The **CONTUR** tool & **long-lived** particles

Simon Jeannot - 2024

Introduction

- Internship at the **LPC**
- Supervised by **Dr. Louie Corpe**
- Discovery of the **CONTUR** tool
- Application to models containing **long-lived** particles

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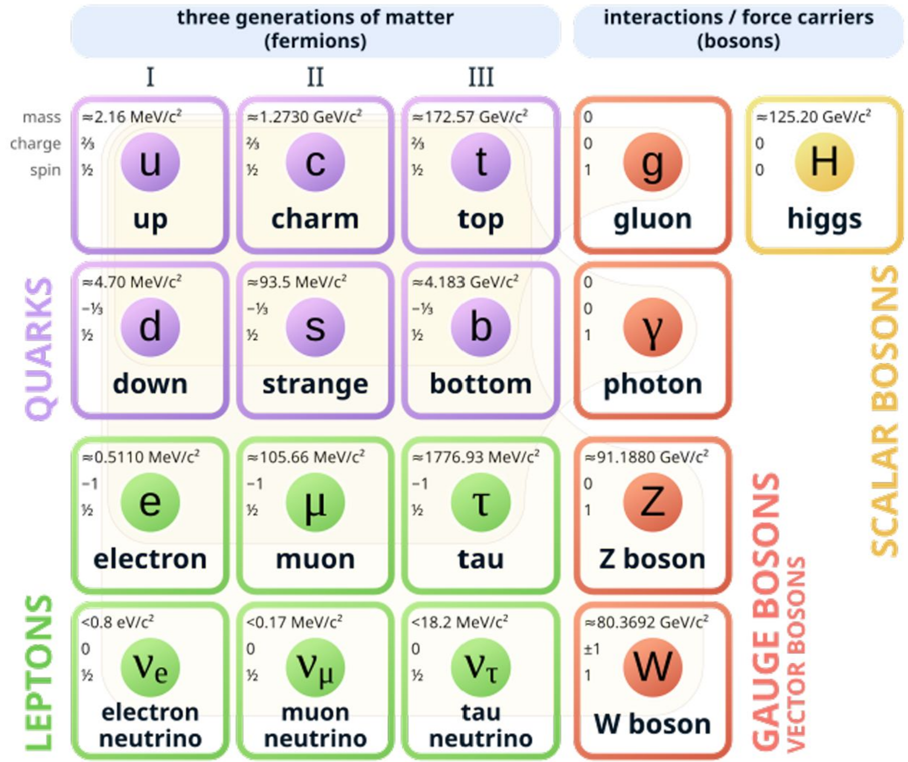
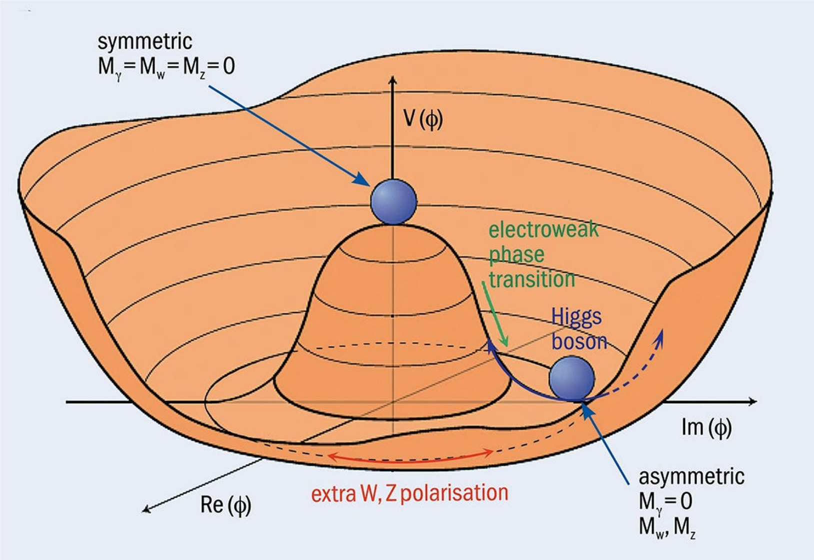
01

Standard Model & beyond

Standard Model (SM)



$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

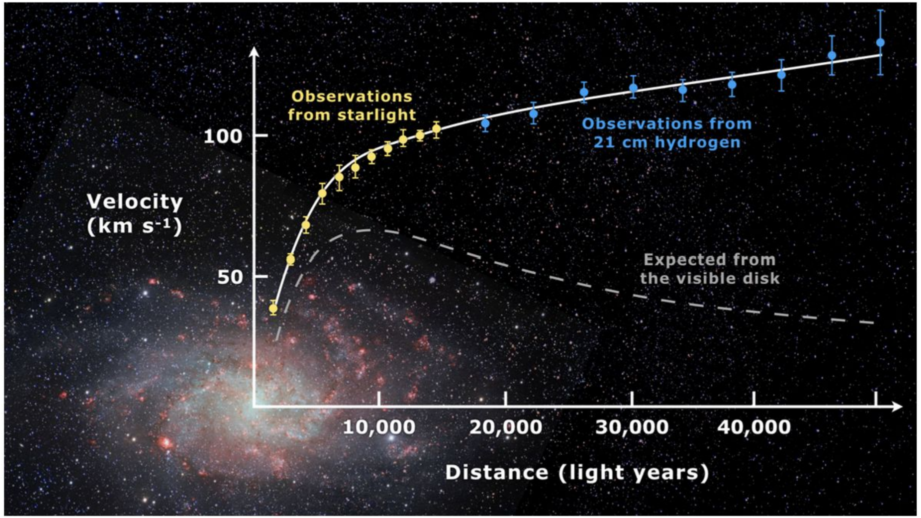


Limitations of the SM

- Dark **Matter**
- Dark **Energy**
- Matter-antimatter **asymmetry**
- Neutrino **masses**
- **Hierarchy** problem
- **Strong** CP problem

Dark Matter (DM)

- Velocity should **decrease** with distance
- Halo of **invisible matter**
- massive objects **distort** the space-time
- % of mass **not interacting** through EM forces



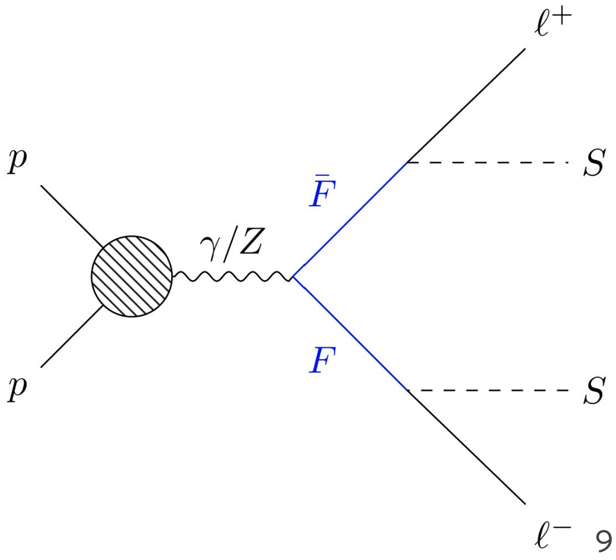
DM Candidates

- **WIMPs:** interact weakly with ordinary matter
- **Axions:** proposed to solve strong CP problem, very light & weakly interacting
- **Sterile neutrinos:** mix with active neutrinos, DM candidates
- **Hidden sectors:** no direct interaction with SM

Freeze-in model

- Charged parent *F* decays into a **FIMP** *S*
- Alternative to the **WIMP** scenario
- LHC signature: Drell-Yan pair production of *F*, decay into *S* along with a **charged lepton**

$$\mathcal{L} \supset \sum_{\ell} y_s^{\ell} \left(s\bar{F} \left(\frac{1+\gamma^5}{2} \right) \ell + \text{h.c.} \right)$$

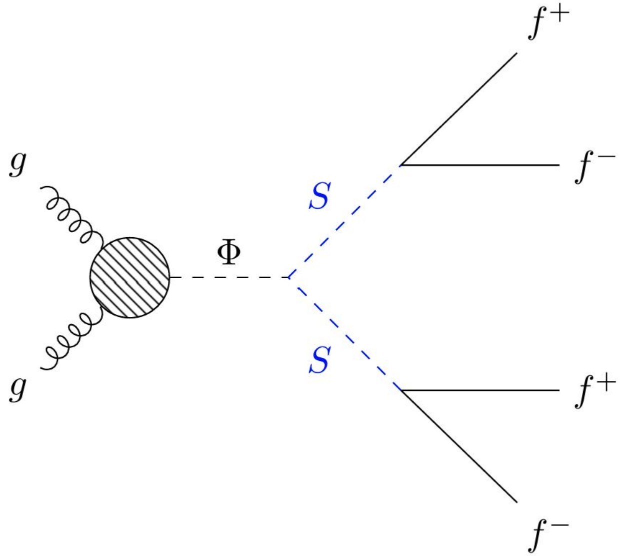


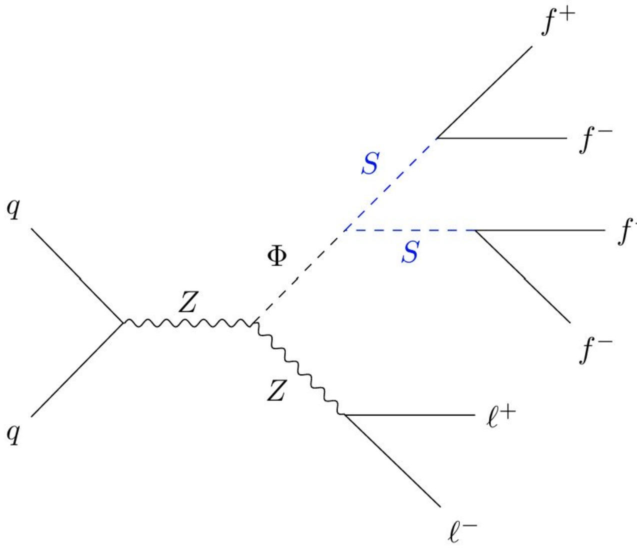
Hidden Sectors (HS)

- **No direct** interaction with SM (or very weak)
- **Portal interaction:** mediator particle couples to SM & HS
- **Scalar** portal
- **Vector** portal
- **Neutrino** portal

Hidden Abelian Higgs Model

- SM linked to a dark sector via a **scalar** mediator Φ
- Mediator can be either the **Higgs** boson or a **novel** boson

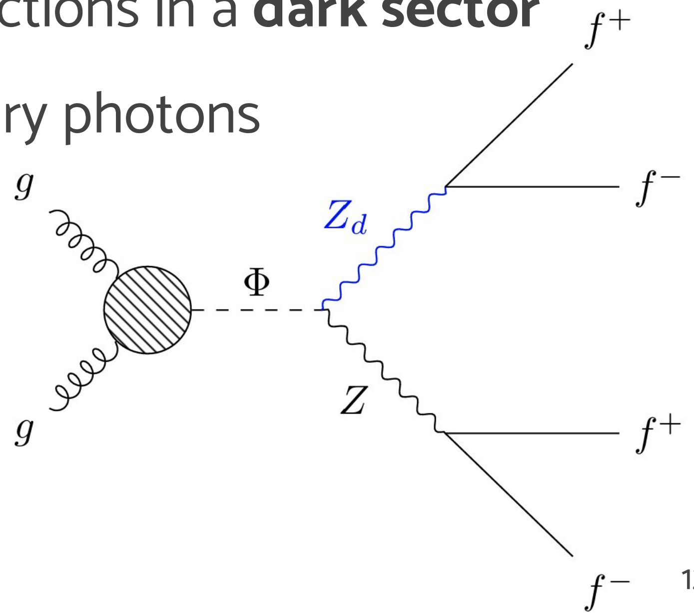




Dark Photons

- Extend concept of **photon** into the realm of DM
- Hidden **gauge boson**, mediates interactions in a **dark sector**
- Kinetic **mixing** (very weak) with ordinary photons

$$\mathcal{L}_{\text{mix}} = -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

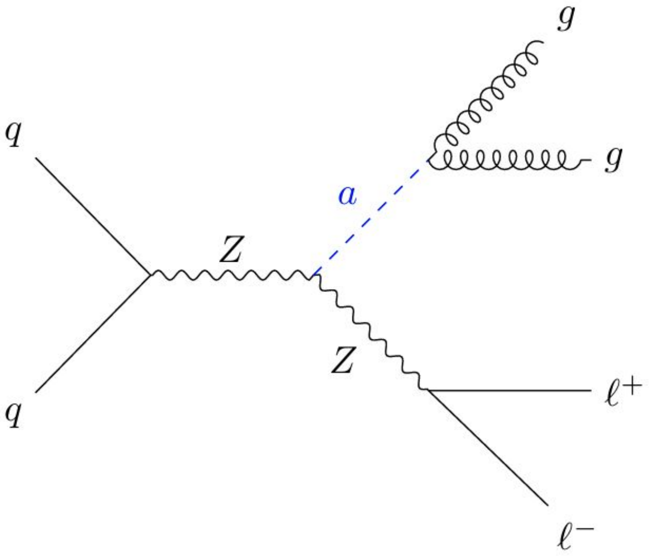


Axion-Like particles

- Extend the concept of the **axion**
- Wider range of **masses** and **couplings**
- Extremely **weak interactions** with ordinary matter
- Could affect the **CMB** radiation, the distribution of **galaxies**, the dynamics of **stars**

Photo-phobic ALP model

- ALPs couple **exclusively** to gluons and decay into jets
- Production via associated **Z boson** production

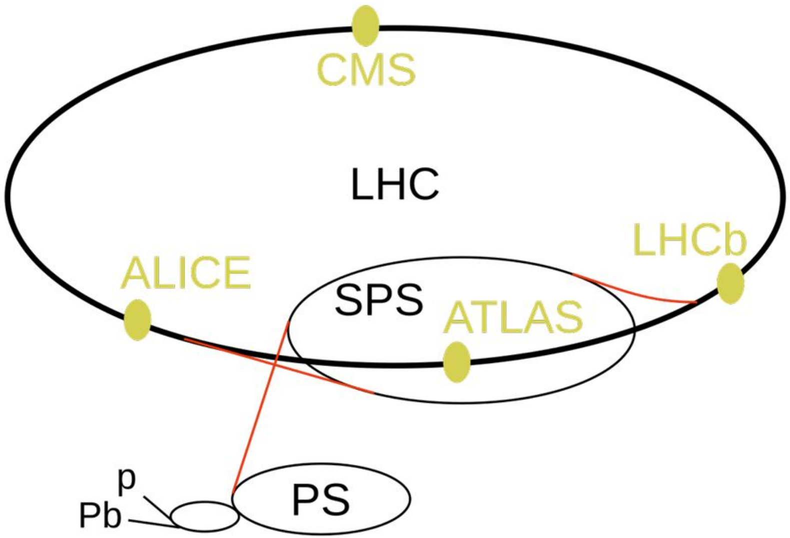


02

Constraining new theories

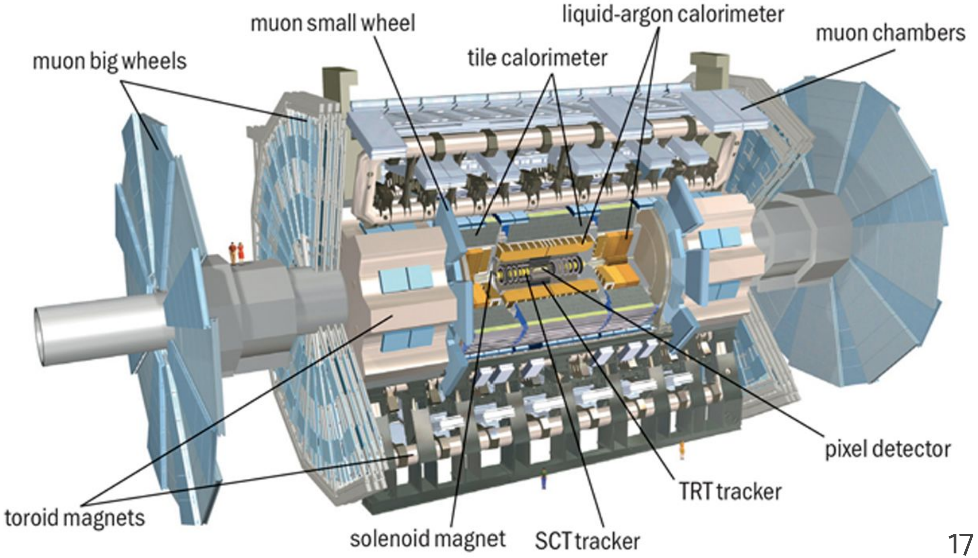
The Large Hadron Collider (LHC)

- 27 km in circumference, 100 m **underground**
- The **HL-LHC** (late 2020s): aims to **increase the luminosity** of the LHC by a factor of 5 to 10



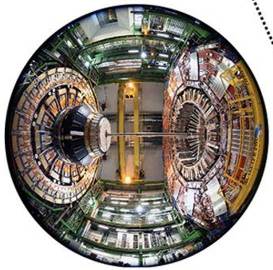
The ATLAS detector

- 46 meters long, 25 meters in diameter, weighs around 7,000 tonnes
- series of **sub-detectors** arranged in **concentric** layers

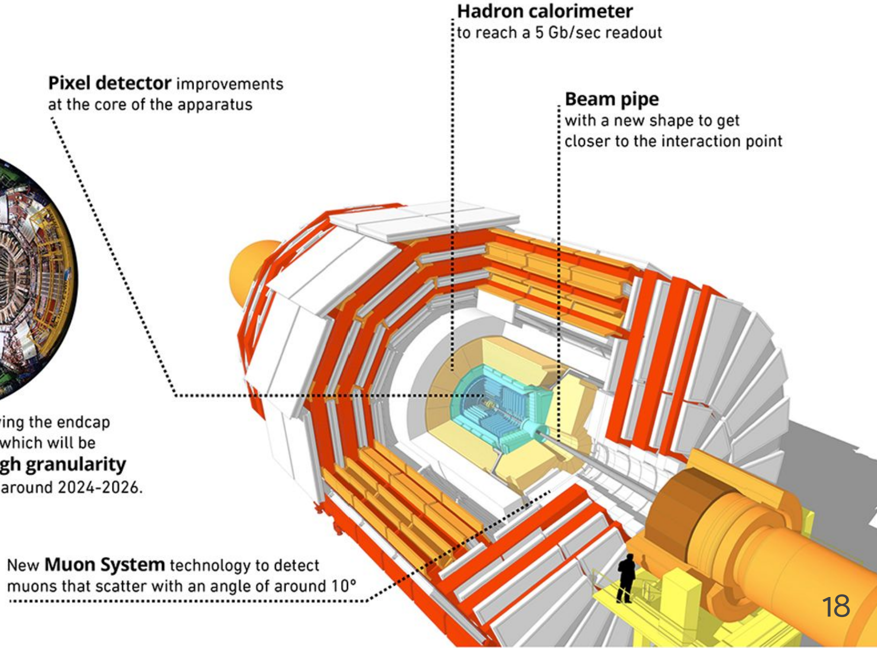


The CMS detector

- 21 meters long, 15 meters in diameter and weighs about 14,000 tonnes
- layered structure **similar** to ATLAS



Open CMS detector, showing the endcap calorimeter sticking out, which will be replaced with the new **high granularity calorimeter (HGCAL)** around 2024-2026.

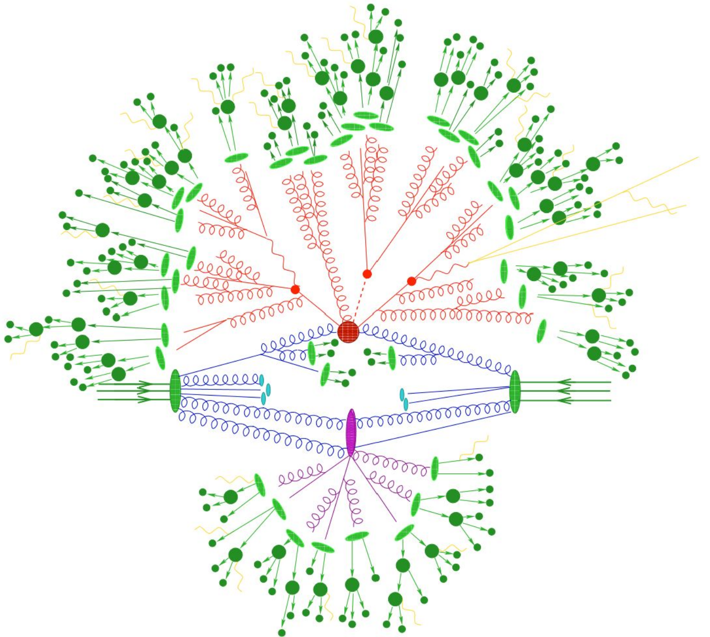


Reinterpretation of searches

- **Reassessing** theoretical models on the basis of new data
- Large amount of data generated by **experiments**
- Gain insights without the need for **new** experiments
- Explore new hypotheses & refine theoretical models more **efficiently**

Event generation

- **Monte Carlo**: use pseudo-**random** number generators (PRNGs) to solve **complex** problems
- Models written in Universal FeynRules Output (**UFO**) format
- MCEGs such as **MadGraph** and **Pythia**
- Simulated events stored in the **HepMC** format



RIVET

- **R**obust **I**ndependent **V**alidation of **E**xperiment and **T**heory
- Facilitate **comparison** of theoretical models with experimental data
- Analysis **routines**: encapsulate specific definitions of **fiducial** regions of experimental analyses
- Produces detailed **histograms** in the YODA format

The CLs method

- Test hypotheses and set **exclusion limits** for theoretical models
- CLs < α: exclude **signal** hypothesis at a confidence level of 1–α
- A **common** choice for α is 0.05, corresponding to a **95%** confidence level

$$CL_{s+b} = P(q \leq q_{\text{obs}} | H_{s+b})$$

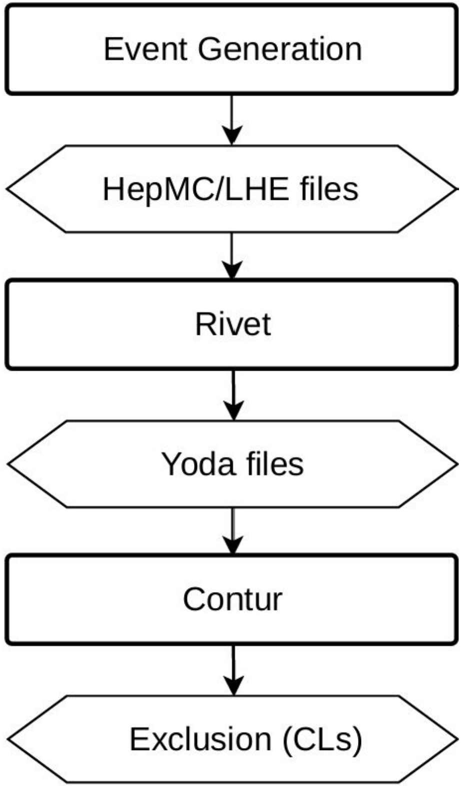
$$CL_b = P(q \leq q_{\text{obs}} | H_b)$$

$$CL_s = \frac{CL_{s+b}}{CL_b}$$

CONTUR

- **C**onstraints **O**n **N**ew **T**heories **U**sing **R**ivet: rethink particle physics research from a **theory-driven** approach to a **data-driven** one
- Probe how a given **BSM model** would modify the hundreds of observables measured in **existing** LHC measurements
- **Negligible** time compared with a **dedicated** search

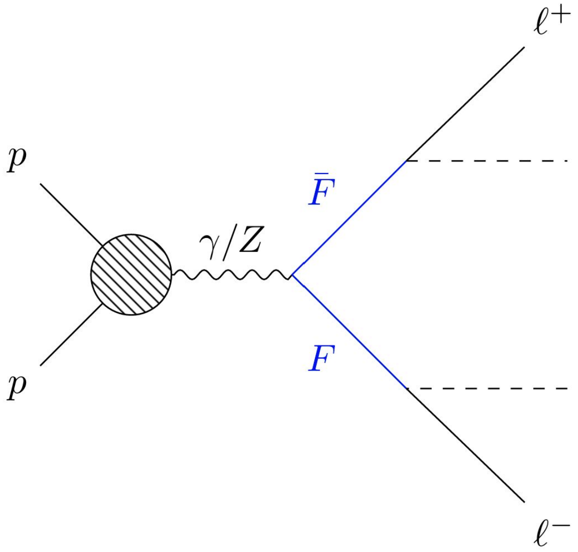
CONTUR workflow

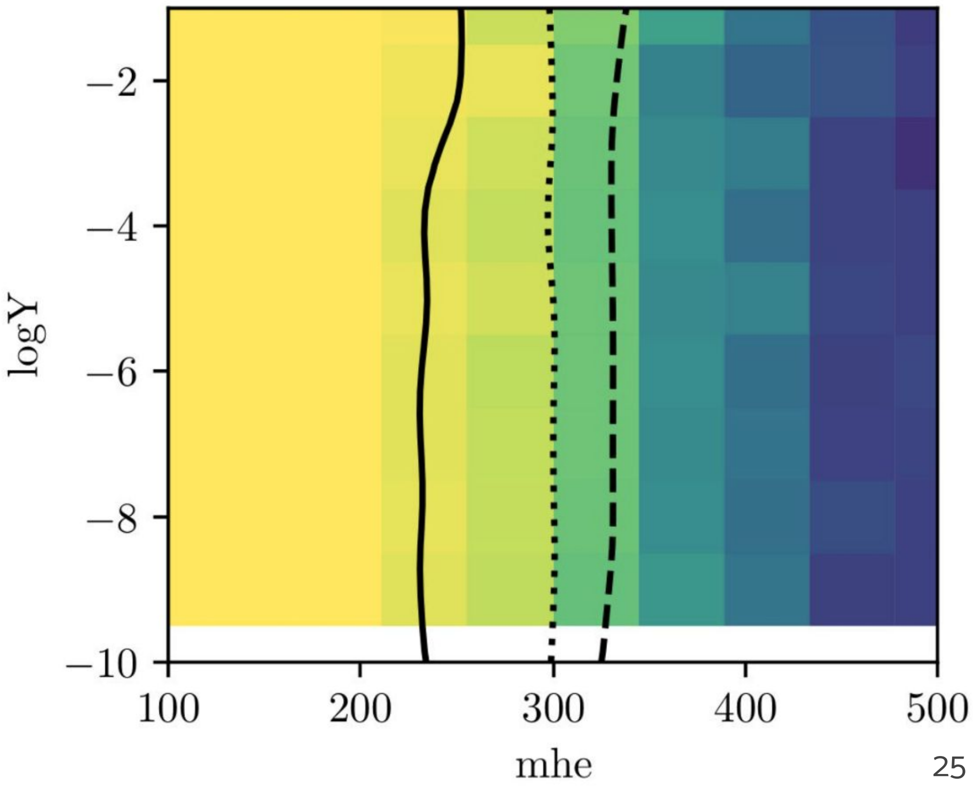


- **Generation** of events with a MCEG
- **Infers** effect of simulated events in LHC measurements
- Determine **regions** of parameter space that are **excluded**
- Luminosity artificially **increased** to match HL-LHC (optional)

Example

$$\mathcal{L} \supset \sum_{\ell} y_s^{\ell} \left(s\bar{F} \left(\frac{1+\gamma^5}{2} \right) \ell + \text{h.c.} \right)$$





03

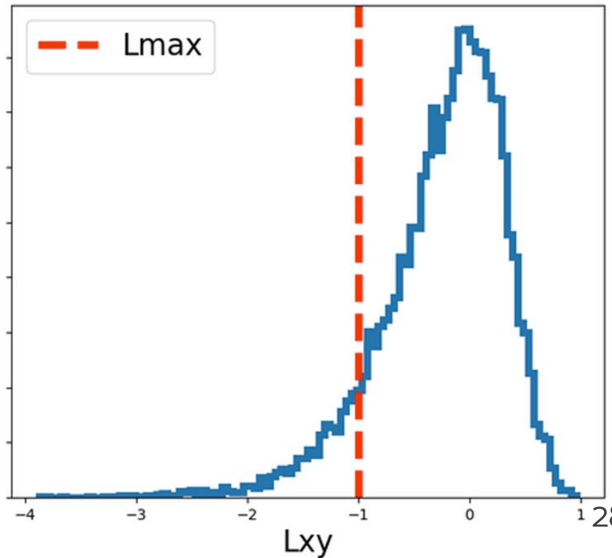
Long-lived particles

Long-lived particles (LLPs)

- Long lifetimes, opportunity to **explore** physics BSM
- May **escape** detection simply because they travel a considerable distance before decaying
- Need **dedicated** searches (take time)
- Crucial to understand DM (**weakly** interacting with visible matter)

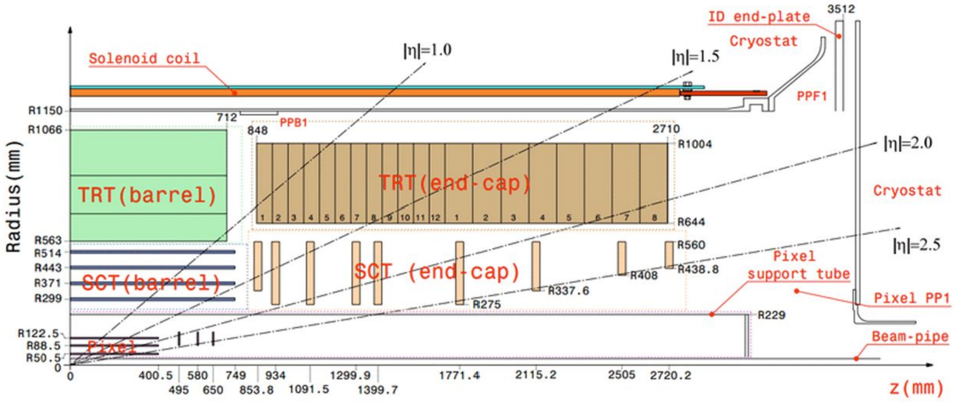
New approach to the LLPs study

- Check whether potentially long-lived particles might have **affected** prompt measurements
- QM: lifetime follows an **exponential** law
- **Scaling** of simulated events to retain only those that contain particles that decay **early enough** to leave a signature visible to the detector



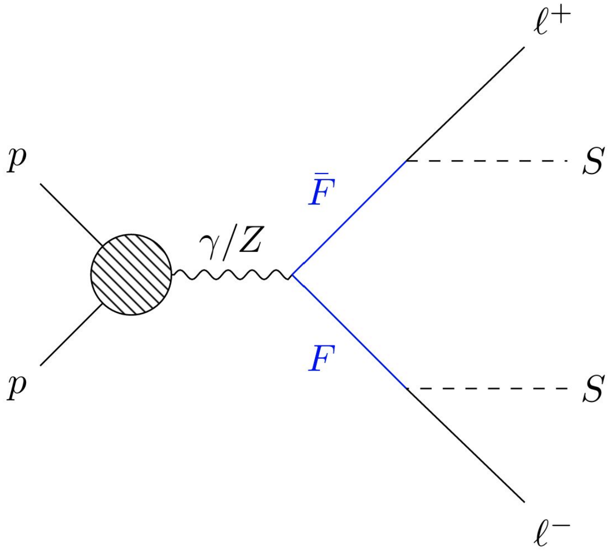
Naive implementation

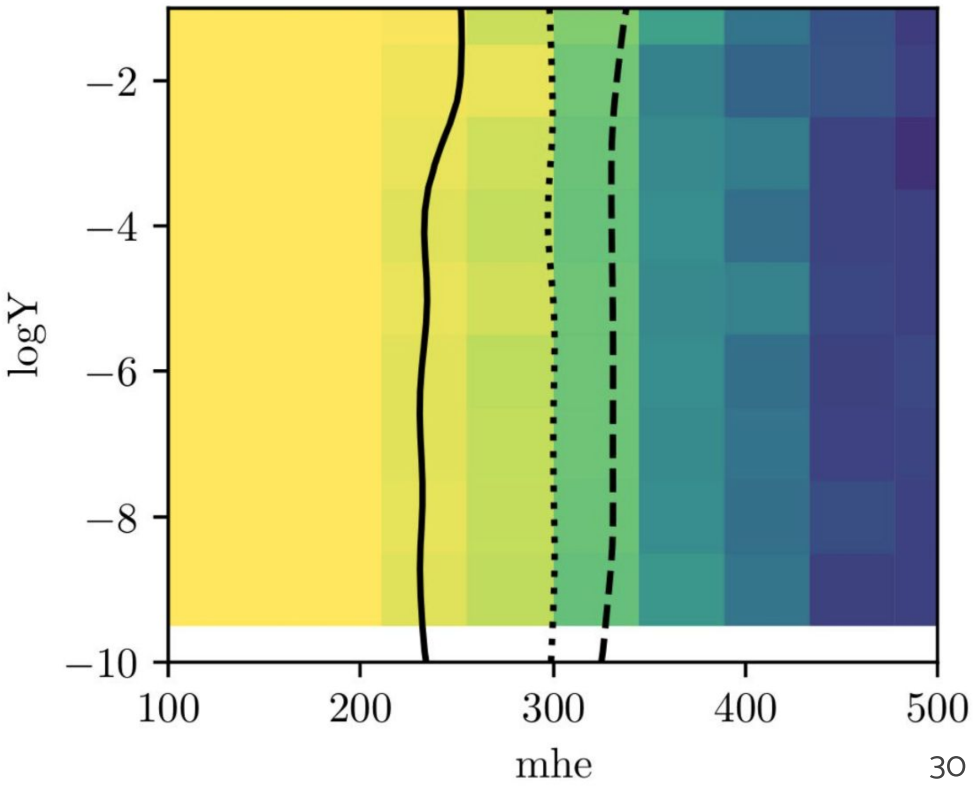
- Extract LLP **kinematics** for each event & compute a random **decay length**
- **Scale factor:** fraction of LLPs decaying **below** the prompt threshold (10cm/60cm)
- Histogram (YODA) file **scaled** for each parameter point in the scan



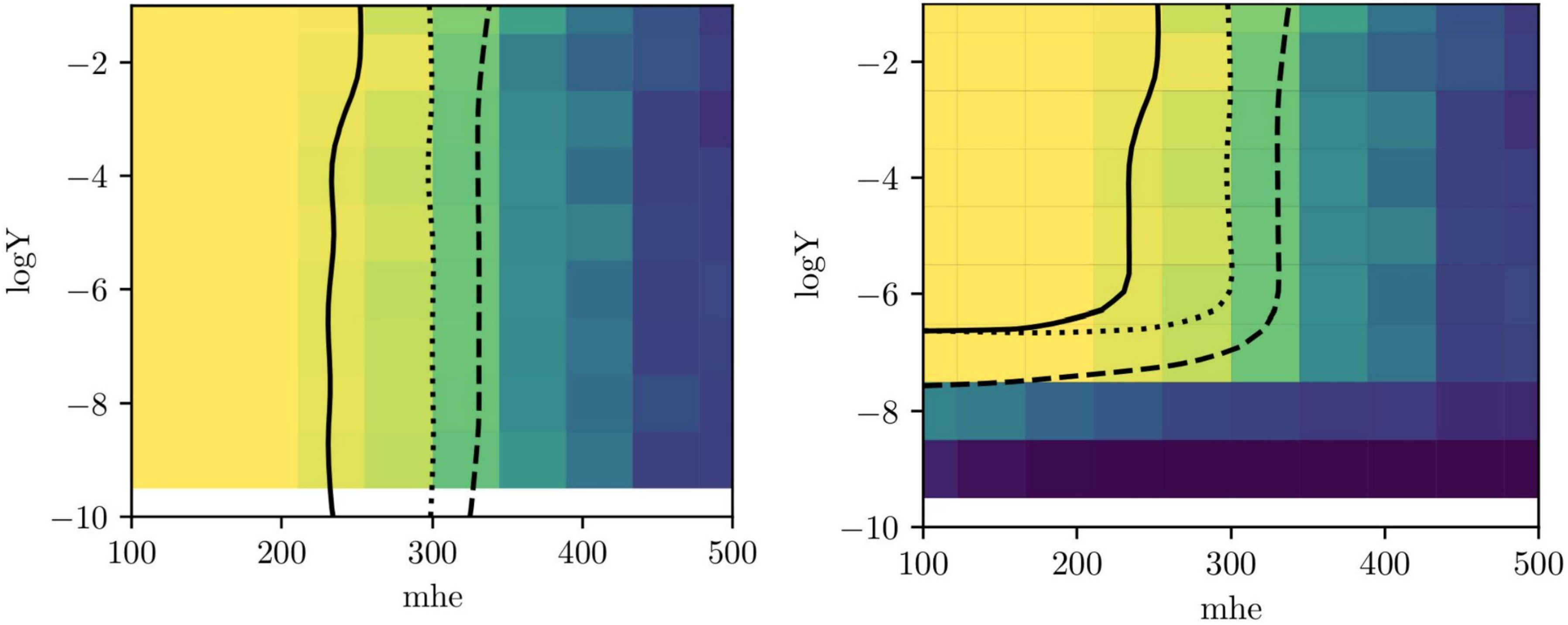
Recall of the freeze-in model

$$\mathcal{L} \supset \sum_{\ell} y_s^{\ell} \left(s\bar{F} \left(\frac{1+\gamma^5}{2} \right) \ell + \text{h.c.} \right)$$

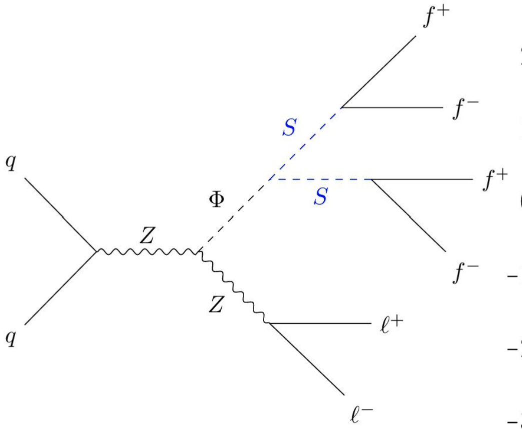


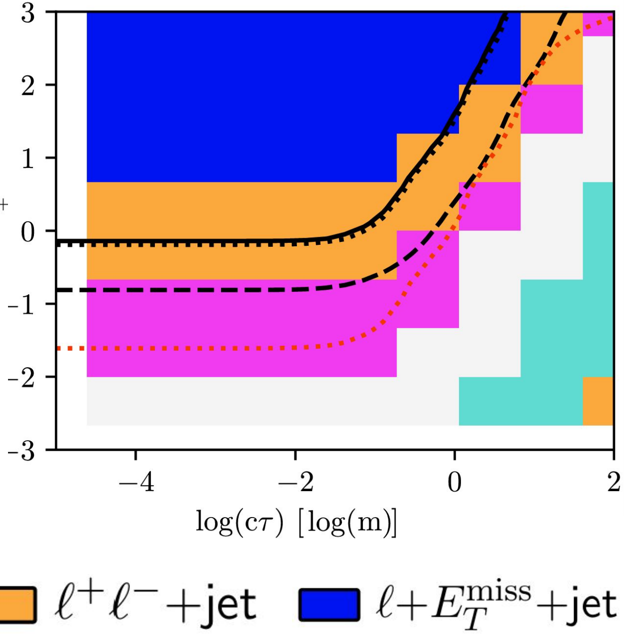


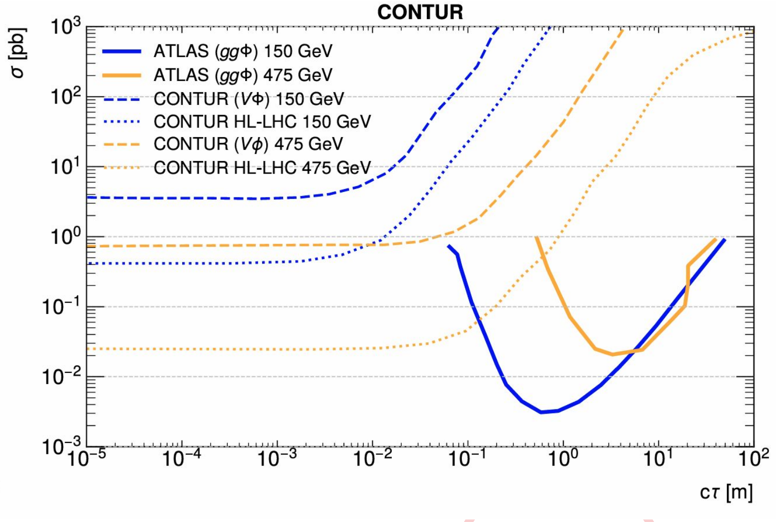
More reliable constraints



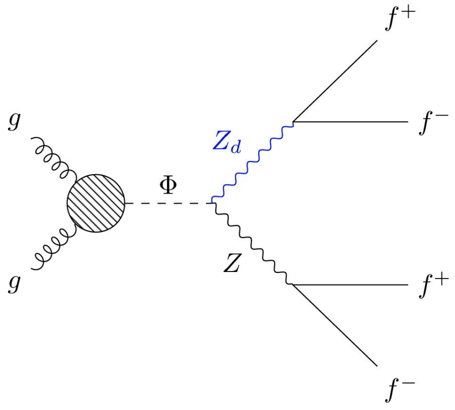
Probing models (HAHM)

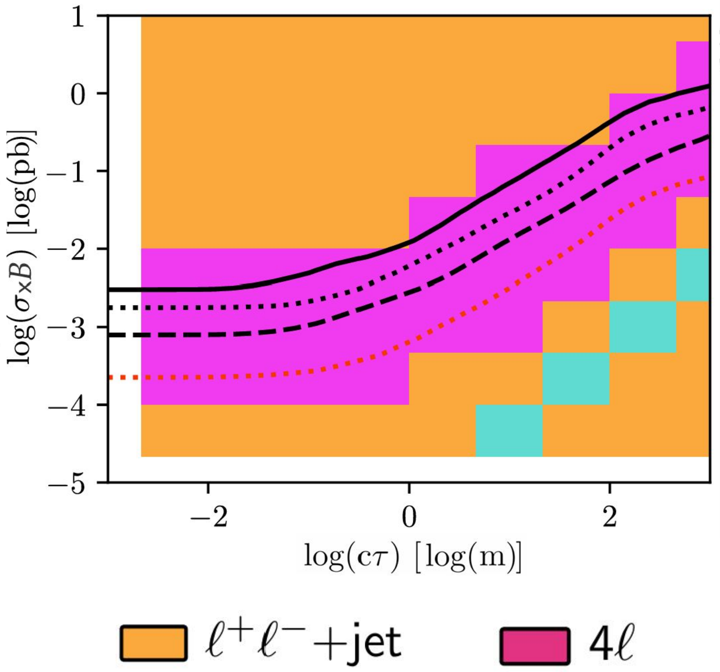


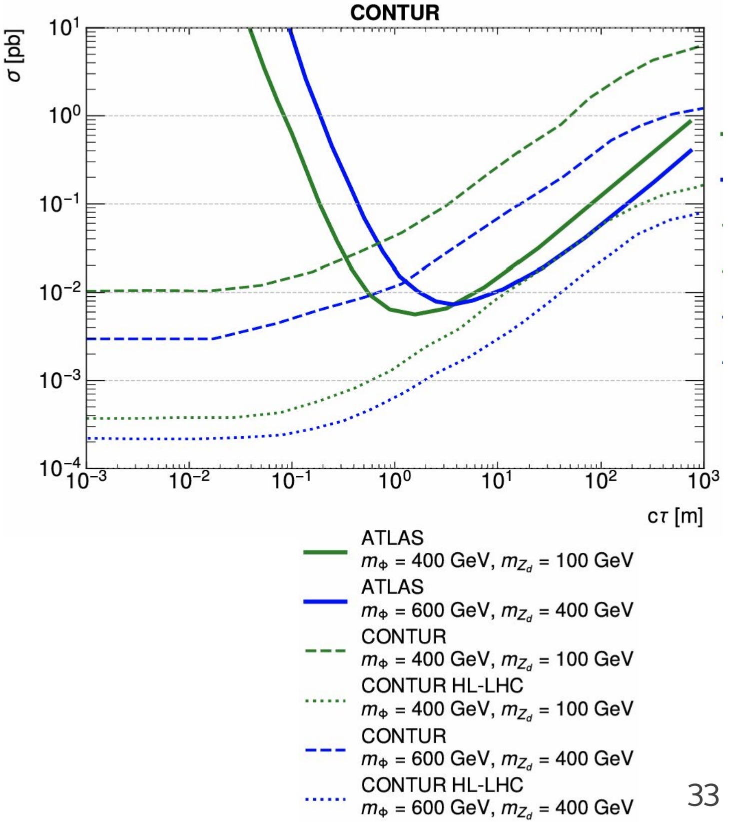




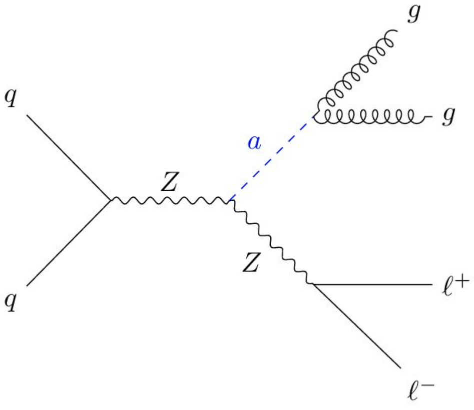
Probing models (Dark Photon)

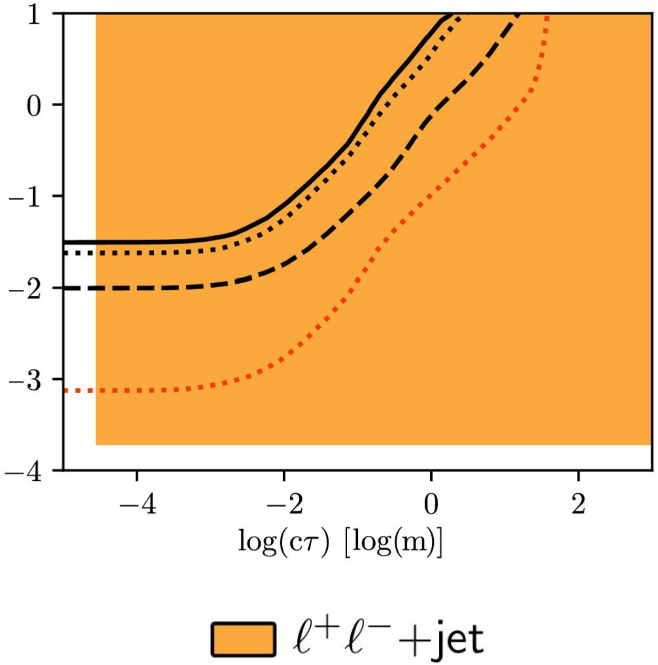


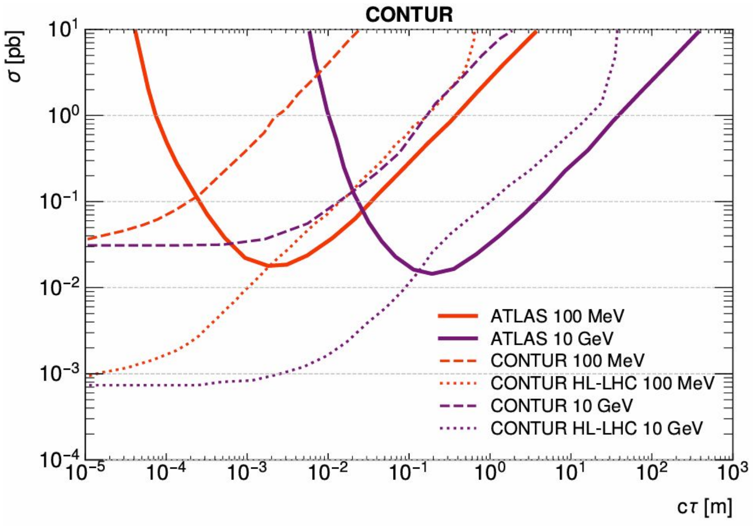




Probing models (ALPs)



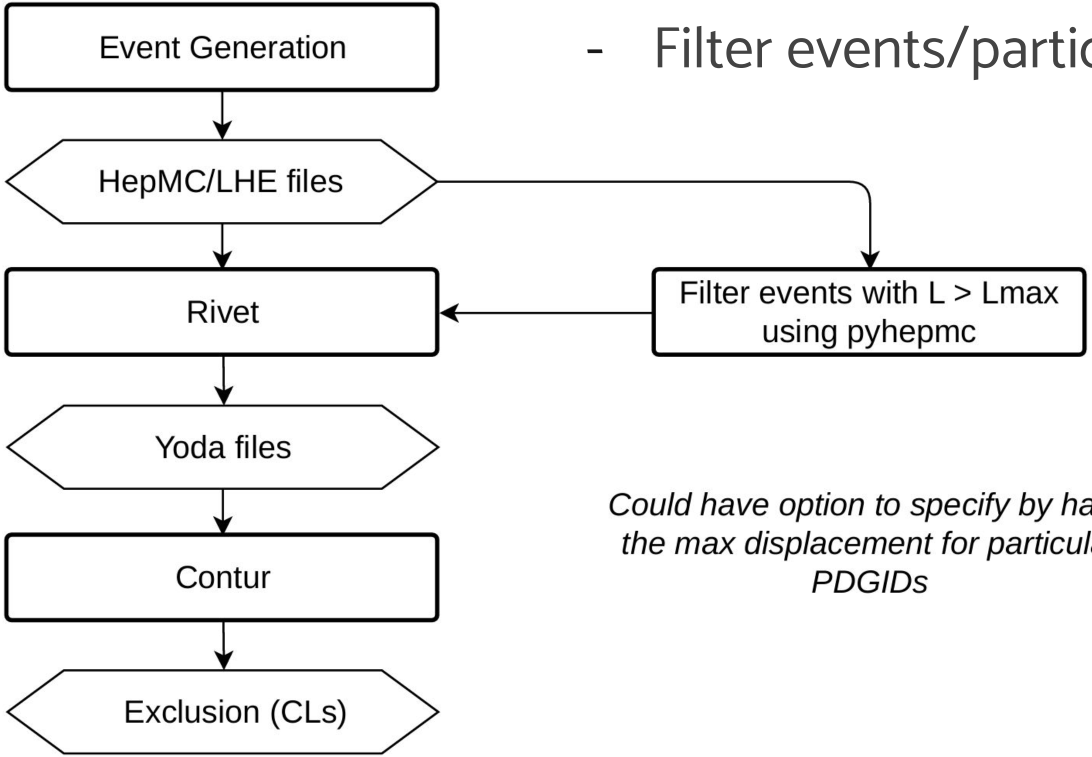




04

Conclusion & next steps

Improving the implementation

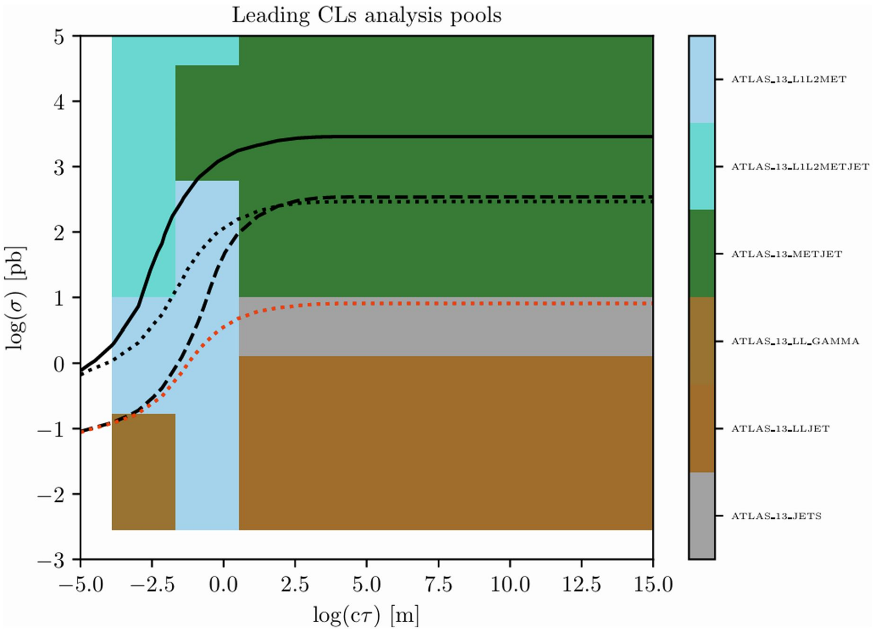


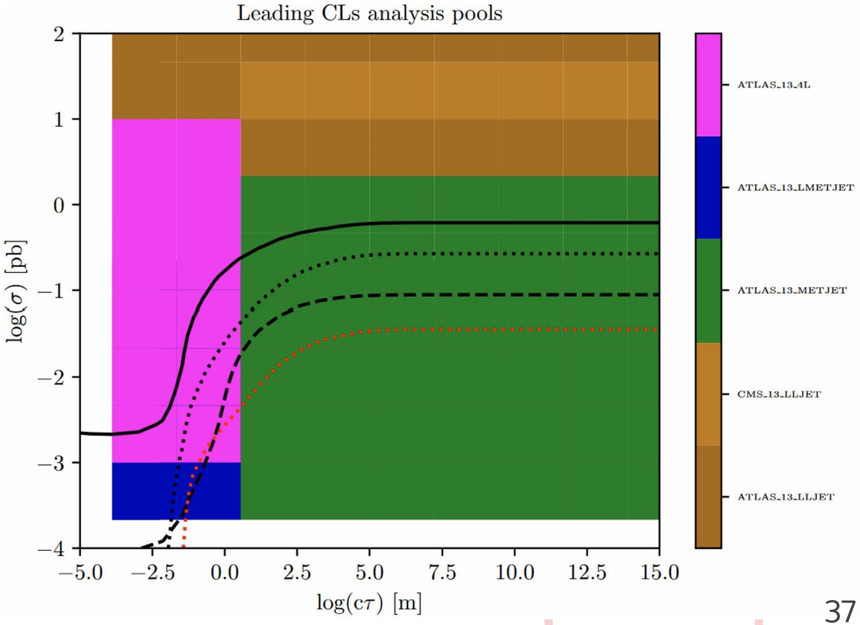
- Filter events/particles with pyhepmc

Could have option to specify by hand the max displacement for particular PDGIDs

Preliminary results

Freeze-in model / Dark Photon





Summary

- **CONTUR:** rethink research from a **theory-driven** approach to **data-driven** one
- Naive implementation of long-lived particles: **scale factor**
- First results are **promising**
- Can be **improved**, still some work to do

Thank you for your attention !

BACKUP

Evaluating a likelihood

- **DataBG:** using the **data** as the background
- **SMBG:** using **SM predictions** as the background
- **EXP:** expected limit, evaluated by moving the data central value to the SM prediction but **keeping** the uncertainties
- **HL-EXP:** expected limit but **reducing** the uncertainties by sqrt of lumi ratio to the projected HL-LHC