



¹University of California San Diego (UCSD)

Search for Dark Matter Mediators

Speaker : Raffaele Gerosa¹

On behalf of CMS and ATLAS Collaborations

Rencontres de Moriond EW, 23th March 2017 (La Thuile)

Introduction

- **Cosmological observations** support that **85%** of the matter component of the universe is **dark matter (DM)**

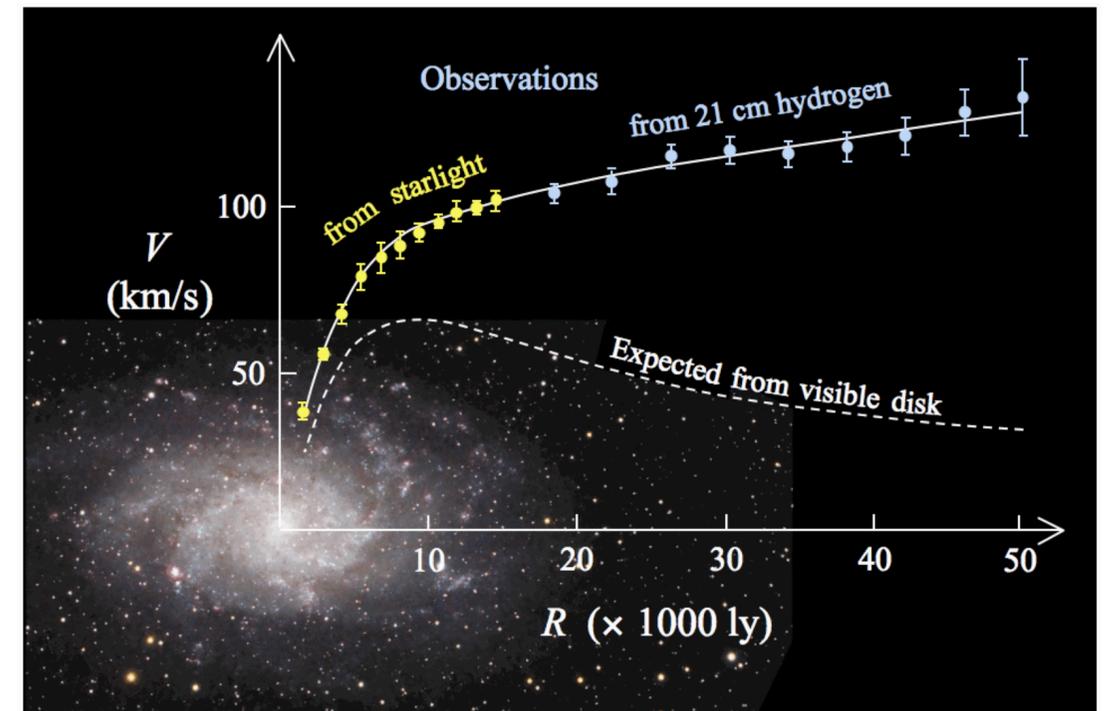
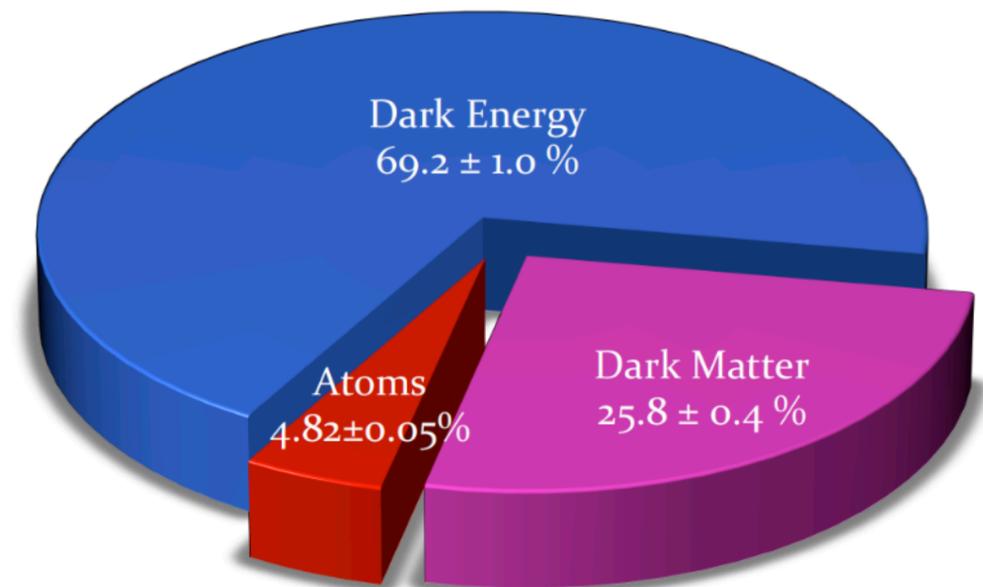
Key Properties

Non baryonic, long-lived, massive i.e gravitationally interacting, dark (no color and no electric charge)

- The hunt of **Dark Matter particles** is an **interdisciplinary effort**
 - From **cosmology** to **particle physics**
 - **Potentially accessible** by a number of **different experiments**
 - **Potentially accessible** by **precision measurements** of the **SM**

Composition Of The Universe

arXiv: 1502.01589

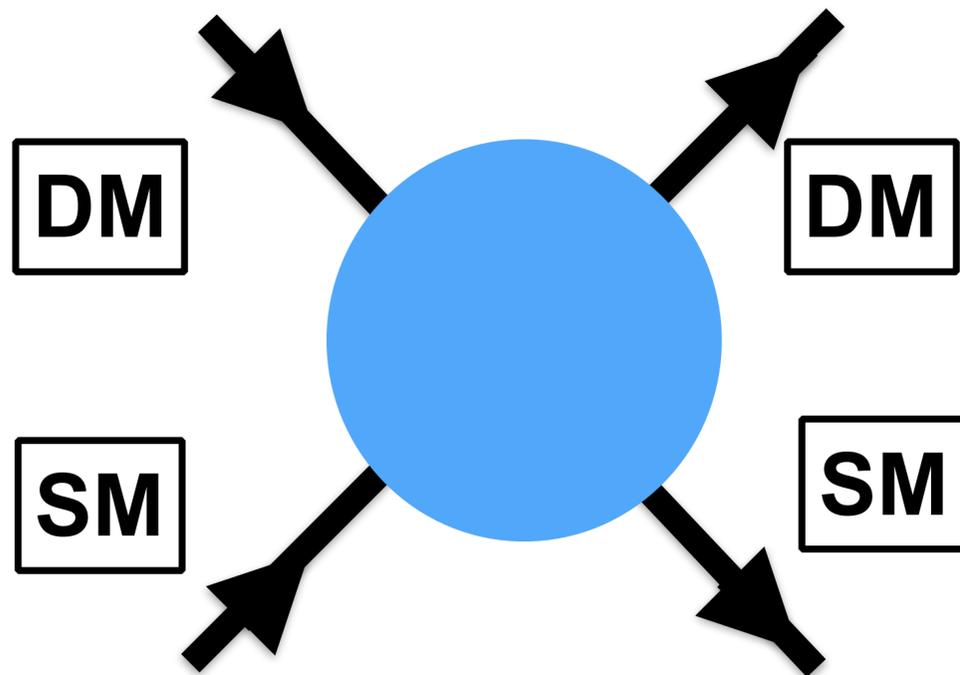


Dark Matter detection

Detection of DM implies its interaction with known matter

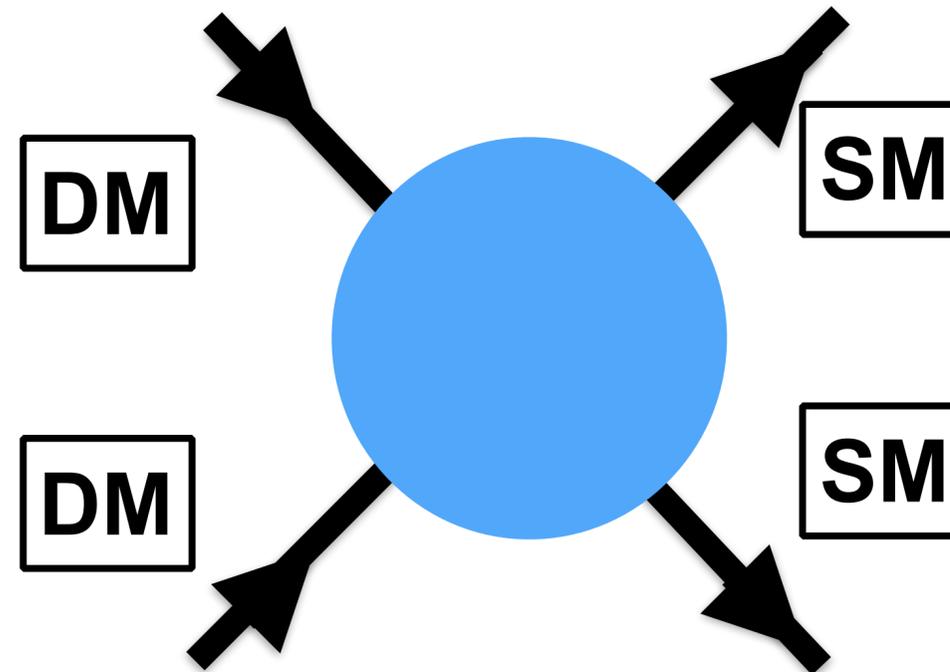
Direct Detection

DM-nucleon scattering



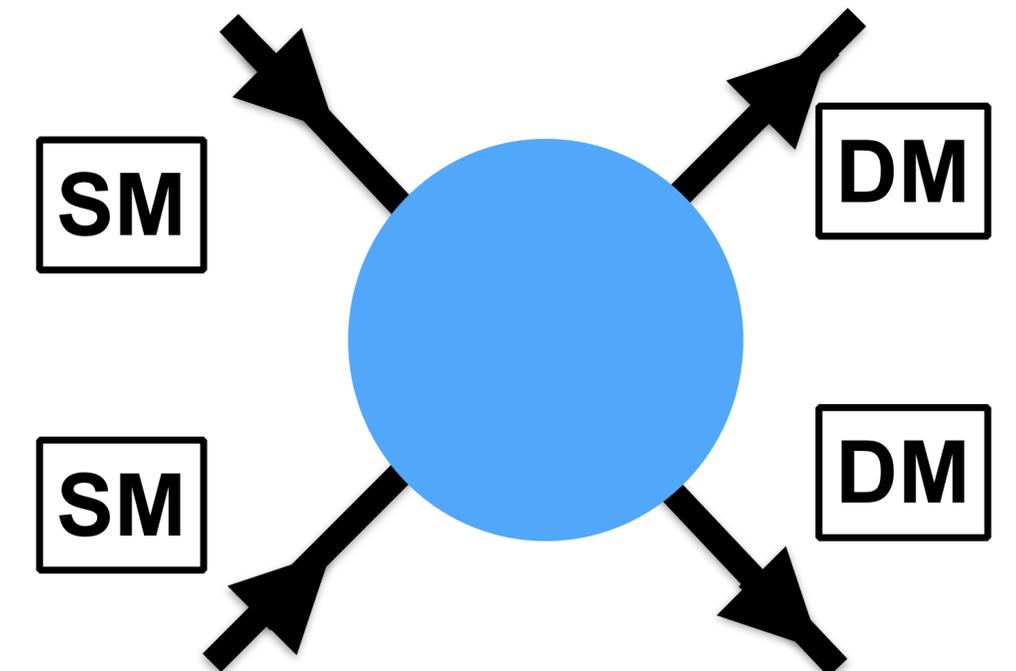
Indirect Detection

DM annihilation



Collider experiments

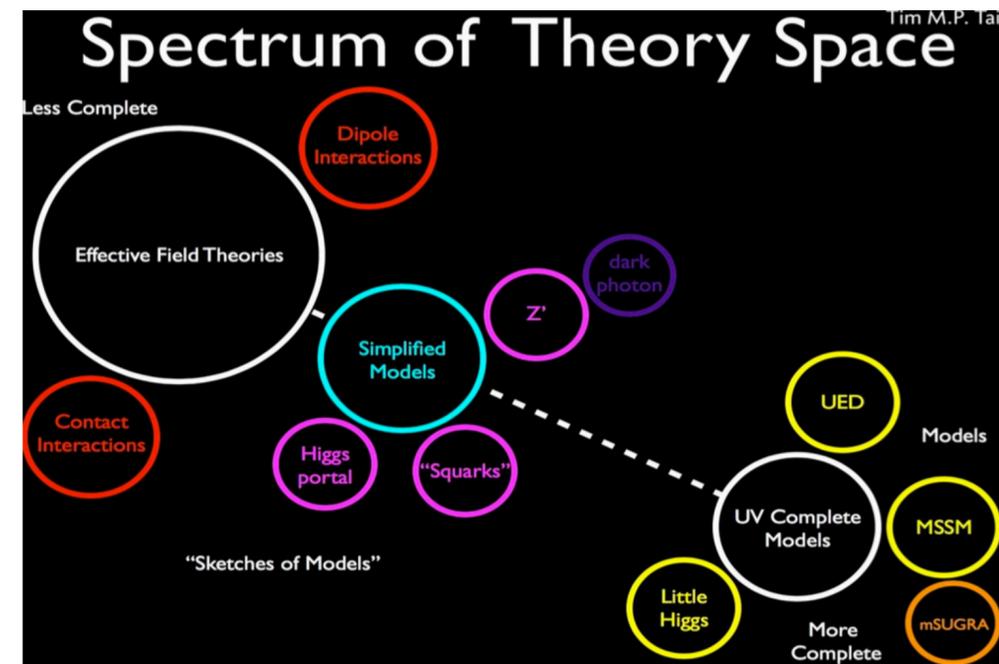
Production of DM



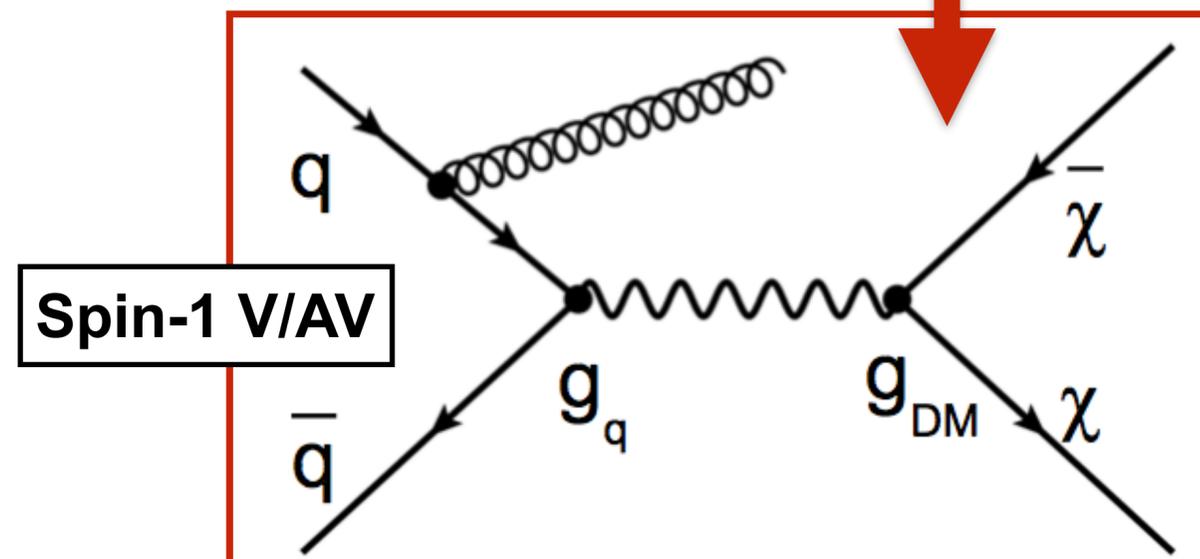
Simplified DM models for collider searches

- Several BSM models provides DM candidates: SUSY, ADD, little Higgs
- **Alternative approach:** use simple models to catch the underlying physics

s-channel simplified DM models → **DMWG @ LHC** [arXiv:1507.00966](https://arxiv.org/abs/1507.00966)



- **DM candidate** assumed to be a **Dirac fermion** with mass (m_{DM})
- Include a **mediator** (m_{MED}) coupled to **SM quarks** and **DM**
- **Coupling** between mediator and SM (DM) particles are free parameters g_{SM} (g_{DM})
- **4 basic currents:** Vector or Axial-Vector, Scalar or Pseudo-scalar



Mono-X searches

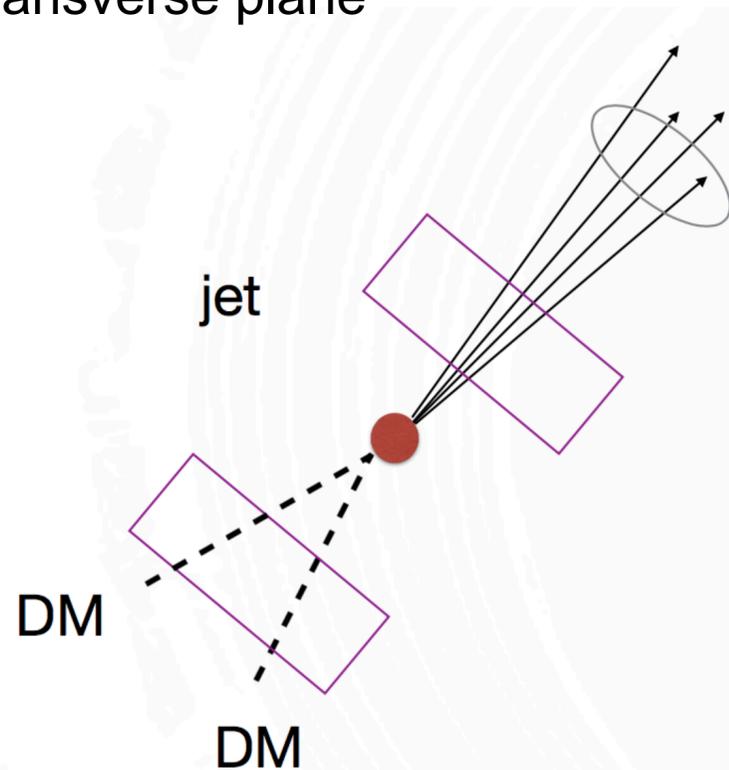
- Experimentally, to detect DM, it needs to recoil against some other objects
- High p_T object balancing large E_T^{miss}
- $X = \text{quark/gluon, photon, W/Z ..}$

Direct DM searches at colliders

- The **mono-X** search which provides the **strongest limits on spin-1 mediators** is the **mono-jet analysis**

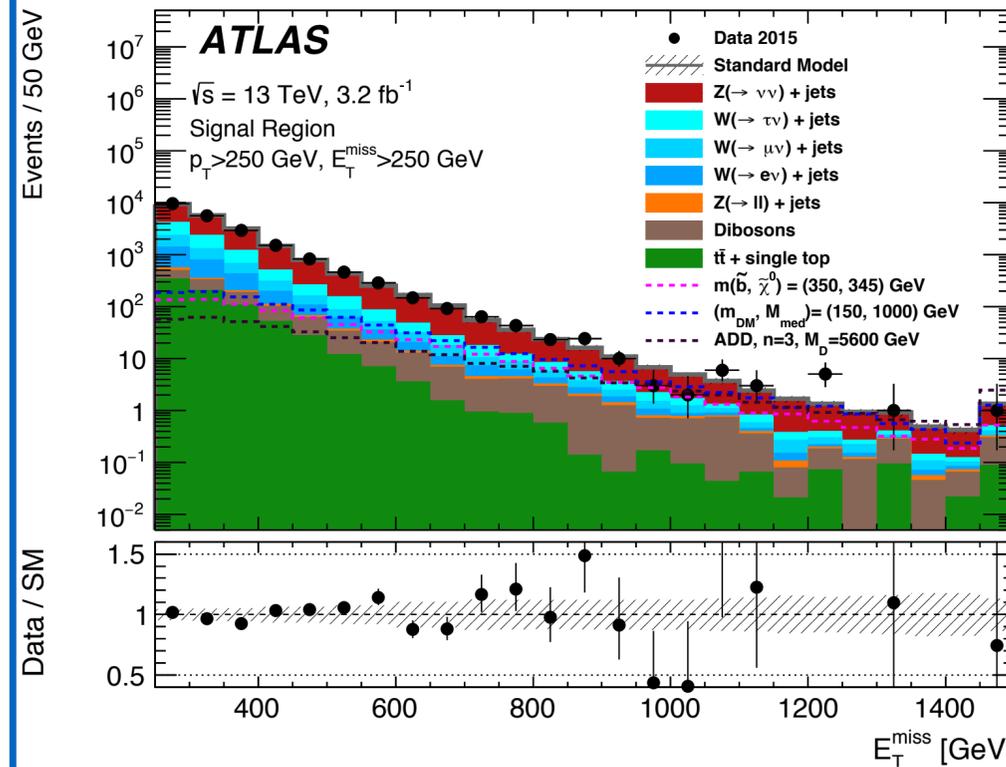
Signature

- Search for **DM mediator** produced in association with a **high p_T jet**
- Select events with $E_T^{\text{miss}} > 200$ GeV
- Jets and E_T^{miss} balanced in the transverse plane



Background estimation

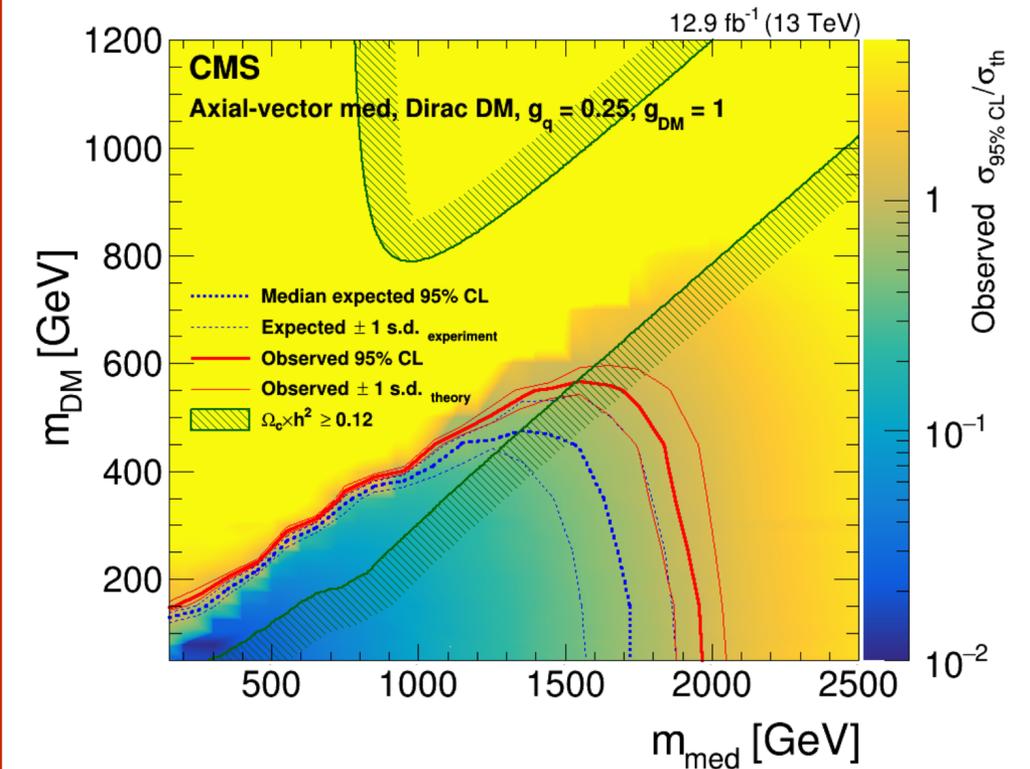
- Major challenge consists in estimate backgrounds
- Main backgrounds are $Z\nu\nu$ and W +jets
- Modelled from control regions in data



PRD 94 (2016) 032005

Interpretation

- 95% C.L. exclusion limit on the signal strength $\mu = \sigma/\sigma_{\text{th}}$
- Exclusion sensitivity** vs m_{MED} and m_{DM} for fixed coupling values ($g_{\text{SM}} = g_q = 0.25, g_{\text{DM}} = 1$)



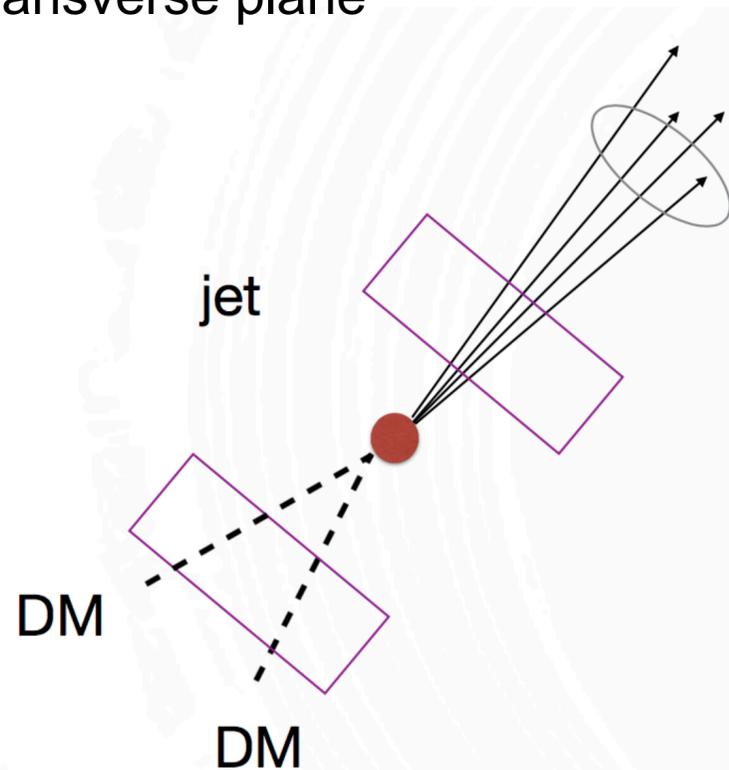
arXiv:1703.01651

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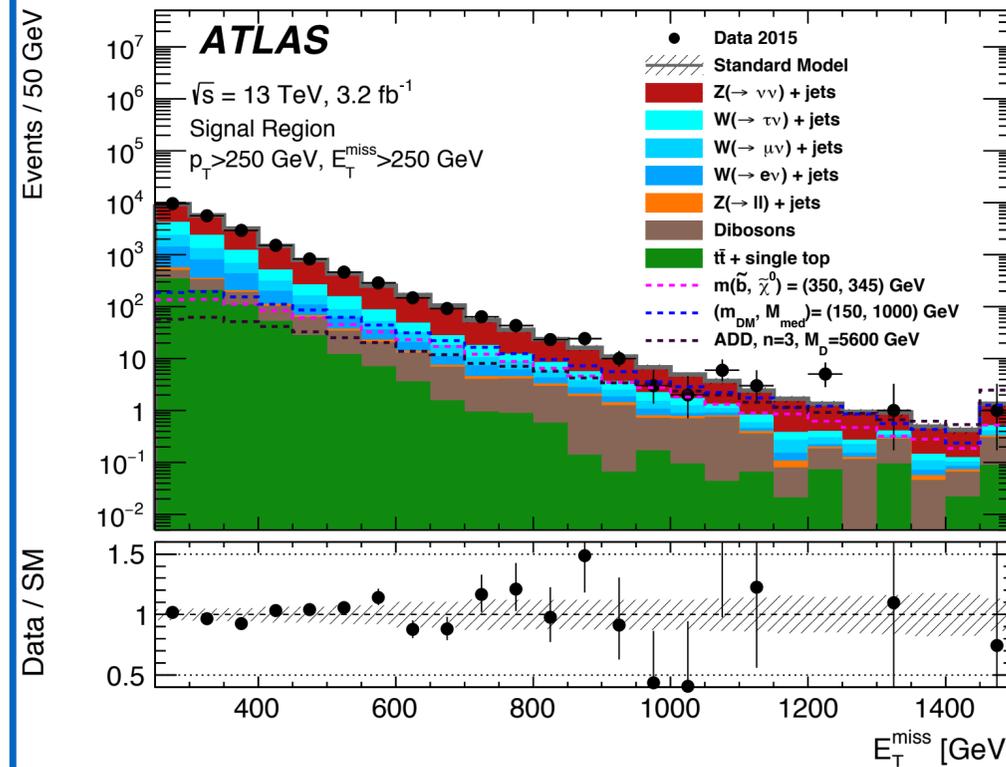
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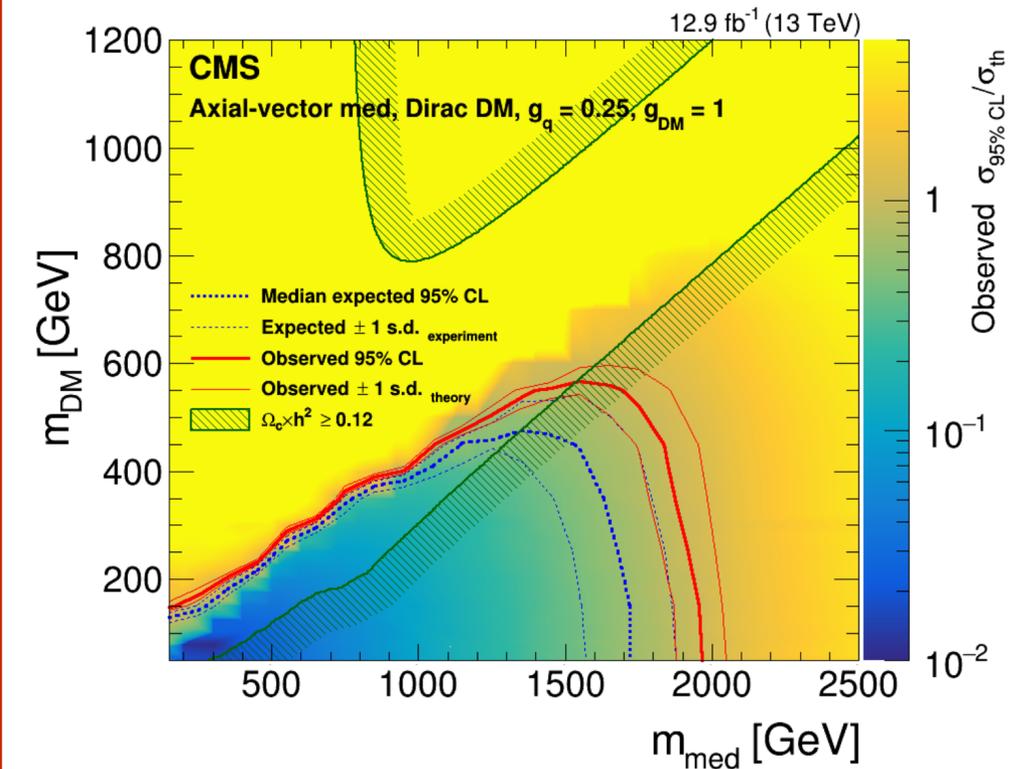
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Are these the only searches constraining DM at colliders?



[PRD 94 \(2016\) 032005](#)



[arXiv:1703.01651](#)

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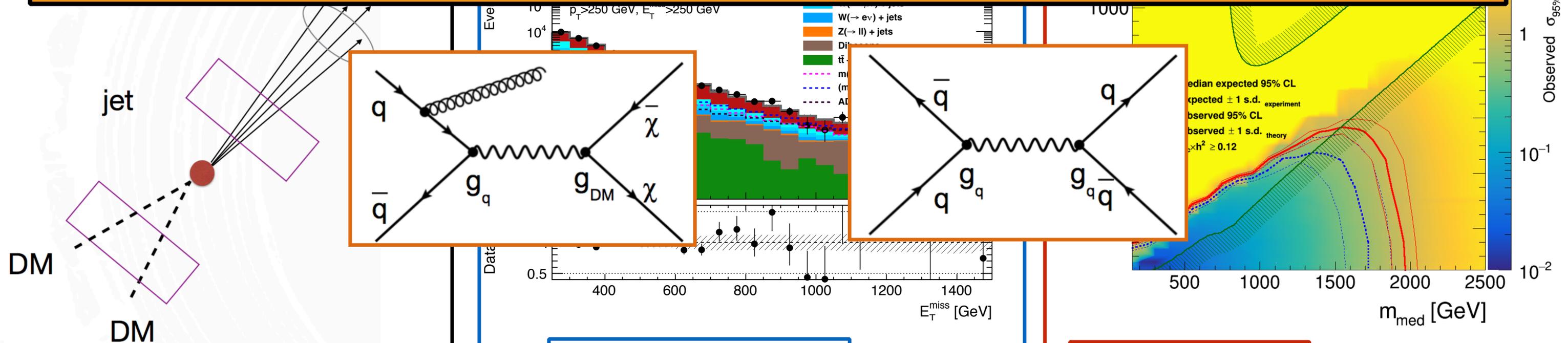
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Constraints on Dark-Matter spin-1 mediators come from resonance searches



PRD 94 (2016) 032005

arXiv:1703.01651

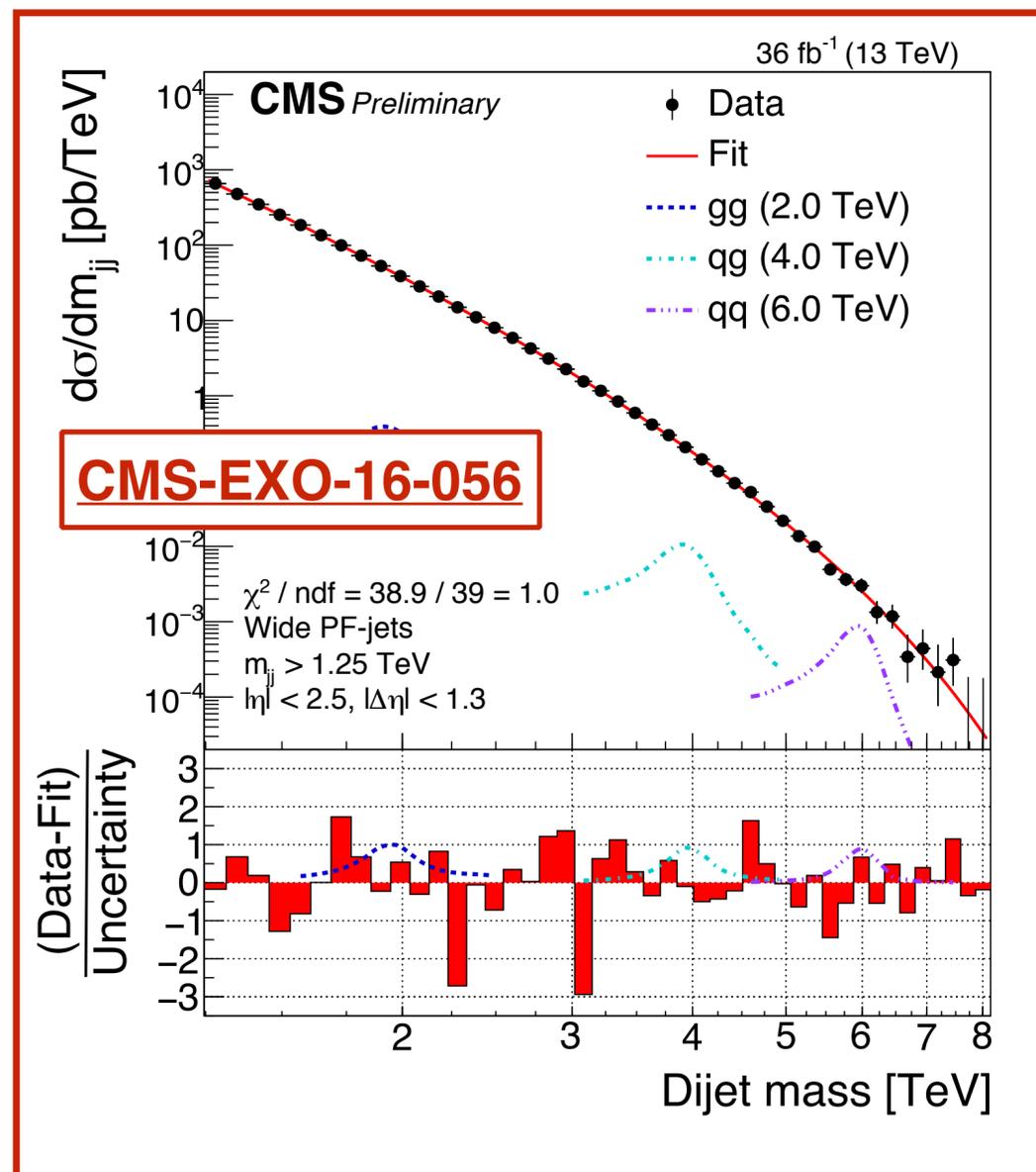
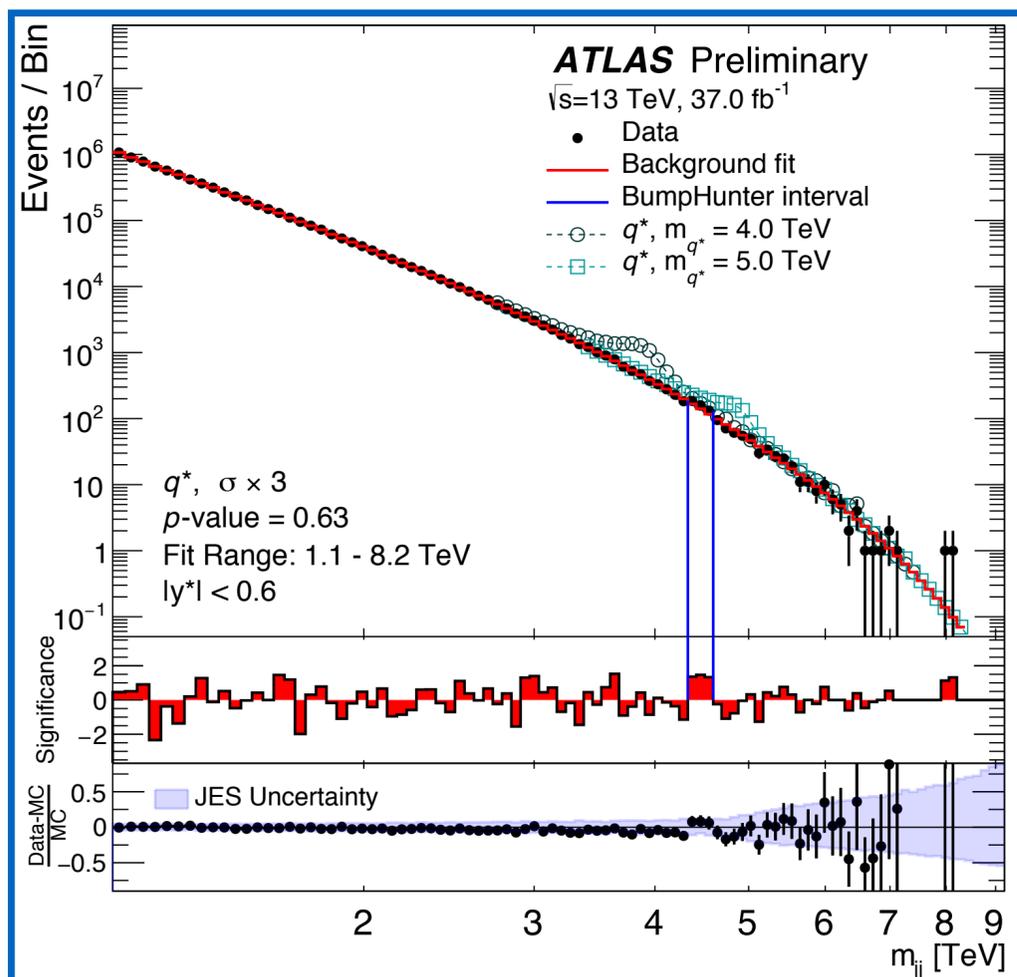
Dijet search



- Search for heavy resonances decaying to qq , qg or gg final states
- Lower limit in the mass reach due to trigger limitations
- Mass reach is extended down to ~ 500 GeV with trigger based analysis (data scouting) \rightarrow otherwise only $m_X > 1$ TeV

ATLAS-EXOT-2016-21

ATLAS-CONF-2016-030



• Selections:

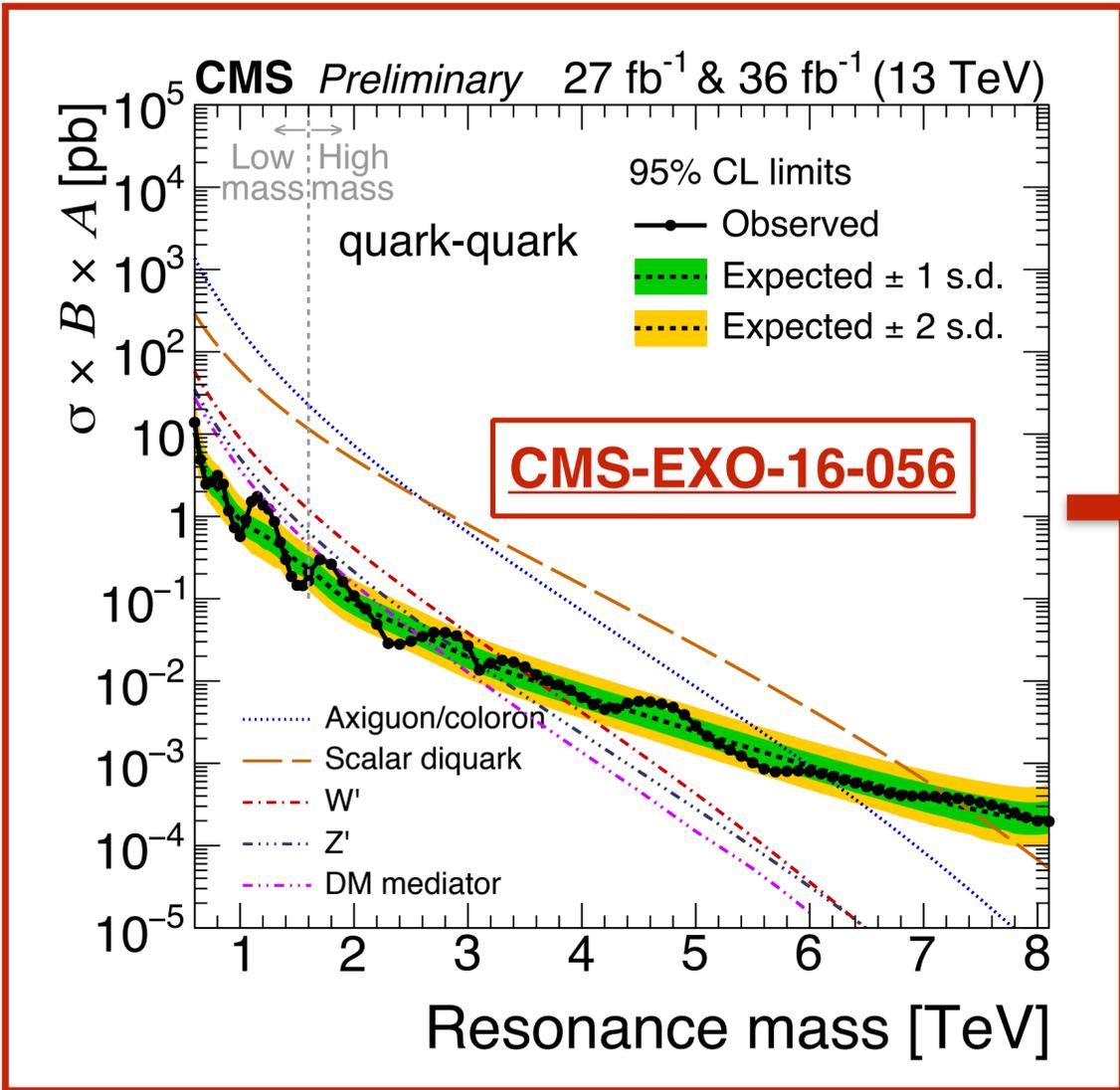
- Require at least two jets, one with high p_T
- Require small rapidity separation between the two jets
- Reconstruct the invariant mass m_{jj}
- Fit the smooth background spectrum
- Look for local excesses along the di-jet mass spectrum

Dijet result: Z' leptophobic

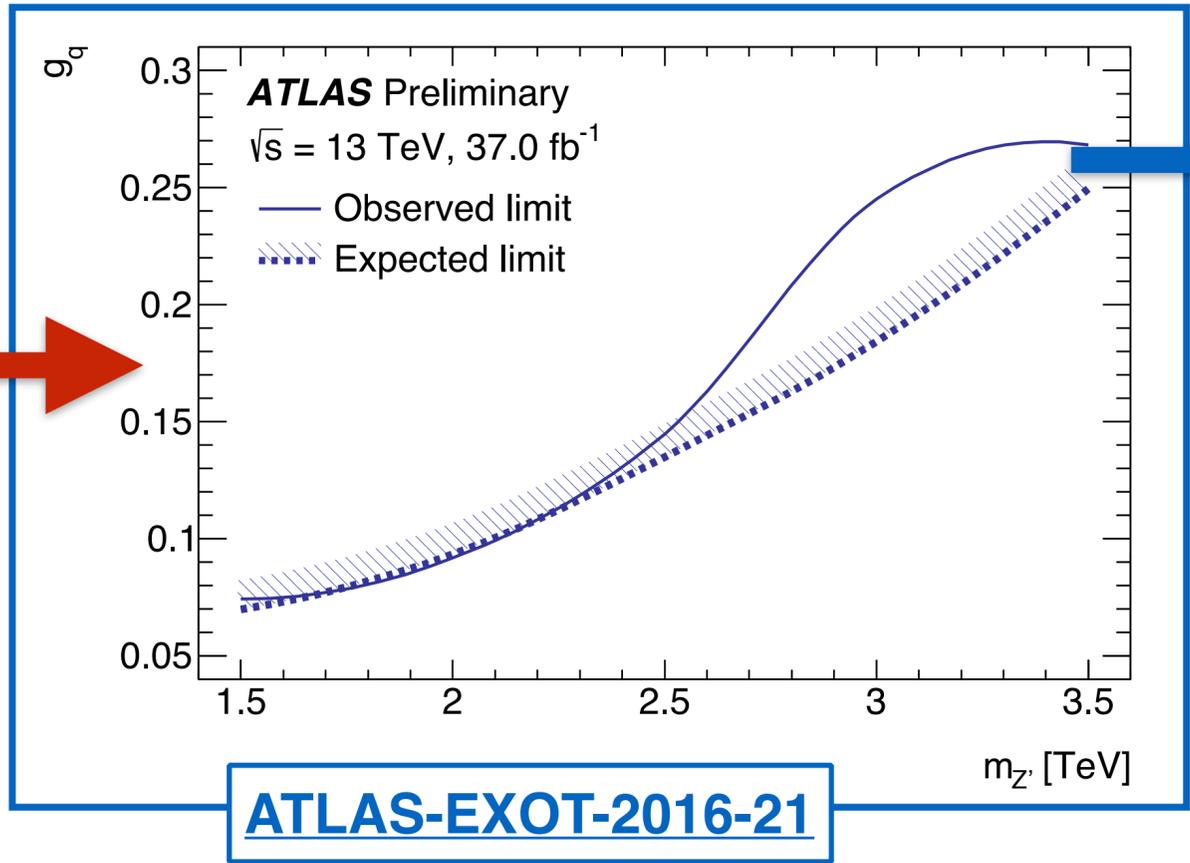


- Exclusion limits are usually expressed in $\sigma \times \text{BR} \times \text{acceptance}$
- Assumptions on the lineshape play a fundamental role \rightarrow **Narrow width approximation** $\rightarrow \Gamma_X \ll \sigma_{\text{exp}}$

Cross section limit for quark-quark resonances



Model dependent result for a leptophobic Z'

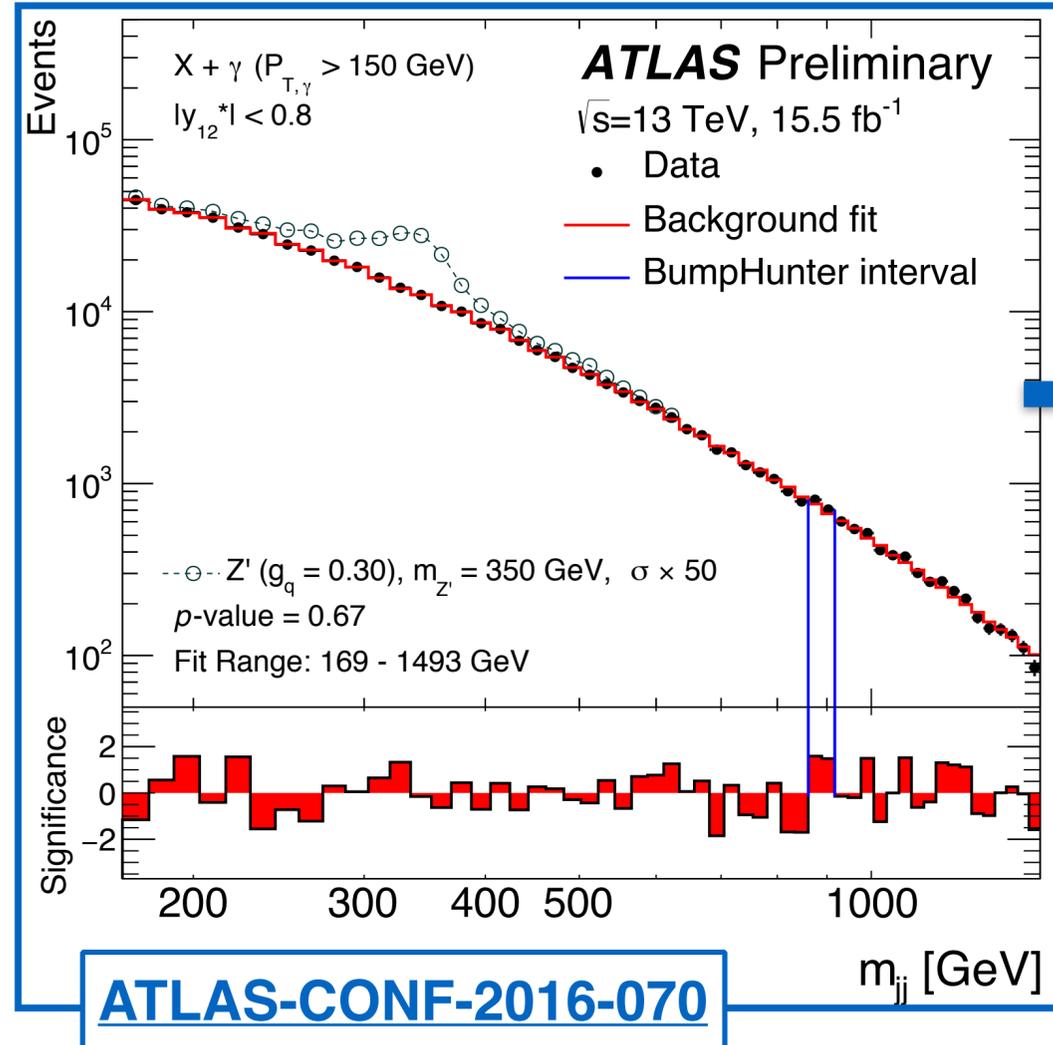
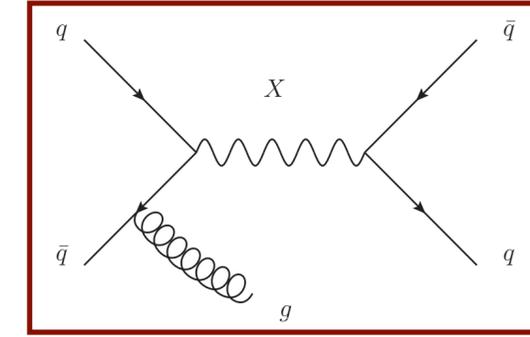
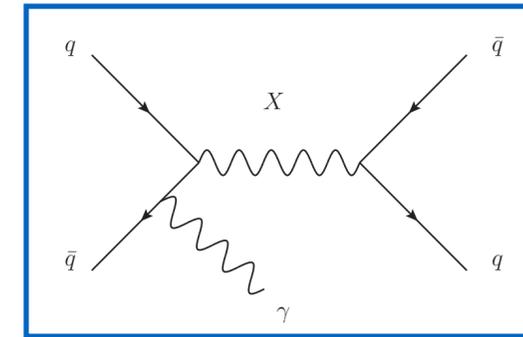


- The **coupling g_q** affects the production cross section through the **total width**
- **Sensitivity to small g_q limited** by small cross section
- For $g_q > [0.5, 0.6]$ \rightarrow **narrow width approximation** not valid anymore

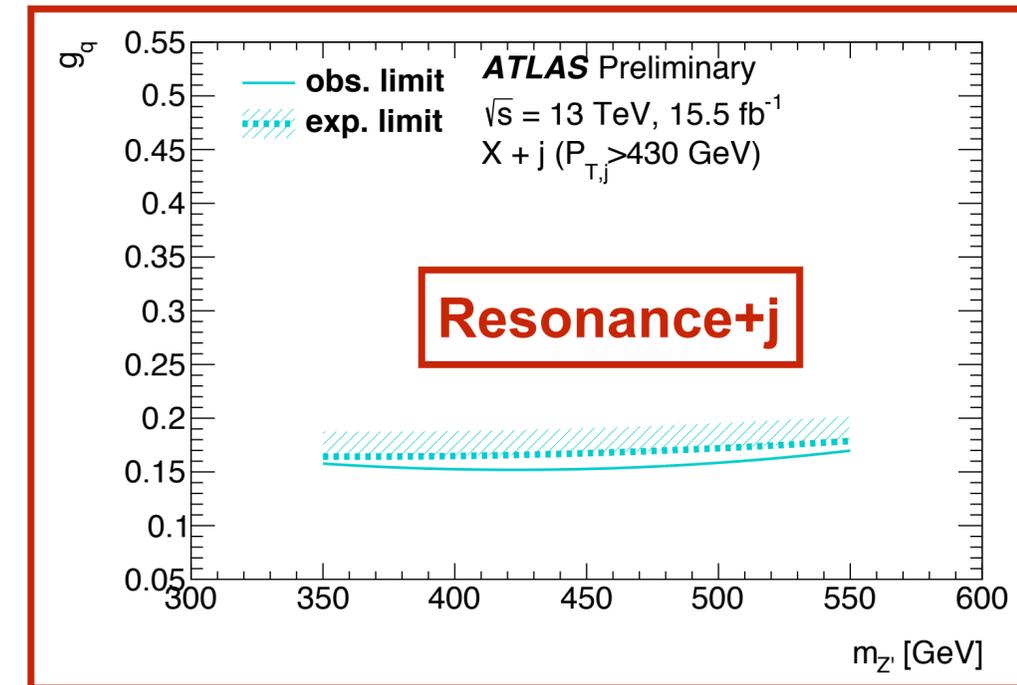
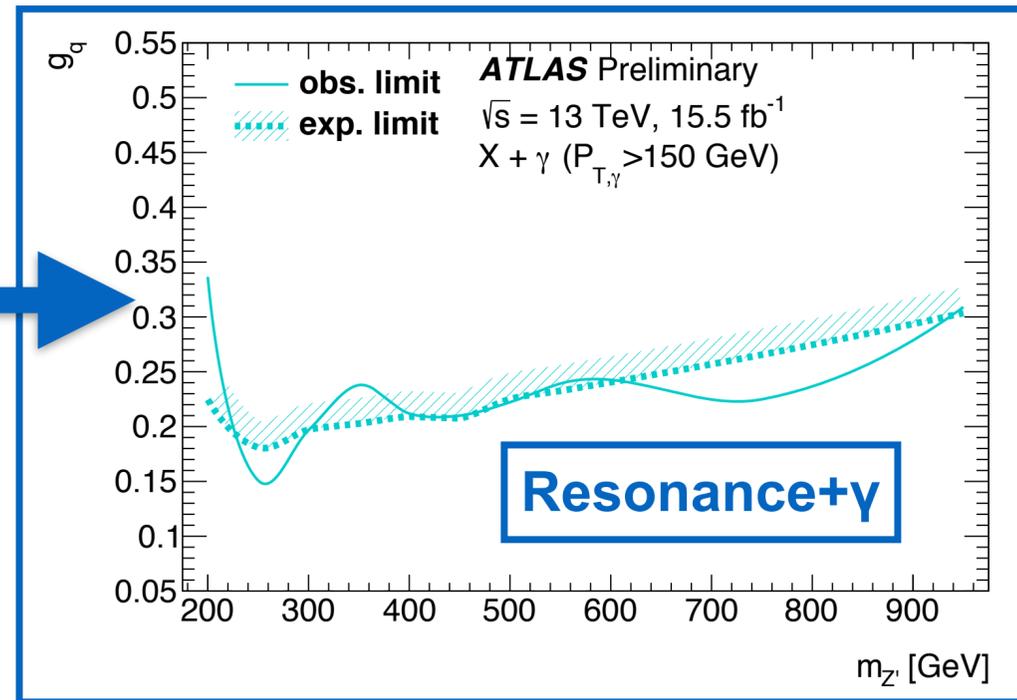
Upper bound on g_q ranges from [0.08, 0.35] in the range $m_{Z'} [0.6, 3.5]$ TeV

ATLAS low mass dijet

- **Goal:** extend the dijet search to lower masses $\rightarrow m_X < 500$ GeV
- **Strategy:** resonance produced in association with a high p_T ISR jet or photon
 - **Resonance + γ :** photon $E_T > 150$ GeV, two jets with $|y^*| < 0.8$
 - **Resonance + j:** one jet $p_T > 430$ GeV, two additional jets with $|y^*| < 0.6$



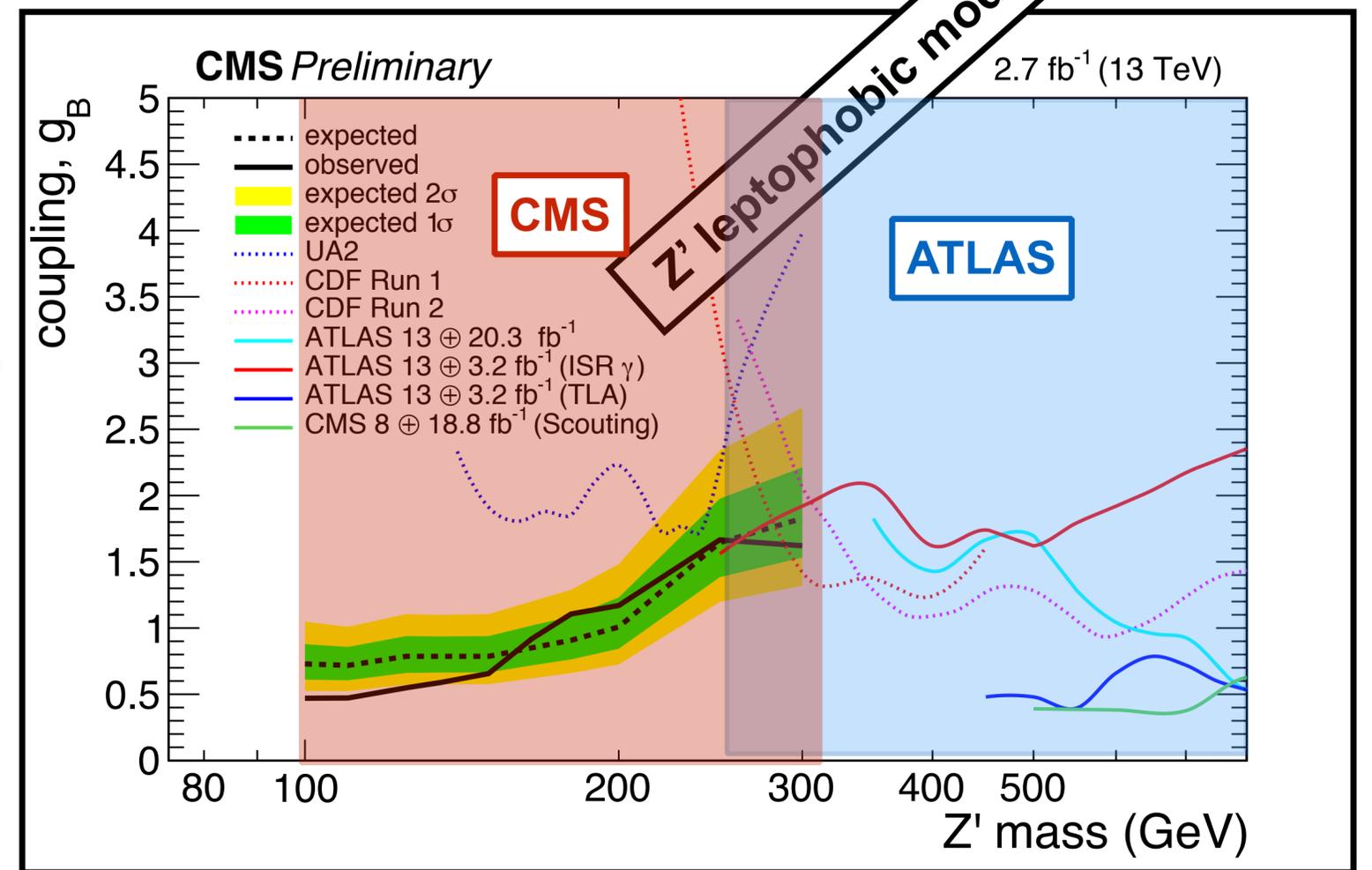
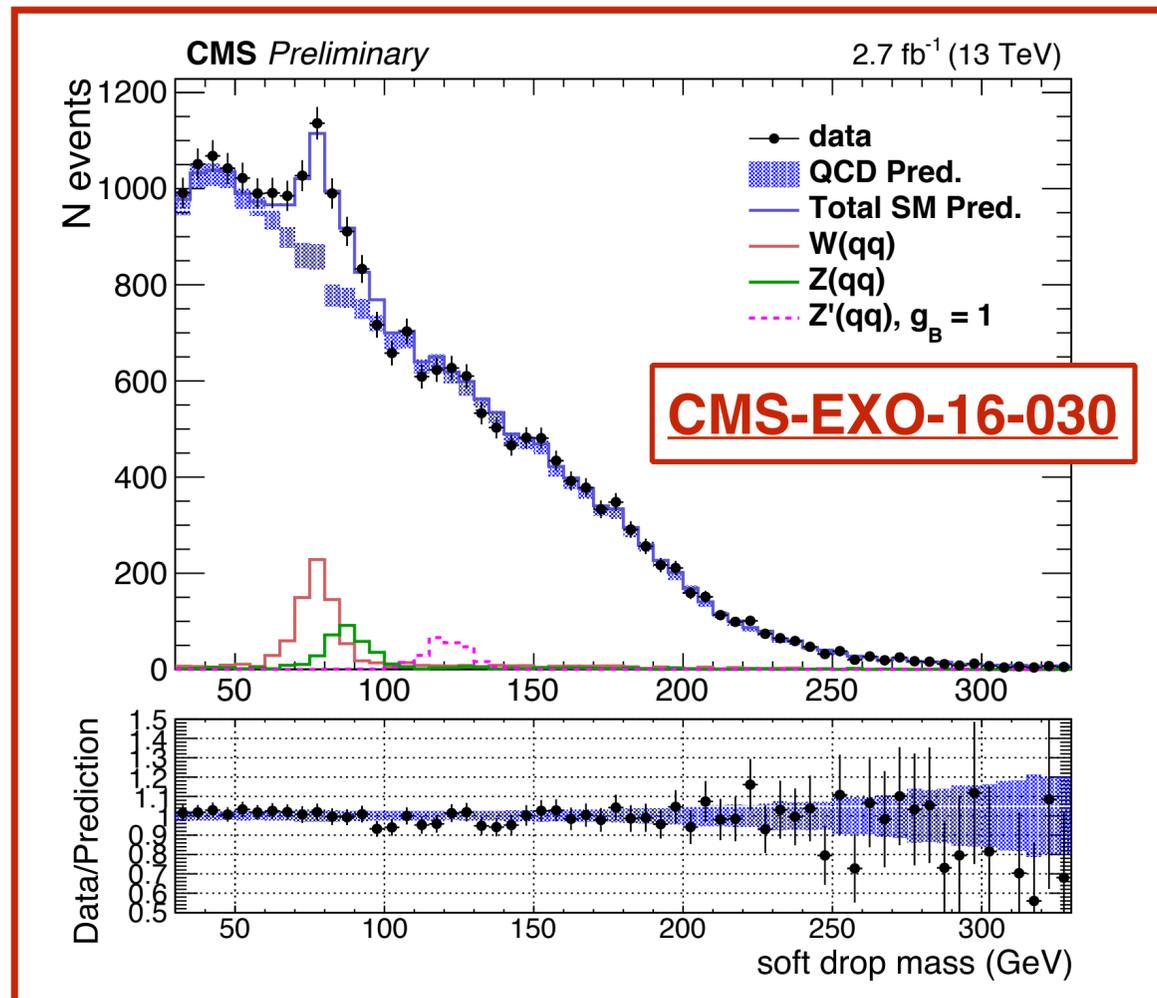
Z' model interpretation



X+j becomes inefficient for $m_X < 350$ GeV cause jets from the resonance becomes close to each other and overlaps in the detector

CMS boosted low mass dijet

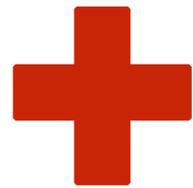
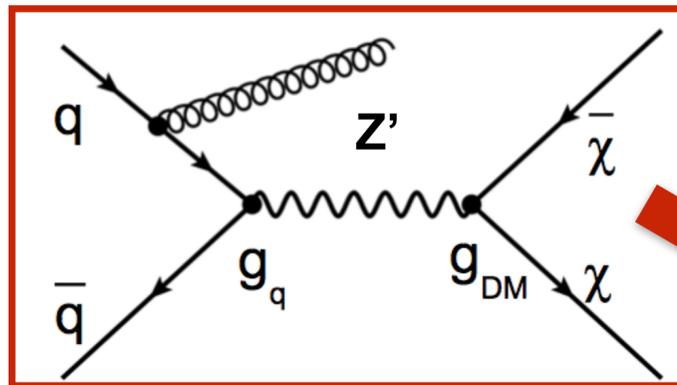
- **Strategy:** look for a **boosted low mass resonance** ($m_X < 300$ GeV) produced in association with an ISR jets
- **Selections:** one large cone (AK8) jet ($p_T > 500$ GeV) which collect the **decay products** of the resonance
jet substructures are used to **suppress QCD-multijet backgrounds** and to reconstruct the resonance invariant mass
- **Signal extraction:** fit to the large cone **soft-drop mass** (m_{SD}) spectrum



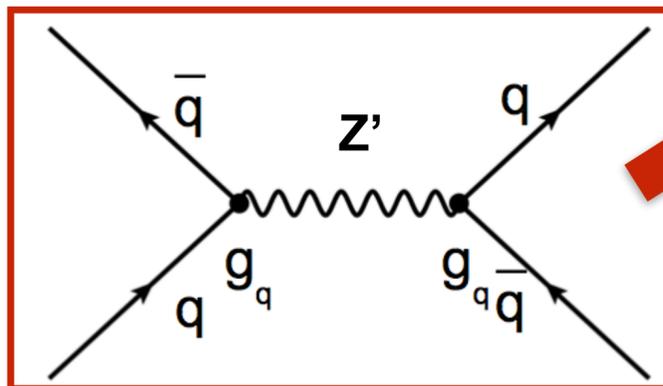
DM interpretation of resonance searches

- **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

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

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

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

Interesting scenarios

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

$g_{\text{SM}} \ll g_{\text{DM}}, g_{\text{DM}} \sim 1$: narrow resonance but BR monojet larger than dijet one

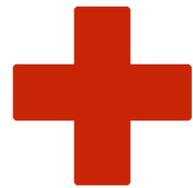
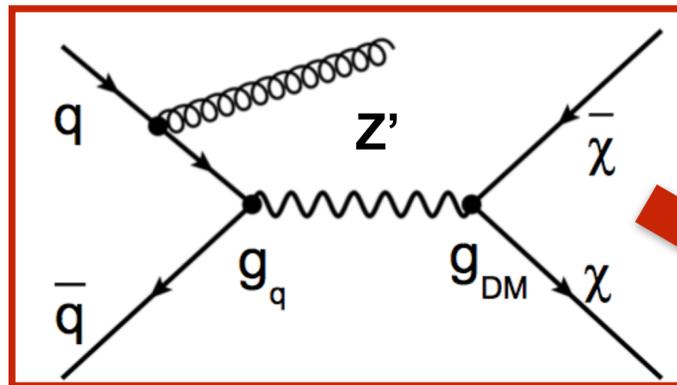
$g_{\text{DM}} \gg g_{\text{SM}}, g_{\text{DM}} > 1$: resonance not narrow anymore BR monojet larger than dijet one

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

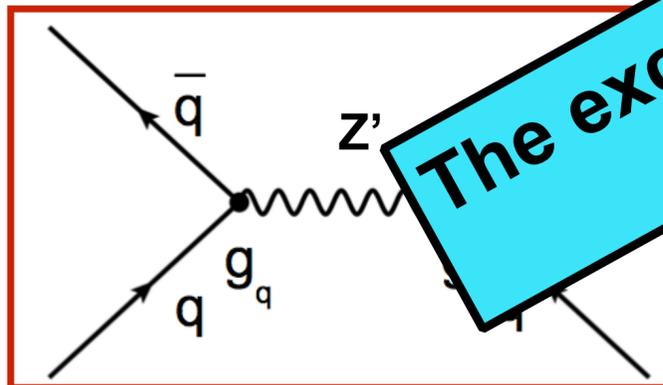
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Monojet production



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Mediator Width

$$\Gamma_{AV}^{\text{tot}} = \Gamma_{AV}^{\chi\bar{\chi}} + 3 \times \sum_{q=u,d,s} \Gamma_{AV}^{q\bar{q}}$$

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

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

The exclusion power of the reinterpretation of resonance searches into DM limits strictly depends on the $(g_{\text{SM}}, g_{\text{DM}})$ values

Limiting scenarios

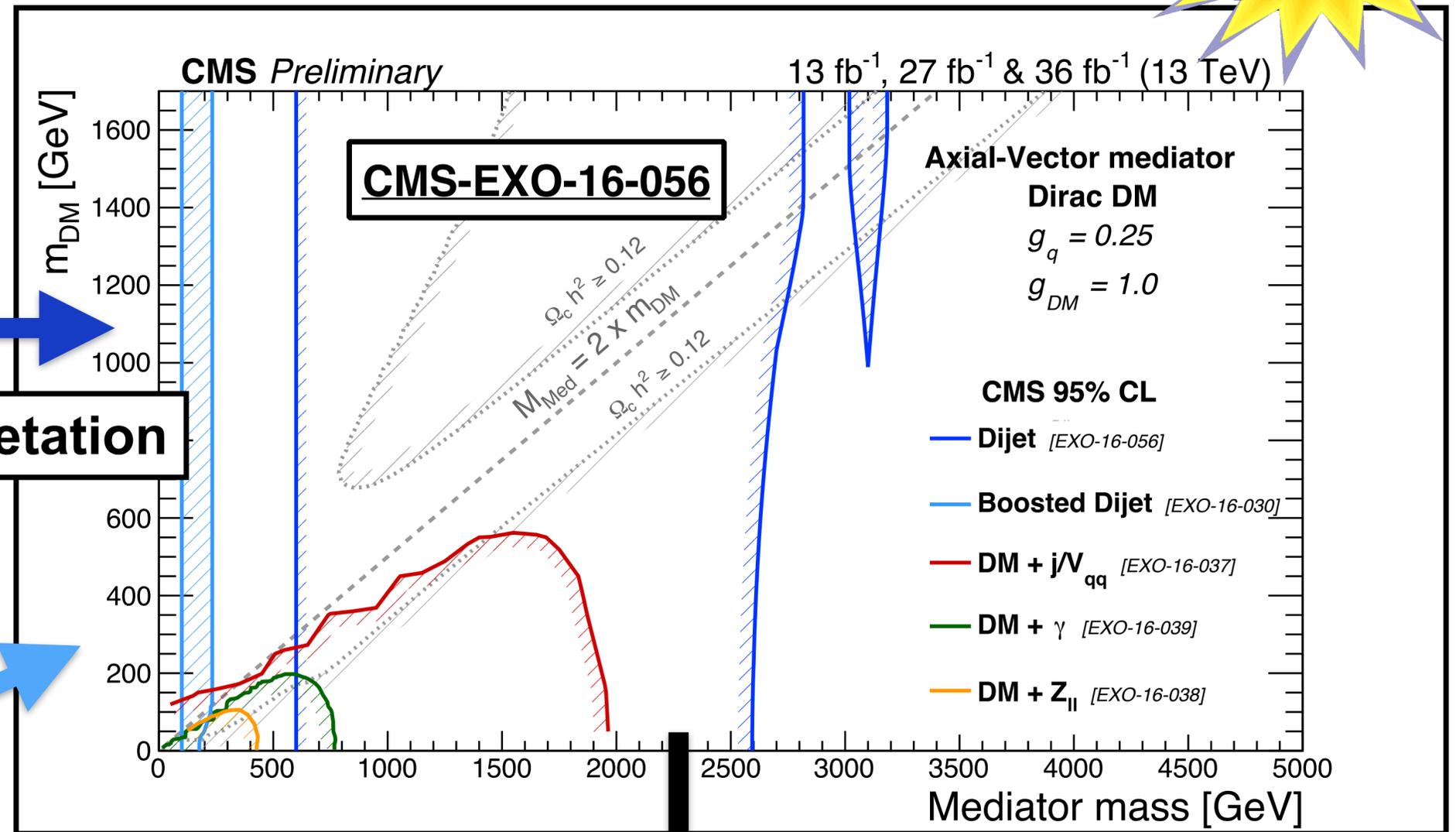
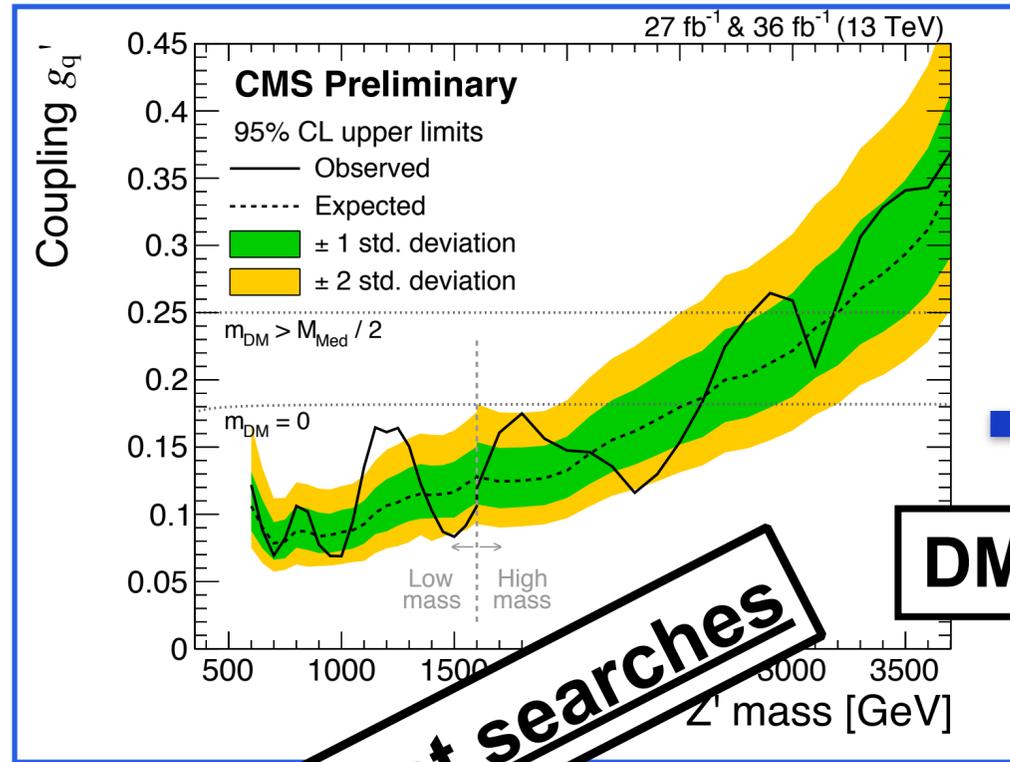
$g_{\text{DM}} > m_{\text{DM}}$: the relative branch fraction for monojet and dijet is proportional to $N_c N_q g_{\text{SM}}^2 / g_{\text{DM}}^2$

$g_{\text{SM}} \ll g_{\text{DM}}, g_{\text{DM}} \sim 1$: narrow resonance but BR monojet larger than dijet one

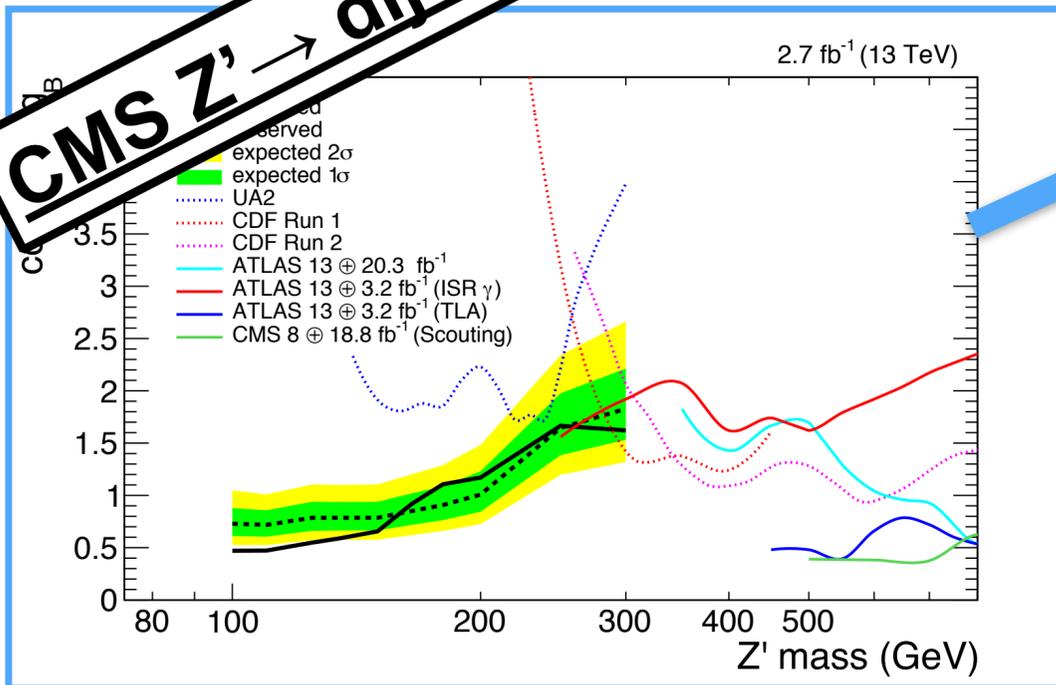
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CMS: direct vs indirect DM searches



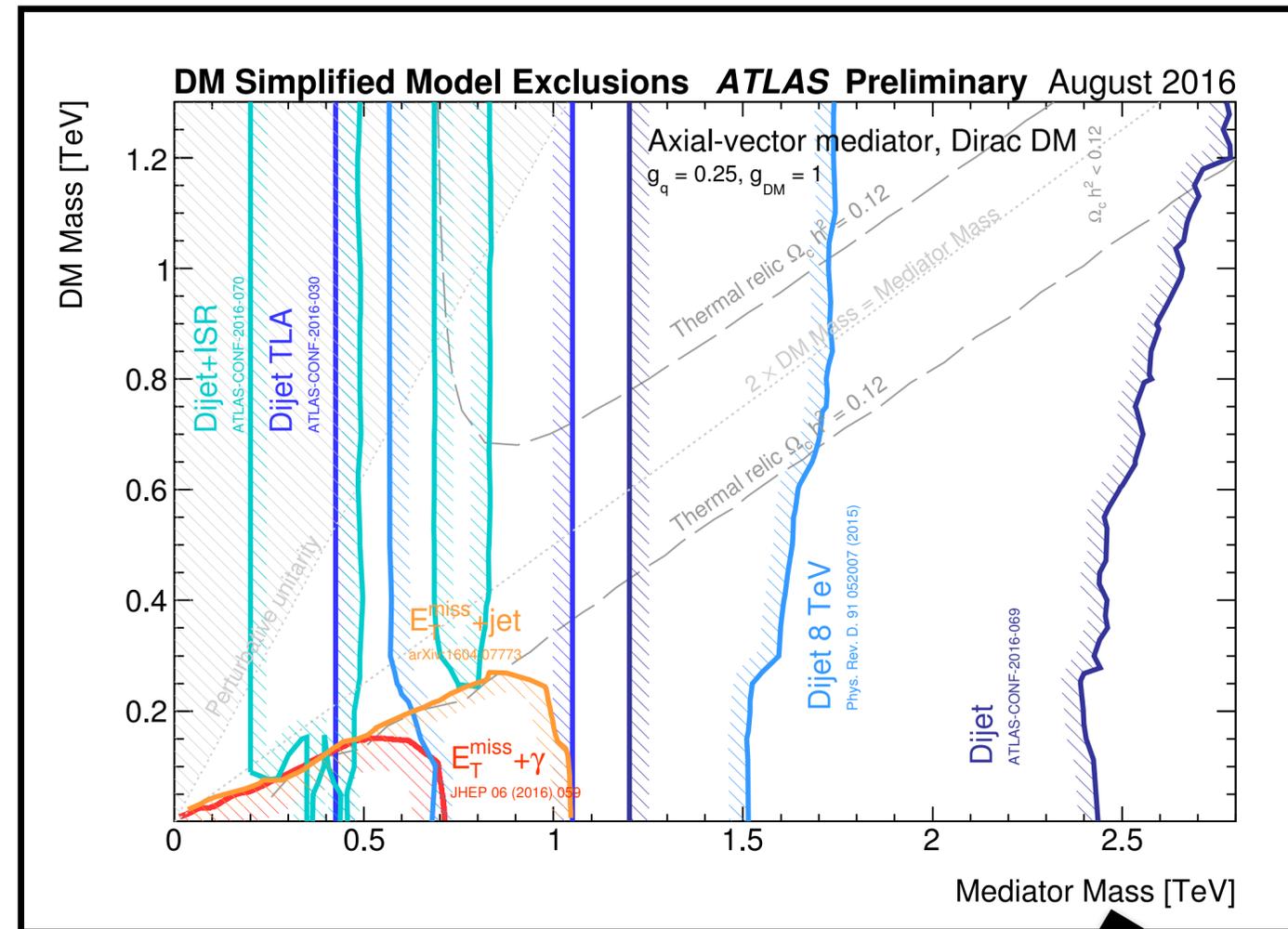
CMS Z' → dijet searches



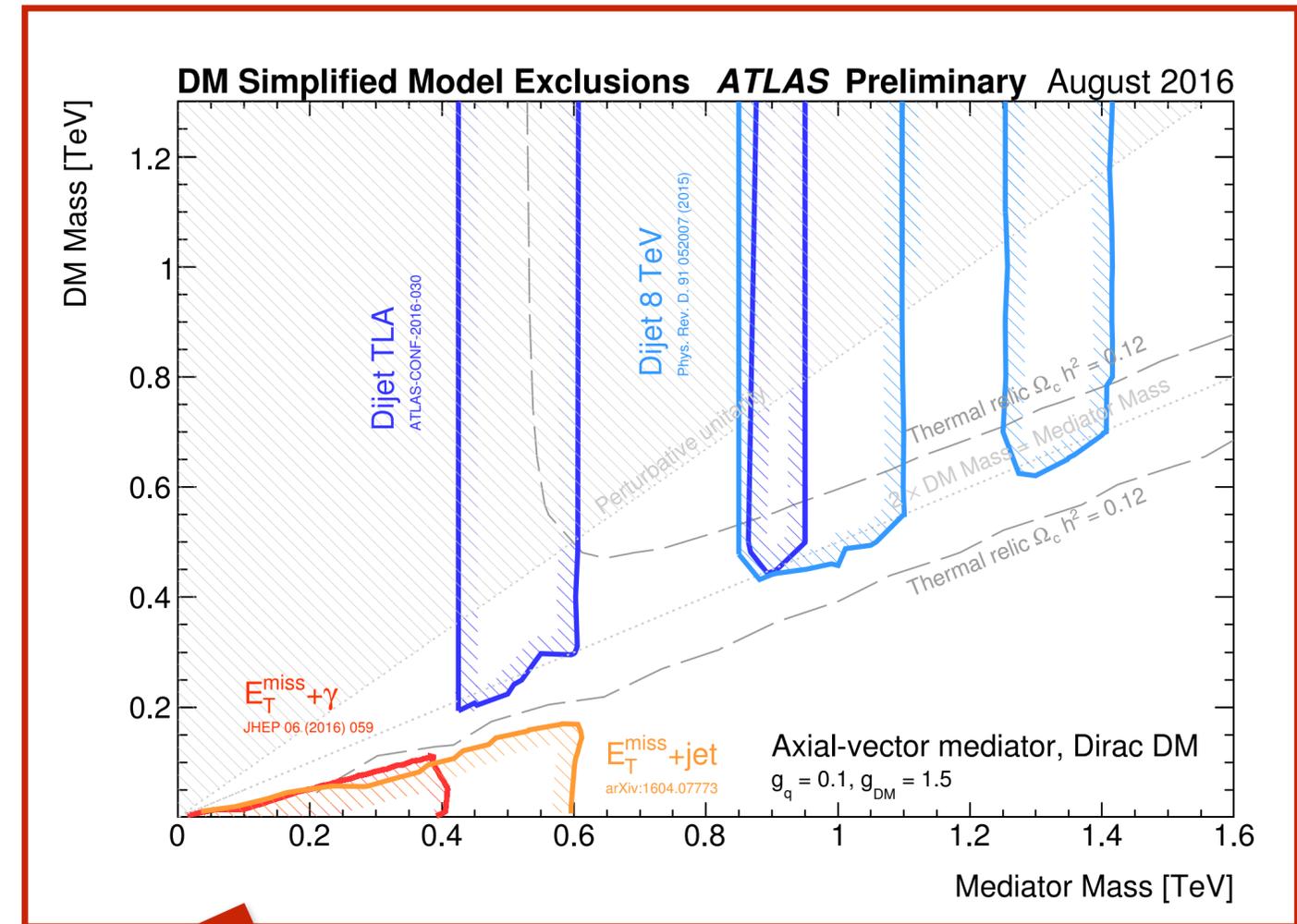
Benchmark: Axial-Vector mediator with $g_q = g_{SM} = 0.25$ and $g_{DM} = 1$
Comparison between mono-X DM searches and dijet bounds
 Given the coupling choice → **dijet bounds are much stronger than mono-X ones in the on-shell region**

ATLAS: direct vs indirect DM searches

$$g_{\text{SM}} = 0.25, g_{\text{DM}} = 1$$



$$g_{\text{SM}} = 0.10, g_{\text{DM}} = 1.5$$

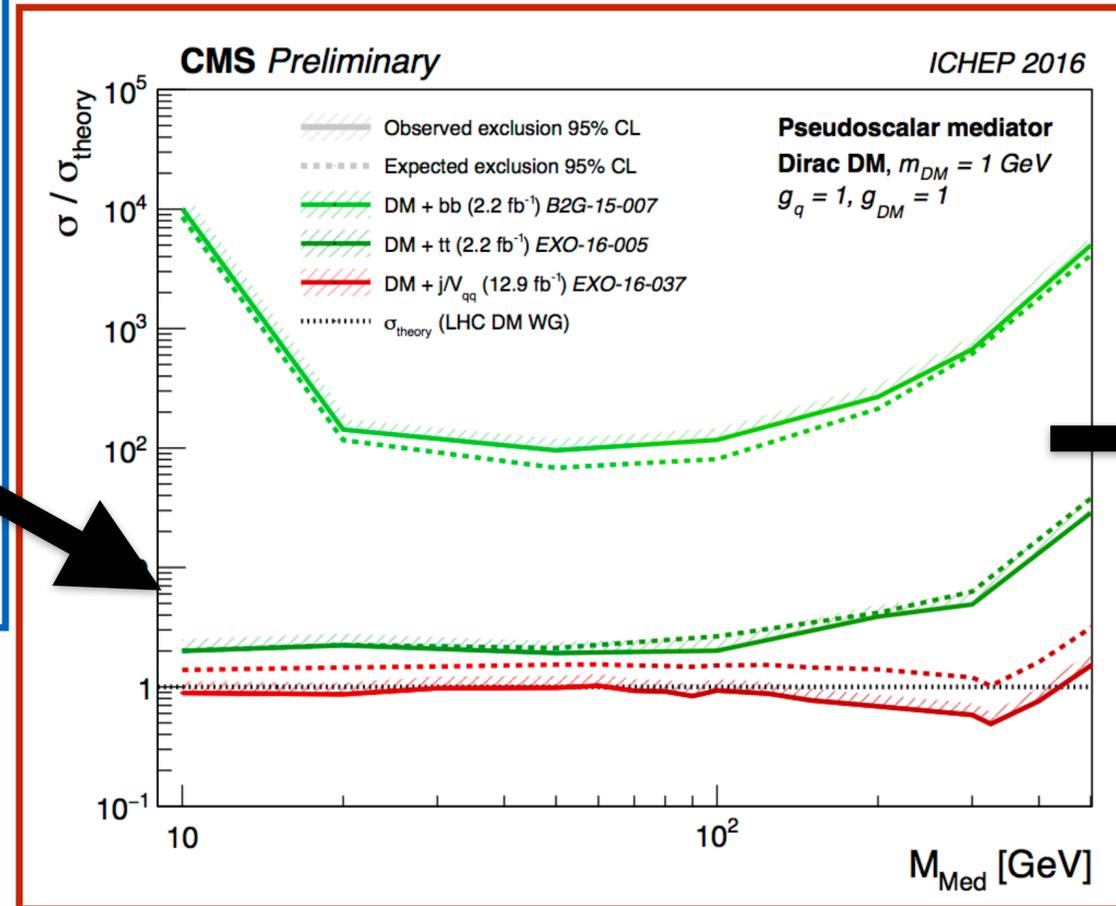
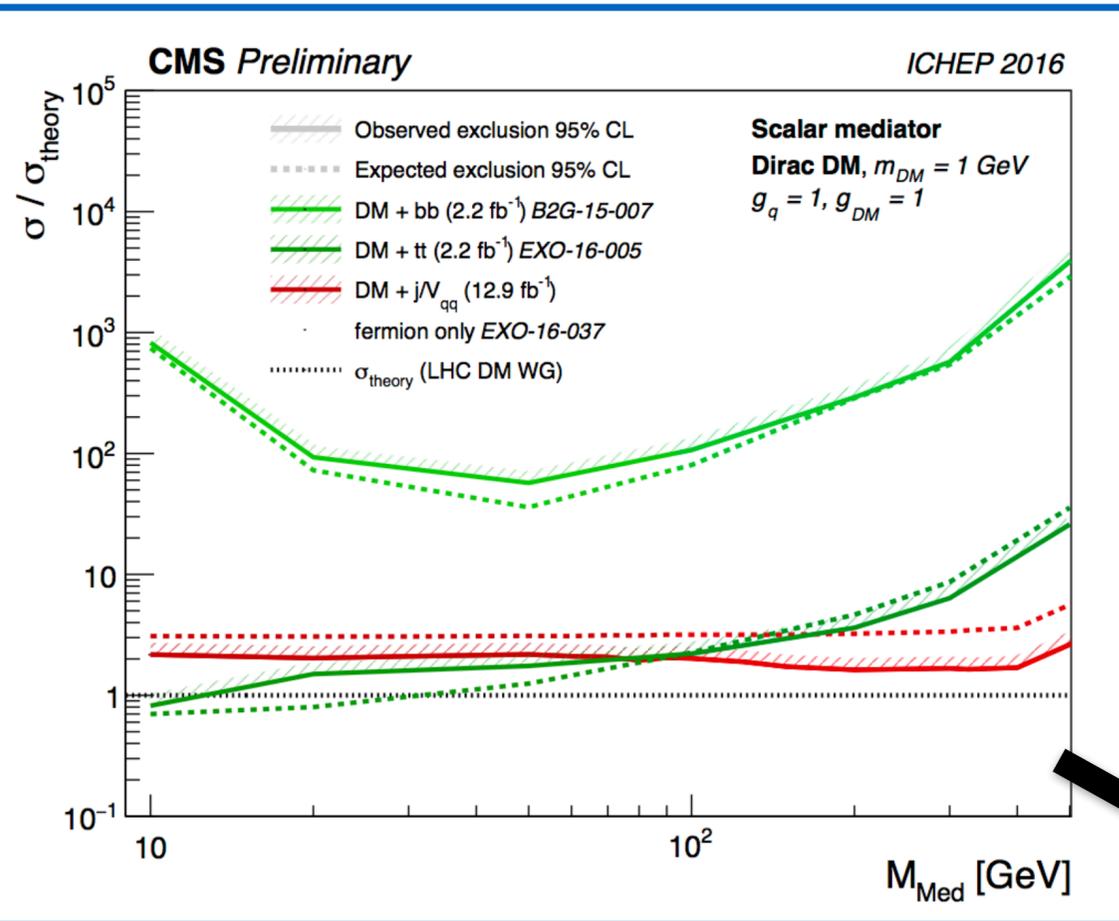
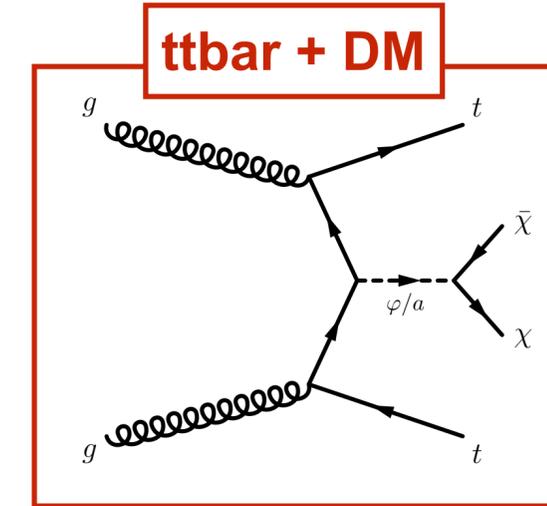
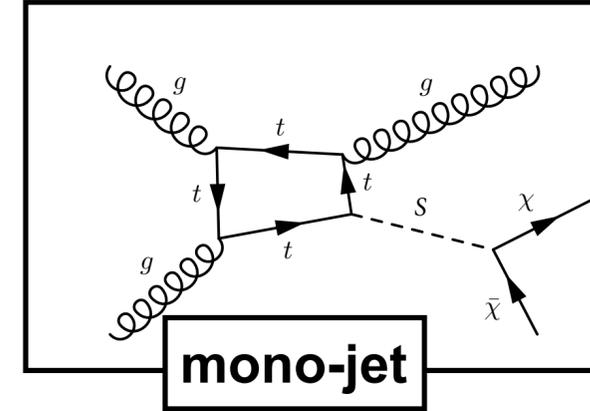


For “relatively large” quark coupling (g_{SM}) → **dijet constraints are very strong**
 As g_{SM} gets weaker compared to g_{DM} → **dijet constraints becomes complementary to mono-X**
Constraining power in the off-shell region remains strong

What about spin-0 DM mediators??

Searches for a spin-0 mediator

- Strongest limits for spin-0 mediators comes from mono-jet and **ttbar + DM**
- No limits / interpretations from high mass resonance searches



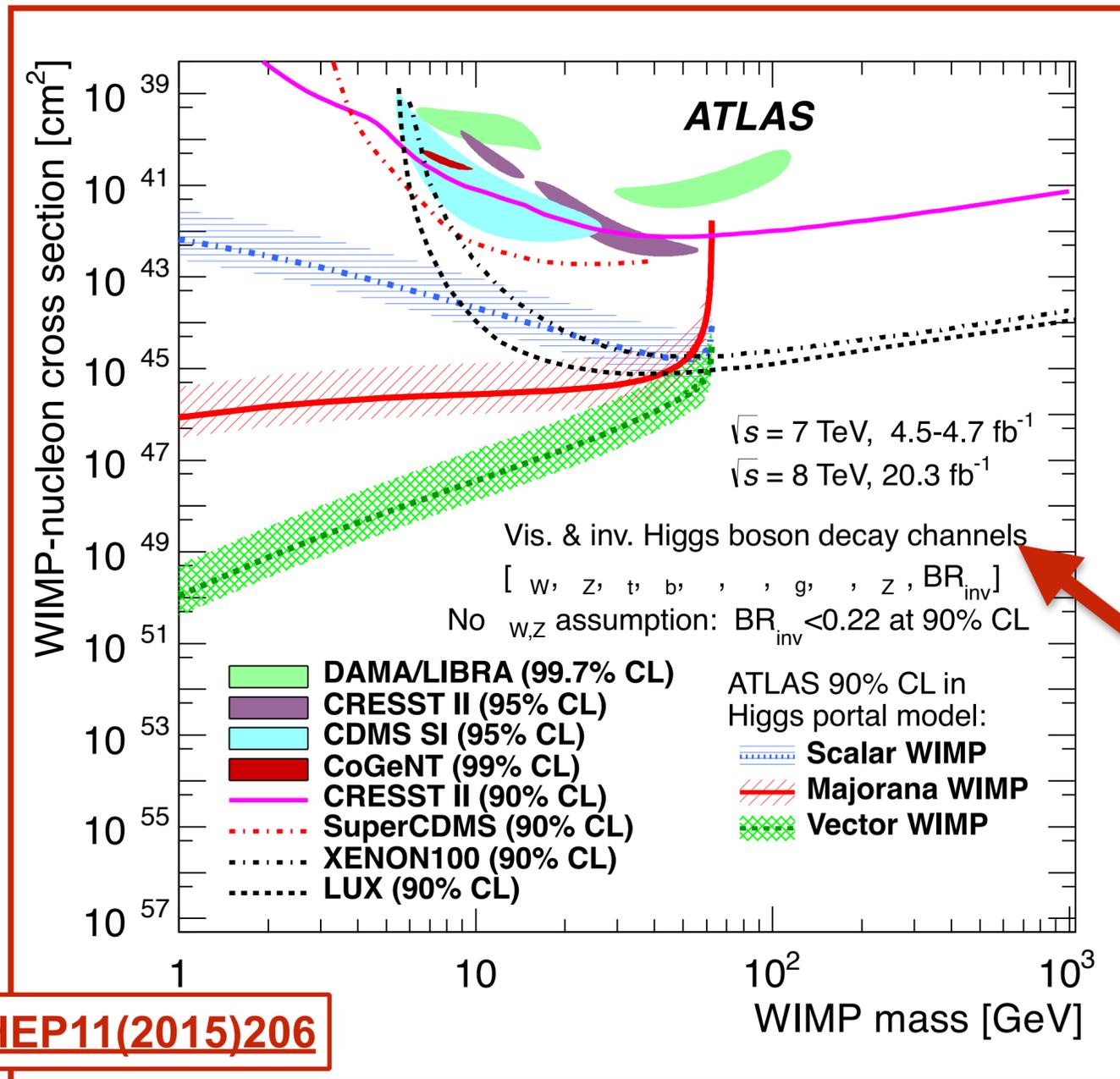
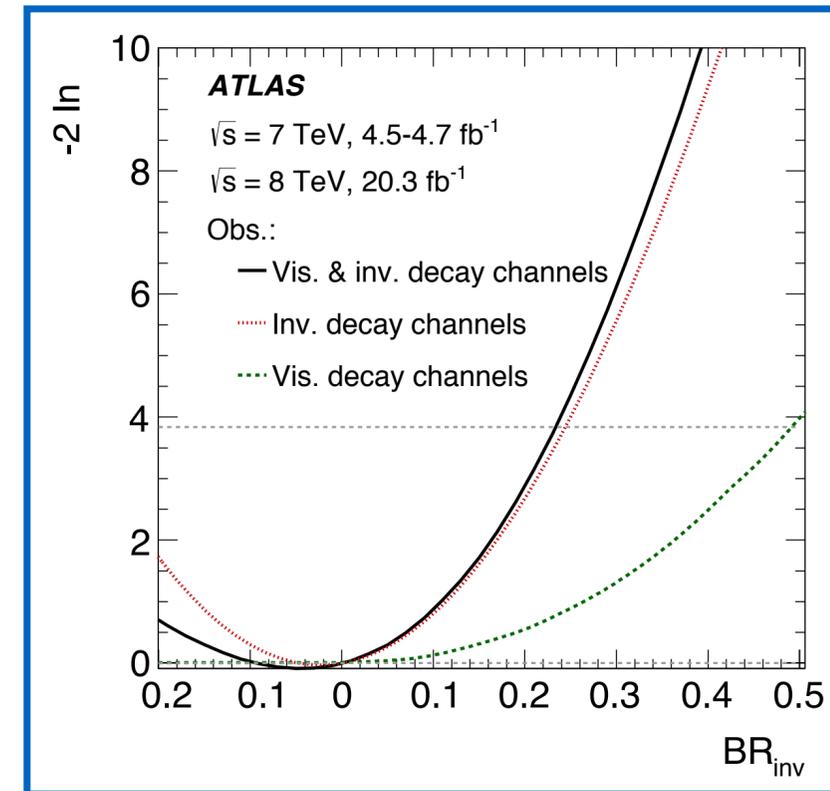
- Coupling choice $g_{SM} = g_{DM} = 1$
- Dark matter mass fixed to be $m_{DM} = 1 \text{ GeV}$
- mono-X searches have exclusion sensitivity for low mass S/PS mediators
- ttbar + DM is the most sensitive search for low mass scalars

CMS-EXO-16-006

arXiv:1703.01651

Higgs boson as portal to DM

- Another place for DM → SM Higgs branching ratio since it couples to everything with mass
- Higgs invisible searches set an upper limit on $BR(H_{inv})$ to be $< \sim 25\%$



JHEP11(2015)206

Higgs portal model ([arXiv:1112.3299](https://arxiv.org/abs/1112.3299))

Hidden sector provides DM particle coupled to SM Higgs boson
BR limits are converted into bounds on DM-nucleon cross section

Collider limits are the most stringent ones for low m_{DM}
Low m_{DM} is a region hard to be explored by direct detection experiment

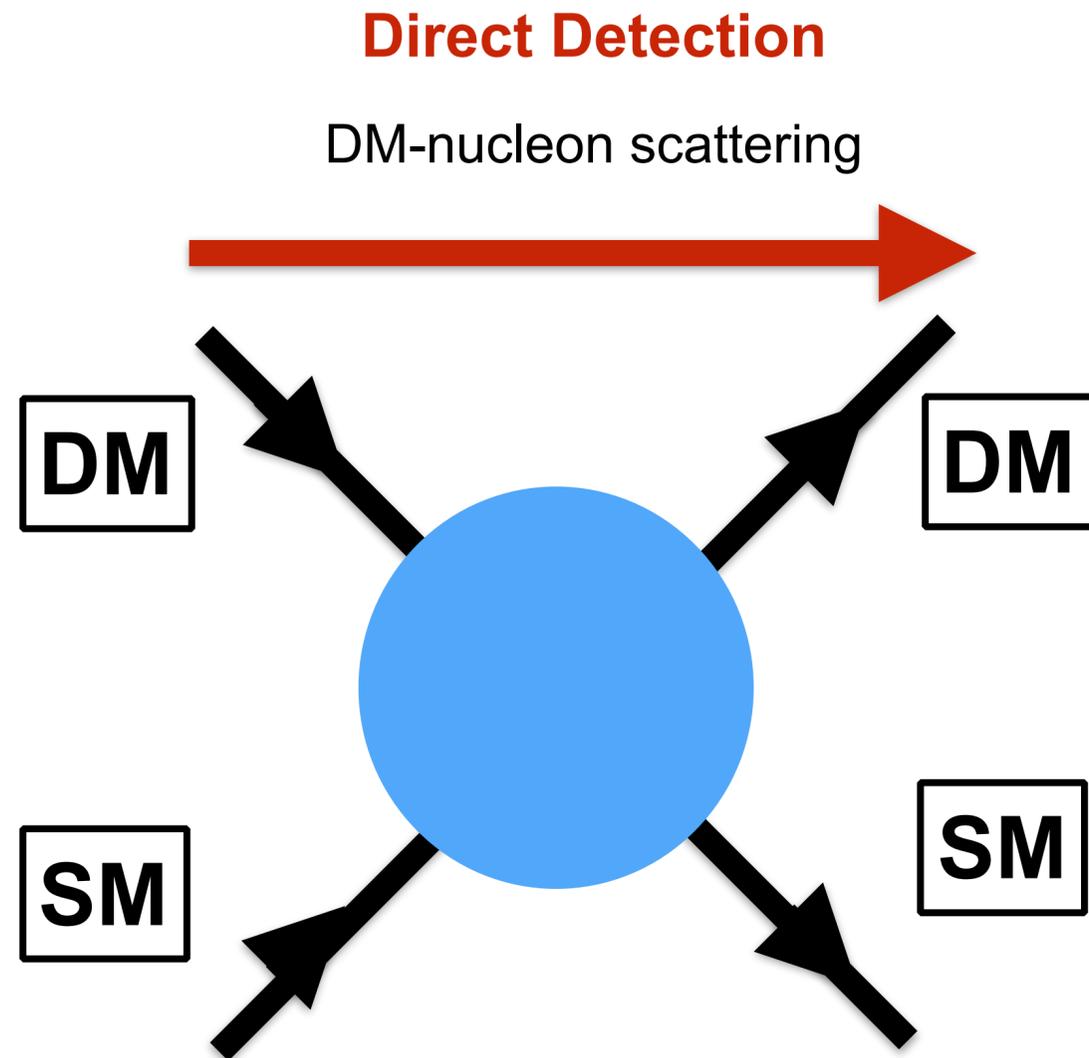
Conclusion

- **Impressive amount of DM searches at colliders:**
 - Large number of signatures have been explored in $E_T^{\text{miss}} + X$ searches
 - Bounds on dark matter mediators comes also from re-cast of resonance searches
 - For $g_q = 0.25$ and $g_{\text{DM}} = 1 \rightarrow$ **dijet search excludes spin-1 mediators with a mass up 2.5-3 TeV**
- **LHC provides complementary results to direct and indirect detection experiments**
 - Results can be compared with direct and indirect detection experiments in terms of DM-nucleon cross section
 - **Colliders provide the strongest bounds for the spin-dependent DM-nucleon cross section**
 - **Colliders provide the strongest bounds for the spin-independent DM-nucleon cross section for $m_{\text{DM}} < 10$ GeV**

Unfortunately **no sign of Dark-Matter** from **collider searches so far**
Nevertheless the hunt of dark matter continues

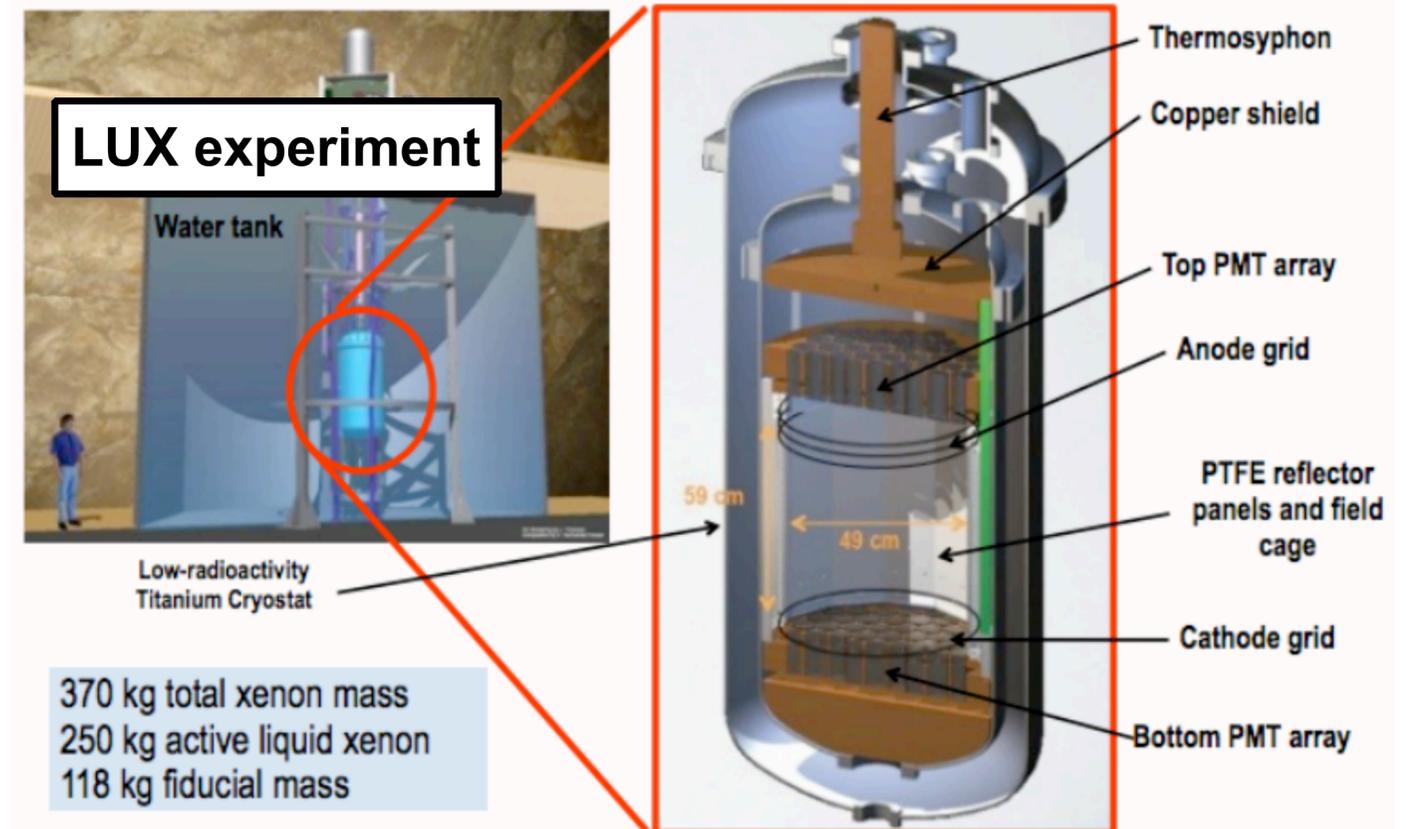
Backup

Direct Detection Experiments



Look for **elastic scattering** of **DM** against **nucleons**
Detector deep underground to minimise backgrounds

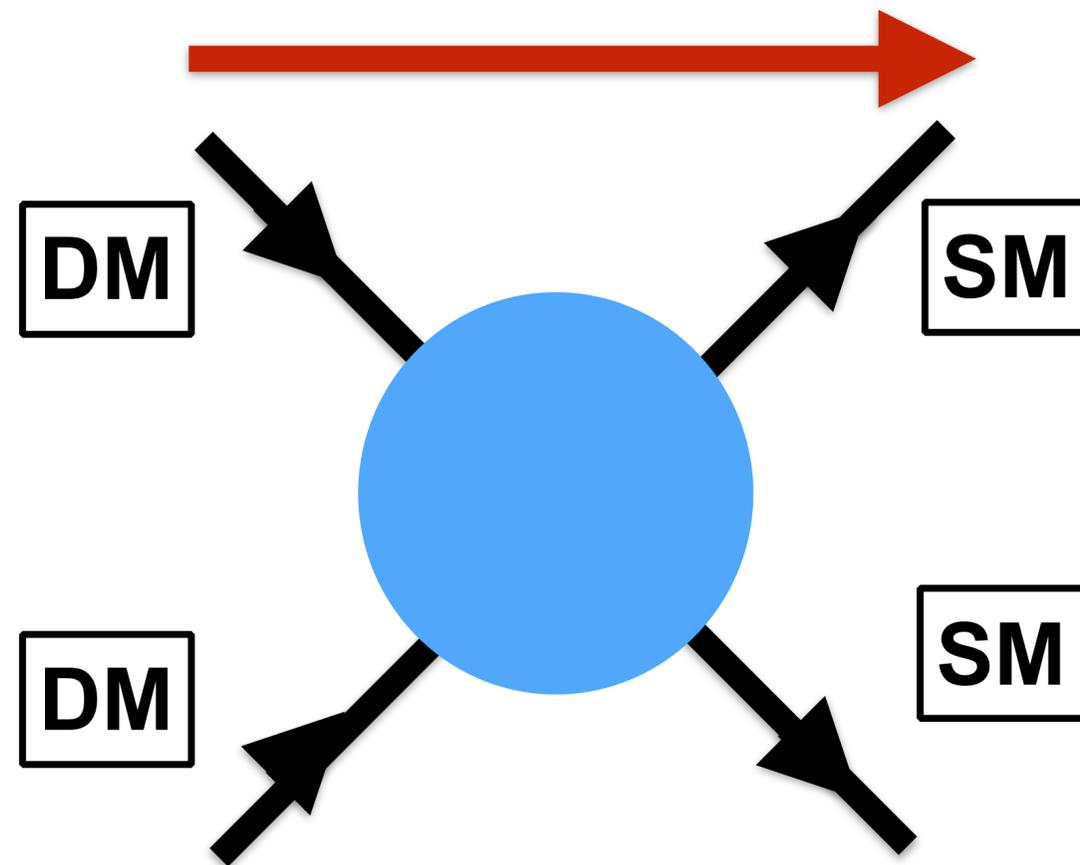
Experiments: LUX, PandaX ..etc



Indirect Detection Experiments

Indirect Detection

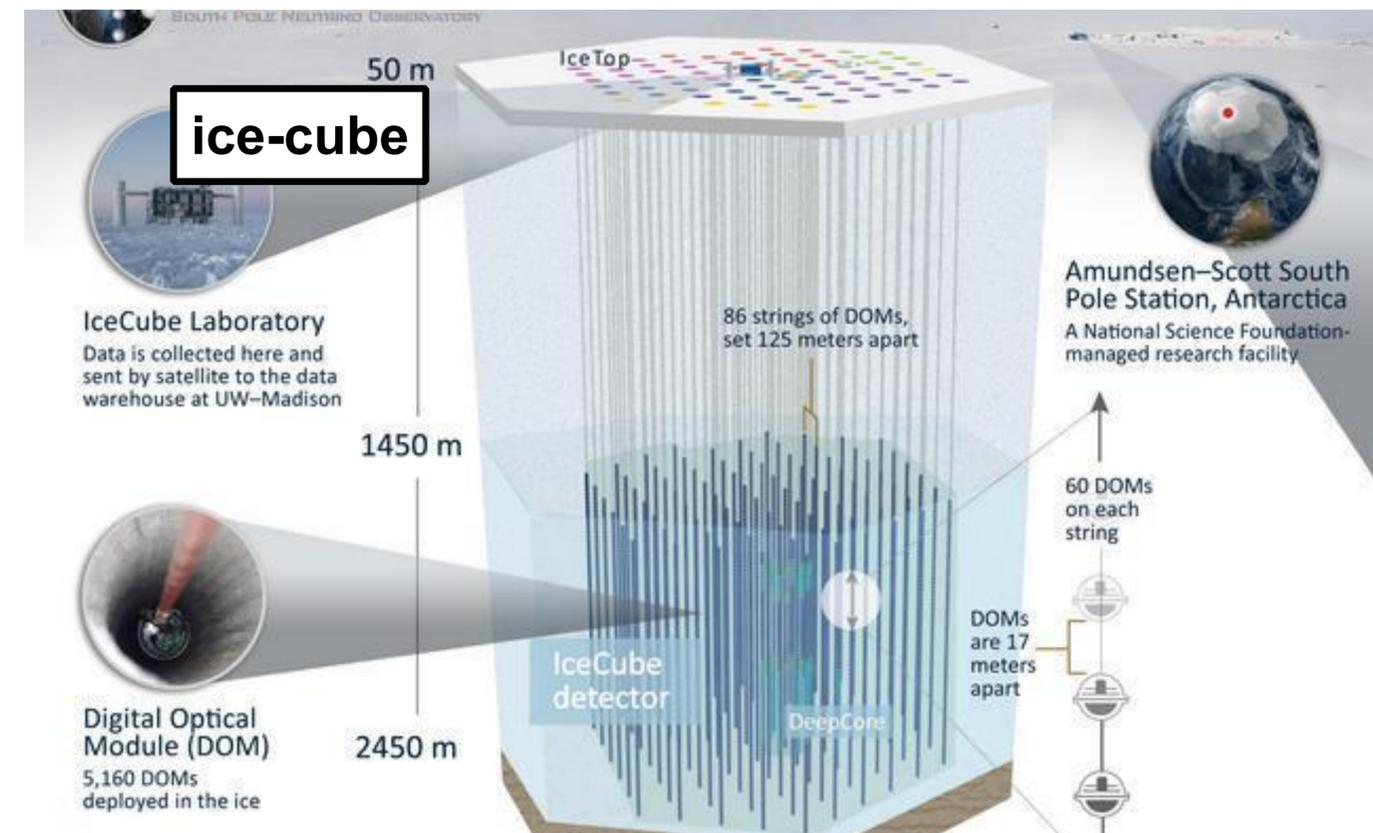
DM annihilation



DM pairs annihilate in galaxy / stars into SM particles

Annihilation happens in region of high density of DM

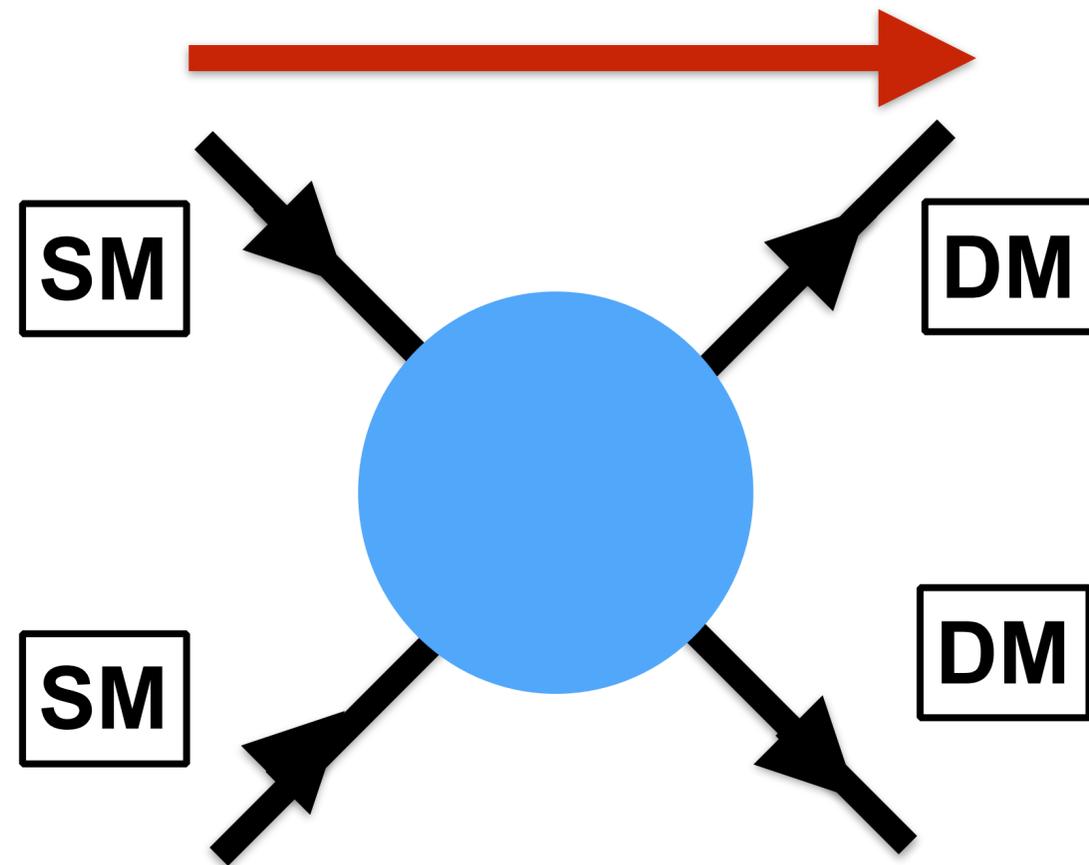
Experiments: ice-cube, super KK, PICO-2L ..etc



Collider Experiments

Collider experiments

Production of DM

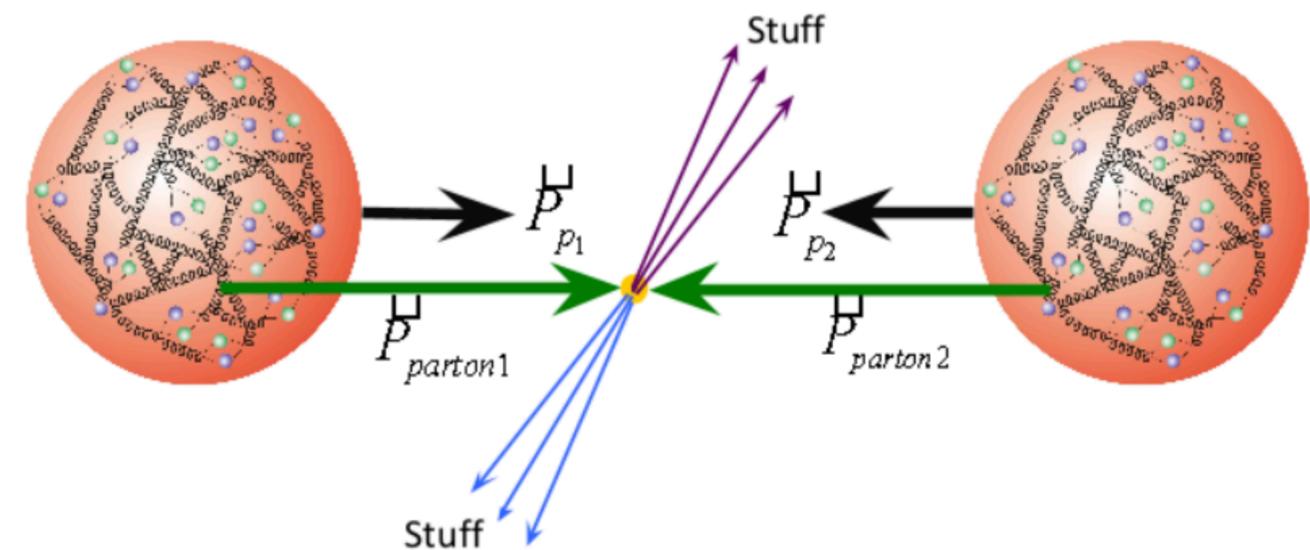
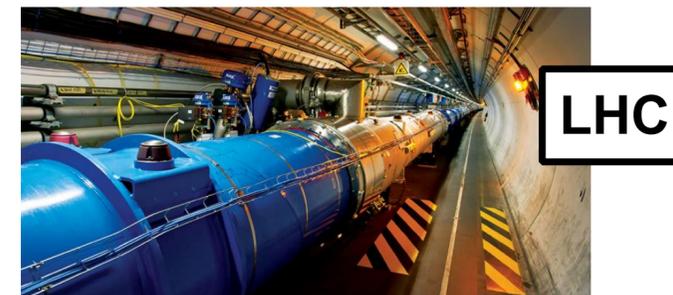


Hadron Colliders

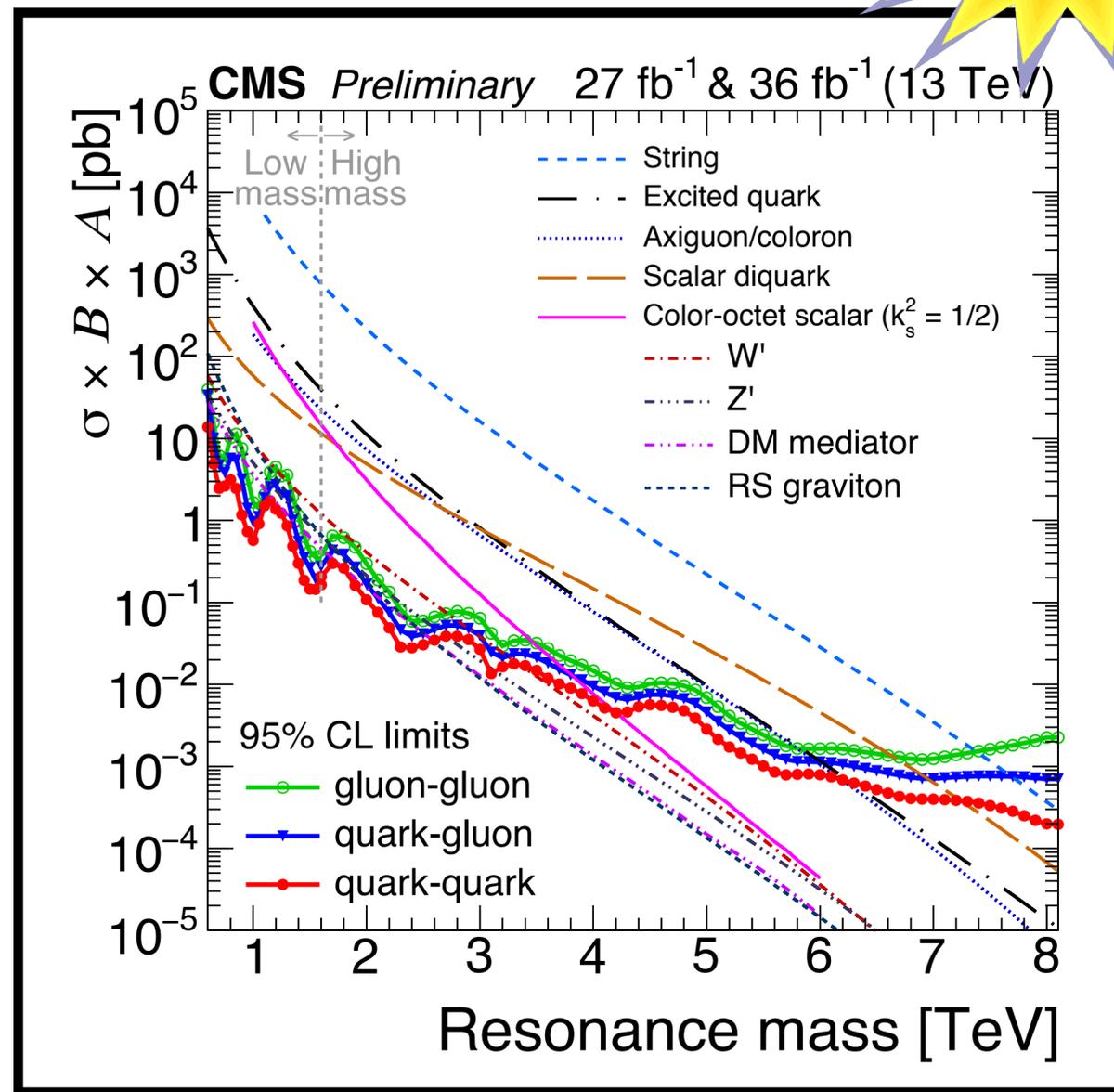
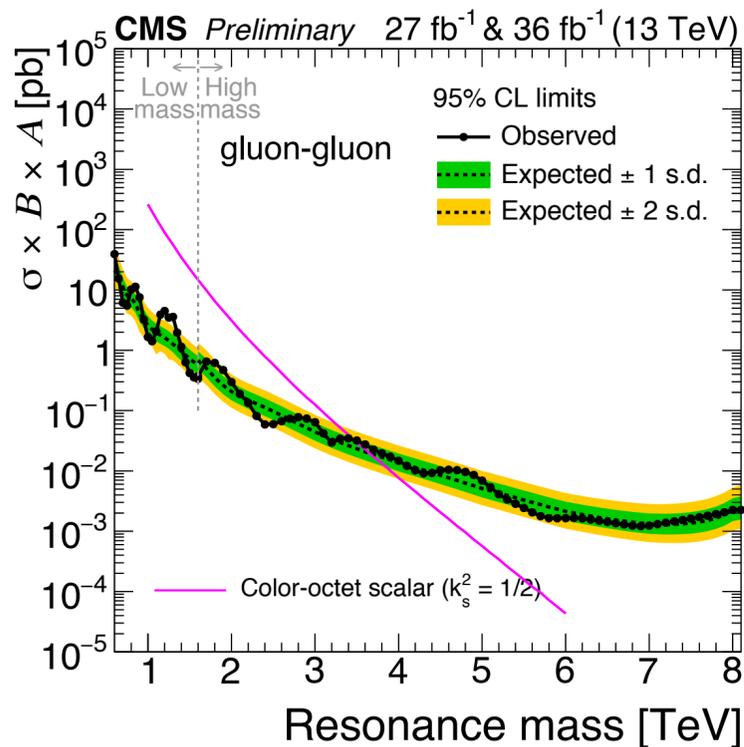
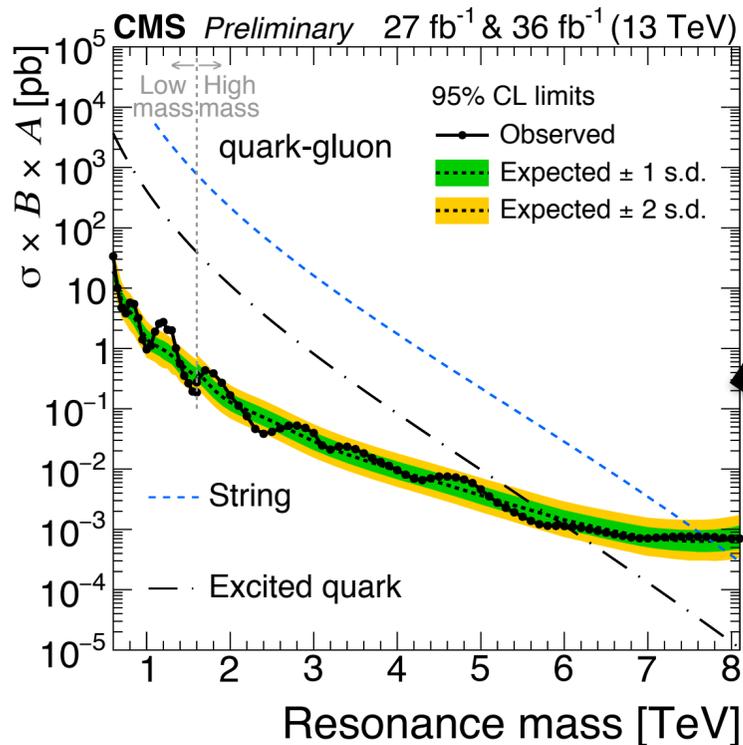
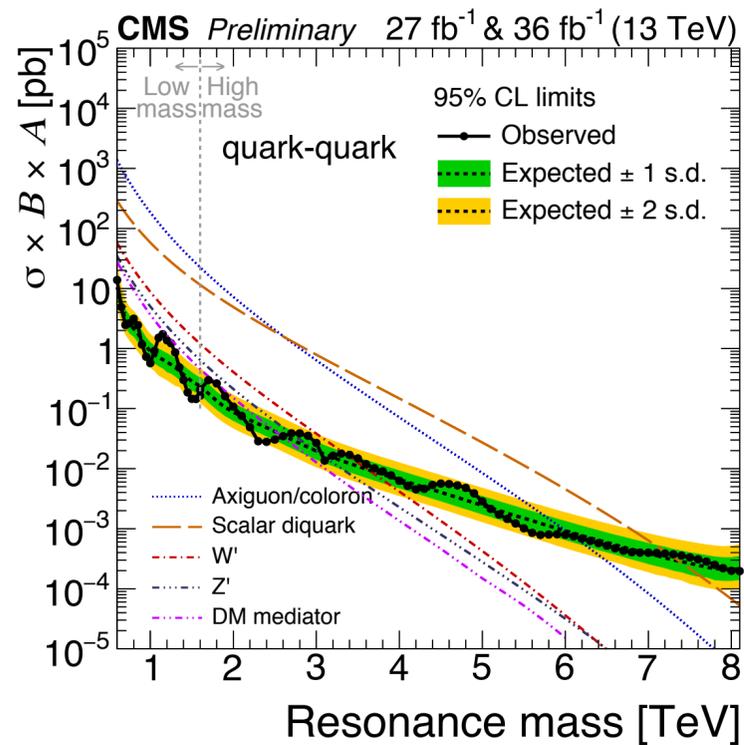
Production of **DM** in high energy **particle collisions**

DM leave the **detector w/o** release energy

DM may be **observed** as **missing transverse energy**

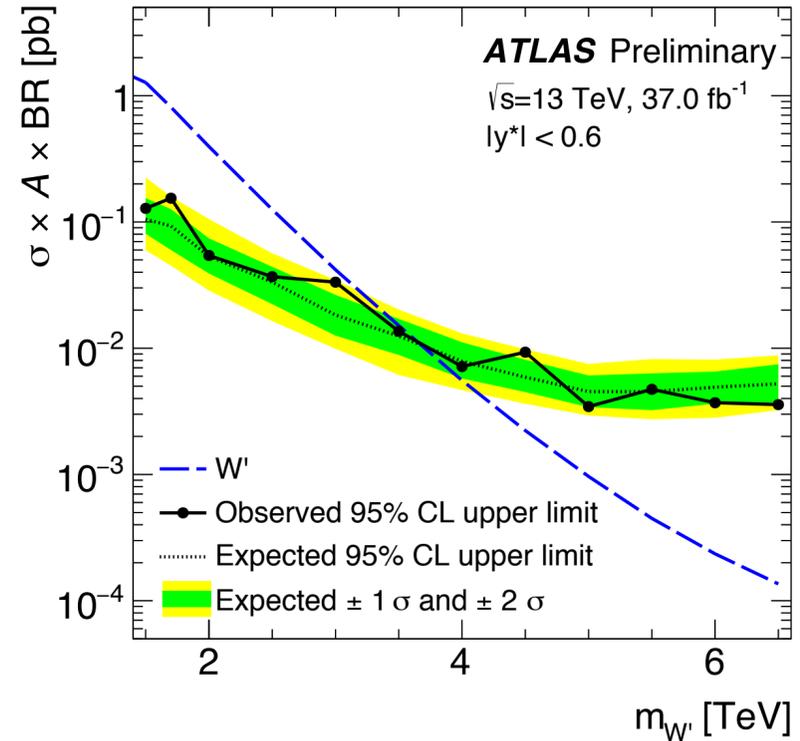
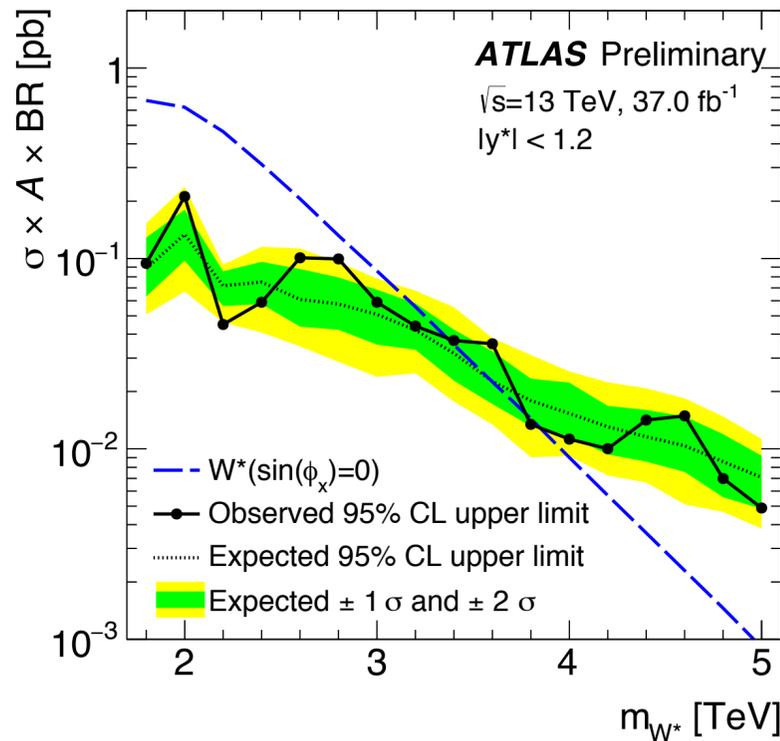
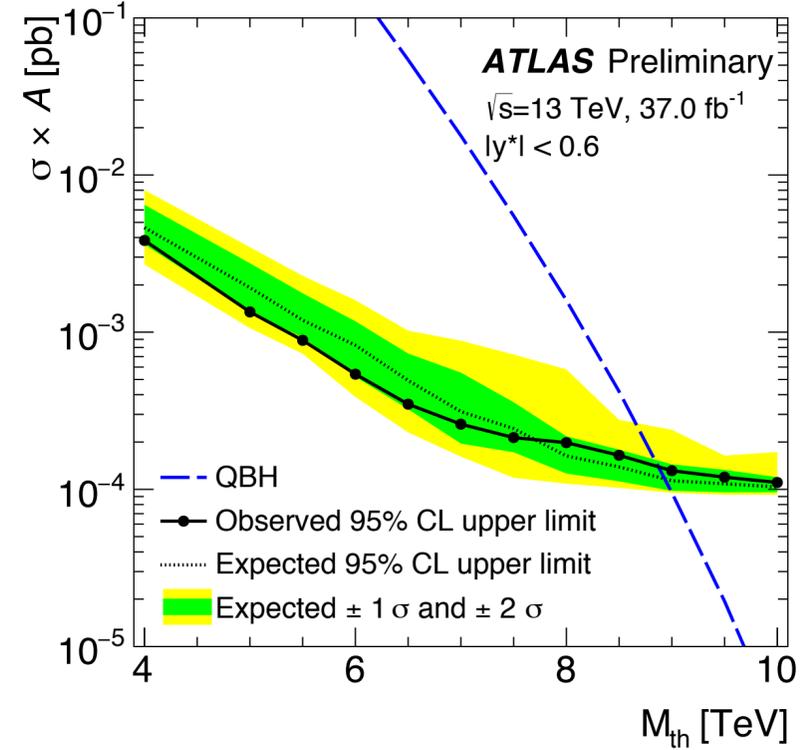
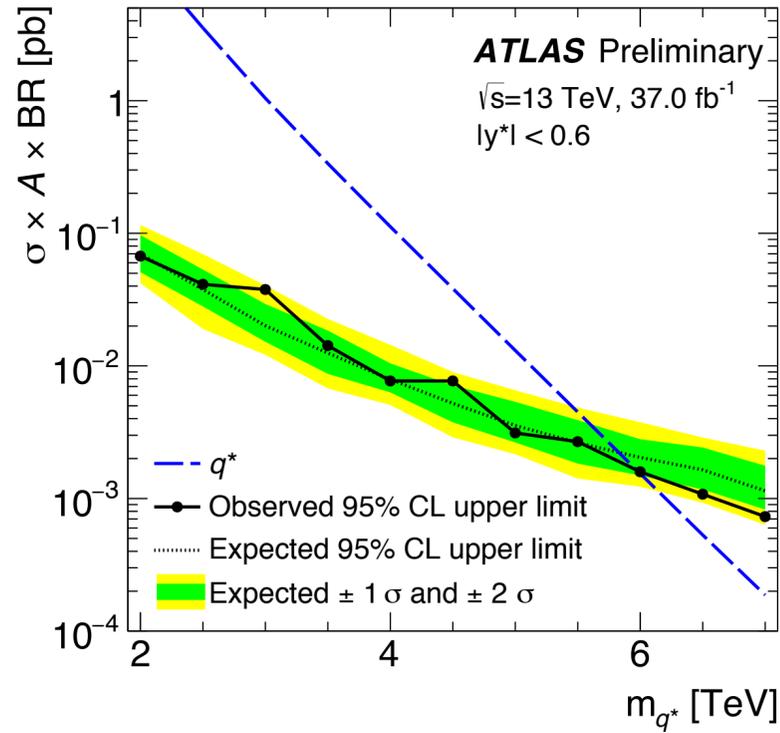


CMS dijet results



Cross section upper limit mainly depends on the partonic decay state which affects the lineshape model

ATLAS dijet results



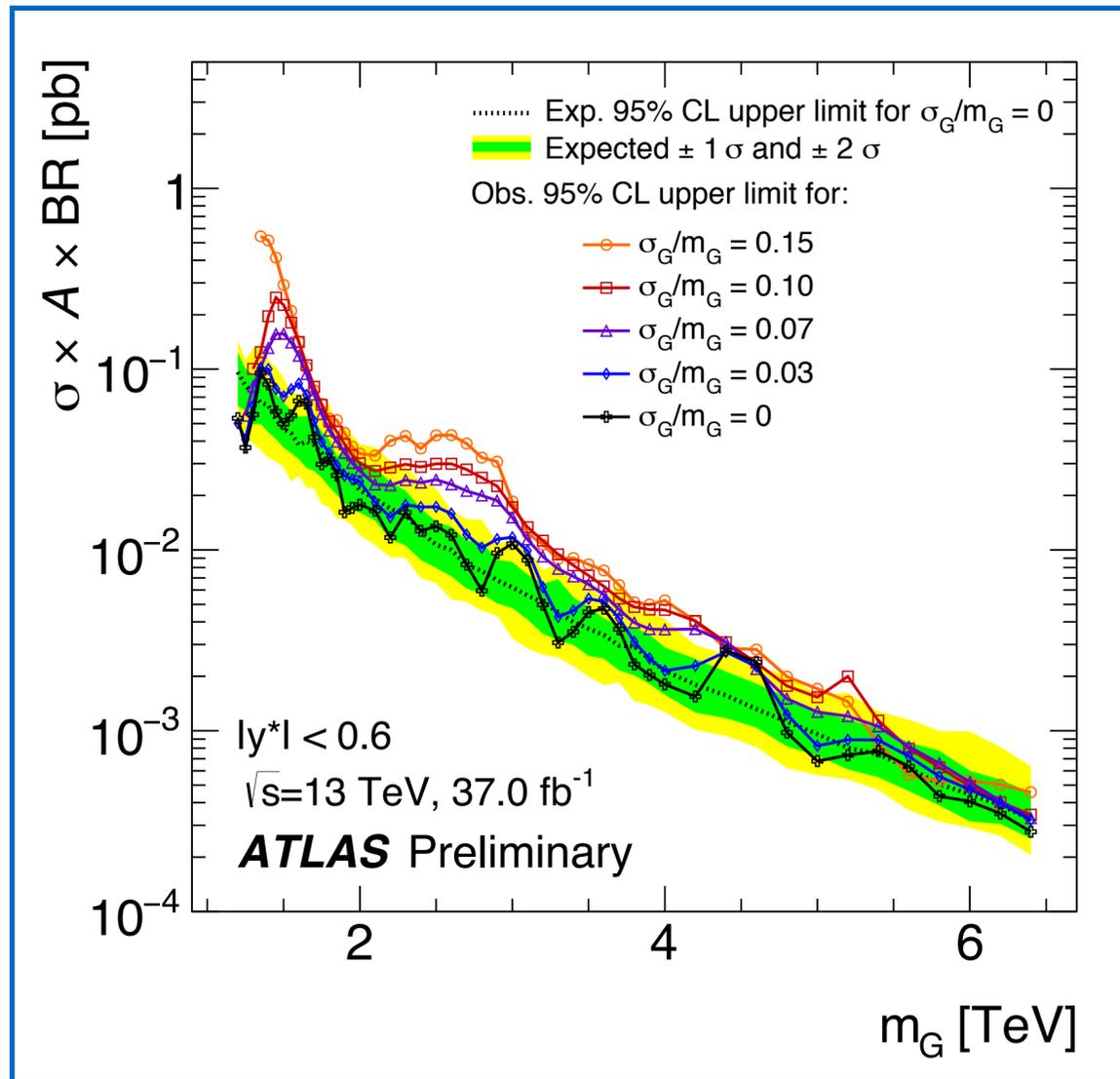
Benchmark models

- Excited quarks
- Extra gauge bosons W' , Z' and W^*
- QBH: RS Graviton and ADD
- **Model dependent limit cause assume a specific lineshape according to the model**

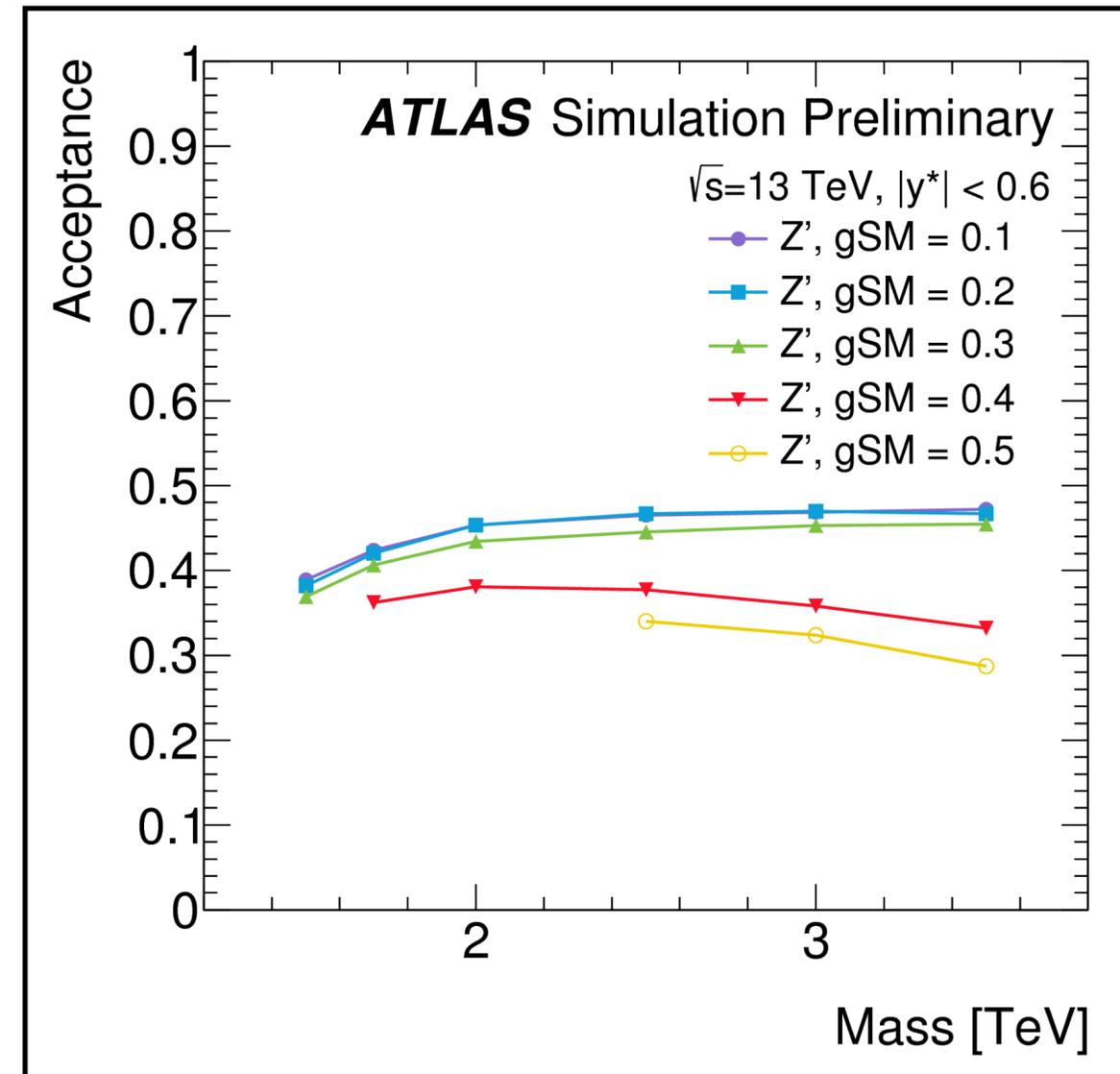
ATLAS dijet results



Model independent limit



Acceptance for Z' vs g_q

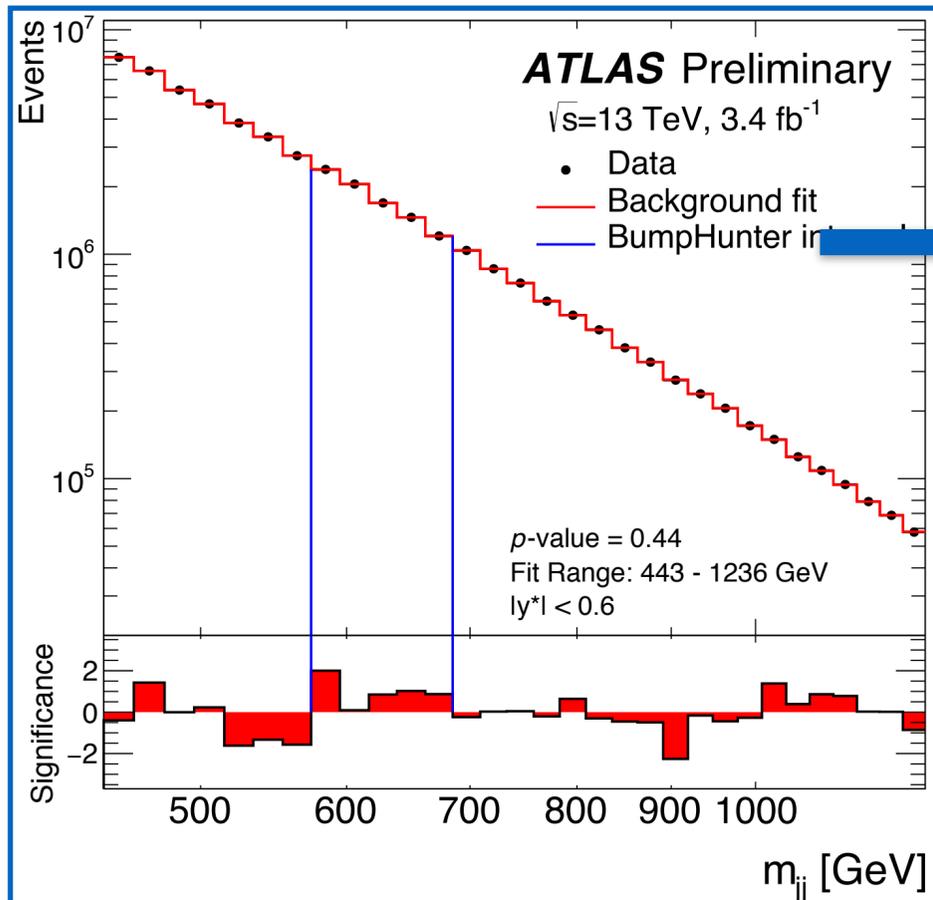


Gaussian core lineshape assumed
95% upper limits for vs intrinsic width

Trigger level analysis

- **Goal:** have access to a **lower mass range** performing a **trigger object based analysis**
 - **Lower thresholds** on leading/subleading jets as well as jet- $H_T \rightarrow$ **increase the trigger rate**
 - **Reduce the event content** to fit in the **bandwidth budget** \rightarrow **store and perform analysis on trigger objects**

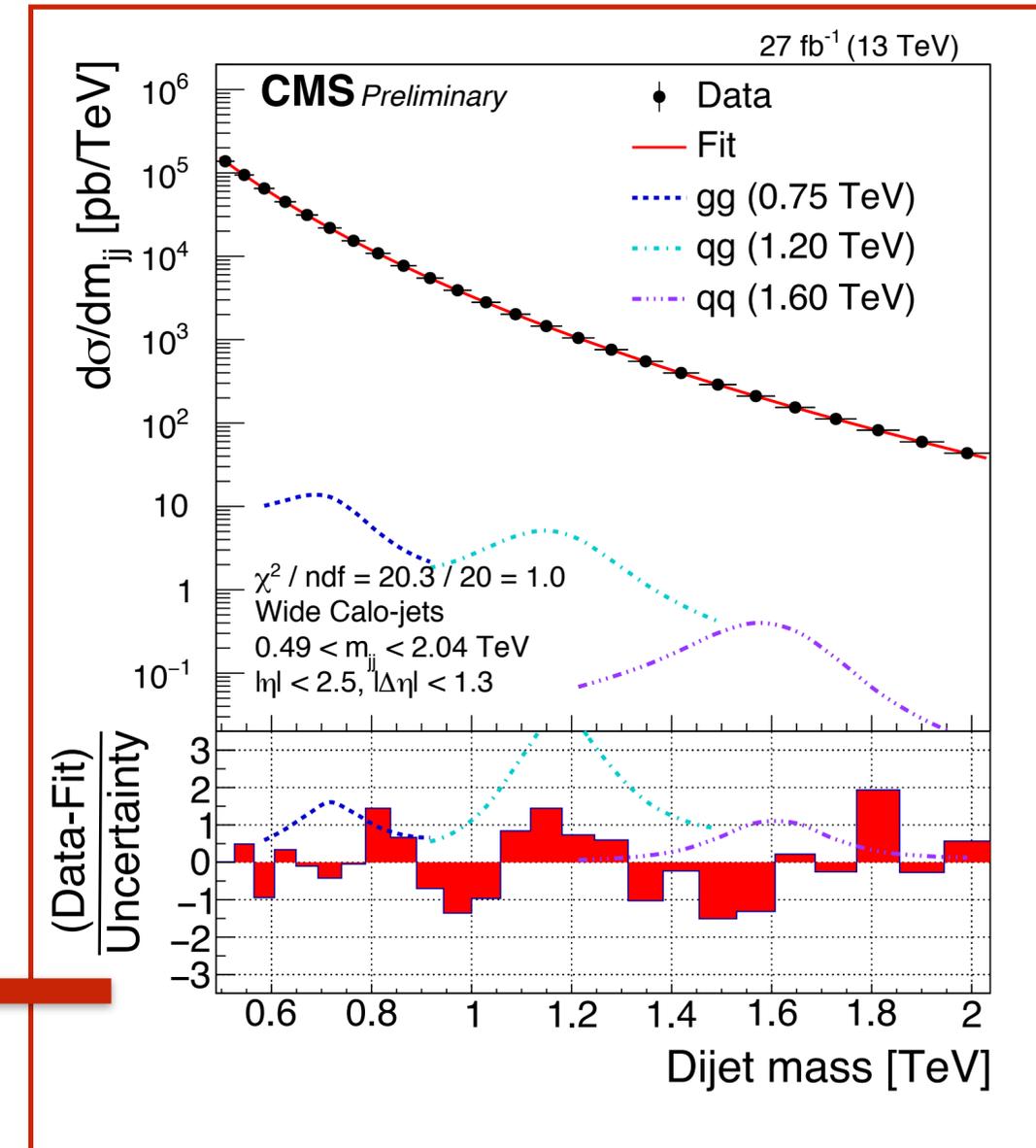
ATLAS-CONF-2016-030



• Selections:

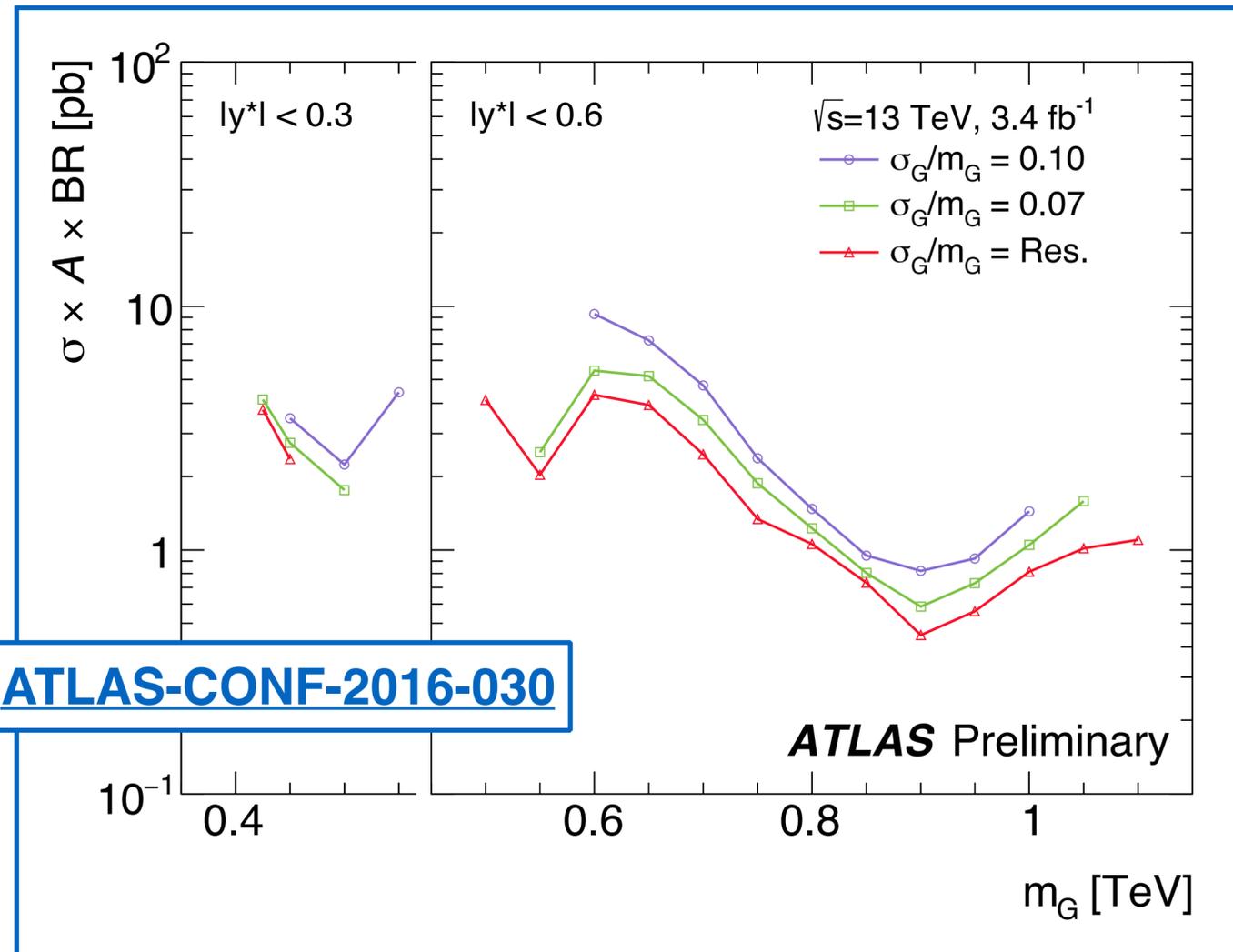
- L1 jet with $E_T > 75$ GeV
- Two jets at HLT with $p_T > 85$ GeV, $|\eta| < 2.8$
- Offline: $p_T > 185$ GeV $|y^*| < 0.6$
- y^* selection helps in having a better turn-on
- Smooth background with analytical function

- Analysis performed on calo-jets @ HLT
- Trigger: $H_T > 250$ GeV (p_T jet > 40 GeV)
- $m_{jj} [450, 1.6]$ TeV, $|\Delta\eta_{jj}| < 1.3$

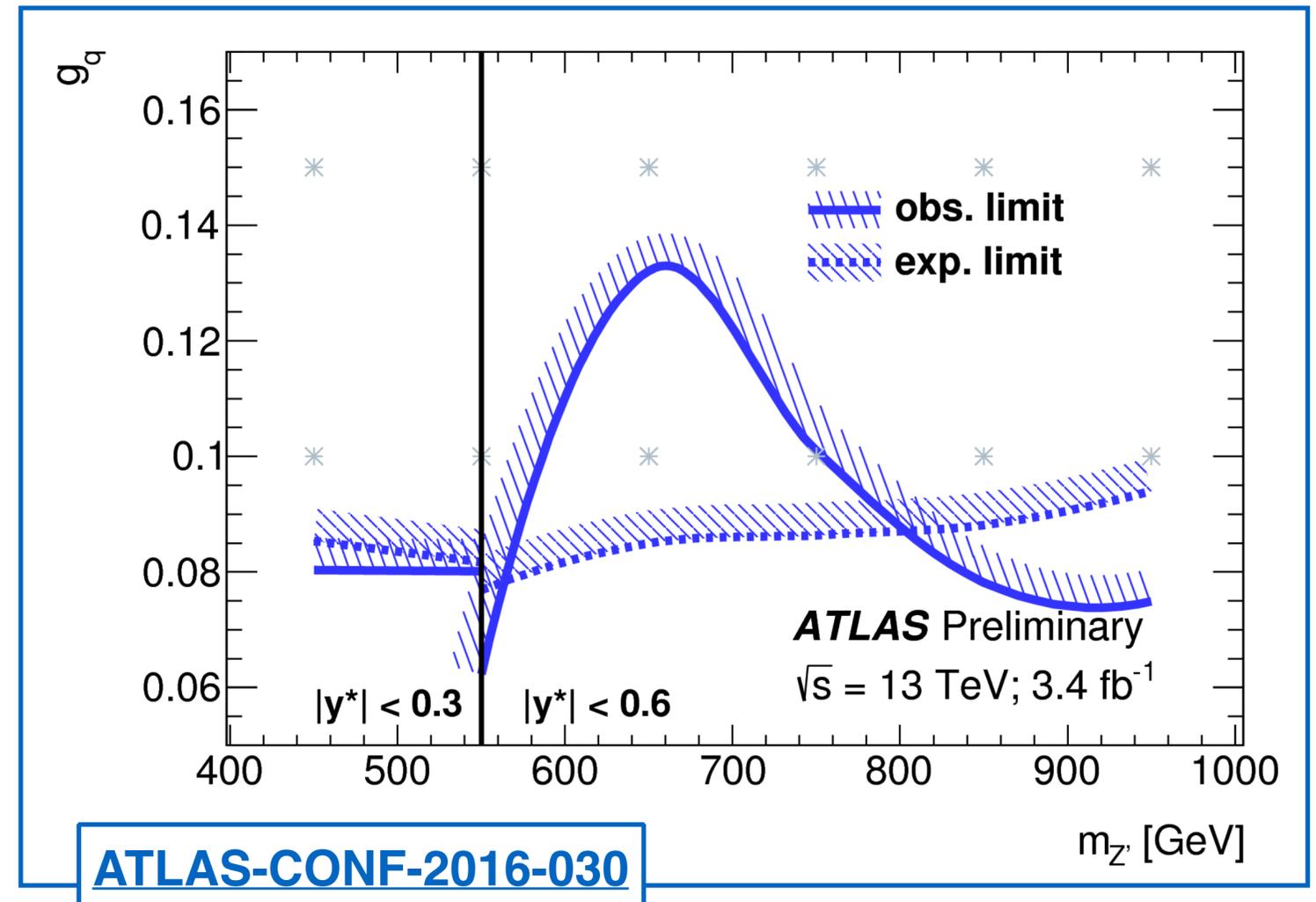


ATLAS TLA analysis

Model independent limit for narrow gaussian resonances

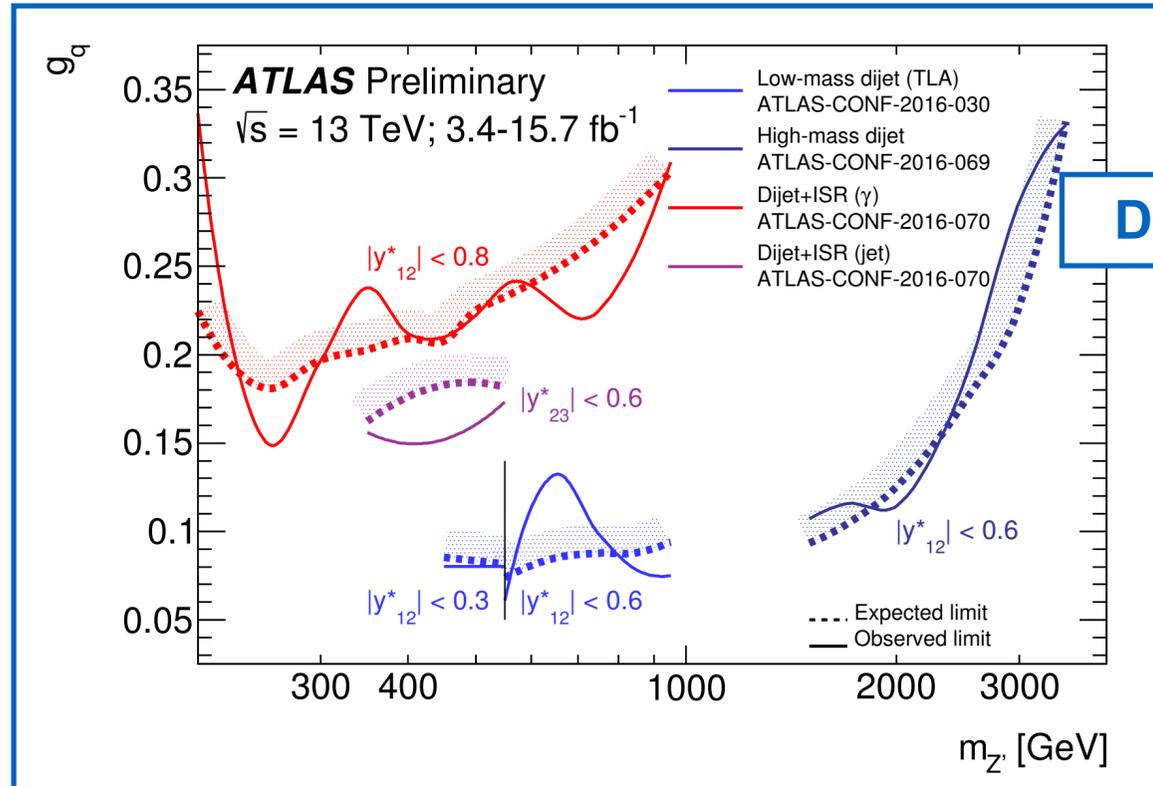


Coupling exclusion for Z' leptophobic

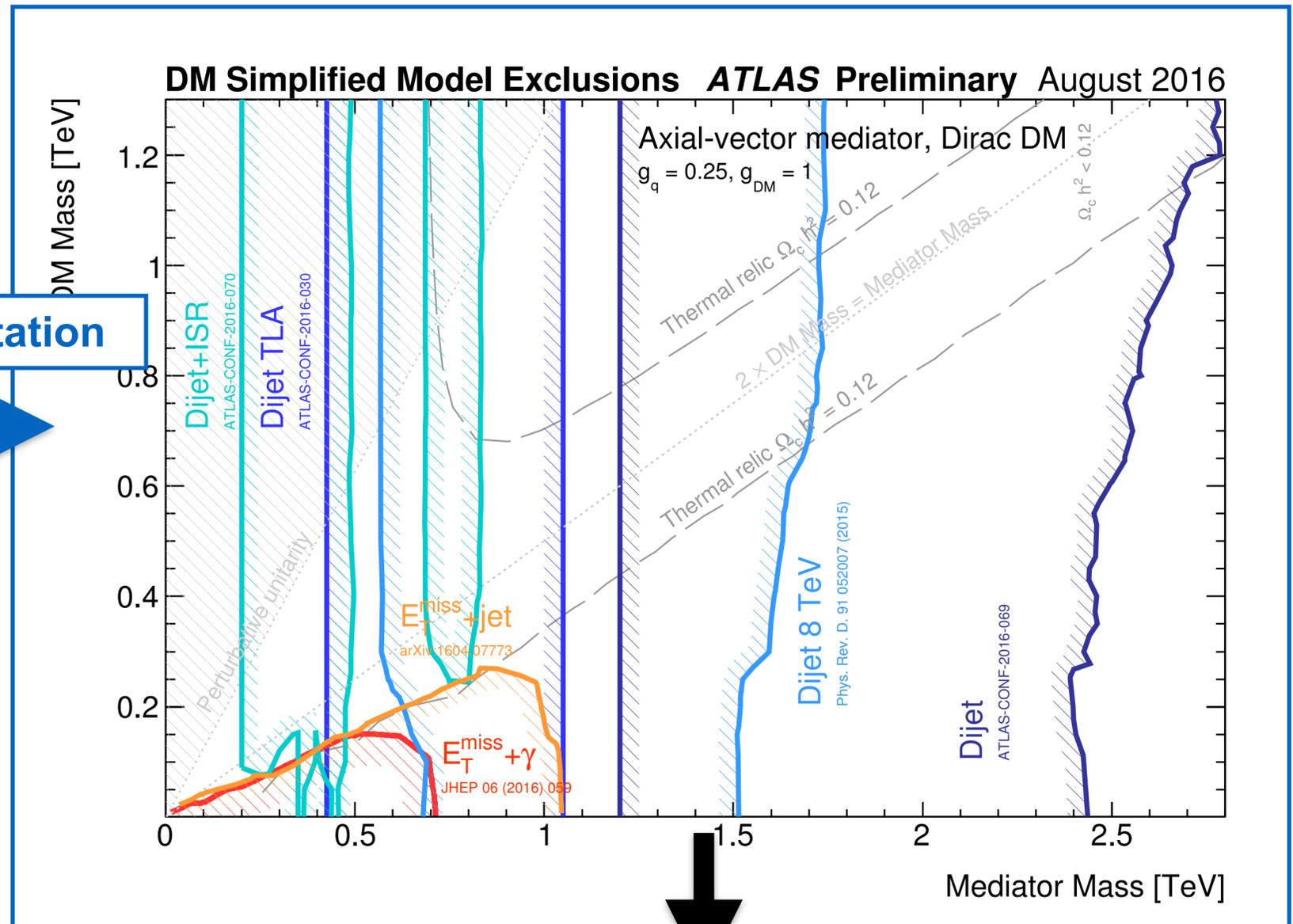


ATLAS: direct vs indirect DM searches

Summary of $Z' \rightarrow$ dijet ATLAS searches



DM Interpretation

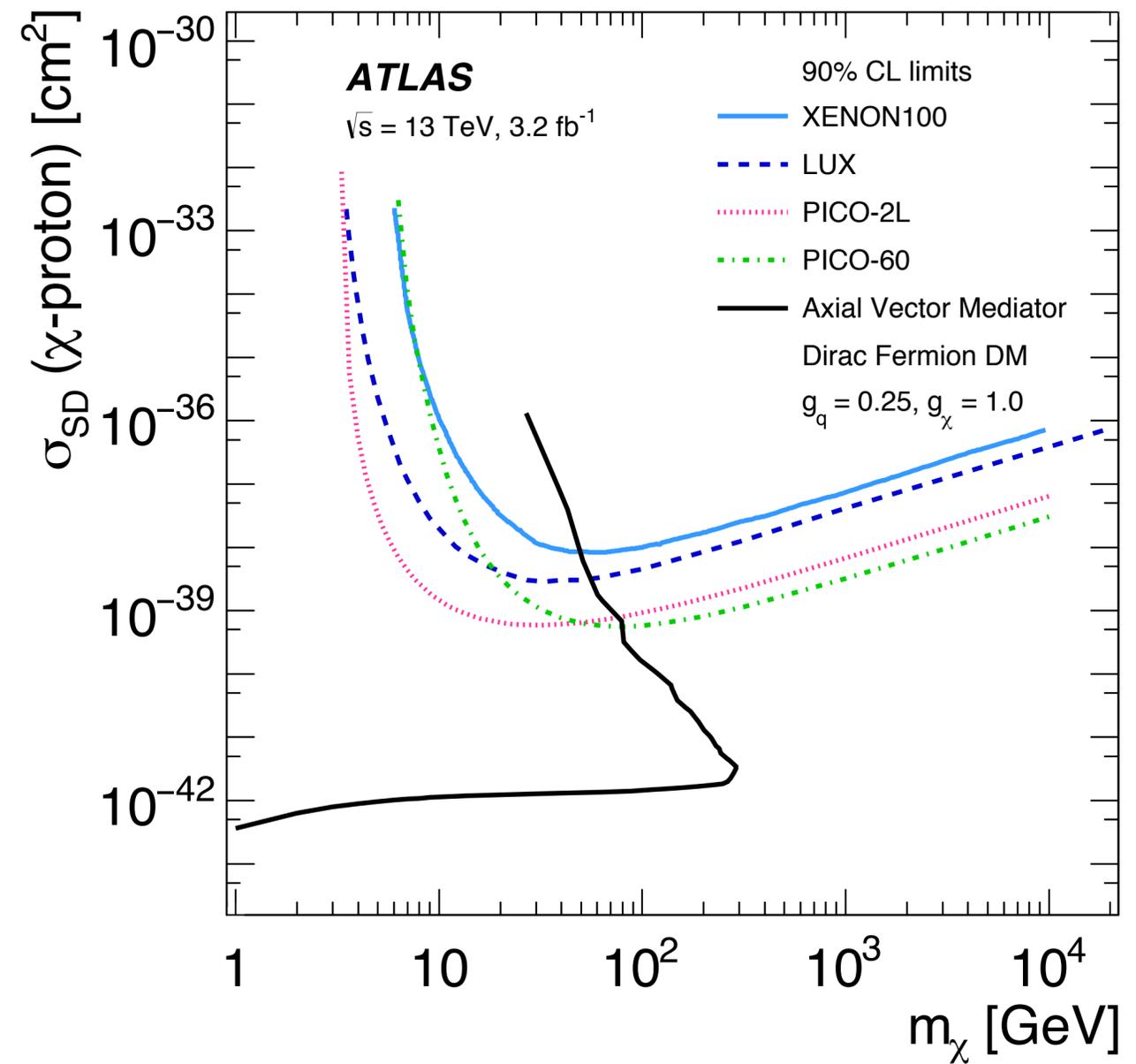
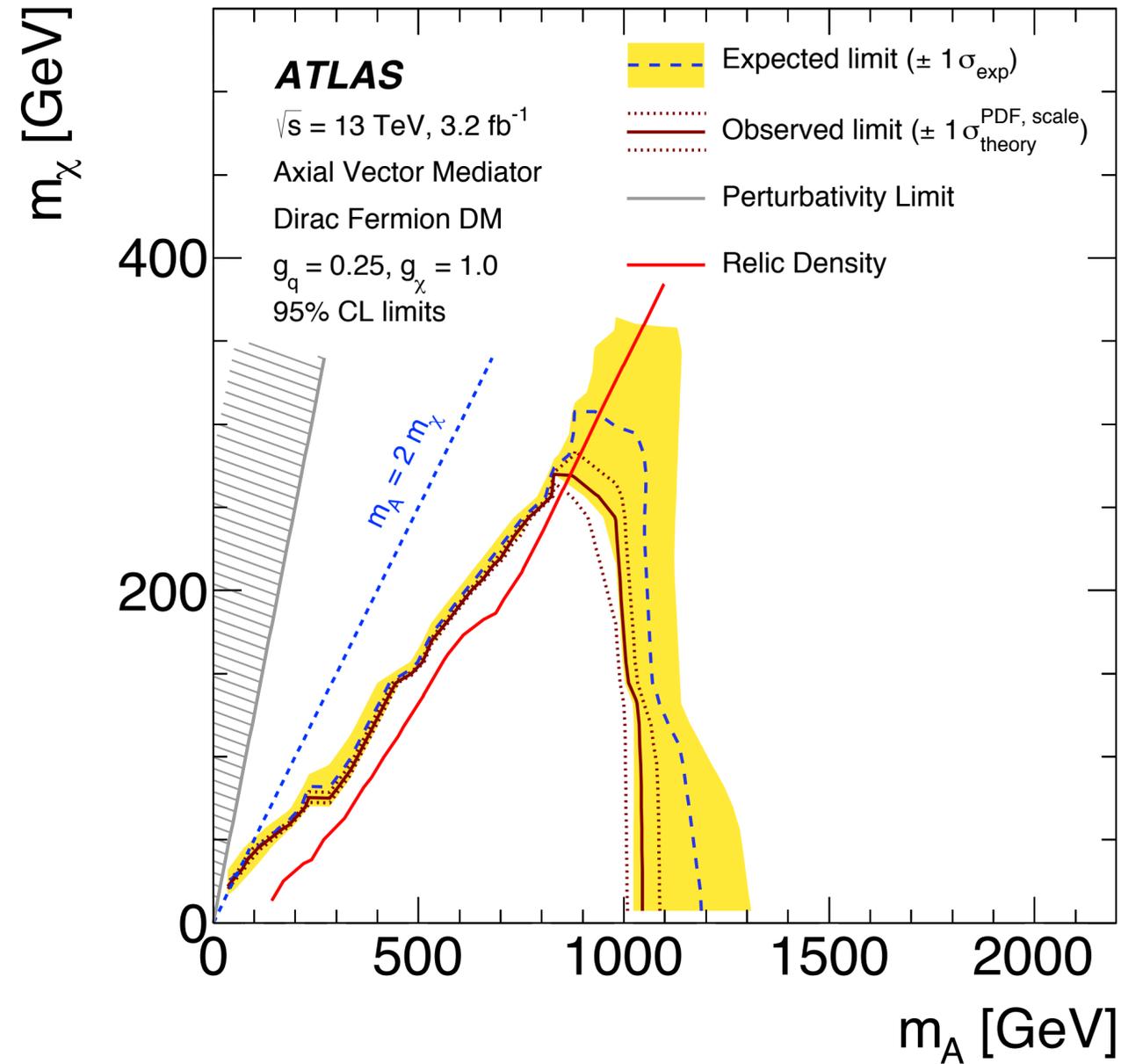


Benchmark: Axial-Vector mediator with $g_q = g_{\text{SM}} = 0.25$ and $g_{\text{DM}} = 1$

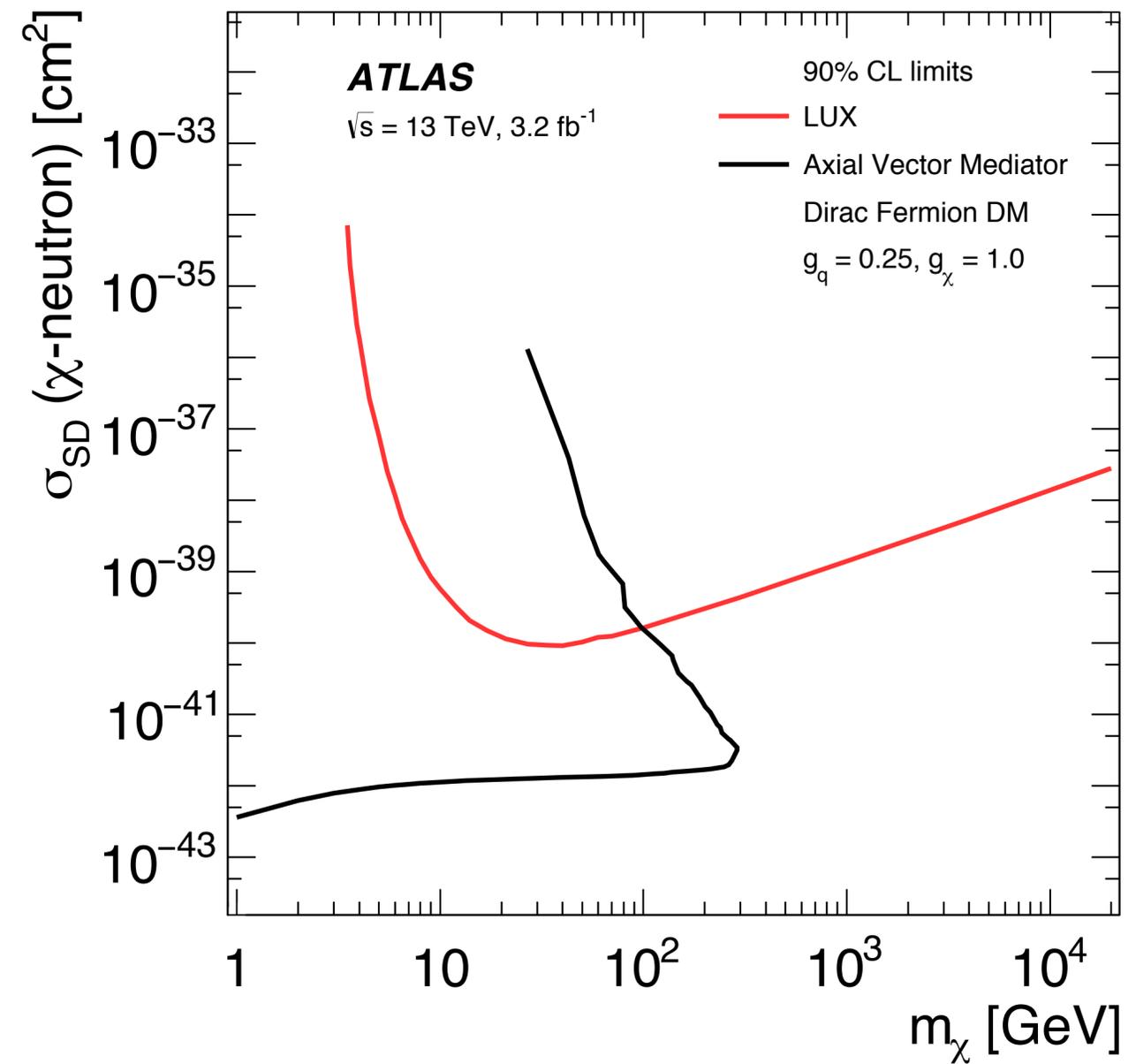
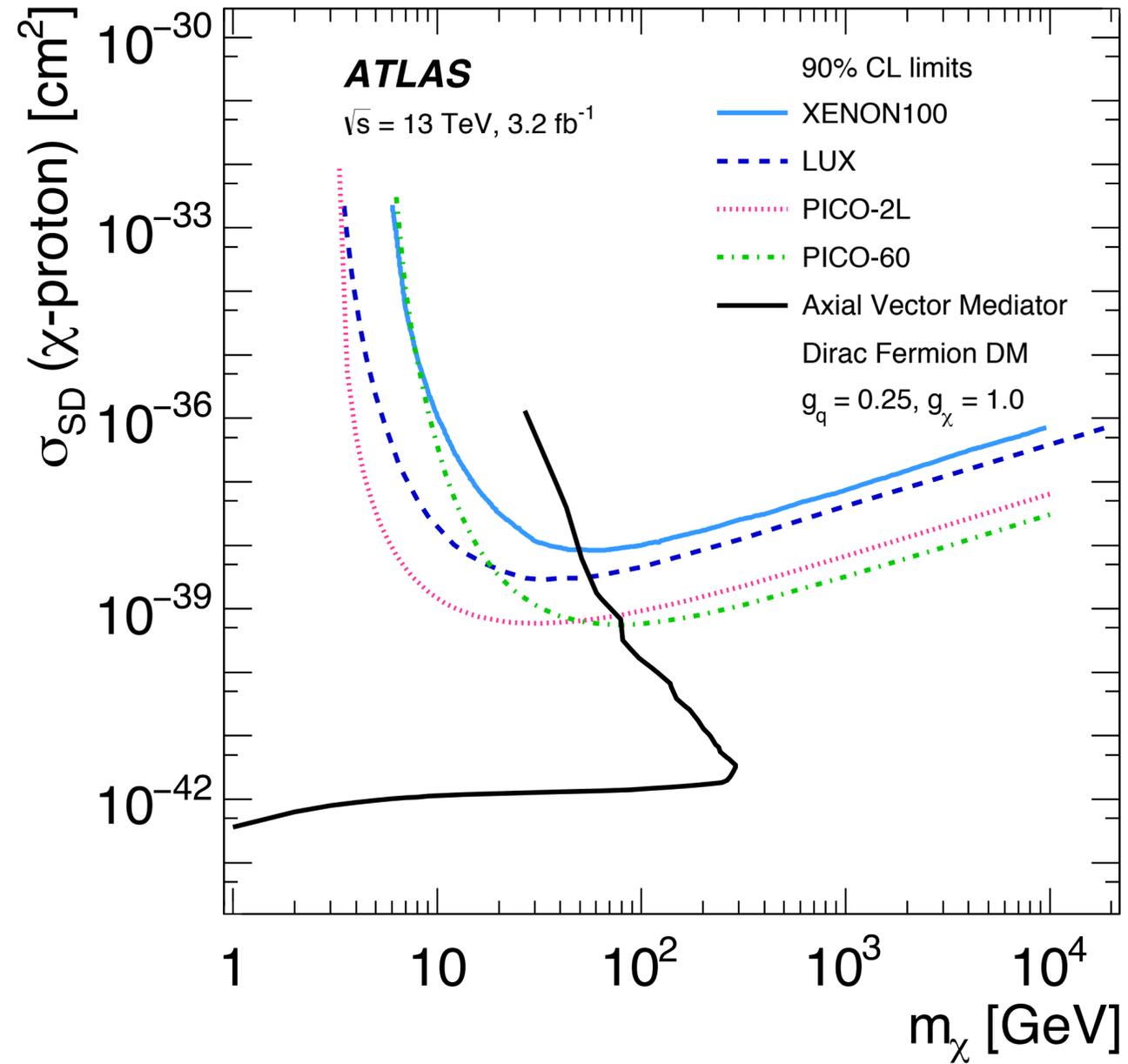
Comparison between direct DM searches in $E_T^{\text{miss}} + \text{jet}$ and $E_T^{\text{miss}} + \gamma$ and dijet bounds

Given the coupling choice \rightarrow **dijet bounds** are **much stronger** than **direct ones** in the on-shell region

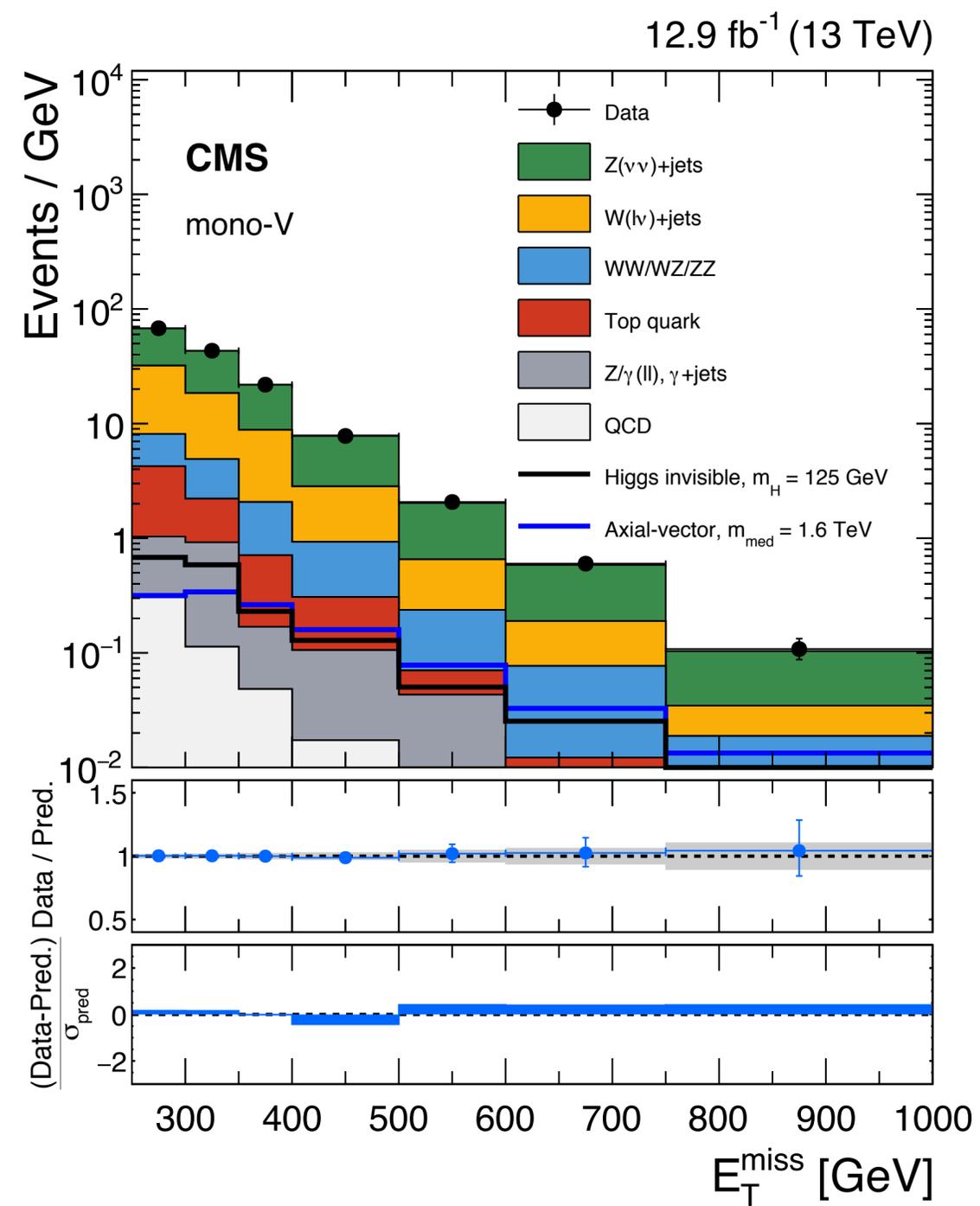
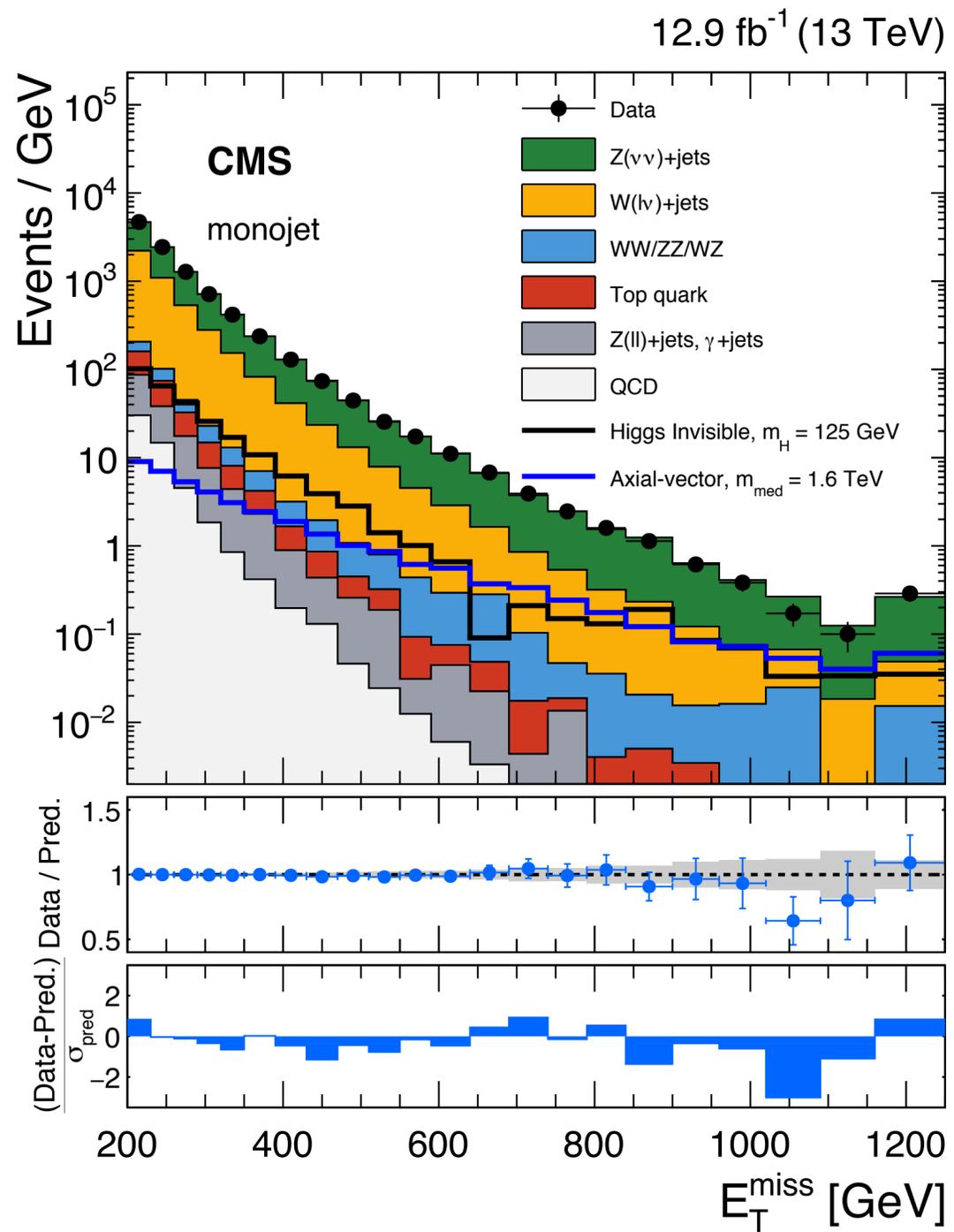
monojet ATLAS



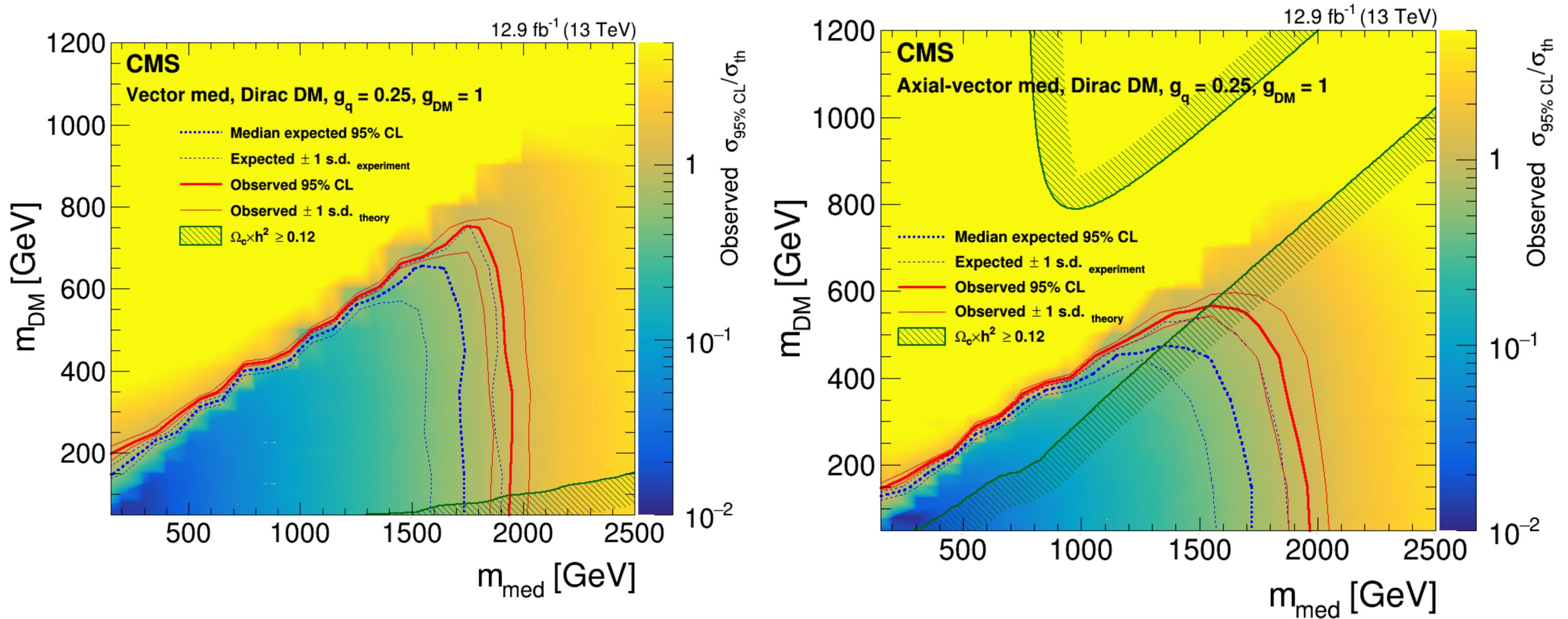
monojet ATLAS



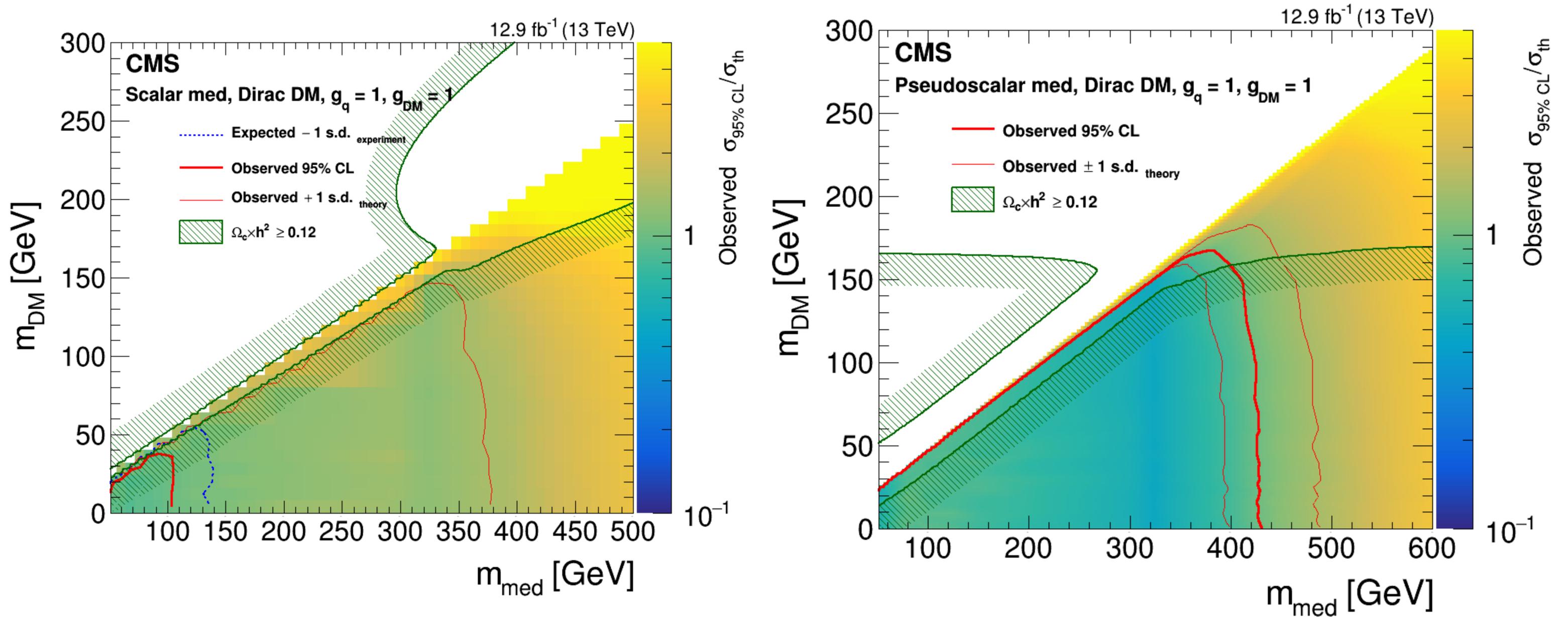
monojet CMS



monojet CMS



monojet CMS

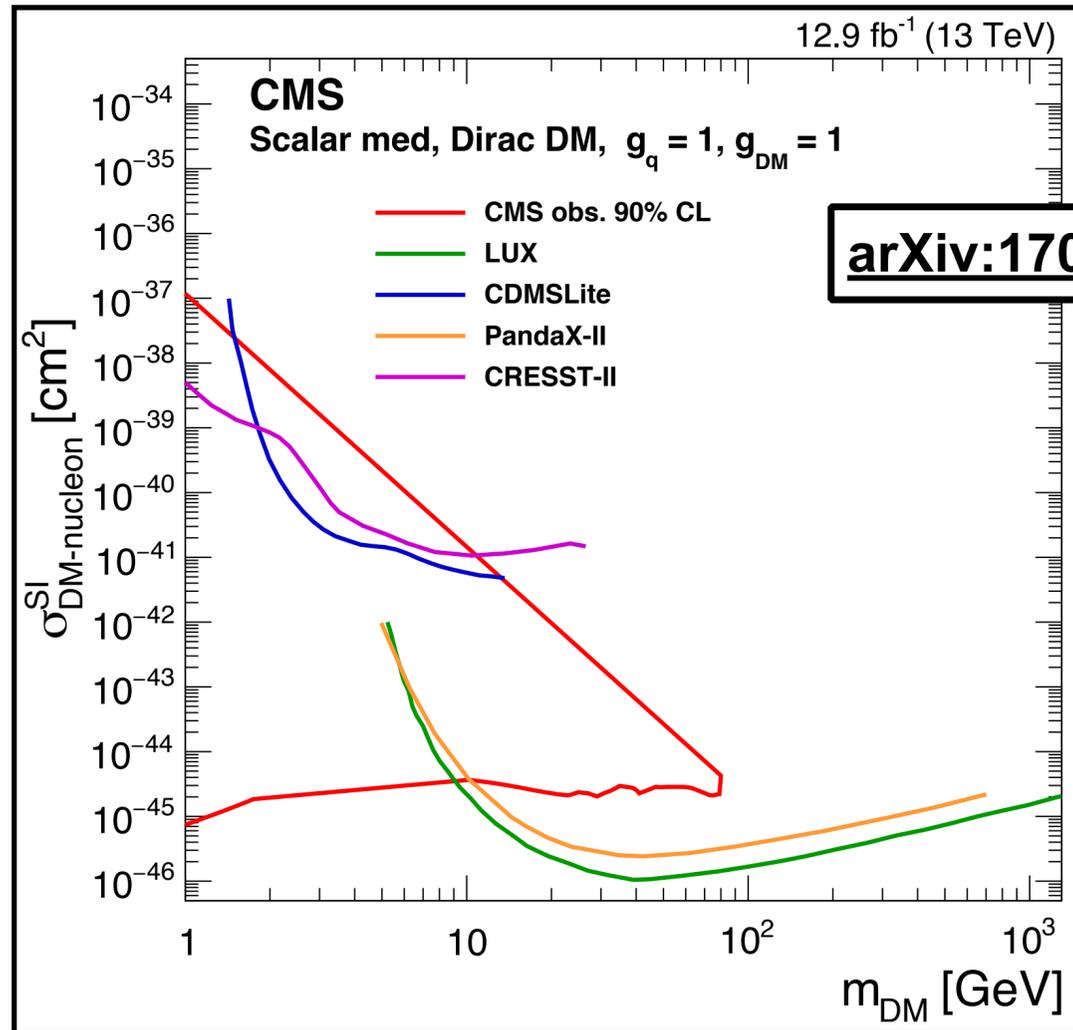


Scalar and PseudoScalar DD limits

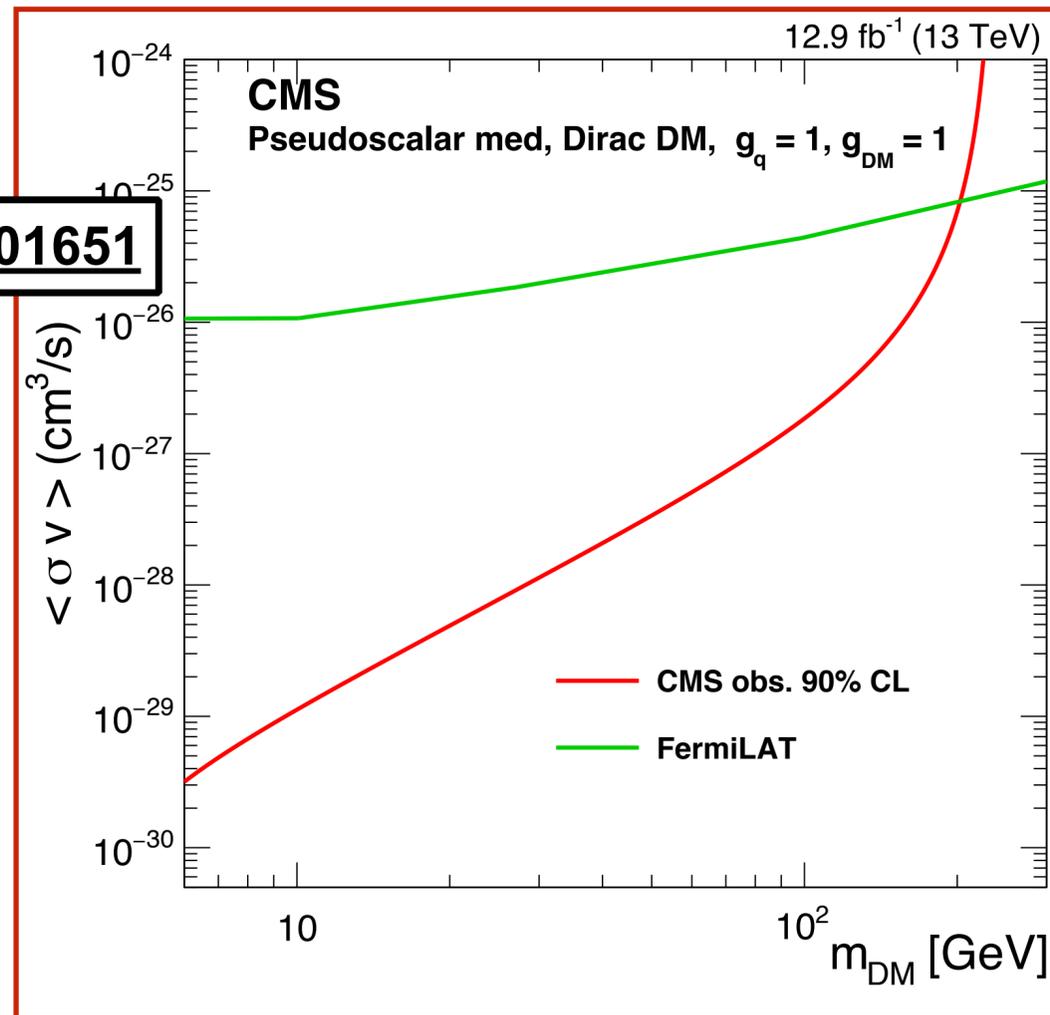
- Collider results are compared to direct detection experiments as 90% CL upper limits on DM-nucleon cross section
- Exclusion in $(m_{\text{MED}}, m_{\text{DM}})$ translated into spin-independent / spin-dependent cross section via ([arXiv:1407.8257](https://arxiv.org/abs/1407.8257))

$$\sigma_{\text{SI}}^0 = \frac{9 g_{\text{DM}}^2 g_q^2 \mu_{n\chi}^2}{\pi M_{\text{med}}^4} \longrightarrow \text{Vector/Scalar interaction}$$

$$\sigma_{\text{SD}}^0 = \frac{3 g_{\text{DM}}^2 g_q^2 (\Delta_u + \Delta_d + \Delta_s)^2 \mu_{n\chi}^2}{\pi M_{\text{med}}^4} \longrightarrow \text{Axial/Pseudo-scalar}$$



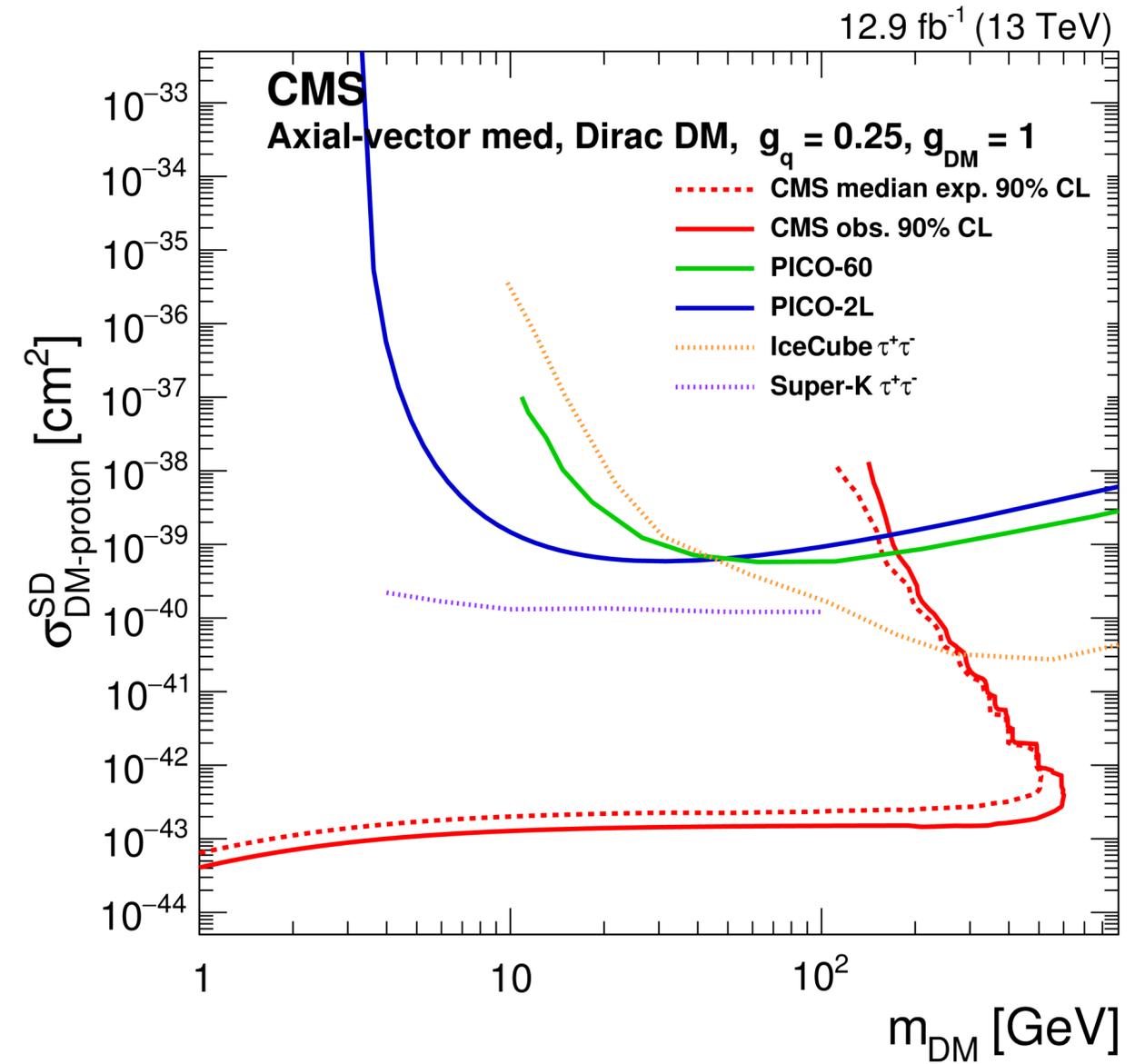
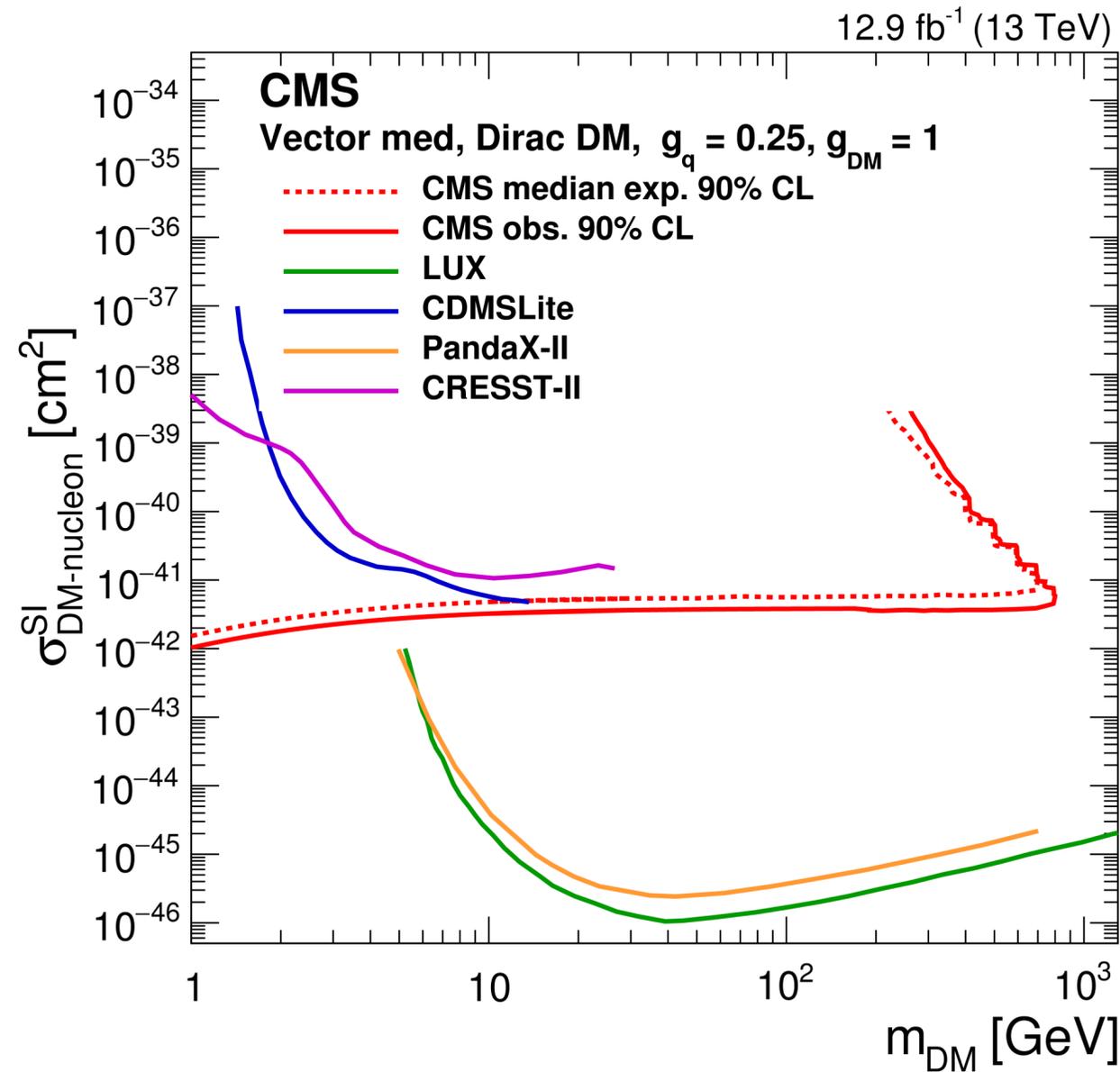
[arXiv:1703.01651](https://arxiv.org/abs/1703.01651)



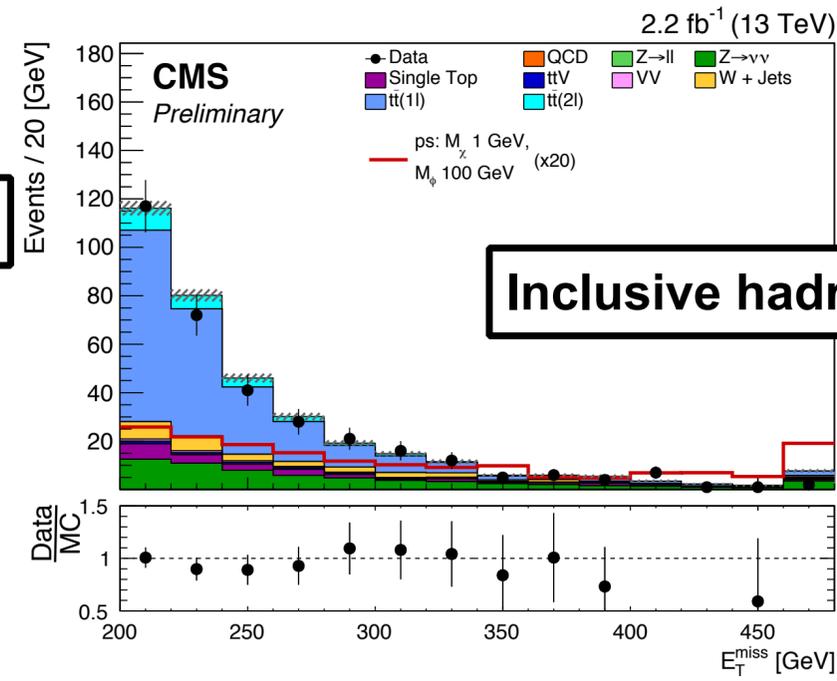
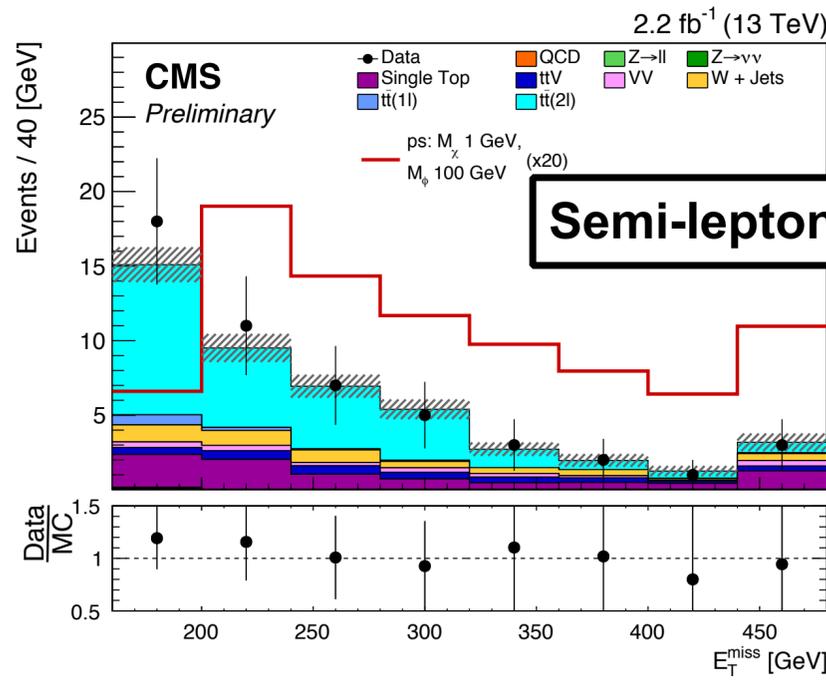
Collider searches provides strongest limits for spin-independent DM-nucleon cross section for low DM masses, i.e. < 10 GeV

Collider searches provides strongest limits for annihilation cross section from Fermi-LAT

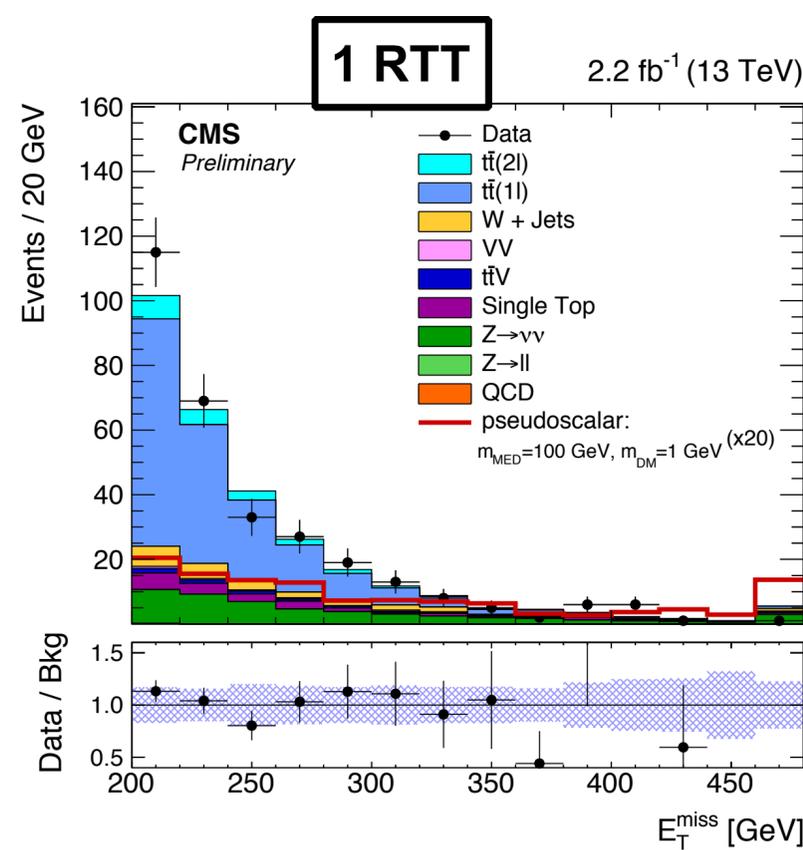
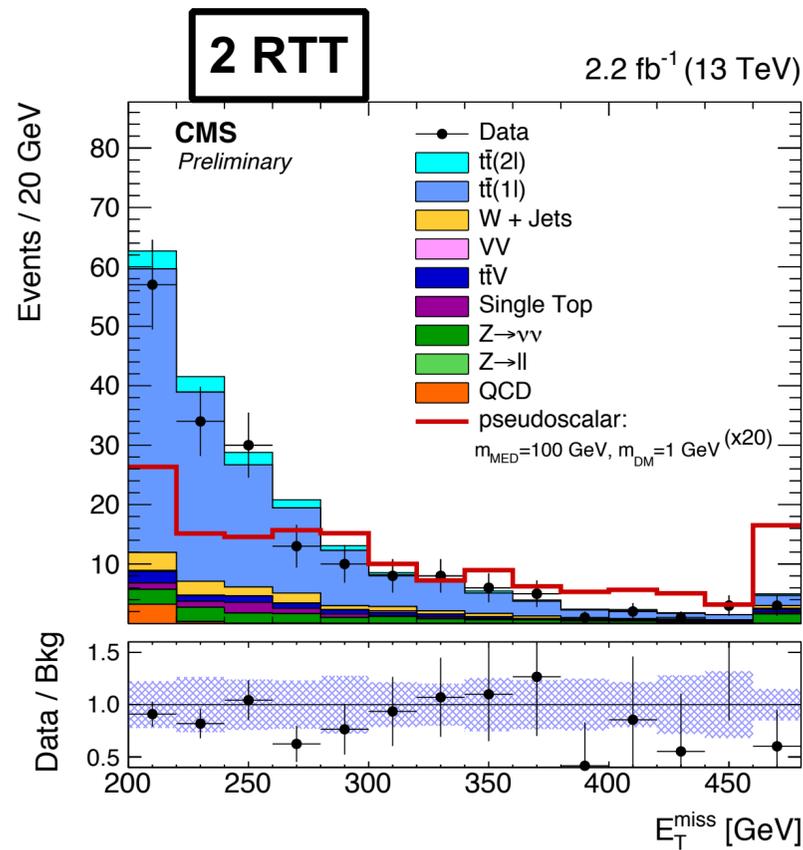
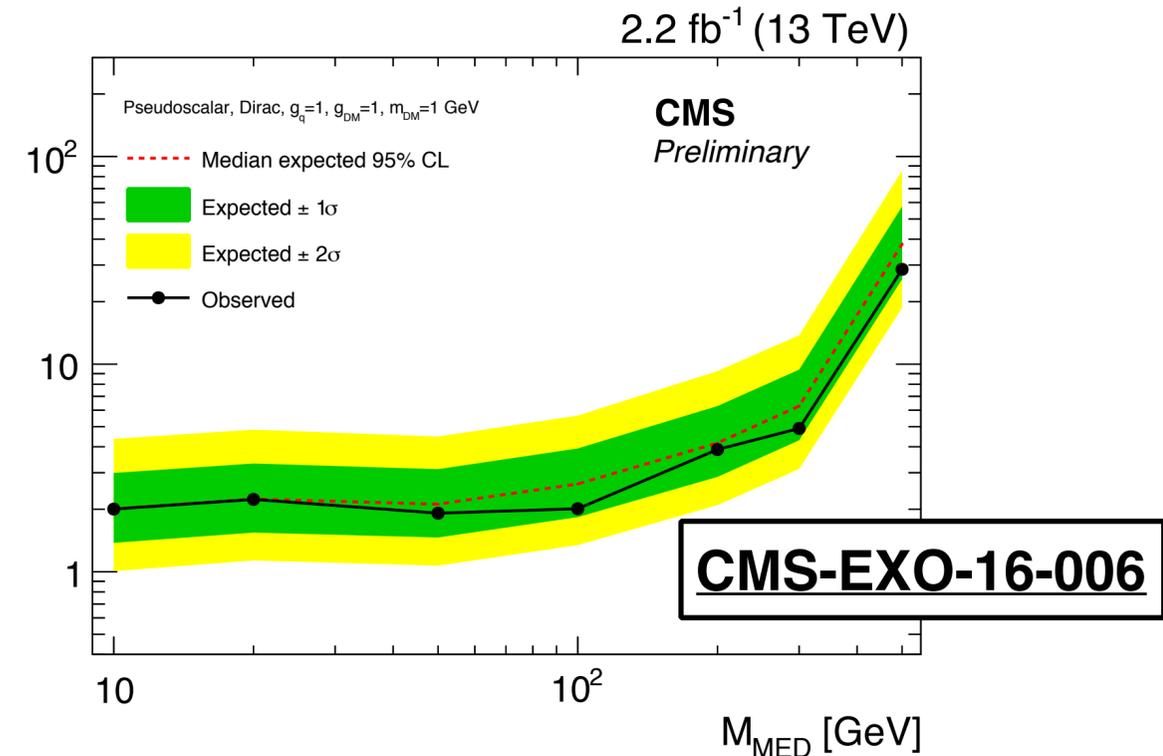
monojet CMS: DD limits



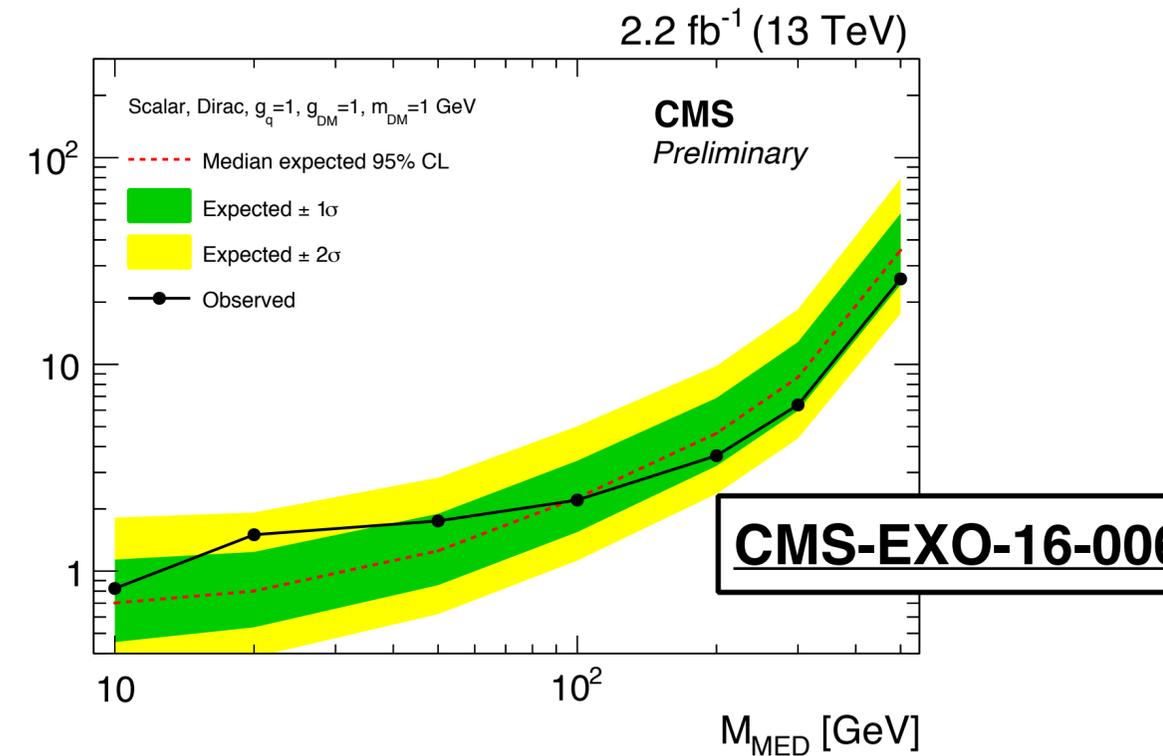
CMS $t\bar{t}$ +DM



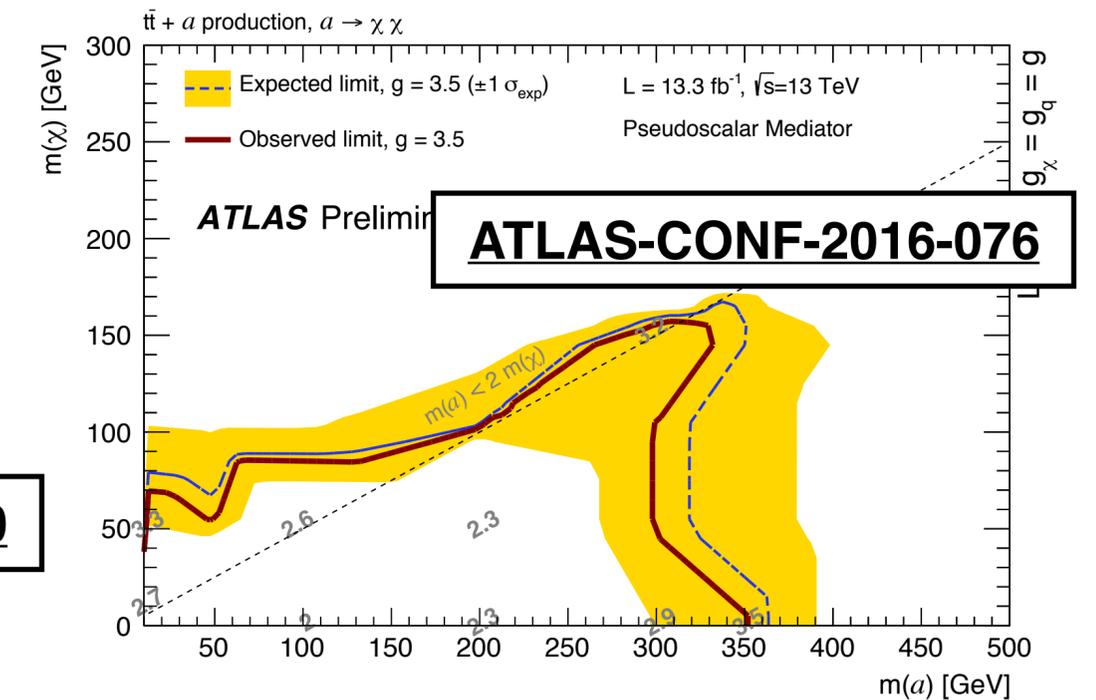
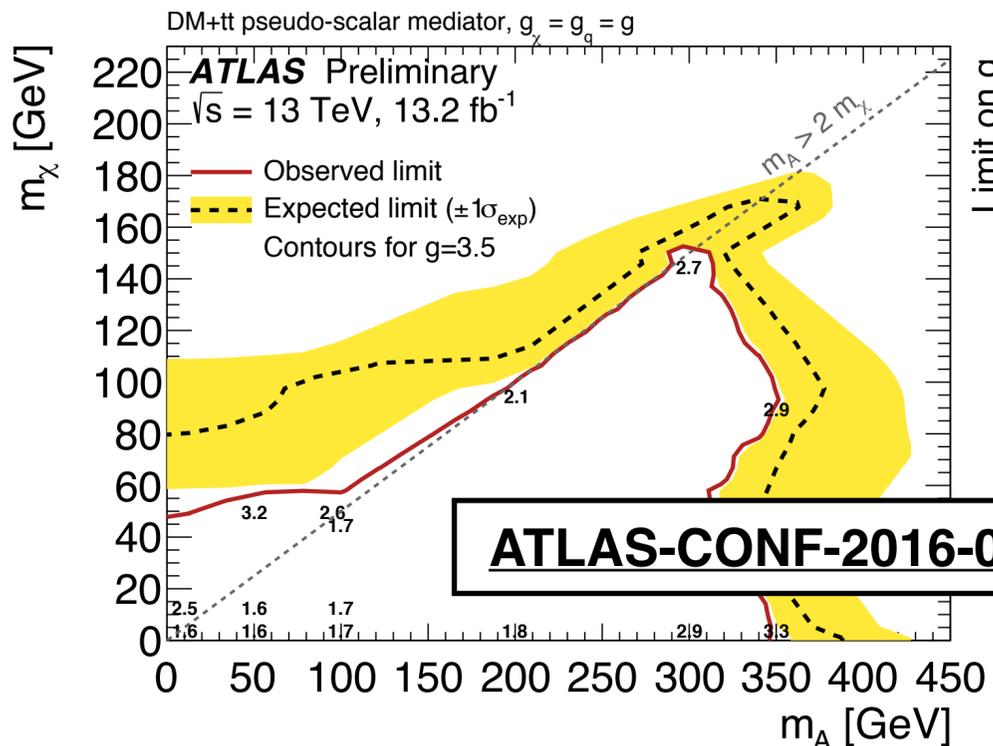
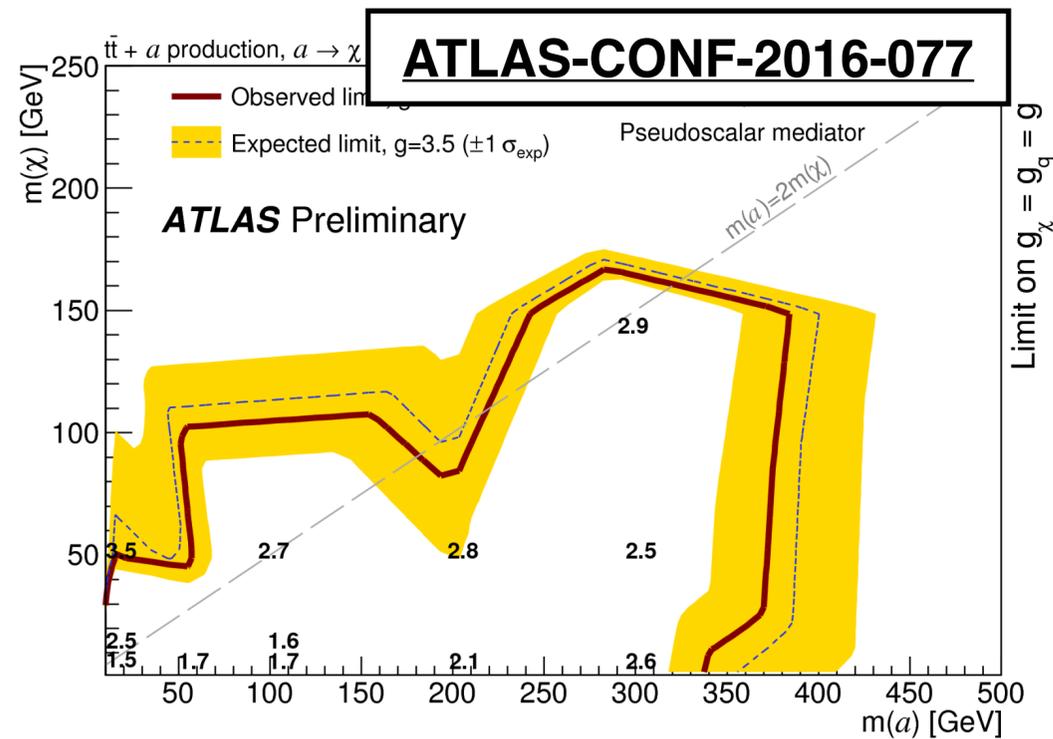
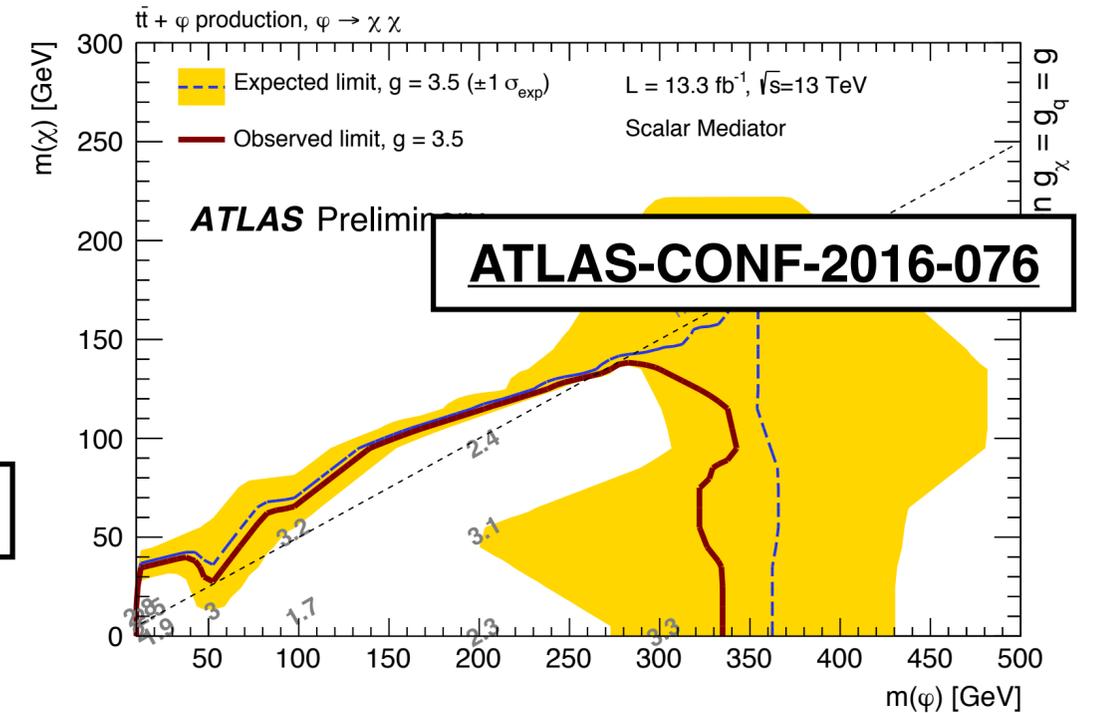
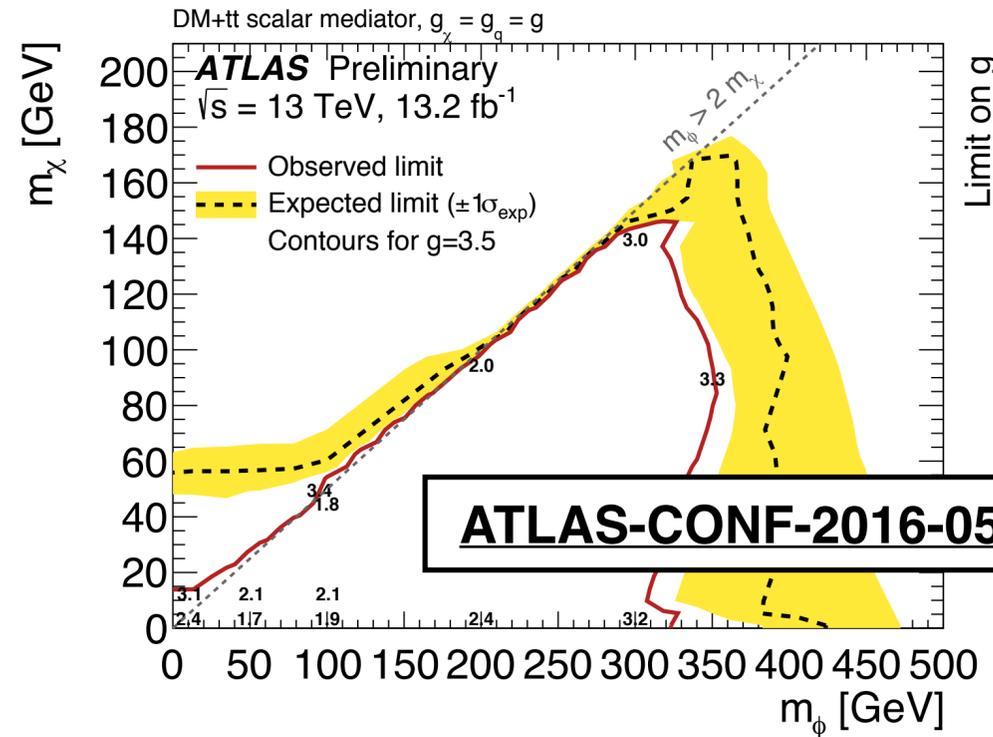
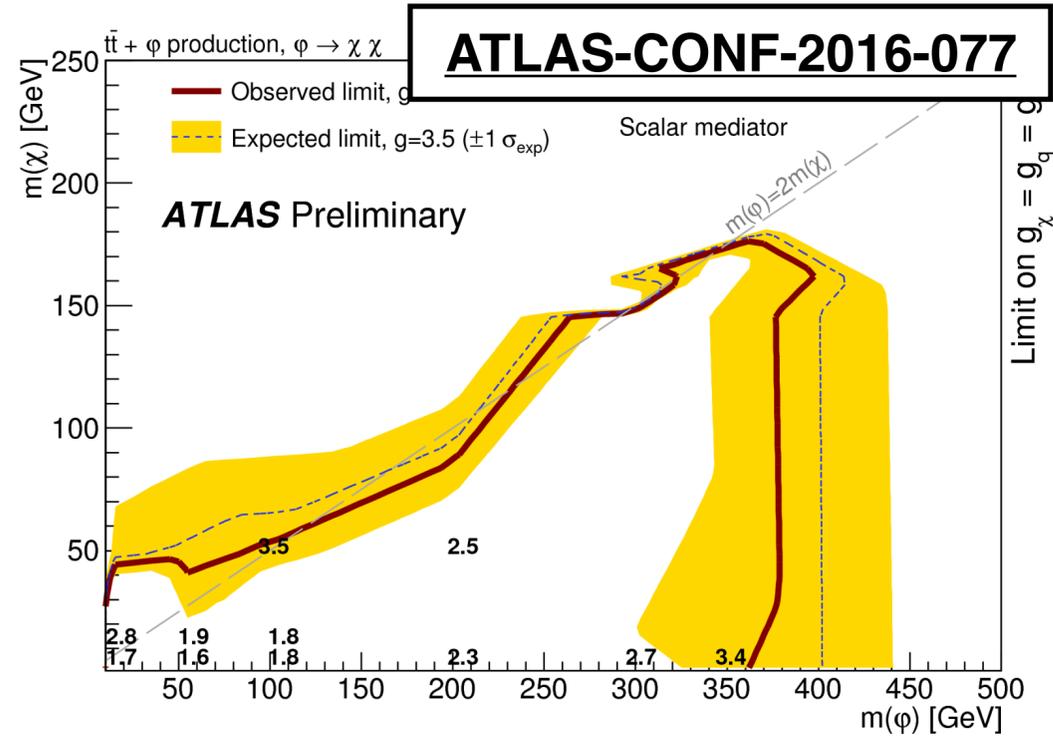
upper limit on σ/σ_0



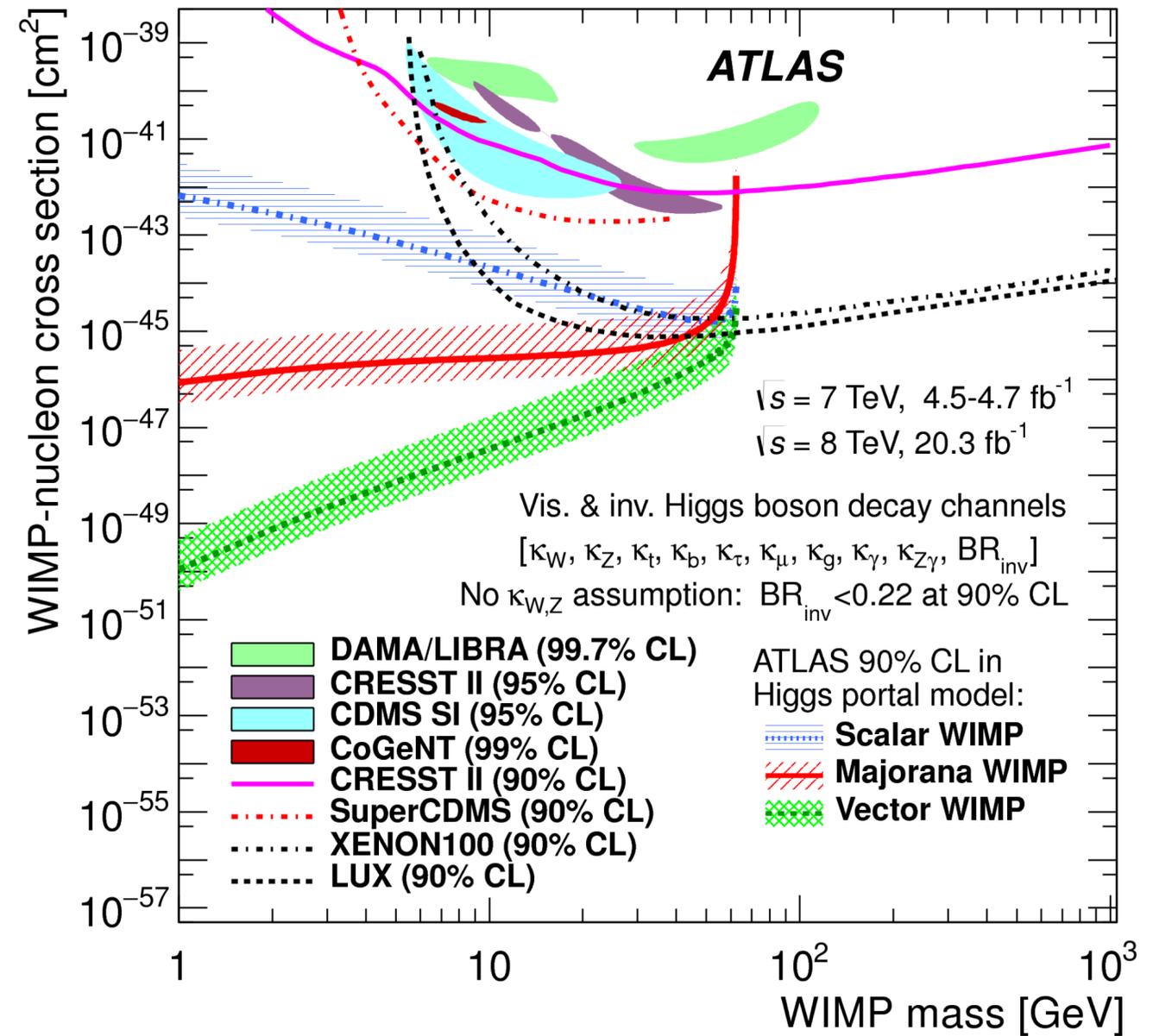
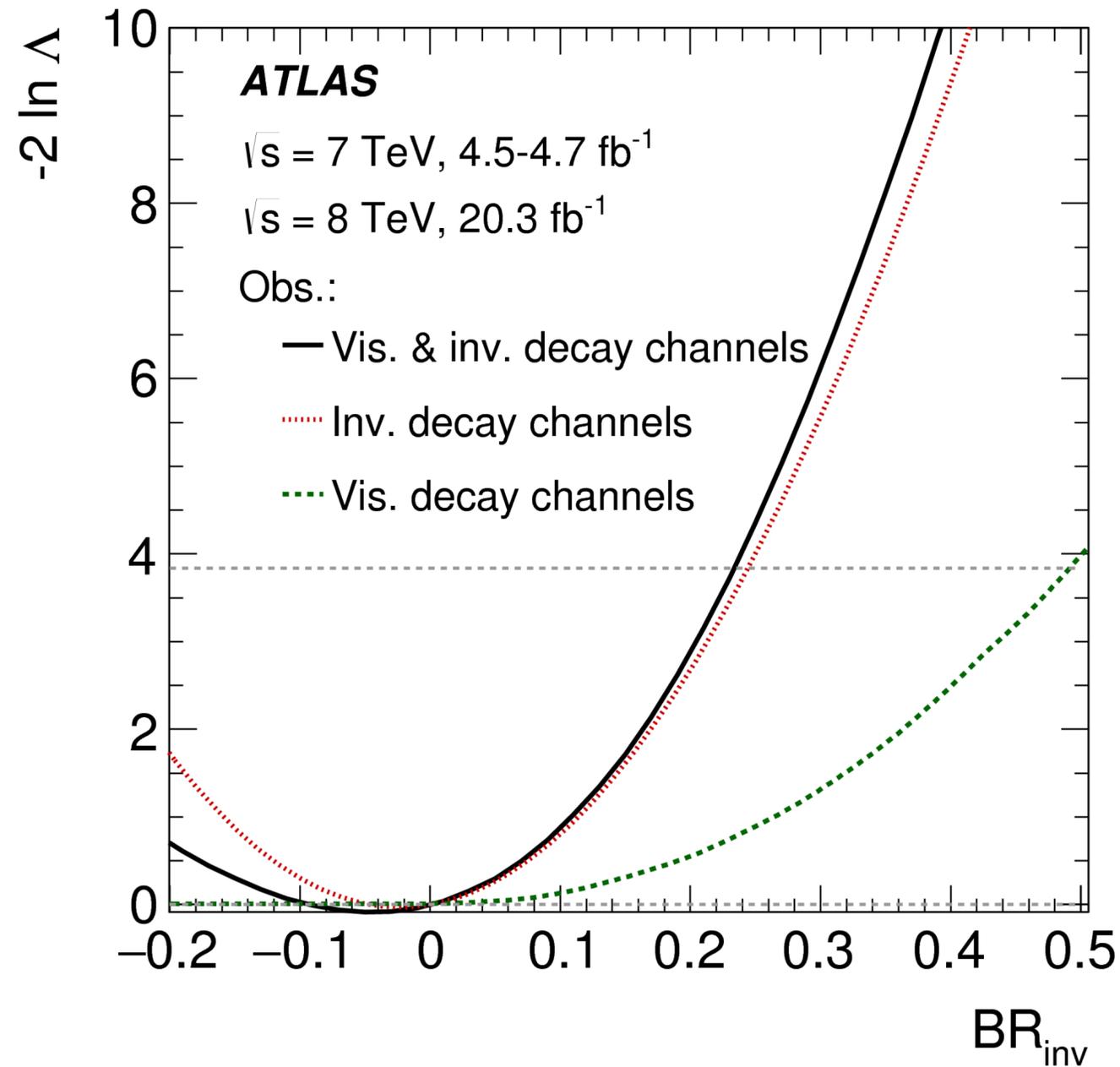
upper limit on σ/σ_0



ATLAS ttbar+DM



Higgs invisible



Higgs invisible

