Au-delà du Modèle Standard

aka BSM

Giulia Negro, Marta Maria Perego

Journée des doctorants

July 10, 2017

Outline

BSM @LHC session introduction:

- Theoretical framework
  - The standard model of particle physics
  - Beyond the standard model

Presented by Giulia

- Experimental apparatus:
  - LHC and detectors (ATLAS & CMS)

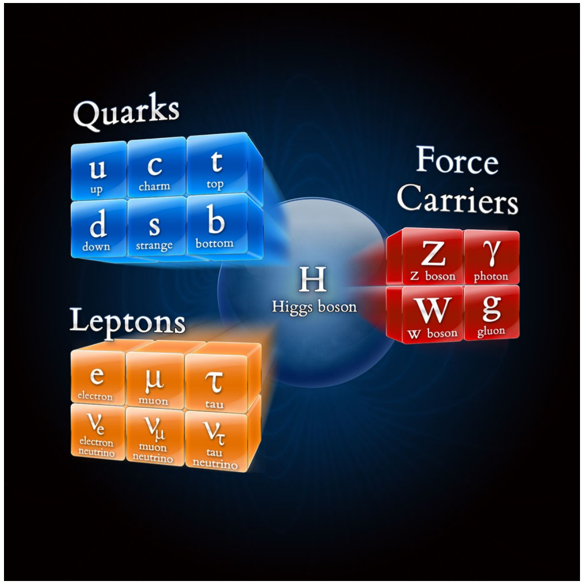
Presented by Marta

BSM @LHC searches at DPhP:

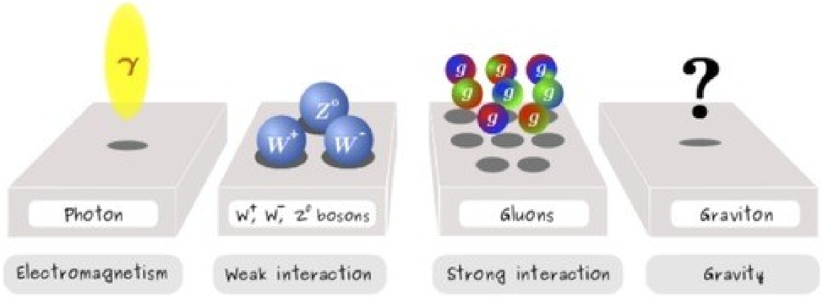
- Giulia's research:
  - Experimental tests of the Minimal Standard Model of neutrinos with the CMS experiment at the LHC
- Marta's research:
  - Dark matter searches in VBF processes with the ATLAS detector:
  - *Focussing here on the invisible decay of the Higgs boson, I am also working on minimal DM models*

The Standard Model

- The Standard Model of particle physics:
  - explains how the fundamental particles interact, governed by four fundamental forces
  - developed in the early 1970s, has successfully explained almost all experimental results and precisely predicted a wide variety of phenomena



Fermions = **quarks** and **leptons** (spin ½):
- each group consists of six particles paired in 3 "generations"
- all stable matter in the universe is made from particles that belong to the first generation



Bosons = mediators of fundamental interactions (particles of matter transfer discrete amounts of energy by exchanging bosons with each other)

Higgs Boson: gives mass to vector bosons and other particles

Beyond Standard Model

- The Standard Model is currently the best description of the subatomic world but:
  - it is still **incomplete**: the theory incorporates only three out of the four fundamental forces omitting **gravity** (whose effect is negligible at the infinitesimal scale of particles)
  - it does not answer important questions:

BSM : antimatter

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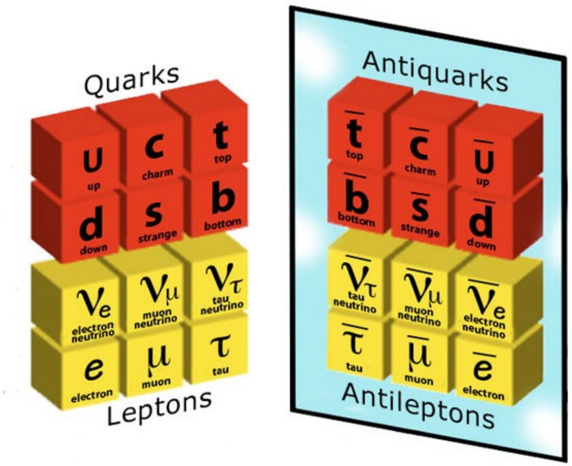
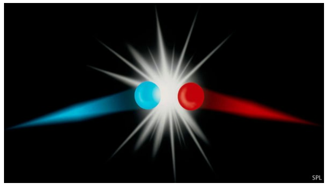
  - it is still **incomplete**: the theory incorporates only three out of the four fundamental forces omitting gravity (whose effect is negligible at the infinitesimal scale of particles)
  - it does not answer important questions:
    - “What happened to the **antimatter** after the big bang?”

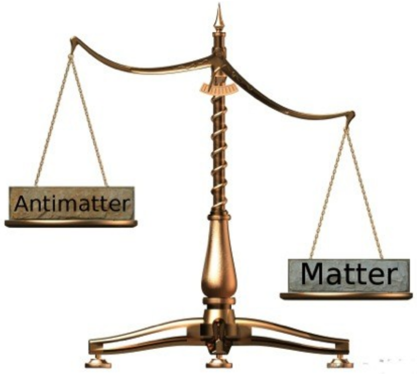


- Antiparticle = fundamental particle with opposite charges

- Annihilation of matter and antimatter if in contact



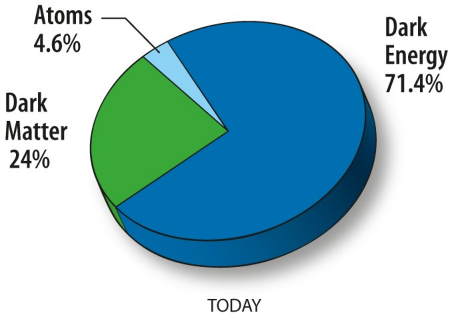
- After Big Bang equal amounts of matter and antimatter but now prevalence of matter
  → break of symmetry due to some unknown mechanism in the early universe

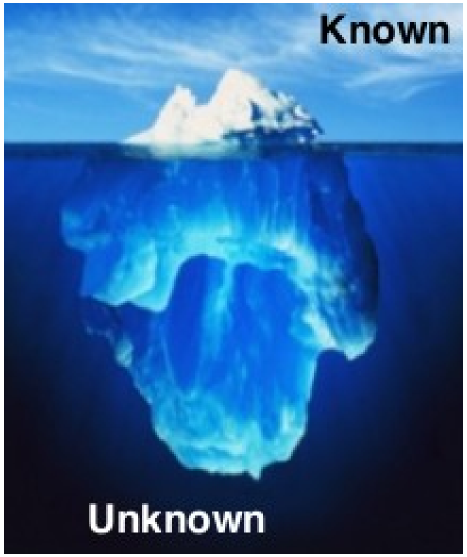


BSM : dark matter

- The Standard Model is currently the best description of the subatomic world but:
  - it is still **incomplete**: the theory incorporates only three out of the four fundamental forces omitting gravity (whose effect is negligible at the infinitesimal scale of particles)
  - it does not answer important questions:
    - "What happened to the antimatter after the big bang?"
    - "What is **dark matter**?"

- The Universe is made of:





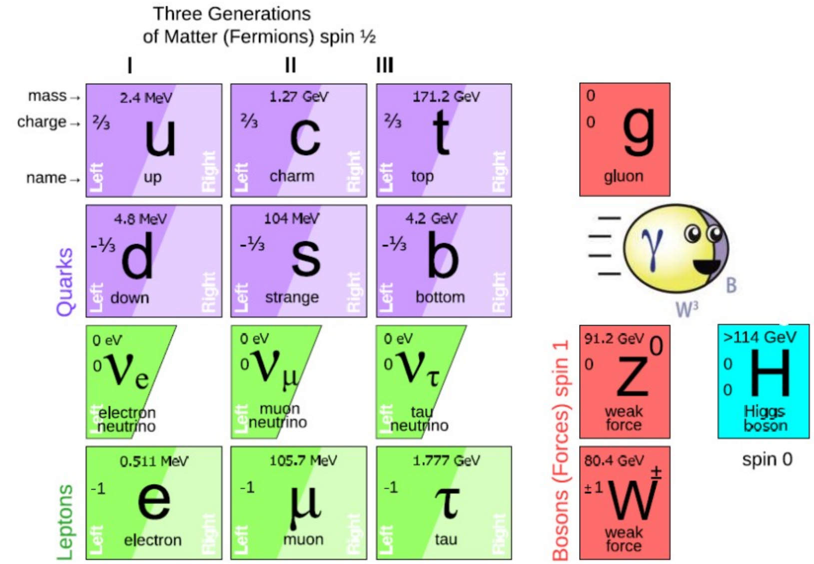
- Astrophysical and cosmological measurements tell us that Dark Matter is out there but:
  - is a new particle → its identity and physical properties are still unknown
  - does not interact with the electromagnetic force → extremely hard to spot

X ray distribution
Gravitational lensing

BSM : masses

- The Standard Model is currently the best description of the subatomic world BUT:
  - it is still **incomplete**: the theory incorporates only three out of the four fundamental forces omitting gravity (whose effect is negligible at the infinitesimal scale of particles)
  - it does not answer important questions:
    - "What happened to the antimatter after the big bang?"
    - "What is dark matter?"
    - "Why are there three generations of quarks and leptons and with such a **different mass scale**?"
    - "Why only **family of νL and not νR**?",

      "Are there also νR?"



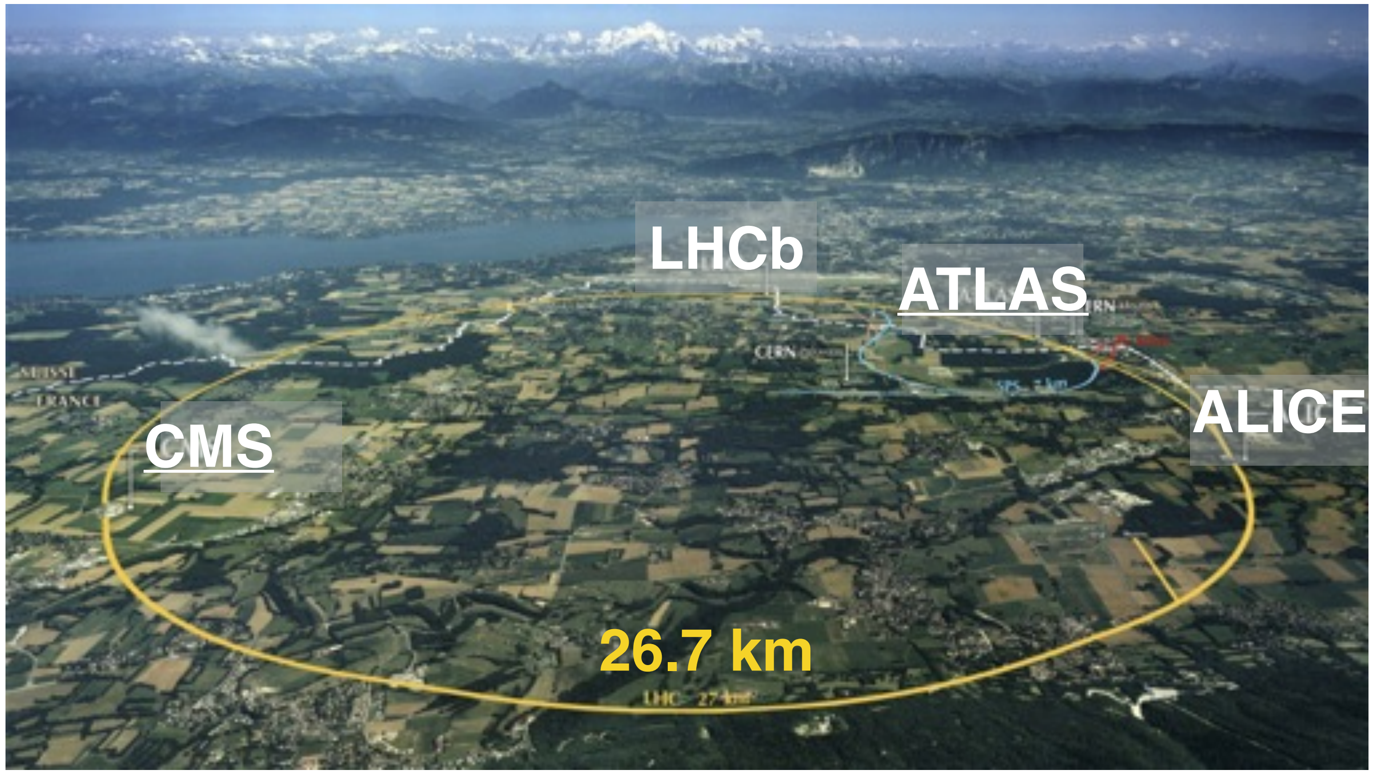
→ new information from experiments at the LHC will help us to find more of these missing pieces

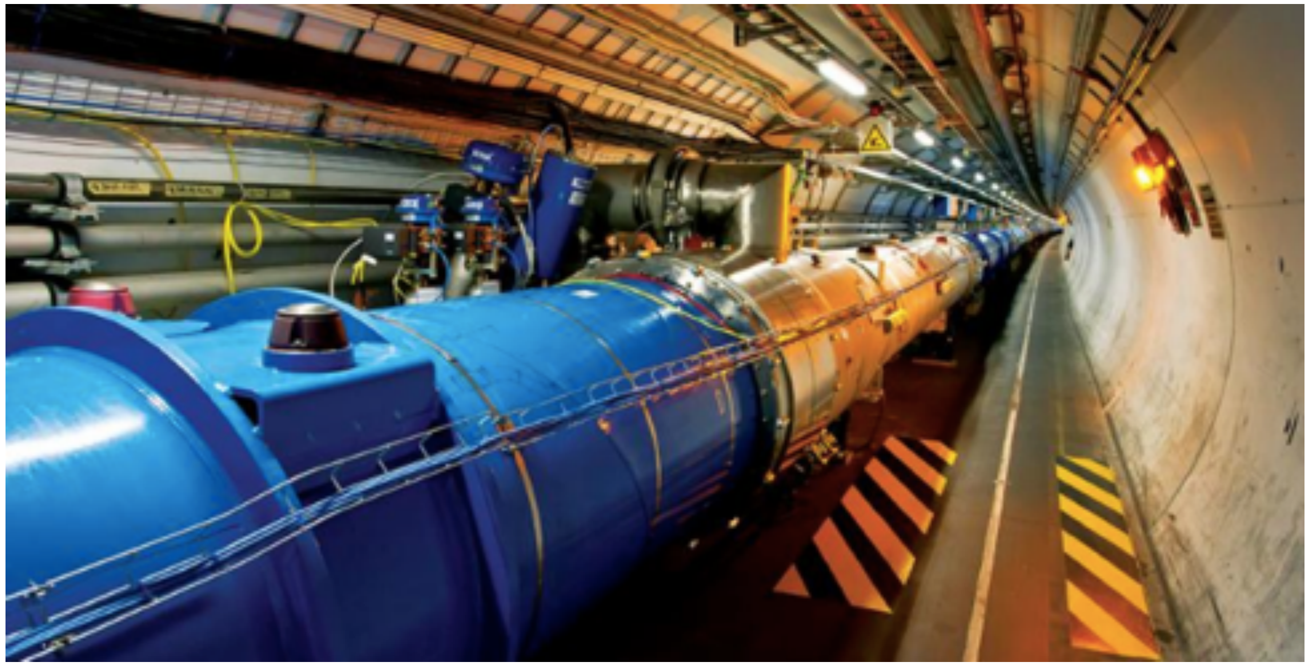
Experimental apparatus - the LHC

- We are both analyzing data produced by the **Large Hadron Collider,** the **largest and highest energy** particle accelerator in the world

- **Large:** Installed in 26.7 km underground tunnel, at CERN, Geneva.

- **Hadron** *:* Designed to collide **proton beams**





- **Collider :** Two separate beams run in opposite directions and collide in 4 **dedicated collision points** where experiments are built

- Currently **running at 13 TeV** (10^{12} eV) c.m.e.

Experimental apparatus - the LHC

FREQUENTLY ASKED QUESTIONS:

- Why so **Large**?
  - The maximum energy is related to its size

- Why **Hadrons**?
  - to be accelerated particles need to be charged
  - in a circular collider heavy particles (protons) have less energy loss synchrotron radiation w.r.t light ones (electrons)
  - lots of interesting physics! see later

- Why a **Collider**?
  - in a collision the energy is the sum of the energies of the two beams
  - the same beam on a fixed target would produce a collision of much less energy

Experimental apparatus - detectors

- For each collision we need to identify all the different particles that are produced

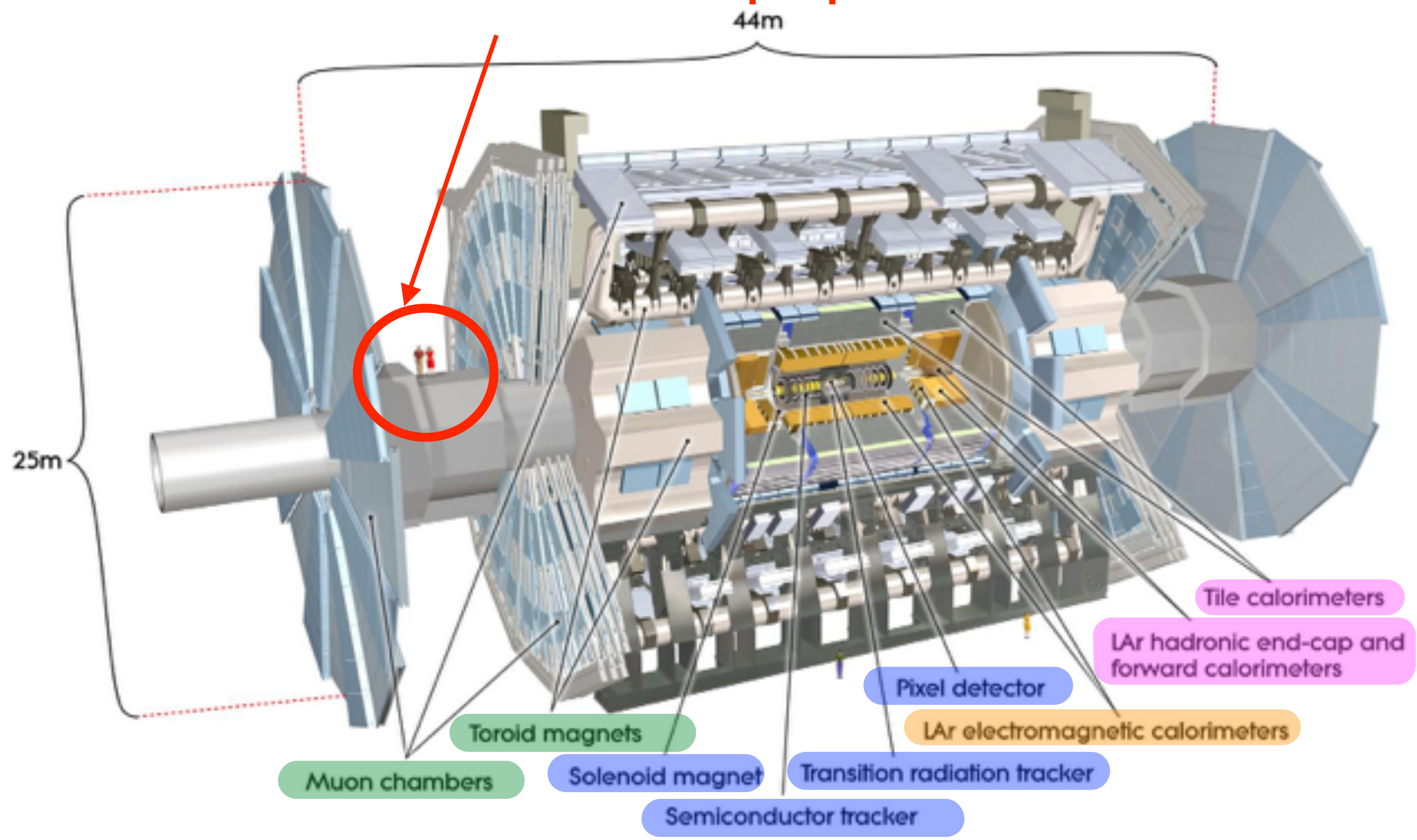
—> How ?

- make sure that the *known (*)* particles interact in the detector
- distinguish particles through their interactions with matter

=> **several subdetectors** devoted to detect different kind of interactions

- Inner detector
- Electromagnetic calorimeter
- Hadron Calorimeter
- Muon Spectrometer

notice the scale: people are here!



this is ATLAS EXPERIMENT

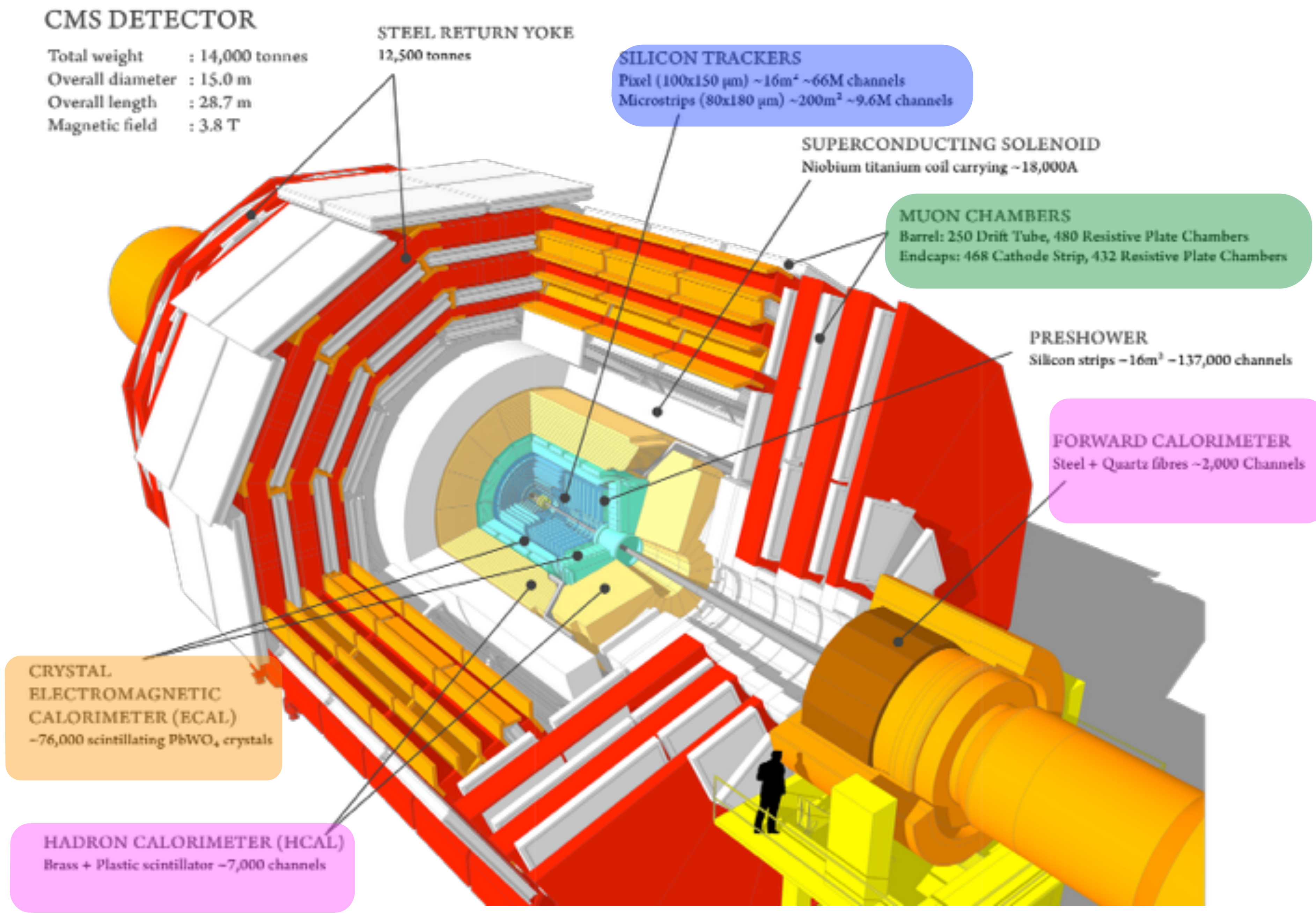
(*) well, apart from neutrinos! (see later)

Experimental apparatus - detectors

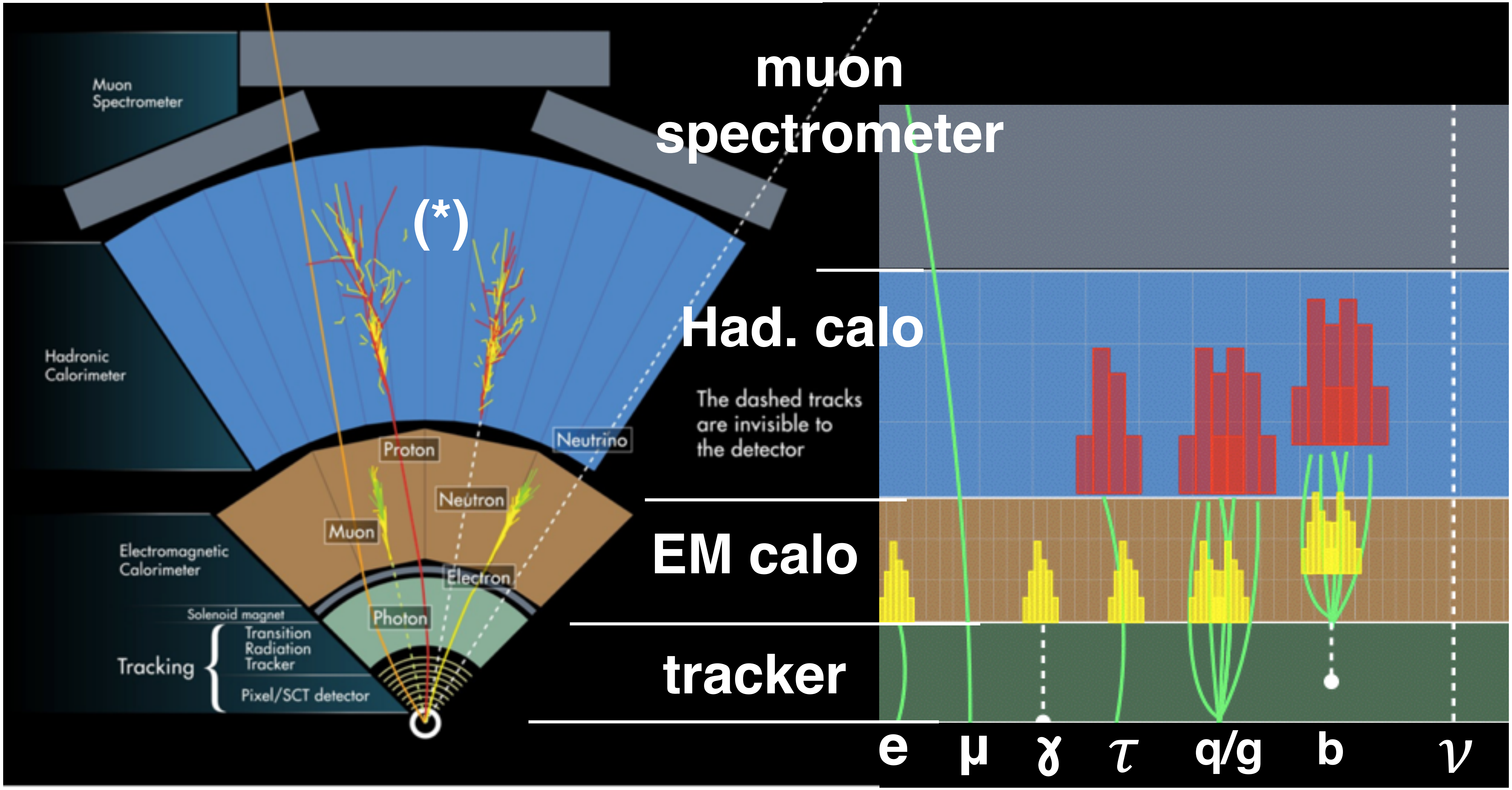
this is

CMS philosophy is the same

- Inner detector
- Electromagnetic calorimeter
- Hadron Calorimeter
- Muon Spectrometer



Experimental apparatus - detectors



(*) taus, quarks, gluons are seen in the detector as ***jets*** *(collimated bunches of hadrons flying roughly in the same direction)*

- What about neutrinos and the other “invisible” particles such as Dark Matter?
- How do we detect them?

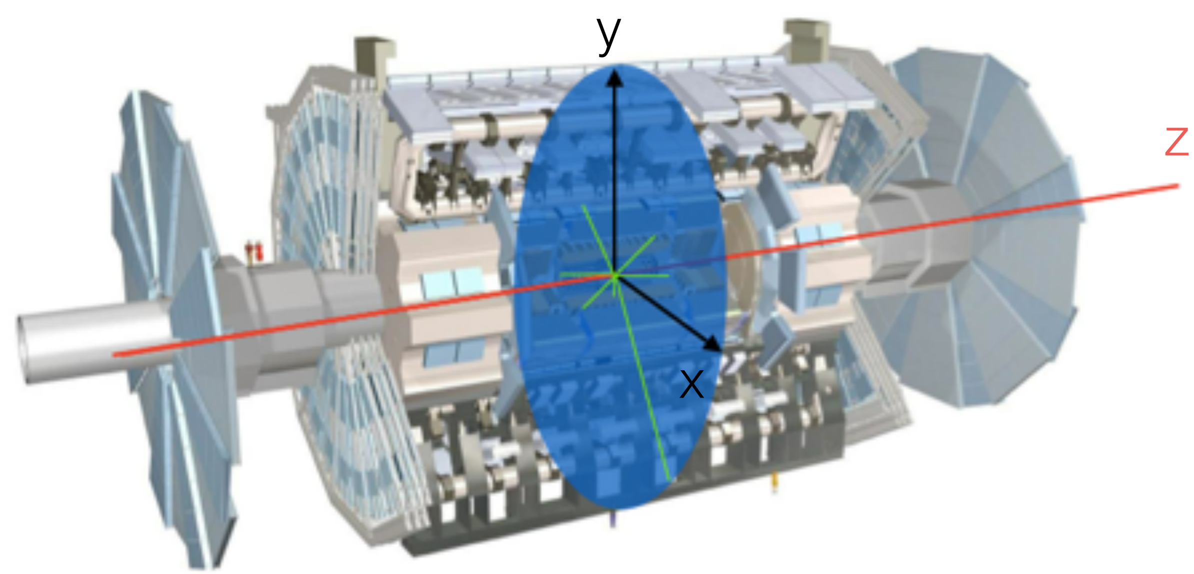
Missing transverse momentum

Neutrinos *(and Dark Matter particles)* escape the detector without any trace, they are invisible to the detector

=> How can we detect them?

- We infer their existence from an **imbalance in the transverse momentum!**
  - *if they recoil against something*

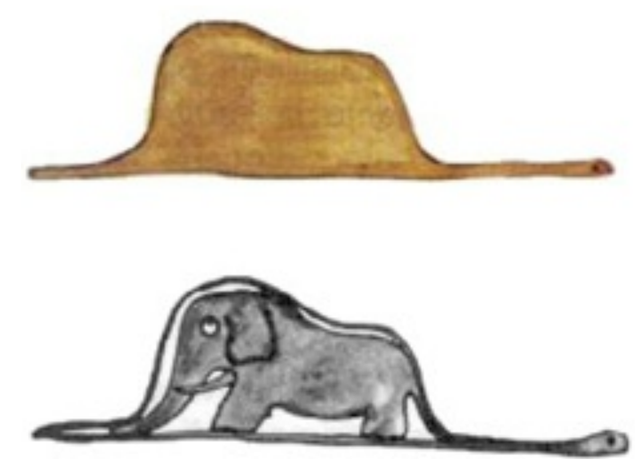
In the transverse plane, the kinematics is closed and energy and momentum are conserved



$$\sum P_{x(y)}(\text{What we do not see}) + \sum P_{x(y)}(\text{What we see}) = 0$$

$$\sum P_{x(y)}(\text{What we do not see}) = - \sum P_{x(y)}(\text{What we see})$$

$$E^{miss}_{x(y)} = - \sum p_{x(y)i}$$

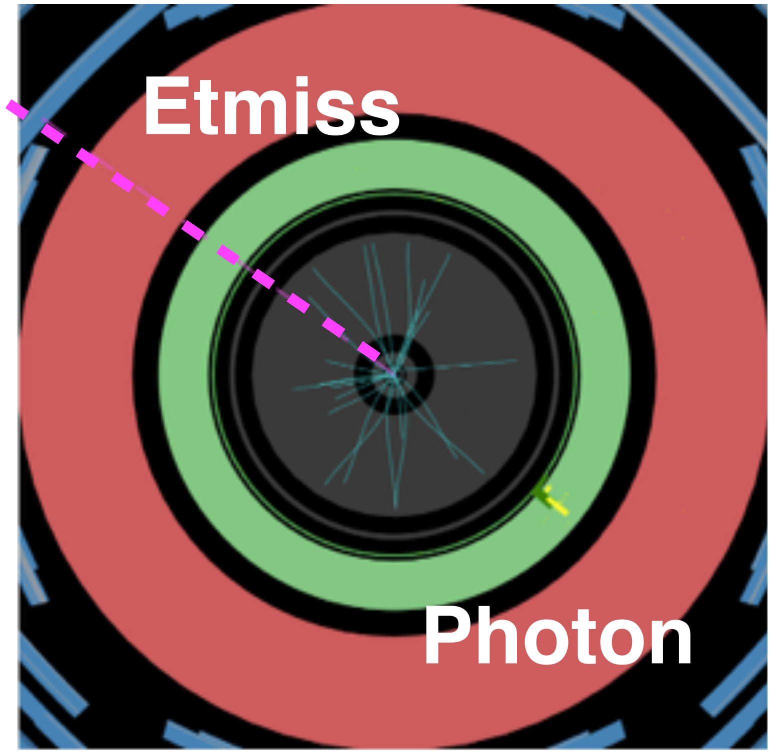


infer the presence of invisible particles from what we see in the detector

Etmiss in Nobel Prize in Physics 1984

Missing transverse momentum

$$E^{miss}_{x(y)} = - \sum p_{x(y)i}$$



Some warnings:

⚠ Nearly full coverage of the detector is needed to reconstruct all the objects

⚠ Both "hard objects" and "soft signals" *(unassociated tracks/deposits in calorimeter)* have to be taken into account:

$$E^{miss}_{x(y)} = - \sum_{hard} p_{x(y)i} - \sum_{soft} p_{x(y)j}$$

=> different algorithm depending on how you build the soft term

i.e. Calorimeter or Track based soft term

⚠ Not only "true" Etmiss caused by non-interacting particles but also fake Etmiss:

- SM interacting particles escaping the acceptance of the detector or poorly reconstructed

=> Etmiss is an important quantity not only in searches with invisible particles!

I worked on Etmiss during my 1st year, ask me if you are interested in more details!

ATL-PHYS-PUB-2015-027

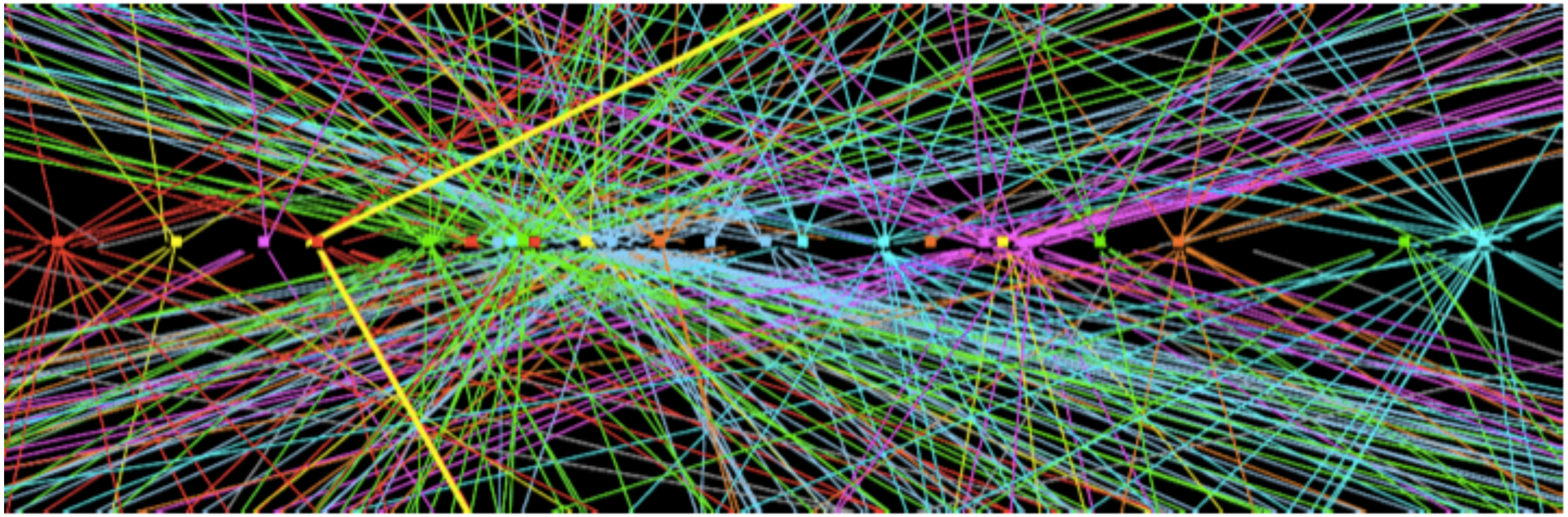
ATL-PHYS-PUB-2015-023

An experimental challenge

IN REAL LIFE…

- Each beam consists of ~3000 bunches of particles and each bunch contains ~100 billion particles
- 25 ns bunch spacing
- About 1 billion particle collisions per second

—> all this is making the environment very busy!!



example of reconstructed vertices in an event

Experimental tests of the Minimal Standard Model of neutrinos with the CMS experiment at the LHC

Giulia Negro

International Cotutelle of thesis between CEA-Saclay and INFN Torino (Italy)

Winner of "2017 Vinci project"

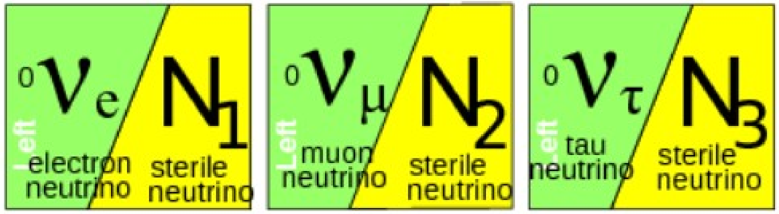
Supervisors:

Federico Ferri (CEA), Stefano Argiro (INFN Torino)

The νMSM

- This model is a minimal extension of the SM :
  - proposed by T. Asaka and M. Shaposhnikov in 2005
  - it introduces **3 massive right-handed neutrinos** with masses below the electroweak scale (→ visible at LHC)
  - the lightest of these 3 neutrinos is proposed as a **dark matter candidate**
  - the heavier two neutrinos can be responsible for the **baryon asymmetry** of the universe

→ it can explain some of the unresolved phenomena in particle physics while remaining consistent with the observation of neutrino oscillations and cosmological data on neutrino masses and mixing



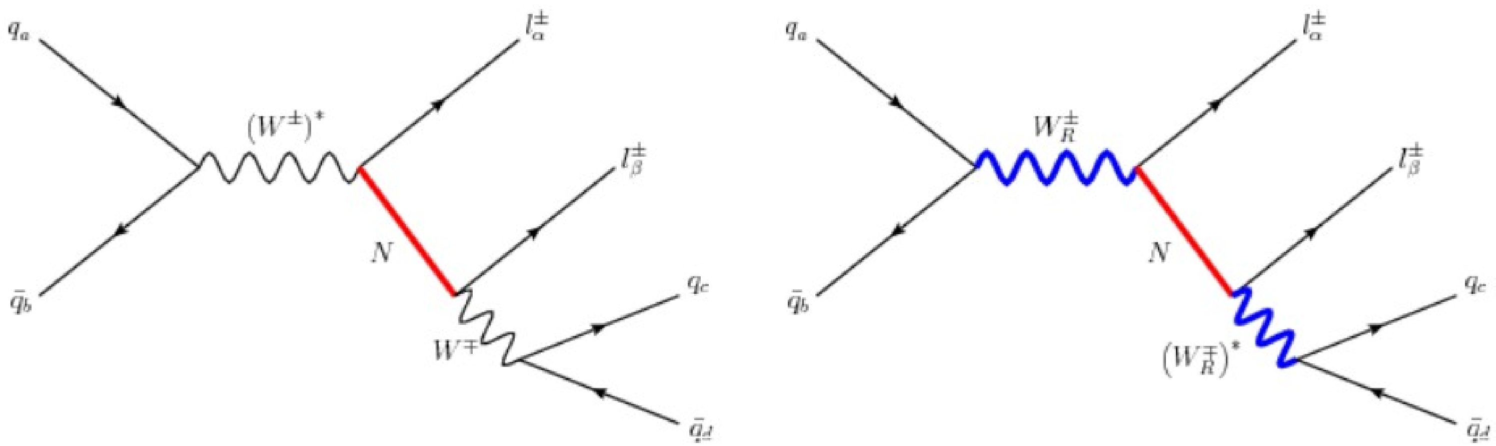
Baryon = hadron composed of 3 quarks

The baryon asymmetry refers to the imbalance in baryonic matter and antibaryonic matter in the observable universe

→ this model could help in gaining a **better understanding of the composition of our universe**

More generally : right-handed neutrinos

- What are we looking for ?
  - $(W^{+/-})^*$ / $W^{+/-}_R$ decaying into lepton + ν_R
  - ν_R decaying into lepton + $W^{+/-}$ / $(W^{+/-}_R)^*$ (where W / W_R * → q+qbar)



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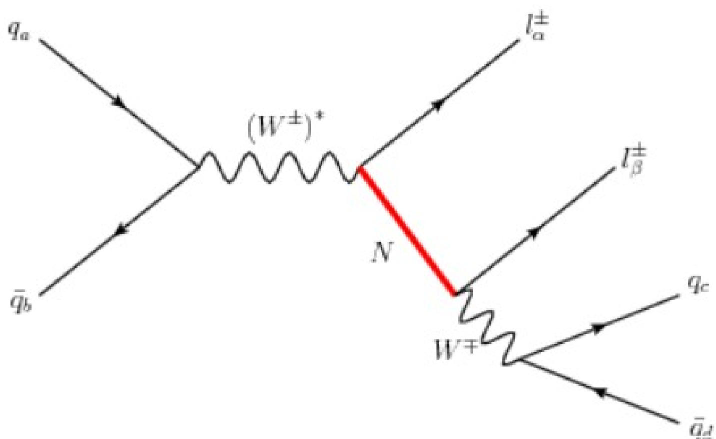
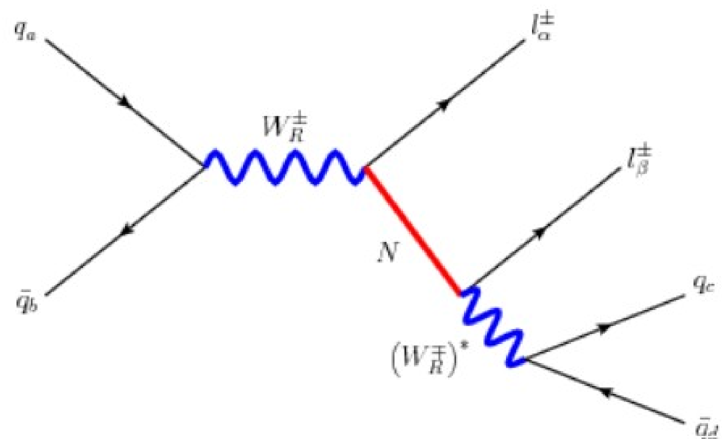
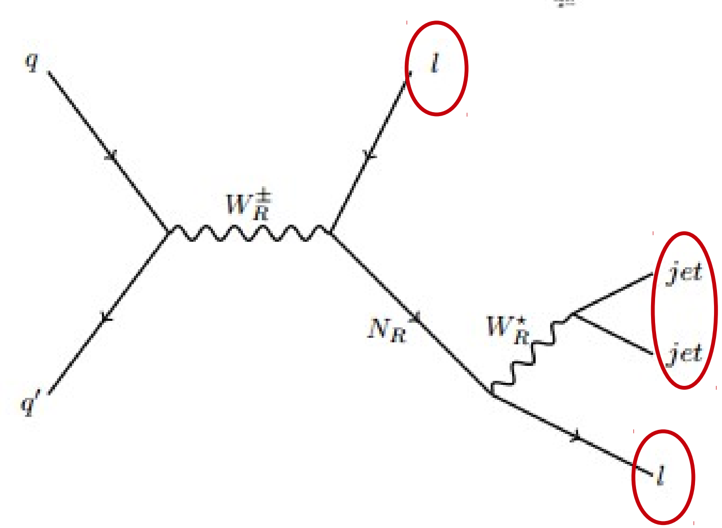


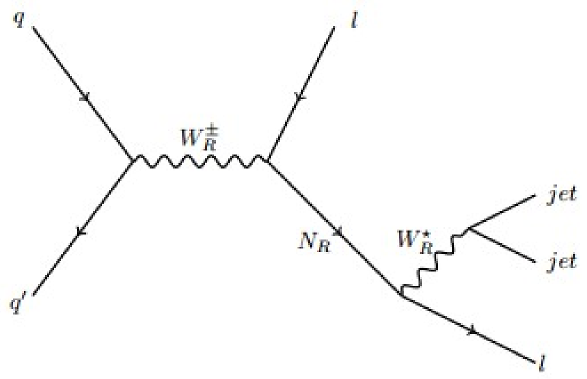


- Early focus of this analysis (easier kinematical case): search for heavy W_R decaying through a ν_R and a W_R* to **2 same flavour leptons** (electrons or muons) + **2 jets**



ν_R: how do we look for them ?

- Analyzing LHC Run2 data @13 TeV collected from CMS experiment ($\sim 36\ fb^{-1}$)
- Probing possible resonances decaying into 2 leptons and 2 jets looking for excesses in the m(lljj) distribution



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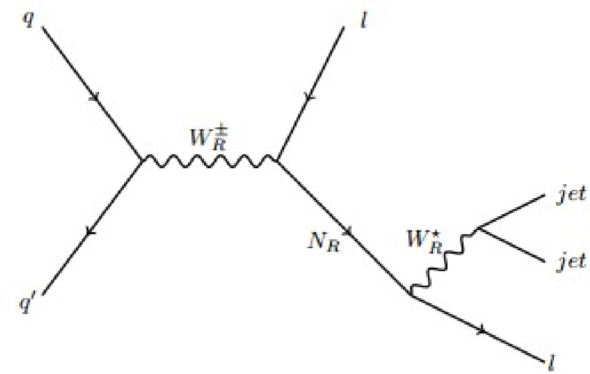
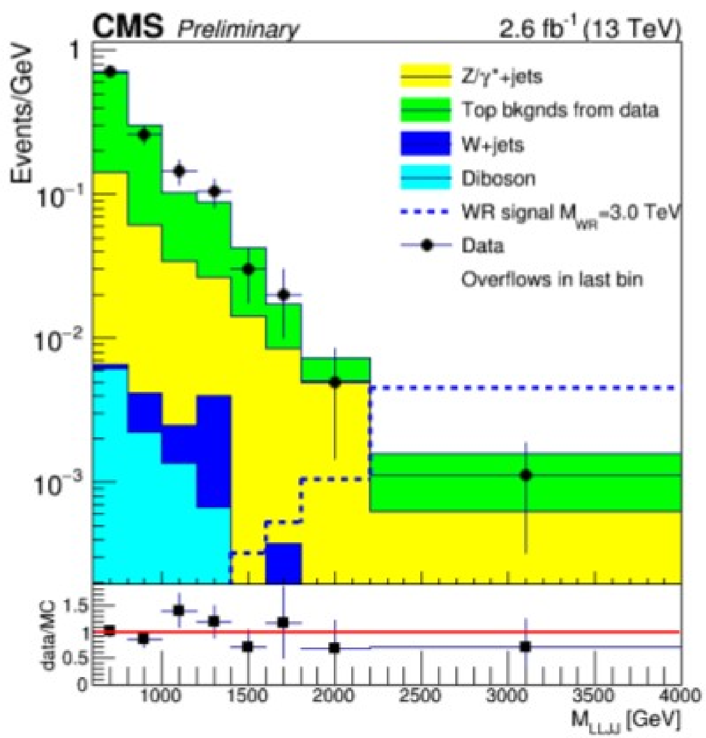


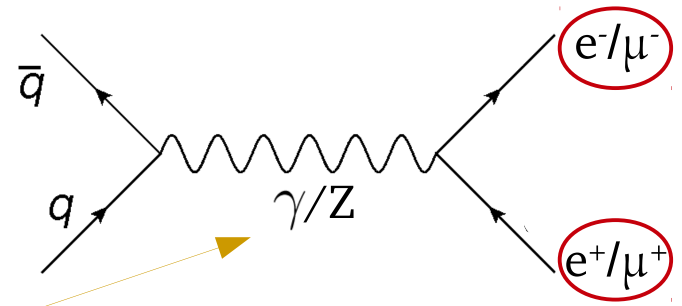
- Analysis strategy :
  - trigger on 2 high-pT leptons (electrons or muons)
  - reconstruction of the 4-object mass m(lljj) from the two hardest leptons and two hardest jets
  - look for an excess in the m(lljj) distribution and set limits on the production (σ * BR) in different

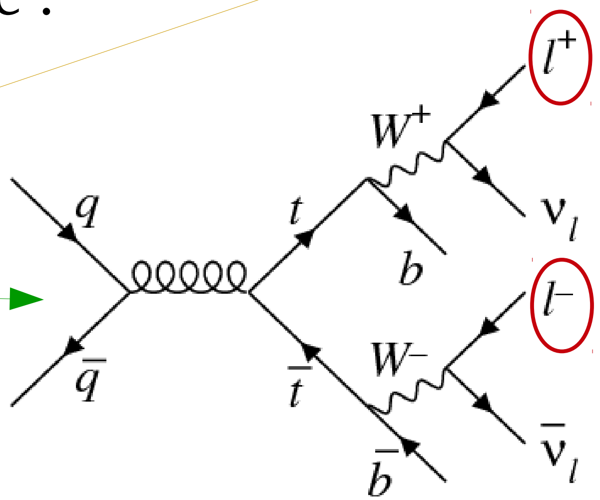
  m(lljj) bins

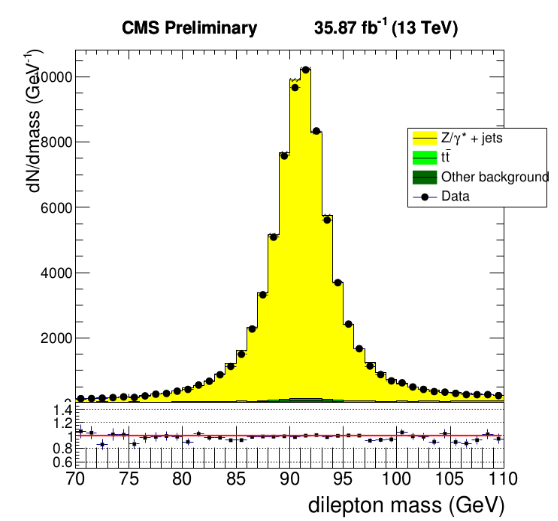


Signal and background regions

- **2 signal regions :**
  - 2 electrons or 2 muons
- Some processes have the same final state :
  - main backgrounds :
    - Drell-Yan (~ 70 %)
    - TTbar (~ 30 %)
  - additional backgrounds :
    W+jets (< 1 %), diboson (~0.8 %), singleTop
  - estimated from simulated samples or with data-driven methods
- Agreement of data with simulated samples verified in control regions with selections orthogonal to the ones for signal region



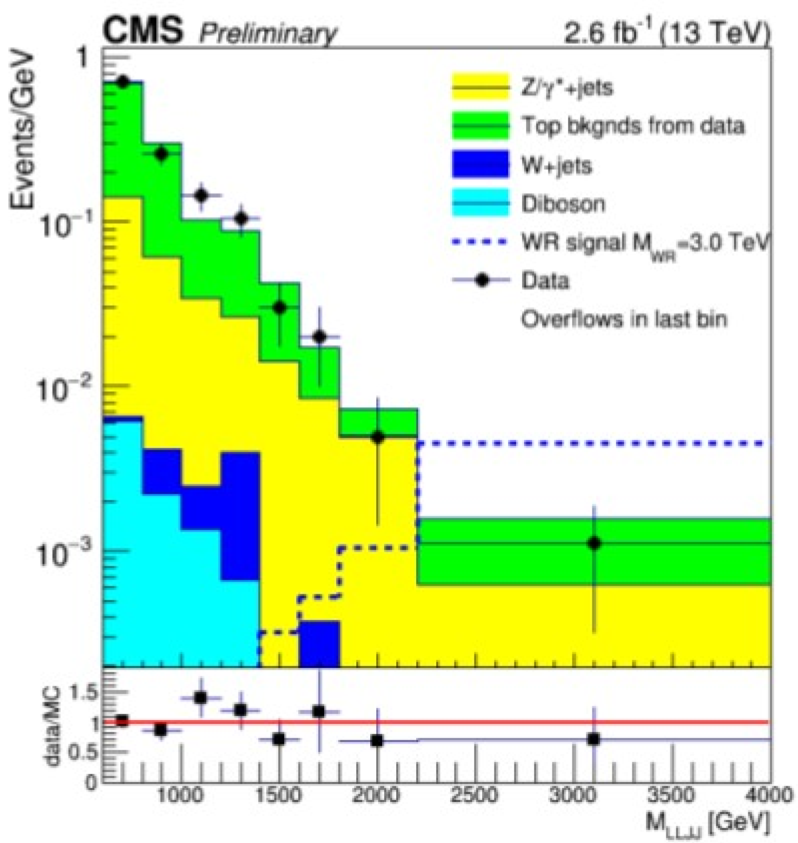




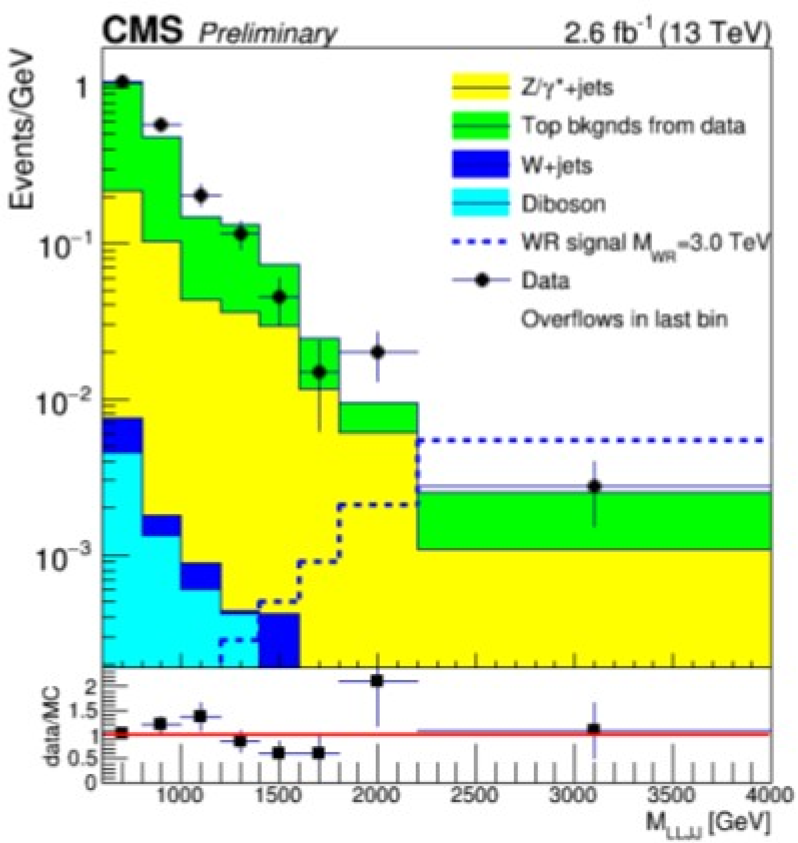
Results

- Results with 2015 data @13 TeV ($\sim$ 2.6 fb^{-1}) already public
- 2016 analysis being approved
- No clear excess seen in the m(lljj) invariant mass distribution

Electrons

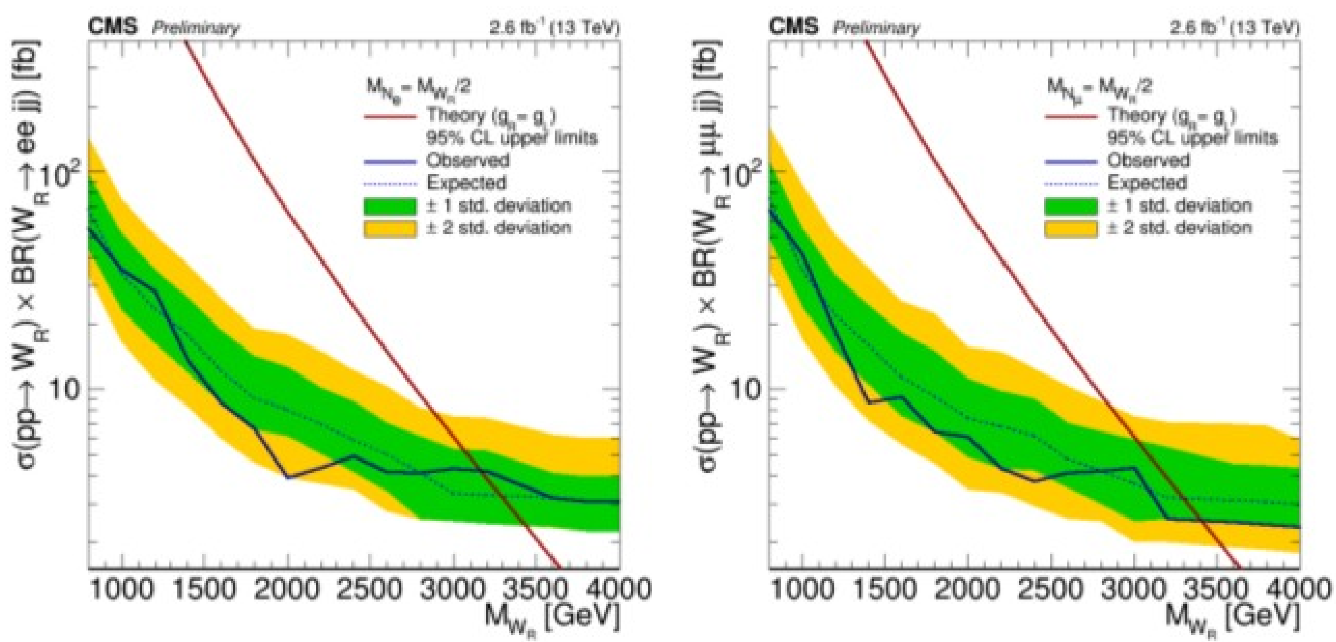


Muons

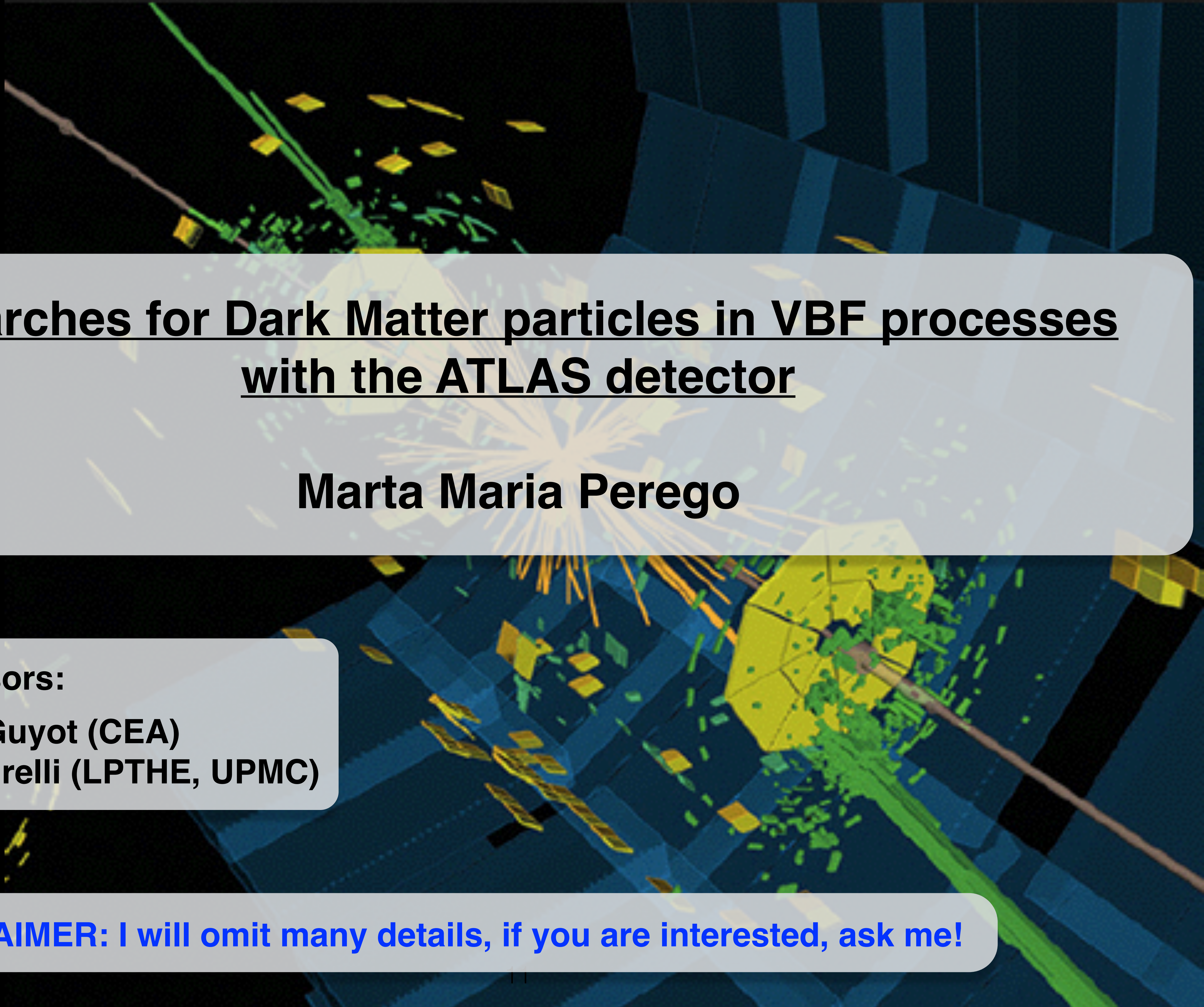


Results & conclusions

- Limits on W_R boson production are calculated using the number of observed events, expected background events and signal events in each mass window
- W_R mass excluded up to **3.3 (3.5) TeV** in electron (muon) channel



- New results with 2016 data @13 TeV will be published soon !
- More to come: more challenging final states (Shaposhnikov's neutrinos)



<u>Searches for Dark Matter particles in VBF processes with the ATLAS detector</u>

Marta Maria Perego

Supervisors:

Claude Guyot (CEA)
Marco Cirelli (LPTHE, UPMC)

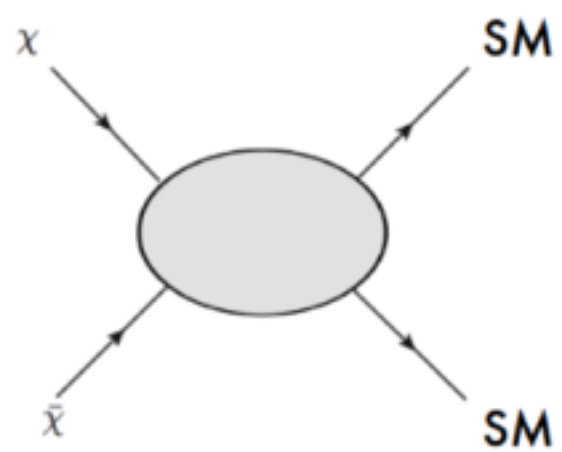
DISCLAIMER: I will omit many details, if you are interested, ask me!

How to look for DM at colliders

- Three main approaches to look for DM

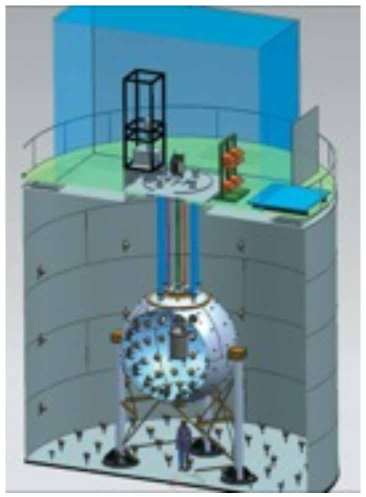
INDIRECT DETECTION

look at its annihilation products



DIRECT DETECTION

look for its scattering with nuclear matter



COLLIDERS SEARCHES *produce it at colliders*

COLLIDER DARK MATTER SEARCHES

There are different strategies:

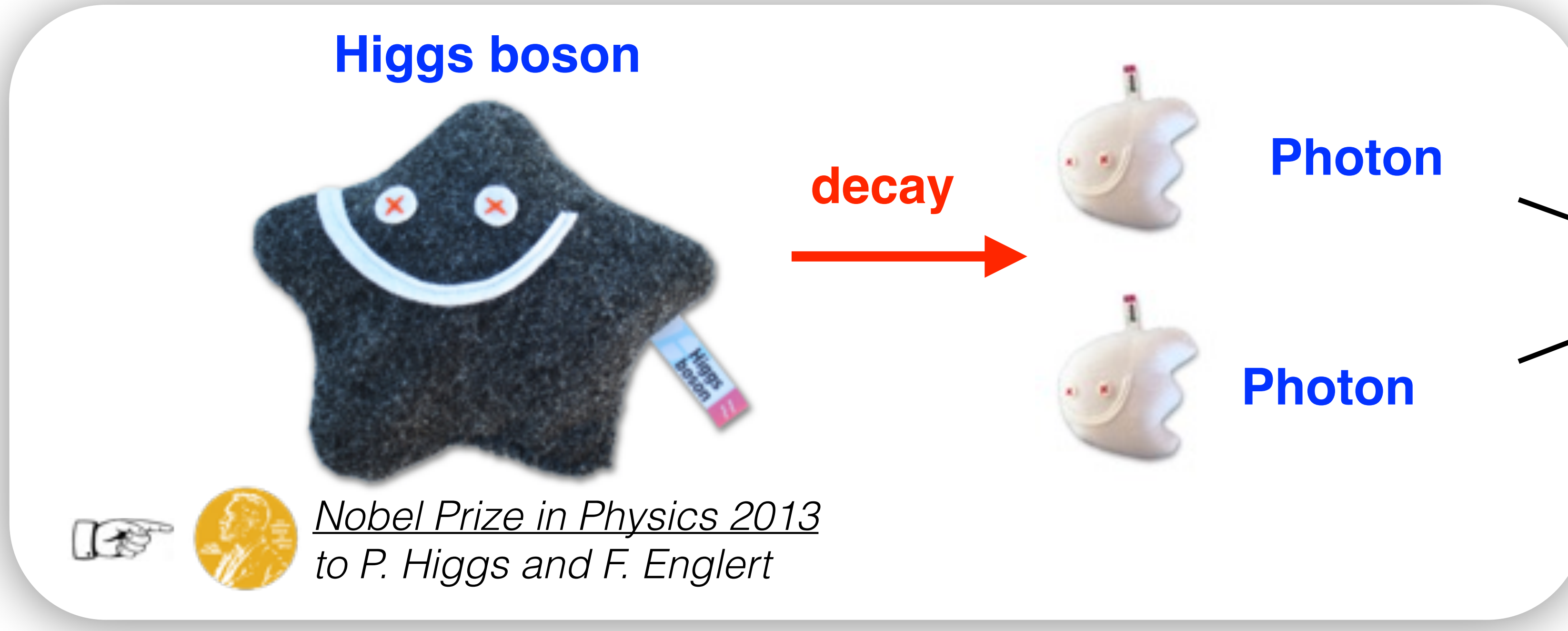
- look for particles and decays predicted by specific theories
- more model independent searches

focusing on this during the talk

- Scenarios where the dark matter has a coupling to a Higgs boson can be tested at the LHC searching for an **invisible decay** mode **of the** 125 GeV **Higgs Boson**

Higgs boson at the LHC

- at 13 TeV, one Higgs boson is produced in 1 billion collisions
- once produced, the Higgs boson rapidly decays and is detected by identifying its decay products:



this is what we see in the detector (for example)

~0.2% of the times decay into 2 photons (1 every 500 produced!)

- The Higgs boson we found in 2012 is very SM like

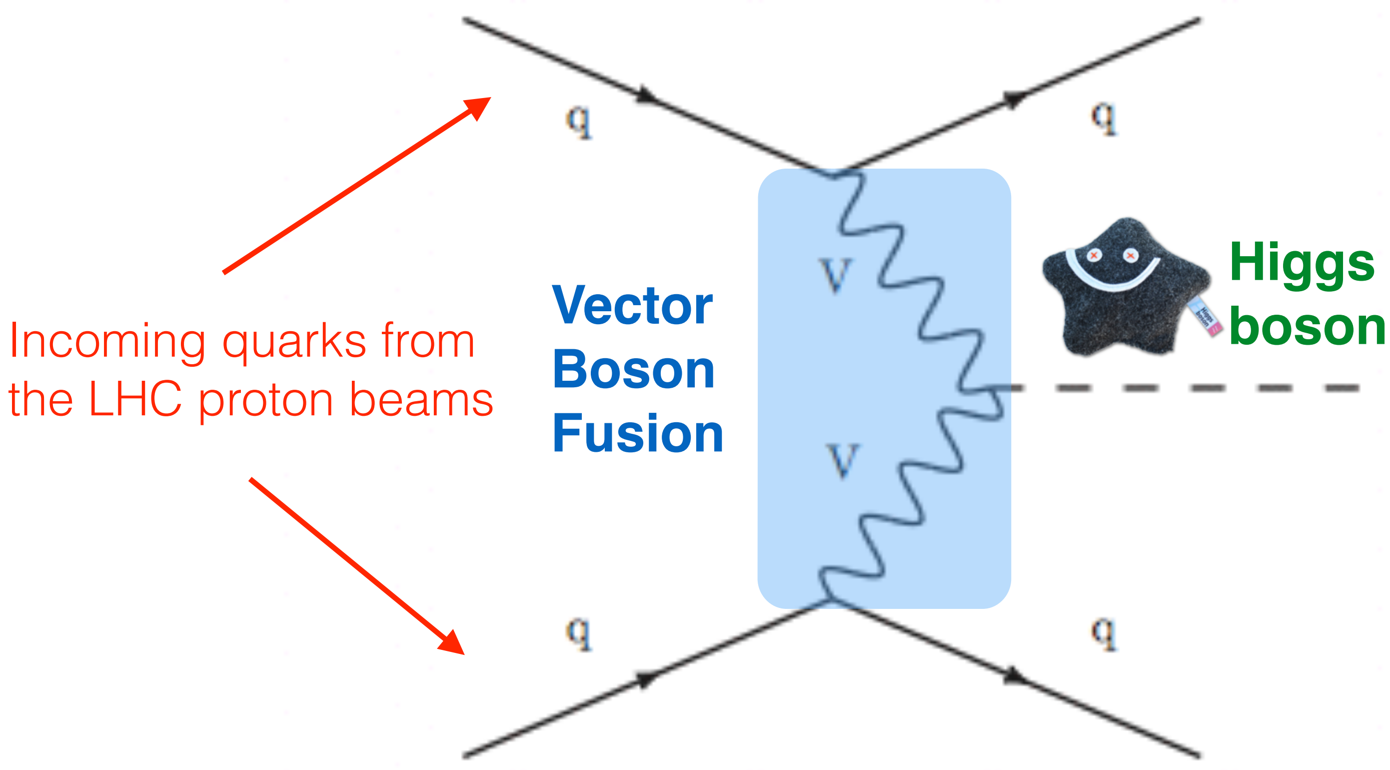
—-> but still there is an **open window for the Higgs invisible decay!**

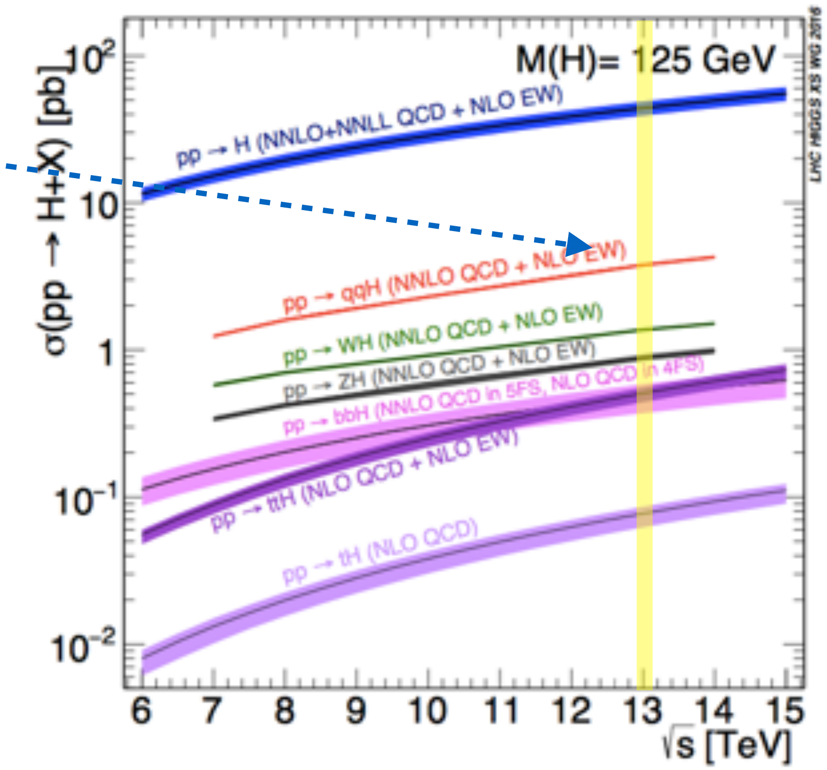
… well, **what does it mean?**

- There is still the possibility that the Higgs decay into feebly interacting (“invisible to the detector”) particles
- These particle can be dark matter particles

Higgs invisible decay - VBF production mode

- How can we look for the invisible decay of the higgs boson?
- The most sensitive channel is the **Vector Boson Fusion** mode:
  - second highest Xsec
  - clear signature





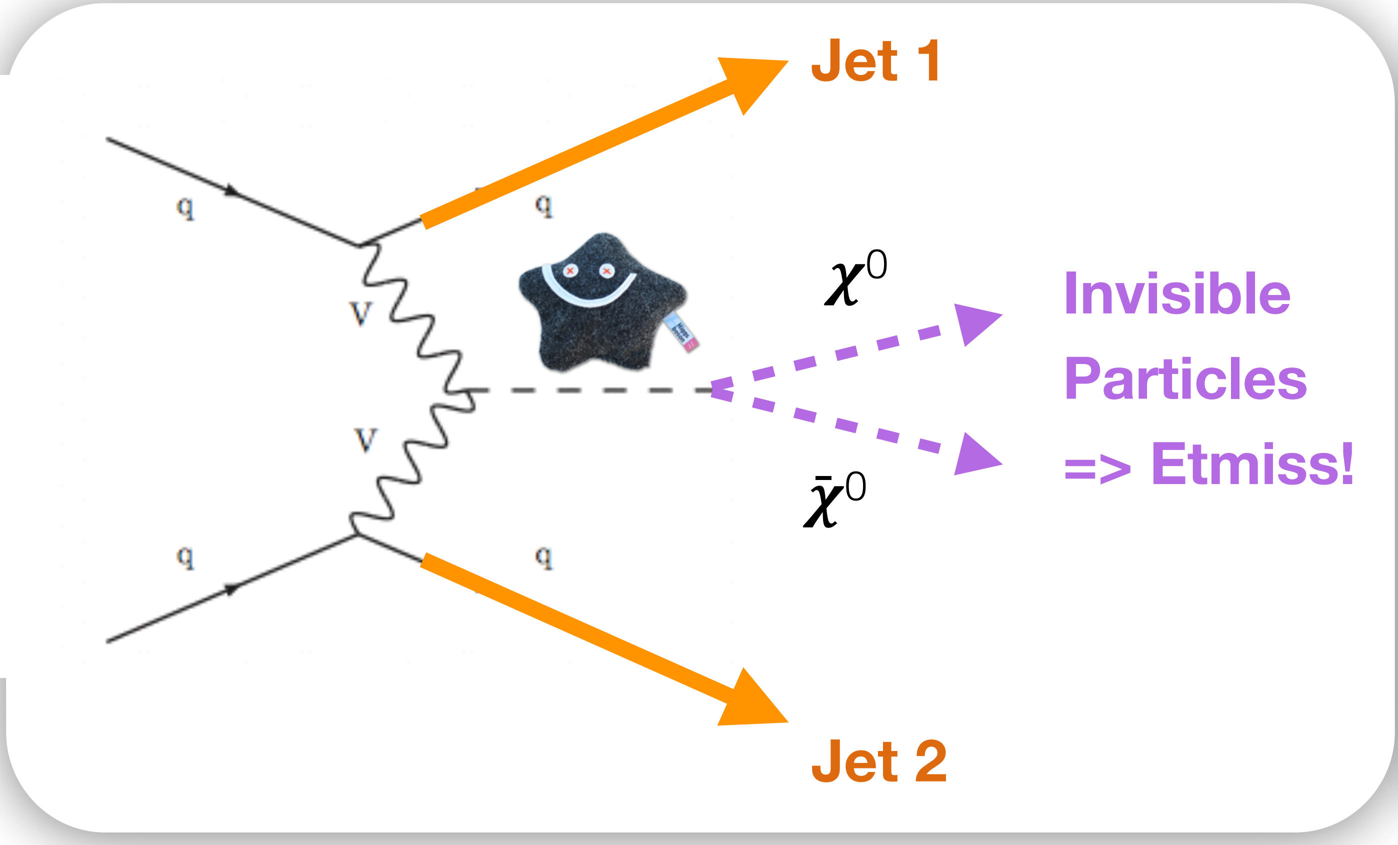
cross sections for the different Higgs production modes

Why a clear signature?

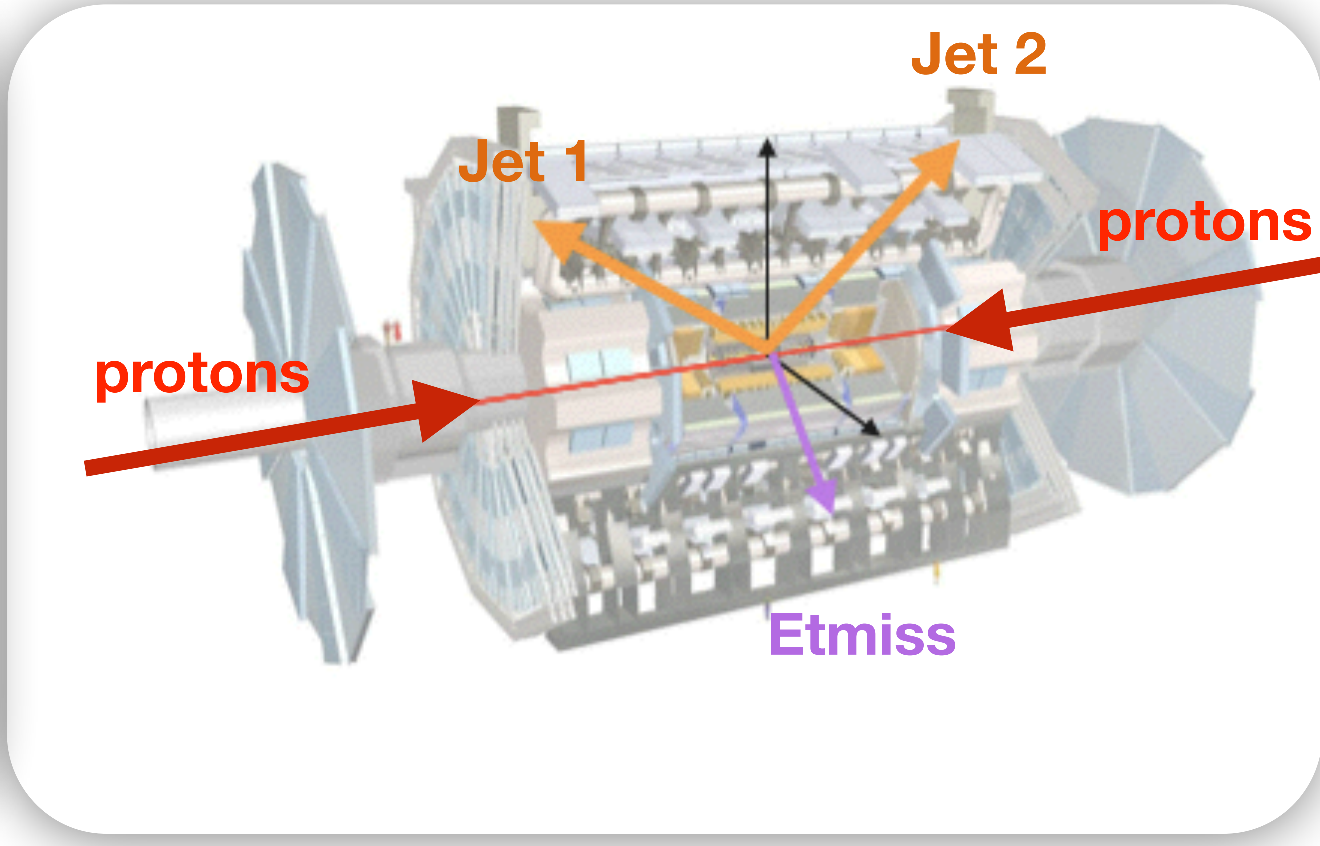
FINAL STATE:

- defined by **2 jets separated in eta** , **large invariant dijet mass** and **large Etmiss**

at fundamental level



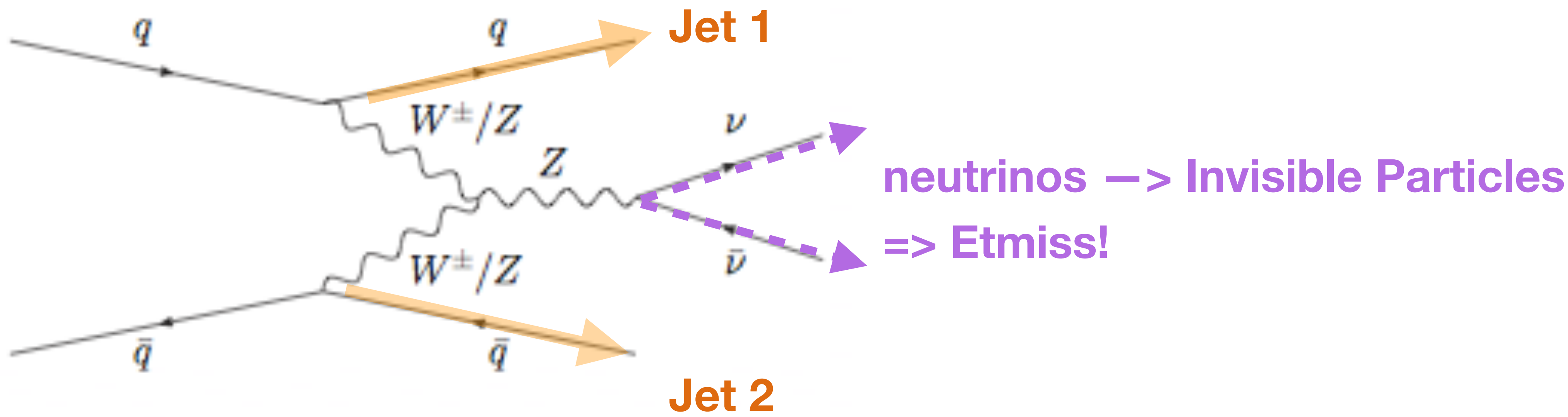
in the detector



VBF Higgs invisible analysis

This is a quite challenging analysis:

- Lots of SM processes have the same final state



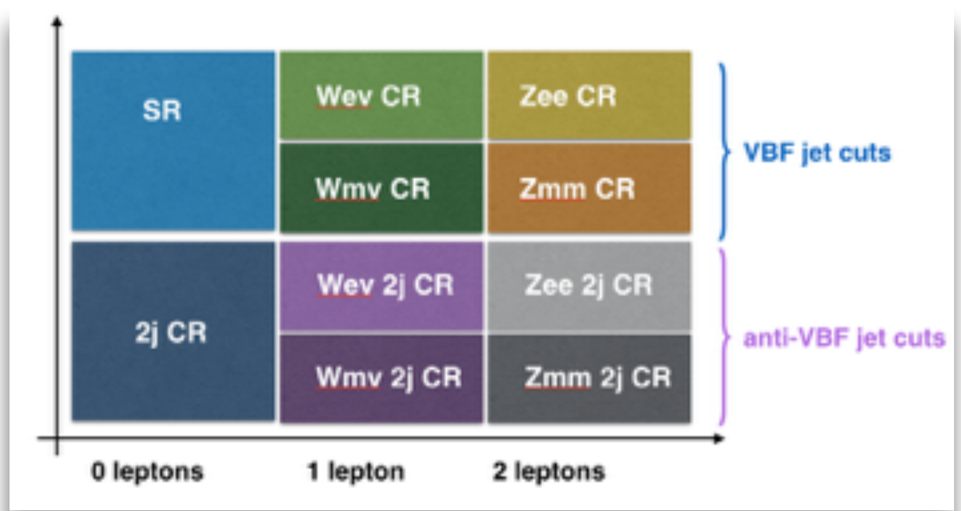
- Events with two jets, passing the analysis requirements, can come from QCD processes
  - …. very hard to deal with!

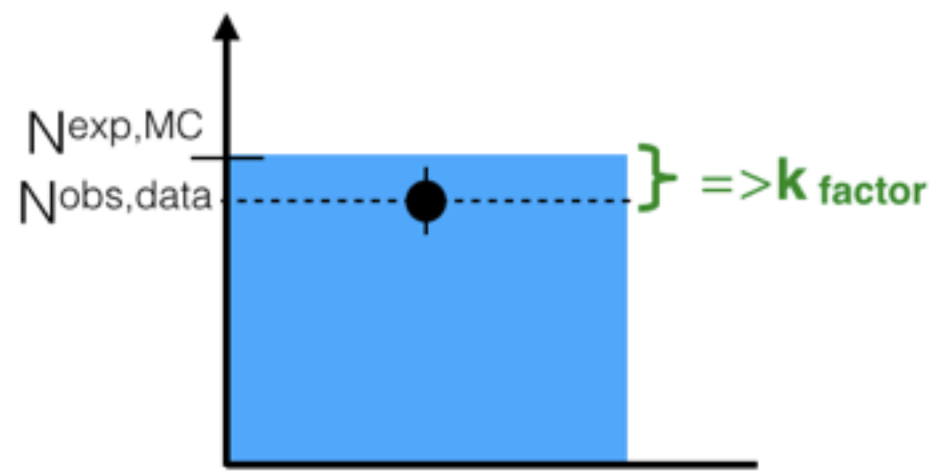
- We are in a corner of the phase space:
  - VBF jets are forward, even outside of the tracker acceptance!

Strategy in 1 slide

Background estimation and limit setting:

- We define Control regions (CR) enriched in W/Z events
- We define scale factors k to match the number of events in data and MC
- We extrapolate in the signal region the backgrounds using the fitted scale factors





- This is done with a simultaneous fit in SR and CRs for background estimation and limit setting by constructing a likelihood function as:

$$L_{\mathbf{reg}}[\mu|N_{obs}] = \mathrm{Poiss}(N^{obs}_{reg} | \mu \times N^{sig,MC}_{reg} + \mathbf{k_{Z/W}} \times N^{W/Z,MC}_{reg})$$

SR, CRs — signal strength — scale factor for W and Z processes

- Set a limit on BR(H—>inv) (μ)

Conclusions and take away messages

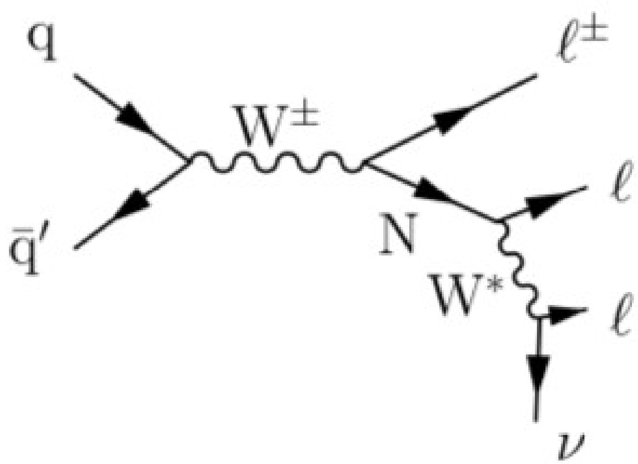
- Lots of interesting physics is possible @LHC
- ATLAS and CMS are very important experiments built to improve our understanding of the nature at fundamental level
- Dark Matter **searches** can be carried out **at colliders** which are potentially dark matter factories
- An important analysis is the search for the **invisible decay of the Higgs boson**
- The best constrain comes from the **VBF channel**
  - **It is quite challenging because of the peculiar topology**
  - I have shown you the idea of the analysis
  - unfortunately I cannot show you any plots/results since it is not yet public

DE LA RECHERCHE À L'INDUSTRIE

BACKUP

Future plans

- Extension of the analysis : study of the νMSM
  - considering 3l (prompt) decays of HNL (mN > 100 GeV)
  - using all combinations of electrons/muons
  - selecting 3 leptons with pT thresholds as low as allowed by the current triggers
  - search at low (mN < mW) and high (mN > mW) mass



Event selections

- **Signal region** :
  - pT > 60 (53) GeV for leading (subleading) lepton
  - pT > 40 GeV for both jets
  - |eta| < 2.4 for leptons and jets
  - R > 0.4 between all final state particles
  - **Mlljj > 600 GeV** (define the search region)
  - **Mll > 200 GeV** (to suppress DY)
- **Flavor Control Region** (ttbar background estimate):
  - same selections of signal region but **1 electron and 1 muon** required
- **Low di-lepton mass CR** :
  - same as signal region but **Mll < 200 GeV**
- **Low 4-object mass CR** (general data/MC agreement) :
  - same as signal region but **Mlljj < 600 GeV**
- **T&P CR** (check scales, smearings, measure SF for DY) :
  - fire dedicated TnP triggers
  - **80 GeV < Mll < 100 GeV**

Signal and Backgrounds

- **Signal region** (blinded) :
  - 1 region for the electron channel (2 electrons required)
  - 1 region for the muon channel (2 muons required)
- Two main backgrounds :
  - Drell-Yan (~ 70 %):
    - estimated from simulation
    - SF = data/MC ratio determined in **T&P CR** near Z peak
    - cross-check in **low di-lepton mass CR**
  - TTbar (~ 30 %):
    - estimated from data in dedicated **flavor CR (**1electron + 1 muon required) = signal free CR (under assumption of lepton flavor conservation in decay chain)
    - Scale events from flavor CR, accounting for different lepton efficiencies (e,μ) estimated on simulation

      → N_ttbar(data) = N_ttbar(MC) * N_eμjj(data)/ N_eμjj(MC)
- Additional backgrounds : W+jets (< 1 %), diboson (~0.8 %), singleTop

Previous CMS analysis in Run1

- Excess of 2.8 sigma observed in electron channel (absent in muon channel) for $mW_R \sim 2$TeV with data @8 TeV
- Regions in the (mW_R , mN_R) mass space are excluded at 95% confidence level
- mW_R excluded up to 3.0 TeV for both channels