B3a: Dark sectors at the LHC

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TRR 257 - Particle Physics Phenomenology
after the Higgs Discovery

Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

Who is B3a?

- **Since 01/2019:** Elias Bernreuther, Felix Kahlhoefer, Michael Krämer, Tilman Plehn
- **01/2019 – 06/2019:** Saniya Heeba
- **01/2019 – 07/2020:** Patrick Tunney
- **Since 10/2020:** Alessandro Morandini
- **Further contributions:** Juliana Carrasco Mejia, Thorben Finke, Hanna Mies, Alexander Mück, Peter Reimitz

- **Talk based on:** arXiv:1907.04346, arXiv:1908.09834, arXiv:1911.11147, arXiv:2005.13551, arXiv:2006.08639 and work in progress

What are dark sectors?

- We know that the Universe is mostly made of dark matter (DM), but its nature is **completely unknown**
- Given the **complexity** of visible matter, it is hardly plausible that DM should be much simpler
- What if the DM particle is part of a larger **dark sector** with various new states and new interactions?

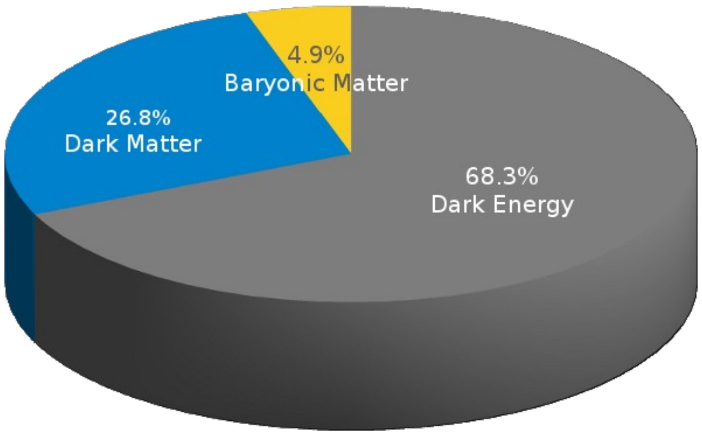
- Challenge: How can we deal with such complexity without **losing all predictivity**?

Guiding principle: Early Universe cosmology

- The **one thing** we know about dark matter is **how much** there is in the Universe:

$$\Omega h^2 = 0.1199 \pm 0.0027$$

- Any model of dark matter must provide a mechanism to **explain this number**



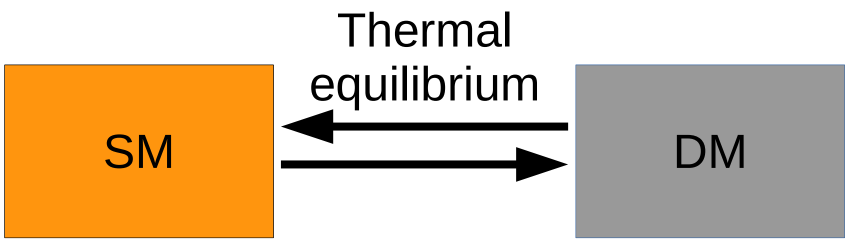
Possible route:

1) Take inspiration from the Standard Model (SM) and construct DM models in **analogy**
2) Require consistent cosmology that **reproduces the observed DM relic abundance**
3) Explore **phenomenological consequences** and constrain parameter space

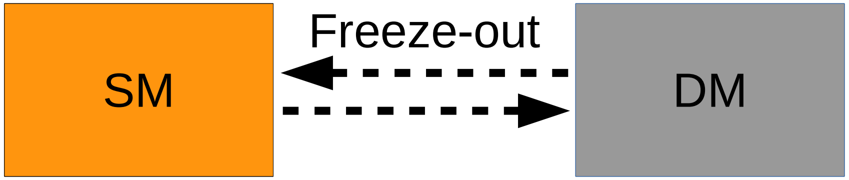
Simplest example: WIMPs

- Assume that DM has interactions that are similar in strength to weak interactions

- **High temperatures** (T >> m_{DM})
  - DM **annihilation and production** processes are in equilibrium



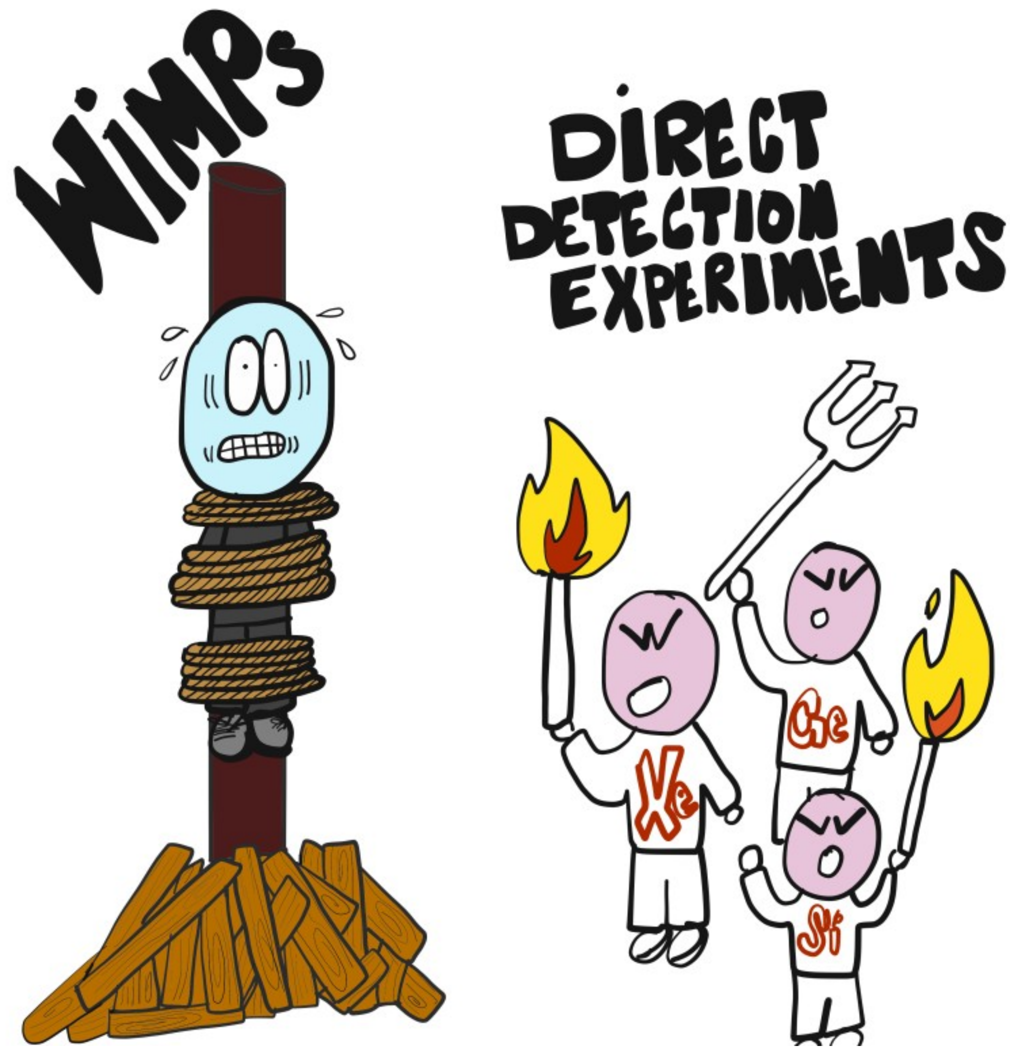
- **Low temperatures** (T << m_{DM})
  - **DM particles decouple** from equilibrium



- DM particles that obtain their relic density in this way are called Weakly Interacting Massive Particles (WIMPs)

Where Is My Particle?

- **Central prediction:** WIMPs should be observable in laboratory experiments
- The **non-observation of DM signals** mounts **substantial pressure** on the WIMP idea
- **Most WIMP models are still viable**, but parameter space **is getting tight!**
- Well-motivated to **question underlying assumptions** and consider alternative dark matter models

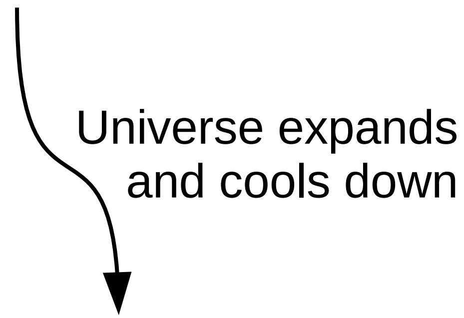


by Saniya Heeba

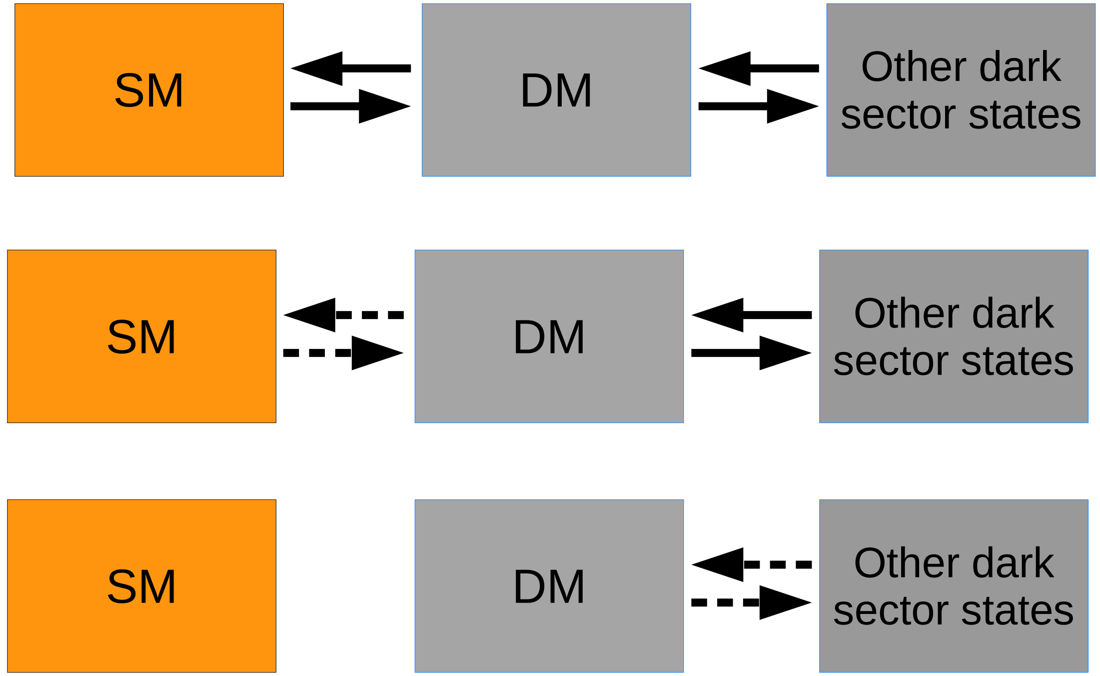
Strongly-interacting dark sectors

- What if the interactions within the dark sector are much stronger?

- **High temperatures** ($T \gg m_{DM}$)
  - All processes are in equilibrium



- **Low temperatures** ($T \ll m_{DM}$)
  - Interactions within the dark sector become inefficient

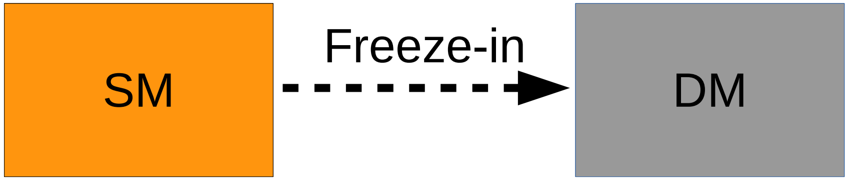


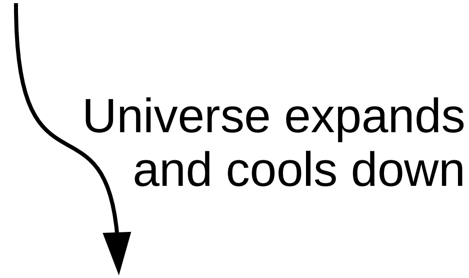
- DM relic abundance determined by the interaction rates within the dark sector

Feebly-interacting dark sectors

- What if interactions between DM and the SM are extremely weak?

- **High temperatures** (T >> m_{DM})
  - Particle production via **“energy leakage”** from the visible sector



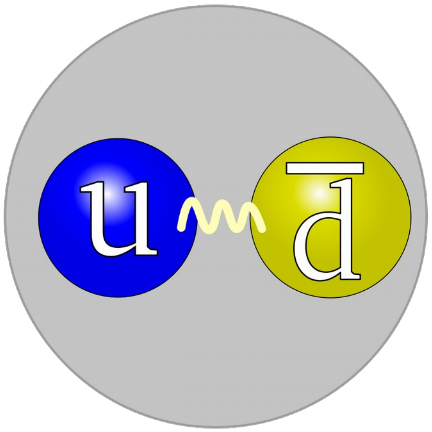


- **Low temperatures** (T << m_{DM})
  - Interactions between the two sectors **completely negligible**

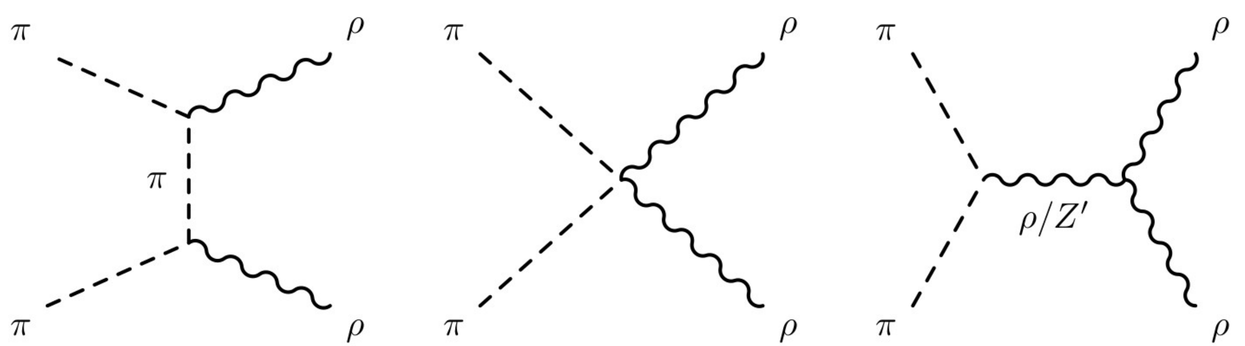
Outline

- Part 1: LHC searches for strongly interacting dark sectors
- Part 2: Phenomenology of dark sectors with feeble interactions
- Part 3: New ideas for WIMPs

Part 1: Strongly-interacting dark sectors

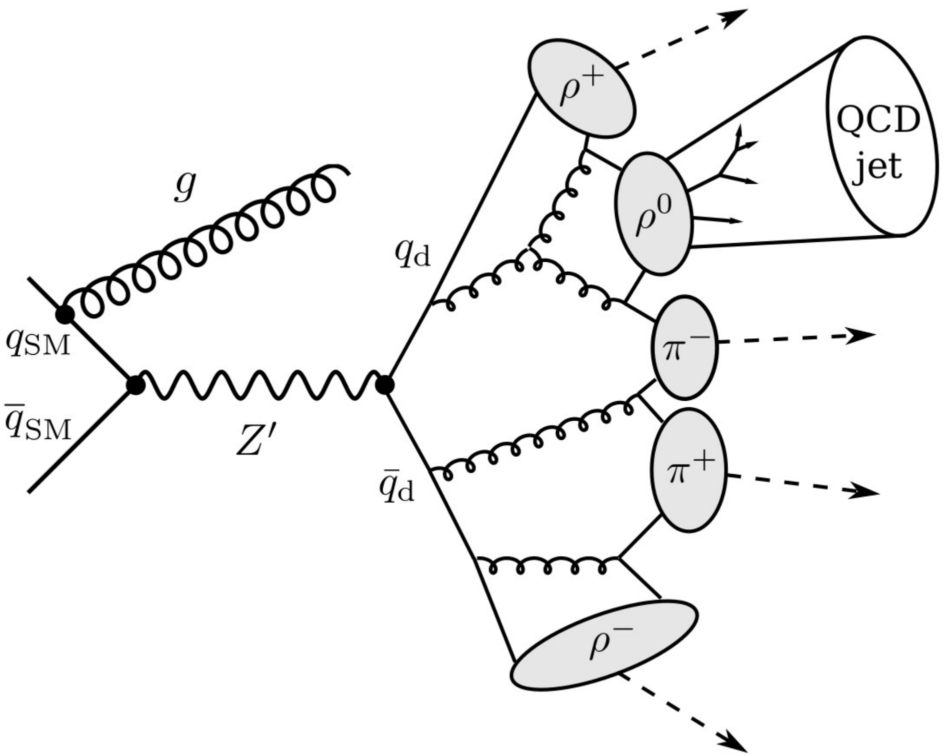


- Consider a dark sector that **resembles QCD**
- For energies below some scale Λ_d the dark sector confines, giving rise to massive **dark pions**
- If there is an additional symmetry some (or even all) of the dark pions are **stable** and make **excellent DM candidates**
- Other mesons in the dark sector (such as the vector mesons analogous to SM ρ mesons) are generally unstable and decay into SM states
- The **relic density** of dark pions is then determined by the **conversion rate** of stable into unstable mesons



Phenomenology: LHC

- If dark quarks can be produced at the LHC, we expect **fragmentation and hadronisation** in the dark sector



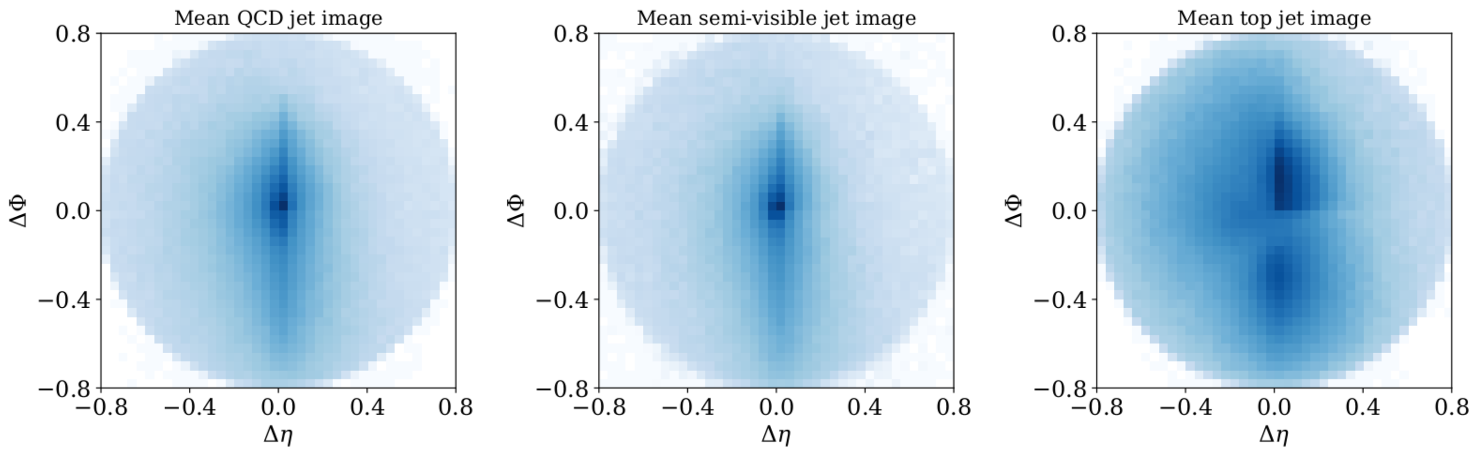
- Result: **dark shower** containing 10–20 dark mesons
- Most dark mesons (on average 75%) are stable and will **escape from the detector**
- Any dark ρ^0 meson will decay into SM particles and give rise to **QCD jets**
- **Result:** Semi-visible jets

Bernreuther, FK, Krämer, Tunney, arXiv:1907.04346

Finding dark showers with machine learning

- **Deep neural networks** are known to show excellent performance in the tagging of boosted top jets

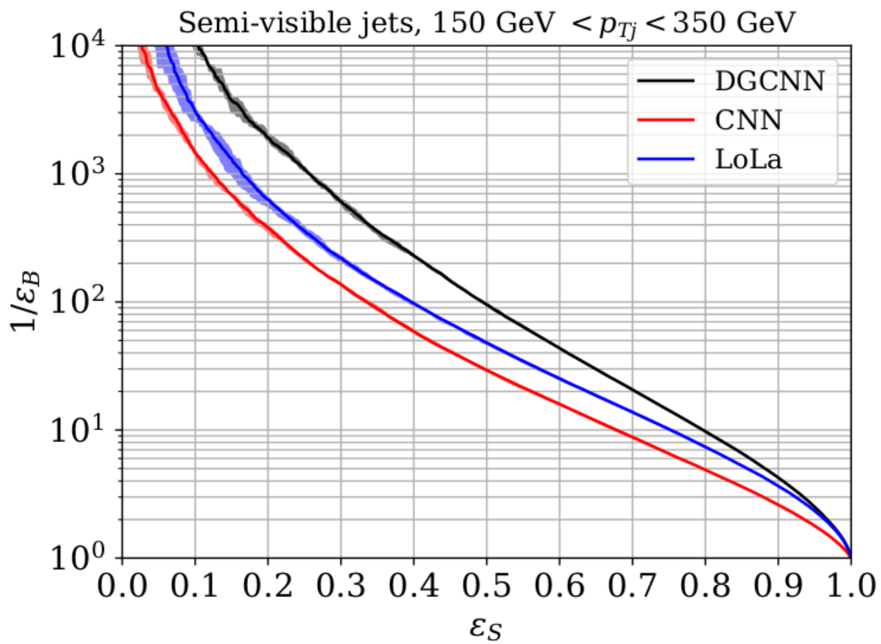
- **Example:** Convolutional neural networks (CNNs) acting on jet images, i.e. histograms of the p_T distribution in pseudo-rapidity η and azimuthal angle φ



- **Problem:** Dark showers look much more similar to ordinary QCD jets than boosted top jets

Catching dark showers with graph nets

- Conventional methods, such as Lorentz-Layer (LoLa) networks or CNNs have difficulties identifying dark showers



- **Promising new approach:** Dynamic graph convolutional neural networks (DGCNN) acting on a "point cloud", i.e. an unordered set of jet constituents that are grouped in a dynamic way by the network

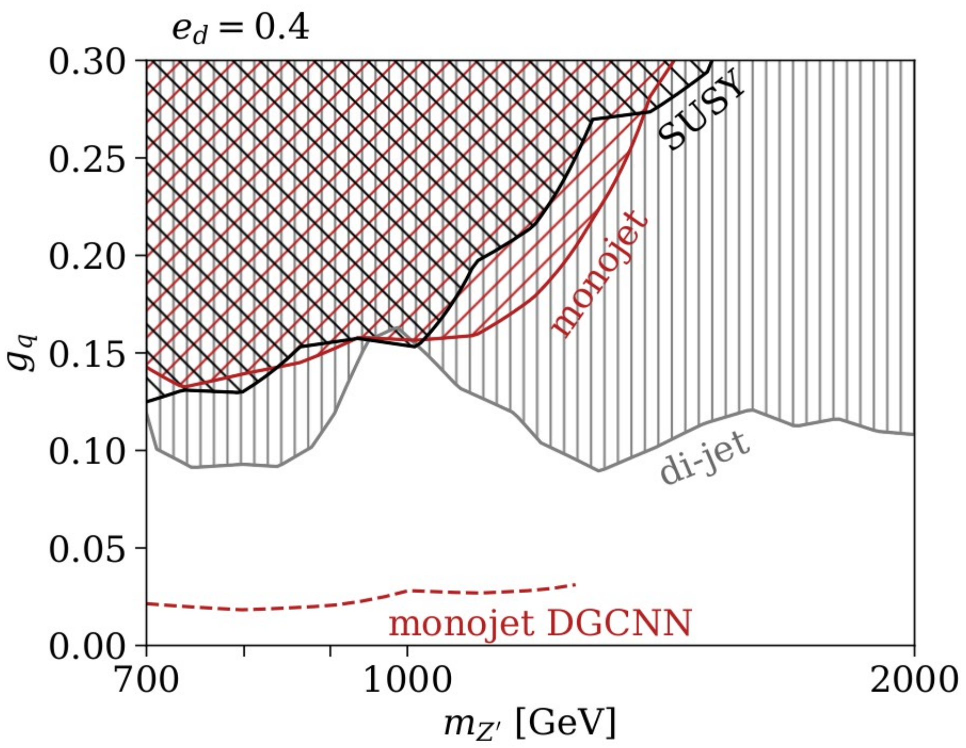
- **Main problem:** Requires supervised training, i.e. labeled data (signal / background)

- To reduce model-dependence one can train on mixed samples (containing e.g. semi-visible jets with different meson masses)

Bernreuther, Finke, FK, Krämer & Mück, arXiv:2006.08639

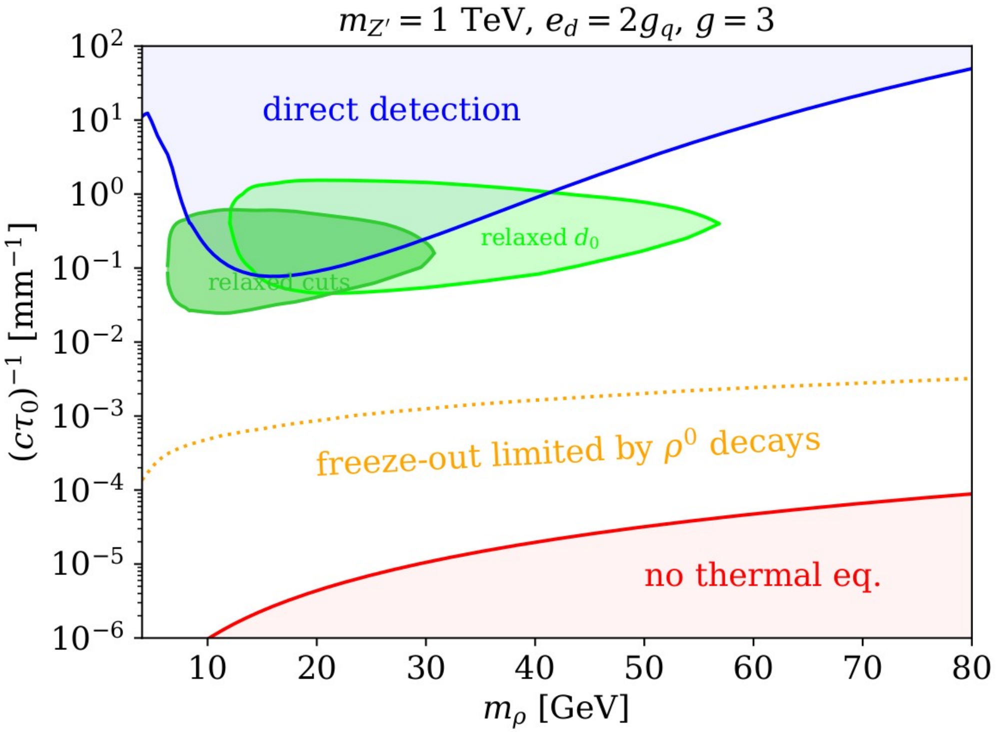
Enhancing LHC sensitivity for dark showers

- We can integrate the deep neural network trained to identify semi-visible jets as a “dark shower tagger” into existing and upcoming analyses of LHC data
- Example: searches for jets + MET (“monojet” searches)
- At 30% signal efficiency, backgrounds can be suppressed by more than two orders of magnitude!



Emerging jets

- For small couplings, the ρ decay length is comparable to the **size of the detector**
- Consequence: QCD jets originating from displaced vertex (so-called **emerging jets**)
- Difficult to reconstruct both the position of the displaced vertex and the mass of the ρ meson (needed for background suppression)
- **New analysis strategy:** Include charged tracks with small impact parameter to probe unexplored regions of parameter space

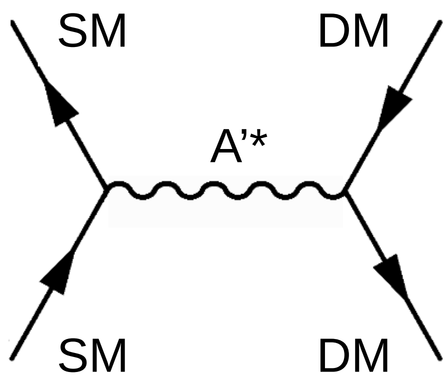


Bernreuther, FK, Krämer & Tunney, in preparation

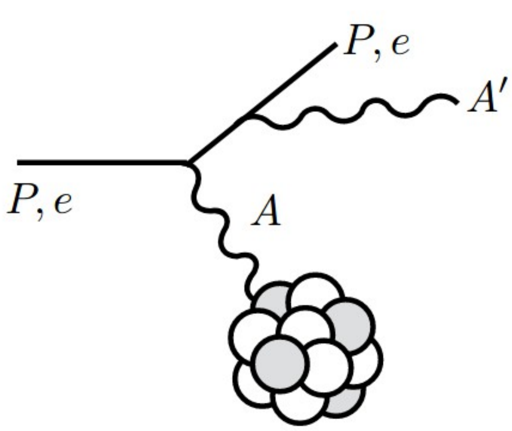
Part 2: Dark sectors with feeble interactions

- Simplest example: a dark fermion *x* coupled to a dark photon *A'*
  (like QED but with much smaller couplings)

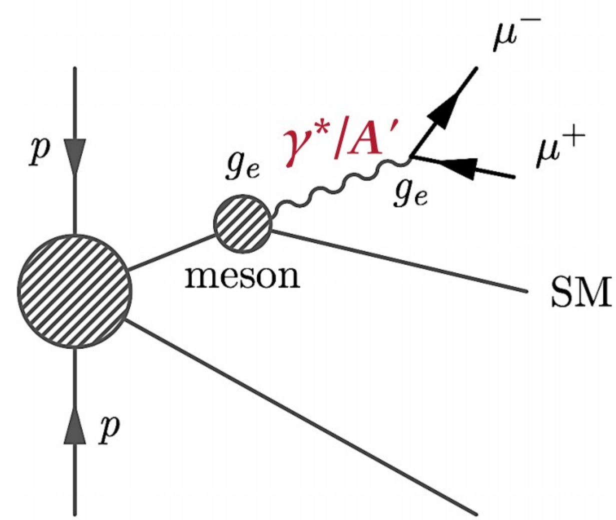
Early Universe:



Laboratory:



Dark Bremsstrahlung



Meson decays

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Early Universe:

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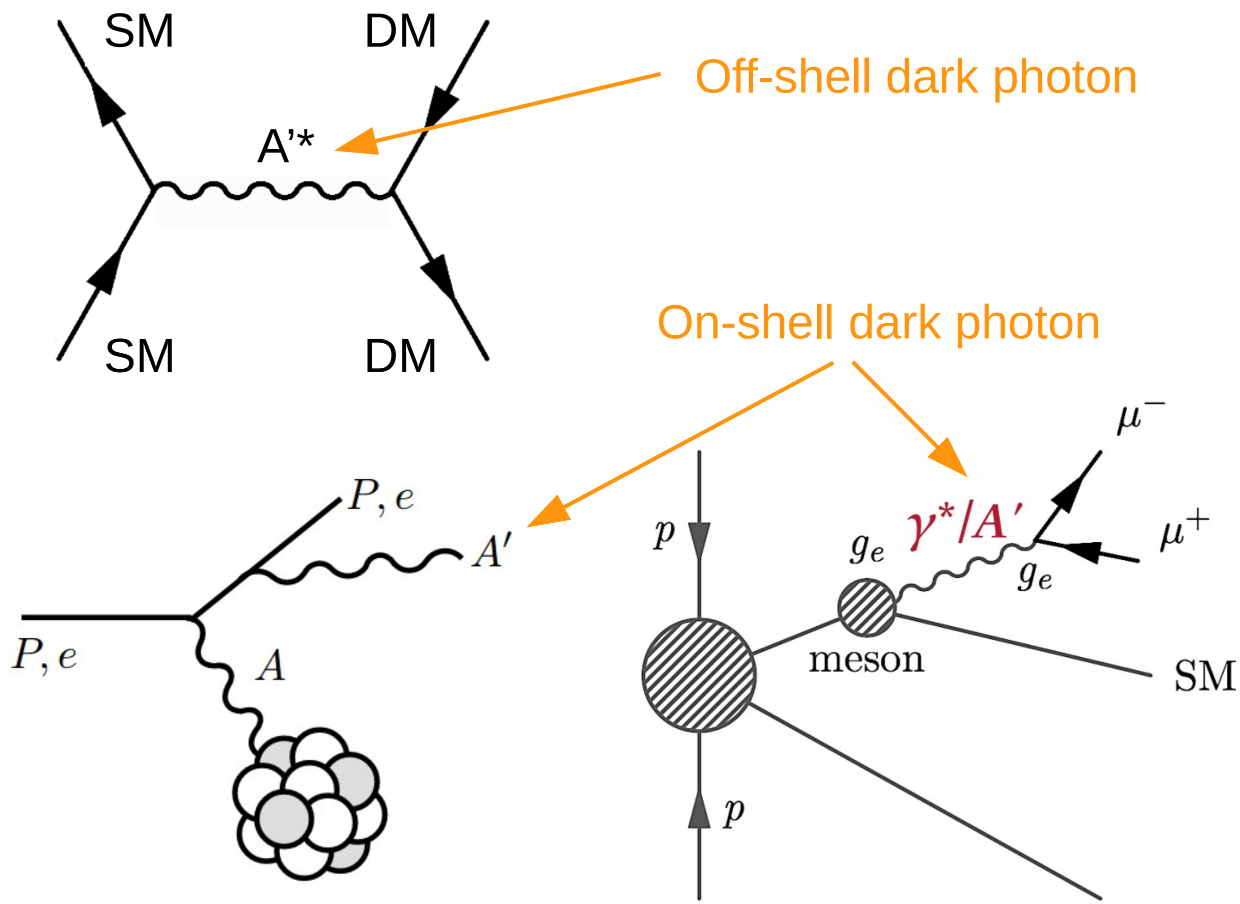
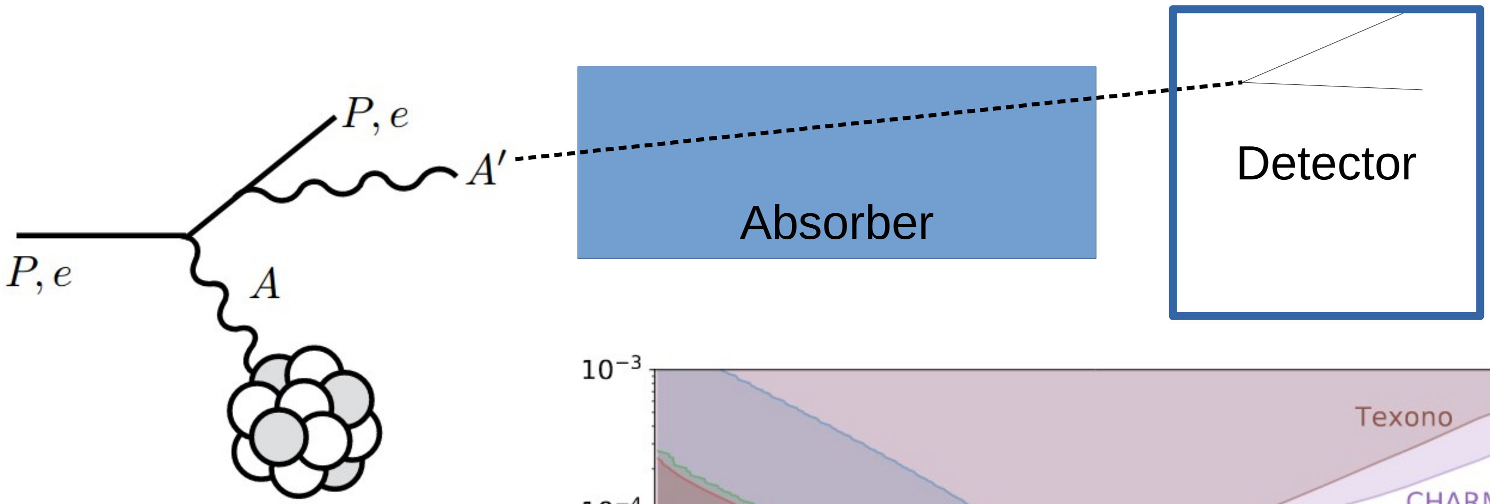
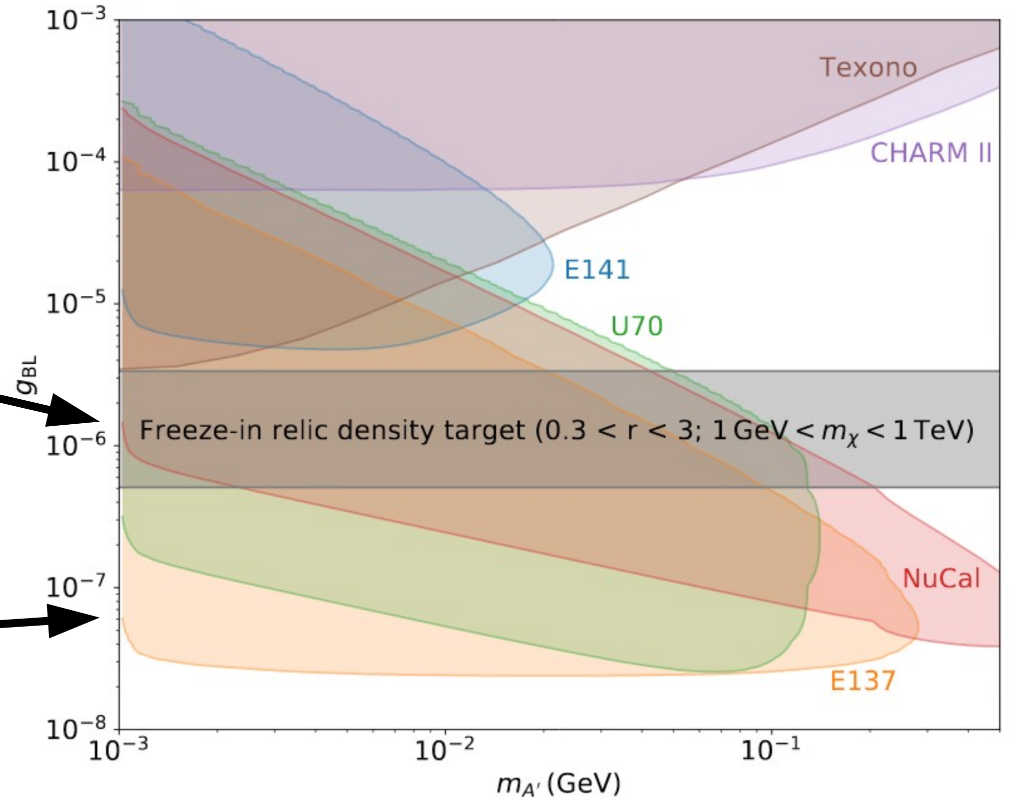


Dark Bremsstrahlung

Meson decays

Dark photon searches

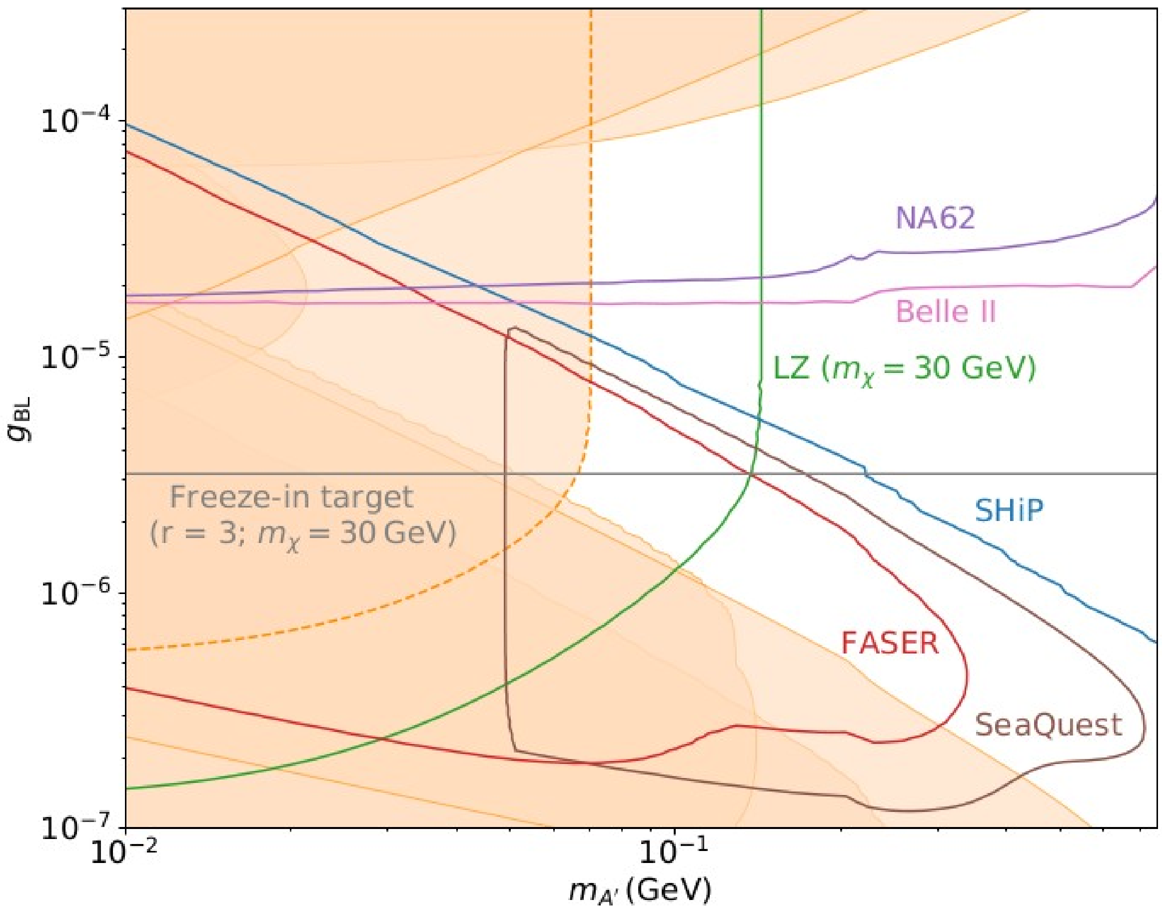




Freeze-in target band for different DM masses and couplings

Constraints from fixed-target experiments

Projections



Large unexplored parameter space!

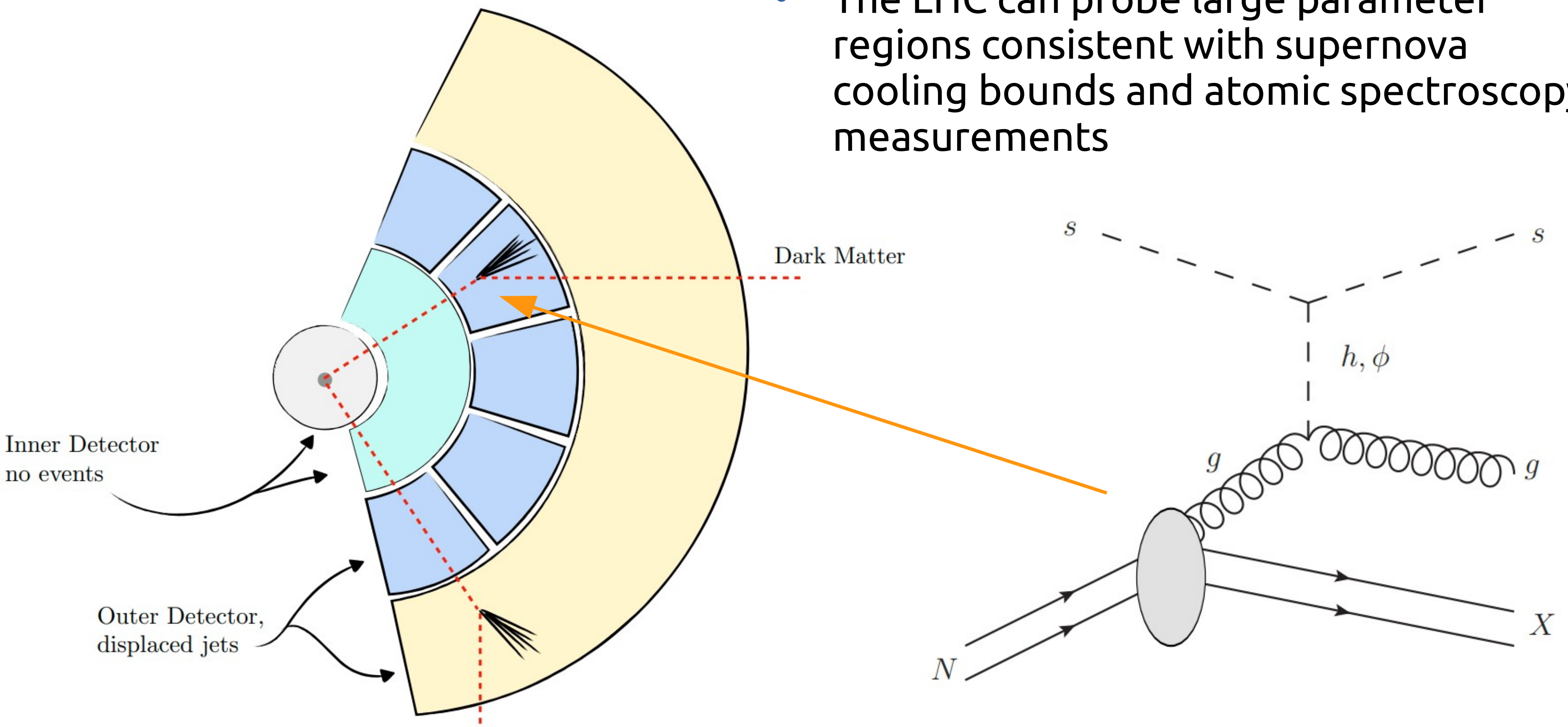
Many plans to improve sensitivity with fixed-target experiments and e^+e^- colliders!

Heeba & FK, arXiv:1908.09834

Light Dark Matter Scattering in LHC Detectors

- **Similar idea:** Ultra-light DM particles produced at the LHC (for example in Higgs decays) scatter inelastically off detector material, producing displaced recoil jets

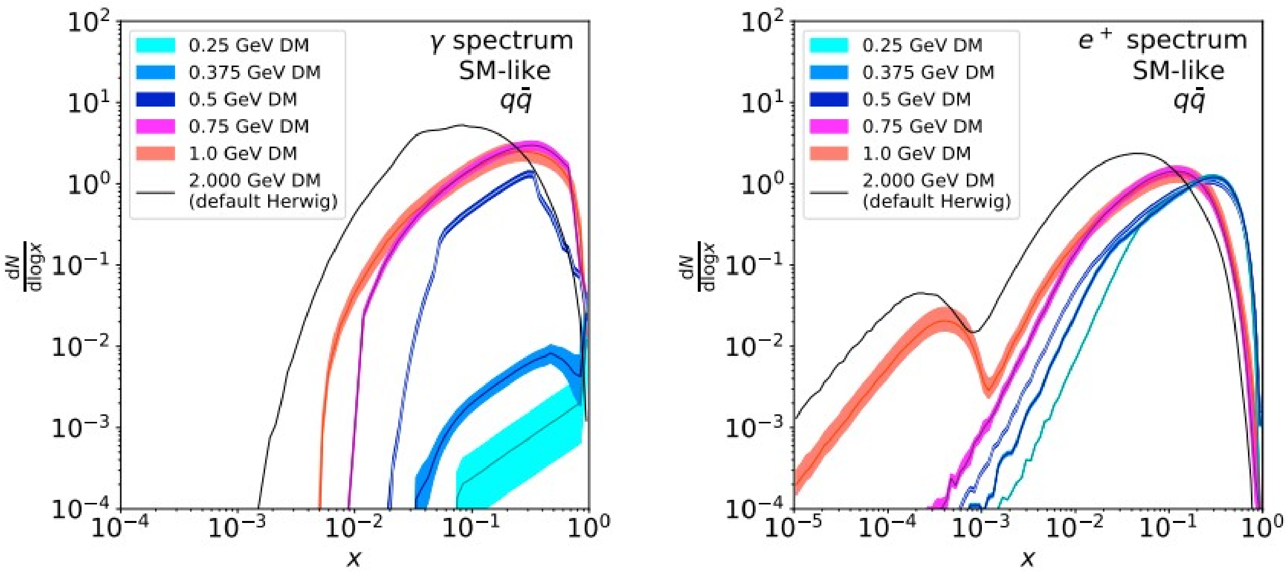
- The LHC can probe large parameter regions consistent with supernova cooling bounds and atomic spectroscopy measurements



Bauer, Foldenauer, Reimitz & Plehn, arXiv:2005.13551

Part 3: New WIMP ideas

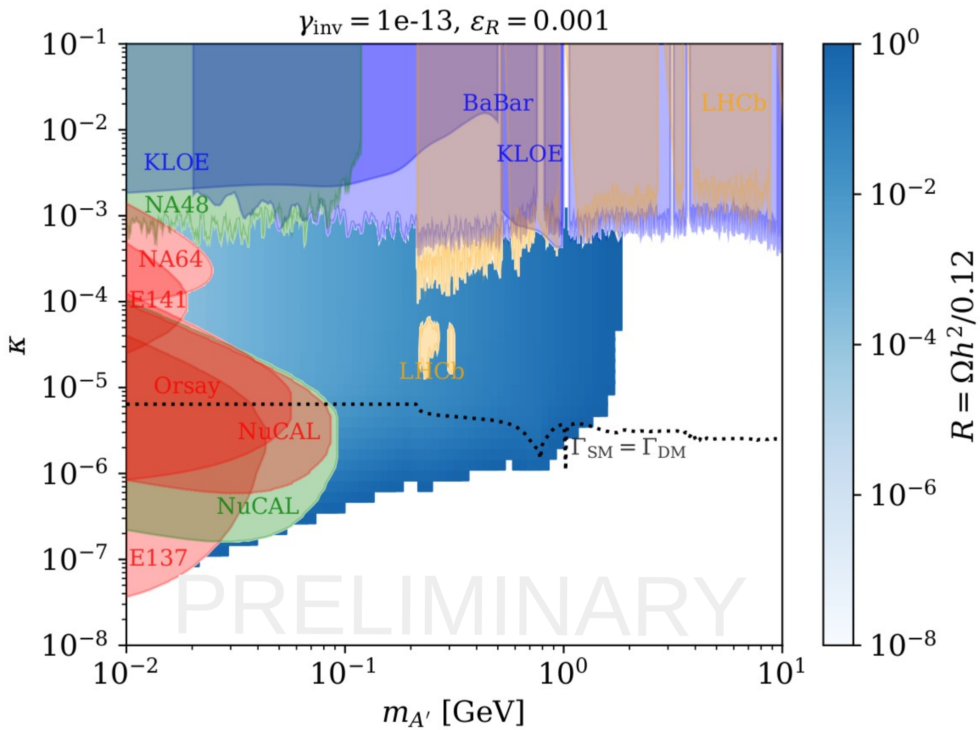
- **Interesting possibility:** DM has typical WIMP interactions but a smaller mass (GeV-scale or below)
- **New challenge:** Accurate prediction of the particle spectra produced by DM annihilations (needed e.g. for the evaluation of CMB constraints)
- **Herwig4DM:** Simulation of hadronic final states for annihilation of sub-GeV DM with updated fits to electron–positron data and several new final states

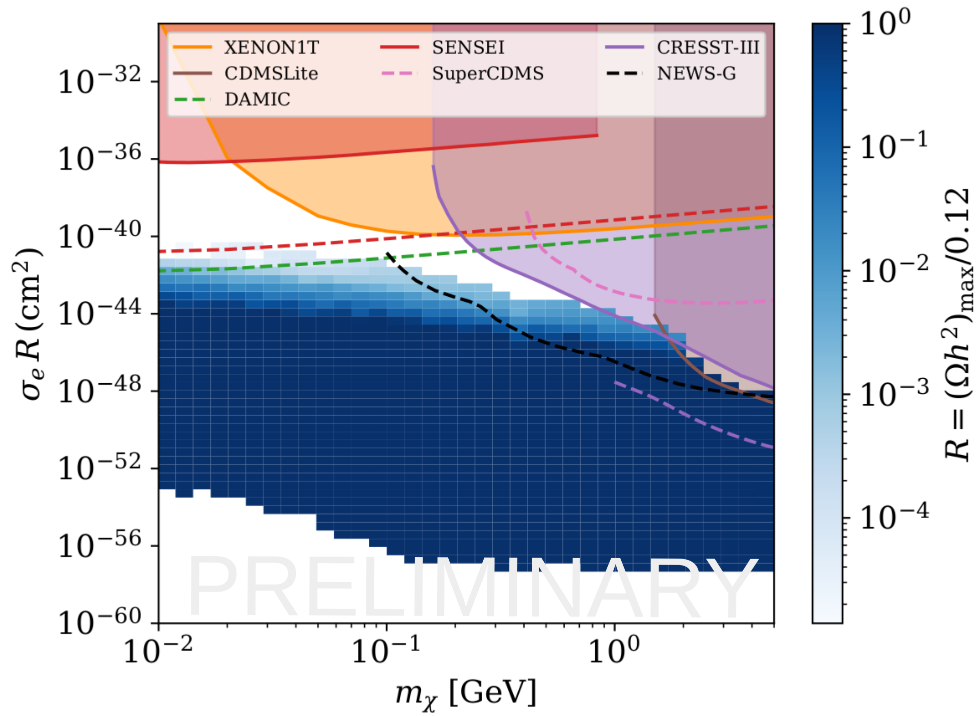


Plehn, Reimitz & Richardson, arXiv:1911.11147

Global fits of sub-GeV DM

- **Aim:** Combine constraints from cosmology and laboratory experiments to perform a global analysis of sub-GeV DM with a dark photon mediator
- **Key result:** If annihilations are resonantly enhanced ($m_{DM} \approx m_{A'}/2$), there is large viable parameter space within reach of future experiments



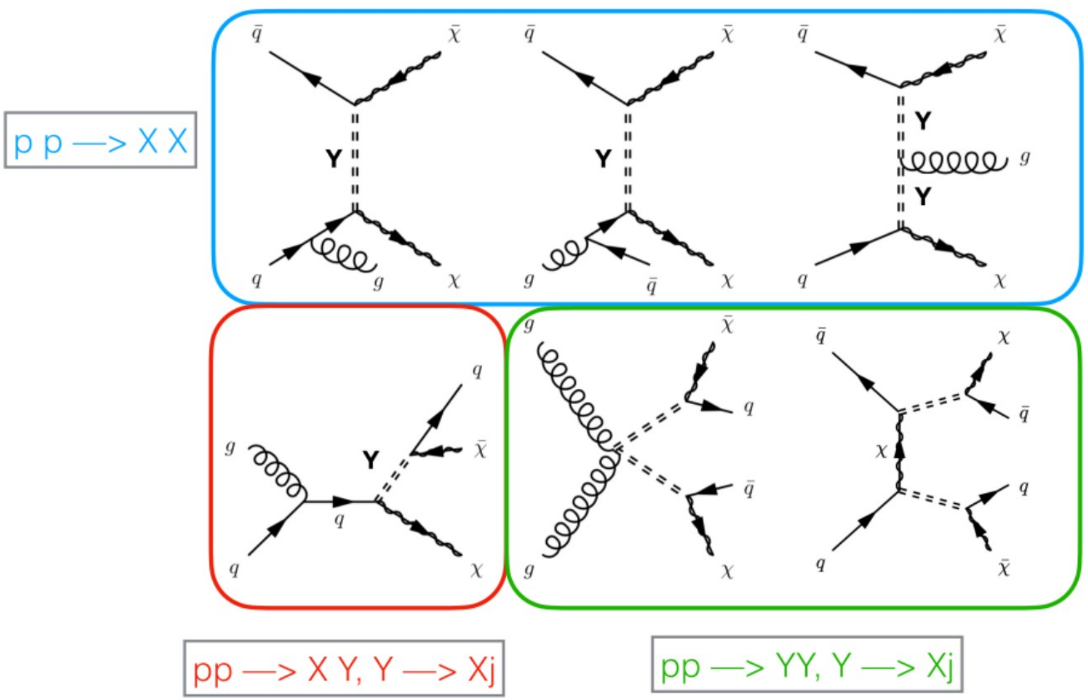


Bernreuther, Heeba & FK, in preparation

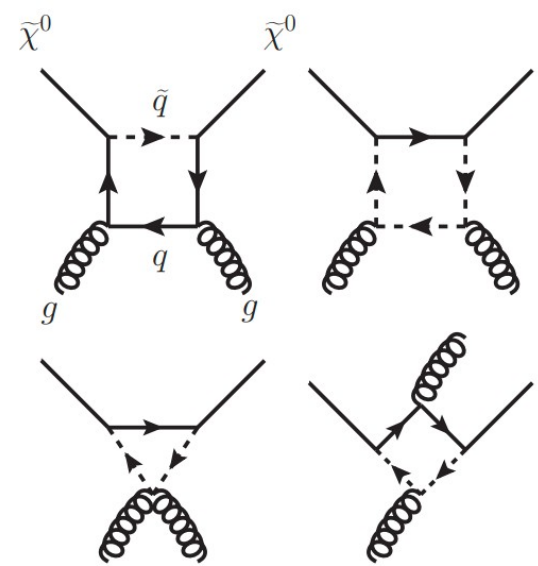
t-channel mediators

- **Another exciting direction:** WIMP models with t-channel mediators
- Highly relevant **NLO corrections** to LHC and (in)direct detection signatures
- Requires implementation of simplified models in various **numerical tools** (FeynRules, NLOCT, MG5_aMC, MadDM)

LHC processes



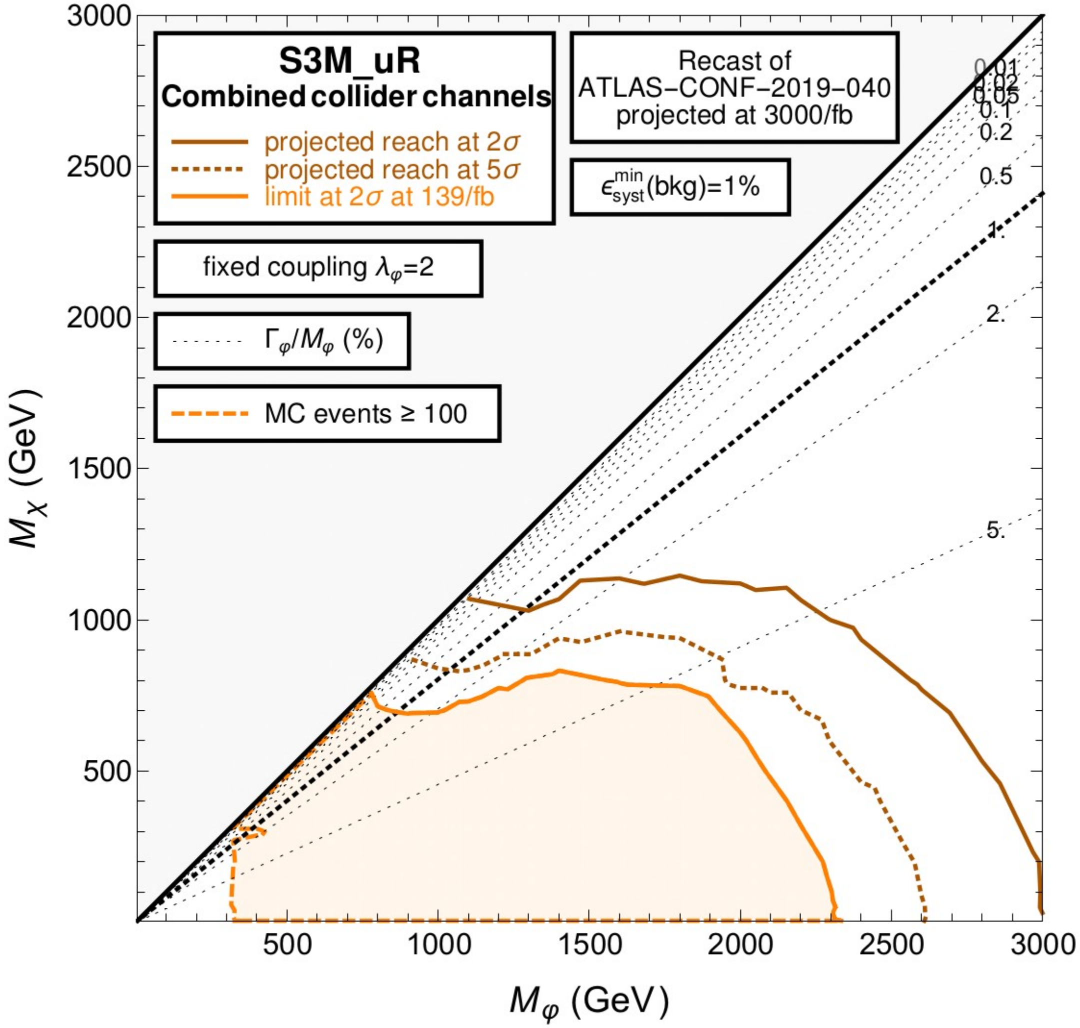
Direct detection



Constraints on t-channel mediators

- **First step:** Reinterpretation of existing SUSY searches with jets and MET in final state (e.g. ATLAS-CONF-2019-040)
- **Outlook:**
  - Combine collider limits with (in)direct detection constraints
  - Find ways to distinguish different models based on their signatures

Arina, Fuks, Heisig, Krämer, Mantani, Mawatari, Mies, Panizzi & Salko, in preparation



Conclusions

- Our ignorance about the nature of DM and the absence of DM signals in laboratory experiments motivates the exploration of more complex dark sectors
- We can build dark sectors in analogy to Standard Model phenomena and explore the implications for cosmology, in particular the DM relic density
- Strongly interacting dark sectors predict many exciting collider signatures such as semi-visible and emerging jets → new analyses strategies needed!
- Dark sectors with feeble interactions can be tested at the intensity frontier (fixed-target experiments, B factories, …)
- WIMPs are not dead! Many exciting ideas regarding sub-GeV DM and models with t-channel mediators