Analytical Reinterpretation

of ATLAS dijet searches for dark matter mediators

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with input from C Doglioni, K Pachal, P Rieck
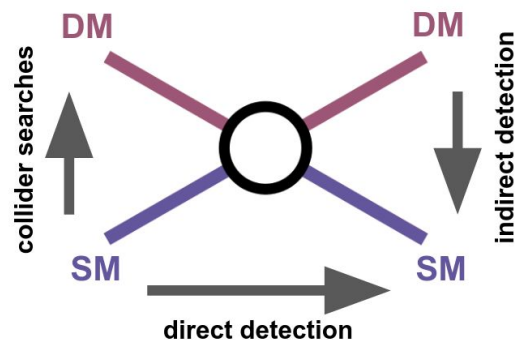
ATLAS
EXPERIMENT

LUND
UNIVERSITY

Spåtind 2020
03 Jan, Skeikampen

background: DM and simplified models

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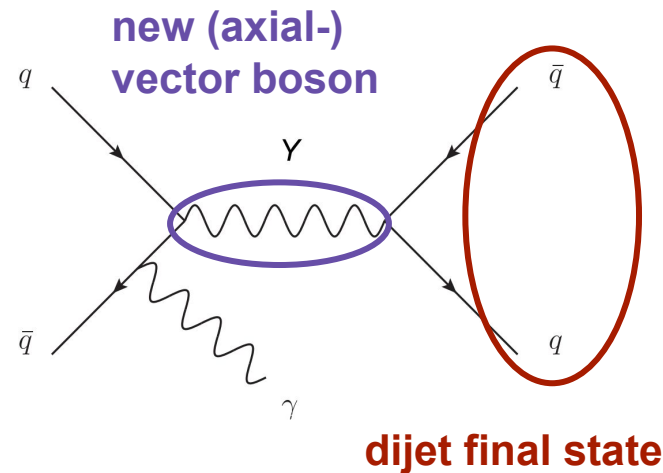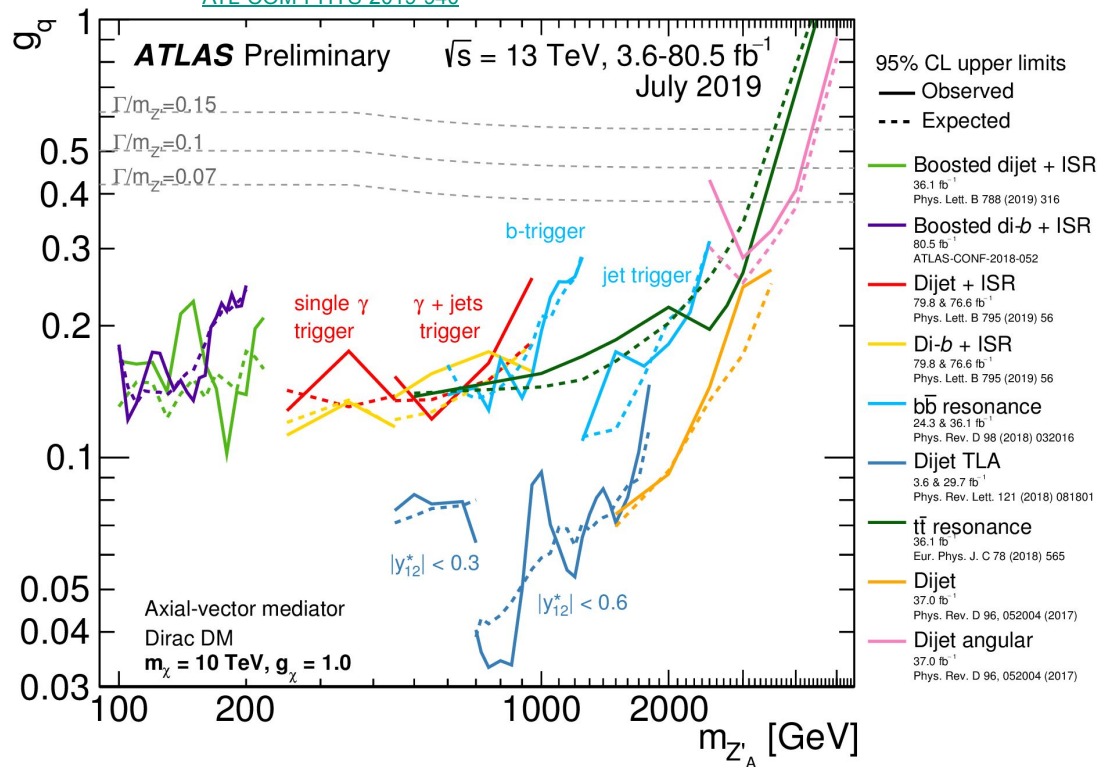
Several detection strategies

- ❖ **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

ATLAS dark matter mediator searches

ATL-COM-PHYS-2019-940

ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 3.6–80.5 fb^{-1}
July 2019

95% CL upper limits
— Observed
- - - Expected

Boosted dijet + ISR
36.1 fb^{-1}
Phys. Lett. B 788 (2019) 316

Boosted di-b + ISR
80.5 fb^{-1}
ATLAS-CONF-2018-052

Dijet + ISR
79.8 & 76.6 fb^{-1}
Phys. Lett. B 795 (2019) 56

Di-b + ISR
79.8 & 76.6 fb^{-1}
Phys. Lett. B 795 (2019) 56

$b\bar{b}$ resonance
24.3 & 36.1 fb^{-1}
Phys. Rev. D 98 (2018) 032016

Dijet TLA
3.6 & 29.7 fb^{-1}
Phys. Rev. Lett. 121 (2018) 081801

$t\bar{t}$ resonance
36.1 fb^{-1}
Eur. Phys. J. C 78 (2018) 565

Dijet
37.0 fb^{-1}
Phys. Rev. D 96, 052004 (2017)

Dijet angular
37.0 fb^{-1}
Phys. Rev. D 96, 052004 (2017)

$\Gamma/m_{Z'}$=0.15
$\Gamma/m_{Z'}$=0.1
$\Gamma/m_{Z'}$=0.07

b-trigger
jet trigger
single γ trigger
γ + jets trigger
$|y^*_{12}| < 0.3$
$|y^*_{12}| < 0.6$

Axial-vector mediator
Dirac DM
m_χ = 10 TeV, g_χ = 1.0

g_q

$m_{Z'_A}$ [GeV]

new (axial-) vector boson

q
$\bar{q}$
Y
$\bar{q}$
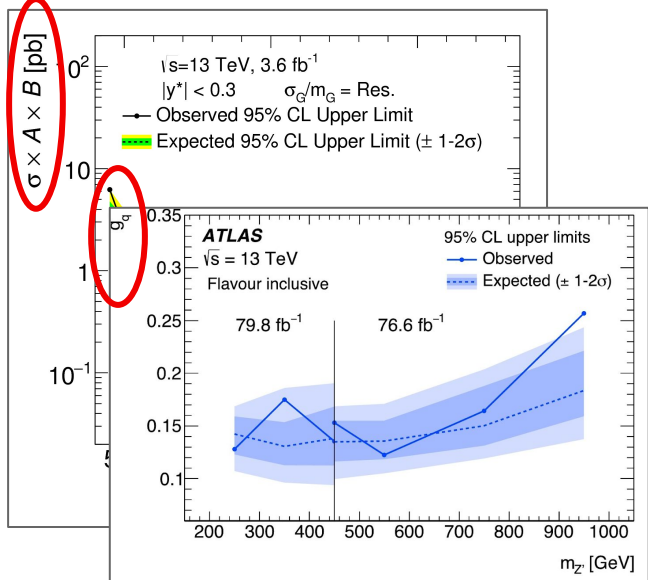q
γ

dijet final state
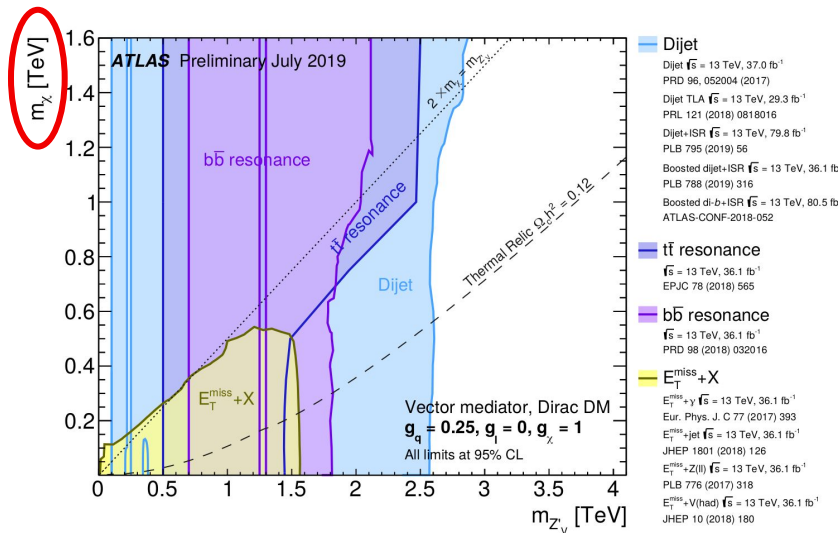
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background: ATLAS DM summaries

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

arXiv:1804.03496

arXiv:1901.10917

ATL-COM-PHYS-2019-940

reinterpretation: old way

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

Previous method for ATLAS 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
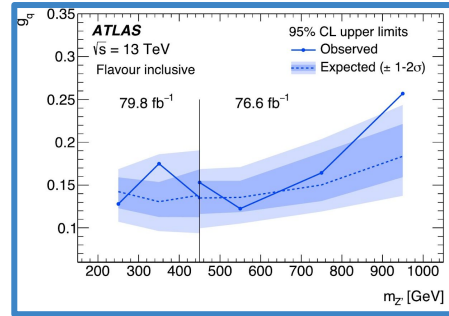
reinterpretation: new way

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 $(g_q, m_{\mathrm{mediator}})$

$$P = \begin{cases} g_q \text{ varying} \\ m_{\mathrm{DM}} \gg m_{\mathrm{mediator}} : \text{no DM decays!} \\ g_{DM} = 0 \\ g_l = 0 \end{cases}$$
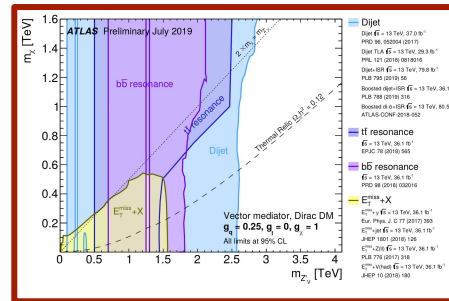

arXiv:1901.10917

summary plot
Parameters and assumptions Q
Plot in $(m_{DM}, m_{\mathrm{mediator}})$

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

ATL-COM-PHYS-2019-940
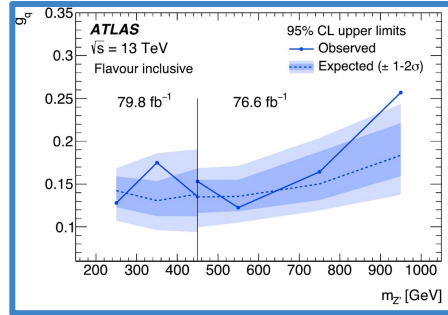
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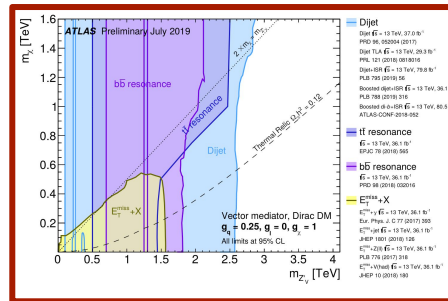

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ATL-COM-PHYS-2019-940

Now equate the excluded cross-sections

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

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   **summary**

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

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 (ATLAS-internal)

❖ 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)
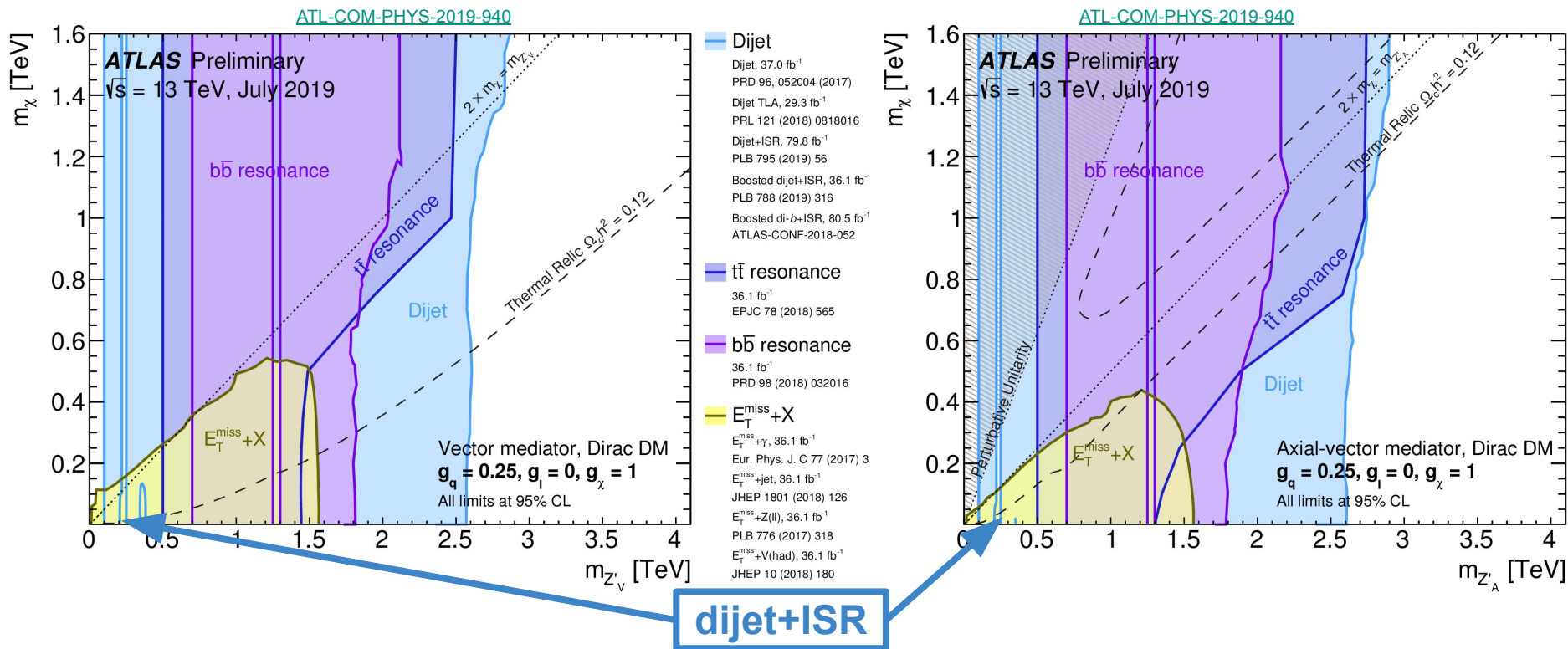
further usage! intermediate coupling values

- V/AV DM simplified model ATLAS [summary plots](#) use **only two values** of g_q in the scenarios from [DMWG](#)

- Recent conferences and workshops: broader DM community asks for **impact of the coupling dependence in a single plot.** (In particular in plots of **DM-nucleon x-sec vs DM mass**, where direct comparison to Direct Detection is made)

- Want to **derive reinterpretations** of monojet and dijet results, **using MC or analytically**, at different couplings

ATL-COM-PHYS-2019-940
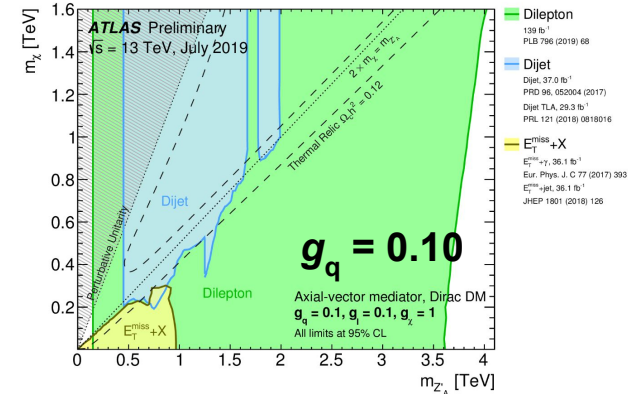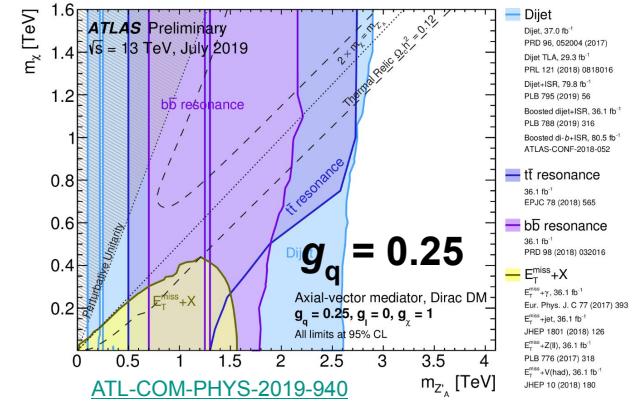
dijet+ISR (Also done: TLA and high-mass dijets)

Since **analytical reinterpretation** can reinterpret **into any model you want => intermediate scenarios!**
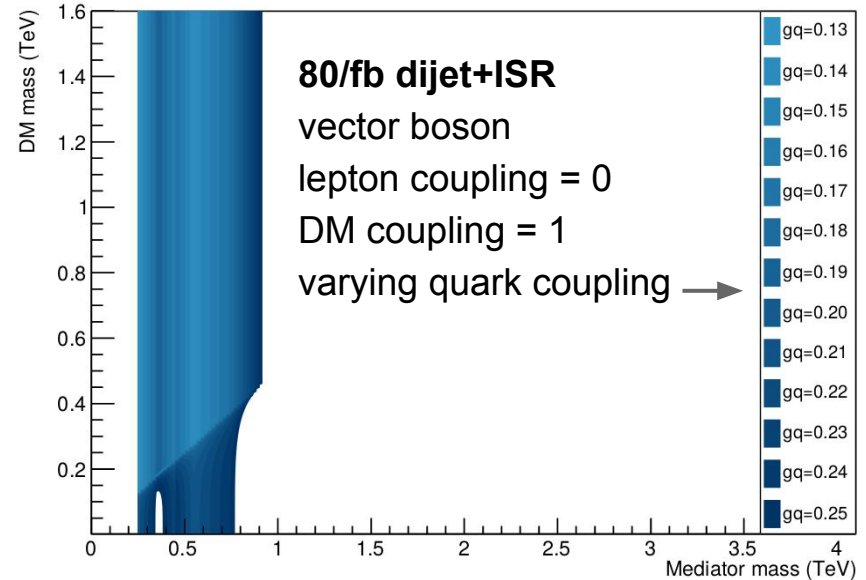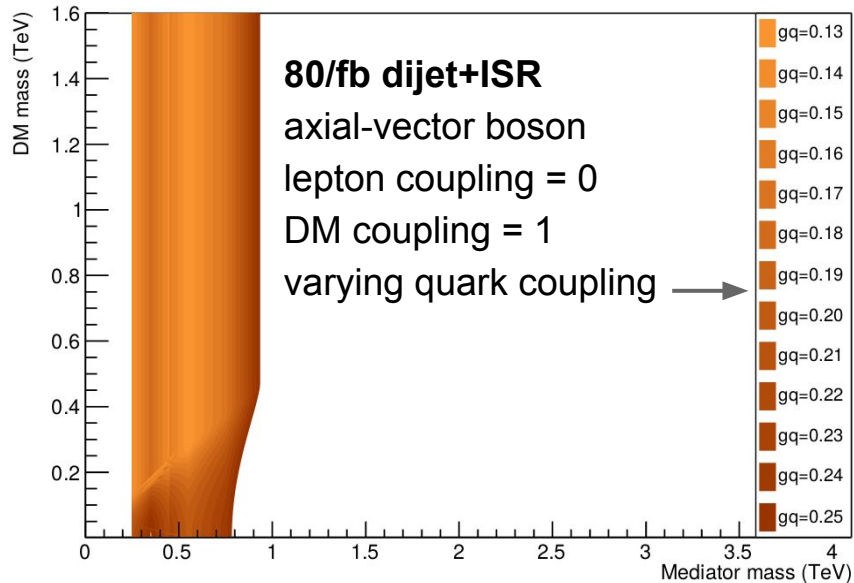
Also: AV.gif, V.gif

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
- ❖ <u>code</u> 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_E45DwzHN2yl8OWxFAcfnY1SEzukfhAWrjXFcP TkE/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

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

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

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

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

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

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

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

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

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

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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!**

01/07/19   E Corrigan, Analytical reinterp
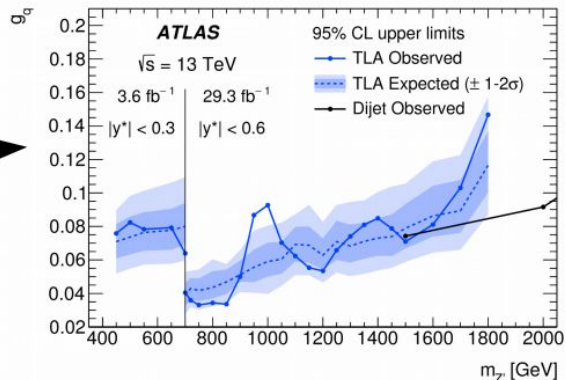
Excellent agreement with analytical method

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"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

gq=0.1; gl=0.1; gchi=1.0

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

reminder

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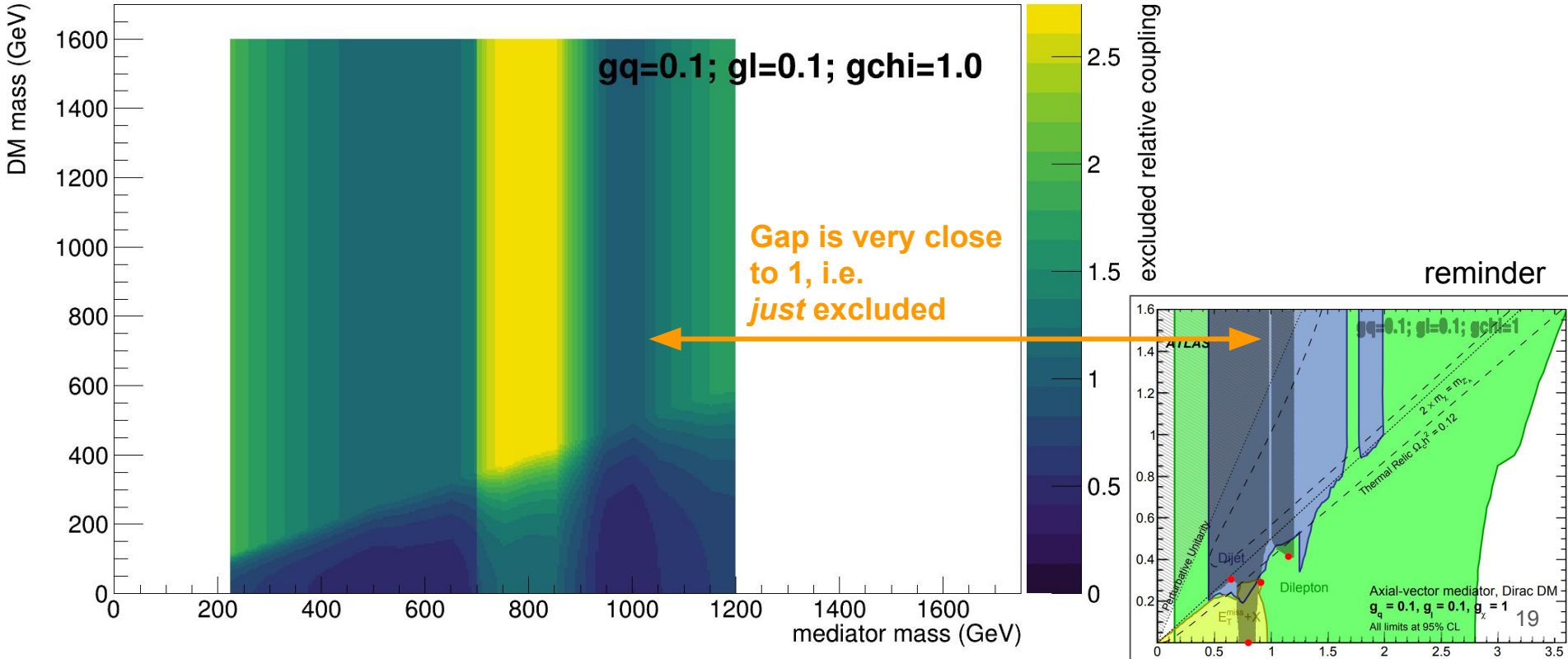
An independent confirmation (Kate's method)

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**

Blue dot: excluded
Red circle: not excluded

Width = 7%

Axial-vector mediator, Dirac DM
$g_q = 0.1$, $g_l = 0.1$, $g_\chi = 1$
All limits at 95% CL

Dijet

Dilepton

E_T^{miss}+X

Perturbative Unitarity

ATLAS