Beyond Standard Model physics vision
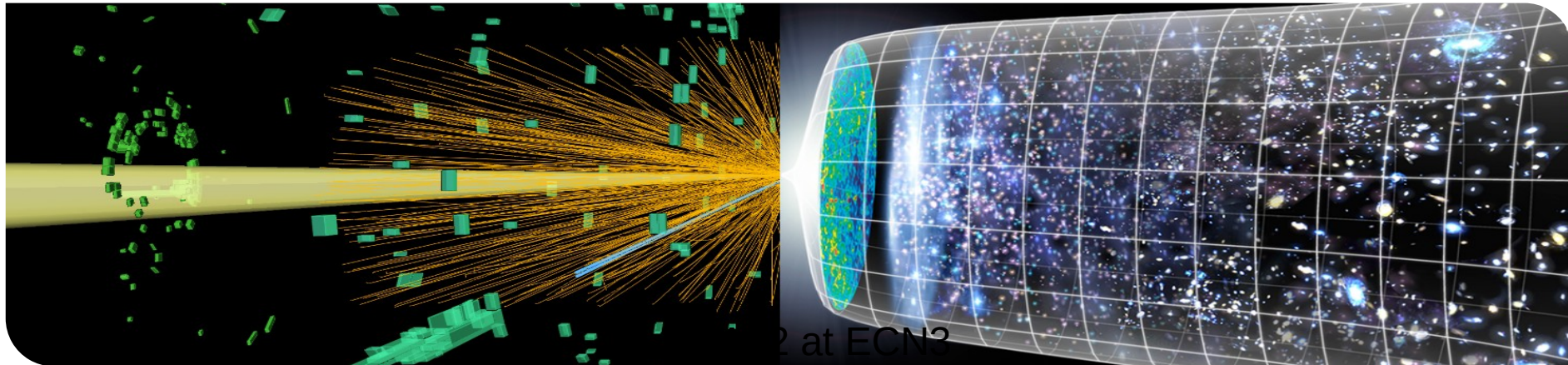
Felix Kahlhoefer
Physics Beyond Colliders Annual Workshop, 25–27 March 2024

What is a physics vision?

Beyond Standard Model physics vision

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

"Wer Visionen hat, soll zum Arzt gehen."

(If you have visions, you should go see a doctor.)

Helmut Schmidt (disputed)

How clear is your physics vision?

Beyond Standard Model physics vision

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Long-range vision: Experiments on the horizon

■ The combination of SHiP and HL-LHC with improved triggers promises a bright future for physics of feebly-interacting particles...

■ … but there are many other exciting experiments and new ideas to search for FIPs and other types of BSM physics

 ■ Forward physics facility

 ■ Large angle detectors

 ■ NA64 upgrades

Dark scalars (BC4)

Excluded

10^{-7}

θ^2

Downstream$_{25\,fb^{-1}}$
Downstream$_{300\,fb^{-1}}$

10^{-10}

SHiP$_{6\times10^{20}\,PoT}$

0.5   1   5   10

m_S [GeV]
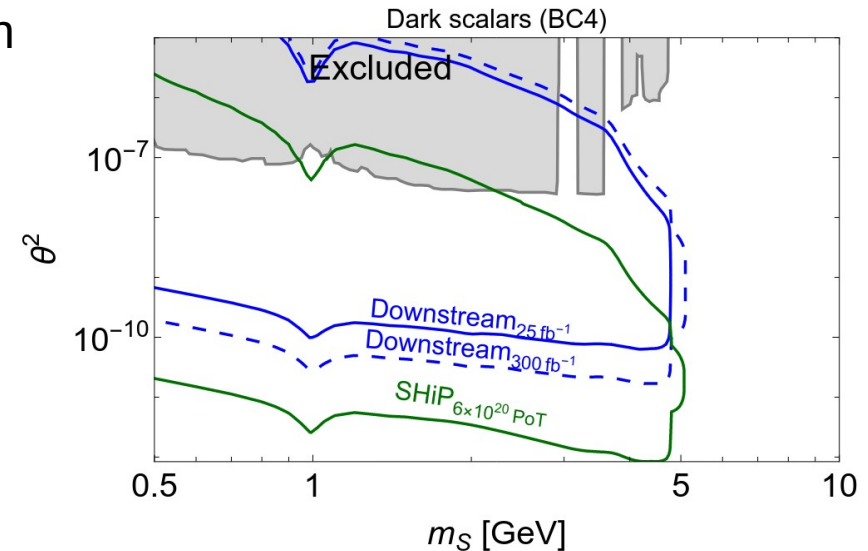
talk by Maksym Ovchynnikov

Beyond Standard Model physics vision

Short-range vision: The case for BSM physics

- One of the great successes of the PBC:

  Development of feebly-interacting particle benchmark scenarios

  → Worldwide industry standard

- Main purpose: Fair comparison of different experimental proposals for distinct signatures

- What is their use after the ECN3 decision?

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)
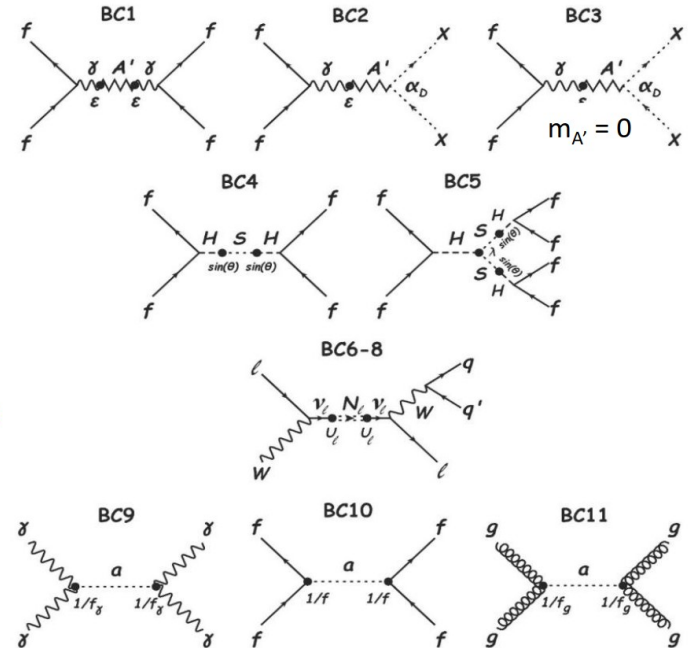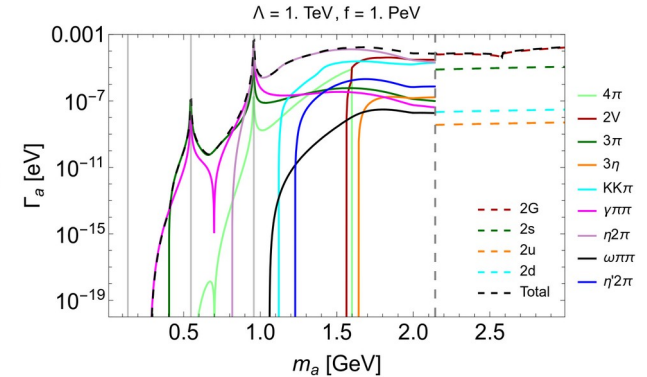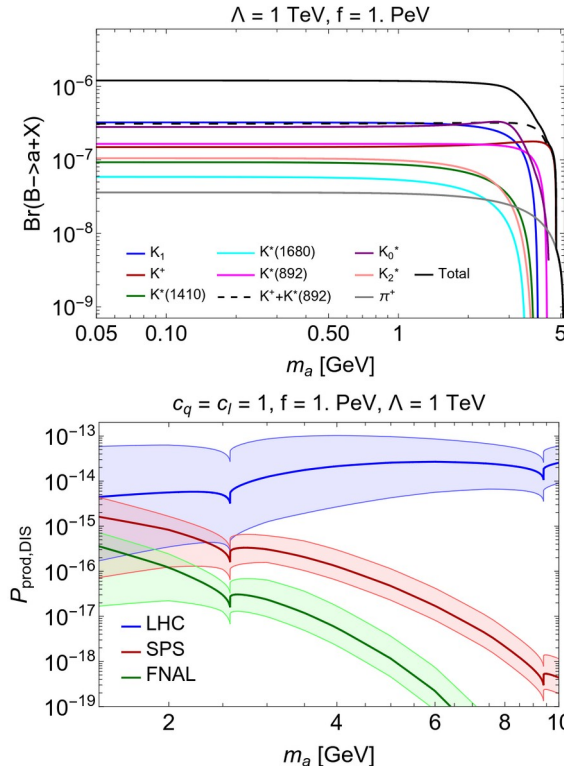
Towards realistic benchmark scenarios

- Simplified comparison of different experiments no longer primary purpose

- To optimise signal sensitivity and background rejection, need to make benchmarks as realistic as possible
  - Plausible combinations of couplings (in particular for ALPs and HNLs)
  - Inclusion of all production and decay modes
  - Reliable estimates of theory uncertainties

- Need to develop the necessary public tools (like ALPINIST, SenseCalc, ...)

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Example 1: fermionic ALPs revisited

- Detailed calculations of ALP production (from B decays, mixing and DIS)
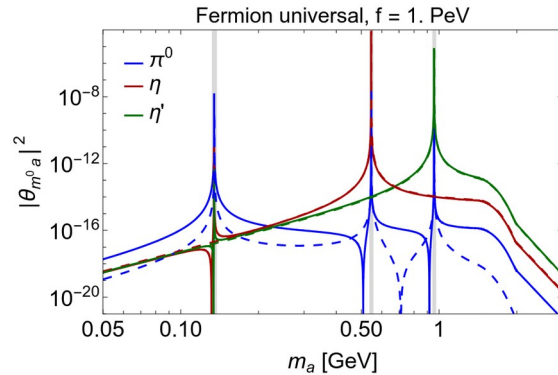
Dalla Valle Garcia, FK et al., arXiv:2310.03524

- Detailed calculations of ALP decays (into leptons, mesons and heavy quarks)

Felix Kahlhoefer
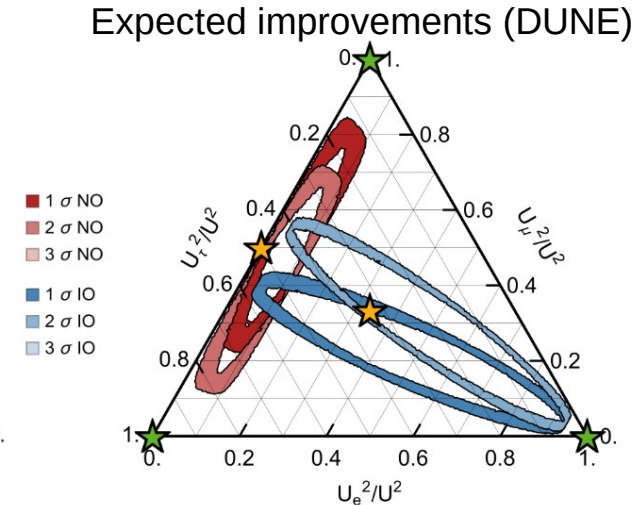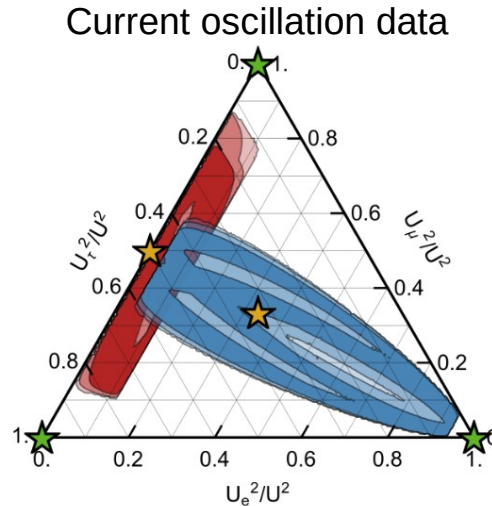Institute for Theoretical Particle Physics (TTP)

Example 2: Realistic heavy neutral leptons

- Existing HNL models are not compatible with realistic neutrino mass models

- Two new proposed benchmark scenarios:

$$U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 1 : 1$$

$$U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 1 : 1$$

- Phenomenology still needs to be worked out in detail

Current oscillation data

Expected improvements (DUNE)

- 1 σ NO
- 2 σ NO
- 3 σ NO
- 1 σ IO
- 2 σ IO
- 3 σ IO

27 March 2024   Beyond Standard Model physics vision

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Towards new benchmark scenarios

- Need to re-consider the case for LHC LLP experiments

- Identify FIP models that are inaccessible for SHiP
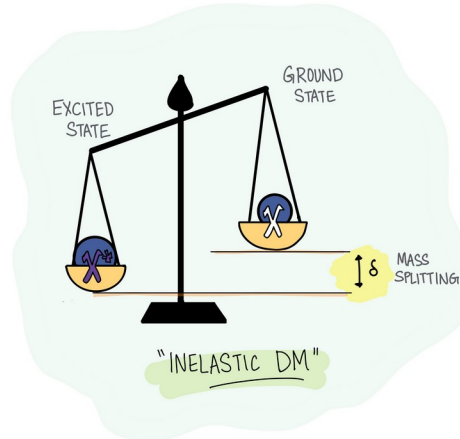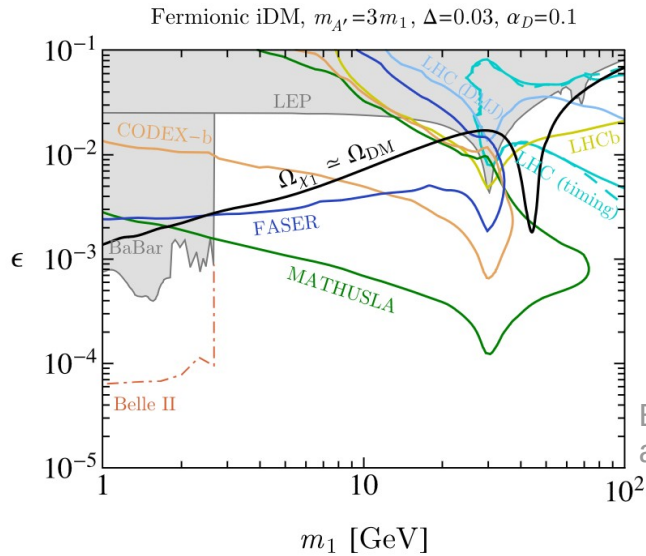
  - Quirks

  - Inelastic dark matter

  - …?
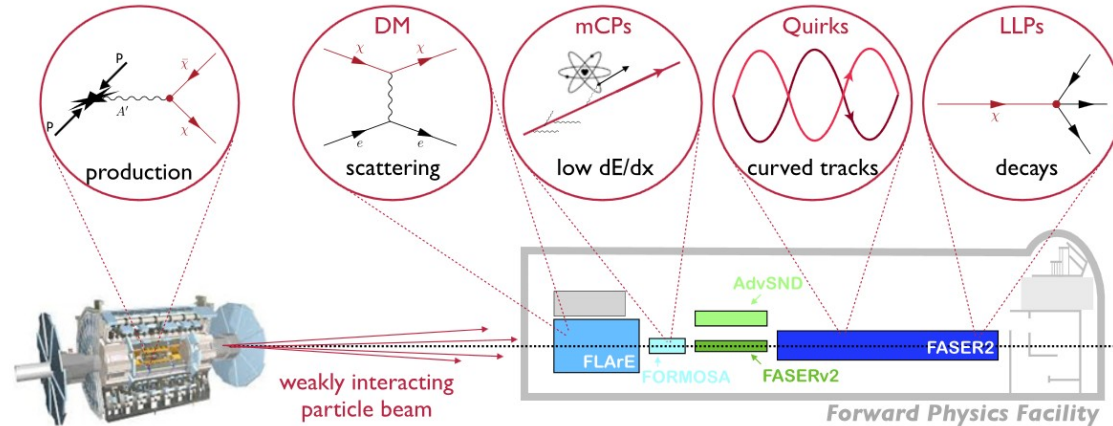
- Take these models seriously!

- What are constraints from other experiments, astrophysics and cosmology?

Beyond Standard Model physics vision

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Example 3: (Not so) inelastic dark matter

■ Inelastic dark matter:

   All transitions involve χ and χ*

Fermionic iDM, $m_{A'}=3m_1$, $\Delta=0.03$, $\alpha_D=0.1$

m_1 [GeV]

■ Not-so inelastic dark matter:

   Elastic interactions contribute

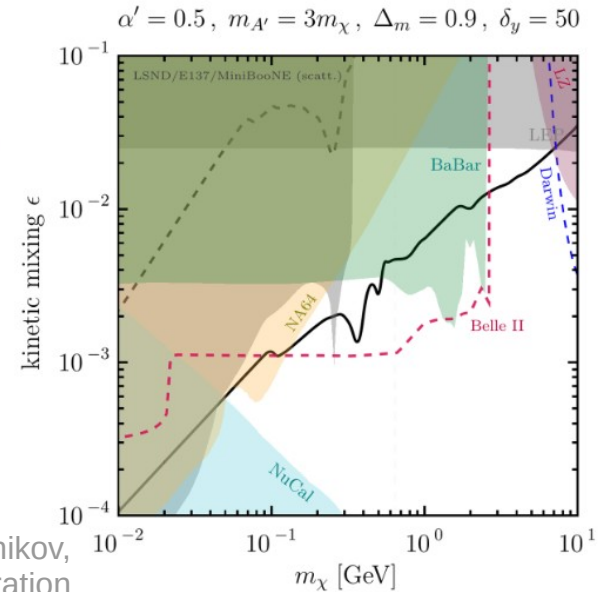$\alpha' = 0.5$, $m_{A'} = 3m_\chi$, $\Delta_m = 0.9$, $\delta_y = 50$

m_χ [GeV]

Credit: Saniya Heeba

Berlin & Kling,
arXiv:1810.01879

Dalla Valle Garcia, FK, Ovchynnikov,
Schwetz, in preparation
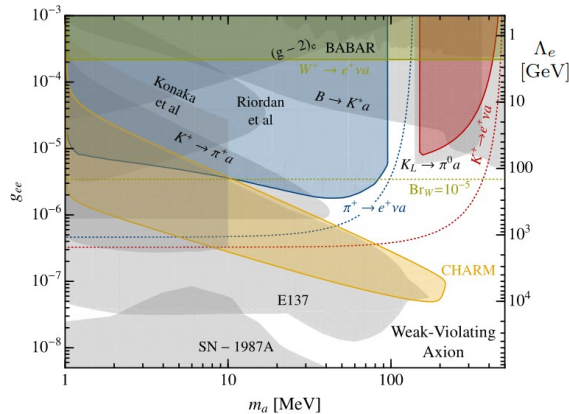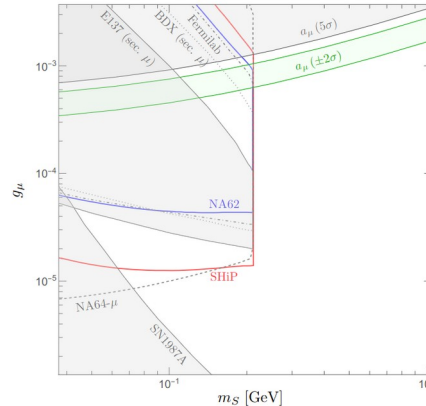
Example 4: Non-trivial flavour structures

- Different couplings to quarks and leptons

- Different couplings to different generations

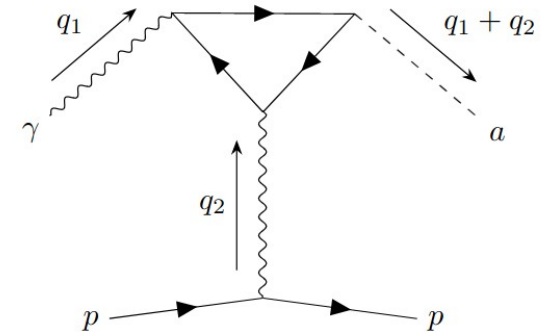- **Example:** Leptophilic ALPs

Rare meson and tau decays | Secondary muons from showers | Loop-induced photon couplings

Altmannshofer et al., arXiv:2209.00665

Rella et al., arXiv:2205.09870

Eberhart, Fedele, FK, Müller & Ziegler, in preparation

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)
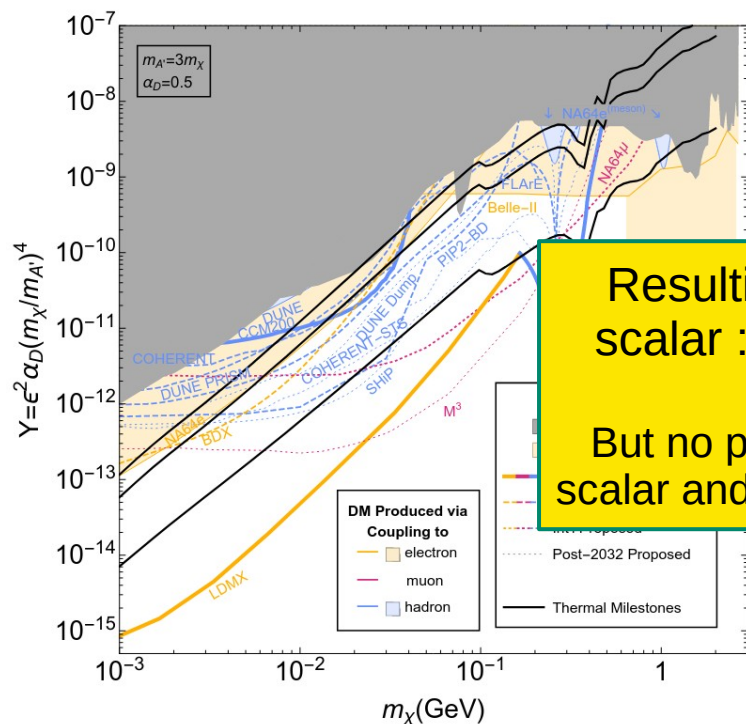
From allowed to preferred parameter regions

■ Not enough to fix model parameters to specific benchmark values

■ Need to explore multi-dimensional parameter space of entire model

   ■ Apply all relevant experimental and observational constraints

   ■ Perform global fit to identify preferred parameter regions

   ■ Bayesian interpretation: Fine-tuning penalty

   ■ Quantify discovery prospects for different experiments

■ Additional possibility: Bayesian model comparison (fine-tuning penalty)
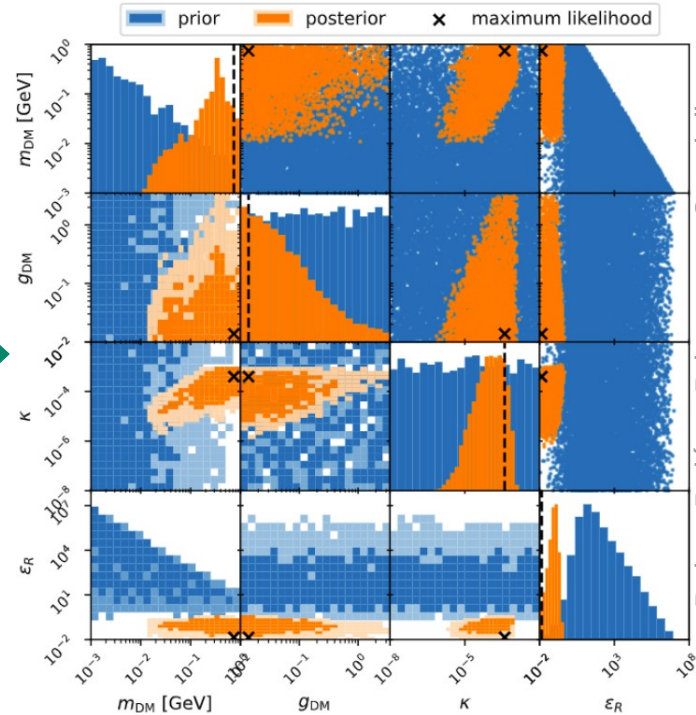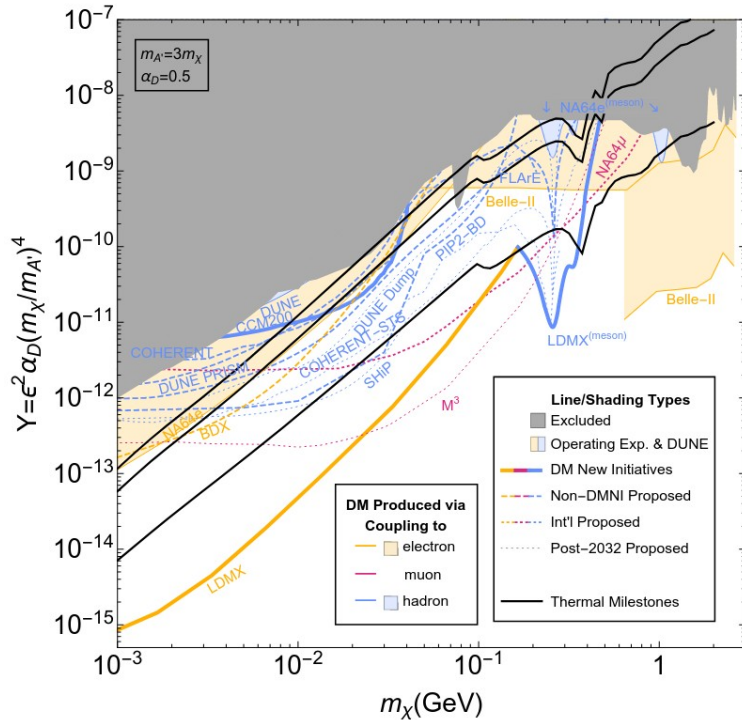
       Beyond Standard Model physics vision   Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Global fits of sub-GeV DM with GAMBIT

Balan, Balázs, Bringmann, Cappiello, Catena, Emken, Gonzalo, Gray, Handley, Huynh, FK and Vincent, in preparation

Beyond Standard Model physics vision

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Global fits of sub-GeV DM with GAMBIT

Resulting Bayes factor
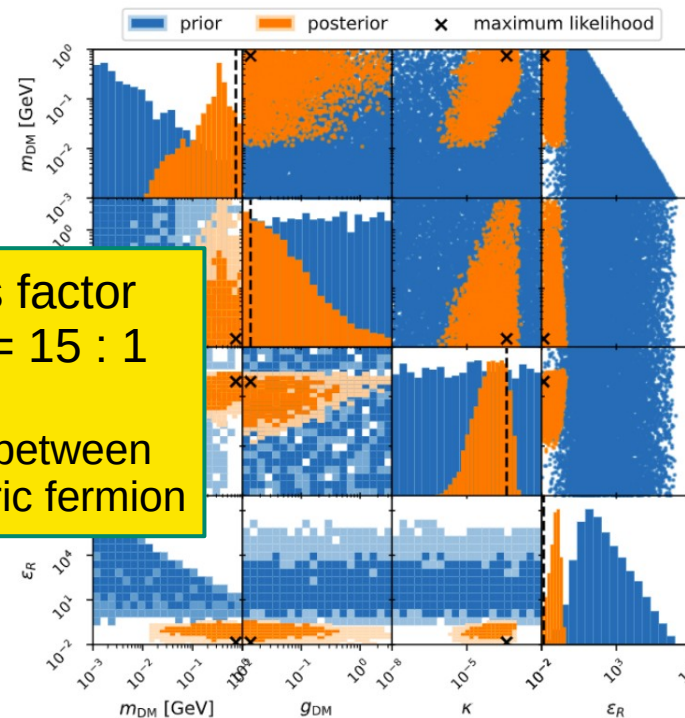scalar : fermion = 15 : 1

But no preference between
scalar and asymmetric fermion

Balan, Balázs, Bringmann, Cappiello,
Catena, Emken, Gonzalo, Gray, Handley,
Huynh, FK and Vincent, in preparation

Away from benchmark scenarios

■ Explore complementary ideas for FIP searches

    ■ Model-independent constraints on the combination of individual production and decay modes as function of LLP mass and lifetime

    ■ Definition of inclusive signal regions (or public likelihood functions) for easy reinterpretation

■ Anomaly detection of signal events on top of unknown background
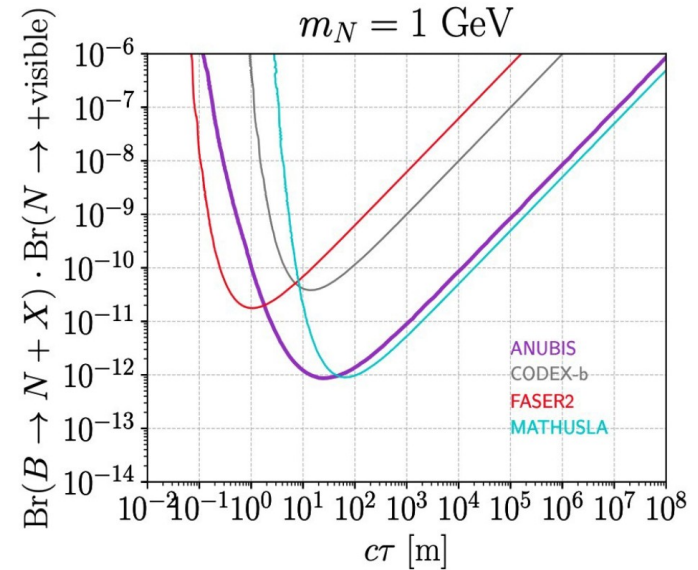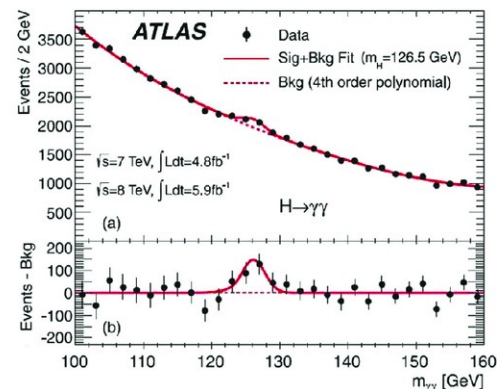

Talk by Michael Revering

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Simulator-based bump hunting

■ Conventional bump hunts rely on high-level observables constructed from low-level features (e.g. invariant mass)

■ What if the optimal high-level observable is unknown?
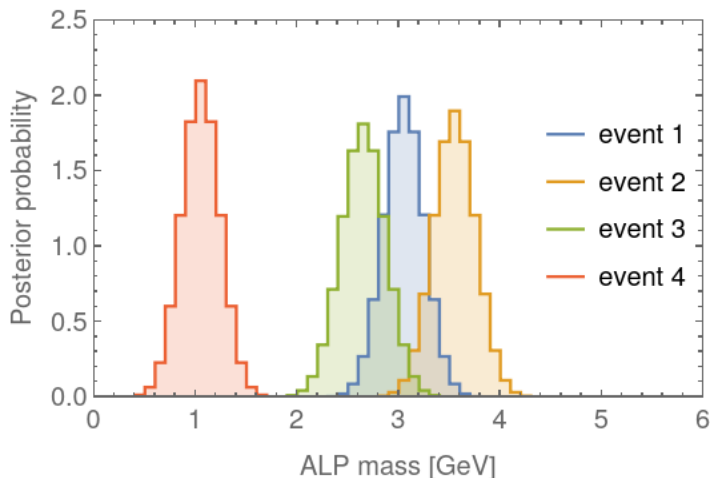
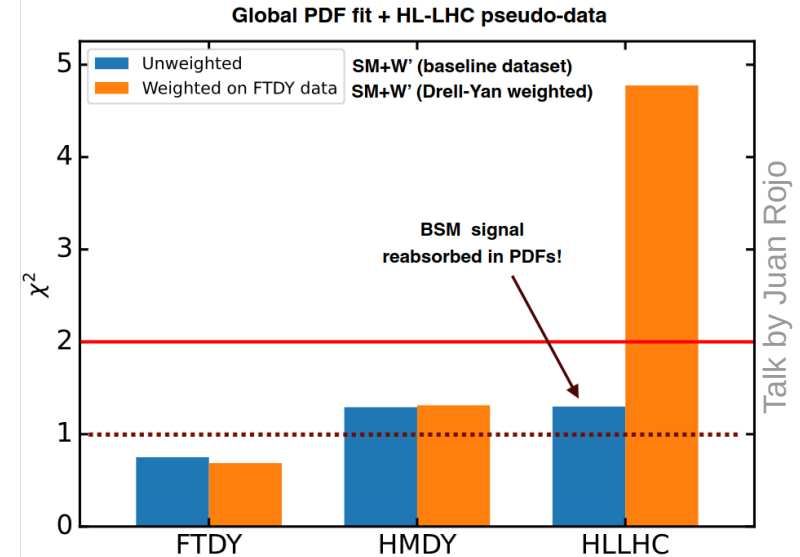■ **New idea:** train neural network to associate model parameters and low-level features

■ Network learns optimal way to reconstruct model parameters from low-level features

→ Perform bump-hunt in model space

Morandini, Ferber, FK, arXiv:2308.01353
Chathirathas, FK, Morandini, in preparation

Beyond Standard Model physics vision

Felix Kahlhoefer
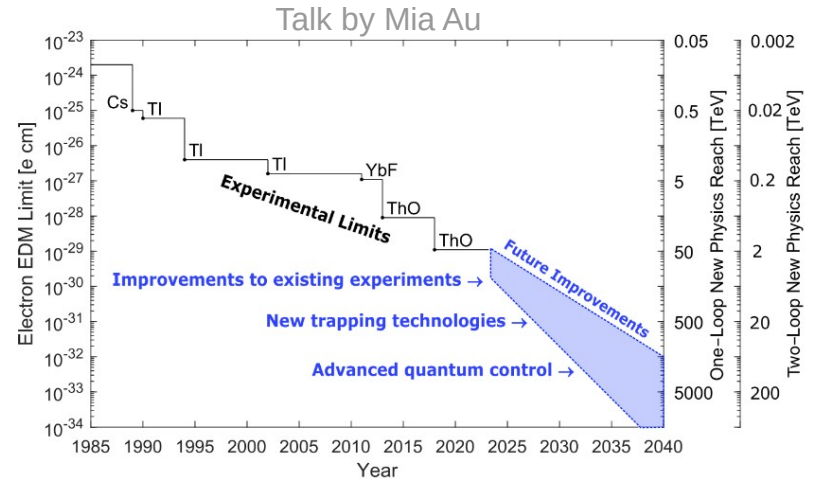Institute for Theoretical Particle Physics (TTP)

Beyond FIPs

- Neutrino physics and QCD are becoming a central science case of FPF

- Important for hadron structure and astroparticle physics

- Reduction of PDF uncertainties essential for BSM searches at the HL-LHC

Global PDF fit + HL-LHC pseudo-data

Legend: Unweighted / Weighted on FTDY data — SM+W' (baseline dataset) / SM+W' (Drell-Yan weighted)

BSM signal reabsorbed in PDFs!

Categories: FTDY, HMDY, HLLHC. Y-axis: χ^2

Talk by Juan Rojo

- Also possible to directly search for new physics with TeV neutrinos (e.g. non-standard neutrino interactions)?

27 March 2024   Beyond Standard Model physics vision

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

Beyond high-energy accelerators

- Many exciting precision searches

  - Electric dipole moments

  - CP violation

  - CPT violation

Talk by Mia Au

- Rapidly growing interest: Axion / wave-like DM / gravitational wave searches

- Rather self-sufficient: No clear need for theory support through the PBC (?)

Beyond Standard Model physics vision

Felix Kahlhoefer
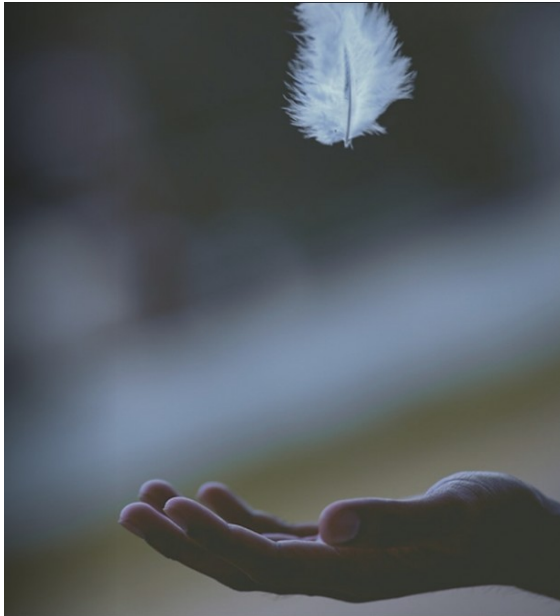Institute for Theoretical Particle Physics (TTP)

The future of PBC Beyond Standard Model

- FIP Physics Centre more important than ever!

- Need input from young physicists (and CERN theory group) to maintain (and increase) momentum

- PBC BSM working group requires readjustment

  - Reduced importance of flavour physics?

  - Increasing importance of neutrino physics?

  - What about low-energy precision measurements?

Beyond Standard Model physics vision

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)

The future of PBC Beyond Standard Model

PBC 2023

PBC 2024

Beyond Standard Model physics vision

Felix Kahlhoefer
Institute for Theoretical Particle Physics (TTP)