Review of benchmark models used for $Z' + E_T^{miss}$ searches

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Roadmap of Dark Matter Models for Run 3
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Introduction

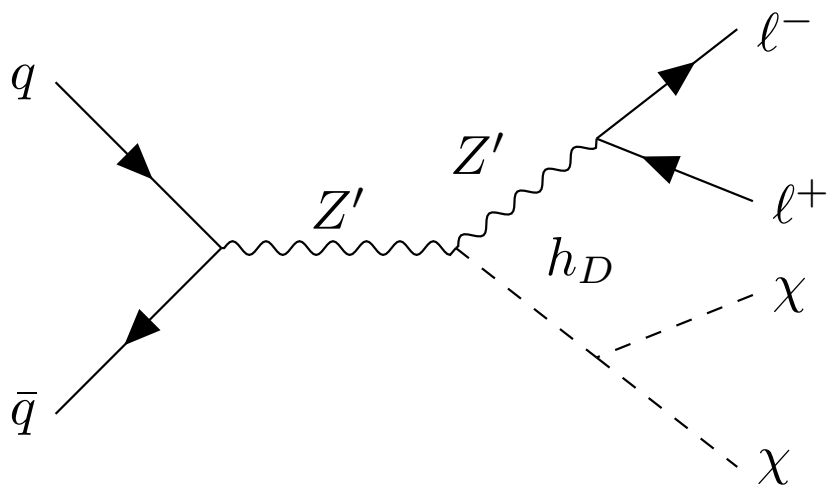
- Following the previous (inclusive) dilepton resonance search(es) in ATLAS we are now looking at *exclusive* $\ell\ell + X$ final states.
- In the analysis described here we are we are searching for dilepton resonances in events with $e^+e^-/\mu^+\mu^-$ and large $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$.
- A CONF note [ATLAS-CONF-2023-045] was published for EPS in August 2023, using a set of $Z' + \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ benchmark models [arxiv.org:1504.01386].
- Search focused on the novelty of the final state and search strategy, and less emphasis on making "interesting interpretations" $\rightarrow$ using available models to optimise the search strategy and set limits.
- Key questions to follow up on:
  - How are the models constrained by other searches?
  - Can the models reproduce the observed dark-matter relic density?
  - Are there other (more interesting) models that can produce this final state?

Outline

1. Overview of models and benchmarks/parameters.
2. Summary of search strategy and results.
3. Model constraints from other searches.
4. Dark matter interpretation.

The dark-Higgs model

- New heavy scalar, h_D, with couplings to Z' and a dark scalar, χ (possible DM candidate).
- The Z' acts as the portal between the SM and the dark sector.
- Assume minimal mixing between h_D and SM Higgs.

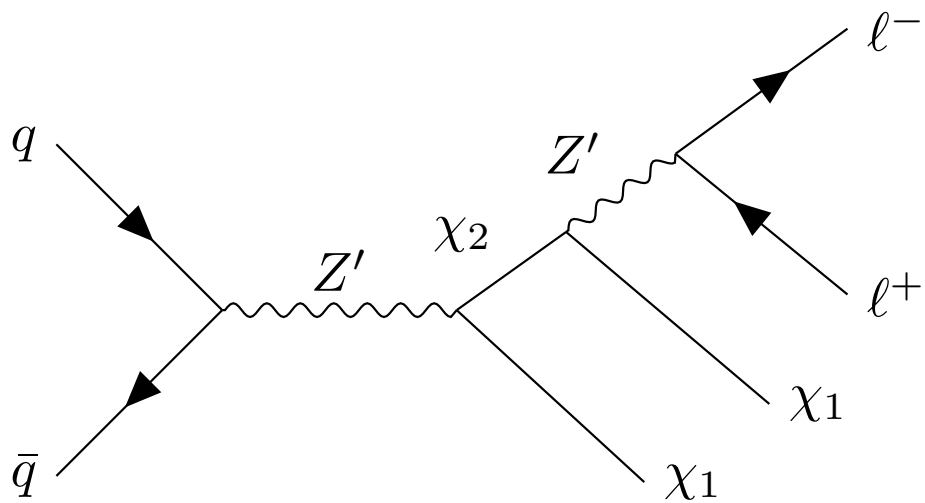


Free parameters

Masses: $m_{Z'}$, m_{h_D}, m_χ
Couplings: g_D, g_q, g_ℓ

The light-vector model

- Relatively light Z' with off-diagonal couplings to two dark fermion states, χ_1 (possible DM candidate) and χ_2.
- The Z' acts as the portal between the SM and the dark sector.
- Requires large mass splitting between χ_1 and χ_2.



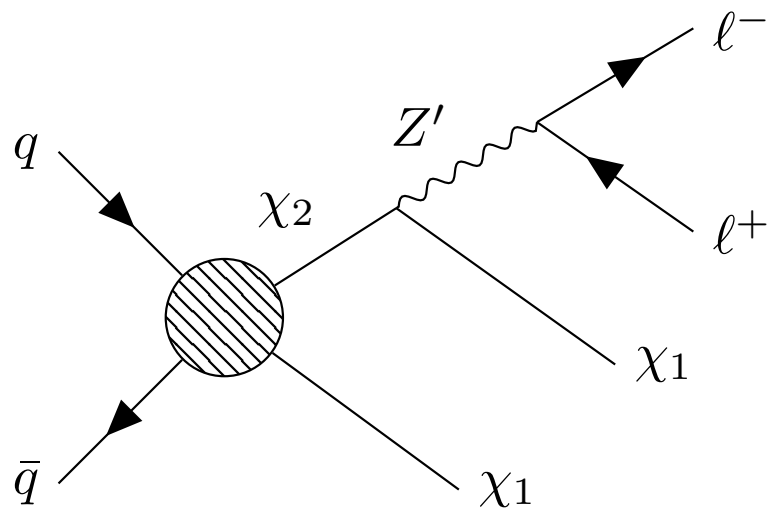
Free parameters

Masses: $m_{Z'}$, m_{χ_1}, m_{χ_2}
Couplings: g_D, g_q, g_ℓ

The light-vector model w/ EFT coupling

Not considered in the CONF note!

- Similar to the light-vector model, but with the first Z' mediator replace by a contact interaction.
- Scale of the EFT coupling given by the parameter Λ.
- May evade dilepton/dijet search constraints if g_q is very small.



Free parameters

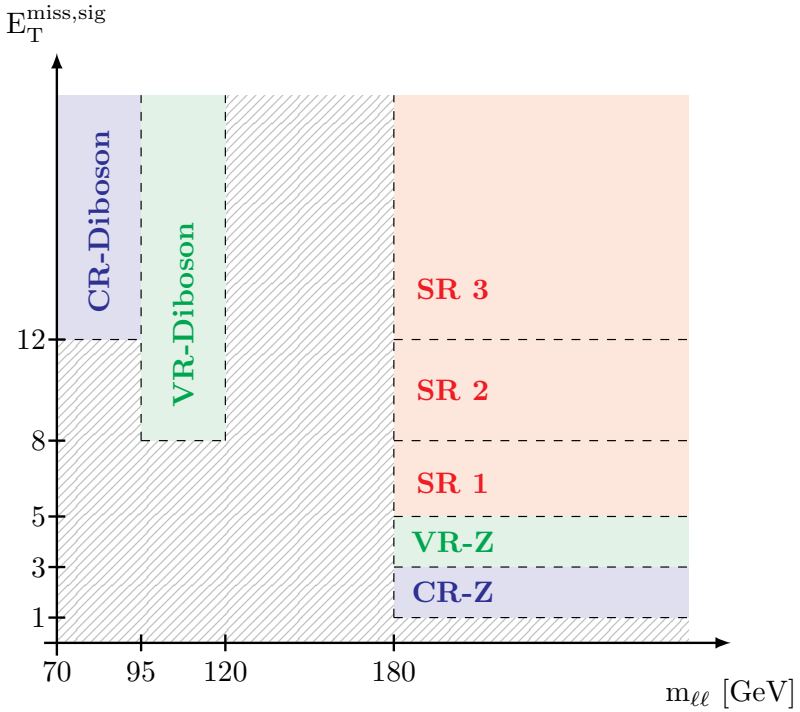
Masses: $m_{Z'}$, m_{χ_1}, m_{χ_2}
Couplings: g_D, g_q, g_ℓ
EFT scale: Λ

Parameters and benchmark scenarios

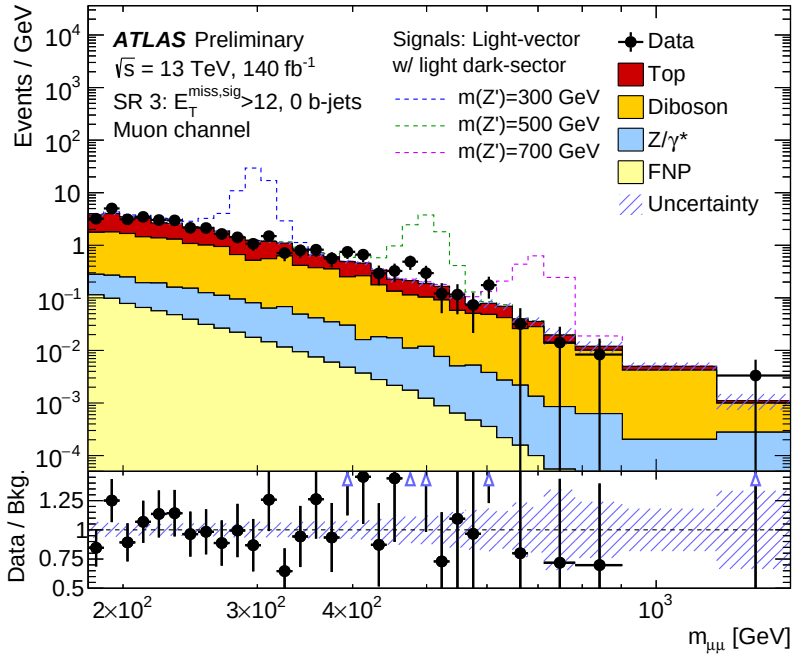
- **Couplings:** $g_D = 1$, $g_q = 0.1$, $g_\ell = 0.01$ (Inspired by V2 scenario from LHC DM WG recommendations.)
- **Z' masses:** 200-1000 GeV
- **Dark sector benchmarks:**

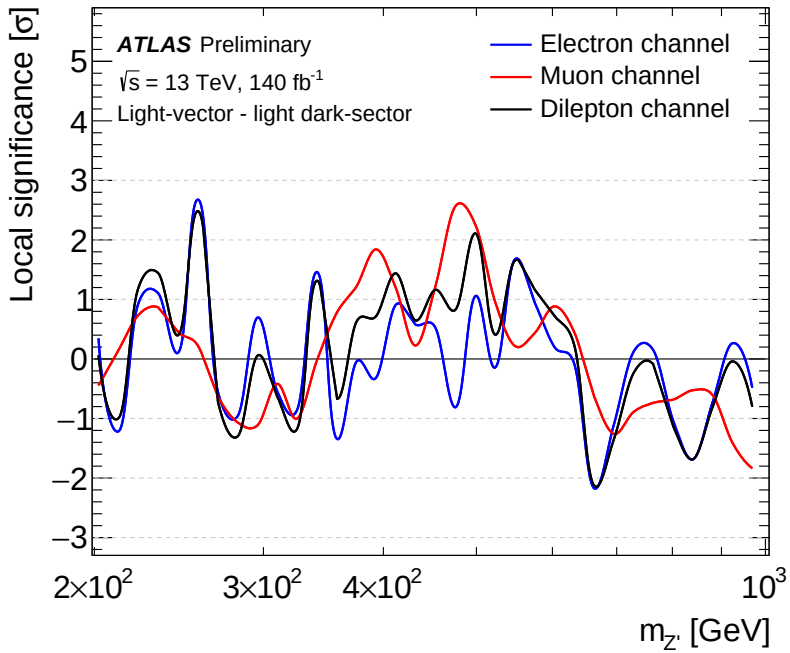
	Dark-Higgs	Light-vector
Light dark-sector	$m_\chi = 5$ GeV $m_{h_D} = 125$ GeV	$m_{\chi_1} = 5$ GeV $m_{\chi_2} = m_{\chi_1} + m_{Z'} + 25$ GeV
Heavy dark-sector	$m_\chi = 5$ GeV $m_{h_D} = m_{Z'}$	$m_{\chi_1} = m_{Z'}/2$ $m_{\chi_2} = 2m_{Z'}$

Search strategy and results

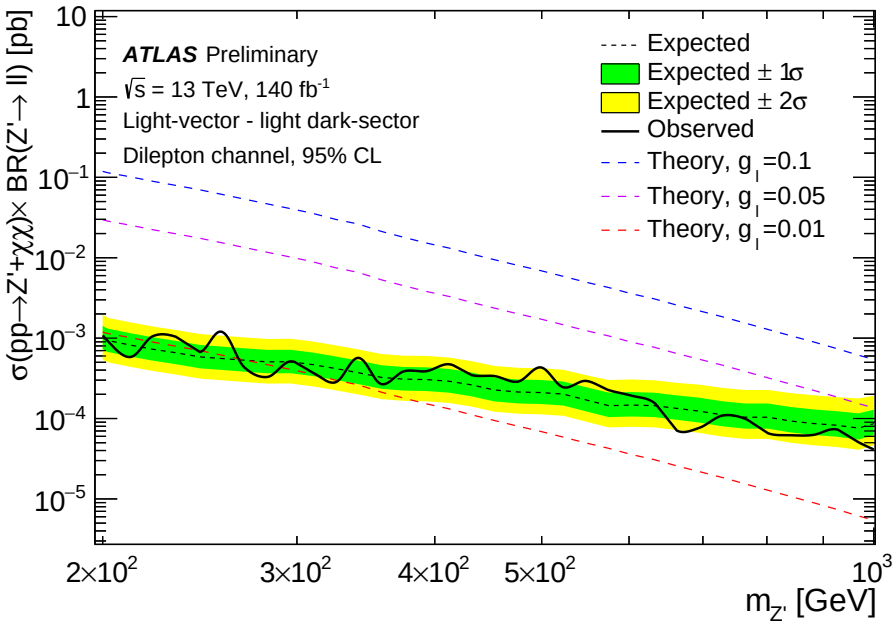


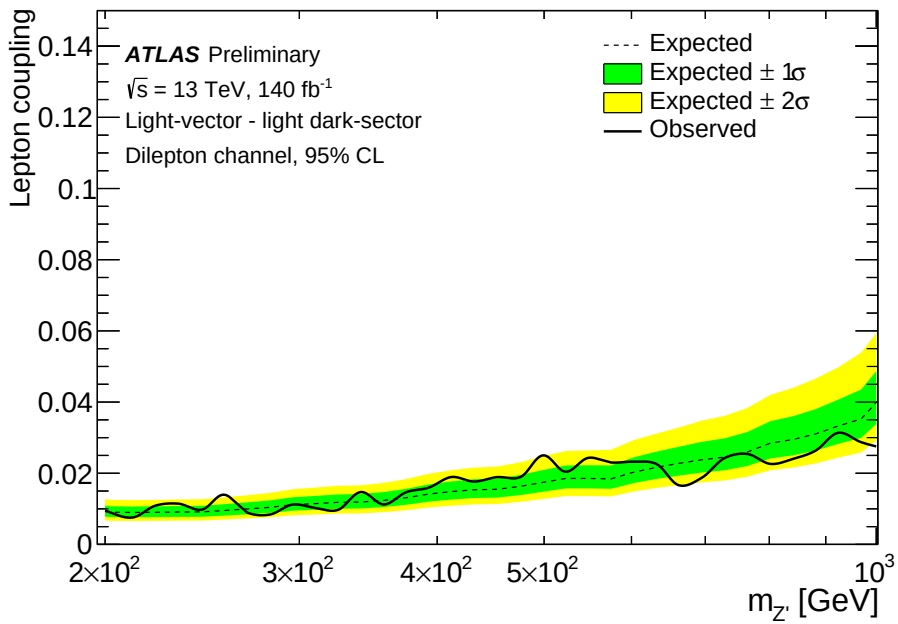
- **SR strategy:**
  - $m_{\ell\ell} > 180$ GeV
  - Three bins in $E_T^{miss,sig}$
  - *b*-jet veto
- No significant excess observed.





Exclusion limits

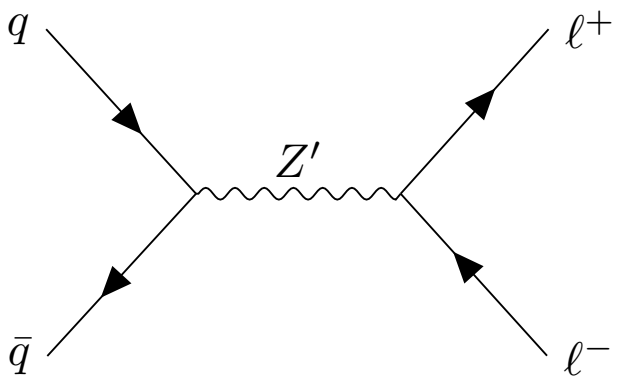




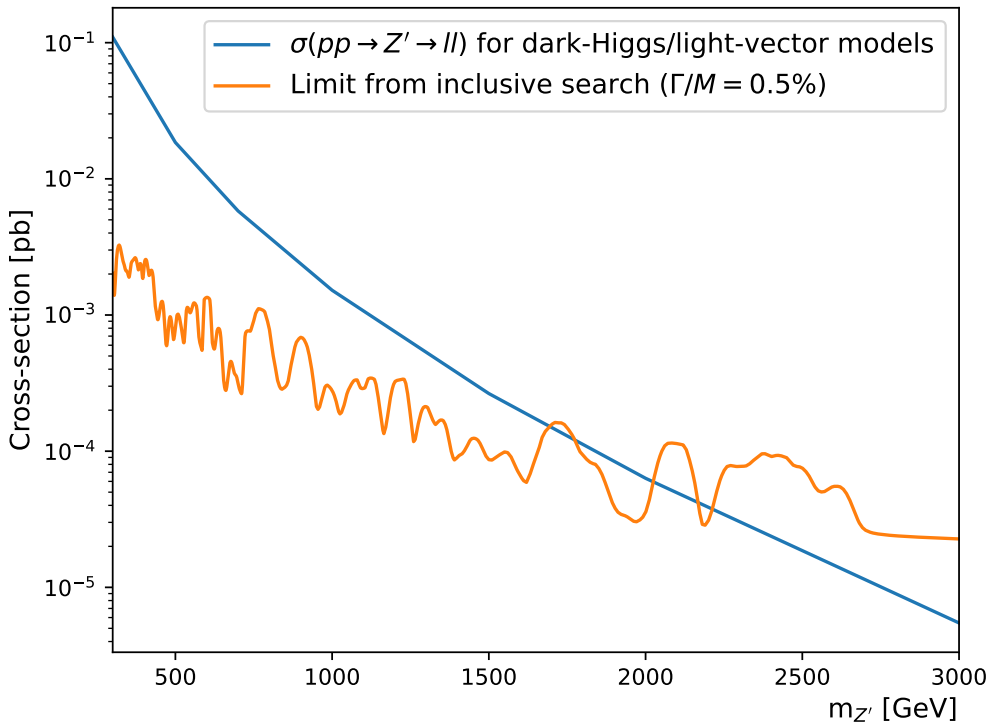
- **Example:** light-vector model w/ light dark-sector benchmark.
- Upper limits on the cross section and the $Z'\ell\ell$ coupling as a function of Z' mass.
- Lepton coupling limits calculated assuming that $\sigma \propto g_\ell^2$.

Constraints from dilepton searches

- The process $pp \to Z' \to \ell\ell$ is possible within the dark-Higgs and light-vector models.

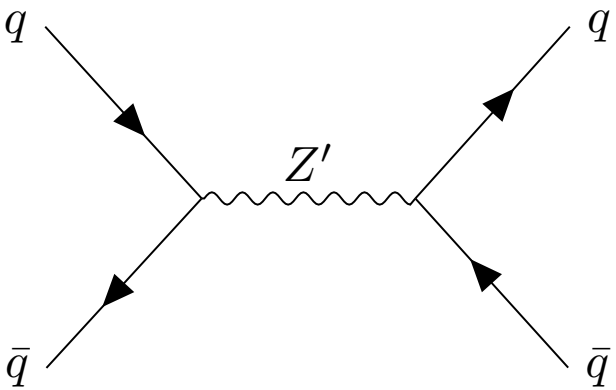


- **Couplings:** $g_q = 0.1$, $g_\ell = 0.01$
- Excluded up to $m_{Z'} \sim 2$ TeV by the inclusive dilepton search by ATLAS. [arXiv:1903.06248]

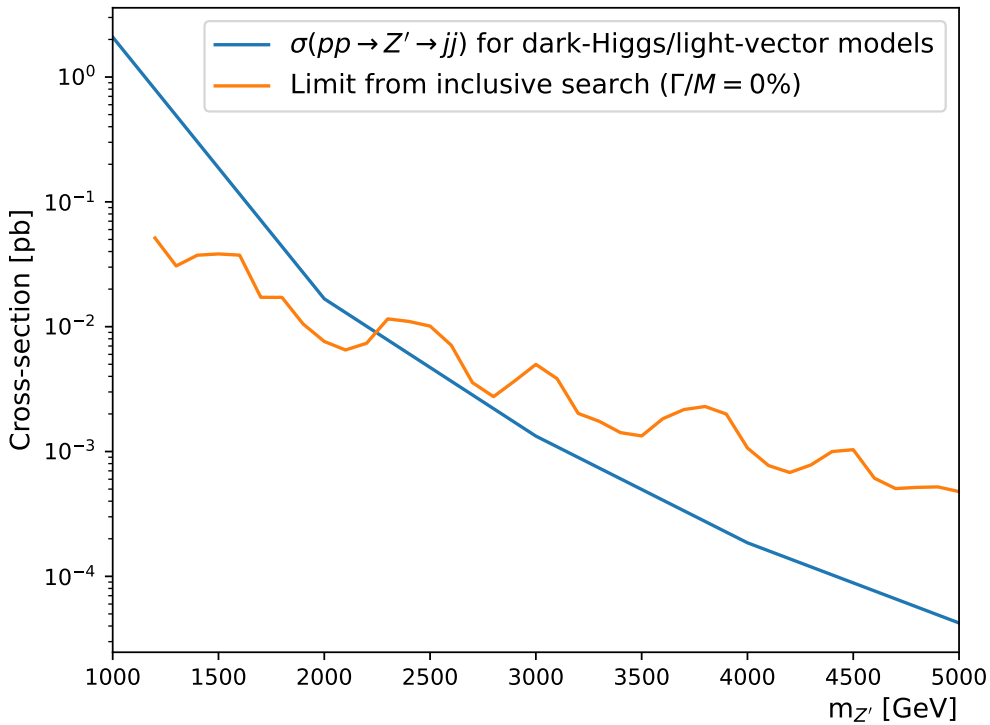


Constraints from dijet searches

- The process $pp \to Z' \to jj$ is possible within the dark-Higgs and light-vector models.

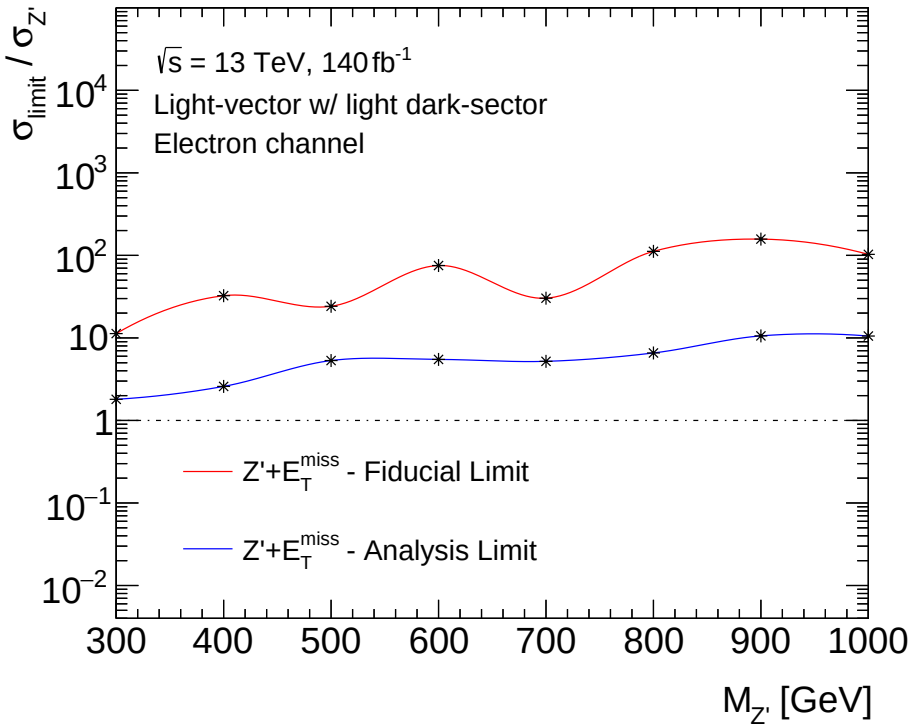


- **Coupling:** $g_q = 0.1$
- Excluded up to $m_{Z'} \sim 2.5$ TeV by the ATLAS high-mass dijet search. [arXiv:1910.08447]

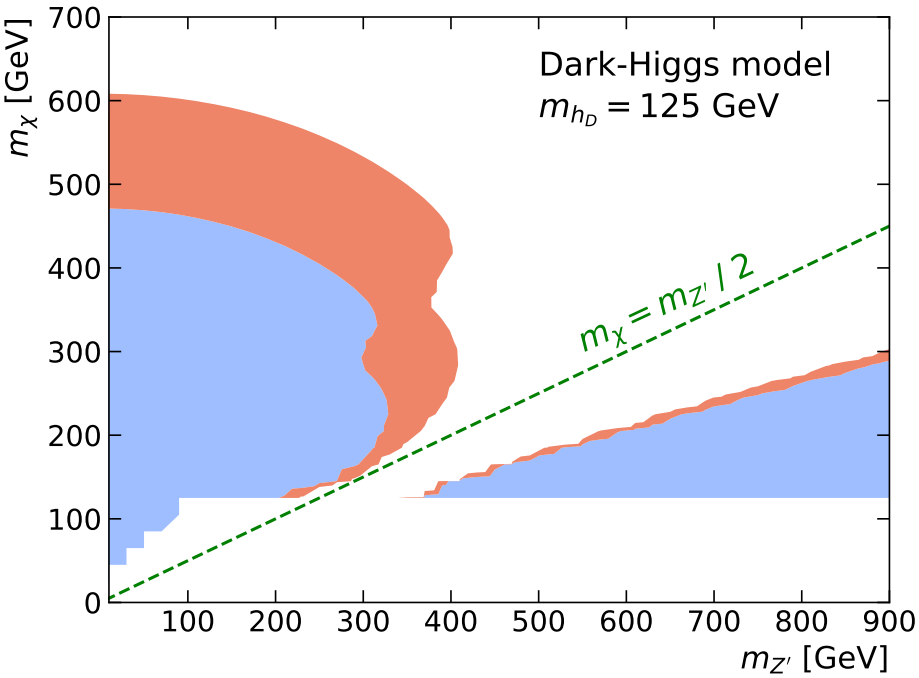


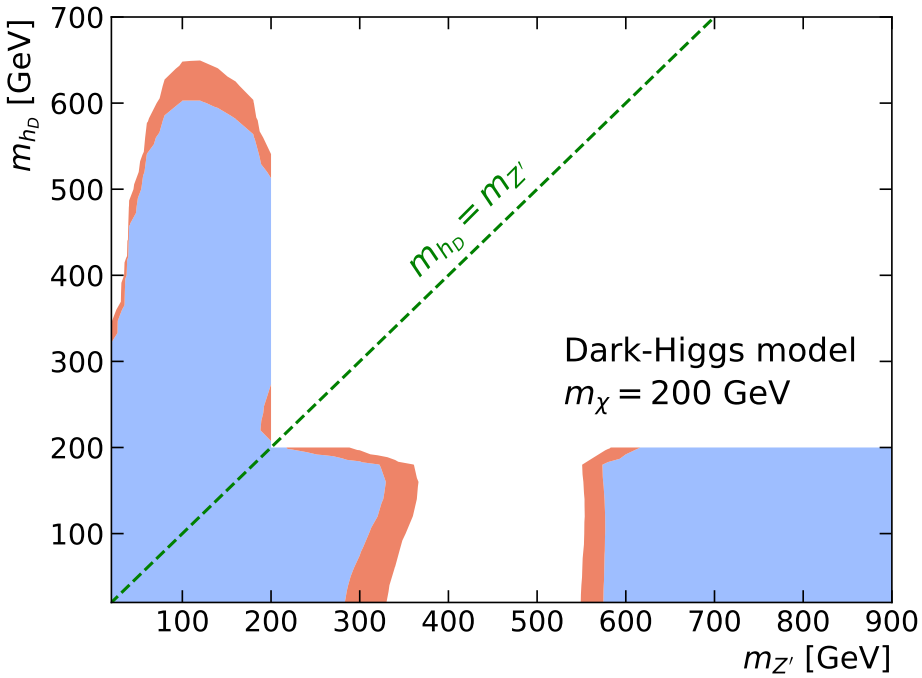
Reinterpretation of ATLAS dilepton inclusive search for $Z' + E_T^{miss}$ processes

- Have compared our limits with the limits obtained by reinterpreting the ATLAS inclusive dilepton search for the models we used,.
- See that our limits are about an order of magnitude stronger for the "$Z' + E_T^{miss}$ specific" processes.
- Important for search reinterpretations in other (more interesting) models with similar final states.



Relic density predictions: **dark-Higgs model**

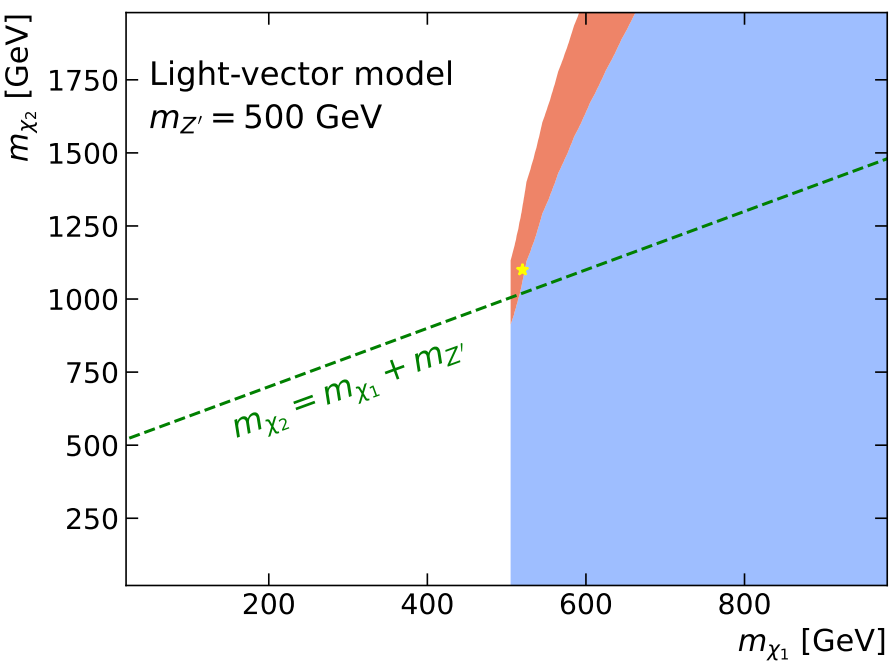


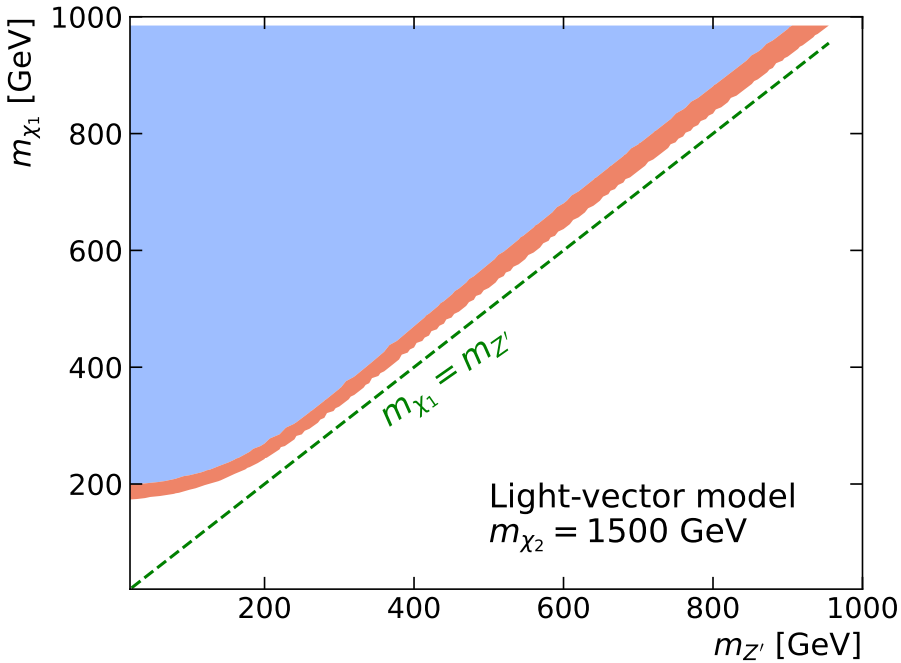


Underabundant Approximately correct Overabundant

- Our benchmarks:
  - **Light dark-sector:** $m_\chi = 5$ GeV, $m_{h_D} = 125$ GeV
  - **Heavy dark-sector:** $m_\chi = 5$ GeV, $m_{h_D} = m_{Z'}$
- DM overproduced in our benchmarks, but ∼correct RD can be reproduced by increasing the masses of the dark-sector particles.

Relic density predictions: **light-vector model**



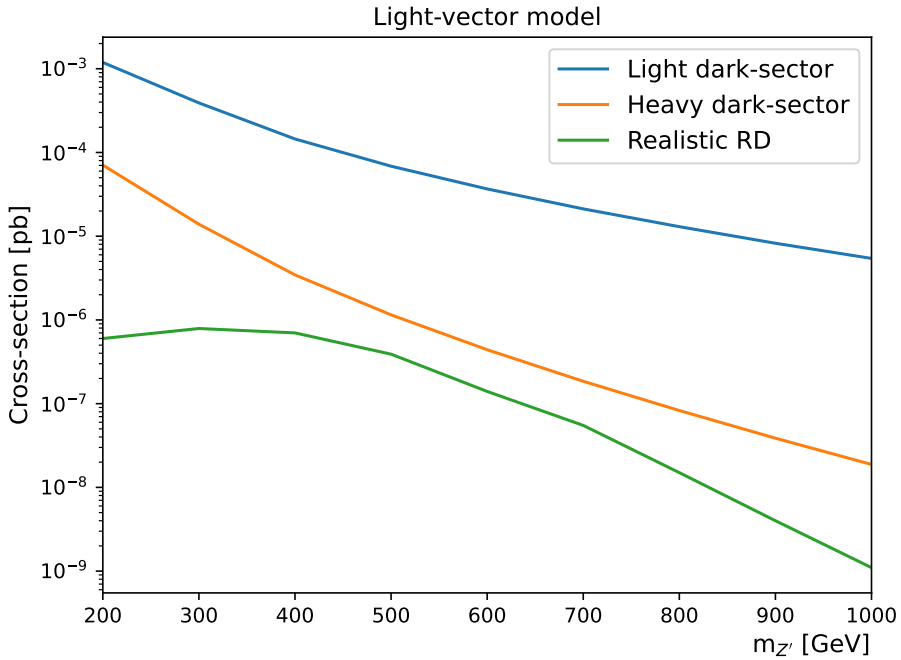


Underabundant Approximately correct Overabundant

- Our benchmarks:
  - **Light dark-sector:** $m_\chi = 5$ GeV, $m_{\chi 2} = m_{Z'} + 30$ GeV
  - **Heavy dark-sector:** $m_\chi = m_{Z'}/2$ GeV, $m_{\chi 2} = 2m_{Z'}$
- DM overproduced in our benchmarks, but ∼correct RD can be reproduced by increasing the masses of the dark-sector particles.

Cross-sections of signals with realistic RD

- **Observation:** The models can be tuned to reproduce the observed relic density by increasing the masses of the dark-sector particles.
- **Consequence:** Dramatic decrease in cross-sections compared to the benchmarks we have considered so far.
- **Conclusion:** Versions of these models with realistic RD predictions seems to be way out of reach.



Green line: "lightest possible" dark-sector scenario that yields realistic RD predictions.

Summary & outlook

- Have performed a search for dilepton resonances in the $\ell\ell + E_T^{miss}$ final state using the full ATLAS Run II data, with focus on the novelty of the final state, and considered a set of dark-sector benchmark models for search optimisation and limit setting.
- The considered models are not ideal, since they are rather strongly constrained by other searches, and do not reproduce the observed DM relic density.
- **Future plans/possibilities:**
  - Provide fiducial limits for the SRs in order to ease reinterpretations in better (more realistic) models. (Run 2 paper.)
  - Consider the EFT model, which seems more promising since it can evade some dilepton/dijet search constraints. (Run 2 paper.)
  - New search techniques and/or extended versions of the Run 2 search. (Future iterations.)
  - Consider other models that can produce the targeted final state, if they exist! Input from theory community needed. (Future iterations.)

Ideas are warmly welcome!