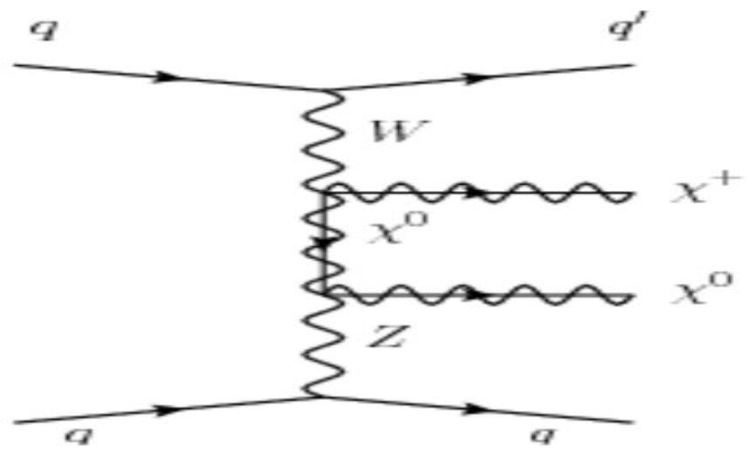
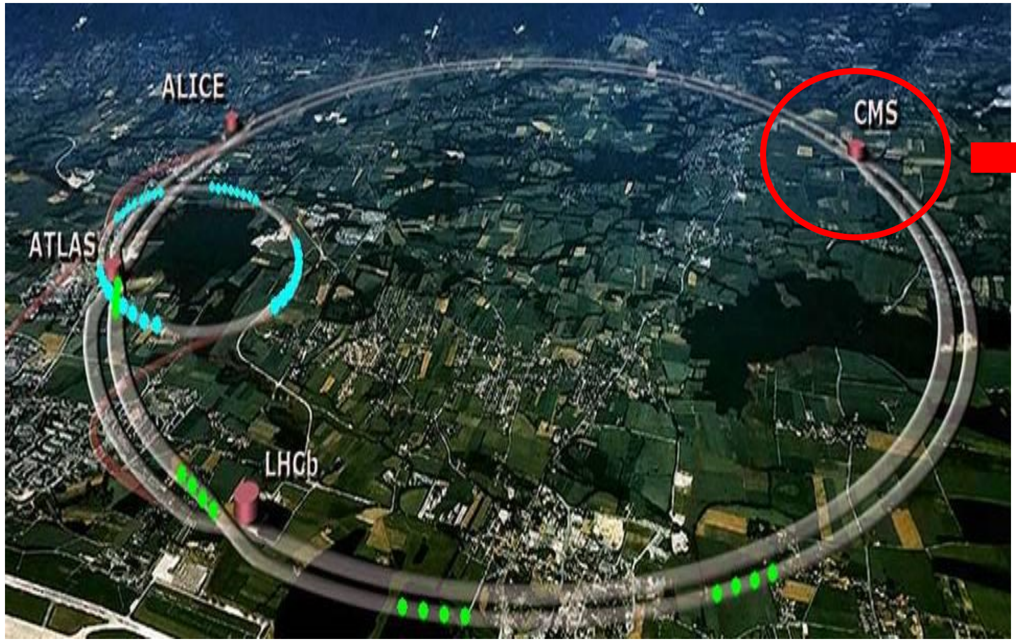
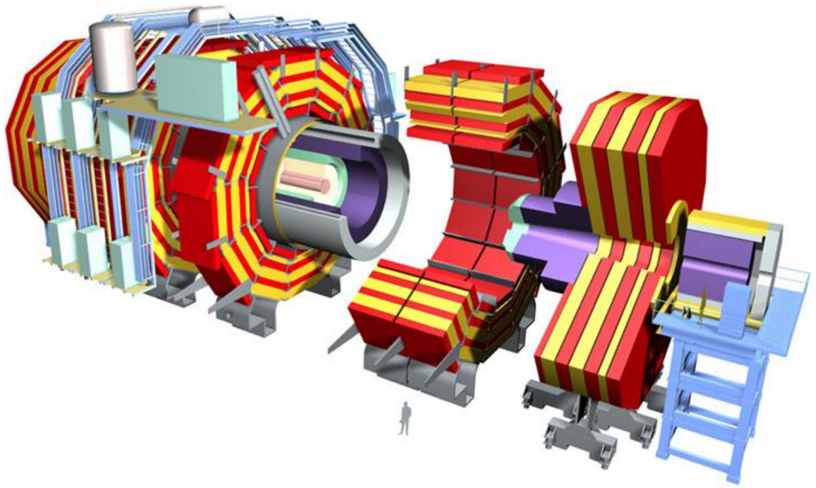
Search for Electroweakinos produced via Vector Boson Fusion with the CMS detector in proton-proton collisions at sqrt(s) = 13 TeV



Carlos Avila

Universidad de los Andes





MOCA 2019

GOAL OF THIS TALK:

Summarize recent published results:

JHEP

Published for SISSA by Springer

Received: *May 30, 2019*
Accepted: *August 6, 2019*
Published: *August 27, 2019*

Search for supersymmetry with a compressed mass spectrum in the vector boson fusion topology with 1-lepton and 0-lepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS collaboration

Combined effort between
Vanderbilt U. +
Texas A&M U. +
Panjab U. +
Kyungpook U. +
UNIANDES
within the CMS
Experiment.

TALK OUTLINE

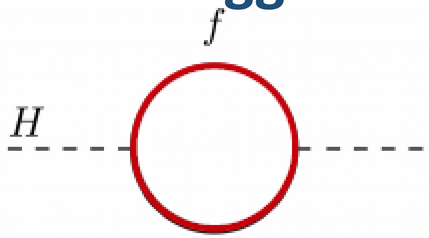
1. **Introduction**
2. **Vector Boson Fusion & Compressed spectra**
3. **CMS Experiment**
4. **Signal Region Optimization**
5. **Background estimation**
6. **Results and Conclusions**

1. Introduction

Why to searh for supersymmetry?

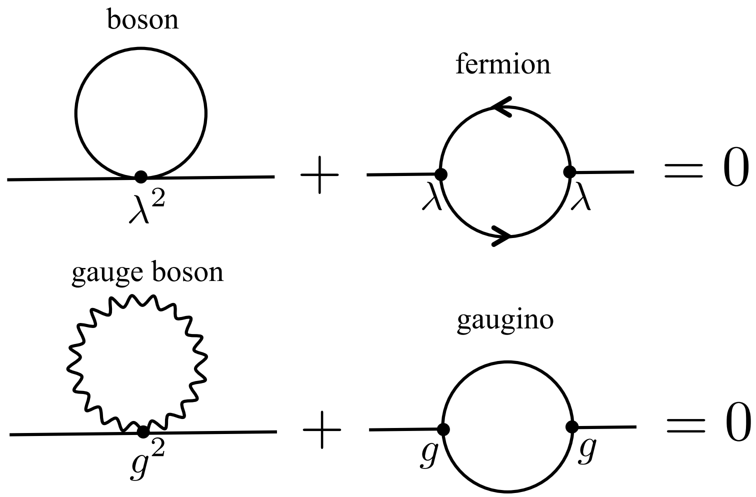
It solves many of the SM problems, among them:

1. SM Higgs Mass Hierarchy problem:

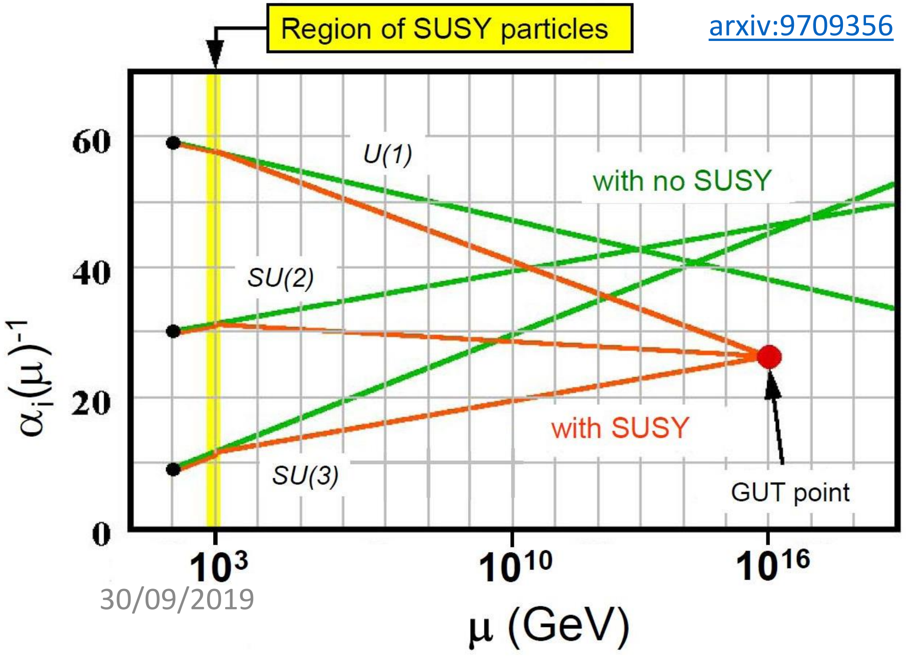


$$(125\text{GeV})^2 = m_H{}^2 = m_{H,0}{}^2 + \Delta m_H{}^2$$

SUSY SOLUTION: Increase the SM particle spectra



2. Unification of gauge couplings :



3. Dark Matter:

In R parity conserved models: LSP is the DM candidate particle. In most of RPC models:

1. $|\tilde{\chi}_1^0>$ =|DM>=|WIMP>
2. SUSY particles produced in pairs

$$R = (-1)^{3(B-L)+2S} = \begin{cases} +1 & for\ SM\ particle \\ -1 & for\ SUSY\ particle \end{cases}$$

MSSM is the supersymmetric extension of the SM with minimal number of particle states = twice SM # particles + extended Higgs sector. SUSY partners for gauge bosons mix as charginos ($\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$) and neutralinos ($\tilde{\chi}_i^0, i = 1,..,4$)

Neutralino and Chargino Mass Matrices

- **Neutralinos are a mixture of the neutral gauginos ($\widetilde{B}, \widetilde{W}^3$) and higgsinos ($\widetilde{H}_u, \widetilde{H}_d$):**

$$M_0 = \begin{pmatrix} M_1 & 0 & -m_Z \sin(\theta_W)\cos(\beta) & m_Z \sin(\theta_W)\sin(\beta) \\ 0 & M_2 & m_Z \cos(\theta_W)\cos(\beta) & -m_Z \cos(\theta_W)\sin(\beta) \\ -m_Z \sin(\theta_W)\cos(\beta) & m_Z \cos(\theta_W)\cos(\beta) & 0 & -\mu \\ m_Z \sin(\theta_W)\sin(\beta) & -m_Z \cos(\theta_W)\sin(\beta) & -\mu & 0 \end{pmatrix}$$

M_1 = Bino mass parameter
M_2 = Wino mass paramater
M = Higgsino mass parameter
tanβ = v2/v1

|eigenvalues| of M_0 = neutralino masses m$\widetilde{\chi}_i^0$, i=1,..,4
(m$\widetilde{\chi}_1^0$<m$\widetilde{\chi}_2^0$<m$\widetilde{\chi}_3^0$<m$\widetilde{\chi}_4^0$)

The possible mixing scenarios define the nature of the neutralinos and charginos and could lead to a different phenomenology:

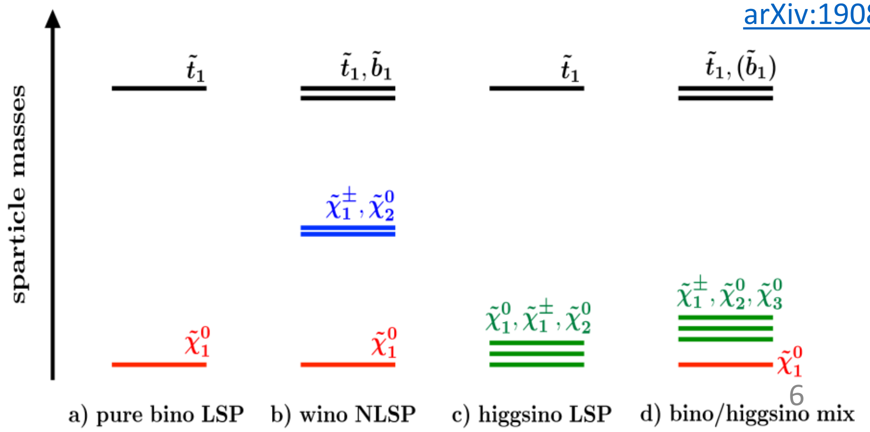
$$M_1 \gg M_2, \mu \Rightarrow \widetilde{\chi}_1^0 \approx \widetilde{B} \longrightarrow \textit{pure Bino}$$

$$M_2 \gg M_1, \mu \Rightarrow \widetilde{\chi}_1^0 \approx \widetilde{W} \longrightarrow \textit{pure Wino}$$

$$\mu \gg M_1, M_2 \Rightarrow \widetilde{\chi}_1^0 \approx \widetilde{H}_h + \widetilde{H}_d \longrightarrow \textit{pure Higgsino}$$

arXiv:1908.09672

- **Charginos are a mixture of charged winos ($\widetilde{W}^{\pm}$) and higgsinos ($\widetilde{H}^{\pm}$):**

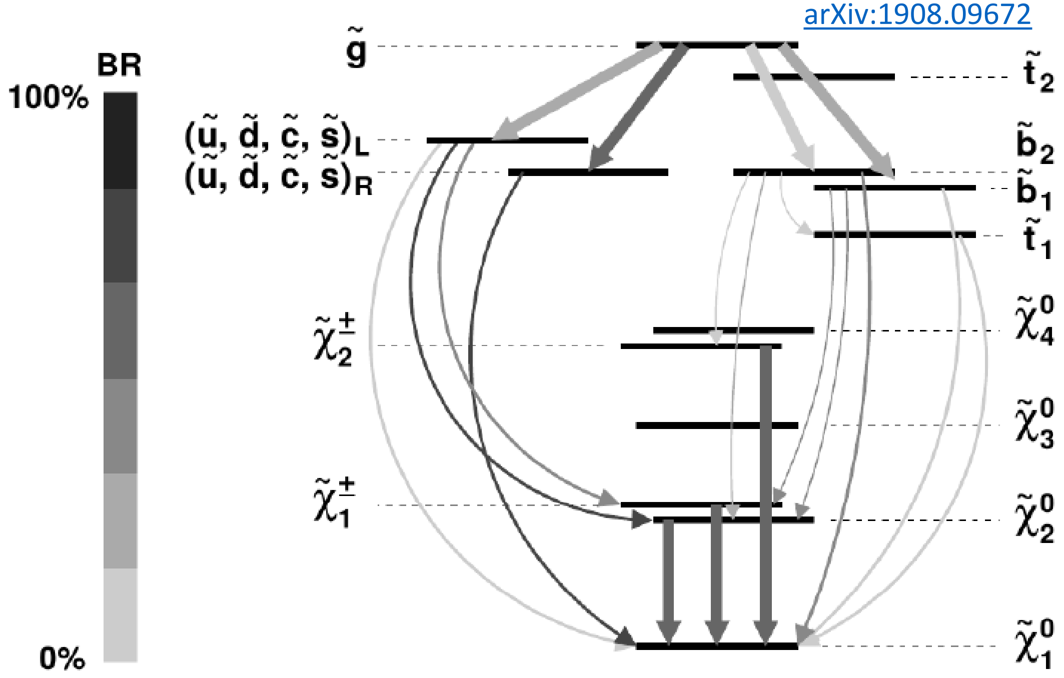


$$\mathcal{M}_{\pm} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin(\beta) \\ \sqrt{2} M_W \cos(\beta) & \mu \end{pmatrix}$$

$$m^2_{\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}} = \frac{1}{2}\left[M_2^2 + \mu^2 + 2m_W^2 \mp \sqrt{(M_2^2 - \mu^2)^2 + 4m_W^4 \cos^2 2\beta + 4m_W^2 (M_2^2 + \mu^2 + 2M_2 \mu \sin 2\beta)}\right]$$

Data interpretation Frameworks

arXiv:1908.09672

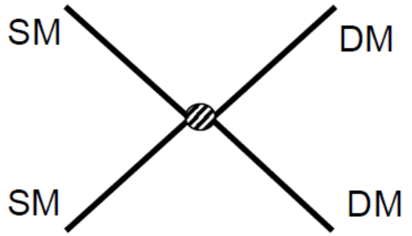


A major difficulty with the MSSM:
Huge parameter space: 124 parameters

Two possibilities to overcome this issue: LHC DM W.G.

1. **Efective Field Theories**
2. **Simplified Models**

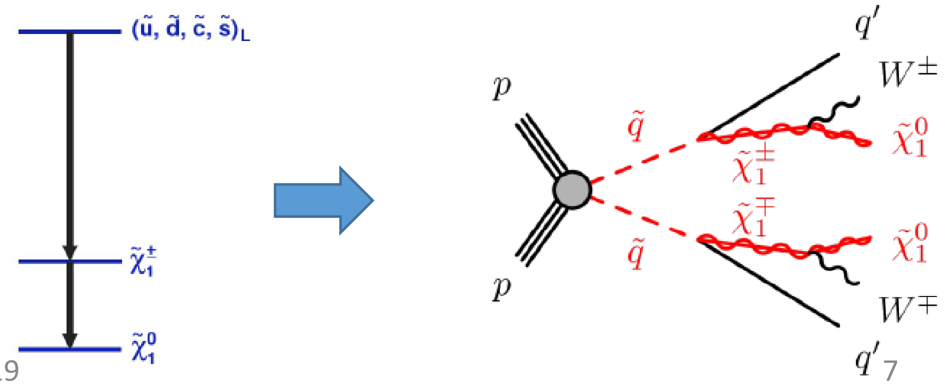
EFECTIVE FIELD THEORIES



- Contact interaction between SM and DM particles
- Few parameters
- Model independent searches
- Valid only for $Q^2 << M_{mediator}$
  → Issue for LHC

SIMPLIFIED MODELS (Adopted for LHC searches):

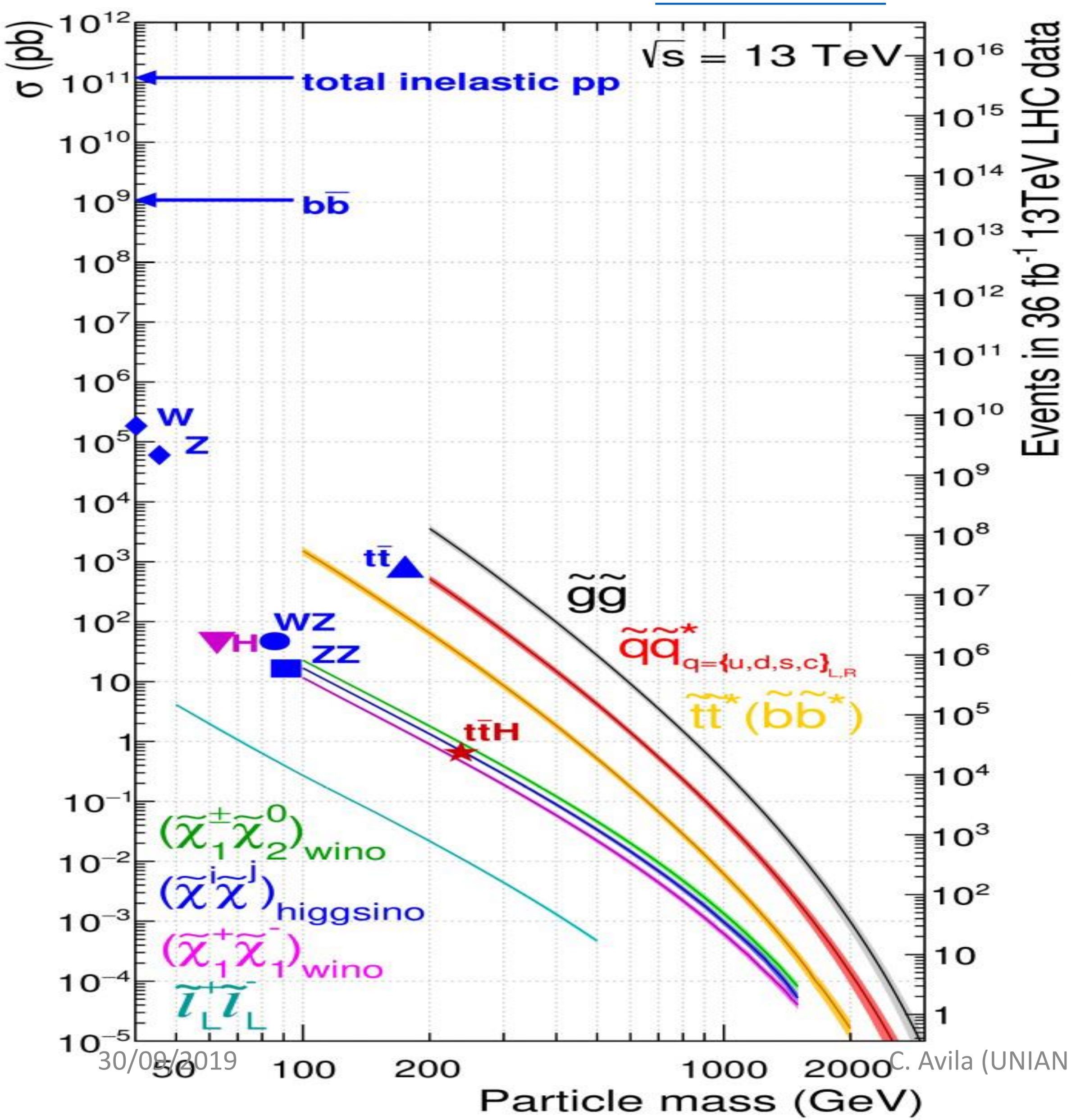
- Emphasize features of a broad set of models
- Drives phenomenolgy for model independent searches
- Usually concéntrate in one specific decay chain:



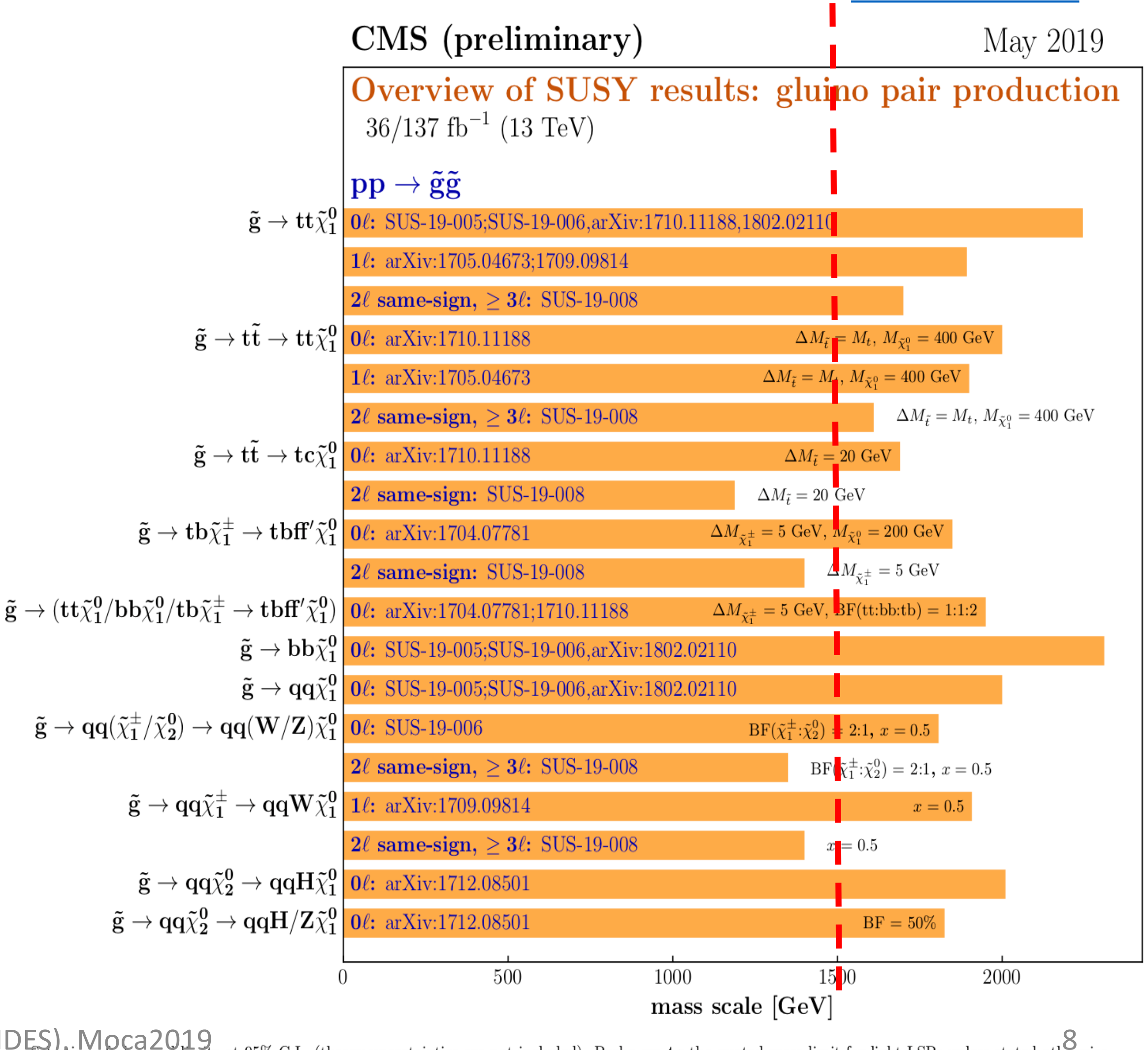
SUSY CROSS SECTIONS

High production cross sections for gluinos & squarks production.
→ discovery channel at energy frontier
Current Mass limits > 1.5 Tev.

LHC x-sections W.G.



CMS SUSY Results



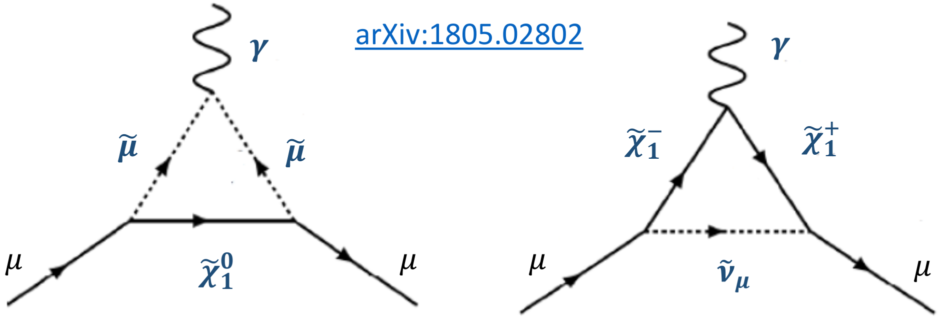
Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

WHY TO STUDY THE SUSY ELECTROWEAK SECTOR ?

- SUSY naturalness favours small Higsino masses.

- Light smuon and chargino are needed to explain the observed 3.6 σ deviation by BNL of the muon anomalous magnetic dipole mment (g-2).

arXiv:1805.02802

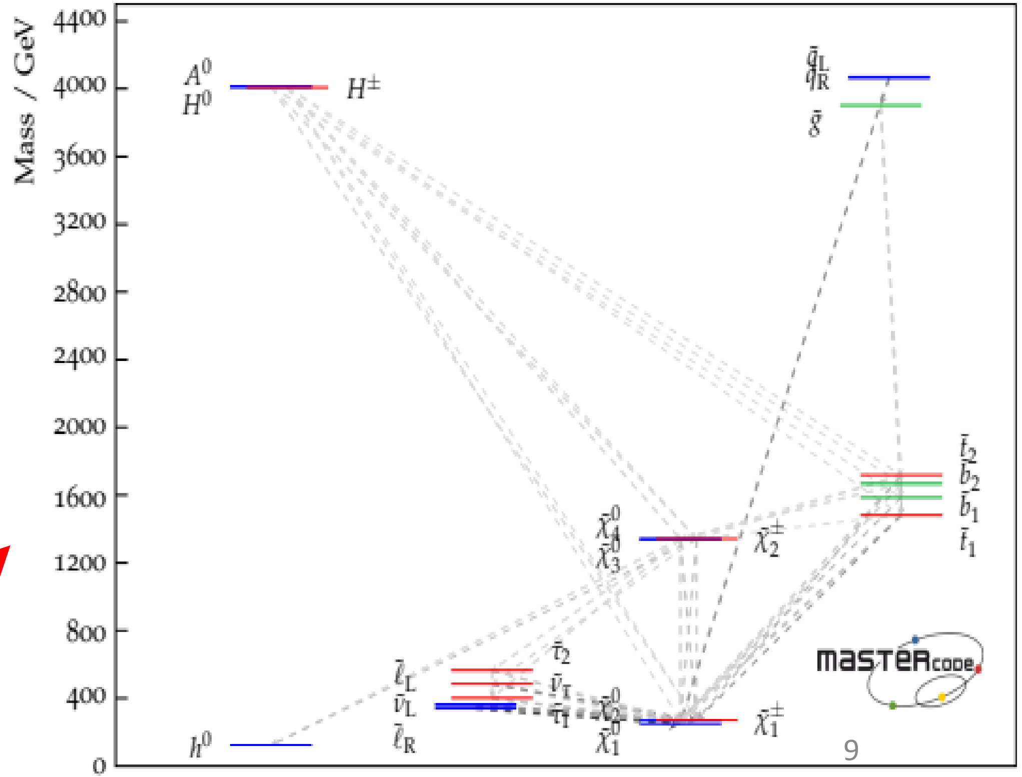


- To explain the observed DM relic density the NLSP particle mass shoud be close to the LSP mass → **Compressed spectra**.

- High exclusion limits on the SUSY colored sector motivates electroweak searches as posible scenarios on the Discovery reach of the LHC.

- Likelihood analysis of experimental constraints predicts light charginos, neutrinos and sleptons.

arXiV:1710.11091

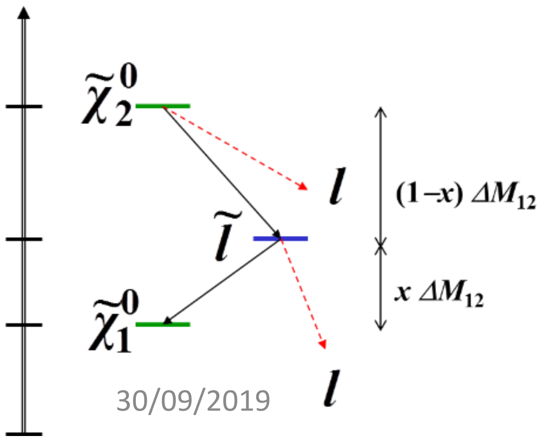


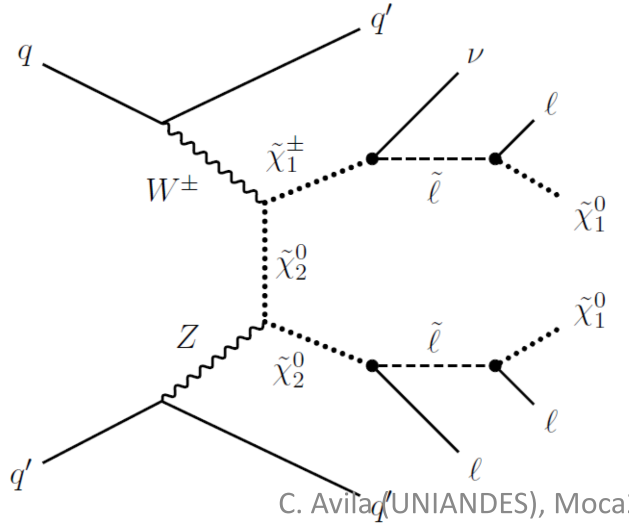
2. Vector Boson Fusion and Compressed Spectra

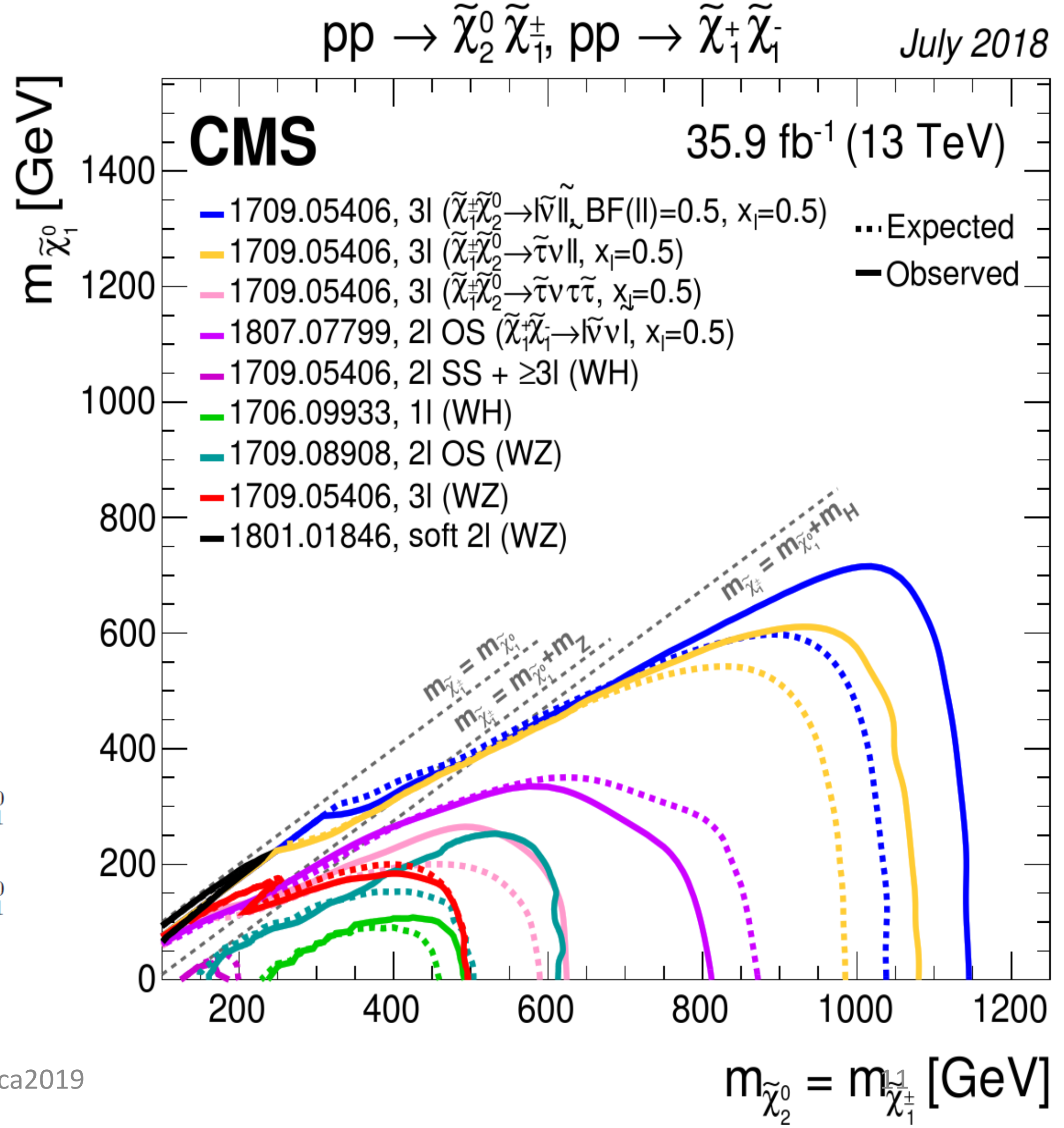
COMPRESSED SPECTRA & VECTOR BOSON FUSION

[CMS SUSY Results](#)

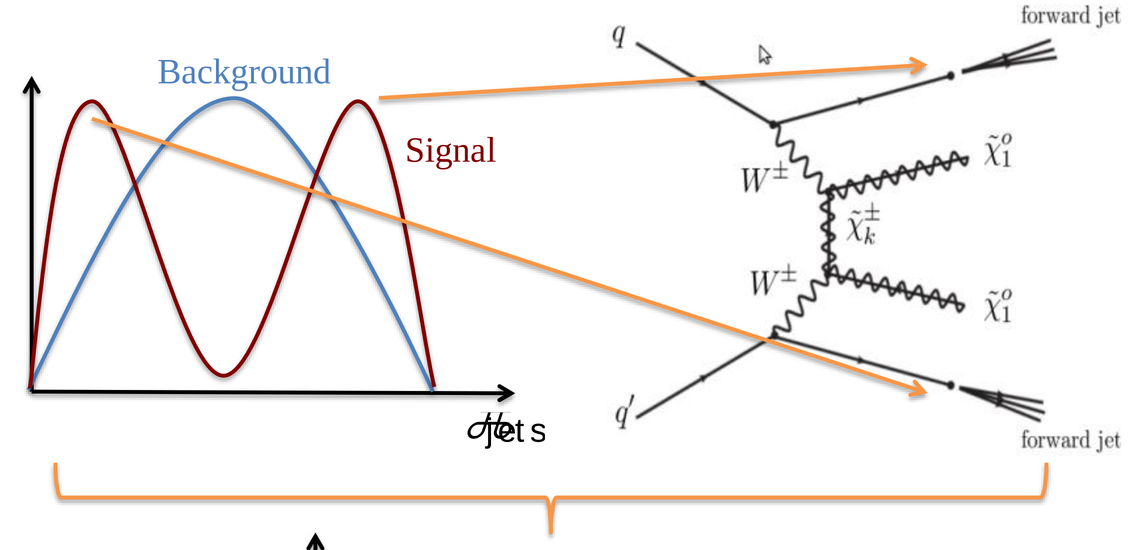
- Most of the searches focus focus on pair produced electroweakinos ($\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$, etc), with final state leptons (1L, 2L , 3L).
- There is limited sensitivity to compressed spectra scenarios: $m(\tilde{\chi}^0) \approx m(\tilde{\chi}_1^{\pm})$ → Soft P_T leptons are expected in the final decay chain given the limited amount of energy available.
- VBF is a useful topology to tackle the compressed scenarios.

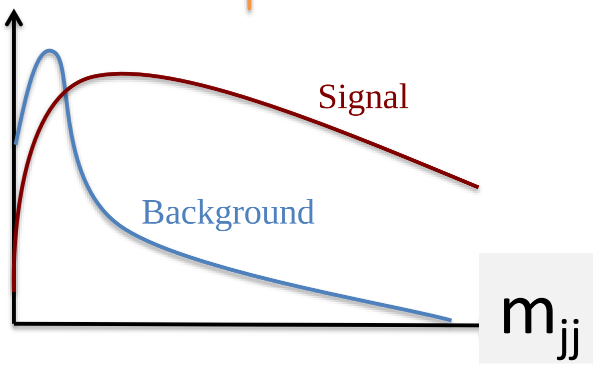


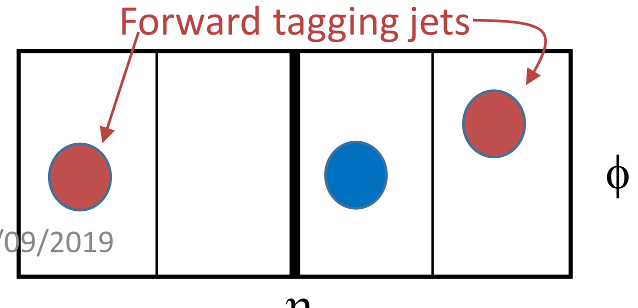




VECTOR BOSON FUSION TOPOLOGY



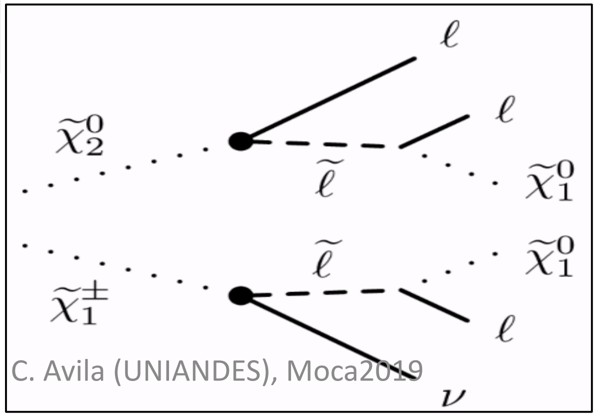




- The outgoing partons in VBF processes must carry relatively large p_T.
- The jets in SM background events are mostly central while signal events are characterized by more forward-like jets.
- VBF pair of jets with high dijet mass:

$$m_{jj} = \sqrt{2 \cdot p^{j_1} p^{j_2} \cosh(\Delta\eta(j_1, j_2))}$$

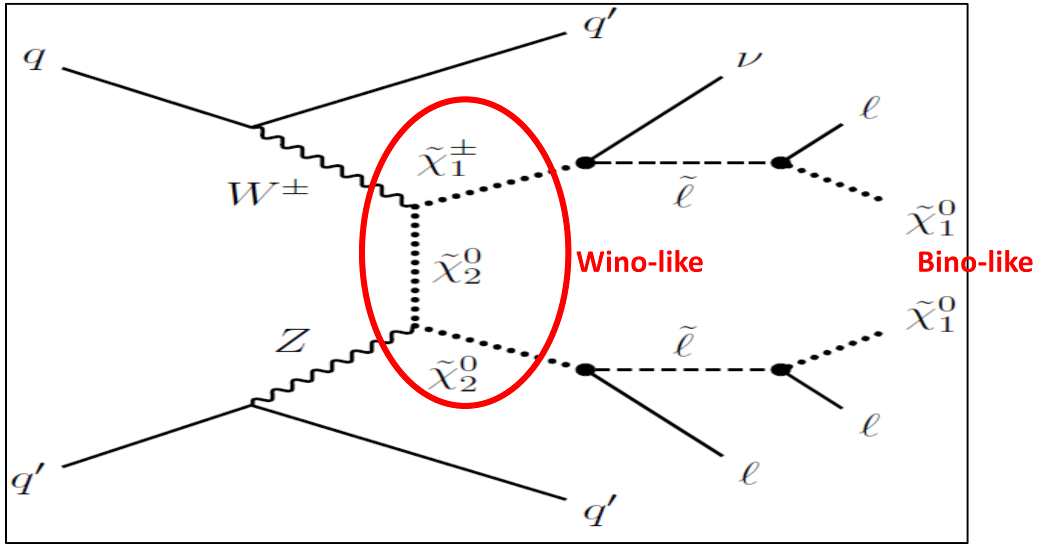
Benchmark Model

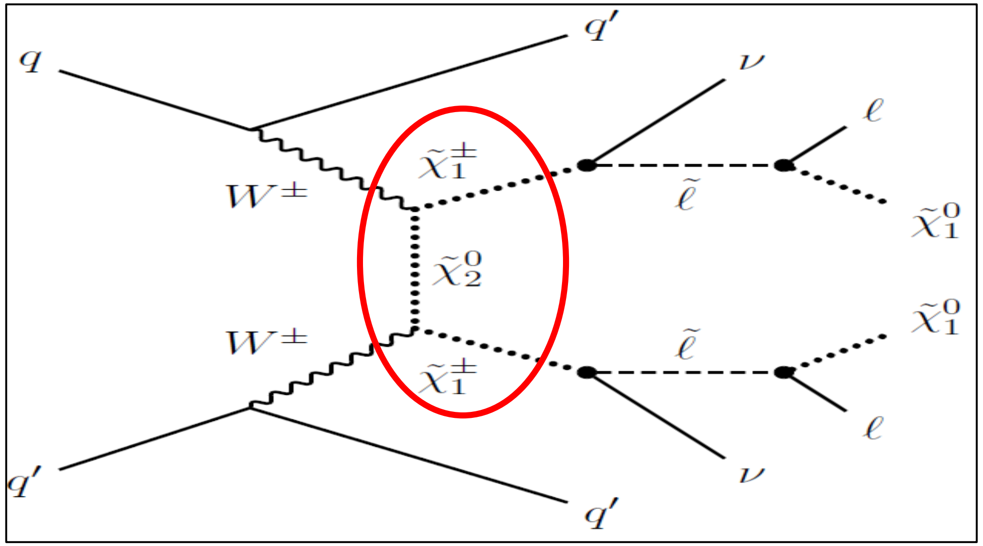


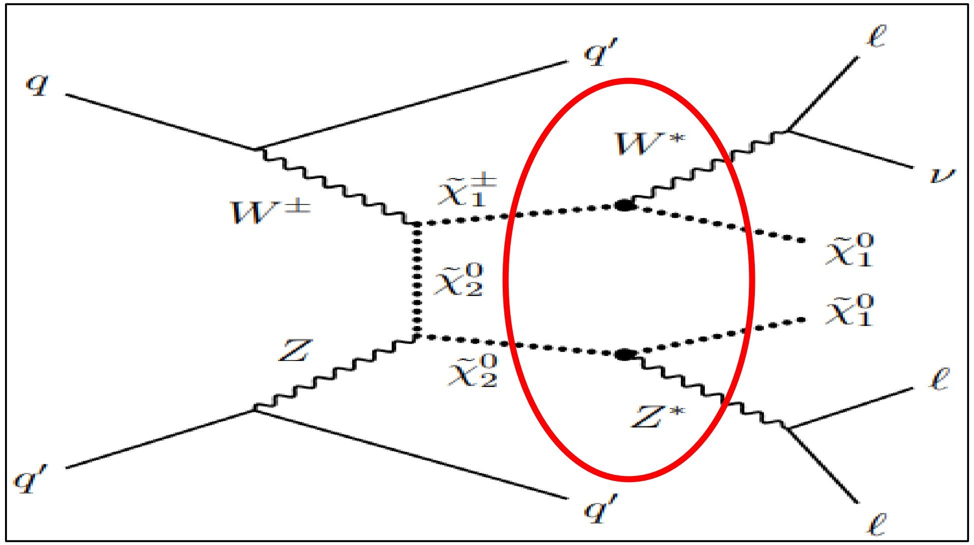
- **VBF jets + MET + μ/e/τ**
- **VBF jets + MET**

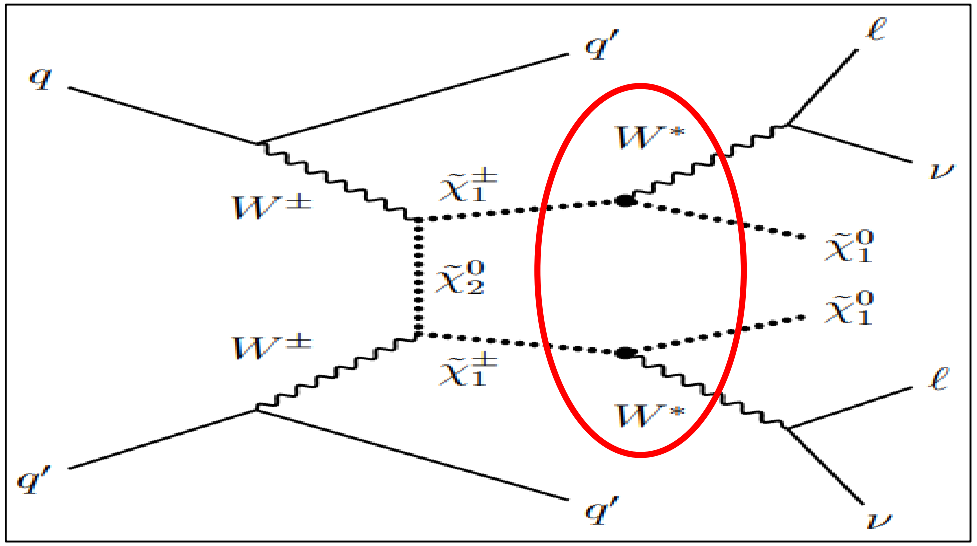
We focus on 0 lepton or one soft-lepton (μ/e/τ) channel given the difficulty to reconstruct multiple soft leptons in compressed spectra scenarios.

$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$ Production Mechanisms considered



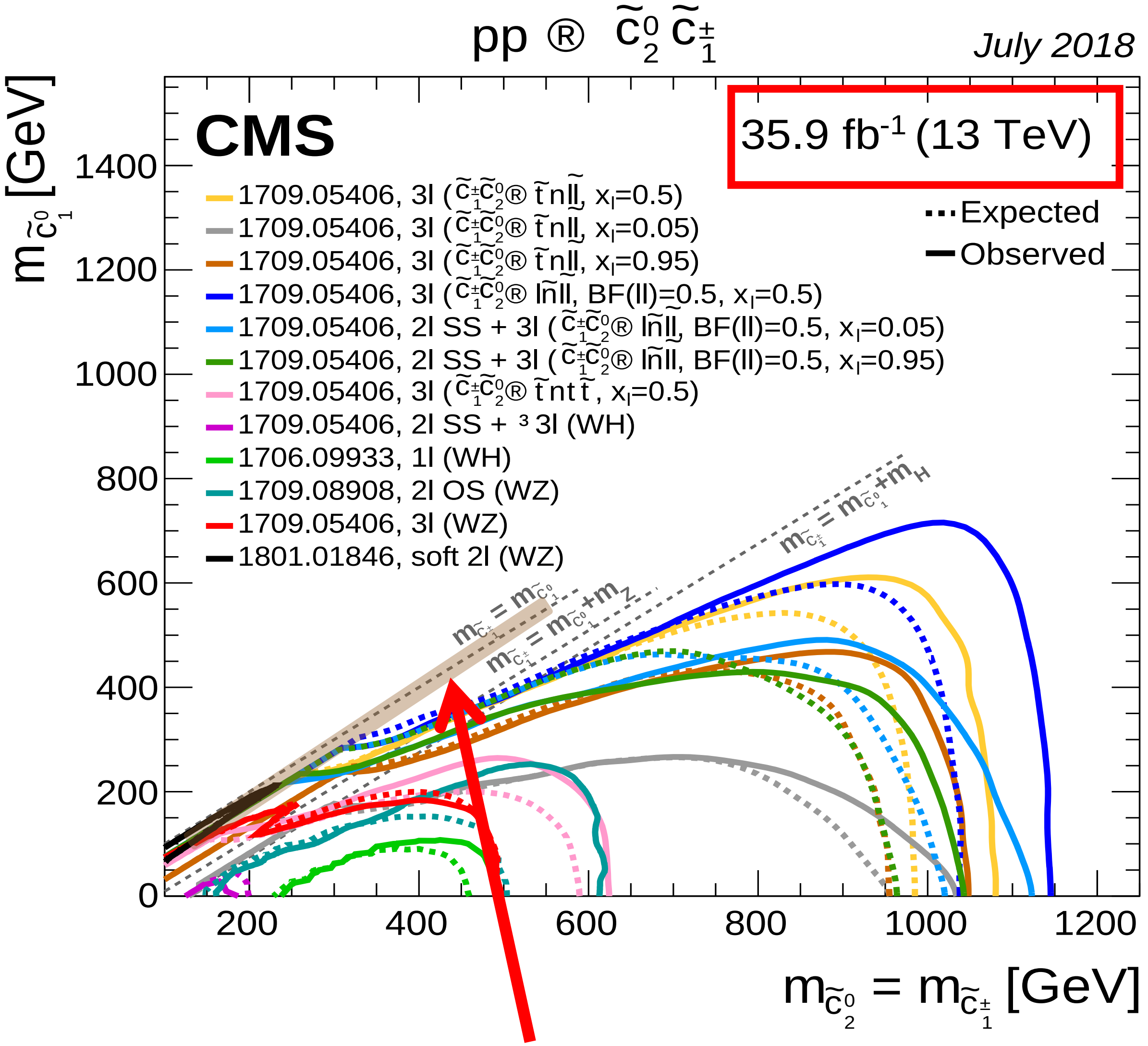






VBF REQUIREMENTS

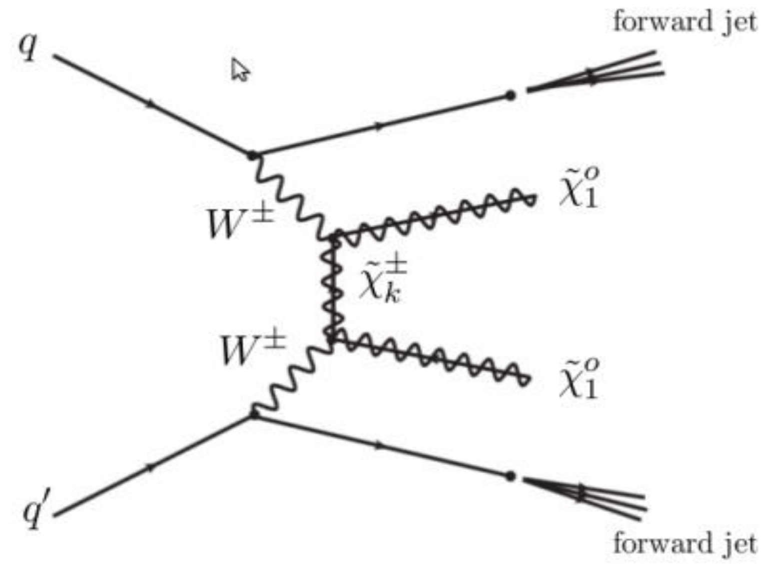
[CMS SUSY Results](#)



Region under exploration:
$\Delta m = m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0) = 1 - 50$ GeV

VBF selection: jet candidates with the following requirements

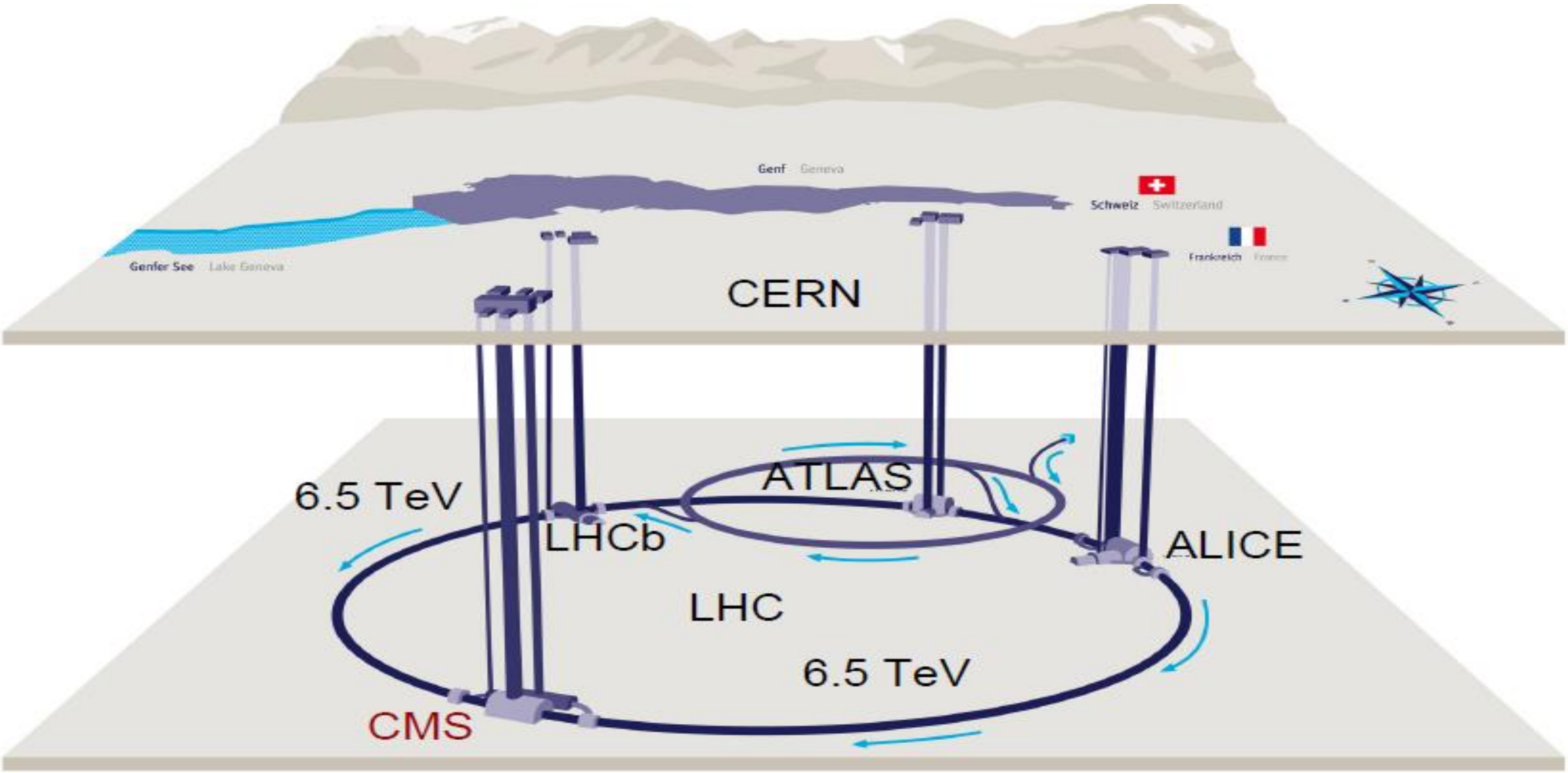
- ✓ large eta separation
- ✓ in opposite hemispheres
- ✓ large dijet invariant mass



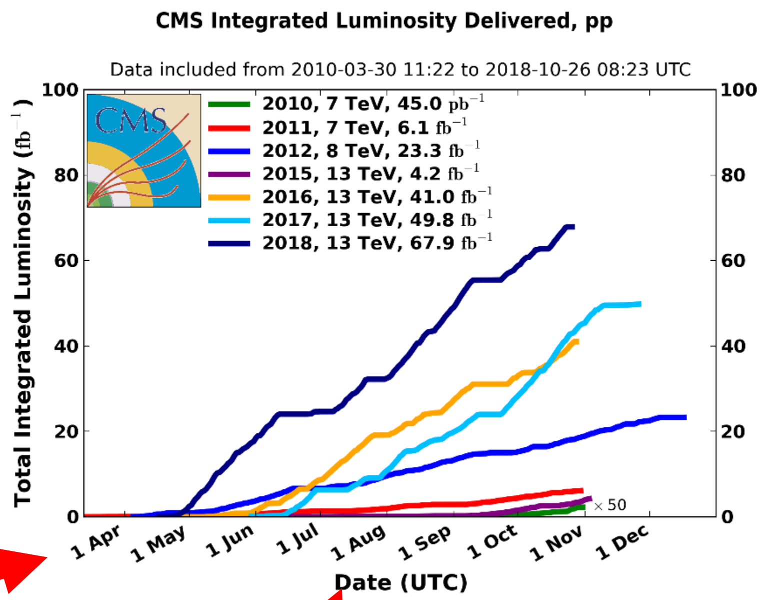
VBF topology suffers from smaller cross sections, but benefits from lower contamination from SM backgrounds.

3. The CMS Experiment

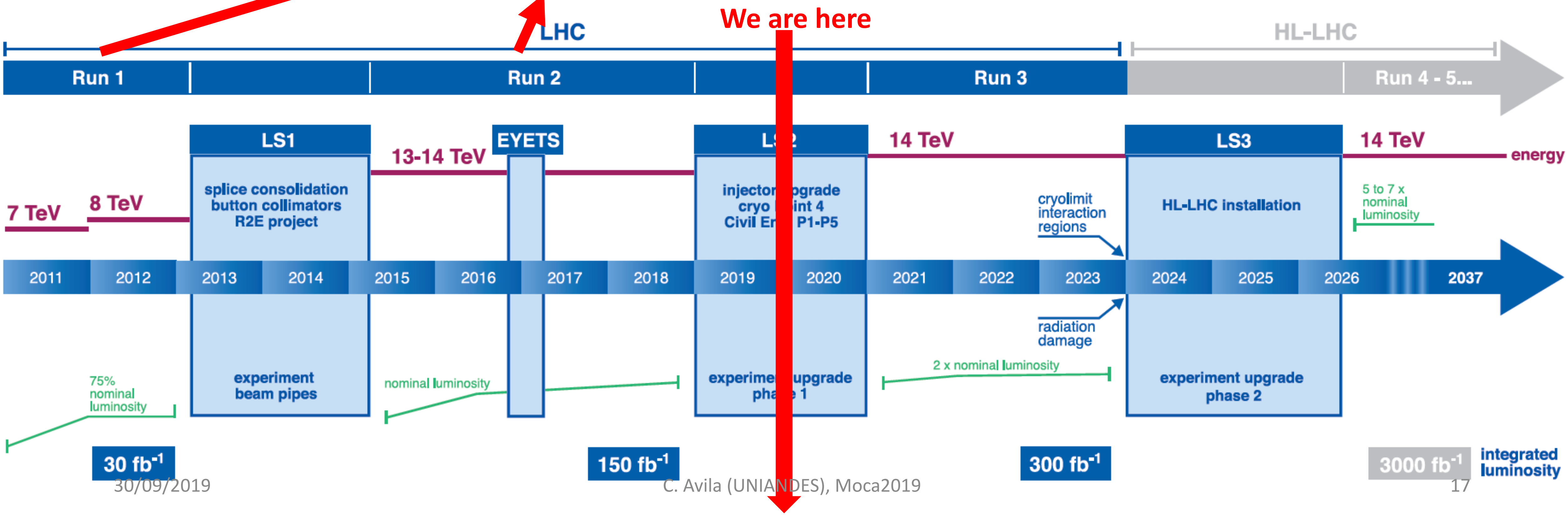
THE LHC ACCELERATOR



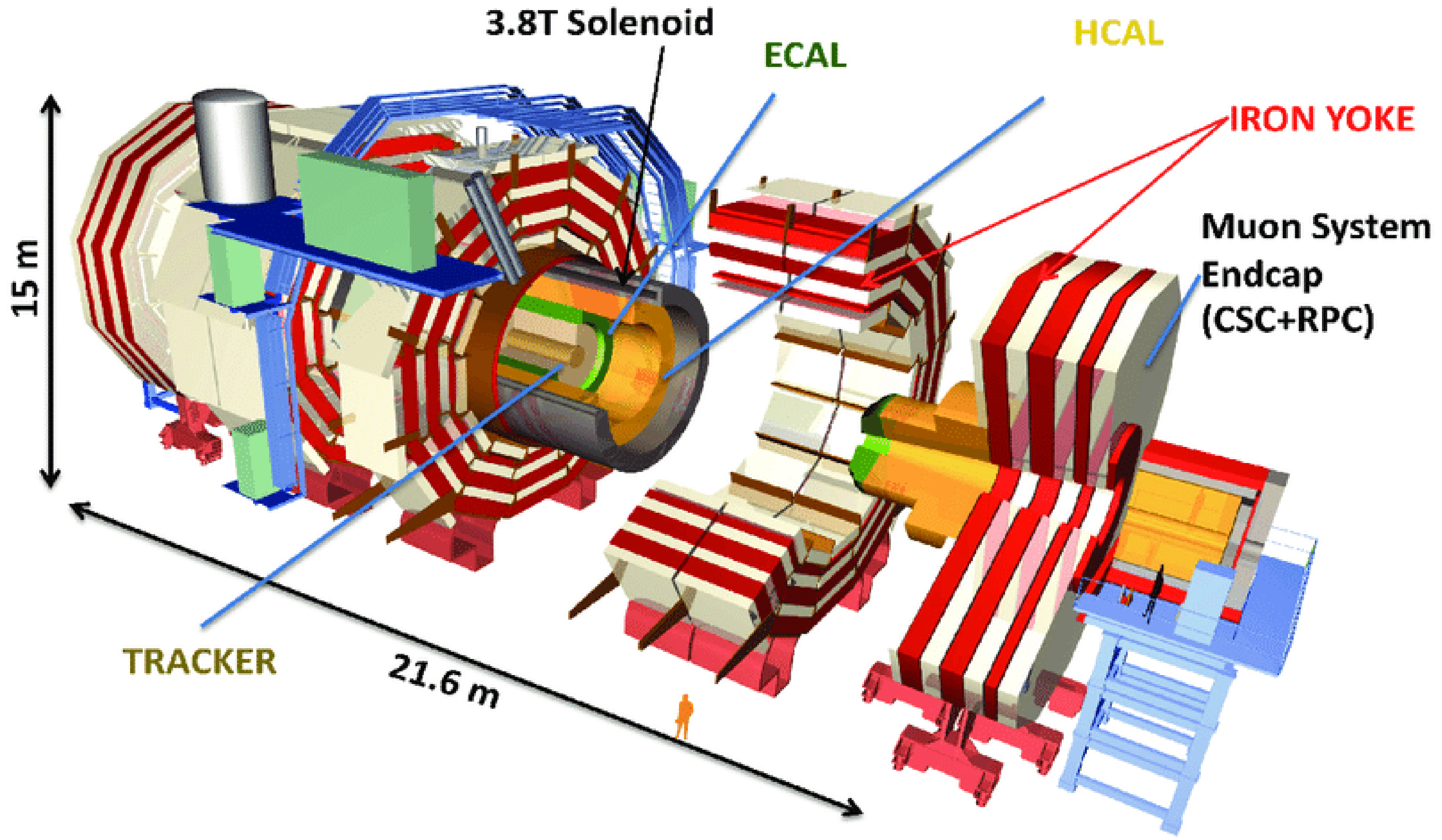
LHC STATUS



- 10 years after LHC start up has allowed to record 50% of the expected integrated luminosity of the LHC expected luminosity and only 5% of the total luminosity expected from the HL-LHC.
- The full 3000 fb^{-1} and new analysis tools (such as machine learning, etc.) will allow to heavily constraint the SUSY parameter space.

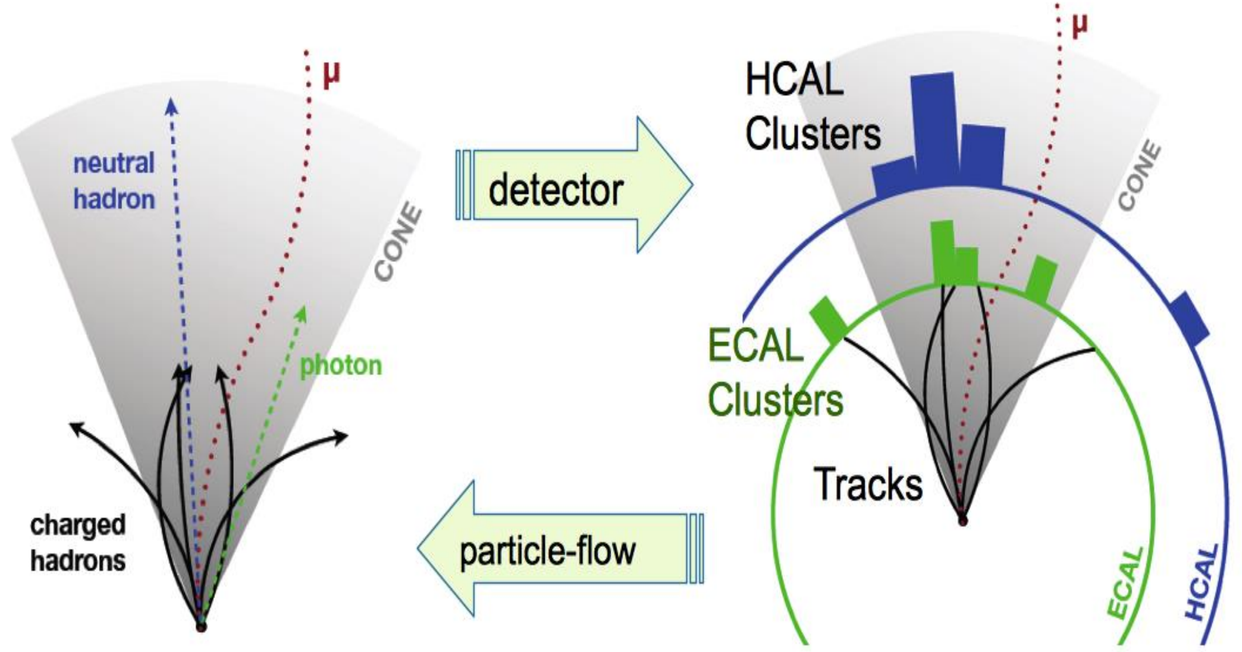


THE CMS DETECTOR @ THE LHC



CMS PARTICLE FLOW

Combine info from all subsystems to generate a list of reconstructed particles to descrcibe the entire event



- Find μ´s and remove
- Find e´s and remove
- Find charged hadrons and remove
- Find photons and remove
- Find neutral hadrons and remove

A large B field, good calorimeter granularity and high resolution tracking are needed for efficiente PF.

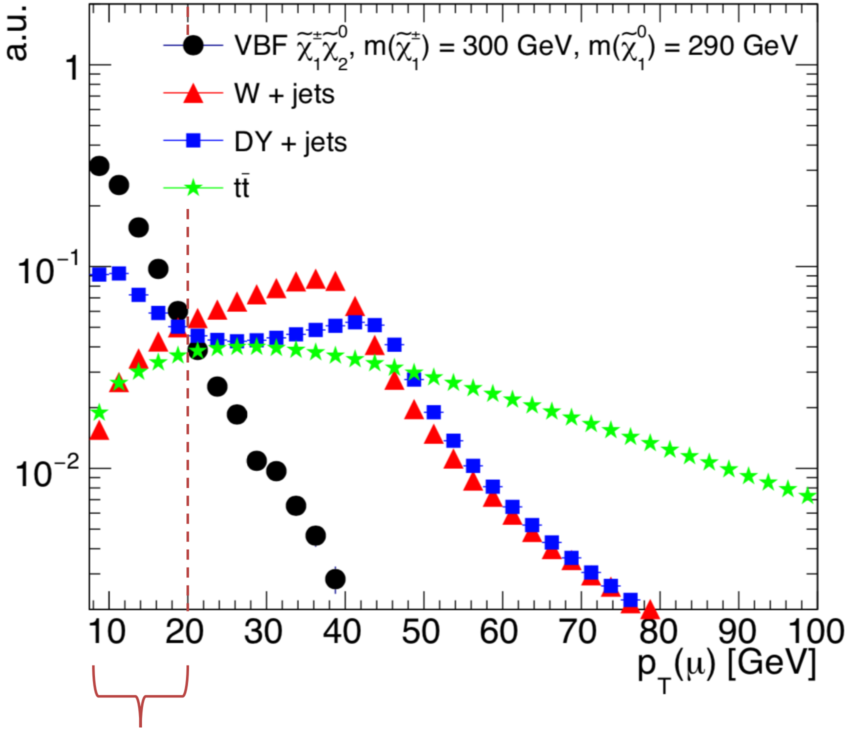
e,μ,γ, charged and neutral hadrons

- Used in the event as a list of generated particles in the event.
- Used to reconstruct jets, taus, Missing energy, isolation and identification of particles in multiple proton-proton collisions.

4. Signal Region optimization

P_T^l DISTRIBUTION

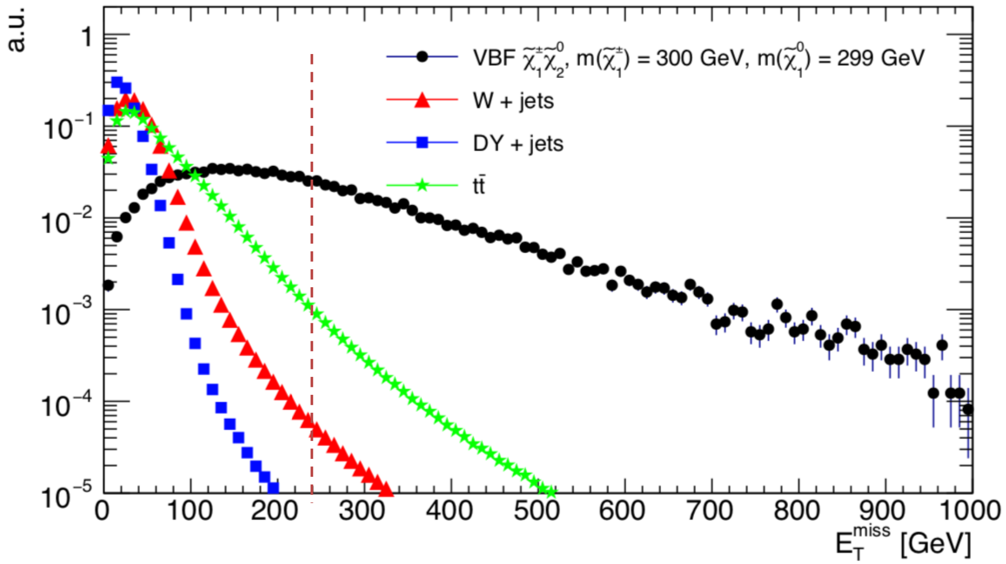
For the case of our interest the LSP mass is slightly lower than the masses of other charginos and neutralinos, which means that the decay products of the SUSY particles produced would have low p_T , which makes it difficult to reconstruct and identify multiple leptons, consequently, we focus on events that have one well-identified soft muon or zero leptons.



For a signal benchmark point with a mass gap $\Delta m = m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0) = 10$ GeV the signal is more pronounced than the backgrounds in the region 8 GeV to 20 GeV, therefore, this region is where we would expect the highest significance.

MET DISTRIBUTION

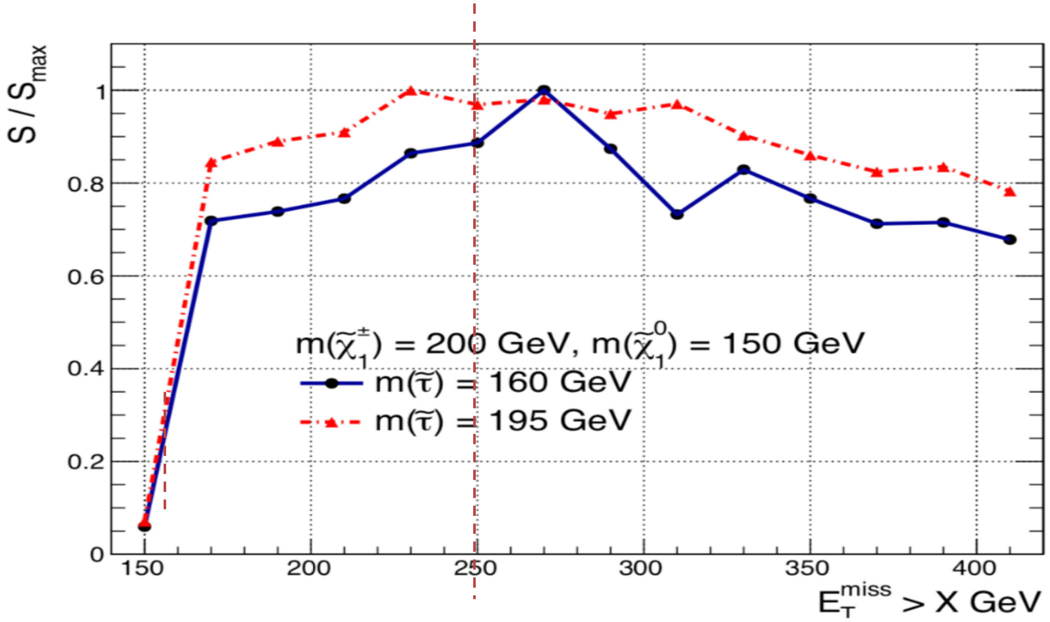
$$E_T^{miss} = \left|\vec{P}_T^{miss}\right| = \left|-\sum_{visible} \vec{P}_{T,i}\right|$$



A high MET requirement (> 250 GeV) suppresses drastically the backgrounds

We would expect a higher MET distribution for a SUSY signal (due to the LSP) than for neutrinos produced by SM backgrounds.

Signal significance S divided by the maximum significance S_{max}, as a function of MET cut for two signal samples. The best signal significance is achieved for MET >250 GeV.

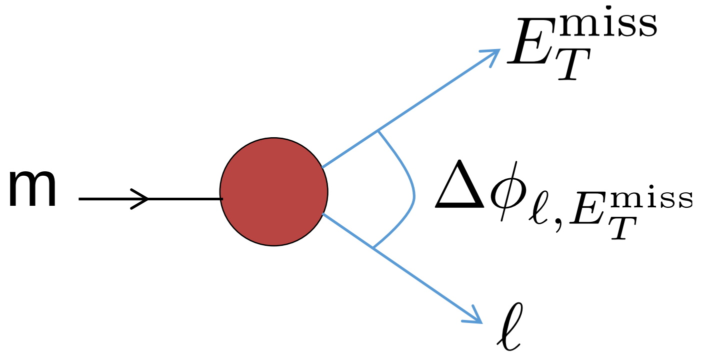


Signal significance:

$$S = \frac{s}{\sqrt{\sigma_s^2 + \sigma_B^2}} = \frac{s}{\sqrt{s + B}}$$

MT DISTRIBUTION

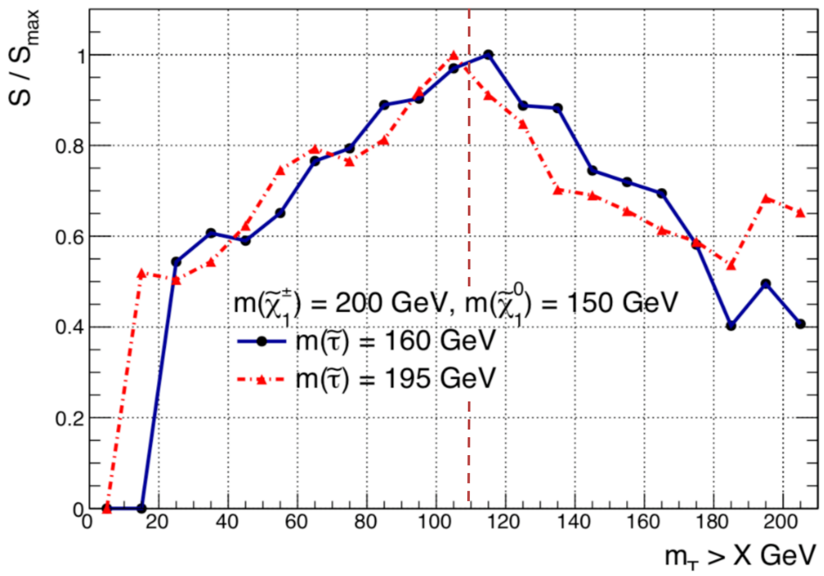
Discriminating variable in signal region for the 1Ljj channel

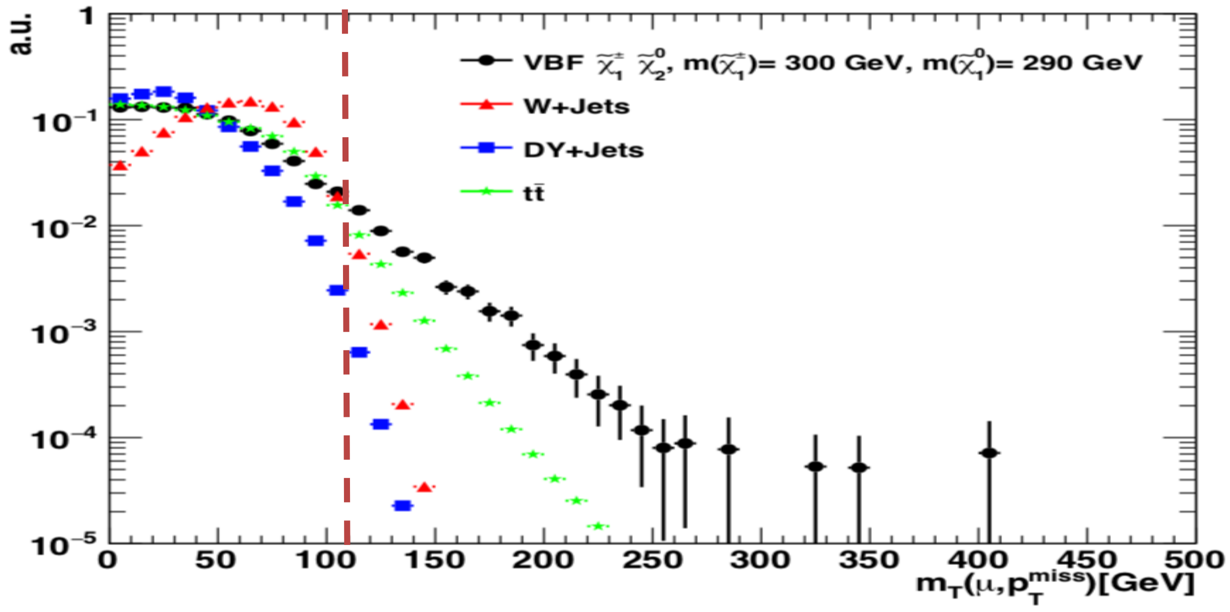


$$m_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\ell,E_T^{\mathrm{miss}}})}$$

m_T distributions normalized to unity for three backgrounds and one VBF signal sample

Signal significance divided by the maximum significance S_{max}, as a function of m_T cut values for two signal samples. m_T > 110 GeV provides the best signal significance.



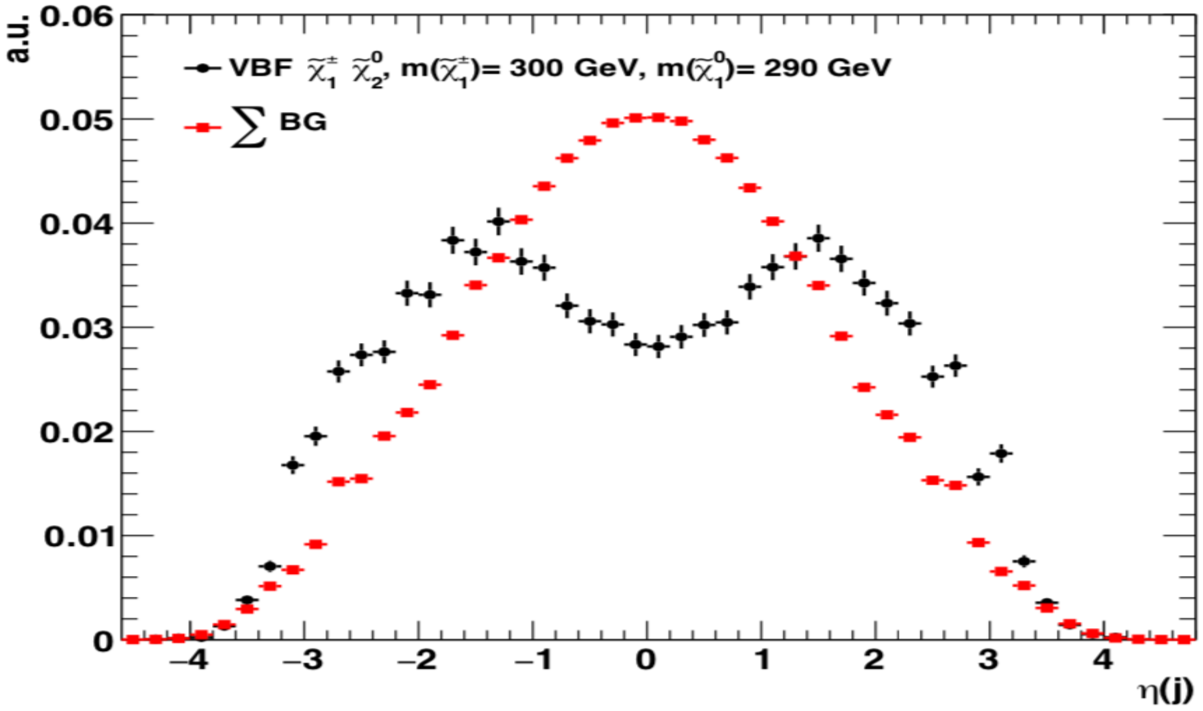


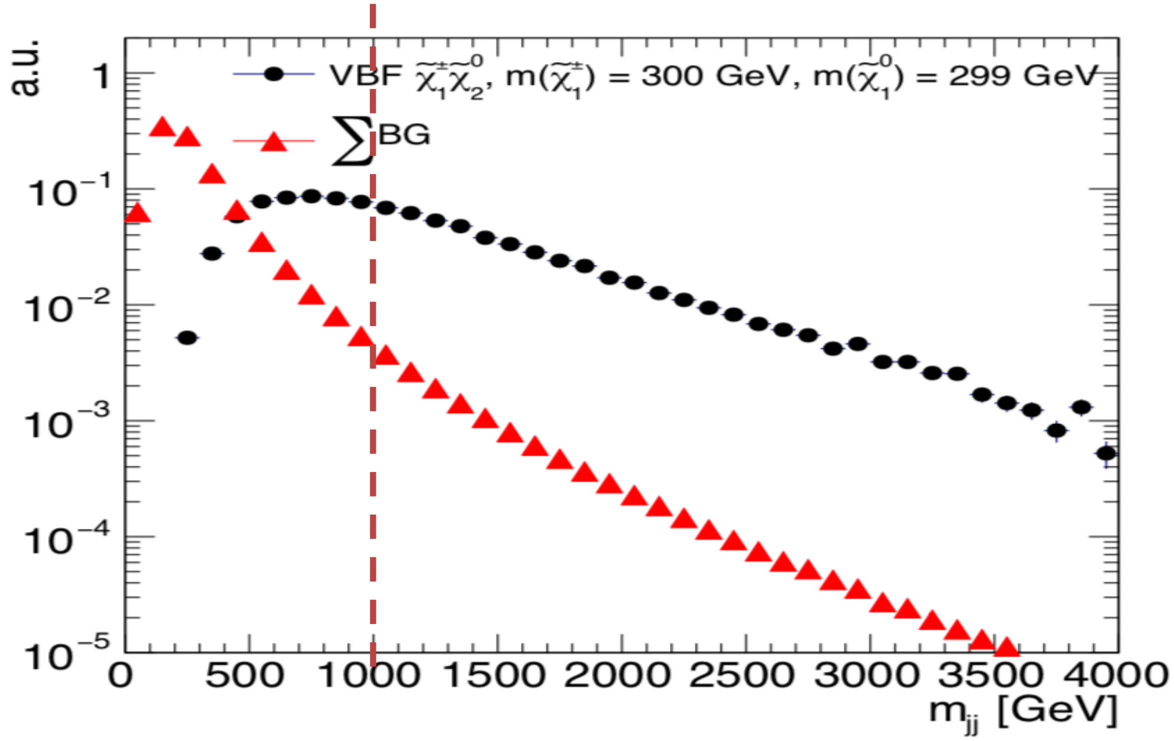
One motivation for applying a requirement of mT greater than 110 GeV is the background supresion. In particular, the W+jets background.

M_{jj} DISTRIBUTION

Discriminating variable in signal region for the 0Ljj channel

The jets produced by background events are mostly in the central region of the detector ($|\eta| \leq 1.8$) and have small dijet invariant masses, while the signal events are characterized by non-central jets with large dijet invariant masses.





VBF selection: jet candidates with the following requirements

- ✓ $|\Delta\eta_{jj}| > 3.8$ (large eta separation)
- ✓ $\eta_{j1} \cdot \eta_{j2} < 0$ (in opposite hemispheres)
- ✓ mjj > 1 TeV (large dijet invariant mass)

We choose the pair of jets with the highest dijet invariant mass.

5. Background Estimation

Irreducible Backgrounds

- **For MET + jj + e/μ channels:**

Dominant Bacgrounds:
- t-tbar
- W+jets

Subdominant backgrounds:
- single top quark,
- diboson (WW, WZ, and ZZ)
- Z+jets

- **For MET + jj + τ channel:**

Dominant Bacgrounds:
- QCD multijets
- W+jets
- t-tbar

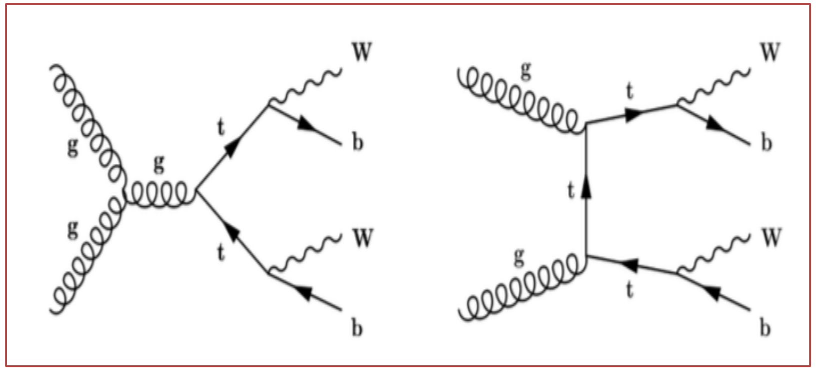
Subdominant backgrounds:
- single top quark,
- diboson (WW, WZ, and ZZ)
- Z+jets

- For MET + jj channel:

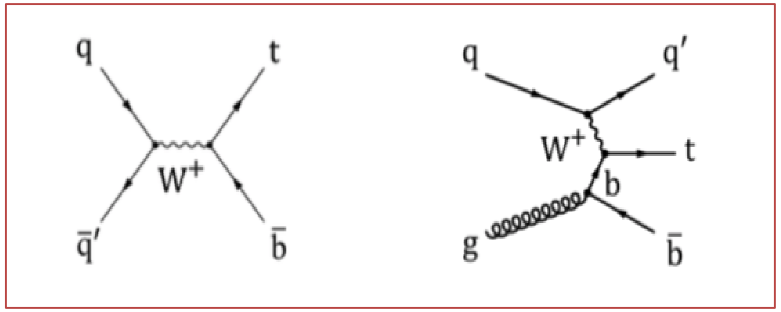
Dominant Bacgrounds:
- Z(→νν) +jets
- QCD multijets

Subdominant backgrounds:
- t-tbar
- diboson (WW, WZ, and ZZ)

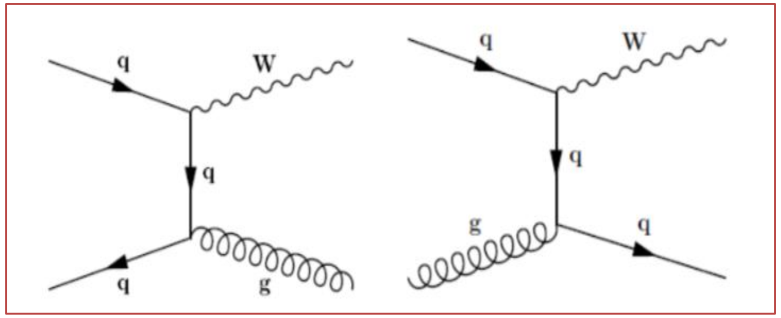
t-tbar



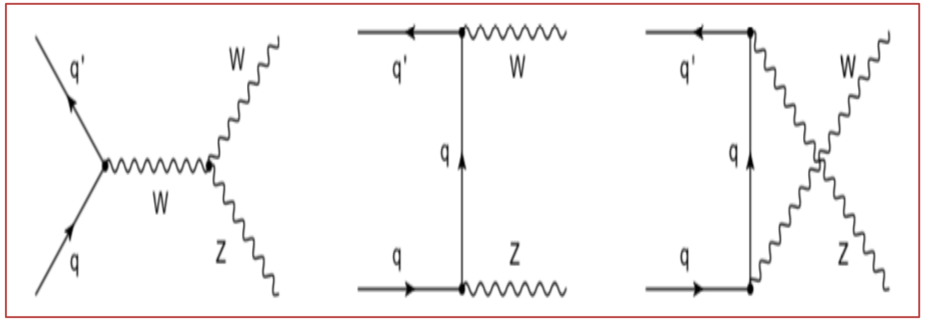
Single top



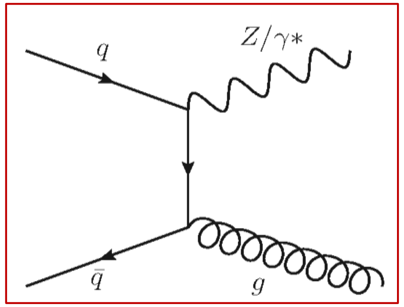
W + jets



Diboson

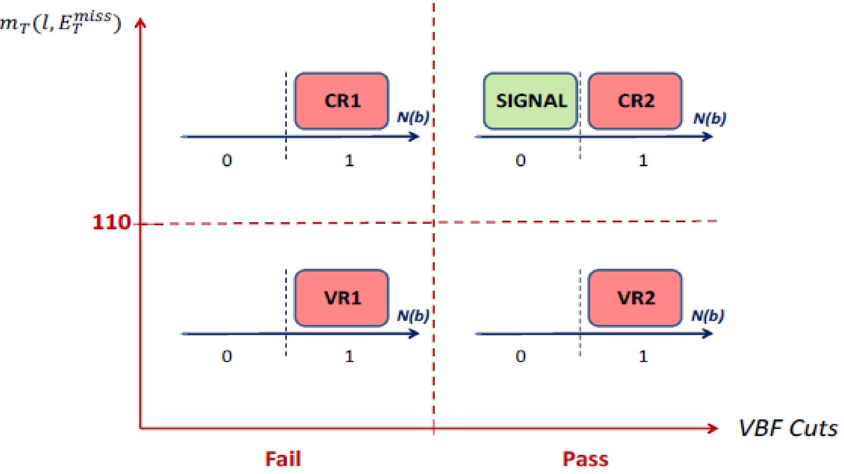


Z + jets



Background CR's

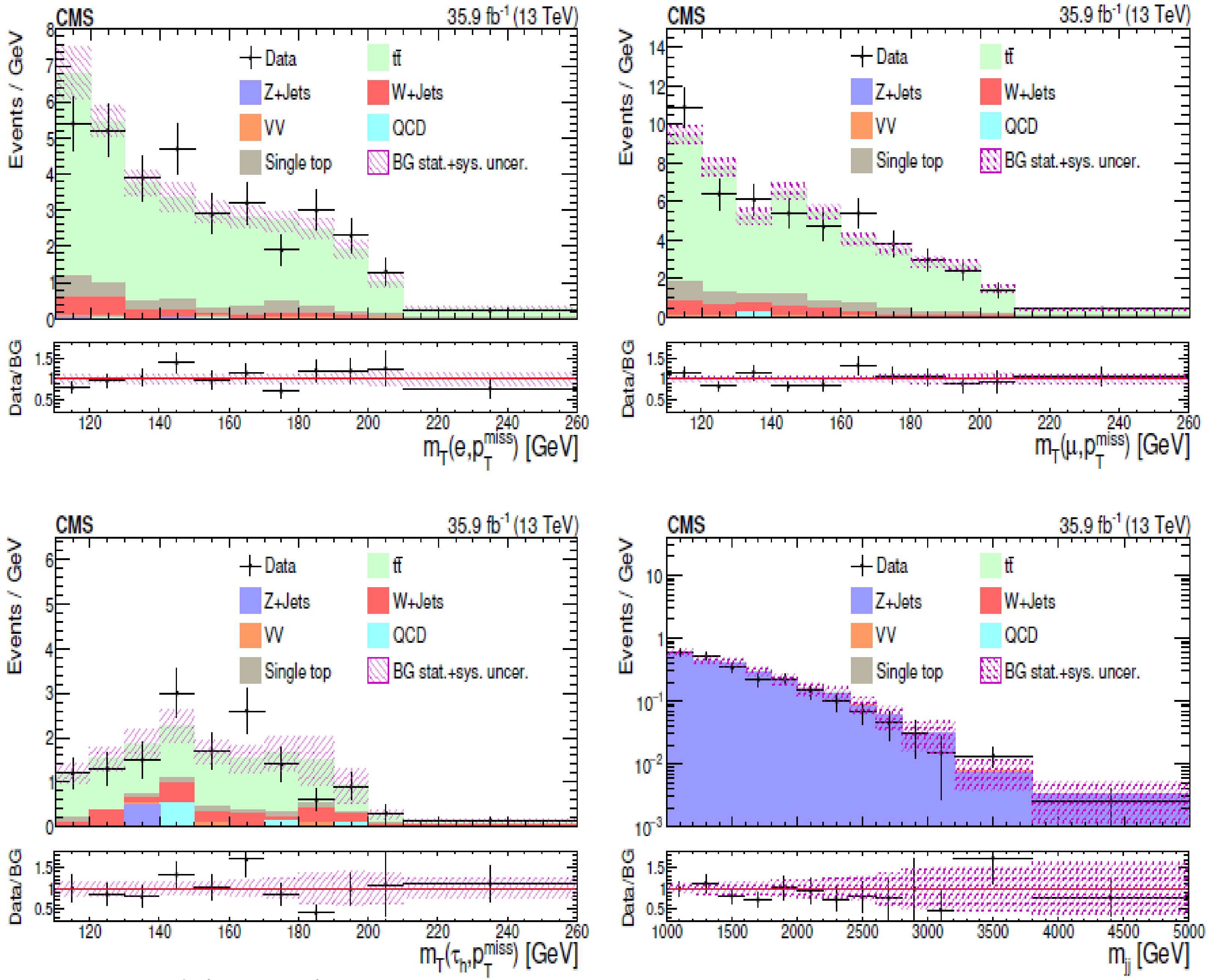
Top Pair Background Estimation & Validation Strategy



$$SF^{\mathrm{CR1}} = \frac{N^{\mathrm{CR1}}(\mathrm{Data}) - N^{\mathrm{CR1}}(\mathrm{other\ BGs})}{N^{\mathrm{CR1}}(t\bar{t})}$$

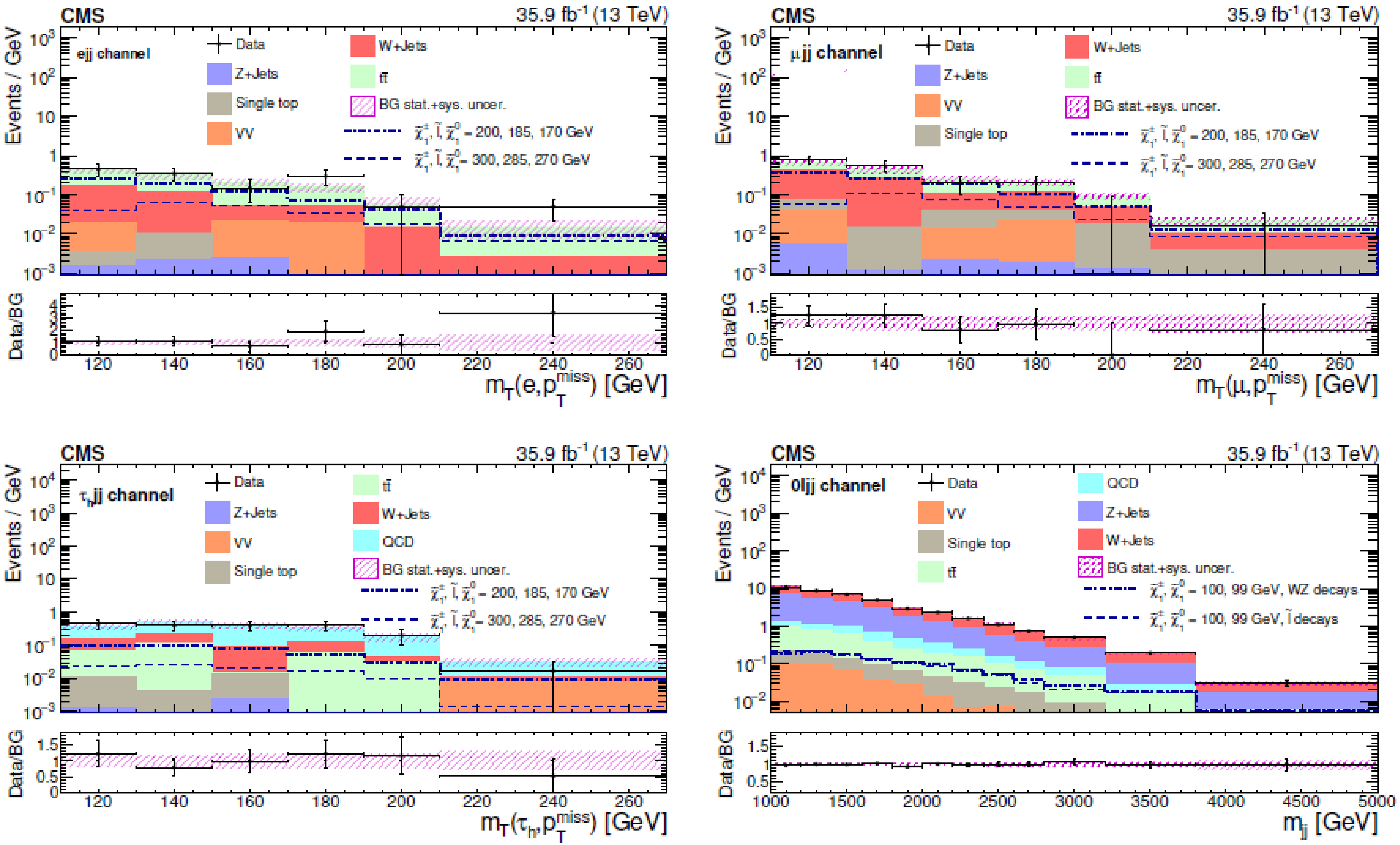
$$SF^{\mathrm{CR2}} = \frac{N^{\mathrm{CR2}}(\mathrm{Data}) - N^{\mathrm{CR2}}(\mathrm{other\ BGs\ })}{N^{\mathrm{CR2}}(t\bar{t}) \cdot SF^{\mathrm{CR1}}}$$

$$N_{t\bar{t}}^{\mathrm{Expected}} = N_{t\bar{t}}^{\mathrm{MC}}(\mathrm{SR\ cuts}) \cdot SF^{\mathrm{CR1}} \cdot SF^{\mathrm{CR2}}$$



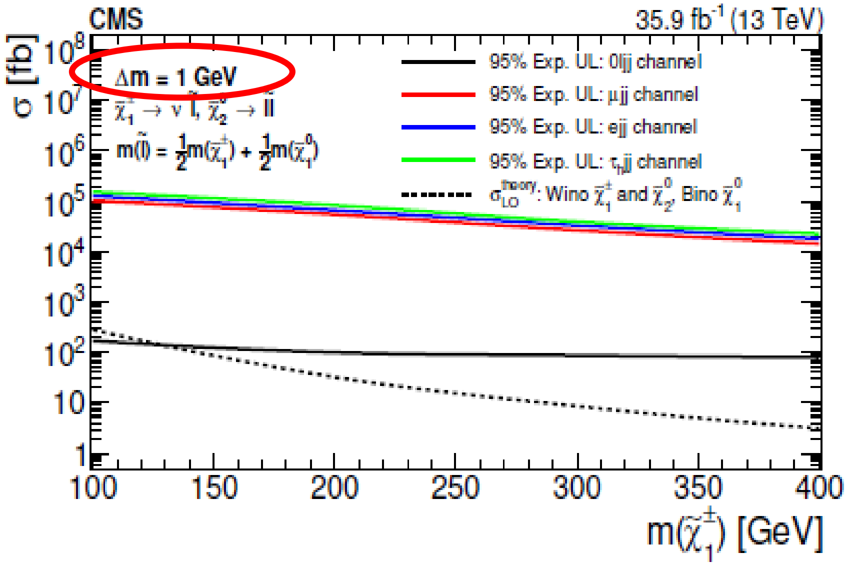
6. Results and Conclusions

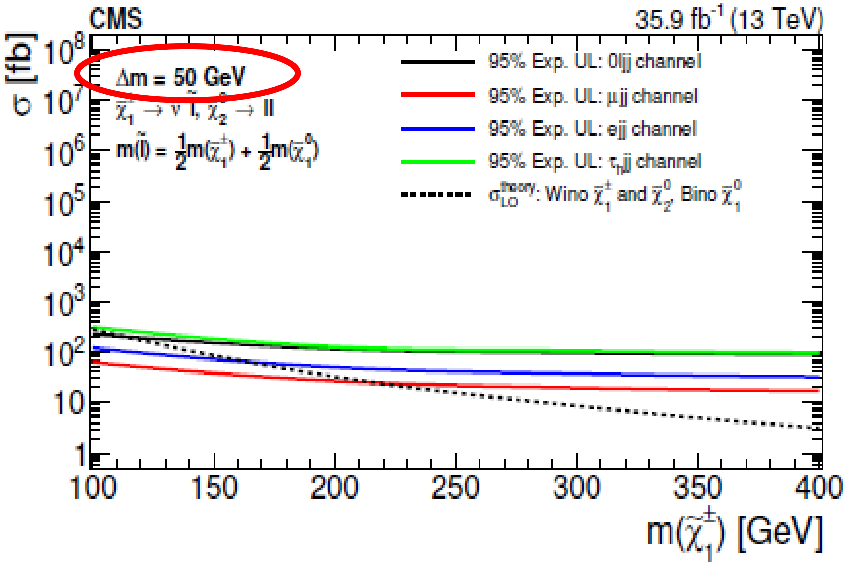
Data vs Estimated BG in SR



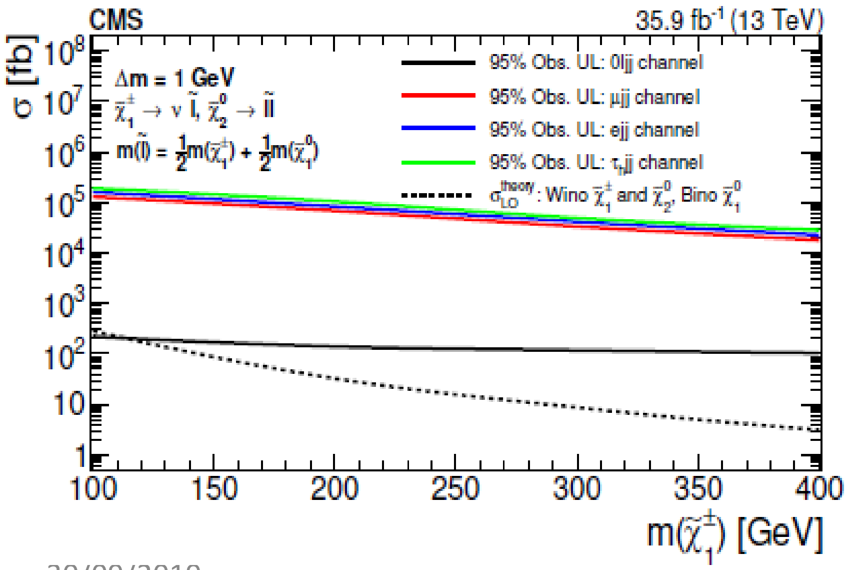
Very good agreement between data and background estimates.
No excess observed
→ Establish exclusion limits

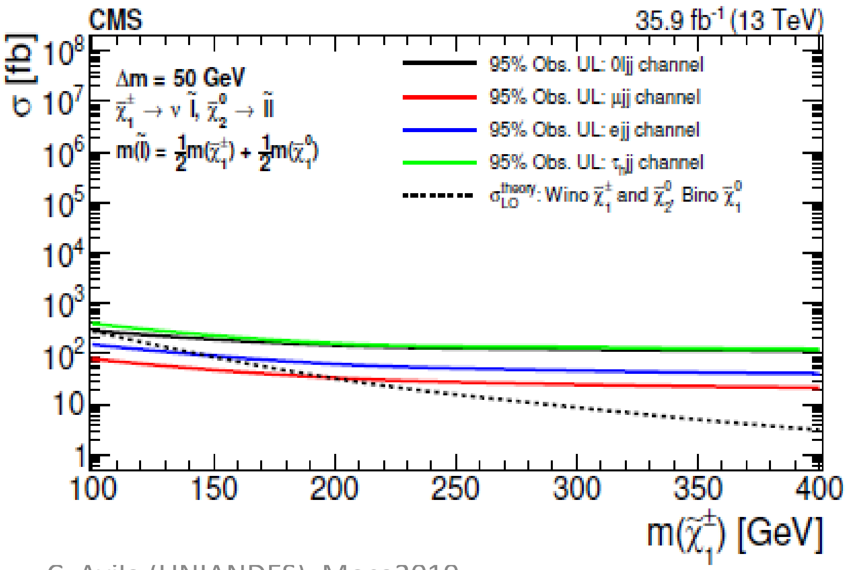
Exclusion Limits





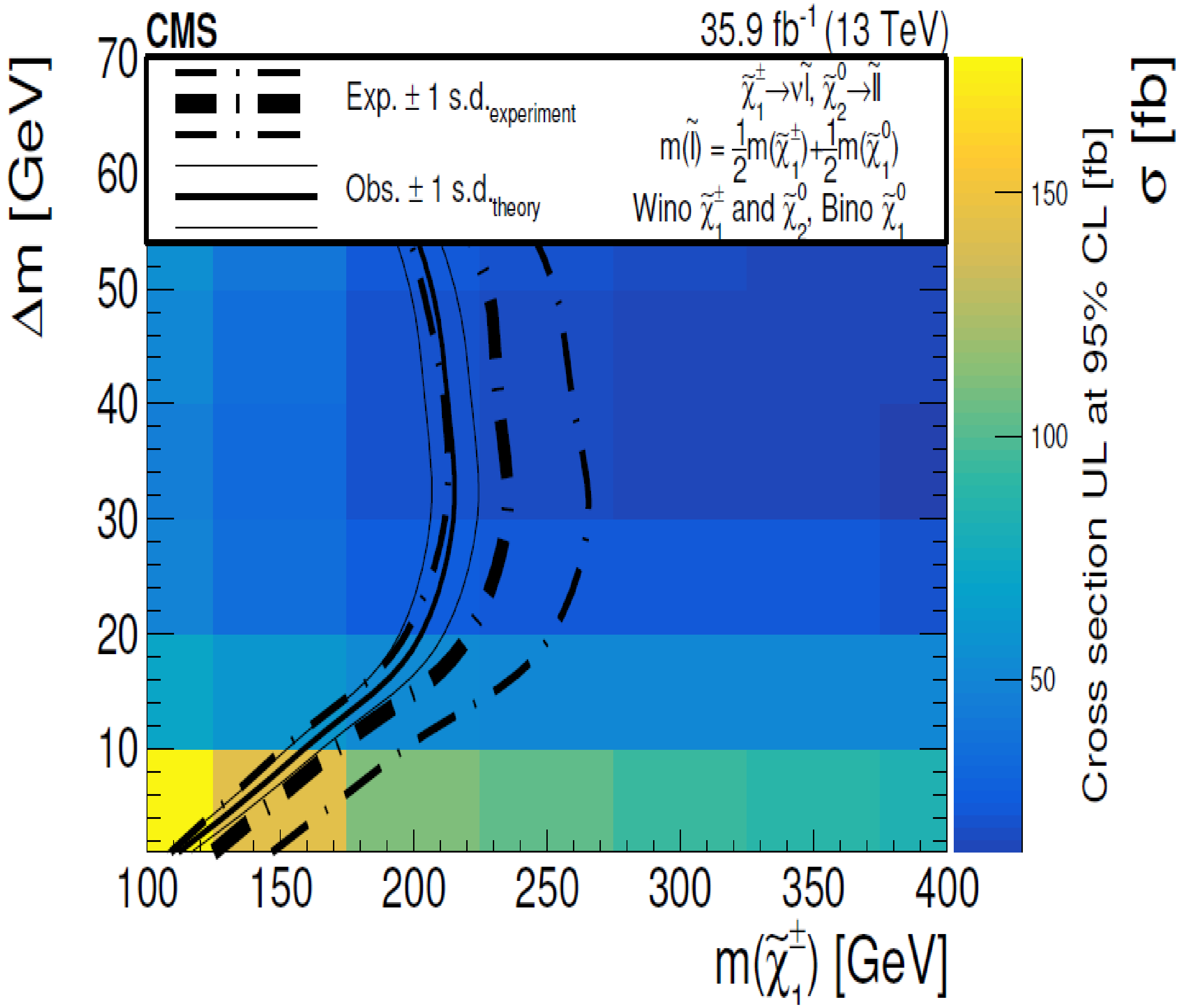
Expected limits

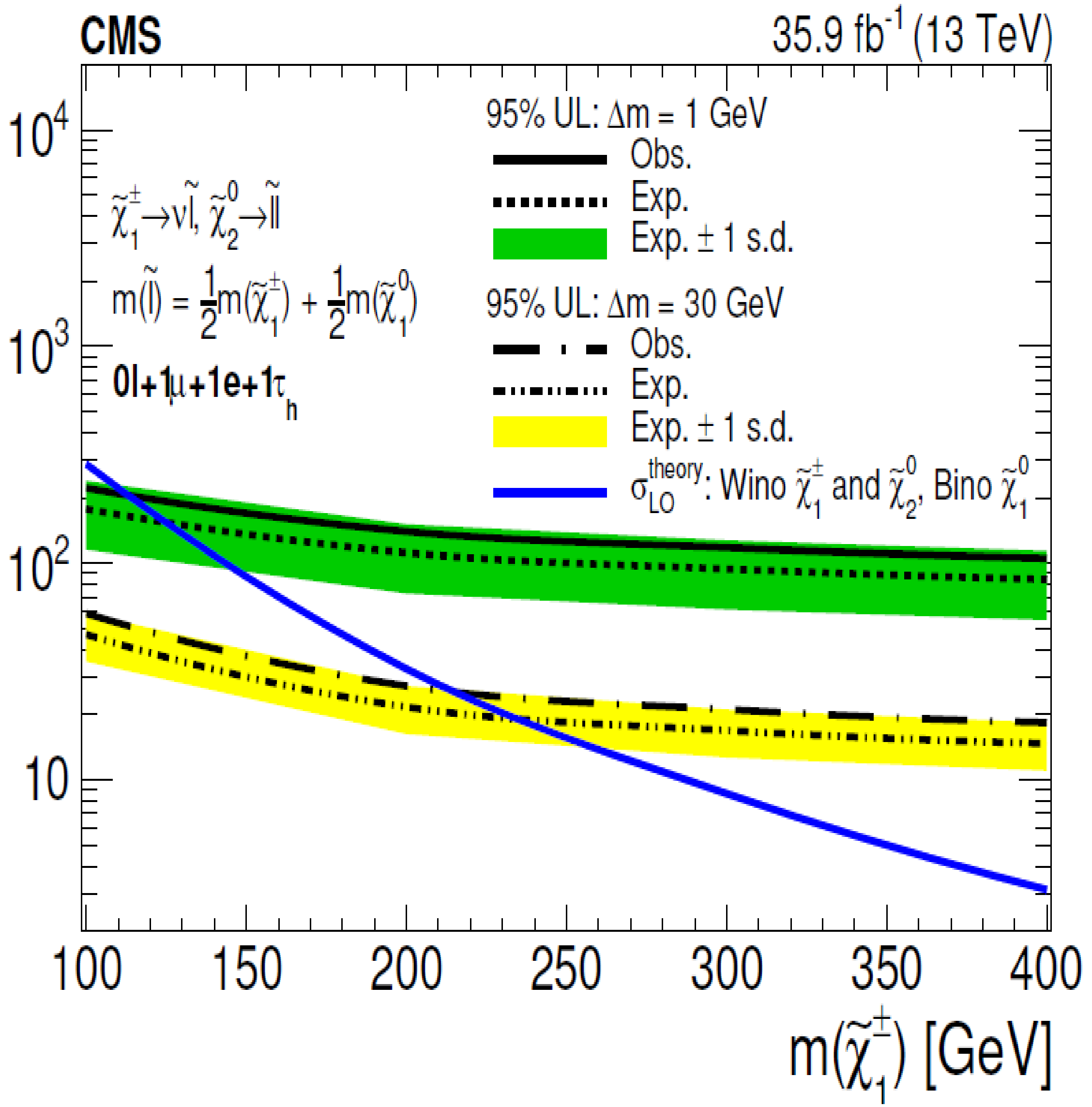




Observed limits

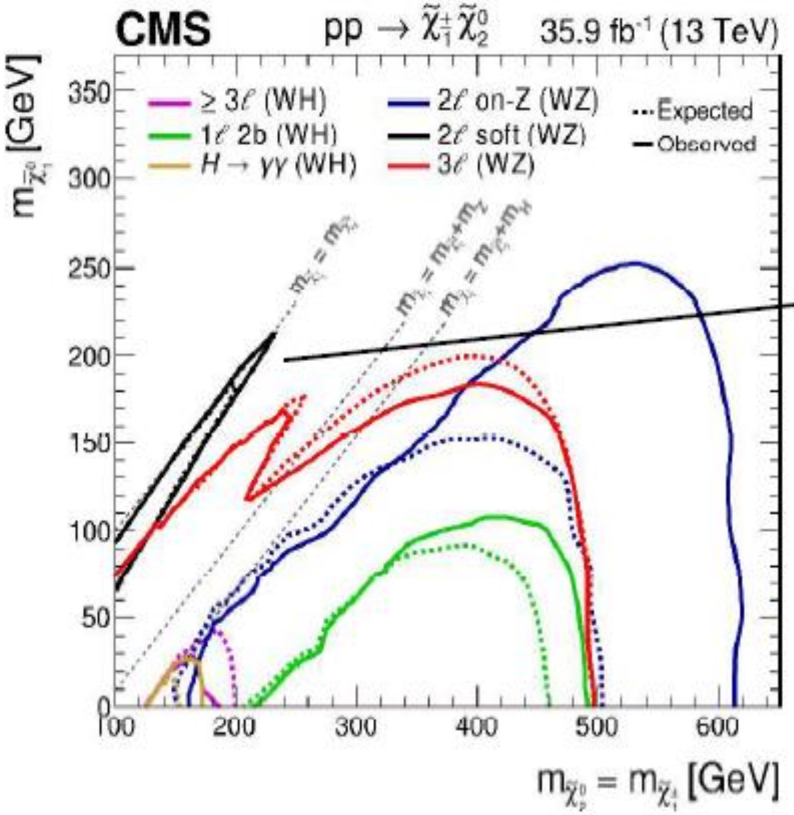
Combined Exclusion Limits

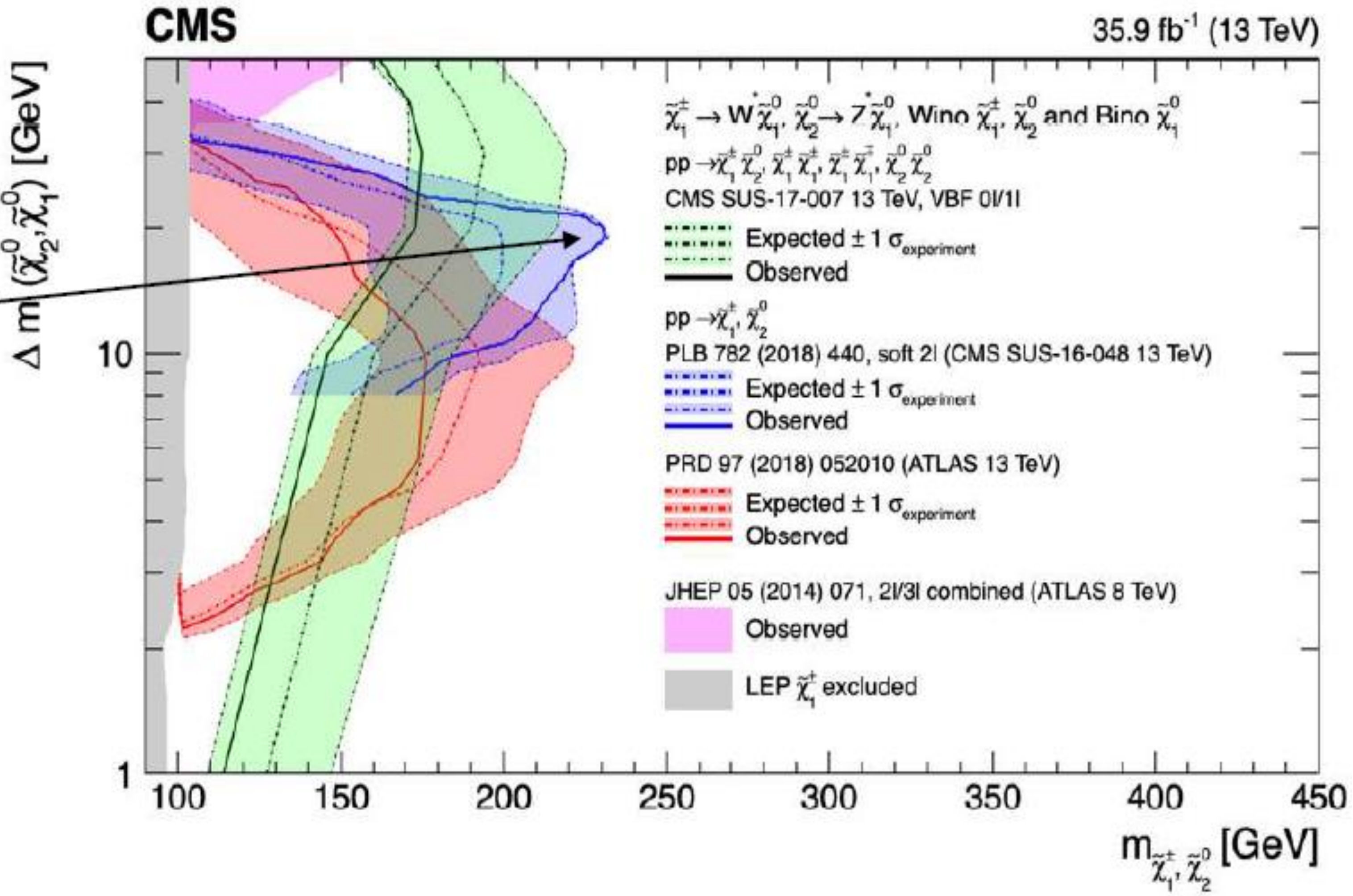




Combined Exclusion Limits

W*/Z* case





CONCLUSIONS

- We performed a data analysis with final states of zero or one lepton, MET and 2jets due to VBF, on a data sample of 35.86 fb^{-1} collected by the CMS experiment in the year 2016. No data excess was observed over the expected SM background yields.

- The non-data excess result was interpreted under the conserving R-parity MSSM assuming electroweakino production through slepton decays with mass gaps between the chargino/neutralino and the LSP < 50 GeV.

- We obtained exclusion limits that extend the sensitivity in the compressed spectrum scenario:
  - ✓ **The exclusion limit (95% CL) obtained for Δm = 30 GeV is 215 GeV.**
  - ✓ **For Δm = 1 GeV is 112 GeV.**

  These results exceed the limits obtained in the previous searches at 8 TeV (<100 GeV).
- For values of Δm above 10 GeV, the channel that has the highest sensitivity for the s-lepton democratic scenarios is the muon channel in comparison with the other leptonic channels.

- For the high compressed spectrum scenario with Δm = 1 GeV, the channel with the highest sensitivity is the invisible channel. This is because the final state lepton p_T is very small.

- Even though we interpreted our results under a specific SUSY scenario, other models can also be tested with our results.

- We have proven that the signature with VBF jets, MET, and one lepton is more sensitive than the two lepton final state because the leptons produced in the compressed scenario have soft p_T.

THANKS !