Synergies between astroparticle, particle and nuclear physics

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Inputs and discussion:
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Outline

General motivations and visions of particle-astroparticle-nuclear physics

Concrete examples:

**New physics discoveries (dark matter)**
- How to discover new particles
- Complementarity of particle and astroparticle physics experiments
  - Weakly Interacting Massive Particles
  - The case of axion(-like) particles

**Handling large, heterogeneous amounts of data**
- LHC: direct and indirect searches for new physics
- Multimessenger astronomy (nuclear astrophysics)

Examples of ongoing synergistics initiatives

Conclusions and path forward

Much inspiration from EPPSU Granada talks, but also some (necessary) personal selection of topics
Astroparticle, particle and nuclear physics in Europe have **strategies and plans** that **recognize the importance of synergies** between the different fields.
Visions: APPEC, ECFA, NuPECC

Some of the **common scientific goals** in the strategy documents:

- Nature of dark matter and dark energy
- Fundamental forces & symmetries
- Properties of neutrinos at all energy scales
- Origin of elements
- Extreme states of matter
More synergies: ”foundations” for common challenges

Astroparticle

Particle

Nuclear

Common theory ground

instrumentation (accelerators, beams, detectors, vacuum & cryogenics, control & automation...)

data acquisition, computing, data sharing & open science

See C. De Los Heros’s talk @ EPSHEP'19
See J. Fiete’s talk @ EPSHEP'19
See I. Irastorza’s talk @ EPSHEP '19

See C. Biscari’s talk in this session
See A. Cattai’s talk in this session
See G. Stewart’s talk in this session
Example of a physics synergy: new physics (of Dark Matter)
A chart of measurements (and discoveries)

Many searches and measurements during first years of the LHC: mapping the Standard Model…

Image from University of Uppsala

Standard Model Total Production Cross Section Measurements

Status: March 2019

ATLAS Preliminary
Run 1.2 $\sqrt{s} = 7, 8, 13$ TeV

- Theory
- LHC pp $\sqrt{s} = 7$ TeV
- Data $4.5 - 4.6$ fb$^{-1}$
- LHC pp $\sqrt{s} = 8$ TeV
- Data $20.2 - 20.3$ fb$^{-1}$
- LHC pp $\sqrt{s} = 13$ TeV
- Data $3.2 - 79.8$ fb$^{-1}$

ATL-PHYS-PUB-2019-010
A chart of measurements (and discoveries)

Many searches and measurements during first years of the LHC: mapping the Standard Model…

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

...and a milestone discovery

Higgs
A chart of searches (and discoveries)

Discovery of the Higgs boson: guided by clues from the Standard Model of particle physics
After mapping the Standard Model, particle physics ventures into the unknown

See C. Grojean’s talk in this session
Expected and unexpected particle discoveries

The Standard Model of particle physics

Years from concept to discovery

Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON

Source: The Economist

The Economist
Expected and unexpected particle discoveries

The Standard Model of particle physics
Years from concept to discovery

- Electron
- Photon
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- Electron neutrino
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- Top
- Tau neutrino
- HIGGS BOSON

Source: The Economist

Particle physics discoveries require large instruments and time

https://cds.cern.ch/record/874049

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

The Economist
Expected and unexpected particle discoveries

Particle physics discoveries require large instruments and time

Where to look next?
Many open problems in astrophysics that need systematic approach to different discovery scenarios

The Economist
Empirical **problem** in the Standard Model of Particle Physics: no explanation for **Dark Matter**

One of the possible **solutions**, guided by **relic density**: invisible **Dark Matter particles** at the **TeV scale**

*(Weakly Interacting Massive Particles)*
Empirical **problem** in the Standard Model of Particle Physics: no explanation for **Dark Matter**

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*(Weakly Interacting Massive Particles)*

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**Complementary experimental strategies & inputs**
Collider, direct and indirect detection

Big Question at Granada symposium:
How will Direct and Indirect DM Detection experiments inform/guide accelerator searches and vice-versa?

• Why we need complementarity:
  • DD/ID can discover DM with cosmological origin

![Diagram](image)
Collider, direct and indirect detection

Big Question at Granada symposium:
How will Direct and Indirect DM Detection experiments inform/guide accelerator searches and vice-versa?

• Why we need complementarity:
  • DD/ID can discover DM with cosmological origin
  • Colliders can produce DM and probe the dark interaction
A simple example: scalar mediator between SM and DM

- Collider constraints on simple models of DM can be shown in terms of DM-nucleon interactions

\[ \sigma_{SI} \approx 6.9 \times 10^{-43} \text{ cm}^2 \cdot \left( \frac{g_{DM}}{g_{SM,f}} \right)^2 \left( \frac{125 \text{ GeV}}{M_{\text{med}}} \right)^4 \left( \frac{\mu_{\chi}}{1 \text{ GeV}} \right)^2 \]


Collider limits at 95% CL, direct detection limits at 90% CL

Preliminary, Granada May 2019

Scalar model, Dirac DM
\[ g_{DM} = 1, \ g_{SM,f} = 1 \]

Collider limits at 95% CL, direct detection limits at 90% CL
A simple example: scalar mediator between SM and DM

- Collider constraints on simple models of DM can be shown in terms of DM-nucleon interactions

\[ \sigma_{SI} \approx 6.9 \times 10^{-43} \text{ cm}^2 \left( \frac{g_D g_{DM}}{1} \right)^2 \left( \frac{125 \text{ GeV}}{M_{med}} \right)^4 \left( \frac{\mu_{\chi}}{1 \text{ GeV}} \right)^2 \]

Keep in mind: these plots are only valid for the couplings specified, in the limited space of a benchmark model!
Synergy: complementary reach for future colliders and direct detection

- **Collider discovery** of invisible particle needs **confirmation of cosmological origin** from DD/DD
- **DD/DD discovery** needs collider **understanding of nature of interaction**
- **A future collider program** that increases sensitivity to invisible particles **coherently with DD/DD** serves these purposes

- Synergies with also in non-WIMP DM, for DD and beam dump experiments

See V. Dutta's talk @ EPSHEP'19
See S. Stapnes's talk @ EPSHEP'19
Introduction  Synergies in: New particles and Data Handling  Initiatives and way forward

What if DM isn’t a WIMP?

Axions/Axion-Like Particles (ALPs):
example of new particle with inter-field connections

also using nuclear physics experiments (EDM rings)

Synergies beneficial for many smaller experiments:
from joint expertise and common discussion platforms

See C. Vallee's talk in this session

Figures taken From I. Irastorza's talk @ EPSHEP '19
Synergies in dark matter searches

Huge progress planned for **direct and indirect detection** for **WIMP DM**

**Future colliders and experiments** can follow:

essential **complementarity** between

**cosmological origin**
astrophysics

**nature of the DM-SM interaction**
particle physics

Similarly, **combination of complementary experiments + theory** needed to identify nature of DM in case of **non-WIMP DM**

How to **strengthen common foundations**?
Many **common challenges**, e.g.
particle detectors and instrumentation,
strategies to handle large amounts of data
Example of a common challenge: analysis of large, complex datasets
Enabling discoveries in particle physics

- Many different theories can explain particle physics shortcomings
- None of these theories is yet favored by data
- Very different signatures in the detector
- Some signals buried in high-rate backgrounds
Enabling discoveries in particle physics

- Many different theories can explain **particle physics** shortcomings
- None of these theories is yet favored by data
- Very different signatures in the detector
  - Some signals buried in **high-rate backgrounds**
  - Some signals **very unusual but rare**

See e.g. C. Ohm's talk @ EPSHEP'19

https://arxiv.org/abs/1810.12602
Enabling discoveries in particle physics

- Many different theories can explain particle physics shortcomings
- None of these theories is yet favored by data
- Very different signatures in the detector

**A key challenge:** within millions p-p collisions/second, select/analyze the interesting ones in real time

LHC data volumes after selection of “interesting” data

See G. Stewart’s talk in this session
The advent of Multimessenger astronomy

• Revolutionary combination of information on the cosmos
• Simultaneous detection of astrophysics events
  • “highly heterogeneous, high-volume, high-velocity datasets”

T. Montaruli, International Workshop on Neutrino Telescopes
The advent of Multimessenger astronomy

- Revolutionary combination of information on the cosmos
- Simultaneous detection of astrophysics events
  - “highly heterogeneous, high-volume, high-velocity datasets”

A key challenge: fast follow-up of interesting events with higher resolution instruments

Light from neutron star mergers can shed light on cosmic origin of heavy elements
Extremely large datasets, in different contexts

C. Fitzpatrick, **LHCb**

E. Bellm, **Large Synoptic Survey Telescope**

The LHC and modern astrophysics surveys are **data firehoses**

Can benefit from **common techniques and tools for data taking & data reduction** (e.g. on-detector / real-time data analysis, machine learning) with applications beyond physics research
Synergy initiatives and outlook
Introduction  Synergies in: New particles and Data Handling  Initiatives and way forward

A constellation of activities and initiatives

Astroparticle  Particle  Nuclear

**CERN Neutrino Platform**

- *About Dark Machines*
  - Dark Machines is a research collective of physicists and data scientists. We are curious about the universe and want to answer cutting edge questions about Dark Matter with the most advanced techniques that data science provide us with.

**LHC Dark Matter Working Group**

- **European Center for Astroparticle Theory (EuCAPT)**

Common theory ground

**instrumentation**
- accelerators, beams, detectors, vacuum & cryogenics, control & automation...

**data acquisition, computing, data sharing & open science**

**APPEC news**, after Granada ‘19: wish to enhance collaboration and discussion between LHC DMWG and DD/ID

Direct Detection collaborations input to EPPSU: strengthen common efforts

**APPEC input to EPPSU**: taking off in 2019 with CERN as first 5-year host

Caterina Doglioni - 2019/07/13 - Joint EPS-ECFA session
Conclusions and outlook

- Answering fundamental physics questions requires **concerted work** from **particle, astroparticle and nuclear physics**
  - Examples: dark matter (in this talk), neutrino physics...
  - Common challenges in terms of foundations (detector, computing...)
- A number of **synergistic initiatives** exist, many **hosted by CERN**
  - What is the best way forward? Discussion started at Granada meeting
- More discussion at the **APPEC-ECFA-NuPECC meeting** in Orsay this October

Thank you for your attention!