Analytical Reinterpretation

of ATLAS dijet searches for dark matter mediators

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with input from C Doglioni, K Pachal, P Rieck

ATLAS EXPERIMENT

LUND UNIVERSITY

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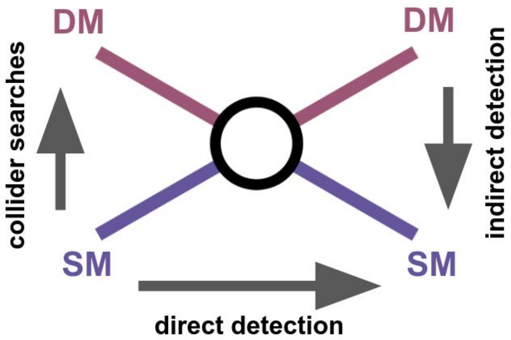
Lund

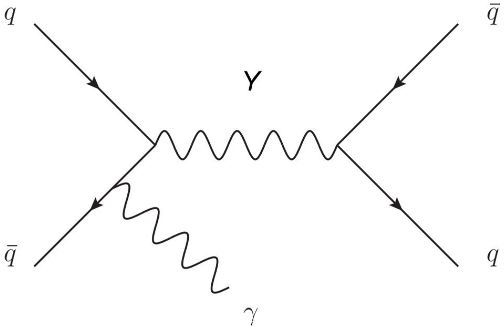
background: DM and simplified models

80% of the matter content of the universe is dark. Understanding is one of our **biggest current challenges**.

Several detection strategies

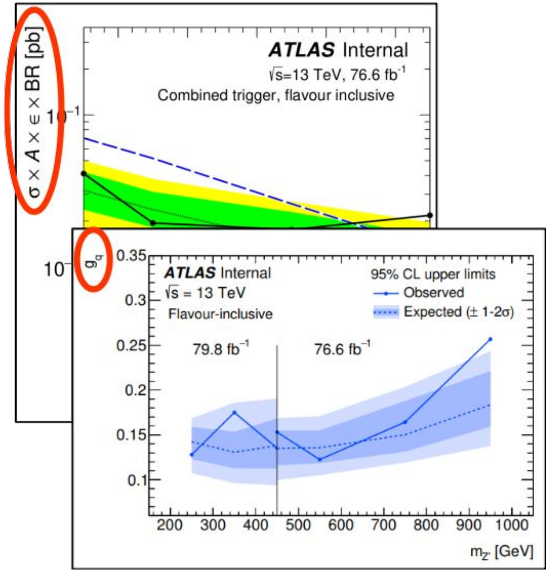
- **direct:** see DM-nuclear scattering in material
- **indirect:** detect annihilation or decay products
- **colliders:**
  - if DM interacts with SM, could **produce at LHC**
  - use **simplified** models for that interaction, such as **mediation by new vector boson**
  - Wide search programme for such models in ATLAS





background: ATLAS DM summaries

Want to collect individual analysis results in **summary plots**.
But: these usually use **different models/assumptions** and are **plotted in a different space**



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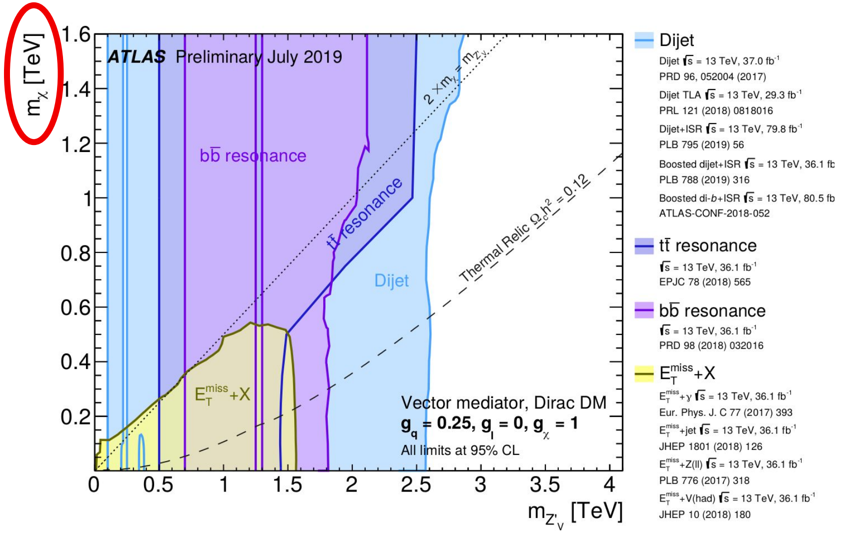

reinterpretation: old way

Individual analysis results need to be **reinterpreted** into a common model space (of parameter values and assumptions)

Previous method for dijet searches

1. **Generate signal MC**, calculate cross section and acceptance
2. **Smear signals** by mass resolution to make “reco” histograms
3. **Truncate** signal of mass *M* to between 0.8**M* and 1.2**M*, get modified acceptance
4. **Compare to Gaussian** observed limit points, calculate exclusion

Issues

- Takes a long time **(days of grid/cluster jobs)**
- generally **quite involved**
- quite **conservative** in certain situations

reinterpretation: new way

New idea (from CMS): **Equate the total excluded cross-sections** in two sets of parameter and assumption choices, use **analytical relations** between widths and cross-sections to convert limits

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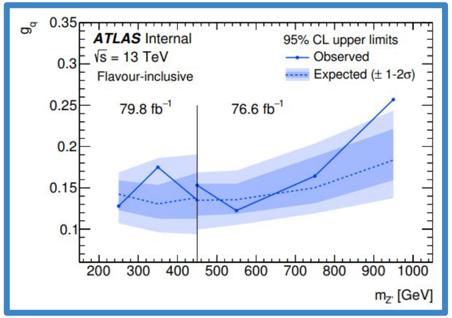
dijet+ISR analysis limits

Parameters and assumptions P

Plot in $(g_q, m_{mediator})$

$$P = \begin{cases} g_q \text{ varying} \\ m_{DM} >> m_{mediator} \quad \text{so no DM decays!} \\ g_{DM} = 0 \\ g_l = 0 \end{cases}$$

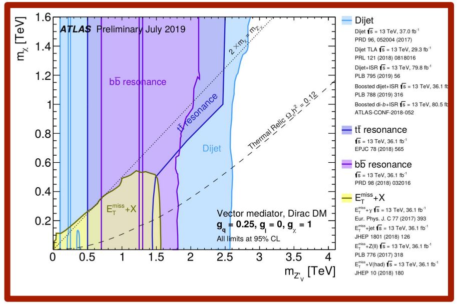


summary plot

Parameters and assumptions Q

Plot in $(m_{DM}, m_{mediator})$

$$Q = \begin{cases} m_{DM} \text{ varying} \\ g_q = 0.25 \\ g_{DM} = 0.1 \\ g_l = 0 \end{cases}$$



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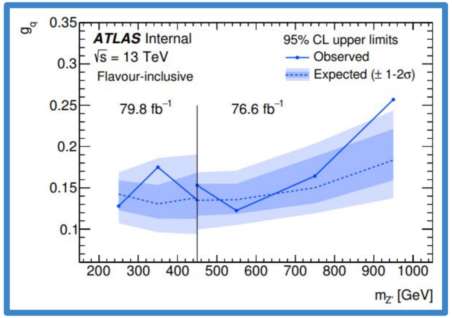

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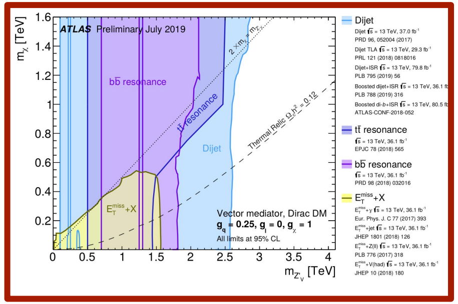

Now equate the excluded cross-sections

$$\sigma^{\text{excluded}}_{\text{analysis}}(g_q, M_{\text{med}}, P) = \sigma^{\text{excluded}}_{\text{reinterpreted}}(m_{\text{DM}}, M_{\text{med}}, Q)$$

Relativistic, narrow Breit-Wigner:

$$\sigma \approx \frac{\Gamma_{\text{initial}}\Gamma_{\text{final}}}{\Gamma_{\text{total}}}$$

Widths depend on P, Q (masses, couplings), so for some f

$$g_q = f(M_{\text{med}}, m_{\text{DM}}, P, Q)$$

analysis (g_q) — summary (m_{DM})

reinterpretation: new way

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Central assumptions

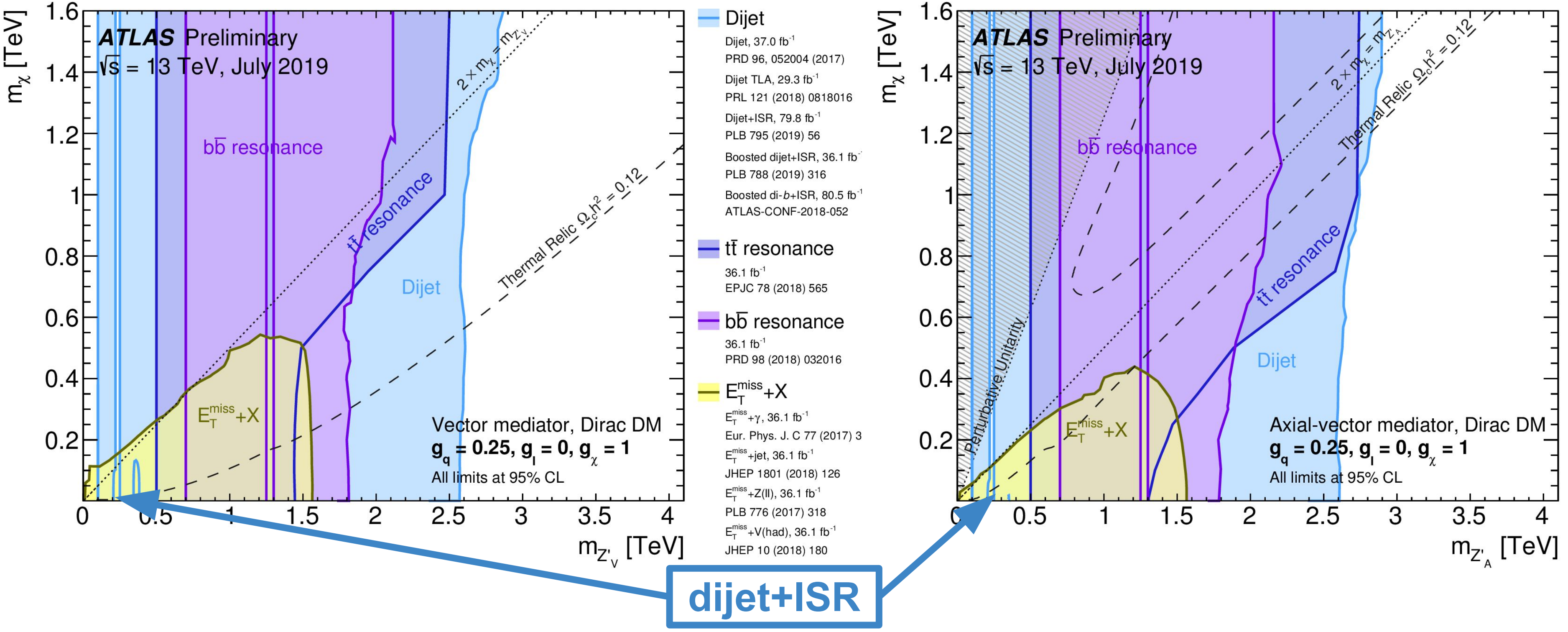
- Narrow width
  - Natural widths are typically less than 5-6%. **Reasonable!**

- Equal acceptance in both model spaces
  - **width of mediator Γ could change** between points with equal x-sec in both model spaces
  - so acceptance could change!
  - analysis studies: acceptance doesn't change with large changes in g_q (which changes Γ as much as anything in this procedure)
  - so acceptance should not change much. **Reasonable!**

cross-checks and validation

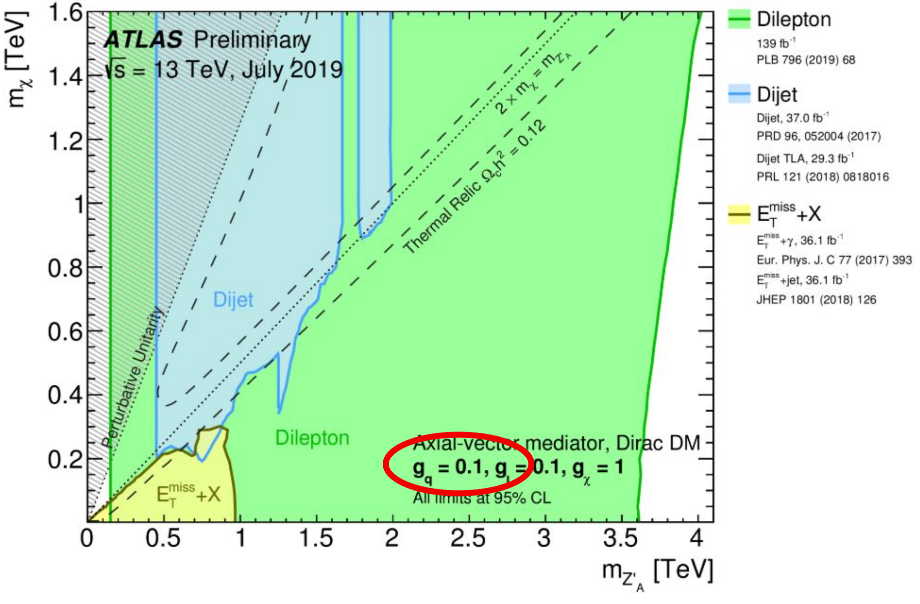
- CMS results: **reproduced** (CDM talk 1)
- Trigger-Level Analysis (TLA) dijets results: **understood** (CDM talk 2)
- MadGraph-calculated “expected” excluded cross-section: **agrees** (CDM talk 1)
- Intermediate method using fixed widths and Gaussian limits: **agrees** (K. Pachal’s talk)
- High-mass dijets results: **understood** (CDM talk 2)
- etc.

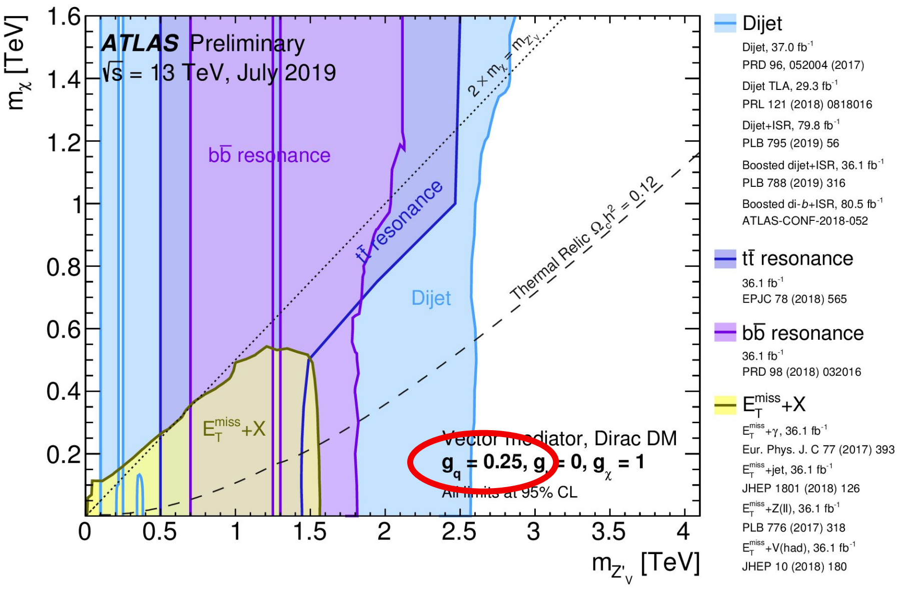
results (ATL-COM-PHYS-2019-940)



further usage! intermediate coupling values

Issue: when we proclaim that we've excluded model X in this region at coupling = 0.25 or 0.10, **it's not clear what happens at 0.24 or 0.17**, and the **broader DM community wants to know**



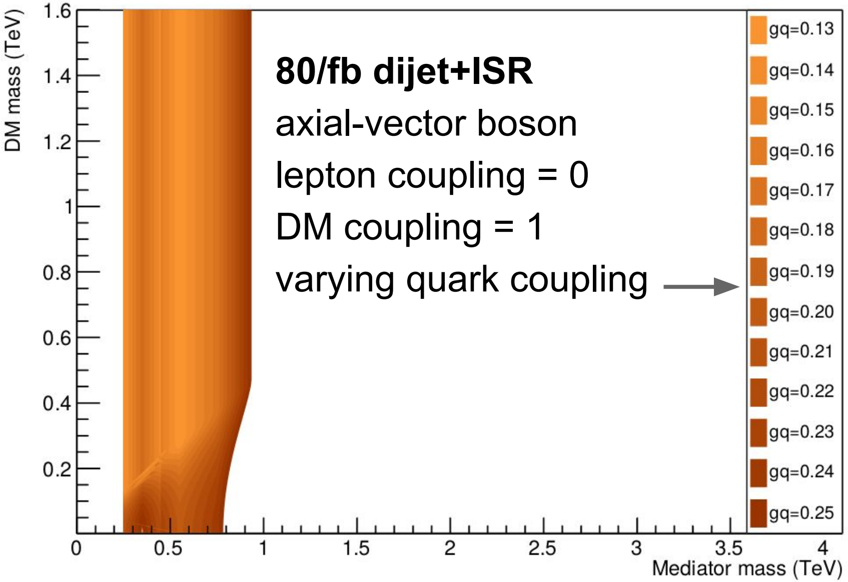


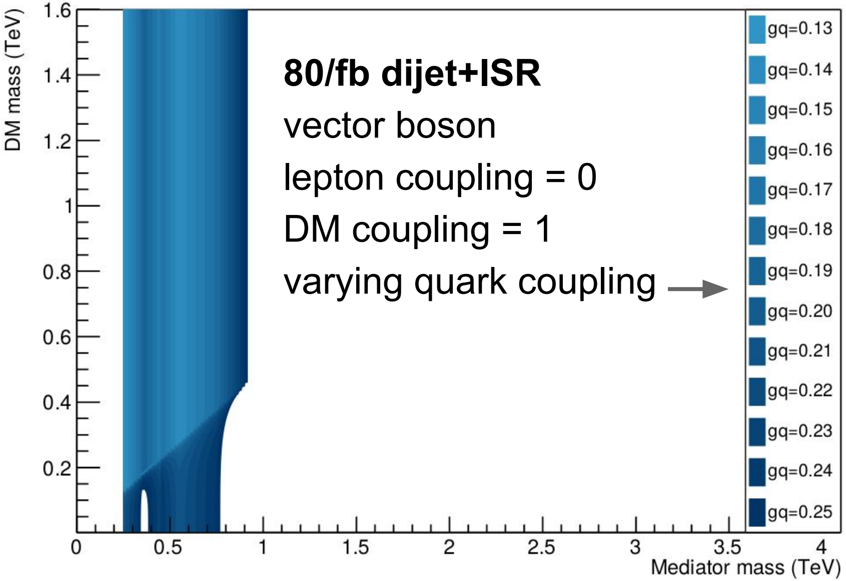
further usage! intermediate coupling values

The benchmark scenarios (at g_q = 0.25, 0.10) were chosen for good reasons, but we want to **understand and convey the coupling dependence** of our exclusions limits.

But the analytical method does exactly this---**we can choose any couplings we want!**

dijet+ISR (TLA and high-mass dijets also done)





Also: through the magic of science, AV.gif, V.gif

summary

Old method

- uses **Gaussian** limits
- no assumptions on acceptance, but:
  - tends to be **overly conservative**
  - involved procedure
  - requires grid time

Analytical method

- uses **Z' model** limits
- makes additional but **reasonable assumptions**
- well-defined, **cross-checked and understood** in several contexts
- **runs in less than a second** on a laptop
- code generalizable to other analyses (just make your own conf!)

New method was made to reinterpret analysis results for summary plots, but also **proving to be useful for various other studies**!

BACKUP

Equal acceptance across model spaces? (points with same cross-section)

https://docs.google.com/presentation/d/1Et_E45DwzHN2yl8OWxFAcfnY1SEzukfhAWrjXFcPTkE/edit?usp=sharing

We know that **changing gq can have large effects on the Z' width**, but we also saw that **changing gq did not significantly affect the acceptance**

Thus the **width can't have a large impact on the acceptance**

2.3 Width formulas and model implementation

Including leptonic couplings the partial decay widths of the vector mediator are given by

$$\Gamma^{\chi\bar{\chi}}_{\text{vector}} = \frac{g_{\text{DM}}^2 M_{\text{med}}}{12\pi} \left(1 - 4 z_{\text{DM}}\right)^{1/2} \left(1 + 2 z_{\text{DM}}\right) , \tag{2.4}$$

$$\Gamma^{q\bar{q}}_{\text{vector}} = \frac{g_q^2 M_{\text{med}}}{4\pi} \left(1 - 4 z_q\right)^{1/2} \left(1 + 2 z_q\right) , \tag{2.5}$$

$$\Gamma^{\ell\bar{\ell}}_{\text{vector}} = \frac{g_\ell^2 M_{\text{med}}}{12\pi} \left(1 - 4 z_\ell\right)^{1/2} \left(1 + 2 z_\ell\right) , \tag{2.6}$$

$$\Gamma^{\nu\bar{\nu}}_{\text{vector}} = \frac{g_\ell^2}{24\pi} M_{\text{med}} , \tag{2.7}$$

where $z_i = m_i^2/M_{\text{med}}^2$ with $i = \text{DM}, q, \ell$, and the three different types of contributions to the decay width vanish for $M_{\text{med}} < 2m_i$. The corresponding expressions for the axial-vector mediator are

$$\Gamma^{\chi\bar{\chi}}_{\text{axial-vector}} = \frac{g_{\text{DM}}^2 M_{\text{med}}}{12\pi} \left(1 - 4 z_{\text{DM}}\right)^{3/2} , \tag{2.8}$$

$$\Gamma^{q\bar{q}}_{\text{axial-vector}} = \frac{g_q^2 M_{\text{med}}}{4\pi} \left(1 - 4 z_q\right)^{3/2} , \tag{2.9}$$

$$\Gamma^{\ell\bar{\ell}}_{\text{axial-vector}} = \frac{g_\ell^2 M_{\text{med}}}{12\pi} \left(1 - 4 z_\ell\right)^{3/2} , \tag{2.10}$$

$$\Gamma^{\nu\bar{\nu}}_{\text{axial-vector}} = \frac{g_\ell^2}{24\pi} M_{\text{med}} . \tag{2.11}$$

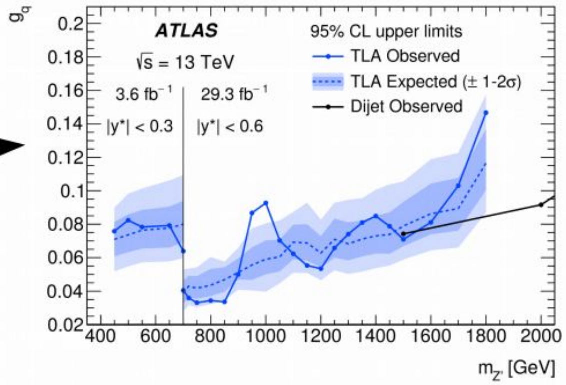
MadGraph studies

Analytical approach, validation on TLA

Idea: can use MadGraph (LO, dmSimp, p p > Y1 > j j)

With analysis limit coupling values

1) choose a mediator mass
2) check excluded coupling
3) run MadGraph to find corresponding excluded cross-section



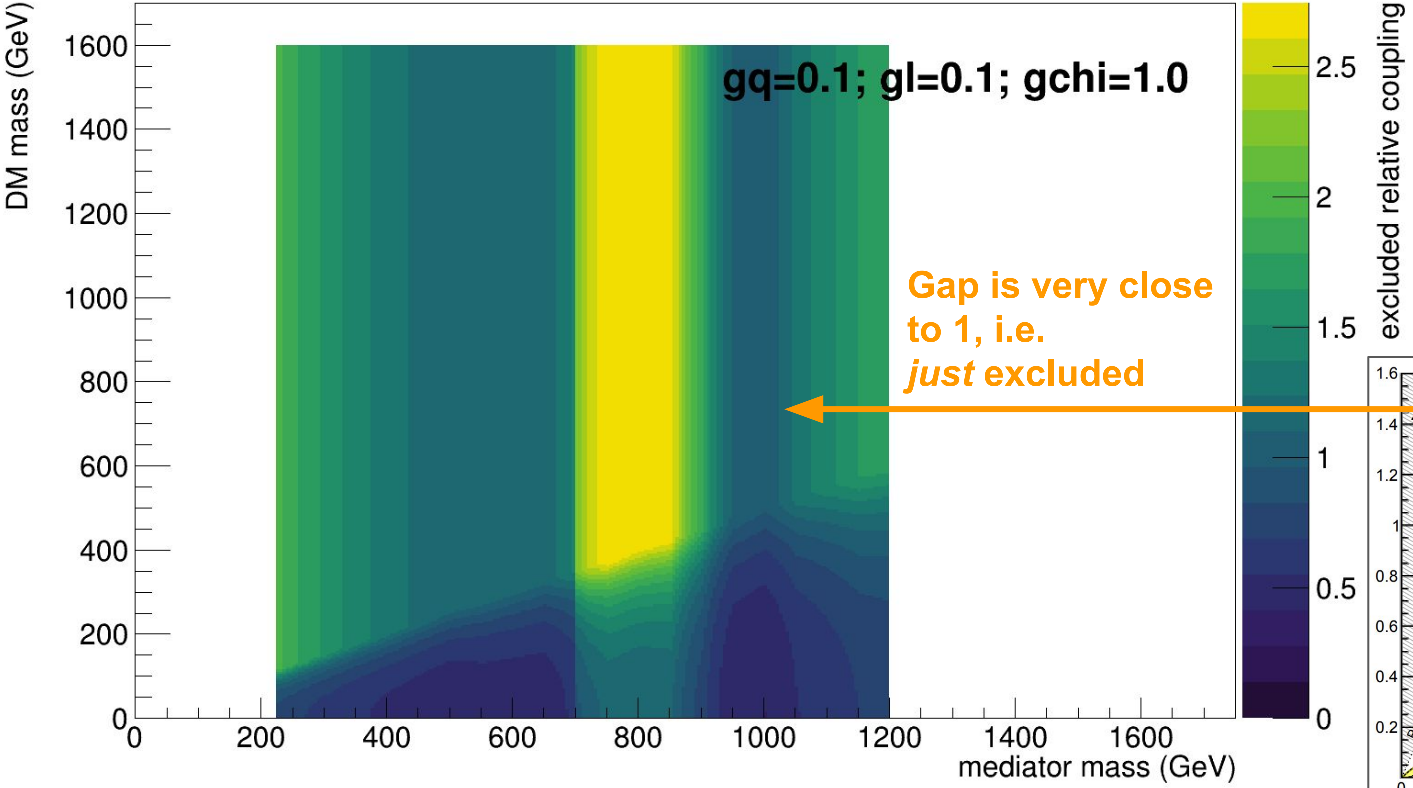
With summary plot coupling values

4) try a DM mass
5) using this mass, MadGraph to calculate corresponding cross-section
6) compare to cross-section in **3)**
if larger, excluded!
if smaller, not excluded!
if ~equal, the chosen DM mass in 4) is your limit!

Excellent agreement with analytical method

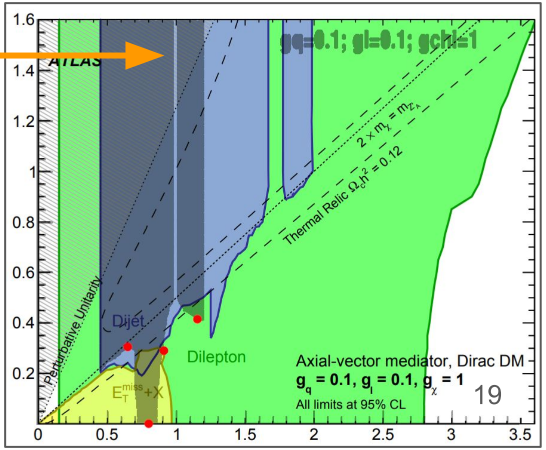
“Exclusion depth” heat map

The z axis is **ratio** of the **calculated coupling** to the **coupling limit**
the **z = 1** contour is the exclusion limit, **z > 1** is more strongly excluded and **z < 1** is not excluded



Gap is very close to 1, i.e. *just* excluded

reminder



An independent confirmation (Kate's method)

This method sees the excluded feature around 800 GeV for **all tested widths** (res. width, 5%, 7%;
10% does not go above 700 GeV)

Using the **Gaussian limits** instead of the Z' limits, and using **full generated analysis acceptances** instead of assuming constant,

this method reproduces the main features seen by the new method

=> constitutes an **important intermediate cross-check**