Colombian Dark Matter Workshop

Connecting dark matter, particle physics and cosmology

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June 27, 2017

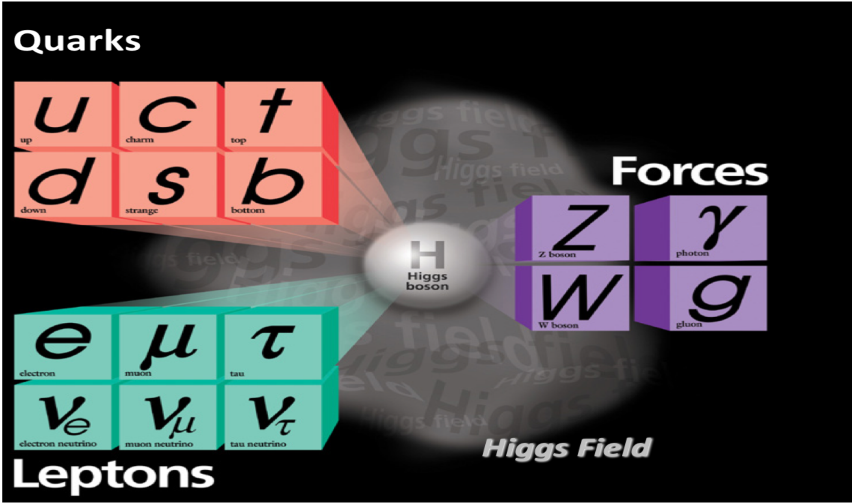
Outline

1. **Motivation**
2. **Electroweak SUSY Searches**
   - Probing SUSY with VBF (CMS-SUS-14005)
3. **Third Generation Heavy Neutrino and LQ Analysis** (CMS-EXO-16016)
4. **Feasibility Study**
   - Search for compressed staus using ISR jets
5. **Summary**

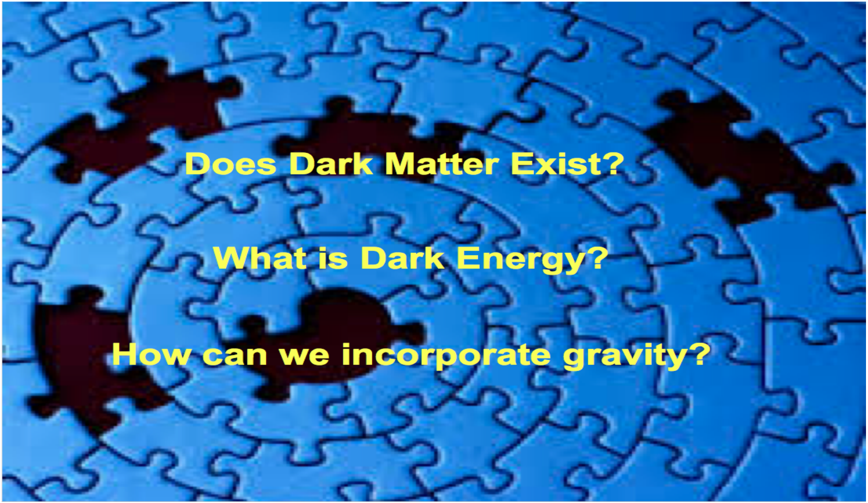
Motivation

- The aim of the talk is to show the first results from CMS on SUSY searches in the electroweak sector, using a VBF-like topology, and the first search for third generation heavy neutrinos and lepto-quarks.
- The VBF topology includes forward jets with a large $\Delta\eta$ gap in opposite hemispheres of the detector.
- VBF SUSY provides a new handle to search for new physics in compressed mass-spectra scenarios where the $\tilde{\tau}$ and the LSP ($\tilde{\chi}_0$) are nearly mass degenerate, which is important to prove models that include co-annihilation.
- Co-annihilation plays an important roll in several thermal dark matter (DM) scenarios in order to obtain the correct relic dark matter density predicted by cosmology.
- In addition, a phenomenological analysis for compressed staus using jets from initial state radiation is presented.

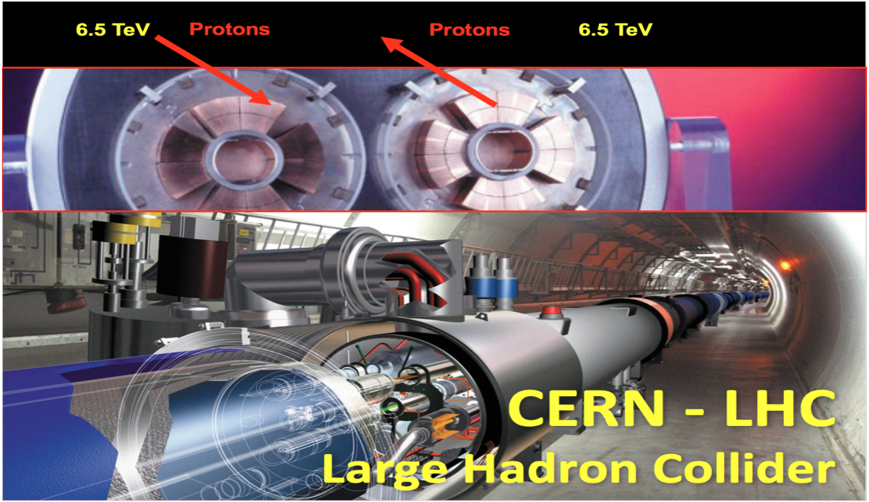
The Standard Model



But......


Does Dark Matter Exist?
What is Dark Energy?
How can we incorporate gravity?

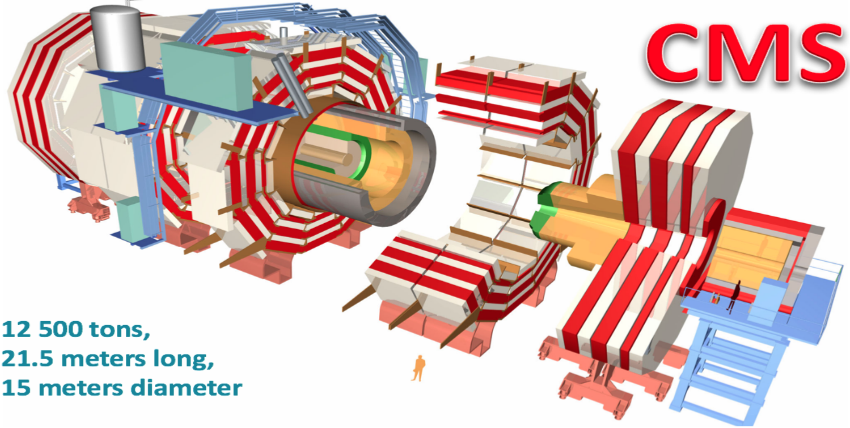
The Large Hadron Collider



CMS Detector

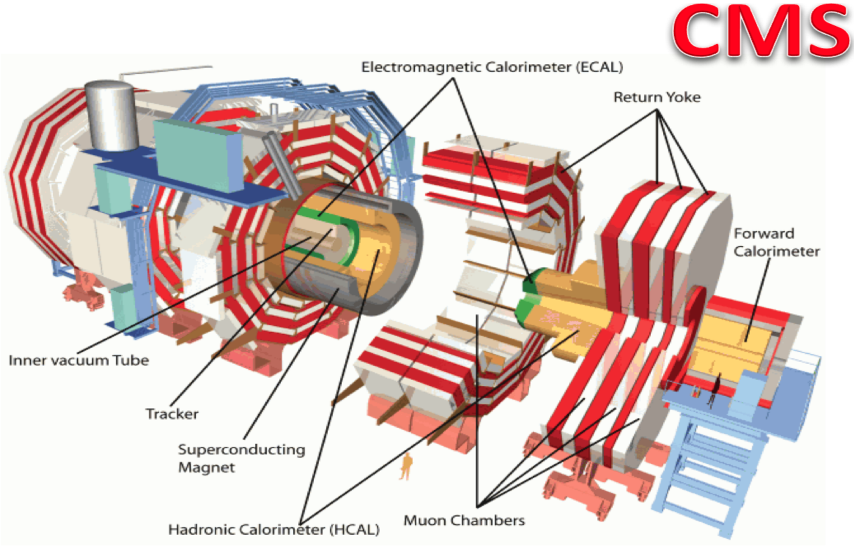
15 millions of detection units, each responding 40 million times per second.

Each second it stores the equivalent to 10 000 British encyclopedias

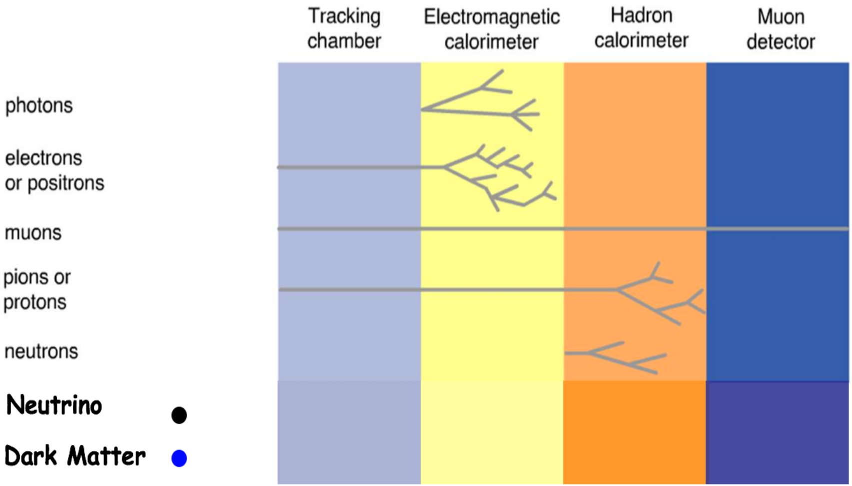


12 500 tons,
21.5 meters long,
15 meters diameter

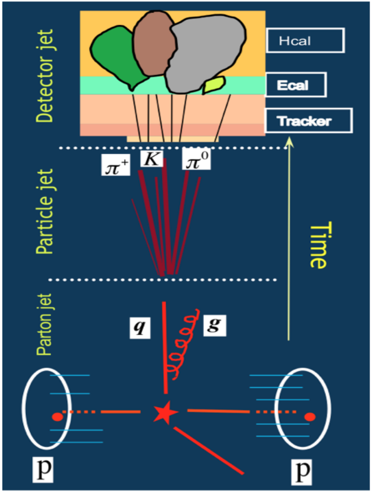
CMS Detector

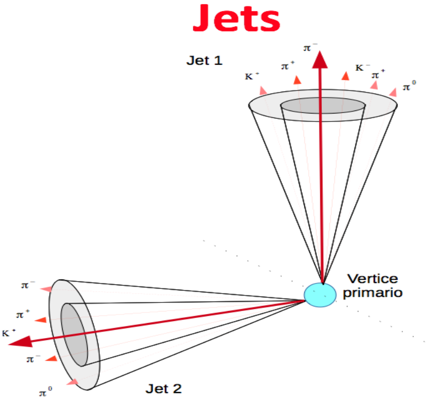


What can we measure?



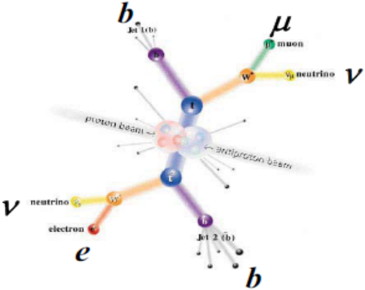
What can we measure?

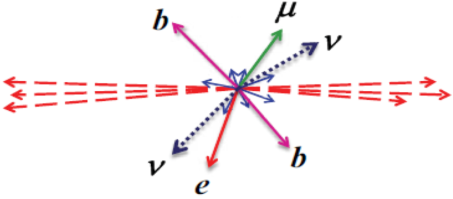




Jet reconstruction

What can we measure?

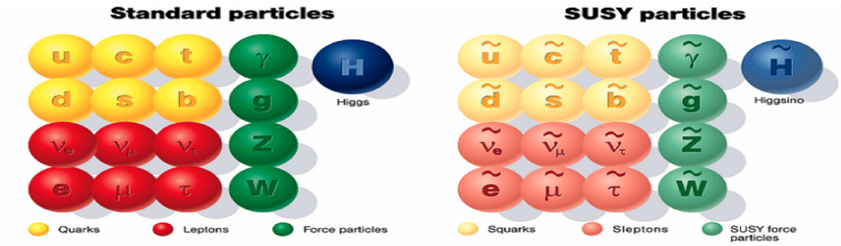


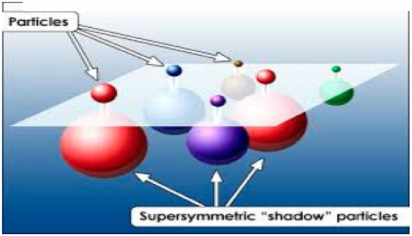


$$\sum_{\nu} \vec{p} + \sum_{visible} \vec{p} = \vec{0} \quad \Rightarrow \quad \sum_{\nu} \vec{p} \approx -\sum_{detected} \vec{p} \equiv \underbrace{\vec{\not{p}}}_{p\ \mathrm{slash}}$$

Experimentally, we measure a momentum imbalance in transverse plane and call it "missing transverse energy" (E_T^{miss} or $\not{E}_T$).

Supersymmetry (SUSY)





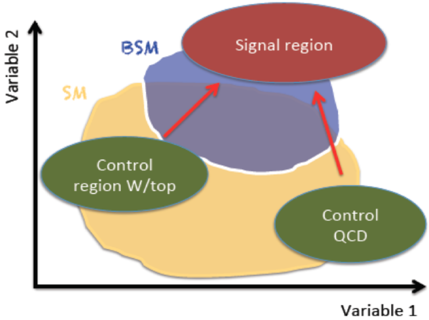
Supersymmetry (SUSY)

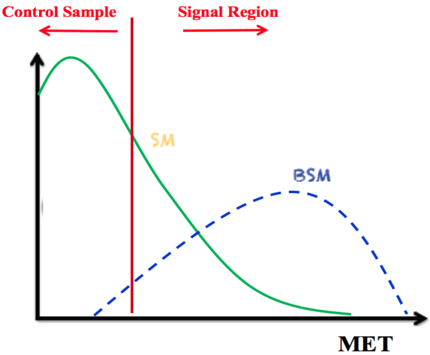
Supersymmetry (SUSY)

How do we search for SUSY ?

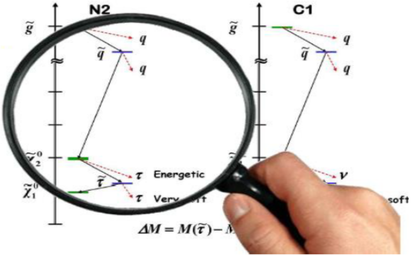
A brief primer ...

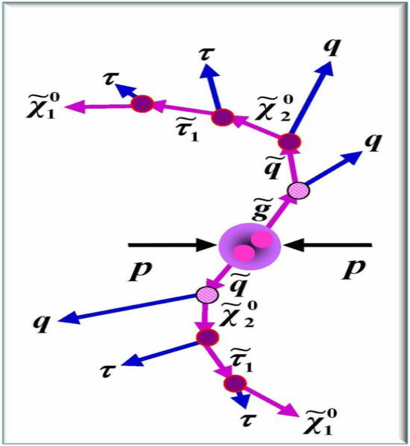
CR → SR transfer factors taken from MC simulation (many systematic effects cancel).





Classic SUSY Searches

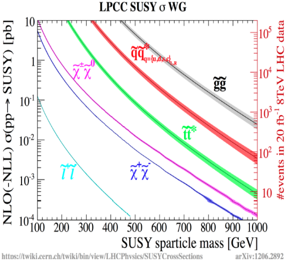




- Initial SUSY searches focused on the color sector.
- These type of signatures have final states with: $E_T^{miss} + jets + leptons(photons)$

Electroweak SUSY Searches

- Searches in the color sector have not yield positive signs of SUSY until now.
- SUSY searches in the electroweak (EWK) sector open a different avenue to find new physics:
  - ✓ Smaller predicted cross sections but lower levels of hadronic activity
  - ✓ Complements the color searches



- **The discovery of the Higgs opens up new SUSY searches:**
  - ✓ Lightest neutral CP–even Higgs (h) expected to be SM–like, if others are heavy.
  - ✓ $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^{0}$ decay to h+LSP (RPC models) or $V_{(W/Z)} + \tilde{\chi}_1^0$ ($\tilde{\chi}_1^0$ LSP)
  - ✓ Would provide evidence for SUSY solution to hierarchy problem.

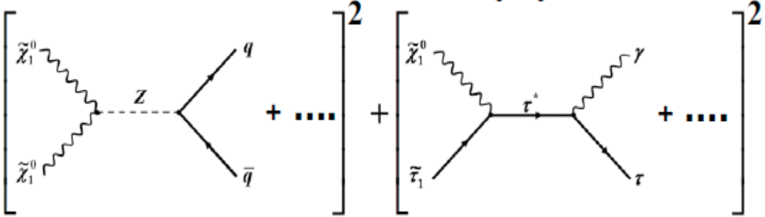
Dark Matter & Cosmology

"Number" density (n) → Ω

$$\frac{dn}{dt} = -3Hn - \langle \sigma \cdot v \rangle \left(n^2 - n_{eq}^2 \right)$$

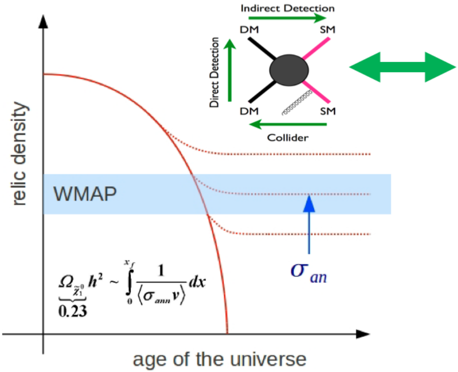
Cross section (σ)

$\sigma_{ann} \propto$



Dark Matter & Cosmology

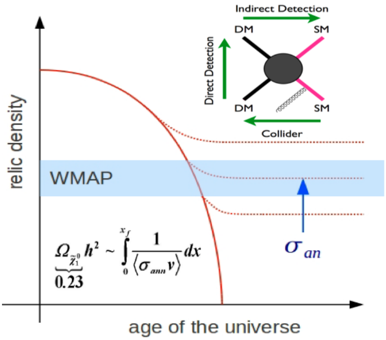
It is important to directly probe the electroweak SUSY sector



It is important to "directly" probe the EWK SUSY sector in order to determine their DM connection

Dark Matter & Cosmology

It is important to directly probe the electroweak SUSY sector



- LSP has large Wino / Higgsino component
  - LSP annihilation cross section is too large to fit observed DM relic density
- LSP is mostly Bino
  - LSP annihilation cross section is too small to fit observed DM relic density

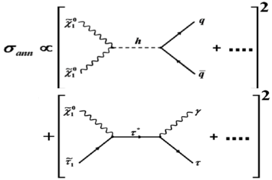
Some problems can be solved if the DM is non-thermal. For thermal DM, some problems can be solved by adding coannhilation, resonance effects, etc.

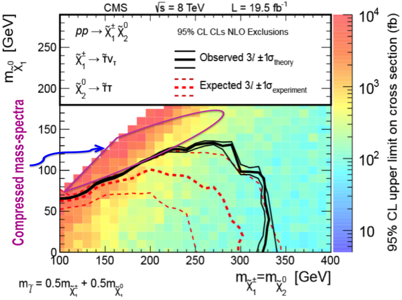
Determining the composition of the LSP for a given mass is *very important* to understand early universe cosmology

Third Generation EWK-SUSY Searches

(CMS-SUS-13006)

- The experimental sensitivity in final states containing third generation particles is limited, especially in compressed spectra scenarios.

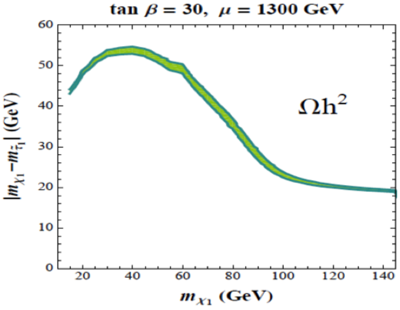




$$\Omega_{\tilde{\chi}_1^0} h^2 \sim \int_0^\infty \frac{1}{<\sigma_{an}\nu>} dx$$

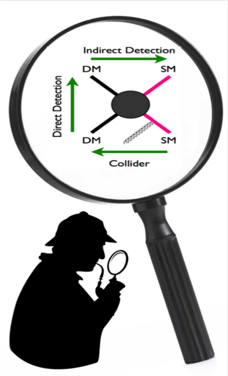
Lian Tao and Marcela Carena

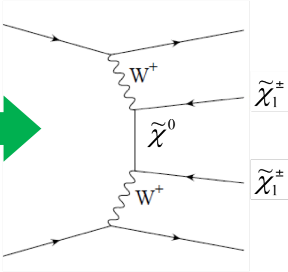
http://arxiv.org/pdf/1205.5842v1.pdf

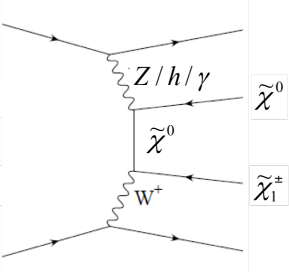


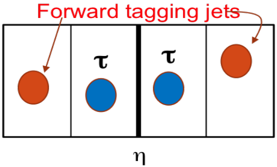
Probing SUSY with VBF

(CMS-SUS-14005)









ϕ **MET + jj + leptons**

- Eight final states: $\mu\mu jj$, $e\mu jj$, $\mu\tau_h jj$, $\tau_h\tau_h jj$ (OS & LS).
- For the $\mu\mu jj$, $e\mu jj$, $\mu\tau_h jj$ channels we use an inclusive single muon trigger, while for the $\tau_h\tau_h jj$ channels we use a di-tau trigger.

Event Selection Criteria

(CMS-SUS-14005)

Summary of the event selection criteria for the different final states considered in the analysis. Note the selections for the $\mu\mu jj$ and $e\mu jj$ channels are presented in one column ($\ell_{(e/\mu)}\mu jj$) as they are very similar.

Cut	$\ell_{(e/\mu)}\mu jj$	$\mu\tau_h jj$	$\tau_h\tau_h jj$
Central Selections			
Trigger	Iso μ $p_T > 24$ GeV	Iso μ $p_T > 24$ GeV	Double τ $p_T > 45$ GeV
$p_T(\mu)[GeV]$	≥ 30	≥ 30	
$p_T(e)[GeV]$	≥ 15 only $e\mu jj$		
$p_T(\tau_h)[GeV]$		≥ 20	≥ 45
$\lvert\eta(\ell_{\mu,e,\tau_h})\rvert$	< 2.1	< 2.1	< 2.1
N_{b-tag} jets (CSVL)	0	0	0
E_T^{miss} [GeV]	> 75	> 75	> 30
$p_T(jets)[GeV]$	$\geq 30/50$	≥ 50	≥ 30
$\lvert\eta(jets)\rvert$	≤ 5	≤ 5	≤ 5
$\Delta R(\ell^1_{e,\mu,\tau_h}, \ell^2_{e,\mu,\tau_h})$	≥ 0.3	≥ 0.3	≥ 0.3
$\Delta R(jet, \ell_{e,\mu,\tau_h})$	≥ 0.3	≥ 0.3	≥ 0.3
VBF Selections			
$\Delta\eta(jet_1, jet_2)$	> 4.2	> 4.2	> 4.2
$\eta^{jet1} \cdot \eta^{jet2}$	< 0	< 0	< 0
$mj, j[GeV]$	≥ 250	≥ 250	≥ 250

- We perform a shape-based analysis, using the m_{jj} distribution as a discrimination variable.

Background Estimation Strategy

(CMS-SUS-14005)

- We use a common BG estimation methodology across channels:
  1. We obtain SFs in high purity CRs to correct for any mismodeling in simulation, after applying central selections (No VBF selections).
  2. When possible, we measure the VBF efficiency from data.
  3. The contribution of a given BG in the SR, estimated with the method described above, is performed using the following formula:

$$N_{\mathrm{BG}}^{\mathrm{Data}} = N_{\mathrm{BG}}^{\mathrm{MC}}(\mathrm{central}) \cdot SF_{\mathrm{central}}^{\mathrm{CR1}} \cdot \epsilon_{\mathrm{VBF}}^{\mathrm{CR2}}(m_{jj})$$

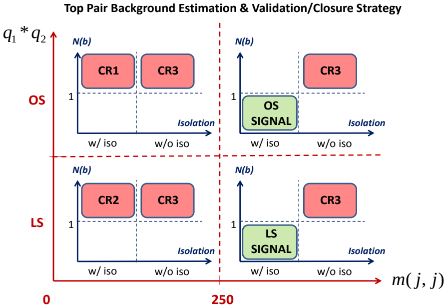
  4. A closure test is performed in MC. The difference between the nominal and predicted yields in the closure test, is taken as a systematic error.
  5. When possible we also perform closure tests with data.
  6. We check that the signal contamination in the CRs is negligible.
- If the BGs are small, when possible we first show that the VBF shapes are well modelled in simulation and then simply correct the MC prediction with a SF:

$$N_{\mathrm{BG}}^{\mathrm{Data}} = N_{\mathrm{BG}}^{\mathrm{MC}}(\mathrm{SR}) \cdot SF_{\mathrm{central}}^{\mathrm{CR1}}$$

$t\bar{t}$ Background Estimation For OS/LS $\mu\mu$

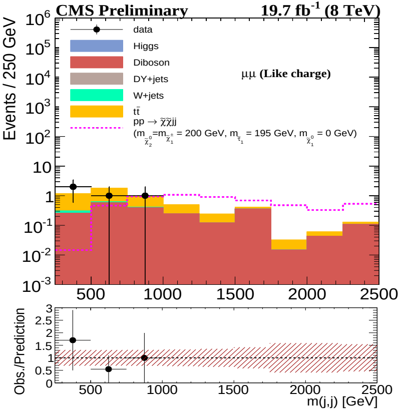
(CMS-SUS-14005)

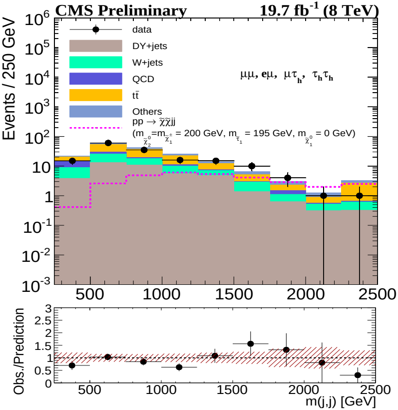
- $t\bar{t}$ is the largest BG source for both $\mu\mu$ channels (OS & LS)
- The estimation of this BG is done in a semi-data-driven way.
- Three CRs are used:
  1. CR1: $SF^{\mathrm{CR1}}_{\mathrm{central}}$ for central selections for OS events.
  2. CR2: $SF^{\mathrm{CR2}}_{\mathrm{central}}$ for central selections for LS events.
  3. CR3: measure VBF efficiency and dijet mass shape from data.



m_{jj} Distributions

(CMS-SUS-14005)



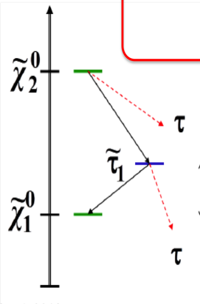


- The band includes the total systematic and statistical uncertainties. Correlations across BGs and across channels have been considered.
- The largest source of systematic uncertainty comes from closure tests in simulation for the BG estimates.

SUSY Scenario 1 – Compressed Mass Spectra & Large Mass Gaps

Slepton mass definition

$$\boxed{m(\tilde{\chi}_1^{\pm}) - m(\tilde{l}) = 5\ GeV}$$



Large mass gap

$$\boxed{m(\tilde{\chi}_1^{0}) = 0}$$

$$\boxed{m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^{0}) = 50\ GeV}$$

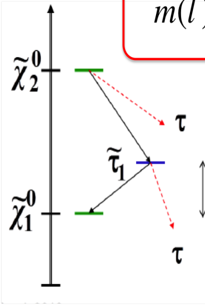
Compressed mass spectra

SUSY Scenario 2 – Compressed Mass Spectra & Large Mass Gaps

(CMS-SUS-14005)

Slepton mass definition

$$m(\tilde{l}) = \frac{1}{2}m(\tilde{\chi}_1^0) + \frac{1}{2}m(\tilde{\chi}_1^\pm)$$



Large mass gap

$$m(\tilde{\chi}_1^0) = 0$$

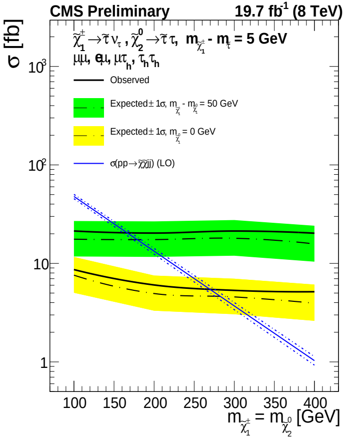
$$m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 50\ GeV$$

Compressed mass spectra

Results - Combined Limits: Scenario 1

(CMS-SUS-14005)

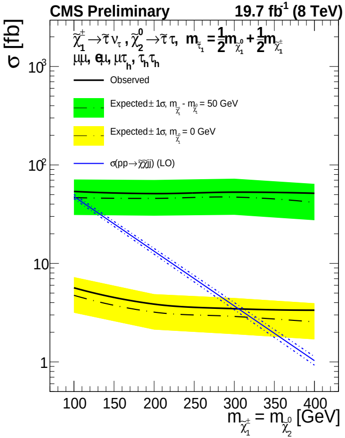
- No excess above the SM background is observed.
- A combined observed upper bound limit of 280 GeV and an expected limit on 295 GeV is set, for the large mass gap scenario where the mass difference between the chargino and the slepton is 5 GeV and the LSP mass is 0 GeV.
- For the compressed mass spectra scenario, where the mass difference between the chargino and the LSP is 50 GeV, we set a combined observed upper bound limit of 170 GeV and an expected limit of 180 GeV.



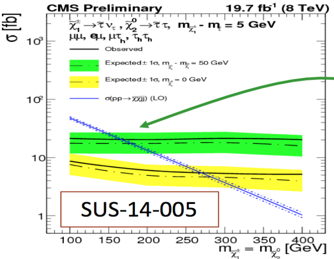
Results - Combined Limits: Scenario 2

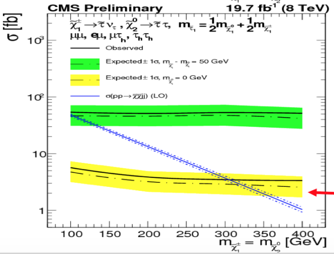
(CMS-SUS-14005)

- No excess above the SM background is observed.
- A combined observed upper bound limit of $\approx$ 300 GeV and an expected limit on $\approx$ 310 GeV is set, for the compressed mass spectra scenario.
- We do not have sensitivity to exclude any masses in the large mass gap scenario, for this slepton mass definition.



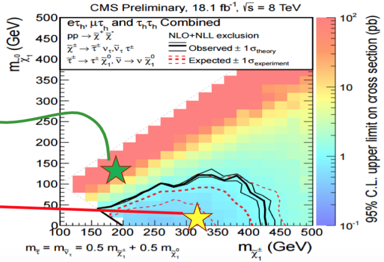
Results





VBF SUSY search nicely complements other searches for EWK SUSY sector

Sensitivity to compressed regions difficult to probe with other searches



VBF Dark Matter

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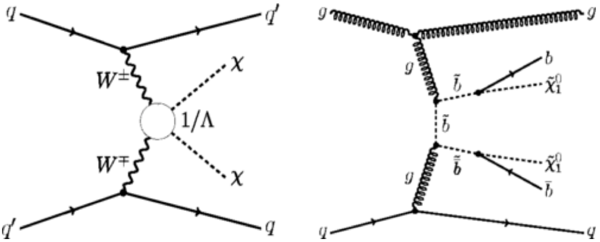
Search for Dark Matter and Supersymmetry with a Compressed Mass Spectrum in the Vector Boson Fusion Topology in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV



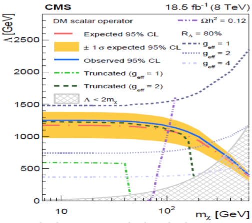
Results

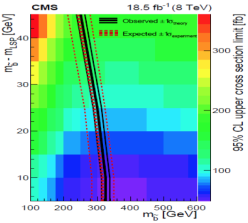
Trigger: MET65+VBFDiJet35

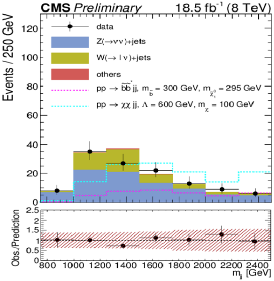
Selection: Two jets (p_T>50 GeV with $\eta_1\eta_2$<0; large rapidity gap $|\eta_1$-$\eta_2|$>4.2 and invariant mass m_{12}>750 GeV; no b-tag); MET>250 GeV; veto further jets (p_T>30 GeV)

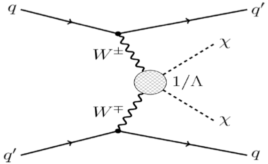
Dominant bgs: $(Z \to \nu\nu) + \text{jets}$ & $(W^{\pm} \to l^{\pm}\nu) + \text{jets}$ estimated from data

Interpretation in models with DM production via contact interaction and $\tilde{b}\tilde{b}\tilde{\chi}^0_1\tilde{\chi}^0_1$ production with $m_{\tilde{b}} - m_{\tilde{\chi}^0_1} = 5$ GeV





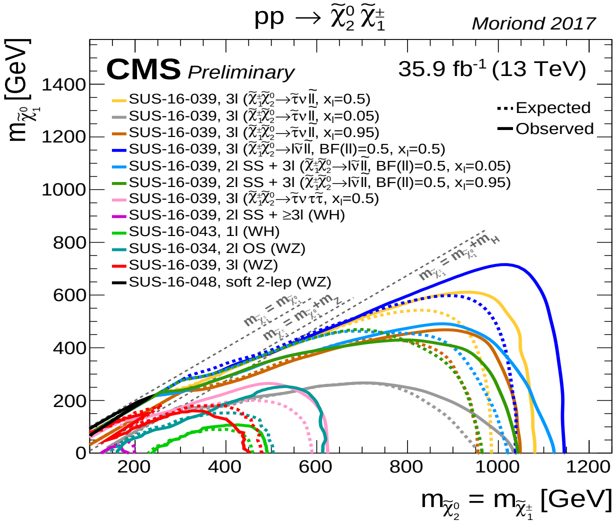




First search for direct DM production via VBF!

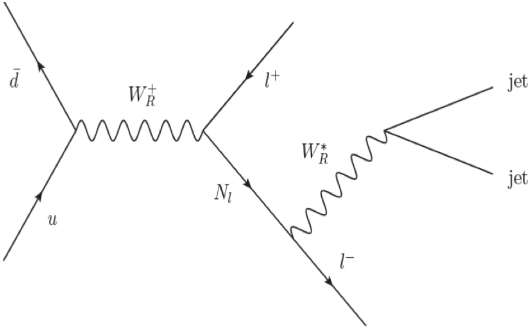
Most stringent limits on compressed colored sector with 8 TeV data

Latest Limits in the Electroweak SUSY Sector



Aim - Third Generation Heavy Neutrinos (N_τ)

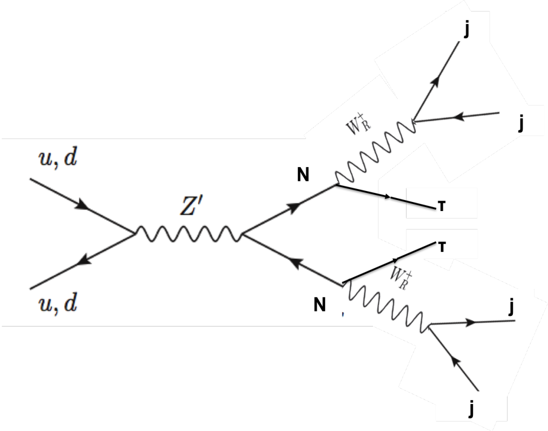
- Observation of neutrino oscillations imply that neutrinos have mass: one way to impart mass is by introducing massive right-handed neutrinos (through the see-saw mechanism)



We consider DY-like production of resonant W_R in the LRSM scenario

Aim - $Z^{'} \to N_\tau N_\tau$

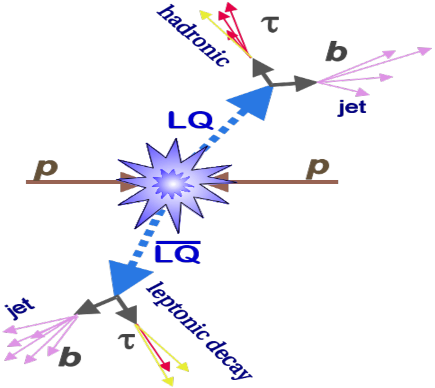
- We also target the production of resonant Z' in the LRSM scenario: $q\bar{q} \to Z^{'} \to N_\tau N_\tau \to \tau\tau jjjj$



- The difference in topology is two different jets. Nevertheless, since we fit to S_T (LQ search) this scenario is covered.

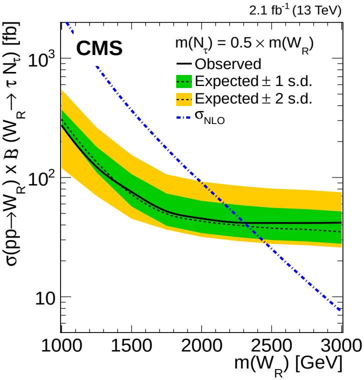
Aim - Third Generation Leptoquarks

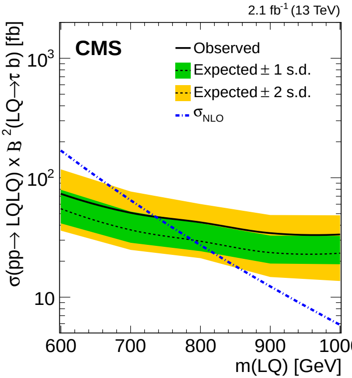
- We also search for third-generation leptoquarks.



- In this scenario, we have two b-jets, which is the reason why we do not veto b-jets.

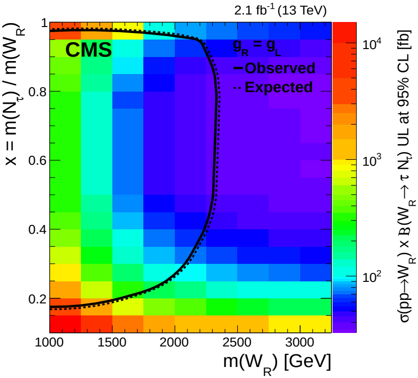
Results





- We assumed that the mass of the N_τ is half of the W_R mass
- Also N_e and N_μ were considered to be too heavy to play a role.

Results



- We performed a 2D scan to show the sensitivity of the analysis, for different values of the $m(N_\tau)/m(W_R)$ ratio, as function of the W_R mass.

Phenomenological Studies

Journal of High Energy Physics
December 2016, 2016:46

Published in 2016

Distinguishing standard model extensions using monotop chirality at the LHC

PHYSICAL REVIEW D
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Published in 2016

Probing the stau-neutralino coannihilation region at the LHC with a soft tau lepton and a jet from initial state radiation

ELSEVIER

Physics Letters B

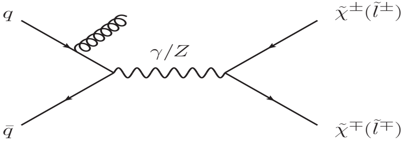
Volume 767, 10 April 2017, Pages 126–132

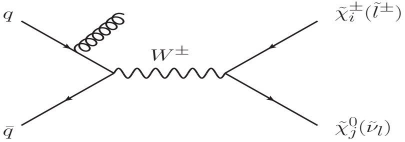
Published in 2017

Searching for new heavy neutral gauge bosons using vector boson fusion processes at the LHC

Electroweak SUSY production of τ with a ISR jet

Production of $\widetilde{\chi}_i^{\pm}$ and $\widetilde{\chi}_i{}^0$ can be obtained through γ (Z) and/or $W^{\pm}$ decays plus an ISR jet.





Direct decay chain $\widetilde{\tau}$

- $\widetilde{\tau}^{\pm}\widetilde{\tau}^{\mp}j \to \tau^{\pm}\tau^{\mp}\widetilde{\chi_1}^0\widetilde{\chi_1}^0 j$

Indirect decay chains $\widetilde{\tau}$

- $\widetilde{\chi_1}^+\widetilde{\chi_1}^- j \to \widetilde{\tau}^+\widetilde{\tau}^-\nu\nu j \to \tau^+\tau^-\nu\nu\widetilde{\chi_1}^0\widetilde{\chi_1}^0 j$
- $\widetilde{\chi_1}^{\pm}\widetilde{\chi_2}^0 j \to \widetilde{\tau}^{\pm}\nu\widetilde{\tau}^{\pm}\widetilde{\tau}^{\mp} j \to \tau^{\pm}\tau^{\pm}\tau^{\mp}\nu\widetilde{\chi_1}^0\widetilde{\chi_1}^0 j$
- $\widetilde{\chi_2}^0\widetilde{\chi_2}^0 j \to \widetilde{\tau}^{\pm}\tau^{\mp}\widetilde{\tau}^{\pm}\tau^{\mp} j \to \tau^{\pm}\tau^{\mp}\tau^{\pm}\tau^{\mp}\widetilde{\chi_1}^0\widetilde{\chi_1}^0 j$

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Probing the stau-neutralino coannihilation region at the LHC with a soft tau lepton and a jet from initial state radiation

Andrés Flórez, Luis Bravo, Alfredo Gurrola, Carlos Ávila, Manuel Segura, Paul Sheldon, and Will Johns

Phys. Rev. D **94**, 073007 – Published 25 October 2016

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ABSTRACT

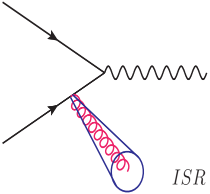
We present a feasibility study, to search for dark matter at the LHC, in events with one soft hadronically decaying tau lepton and missing transverse energy recoiling against a hard p_T jet from initial state radiation. This methodology allows the search for supersymmetry in compressed mass spectra regions, where the mass difference between the lightest neutralino, $\tilde{\chi}_1^0$, and the stau (the tau superpartner), $\tilde{\tau}$, is small. Several theoretical models predict a direct connection between thermal bino dark matter and staus within this scenario. We show that compressed regions, not excluded by ATLAS nor CMS experiments, are opened up with the increase in experimental sensitivity reached with the proposed methodology. The requirement of a hard jet from initial state radiation combined with a soft tau lepton is effective in reducing Standard Model backgrounds, providing expected significances greater than 3σ for $\tilde{\chi}_1^\pm$ masses up to 300 GeV and $\tilde{\tau} - \tilde{\chi}_1^0$ mass gaps below 25 GeV with only $30\,\mathrm{fb}^{-1}$ of 13 TeV data from the LHC.

Feasibility study

Event Selection Criteria - Pheno

Criteria	Value
$N(j)$	≥ 1
$p_T(j)$	> 100 GeV
$\lvert\eta(j)\rvert$	≤ 2.5
$N(\tau_h)$	1
$N(e^-/\mu^-)$	0
$N(b-jet)$	0
$p_T(\tau_h)$	> 15 & < 35 GeV
$\lvert\eta(\tau_h)\rvert$	≤ 2.3
$\Delta R(\tau_h, j)$	> 0.4
E_T^{miss}	> 230 GeV

ISR emission during any hard scattering process



Without ISR

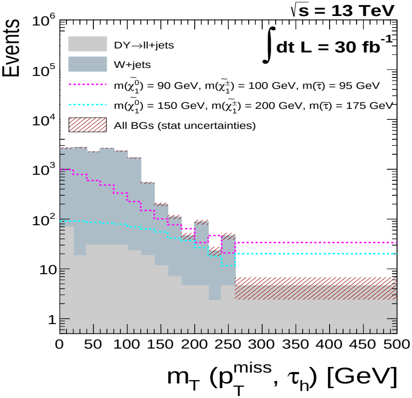
$$
\begin{aligned}
p_T^i &= p_T^f \\
0 &= p_T(\tau^+) + p_T(\tau^-) + p_T^1(\widetilde{\chi 1}^0) + p_T^2(\widetilde{\chi 1}^0) \\
p_T^1(\widetilde{\chi 1}^0) &= -p_T^2(\widetilde{\chi 1}^0)
\end{aligned}
\tag{1}
$$

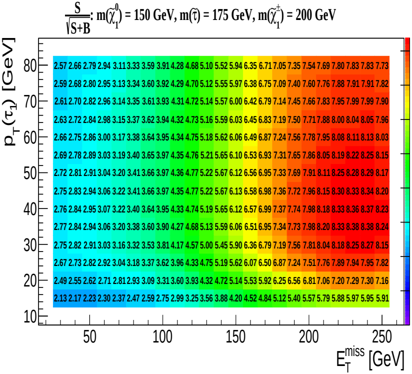
With ISR

$$
p_T^1(\widetilde{\chi 1}^0) = -p_T^2(\widetilde{\chi 1}^0) + p_T^{ISR}(j), \tag{2}
$$

where we have taken in to consideration the fact that the τ's in compressed-mass spectra scenarios have low momentum with respect to $\widetilde{\chi}_0^1$'s

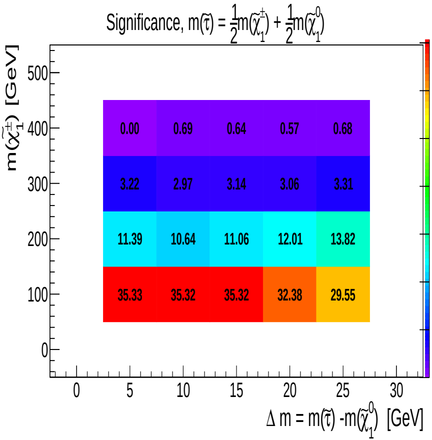
Phenomenological study (ISR jet technique + soft τ lepton)

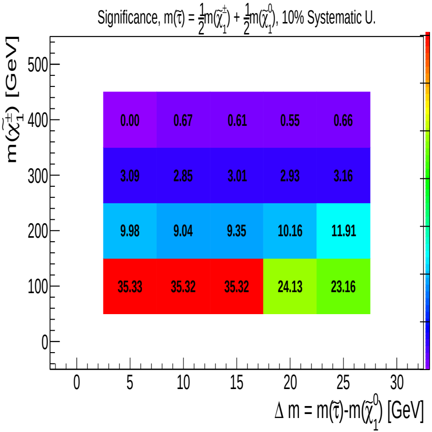




Phenomenological study. Transverse mass for two mass compressed signal points (left), and 2D signal significance scan of E_T^{miss} vs $p_T(\tau)$ lepton (right)

Signal significance (Results)





Signal significance, using a shape based statistical analysis of the m_T distribution. No systematic effects (left) and with systematic effect (right)

Summary

- The first VBF SUSY and third generation heavy neutrinos searches from CMS have been presented. These searches have a strong connection with dark matter.
- The stau plus ISR search is currently being performed by our group at CMS.
- The VBF and ISR searches are a promising avenue to target compressed-mass-spectra scenarios with taus.
- Our group has been performing phenomenological studies, proposing new ideas to be explored at the LHC. We are very interested to collaborate so please do not hesitate to contact us (ca.florez@uniandes.edu.co)

BACKUP

Final yields: OS Channels

(CMS-SUS-14005)

Number of observed events in data and estimated background rates for the OS search channels. The uncertainties are based on the number of observed events in the CRs as well as the statistics in simulation.

Process	$\mu^{\pm}\mu^{\mp}jj$	$e^{\pm}\mu^{\mp}jj$	$\mu^{\pm}\tau_h^{\mp}jj$	$\tau_h^{\pm}\tau_h^{\mp}jj$
DY + jets	4.3 ± 1.7	$3.7\pm^{2.1}_{1.9}$	19.9 ± 2.9	12.3 ± 4.4
W + jets	< 0.01	$4.2\pm^{3.3}_{2.5}$	17.3 ± 3.0	2.0 ± 1.7
VV	2.8 ± 0.5	3.1 ± 0.7	2.9 ± 0.5	0.5 ± 0.2
$t\bar{t}$	24.0 ± 1.7	$19.0\pm^{2.3}_{2.4}$	11.7 ± 2.8	–
QCD	–	–	–	6.3 ± 1.8
Higgs	1.0 ± 0.1	1.1 ± 0.5	–	1.1 ± 0.1
VBF Z	–	–	–	0.7 ± 0.2
Total	32.2 ± 2.4	$31.1\pm^{4.6}_{4.1}$	51.8 ± 5.1	22.9 ± 5.1
Observed	31	22	41	31

Final yields: LS Channels

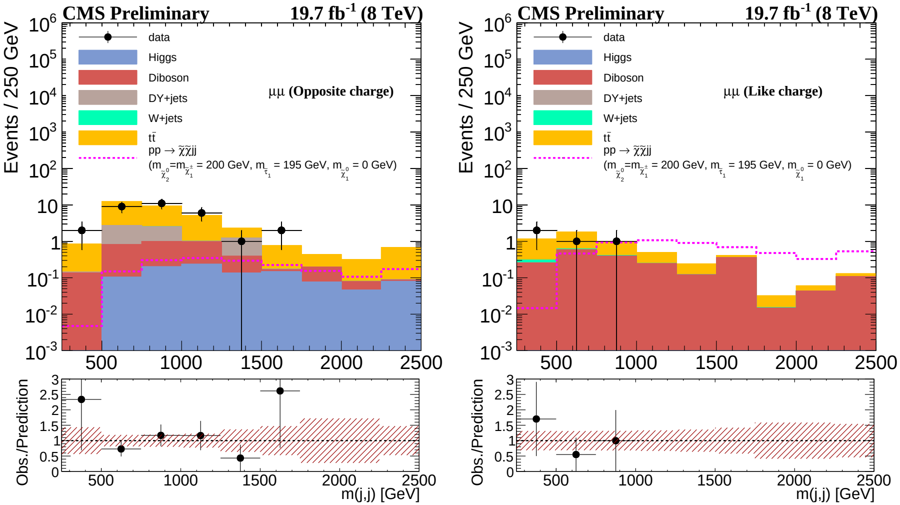
(CMS-SUS-14005)

Number of observed events in data and estimated background rates for the LS channels. The uncertainties are based on the number of observed events in the CRs as well as the statistics in simulation.

Process	$\mu^{\pm}\mu^{\pm}jj$	$e^{\pm}\mu^{\pm}jj$	$\mu^{\pm}\tau_h^{\pm}jj$	$\tau_h^{\pm}\tau_h^{\pm}jj$
DY + jets	< 0.01	$0\pm^{1.7}_{0}$	0.5 ± 0.2	< 0.01
W + jets	$0.1 \pm 8.2 \times 10^{-4}$	$0\pm^{3.0}_{0}$	9.3 ± 2.3	0.5 ± 0.1
VV	2.1 ± 0.3	$1.9\pm^{0.4}_{0.2}$	1.1 ± 0.2	$0.1 \pm 6.5 \times 10^{-2}$
$t\bar{t}$	3.1 ± 0.1	$3.5\pm^{0.7}_{0.9}$	6.7 ± 2.8	$0.1 \pm 1.2 \times 10^{-2}$
Single top	–	–	–	< 0.1
QCD	–	–	–	7.6 ± 0.9
Higgs	–	–	–	< 0.01
Total	5.4 ± 0.3	$5.4\pm^{3.5}_{0.9}$	17.6 ± 3.8	8.4 ± 0.9
Observed	4	5	14	9

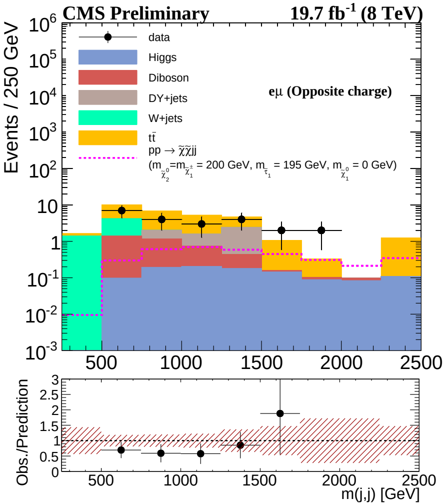
$\mu\mu jj$ - m_{jj} Distributions

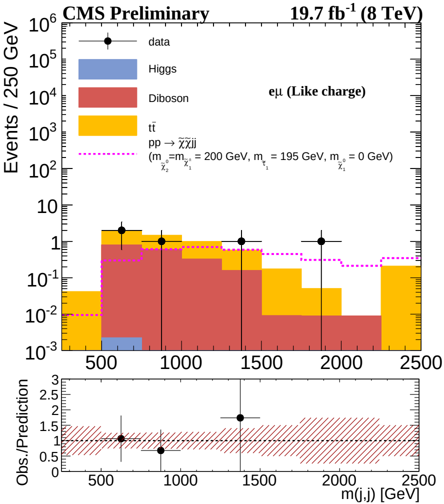
(CMS-SUS-14005)



$e\mu jj$ - m_{jj} Distributions

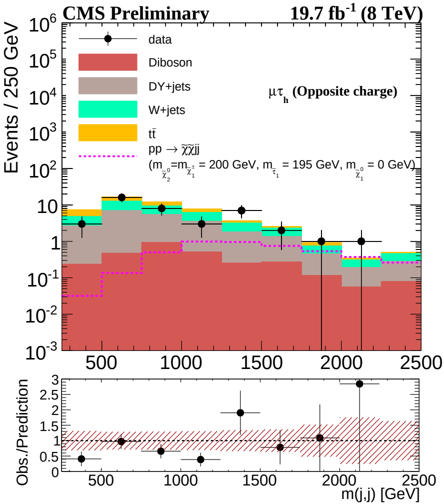
(CMS-SUS-14005)

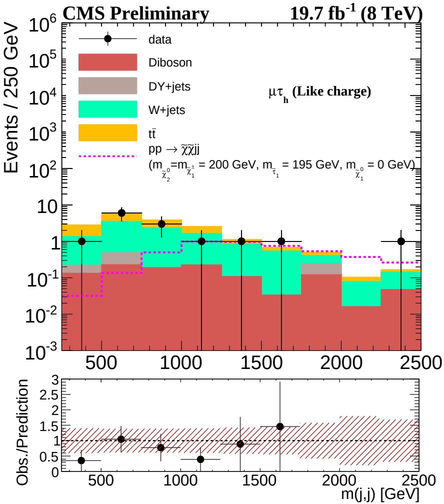




$\mu\tau_h jj$ - m_{jj} Distributions

(CMS-SUS-14005)





$\tau_h\tau_h jj$ - m_{jj} Distributions

(CMS-SUS-14005)