# Search for chargino and neutralino production in final states with two same-sign leptons, jets and missing transverse momentum at $\sqrt{s} = 13$ TeV with the ATLAS detector

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# Introduction

# Standard Model : Fundamental Particles

- Standard Model(SM) is the current mainstream theory to describe the electromagnetic force, weak force and strong force.

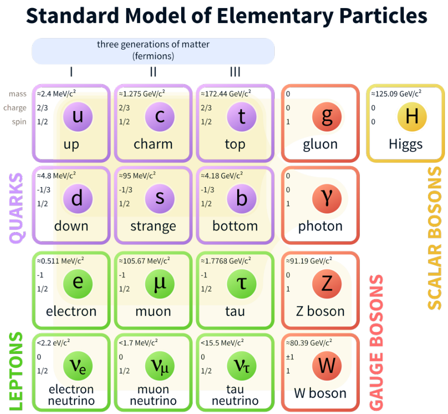



Figure: The "periodic" table for all fundamental particles in SM.

# Standard Model : Fundamental Interaction

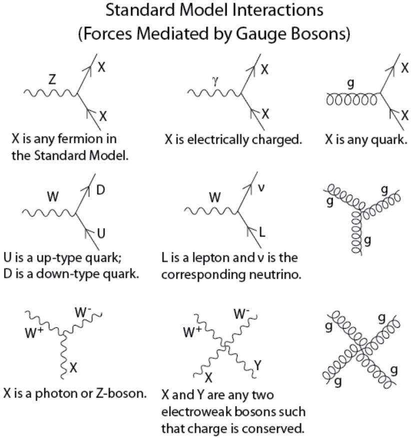



Figure: All allowed fundamental Feynman vertices in SM, except higgs-related vertices.

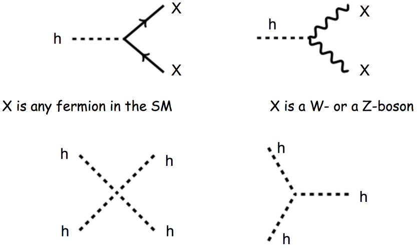



Figure: All allowed fundamental higgs-related Feynman vertices in SM.

# Standard Model : Limitation

- SM cannot explain gravity.
- SM cannot explain the nature of dark matter.
- The hierarchy problem
  - Why the weak force is stronger than the gravity by $10^{24}$.
  - Why the Higgs mass is much lighter than the Planck mass.
  - At very high energy scale, the Higgs boson mass is strongly sensitive to quantum corrections.

# Supersymmetry

- Supersymmetry(SUSY) is a theoretical extension of the Standard Model.
- It is one of the most promising theory.
- It can solve the hierarchy problem of Higgs mass.
- It can explain the nature of dark matter.

# Supersymmetry : MSSM

- Minimal Supersymmetric Standard Model(MSSM) is the simplest realization of the supersymmetry.
- It predicts that each particle in the Standard Model has its own partner particle, called the superpartner.
- The spin of the superpartner will differ from the Standard Model particle by 1/2.
- A symmetry between the fermions and bosons.

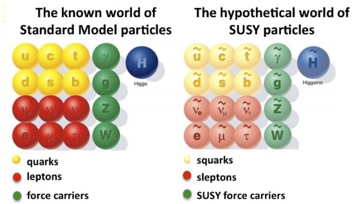



Figure: The particles in Standard Model and their corresponding superpartners and their names.

# Supersymmetry : Superpartners

- In the MSSM, one more neutral Higgs filed $H$ and two more charged Higgs fileds $H^+$, $H^-$ needed to be introduced.
- In SM electro-weak bosons, there are in total 4 neutral bosons: $\gamma$, $Z$, $h$ and $H$, and 4 charged bosons: $W^+$, $W^-$, $H^+$ and $H^-$.
- The superpartners of the 4 neutral bosons together form 4 mass eigenstates, called neutralinos: $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$ and $\tilde{\chi}_4^0$.
- The superpartners of the 4 charged bosons together form two mass eigenstates with electric charge $\pm1$, called charginos: $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^\pm$.

| Type | SM particle | Symbol | Spin | R-parity | Superpartner | Symbol | Spin | R-parity |
|---|---|---|---|---|---|---|---|---|
| Fermions | Quark | $q$ | $\frac{1}{2}$ | +1 | Squark | $\tilde{q}$ | 0 | -1 |
| | Lepton | $l$ | $\frac{1}{2}$ | +1 | Slepton | $\tilde{l}$ | 0 | -1 |
| Gluon | Gluon | $g$ | 1 | +1 | Gluino | $\tilde{g}$ | $\frac{1}{2}$ | -1 |
| Neutral EW Bosons | Photon | $\gamma$ | 1 | +1 | | | | |
| | Z Boson | $Z$ | 1 | +1 | Neutralinos | $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$ | $\frac{1}{2}$ | -1 |
| | Neutral Higgs | $h$,$H$ | 0 | +1 | | | | |
| Charged EW Bosons | W Boson | $W^+$, $W^-$ | 1 | +1 | Charginos | $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$ | $\frac{1}{2}$ | -1 |
| | Charged Higgs | $H^+$, $H^-$ | 0 | +1 | | | | |

Table: The spin and R-parity for the Standard Model particles and their superpartners.

# Supersymmetry : R-parity

- The baryon number $B$ is defined by $\frac{1}{3}(n_q - n_{\bar{q}})$, where $n_q$ is the number of quarks and $n_{\bar{q}}$ is the number of anti-quarks.
- The lepton number $L$ is defined by $n_l - n_{\bar{l}}$, where $n_l$ is the number of leptons and $n_{\bar{l}}$ is the number of anti-leptons.
- In SM, $(B - L)$ is conserved. But in MSSM, it is no longer conserved.
- To keep $(B - L)$ conservation and prevent the proton decay, the R-parity $P_R$ is introduced.

$$P_R = (-1)^{3(B-L)-2s}$$

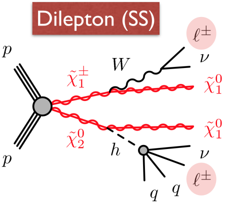
where s is the spin.

# Supersymmetry : R-parity

- All SM particles have R-parity $+1$, while all SUSY particles have R-parity $-1$.
- If the R-parity is conserved, the lightest supersymmetric particle (LSP) cannot decay and is stable.
- If the LSP is electrically neutral and interacts with matter only by the weak interaction and gravity, it could be a candidate for dark matter, for example the lightest neutralinos $\tilde{\chi}_1^0$.
- In this thesis, the R-parity is assumed to be conserved, and the lightest neutralino $\tilde{\chi}_1^0$ is assumed to be the LSP.
- Due to the conservation of R-parity, the supersymmetric particles can only be pair-produced, and will eventually decay into SM particles and the lightest neutralino $\tilde{\chi}_1^0$ (i.e. LSP).

# Our Signal Scenario : Motivation

- In the recent searches for the squarks ($\tilde{q}$) and gluinos ($\tilde{g}$), the masses of gluinos and the first and second generation squarks are suggested to be larger than 1 TeV, while the masses of the third generation squarks are still allowed to be below 1 TeV.
- In this case, the direct pair production of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ may be the dominant SUSY production process at the LHC, if the masses of them are below 1 TeV.
- In this thesis, their masses are assumed to be the same, and denoted by $m_{\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0}$.



# Our Signal Scenario : Decay Processes

- If all the slepton ($\tilde{l}$) are heavier than $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ :
  1. $\tilde{\chi}_1^{\pm}$ will decay to W boson and $\tilde{\chi}_1^0$ :
     $\tilde{\chi}_1^{\pm} \rightarrow W^{\pm} + \tilde{\chi}_1^0$
  2. $\tilde{\chi}_2^0$ will decay to the lightest MSSM Higgs boson $h$ and $\tilde{\chi}_1^0$ :
     $\tilde{\chi}_2^0 \rightarrow h + \tilde{\chi}_1^0$

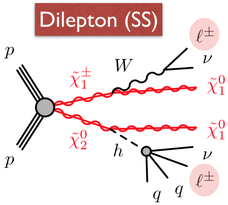
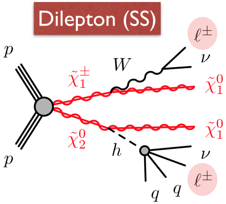



Figure: The Feynman diagram for our Wh same-sign signal scenario.

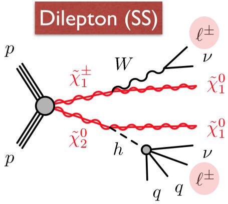
# Our Signal Scenario : Decay Processes

- The W boson will further to one lepton (electron or muon) and one neutrino with the SM branching ratio : $W^{\pm} \to \ell^{\pm} + \nu$
- The Higgs boson $h$ will eventually decay to one lepton (electron or muon), quarks (i.e. jets) and neutrino(s) by various decay modes with the SM branching ratios. (For example, $h \to W^{+}W^{-}$ and $h \to \tau^{+}\tau^{-}$)
- From now on, a lepton $\ell^{\pm}$ only refer to an electron or muon, but not $\tau$ lepton or neutrino.



# Our Signal Scenario : Signal Signature in the Final State

- In this thesis, we only search for two same-sign(SS) leptons, in order to suppress the SM backgrounds.
- A large missing energy is expected, due to the undetected neutralinos $\tilde{\chi}_1^0$ and neutrinos $\nu$.
- Each quark will eventually become a particle shower within a narrow cone, called a jet, by the process of hadronization.
- The mass difference between the two lightest neutralinos $(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$ should be larger than the Higgs mass ($\sim$ 125 GeV).



# Our Signal Scenario : Sensitive Region

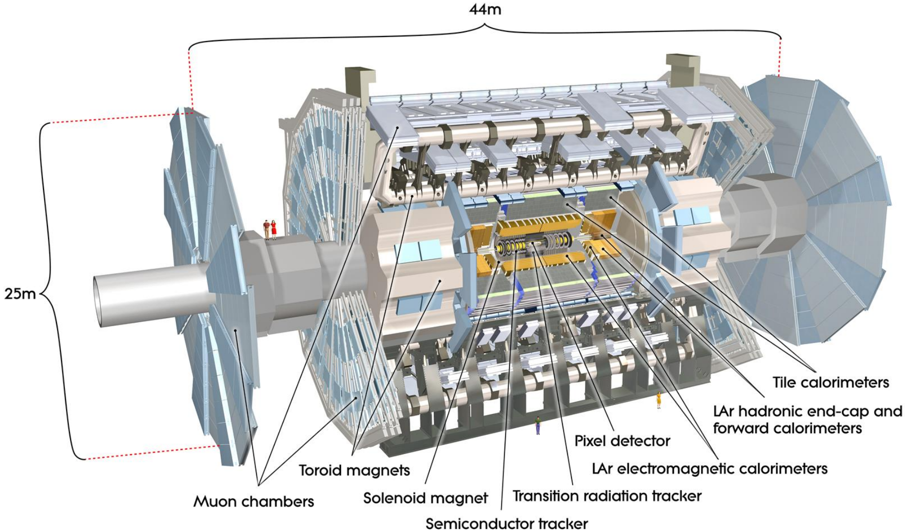
- If the mass difference $(m_{\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$ is slightly larger than the Higgs mass, it is called the compressed region.
- In the compressed region, one of the lepton may have low energy, due to the low momentum of the Higgs boson, and hence it may not be detected.
- In this case, there may be originally 3 leptons, but only 2 leptons are detected.
- This allows more decay modes for Higgs boson, which produce two leptons. (For example, $h \to ZZ$)
- Hence, the signal will be more sensitive in the compressed region.

# Experimental Setup

# Experimental Setup : LHC

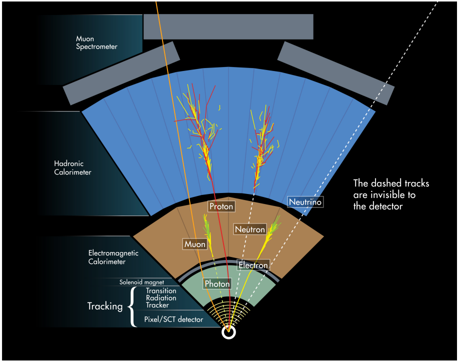
- The Large Hadron Collider (LHC) is the most powerful circular particle accelerator in the world.
- Its circumference is 27 km.
- Two beams of protons will be accelerated in opposite direction to centre-of-mass energy 13 TeV.
- They will be finally collided at the ATLAS detector.

# Experimental Setup : ATLAS detector



# Experimental Setup : ATLAS detector

- The ATLAS detector consists of 3 main components:
  1. Inner detector: It is a particle tracker. It measures the tracks of charged particles.
  2. Calorimeter: It measures the energy of the particle and stops the particle. It consists of electromagnetic and hadronic calorimeters.
  3. Muon spectrometer: It is a particle tracker for muons.



# Challenges

# Challenges

Estimation of the signal sensitivity

- Cross section for our signal $\sim 0.1$ pb
- Total luminosity in one year $\sim 10^4$ pb$^{-1}$
- Expected number of signal events in one year $\sim 10^3$

- Time interval between each collision $= 25$ ns
- Total number of events in one year $\sim 10^{15}$
- The probability to have a signal event $\sim 10^{-12}$
- Conclusion: the SUSY signal is very rare.

# Strategy

In order to extract the signal, the following strategies are used.

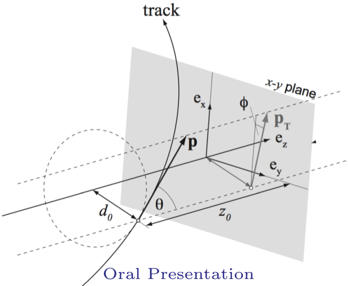
- A hardware trigger system are used when taking the data (online), to only store the interested events in the disk.
  (40 MHz $\rightarrow$ 100 kHz $\rightarrow$ 1 kHz)
- Some discriminant variables (based on the kinematic variables) are defined, to help distinguish the signal and the background (i.e. noise).
- Two dedicated signal regions are defined based on the discriminant variables, to maximize signal sensitivity (like the signal-to-noise ratio).

# Signal Region

# Signal Region : Basic kinematic variables

- The z-axis is in the proton beam direction.
- The direction of the momentum **p** of the particle can by specified by the azimuthal angle $\phi$ and the polar angle $\theta$, as usual in the spherical coordinate system.
- The transverse momentum $\mathbf{p_T}$ is the projection of **p** onto the x-y plane. The magnitude of $\mathbf{p_T}$ is denoted by $p_T$

$$p_T = \sqrt{p_x^2 + p_y^2}$$



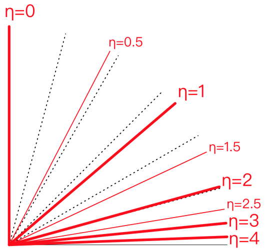
# Signal Region : Basic kinematic variables

- The pseudorapidity $\eta$ is defined by

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

- The values of pseudorapidity $\eta$ have reflective symmetry about the x-y plane. (Negetive value for $90^\circ < \theta < 180^\circ$)
- The angle separation $\Delta R$ of two particles is defined as:

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = \sqrt{(\phi_2 - \phi_1)^2 + (\eta_2 - \eta_1)^2}$$



# Signal Region : discriminant variable

- The missing momentum $\mathbf{p}^{\text{miss}}$ due to undetected particle is defined by

$$\mathbf{p}^{\text{miss}} = -\sum_{\text{All detected particles}} \mathbf{p}$$

- The transverse missing erengy, denoted by $E_T^{\text{miss}}$ or MET, is defined by

$$E_T^{\text{miss}} = |\mathbf{p}_T^{\text{miss}}| = \sqrt{(p_x^{\text{miss}})^2 + (p_y^{\text{miss}})^2}$$

- $p_T^1$ and $p_T^2$ are $p_T$ of the two leptons, with $p_T^1 \geq p_T^2$. The lepton with larger $p_T$ is called the leading lepton, while the lepton with smaller $p_T$ is called the sub-leading lepton.

# Signal Region : discriminant variable

- $n_{\text{jets}}$: Number of signal jets:
- $n_{\text{b-jets}}$: Number of $b$-jets (jet from b quark).
- $$\Delta\eta_{ll} = |\eta_1 - \eta_2|$$
- $$m_{\text{eff}} = p_T^1 + p_T^2 + E_T^{\text{miss}} + \sum_{\text{signal jets}} p_T$$
- $m_{ll}$: The invariant mass of the 4-momentum sum of the two leptons
$$(m_{ll})^2 = (p_1 + p_2)^2$$

# Signal Region : discriminant variable

- $m_T$: It is designed to reconstruct the mass of the W boson.

$$m_T = \sqrt{2 p_T^1 E_T^{\text{miss}} (1 - \cos \Delta\phi)}$$

where $\Delta\phi$ is the azimuthal angle between the leading lepton and the missing transverse momentum.

- $m_{T2}$: It is designed to set a lower bound on the masses of the unseen pair of charginos $\tilde{\chi}_1^{\pm}$ and neutralinos $\tilde{\chi}_2^0$.

$$m_{T2} = \min_{\mathbf{q}_T} \left[ \max \left( m_T(\mathbf{p}_T^1, \mathbf{q}_T), m_T(\mathbf{p}_T^2, \mathbf{p}_T^{\text{miss}} - \mathbf{q}_T) \right) \right]$$

$$m_T(\mathbf{p}_T, \mathbf{q}_T) = \sqrt{2 p_T q_T (1 - \cos \Delta\phi)}$$

# Signal Region : discriminant variable

- $m_{lj}$ or $m_{ljj}$: It is designed to reconstruct the mass of the Higgs boson.

$$p_{\text{jet-system}} = \begin{cases} p_{\text{jet1}} & \text{for SRjet1} \\ p_{\text{jet1}} + p_{\text{jet2}} & \text{for SRjet23} \end{cases}$$

$$p_{\text{closest-lepton}} = \begin{cases} p_{\ell 1} & \text{if } \Delta R(p_{\ell 1}, p_{\text{jet-system}}) \leq \Delta R(p_{\ell 2}, p_{\text{jet-system}}) \\ p_{\ell 2} & \text{if } \Delta R(p_{\ell 1}, p_{\text{jet-system}}) > \Delta R(p_{\ell 2}, p_{\text{jet-system}}) \end{cases}$$

$$(m_{lj(j)})^2 = (p_{\text{closest-lepton}} + p_{\text{jet-system}})^2$$