Dark Matter at colliders: Theory.

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Dark Matter.

- There is clear observational evidence of the existence of Dark Matter (DM) in gravitational interactions.

- DM could consist of particles that lie Beyond the Standard Model.

- If DM is a particle then it could be searched for at colliders!

- However, if there are several ways/models to incorporate DM into the SM, how can we test it in the LHC?
Dark Matter.

\[ \sim 100 \text{ GeV} \]

- Indirect Detection
- Thermal Freeze-Out

\[ \sim 200 \text{ MeV} \]

- Direct Detection

\[ \sim \text{TeV} \]

Production at colliders
This diagram is invisible to the detectors. Something should be used to tag the dark matter production.
We can make use of the initial state radiation. A SM particle is radiated so we can tag it and it can produce a balance in the transverse momentum.
In order to estimate the dark matter production we need input from theory.
Dark Matter description.

Complete models.

- MSSM
- 2HDM
- B-L
- Extra dimensions
- NMSSM

Simple.
Defined number of parameters.

Effective Field Theories
The EFT is not a good description usually in the regions where the EFT is valid.

$$\frac{g_q g_X}{Q^2 - M^2} = -\frac{g_q g_X}{M^2} \left( 1 + \frac{Q^2}{M^2} + O \left( \frac{Q^4}{M^4} \right) \right)$$

$$1 \overset{\Lambda^2}{=} \frac{g_q g_X}{M^2}$$

The EFT is not a good description.

$$Q^2 > \Lambda^2$$

$$\Gamma_{\text{med}} \geq M_{\text{med}}$$ usually in the regions where the EFT is valid.

(Fox, Harnik, Kopp, Tsai, 1109.4398)

(Buchmuller, Dolan, McCabe, 1308.6799)

(Buchmuller, Dolan, Malik, McCabe, 1407.8257)
Dark Matter description.

Complete models.

MSSM
2HDM    NMSSM
Others...    B-L
Extra dimensions

Simplified Models

Simple.
Defined number of parameters.

Effective Field Theories
Simplified Models.

- The presence of the mediator allows to cover all the parameter space.
- Additional signatures are present (searches for the mediator itself).
- It allows a better comparison with direct detection experiments.

(Buchmuller, Dolan, Malik, McCabe, 1407.8257)
(LHC Dark Matter Working Group, 1603.04156)
Simplified Models.

Mediator Nature: Vector, Axial-Vector, Scalar, Pseudoscalar

DM Nature: Dirac Fermion, Majorana Fermion, Real Scalar, Complex Scalar

Parameters of the model:
(minimum content)
- Mediator mass ($M_{\text{med}}$)
- DM mass ($M_{\text{DM}}$)
- SM coupling ($g_{\text{SM}}$)
- DM coupling ($g_{\text{DM}}$)
Mono-X searches.

Mono-jet

\[ q \xrightarrow{g} g_{q} \cdot g_{X} \cdot Z_{A} \cdot q \xrightarrow{g} \chi \]

Mono-photon

\[ q \xrightarrow{\gamma} g_{q} \cdot g_{X} \cdot \text{med} \cdot q \xrightarrow{\gamma} \chi \]

Mono-Z/W

\[ q \xrightarrow{W, Z} \cdot g_{q} \cdot g_{X} \cdot Z' \cdot q \xrightarrow{W, Z} \chi \]

(See Varum Sharma's talk)

Mono-top

\[ q \xrightarrow{u} u_{med} \cdot g_{u} \cdot v_{med} \cdot t \xrightarrow{t} \chi \]

Mono-Higgs

\[ q \xrightarrow{Z'} h \cdot g_{q} \cdot t \xrightarrow{t} \chi \]

(See Mariana Toscani's talk)
Mono-jet searches.

Complementarity between monojet and direct detection Dark Matter searches. (Buchmuller, Dolan, Malik, McCabe, 1407.8257)

Easy to compare with simplified models but also with complex models. (For example: Schwaller, Zurita 1312.7350)
Mono-jet searches.

Theory: Search recast available in CheckMate, MadAnalysis and Z’ Explorer 2.0 (soon).

One can also use DeepLearning to test against LHC data. (Arganda, Medina, Perez, Szynkman, 2105.12018)
Mediator searches (Z’).

Mediator searches in SM decays.

One can set limits on the mediator mass and its couplings to SM particles.

Dedicated searches to low mass and high mass regions.

(Low mass: see Silvio Donato’s talk)

(High mass: see Claudio Quaranta’s talk)

Direct comparison with the theoretical input.

(Z’ Explorer: Alvarez, Estevez, Sanda-Seoane, 2005.05194)
Mediator + Mono-X searches.

Vector Mediator

(ATLAS, 1903.01400)
Mediator + Mono-X searches.

Axial-Vector Mediator

(ATLAS, 1903.01400)
Collider vs. Direct Detection.

Complementarity:
- Collider searches:
  ~ Almost independent on DM mass.
  ~ Better performance for low DM masses.
- Direct detection searches:
  ~ Better performance for DM masses > 10 GeV.
- Complementarity between collider searches and direct detection searches

It is also possible to compare the limits against indirect detection searches. (Buchmuller, Malik, McCabe, Penning, 1505.07826)
Conclusions.

- If DM particle exists it could be produced in colliders.

- Collider searches for Dark Matter:
  ~ Complete models (SUSY, 2HDM, axions, etc)
  ~ UV model independent searches:
    * EFT: Physical limitations.
    * Simplified Models: Improvement over EFT, additional signatures, better comparison against other DM searches.

- Complementarity between colliders and direct detection.
  Collider searches present better performance at low DM masses.
Thank you!