UiO, November 2019

Strongly interacting dark sectors in the early Universe and at the LHC

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Based on arXiv:1907.04346, with Elias Bernreuther, Felix Kahlhoefer and Patrick Tunney

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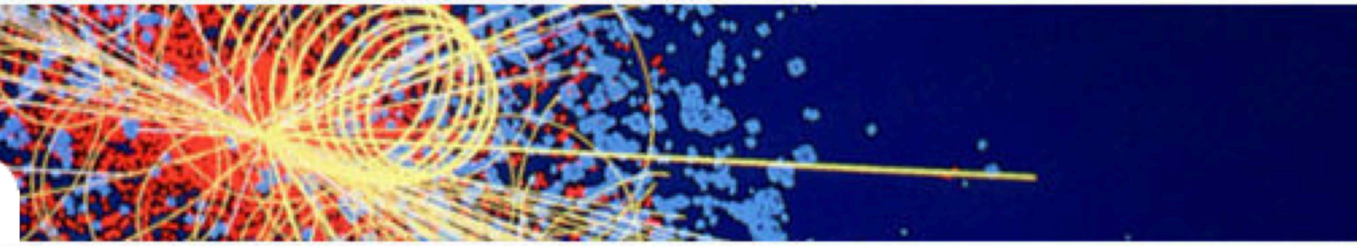
Collaborative Research Center TRR 257



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Welcome

The Collaborative Research Center "Particle Physics Phenomenology after the Higgs Discovery'' is a joint venture of theoretical particle physicists from Karlsruhe Institute of Technology, RWTH Aachen University, University of Siegen and Heidelberg University. It is supported by the German Research Foundation (DFG).

Particle physics has long established itself as an important research discipline focused on understanding Nature at a fundamental level. The current knowledge is summarized in a theory called the Standard Model (SM) of particle physics that describes strong and electroweak interactions. The recent discovery of the Higgs boson formally completes the SM and provides us with a consistent mathematical framework that can be used to describe Nature in fine detail. However, several aspects of the SM force us to raise questions about the foundations of this theory. Many proposed answers to these questions suggest that the SM is a low-energy approximation to a much more fundamental theory that we strive to discover.

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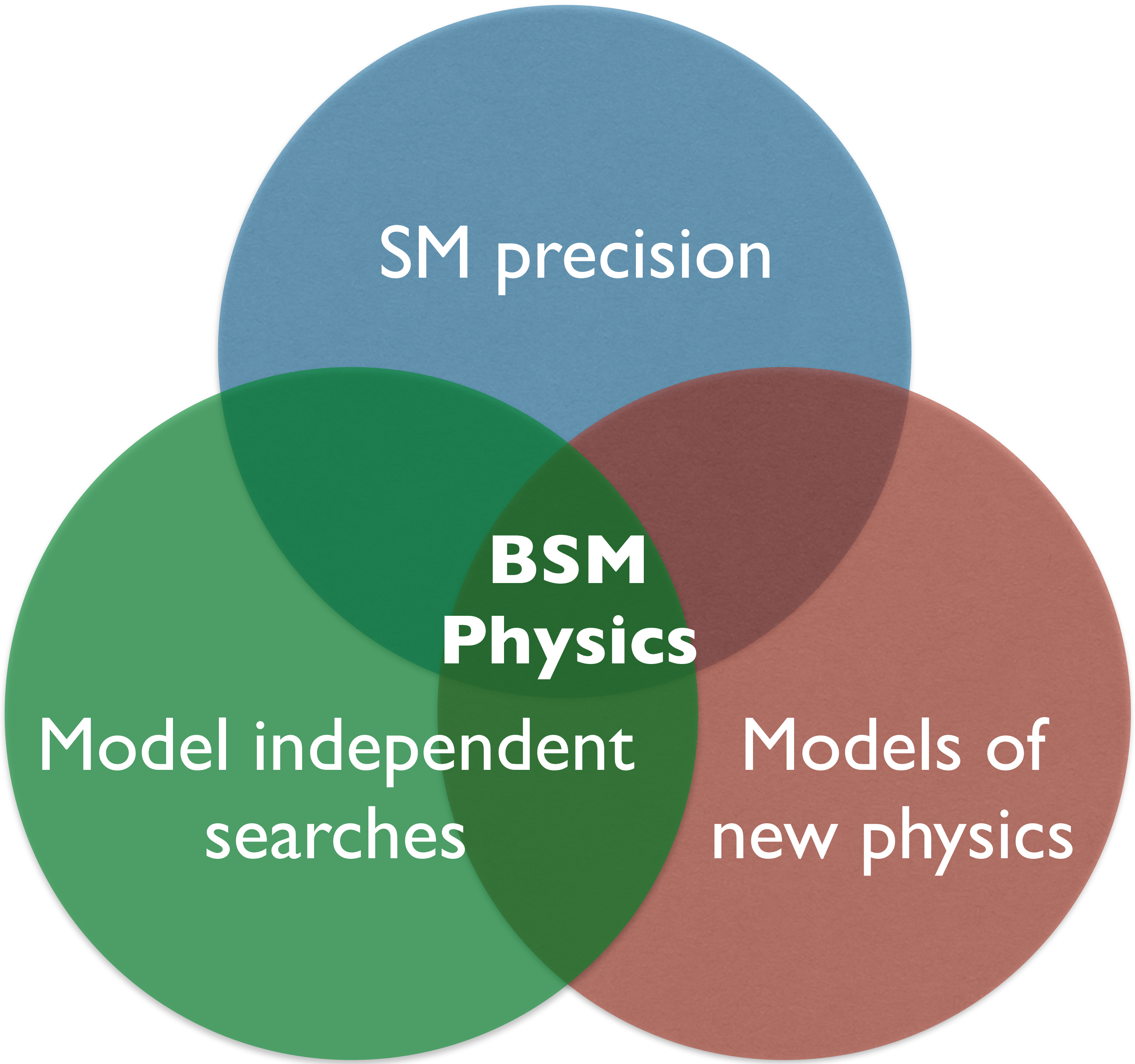
Open positions

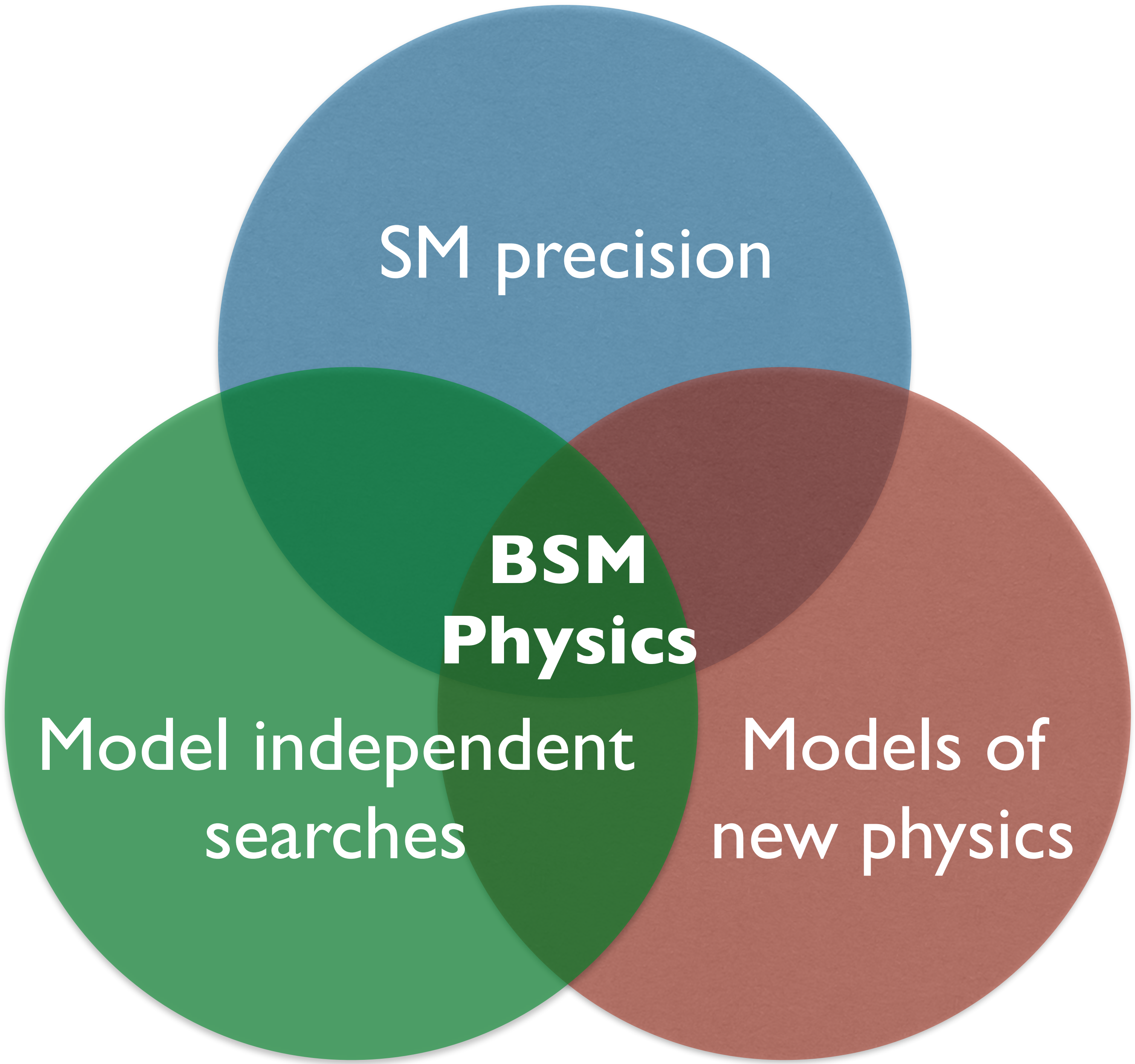
Postdoctoral and PhD positions
The Collaborative Research Center invites applications for a number of postdoctoral and Ph.D. positions. More informations can be found here or directly contact principal investigators.

Institutes

Searches for physics beyond the Standard Model



Searches for physics beyond the Standard Model



Models of new physics

- allow to connect collider physics, indirect searches, as well as astroparticle physics and cosmology;
- predict new experimental signatures.

A voyage into dark sectors

Artwork by Sandbox Studio, Chicago with Ana Kova, from Symmetry Magazine

Why dark sectors?

- **Consistent dark matter models** may require a non-minimal structure.
- Given the **complexity of the Standard Model**, it is plausible that the dark sector is complex, too.
- Dark sectors often predict a **novel cosmology** and **collider phenomenology**.

Which dark sectors?

Take inspiration from the Standard Model and consider

- **Weakly-Interacting Massive Particles (WIMPs)**,
- **Strongly-Interacting Massive Particles (SIMPs)** and
- **Feebly-Interacting Massive Particles (FIMPs)**,

which exhibit features known from the weak, strong and electromagnetic interactions, respectively.

How to explore dark sectors?

Require a consistent cosmology, with the correct relic abundance, and explore the collider phenomenology.

This involves the

- **re-interpretation of existing BSM searches;**
- **design of novel search strategies;**
- **use of advanced analysis techniques, such as machine learning.**

Outline

- **A strongly interacting dark sector**
- **The relic density and direct detection bounds**
- **Dark sectors at the LHC:**

  Missing energy searches

  Semi-visible jets
- **Outlook:**

  Displaced vertices

  Machine learning

A strongly interacting dark sector

We consider a dark sector with a **SU(3) dark gauge group**:

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

and **N_f = 2 flavours** of dark quarks.

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The dark sector interacts with the SM through a **Z' mediator**:

$$\mathcal{L} \supset -e_{\rm d} Z'_\mu \left(\overline{q}_{{\rm d},1} \gamma^\mu q_{{\rm d},1} - \overline{q}_{{\rm d},2} \gamma^\mu q_{{\rm d},2} \right) = -e_{\rm d} Z'_\mu \overline{q}_{\rm d} Q \gamma^\mu q_{\rm d}$$

We consider a universal coupling of the Z' to all SM quarks:

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

A strongly interacting dark sector

$SU(3)_{dark} \otimes U(1)_{mediator} \otimes SM$

2 flavours of dark quarks q_d

Z' mediator with mass of O(TeV), with coupling to q_d and q_{SM}

Confinement at scale Λ_d

Dark mesons: $\pi^{\pm}$, π^0, $\rho^{\pm}$, ρ^0 with mass of O(GeV)

Z' $\pi^+\pi^-$, Z'$\rho^+\rho^-$ couplings;

Z'-ρ^0 mixing

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Z'-$\boldsymbol{\rho}^0$ mixing

Sector	Particles	Parameters
$SU(3)$	$q_{\mathrm{d},i}$ $(i=1,2)$, A_d (dark gluon)	m_q, Λ_d
Chiral EFT	$\pi^{\pm}$, π^0, $\rho^{\pm}$, ρ^0	m_π, m_ρ, g
$U(1)'$	Z'	$m_{Z'}$, e_d, g_q

(See also Berlin et al., Phys. Rev. D97 (2018), no. 5 055033)

A strongly interacting dark sector

- The conserved U(1)' charge implies that the **$\pi^\pm$ mesons** are stable; they are thus viable **dark matter candidates**.

- Decays of the **neutral pion π^0** are strongly constrained by cosmology (CMB, BBN, Ω_{DM}); the π^0 **can be stabilised** by a discrete symmetry if $N_f = 2$ and $Q = (1, -1)$.

- The **$\rho^\pm$ are** effectively **stable** if $m_\rho < 2\, m_\pi$.

- The Z'-ρ^0 mixing induces **ρ^0 decays into SM quarks**:

$$\rightarrow \quad c\tau_{\rho^0} \approx 3.2\ \text{mm} \times \left(\frac{g_q}{0.01}\right)^{-2} \left(\frac{e_d}{0.4}\right)^{-2} \left(\frac{m_\rho}{5\ \text{GeV}}\right)^{-5} \left(\frac{m_{Z'}}{1\ \text{TeV}}\right)^{4}$$

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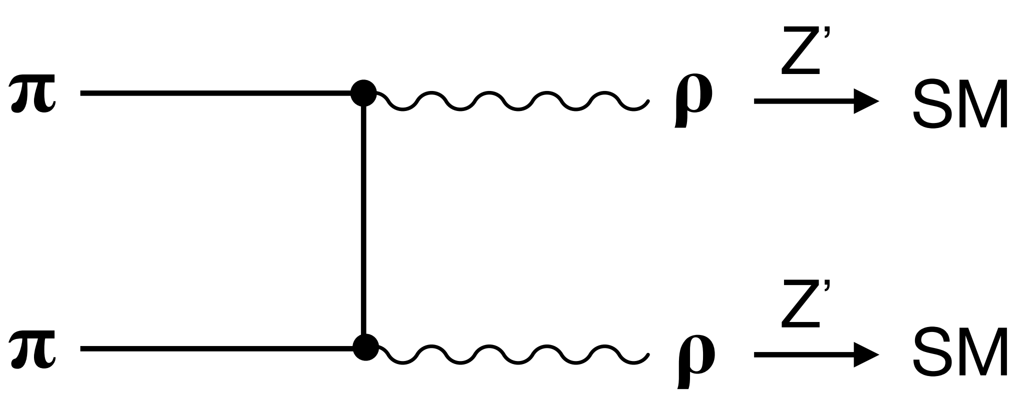
Relic density

The dominant **freeze-out process is $\pi\pi \rightarrow \rho\rho$** and is **set by dark sector parameters**: g, m_π, m_ρ.

(Note: the ρ mesons are expected to be heavier than the π mesons, and hence these processes are allowed only at finite temperature.)



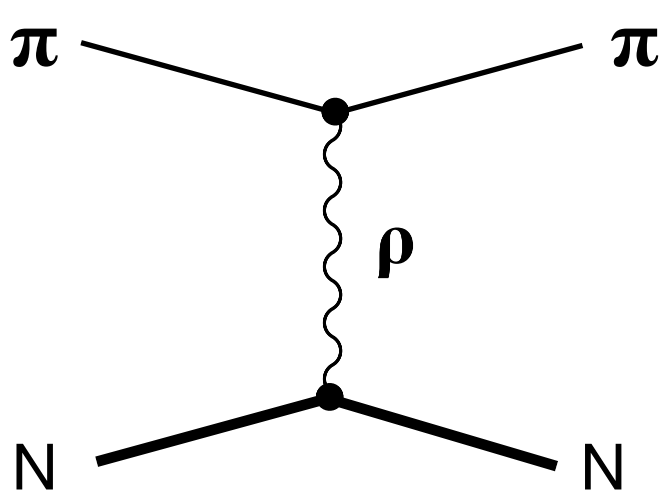
$$\sigma_{\pi\pi\rightarrow\rho\rho} \propto \frac{g^2}{m_\pi^2}\, e^{-2\Delta x_f}$$

$$\Delta = \frac{m_\rho - m_\pi}{m_\pi} \sim 0.2 \text{ - } 0.5$$

Example: m_π = 4 GeV, m_ρ = 5 GeV, and g = 1 yields $\Omega_{DM}h \approx 0.1$.

Direct detection

The exchange of ρ^0 mesons leads to a spin-independent DM-nucleon scattering cross section:



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

Direct detection

We combine limits from CRESST-III, CDMS-Lite, PICO-60, Panda-X and XENON1T using DDcalc:

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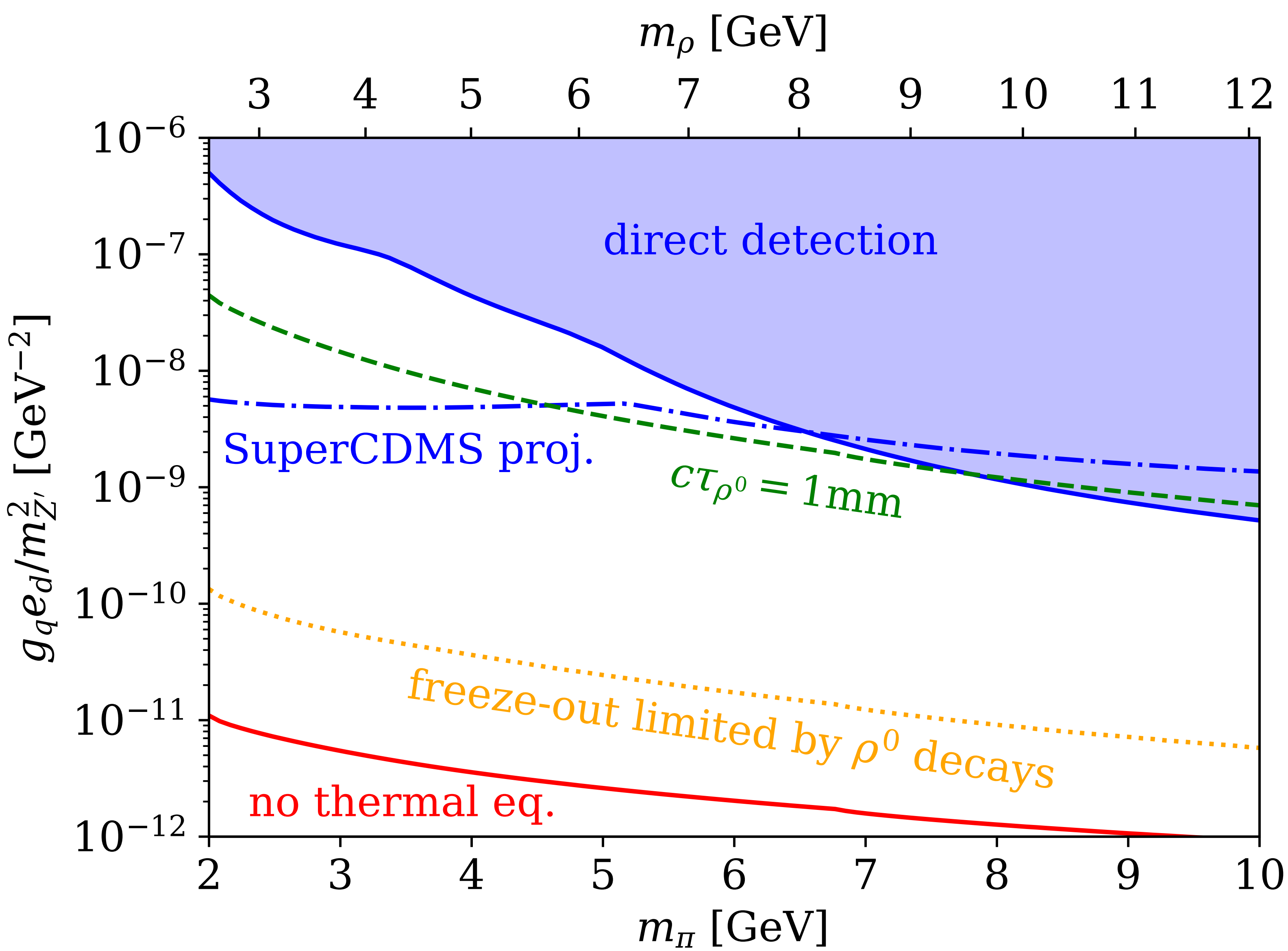

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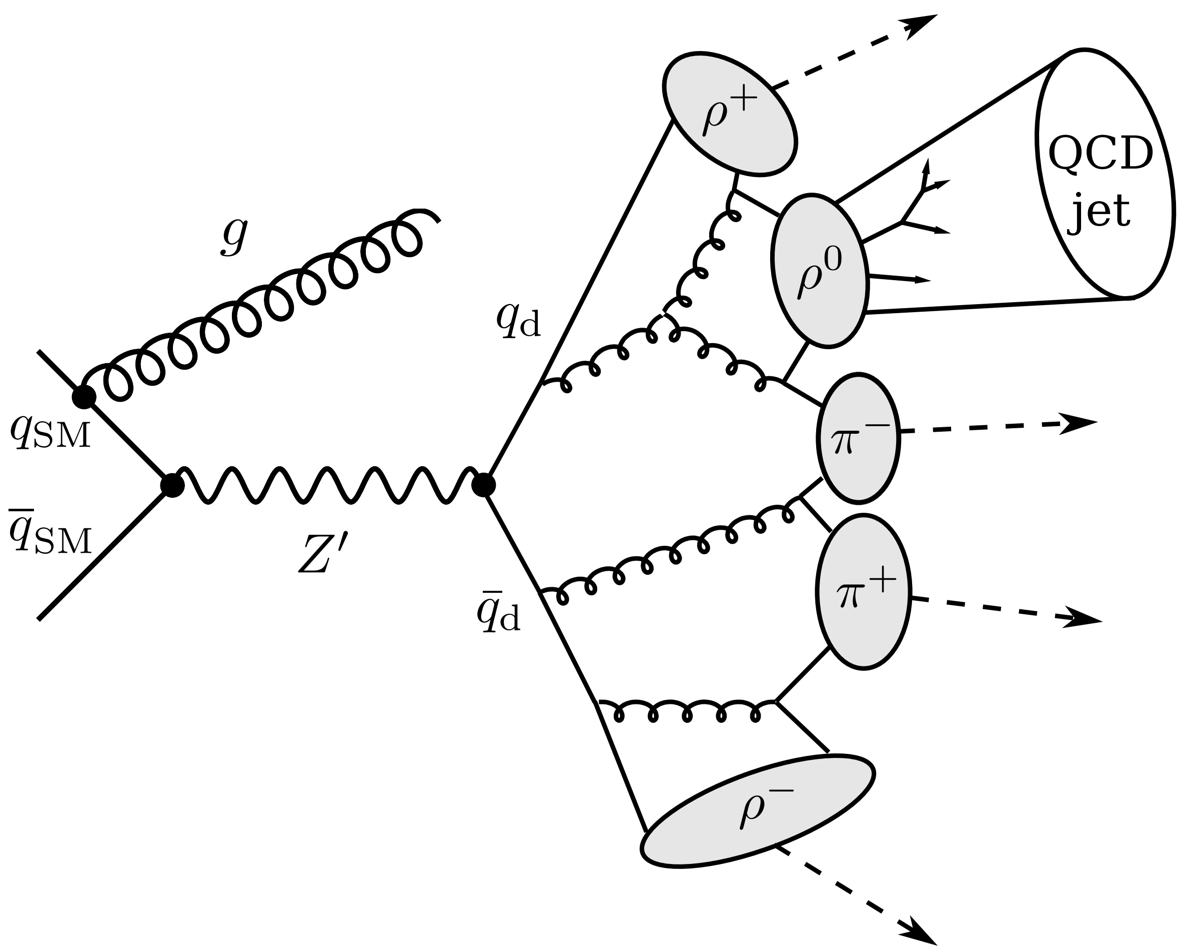
Dark sectors at the LHC

Novel signature: Z' production with decays into dark quarks, followed by fragmentation and hadronisation in the dark sector



- Z' decays produce a dark shower with $O(10)$ dark mesons.
- About 75% of the dark mesons are stable and escape detection.
- The ρ^0 mesons decay into SM quarks and produce QCD showers.

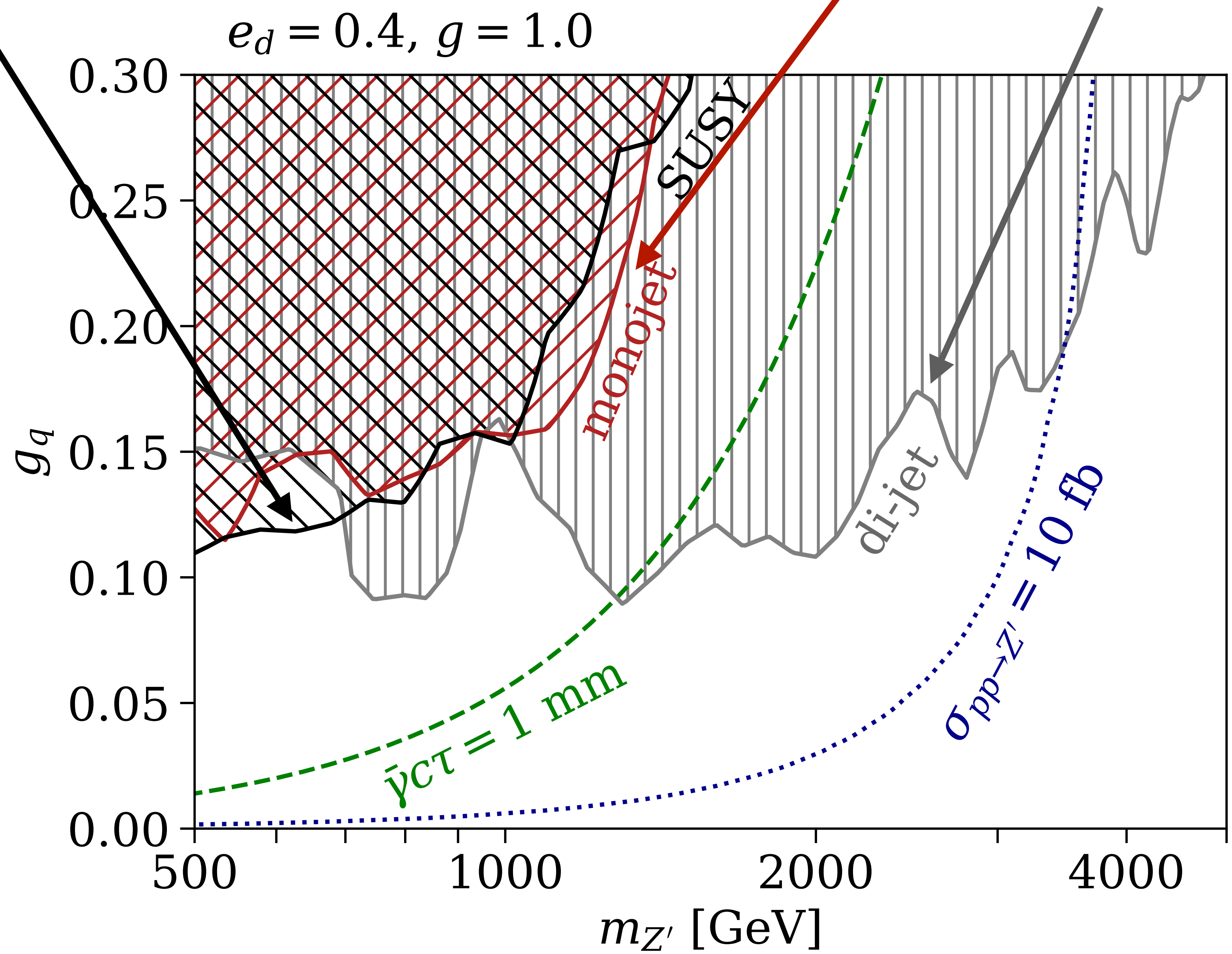
→ **semi-visible jets** (cf Hidden Valley models, Strassler & Zurek, Phys.Lett. B651 (2007) 374-379)

Recasting existing di-jet resonance, SUSY and mono-jet searches:

CMS **SUSY** (PRD96 (2017) 032003)

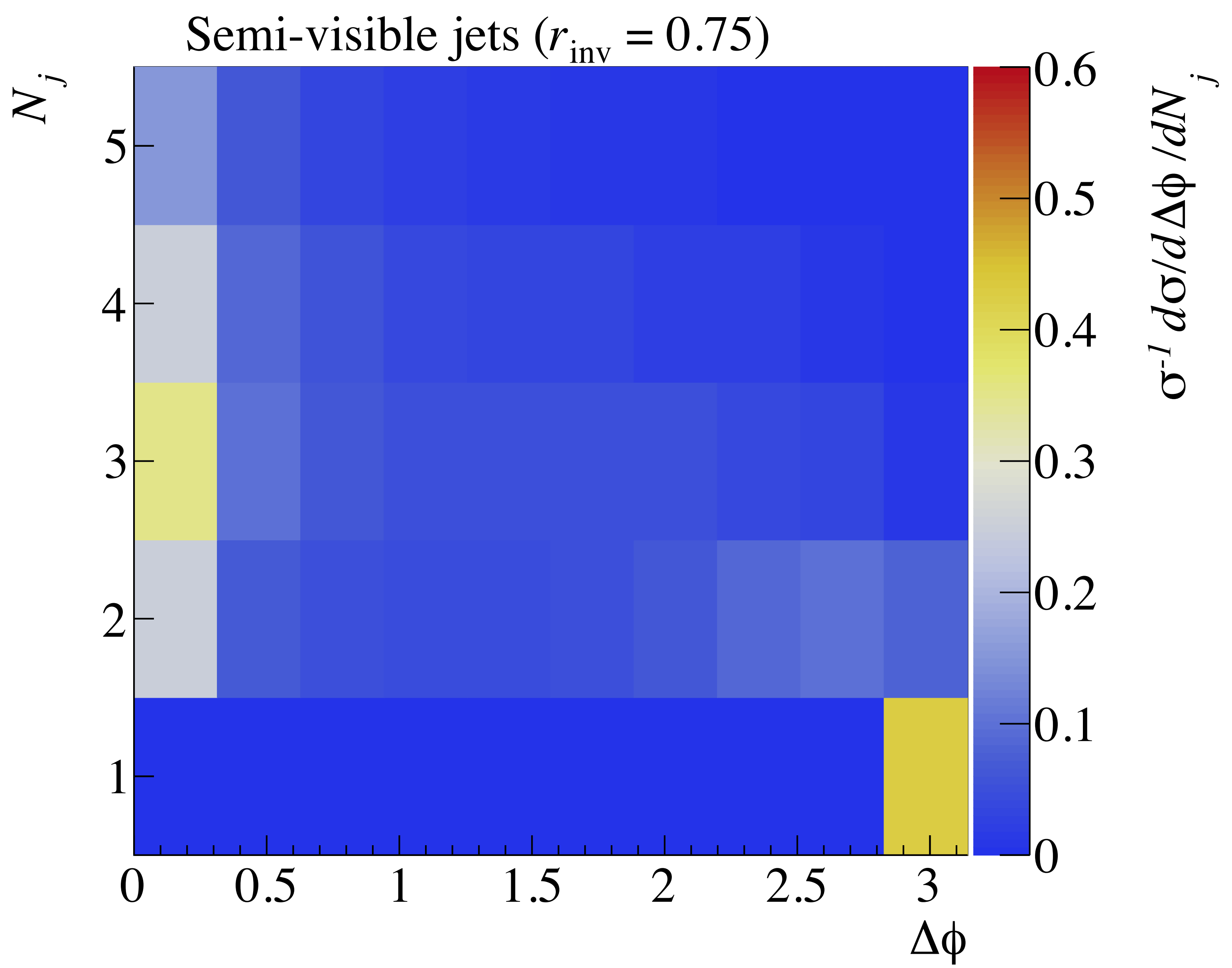
ATLAS **mono-jet** (JHEP 01 (2018) 126)

ATLAS **di-jet** (ATLAS-CONF-2019 007)



Prospective searches for semi-visible jets:

The missing energy is often aligned with QCD jets. Hence search for events with small angular distance $\Delta\phi = \min_j \Delta\phi(j, \not{E}_T)$ (Cohen et al., PRL115 (2017) 171804, JHEP11 (2017) 196)



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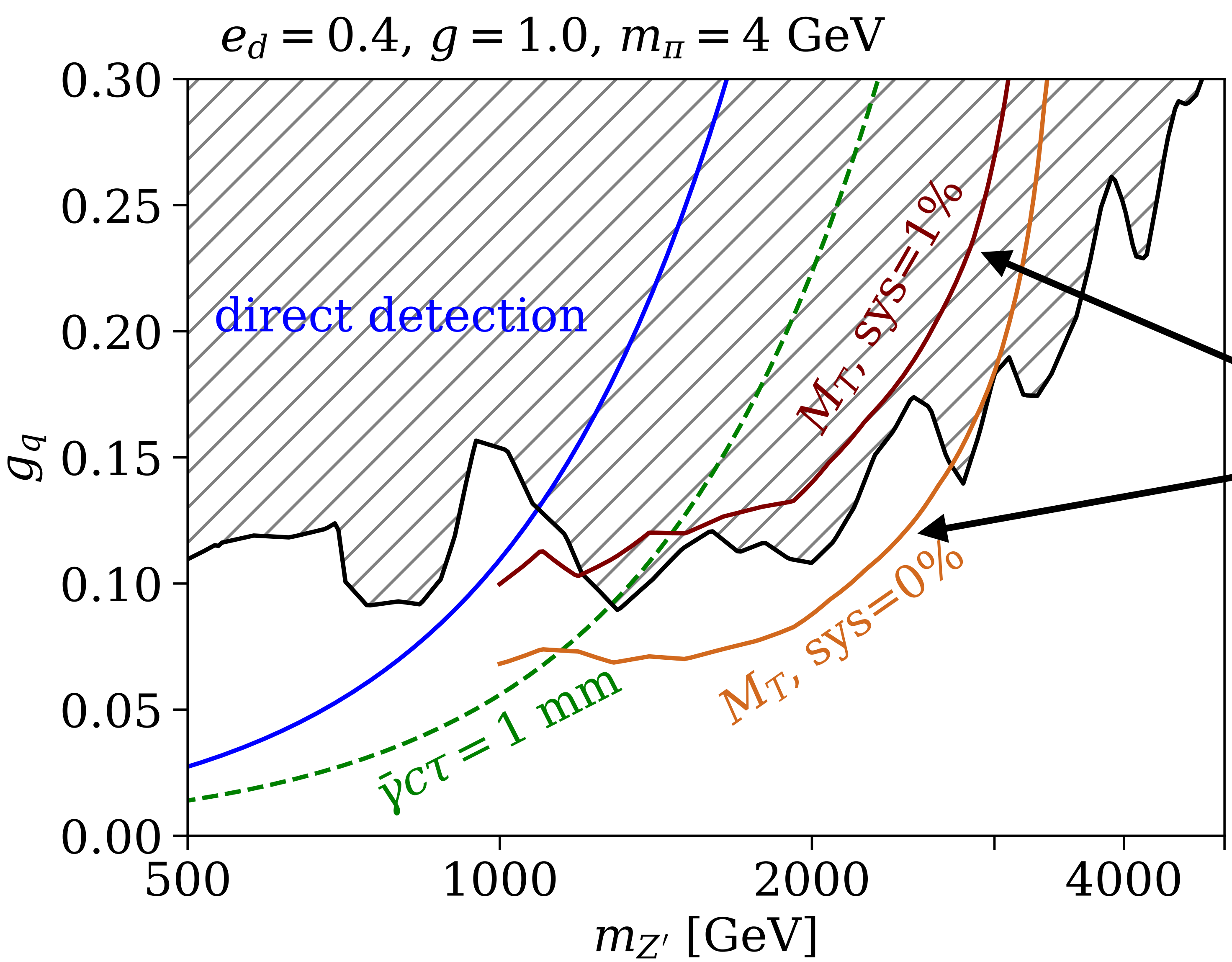

Invert the standard mono-jet cut, $\Delta\phi < 4$, and search for features in the transverse mass M_T.

Results are shown for different assumptions on the systematic background uncertainty.

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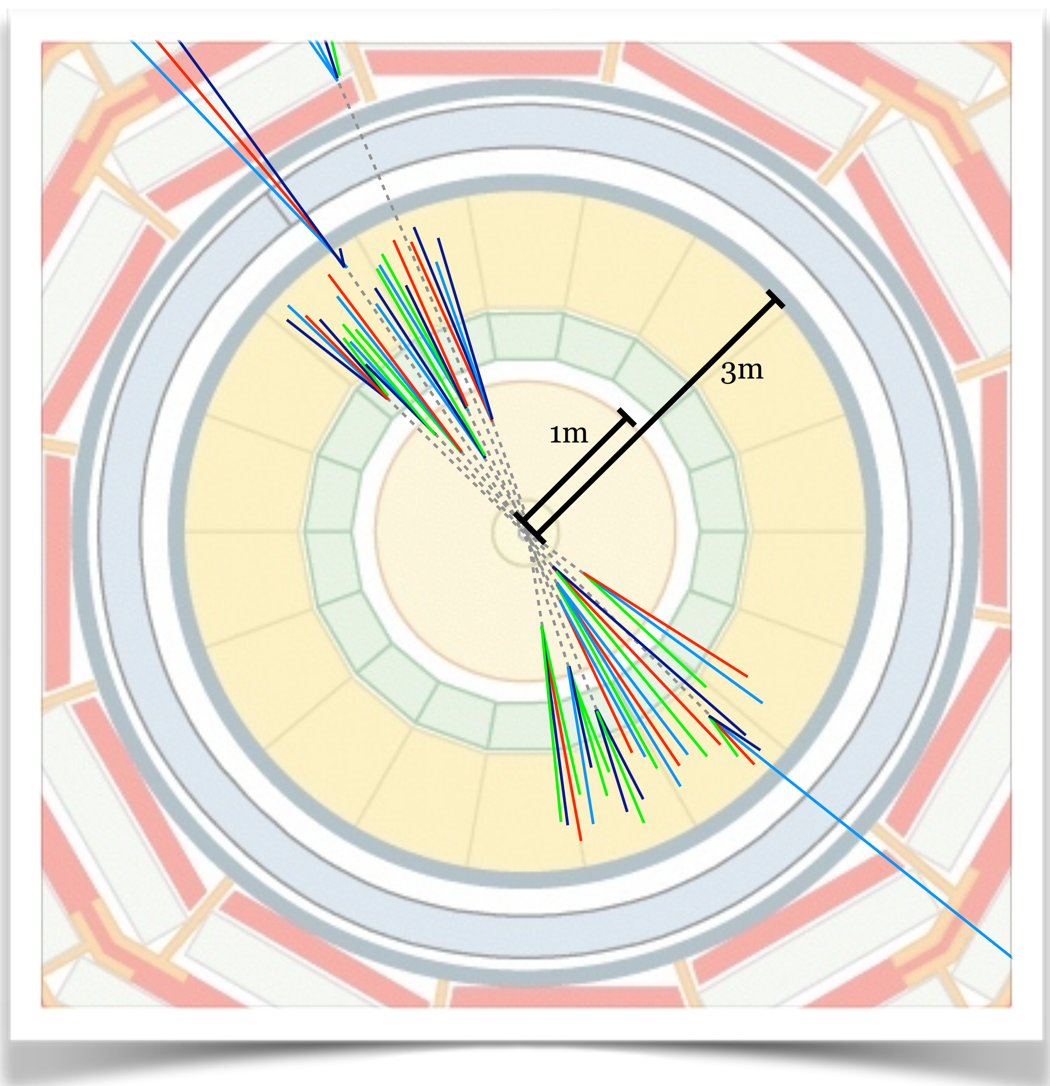
Displaced vertices

For small g_q, the ρ^0 decay length is of O(mm); we thus expect jets originating from displaced vertices.



Schwaller, Stolarski, Weiler, arXiv:1502.05409 [hep-ph]

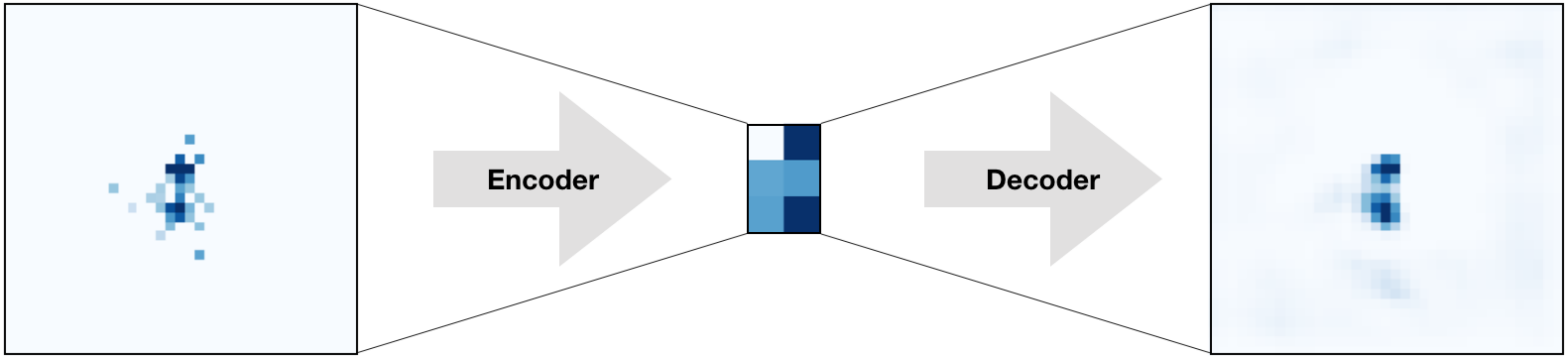
Many searches for long lived SUSY particles (e.g. ATLAS, PRD 97 (2018) 052012) require a **large vertex mass and track multiplicity** to suppress instrumental backgrounds.

These searches are optimised for heavy long-lived particles and are **not sensitive to our scenario**.

Machine learning

Searches for missing transverse energy and features in the transverse mass distribution do not use information on the jet-substructure.

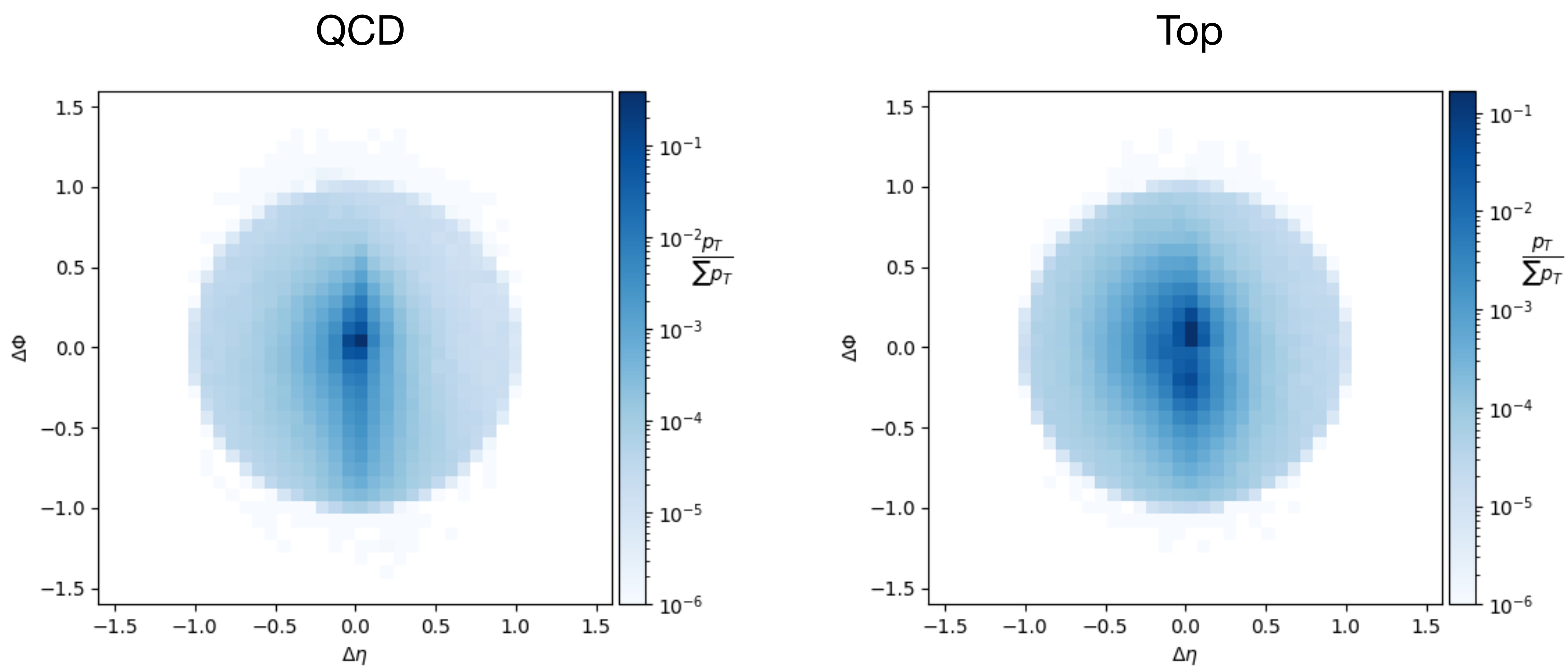
Is it possible to use neural networks, such as **autoencoders**, for classifying jet images into QCD (background) and dark showers?



See Heimel et al., SciPost Phys. 6 (2019) no.3, 030 and Farina et al. arXiv:1808.08992 [hep-ph]

Machine learning

Autoencoders are efficient in classifying jet images into QCD and top-quark jets:

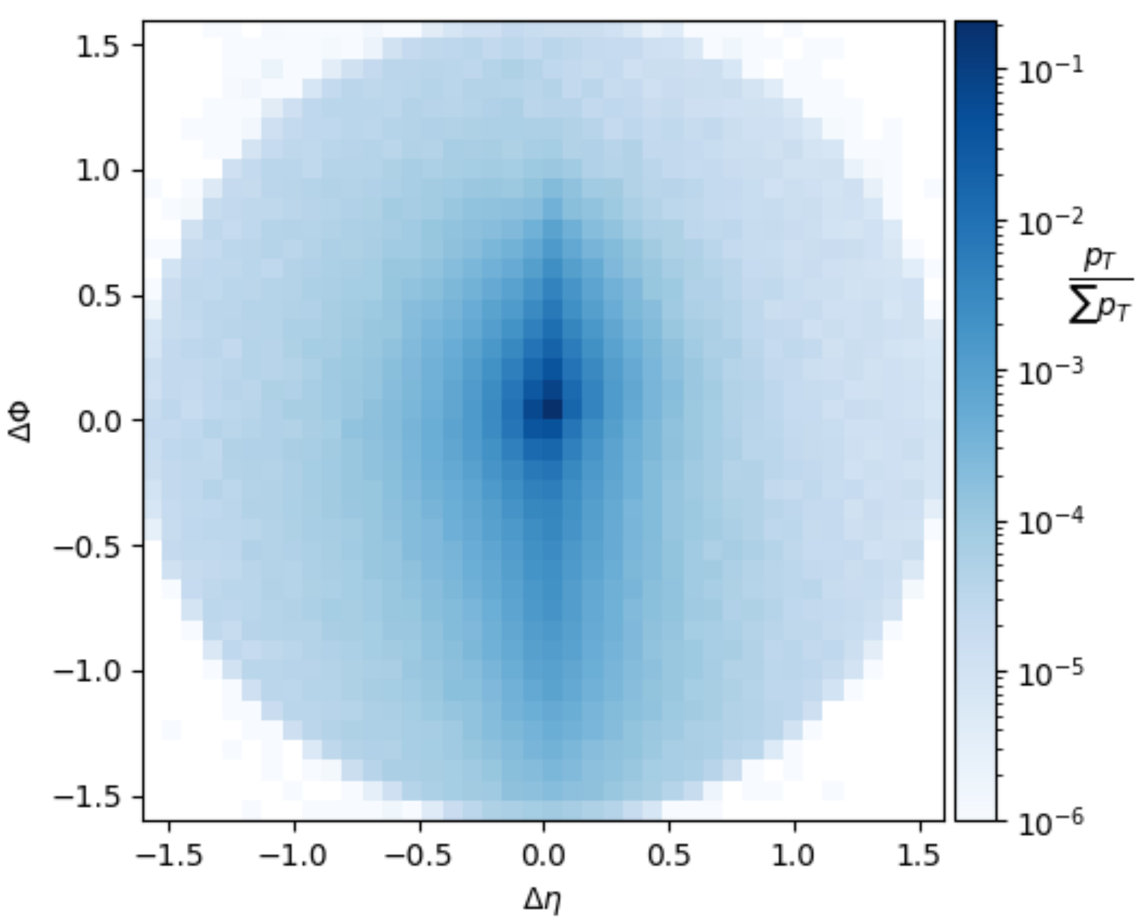


with Thorben Finke and Alexander Mück

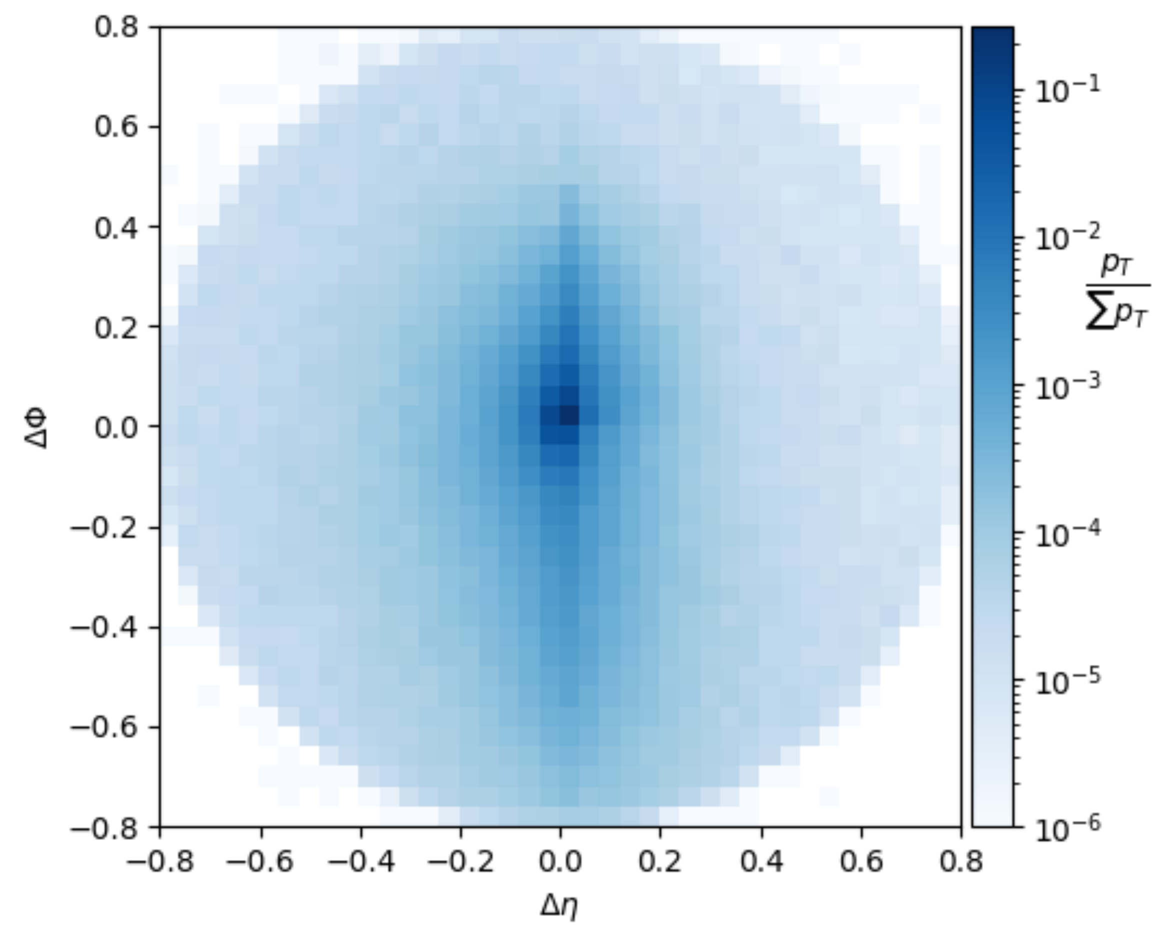
Machine learning

Autoencoders may be less efficient in discriminating QCD jets from dark showers:

QCD



Dark shower



with Thorben Finke and Alexander Mück

Summary

Exploring BSM physics at the LHC requires a variety of theoretical approaches, including

- the re-interpretation of **Standard Model precision** measurements;
- more **model-independent searches** for BSM effects, using e.g. effective field theories or machine learning;
- and searches for **novel or subtle signatures**, motivated by explicit new physics models, such as strongly interacting dark sectors.

Summary

Strongly interacting dark sector models, with a simple Z’ portal to the SM, are cosmologically viable and produce interesting LHC phenomenology:

- Cosmological and astrophysical constraints, and the re-interpretation of current BSM searches at the LHC leave a large model parameter space with **interesting LHC signatures**.
- Searches for **displaced vertices** will allow to probe the model for smaller couplings.
- **Machine learning** techniques may help to discriminate dark showers and SM background from QCD jets.

Thank you