Measurement of the W-boson mass at LHC

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Motivation

The Standard Model (SM) of particle physics describes matter in terms of fundamental particles and their interactions.

- **Z/W/γ** mediate the electroweak (EWK) interaction
  - Z/W experimentally **massive**
  - **spontaneous symmetry breaking** to explain their mass

- **m_W** depends on EWK parameters

\[
m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi \alpha}{\sqrt{2}G_F} (1 + \Delta r)
\]

- **higher order corrections** modify **m_W**
  - main contributions from heavy particles (top quark and Higgs boson)
  - **new particles would also contribute**

Precise measurement of m_W is a crucial test of the SM.
The Large Hadron Collider (LHC)

### Center of mass energy [TeV]

<table>
<thead>
<tr>
<th>Energy [TeV]</th>
<th>Period</th>
<th>Data (CMS) [fb⁻¹]</th>
<th>pp→WX (W→ ℓν) # events</th>
<th>simultaneous pp collisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>2010-2011</td>
<td>≈ 5</td>
<td>5 \cdot 10^7</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>2012</td>
<td>≈ 20</td>
<td>2.4 \cdot 10^8</td>
<td>21</td>
</tr>
<tr>
<td>13</td>
<td>2015-2016</td>
<td>≈ 40</td>
<td>8 \cdot 10^8</td>
<td>25</td>
</tr>
</tbody>
</table>
The Compact Muon Solenoid (CMS)

- muon
- electron
- charged hadron (e.g. $\pi^+$)
- neutral hadron (e.g. neutron)
- photon

we focus on $W \rightarrow \mu \nu$ and $W \rightarrow e \nu$ decay
Seeing the invisible

colliding partons carry a fraction of proton momentum according to parton distribution functions (PDF)
\[ \rightarrow \text{initial state longitudinal momentum unknown} \]

can still rely on momentum conservation in transverse plane (orthogonal to beam axis)

neutrinos do not interact with the detector
- measure their momentum as missing transverse energy \( E_T^{\text{miss}} \)

\[ \vec{E}_T^{\text{miss}} = - \sum \vec{p}_T \]

\( \vec{p}_T \): momentum in transverse plane

event candidate for \( Z(\nu\bar{\nu})+\text{jet} \)
1) Master’s degree, 2015

2) search for dark matter (DM) in monoJet events (also master thesis)
   2015-2016

3) (ECAL) energy response intercalibration with $\pi^0/\eta \rightarrow \gamma\gamma$
   2016 - ongoing

4) Monitoring and optimization of the $\pi^0/\eta$ High Level Trigger (HLT) stream
   2016 - ongoing

5) Search for DM from decays of Higgs-like particles produced through vector boson fusion (VBF)
   2016 - early 2017

6) Measurement of the W-boson mass
   2017, Ph.D project
Search for dark matter

1) Master’s degree, 2015

2) **search for dark matter** (DM) in monoJet events (also master thesis)  
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   2017, Ph.D project
**MonoJet and H→inv analysis**

**monojet**: most sensitive DM search channel  
**VBF topology**: rarer but cleaner process

**Signal:**  
- missing transverse energy ($E_T^{\text{miss}}$) due to DM  
- one or more jets from initial state radiation (trigger)

**Main backgrounds:**  
- $Z(\nu\nu)/W(l\nu) + \text{jets}$ (irreducible, ≈ 95%)

**My contributions:**  
- study of $E_T^{\text{miss}}$ response and resolution  
- development of strategy and data-driven techniques for estimation of background events
Public results

- **monoJet paper** will be published soon
  - based on **12.9 fb⁻¹ @ 13 TeV**
  - **exclusion limits** on DM and mediator masses for (axial-)vector, (pseudo-)scalar mediator
  - limits compared to non-collider searches

- **full dataset analysis** (36.4 fb⁻¹ @ 13 TeV) also expected **to be published** (summer timescale)

- **VBF H→inv analysis** should be presented for publication by next summer
  - based on **36.4 fb⁻¹ @ 13 TeV**
  - **exclusion limits** on H→inv decay branching ratio
Detector activities

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**ECAL intercalibration with $\pi^0/\eta$**

- **e/$\gamma$** release most of their energy in ECAL
  - homogeneous calorimeter
  - 75848 PbWO$_4$ crystals

- accurate calibration fundamental to achieve excellent energy resolution
  - crucial for analysis with e/$\gamma$ in their final states

\[
\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} + \frac{12\%}{E(\text{GeV})} + 0.3\%
\]

- **constant term** dominant at high energy
  - largest contribution from crystal-to-crystal response variation

exploit **diphoton invariant mass** peak from $\pi^0/\eta \rightarrow \gamma\gamma$ to equalize the energy response among ECAL crystals

* as measured in electron test beam
Thesis project

1) Master’s degree, 2015

2) search for dark matter (DM) in monoJet events (also master thesis)
   2015-2016

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   2016 - early 2017

6) **Measurement of the W-boson mass**
   2017, Ph.D project
Previous measurements of $m_W$

- **first measurement** by UA1 collaboration at Sp$ar{p}$S synchotron (CERN)
  - $m_W = 81 \pm 5$ GeV
  - W and Z boson just discovered by UA1 in 1983
  - Rubbia and Van Der Meer won the Nobel Prize for this discovery (1984)

- **LEP collider** (CERN) in $e\bar{e}$ collisions
  - $m_W = 80376 \pm 33$ MeV

- **CDF + D0 experiments** at Tevatron (Fermilab) in $p\bar{p}$ collisions (2014)
  - $m_W = 80387 \pm 16$ MeV

- **ATLAS collaboration** at LHC (CERN) in $pp$ collisions (2016)
  - $m_W = 80370 \pm 19$ MeV

- **current experimental world average** (no ATLAS) is $m_W = 80385 \pm 15$ MeV

- **theoretical indirect estimate** from global EWK fit to SM parameters
  - $m_W = 80358 \pm 8$ MeV
  - experiments must target $\delta m_W < 10$ MeV
Measurement of the $W$-boson mass

$W \rightarrow \mu \nu$ and $W \rightarrow ev$ decay channels

- undetected neutrino $\rightarrow$ can’t compute $m_W$ from the Lorentz 4-vector mass extracted from the Jacobian edge in two kinematic distributions:
  - $p_T^l$: clean observable but **large theoretical uncertainties** ($p_T^W \leftrightarrow$ PDF, QCD corrections ...)
  - $m_T^W$: **large experimental uncertainties** (neutrino $\leftrightarrow E_T^{\text{miss}}$ resolution)

\[
m_T^W = \sqrt{2 \cdot p_T^l \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta \phi_{l\nu})}
\]

$\phi$: angle in transverse plane
There is more to it than meets the eye ...

Experimental systematic uncertainty:
• lepton *momentum scale* → muon chambers alignment, ECAL calibration ...
• hadronic *recoil resolution* \( p_T^W \neq 0 \) in lab frame → W recoils against jets

Theoretical systematic uncertainty:
• incomplete *knowledge of PDF* → dominant uncertainty
• QCD *modelling* → higher order corrections
• EWK *corrections* → QED initial and final state radiation of photons from leptons

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W at rest:
- Jacobian edge at \( m/2 \)
- Endpoint at \( m \)
Cross-check with Z boson

Crucial to get precise templates

- deep understanding of detector performance
- fine tuning of the Monte Carlo simulations

- method validation with Z sample
  - measure $m_Z$ in a W-like manner by neglecting one lepton (done by CMS @ 7 TeV)
  - $m_Z$ well known $\rightarrow$ tune physics modelling

- constrain theoretical uncertainty on $p_T^{W}$ distribution
  - take Z as standard candle and extrapolate to W (rely on theory)
  - many uncertainties cancel out in the W/Z ratio

$\nu_l$
Plans and prospects

I will work on the completion of all the aspects of the analysis for both \( W \rightarrow \mu \nu \) and \( W \rightarrow e \nu \) decay channels

- background modelling
- \( W \) mass fitting
- PDF modelling and uncertainty

I will focus on the introduction and development of the electron channel

- efficiency, energy scale with \( Z \rightarrow e e \) events

Expected publication on the measurement by the end of the Ph.D

- likely more than one \( \rightarrow \) many related and important measurement from CMS still missing
BACKUP
COMPACT MUON SOLENOID

CMS DETECTOR
Total weight: 14,000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm) ~16 m² ~66M channels
- Microstrips (80x180 μm) ~200 m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16 m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibers ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels
CMS longitudinal view

\[
\eta = -\ln \tan \frac{\theta}{2}
\]

\(\eta\) differences are Lorentz invariant for high energy particles
Parton distributions functions (PDF)

Collisions occur between proton constituents (quarks or gluons)
- energy fraction carried by each parton distributed according to PDF

→ **final state longitudinal momentum unknown**
can still rely on momentum conservation in transverse plane (orthogonal to beam axis)

\[
\sigma_{AB \rightarrow X} = \sum_{a,b} \int_0^1 dx_a dx_b f(x_a, Q^2) f(x_b, Q^2) \cdot \hat{\sigma}_{ab \rightarrow X}(x_a, x_b, Q^2)
\]
Searching for dark matter (DM)

3 types of searches, with high degree of complementarity

**indirect**
- DM annihilation to SM particles
- constraints from cosmological parameters measurements

**direct**
- DM scattering on nuclei
- sensitive to $m_{DM} \gtrsim 10$ GeV

**colliders**
- DM production in pp collisions
- rich phenomenology
Dark Matter at colliders

MET+X searches:
- DM seen as missing transverse energy (MET)
- X is a Standard Model (SM) particle(s) from initial state radiation (ISR)
  → trigger on the event
- signal: excess of events in the high MET region

monoTop

one topology, many final states

MONOMANIA!
Other interesting channels:

- **multijet + MET**
  - from Susy searches
  - gluinos/squarks decay to quarks and lightest supersymmetric particle
- **t\(\bar{t}\) + MET, b\(\bar{b}\) + MET**
- **Higgs + MET**
  - Higgs ISR suppressed
  - probe Higgs’ coupling to DM
- **dijet**
  - MET-less, but provides DM interpretation

**Examples of signal diagrams**:

- **MET + heavy quarks**
- **monoHiggs**
- **MET + (lots of) jets**
- **dijet**
Theoretical overview

Interpretation with simplified models

- Dark Matter Forum prescriptions \( \rightarrow \) arXiv:1507.00966
- benchmark of Run2 interpretation
- new mediator connecting SM and DM
- free parameters: \( m_{DM}, M_{med}, g_{DM}, g_{q} \)

Assumptions:

- DM is a Dirac fermion
- DM produced on-shell in pairs
- minimal decay width for mediator
- minimal flavour violation
- \( g_{DM} = 1 \) and \( g_{q} = 0.25 \)

limits strongly depends on the couplings choice and model

\( \rightarrow \) change in couplings affects mediator’s width
\( \rightarrow \) more details: arXiv:1603.04156v1
Comparison of some channels ($g_1 = 0$)

Dijet search dominates the picture (no DM production but limits on mediator mass)

Plot from Tristan du Pree, EXO Workshop 2016
Comparison of some channels \((g_l = g_q)\)

\[ Z'(ee) \text{ most sensitive probe, if allowed.} \]

Exclusion (or discovery) potential driven by couplings choice and \(M_{\text{med}}\)

plot from Tristan du Pree, EXO Workshop 2016
Comparison of some channels (smaller $g_1$)

Exclusion (or discovery) potential driven by couplings choice and $M_{\text{med}}$

plot from Tristan du Pree, EXO Workshop 2016
Comparison of some channels (smaller $g_q$ and $g_l$)

Monojet dominates when coupling to DM bigger than that to quarks or leptons

plot from Tristan du Pree, EXO Workshop 2016
Theoretical overview

Limits typically @ 95% CL in the $m_{DM}, M_{med}$ plane

- switch to limits on cross section as a function of $m_{DM}$
- 90% CL used to compare with direct searches

Collider searches limits flat with respect to $m_{DM}$ and sensitive also to low $m_{DM}$
ICHEP summary plots

monojet most sensitive channel for vector mediator direct searches more sensitive than collider searches for $m_{\text{DM}} > \text{few GeV}$

CERN-CMS-DP-2016-057  https://cds.cern.ch/record/2208044
monojet most sensitive channel for axial-vector mediator collider searches more sensitive than direct searches everywhere
MonoJet analysis

Signal:
• missing transverse energy ($E_T^{\text{miss}}$) due to DM
• one or more jets from initial state radiation → trigger on the event

Main backgrounds:
• $Z(\nu\nu)/W(l\nu) + \text{jets}$ (irreducible, $\approx 95\%$)

Analysis strategy:
• data driven estimate of main backgrounds
  • five control regions (CR)
  • $Z(ll)/W(l\nu)/\gamma + \text{jets}$ ($l = e, \mu$)
• signal from fit to $E_T^{\text{miss}}$ distribution

My contributions:
• study of $E_T^{\text{miss}}$ response and resolution
• development of leptons CR
• photon purity studies for $\gamma$+jets CR
Background estimate

\[ L(\mu, \mu^{Z\to vv}, \mu^{W\to lv}, \theta) = \prod \text{Poisson} \left( d_i^L | B_i^L(\theta) + \mu_i^{Z\to vv} R_i^L(\theta) \right) \]

\[ \prod \text{Poisson} \left( d_i^Z | B_i^Z(\theta) + \mu_i^{Z\to vv} R_i^Z(\theta) \right) \]

\[ \prod \text{Poisson} \left( d_i^W | B_i^W(\theta) + \mu_i^{W\to lv} R_i^W(\theta) \right) \]

\[ \prod \text{Poisson} \left( d_i | B_i(\theta) + \mu_i^{Z\to vv} + \mu_i^{W\to lv} + \mu_i S_i(\theta) \right) \]
MonoJet/V limits

CMS

Vector med, Dirac DM, $g_q = 0.25, g_{cm} = 1$

- Median expected 95% CL
- Expected $+1\sigma_{\text{experiment}}$
- Observed 95% CL
- Observed $+1\sigma_{\text{theory}}$
- $\Omega_c h^2 \geq 0.12$

CMS

Axial-vector med, Dirac DM, $g_q = 0.25, g_{cm} = 1$

- Median expected 95% CL
- Expected $+1\sigma_{\text{experiment}}$
- Observed 95% CL
- Observed $+1\sigma_{\text{theory}}$
- $\Omega_c h^2 \geq 0.12$

CMS

Scalar med, Dirac DM, $g_q = 1, g_{cm} = 1$

- Expected $+1\sigma_{\text{experiment}}$
- Observed 95% CL
- Observed $+1\sigma_{\text{theory}}$
- $\Omega_c h^2 \geq 0.12$

CMS

Pseudoscalar med, Dirac DM, $g_q = 1, g_{cm} = 1$

- Observed 95% CL
- Observed $\pm 1\sigma_{\text{theory}}$
- $\Omega_c h^2 \geq 0.12$
VBF H→inv analysis

- **VBF topology as a 2-jets category** in the monoJet analysis
  - monoJet focus on DM mediator coupling only to fermions
  - VBF channel probes coupling to vector bosons

- Benchmark: **VBF Higgs (125) → invisible**
  - distinctive topology: two high pT forward jets and $E_T^{\text{miss}}$

- signal **discriminating variables**:
  - $\Delta\eta_{j_1,j_2}$ and dijet invariant mass $M_{j_1,j_2}$

**My contributions:**
- set up the analysis
  - selection optimization
  - control regions
  - fit to extract signal
- improve **analysis strategy** (shape analysis of $\Delta\eta_{j_1,j_2}$, $M_{j_1,j_2}$)

* $\eta = -\ln tg^2 \theta$, $\theta$ is the polar angle wrt the beam axis
Discriminating variables:

- MET does not separate signal and background
- $\Delta\eta_{j1,j2}$ and $M_{j1,j2}$ are good variables (correlated)
- other variables are $\Delta\phi(\text{jets,MET})$ and $\Delta\phi(j1,j2)$ (embed information on boson’s spin)
ECAL

75848 PbO$_4$ crystals
- 61200 in the barrel (EB)
- 7324 for each endcap (EE)

EB:
- 36 supermodules with 4 modules for each
- 360-fold granularity in $\phi$
- 85-fold granularity in $\eta > 0$

EE:
- crystals arranged in 5x5 towers

ES (preshower):
- enhance $\gamma$ identification capabilities
ECAL intercalibration with $\pi_0/\eta$

**e/\gamma release most of their energy in ECAL**
- homogeneous calorimeter
- 75848 PbWO$_4$ crystals

**accurate calibration fundamental to achieve excellent energy resolution**
- crucial for analysis with e/\gamma in their final states

\[
\frac{\sigma_E}{E} = \frac{2.8 \%}{\sqrt{E \text{(GeV)}}} \oplus \frac{12 \%}{E \text{(GeV)}} \oplus 0.3 \%
\]

**Constant term** dominant at high energy
- largest contribution from crystal-to-crystal response variation

* as measured in electron test beam
ECAL intercalibration with $\pi_0/\eta$

- exploit **diphoton invariant mass** peak from $\pi_0/\eta \rightarrow \gamma\gamma$ to **equalize the energy response** among ECAL crystals

- **CMS $\gamma$ reconstruction** optimized for high $p_T$ physics ($\approx 60$ GeV), while typical $p_T(\pi_0/\eta \rightarrow \gamma\gamma)$ is only few GeV

select calibration sample with **dedicated HLT stream**
  - ad hoc clustering algorithm (**3x3 crystal matrix**)
  - significantly **reduce event size**
  - allow for **higher trigger rate** (15 kHz)

**larger calibration sample** with respect to Z bosons
  - allow for **calibration in early stage of data taking**
  - need at least 3000 $\gamma$/crystal to achieve statistical uncertainty < 0.5% in the barrel
Cross-check with Z boson

- \( Z \rightarrow ll \) events used for detector calibration

- method **validation with Z sample**
  - measure \( m_Z \) in a W-like manner by neglecting one lepton (done by CMS @ 7 TeV)
  - \( m_Z \) well known \(\rightarrow\) tune physics modelling

- **constrain theoretical uncertainty on** \( p_T^W \) **distribution**
  - take Z as standard candle and extrapolate to W (rely on theory)
  - many uncertainties cancel out in the W/Z ratio
  - **CAVEAT**: different initial state (PDF), background, \( Z \rightarrow W \) extrapolation uncertainty

![differential cross section](image1.png)

![W/Z cross section ratio](image2.png)
There is more to it than meets the eye …

**Strategy:**
1. build simulated templates for several $m_W$ values (1-10 MeV steps)
2. perform compatibility test with observed distribution
3. extract $m_W$ minimizing the test statistics

Crucial to get precise templates

- deep understanding of detector performance
- fine tuning of the Monte Carlo simulations

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**Systematic uncertainties**

**Experimental:**
- lepton momentum scale and resolution $\rightarrow$ muon chambers alignment, ECAL calibration …
- hadronic recoil resolution ($p_T^W \neq 0$ in lab frame $\rightarrow$ W recoils against jets)

**Theoretical:**
- incomplete knowledge of PDF $\rightarrow$ dominant uncertainty
- QCD modelling $\rightarrow$ parton shower, missing higher orders in the perturbative expansion of the strong coupling constant $\alpha_S(m_Z)$
- EWK corrections $\rightarrow$ QED initial and final state radiation of photons from leptons
Systematic uncertainties

**Experimental:**
- lepton **momentum scale and resolution** → muon chambers alignment, ECAL calibration ...
- hadronic **recoil resolution** \( p_T^W \neq 0 \) in lab frame → W recoils against jets

**Theoretical:**
- incomplete **knowledge of PDF** → dominant uncertainty
- **QCD modelling** → parton shower, missing higher orders in the perturbative expansion of the strong coupling constant \( \alpha_S(m_Z) \)
- **EWK corrections** → QED initial and final state radiation of photons from leptons

**Example:**
tracker alignment affect muon momentum scale

\[ p_T[\text{GeV}] = 0.3 \cdot R[\text{m}] \cdot B[\text{T}] \]

B: magnetic field
R: curvature radius
**W production asymmetry**

- W bosons are produced with valence quarks and sea quarks
- \( N(u_v) > N(d_v) \)
  \( \Rightarrow \) Total \( N(W^+) > N(W^-) \)

The inclusive ratio of cross sections for \( W^+ \) and \( W^- \) bosons production was measured by CMS to be \( 1.43 \pm 0.05 \) CMS-EWK-10-006