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
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**

- 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**
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

- 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

![LHC Diagram](image)
Atmosphere 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

(*) well, apart from neutrinos! (see later)
What about neutrinos and the other invisible particles such as Dark Matter?

How do we detect them?
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

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

\[ E_{\text{miss}}^{x(y)} = - \sum p_{x(y)i} \]

Etmiss in Nobel Prize in Physics 1984
Missing Transverse Momentum

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:

\[ E_{\text{miss}}(x,y) = - \sum_{\text{hard}} p_{x(y)i} - \sum_{\text{soft}} p_{x(y)j} \]

=> 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!
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

- 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**

- VBF provides a clear signature
IN REAL LIFE...

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

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

- All these make analysis a nightmare.
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 $M_{jj}$
  - lepton veto (muons and electrons)

The main **backgrounds** are:

**EW produced**

- $W(\rightarrow lv) + \text{jets}$
- $Z + \text{jets}$

**Strong produced**

- $W^\pm/Z$ jets

\[ \text{lost lepton} \]
\[ \text{neutrinos} \]

\[ \text{suppress } W/Z/\text{top bkg} \]

\[ \text{VBF jets cuts} \]

- 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:

$$L_{reg}[\mu|N_{obs}] = \text{Poiss}(N_{obs,reg}^{|\mu} \times N_{\text{sig},MC_{reg}} + k_{Z/W} \times N_{W/Z,MC_{reg}})$$

- Set a limit on $\text{BR}(H \rightarrow \text{inv})$ ($\mu$)
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](https://arxiv.org/abs/1407.7058)):

\[ \chi (\chi^+, \chi^0, \chi^-) \]

- 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 **$E_{\text{miss}}$** 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)

---

Stay tuned! results will come soon!
More on Etmiss

How do we reconstruct 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:

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

where

\[ E_{\text{miss, i}}^{x(y)} = -\sum_i p_{\text{miss, i}}^{x(y)} \]

### Soft term
- Unmatched tracks and clusters
- Soft jets with 7GeV<pT<20GeV
More on Etmiss

Soft Term

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

- 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 \( E_T^{\text{miss}} \)
- use only cells belonging to three-dimensional calorimeter clusters (topoclusters) — >noise suppression

- CST soft term includes soft contributions from all interactions
  => CST \( E_T^{\text{miss}} \) is very sensitive to pileup
More on Etmiss

Soft Term

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

• 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 \(\text{while not in CST}\)
• Limited Tracker acceptance \(\text{while for CST full calorimeter acceptance}\)
· Considering the VBF production mode

chi (chi+, chi-, chi0)

Xsec: 0.1119 +- 0.0001281 pb
Minimal DM

• With the same final state, we can test other DM models:
  • models with pure WIMPs (weak interactions, charged under SU(2)L x 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

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

\[ \chi (\chi^+, \chi^0, \chi^-) \]

\[ \begin{align*}
q & \rightarrow \chi^0, \chi^- \\
q' & \rightarrow \chi^+, \chi^- \\
W^- & \rightarrow \chi^0, \chi^- \\
W^+ & \rightarrow \chi^+, \chi^- \\
\end{align*} \]

• \( \chi^\pm \rightarrow \chi^0 \) soft-pions
• \( \eta_{\text{miss}} \) not reconstructed
• \( \chi^0/\chi^\pm \) are almost degenerate in mass
• \( \Rightarrow \) 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