Strongly interacting dark sectors at the LHC

Felix Kahlhoefer

HEP Science Coffee, Lund University
12 June 2020

Based on
arXiv:1907.04346, **arXiv:2006.0XXXX** and **ongoing work**
in collaboration with
Elias Bernreuther, Juliana Carrasco, Thorben Finke,
Michael Krämer, Alexander Mück and **Patrick Tunney**

TRR 257 - Particle Physics Phenomenology
after the Higgs Discovery

Emmy
Noether-
Programm

DFG Deutsche
Forschungsgemeinschaft

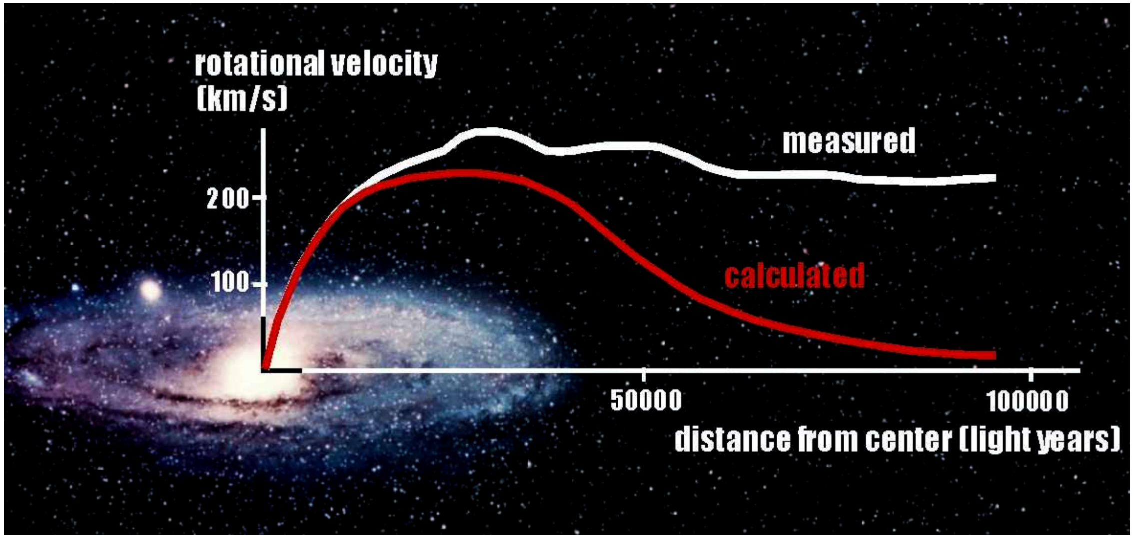
TTK Institute for
Theoretical
Particle Physics
and Cosmology

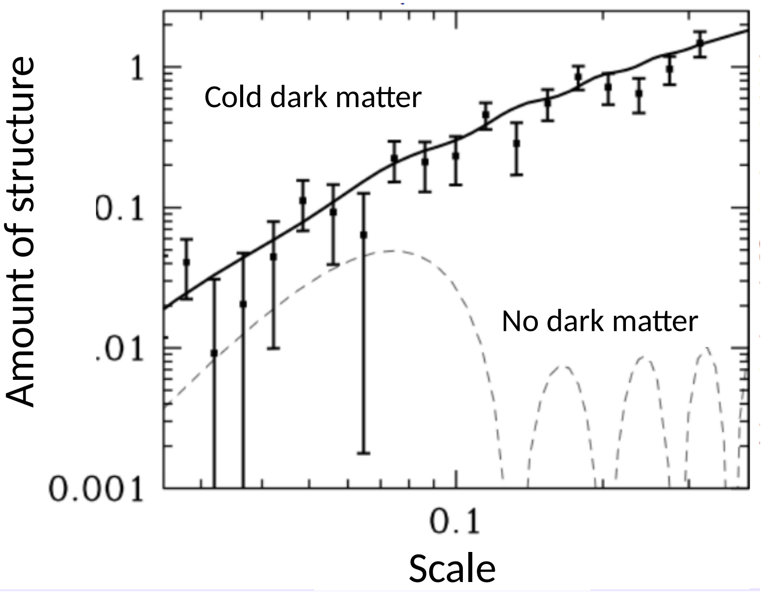
RWTH AACHEN
UNIVERSITY

Outline

- Motivation for dark sectors
- Part 1: Introduction to strongly-interacting dark sectors
- Part 2: Phenomenological implications
- Part 3: Using deep neural networks to search for dark showers
- Part 4: Improving searches for displaced vertices

Dark matter – pieces of the puzzle





- In spite of the astrophysical and cosmological evidence for dark matter (DM), its particle physics nature and properties remain unclear

Guiding principle: Early Universe cosmology

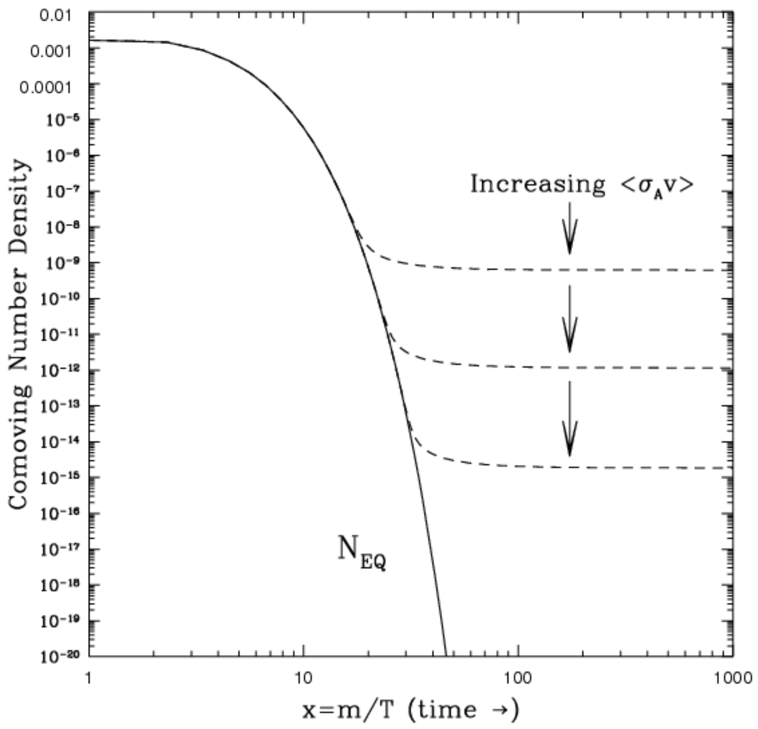
- The **one thing** we know about dark matter is **how much** there is in the Universe:

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

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

- Most widely studied paradigm:

  Thermal freeze-out
  - Dark matter was in **thermal equilibrium** with all other particles in the early Universe
  - Annihilation and production processes happened frequently
  - As the Universe cools down, interactions become less frequent
  - Finally, dark matter particles **decouple from equilibrium**



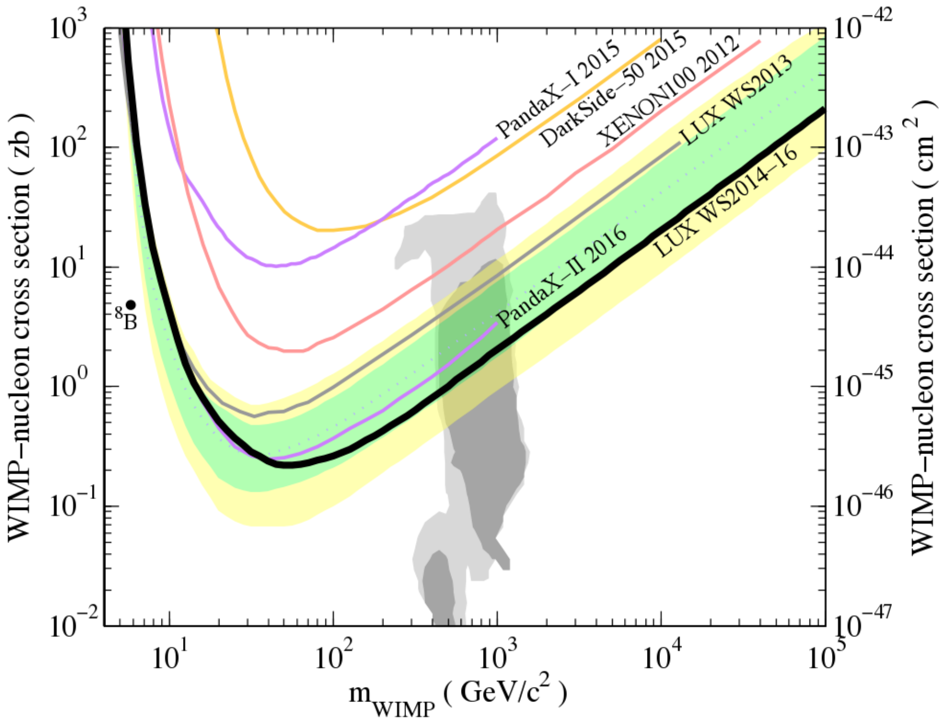
Where are the WIMPs?

SCIENTIFIC AMERICAN.

In the Dark about Dark Matter

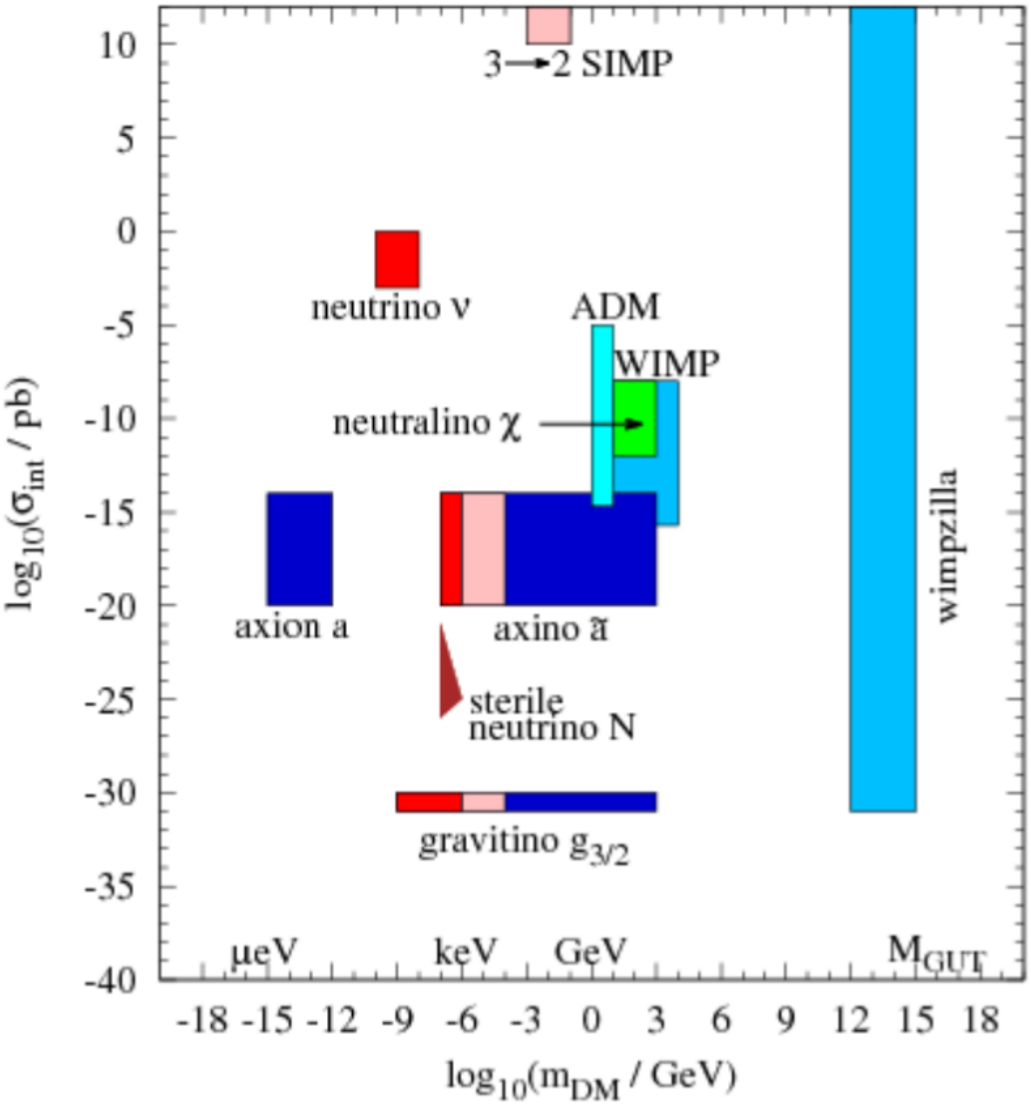
Recent disappointments have physicists looking beyond WIMPs for dark matter particles

- The typical cross sections favoured by the freeze-out paradigm are in **tension** with experiments **not observing any dark matter signals**
- Many **new ideas** for how DM can be **produced in the Early Universe**
  - Non-equilibrium production (FIMPs)
  - Number-changing processes (SIMPs)
  - …



Looking beyond WIMPs

- Renewed interest in alternative DM candidates, such as **axions** or **sterile neutrinos**
- **Problem:** The space of viable DM models is **extremely large**
- Possible DM mass and cross section span **many orders of magnitude**
- Conceivable that the DM particle does not appear in isolation, but as part of a **richer dark sector**



Dark sectors

- Given the **complexity** of the visible sector (making up only 5% of the Universe), it is hardly plausible that the dark sector should be much simpler
- But how should we deal with such a complexity without **losing all predictivity**?

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

Part 1: Strongly interacting dark sectors

- Consider a dark sector that **resembles QCD**

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + \overline{q}_\mathrm{d} i \not{D} q_\mathrm{d} - \overline{q}_\mathrm{d} M_q q_\mathrm{d}$$

F^a: dark gluons (N_d colours)

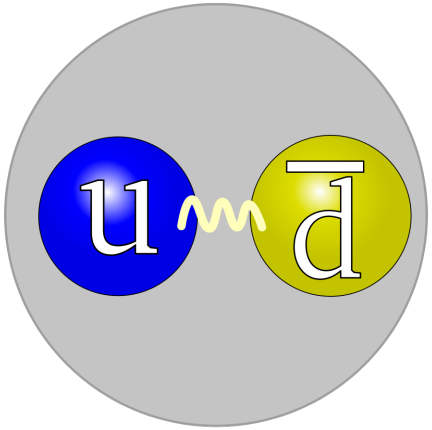
q_d: dark quarks (N_f flavours)

M_q: quark mass matrix

- **Simplifying assumptions** for this talk: $N_\mathrm{d} = 3$ and $M_\mathrm{q} = \mathrm{diag}(m_\mathrm{q})$

- Not necessary to specify interactions with the visible sector

Dark sector bound states



- For energies below some scale Λ_d the dark sector **confines**
- This symmetry breaking gives rise to $N_f^2 - 1$ **Goldstone bosons**, which are called **dark pions**: $\pi = \pi^a T^a$.
- For $m_q > 0$ the dark pions are massive (i.e. Pseudo-Goldstone bosons), because the chiral symmetry is explicitly broken by the mass term
- Moreover, if there is a conserved charge (and no lighter particle with the same charge) at least some of the pions are **guaranteed to be stable**
- Dark pions therefore make **excellent dark matter candidates**!
- How do they **obtain their relic abundance**?

Thermal contact

- Assume that dark quarks can **interact with the SM** and enter into **thermal equilibrium**

- For concreteness consider a ***Z'* mediator**

$$\mathcal{L} \supset -e_\mathrm{d} Z'_\mu \, \overline{q}_\mathrm{d} Q \gamma^\mu q_\mathrm{d}$$

Q: Charge matrix for dark quarks

- The dark pions **inherit the interactions of the dark quarks** with the Z' boson and hence with the Standard Model

- For $N_f = 2$ and $Q = \mathrm{diag}(1, -1)$ pion decays can be forbidden and one obtains three stable pions with charge +2, 0 and -2

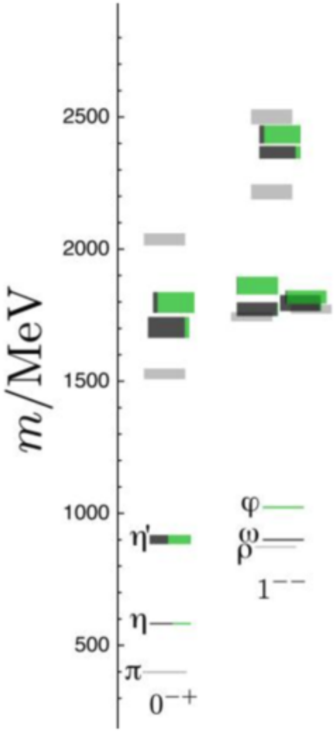
Annihilations into other dark sector states

- Pions are not the only mesons in QCD → expect also more mesons in the dark sectors

- Most interesting: **Vector mesons** (analogous to SM ρ mesons)

- The ρ^0 meson has the same quantum numbers as the Z', and the two vector bosons will in general mix (like SM ρ-γ mixing)

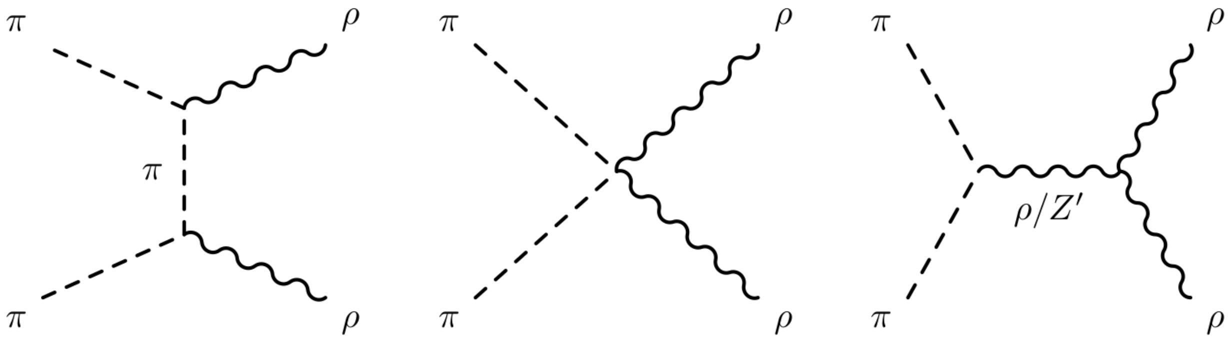
- As a result, the **ρ^0 inherits the couplings of the Z'** and can decay into SM particles



- The DM relic abundance then depends on how efficiently dark pions are converted into ρ mesons (and vice versa)

Forbidden annihilations

D'Agnolo & Ruderman, arXiv:1505.07107



- The ρ mesons are generally expected to be **heavier than the pions** and hence conversion processes are only allowed at finite temperature
- However, for $m_q \sim \Lambda_d$ the masses of the different mesons can be comparable and processes **remain efficient** down to small temperatures
- Example: m_π = 4 GeV, m_ρ = 5 GeV, g = 1 gives **$\Omega h^2 \sim 0.1$** (close to observed value)
- Mechanism very flexible and works for a wide range of DM masses!

Part 1: Summary

- Dark quarks in a strongly-interacting dark sector form dark pions at low energies
- Some or all of these dark pions can be stable and therefore DM candidates
- Interactions between the dark sector and the SM can bring the dark pions into thermal equilibrium in the early Universe
- Relic abundance determined from number-changing processes or via conversion of dark pions into dark vector mesons
- Idea can be realised across different scales and for different types of interactions

Phenomenology: Self-interactions

- Strongly interacting dark sectors can have **large self-interactions**: $\sigma_{\text{self}} \sim g^4/m_\pi^2$
- Potentially **interesting implications** on astrophysical scales (e.g. core formation)
- Bullet Cluster: $\boldsymbol{\sigma_{\text{self}} / m < 1\ \text{cm}^2 / \text{g}}$
- Implies $\boldsymbol{m_\pi > 50\ \text{MeV}}$ for $g \sim 1$
- Probably difficult to solve cusp-core problem in this model due to lack of velocity dependence in self-interaction cross section
- In the following focus on m_π **in GeV range** (study of smaller masses still ongoing)

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Phenomenology: Direct detection

- So far there was no need to specify the Z' mass or its interactions with the SM

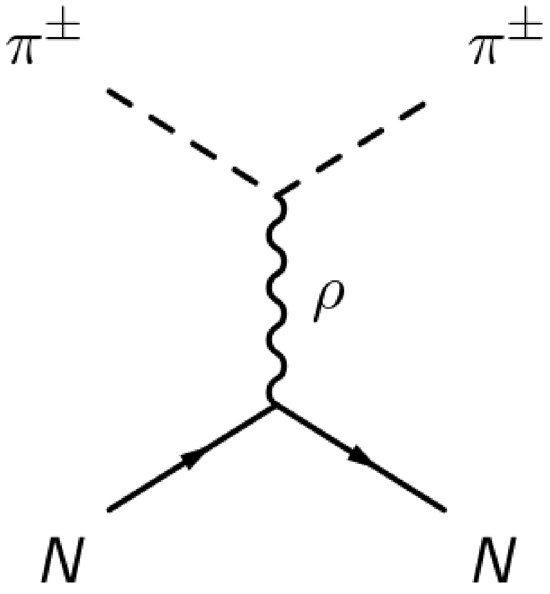
- Now let us be more specific and assume that the Z' has **couplings to SM quarks**

$$\mathcal{L} \supset -Z'_\mu \, g_q \sum_{q_\mathrm{SM}} \bar{q}_\mathrm{SM} \gamma^\mu q_\mathrm{SM}$$

- At low energies: Interactions between (charged) dark pions and SM nuclei

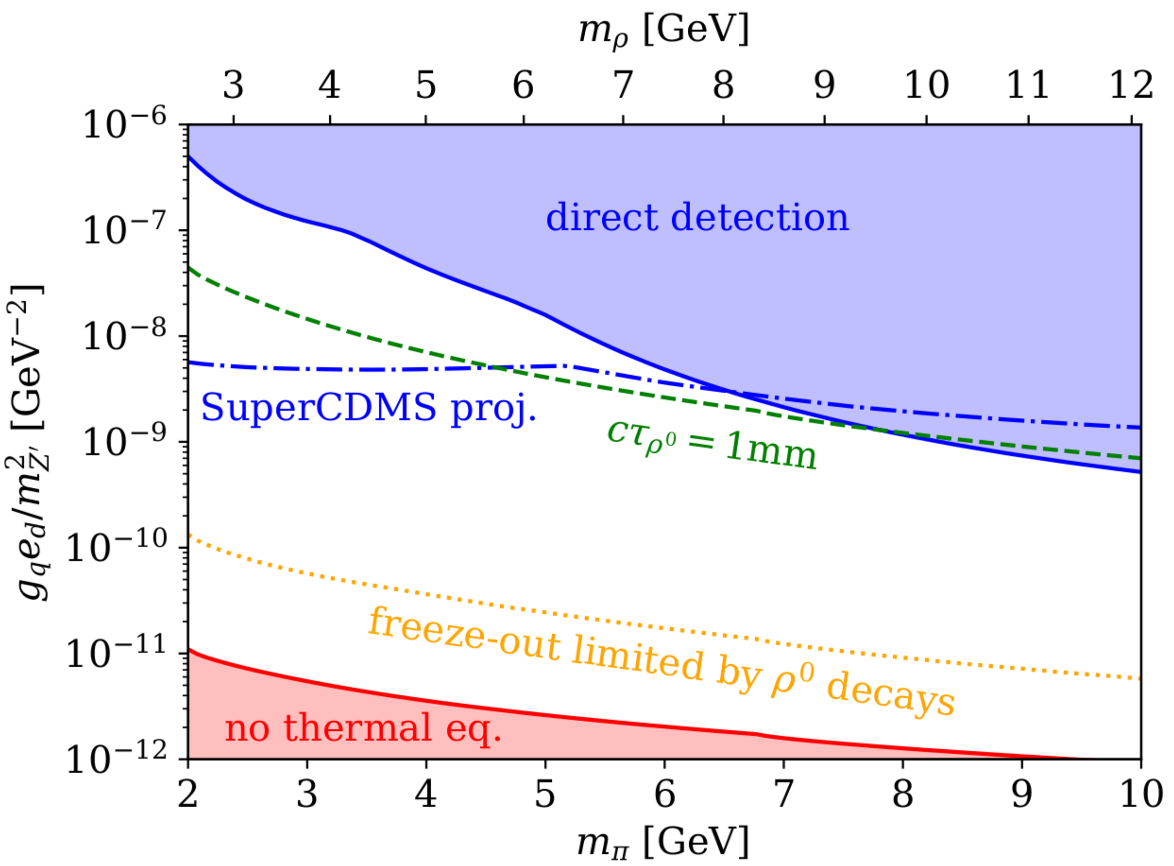
$$\sigma_N^\mathrm{SI} = \frac{36 \, e_\mathrm{d}^2 \, g_q^2 \, \mu_{\pi N}^2}{\pi \, m_{Z'}^4}$$

- Relevant constraints from **direct detection experiments**



Direct detection constraints

Vector meson mass determined from freeze-out



Effective interaction

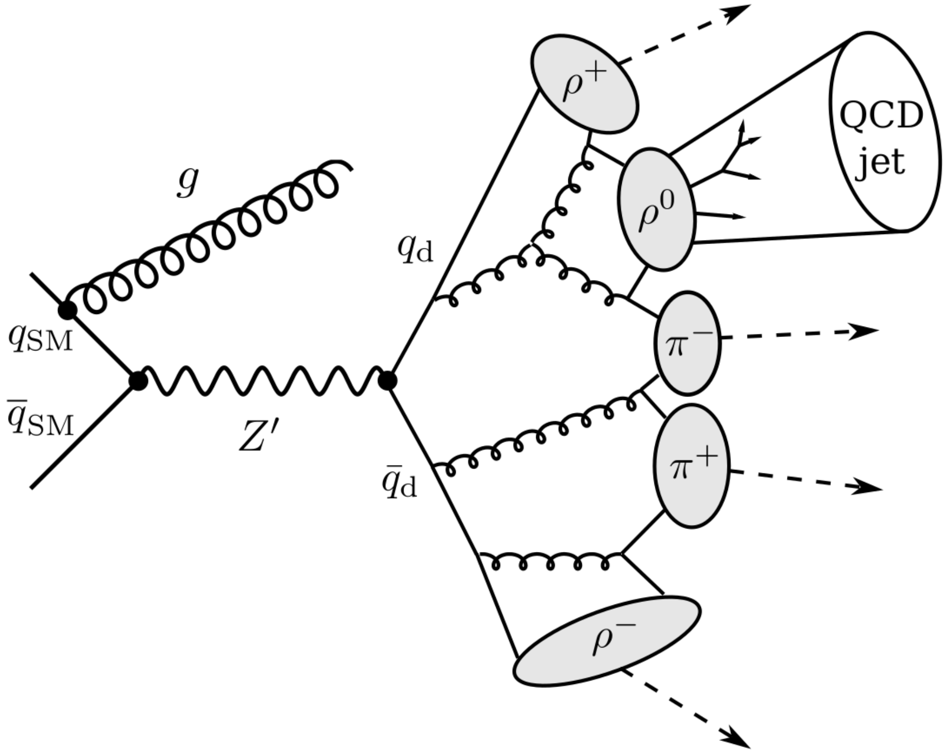
Dark matter mass

Require TeV-scale Z' mass
(or tiny couplings)

Phenomenology: LHC

- At the LHC the Z' can be directly produced and we can search for its **decay products**

- Most exciting: Decays into dark quarks, followed by **fragmentation and hadronisation** in the dark sector



- Result: **dark shower** containing 10–20 dark mesons

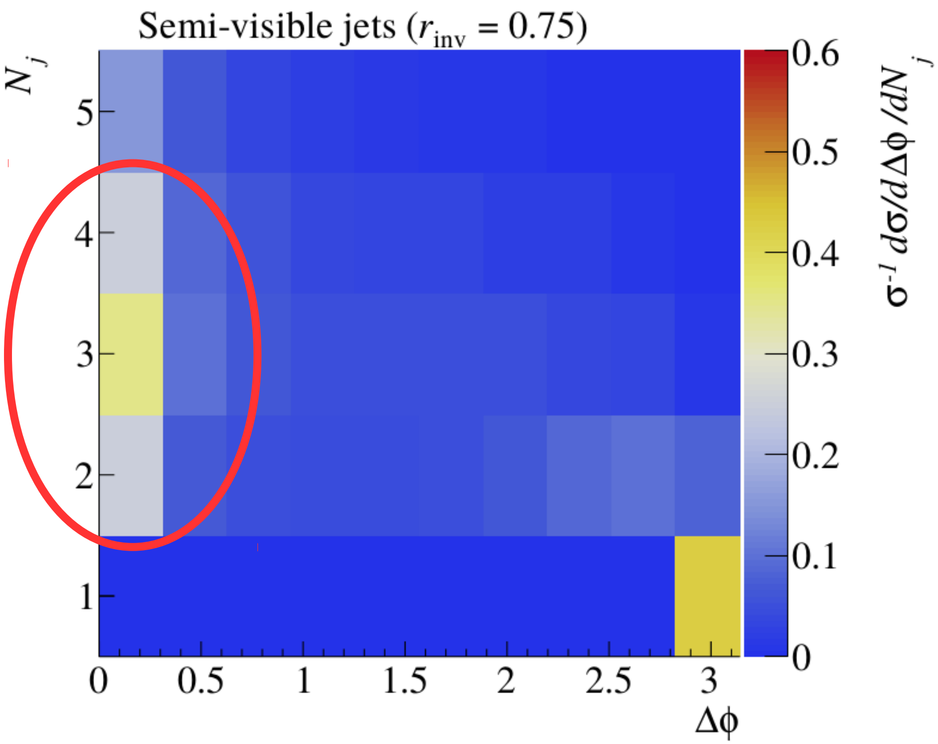
- Most dark mesons (on average 75%) are stable and will **escape from the detector**

- Any ρ^0 meson will decay into SM particles and give rise to **QCD jets**

Seaching for semi-visible jets

- Signature: jets + missing energy
- **Peculiar feature**: Since missing energy and QCD jets arise from the same dark shower, they will often point in the same direction
- Expect small angular separation

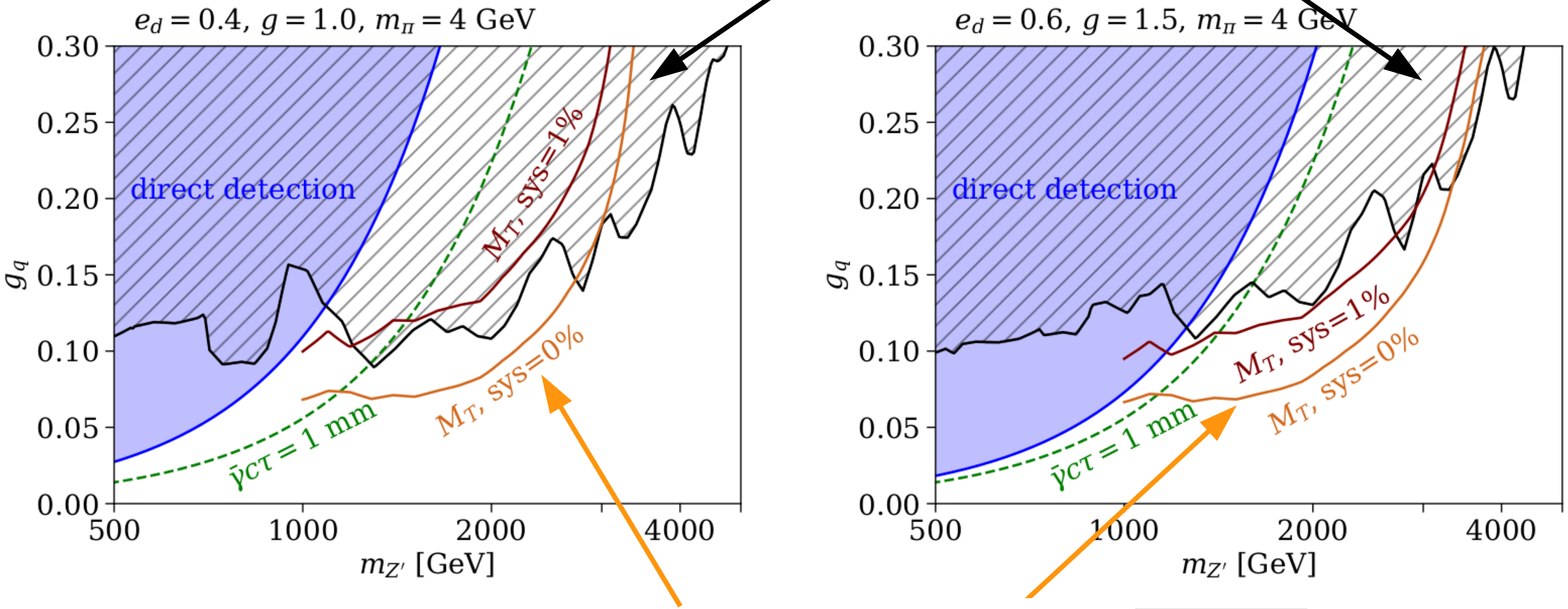
$$\Delta\phi = \min_j \Delta\phi(j, \not{E}_T)$$



- Unfortunately, events with small Δφ are vetoed in most analyses because of challenging backgrounds from misreconstructed jets
- Note: CMS search for this signature under preparation

Sensitivity estimates

Excluded by existing LHC constraints
(mono-jet, di-jet and SUSY searches)



Proposed search based on $M_T = \left(M_{jj}^2 + 2\left(\sqrt{M_{jj}^2 + p_{Tjj}^2}\,\not{E}_T - \vec{p}_{Tjj}\cdot\vec{\not{E}}_T\right)\right)^{1/2}$

Cohen et al., arXiv:1503.00009, arXiv:1707.05326

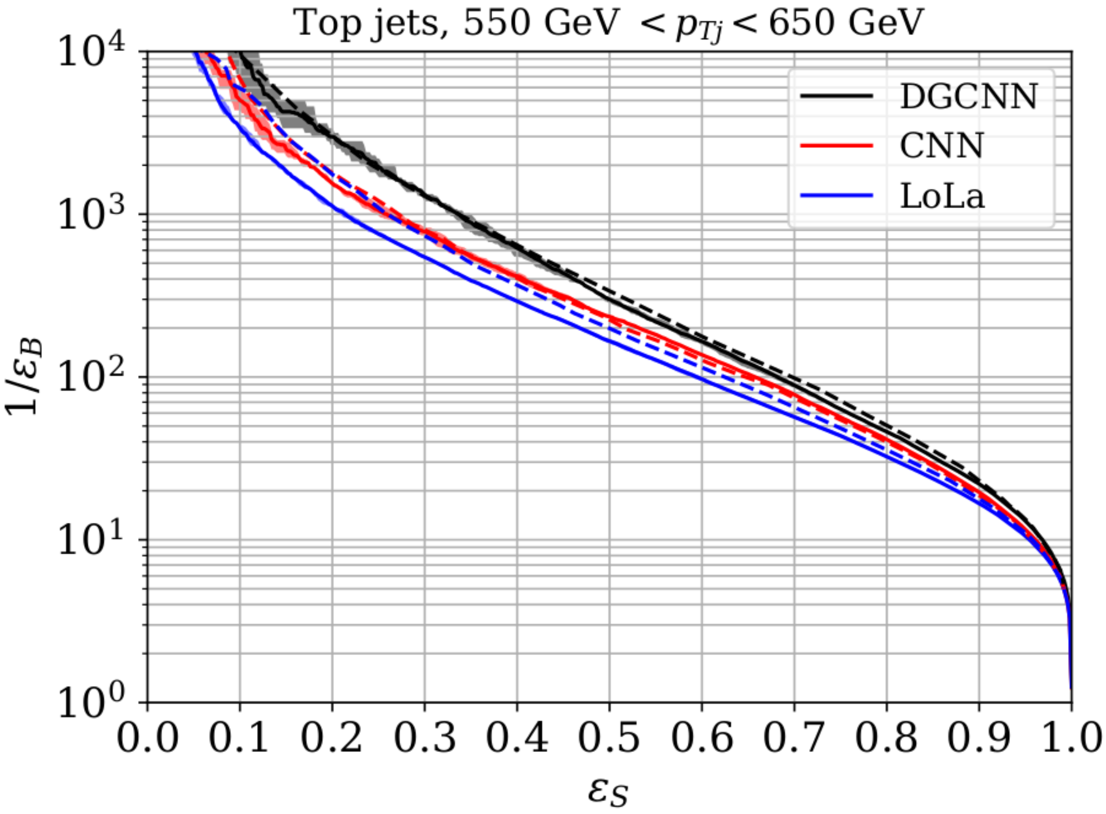
Part 2: Summary

- Interesting parameter range: GeV-scale dark mesons with TeV-scale Z' mediators
- Large parameter space allowed by direct detection and self-interaction constraints
- At the LHC: Dark showers leading to semi-visible jets (benchmark: rinv = 0.75)
- Conventional searches challenging (signal peaked at small $\Delta\varphi$, very broad distribution of M_T)
- Existing searches sensitive to couplings of order 0.1

Part 3: Doing better with machine learning

- Deep neural networks have shown excellent performance in the tagging of boosted top jets

Butter et al., arXiv:1902.09914
Larkoski et al., arXiv:1709.04464



LoLa: Lorentz-Layer network based on four-vectors of jet constituents and quantities that can be calculated from their linear combinations (e.g. invariant masses)

Macaluso & Shih, arXiv:1803.00107

CNN: Convolutional neural network acting on jet images, i.e. histograms of the p_T distribution in pseudo-rapidity η and azimuthal angle φ

Butter et al., arXiv:1707.08966

DGCNN: Dynamic graph convolutional neural networks acting on a “point cloud”, i.e. an unordered set of jet constituents that are grouped in a dynamic way by the network

Wang et al., 1801.07829
Qu & Gouskos, 1902.08570

Dynamic graph convolutional neural networks

- Originally from computer vision, but recently used as jet tagger (ParticleNet)

Wang et al., 1801.07829, Qu, Gouskos, 1902.08570

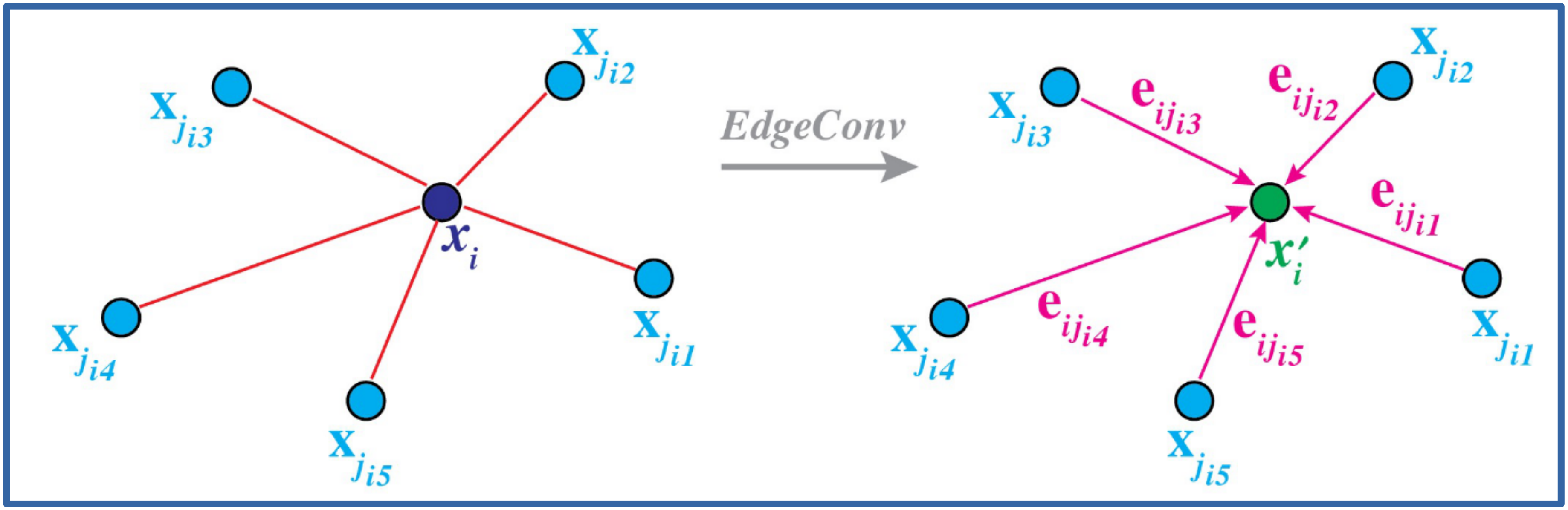
- Idea: Every jet constituent is represented by a point in a high-dimensional feature space
- Initial features are for example the direction of the constituent, its p_T and its energy (relative to the jet)
- Initially, points are unordered, but the network then constructs a graph of k nearest neighbours based on some metric (e.g. angular separation)
- The edges of this graph (i.e. pairs of neighbouring points) are then taken as input for a convolution layer producing a new set of points in a (higher-dimensional) feature space
- One then constructs a new graph of nearest neighbours and performs another edge convolution etc.
- This approach allows points that are initially far apart to become close in feature space, which enables the network to access long-range correlations and learn the graph structure that offers most information

Dynamic graph convolutional neural networks

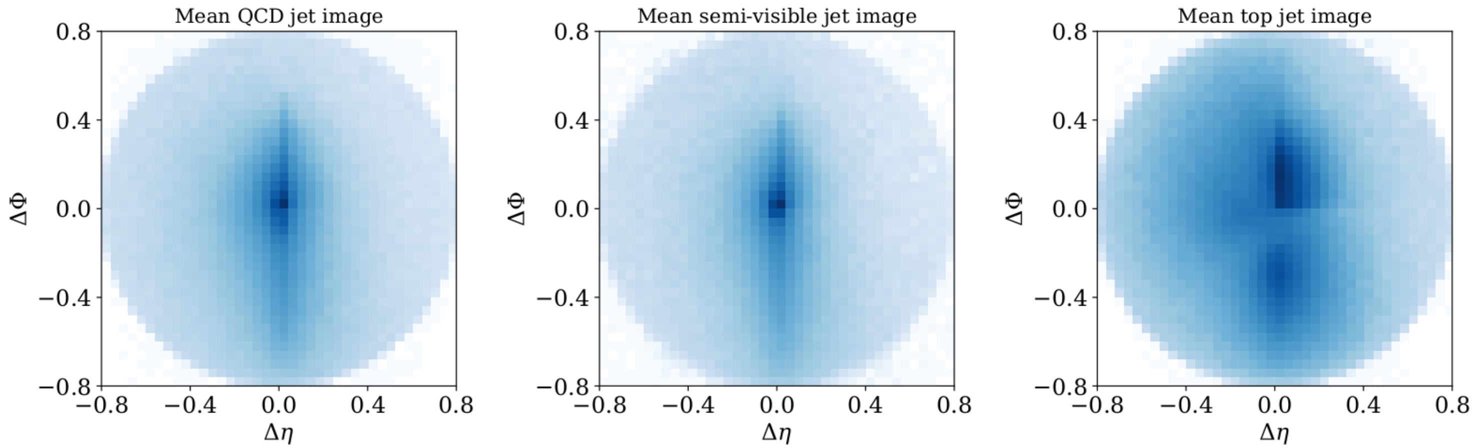
- Originally from computer vision, but recently used as jet tagger (ParticleNet)

Wang et al., 1801.07829, Qu, Gouskos, 1902.08570

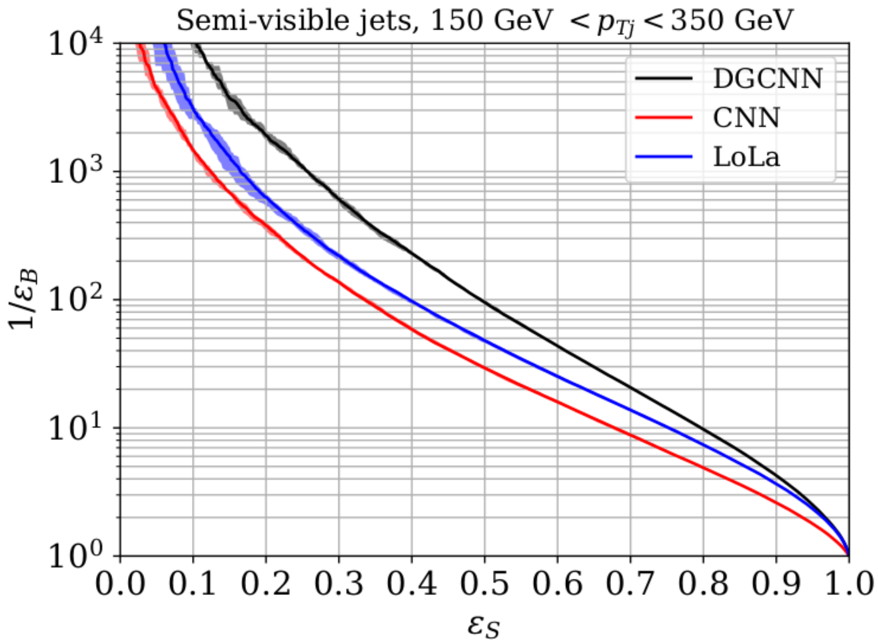
- Idea: Every jet constituent is represented by a point in a high-dimensional feature space
- Initial features are for example the direction of the constituent, its p_T and its energy (relative to the jet)
- Initially, points are unordered, but the network then constructs a graph of k nearest neighbours based on some metric (e.g. angular separation)



Identifying semi-visible jets is hard!

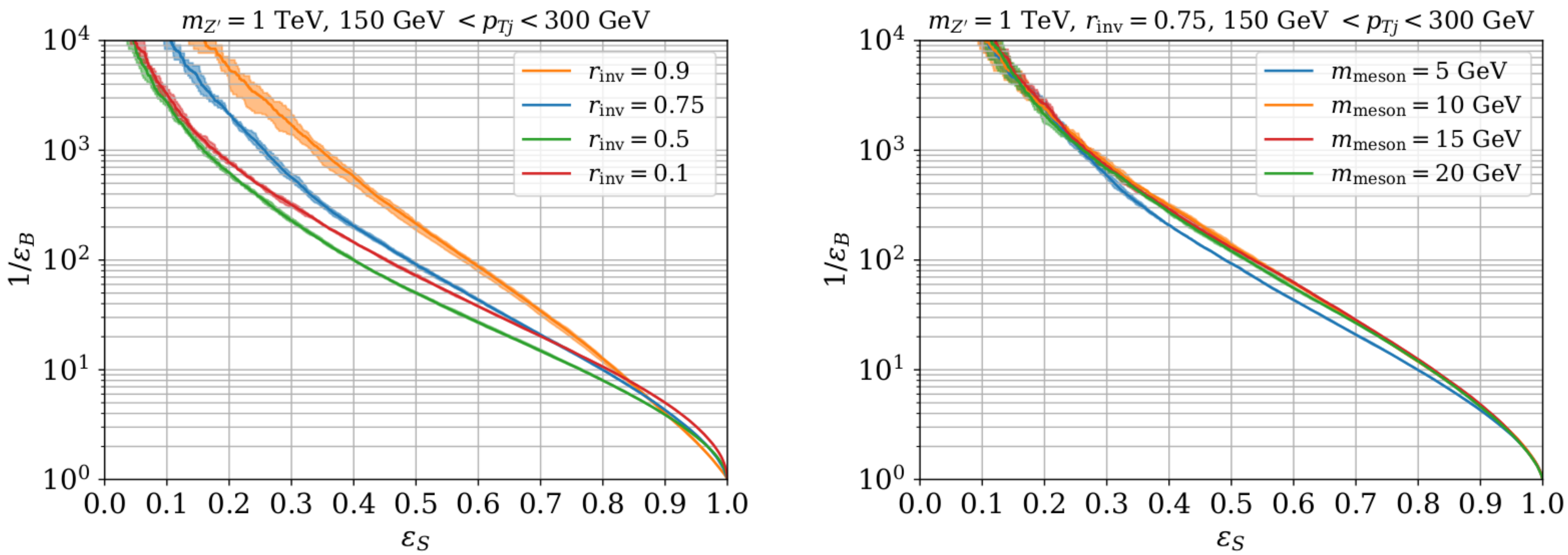


- Mean top jet image can be distinguished from QCD by eye
- The mean semi-visible jet image looks however very similar to QCD
- CNN and LoLa perform much worse than for top jets, but the DGCNN still performs really well (AUC: 0.926)



Model-dependence of performance

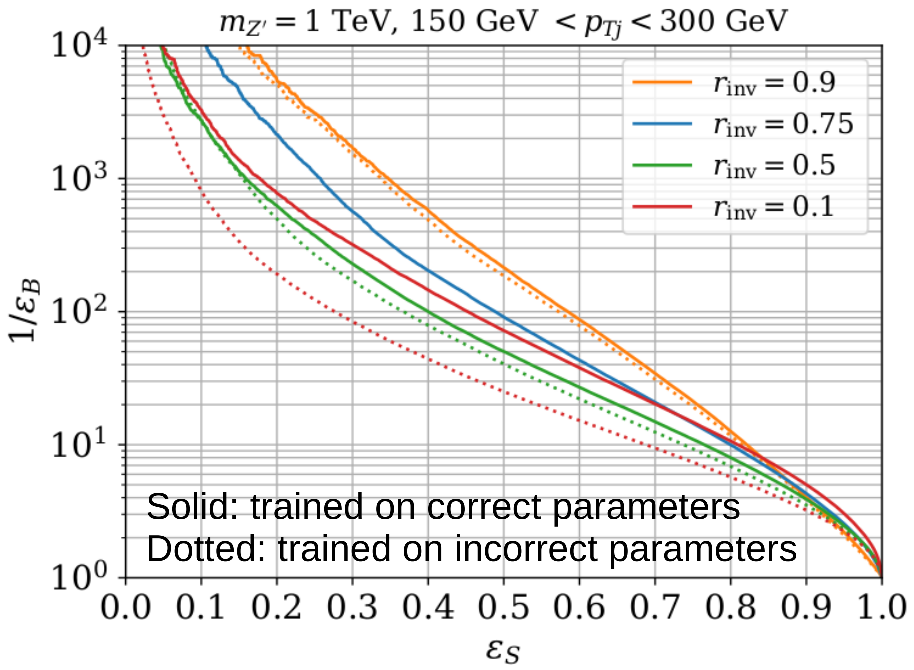
- So far we have only considered semi-visible jets with $r_{\mathrm{inv}} = 0.75$ and $m_{\mathrm{meson}} = 5$ GeV



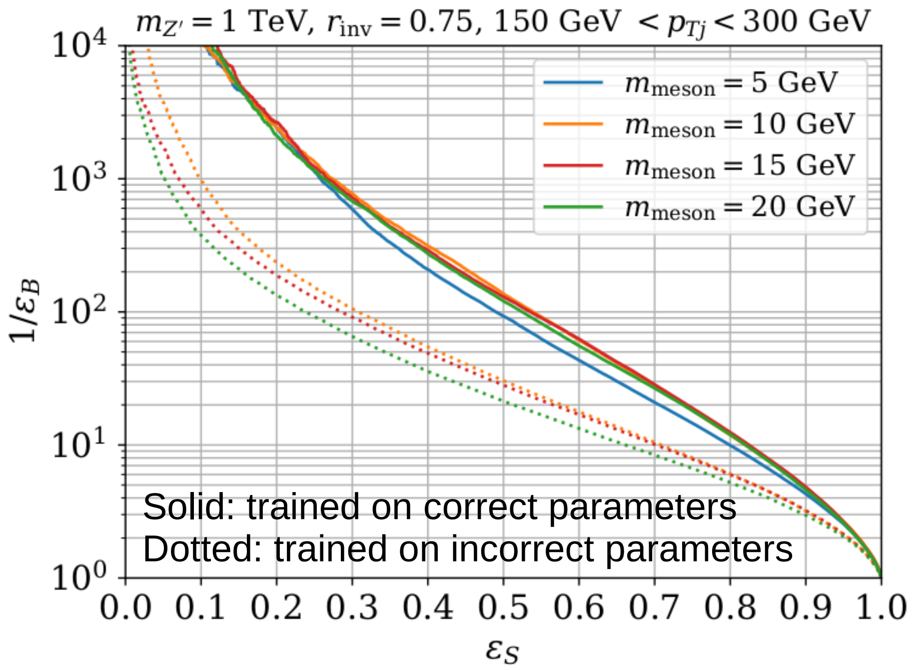
- Increasing r_{inv} makes semi-visible jets more different from QCD and therefore improves the performance of the network
- Changing the mesons mass has essentially no impact on performance

The problems with supervised training

- So far, we have assumed that the parameters of the semi-visible jet are known, i.e. we have performed training and testing with the same values of r_{inv} and m_{meson}
- What happens if we train and test on different values?



Solid: trained on correct parameters
Dotted: trained on incorrect parameters

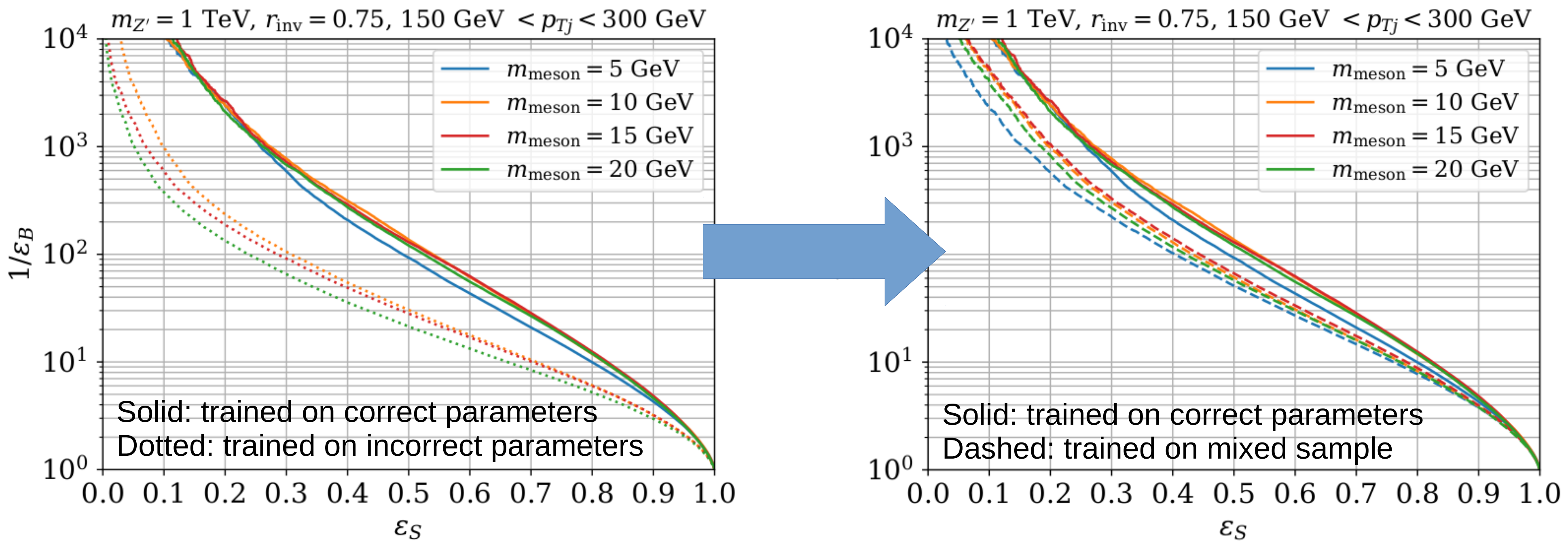


Solid: trained on correct parameters
Dotted: trained on incorrect parameters

- Performance deteriorates drastically when an incorrect meson mass is assumed

Mitigation strategy: Training on mixed samples

- Instead of training on a specific value of m_{meson}, we can train on a sample containing semi-visible jets with different meson masses



Solid: trained on correct parameters
Dotted: trained on incorrect parameters

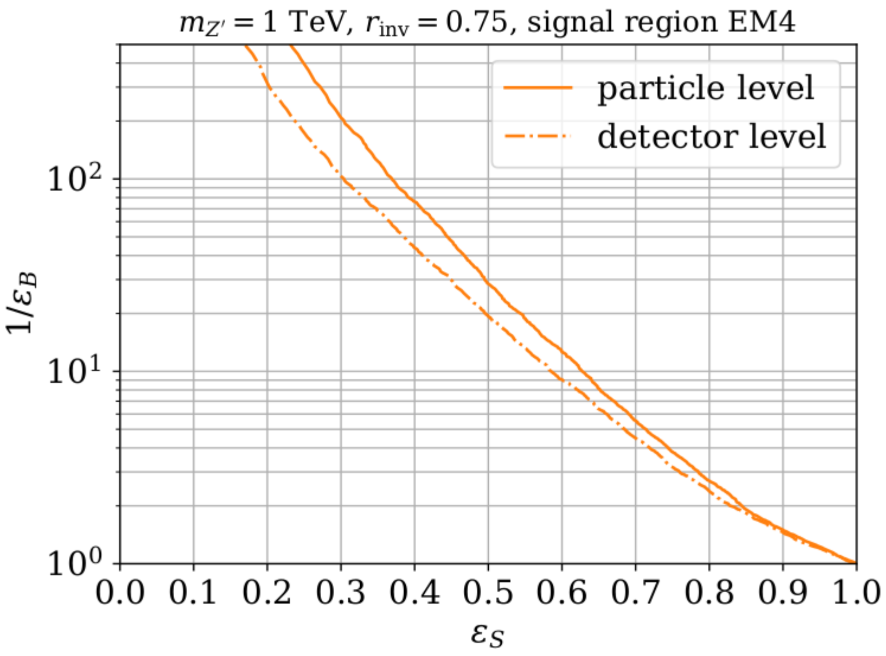
Solid: trained on correct parameters
Dashed: trained on mixed sample

- This approach yields a much more robust and general classifier that performs reasonably well across a range of meson masses

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: ATLAS mono-jet analysis, signal region EM4 (400 GeV < MET < 500 GeV)

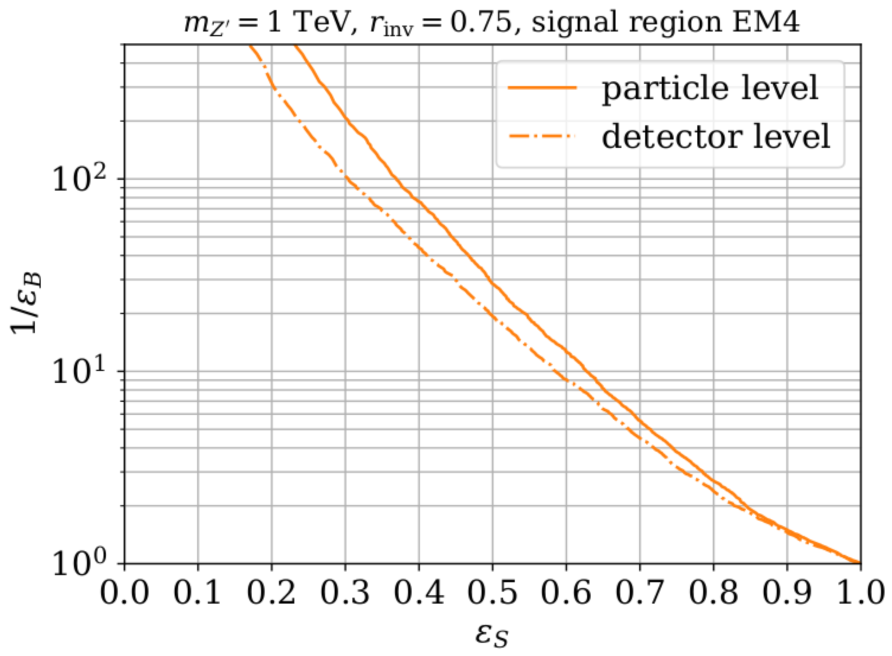
arXiv:1711.03301



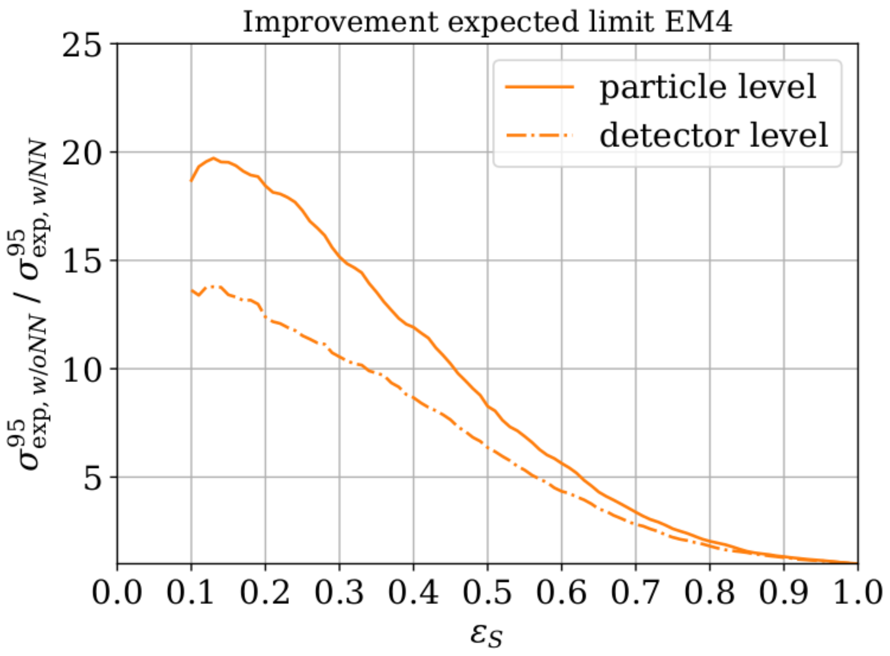
- At 30% signal efficiency, backgrounds can be suppressed by more than two orders of magnitude!

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: ATLAS mono-jet analysis, signal region EM4 (400 GeV < MET < 500 GeV)



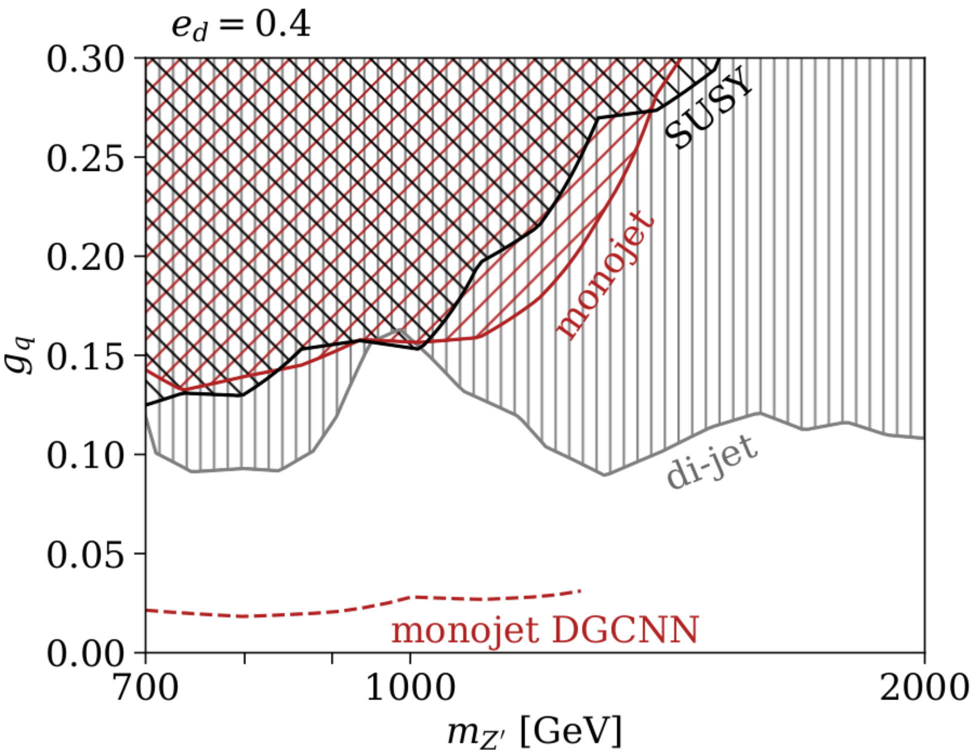
$m_{Z'} = 1$ TeV, $r_{\mathrm{inv}} = 0.75$, signal region EM4



Improvement expected limit EM4

- The resulting sensitivity (in terms of the dark shower production cross section) improves by more than an order of magnitude

Projected sensitivity



- With improved background rejection, sensitivity limited by statistical uncertainties
- Possibly room to relax cuts on the event topology (in particular Δφ) to further increase sensitivity

Part 3: Summary

- Dark showers are difficult to identify with conventional methods – great opportunity for machine learning
- Graph nets are particularly well suited to this task
- Model dependence can be mitigated, e.g. with mixed training
- LHC sensitivity can be increased by an order of magnitude even when all other cuts remain the same
- Currently rely on Monte Carlo simulations to produce labelled data for supervised training – need to explore unsupervised methods for training on real data

Part 4: Displaced decays

- For $g_q < 0.1$ the ρ^0 decay length becomes comparable to the **size of the detector**

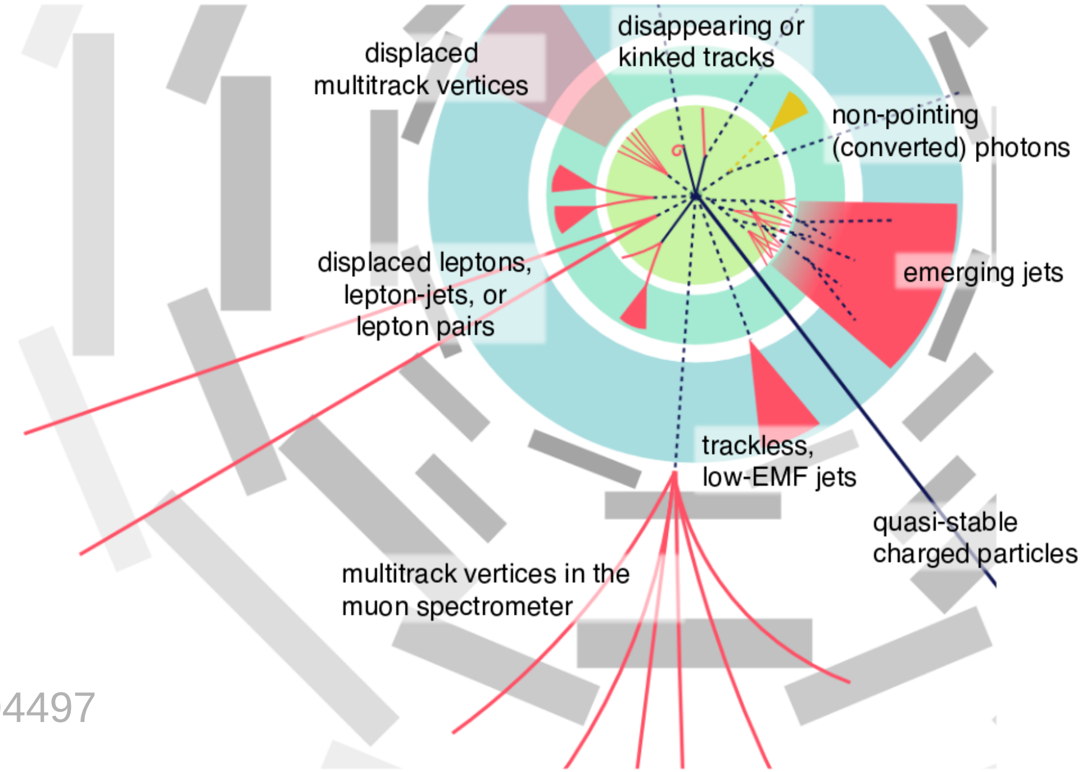
- Consequence: QCD jets originating from displaced vertex (so-called **emerging jets**)

Schwaller et al., arXiv:1502.05409

- Dark shower production cross section can be quite large

- Conceivably thousands of such emerging jets have already been produced but **gone unnoticed**

- Development and implementation of **new searches for long-lived particles** is a very active field



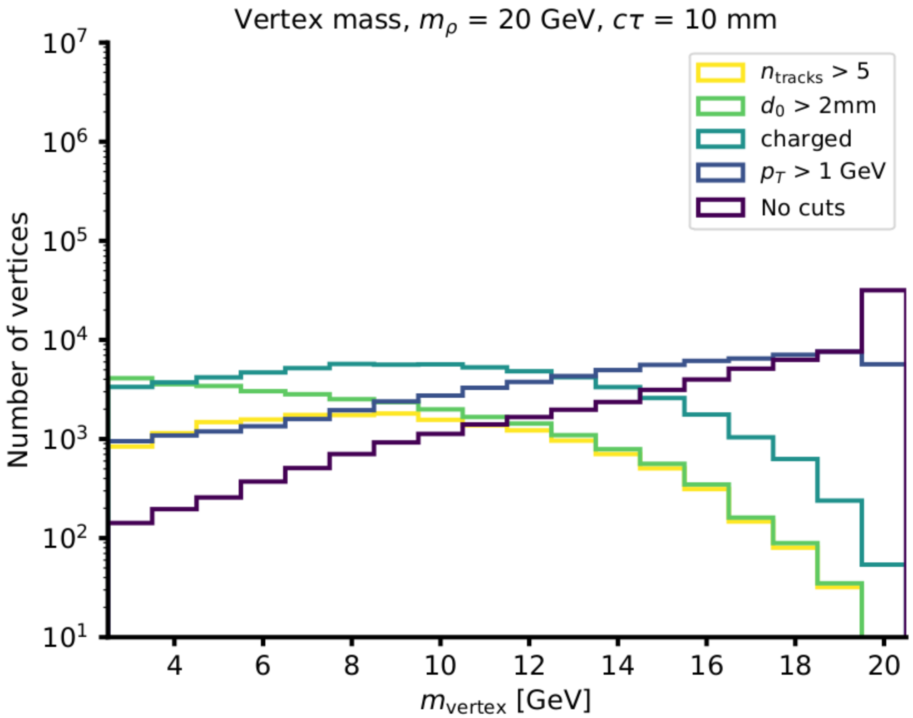
Alimena et al., arXiv:1903.04497

Challenge: low-mass displaced vertices

- Most searches for displaced vertices (DVs) are optimised for particles with mass greater than 100 GeV

- Example: ATLAS search for DV + MET

arXiv:1710.04901



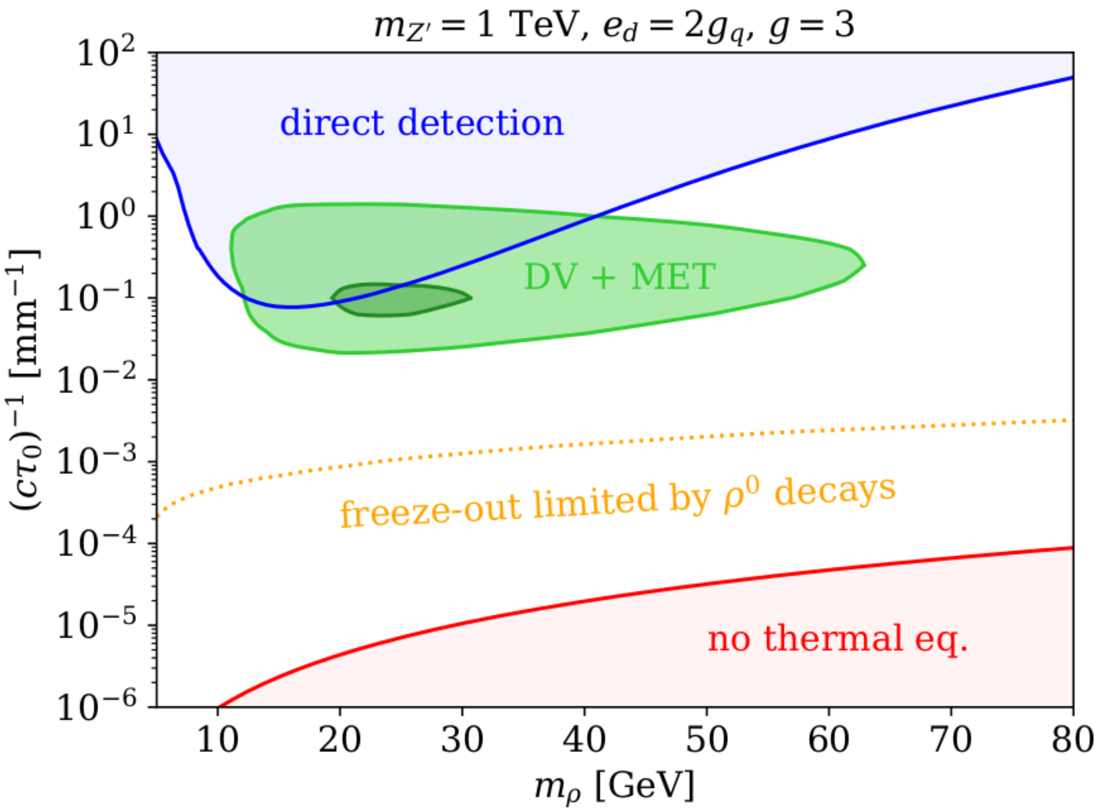
- Require at least 5 charged tracks with
  - Transverse momentum $p_T > 1$ GeV
  - Impact parameter $d_0 > 2$ mm

- Problem: when using only these tracks to calculate the mass of the DV, there is a strong bias to smaller values

- Even for $m_\rho = 20$ GeV most events fail the requirement $m_{DV} > 10$ GeV

Room for improvement

- In principle two charged tracks with d_0 > 2mm are sufficient to identify a DV
- If we include additional charged tracks with small impact parameter, the bias in the DV mass is reduced and the sensitivity of the analysis is enhanced



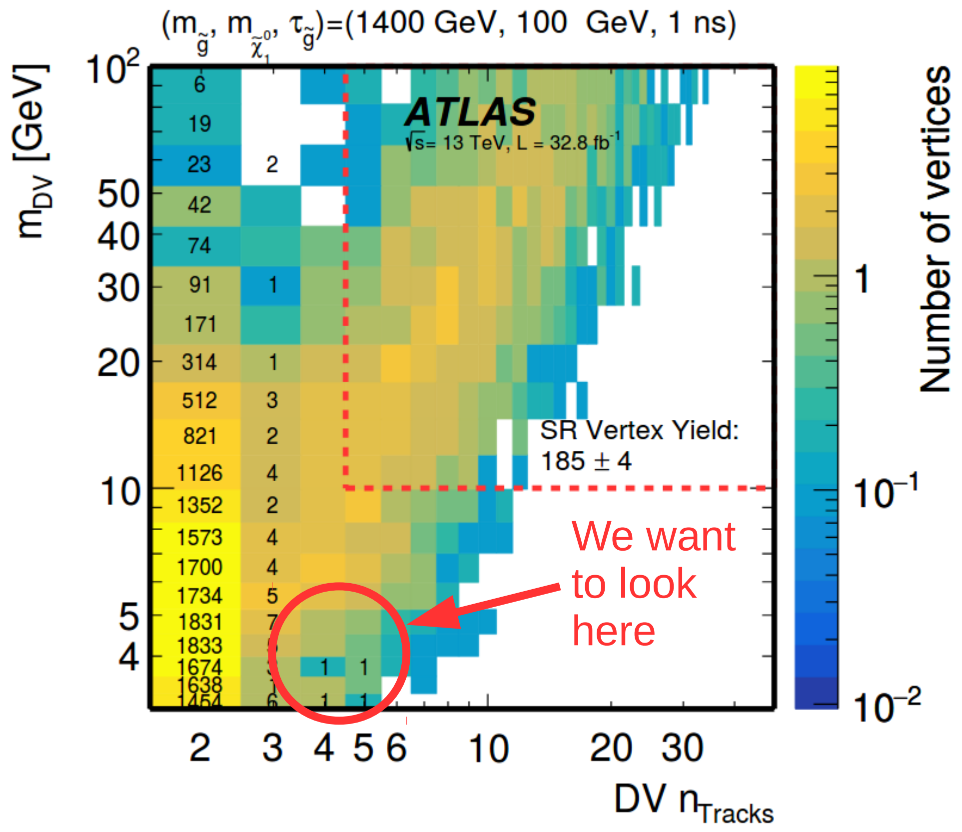
Dark green: Original analysis

Light green: Relaxed d_0 requirement

Note that we assume that the efficiency of the modified analysis is similar to the original one and that backgrounds are still negligible

A more radical approach

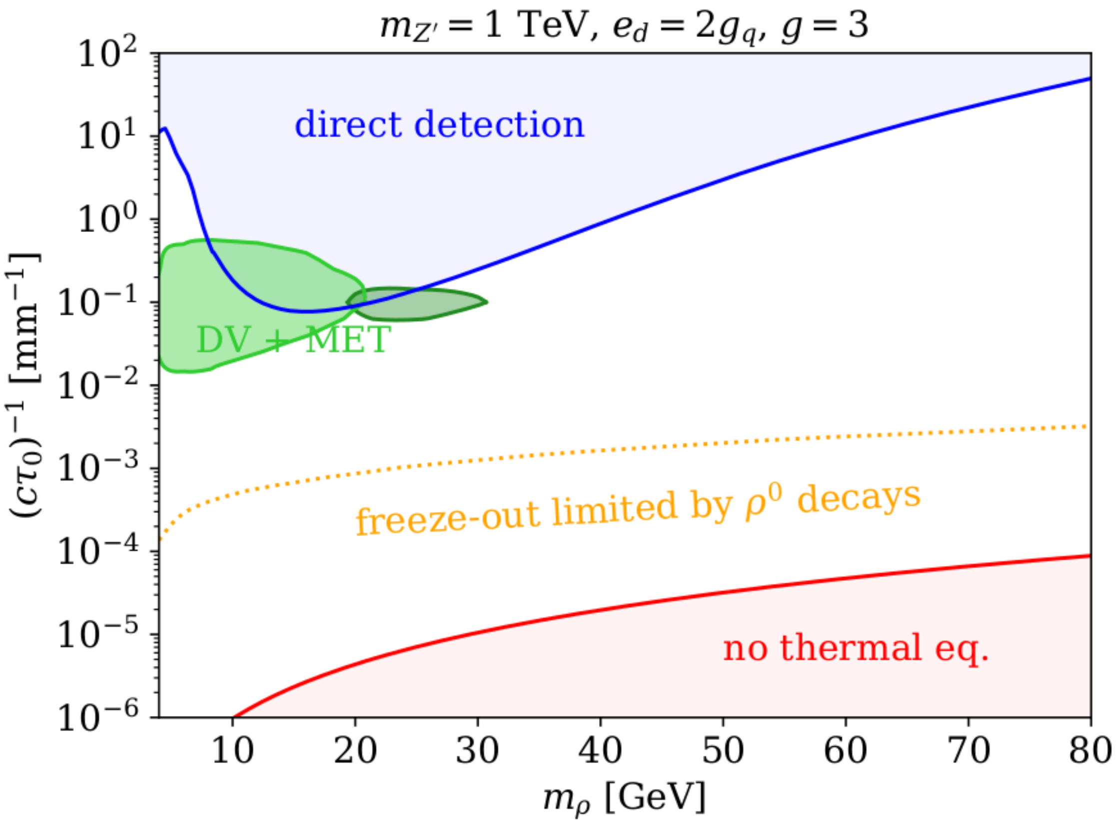
- In principle, one could also simply relax the cuts on m_{DV} and n_{tracks}
- The problem is how to deal with non-negligible and hard-to-estimate backgrounds
- One possible approach: Treat background as completely unknown nuisance parameter
  - Can only exclude signal hypotheses that significantly exceed the observed background
  - Although conservative, potentially yields strong exclusion limits (well known from DM direct detection)
  - Impossible to see an excess (or make a discovery) with this approach



We want to look here

DV searches with unknown background

- Example: Require $m_{DM} > 3$ GeV, $n_{tracks} > 4$
- Observed background events: 4
- Parameter points excluded at 95% C.L. if they predict more than 9.15 signal events



Dark green: Original analysis

Light green: Relaxed d_0 requirement

Note that we assume that the efficiency of the modified analysis is similar to the original one

Part 4: Summary

- Dark mesons are long-lived in large parts of parameter space, giving rise to displaced vertices at the LHC
- Existing searches tend to target higher meson masses, so new efforts are required to explore mass range below 10 Gev
- Interesting to explore relaxed cuts and regions with non-zero background
- A promising way to reduce background: Require two (or more) DVs per event

Conclusions

- Dark pions from a strongly-interacting dark sectors are a well-motivated alternative to traditional dark matter models
- The observed dark matter relic abundance can be reproduced across a large range of parameter space
- Specific example: Dark pions with mass in the GeV range, Z' with quark couplings in the TeV range
- Large allowed parameter space predicting exciting LHC signatures
- Dark showers difficult to identify with conventional methods but substantial progress possible using deep neural networks
- Searches for displaced vertices may allow to probe the model for smaller couplings