DM@Collider summary plots for Snowmass

Progress & ongoing work

Boyu Gao (Duke)

Inputs and past/present supervision by:
Antonio Boveia (OSU)
Caterina Doglioni (Lund University)
Ashutosh Kotwal (Duke)

List of focused questions from Snowmass EF10 (DM @ Colliders)

Work I have contributed to:

1. How can we best test the **WIMP** paradigm?
   - Through the simplest/minimal WIMP models (EW multiplets) and their extensions
   - Using simple mediator models (s-channels/t-channels) already used for collider searches
   - Through the Higgs portal, since the Higgs boson is the most relevant portal operator between SM and DM and there are connections to precision measurements

2. How can we best explore **beyond-WIMP** scenarios?
   - Using portals that privilege light dark sectors / dark matter
   - Focusing on less-explored signatures of dark sectors that can highlight present/future blind spots

3. How to best exploit **synergies & complementarity** between DM@colliders & other TGs and Frontiers
   - In terms of different experiments / observations answering the same physics question on the nature of DM
   - In terms of detector, data acquisition and trigger design [e.g. IF04 kick-off]

Goal: summary plots of DM at colliders

- *Types of DM summary plots:*
  - We have proposed four kinds of summary plots **(LOI1)** that show DM complementarity between Collider searches and other Frontiers (also see backup slides 1-5)
- *List of analyses & collider choices:*
  - Analyses (not all will be available):
    - Jet+MET; Photon+MET; ttbar + MET; Di-jet / di-lepton; Higgs..
  - Colliders:
    - HL-LHC; Future colliders (muon collider, FCC-eh, FCC-ee, FCC-hh..)
    - We will need inputs from future colliders!
      - Last year I developed a MC generation framework to validate signal, and validating coupling interpretation, smoothing curve to aid future colliders develop inputs we need
- *Models & coupling choices:*
  - DM simplified models with variable SM couplings **(LOI2)**
- *Final goal:* Connect DM@Collider results to other frontiers **(LOI3)**

LOI1 - Summarizing experimental sensitivities of collider experiments to Dark Matter models and comparison to other experiments:
https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF9_EF10-RF6_RF0-CF1_CF3_Boyu_Gao-160.pdf

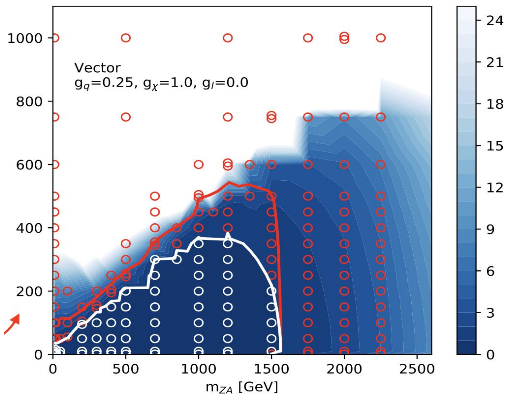
LOI2 - Displaying dark matter constraints from colliders with varying simplified model parameters:
https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF10_EF9_Andreas_Albert-094.pdf

LOI3 - Dark Matter Complementarity:
https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF7-EF10_EF0-RF6_RF0-TF9_TF0-150.pdf

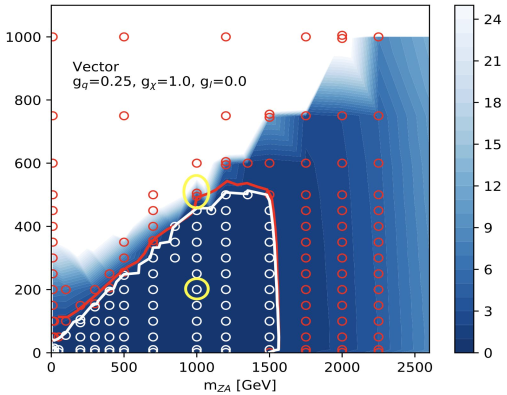
Analytical coupling interpretation [LOI2]

- We can't afford to generate/analyse too much signal MC
  → generate only a few points with fixed couplings, then rescale the results
- LHC DM Working Group developing a method to analytically rescale couplings for di-jet and mono-X signatures in vector / axial vector DM simplified models for hadron colliders
  - This will allow us to connect to dark photon experiments in the Rare & Precision frontier
- Ongoing discussions on coupling interpretation for scalar simplified models (with Higgs connections) - more people are encouraged to join!

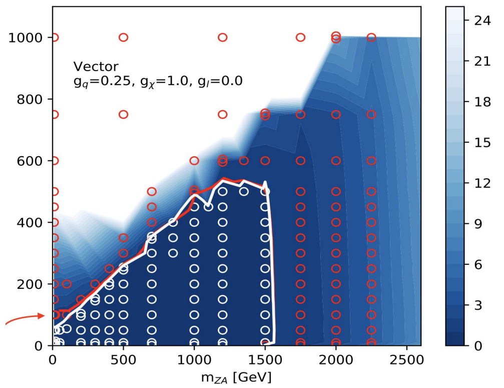
Example of analytical interpretation (white) compared to full limit (red) - monojet



Propagator only



Full integration



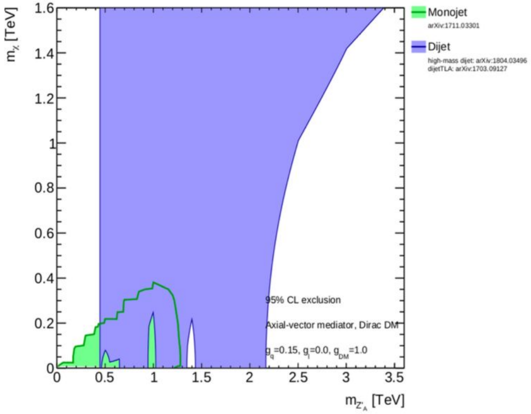
Final, after PDF

Work with Andreas Albert, Katherine Pachal, David Yu, Philip Harris and others

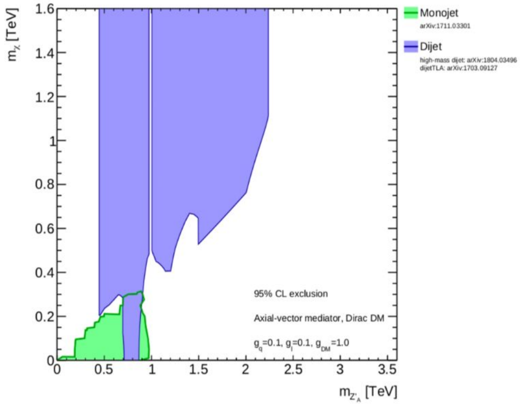
Example of how varying couplings varies collider sensitivity

Dark matter mass - mediator mass plane for monojet and di-jet searches (using public results from LHC searches)

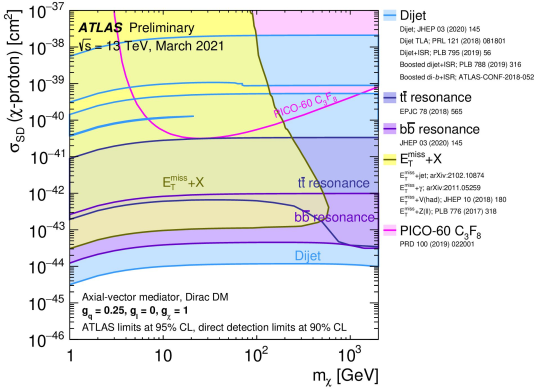
Higher SM-mediator couplings

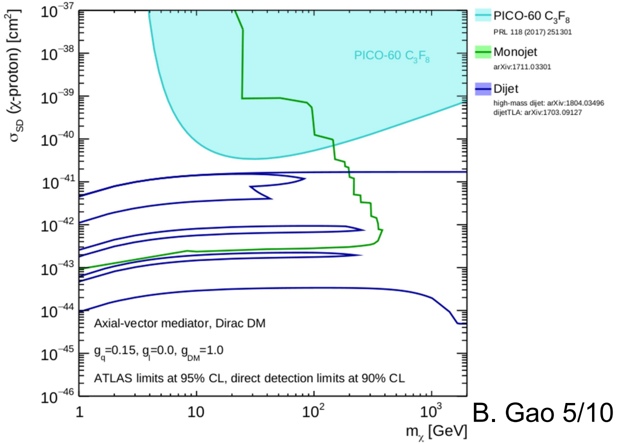


Lower SM-mediator couplings

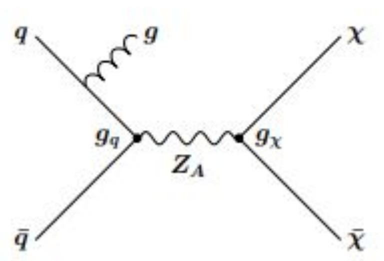


Comparison with direct detection experiments

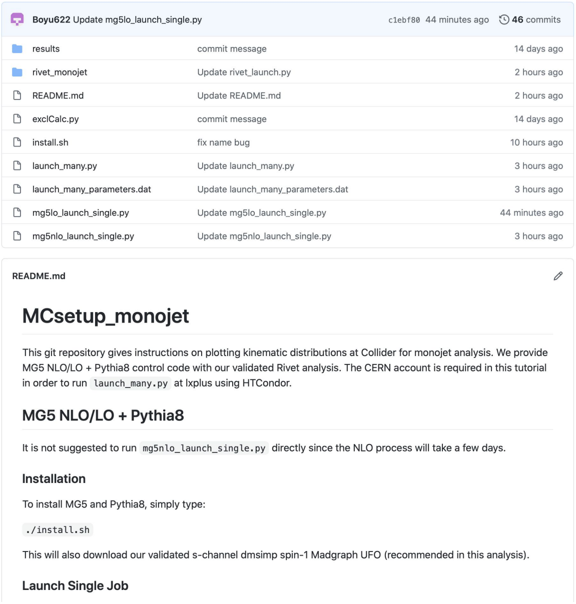




Helping collaborations provide inputs: Signal generation framework



- Models of interest
  - s-channel DM simplified models, V / AV mediator exchange
  - Four model parameters: g_q, g_DM, mDM and mMed
- Our framework on monojet MC setup hopes to:
  - Provide MG5 NLO/LO + Pythia8 control code for the above models
  - Validate HTCondor script (this will enable multi-tasking and NLO generation)
    - This can be changed into OSG scripts
  - Provide Rivet analysis code for monojet
  - Automate the above procedures
- Github repository
  - https://github.com/Boyu622/MCsetup_monojet.git
  - Please see the README for more information



Boyu622 Update mg5lo_launch_single.py c1ebf80 44 minutes ago 46 commits

results	commit message	14 days ago
rivet_monojet	Update rivet_launch.py	2 hours ago
README.md	Update README.md	2 hours ago
exclCalc.py	commit message	14 days ago
install.sh	fix name bug	10 hours ago
launch_many.py	Update launch_many.py	3 hours ago
launch_many_parameters.dat	Update launch_many_parameters.dat	3 hours ago
mg5lo_launch_single.py	Update mg5lo_launch_single.py	44 minutes ago
mg5nlo_launch_single.py	Update mg5nlo_launch_single.py	3 hours ago

README.md

MCsetup_monojet

This git repository gives instructions on plotting kinematic distributions at Collider for monojet analysis. We provide MG5 NLO/LO + Pythia8 control code with our validated Rivet analysis. The CERN account is required in this tutorial in order to run `launch_many.py` at lxplus using HTCondor.

MG5 NLO/LO + Pythia8

It is not suggested to run `mg5nlo_launch_single.py` directly since the NLO process will take a few days.

Installation

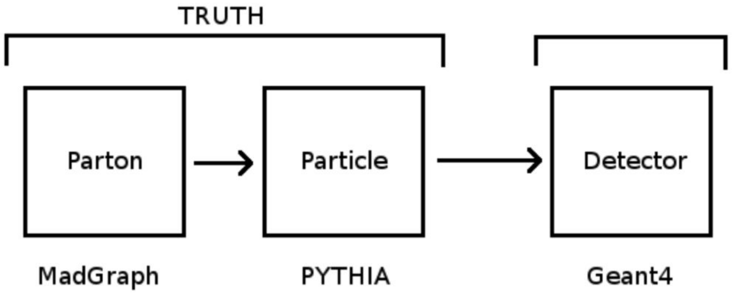
To install MG5 and Pythia8, simply type:

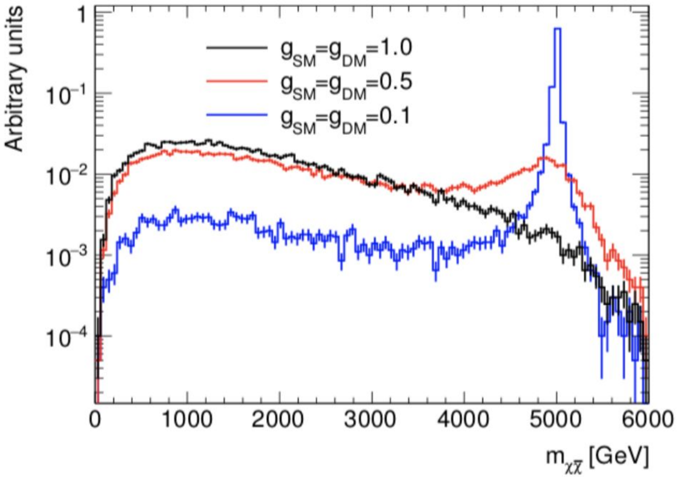
```
./install.sh
```

This will also download our validated s-channel dmsimp spin-1 Madgraph UFO (recommended in this analysis).

Launch Single Job

Signal generation framework: Parton level validation

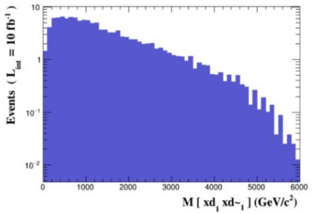




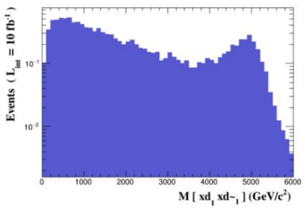
1507.00966

Vector
Mmed = 5 TeV
mDM = 10 GeV

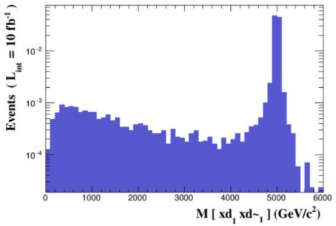
g_SM = g_DM = 1.0



g_SM = g_DM = 0.5

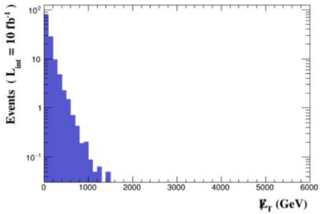


g_SM = g_DM = 0.1

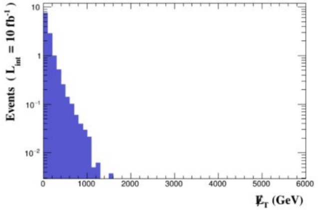


MET depends mostly on the mediator mass, rather than on the coupling, because that's what the ISR jet recoils against.

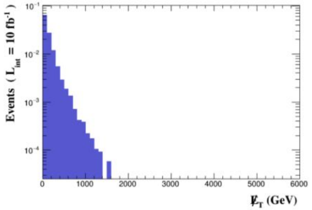
g_SM = g_DM = 1.0



g_SM = g_DM = 0.5

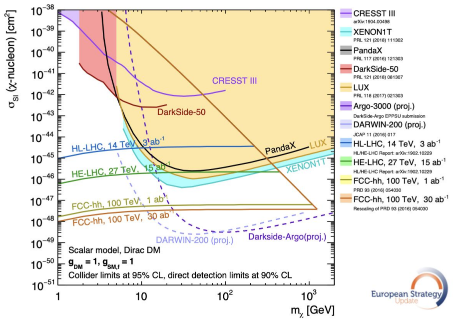


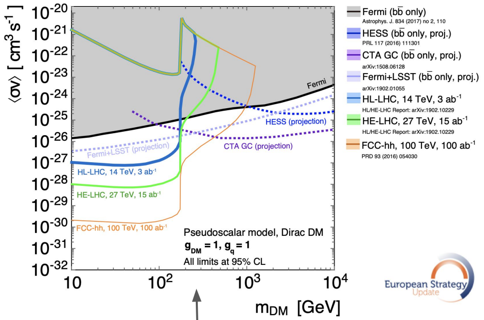
g_SM = g_DM = 0.1



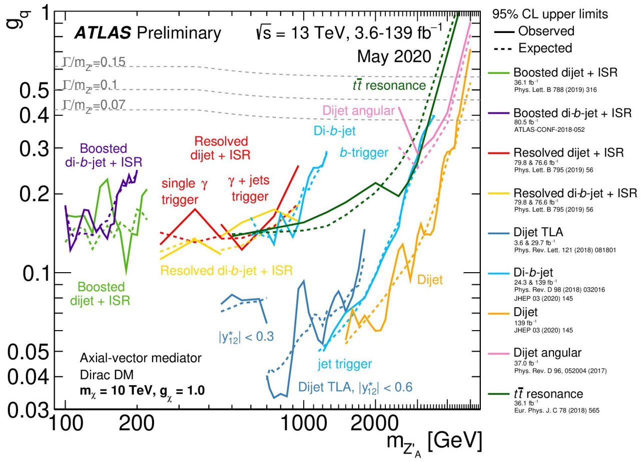
Future: next steps on DM summary plots

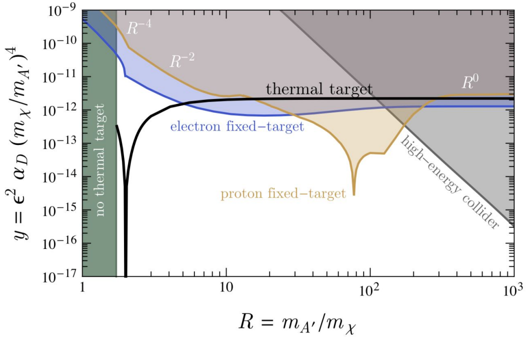
- Plots we would like to have in the whitepapers / final reports:
  - [1] DM mass vs mediator mass with varying SM couplings
  - [2] SM coupling vs mediator mass
  - [3] Collider results with varying SM couplings on direct detection plane





  - [4] Collider results with varying SM couplings on indirect detection plane
  - [5] (Provide inputs for) High energy colliders and low-mass experiments





- Models:
  - Vector mediator model (related to dark photon)
  - Scalar mediator with Higgs mixing (needs more discussion with EF01-03)
  - Higgs to invisible

Future: next steps on DM summary plots

- What we are missing to make these plots:
  - Coupling-mass scaling formulas for
    - Scalar
    - Lepton searches for hadron colliders
    - Lepton colliders
  - Future collider projections beyond European Strategy
    - e.g. muon colliders, more mass points for FCC-hh
    - we will e-mail the contacts of the various colliders

- We have many plans for whitepapers
  → we will work on these, and we welcome more help

Participants to initial discussions, will have more and everyone is welcome to join:
Antonio Boveia
Caterina Doglioni
Boyu Gao
Josh Greaves
Ashutosh Kotwal
Jinging Pan
Kate Pachal

Inputs from:
Liantao Wang
Andreas Albert
David Yu
Phil Harris

Thanks to the SEC for connecting us all!

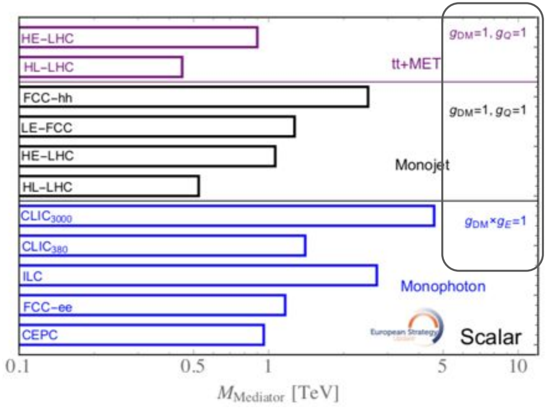
Thank you!

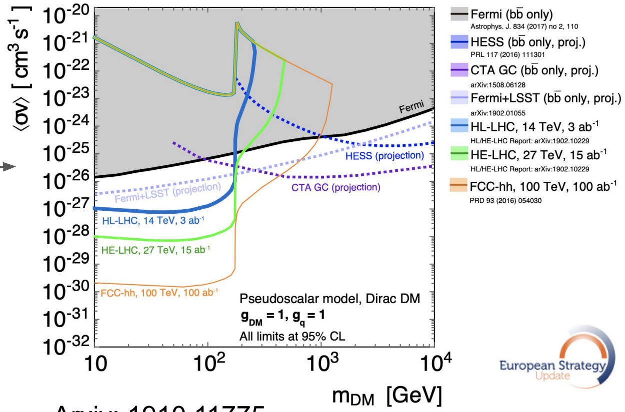
Backup slides

Our goal for DM@Collider plots for Snowmass

- Prepare Dark Matter summary plots like European strategy for HL-LHC and future colliders, for <u>DM simplified models with varying couplings</u>
  - Models used so far: from LHC Dark Matter Working Group [arxiv 1507.00966]
    - Vector/axial vector simplified model
    - Scalar/pseudoscalar simplified model
- Connect these plots to other experiments and Frontiers
  - Rare/precision Frontier: accelerator-based / fixed target experiments
  - Cosmic Frontier: direct detection and indirect detection
  - Will need to agree on benchmarks models and presentation of results with them

European Strategy:
fixed couplings

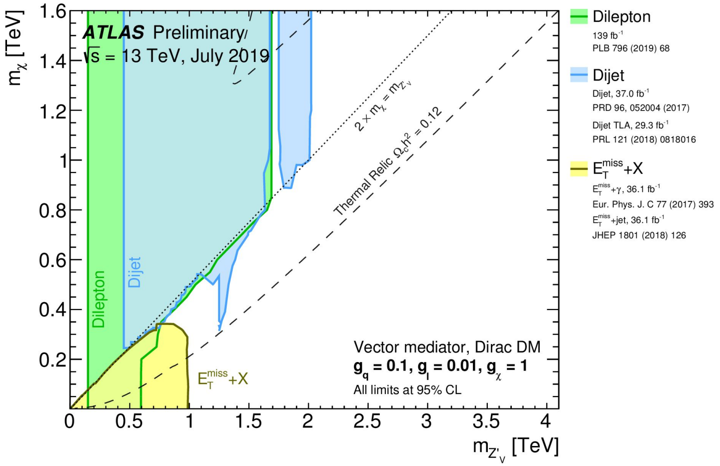




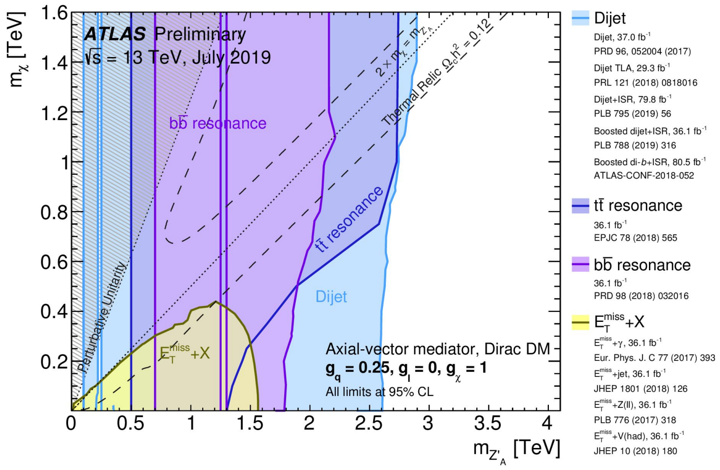
Arxiv: 1910.11775

Proposed summary plot #1: DM mass/mediator mass

- Vector/axial vector simplified models
  - Exclusions (shaded area) on Dark Matter mass - mediator mass plane with various couplings:
    - Vector simplified model (right figure)
    - Axial-vector simplified model (bottom figure)

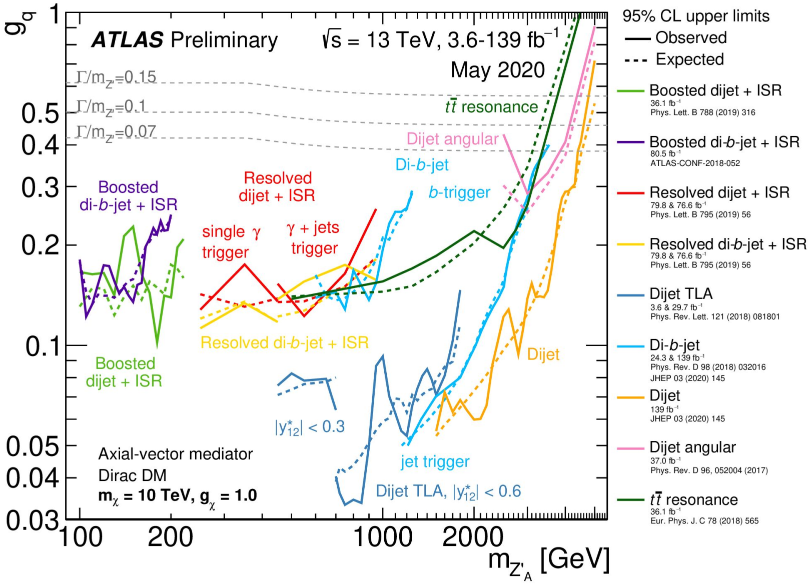


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/



Proposed summary plot #2: coupling vs mediator mass

- Vector/axial vector simplified models
  - Axial-vector simplified model (bottom figure): upper limits on mediator-quark coupling



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

Proposed summary plot #3: colliders and direct detection

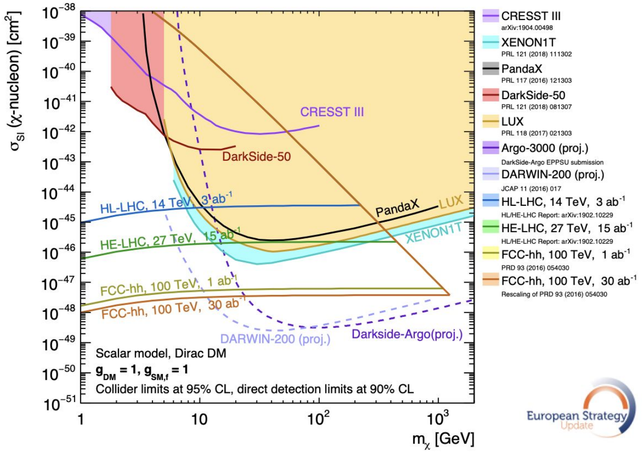
- Vector/axial vector simplified models
  - For axial vector mediator, the interaction is spin dependent: formula from arxiv 1603.04156

$$\sigma^{\mathrm{SD}} \simeq 2.4 \times 10^{-42}\ \mathrm{cm}^2 \cdot \left(\frac{g_q g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\mathrm{GeV}}\right)^2 \quad [1]$$

- Scalar/pseudoscalar simplified models
  - For scalar mediator, the interaction is spin independent:

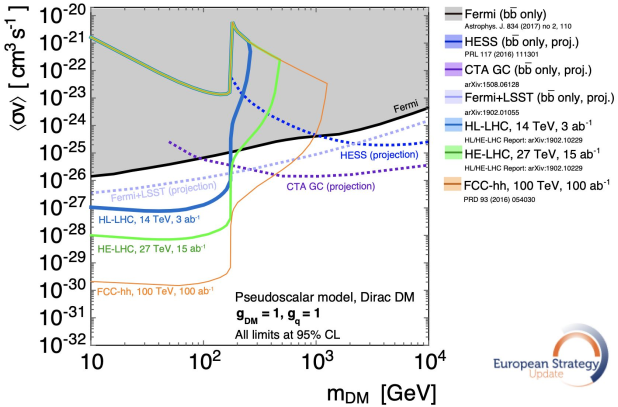
$$\sigma_{\mathrm{SI}} \simeq 6.9 \times 10^{-43}\ \mathrm{cm}^2 \cdot \left(\frac{g_q g_{\mathrm{DM}}}{1}\right)^2 \left(\frac{125\,\mathrm{GeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\mathrm{GeV}}\right)^2 \quad [2]$$

  - Translated results for future colliders are shown on the right

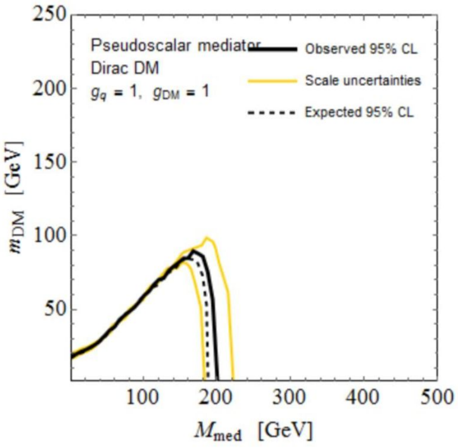


Arxiv: 1910.11775

Proposed summary plot #4: colliders and indirect detection



- Scalar/pseudoscalar simplified models
    - Fermi-LAT results are for Majorana DM: multiply Fermi bound by a factor of 2
    - Below is an limit translation example for pseudoscalar mediator

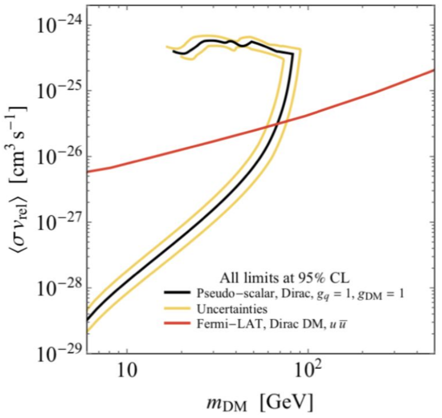


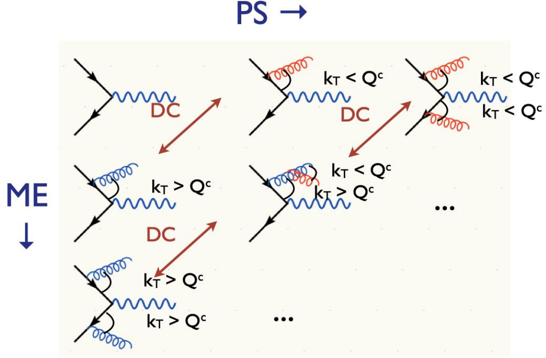
$$\langle\sigma v_{\rm rel}\rangle_q = \frac{3m_q^2}{2\pi v^2}\,\frac{g_q^2 g_{\rm DM}^2 m_{\rm DM}^2}{(M_{\rm med}^2-4m_{\rm DM}^2)^2+M_{\rm med}^2\Gamma_{\rm med}^2}\sqrt{1-\frac{m_q^2}{m_{\rm DM}^2}}$$

$$\Gamma^{\chi\bar{\chi}}_{\text{pseudo-scalar}} = \frac{g_{\rm DM}^2 M_{\rm med}}{8\pi}\left(1-4z_{\rm DM}^2\right)^{1/2},$$

$$\Gamma^{q\bar{q}}_{\text{pseudo-scalar}} = \frac{3g_q^2 y_q^2 M_{\rm med}}{16\pi}\left(1-4z_q^2\right)^{1/2},$$

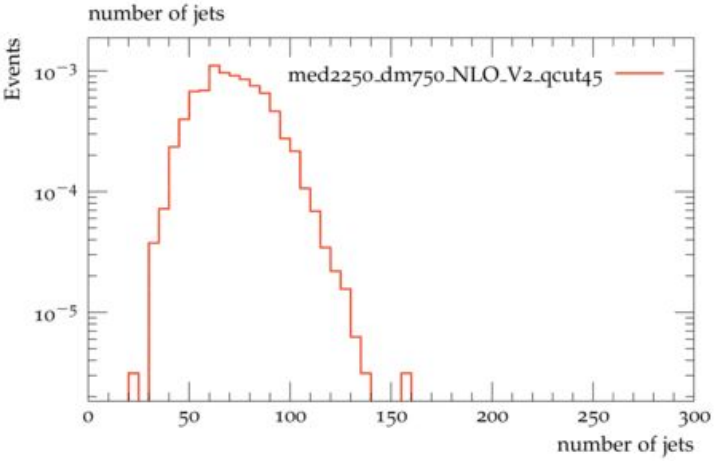
Arxiv: 1603.04156

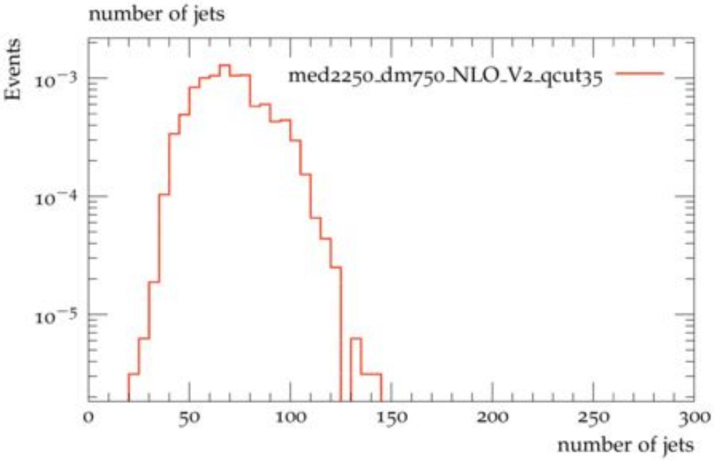




Particle level

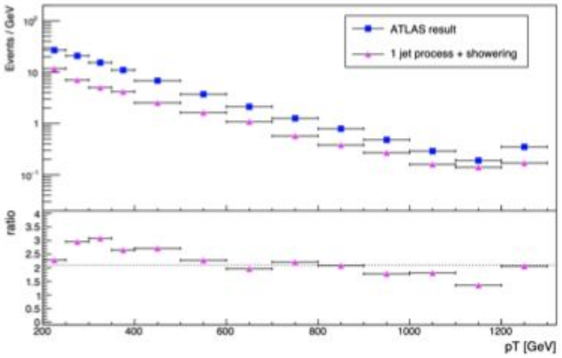
- 1 jet + showering scenario
- 2 jets + showering scenario
  - Validate matching and merging by observing discontinuity in nj / jet pt
    - MLM algorithm for LO and FxFx algorithm for NLO
    - Nj distribution right: q_cut = 45 GeV / left: q_cut = 35 GeV

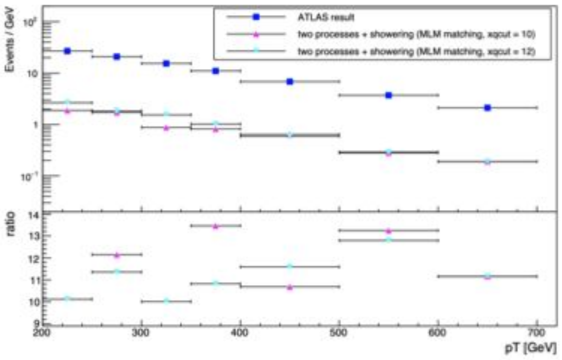




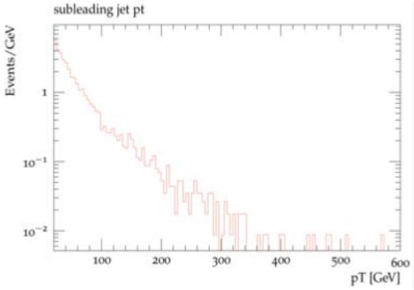
Particle level results

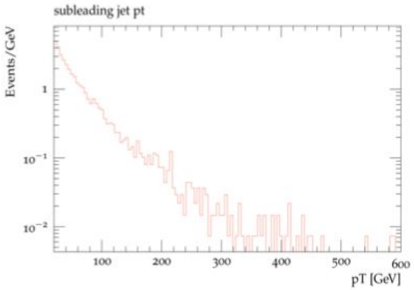
- 1 jet + showering scenario
- 2 jets + showering scenario





Name	$N_{evts}^{1process}$ (framework)	$percent_{evts}^{1process}$ (framework)	$percent_{evts}$ (ATLAS)
After evt cleaning ($p_T^{MET} > 150$GeV)	3867	100%	98.14%
Lepton veto	3756	97.13%	95.19%
Number of jets	3276	84.72%	91.95%
Azimuthal separation	2922	75.56%	88.54%
Leading jet quality	N/A	N/A	87.17%
Leading jet p_T, η	2899	74.97%	64.60%
MET p_T 200GeV	2092	54.10%	51.71%





Cuts implemented in MC signal analysis framework

<table>
<tr><th>Name</th><th>Description</th><th>Rivet implementation</th></tr>
<tr><td>Jet reconstruction</td><td>• Anti-k_t algorithm with $R = 0.4$
Calorimeter covers the pseudorapidity range $|\eta|< 4.9$
• Jets with pT > 20GeV and $|\eta|< 2.8$ are considered in the analysis
• Discard jets if separation $\Delta R_{j,e}$ is less than 0.2
Discard jets with pT > 30GeV and < 3 tracks with pT > 500MeV,
if $\Delta R_{j,\mu}$ is less than 0.4</td><td>• FastJets jets(FinalState(Cuts::abseta < 4.9), FastJets::ANTIKT, 0.4);

• const Jets jets = apply⟨JetAlg⟩(event, “Jets”).jetsByPt(Cuts::pT > 20*GeV && Cuts::abseta < 2.8);
• const Jets isojets = filter_discard(jets, [&](const Jet& j) {if (any(elecs, deltaRLess(j, 0.2))) return true;
if (j.pT() > 30*GeV && j.particles(Cuts::pT > 0.5*GeV).size() < 3
&& any(mus, deltaRLess(j, 0.4))) return true;});</td></tr>
<tr><td>Electron reconstruction</td><td>• Required to have pT > 7GeV and $|\eta|< 2.47$
• Remove electrons separated by ΔR,
between 0.2 and 0.4 from any remaining jet</td><td>• FinalState electrons(Cuts::abspid == PID::ELECTRON && Cuts::abseta < 2.47 && Cuts::pT > 7*GeV);
• const Particles isoelecs = filter_discard(elecs, [&](const Particle& e) {for (const Jet& j : isojets)
{if (deltaR(j,e) > 0.2 && deltaR(j,e) < 0.4) return true;} return false;});</td></tr>
<tr><td>Muon reconstruction</td><td>• Required to have pT > 7GeV and $|\eta|< 2.5$
• Discard muon if it is matched to a jet with pT > 30GeV,
that has at least three tracks associated with it</td><td>• FinalState muons(Cuts::abspid == PID::MUON && Cuts::abseta < 2.50 && Cuts::pT > 7*GeV);
• const Particles isomus = filter_discard(mus, [&](const Particle& m) {for (const Jet& j : isojets)
{if (deltaR(j,m) > 0.4) continue; if (j.pT() > 30*GeV && j.particles().size() > 3) return true;} return false;});</td></tr>
<tr><td>MET reconstruction</td><td>• Reconstructed from negative vectorial sum of the transverse momenta of
electrons, muons, τ leptons, photons, and jets
with pT > 20GeV and $|\eta|< 4.9$</td><td>• VisibleFinalState calofs(Cuts::abseta < 4.5 && Cuts::pT > 20*GeV);
• MissingMomentum met(calofs);
• const Vector3& vet = apply⟨SmearedMET⟩(event, "MET").vectorEt();
• const double etmiss = vet.perp();</td></tr>
<tr><td>First MET p_T cut</td><td>$p_T > 150$GeV</td><td>if (etmiss < 150*GeV) vetoEvent;</td></tr>
<tr><td>Lepton veto</td><td>Veto event with lepton in the final state</td><td>if (!isoelecs.empty() || !isomus.empty()) vetoEvent;</td></tr>
<tr><td>Number of jets</td><td>Require up to four jets in the final state</td><td>if (isojets.size() > 4) vetoEvent;</td></tr>
<tr><td>Azimuthal separation</td><td>Greater than 0.4 between MET direction and jets</td><td>if (any(isojets, deltaPhiLess(-vet, 0.4))) vetoEvent;</td></tr>
<tr><td>Leading jet p_T, η</td><td>$p_T > 150GeV$, $|\eta|< 2.4$</td><td>if (filter_select(isojets, Cuts::pT > 150*GeV && Cuts::abseta < 2.4).empty()) vetoEvent;</td></tr>
<tr><td>Second MET p_T cut</td><td>$p_T > 200$GeV</td><td>if (etmiss < 200*GeV) vetoEvent;</td></tr>
</table>