Part II

Lepton sector: lepton flavours and massive ν

Lepton flavours: from ν oscillations...

SM lepton sector: (strictly) **massless neutrinos**
conservation of lepton flavours and total lepton number
tiny leptonic **EDMs** (4-loop... $d_e^{\text{CKM}} \leq 10^{-38} e$ cm)

Confirmation of **neutrino oscillations** - clear **departure from the SM**

⇒ first "laboratory" observation of New Physics!

⇒ **neutrinos are massive** and (neutral) **lepton flavours** are **not conserved!**

NuFIT 5.0 (2020)

		Normal Ordering (best fit)	
		bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$
	$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$
	$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$
	$\delta_{\text{CP}}/^\circ$	195^{+51}_{-25}	$107 \to 403$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$

Comprehensive experimental programme (world-wide) "precision"-measurements

But much remains **to be clarified:** θ_{23} octant, δ_{CP}, absolute mass scale & ordering and ν nature (Dirac vs Majorana), ...

Lepton flavours: from ν oscillations... (2)

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Comprehensive experimental programme (world-wide) "precision"-measurements

But much remains **to be clarified:** θ_{23} octant, δ_{CP}, absolute mass scale & ordering and ν nature (Dirac vs Majorana), ...

⇒ **Theoretical developments** in close proximity with **Super-K, Hyper-K, JUNO, DUNE**

@ IN2P3: M.C. Volpe (APC, JUNO collaboration)

⇒ **EFT** approach to **nuclear β-decays** (determination of m_β)

@ IN2P3: A. Falkowski (IJCLab)

Lepton flavours: from ν oscillations... (3)

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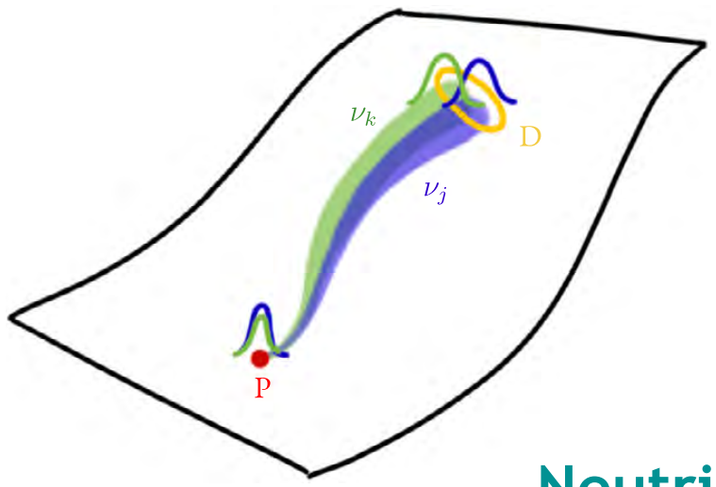


[1906.12152]

But much remains **to be clarified:** θ_{23} octant, δ_{CP}, absolute mass scale & ordering and ν nature (Dirac vs Majorana), ...

And **full characterisation of neutrino properties:**
standard and non-standard **interactions**, **propagation** in (dense) media, effects of **gravitation**...

Neutrino decoherence effects and **strong gravitational fields**
(wave packet separation in curved space-time)
Role of **wave packet decoherence** in (suppressing) **flavour evolution?**
Impact for **supernovae neutrino dynamics?**

@ IN2P3: M.C. Volpe (APC)

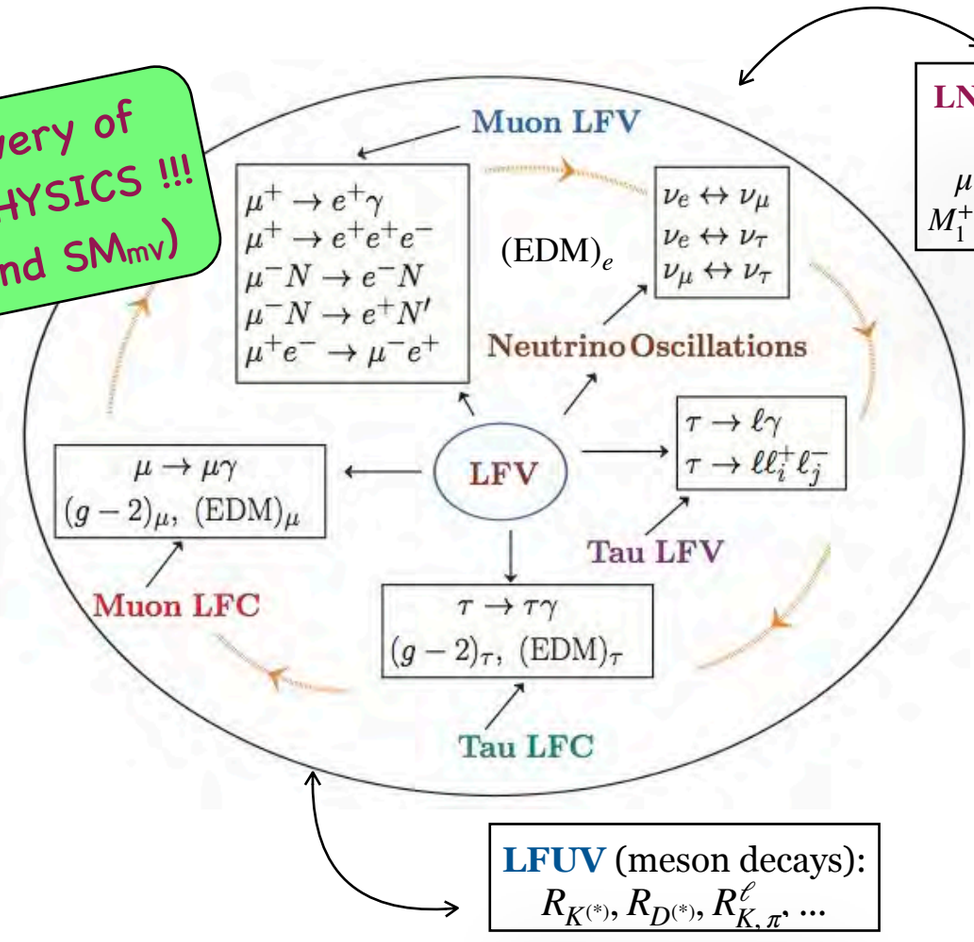
(Charged) lepton flavours & BSM

ν oscillations: **violation** of L_α and (if **Majorana** neutrinos!) non-conservation of L_{tot}

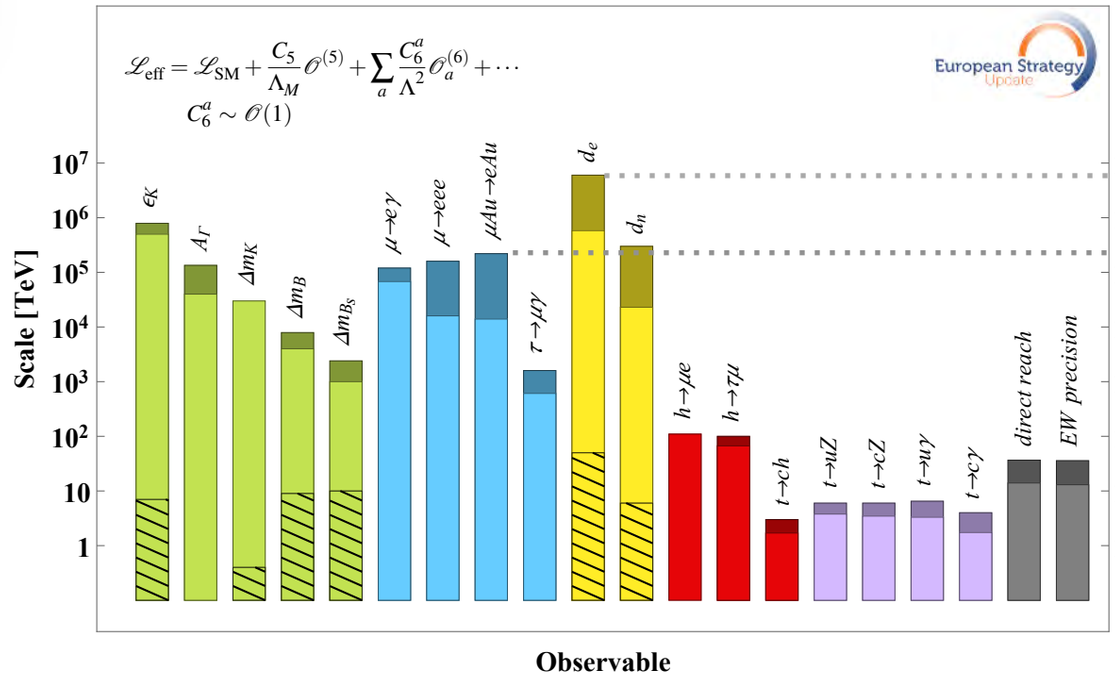
$\Rightarrow$ charged lepton flavour violation (cLFV), lepton number violation (LNV)

new contributions to CP violating electric dipole moments (EDMs), ...

Discovery of NEW PHYSICS !!! (beyond SM$_{m\nu}$)



... possibly (but not necessarily!) in relation to ν mass generation...



Very **sensitive & powerful probes** of new physics @ intensity frontier!

$\Lambda_{NP} \sim \mathcal{O}(10^{5-7}\ \text{TeV})$ **beyond direct collider reach!**

@ IN2P3: A. Abada (IJCLab), S. Davidson (LUPM),
A.M. Teixeira (LPC, COMET collaboration)

Lepton flavours: cLFV in the $\mu - e$ sector

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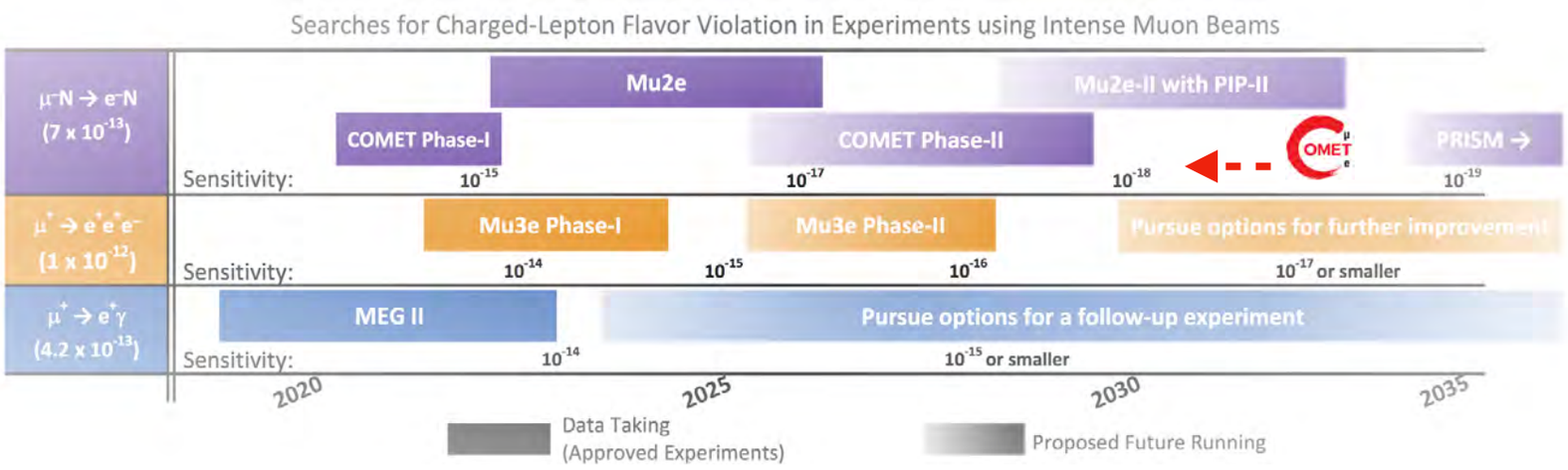
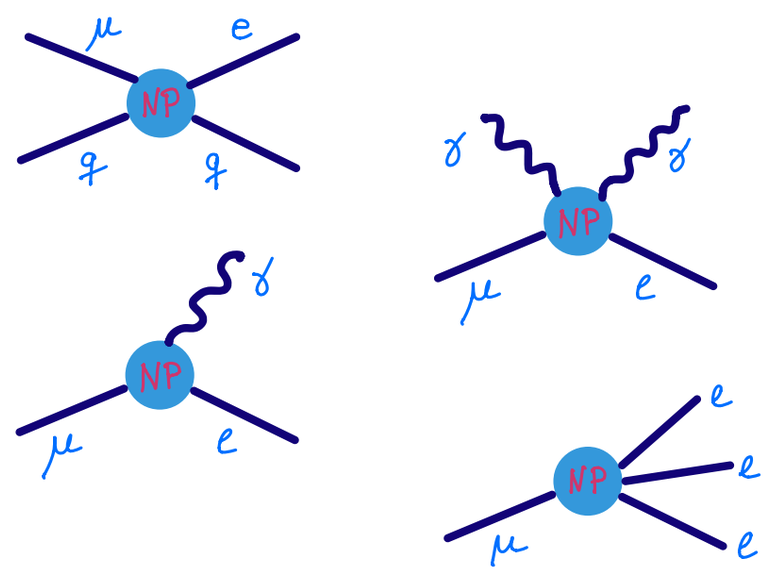
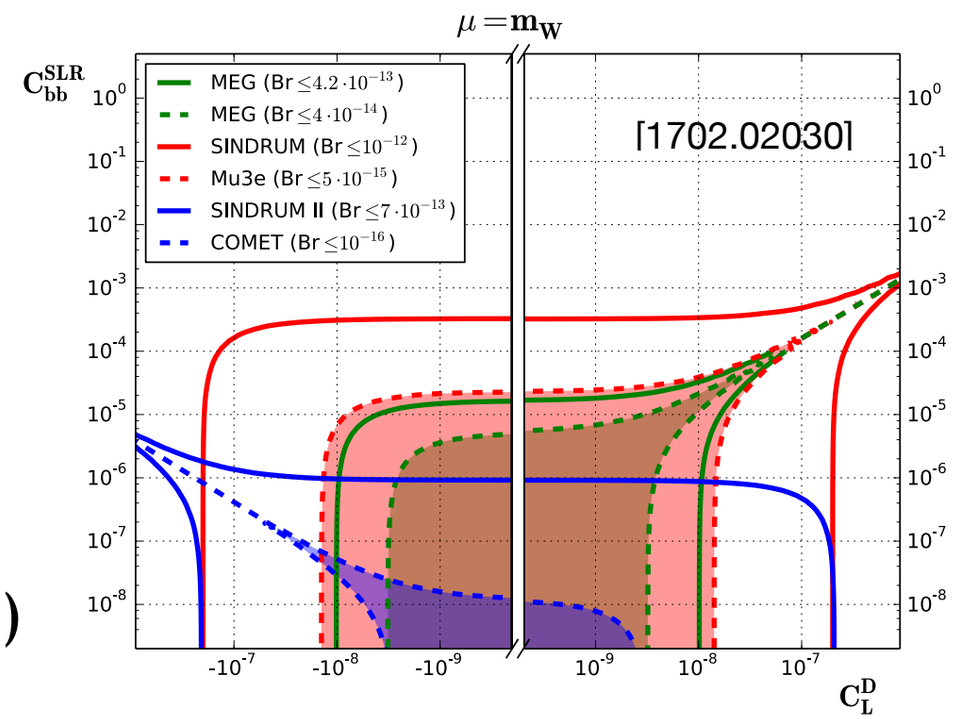
cLFV in muon transitions and decays: clean experimental **environment**, excellent **prospects (sensitivity)**





Exploration of muon-electron conversion in nuclei:

EFT comprehensive studies,
spin-independent and **spin-dependent** contributions,
choice of **target** material,
contributions of **new (contact) interactions**,
new associated **observables**, ...



EFT approach towards complementary constraints
on **cLFV operators** ($\mathcal{O}_6^a$) from $\mu \to e\gamma$ (MEG II)
$\mu \to 3e$ (Mu3e)
$\mu - e$ conversion (Mu2e, COMET)

@ IN2P3: S. Davidson (LUPM), A.M. Teixeira (LPC, COMET)

Lepton flavours: leptonic CP violation (EDMs)

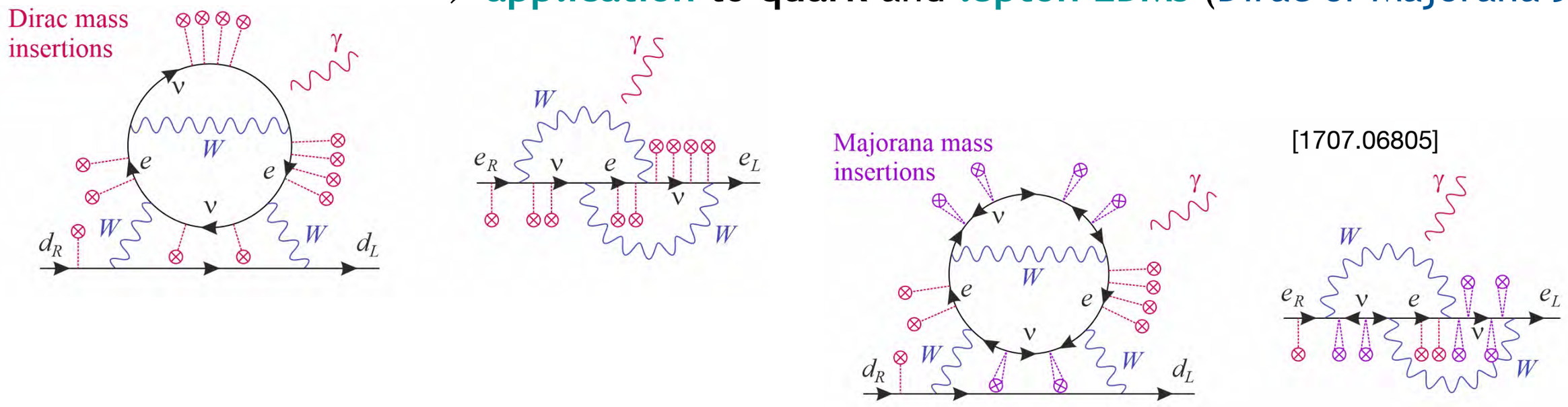
Electric dipole moments: CP violating observables (& most sensitive NP probes!)

⇒ contributions to **lepton EDMs** sensitive to ν **nature** (Dirac/Majorana)

EFT approach, spurion techniques derived from Minimal Flavour Violation

⇒ minimal **Jarlskog-like invariants** (& non-invariant structures)

⇒ **application** to **quark** and **lepton EDMs** (Dirac or Majorana ν)



- Powerful formalism; interplay between new **(Majorana)** phases and possible **B- and L-violating interactions**

@ IN2P3: A. Abada (IJCLab), J. Quevillon, C. Smith (LPSC)

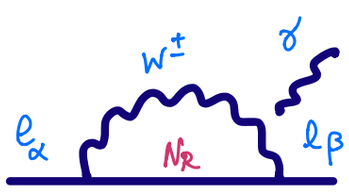
Lepton flavours: BSM phenomenology

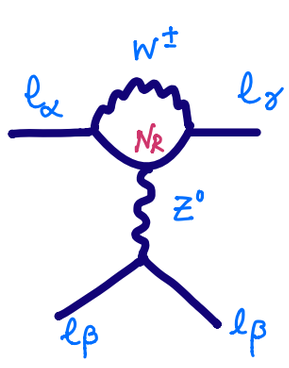
NP in the lepton sector: massive neutrinos and beyond

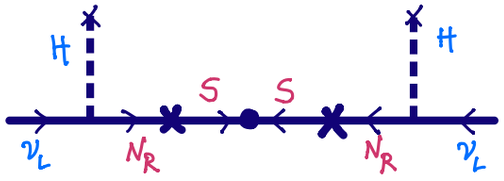
Uniquely **light (Majorana) fermions** - new mechanisms of mass generation?
Seesaw (type I, II, III and variants), radiative, ..., from GUT scale to EW...

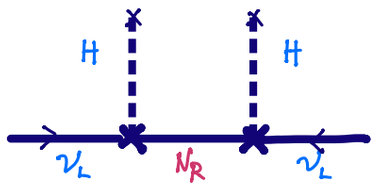
Many **well-motivated (minimal)** extensions via sterile **"heavy" neutral leptons (HNL):**
- theoretically appealing
- rich phenomenology (testability!)
- possible links to the BAU (leptogenesis) and to the DM problem

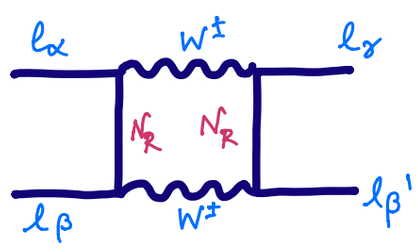
$$M_{\text{Type-I}} = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}$$











$$M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$$

Phenomenology of SM extensions via HNL: low-energies, high-intensities and colliders
identify distinctive signal/signatures, constrain realisations, interpretation of data...
impact for baryon asymmetry of the universe, dark matter candidates...

@ IN2P3: A. Abada (IJCLab), J. Orloff, A.M. Teixeira (LPC)

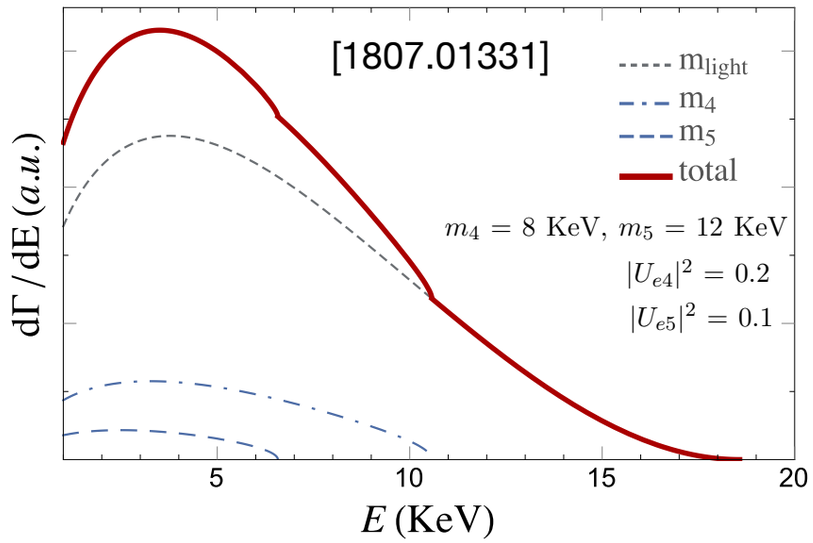
Lepton flavours: BSM phenomenology (2)

Phenomenology of SM extensions via HNL: low-energies, high-intensities and colliders
identify distinctive signal/signatures, constrain realisations, (re)interpret data...

At very low energies: impact for $0\nu2\beta$ **and** β**-decays**

$0\nu2\beta$ **signal** (near future) - compatible with **both orderings of** ν **spectrum** if additional HNL

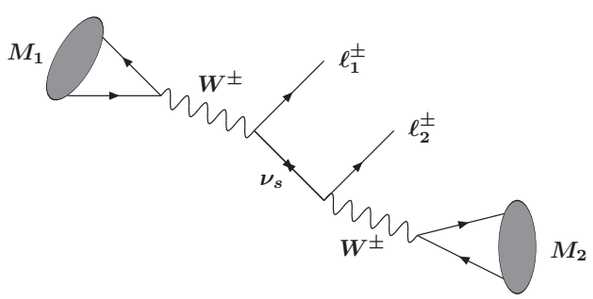
Additional **"kinks" in Kurie plot** for Tritium β-decays

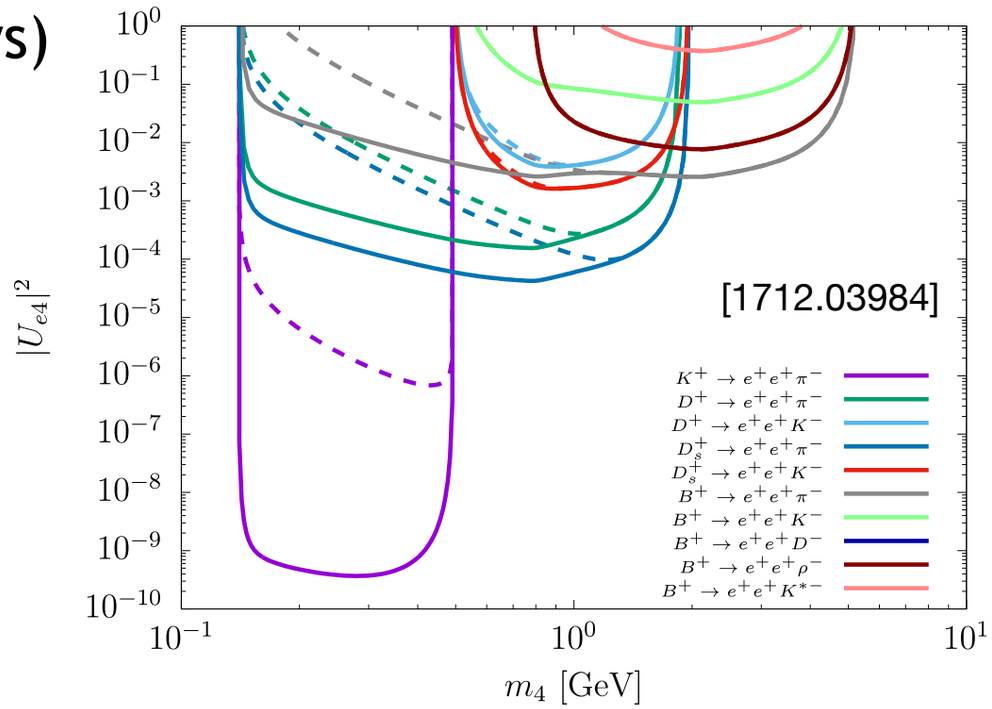


At high-intensities: cLFV and LNV semileptonic decays

Potentially abundant **cLFV signals** (rare μ and τ decays)

Contributions to **numerous LNV & cLFV** (meson & τ) **semileptonic decays**: updated constraints





Interpretation of data: if n_S HNL $\Rightarrow$ interference effects!

New Physics models: from theory to colliders

New physics models: from theory to colliders

New Physics is required! From **observational** and **theoretical arguments:**
hierarchy problem(s), naturalness, gauge unification, ... ⇒ new states & interactions

At colliders: discovery of new "exotic" resonances or
deviation from SM predictions (EW precision observables, Higgs/top couplings, ...)

⇒ **Phenomenological studies** of **well-motivated** models
(SUSY, extra-dims, compositeness, ...)

⇒ Proposal of **new signals/search strategies**

⇒ **Interpretation of LHC data** (and model constraining!)

⇒ **High-precision SM calculations** (reduce theory uncertainties)

Intense activity, in close contact with experimental searches

Changes in paradigm: from **preferred TeV-scale realisations towards a signal-oriented approach**, considering **difficult** and **non-standard scenarios**, ...

@ IN2P3: A. Abada, A. Falkowski, G. Moreau, O. Sumensari (IJCLab)
A. Arbey, G. Cacciapaglia, A. Deandrea, F.N. Mahmoudi (IP2I)
M. Rausch de Traubenberg (IPHC), A. Goudelis, A.M. Teixeira (LPC),
S. Kraml, I. Schienbein, J. Quevillon, C. Smith (LPSC),
F. Brümmer, C. Hugonie (LUPM),...

New physics models: from theory to colliders (2)

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⇒ **Phenomenological studies** of **well-motivated** models

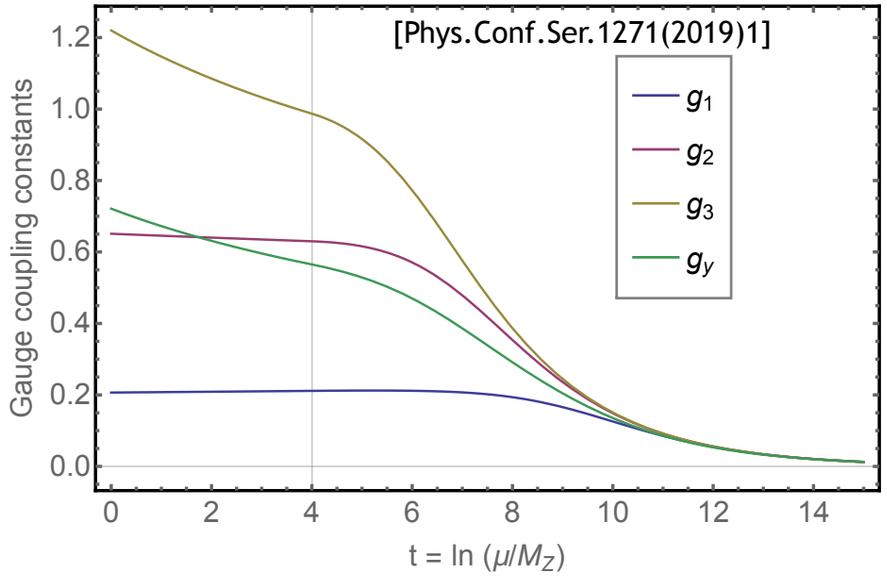
Models with (large) extra spatial dimensions:

explain $\Lambda_{EW} \ll \Lambda_{Planck}$ (weak & Planck scales), address hierarchy problem!

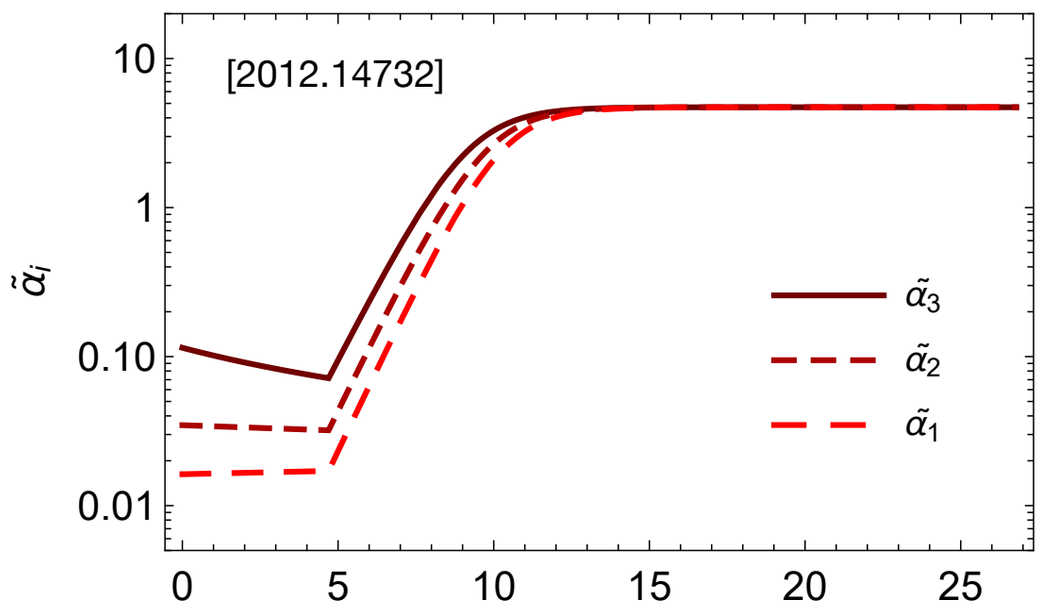
⇒ Conceptual problems, new DM candidates, Higgs prospects, phenomenological studies of new heavy particles (KK excitations, ...)

Attempts at **Unification** (interactions, ...):

Successful **gauge-Yukawa unification!**



Asymptotic unification (gauge)
non-SUSY SU(5) in compact $S^1/(Z_2 \times Z_2')$ orbifold



@ IN2P3: G. Moreau (IJCLab), G. Cacciapaglia, A. Deandrea (IP2I), ...

New physics models: from theory to colliders (3)

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Supersymmetric models:

minimal SM-extensions, address hierarchy problem, gauge coupling unification, ...

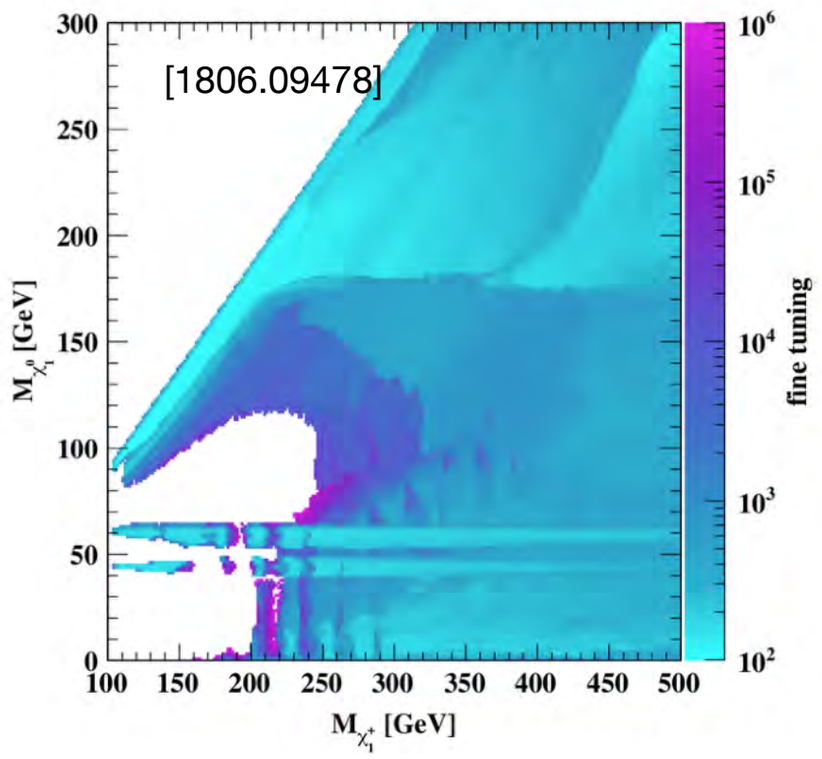
⇒ intensive studies on a variety of models and realisations

From general Minimal Supersymmetric Standard Model (**MSSM**),
to constrained MSSM, phenomenological MSSM (**pMSSM**), input-Higgs MSSM (**hMSSM**),
next-to-minimal SSM (**NMSSM**), R-parity violating MSSM, **Dirac-gaugino** realisations, ...

Next-to-minimal supersymmetric models:

difficult scenarios, new signatures

⇒ **combined constraints from LHC**
and DM searches



Reconstructing / constraining SUSY parameter space

⇒ **complementarity** of Higgs and SUSY searches

⇒ constraints from numerous **flavour and CP observables**

@ IN2P3: G. Moreau (IJCLab), A. Arbey, F.N. Mahmoudi (IP2I), A.M. Teixeira (LPC), S. Kraml, J. Quevillon, I. Schienbein (LPSC), C. Hugonie (LUPM), ...

New physics models: from theory to colliders (4)

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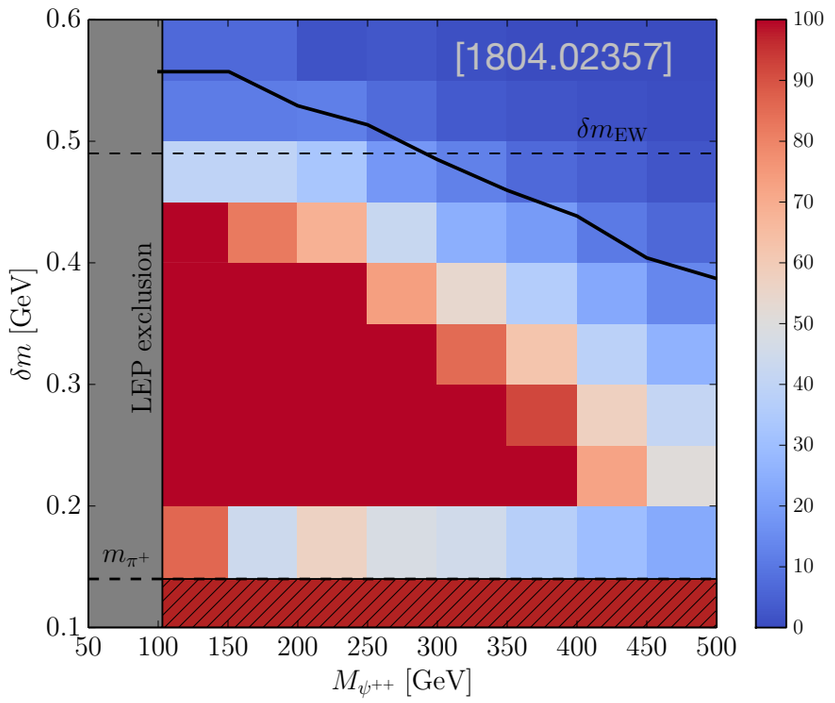
Multi-Higgs doublet models & extended Higgs sector

Two-Higgs doublet models (2HDM) & Inert doublet models,

additional singlets, triplet scalars, (and pseudoscalars), ...

LHC phenomenology of (non-SUSY) "exotics":

heavy vector-like fermions, LQs, top partners, HNL,
(generic) light pseudoscalars (& axions), composite-states, ...



Dark matter searches at LHC: complementary probes!

⇒ minimal scenarios (singlet & SU(2) *n*-plet fermions)

Exploring (generic) **LHC windows into New Physics:**

- promising **production** modes & **channels (sensitive to NP)**
- **difficult** and/or **stealth** scenarios
- **peculiar signatures** (displaced vertices, long lived particles, ...)

High-precision calculations: NLO calculations, RGEs at higher orders, ...

[Tools: PBZp, PBVp, PyR@TE, ...]

@ IN2P3: A. Abada, A. Falkowski, G. Moreau, O. Sumensari (IJCLab), A. Goudelis, A.M. Teixeira (LPC)
A. Arbey, G. Cacciapaglia, A. Deandrea, F.N. Mahmoudi (IP2I), F. Brümmer, C. Hugonie (LUPM)
S. Kraml, I. Schienbein, J. Quevillon, C. Smith (LPSC), ...

NP searches: (re)interpretation of LHC results

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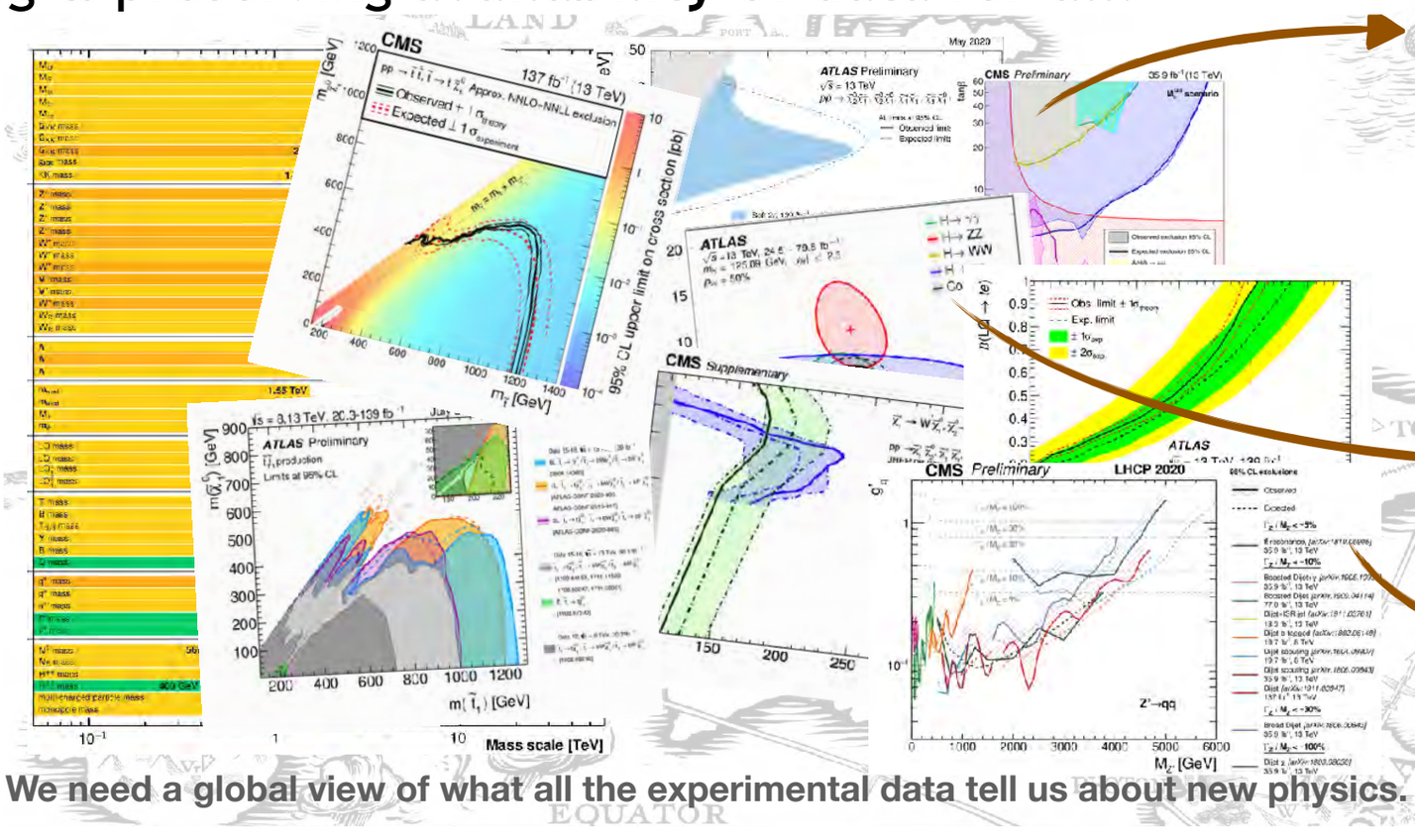
⇒ Fully explore LHC potential!

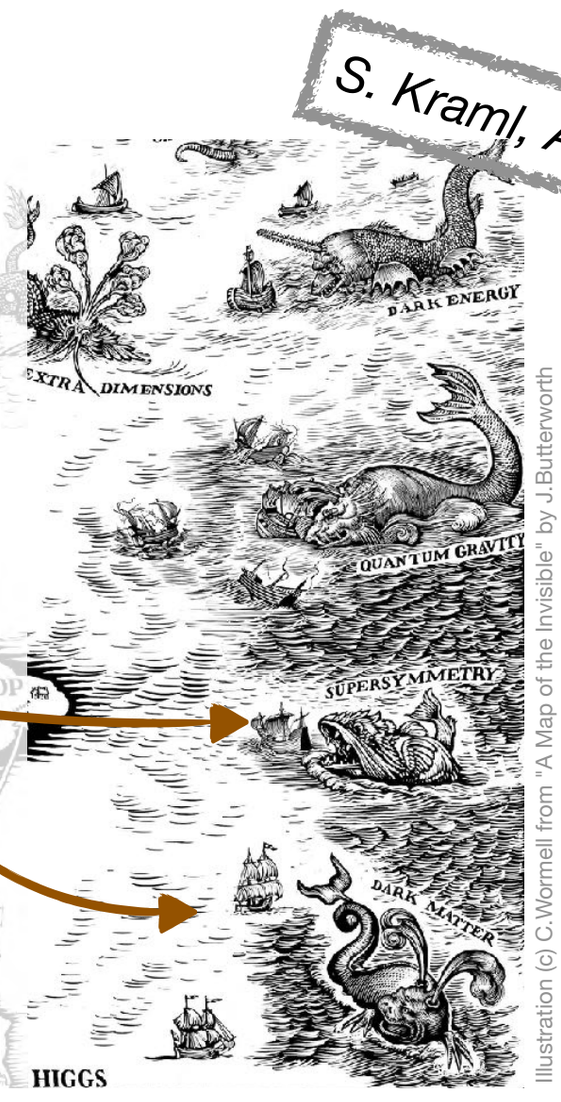
Many BSM constructions **explored** (but only **tiny subset**)...

What information does data actually convey about the NP model?

Are models efficiently constrained? Are certain realisations really excluded?

Phenomenological studies, model-dedicated/independent,
new **search strategies** (close interaction of exp. and th.)
ensuring & preserving **availability of data for all!**





We need a global view of what all the experimental data tell us about new physics.

@ IN2P3: S. Kraml, J. Quevillon, I. Schienbein (LPSC), F.N. Mahmoudi (IP2I)

NP searches: (re)interpretation of LHC results (2)

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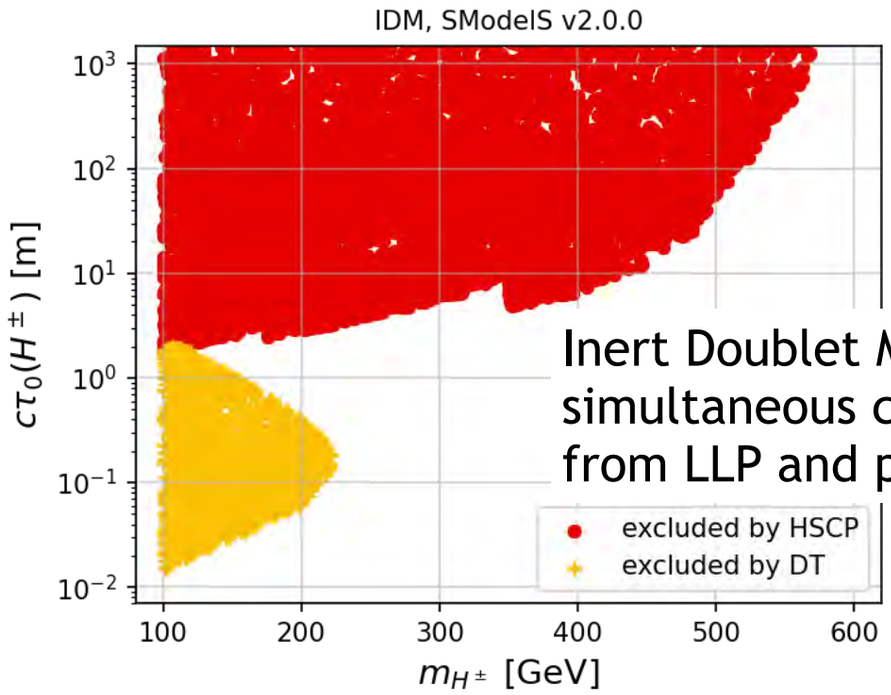
SModelS

Constrain full-BSM constructions from simplified model results



Inert Doublet Model & SModelS 2.0
simultaneous constraints
from LLP and prompt searches

[S.Kraml, in progress]

PROTOMODEL BUILDER

Novel statistical algorithm to identify "dispersed signals" in LHC data (in agreement with constraints)

Lilith

Constrain BSM extensions from 125 GeV Higgs signal strength measurements

MADAnalysis 5

Public analysis database

CONTUR

method

among many others!

NP searches: (re)interpretation of LHC results (3)

Joint theory-experiment endeavours

Public likelihoods: availability of **full statistical model** (used in analyses collaborations); benefit re-use of experimental results.

FAIR principles: **reproduce** analysis and results; ensure **preservation of data**

@ IN2P3: S. Kraml(LPSC), F.N. Mahmoudi (IP2I), ...

Back to more formal approaches

And back to more formal approaches

Formal **Quantum Field Theory** studies - integral part of particle physics studies!

⇒ correct, precise description of phenomena

⇒ alternative ways to address or understand problems of the SM

Renormalisation group equations (RGEs):

general renormalisable gauge theories at **higher loop order**
revision of **two-loop RGEs**, impact for the running of **dimensionful** parameters

Public tool: PyR@TE (running of the Lagrangian parameters $\Lambda_{EW} \leftrightarrow \Lambda_{NP}$)

New regularisation/renormalisation schemes:

finite elementary amplitudes in physical conditions
application to **SM naturalness problems** (Higgs mass fine-tuning and axial anomaly)

Revisit "Multiple Point Principle", "Asymptotic Safety"

tackle **naturalness problems,** explain Higgs mass and apparent fine-tuning

@ IN2P3: I. Schienbein (LPSC), J.-F. Mathiot (LPC), ...

TH particle physics @ IN2P3: outlook

Outlook

Despite extensive **SM's success** in describing particle physics phenomena

⇒ many **fundamental theoretical questions** remain to **be answered**

⇒ cannot explain **observational problems** (m_ν, BAU, DM, flavour "anomalies", ...)

Need to **go beyond the SM**: **New Physics!** But which model? At which scale?

Many appealing well-motivated constructions...

Powerful model-independent methods (EFTs)

Particle Physics Theory @ IN2P3: intense activity on numerous fields

Higgs physics, neutrino physics, flavour physics, BSM phenomenology, searches at colliders, precision observables, ...

Closely following & contributing to the experimental developments on several frontiers

LHC, ν physics, flavour physics, ... and actively preparing future experiments!

Fruitful long-standing dialogue between theory and experiment:

new theory ideas emerge to understand data

theoretical proposals help **paving the way to new experimental quests**

Purely theoretical approaches: source of new ideas, and methods!

Further information

TH particle physics at IN2P3 Laboratories

Laboratory	People
APC Paris (UMR 7164)	D. Semikoz, J. Serreau, M. C. Volpe
IJCLab Orsay (UMR 9012)	A. Abada, D. Bečirević, V. Bernard, B. Blossier, S. Descotes-Genon, A. Falkowski, S. Friot, E. Kou, G. Moreau, O. Sumensari
IP2I Lyon (UMR 5822)	A. Arbey, G. Cacciapaglia, A. Deandrea, F. N. Mahmoudi
IPHC Strasbourg (UMR 7178)	M. Rausch de Traubenberg
LPC Clermont (UMR 6533)	A. Goudelis, J.-F. Mathiot, V. Morénas, J. Orloff, A. M. Teixeira
LPSC Grenoble (UMR 5821)	S. Kraml, M. Mangin-Brinet, J. Quevillon, I. Schienbein, C. Smith
LUPM Montpellier (UMR 5299)	F. Brümmer, S. Davidson, C. Hugonie

Further information - Atelier PT2I

Atelier Physique Théorique deux Infinis

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Numerous contributions!

Astroparticules | Physique Hadronique | Physique des Particules | Welcome

09:00	**Welcome**	*Reynald Pain* 09:00 - 09:15
	Flavour physics and indirect searches for new physics	*Nazila Mahmoudi* 09:15 - 09:30
	Flavor physics at high-pT	*Olcyr Sumensari* 09:30 - 09:45
	Hadronic matrix elements from lattice QCD	*Dr Antoine Gérardin* 09:45 - 10:00
10:00	**EFT description of LFV and LNV processes**	*Michele FRIGERIO* 10:00 - 10:15
	Heavy neutral fermions	*Prof. Asmaa Abada* 10:15 - 10:30
	(Re)interpretation of LHC results for new physics	*Sabine Kraml* 10:30 - 10:45
	Compositeness from particle collisions to space	*Giacomo Cacciapaglia* 10:45 - 11:00
11:00	**Assorted Topics (Discussion)**	*Damir BECIREVIC* 11:00 - 11:15

Lively participation and discussion, 7-8 June 2021

Further information - Master Projects
Research federations
International collaborations

IN2P3 Theory "Master Projects" (2017-2021)

- **"Speedy Charmonia"** (PI: B. Blossier, IJCLab) [2020 - 2022]:
  B. Blossier (IJCLab), M. Mangin-Brinet (LPSC), S. Zafeiropoulos (CPT), ...

- **"Lattice calculations in hadronic physics"** (PI: V. Morénas, LPC [2017-2020]:
  M. Mangin- Brinet (LPSC), B. Blossier, O. Pène (LPT Orsay), V. Morénas (LPC),
  S. Zafeiropoulos (CPT)

- **"SlowSUGRA"** (PI: M. Rausch de Traubenberg, IPHC) [2018 - 2020]:
  R. Ducrocq, E. Conte, M. Rausch de Traubenberg (IPHC), C. Hugonie, J. Lavalle, G. Facchinetti (LUPM), G. Moultaka (L2C), V. Venin (APC)

- **"LHCiTools"** (PI: S. Kraml, LPSC) [2017 – 2019]:
  S. Kraml, J. Quevillon, I. Schienbein (LPSC)

- **"BSMGA"** (PI: S. Kraml, LPSC) [2020 - 2022]:
  S. Kraml, J. Quevillon, I. Schienbein (LPSC)

- **"Lepton flavours: probes of New Physics"** (PI: A. M. Teixeira, LPC) [2017-2019]:
  A. Abada (LPT Orsay), S. Monteil, J. Orloff, A. M. Teixeira (LPC)

- **"Flavour probes: lepton sector and beyond"** (PI: A. M. Teixeira, LPC) [2020-2022]:
  A. Abada (IJCLab), A. Goudelis, S. Monteil, V. Morénas, J. Orloff, A. M. Teixeira (LPC)

Research Federations and Platforms

Groupements de Recherche & International Research Networks

GdR “Intensity Frontier”
Scientific steering: S. Descotes-Genon (IJCLab), F. N. Mahmoudi (IP2I), C. Smith (LPSC)
W.G. responsibilities: E. Kou (IJCLab, “Heavy flavour production and spectroscopy”),
C. Smith (LPSC, “CP violation”),
O. Sumensari (IJCLab, “Quark-lepton interplay”),
A.M. Teixeira (LPC, “Quark-lepton interplay”)

IRN “QCD”
W.G. responsibilities: B. Blossier (IJCLab, “Low energy QCD”)

IRN “Neutrino”
Scientific steering: A. Abada (IJCLab), A. M. Teixeira (LPC)
W.G. responsibilities: A. M. Teixeira (LPC, “BSM”)

IRN “Terascale”
Scientific steering: C. Hugonie (LUPM), J. Orloff (LPC)
W.G. responsibilities: J. Quevillon (LPSC, “BSM”), A. M. Teixeira (LPC, “BSM”)

Research Federations and Platforms

European Networks

EU ITN "Elusives" & EU RISE "Invisibles Plus"
Steering (CNRS node): A. Abada (LPT)

EU ITN "HIDDeN"
Steering (CNRS node): A. Abada (IJCLab)

International Platforms and Forums

"Forum on the Interpretation of the LHC Results for BSM studies" CERN (Th-Exp)
Founder and main coordinator: S. Kraml (LPSC)
Scientific steering: F. N. Mahmoudi (IP2I)

RAMP "Reinterpretation: Auxiliary Material Presentation" (Th-Exp)
Organiser: S. Kraml (LPSC)

Updates of EU and USA Particle Physics Strategies (10 year)

SNOWMASS 2021 (USA)
Topical steering "cLFV": S. Davidson (LUPM)
Coordination of "White Paper on analysis preservation and reuse" S. Kraml (LPSC)

European Particle Physics Strategy Update 2020 (EPPSU2020)
Scientific secretariat (and co-authorship) of "Flavour Physics": A. M. Teixeira (LPC)
IN2P3's contribution to EPPSU 2020 (co-author): A. M. Teixeira (LPC)

International collaborations (theory & experiment)

Alpha Collaboration (Th, **LQCD**)
B. Blossier (IJCLab)

ETM Collaboration (Th, **LQCD**)
D. Becirevic, B. Blossier (IJCLab), M. Mangin-Brinet (LPSC), V. Morénas (LPC)

CKMFitter Collaboration (Th-Exp, **Flavour**)
S. Descotes-Genon (IJCLab), J. Orloff (LPC)

Belle II Collaboration (Exp, **Flavours**)
E. Kou (IJCLab)

COMET Collaboration (Exp, **cLFV**)
A.M. Teixeira (LPC)

JUNO Collaboration (Exp, **Neutrinos**)
M. C. Volpe (APC)

SModelS Collaboration (Th, **LHC results**)
S. Kraml (LPSC)

Further information - Public Tools

Public Tool development

“NMSSMTools”: https://www.lupm.univ-montp2.fr/users/nmssm/index.html

“SuperIso”: http://superiso.in2p3.fr/

“SModelS”: https://smodels.github.io/

“MadAnalysis5 PAD”: http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase

“Lilith”: https://lpsc.in2p3.fr/projects-th/lilith/

“Proto-model builder”: https://smodels.github.io/protomodels/

“PBZp”: provide K factors to ATLAS and CMS collaborations for heavy-resonance searches using top-quark pair observables (available on demand)

“PBVp”: inclusion of NLO QCD corrections to the hadroproduction of top-quark pairs for new heavy spin-1 resonances; implemented in the CONTUR/RIVET framework

“PyR@TE 3.0”: https://github.com/LSartore/pyrate

Further information - Contributions

Contributions

APC — Theoretical Neutrino Physics and Astrophysics

M.C. Volpe

Investigation of standard and non-standard neutrino properties and interactions: impact on astrophysical environments and the Early Universe

Froustey, Pitrou, Volpe, JCAP 12 (2020)

Chatelain, Volpe, PRD95 (2017) ; Chatelain, Volpe, PRD98 (2018)

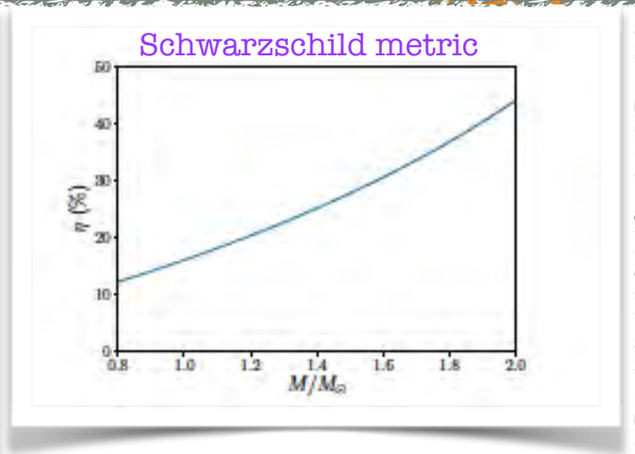
Derivations of extended neutrino evolution equations, for dense environments, in flat and curved spacetime, decoherence effects in presence of strong gravitational fields and formal connections to other domains such as condensed matter and atomic nuclei

Volpe, Int. J. Mod. Phys. E24 (2015)

Volpe, Väänänen, Espinoza, PRD87 (2013)

Predictions for (and physics potential of) upcoming neutrino experiments, including
Super-Kamiokande, Hyper-K, JUNO, DUNE
(also important in relation with future kilonova observations)

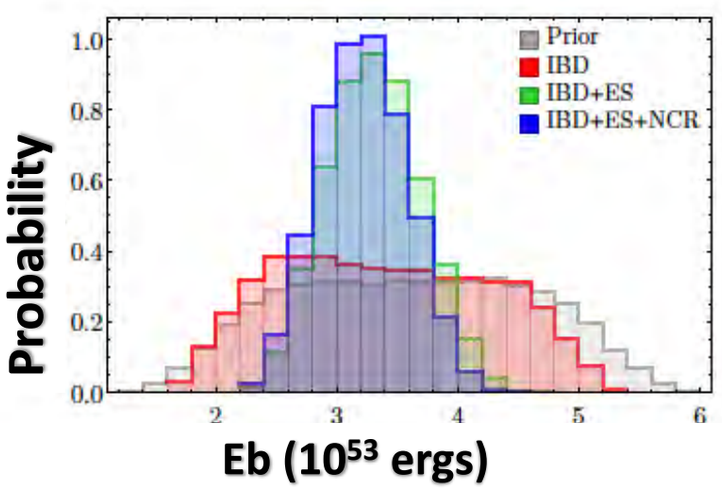
D. Becirevic, A.M. Teixeira



$$E = 11\ MeV\ r_P = 10\ km\ \sigma_x = 4 \times 10^{-12} cm$$

Neutrino wave packet decoherence in presence of strong gravitational field nearby a compact object.

Chatelain and Volpe, Phys. Lett. B 801 (2020)



A likelihood analysis of the events in a galactic supernova shows the gravitational binding energy can be reconstructed with 11% accuracy in Super-K, 3% accuracy in Hyper-K

Gallo Rosso, Vissani, Volpe, JCAP11, 2017; JCAP 04, 2018

Contributions

IJCLab (excerpts!)

A. Abada

1) Effects of HNL at very low energy (beta and neutrinoless double beta decay)

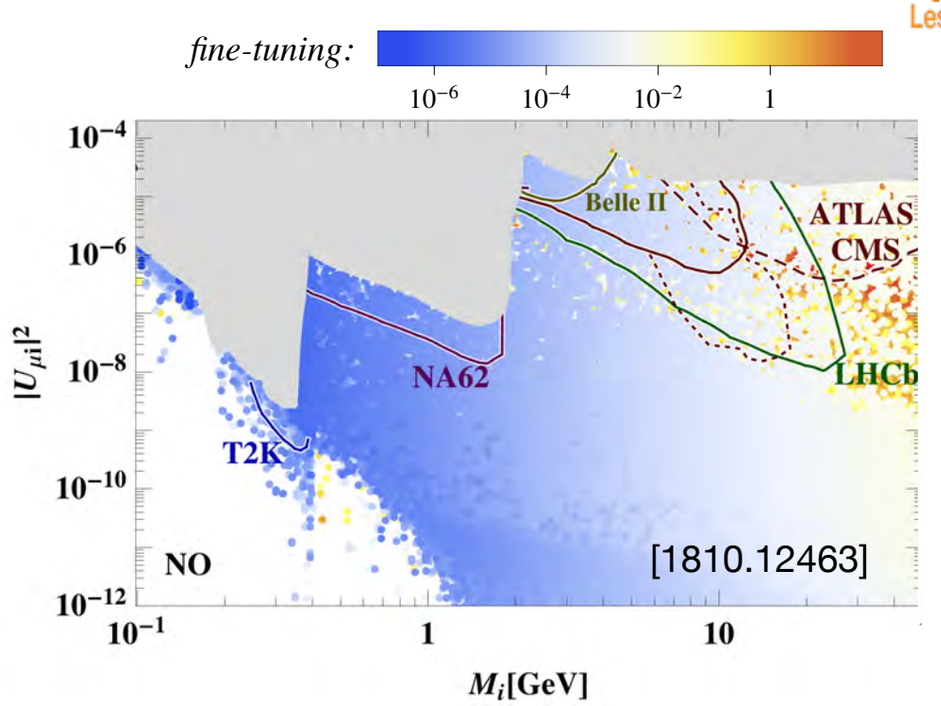
A) explore the viability of minimal extensions of the SM with N HNL (one of them in KeV mass regime) with possible impact in both the beta energy spectrum and the neutrinoless double beta decay effective mass, for the two possible ordering cases for the light neutrino;

B) In the case we have N= 2 that are embedded in a Seesaw realization (Type I and ISS+LSS variants) with one of the two RH neutrinos is within KATRIN's sensitivity (a kink in the energy spectrum, i.e in the KeV) [1807.01331]

2) Displaced Vertices HNL

HNL they can be long-lived and lead to events with displaced vertices, giving rise to promising signatures due to the low background. We revisit the opportunities offered by the LHC to discover these long-lived states via searches with displaced vertices. Study implication on the parameter space sensitivity when **all mixings to active flavours are taken into account** [1807.10024]

3) EDMS in the Scotogenic model: light neutrino masses (radiative masses), dark matter and electron EDM within ACME sensitivity [1802.00007]



4) Neutrino masses, leptogenesis and dark matter from small lepton number violation?

A) improved parametrisation of seesaw models and derive a linearised system of Boltzmann equations to describe the leptogenesis process; perform a systematic study of the **strong washout regime of leptogenesis**. Successful leptogenesis at the temperature of the electroweak scale through oscillations between two sterile states with a
natural origin of the (necessary) strong degeneracy in their mass spectrum [1709.00415]

B) Considered the case of **3 RH neutrinos,** qualitatively new behaviours as a result of LNV oscillations and decays, strong flavour effects in the washout and a resonant enhancement due to matter effects. Particularly efficient for large heavy neutrino mixing angles near the current experimental limits, a regime in which leptogenesis is not feasible in the minimal scenario with two heavy neutrinos (low-scale leptogenesis is testable by the LHC and other existing experiments). [1810.12463]

Contributions

IJCLab (excerpts!)

S. Descotes-Genon

1. **Research activities**:

- CP-violation in the quark sector : metrology of the CKM matrix in the SM, studies of generic NP models, global fits and associated statistical methods

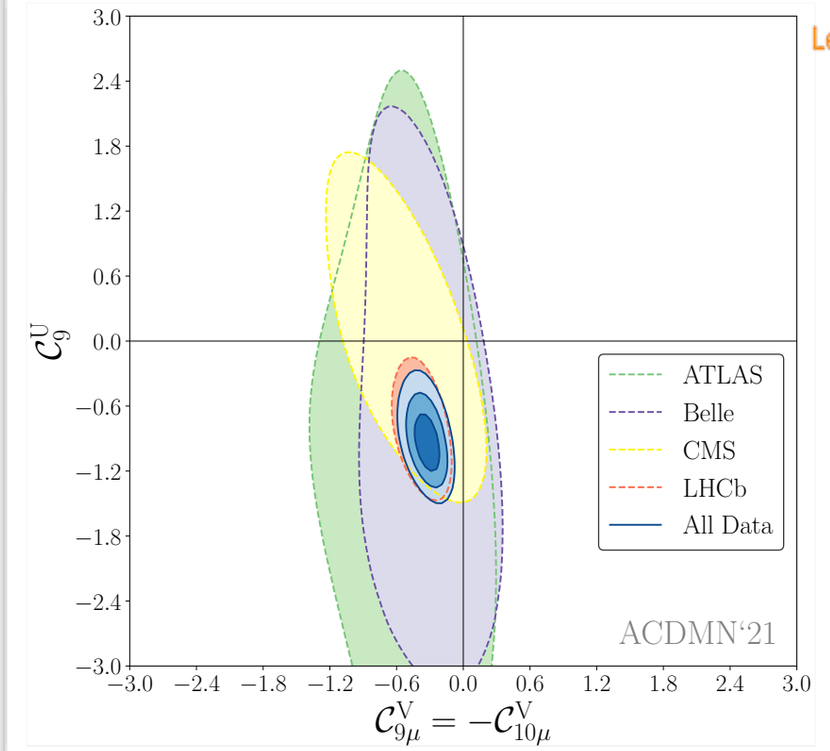
- rare B-decays in the SM and beyond : global fits to b->s ll data ("B-anomalies"), determination of hadronic inputs, study of new hadronic modes and design of additional observables with improved sensitivity to NP, model building and connection to other families, hadronic penguin modes

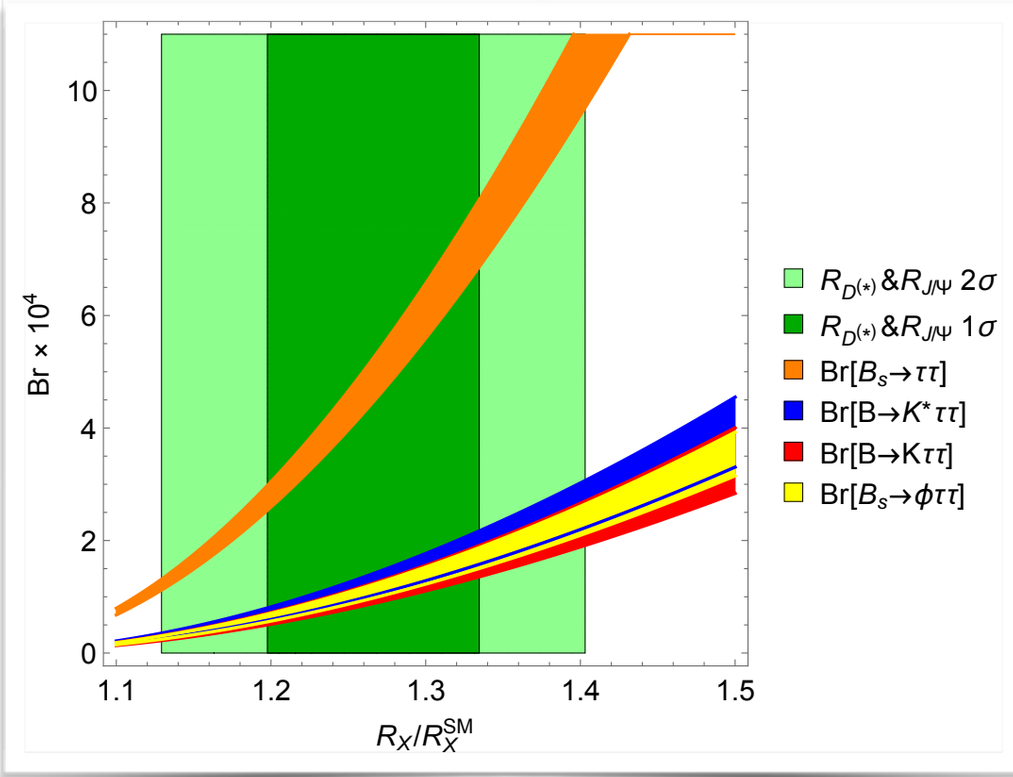
Tools: EFT; nonperturbative methods (dispersion relations, sum rules...); statistical tools

2. **Recent highlights**

- Global fits to b->sll decays
* consistency of the patterns of deviations in the context of simple NP scenarios involving one or two operators in weak EFT
* relevance of the LFUV observable Q_5 (difference of P_5' in e and mu) to separate these scenarios
* role of lepton-flavour universal contributions of NP in these fits

- New observables to probe flavour anomalies:
* time-dependent analysis of rare B decays (with mixing) B_d->K*ll, B_d-K_Sll, B_s->phill
* Lambda_b-> Lambda(1520)ll and study of prospects at LHCb
* huge NP enhancement of b->s tau tau in the context of simple NP models for b->c l nu anomalies





Contributions

IJCLab (excerpts!)

G. Moreau

Model building in scenarii with extra spatial dimensions aimed at addressing one of the deepest problems of the Standard Model of elementary particles, by unifying the Gravity scale (Planck energy) and the ElectroWeak symmetry breaking scale:
- conceptual problems in higher-dimensional field theories (e.g. about boundary localization of scalar fields, coupled to bulk fermions, like the Higgs boson),
- classification of compact spaces and dual geometries,
- studying quantum field theories in curved spaces.

Research at HL/HE-LHC and futur Linear Colliders (LC) of direct or indirect effects of new heavy particles like Kaluza-Klein excitations of bosons and fermions arising from specific extra-dimensional models constructed [see above] or of Vector-Like fermions [single/pair productions] for an effective probe of more general field contents covering bounded states issued from composite Higgs models.

In particular, precise calculations of the contributions of heavy fermion exchanges in the triangular loops contributing to deviations to SM-like Higgs couplings like H-digluon or H-diphoton. The motivation being that future LC could be sensitive to tiny deviations of the Higgs couplings: those colliders are indeed expected to reach uncertainties at the percent level in the precision measurement of the H-diphoton
interaction for instance.

Improving the fits of the data on the Higgs rates/couplings, combining the HL/HE-LHC and LC result expectations, by careful implementations of the correlation matrices among the theoretical errors (of mainly QCD origin: PDF uncertainties, factorization/ renormalization scale dependences of the strong coupling g_s and Higgs production cross sections at hadron colliders...), since these theoretical uncertainties will become progressively dominant as the statistics and systematics errors will be improved in the next generation ofhigh-energy colliders.

Scrutinizing the data and models to find some light (down to a few ten's of GeV or even lower) effective scalar φ [extra Higgs, radion, dilaton, axion,...] at colliders which would have been missed so far by the LEP, Tevatron and LHC investigations. Several reactions are relevant in this context like $pp \to Z\varphi$
[to tag the Z], $pp \to qq\varphi$ (vector boson fusion) or the rare decay $H \to \varphi Z(*)$ where 'q' denotes a quark, 'p' a proton, 'H' the Higgs boson and $Z(*)$ the (virtual) neutral electroweak gauge boson.

Contributions

IJCLab (excerpts!)

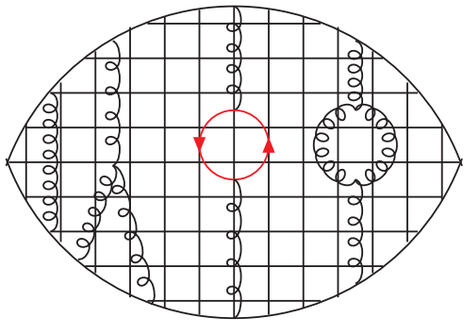
Lattice QCD effort in flavour physics

B. Blossier

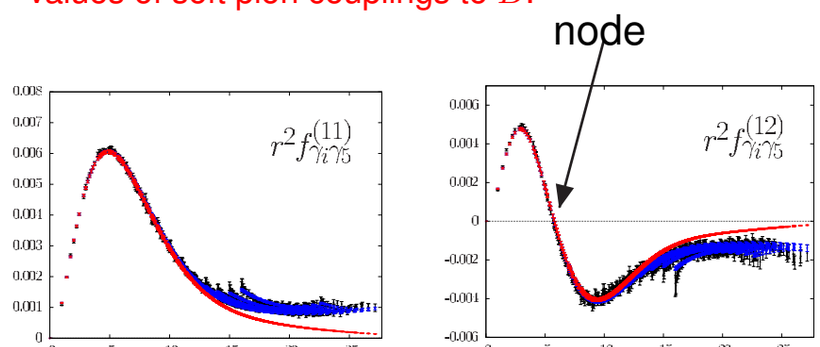
Aim: extract hadronic quantities (spectrum, hadronic matrix elements) using Monte-Carlo simulations of QCD

Ab-initio method to solve QCD in the non-perturbative regime

Effort put in B physics, theoretical inputs to New Physics tests in the quark sector



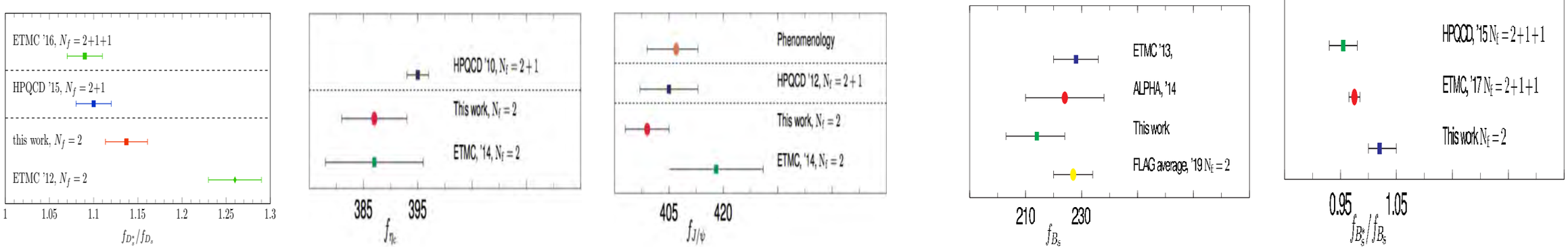
- Probe the internal structure of B meson [B. Blossier and A. Gérardin: 2016]
  Correlation functions show similar patterns to the wave functions of quantum mechanics regarding radial excitations. Understanding of the dynamics to explain values of soft pion couplings to B.



Simulate heavy quarks Q, $m_c \lesssim m_Q < m_b$:

Lattice data: extrapolation to the physical point of the sequential ratios $R_i^{\mathrm{HQET}}(a, m_\pi^2)$

- Extraction of $f_{D_s^{(*)}}$, $f_{\eta_c(J/\psi)}$, f_{B_s} [R. Balasubramanian, B. Blossier *et al*: 2018, 2020]



Contributions

E. Kou

Collaboration with IJCLab
LHCb - Belle II - ILC groups

- New physics search at Belle II with Radiative B decay
  - Photon polarisation determination using the $B \to K\pi\pi\gamma$ decay
- Charmed baryon Magnetic Moment measurement at LHCb and SMOG
  - Λ_c polarisation measurement using $\Lambda_c \to pK\pi$ decay
- CKM unitarity triangle angle γ measurement at LHCb
  - Λ_b baryon multi body decay to determine the CKM unitarity triangle angle γ
- Charmonium investigation using its hadronic final state at LHCb
  - $B_s \to 3\,\phi$ decay to investigate the charmonium nature
- Top quark anomalous coupling determination at ILC
  - NLO electroweak correction for $e^+e^- \to t\bar{t}$ decay

Collaboration with IJCLab theorist

- Dispersive method to determine CKM unitarity triangle angle γ at Belle II
  - $D \to K\pi\pi$ decay in dispersive method (with B. Moussallam (Theory-IJCLab))

International Collaboration

- PRC Russia (Moscow state university with H.Sazdjian (Theory-IJCLab))
  - Charm penguin contribution to $b \to s\gamma$ in QCD sum rule
- TYL France-Japan (KEK/Niigata U. with Z. Huang (Postdoc IN2P3) & Belle II-IJCLab)
  - Hadronic τ decays, New physics search with $B \to D^* l\nu$, Belle II Physics book
- Melbourne U. - CNRS agreement (Melbourne University with Z. Huang)
  - New physics search with $B \to D^* l\nu$, ALPs search at Belle II, Belle II Physics book

The projects in red use the **"Amplitude Analysis method"**, which determines **simultaneously** the physics parameters in question (e.g. BSM parameters) and the parameters coming from the hadronic effects (form factors etc). Together with ILC/Belle II group in IJCLab, we have developed a multidimensional fit method and we are currently applying this technique to various other projects. A GDR workshop/school was organised on this topic in December 2020 (with Theory/LHCb-IJCLab & CEA).

Contributions

IP2I (excerpts!)

Theoretical Particle Physics at IP2I (G. Cacciapaglia, A. Deandrea, N. Mahmoudi, A. Arbey)

1. **Research activities carried in the group (2016-2021)**

   The group has a wide range of activities in particle theory, all strongly linked among them and with the experimental research programs present in the IN2P3 laboratories, including collider physics, dark matter, astroparticle physics and cosmology.
   We are involved in the scientific preparation of future colliders, and eagerly awaiting the start of the HL-LHC. Different new physics scenarios are studied by the different members, such as supersymmetry, models with extended Higgs sectors, composite models and extra-dimensional scenarios. In addition, in recent years, flavour physics has become an emerging sector to probe new phenomena, mainly due to the appearance of several discrepancies with the Standard Model in the semileptonic decays of B mesons. The theory group will continue to play a major role in this respect, and to further develop the SuperIso code, which is a public tool to reinterpret the experimental results in new physics models. Furthermore, the links with astroparticle physics and cosmology are of great importance to understand the properties of physics beyond the SM, in particular through its relation with dark matter.

Higgs physics: The discovery of the Higgs particle gave us new tools for the study of the physics of the spontaneous breaking of electroweak symmetry. We have proposed a parameterization of the Higgs couplings, which allows to directly extract the loop contributions of the New Physics. We have extended our studies with the inclusion of a second Higgs boson, and are collaborating with CMS in the interpretation of the low mass results. We are working on the characterization of the Higgs sector beyond the standard model and the prospects for future colliders, in particular for their link with composite Higgs models and flavour observables.

Collider phenomenology: High energy proton collisions continue to furnish new high-precision results in energy regions hitherto unexplored. These results can be used to test theories beyond the Standard Model. We have developed international level expertise in the phenomenology of heavy vector quarks and supersymmetry, and have developed several numerical tools for the detection of such particles at LHC. We have implemented vector quarks with generic couplings in Monte Carlo tools such as MadGraph and FeynRules, allowing for model independent studies. NLO effects in QCD are also included and our tools are routinely used by experimental collaborations, such as CMS, for the production of Monte Carlo data.

Physics Beyond the Standard Model: We have developed expertise in various classes of models: extra dimensions, composite models, extended scalar sectors, dark matter. N. Mahmoudi has specific and internationally recognized expertise in flavour physics. In particular, the public code SuperIso for the calculation of flavour physics observables has been vastly improved in recent years. G.Cacciapaglia and A.Deandrea have proposed new models with extra dimensions for dark matter candidates arising from geometric symmetries. We have developed composite Higgs, and dark matter models. We have studied “Gauge-Higgs Unification” models, and showed the possibility of gauge-Yukawa unification. We have studied the flavour constraints on composite models and models with extra dimensions. We also participate in the development of GAMBIT, a comprehensive software tool for performing global statistical fits of generic BSM physics models, which was released in 2017, after five years of efforts. Recently we have proposed a new approach to unification, called Asymptotic Unification, based on the idea of reaching asymptotically a common fixed point rather than a crossing of gauge couplings at a particular high energy scale.

Astroparticles: Our activities focus on searches for new particles by direct or indirect detection, relic density of dark matter, and the links with collider physics. The code SuperIso Relic was developed in order to provide a calculational tool for different observables in connection with dark matter and particle physics. Until recently devoted to supersymmetry, the code allows a flexible and generic implementation of all types of scenarios of BSM physics. Moreover, we have studied the links with primordial cosmology and shown that the discovery of new particles will allow to obtain information on the content of the universe before primordial nucleosynthesis, despite the fact that this era is currently unobservable.

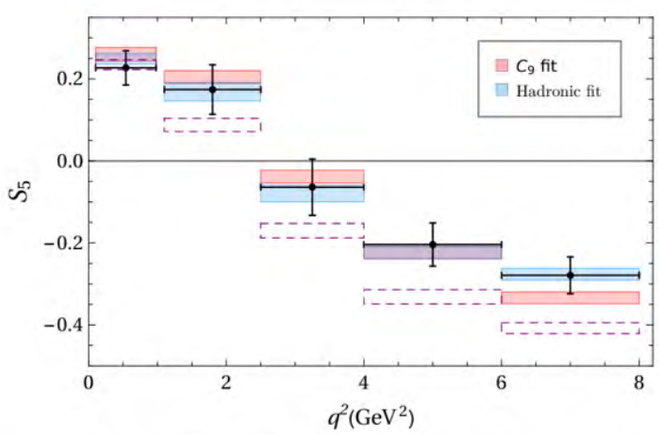


Figure 1: The angular observable $S_5(B \to K^*\mu^+\mu^-)$ with the SM predictions in dashed purple. The C_9 and hadronic best-fit scenarios are shown with red and blue boxes, respectively. The black crosses correspond to LHCb measurements [6].

Contributions

LPC (excerpts!)

A. Goudelis, J.F. Mathiot, V. Morénas, J. Orloff, A.M. Teixeira

Regularisation/renormalisation:
Development of a new schemes leading to completely finite elementary amplitudes in physical conditions. Application to the naturalness of the SM and to the understanding of anomalies. Application of the Taylor-Lagrange renormalization/regularization scheme to the fine-tuning of the Higgs mass and axial anomaly

Lattice QCD:
Study of charmonium $c\bar{c}$ states. Computation of the spectroscopy of the non-orbitally excited ($L = 0$) pseudo-scalar $\eta_c(1S)$ and vectorial J/Ψ states (as well as the corresponding first radially excited states ($\eta_c(2S)$ and $\Psi(2S)$) within the framework of LQCD. Theoretical predictions of associated decay constants

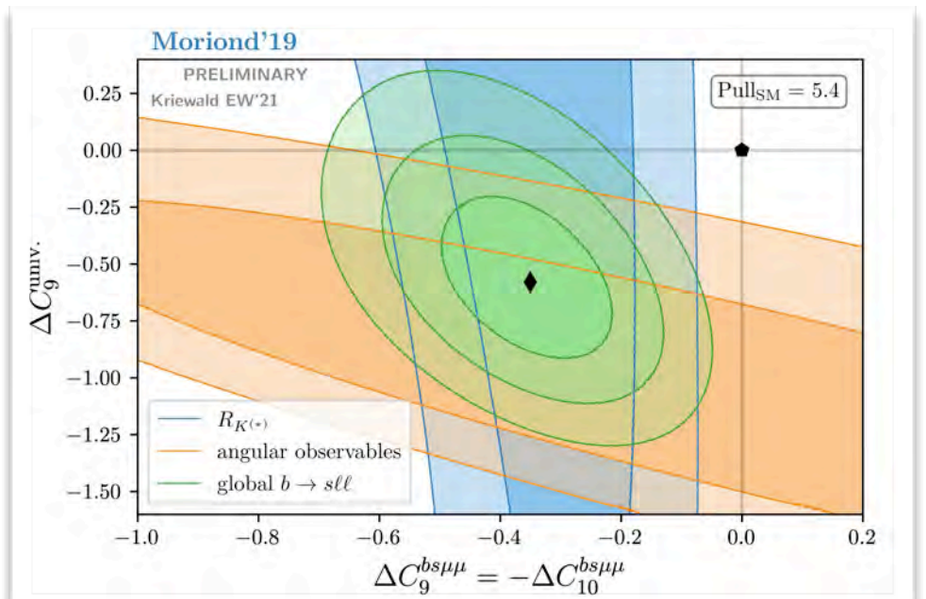
Heavy Flavours and relativistic quark models:
Using covariant Bakamjian-Thomas matrix elements construction, and realistic description of heavy baryon bound states, study of the semileptonic decays $\Lambda_b \to \Lambda_c(1/2^{\pm 1})\ell\bar{\nu}$ in the infinite mass limit for the heavy baryons. Derivation of integral formulae for the decay form factors and computation of physical observables

LFUV (B-meson anomalies and beyond):

Model-independent (generic) fits, and phenomenological studies of several (simplified and complete) models. Interpretation of a possible ATOMKI anomaly and LFUV in anomalous magnetic moments (e and mu). Phenomenology of SM extensions (via two scalar $SU(2)_L$ triplet leptoquarks and three triplet Majorana fermions): explanation of $R_{K(*)}$, (radiative) neutrino masses and viable DM candidate. SM extensions via a single vector leptoquark to simultaneously account for $R_{K(*)}$ and $R_{D(*)}$, from effectively nonunitary LQ-q-l mixings (presence of heavy fermions). Viable isodoublet heavy lepton realisations testable via mu-e conversion.

SM extensions via sterile fermions: cLFV and LNV

If mixings of heavy sterile with the active (light) neutrinos is not negligible, and their mass not excessively heavy, the presence of the sterile fermions can lead to modifications of the leptonic charged current interaction ($W^{\pm}l\nu$), manifest as a deviation from unitarity of the leptonic mixing matrix, U_{PMNS}. Impact of new active-sterile mixings, and new sources of CPV (for simplified models or associated with neutrino mass generation mechanisms) for signatures both at hight intensities and at colliders; study of transitions occurring in the presence of muonic atoms, such as muon-electron conversion in nuclei CR(μ − e, N), decays of muonic atoms into a pair of electrons, Muonium conversion and decay, Mu − Mu and Mu → e^+e^-. Study of cLFV and LNV destructive and constructive interferences in kaon semileptonic decays; impact for interpretation upon future observation of kaon decays at NA62. Update on the bounds on the active-sterile mixing elements, $|U_{\ell_\alpha 4} U_{\ell_\beta 4}|$; proposal of enlarged definition of 3×3 "effective" Majorana neutrino mass matrix $m_{\alpha\beta}$, and extraction of constraints on all its entries.



Contributions

LPC (excerpts!)

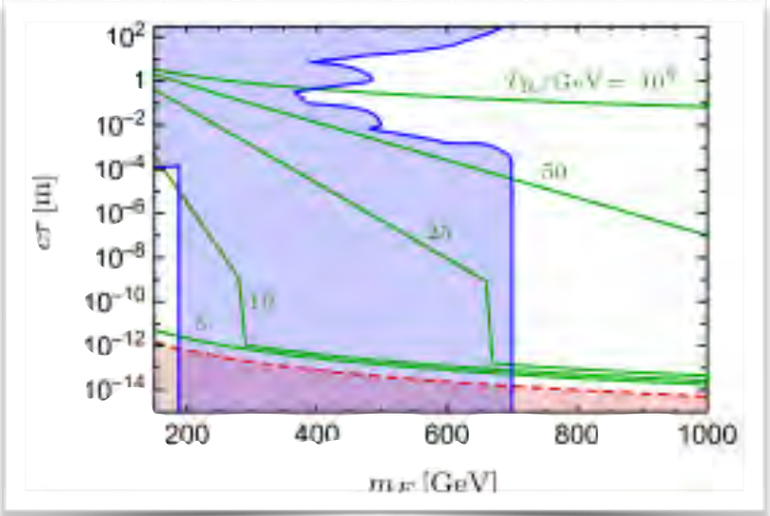
A. Goudelis, J.F. Mathiot, V. Morénas, J. Orloff, A.M. Teixeira

Collider phenomenology: NMSSM studies

Peculiar features of the NMSSM leading to very different signatures at colliders - “difficult scenarios”, associated with specific decay cascades and low MET, as well as light LSPs; proposal of dedicated search strategies to discover the stealth scenarios (in association with CMS)

Collider phenomenology: DM and LLPs at the LHC

Study of numerous signatures of dark matter models at the LHC (kinematic observables to disentangle different frameworks effectively giving rise to a diphoton-like signature); existence of the so-called “threshold enhancement mechanism”; Collider searches for long-lived particles: set of simple freeze-in DM models predicting the existence of charged long-lived particles at the LHC. Feasibility of observation and reconstruction of LLPs properties (masses, lifetimes, …) at the HL-LHC; Reconstruction of the LLPs lifetime – as well as several other properties – of long-lived particles; feasibility of study both for specific SM extensions and for *model-independent* reconstructions.



Contributions

LPSC (excerpts!)

Contribution TH@LPSC Grenoble:
Re-interpretation of LHC results for new physics

Sabine Kraml

1. Research activities

- BSM collider phenomenology (mostly SUSY, non-standard Higgs and dark matter)
- Re-interpretation of LHC results to evaluate limits and loopholes for new physics beyond the (often simplified/vanilla) scenarios considered by the experimental collaborations
- development of methods and public tools for this purpose

The fundamental question is the quest for new physics at the TeV scale. This includes the question what the current data really tell us about new physics, how they constrain particular models, what scenarios still elude us (often despite the experimental summary plots suggestion otherwise) and, last but not least, how we can ensure that the LHC results can be used/re-assessed in the future when perhaps new theoretical ideas emerge.

Public tools: SModelS, MadAnalysis5 PAD, Lilith, Proto-model builder
More recently also contributing to CONTUR[1]

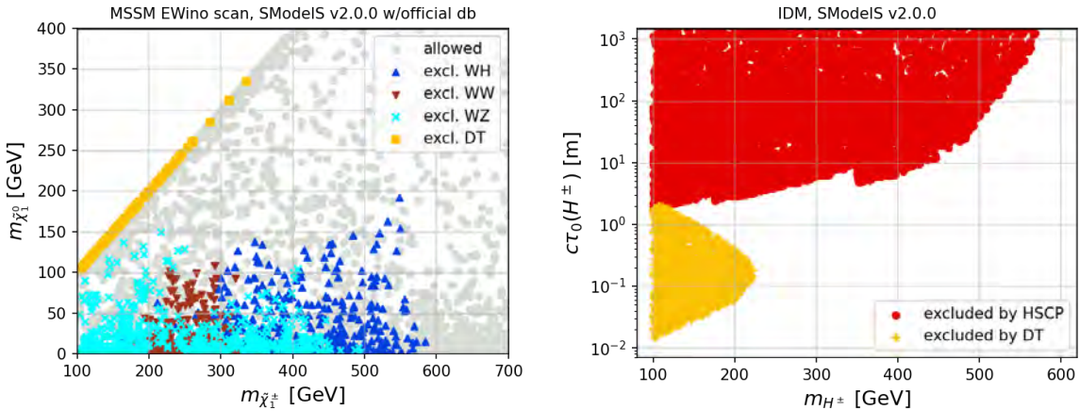


Figure 2: Examples of model constraints with SModelS 2.0, on the left chargino/neutralino limits in the MSSM, on the right limits on long-lived charged scalars in the Inert Doublet Model. DT stands for disappearing track, HSCP for Heavy Stable Charged Particle searches. WH, WW, WZ are the decay channels considered in the prompt SUSY searches. SModelS is so far the only tool that can treat constraints from prompt and LLP searches simultaneously. -work in progress-

Contribution TH@LPSC Grenoble:
Precise calculations for BSM physics

Ingo Schienbein

1. Research activities

- Precise calculations for LHC observables in the presence of W'/Z' resonances
- Renormalization group equations for general renormalisable gauge theories

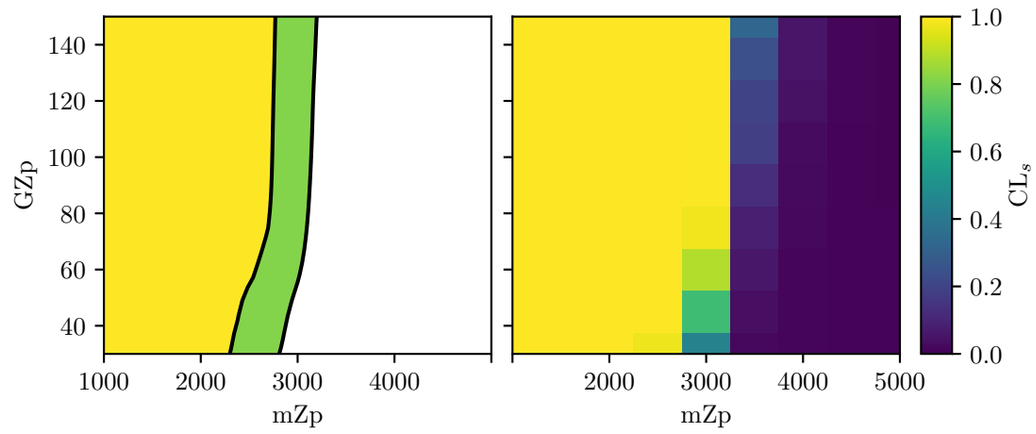


Figure 4.2: `Contur` 2D heatmap for the leptophobic TC model, in the Z' mass (GeV) versus the Z' total decay width (GeV). The 95% CL (yellow) and 68% CL (green) exclusion limits are superimposed considering the data as background.

- **Release of PBZp (2015)** based on the calculation in arXiv:1511/08185. This code has been used to provide K-factors to the ATLAS and CMS groups in their heavy resonance searches using top-quark pair observables. Available by contacting Tomas Jezo.
- **Release of PBVp (2021)** based on the calculation in arXiv:2012.14855. This code generales and improves the older calculation from 2015 in various respects. The code has been renamed to PBVp since W' contributions are now included. It has been implemented into the public CONTUR framework (see arXiv:2012.04377). It will soon be made publicly available (once the documentation has been written).
- **Release of PyR@TE 3.0 (2020)**, arXiv:2007.12700, https://github.com/LSartore/pyrate The new code has many important improvements over the previous versions of PyR@TE, in particular it is faster by factors of order 10000 which has important practical consequences concerning the complexity of models that can be studied.

Contributions

IN2P3
Les deux infinis

LPSC (excerpts!)

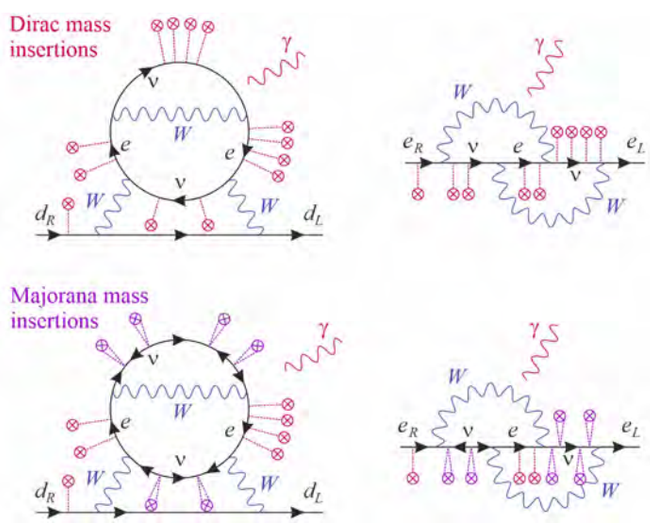
Effective theories: Construction and application

J. Quevillon, C. Smith, S. Touati, H. Vuong

EFTs have always played a prominent role in particle phenomenology. From early applications in the Heisenberg-Euler action of QED, the Fermi theory of weak interactions, or the chiral Lagrangian of pions, the framework has since been used to describe neutrino, nuclear, flavor, electroweak and Higgs physics, to name but a few examples. More recent developments include EFTs for dark matter, inflation and cosmology, as well as the Standard Model EFT.

The applications of EFT have seen a resurgence lately in particle physics, due in part to the lack of new physics at the weak scale. If new physics is indeed decoupled at heavier scales, as nature seems to be indicating, then the SM should be properly considered as an EFT supplemented by higher-dimensional operators. The coefficients of these higher-dimensional operators encapsulate the new physics that we are looking for, that is integrated out at some heavier energy scale. Calculating these coefficients is crucial since they link the UV theories to a distortion of the SM that might be observable and has traditionally been performed using Feynman diagrams, where amplitudes involving the heavy degrees of freedom are ``matched'' to the EFT amplitudes. A more elegant approach (because there are fewer redundancies) is to ``integrate out'' the heavy particles by evaluating the path integral directly. However, its adoption for practical calculations has been limited in the past by cumbersome expansion techniques.

Currently, part of our work on effective theories falls within the context of axion physics, and is described separately. Our recent works purely in the context of effective theories are listed below.



Axions : from Particle Physics to Cosmology

LPSC : Killian Martineau, Jérémie Quevillon, Christopher Smith, Hoa Vuong.

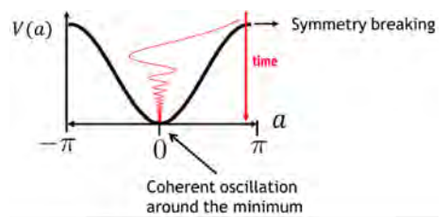
LUPM: Sacha Davidson, Marco Ardu.

Postdoc du labex Enigmass : Fernando Arias Aragon (2021-2023).

Experimental collaborations: this project has strong connection with the GrAHal experiment at Néel Institute and LNCMI (INP), aiming at building and operating a new haloscope in Grenoble. Also, collaborations are expected with the local experimental teams, for example ATLAS (on the ALP aspects), the MIcro-tpc MAtrix of Chambers (MIMAC) aiming at operating as an helioscope, and the Ultra Cold Neutron (UCN) involved in the n2EDM experiment, and planning to search for transcient axion effects.

Abstract

New light particles such as axions, which address the strong CP problem of the Standard Model, have a variety of curious, potentially observable effects in experiments, as well as a complex and eventful cosmological history that requires study at almost every timescale and can result in axion dark matter. In addition, axions are naturally present in string theory. In space, on earth and deep underground, experiments probing axions are flourishing: we propose theoretical and phenomenological efforts to improve theory predictions and identify promising benchmarks.



"Astroparticle physics" ...

Contributions

LUPM (excerpts!)

F. Brümmer, S. Davidson, C. Hugonie

2. Recent highlights

"Axion absorption and the spin temperature of primordial hydrogen," A Auriol, S Davidson, G Raffelt, PRD 99 (2019) 2, 023013, investigating a possible link between DM axions and the 21cm line, written together with an M1 master student.

"The higgsino–singlino sector of the NMSSM: combined constraints from dark matter and the LHC," Ulrich Ellwanger and Cyril Hugonie, Eur.Phys.J.C 78 (2018) 9, 735

Abstract: A light singlino is a promising candidate for dark matter, and a light higgsino is natural in the parameter space of the NMSSM. We study the combined constraints on this scenario resulting from the dark matter relic density, the most recent results from direct detection experiments, LEP and the LHC. In particular limits from a recent search for electroweak production of charginos and neutralinos at sqrt(s) = 13 TeV after 35.9 fb−1 by CMS and constraints on spin- independent dark matter-nucleon cross sections from XENON1T after one tonne×year exposure are considered. We find that scenarios with higgsino masses below ~ 250 GeV as well as singlino masses below ~ 100 GeV are strongly constrained depending, however, on assumptions on the bino mass parameter M1. Benchmark points and branching fractions for future searches at the LHC are proposed.

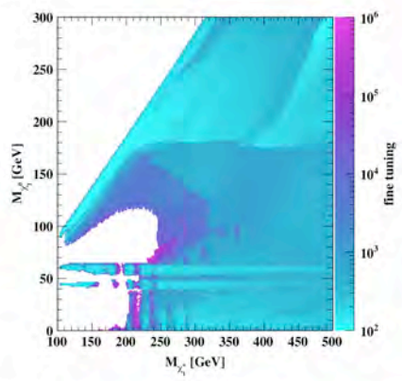
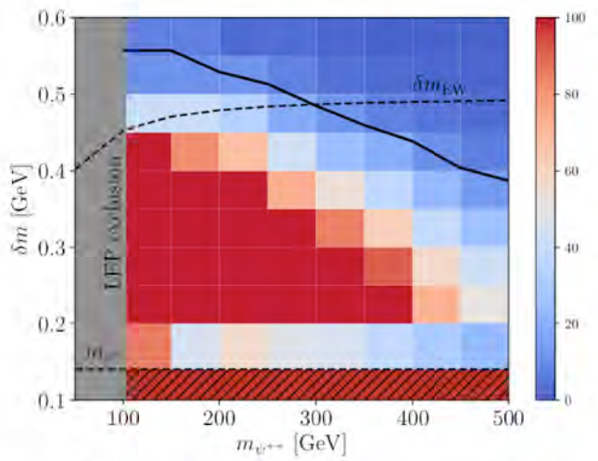


Figure 3: Points with minimal fine tuning in the NUH-NMSSM satisfying the combined constraints from the dark matter relic density, dark matter direct detection and CMS.

"Next-to-minimal dark matter at the LHC," A. Bharucha, F. Brümmer, N. Desai, JHEP 11 (2018) 195.

We examine the collider signatures of a WIMP dark matter scenario comprising a singlet fermion and an SU(2) n-plet fermion, with a focus on n = 3 and n = 5. The singlet and n-plet masses are of the order of the electroweak scale. The n-plet contains new charged particles which will be copiously pair-produced at the LHC. Small mixing angles and near-degenerate masses, both of which feature naturally in these models, give rise to long-lived particles and their characteristic collider signatures. The n = 3 model is further constrained by soft di-lepton searches irrespective of whether any of the new particles are long-lived.



Exclusions from the CMS displaced electron-muon search, as a function of the doubly charged 5-plet mass eigenstate and the mass splitting.

D. Becirevic, A.M. Teixeira

A23