version 1.3, as of 20/01/2014

Interactions Fondamentales, Astroparticules et Cosmologie

Team Overview

C. Hugonie for the team

AERES committee visit

January 20-22, 2014

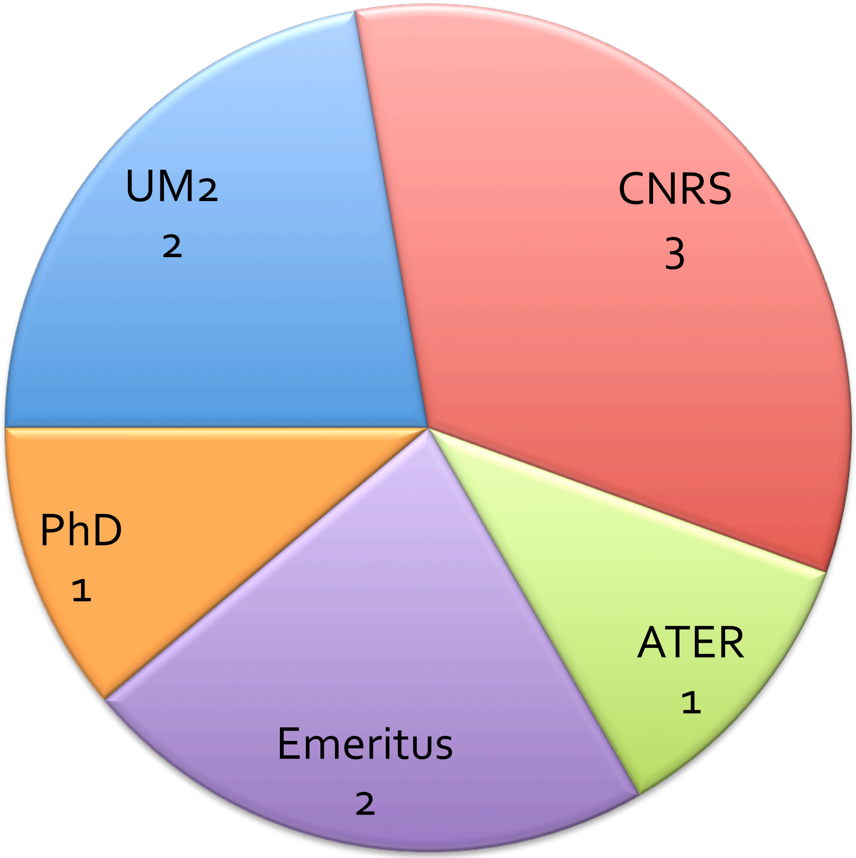
Scientific quality and outputs
Academic reputation and appeal
Interaction with the social, economic and cultural environment
Organization and life
Involvement in training through research
Strategy and the five-year plan

LABORATOIRE MONTPELLIER UNIVERS & PARTICULES

UNIVERSITÉ MONTPELLIER 2 SCIENCES ET TECHNIQUES

Members of the team

As at 30/06/2013



Unit workforce	As at 30/06/13	As at 01/01/15
N1: Permanent professors	2	2
N2: Permanent researchers	3	3
N3: Other permanent staff	0	0
N4: Other professors	1	0
N5: Other researchers	2	4
N6: Other contractual staff	0	0
Doctoral students	1	2
Theses defended	3	3
Post-doc students	1	2
Number HDR taken	0	2
Supervisors with an HDR	2	3

(cf. back up slides for names and details)

- 1 UM2 retired in 2013 (will be "replaced" in 2014)
- 1 ATER left and 2 OCEvU LabEx post-doc started (09/2013)
- 1 OCEvU LabEx PhD will start (09/2014)
- 3 PhD students are (co-)supervised outside (Madagascar, Morocco)

Scientific production

- **Theory and phenomenology beyond the Standard Model**

  Supersymmetric extensions of the Standard Model: minimal (MSSM) and non-minimal (NMSSM). Development of computer codes for spectrum calculation (NMSSMTools). Phenomenology at accelerators (LHC, ILC) and complementarity through dark matter searches. GUT theories. Flavour physics. SUSY and non-SUSY models (Higgs triplet).

- **Astroparticle Physics**

  SUSY dark matter candidates (neutralinos, gravitinos, singlinos). WIMPs and FIMPs. Dark matter direct/indirect detection and sub-halos. Cosmic rays.

- **Cosmology**

  Primordial cosmic magnetic fields. Big Bang Nucleosynthesis and the ^{7}Li problem. Semi-analytical methods in magneto-hydrodynamics. Cosmological simulations.

- **Quantum Chromo Dynamics (QCD)**

  Non perturbative QCD. Spectral sum rules. Computation of hadron spectrum and properties. Precision tests. Implications for LHCb. New states (quark molecules).

- **Quantum Field Theory**

  Formal aspects in Quantum Field Theory. Alternative quantification methods.

Scientific production

- **Collaborations**
  - **Local:** strong interactions with the EMA team and the L2C theory department
  - **Regional**: link with Marseille (CPT, CPPM, LAM) strengthened by LabEx OCEvU
  - **National**: regular collaborations with Annecy, Clermont-Ferrand, Orsay, Paris…
  - **International**: Stanford, Oxford, Marrakech, Madrid, Sao Paulo, Madagascar…
  - **Invitations**: K. Jedamzik spends 1 month/year in Stanford/Berkeley (**1 publication**)
    S. Narison spends 3 month/year in Madagascar (**2 publications**)
    U. Ellwanger (Orsay) comes 2 weeks/year (**2 publications**)…
  - **Co-supervised PhD:** R. Albuquerque (Sao Paulo), J. Ramadan (Marrakech) come 3 m/y
  - **Seminar:** special budget for longer stays (up to 1 week)
- **Publications** (as of 30/06/2013)
  - **35** publications in peer reviewed journals + **2** preprints (papers submitted in 2013)
  - **7** conference proceedings (including QCD12 and HEPMad11)
  - **1** research report (Les Houches 2011) + **4** invited conferences
  - **Total: 45** publications for 5 permanent members + 2 emeritus over **2,5 years**
  - **Topcite:** *Higgs bosons near 125 GeV in the NMSSM with constraints at the GUT scale*
    U. Ellwanger, C. Hugonie, Adv. High Energy Phys. 2012 625389, **74 citations** (15/01/2014)

Visibility and attractiveness

- **National networks**
  - GDR Terascale (1996-2017)
  - PEPS IFAC-CPPM (2010-2011)
  - LabEx OCEvU (2012-2020)
  - Théorie-LHC-France (IN2P3)
- **International networks**
  - LIA ILCP (France-Maroc, 2009-2013)
  - LIA TCAP (France-Russie, 2012-)
  - FAPESP (Sao Paulo, 2010-2012)
  - PICS (Cracow, 2010-2012)
- **ANRJ**
  - *Test et Analyse de la Physique Au-delà du Modèle Standard* (2009-2013)
- **Recruitments**
  - 1 ATER (2012-2013): A. Villanova del Moral
  - 2 OCEvU LabEx post-docs started in 09/13: C. Torero (CPT), S. Diglio (CPPM)
  - 1 CR1 CNRS (commission 02) in 2011: J. Lavalle (+25% permanent since 01/11)
  - 1 MCF section 29 in 2014 (replacement): >50 potential candidates
  - Many CNRS candidates are interested by IFAC (3 out of 10 for CR1/02 in 2013)

Visibility and attractiveness

- **Expertise**
  - LabEx OCEvU: 2 elected members in the Scientific Council
  - Comité de Financement de la Théorie (IN2P3): 1 nominated member
  - Comité ANR SIMI-5: 1 nominated member
  - All members of the team are referees in PhD committees and rank A journals
- **International Conferences**
  - QCD (Montpellier, 2012 & 2014): *130 participants*
  - HEPMad (Madagascar, 2011 & 2013): *60 participants*
  - Lithium in the Cosmos (Paris, 2012): *70 participants*
  - Identification of Dark Matter (Chicago, 2012): *180 participants*
- **National meetings and workshops**
  - Rencontres de physique des particules (Montpellier, 2012): *55 participants*
  - GDR Terascale general meeting (Montpellier, 2013): *53 participants*
  - Cosmic ray physics and dark matter searches (Montpellier, 2012): *20 participants*
  - News from the Dark (Montpellier, 2013): *25 participants*

Outreach activities

- **Popular science:** internships for pupils, lectures in high schools, general public conferences, interviews in the local press/radio…
- **Agora des Savoirs:** Le boson de Higgs, C. Hugonie (2012)
- **Planétarium de Montpellier:** L'énigme de la matière noire, J. Lavalle (2013)
- **Pour la Science (2012):** Les trous noirs de masse intermédiaire, J. Lavalle
- **Fête de la Science (annual):** De l'infiniment petit à l'infiniment grand (2013)

Life of the team

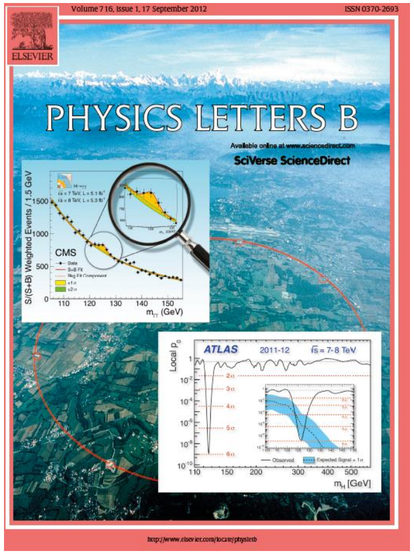
- **Structure**
  - Half of the former IFAC-LPTA team stayed in the LUPM, half moved to the L2C theory department
  - At present: 4 permanent staff, 1 long term visitor, 2 emeritus, and 1 PhD (+2 shared post-docs)
  - 1 person in charge, centralising administrative/scientific issues (C. Hugonie)
- **Representation in steering committees**
  - **Comité de direction:** regular meetings to discuss budget, projects, job profiles, etc…
  - **Conseil de laboratoire:** 2 members (C. Hugonie, K. Jedamzik), 4 meetings/year
  - **Conseil Scientifique:** 1 member (J. Lavalle), 2 meetings in 2013
- **Scientific animation**
  - **Common seminars with L2C:** ~30 seminars/year in 2011-2013, 2/week scheduled for early 2014
  - **Weekly journal club** (common with L2C): recent papers, new ideas, informal talks with guests
  - **Journées du labo:** future projects, job profiles, share with other teams (+invited L2C members)
- **Premises:** Offices shared with the L2C theory department (bat. 13, 1st floor)
- **Access to shared resources:** Computing grid (MSFG)
- **Web page:** 1 person in charge for the team (J. Lavalle)

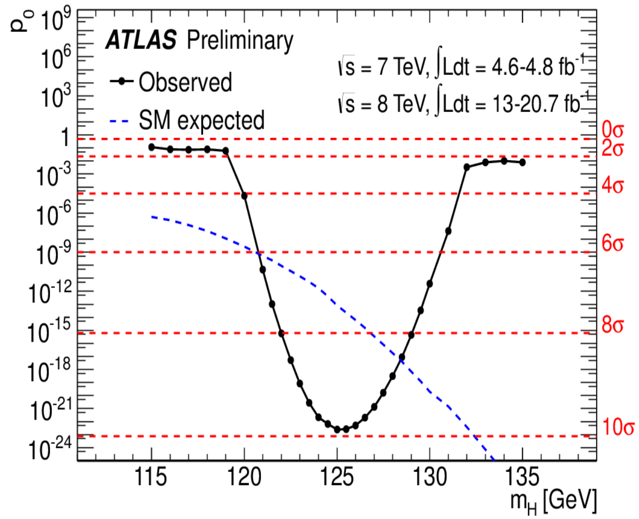
Training through research

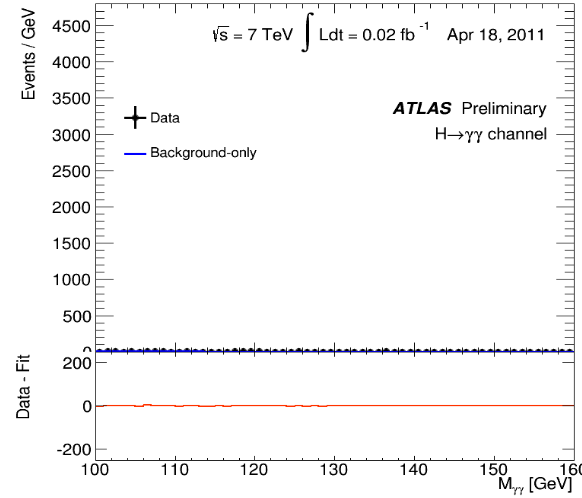
- **Master Cosmos Champs et Particules (CCP)**
  - Average per year: **10** students including **1** Erasmus, leading to **7** PhDs
  - **Responsibility of the Master** + **training courses** (M1 and M2)
    + **Physique des Hautes Energies** (M1 and M2): C. Hugonie
  - **Physique Quantique Avancée** (M1): M. Capdequi-Peyranère
  - **Matière Noire** (M2): J. Lavalle
- **Summer schools**
  - **African School of Physics:** S. Narison (international committee)
  - **École de Physique des Astroparticules:** J. Lavalle (scientific committee)
  - **École de GIF de Physique:** C. Hugonie (organisation committee), J. Lavalle (2013)
- **Number of PhD students: 7**
  - **4** (co-)supervised in LUPM of which **3** were defended + **3** (co-)supervised outside
  - **1** shared OCEvU LabEx PhD will start in 09/2014 (with CPPM)
  - Dedicated budget for summer schools and national/international conferences
  - Participation to outreach activities of the team (eg Fête de la Science)

Scientific context

- **A major discovery was announced on the 04/07/2012**







Results presented in Moriond (03/2013)

- **A new boson with mass ~ 125.6 GeV has been observed!**

Results confirmed by Tevatron (competitive on bb, excess in γγ)

➢ **Is it the Higgs boson predicted by the Standard Model?**

✓ Check its spin/parity (0^+), no surprise is expected

✓ Check its production/decay modes (its couplings)

✓ Check the Higgs mechanism (its self coupling λ)

Beyond the Standard Model

- (Almost) everything seems to indicate that the SM is correct. It is a renormalisable theory. Is it the end of the story?
- **Or is there New Physics at a scale $\boldsymbol{\Lambda_{NP}}$?**
  - ☐ Triviality ($\lambda<+\infty$): no information on Λ_{NP} ($>\Lambda_{Planck}$)
  - ☐ Stability ($\lambda>0$): our (electroweak) vacuum is meta-stable…
  - ☑ Quantum gravity: new paradigm beyond Λ_{Planck}
  - ☑ Baryogenesis: electroweak phase transition not strong enough
  - ☑ Dark matter: no candidate in the Standard Model
  - ☑ Flavours: neutrino masses, families, mass hierarchy?
  - ☑ GUT theories: imperfect unification, proton decay too fast
- **New Physics $\Longrightarrow$ Hierarchy problem:** $\boldsymbol{\delta M_h^2 \sim \Lambda_{NP}^2}$

Supersymmetry (SUSY)

- **New symmetry between bosons and fermions**
- Minimal SUSY extension of the Standard Model (MSSM):
  - SM fermions (quarks , leptons) ⇔ sfermions (spin 0)
  - Gauge and Higgs bosons ⇔ gauginos, higgsinos (spin ½)
  - 2 Higgs doublets ⇒ 2 scalars, 1 pseudo-scalar, 1 charged Higgs

☑ **Technical solution to the hierarchy pb**: $\delta M_h^2 \sim m_B^2 - m_F^2$

☑ **Coherent GUT theories** ($\Lambda_{GUT} \sim 10^{16}$ GeV, $\tau_{proton} > 10^{32}$ years)

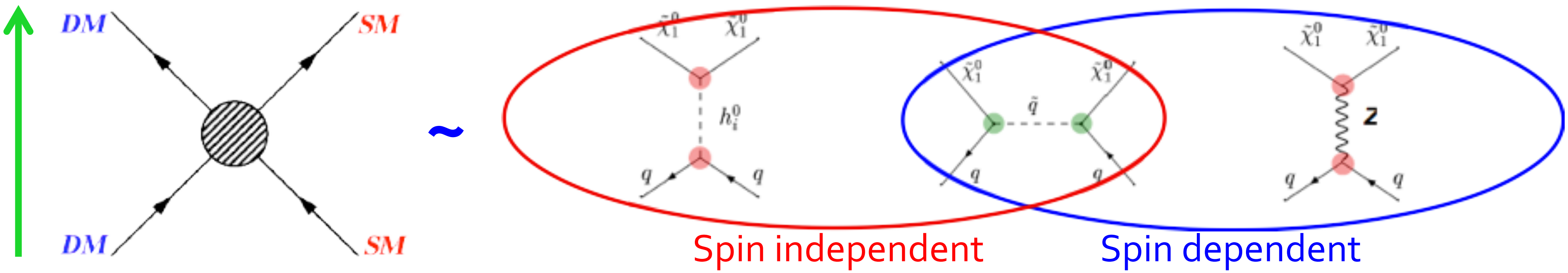
☑ **Possible baryogenesis** (1^{st} order phase transition)

☑ LSP (Lightest SUSY particle) = **dark matter candidate (WIMP)**

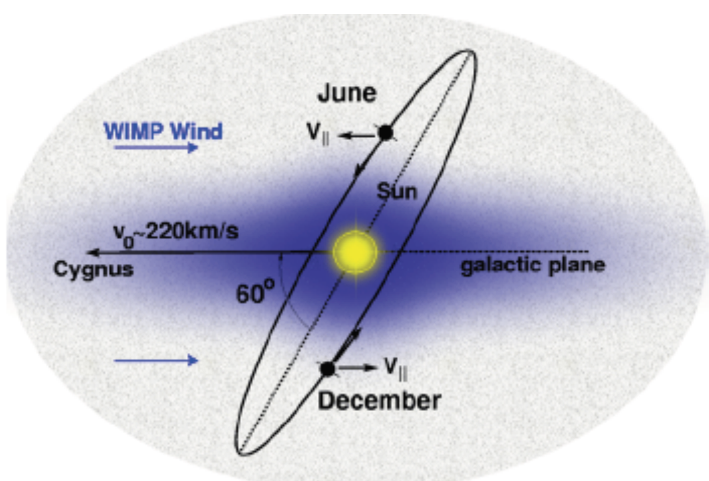
➢ **Design and evolution of the code NMSSMTools:** properties of (s)particles in the Next-to-Minimal SUSY model (C. Hugonie)

➢ **Collaboration with ATLAS-CPPM:** 1 post-doc + 1 PhD LabEx OCEvU

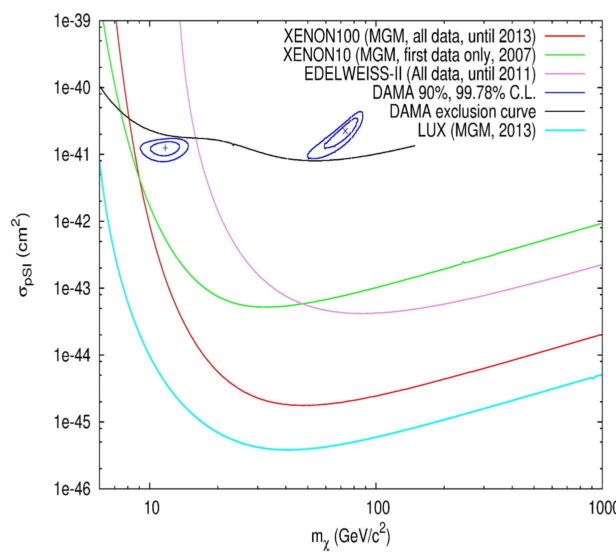
Dark matter: direct detection



Study of astrophysical uncertainties: halo shape, earth velocity resp. to the halo, WIMPs escape velocity + complementarity with indirect detection (J. Lavalle, S. Magni)

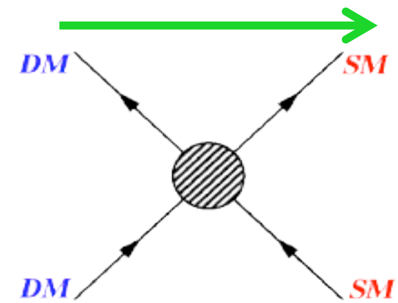


⇒ Development of a code to reproduce experimental results as a function of astrophysical hypothesis and make prediction for the next generation detectors

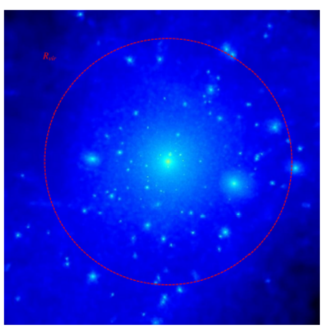


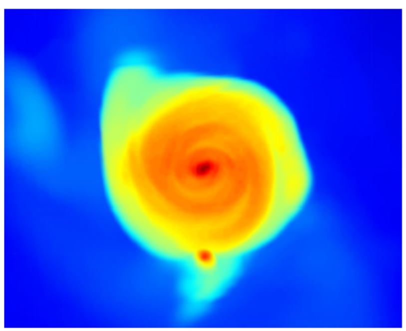
Collaboration with L. Lellouch (CPT, Marseille): **study of nuclear uncertainties** for the computation of σ_p (Lattice QCD) ⇒ post-doc LabEx OCEvU (C. Torrero)

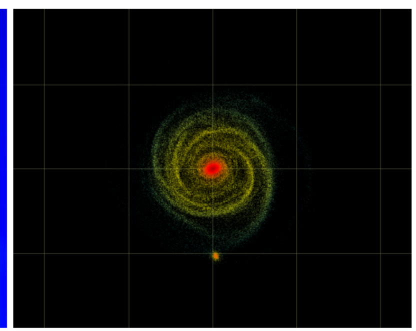
Dark matter: indirect detection



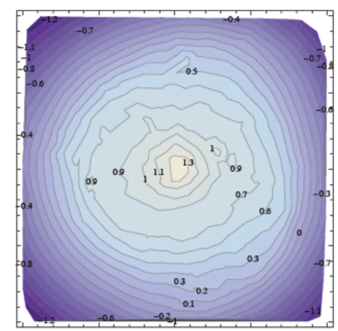
- **WIMPs annihilation in the galaxy:** production of photons, electrons, positrons, (anti)protons…
- Local expertise on γ ray detection (HESS, Fermi, CTA)
- Expertise on anti-matter cosmic rays + sub-halos: J. Lavalle
- Collaboration with E. Nezri (LAM, Marseille) and R. Teyssier (CEA Saclay): **cosmological simulations including cosmic rays** and multi-wavelength associated signals ⇒ study of the WIMPs signal over astrophysical noise


WIMPs

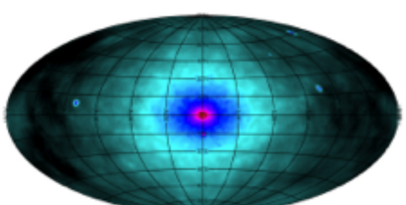

gas

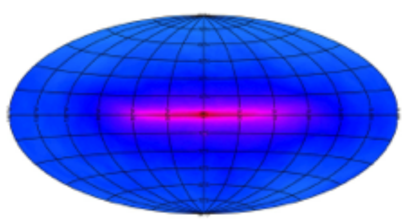

stars + SNRs

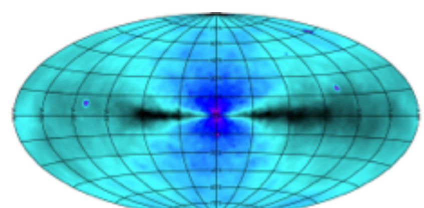
+


rayons cosmiques

=

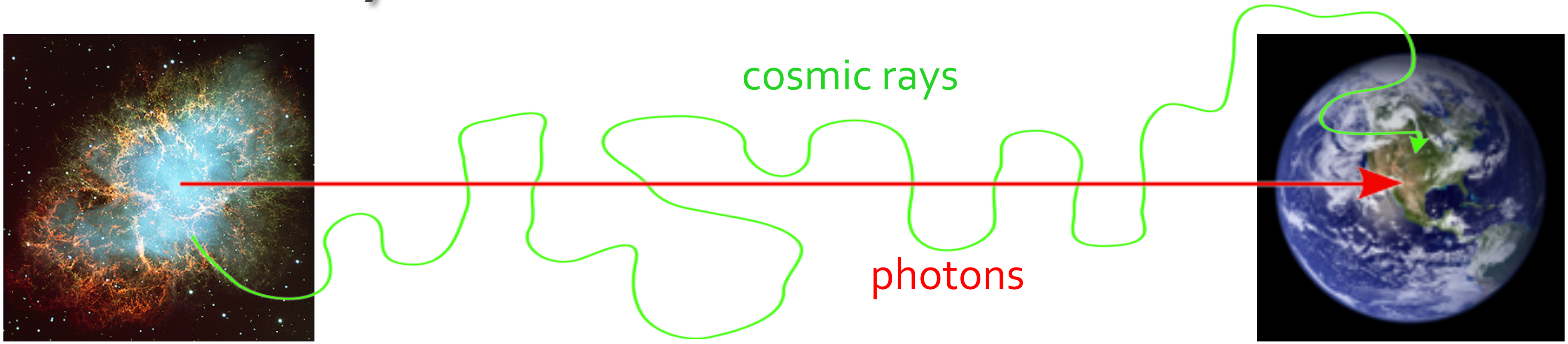

signal

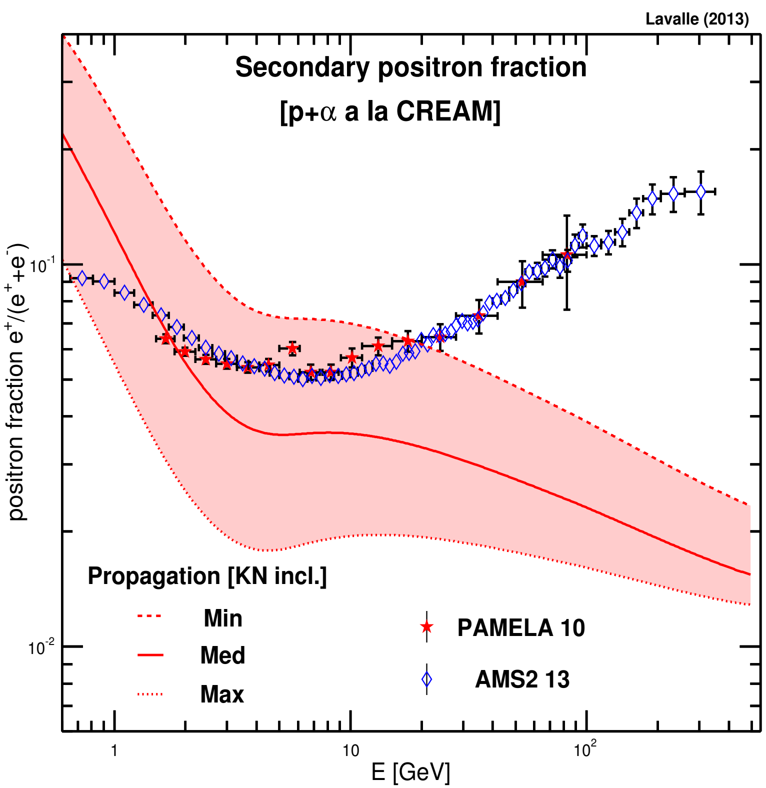

noise


ratio

Diffuse emission (from radio to gamma rays)

Cosmic rays





- **Modelling of local e^+e^- sources:**

  ⇒ High energy positron excess

  Study of the coupled evolution of cosmic rays magnetic fields (J. Lavalle + EMA)

- **Cosmic ray propagation** (J. Lavalle)**:**

  Magnetic fields (+K. Jedamzik, A. Marcowith)

  Diffuse emission (+HESS, Fermi, CTA)

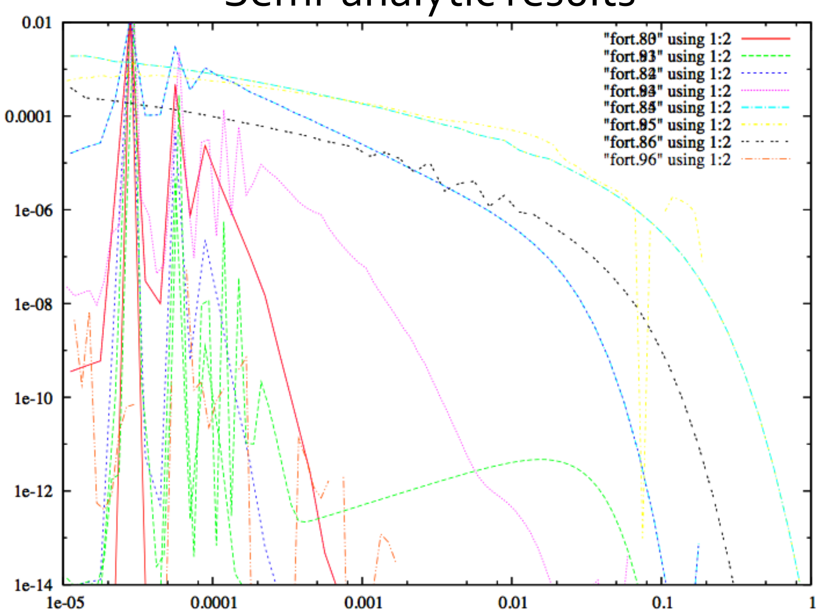
  Study of anisotropies (+P. Salati)

  Constraints from AMS data (+D. Maurin)

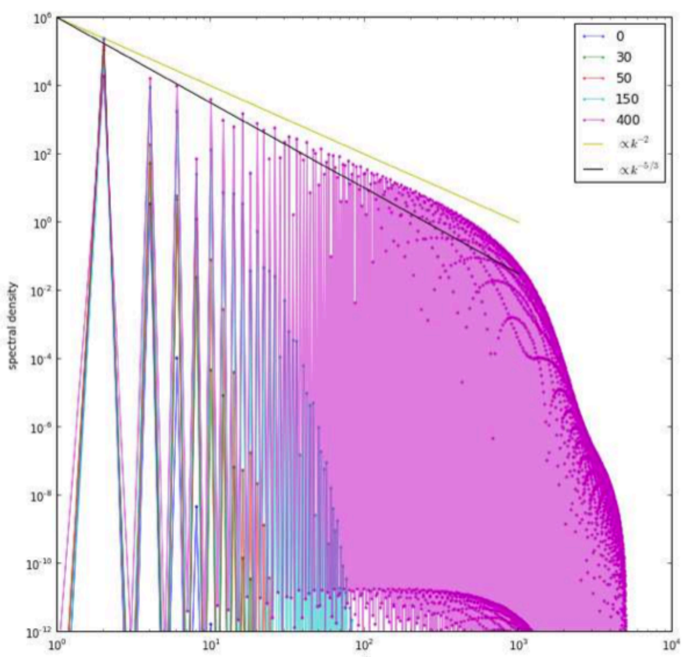
MHD semi-analytical methods

- **Semi-analytical methods in Magneto-Hydro Dynamics**: developed by K. Jedamzik so as to predict the evolution of astrophysical and cosmological fluids, with applications to cosmic rays/magnetic fields (interface with EMA/AS)
- Precise predictions over large dynamical ranges:

Semi-analytic results



Numerical simulation



Non-perturbative QCD

- **QCD sum rules methods:** invented in ’79 by M. Shifman, A. Vainshtein and V. Zakharov, developed by S. Narison
- Link quantities in perturbative and **non-perturbative QCD** (difficult to compute) with **experimentally measured quantities**: $e^+e^- \rightarrow$ hadrons cross section, τ decay width…
- Allows to compute **perturbative parameters** (α_S, m_s, m_c, m_b), **non-perturbative quantities** (quark or gluon condensates), **light hadrons properties** (scalar meson masses), **heavy hadrons properties** (B and D mesons decay constants) and **new states** (quark molecules)
- **Comparison with lattice QCD** (+ L. Lellouch, CPT-Marseille)
- **Comparison with AdS/CFT** (+ F. Jugeau, Rio de Janeiro)
- **Collaboration with experimentalists** (LHCb)

S.W.O.T.

Strengths and weaknesses

- Strong tradition in **particle physics phenomenology** covering hadron physics, the Higgs sector and Beyond the Standard Model physics
- Design and evolution of **public tools** to explore the phase space of SUSY
- A world-class expertise on the study of the **primordial universe**
- Opening towards astroparticle physics, through the study of **dark matter**, leading to fruitful interactions with the members of the EMA team
- **Small number** of (non-)permanent staff

Opportunities and threats

- Recruitment of a **Maître de Conférence** in 2014 will strengthen the group
- **Various sources of funding** (LabEx OCEvU, IN2P3 theory projects, LIA ILCP)
- Strong **links with experimentalists** (GDR Terascale and LabEx OCEvU)
- Close relations with the **theory department of L2C**

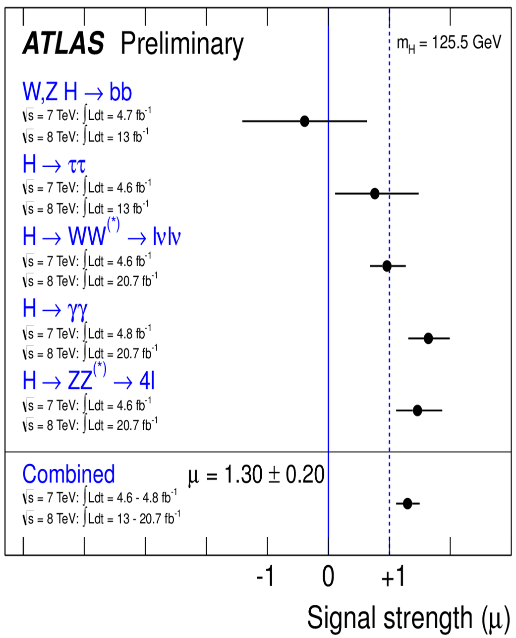
Back up

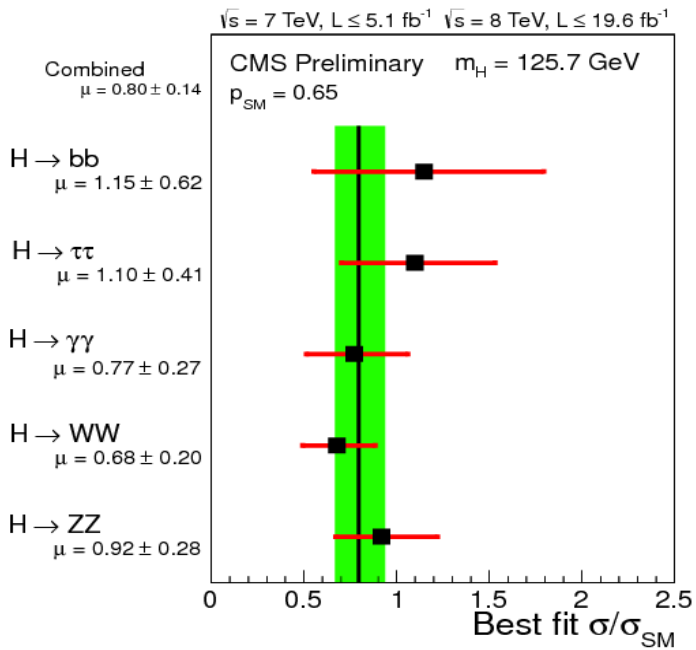
Members of the team (details)

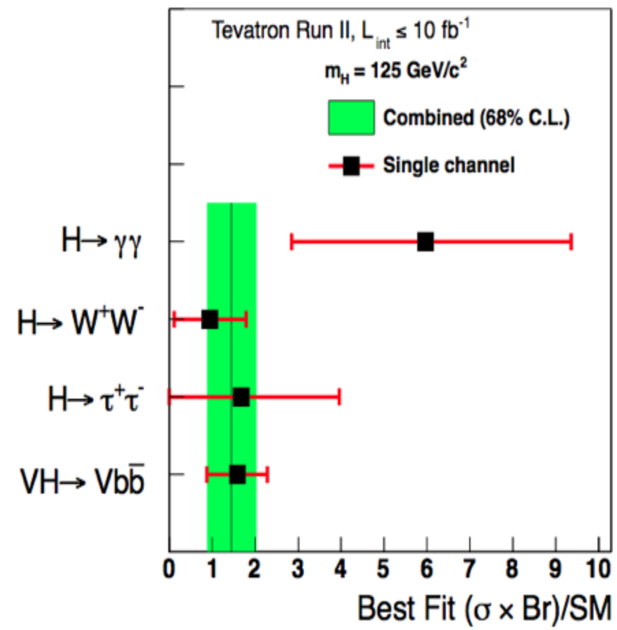
- **Permanent staff: 5**
  - Julien Lavalle: CR1 (HDR in preparation)
  - Karsten Jedamzik: CR1
  - Stephan Narison: DR1 HDR
  - Cyril Hugonie: MCF (HDR in preparation)
  - Michel Capdequi-Peyranère: MCF HDR (retired in 09/2013)
- **Associates: 2**
  - Pierre Grangé: emeritus
  - Fernand Renard: emeritus
- **Post-docs: 3**
  - A. Villanova del Moral: post-doc IN2P3/ATER (2009-2013)
  - 2 OCEvU LabEx shared post-docs started in 09/13: C. Torero (CPT), S. Diglio (CPPM)
- **PhD students: 7**
  - B. Mutet: co-supervised by P. Grangé, J. F. Mathiot (LPC Clermont), defended 01/2011
  - G. Espitalier-Noël: co-supervised by C. Hugonie, J.L. Kneur (L2C), defended 11/2012
  - R. Albuquerque: co-supervised by S. Narison, M. Nielsen (Sao Paulo), defended 02/2013
  - S. Magni: supervised by J. Lavalle, since 2012
  - J. Ramadan: co-supervised by M. Capdequi-Peyranère, M. Chabab (Marrakech), since 2009
  - A. Rabemananjara, F. Fanomezana (Madagascar): supervised by S. Narison, since 2010

Higgs decay channels

Observed in various channels: $\mu_i = \frac{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{observed}}{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{SM}}$



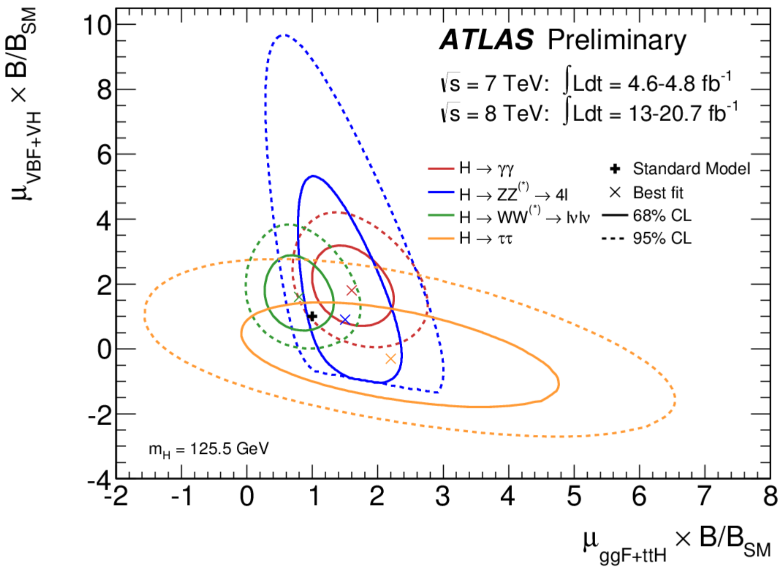


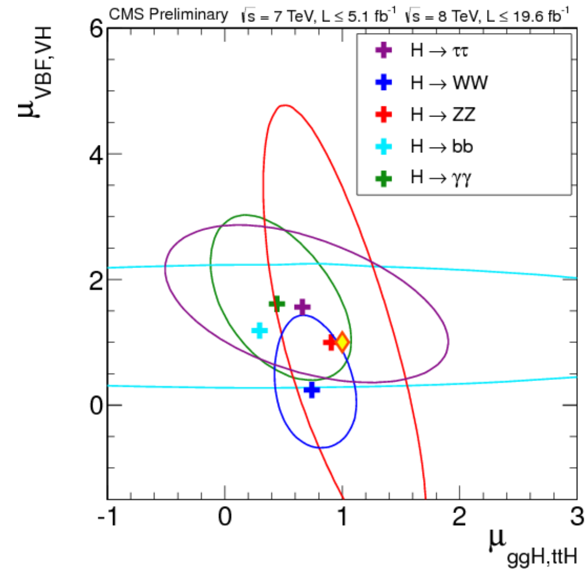


But: new physics can also modify the Higgs production modes

Higgs production modes

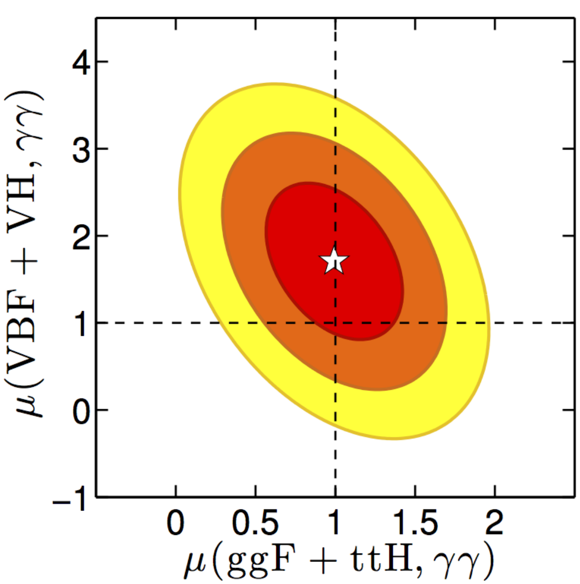
- The most useful results from ATLAS and CMS

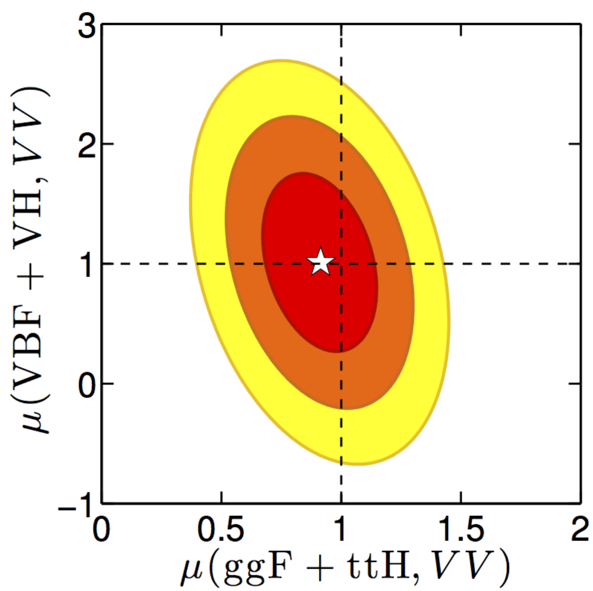




- Combination by B. Dumont (ex Master CCP), S. Kraml, G. Bélanger, U. Ellwanger, J. Gunion

- **In progress:** fit of the (N)MSSM parameters





Minimal SUSY model (MSSM)

- Historical topic, initiated by F. Renard
  - Determination of $\tan\beta$ ($= v_u/v_d$) through $A_{LR}(t)$ in $bg \rightarrow tH^-$ at the LHC
  - Determination of R_{bb} through $A_{LR}(Z)$ in $bg \rightarrow bZ$ at the LHC
  - Supersimplicity: SUSY confers a remarkable helicity conservation property to electroweak diffusion amplitudes at high energy. Use of $gg \rightarrow VV'$ or $\chi\chi'$ (LHC) and $e^+e^- \rightarrow tt$ or W^+W^- (ILC) as a test of SUSY/SM.
- **SuSpect public code:** widely used by the community
  - Computes (s)particles masses and couplings starting from SUSY breaking parameters at the GUT scale (Renormalisation Group Eqs.)
  - Developed in Montpellier by A. Djouadi, J.L. Kneur, G. Moultaka ('96)
  - Translated to C++ in collaboration with M. Ughetto (PhD L2C/CPPM) and D. Zerwas (LAL): automated calculations, flexibility (new models)

Next-to-minimal model (NMSSM)

- **Extended Higgs sector:** 2 doublets H_u, H_d + 1 singlet S
- **Solution to the MSSM μ problem:** $\mu \sim \Lambda_{weak} \sim \Lambda_{Susy}$?
  - $\mu = 0$ is experimentally excluded, $\mu = \Lambda_{planck} \Rightarrow$ hierarchy problem
  - Replacing $\mu H_u H_d$ by $\lambda S H_u H_d$: after EW symmetry breaking $\mu_{eff} = \lambda \langle S \rangle \sim \Lambda_{weak}$
- **Richer phenomenology** (+2 Higgs states, +1 singlino)
  - singlino LSP $\Rightarrow$ additional cascade in sparticle productions
  - Very light (singlet) Higgs not excluded by LEP (difficult to see at the LHC)
  - Mass of lightest Higgs doublet higher than in the MSSM (< M_Z at tree level)
- **Public code NMSSMTools**: C. Hugonie, U. Ellwanger (LPT-Orsay)
  - **Study of the impact of the non-observation of sparticle at the LHC** (C. Hugonie, G. Espitalier-Noël): less fine-tuning than in the MSSM
  - **125 GeV Higgs state with an enhanced γγ rate** can be obtained naturally together with a possible lighter Higgs state (C. Hugonie, U. Ellwanger)
  - **Will it be possible to detect this new Higgs boson at the LHC new run?**

Composite models

- To protect the Higgs mass, one can suppose it is not a fundamental state but a **composite state** $(h \sim \psi\overline{\psi})$
- **Idea coming from QCD** where light scalar states exists with no hierarchy problem: $m_\pi < \Lambda_{QCD} << \Lambda_{Planck}$ ⇔ appear for $\alpha_S >> 1$

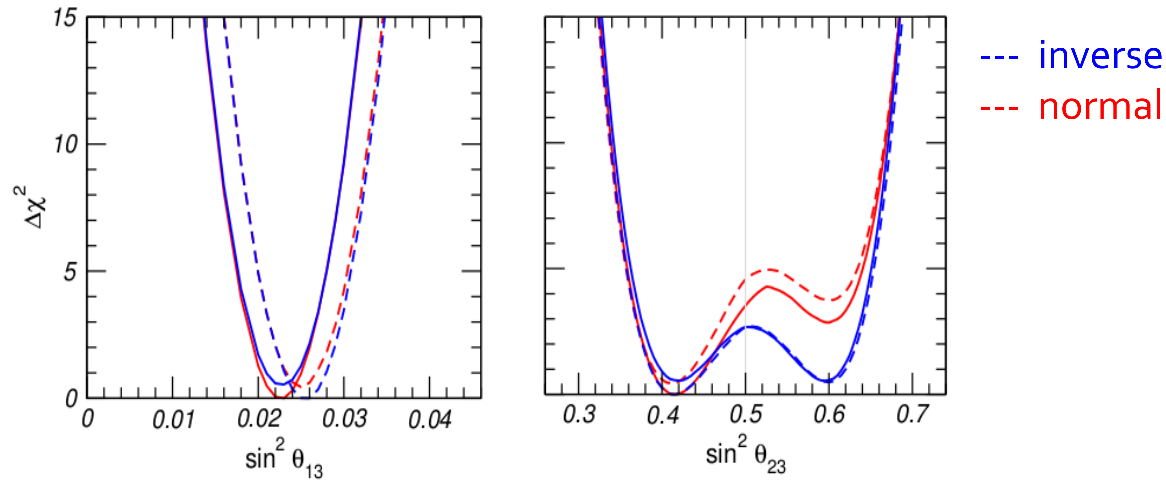
  QCD + (u,d): accidental global symmetry $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$ broken by $\langle q\bar{q} \rangle \neq 0$

  ⇒ 3 Goldstone bosons (π) but $m_\pi \sim m_q$ because m_q breaks explicitly $SU(2)_L \times SU(2)_R$
- One assumes that the Higgs is a **pseudo-Goldstone** of a global symmetry broken by a new strong interaction condensate
  - **Minimal model:** $SO(5) \rightarrow SO(4)$, 4 Goldstone bosons = 1 Higgs doublet h
  - **Dark matter:** $SO(6) \rightarrow SO(5)$, 5 Goldstone bosons = 1 doublet h + 1 singlet η
- M. Frigerio, J.L. Kneur, N. Bizot (PhD LabEx OCEvU L2C/CPT)

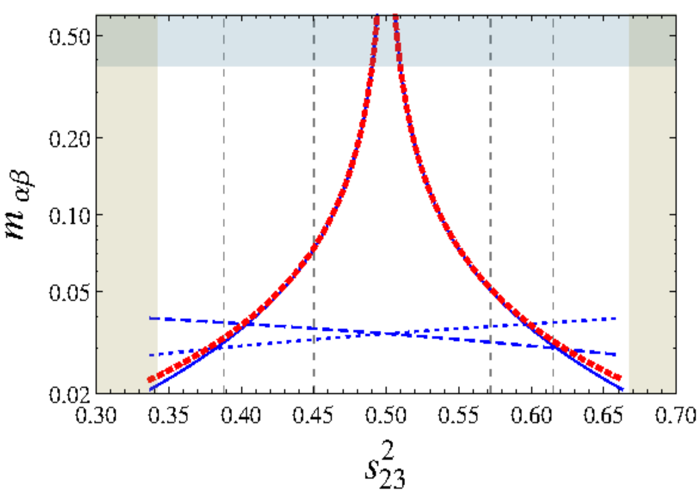
  + collaboration with ATLAS-CPPM, LabEx OCEvU post-doc (S. Diglio)

Neutrino masses

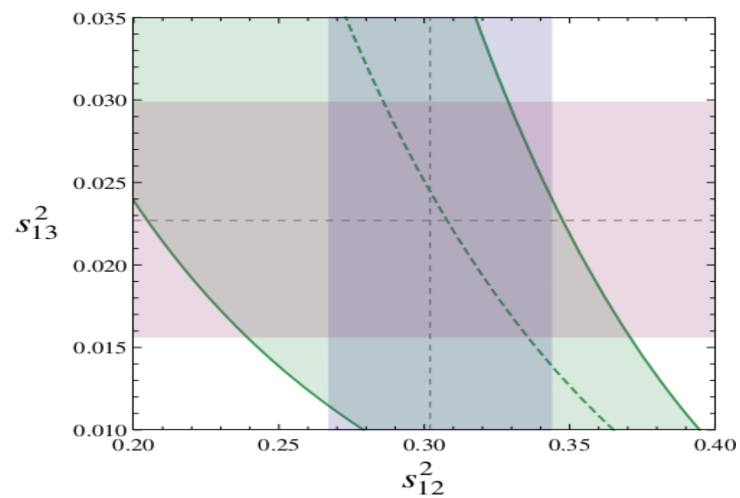
- Daya Bay (2012) : $\theta_{13} \neq 0$
  $\Rightarrow$ exp. fits: $\theta_{23} \neq 45°$
  Predictions: $\theta_{23} = 45°$
- **Models to reproduce this with Q_6, A_4 symmetries**
  (M. Frigerio, A. Villanova)



- $$m = \begin{pmatrix} a & b & c \\ b & 0 & d \\ c & d & 0 \end{pmatrix}$$



- $$m = \begin{pmatrix} a & b & c \\ b & a & d \\ c & d & a \end{pmatrix}$$



Higgs triplet

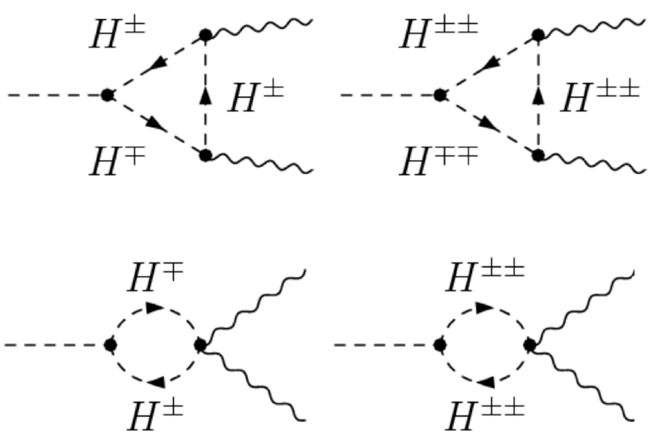
- Appears in neutrino mass models (type II see-saw):

$$\mathcal{L}_{Yukawa} \supset L^T C \otimes i\sigma^2 \Delta L \quad \text{where } Y_\Delta = 2 \Rightarrow \Delta = \begin{bmatrix} \delta^+ & \delta^{++} \\ \delta^0 & -\delta^+ \end{bmatrix} + \text{Higgs doublet } H = \begin{bmatrix} \phi^+ \\ \phi^0 \end{bmatrix}$$

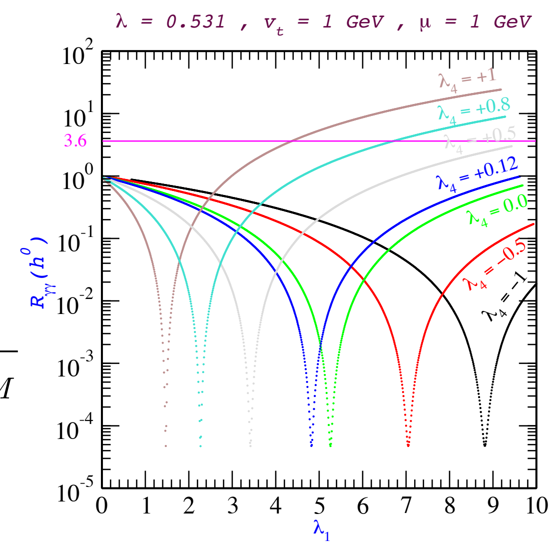
- The model contains 8 parameters, 1 being fixed par M_Z (7 free parameters):

$$V(H,\Delta) = -m_H^2 H^\dagger H + M_\Delta^2 Tr(\Delta^\dagger \Delta) + [\mu(H^T i\sigma^2 \Delta^\dagger H) + \text{h.c.}] + \frac{\lambda}{4}(H^\dagger H)^2$$
$$+\lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) + \lambda_2 (Tr \Delta^\dagger \Delta)^2 + \lambda_3 Tr(\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H$$

+ 7 physical states (h, H, A, $H^\pm$, $H^{\pm\pm}$) contributing to $h \to \gamma\gamma$:



$$R_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}}$$



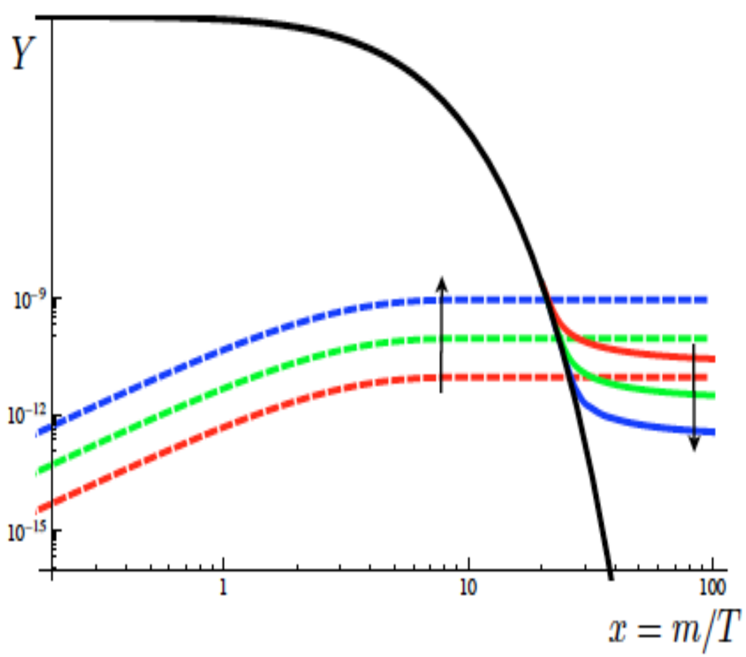
(M. Capdequi-Peyranère, J. Ramadan)

FIMPs: freeze-in

- **Freeze-in:** new mechanism to produce dark matter implying **FIMPs** = **Feebly Interacting Massive Particles,** proposed by K. Jedamzik, L. Hall (Berkeley), S. West, J. March-Russel (Oxford)

- In primordial universe: FIMPs out of thermal equilibrium, but residually produced

$$\frac{dY_\chi}{dx} \propto -\langle \sigma v \rangle \left\{ \cancel{Y_\chi^2} - Y_{\rm eq}^2 \right\}$$



- The stronger the interactions, the larger the FIMPs relic density (as opposed to freeze-out)
- **Various scenarios:** dark matter is either made of FIMPs or comes from its decays
  - Metastable charged particles at LHC ?
  - FIMP decays during BBN (^{7}Li solution)?
  - Enhanced indirect production?
- **The NMSSM singlino could be FIMP?** (C. Hugonie, K. Jedamzik, S. West)

Primordial magnetic fields

Assuming magnetic fields on 1 kpc and of 10^{-11} G at recombination time

- Density fluctuations (up to ~1) for baryons/electrons are generated
- Effects on recombination time and CMBR, measurable by Planck
- Actual limits on such fields ~ 10^{-9} G for large scale fields (~ 10 Mpc)