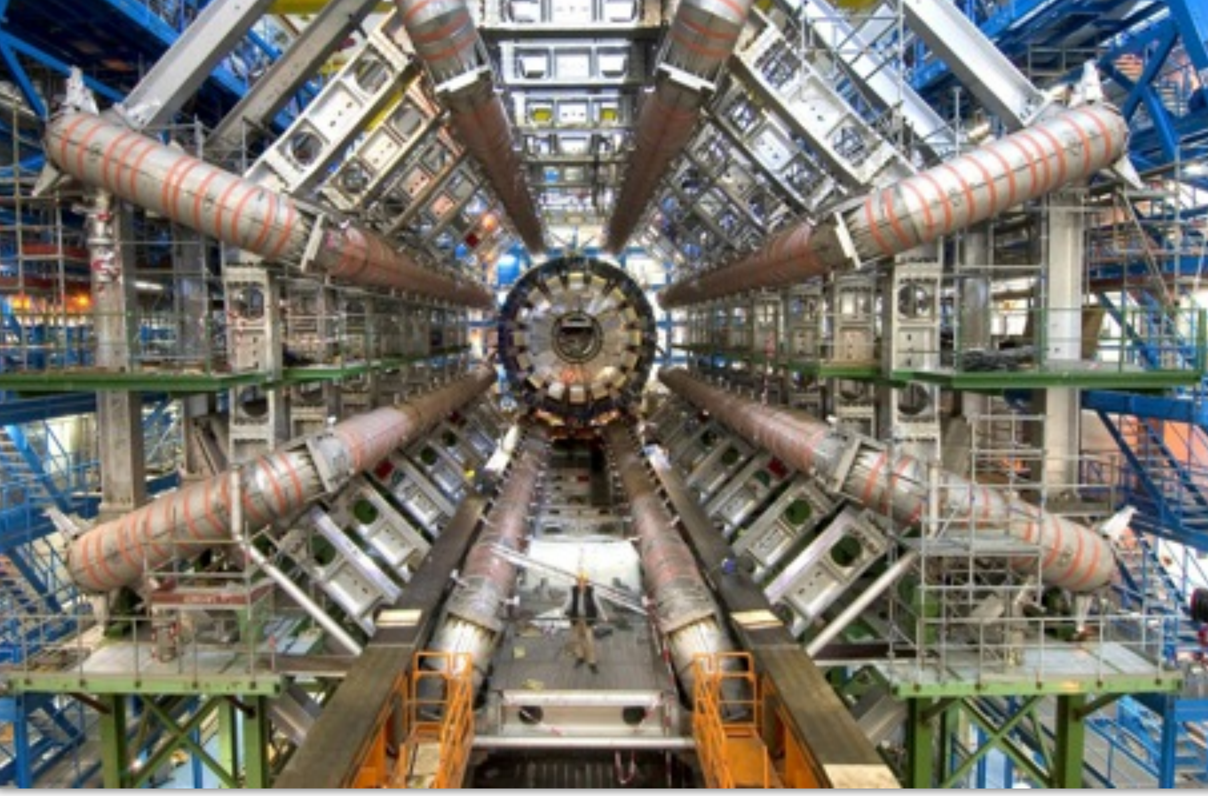


Searches for dark matter particles produced in Vector Boson Fusion processes in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector

Marta Maria Perego

Supervisors: C. Guyot (CEA Saclay) , M. Cirelli (LPTHE, UPMC)

May 31, 2017

@Pheniics Fest
Particules, Hadrons, Énergie, Noyau, Instrumentation, Imagerie, Cosmos et Simulation

Outline

I will talk about:

- The dark Matter and collider dark matter searches
- The LHC and the ATLAS detector
- The VBF Higgs invisible analysis
- Minimal Dark Matter in VBF processes

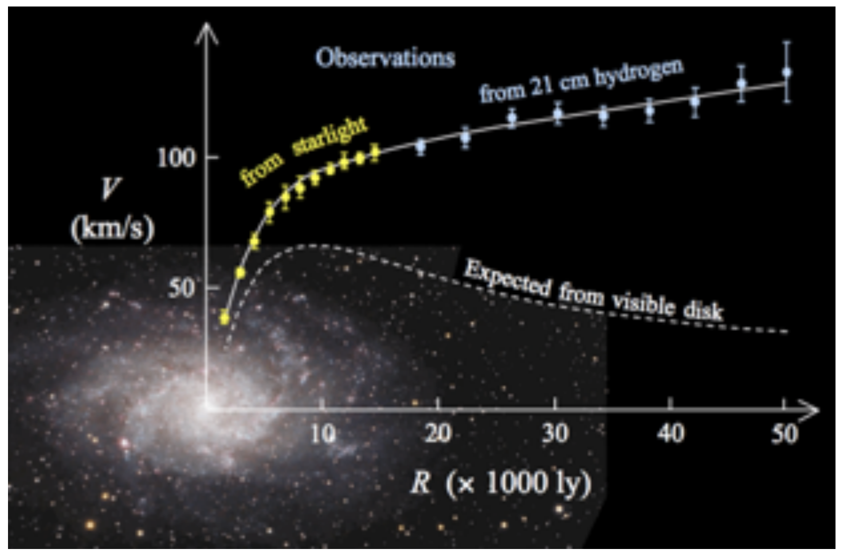
-> Disclaimer:

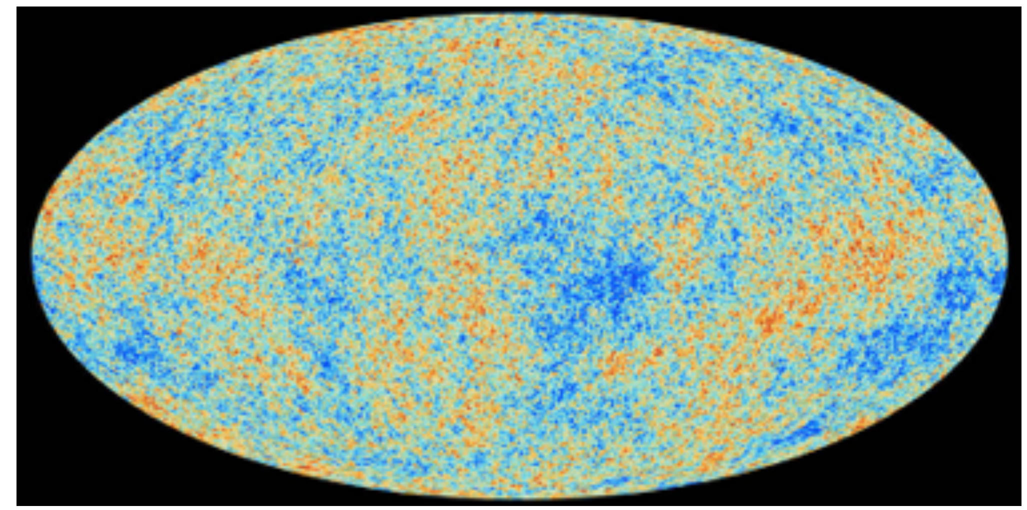
- I will omit many details, if you are interested ask me!

Dark Matter

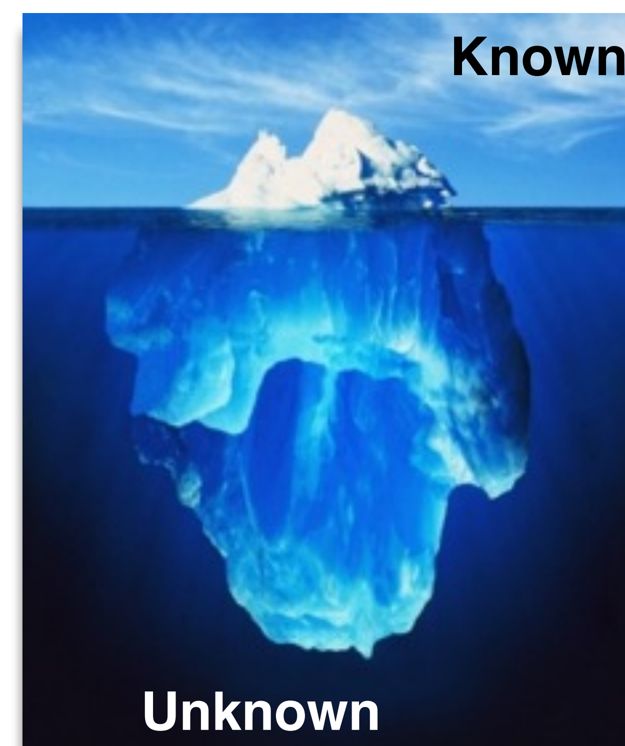
- Astrophysical and cosmological measurements tell us that **Dark Matter (DM) is out there**

X ray distribution
Gravitational lensing





- Known matter makes up ~4% of the Universe, Dark matter constitutes 23%
- Its identity and physical properties are still **unknown**
  - new particle
  - stable
  - feebly interacting
  - neutral

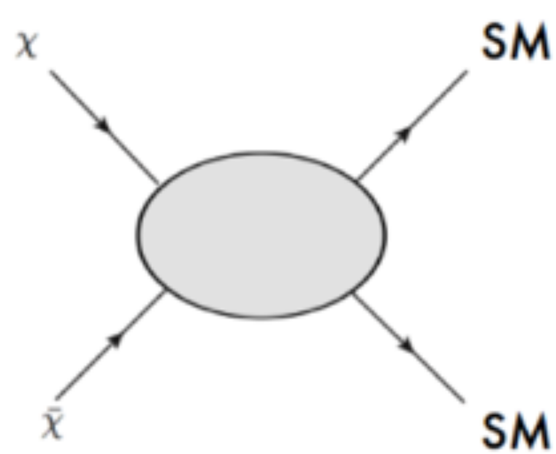


How can we detect DM?

- Three main approaches to look for DM

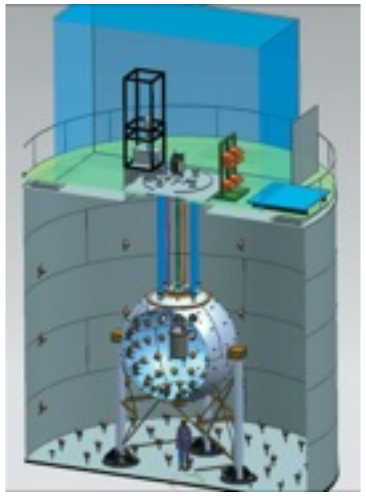
INDIRECT DETECTION

look at its annihilation products



DIRECT DETECTION

look for its scattering with nuclear matter



COLLIDERS SEARCHES *produce it at colliders*

How can we detect DM?

- Three main approaches to look for DM

INDIRECT DETECTION

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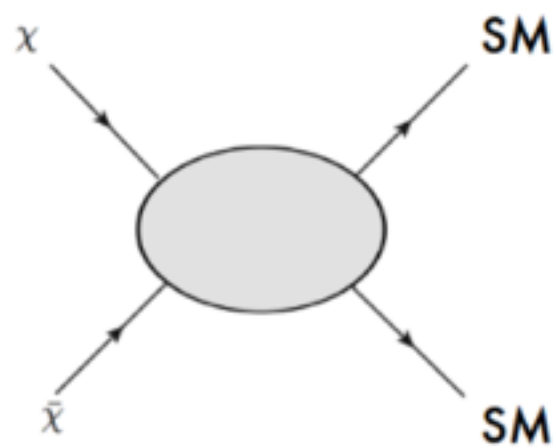

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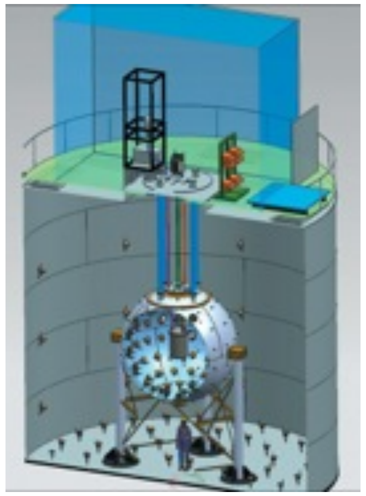


COLLIDERS SEARCHES *produce it at colliders*

COLLIDER DARK MATTER SEARCHES

There are different strategies:

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

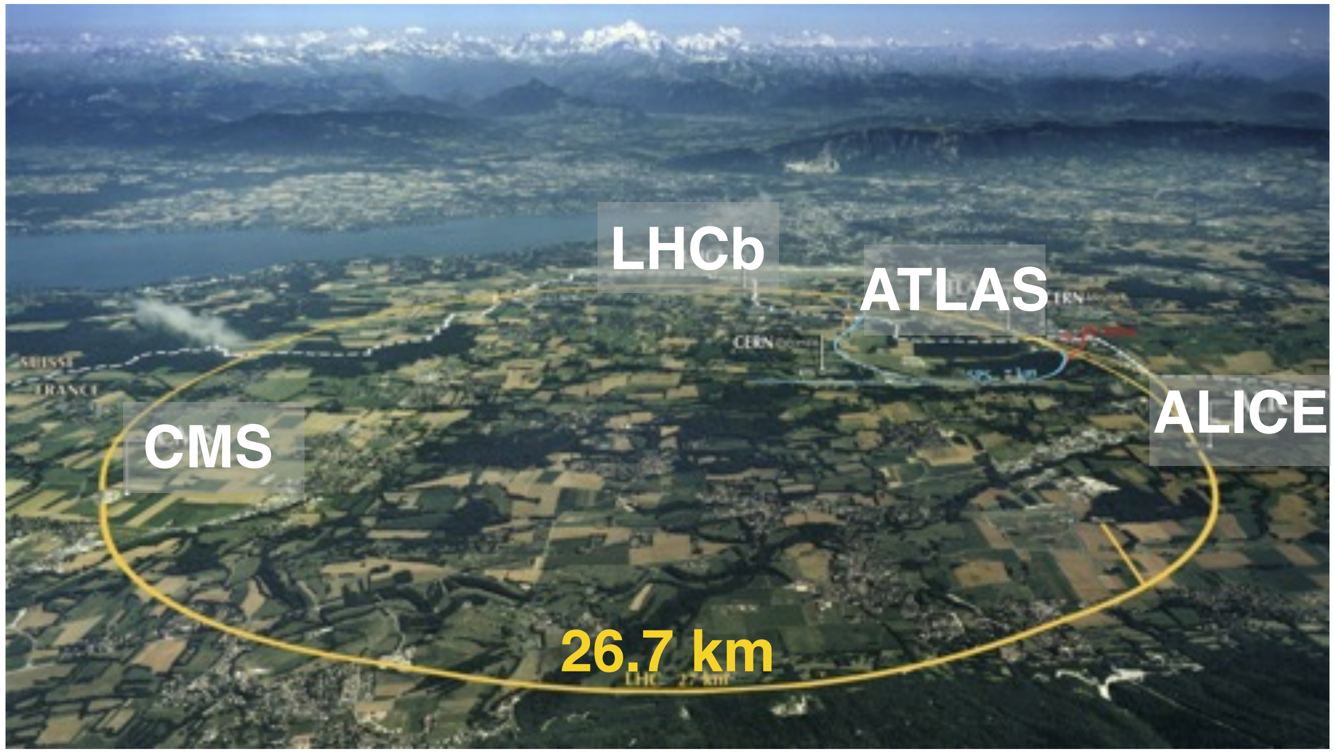
—> broad program to try to cover *all* the possible final states

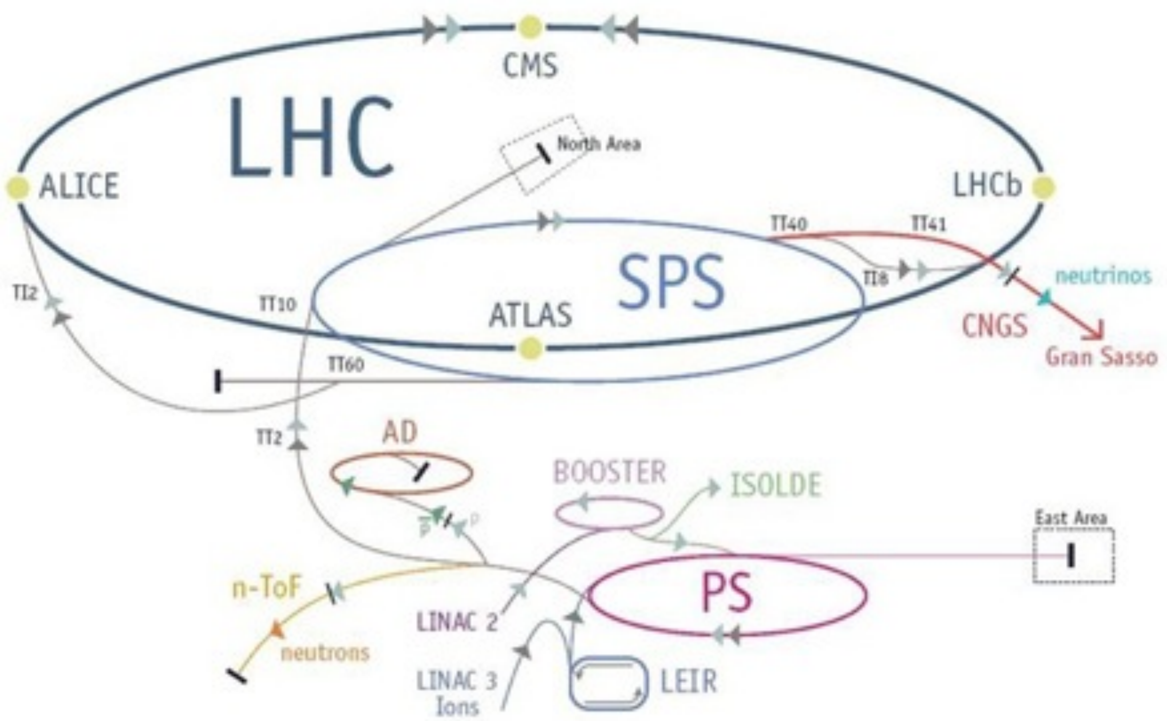
focusing on this during the talk

- 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**

Large Hadron Collider

- The LHC is a two-ring, circular, superconducting hadron accelerator and collider
- The **largest and highest energy** particle accelerator in the world
- Installed in 26.7 km underground tunnel, at CERN, Geneva.
- Designed to collide **proton beams** *(can also collide heavy ions, Pb, not discussed here)*





- The LHC is the final step of a multi-stage accelerator system
- Currently **running at 13 TeV** c.m.e.
- Two separate beams (*bunches of protons*) are run in opposite directions *(25 ns bunch spacing)*
- Beams collide in 4 **dedicated collision points**, where experiments are built
  - one which hosts the **ATLAS** experiment

Atlas experiment

- **Multi purpose detector**: broad physics programme
- Surrounds one of the LHC interaction points
- **Giant** detector: 44 m long, 25 m diameter
- Forward- backward symmetric cylindrical geometry

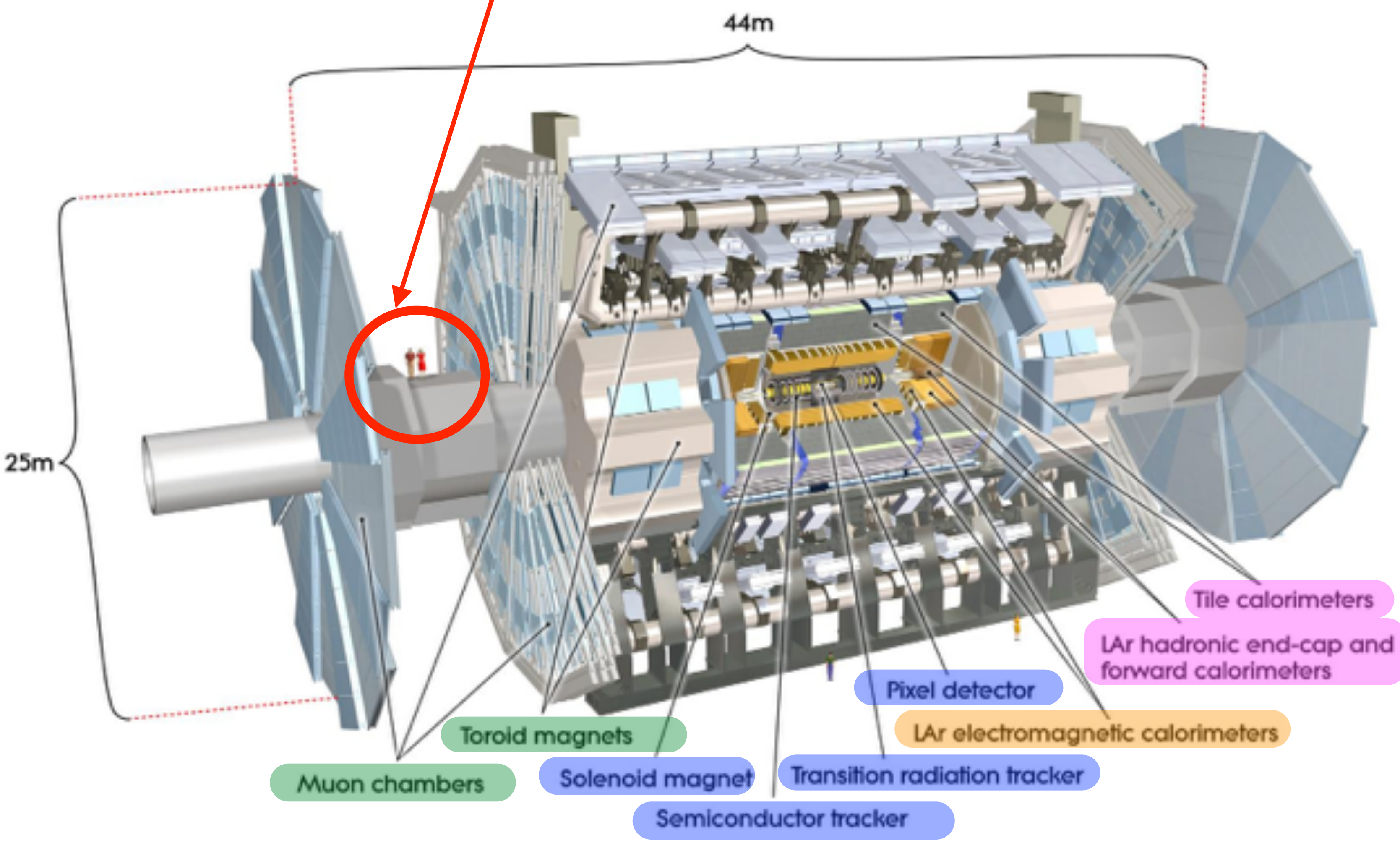
IDEA:

- 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

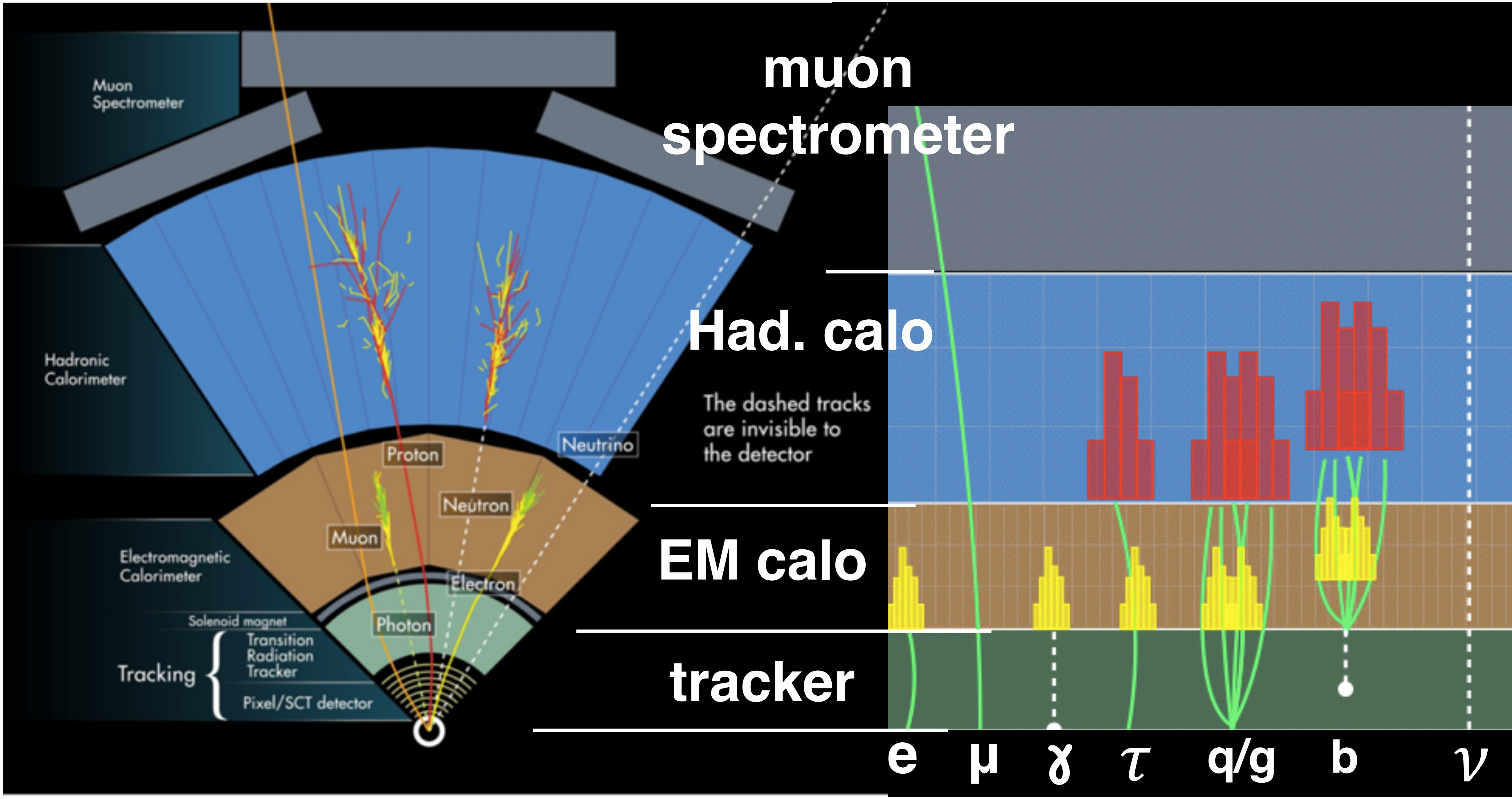
- Inner detector
- Electromagnetic calorimeter
- Hadron Calorimeter
- Muon Spectrometer

notice the scale: people are here!



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

Atlas experiment



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

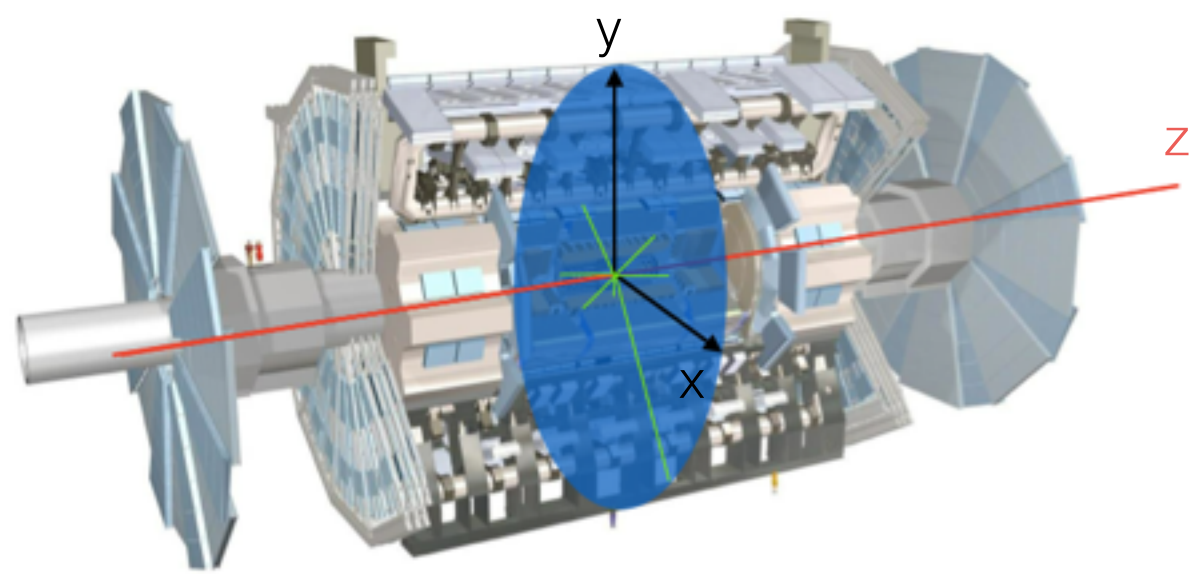
Missing Transverse Momentum

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*

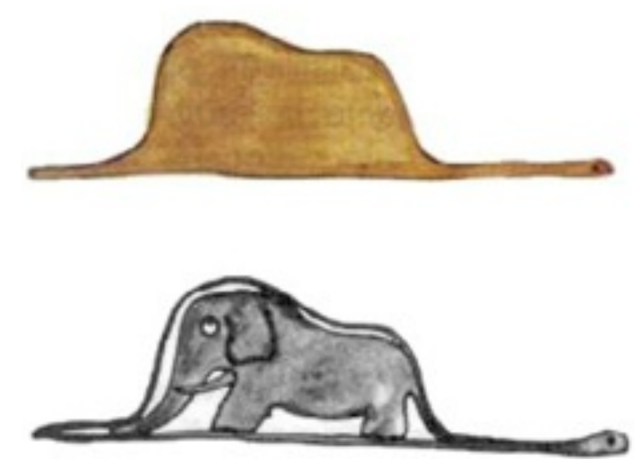
In the transverse plane, the kinematics is closed and energy and momentum are conserved



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

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

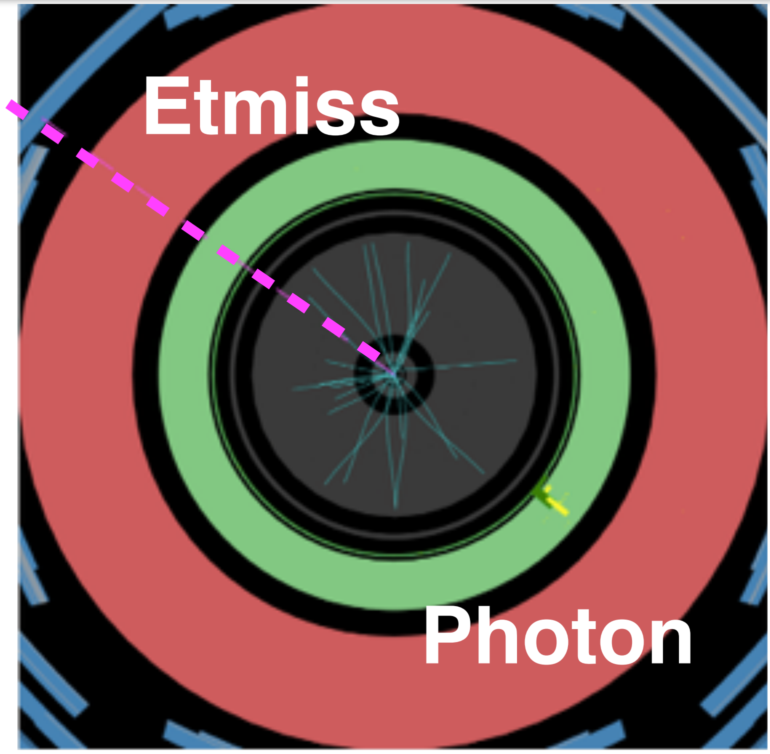
$$E^{miss}_{x(y)} = - \sum p_{x(y)i}$$



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

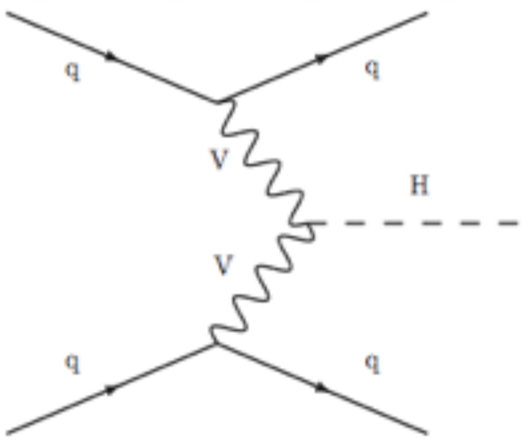
ATL-PHYS-PUB-2015-023

Higgs invisible decay

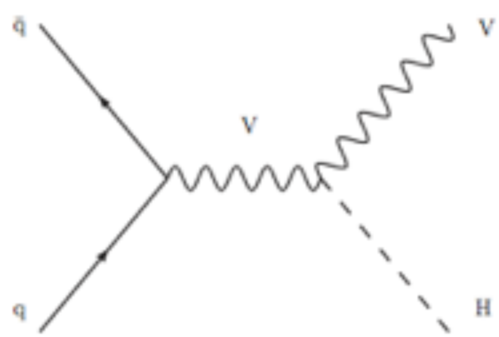
- Scenarios where the dark matter has a coupling to a Higgs boson can be tested at the LHC searching for an invisible decay mode of the 125 GeV Higgs Boson

CURRENT STATUS:

- There is still a window for the invisible decay of the Higgs into BSM particles:
  - from direct searches: 0.24 (0.23) at 95% CL

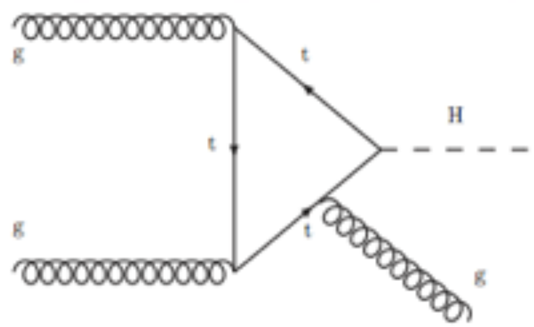


Vector Boson Fusion (VBF) production mode

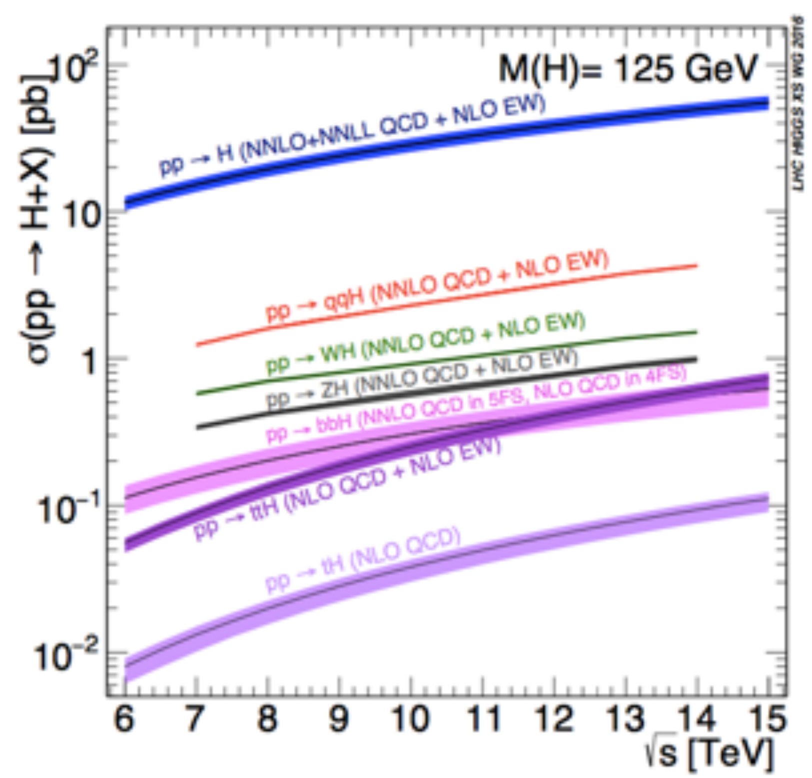


Higgs strahlung

V boson associate production



gluon gluon fusion



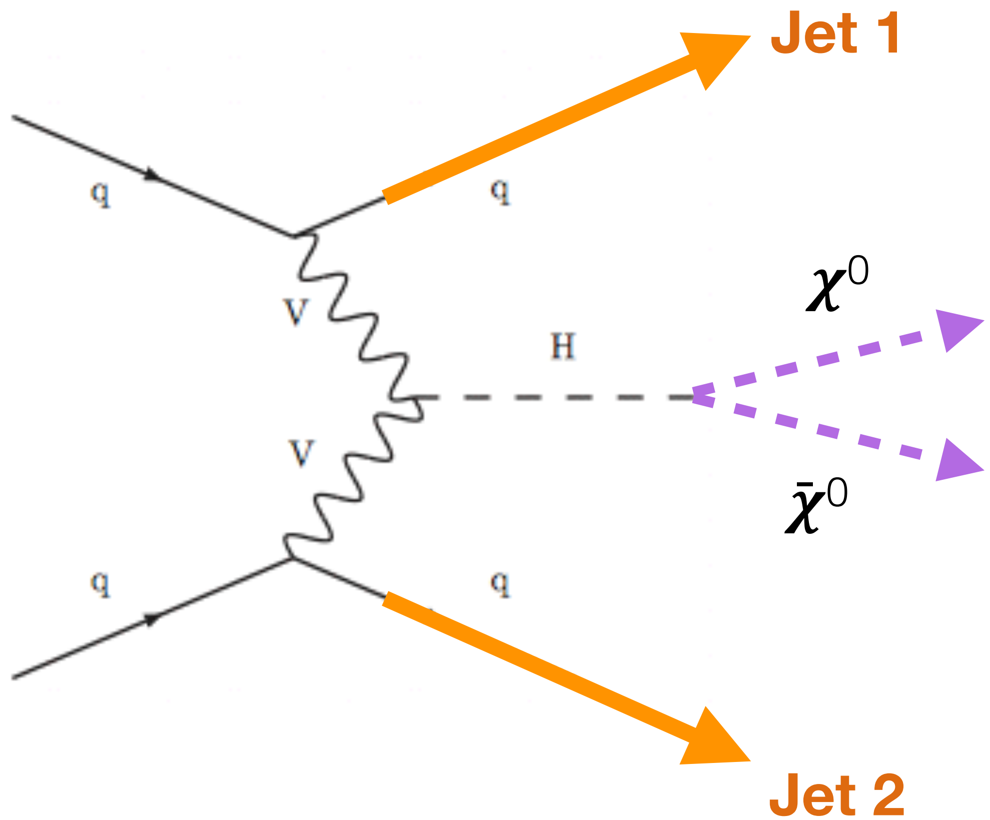
  - most stringent limits from VBF
    - second highest Xsec
    - clear signature

- *from limits on fit: the BR(Higgs->invisible) may be up to 34% (at 95% CL)* https://arxiv.org/abs/1606.02266

VBF Higgs invisible analysis

FINAL STATE

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



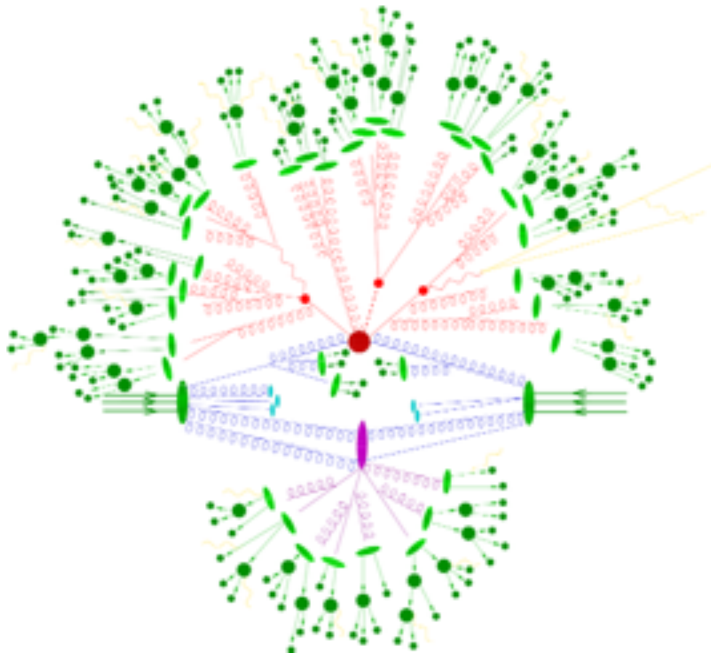
Invisible Particles
=> Etmiss!

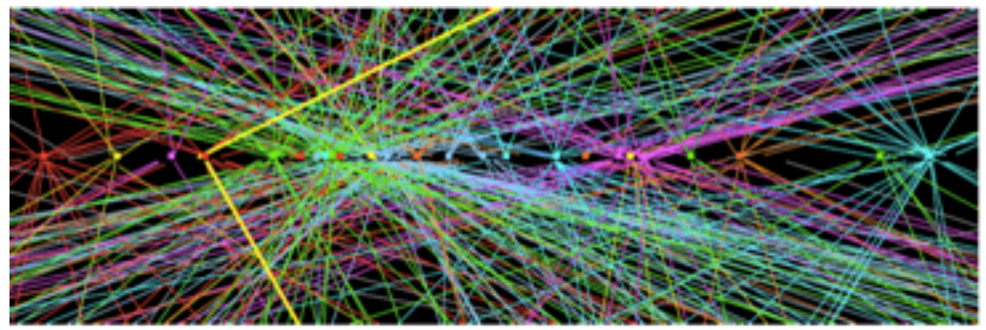
- VBF provides a clear signature

Experimental challenge

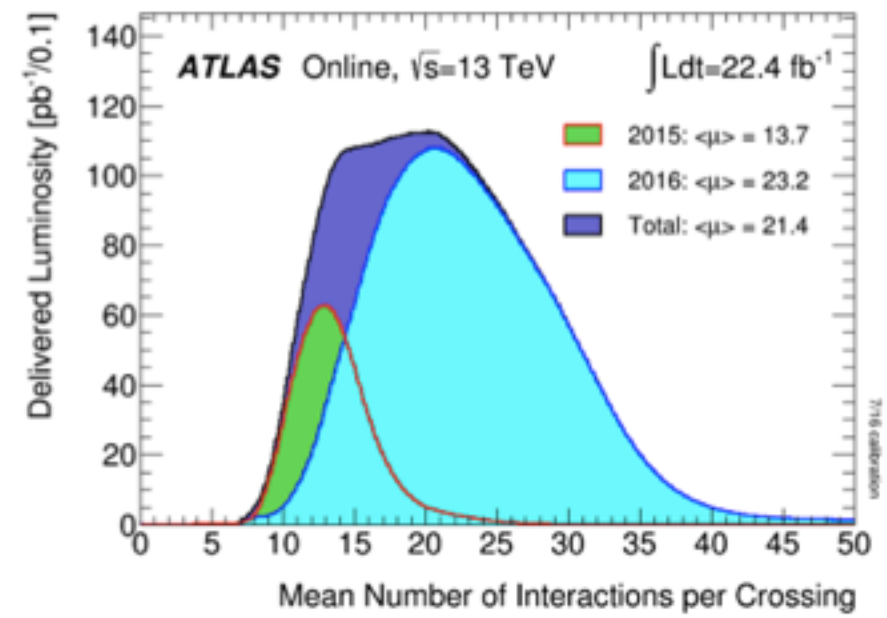
IN REAL LIFE…

- 25 ns bunch spacing, underlying events, pile up … need to separate the hard processes from the rest

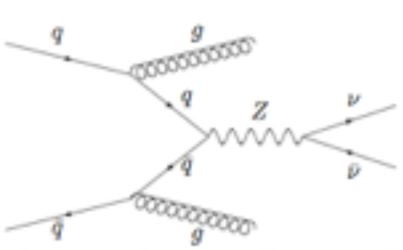


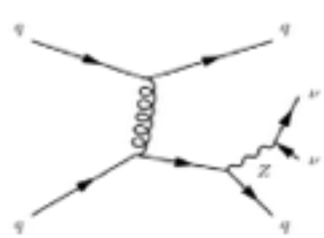


example of reconstructed vertices in an event



- Lots of SM processes with the same signature (i.e. backgrounds)





Z(—> νν) + jets just as an example

- All these make analysis ~~a nightmare~~ *quite challenging*

How we select events

- We define a **Signal Region** to select signal-like events and to suppress the backgrounds:
  - Etmiss trigger
  - cuts on pT of the two leading jets
  - require the two jets to be:
    - well separated in pseudorapidity $\Delta\eta(jj) > 4.8$
    - not back to back $\Delta\phi(jj) < 1.8$
  - third jet veto (reduce QCD bkg)
  - high Mjj
  - lepton veto (muons and electrons)

} **VBF jets cuts**

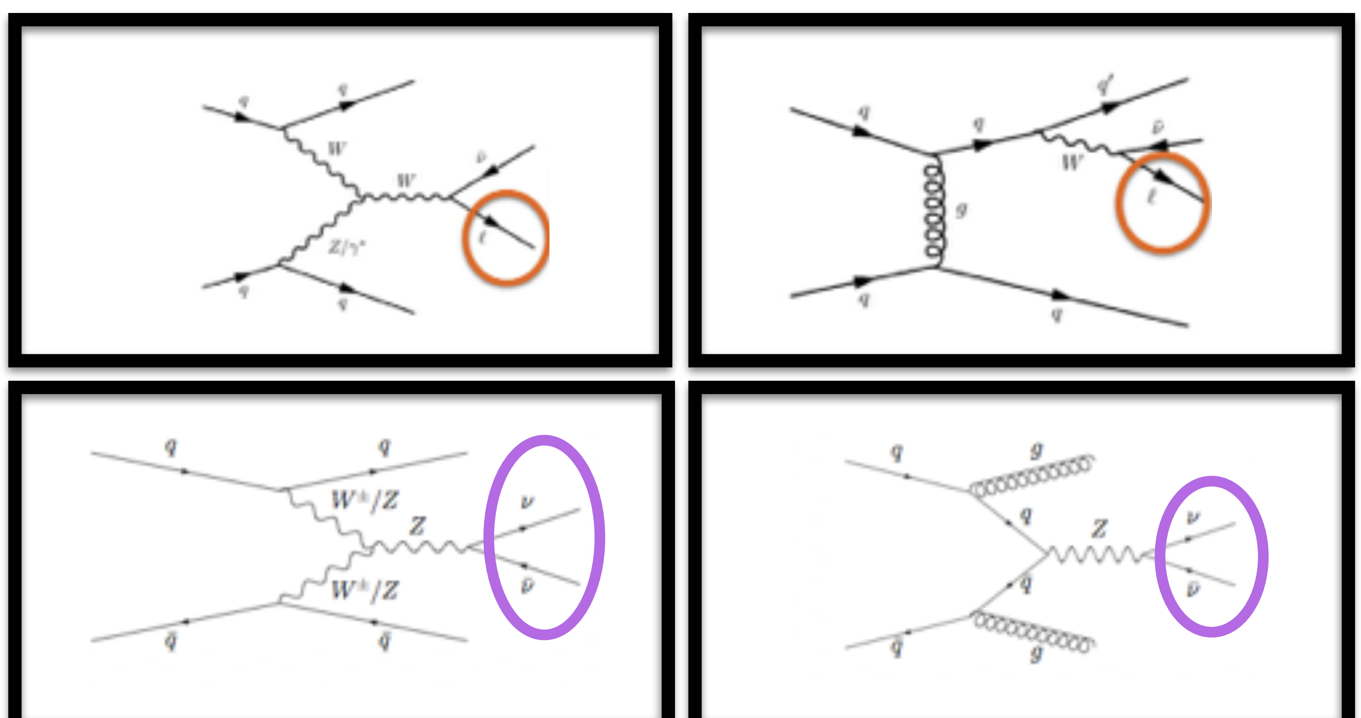
} **suppress W/Z/top bkg**

The main **backgrounds** are:

EW produced | **Strong produced**

W(—>lν)+jets — **lost lepton**

Z +jets — **neutrinos**

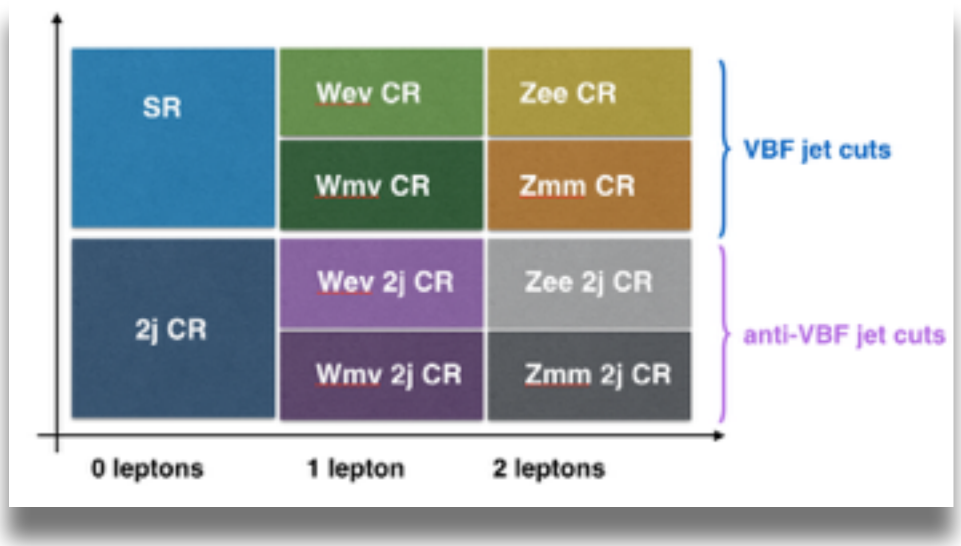


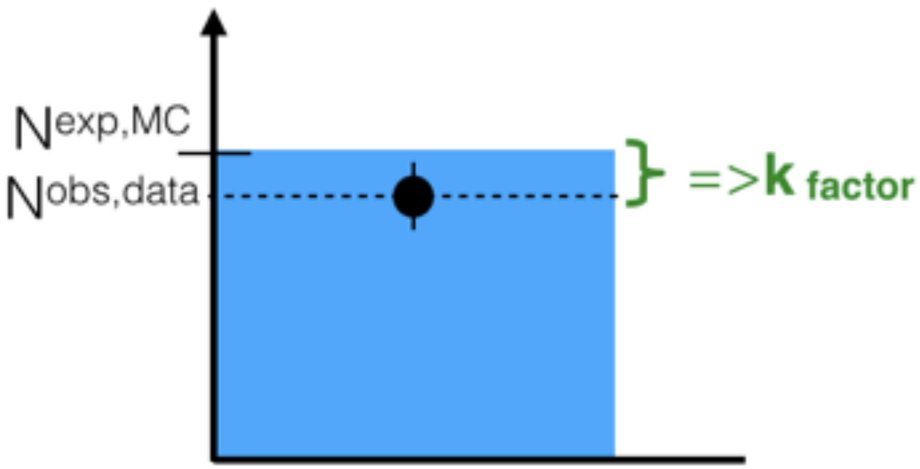
⚠ • also multijet background constitutes an issue!

Strategy *(in 1 slide)*

Background estimation and limit setting:

- We define Control regions (CR) enriched in W/Z events *i.e. regions where there is only background (0 signal)*
- 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)

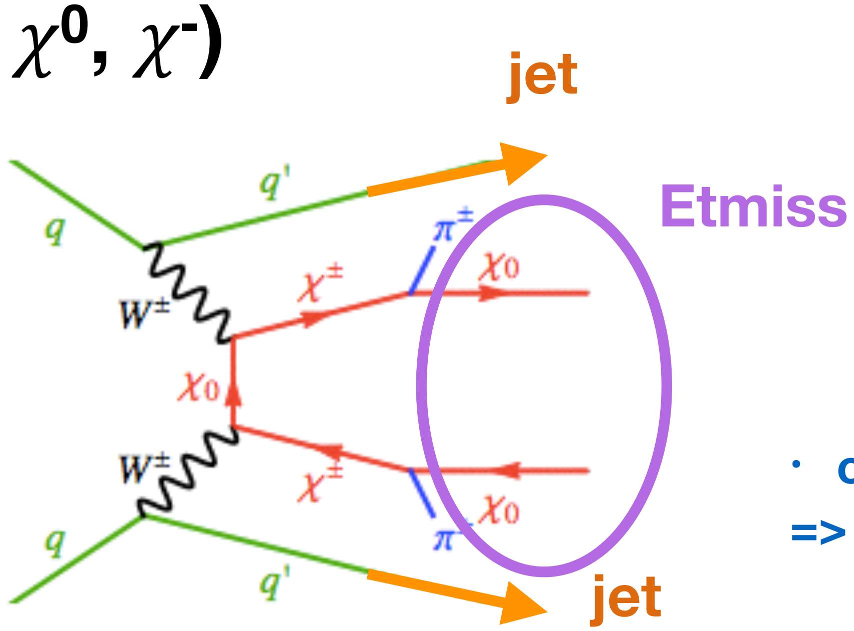
Minimal DM

- With the same final state, we can **test other DM models**:
    - models with *pure WIMPs* such as Minimal DM models and Wino-like DM

- Minimalistic approach: add to the SM the minimal amount of new physics (just one extra EW multiplet) and search for the minimal assignments of its quantum number that makes it a good DM candidate
    - *3-plet: relax the request of full minimality. Wino-like DM*

Let's consider the **EW fermion triplet produced via VBF** (https://arxiv.org/abs/1407.7058) :

χ $(\chi^{+}, \chi^{0}, \chi^{-})$



$\chi^{\pm} \rightarrow \chi^{0}$ **soft-pions**

Etmiss

not reconstructed

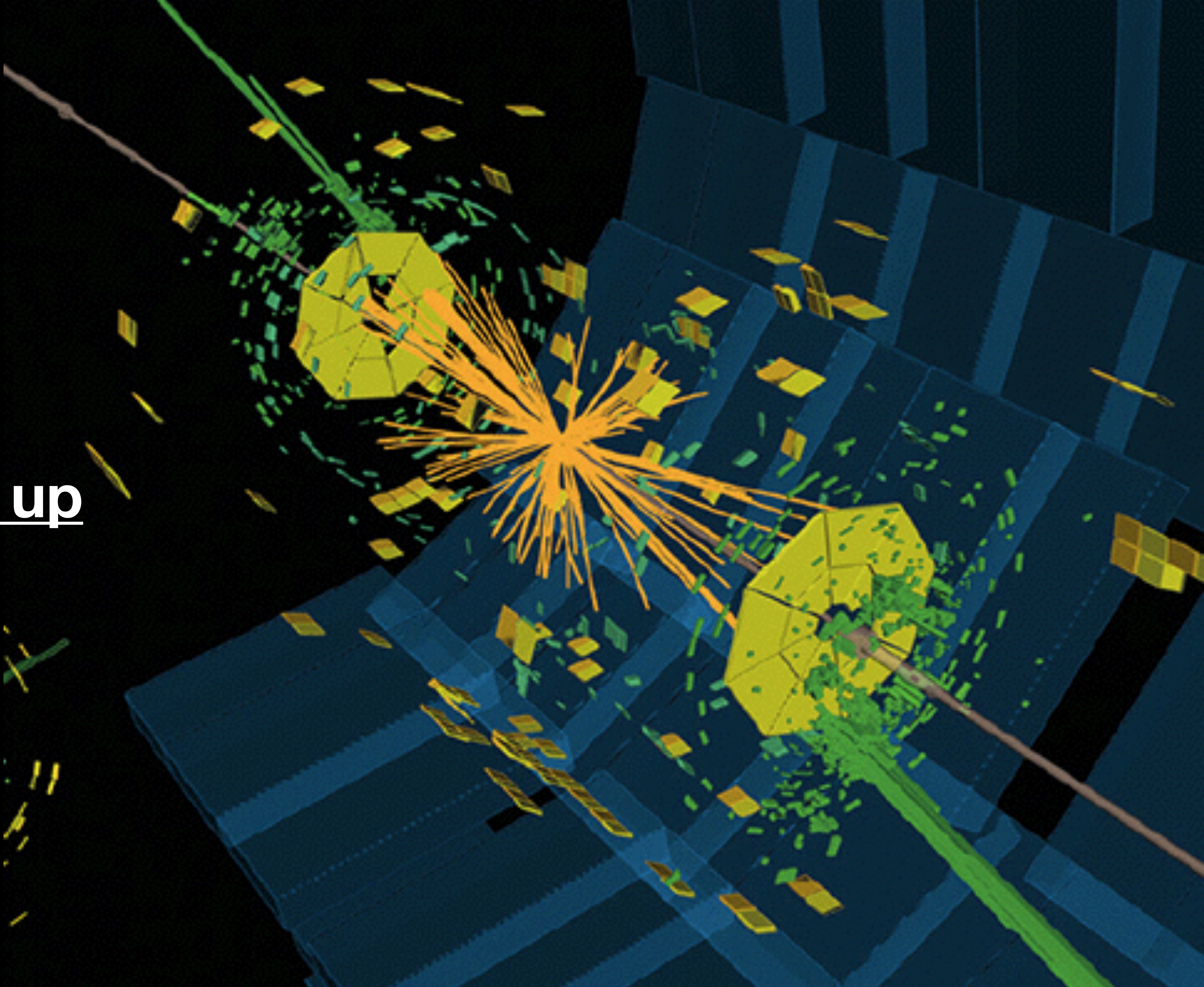
- **chi0/chi+- are almost degenerate in mass**
=> pions are so soft that are not reconstructed

- Same signature as VBF Higgs invisible analysis
- I worked on the MC (Madgraph+Pythia) generation to introduce the model in ATLAS

Summary & Conclusions

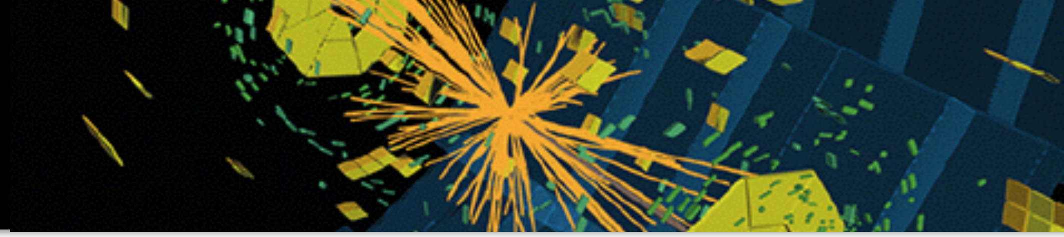
- Today, one of the most pressing question is about the **nature of Dark Matter**
- Dark Matter **searches** can be carried out **at colliders** which are potentially dark matter factories
- LHC is currently taking data at 13 TeV: the LHC delivered stable beams for the first time in 2017 last week. **ATLAS is collecting data**
- The principle of **Etmiss** reconstruction has been shown: it is an important quantity for searches with invisible particles *(but not only!)*
- An important analysis is the search for the **invisible decay of the Higgs boson**
- The best constrain comes from the **VBF channel**
  - I have shown you the idea of the analysis
  - unfortunately I cannot show you any plots/results since it is not yet public

- The same final state can be used to test other compelling DM models, such as **models with pure wimps** *(Minimal DM model, Wino like DM)*



Back up

More on Etmiss



How do we recontruct it?

- Reconstructed from the negative vector sum of the transverse momenta (pT) of all detected particles
- The Etmiss of an event is built as a sum of terms:

$$E_{x(y)}^{miss} = E_{x(y)}^{miss,\,ele} + E_{x(y)}^{miss,\,photon} + E_{x(y)}^{miss,\,tau} + E_{x(y)}^{miss,\,jets} + E_{x(y)}^{miss,\,muons} + E_{x(y)}^{miss,\,soft}$$

where $E_{x(y)}^{miss,i} = -\Sigma_i \, p_{x(y)}^{miss,\,i}$

Hard terms

Soft term

- Unmatched tracks and clusters
- soft jets with 7GeV<pT <20GeV

More on Etmiss

Soft Term

$$E_{x(y)}^{miss} = E_{x(y)}^{miss,\, ele} + E_{x(y)}^{miss,\, photon} + E_{x(y)}^{miss,\, tau} + E_{x(y)}^{miss,\, jets} + E_{x(y)}^{miss,\, muons} + E_{x(y)}^{miss,\, soft}$$

- Two versions:
  - Calorimeter based soft term (CST)
  - Track based soft term (TST)

How do we reconstruct the CST soft term?

- from the energy deposits in calorimeter cells
- not associated with reconstructed hard objects used in the E_T^{miss}
- use only cells belonging to three-dimensional calorimeter clusters (topoclusters) —>noise suppression

- CST soft term includes soft contributions from all interactions
  => CST E_T^{miss} is very sensitive to pileup

More on Etmiss

Soft Term

$$E_{x(y)}^{miss} = E_{x(y)}^{miss,\ ele} + E_{x(y)}^{miss,\ photon} + E_{x(y)}^{miss,\ tau} + E_{x(y)}^{miss,\ jets} + E_{x(y)}^{miss,\ muons} + E_{x(y)}^{miss,\ soft}$$

- Two versions:
  - Calorimeter based soft term (CST)
  - Track based soft term (TST)

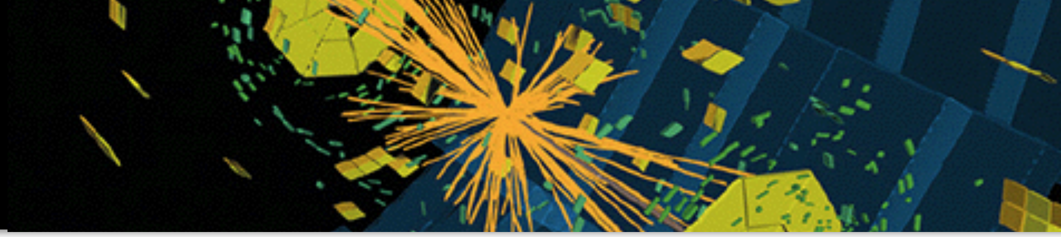
How do we reconstruct the TST soft term?

- Tracks coming from the primary vertex unassociated to physics objects
- Tracks belonging to soft jets with 7 GeV < pT <20 GeV with JVT cut

in TST:

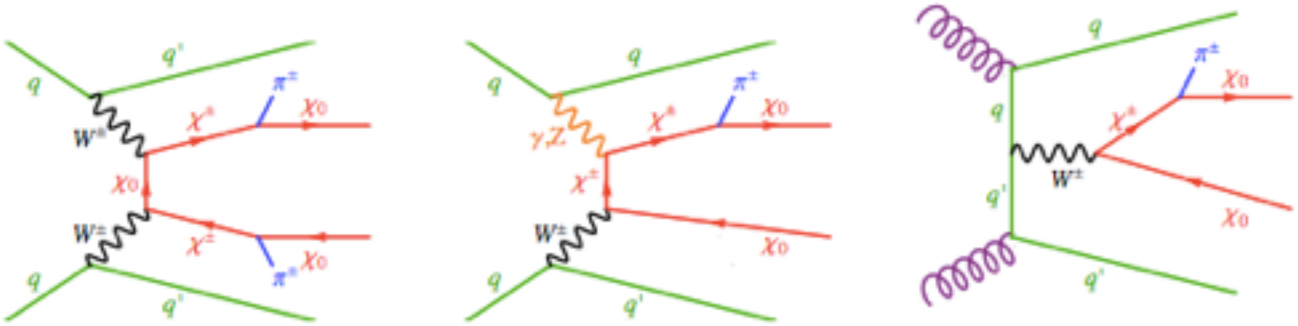
- Pile up suppressed
- neutrals particles are lost (*while not in CST*)
- Limited Tracker acceptance (*while for CST full calorimeter acceptance*)

MDM



- Considering the VBF production mode

chi (chi+, chi-, chi0)



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Xsec: 0.1119 +- 0.0001281 pb
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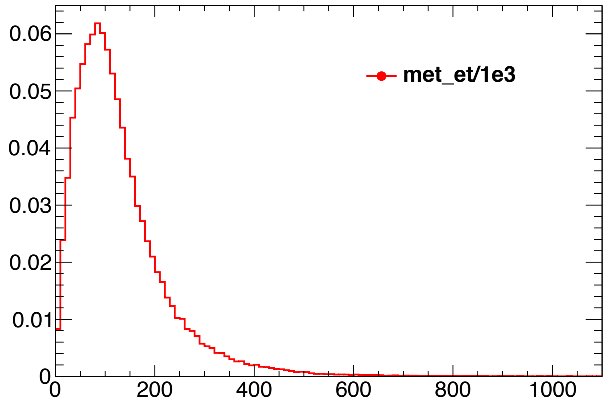

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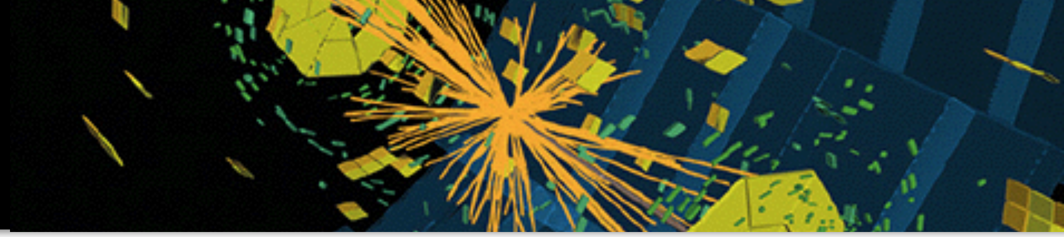

- With the same final state, we can **test other DM models**:
    - models with *pure WIMPs* (weak interactions, charged under $SU(2)_L \times U(1)_Y$) such as Minimal DM models and Wino-like DM

- Minimalistic approach: add to the SM the minimal amount of new physics (just one extra EW multiplet) and search for the minimal assignments of its quantum number that makes it a good DM candidate
    - 3-plet: relax the request of full minimality. Phenomenology like the one of SUSY models where the Wino is the lightest sparticle

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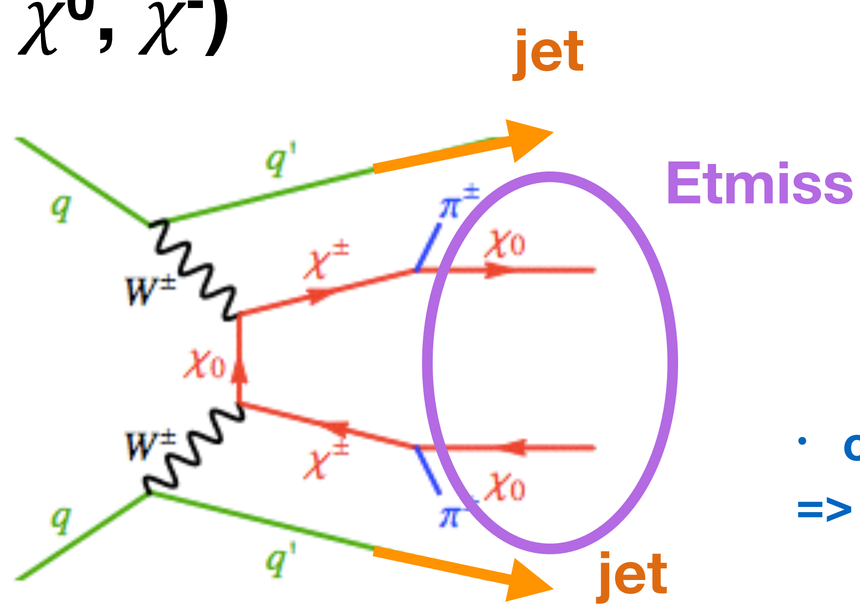
$\chi \ (\chi^+, \chi^0, \chi^-)$



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