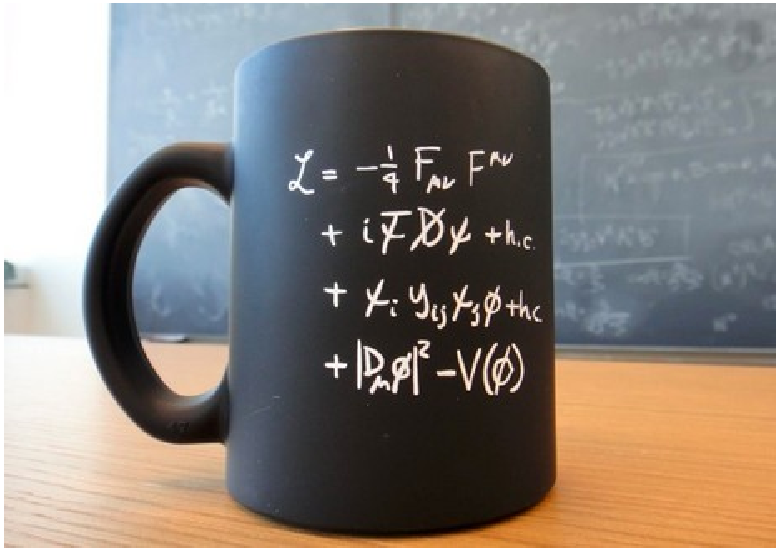
The CMS group at IPHC

(et sujets de stages/thèses)

Jeremy Andrea,
On behalf of CMS-IPHC group

The status of the SM

- The SM was successfully validated by many experimental measurements performed over many years.



- The LHC results have even more consolidated the SM :
  - with new extremely precise measurements,
  - with the discovery of predicted SM processes/particles : the Higgs boson is the brightest example.

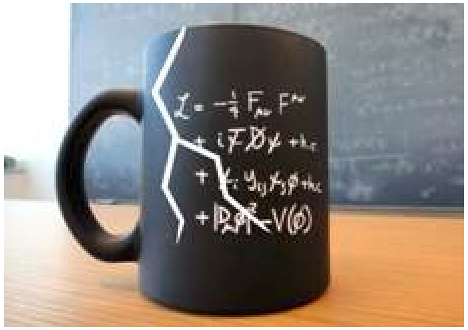
- However the MS is incomplete!

- There are new (elementary) particles to be found !

- One of the goals of the LHC : probe SM physics and find new physics.

Beyond the Standard Model

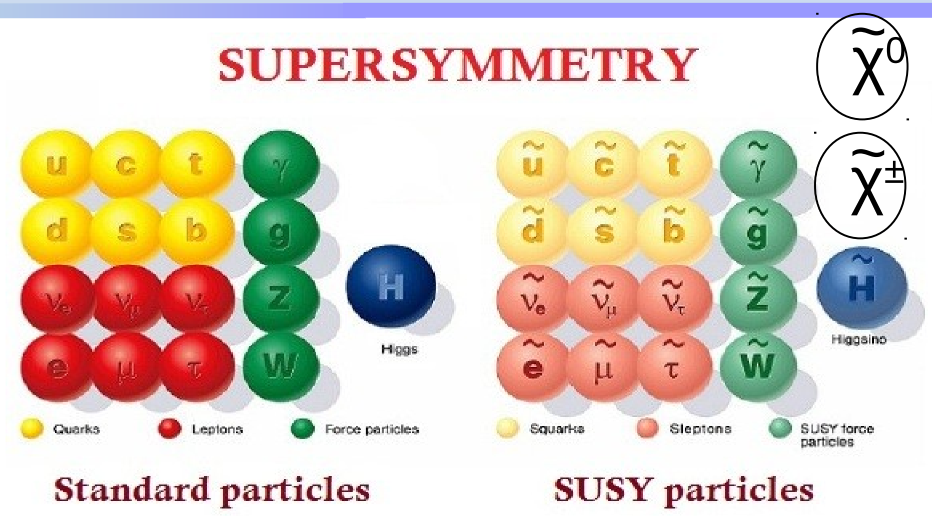
- Despite it's successful predictions, the SM suffers from limitations/imperfections :
  - Not predicting the Dark Matter (DM) nor the Dark Energy,
  - No explanation for matter/antimatter asymmetry,
  - No massive neutrinos,
  - No explanation for the observed hierarchy of masses,
  - “Unstable” Higgs mass and fine tuning,
  - Not compliant with the GUT,
  - Etc...



- Many models on the market, proposing solutions to these “problems” :
  - Super-symmetry (SUSY),
  - Extra-dimension, Higgs compositness
  - etc...

- How can we search for New Physics at colliders ?
  - Direct searches of new particles ! Many (almost infinite number of) channels, model dependent but has the best sensitivity.
  - Indirect searches ! Re-interpretation of precision measurements (anomalous couplings, close signatures) or suppressed processes.

Direct searches : Supersymmetry



Good features of SUSY:

- Propose a candidate for Dark Matter
- Solve the hierarchy problem
- Unification of the couplings at high energy
- It's a generic concept (add a boson/fermion symmetry).
- There are many SUSY models.
- Number of parameters range from 5 (more constrained) to > 100

- Susy has an extended Higgs sector => can be revealed by observing new Higgs bosons.
- SM : Higgs field is a complex $SU(2)_L$ doublet, choose minimum → one scalar Higgs field, give mass to bosons and fermions (Yukawa),
- SUSY : needs at least 2 Higgs doublets, more Higgs boson and Higgs-Higgs couplings.
  - MSSM : 2 scalars, 1 neutral pseudo-scalars and 2 charged Higgs,
  - N-MSSM : 3 scalars, 2 neutral pseudo-scalars and 2 charged Higgs

	Names	Spin	P_R	Mass Eigenstates	Gauge Eigenstates
MSSM	Higgs bosons	0	+1	$h^0\ H^0\ A^0\ H^\pm$	$H_u^0\ H_d^0\ H_u^+\ H_d^-$
N-MSSM				$H_1, H_2, H_3\ A_1, A_2\ H^+, H^-$	$H_u^0\ H_u^+\ H_d^0\ H_d^-\ S$

Model independent searches

- Model independent search :
  - Search for deviations from SM predictions <=> precision measurements,
  - Search for processes that are not existing in the SM (with no new particles involved at tree level).

- Effective field theory approach :
  - New particles contributes at the loop level,
  - If the new particles are heavy => modelled as “effective” new vertex that links only SM particles.

- Example : Flavour Changing Neutral Current
  - Highly suppressed in the SM because of the GIM mechanism,
  - Largely enhanced in many new physics models.

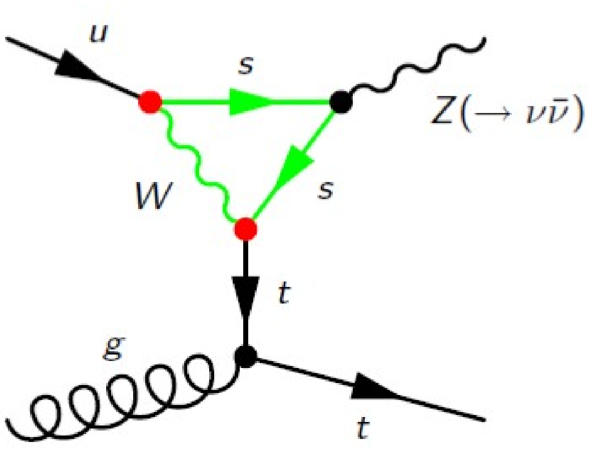


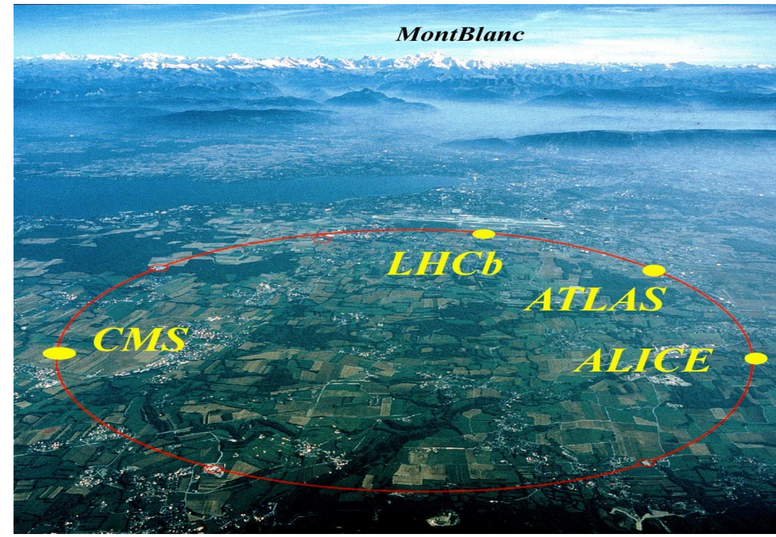
TABLE I. Branching ratios for FCNC decays of the top quark in the SM and several possible extensions: the quark-singlet model (QS), the two-Higgs doublet model (2HDM), the minimal supersymmetric model (MSSM) and supersymmetry (SUSY) with R-parity violation. See Refs. [14,15] for details.

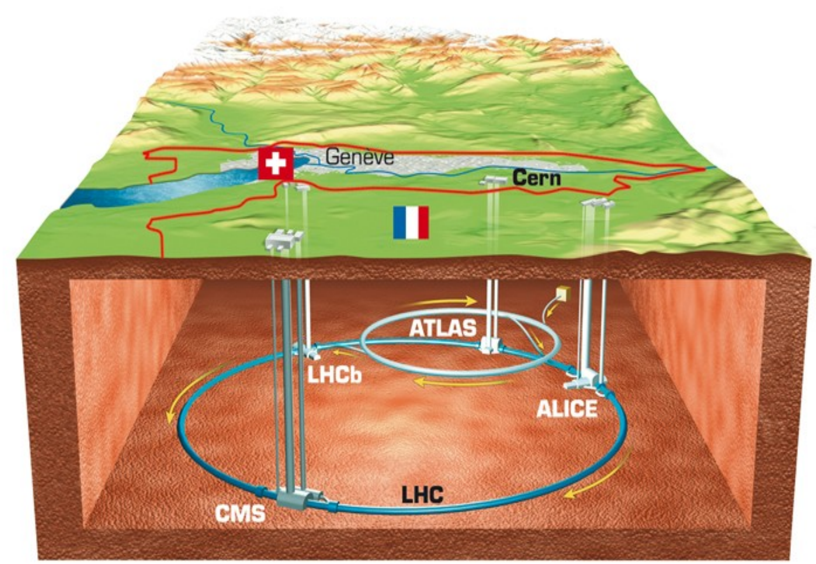
Process	SM	QS	2HDM	MSSM	$\not R$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	$\cdots$	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	$\cdots$	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	$\cdots$	8×10^{-5}	2×10^{-4}
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	8×10^{-5}	2×10^{-4}

Experimental setup

The Large Hadron Collider

- CERN is one of the largest laboratories in the world, located in the Franco-Swiss border.
- One of the biggest European institutions (20 countries).
- It involves about 10000 scientists from all over the world.
- Large Hadron Collider : the most powerful accelerator of particles => colliding protons at 7/8 and now 13 TeV.
- Four experiments/collaborations to detect particles:
  - Two multi-purpose experiments : ATLAS and CMS.
  - ALICE : studying “dense” collisions (Lead-Lead).
  - LHCb : study of matter-antimatter asymmetries.



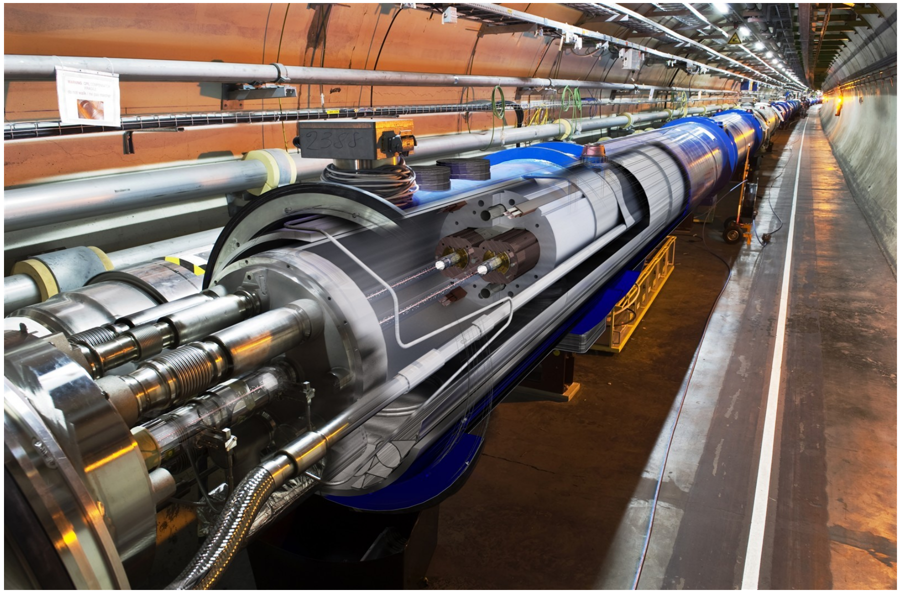


The LHC in numbers

- LHC is (mainly) composed of :
  - Accelerating cavities, to accelerate protons.
  - >9000 magnets, providing a B field of 8.5 T, to bend the proton beams.

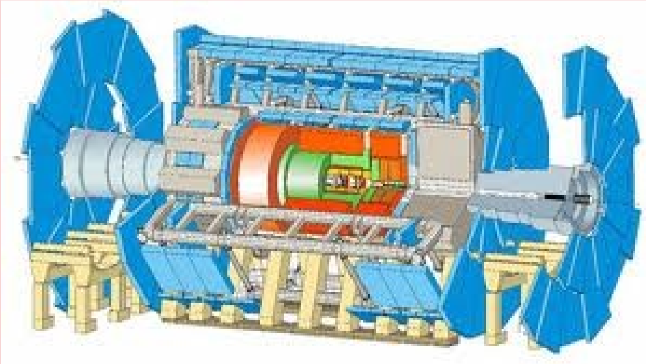
- Colliding protons (heavy ions) underground (-100 m), 27km long.
  - First 7 TeV collisions in 2010, then 8 TeV, stopped fall 2012 for maintenance.
  - Long shutdown ongoing, 13 TeV collisions started in 2015.

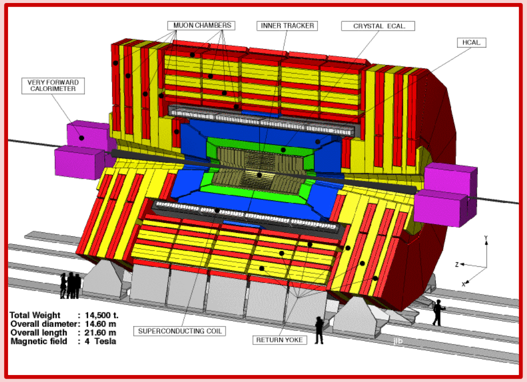
- 25 years of developments and construction.

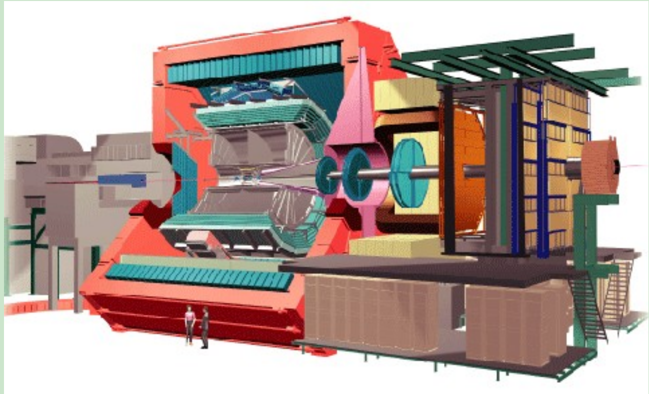


The LHC experiments

- ATLAS and CMS : multi-purpose detectors (SM, Higgs, new physics).

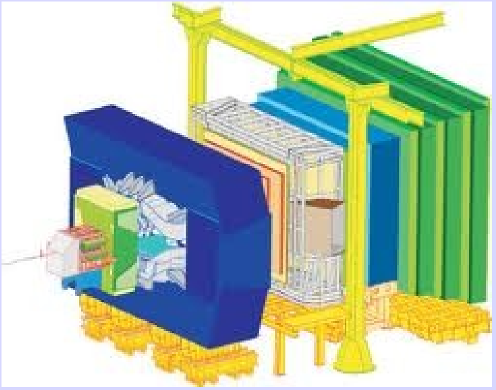




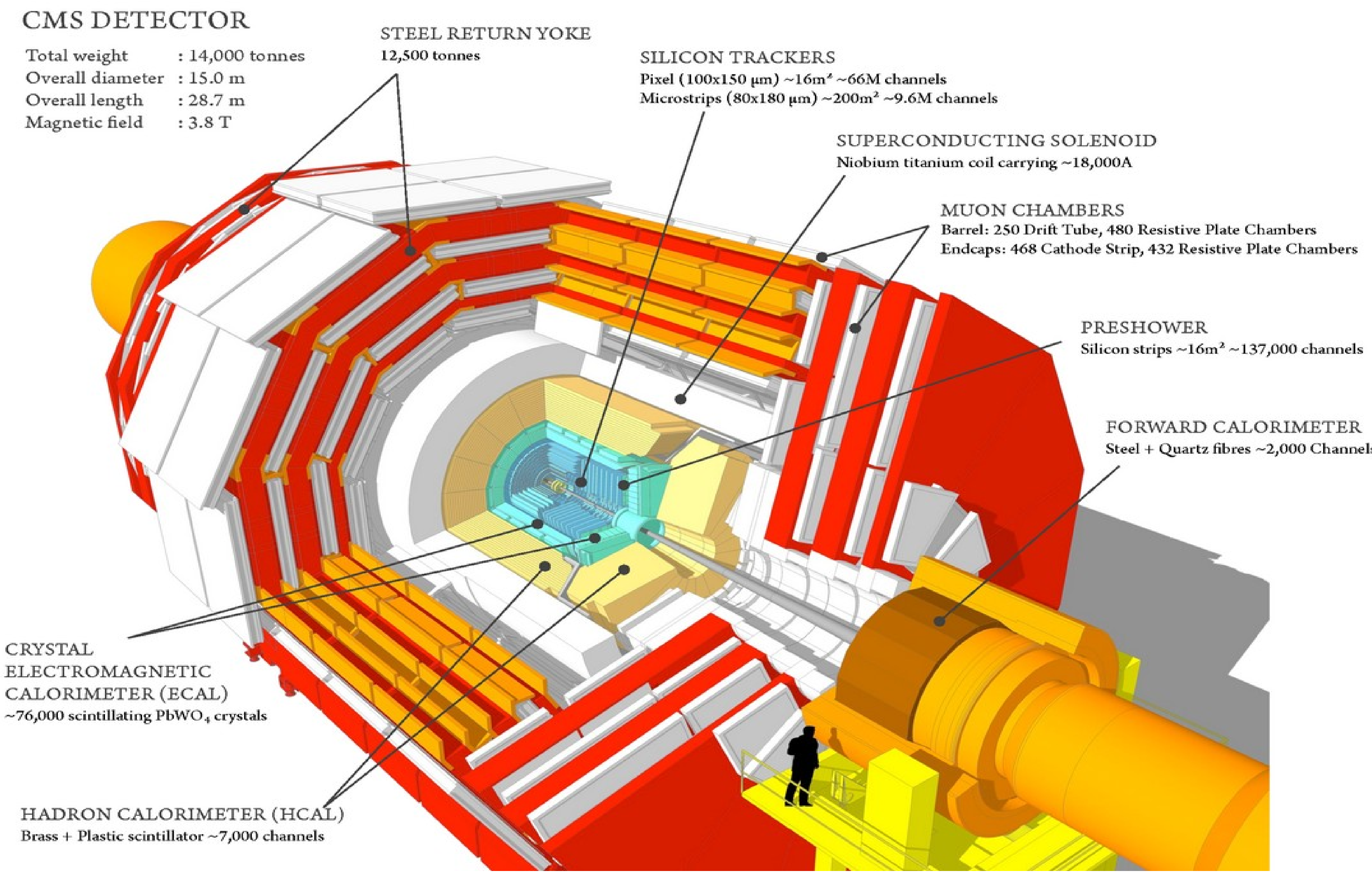


- ALICE : dedicated to the study “dense” collisions : ions-ions => study the matter in conditions of the early universe.

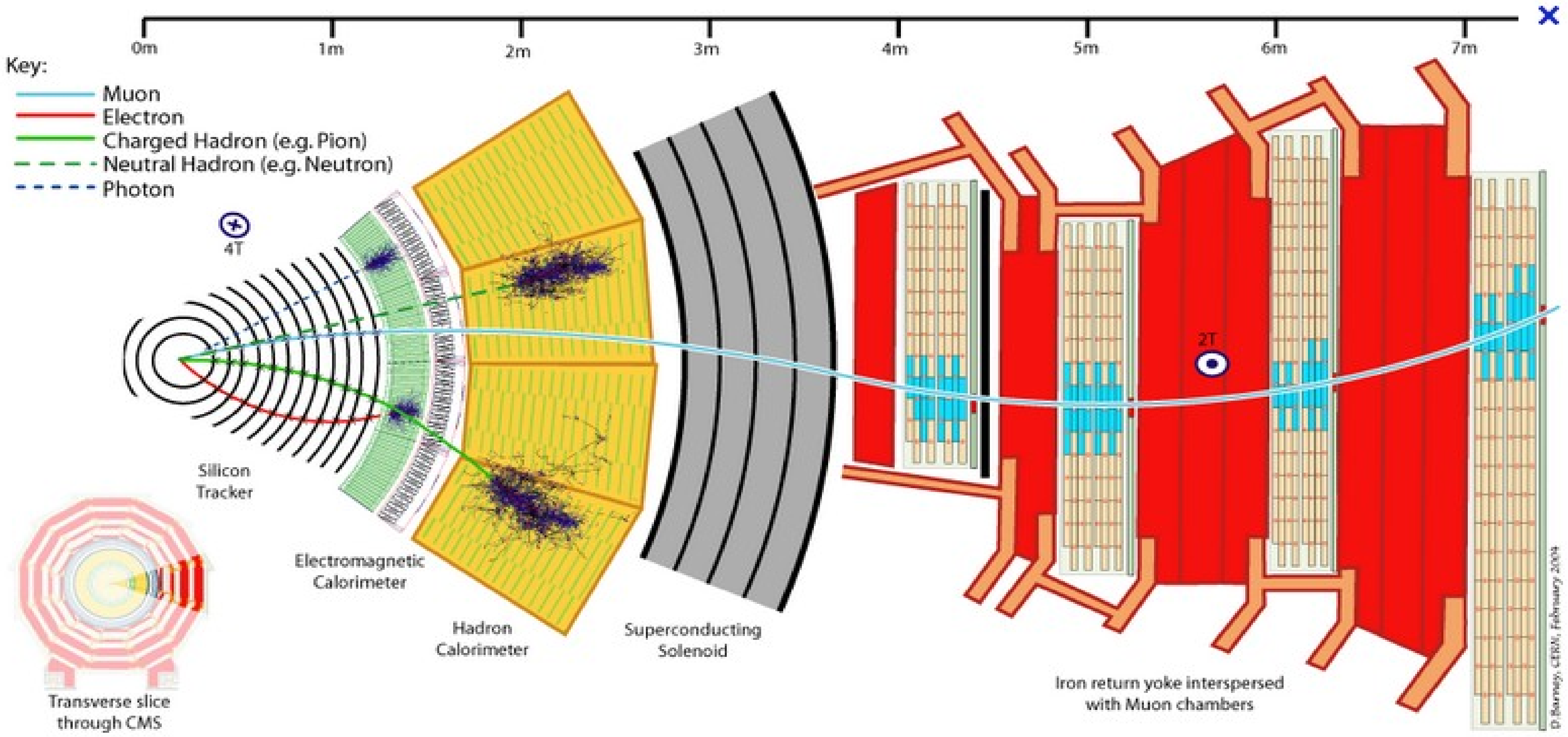
- LHCb : dedicated to the study matter-antimatter asymmetries.



The CMS detector

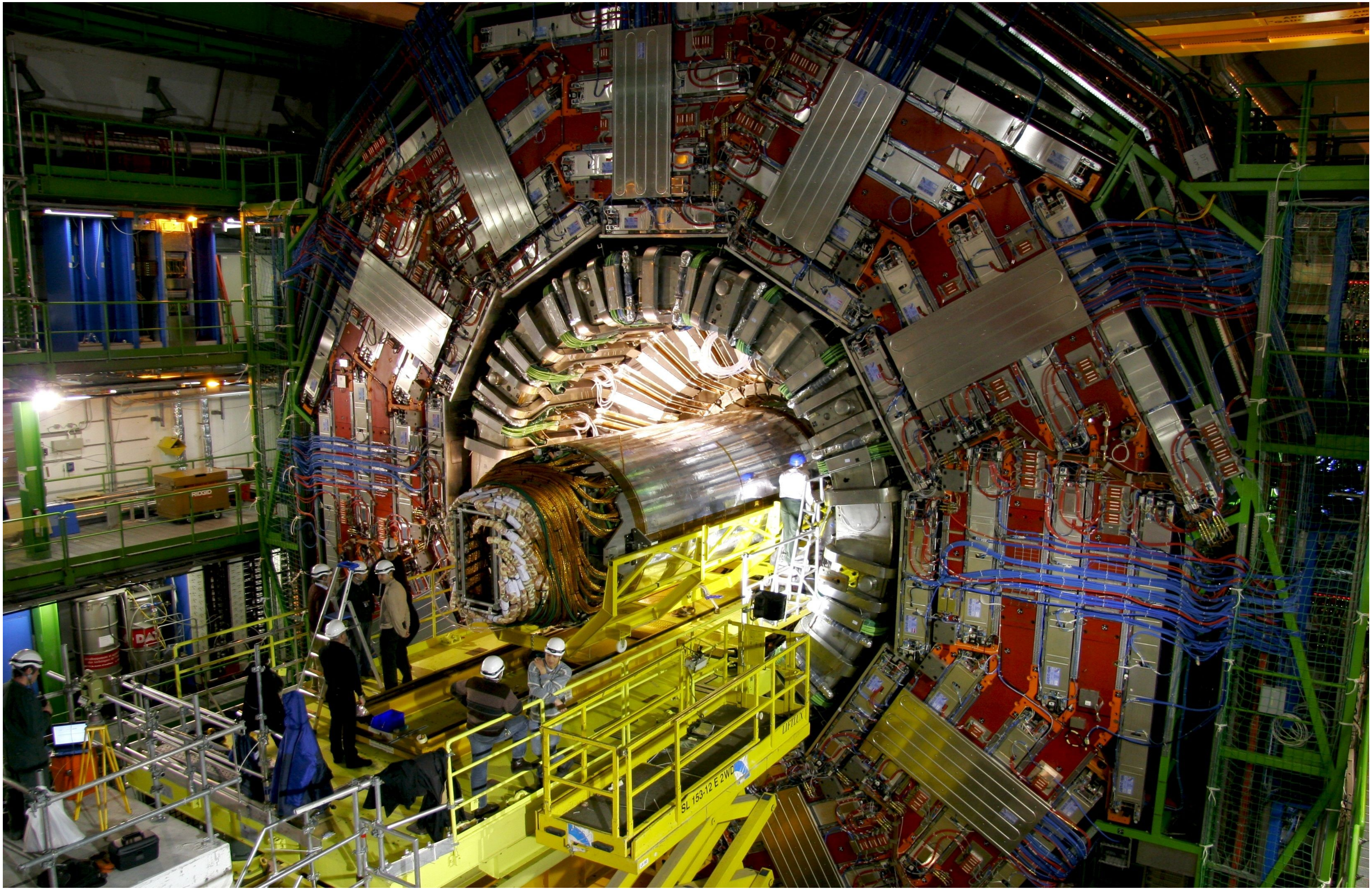


Object reconstruction in CMS



- Reconstructing particles with CMS :
  - Muons, electrons, photons, charged and neutral hadrons,
  - Based on the particle flow algorithm : combine in an optimal way the information from the different sub-detectors.

The CMS detector



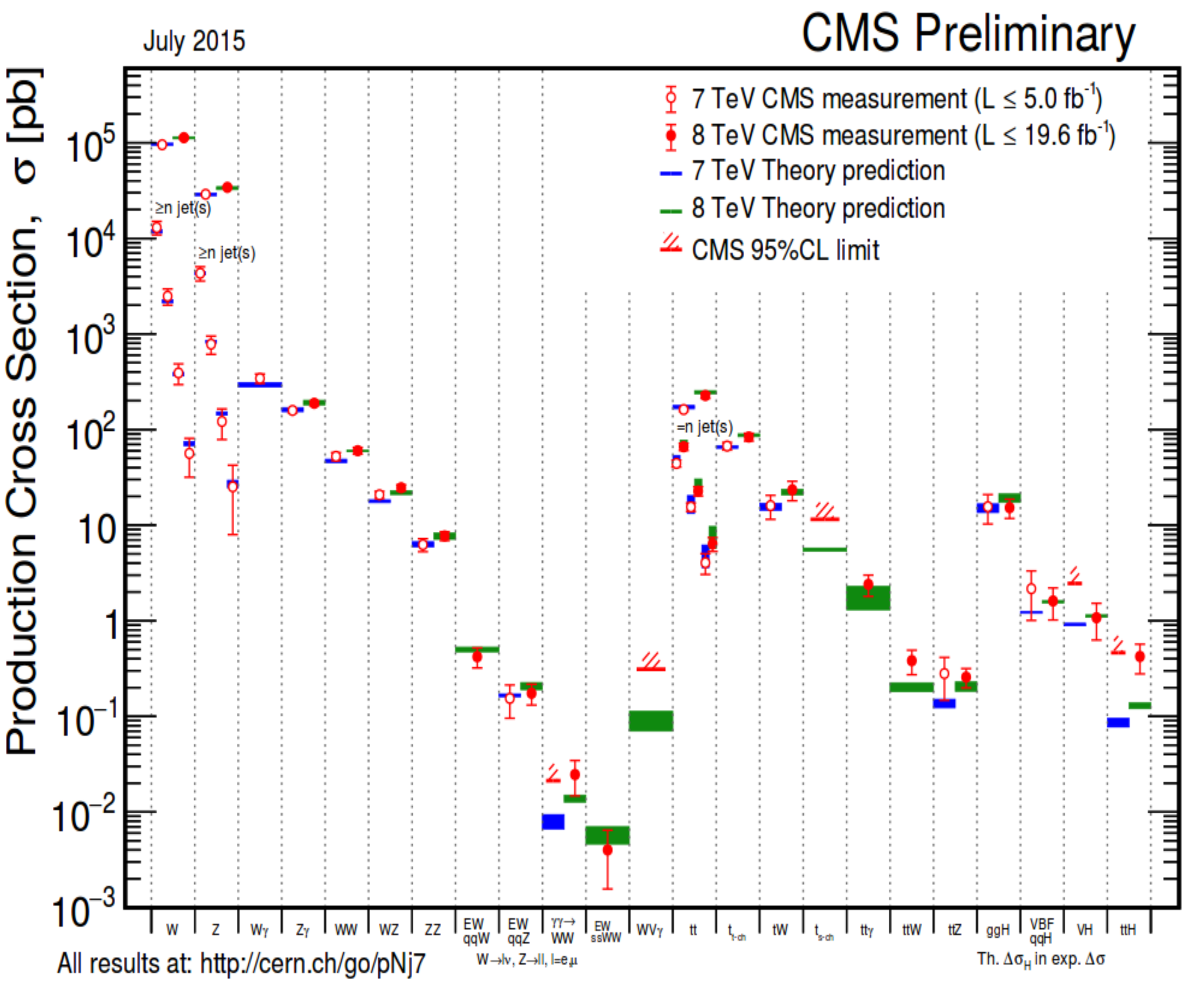
CMS physics during run I

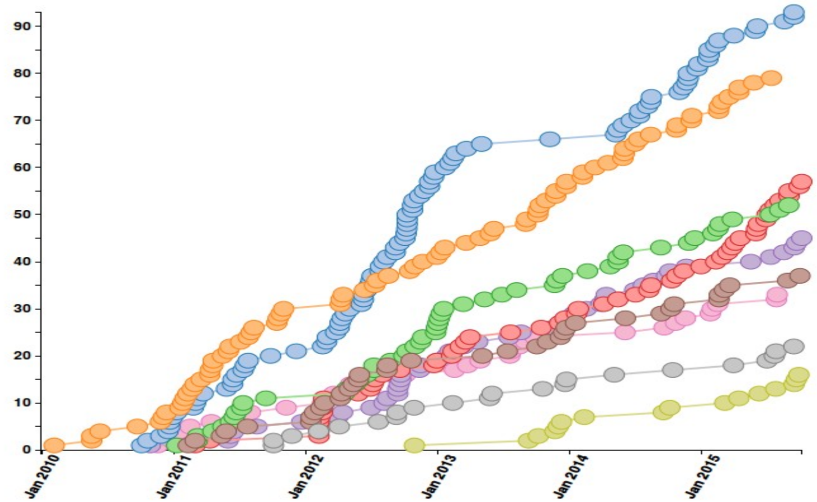
Contributions from CMS@IPHC

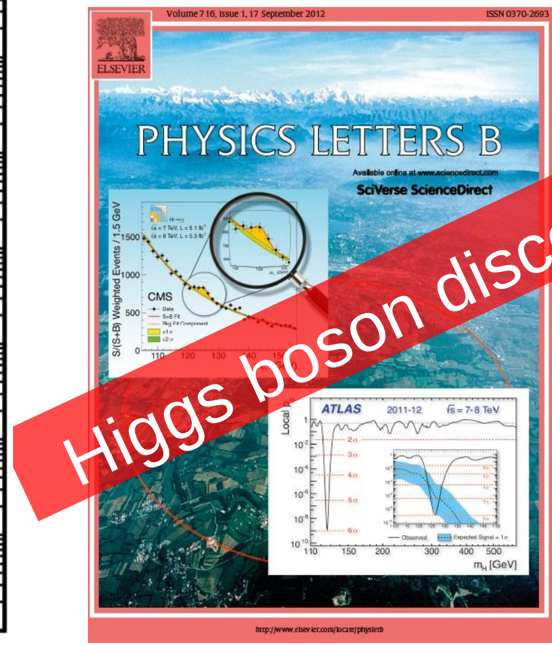
Show all | Total | Exotica | Standard Model | Supersymmetry | Higgs

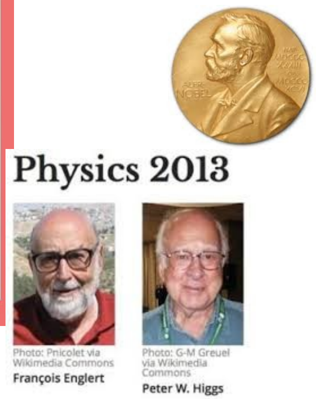
Top Physics | Heavy Ion | B Physics | Forward Physics | Beyond 2 Generations

433 papers submitted as of 2015-10-06









Luminosity at run I and II

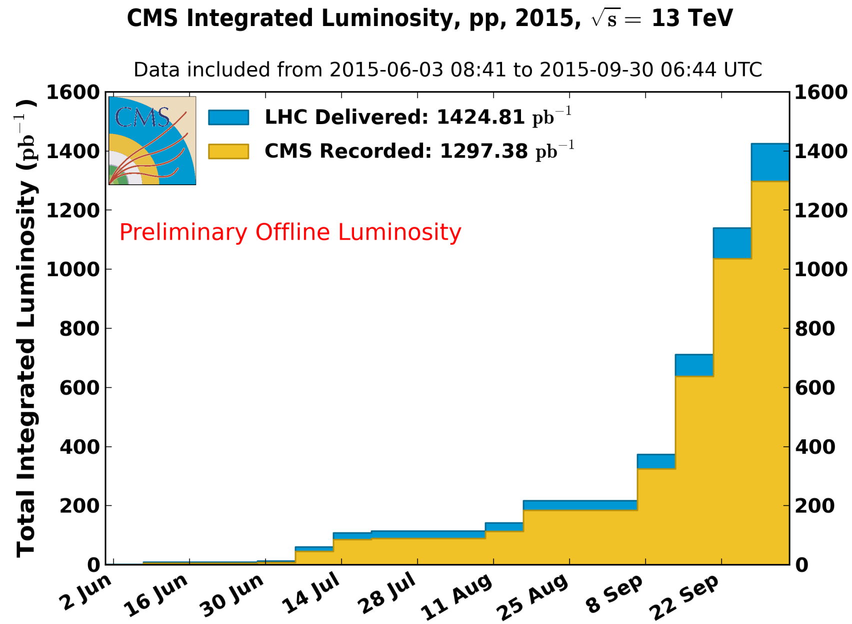
Luminosity

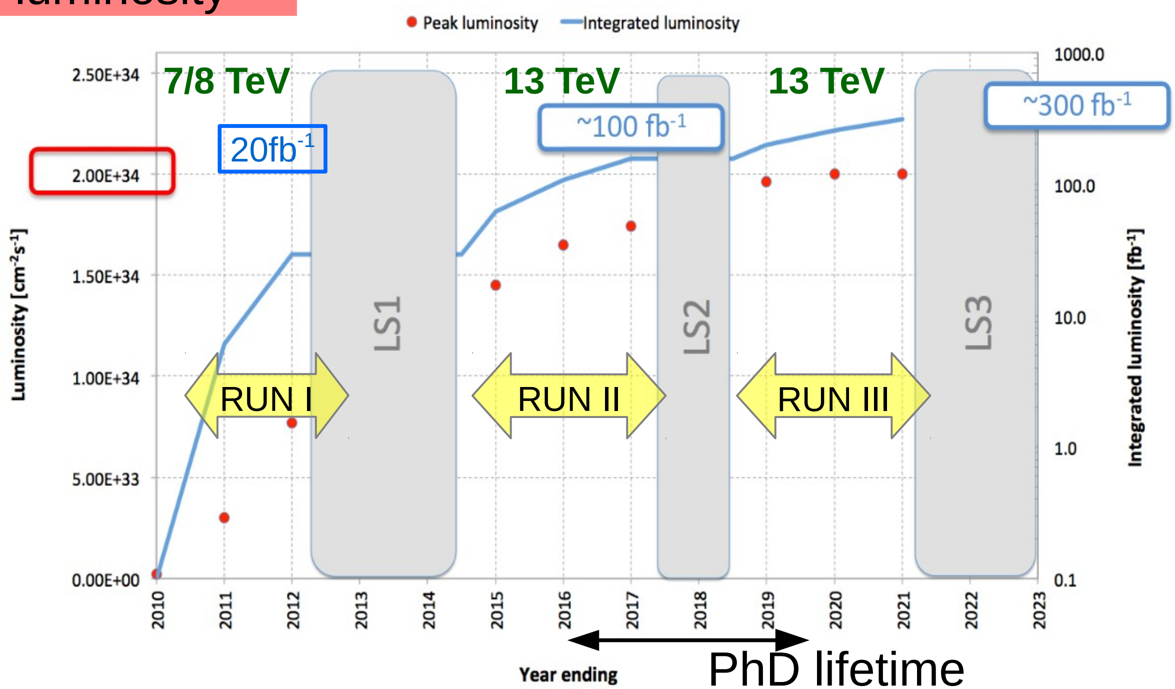
$$L = \frac{N^2 k_p f}{4 \pi \sigma_x \sigma_y}$$

- Proton/bunch (N)
- Nof bunches (k_p)
- Frequency (f)
- Beam resolution ($\sigma_x \sigma_y$)

$$N^{sig} = \sigma^{sig} \int L dt$$

Number of events proportional to the integrated luminosity



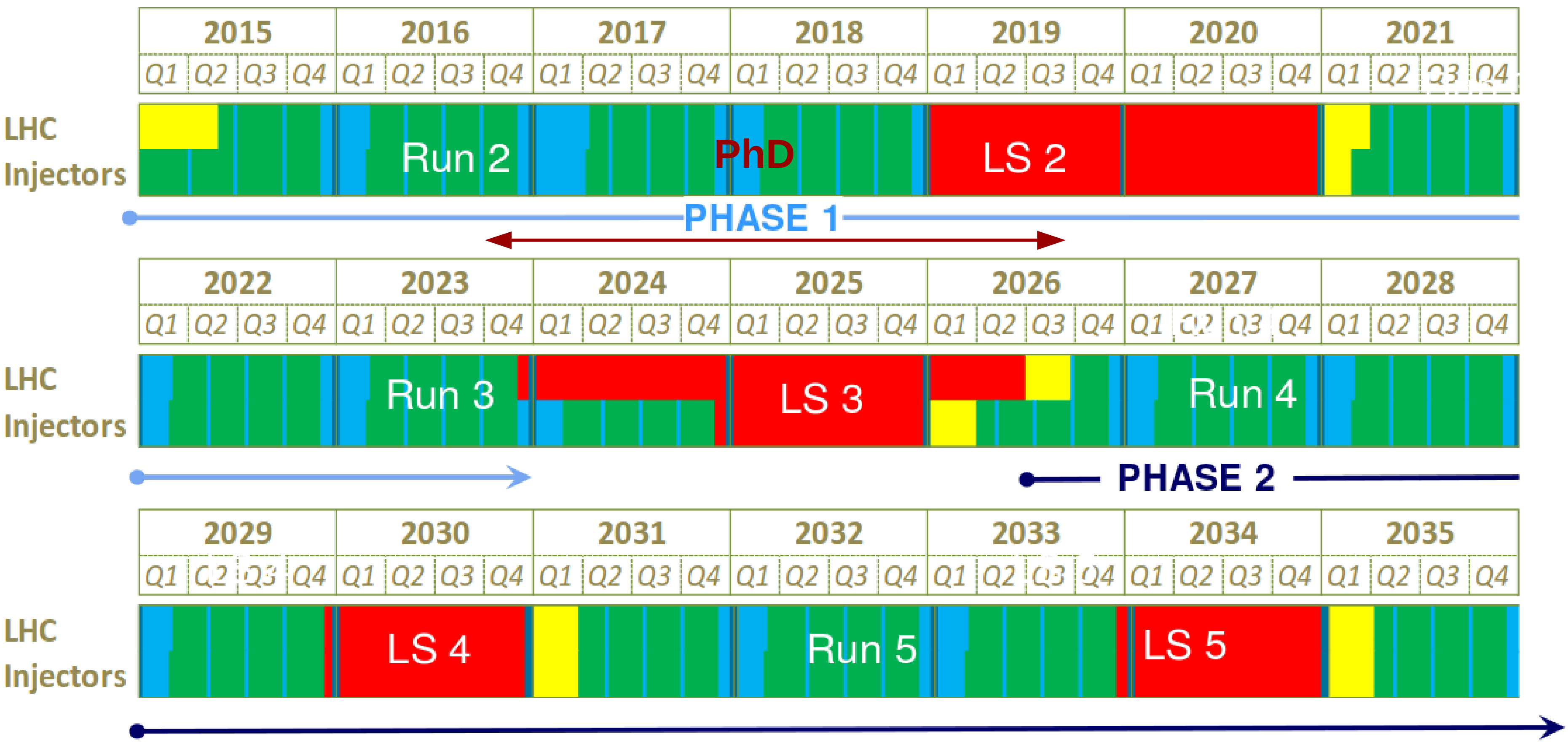


LHC road map

LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

- Physics
- Shutdown
- Beam commissioning
- Technical stop



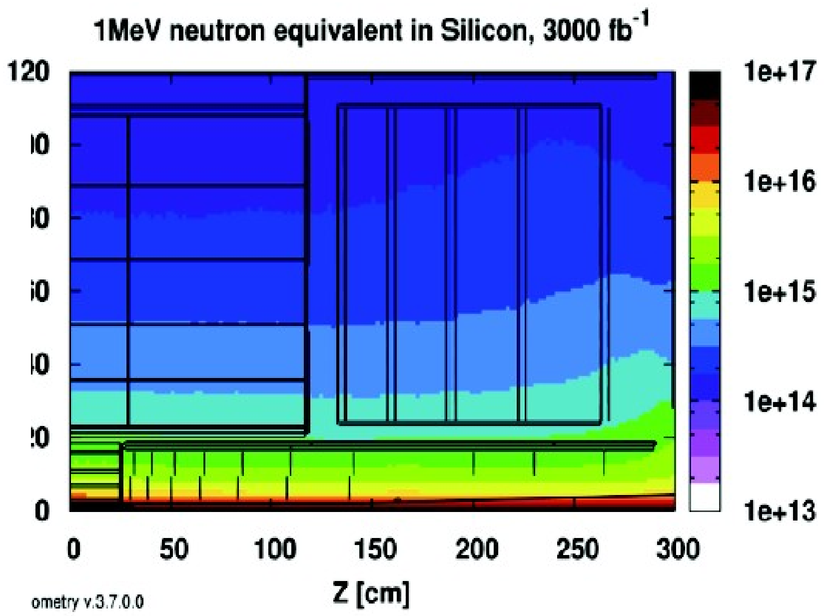
Increase of the luminosity requires an upgrade of the detector.
Detector upgrade for phase II requires R&D studies now !

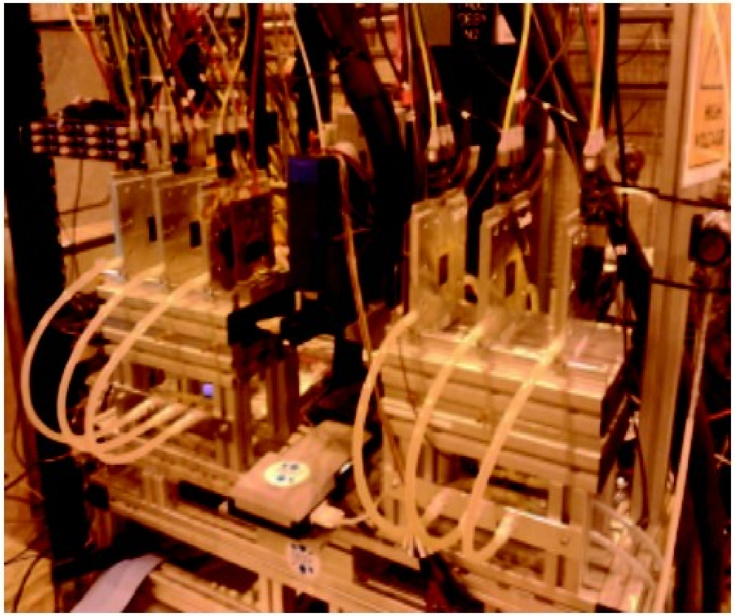
CMS Tracker upgrade for HL-LHC

- **High-Lumi LHC (phase 2 - 2025):**
  - 200 pile-up, luminosity up to 1e+35cm^{-2}s^{-1}

- **Tracker upgrade**:
  - Replace with a detector more radiation-hard (fluence 5e+14 neq/cm^2)
  - Will contribute to data acquisition at level 1 trigger
  - Needs upgrade of the data acquisition (DAQ) electronics to sustain rates

- **IPHC**:
  - CMS IPHC in charge of the CMS DAQ for tracker upgrade phase 2
  - Co-development of a back-end card with CERN
  - Involvement in beam tests: sensor efficiency, DAQ setup, data analysis

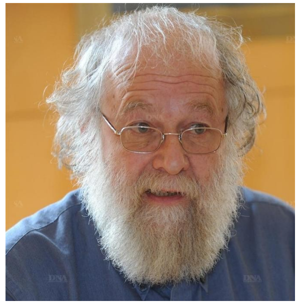




The CMS team at IPHC

L'équipe CMS de l'IPHC

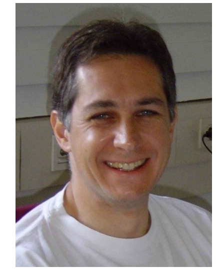
Jean-Marie Brom



Nicolas Chanon

Pierre Van Hove

Denis Gelé



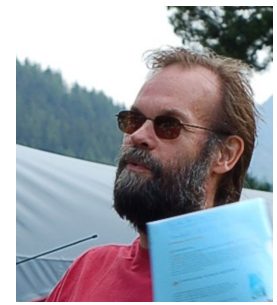
Jeremy Andrea

Caroline Collard

Jean-Charles Fontaine

Jean-Laurent Agram

Ulrich Goerlach

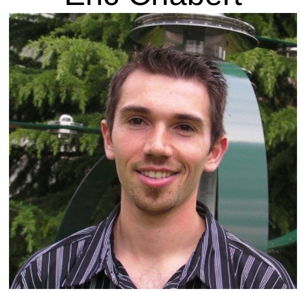


Kirill Skovpen

Laurent Gross

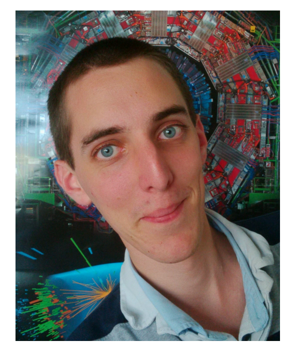
Anne-Catherine Lebihan

Eric Chabert



Marketa Jansona

Xavier Coubez



Michael Buttignol

Benjamin Fuks

Jean-Eric Conte

Jun Guo

6 Professeurs, directeurs de recherche
8 Enseignants-chercheurs, chargés de recherche
1 postdoc (+1 visitor in pheno),
3 PhD (+1 at CERN),
+ 5 ITAs !

CMS@IPHC : Physics

top quark

- Top pair cross-section
- Ttbar spin correlation

Precision measurements

- New physics from ttbar
- Top FCNC
- Search for monotop
(top+ invisible)

New physics with top

Higg boson

- Search for ttH,
- Measurement the WZ background

SM Higgs couplings with top

SUSY particles

- Direct search for stop pair production
- Indirect search from ttbar
- Search for SUSY Higgs

Search for SUSY

Strong connections with theorists : phenomenology

Intern-ships and PhD Thesis

Search for the associated production of a **single-top quark** and a **Z or a H boson**

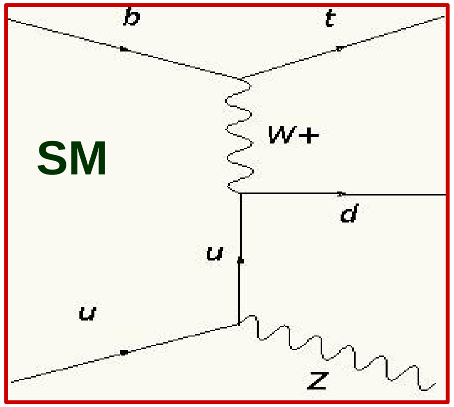
SuperSymmetry and the **Higgs bosons**(s): The Next to Minimal Super Symmetric Model (N-MSSM)

Associated production of a single top quark with a Z or H boson and search for new physics

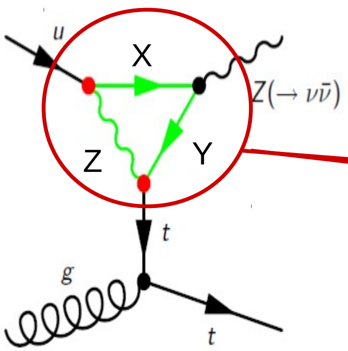
Nicolas Chanon (nicolas.pierre.chanon@cern.ch),
Jeremy Andrea (jandrea@cern.ch)

Search for tZ(q) and tH(q)

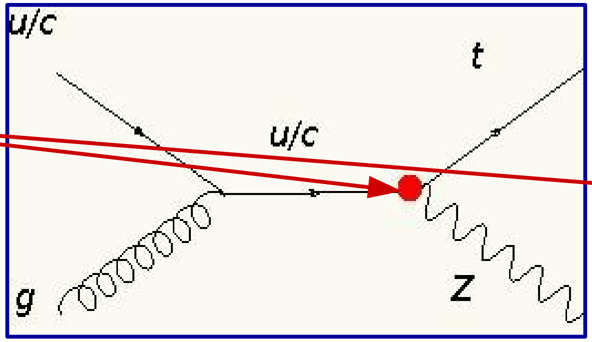
- Intern-ship : search for the associated production of a top quark and a Z boson.
- Non-observed process, predicted by the SM.
- Accessible with the 13 TeV dataset.



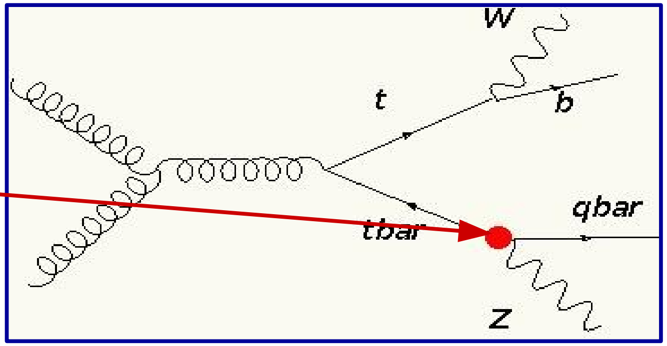
- Important for the search for new physics : FCNC has similar experimental signatures.



FCNC single top



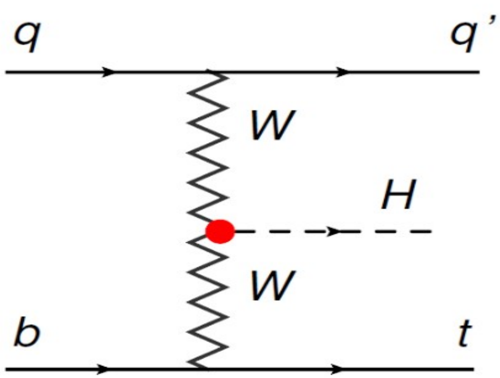
FCNC ttbar

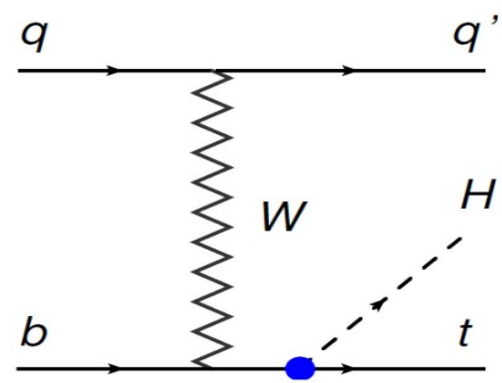


- Intern-ship :
  - Uses the 3 lepton channels,
  - Develop an event selection based on simulation,
  - Apply the event selection on 13 TeV data,
  - Estimation of backgrounds,
  - (Optional) Discrimination against dominant background : multivariate technique vs matrix element

Search for tZ(q) and tH(q)

- PhD thesis : continuation of the tZ(q) analysis and extension to tH(q).
  - Important test of the top-quark couplings to the Higgs boson,
  - probe negative t-H Yukawas : large enhancement of the tHq cross-section,
  - Other possible enhancement from top-Higgs FCNC couplings,
  - Use 3 leptons and 2 same sign leptons, with multivariate technique and/or Matrix Element

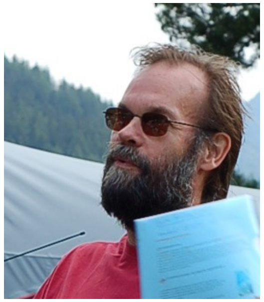




- Instrumental aspects of the thesis :
  - Design and construction of the upgraded CMS for HL-LHC should start many years in advance,
  - Participate to the development of the new tracker,
  - Test the acquisition of new sensors with test-beam and perform the related analysis of data.

Search for supersymmetry in the Higgs sector

Ulrich Goerlach (ulrich.goerlach@iphc.cnrs.fr)



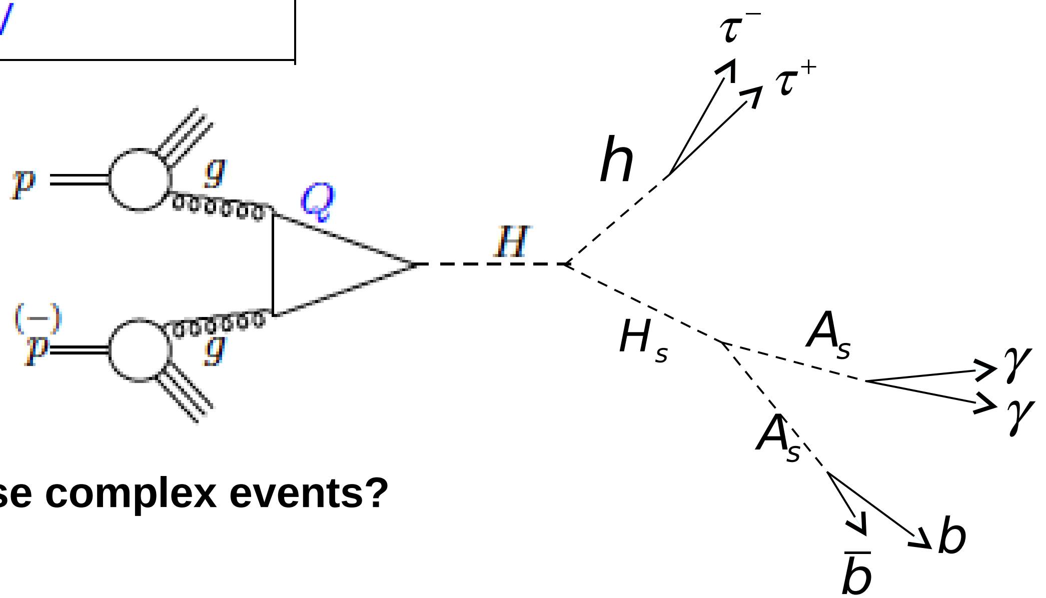
Experimental search for SUSY Higgs

- All extensions of the SM have to contain at least one SM-like Higgs boson.
- The extended Higgs sector allows for new additional Higgs bosons: new particles to find.
- Higgs-Higgs couplings and decays $H \rightarrow h, H_s$ and $H_s \rightarrow A_s, A$
- Depending on mass hierarchy, spectacular signatures like for example:

M_h, M_{H_s}, M_H	124.6 GeV	181.7 GeV	322.6 GeV
M_{A_s}, M_A	72.5 GeV	311.7 GeV	

- Gluon Fusion

$pp \rightarrow gg \rightarrow H$



- How to reconstruct and to analyse these complex events?
- Topic of inter-ship and PhD thesis!

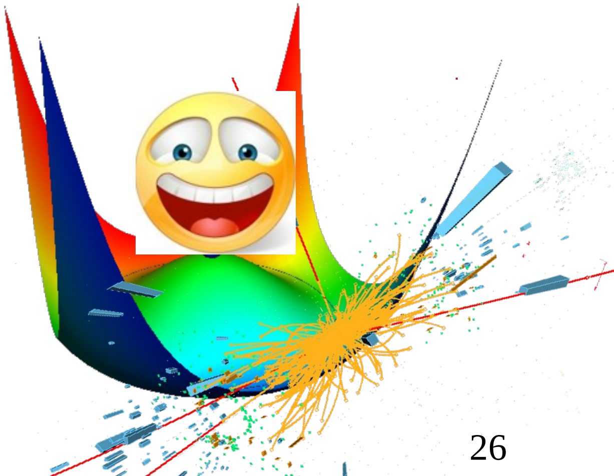
Intership and PhD thesis

Stage (4 months)

- Introduction to SUSY, Higgs and N-MSSM
- Use programs NMSSMtools (mass spectra and branching ratios)
- Process with Pythia (decays and hadronisation) / DELPHES: detector simulation
- Analyse ntuples (Root) from simulated data with Madgraph and Mad_analysis
- Estimate the feasibility for some channels

PhD thesis (3 years)

- Apply and further develop the analysis on data for different search channels to find a non-SM Higgs boson at the run 2 of the LHC
- Work on b-jet and tau id
- Discovery
  - Characterisation of new particle
  - MSSM or N-MSSM or ??
- Place a limit or rule out SUSY-models



Backups

Ulrich.Goerlach@iphc.cnrs.fr, M2 –PSA 2014

Super Symmetry and the Higgs boson

- **Super symmetry postulates a Super partner for each particle of the Standard model**
- **Fermions (lepton and quark) ⇔ s-boson (slepton and squark)**
- **Boson (gamma, W, Z, gluons) ⇔ sfermion (photino, Wino, Bino, gluino)**

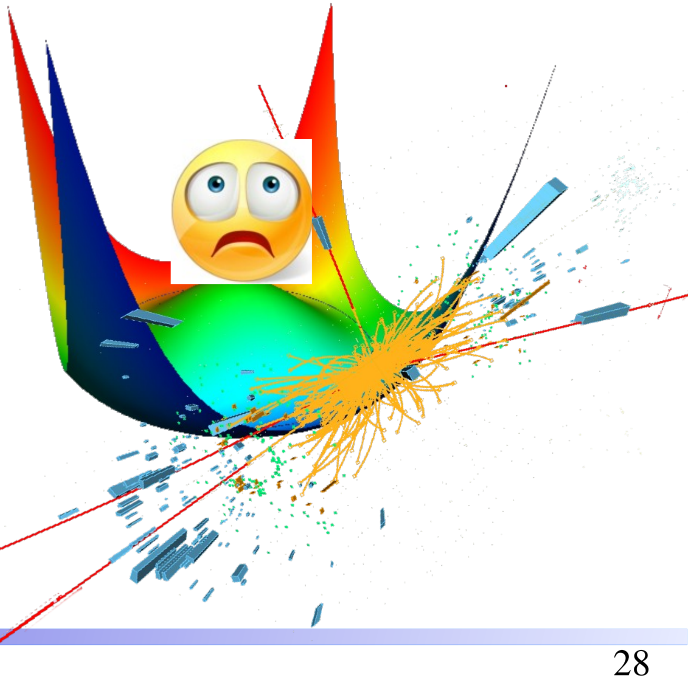
Q|Boson, spin J> = |Fermion, spin J + ½>

Q|Fermion, spin J> = |Boson, spin J - ½>

- **Super symmetry is a "broken" symmetry ⇒ look for heavy new sparticles**
- **Nothing found so far !!!!!**

- **LHC-RUN 2015:**

  Look for sparticles with even higher mass



Supermultiplets

- **Chiral Supermultiplet**

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\tilde{u}_L \ \ \tilde{d}_L)$	$(u_L \ \ d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
($\times 3$ families)	$\overline{u}$	$\tilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\overline{d}$	$\tilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\tilde{\nu} \ \ \tilde{e}_L)$	$(\nu \ \ e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
($\times 3$ families)	$\overline{e}$	$\tilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \ \ H_u^0)$	$(\tilde{H}_u^+ \ \ \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \ \ H_d^-)$	$(\tilde{H}_d^0 \ \ \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

H_d and H_u needed to give masses to down- and up-type fermions

- **Vector Supermultiplet**

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^\pm \ \ \widetilde{W}^0$	$W^\pm \ \ W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

SUSY Primer, S.P. Martin hep-ph/9709356

The Higgs Mechanism

- **Standard Model:**

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \; SU(2) \text{ doublet}, \; \phi^+, \phi^0 \in \mathbb{C}; \quad \phi^+ = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \qquad \phi^0 = \frac{1}{\sqrt{2}}(\phi_3 + i\phi_4)$$

Spontaneous symmetry breaking in $SU(2)$ space. We can chose (local gauge invariance)

$$\phi_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_0 \end{pmatrix}; \phi_1 = \phi_2 = \phi_4 = 0; \quad \phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_0 + H(x) \end{pmatrix}; \; \phi_C(x) = \frac{-1}{\sqrt{2}}\begin{pmatrix} v_0 + H(x) \\ 0 \end{pmatrix}$$

Yukawa coupling of ϕ and ϕ_C gives mass to down-type and up-type quarks, respectively

- **SUSY:**

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}; \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix};$$

two Isopsin doublet fields to give mass to L, R fermions and their SUSY partners

$N-MSSM$ add. scalar field S

Coupling of Higgs superfields, Superpotential $W = \ldots + \mu H_u \times H_u$ μ free parameter, to be "fine" tuned

N-MSSM, add scalar field S, $W = \ldots + \lambda S \times H_u \times H_u$; μ replaced by vacuum expectation value of S

$MSSM$: Simplest Higgs field
- h, H scalars
- A pseudo scalar
- H^+, H^- charged

$\xrightarrow{N-MSSM}$

Next to simplest Higgs field
- H_1, H_2, H_3 scalars
- A_1, A_2 pseudo scalar
- H^+, H^- charged

} new and complex Higgs sector

Benchmark $H_1 = h$ and $\tan\beta$ small

B.1 (Point ID Poi2a)	Scenario		
M_h, M_{H_s}, M_H	124.6 GeV	181.7 GeV	322.6 GeV
M_{A_s}, M_A	72.5 GeV	311.7 GeV	
$\lvert S_{H_2 h_s}\rvert^2, \lvert P_{A_1 a_s}\rvert^2$	0.90	1	

$$\text{BR}(A_s \to \gamma\gamma) = 0.84\,, \quad \text{BR}(H_s \to A_s A_s) = 0.97\,, \quad \text{BR}(H \to h H_s) = 0.51$$

$\sigma(ggH_s)\text{BR}(H_s \to A_s A_s \to b\bar{b} + b\bar{b})$	5.87 fb
$\sigma(ggH_s)\text{BR}(H_s \to A_s A_s \to \gamma\gamma + b\bar{b})$	67.33 fb
$\sigma(ggH_s)\text{BR}(H_s \to A_s A_s \to \gamma\gamma + \gamma\gamma)$	193.22 fb

$\sigma(ggH)\text{BR}(H \to hH_s \to h + A_s A_s \to bb + 4\gamma)$	712.47 fb
$\sigma(ggH)\text{BR}(H \to hH_s \to h + A_s A_s \to \gamma\gamma + 4b)$	248.02 fb
$\sigma(ggH)\text{BR}(H \to hH_s \to h + A_s A_s \to \tau\tau + 4\gamma)$	74.60 fb
$\sigma(ggH)\text{BR}(H \to hH_s \to h + A_s A_s \to \gamma\gamma + 4\tau)$	2.47 fb
$\sigma(ggH)\text{BR}(H \to hH_s \to h + A_s A_s \to 6\gamma)$	2.69 fb
$\sigma(ggH)\text{BR}(H \to hH_s \to h + A_s A_s \to \tau\tau + \gamma\gamma + b\bar{b})$	49.55 fb

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