

# Theoretical particle physics, phenomenology, and cosmology

Gauthier Durieux

(FNRS research associate & UCLouvain professor)



IRMP

 UCLouvain

**fnrs**  
LA LIBERTÉ DE CHERCHER

## 12 PhD's



Mubarak  
Abdallah

Tommaso  
Armadillo

Baptiste  
Blachier

Clémentine  
Dassy

Yannis  
Georis

Matteo  
Maltoni

Daniele  
Massaro

Guillaume  
Suchet-  
Bernard

Simone  
Tentori

Julien  
Touchèque

Ze-Qiang  
Wang

Valentin  
Weber

## 6 postdocs



Pierre  
Auclair

Hao-Lin  
Li

Isabel  
Oldengott

Shahram  
Vatani

Ramon  
Winterhalder

Sebastian  
Zell

## 4 + 3 part-time staff members



Chiara  
Arina

Céline  
Degrande

Marco  
Drewes

Gauthier  
Durieux

Fabio  
Maltoni

Olivier  
Mattelaer

Christophe  
Ringeval

## 2 emeriti



Jean-Marc  
Gérard

Jan  
Govaerts

What are the fundamental particles  
and interactions?

What phenomena do they lead to?

How did the universe evolve into  
what we observe today?

# New precision in cosmology

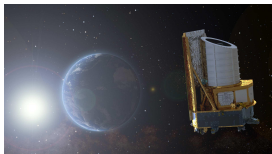
## Unprecedented galaxy surveys

DESI:



- started in May 2021, 5y operation
- 40M galaxies and quasars
- validation data released last June, first-year data analyses just out

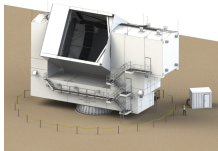
Euclid:



- launched in July 2023, 6y operation
- 1.2m diameter mirror (half Hubble)  
600M pixels in visible, 65M in near-IR
- 36% sky, redshift  $\leq 2$
- 10B sources, 1B for weak lensing,  
30M with spectroscopic redshift

## Next-generation CMB measurements

CMB-S4:



- in R&D, 7y operation from  $\sim 2030$
- Atacama Desert and South Pole sites
- improved small scales and polarisation
- $\Delta N_{\text{eff}} < 0.06$  notably targeted

# Cosmology, Universe and Relativity at Louvain

## Current members



Baptiste Blachier  
(PhD FNRS)



Pierre Auclair  
(postdoc ARC+ESA)



Christophe Ringeval  
(academic, teaching 165 h/y)

## Research topics (2017-2022)

- Cosmic Inflation: slow-roll, strong quantum effects, model comparison & data analysis, numerical General Relativity (GRChombo)
- Cosmic Strings & Gravitational Waves (LISA, EPTA, theory predictions)
- CMB & Large Scale Structures, Belgian Euclid Science Exploitation

## Publications (2017-2022)

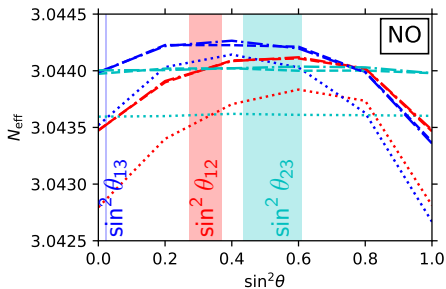
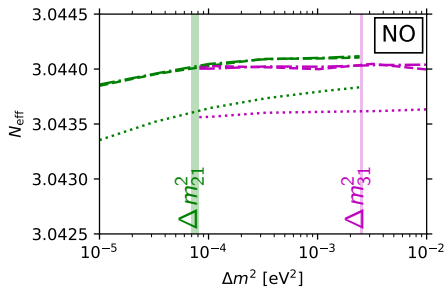
- $\sim 40$  papers: <https://curl.irmp.ucl.ac.be/publications.html>

$$N_{\text{eff}}^{\text{SM}} = 3.0440 \pm 0.0002$$

used in PDG, CAMB and CLASS codes, large collaborations like DES, DESI, etc.

Includes finite temperature corrections at NLO in QED,  
larger than neutrino oscillation effects.

Includes (subdominant) uncertainties on the oscillation parameters.



# Dark matter phenomenology made easy

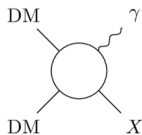
Relic density, direct and indirect detection with MadGraph



MadDM v3

[Arina, Maltoni, Mattelaer et al. '18]

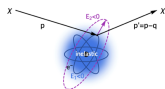
indirect det. from tree-level 2-to- $n$  annihilation  
model parameter sampling (scans, MultiNest)



MadDM v3.2

[Arina, Heisig, Massaro, Maltoni, Mattelaer '21]

automatised loop-induced direct detection ( $\gamma$ -ray lines)



MadDM v4

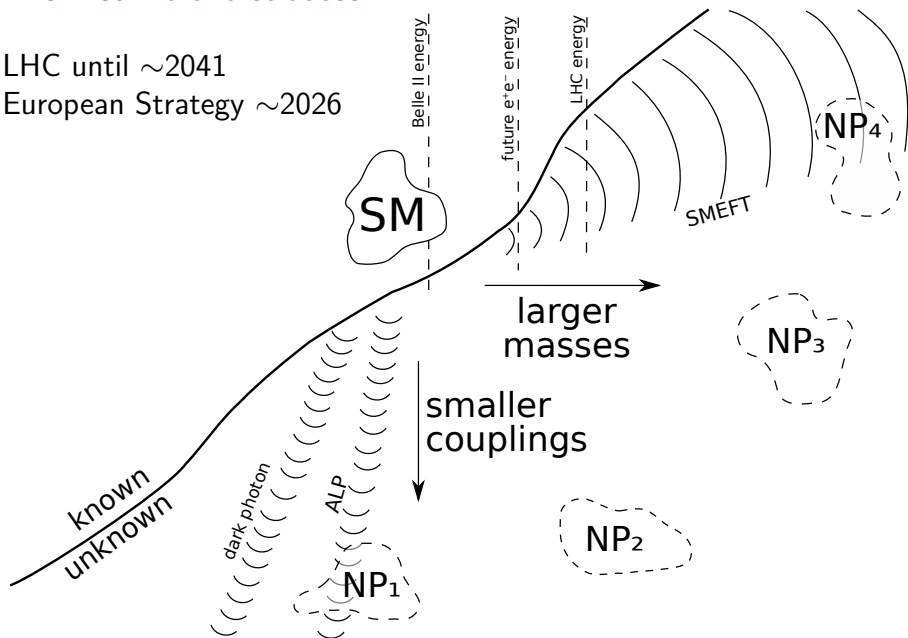
[Arina, Massaro, Maltoni, Mattelaer et al., in progress]

direct detection from electron scattering (unique!)  
energy spectra and anti-deuteron fluxes in indirect det.

# SM's insufficient success

LHC until  $\sim 2041$

European Strategy  $\sim 2026$

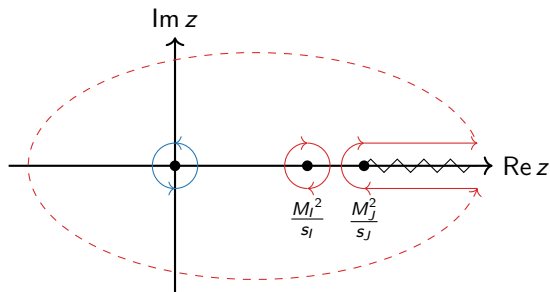




# Connecting low and high energies

New heavy particles can effectively be described at low energies  
by new interactions between known particles

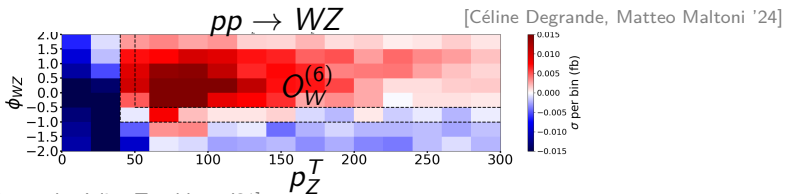
These low-energy interactions can be determined from the analytic  
structure of the high-energy scattering amplitudes



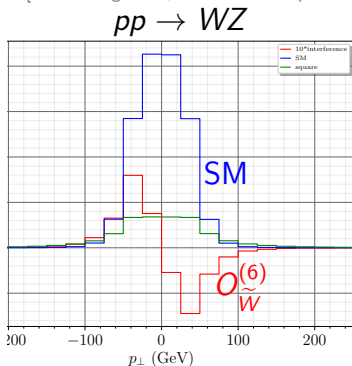
$$\text{Res}_{z=0} \frac{\hat{\mathcal{F}}^{\text{low}}(z)}{z^{n+1}} = c_n \text{poly}_n(s_K) = \left[ \sum \text{Res} + \int \text{Disc} + \int_{\infty} \right] \frac{\hat{\mathcal{F}}^{\text{high}}(z)}{z^{n+1}}$$

# More sensitive probes for new low-energy interactions

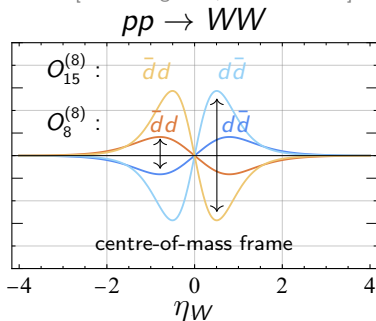
Avoiding signal cancellations, including better predictions



[Céline Degrande, Julien Touch  que '21]

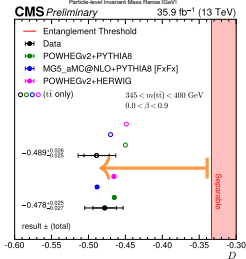
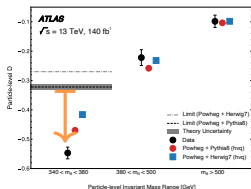


[Céline Degrande, Hao-Lin Li '23]



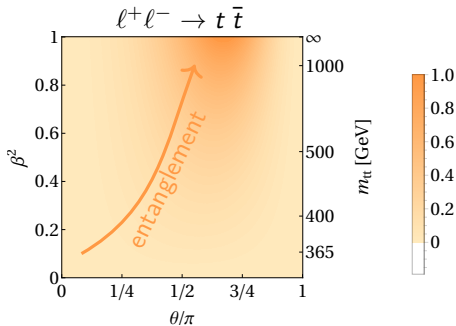
# Quantumness at high energies

Accessing genuine *quantumness* is challenging!  
We had not probed that regime yet.



Spin entanglement  
observed in  $pp \rightarrow t\bar{t}$ !

[Fabio Maltoni, Simone Tentori, et al. '24, '24]



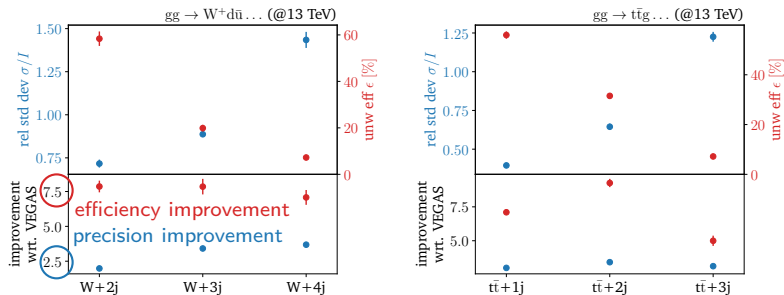
Much more ongoing!

# Better collider simulation

MadGraph is one of the leading collider simulation tools.

Recent machine-learning developments for numerical integration: MadNIS

Reduced prediction uncertainties and improved simulation efficiency



[Fabio Maltoni, Olivier Mattelaer, Ramon Winterhalder, et al. '22, '23]

Rich continuum of theory activities  
between particle physics  
and cosmology!

Extras

# Former PhD's (2017-22)

1. Federico Demartin, *Higgs boson interaction with the top quark: CP properties at the LHC* (Fabio Maltoni, 24/02/2017)
2. Ioannis Tsinikos, *Precision top-quark physics at the LHC* (Fabio Maltoni, 03/07/2017) → postdoc in Munich+Lund, now outside academia
3. Elvira Cervero Garcia, *Minimal Flavour Violation in a custodial Two Higgs Doublet Model* (Jean-Marc Gérard, 07/07/2017)
4. Benoît Hespel, *Loop-induced production of scalar particles in the Two-Higgs-Doublet Model at the LHC* (Fabio Maltoni, Jean-Marc Gérard, 04/09/2017)
5. Nicolas Deutschmann, *Precision calculations in effective theories for Higgs production* (Fabio Maltoni, Aldo Deandrea, 08/09/2017) → postdoc at ETH, now outside academia
6. Antony Martini, *Dark matter searches in the context of simplified models* (Fabio Maltoni, 15/09/2017)
7. Bram Verbeek, *Transcendental weight in supersymmetric field theories* (Claude Duhr, 21/08/2019) → postdoc Uppsala
8. Zhengwen Liu, *Novel aspects of scattering equations* (Claude Duhr, 22/08/2019) → postdocs at DESY, junior Niels Bohr
9. Robin Marzucca, *Novel paths from special functions to scattering amplitudes* (Claude Duhr, 23/08/2019) → postdocs at Niels Bohr, and Zurich
10. Martin Michel, *Quadruple splitting functions in QCD* (Claude Duhr, Fabio Maltoni, 25/08/2020)
11. Gilles Buldgen, *Quantum and thermal effects on inflation and neutrino dynamics in the early Universe* (Marco Drewes, Fabio Maltoni, 25/08/2020)
12. Philipp Klose, *Aspects of bottom-up hidden sector models* (Jean-Marc Gérard, Chiara Arina, 27/08/2020) → postdocs in Bern, and Bielefeld
13. Xiaoran Zhao, *Probing the Higgs potential at current and future colliders* (Fabio Maltoni, 18/09/2020) → postdoc in Rome III
14. Luca Mantani, *Searches for new interactions within the SMEFT framework at present and future colliders* (Fabio Maltoni, 02/08/2021) → postdoc in Cambridge, MSCA PF in Valencia next fall
15. Cristian Joana Velasco, *Cosmic inhomogeneities in the early universe : a numerical relativity approach* (Christophe Ringeval, Sébastien Clesse, 22/12/2022) → postdoc in Beijing
16. Andres Vasquez Tocola, *New physics probes through loop computation in effective theories* (Celine Degrande, Rogerio Rosenfeld, 22/12/2022) → postdoc in Bohn

## Former postdocs (2017-22)

1. Samuel Abreu (2018-21) → staff at CERN and Edimburgh
2. Wen-Yuan Ai (2019-21) → postdoc at Kings
3. Rafael Aoude (2020-23) → postdoc in Edimburgh
4. Matteo Becchetti (2018-20) → postdocs in Turin, and Bologna
5. Ankit Beniwal (2019-21) → postdoc at King's
6. Disrael Camargo Neves da Cunha (2019-22)
7. Marina Cermeño (2019-22) → postdoc in Madrid
8. Garv Chauhan (2021-22) → postdoc at Virginia Tech
9. Andrew Cheek (2019-21) → postdoc in Warsaw
10. Sébastien Clesse (2017-20) → staff in Brussels
11. Drazen Glavan (2019-20) → postdoc in Prague
12. Jan Hajer (2017-21) → postdocs in Basel, and Lisbon
13. Jan Heisig (2018-22) → postdocs in Virginia, and Aachen
14. Juraj Klarić (2021-23) → postdoc in Amsterdam/Nikhef
15. Jamie McDonald (2020-23) → postdoc in Manchester
16. Ken Mimasu (2016-20) → postdoc at Kings, staff in Southampton
17. Liam Moore (2016-18)
18. Richard Ruiz (2018-20) → postdoc, then staff in Cracow
19. Ambresh Shivaji (2016-18) → staff in IISER
20. Sandro Vitenti (2017-18) → staff at Londrina
21. ...



# Joint activities with experiments

- MadGraph hardware acceleration with CERN IT (Olivier Mattelaer) [github]
- ARC on gravitational waves (Christophe Ringeval, Giacomo Bruno)
- Long-lived particles in heavy ion collisions (Marco Drewes, Andrea Giammanco) '18, '19
- Heavy neutral leptons in NA62 (Marco Drewes, Jan Hajer, Juraj Klarić) '18
- ATLAS  $pp \rightarrow t\bar{t}t\bar{t}$  observation (Gauthier Durieux) '23
- LHC Higgs WG · Fabio Maltoni (steering committee 2014-16)
  - 31 UCLouvain contributions on Indico
- LHC EW WG · Céline Degrande (multiboson convener 2020-present)
  - 11 UCLouvain contributions on Indico
- LHC TOP WG · Fabio Maltoni (convener 2021-present)
  - 15 UCLouvain contributions on Indico
- LHC EFT WG · Céline Degrande (founding convener 2020-22)
  - Gauthier Durieux (founding convener 2020-24)
  - 6 UCLouvain contributions on Indico
- LHC DM WG · 10 UCLouvain contributions on Indico
- LHC ML WG · 31 UCLouvain contributions on Indico
- Physics Beyond Colliders · 4 UCLouvain contributions on Indico
- ECFA, FCC, MuCol, ...