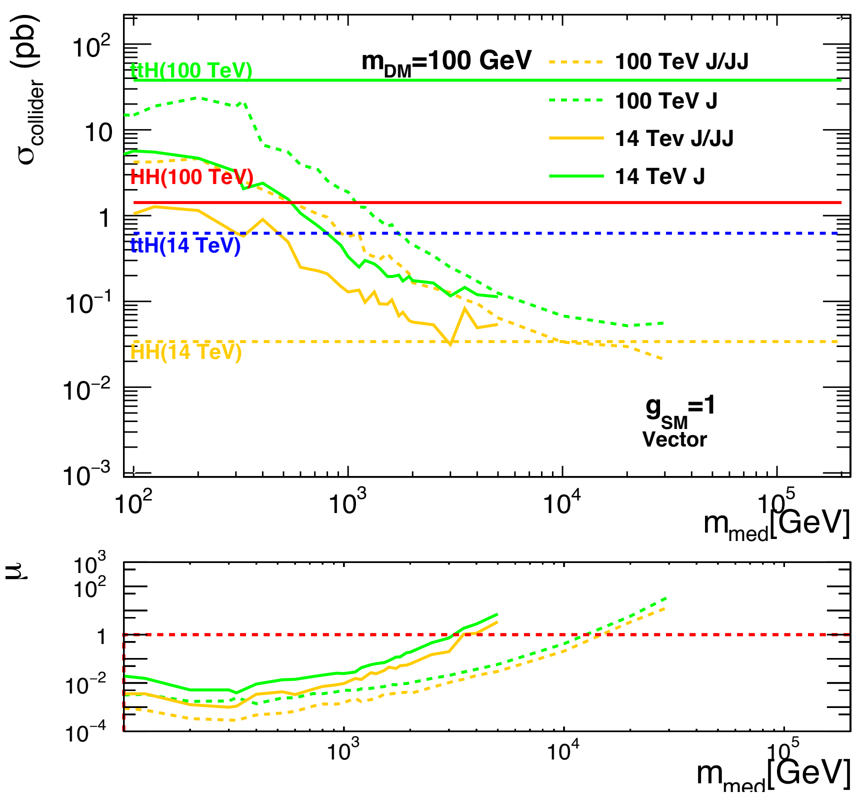


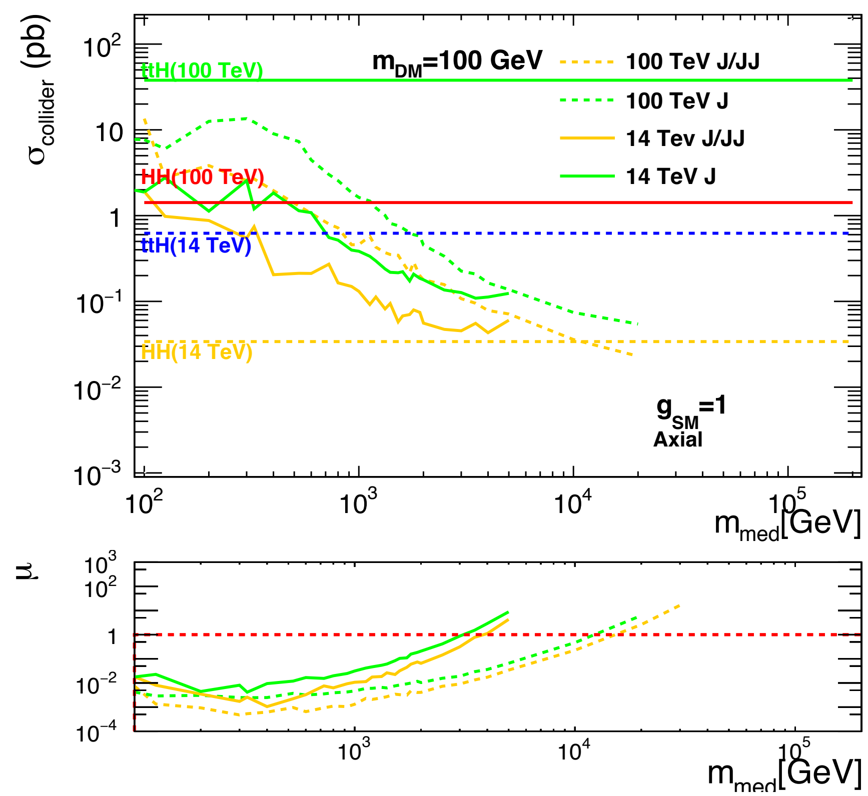
Simplified Models for Dark Matter at Colliders

Jets + MET topology

Collider cross section limits and projections at 14 and 100 TeV [Preliminary]
μ is the ratio of the exclusion $\sigma_{\rm coll}$ to the predicted $\sigma(g_{\rm DM} = 1, g_{\rm SM} = 1)$

- **Vector and Axial-vector mediators:**





P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1509.02904

Simplified Models for Dark Matter at Colliders

Jets + MET topology

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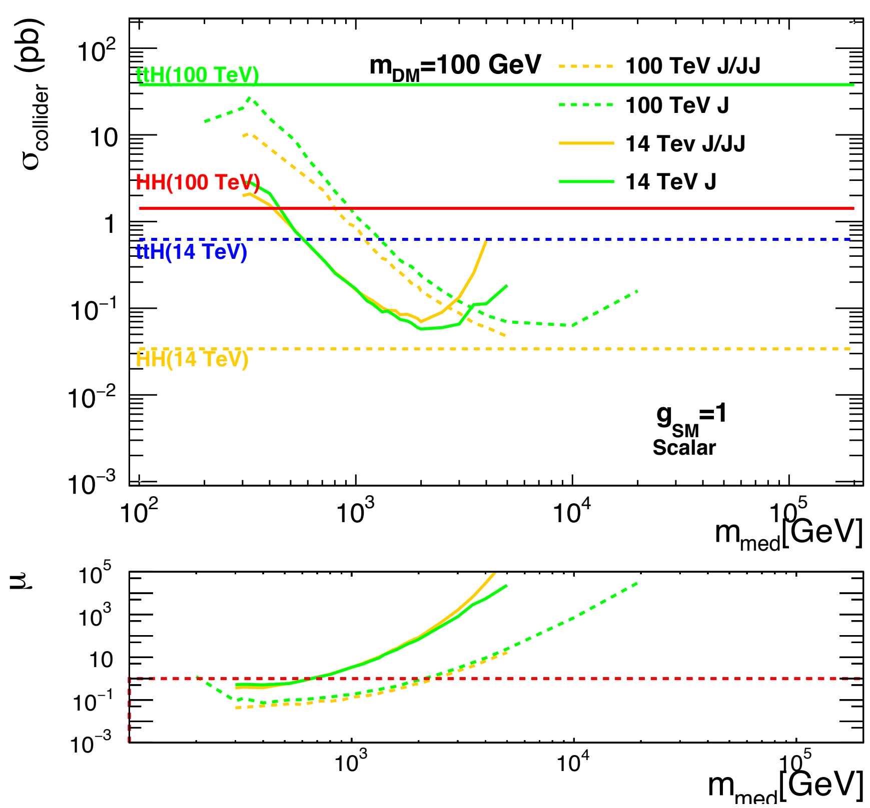
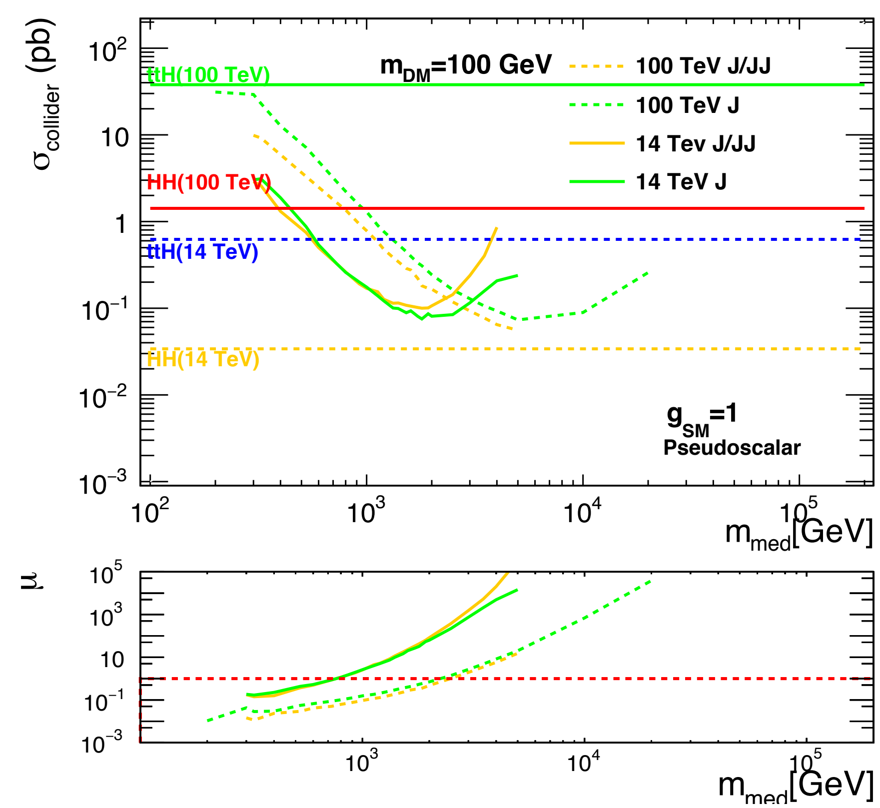
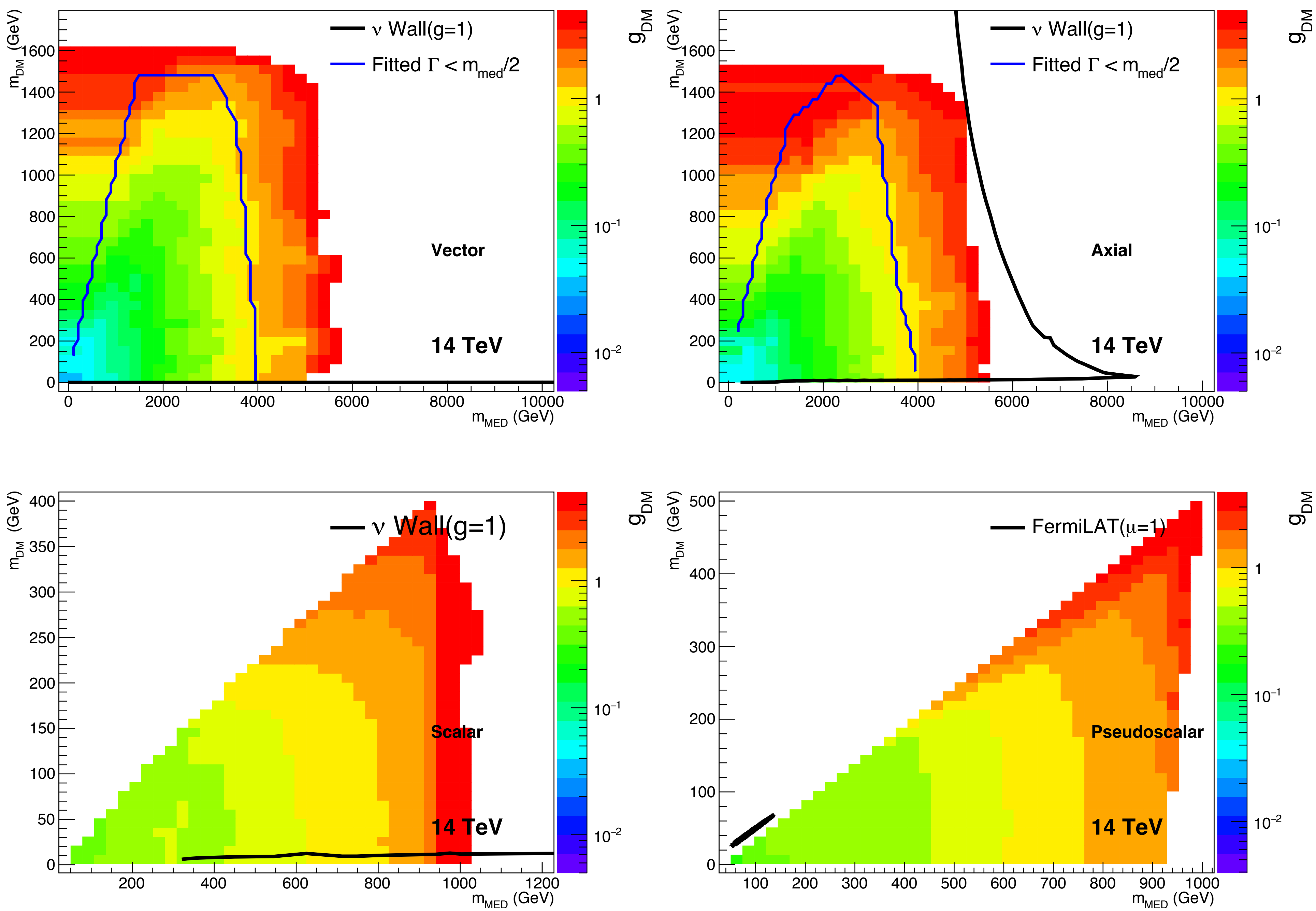
- **Scalar and Pseudo-scalar mediators:**





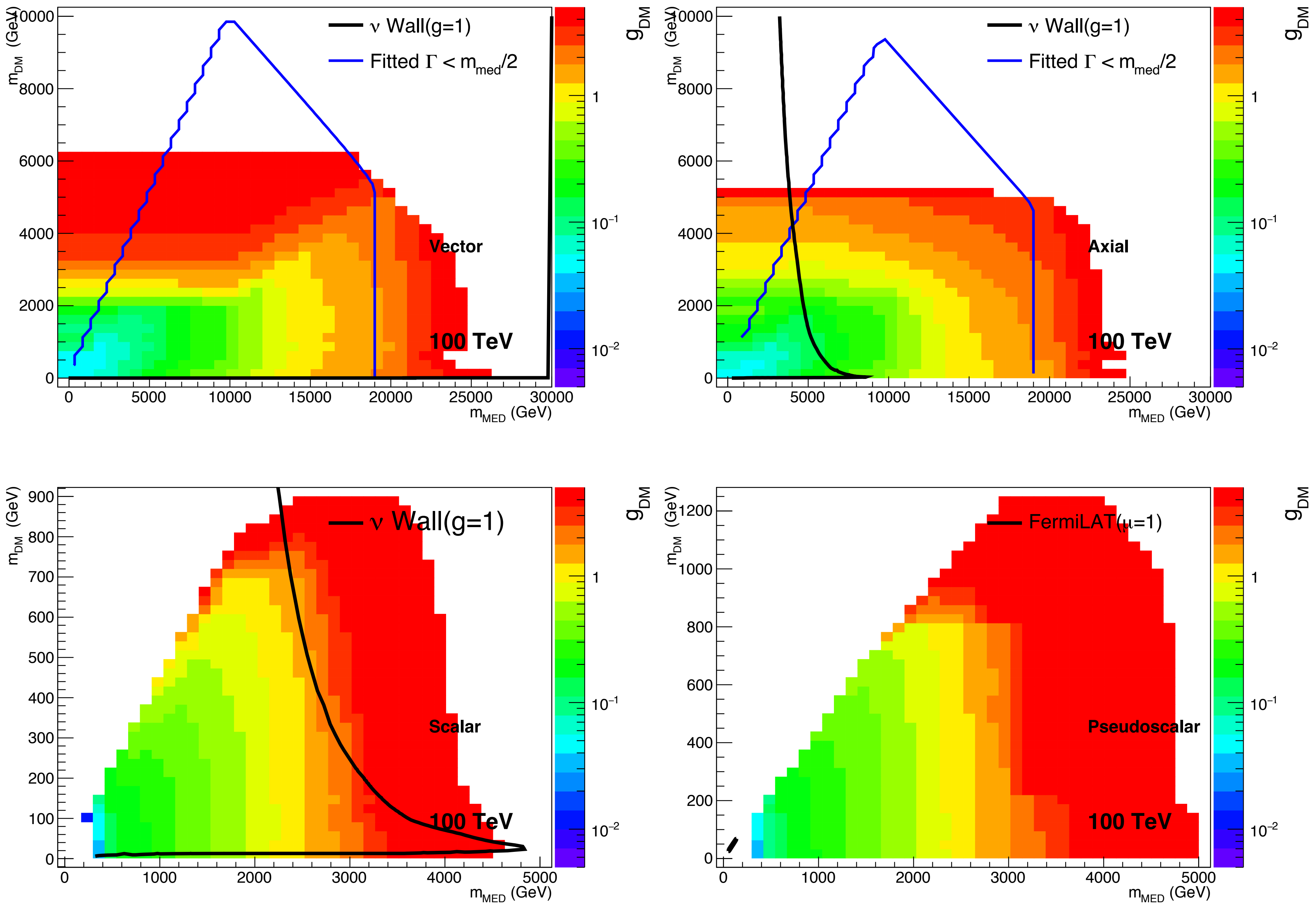
P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1509.02904

Exclusion limits on mediator mass vs DM mass at 14 TeV:



P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1509.02904

Exclusion limits on mediator mass vs DM mass at 100 TeV:



P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1509.02904

Followed by a concerted DM@colliders effort (2015-16 experiment-theory papers) incl.:

arXiv:1507.00966v1 [hep-ex] 3 Jul 2015

Dark Matter Benchmark Models for Early LHC Run-2 Searches:
Report of the ATLAS/CMS Dark Matter Forum

August 8, 2016

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arXiv:1606.00947v1 [hep-ph] 3 Jun 2016

CERN-TH-2016-111

Physics at a 100 TeV pp collider: beyond the Standard Model phenomena

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arXiv:1607.06680v2 [hep-ex] 22 Aug 2016

Towards the next generation of simplified Dark Matter models

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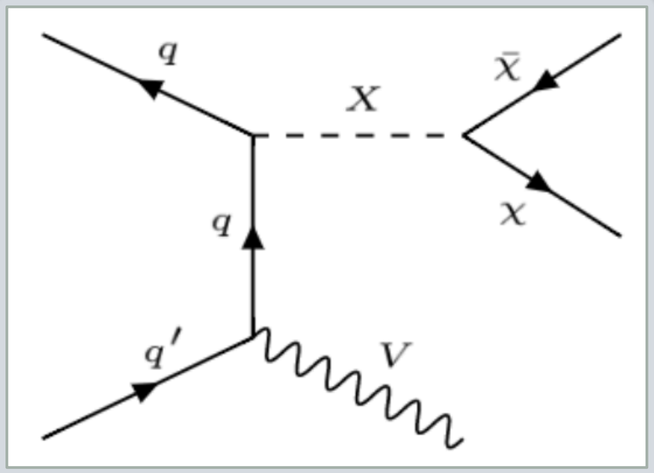
+ now: LHC Dark Matter WG meetings

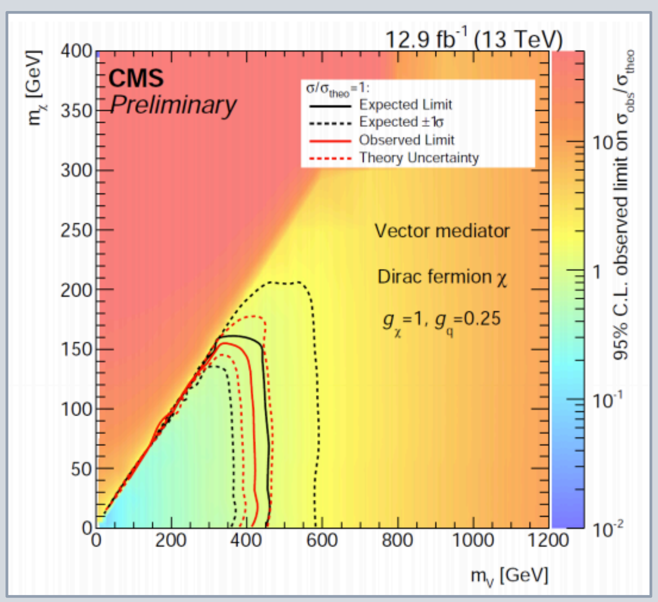
Vector & Axial-Vector Mediators

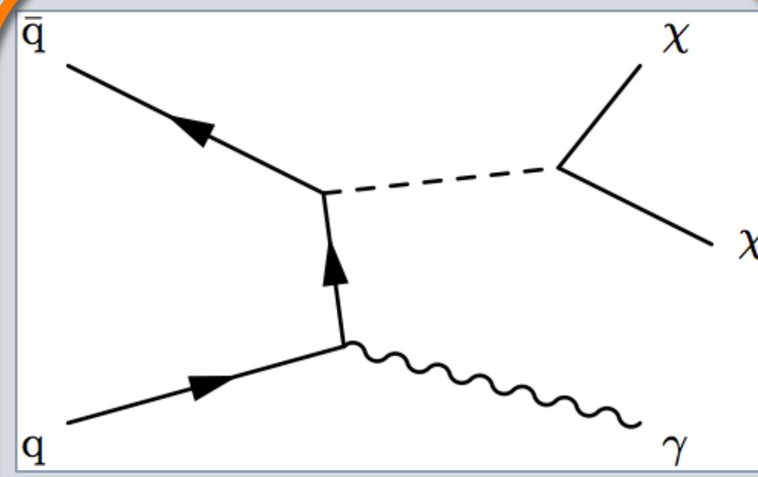
DM+Z: **CMS PAS EXO-16-038**
DM+γ: **CMS PAS EXO-16-039**
DM+j: **CMS PAS EXO-16-037**

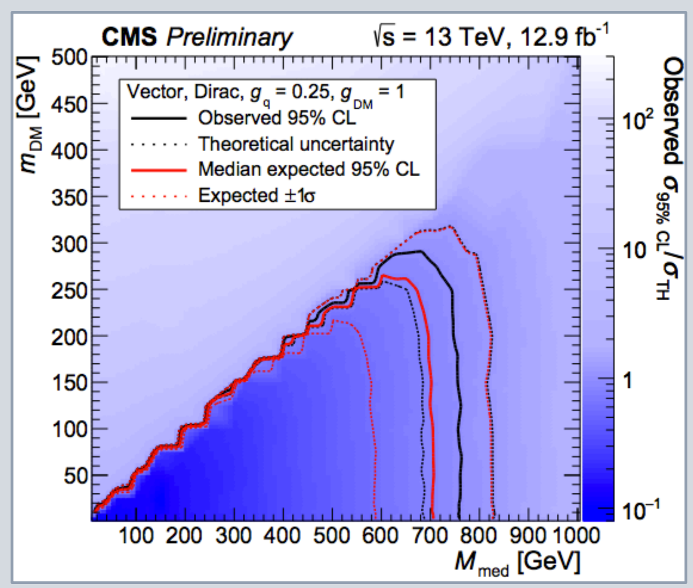
$g_q = 0.25,\ g_{DM} = 1$

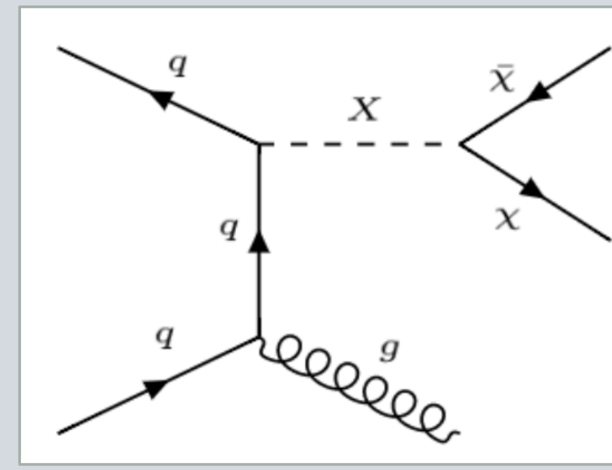
CMS DM+Z, DM+γ, DM+j

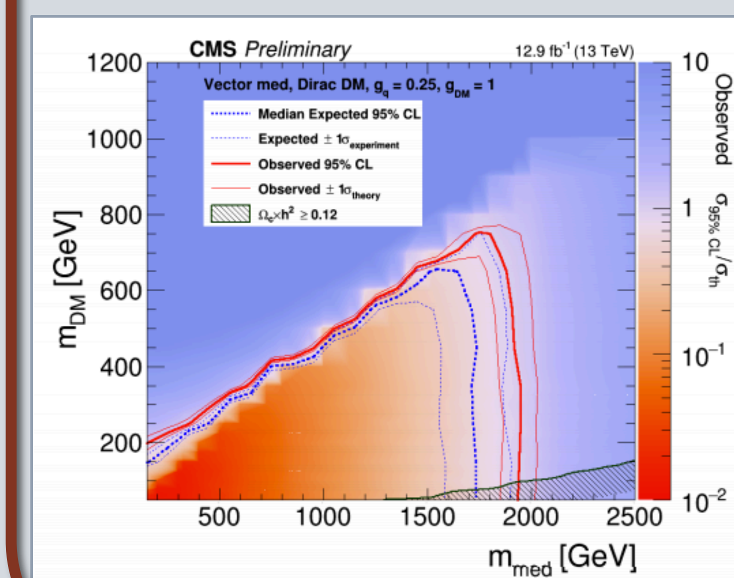








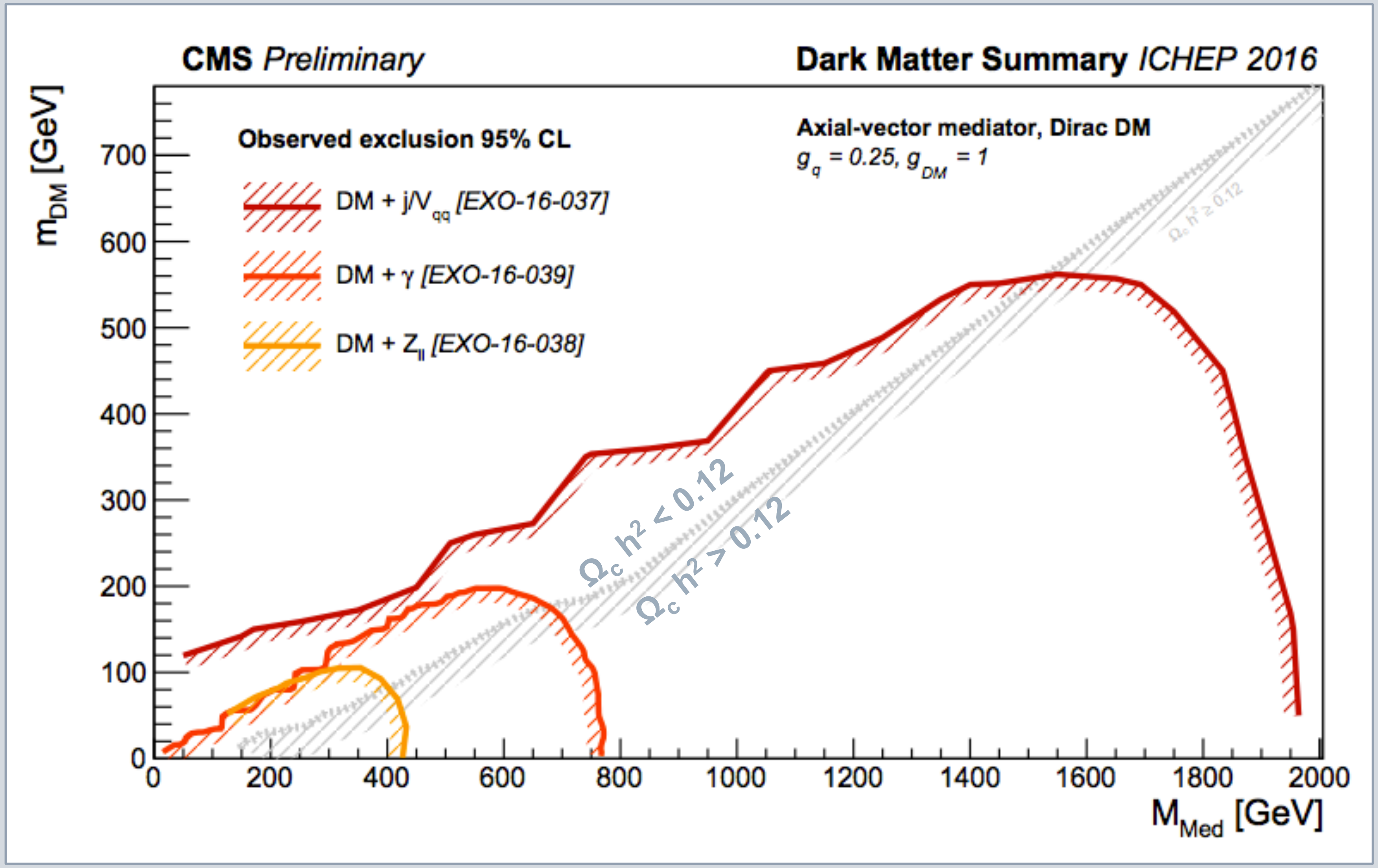




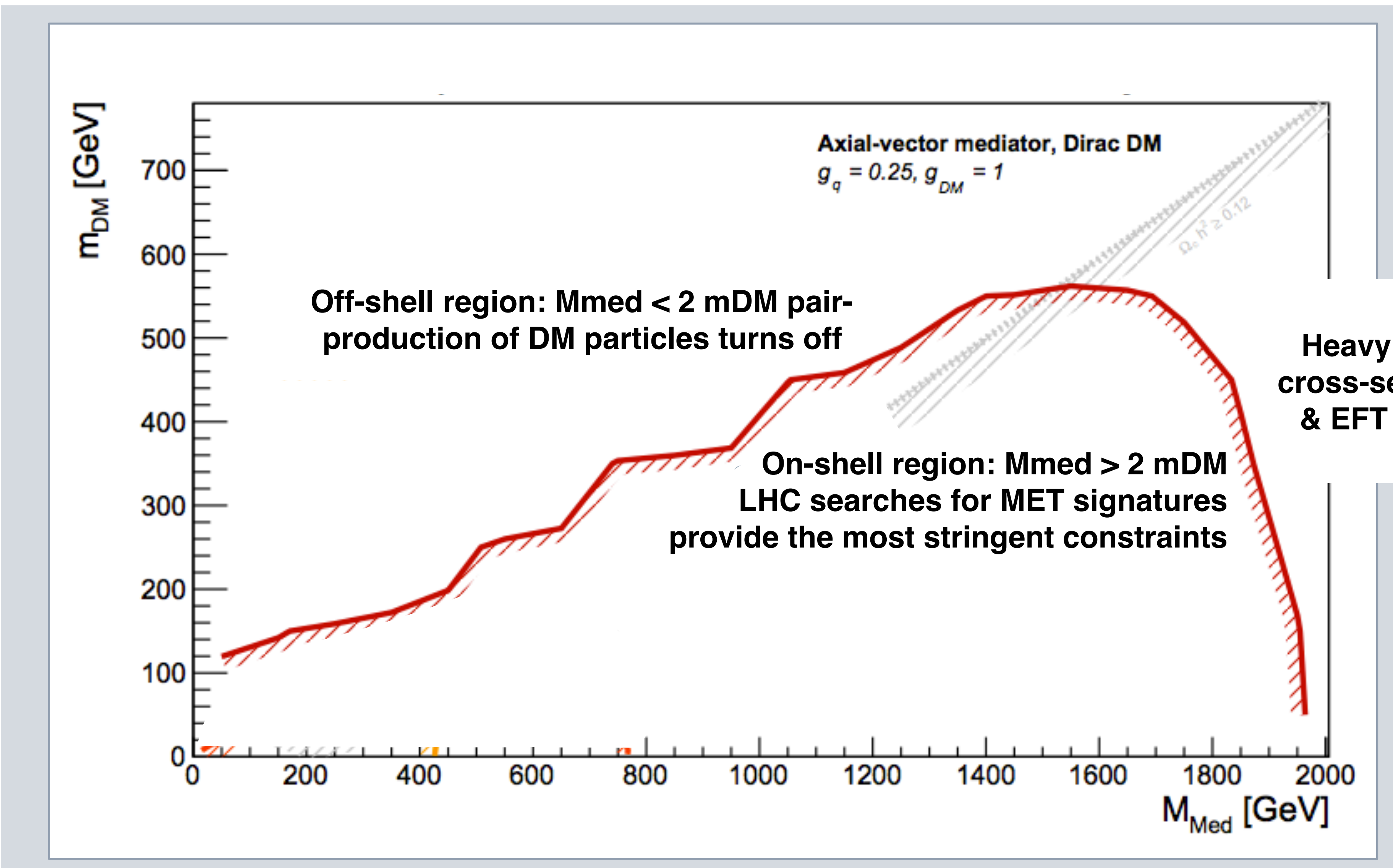
Axial-Vector Mediators Summary

CERN-CMS-DP-2016-057
https://cds.cern.ch/record/2208044

- DM+Z / DM+γ / DM+jet



- Limits: $\mathbf{M_{Med}}$ **~ 2 TeV,** $\mathbf{m_{DM}}$ **~ 600 GeV** *(g_q = 0.25, g_{DM} = 1)*
  - Mono-jet most stringent - all channels contribute to interpretation

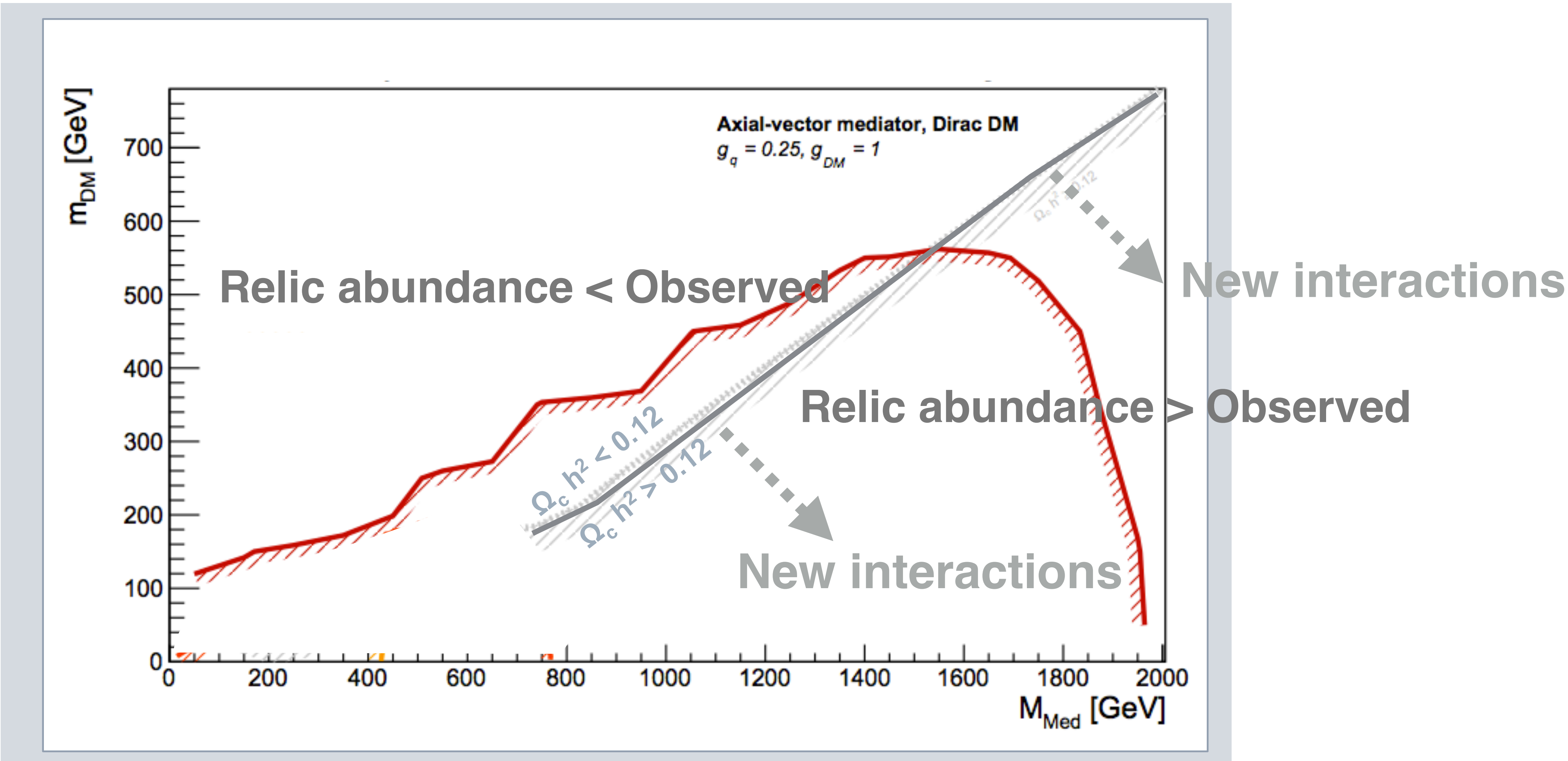


Heavy Mediator limit:
cross-section turns off
& EFT can be applied

Relic Density as an indication

Relic density can be computed in a specific simplified model with a single mediator, as if it was the full theory, and overlaid on the mass-mass collider exclusion contour.

Note that other interactions present in the complete theory but not in the simplified model would increase the DM annihilation cross section and decrease the value of the relic abundance.

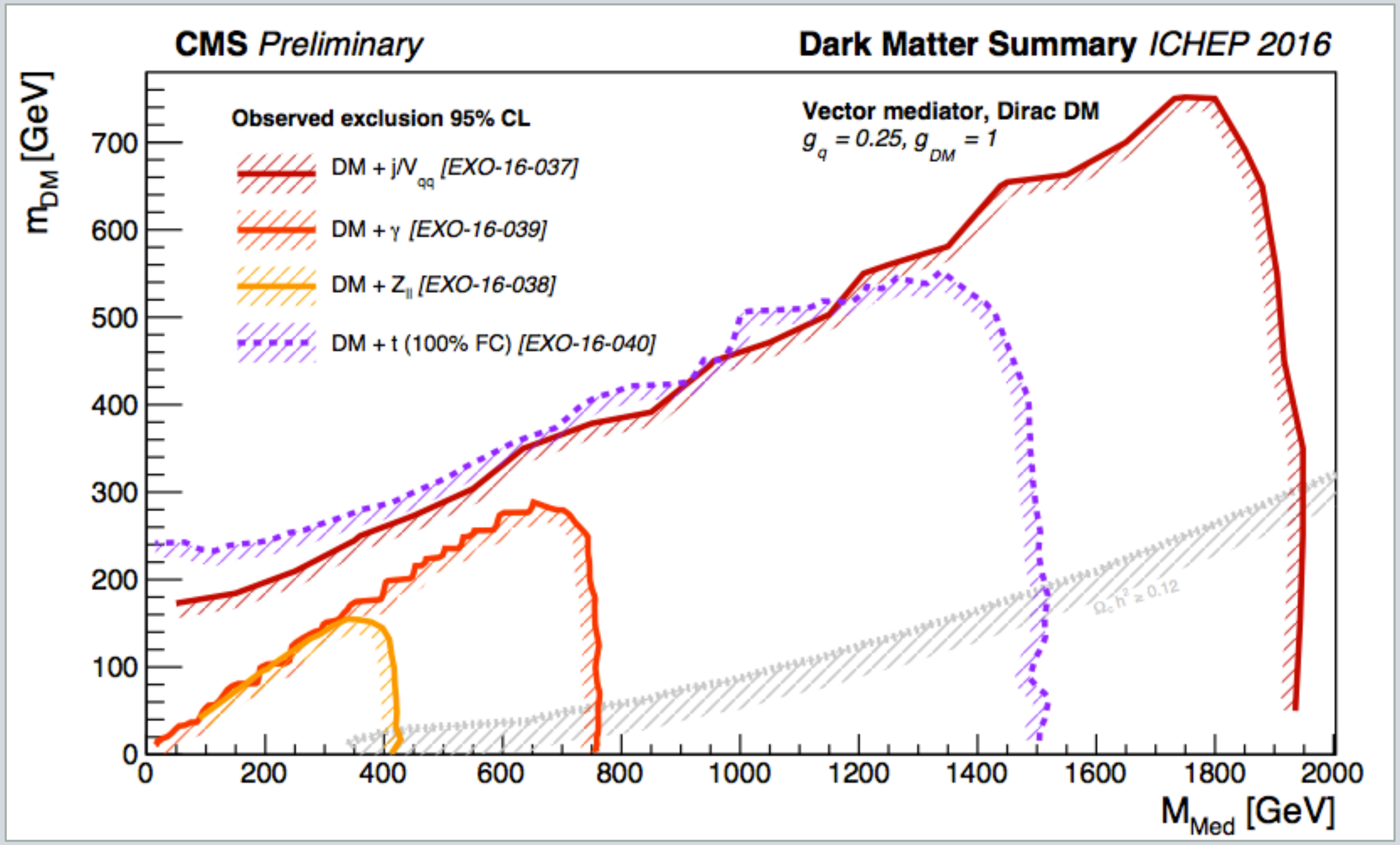


Also assumes that all MET particles produced are cosmologically stable

Vector Mediators Summary

CERN-CMS-DP-2016-057
https://cds.cern.ch/record/2208044

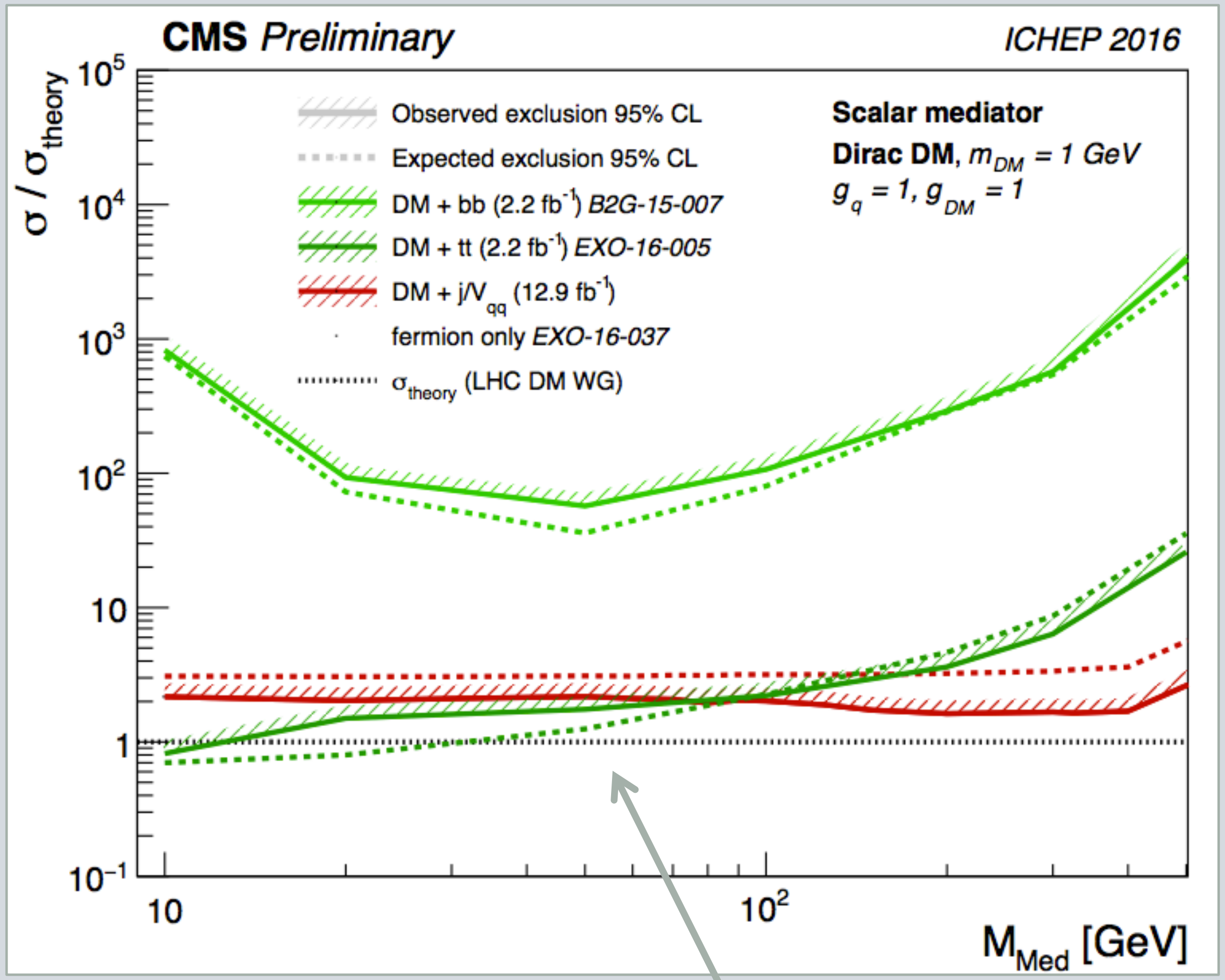
- **MET+X** & **Mono-top**

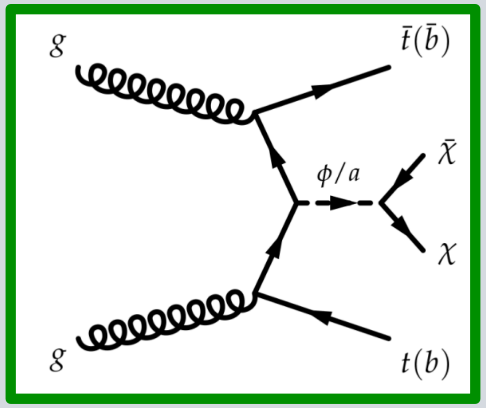


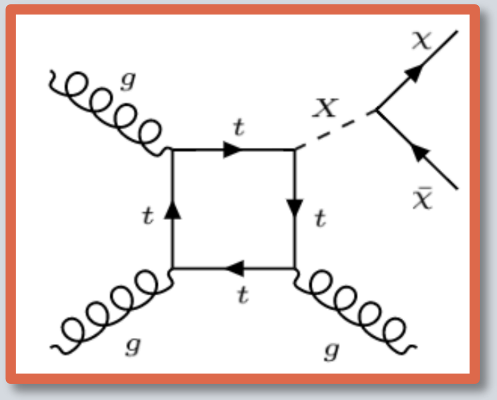
Scalar summary

CERN-CMS-DP-2016-057
https://cds.cern.ch/record/2208044

- DM+bb & DM+tt & mono-jet *(f-only)*





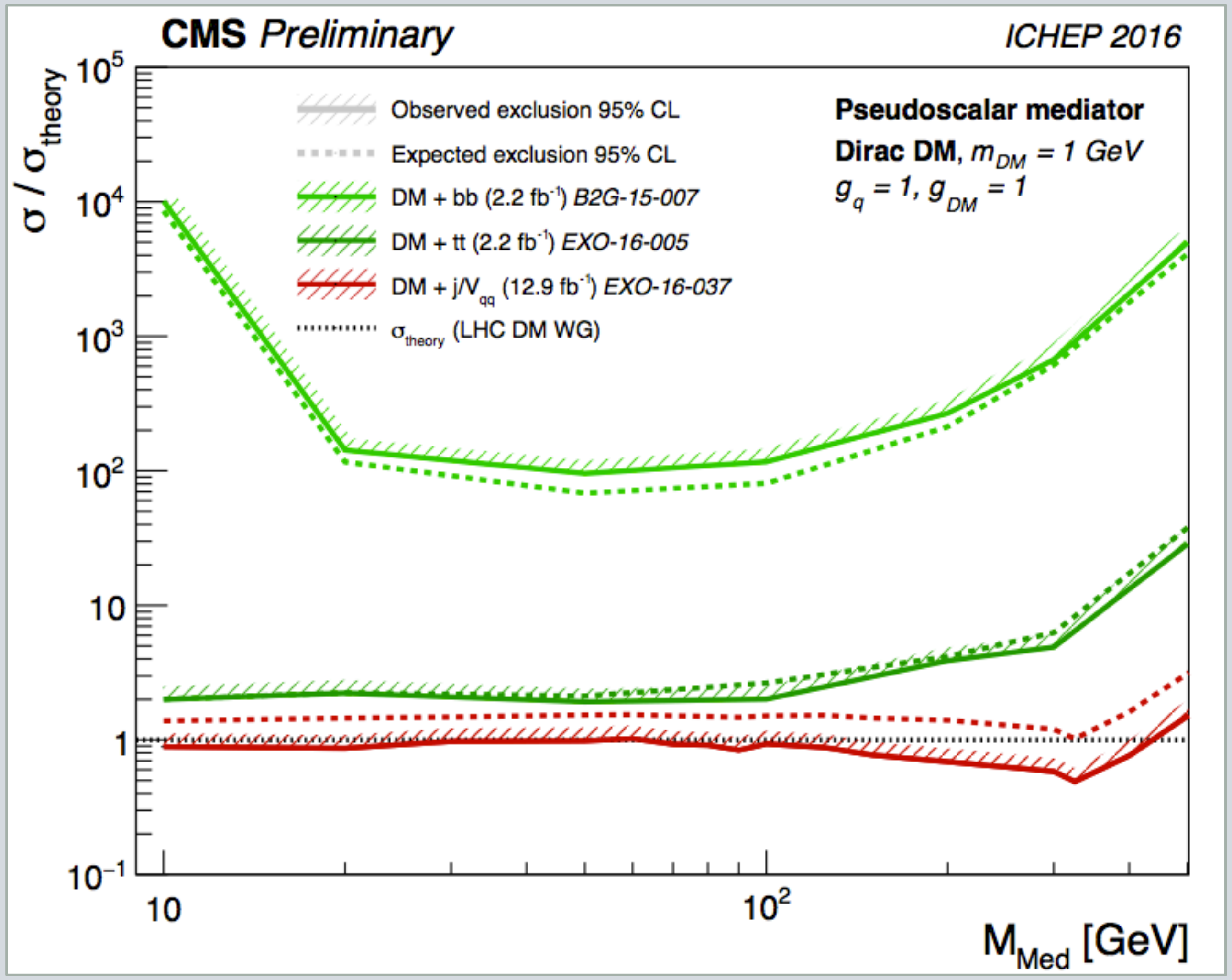


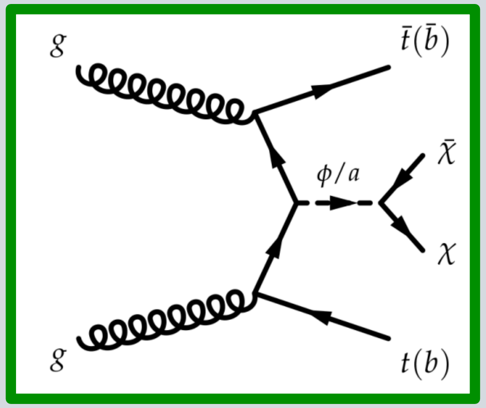
- Low M_{Med}: sensitivities similar and approaching σ/σ_{theory} ~1
  - *Case for combined interpretation?*

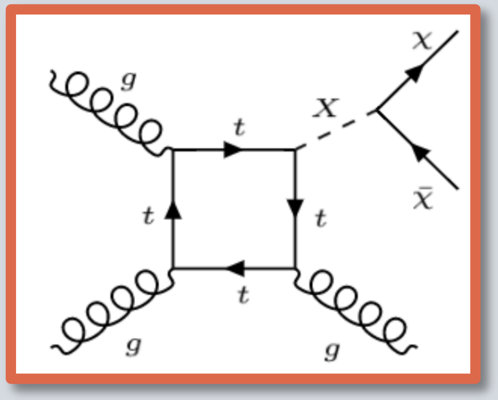
Pseudoscalar

CERN-CMS-DP-2016-057
https://cds.cern.ch/record/2208044

- **DM+bb** & **DM+tt** & **mono-jet**





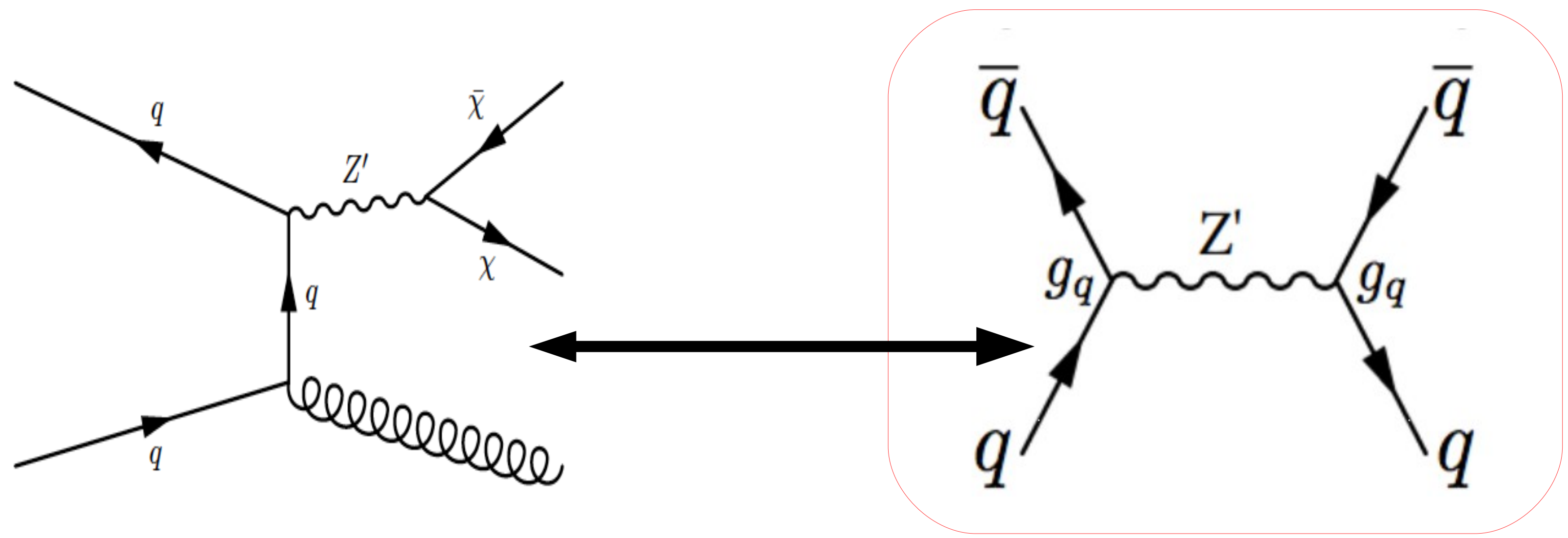


- **Low M_{Med}: sensitivities similar and close to σ/σ_{theory} ~1**
  - *Case for combined interpretation?*

Axial/Vector Mediators:

What else?

- Without loss of generality we also have dijets



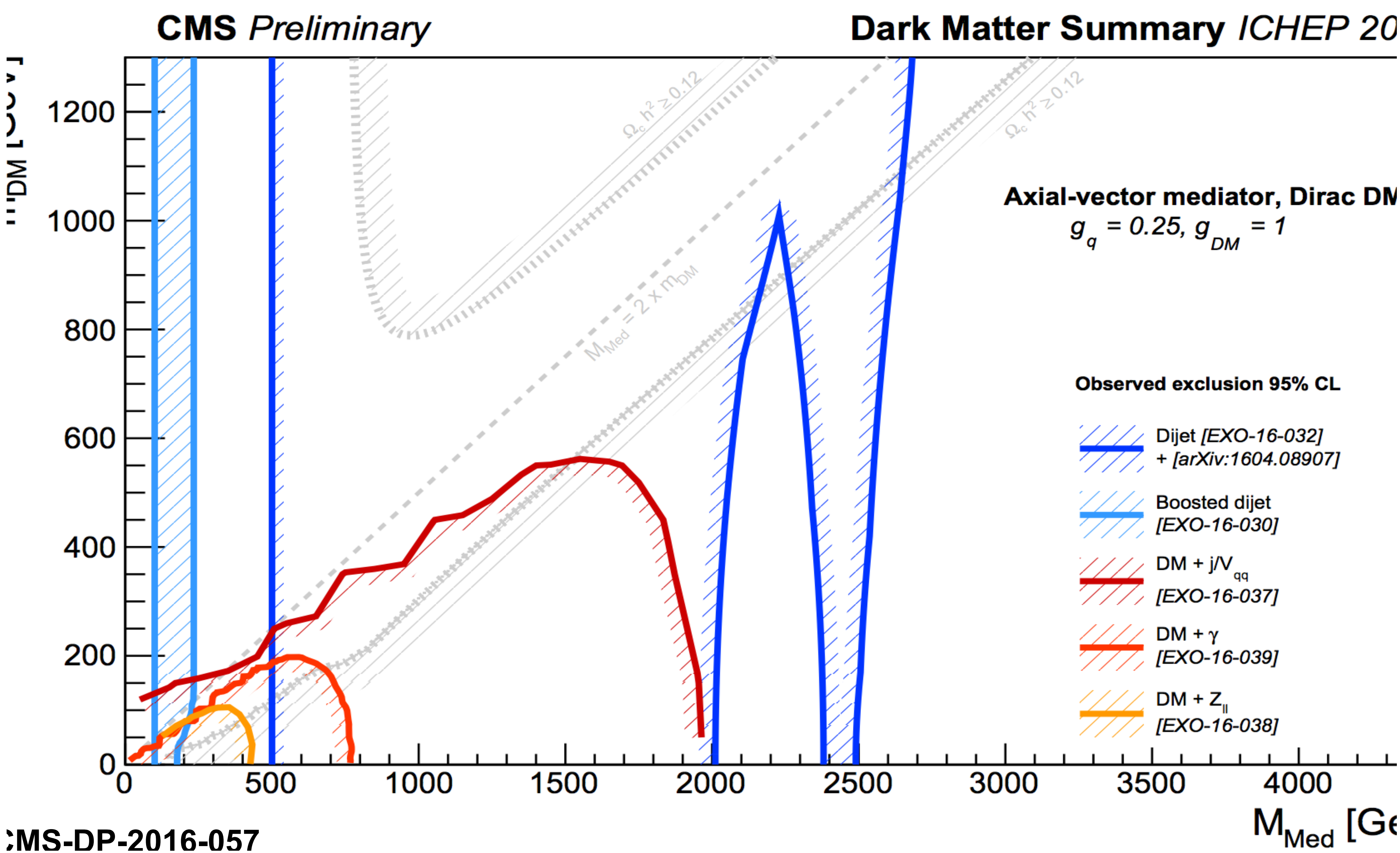
Can also just do a plain diet search

Dijet search puts significant bounds at high mass

$BR(Z' \to qq) \approx 0.5 BR(Z' \to \quad)$

Axial-Vector Mediator:

CMS

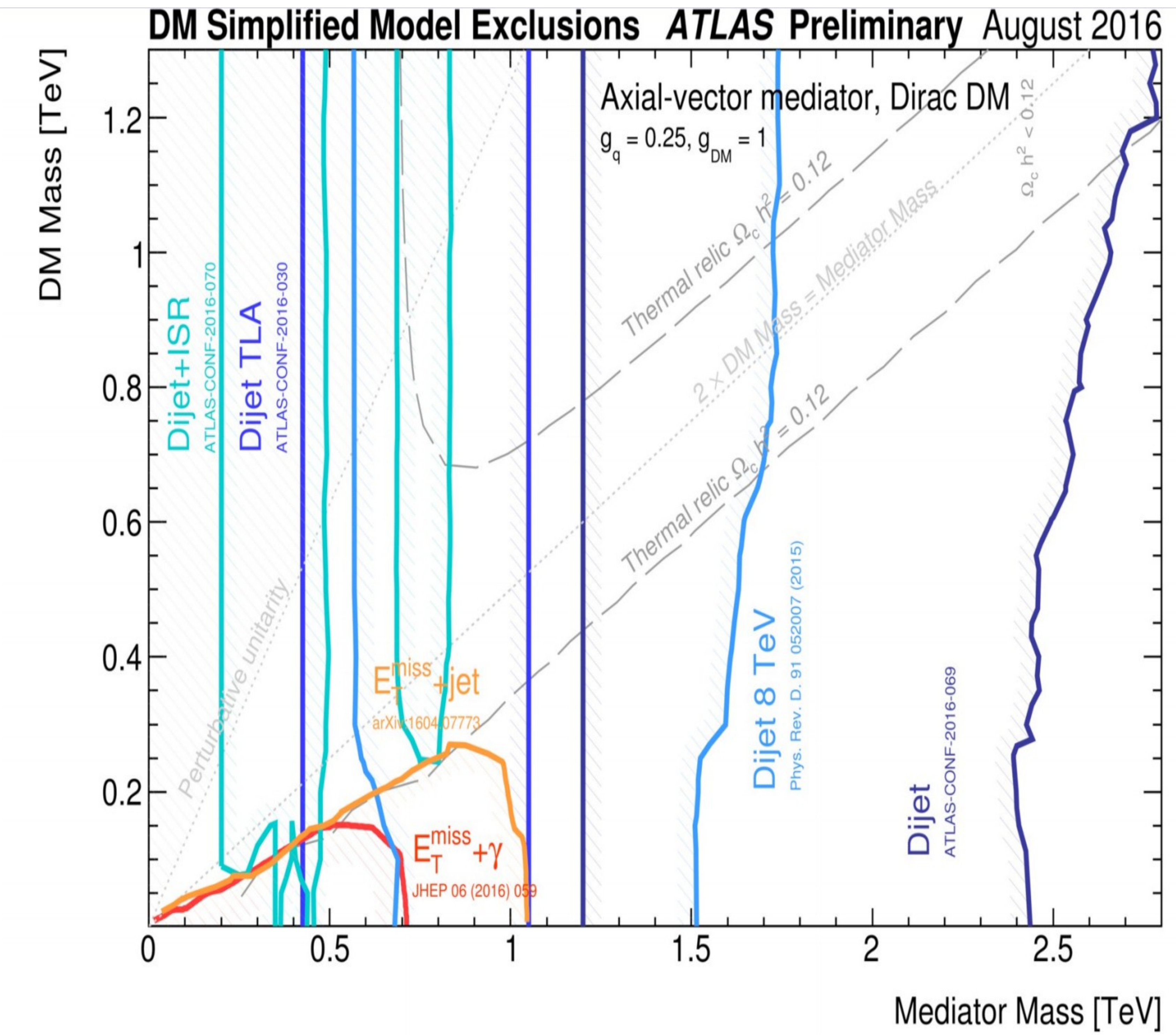


CMS-DP-2016-057

Axial-Vector Mediator:

ATLAS DM bounds

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html#

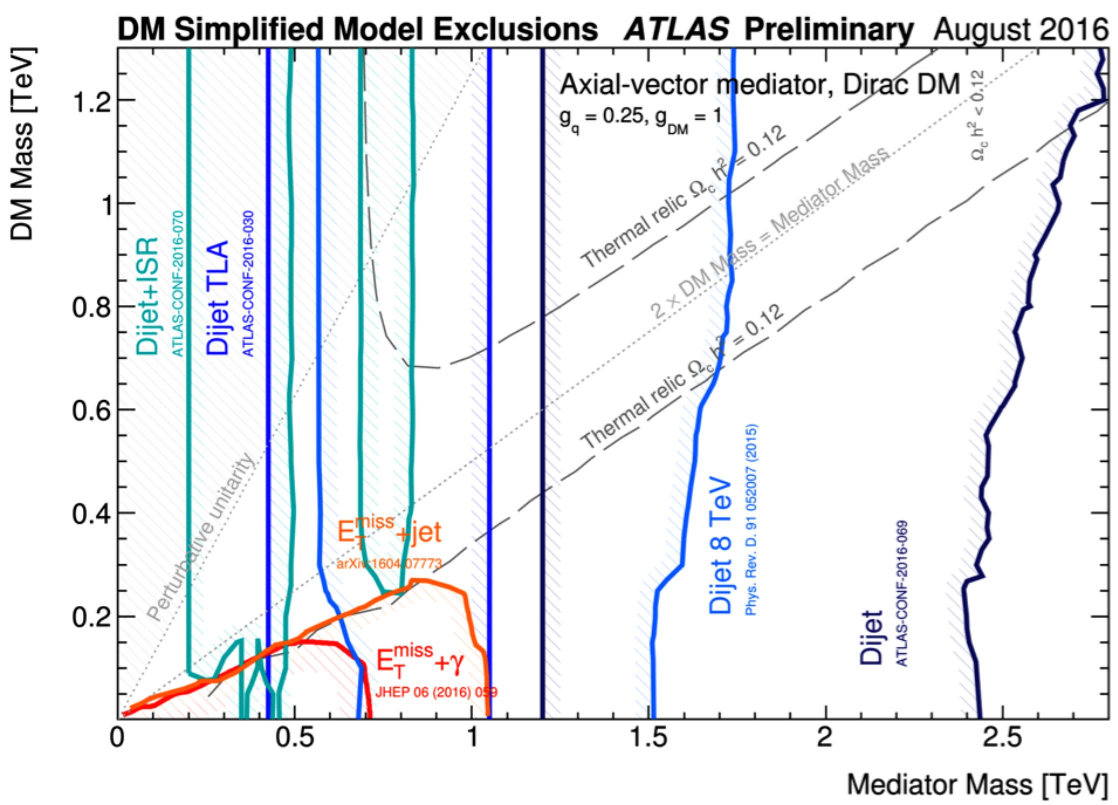


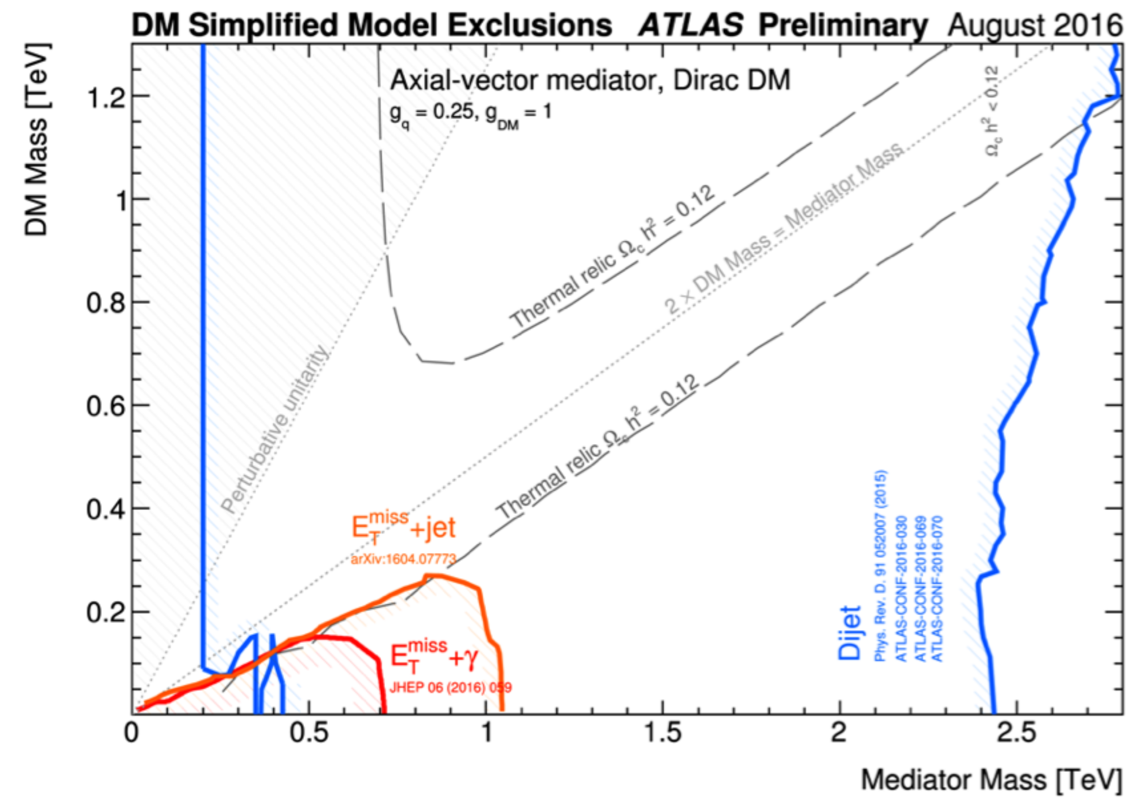
$g_{SM}=0.25$
$g_{DM}=1$

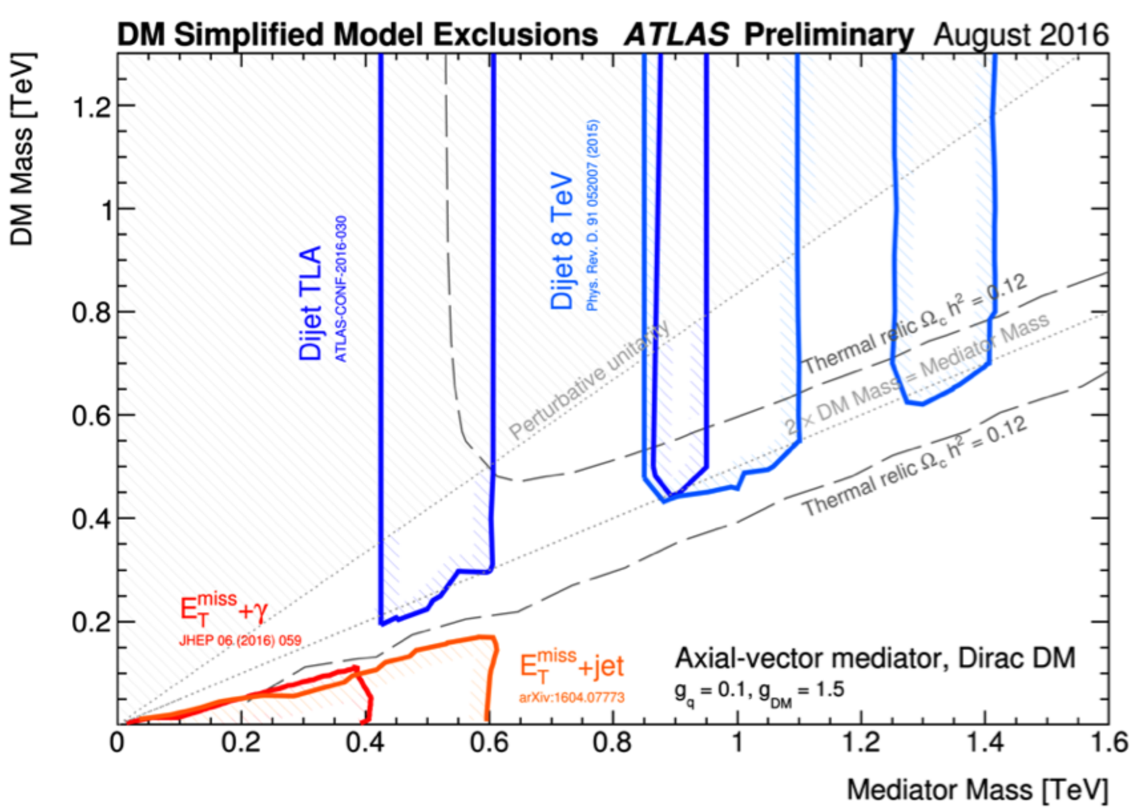
ATLAS summary plots

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html

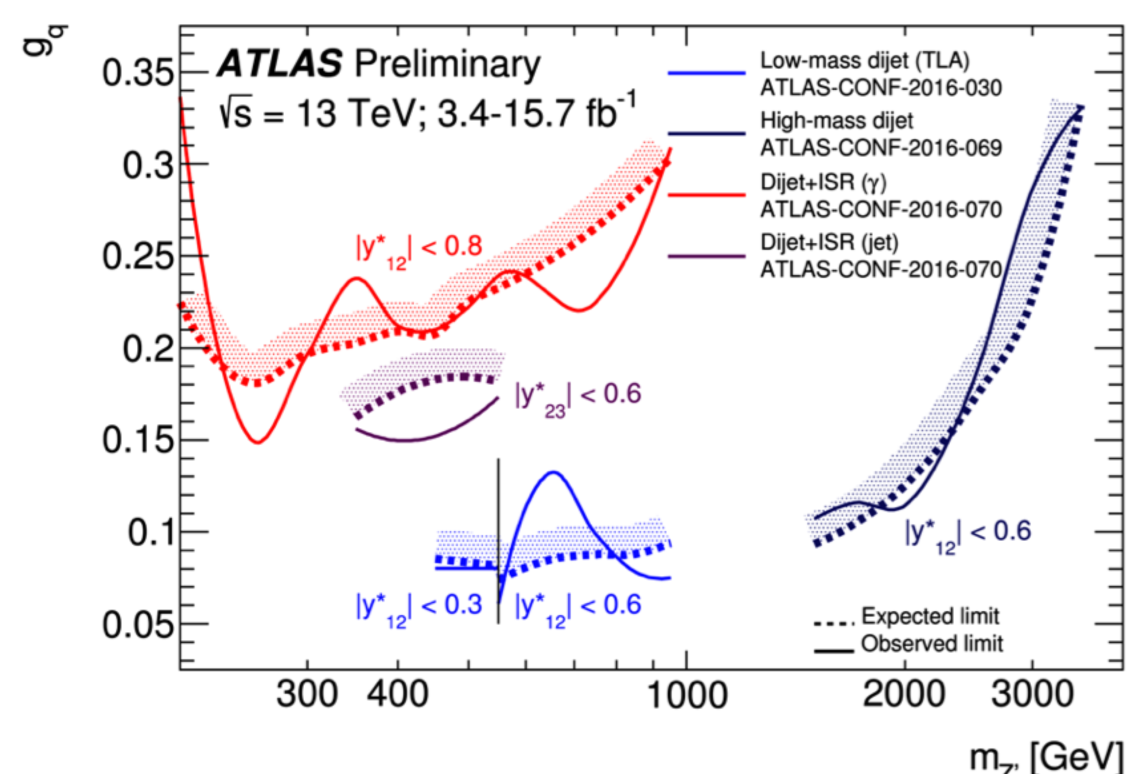
DM mass - Mediator mass, fixed couplings
Mono-jet/photon and dijet searches



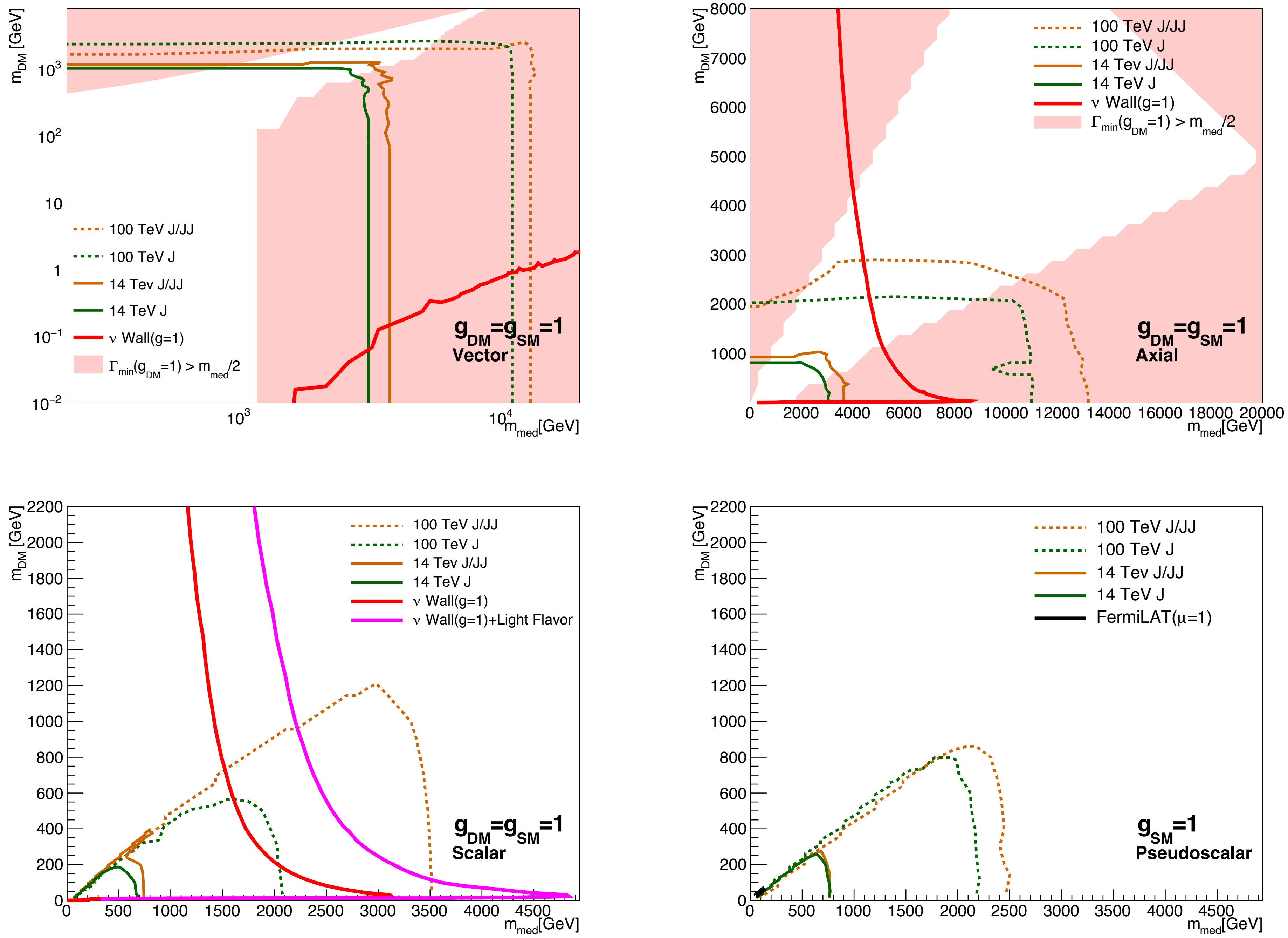




SM coupling - Mediator mass
Fixed DM mass (off-shell), dijet searches only

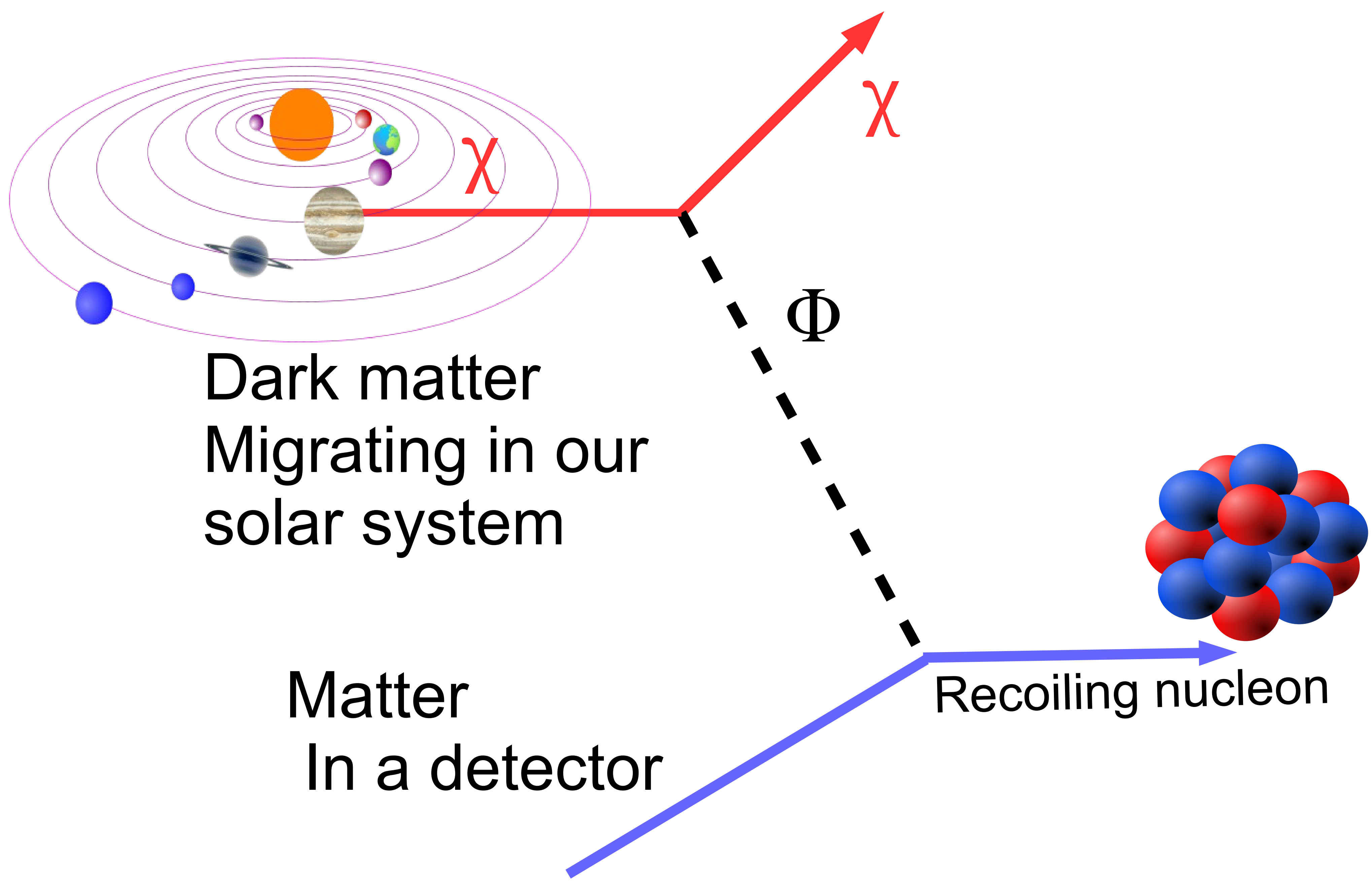


Mass limits using single-jet and multi-jet analysis at 14 & 100TeV:



P. Harris, VVK, M. Spannowsky and C. Williams, arXiv:1509.02904

Direct Detection



Direct Detection

- Probes the rate of DM-nucleon interactions in earth-based experiments. DD search for nucleus recoil from a DM particle traversing the detector.

- Two classes of interactions: Spin-independent (SI) and Spin-dependent (SD) nucleon-mediator interactions

- SI cross-section relevant for scalar and vector mediator models. Higher sensitivity to SI

  $\mu_{n\chi} = m_n m_{\mathrm{DM}}/(m_n + m_{\mathrm{DM}})$

  The mediator-nucleon coupling is $f(g_q)$

$$\sigma_{\mathrm{SI}} = \frac{f^2(g_q) g_{\mathrm{DM}}^2 \mu_{n\chi}^2}{\pi M_{\mathrm{med}}^4} ;$$

- SD cross-section relevant for axial-vector and pseudo-scalar mediators. However pseudo-scalar crosssection has additional velocity-suppression [non-relativistic limit].

$$\sigma_{\mathrm{SD}} = \frac{3 f^2(g_q) g_{\mathrm{DM}}^2 \mu_{n\chi}^2}{\pi M_{\mathrm{med}}^4} .$$

Direct Detection

- A large number of DD experiments with different target nuclei and different detector technologies.

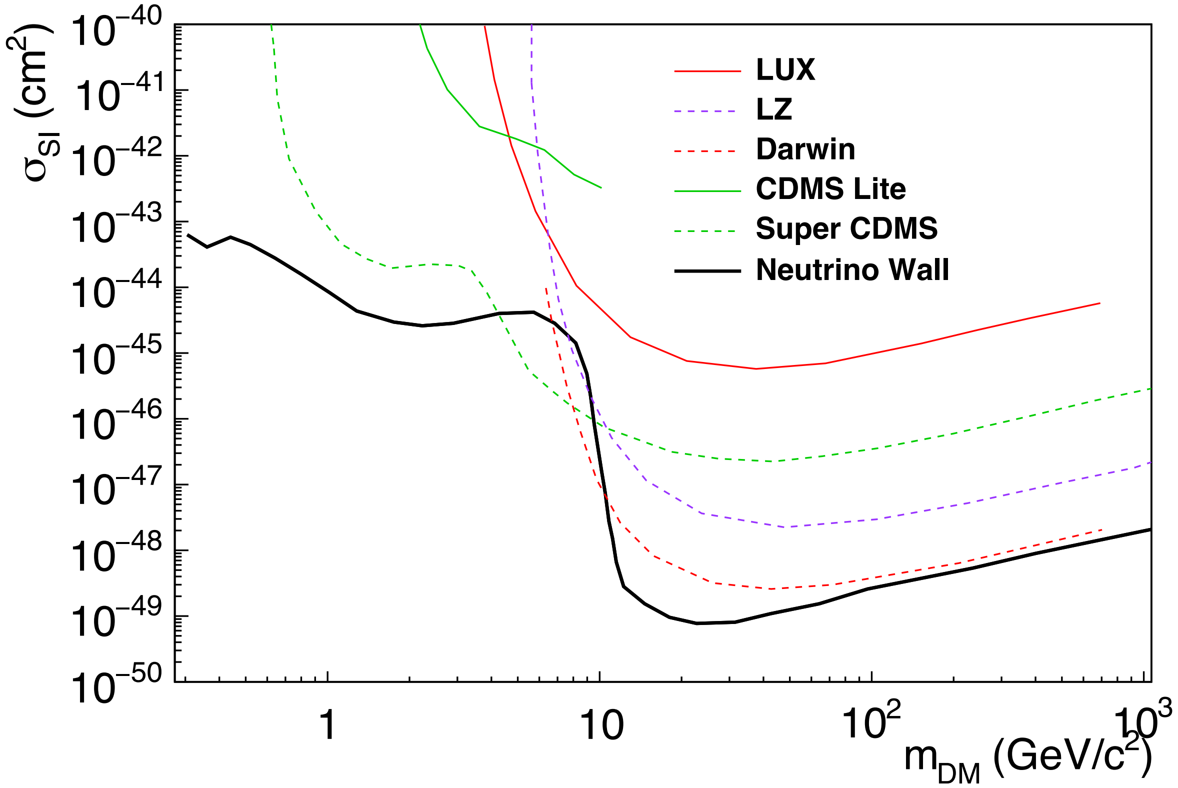
- For SI interactions and heavy DM > O(10 GeV), the most sensitive are two-phase Xenon experiments: LUX (current) and XENON1T (1st run later this year) and LUX extensions - LZ and Darwin.

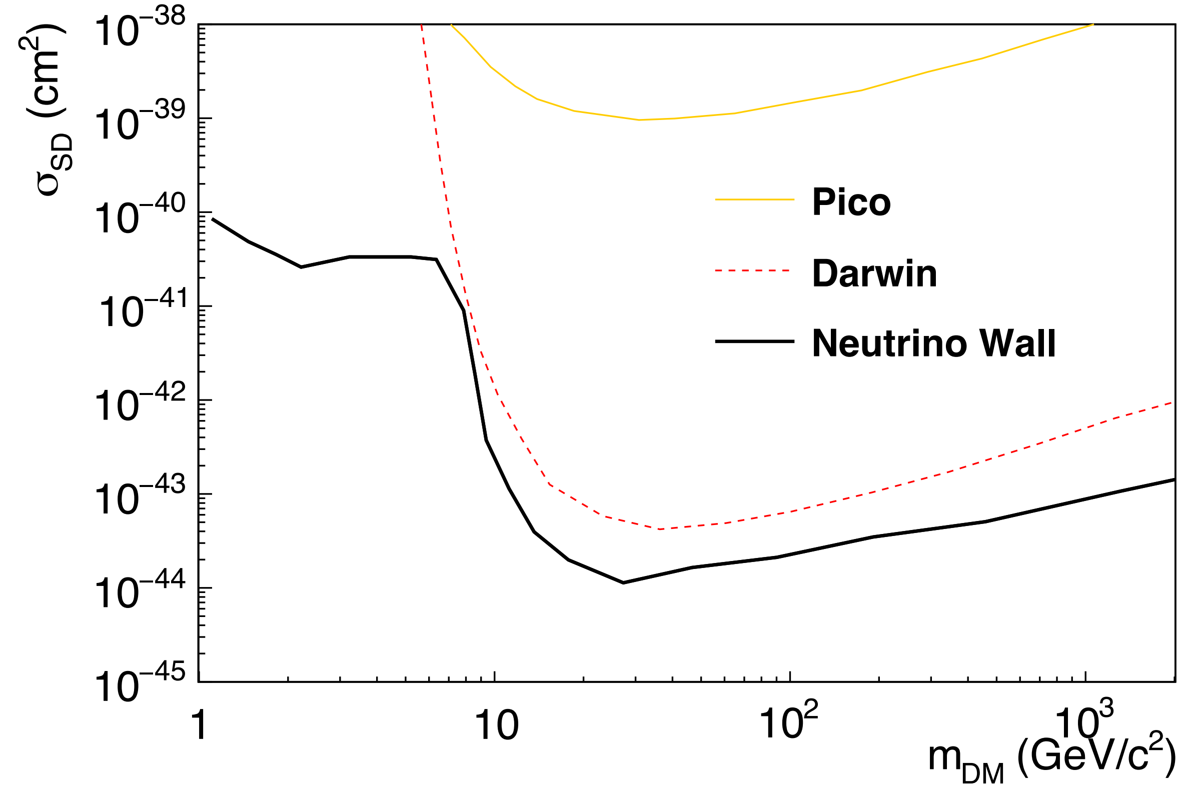
- For SI interactions and lighter DM < O(10 GeV), solid state cryogenic detectors are more constraining than Xenon experiments and their energy threshold is lower: SuperCDMS and CRESST-II collaborations.

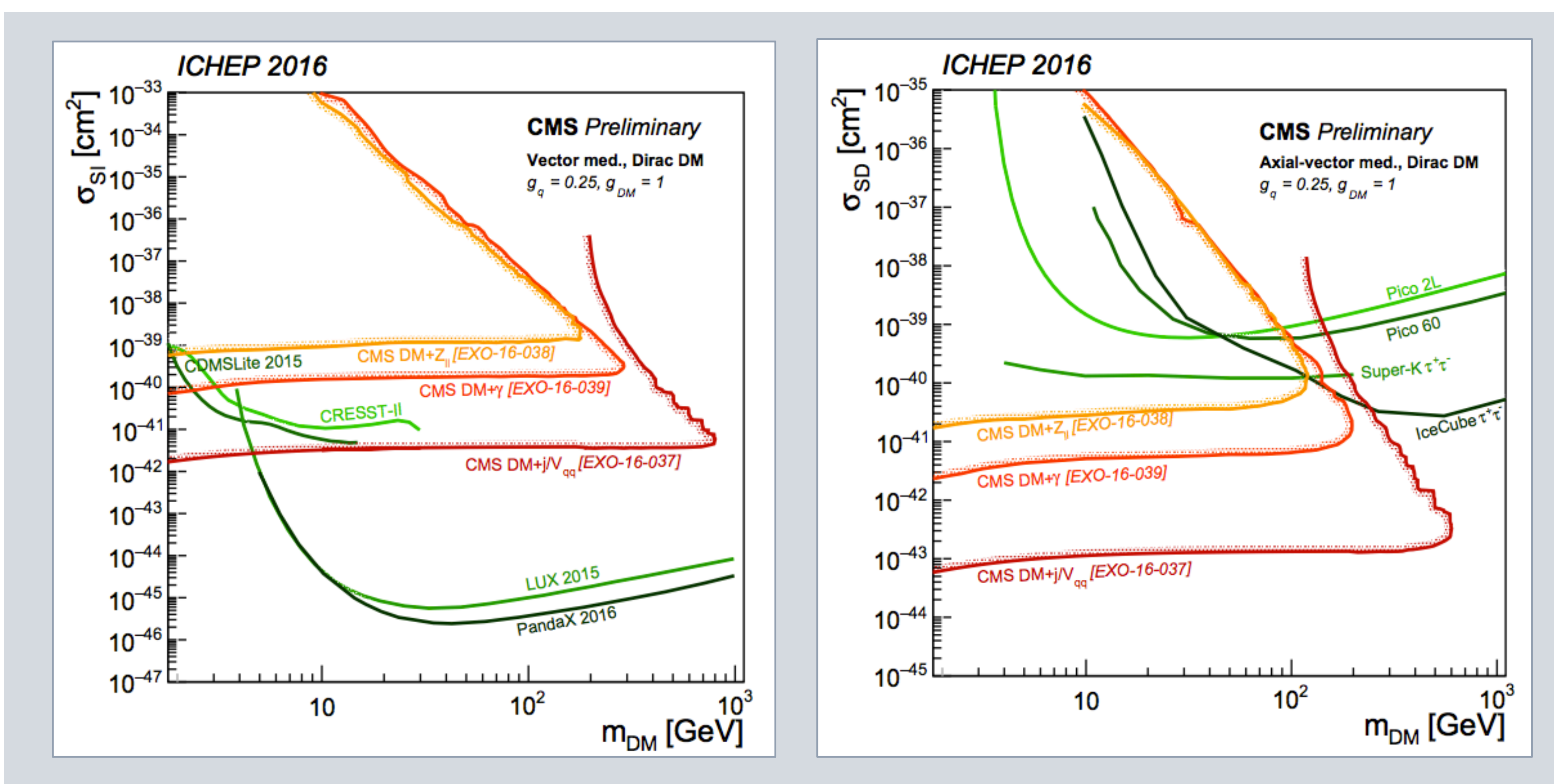
- For SD proton-DM interactions strongest limits are from PICO, and for neutron-DM are from LUX.

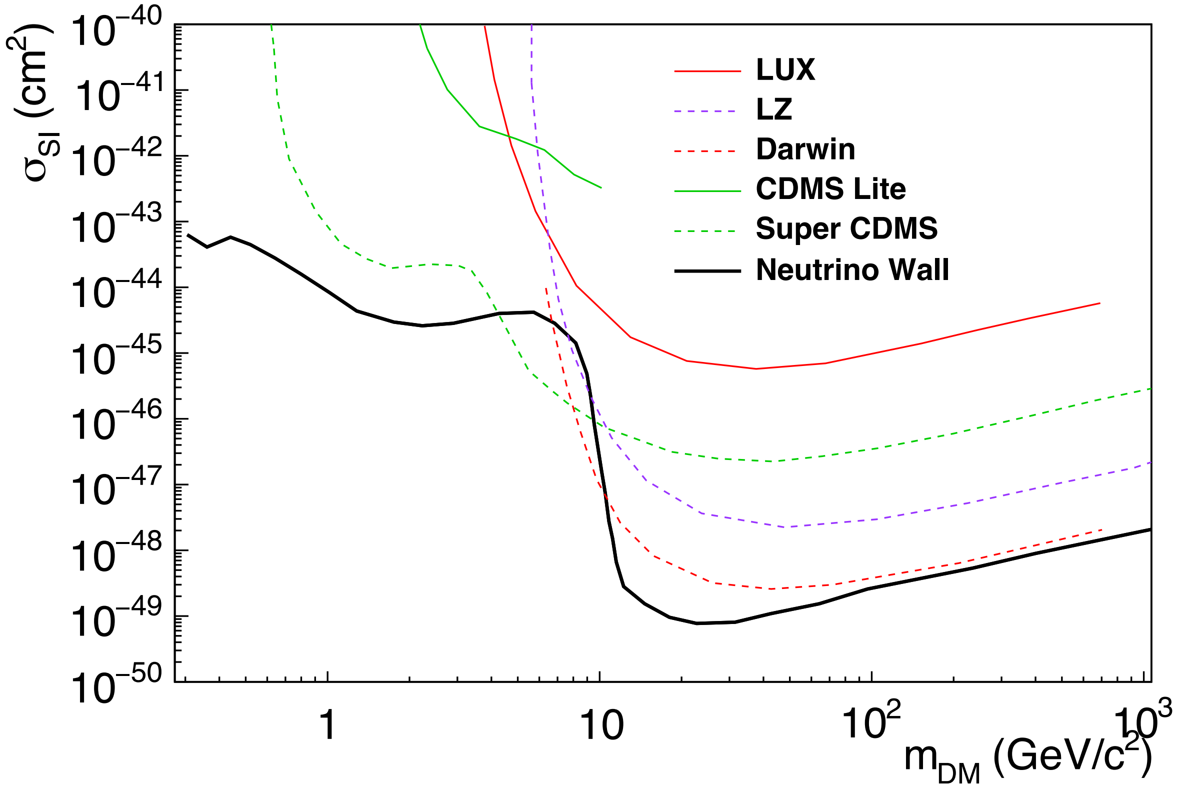
- An ultimate bound for DD comes from neutrino interactions in the detectors. This **neutrino wall** background is irreducible - cannot be distinguished from DM interactions. [But the directional DM detection can work in future - no current planned experiment.]

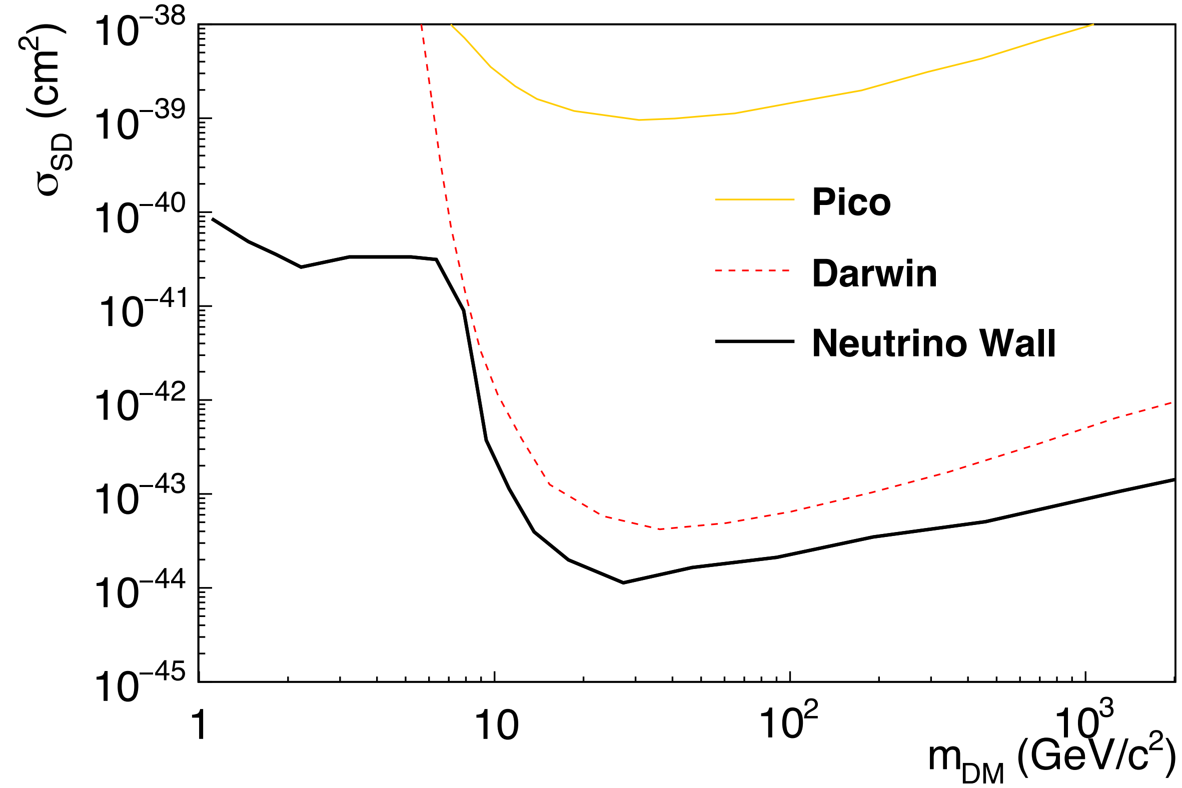
- Neutrino observatories IceCube and Super-Kamiokande are also able to constrain SD and SI crosssections. After elastic scatterings in the Sun, DM becomes gravitationally bound and self-annihilations of DM produce neutrinos directly or in showering.

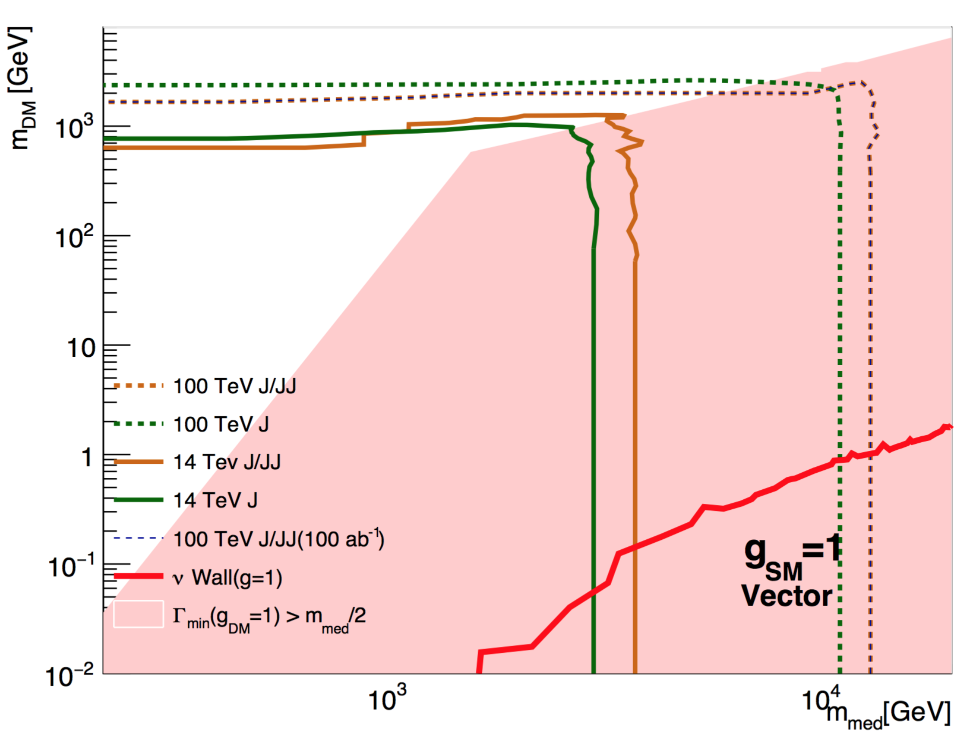

LUX
LZ
Darwin
CDMS Lite
Super CDMS
Neutrino Wall
σ_{SI} (cm^2)
m_{DM} (GeV/c^2)

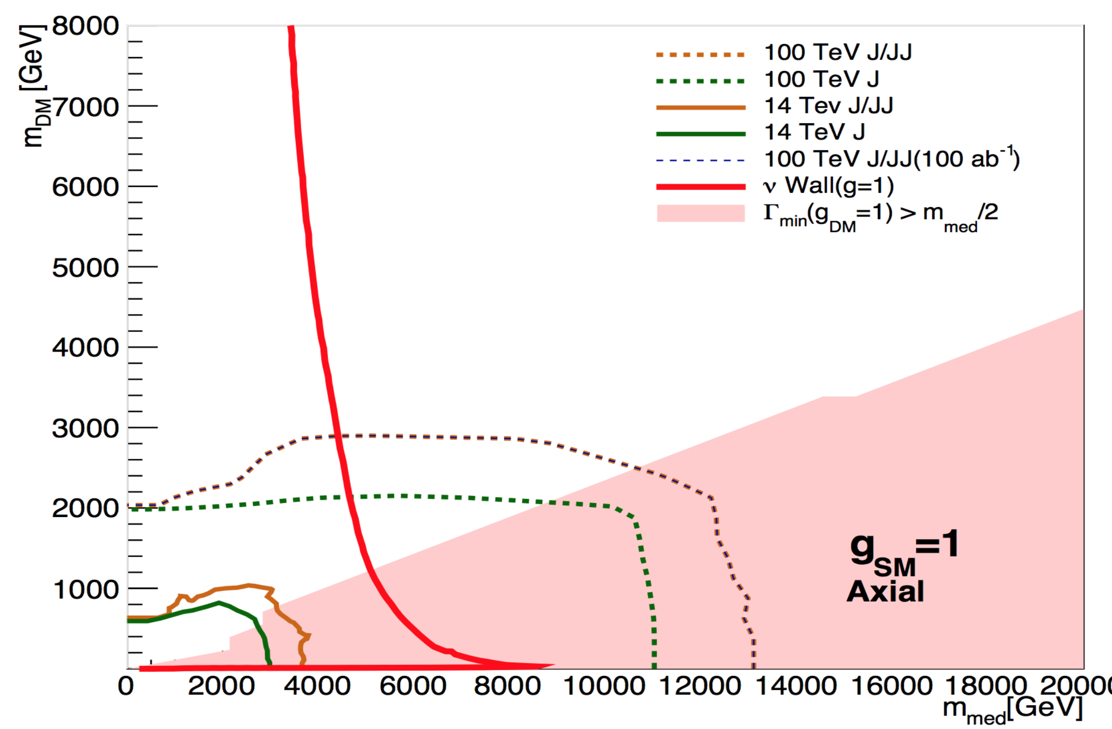

Pico
Darwin
Neutrino Wall
σ_{SD} (cm^2)
m_{DM} (GeV/c^2)


ICHEP 2016
CMS Preliminary
Vector med., Dirac DM
g_q = 0.25, g_{DM} = 1
CDMSLite 2015
CMS DM+Z_{ll} [EXO-16-038]
CMS DM+γ [EXO-16-039]
CRESST-II
CMS DM+j/V_{qq} [EXO-16-037]
LUX 2015
PandaX 2016
σ_{SI} [cm^2]
m_{DM} [GeV]
ICHEP 2016
CMS Preliminary
Axial-vector med., Dirac DM
g_q = 0.25, g_{DM} = 1
Pico 2L
Pico 60
Super-K $\tau^+\tau^-$
IceCube $\tau^+\tau^-$
CMS DM+Z_{ll} [EXO-16-038]
CMS DM+γ [EXO-16-039]
CMS DM+j/V_{qq} [EXO-16-037]
σ_{SD} [cm^2]
m_{DM} [GeV]







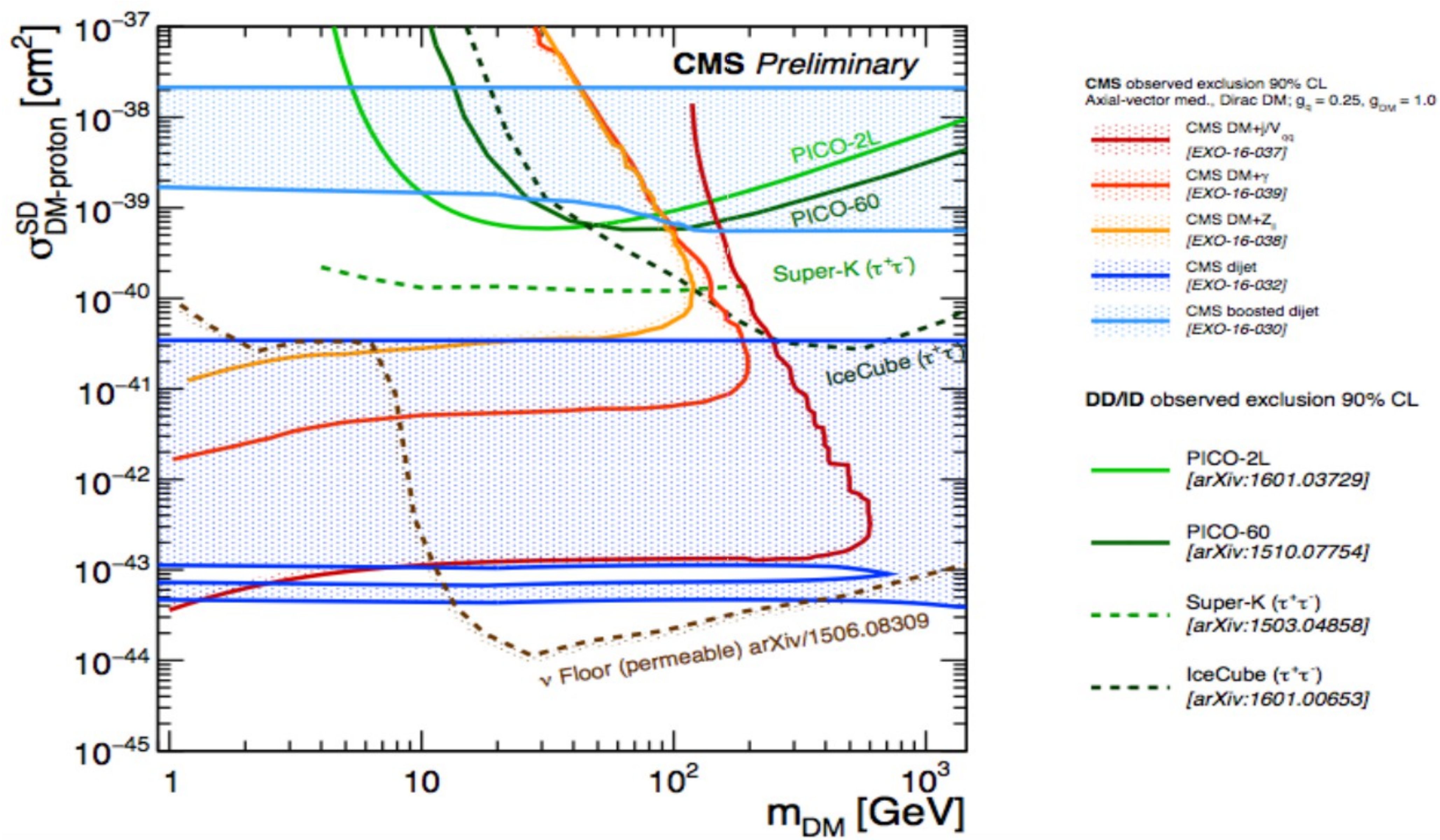


For the axial mediator we exceed the bounds of the wall
Can safely push the bounds up to 12-15 TeV in mediator

100TeV

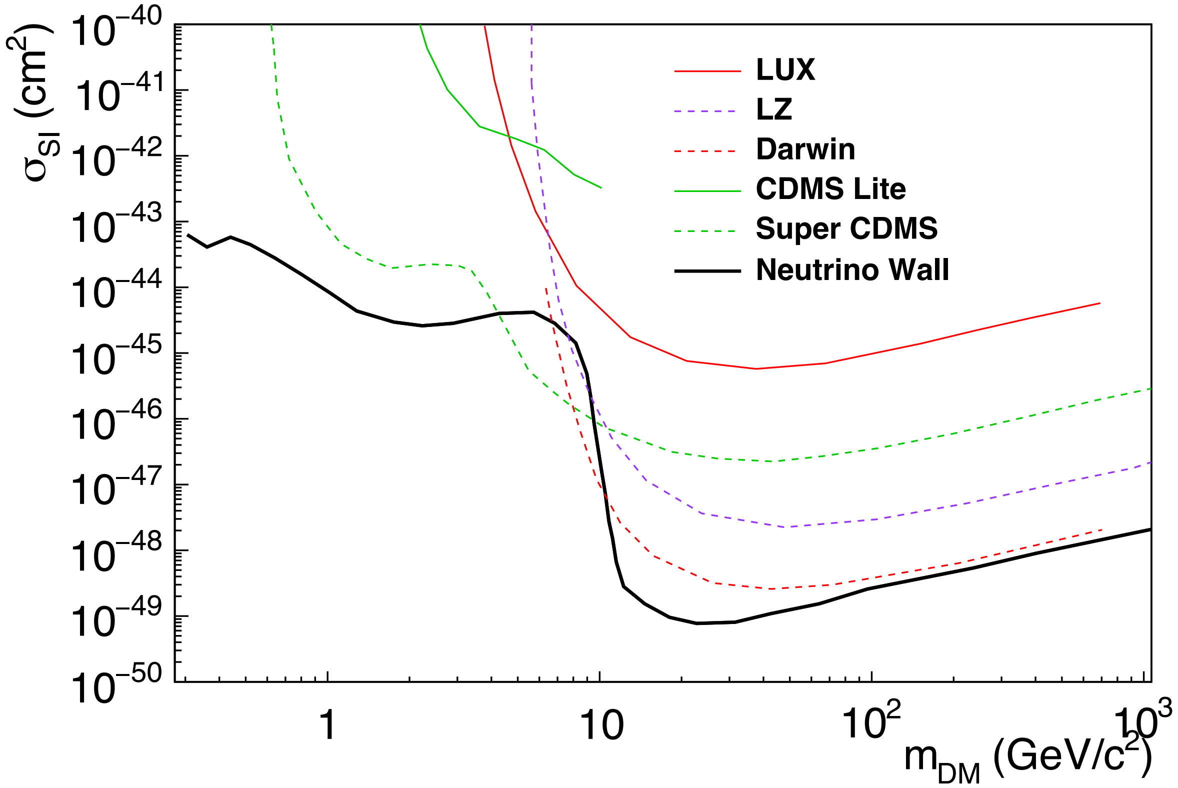
Axial-Vector Mediator:

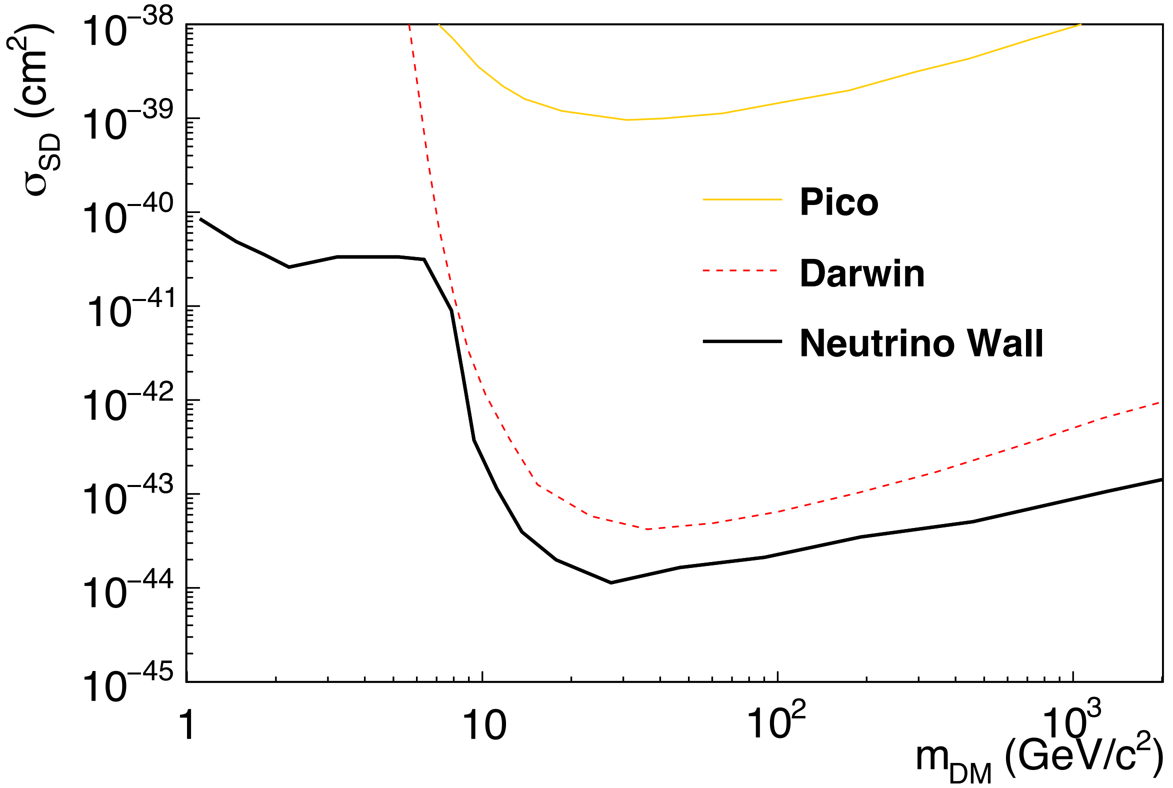
Direct Detection



CMS-DP-2016-057

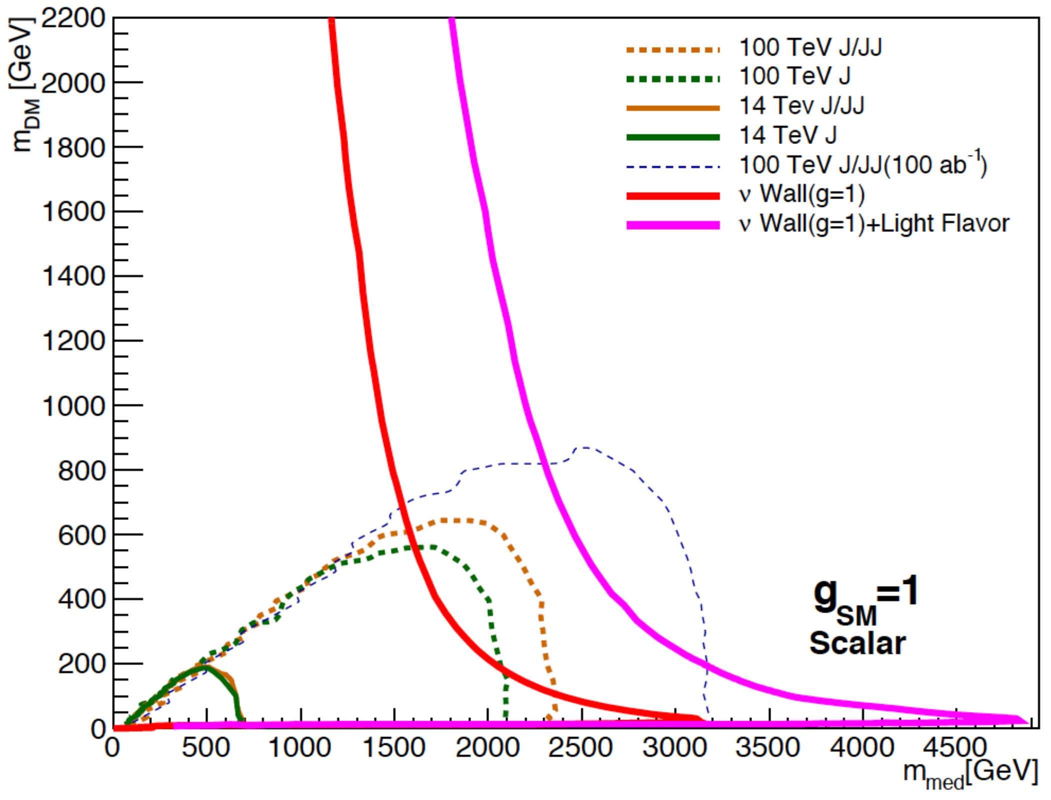
Spin-0 mediators



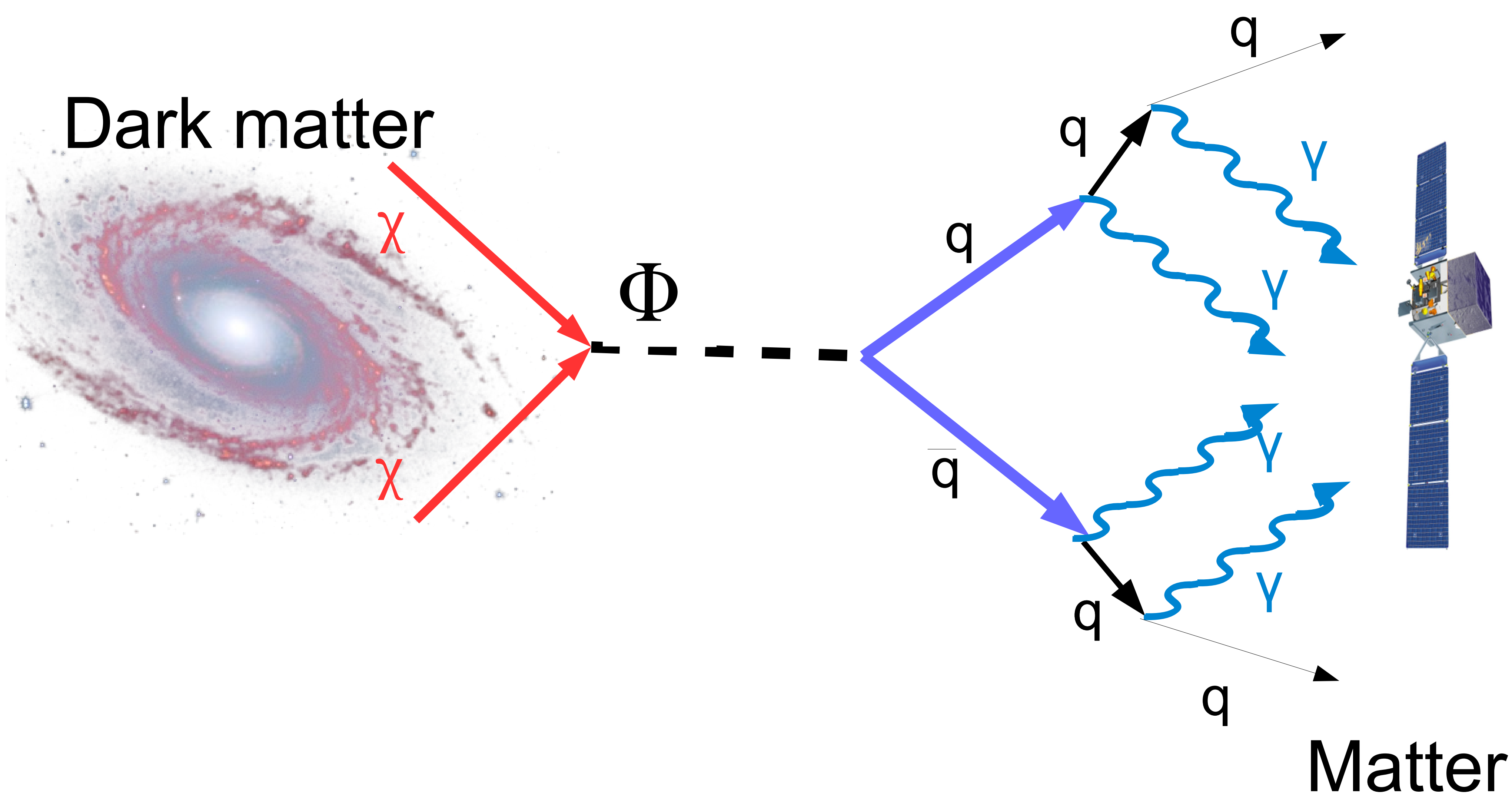


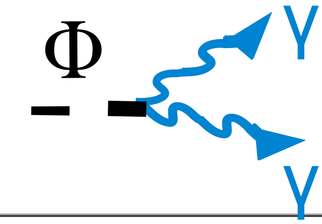
100TeV

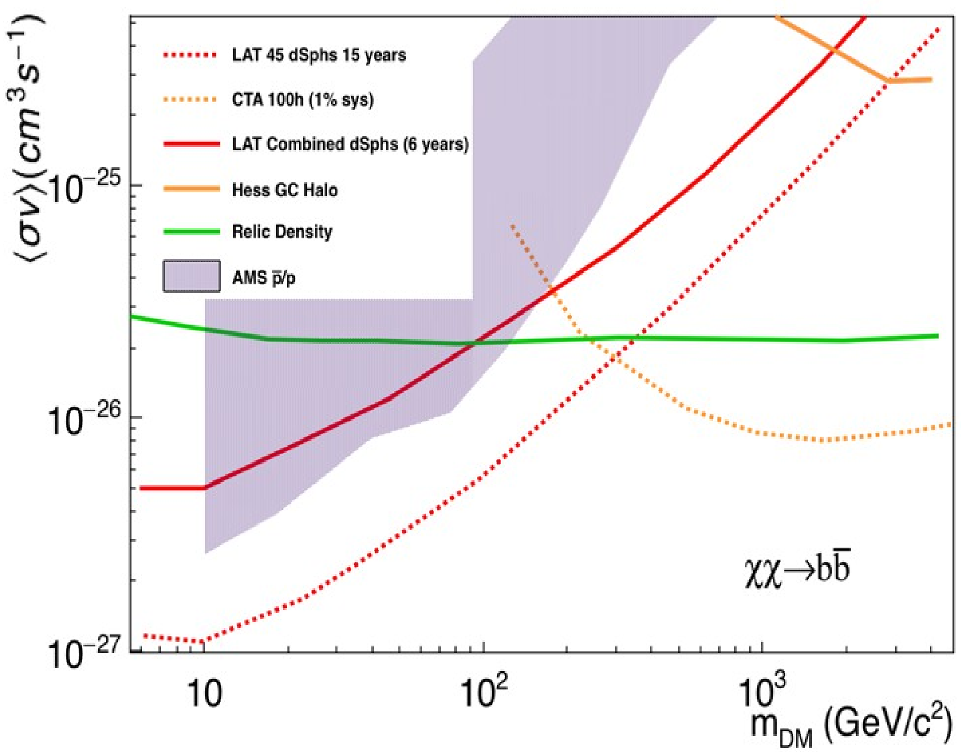
- Scalar also breaches the neutrino wall

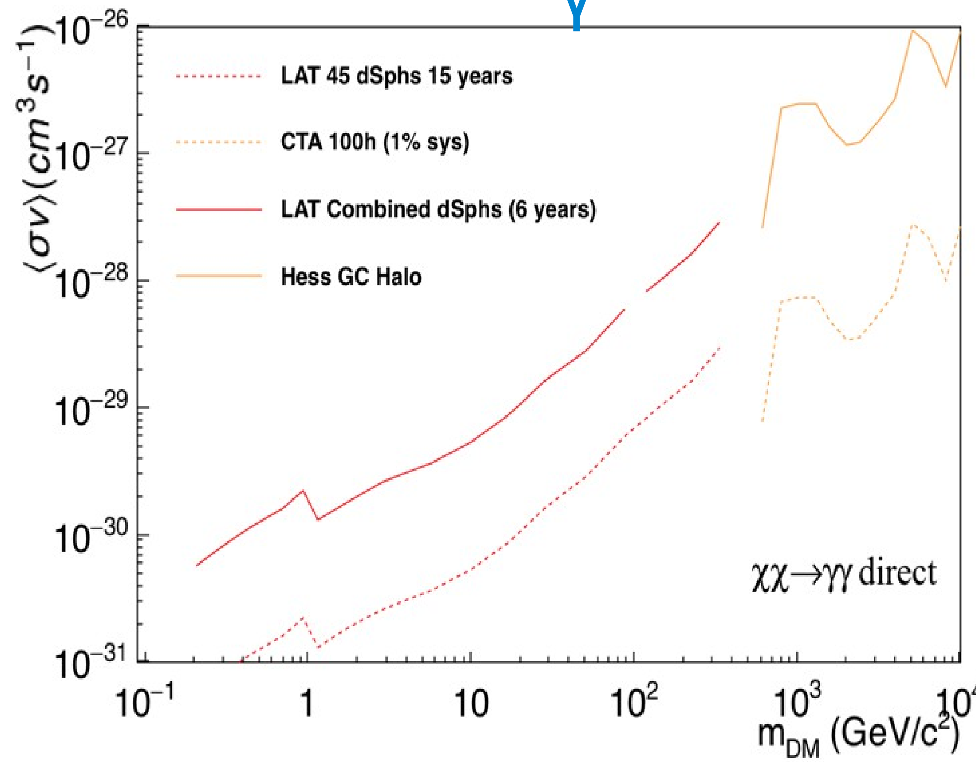


Indirect Detection

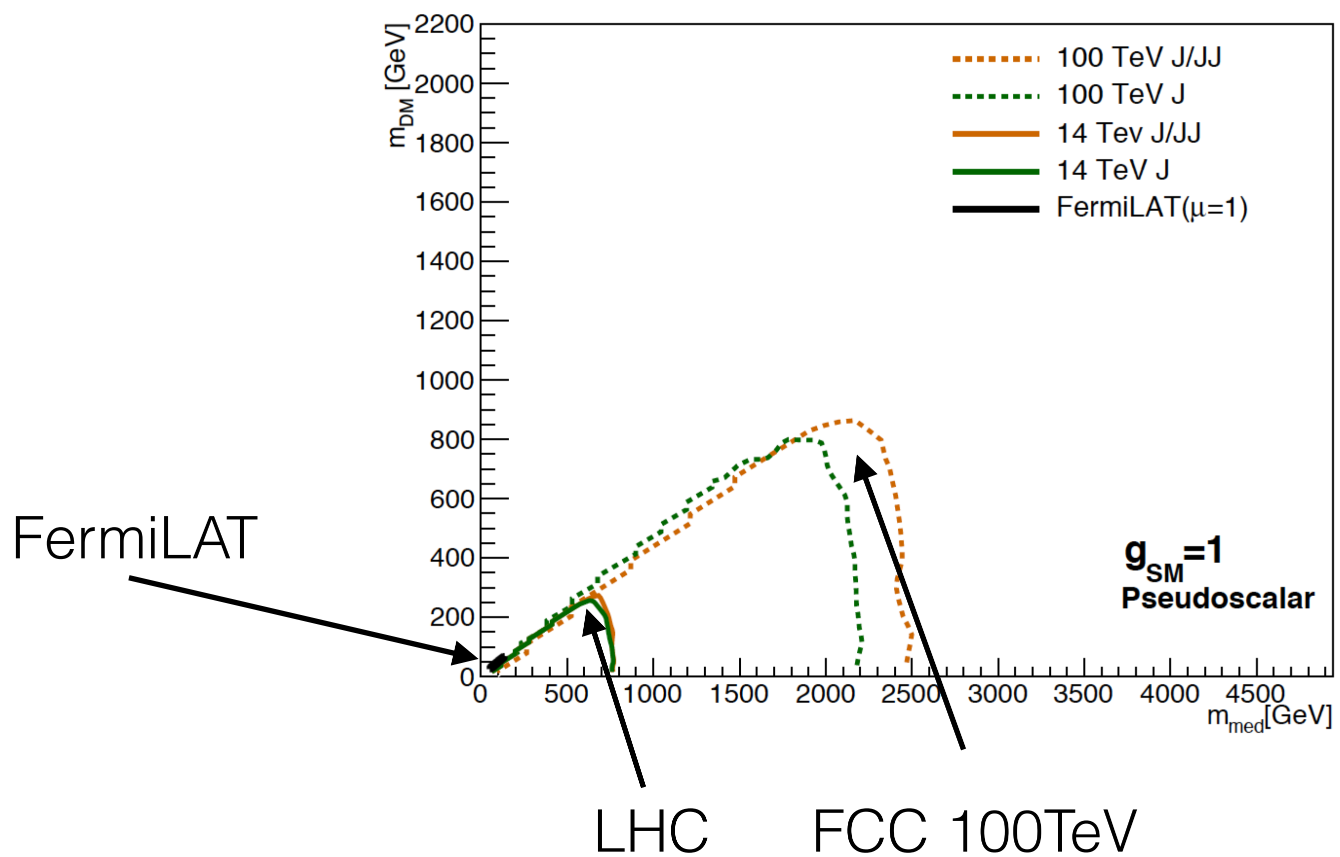






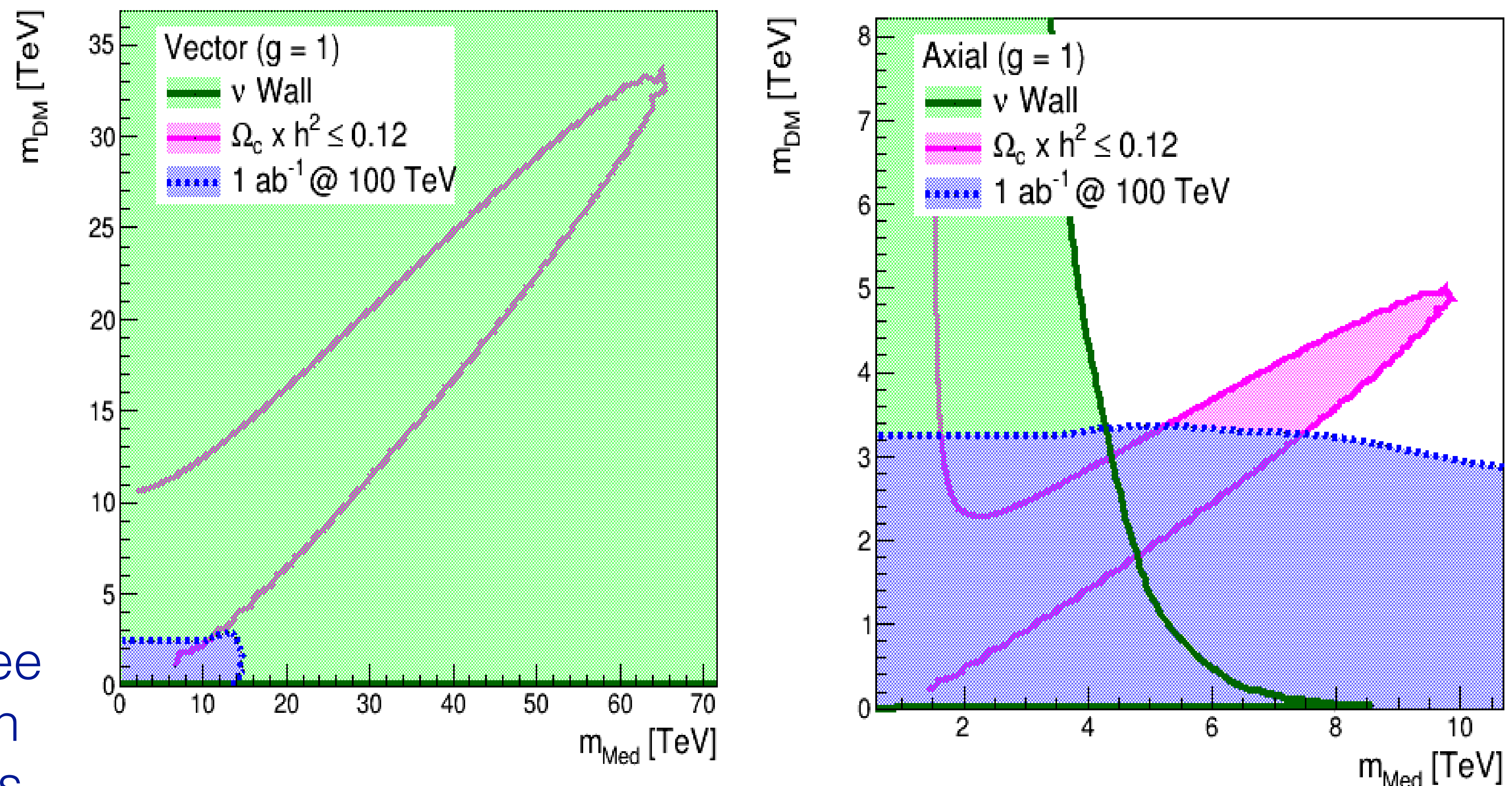


Pseudoscalar
ID vs Colliders



Combining 100TeV future collider projections with future Direct Detection (i.e. neutrino wall bound) and the relic abundance constraint

Caution: Recall the limitations of the Simplified Model treatment for the relic density and DD.

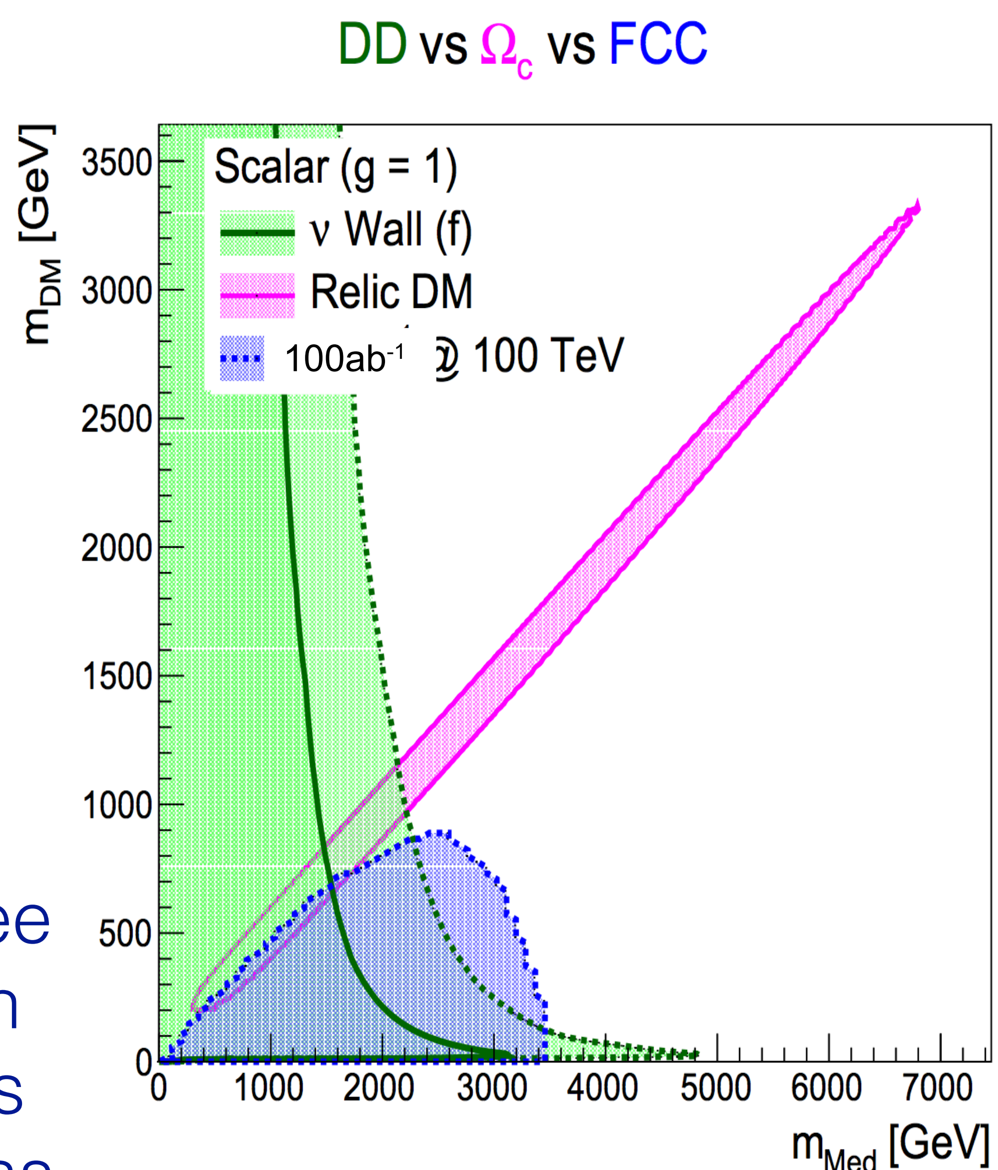


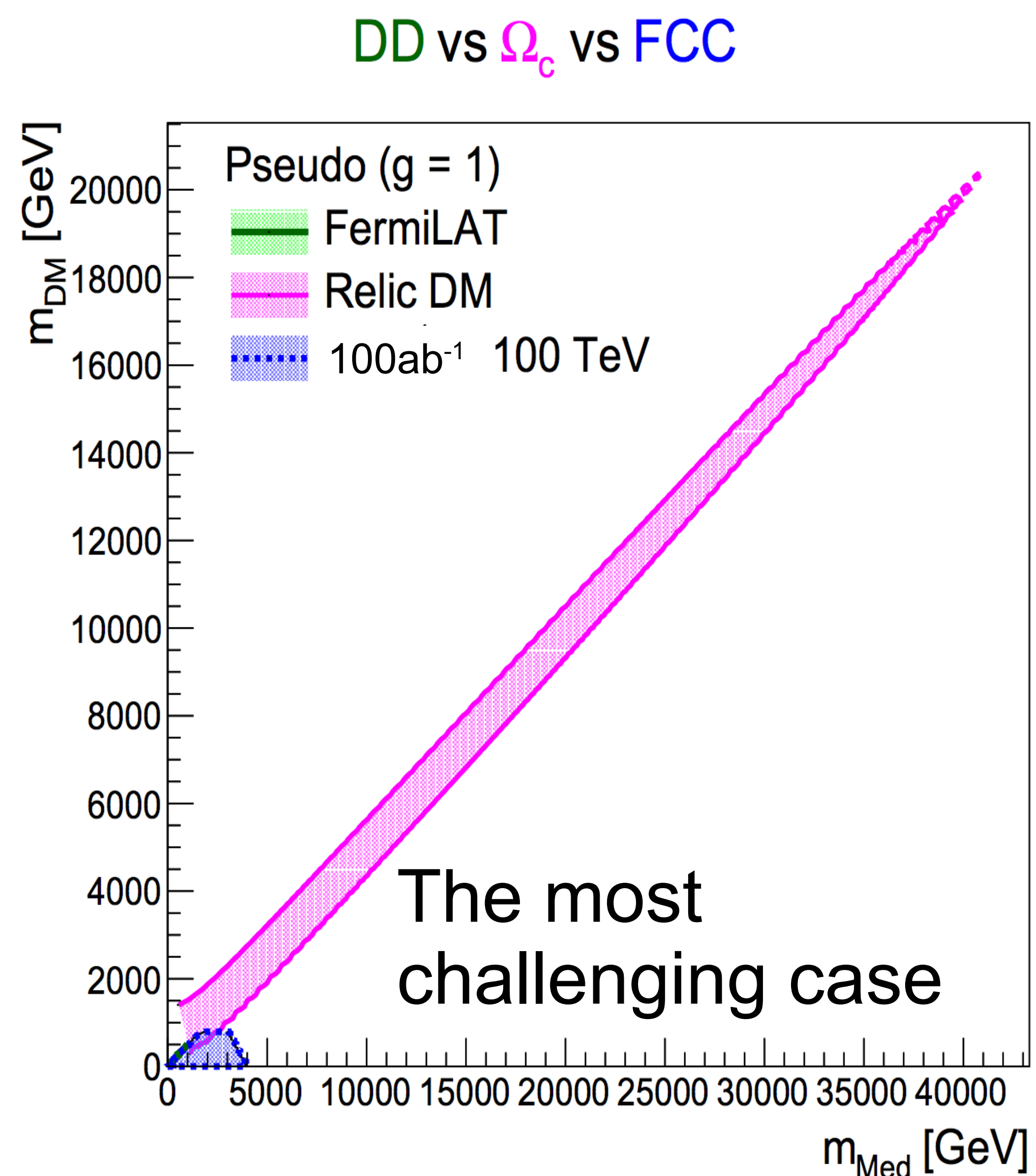
T.du Pree
K.Hahn
P.Harris
C.Roskas
1603.08525

Vector and Axial-vector mediators

Combining 100TeV future collider projections with future Direct Detection (i.e. neutrino wall bound) and the relic abundance constraint

Caution: Recall the limitations of the Simplified Model treatment for the relic density and DD.





T.du Pree
K.Hahn
P.Harris
C.Roskas
1603.08525

Scalar and Pseudo-scalar mediators

Summary

- we have very simple and less simple models of DM [theory input]
- huge effort and prospects on the experimental side
- present and future colliders 13-100TeV, Direct and Indirect Detection, cosmological bounds
- [DM simplified models — use caution when comparing collider and non-collider searches]

Appendix:

Scalar singlet mediator Model with Mixing SMM

Towards the next generation of simplified Dark Matter models

Martin Bauer,[1] Oliver Buchmueller,[2] Jim Brooke,[3] David G. Cerdeño,[4] Matthew Citron,[2] Gavin Davies,[2] Annapaola de Cosa,[5] Albert De Roeck,[6,7] Andrea De Simone,[8] Tristan Du Pree,[6] John Ellis,[9,10] Henning Flaecher,[3] Malcolm Fairbairn,[9] Alexander Grohsjean,[11] Kristian Hahn,[12] Ulrich Haisch,[9,13] Philip C. Harris,[6] Valentin V. Khoze,[4] Greg Landsberg,[14] Christopher McCabe,[15] Bjoern Penning,[2] Veronica Sanz,[16] Christian Schwanenberger,[11] Pat Scott,[17] and Nicholas Wardle[6]

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arXiv:1607.06680v2 [hep-ex] 22 Aug 2016

Scalar mediator with mixing SMM vs simple scalar (DMForum) model

The SMM

Starting point: the simplified model in VVK-Ro-Spannowsy1505.03019

Simplest extension of the SM that includes DM

- Fermion DM
- Scalar mediatior portal

$$\mathcal{L} \supset -y_{\rm DM}\, s\, \bar{\chi}\chi - \mu\, s\, |H|^2$$

Usual mediator-DM coupling, as in DMF models

New portal interaction

Portal interaction induceds scalar/Higgs boson mixing

- Mass eignestates: h1 & h2
- Take h1 to be observed 125 GeV state

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

h1,h2 couplings to DM & SM fermions,W,Z through mixing

$$\mathcal{L} \supset -\, y_{\rm DM} \left(\sin\theta\; h_1 + \cos\theta\; h_2\right) \bar{\chi}\chi$$

$$+ \left(\cos\theta\; h_1 - \sin\theta\; h_2\right) \left(\frac{2M_W^2}{v}\, W_\mu^+ W^{-\,\mu} + \frac{M_Z^2}{v}\, Z_\mu Z^\mu - \sum_f \frac{m_f}{v}\, \bar{f} f \right)$$

SMM *vs* DMF scalar models

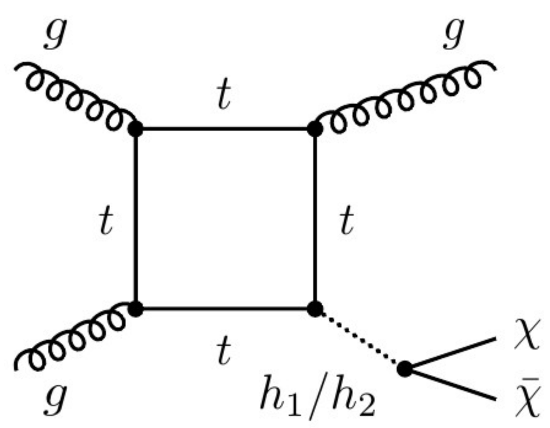
Modified coupling structure
with respect to DMF

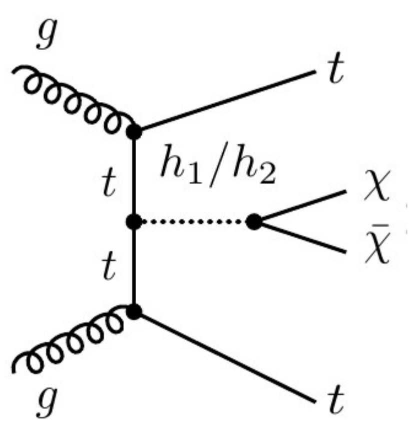
NB: Run-I Higgs global fit → sinθ < ~0.4

$$g_{\mathrm{DM}} \longrightarrow y_{\mathrm{DM}} \cos\theta$$

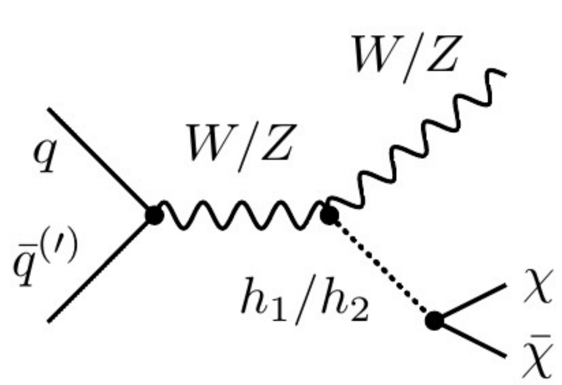
$$g_{\mathrm{SM}} \longrightarrow -\sin\theta$$

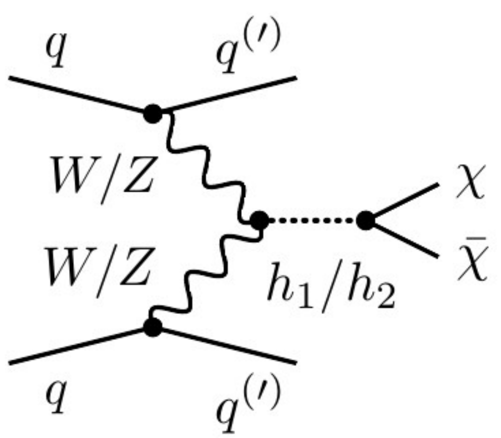
Usual monojet and HF+DM
processes, as in DMF





New VBF & mono-V
diagrams





Scenario A : $m_{h_2} > 2m_\chi > m_{h_1}$

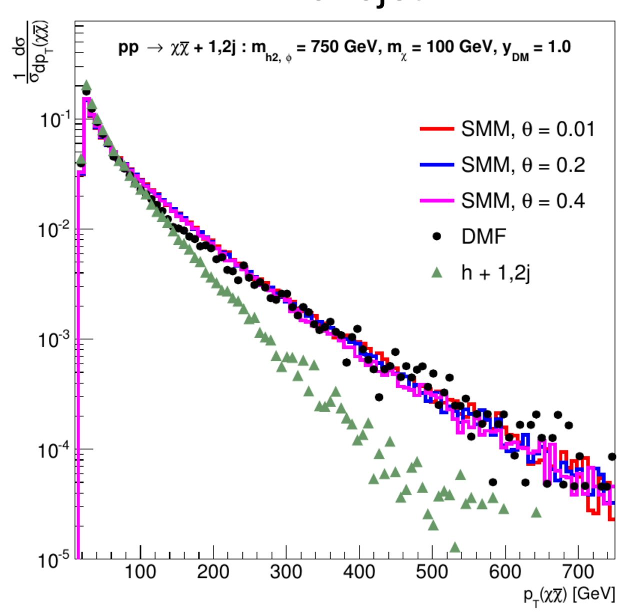
Kinematics

- New h2 scalar mediator can decay into DM
- SSM kinematics generally map to those of DMF
  - Disagreement in monojet near pT(χχ) ~ 150 GeV from new diagrams

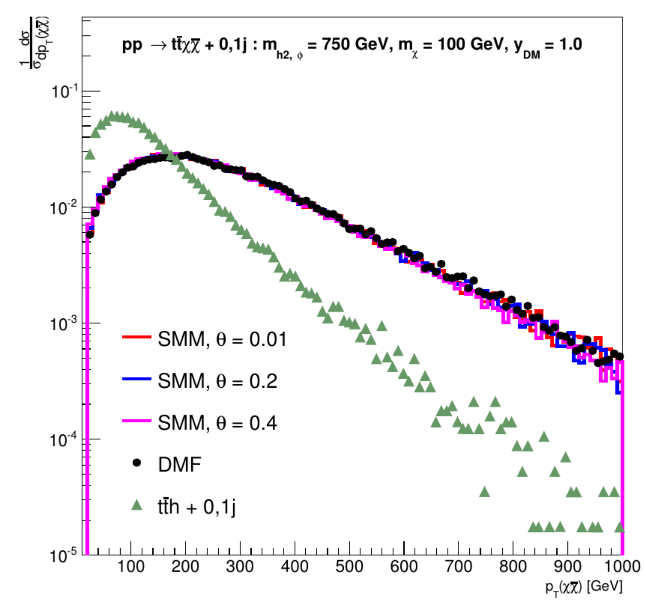
Cross section

- Suppressed relative to DMF and SM

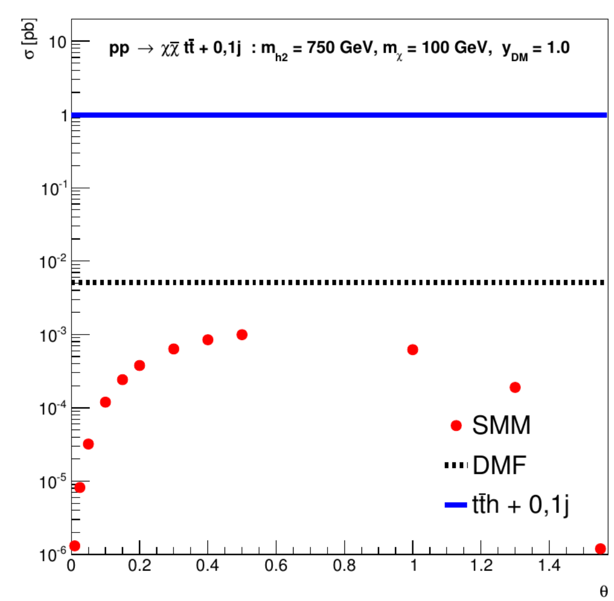
monojet



tt+DM



tt+DM



Scenario B : $m_{h_1} > 2m_\chi > m_{h_2}$

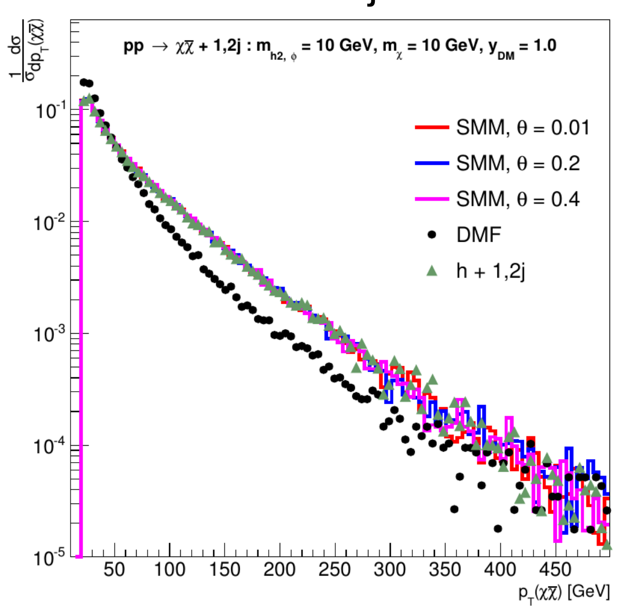
Kinematics

- h1 can decay into DM, new h2 mediator can't
- SSM kinematics map directly to those of SM Higgs

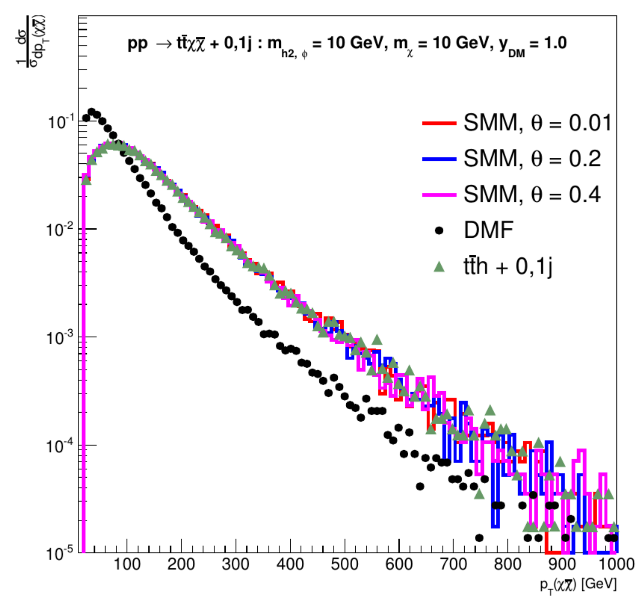
Cross section

- Approaches SM, higher than in DMF
  - Only off-shell decays in the DMF scenario ...

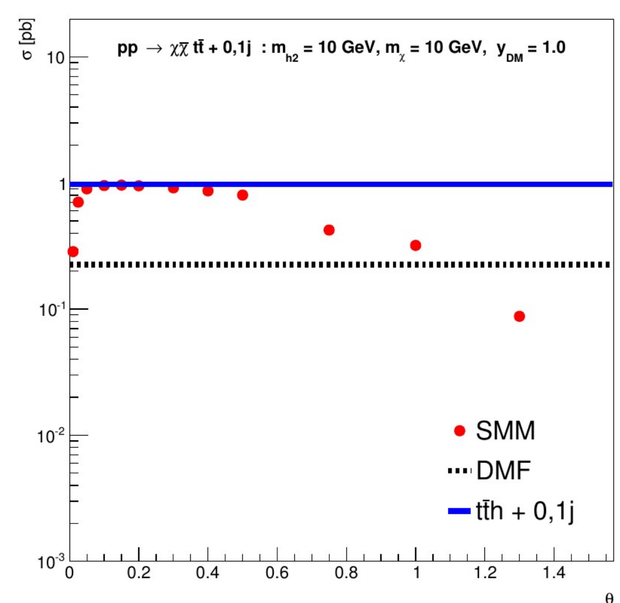
monojet



tt+DM



tt+DM

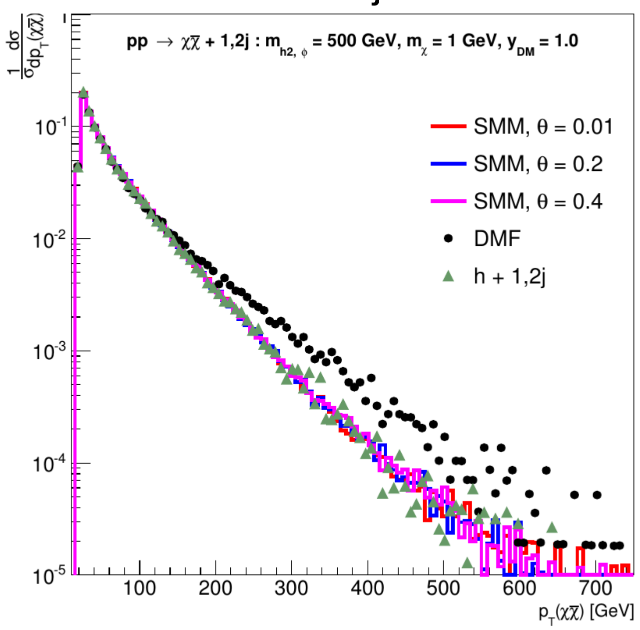


Scenario C : $m_{h_2} > m_{h_1} > 2m_\chi$

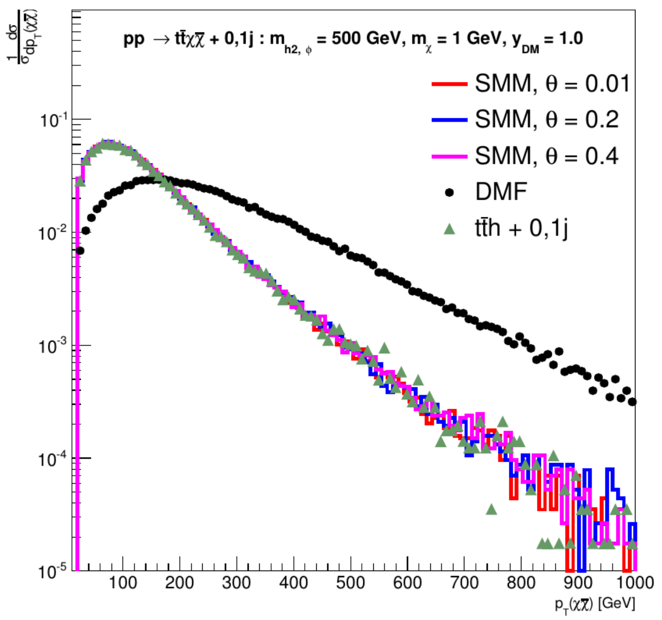
Kinematics

- h1 → DM resonantly enhanced due to small h1 width
- SSM kinematics map to those of SM Higgs

monojet



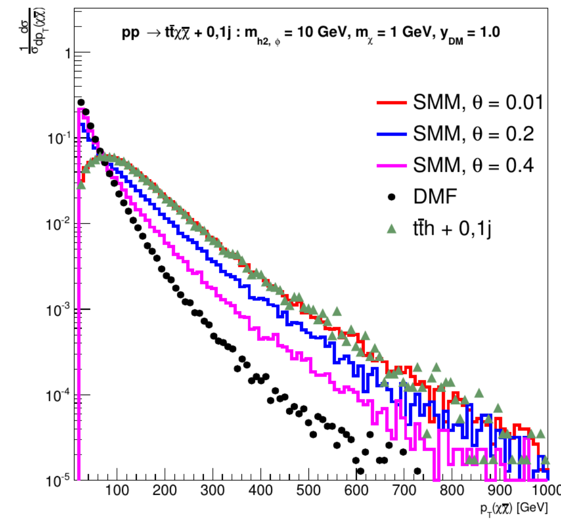
tt+DM

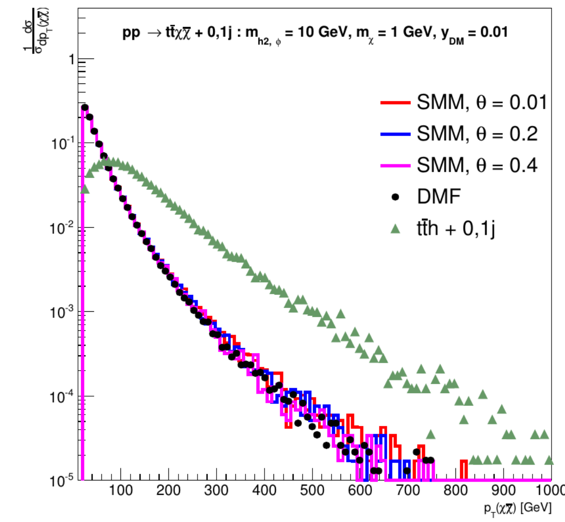


Scenario D : $m_{h_1} > m_{h_2} > 2m_\chi$

Kinematics

- Impact of mixing clear for nominal (yDM = 1.0) couplings
- Both h1 → DM and h2 → DM on-shell
- Both processes important if Γh1 and Γh2 comparable
- Kinematics evolve toward DMF as coupling is lowered

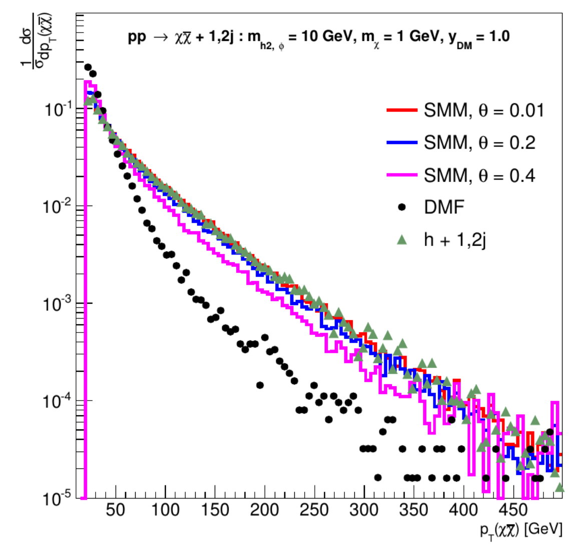


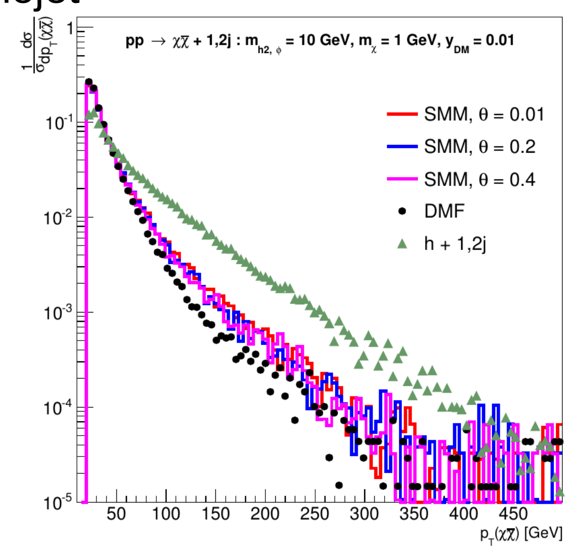


tt+DM

yDM = 1.0 yDM = 0.01

monojet

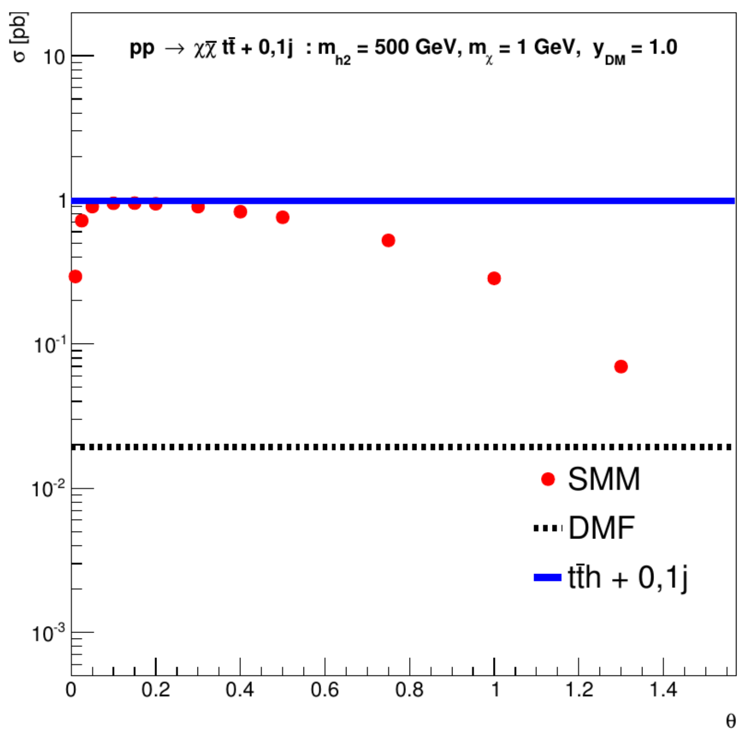




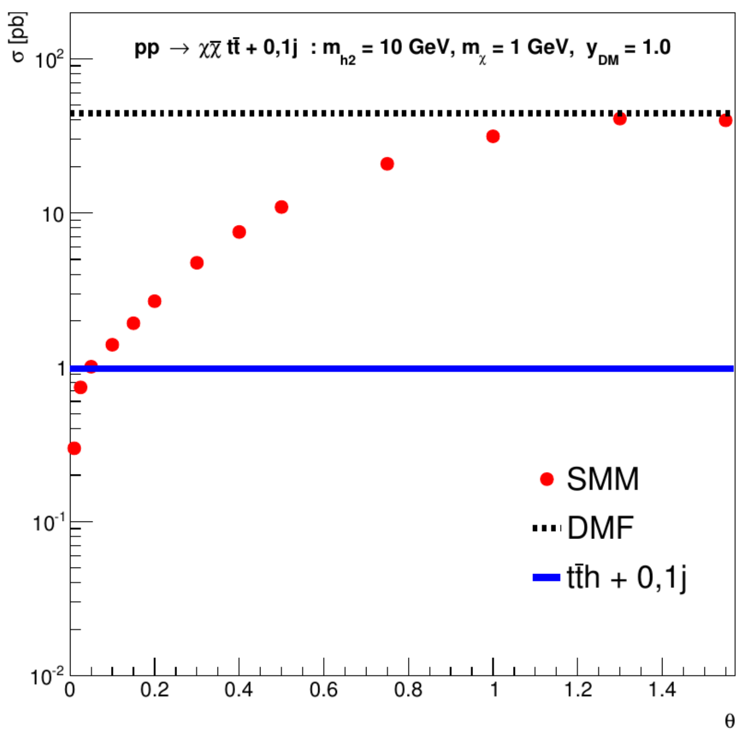
Scenario C/D Cross Sections

Approaches SM Higgs for Scenario C, > σDMF

Generally between σSM and σDMF for Scenario D



Scenario C



Scenario D

Higgs mixing is the simplest extension to the current DMF scalar models & one can play with 4 regions

In several regimes, kinematics & cross section differ significantly from those of the DMF models