Searches for Supersymmetry in Compressed Stau-neutralino Scenario at the LHC

Alejandro Segura[1]
On behalf of **CMS Collaboration**

December 5, 2018

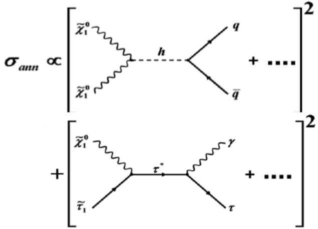
Universidad de Los Andes[1]

Outline

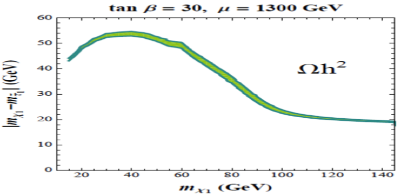
1. Motivation for the experimental study
2. Phenomenological Study
3. Experimental study
4. Background estimation strategy
    - ISR-Z boost weights
    - W+Jets
    - $t\bar{t}$
    - QCD-Multijets
    - Full Data Driven QCD closure test
5. Summary: SR for 2016 Data
6. Conclusions

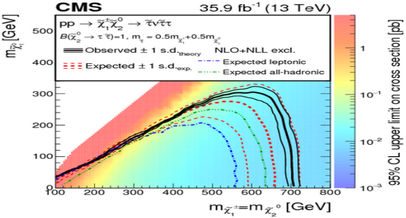
Particle Physics, Cosmology, and Dark Matter

- to obtain a relic DM density consistent with the astronomically measured value, stau-neutralino *coannihilation* is one of the scenarios.
- The DM relic density is extremely sensitive to the mass difference between the stau ($\tilde{\tau}$) and the neutralino ($\tilde{\chi}^0_1$) → motivates a search for *compressed spectra* ($\Delta m < 50$ GeV).



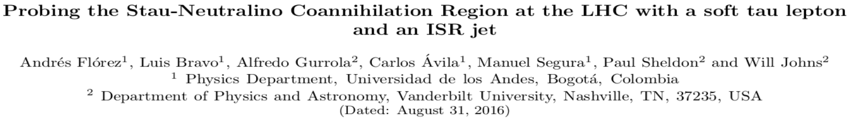
Review of SUS-17-003
`http://dx.doi.org/10.1007/JHEP11(2018)151`





Phenomenological study

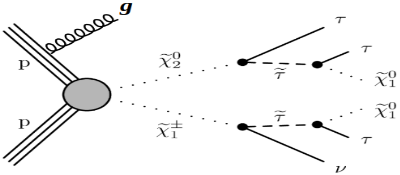
Third generation EWK-SUSY



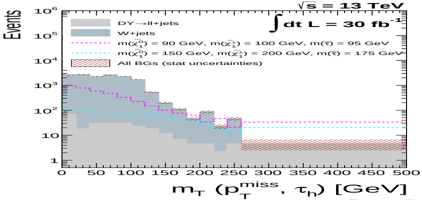
Probing the Stau-Neutralino Coannihilation Region at the LHC with a soft tau lepton and an ISR jet

Andrés Flórez[1], Luis Bravo[1], Alfredo Gurrola[2], Carlos Ávila[1], Manuel Segura[1], Paul Sheldon[2] and Will Johns[2]
[1] Physics Department, Universidad de los Andes, Bogotá, Colombia
[2] Department of Physics and Astronomy, Vanderbilt University, Nashville, TN, 37235, USA
(Dated: August 31, 2016)

Criteria	Value
$N(j)$	≥ 1
$p_T(j)$(Boost)	100 GeV
$\|\eta(j)\|$	≤ 2.5
$N(\tau_h)$	1
$N(e^-/\mu^-)$	0
$N(b-jet)$	0
$p_T(\tau_h)$	> 15 & < 35 GeV
$\|\eta(\tau_h)\|$	≤ 2.3
$\Delta R(\tau_h, j)$	> 0.3
E_T^{miss}	> 230



$$m_T(\ell, E_T^{miss}) = \sqrt{2|\vec{p}_\ell||E_T^{miss}|[1-\cos\Delta\phi_{\ell, E_T^{miss}}]} \longrightarrow$$



Optimization of SR

- The optimization study for the $p_T(\tau)$ and $p_T^{lead}(j)$ selections is mandatory.
- The maximum of the figure of merit returns the optimized value.

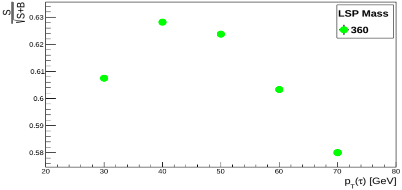
$$\mathcal{S} = \frac{N_s}{\sqrt{N_s + N_b}}$$

Event Selection Criteria for optimization

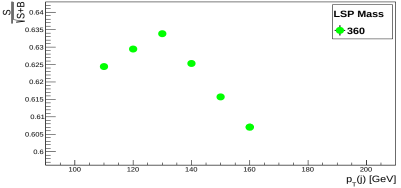
$N(\tau_h)$	$== 1$
$p_T(\tau_h)$	> 20 GeV
$\lvert\eta(\tau_h)\rvert$	< 2.3
$N(jet)$	≥ 1
$p_T^{lead}(jet)$	> 100 GeV
$\lvert\eta^{lead}(jet)\rvert$	< 2.5
N_{b-jets}	0
E_T^{miss}	> 230 GeV
Overlaps removal	$\Delta R > 0.3$

As a example: for signal point where LSP mass is "360 GeV"

$p_T(\tau)$ optimization: $max(40 GeV)$



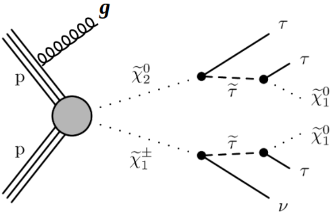
$p_T^{lead}(j)$ optimization: $max(130 GeV)$



Experimental study

Event Selection

- Basic Selection and Event Cleaning
  - PV, remove cosmics, instrumental backgrounds
  - MET filters
- $20 < p_T(\tau_h) < 40$ GeV
- $N(\tau_h) =$ Exactly 1 τ_h
- $|\eta(\tau_h)| < 2.1$
- ≥ 1 jet with $p_T(j) > 30$ GeV, $|\eta| < 2.4$, & “loose” ID
  - $p_T^{ISR}(j) = p_T^{lead}(j) > 100$ GeV
- jet cross-cleaned with τ_h
- $E_T^{miss} > 230$ GeV (PFMet with HF and type-1 corrections)
- QCD rejection: $|\Delta\phi(j_{lead}, E_T^{miss})| \geq 0.7$
- old decay mode finding with 1 prong + “Tight” isolation
- Veto other leptons and b-jets.
- Trigger: HLT_PFMETNoMu120_PFMHTNoMu120_IDTight



- **Status**
  1. We are working on BG's estimation for 2017 data.
  2. Dominant backgrounds: $Z/W/t\bar{t}/QCD$
  3. $36.9\ fb^{-1}$ (13 TeV). ≈ 2500 trillion pp collisions.

Background estimation

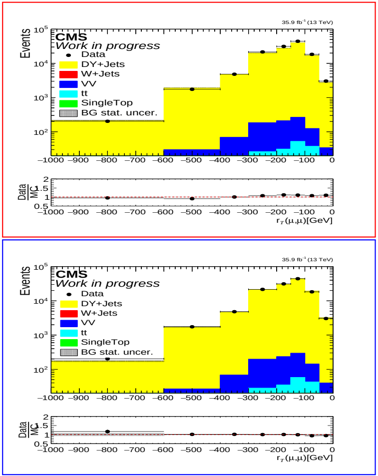
Results of the $Z(\rightarrow \mu^+\mu^-)$+ISR Control Region

Table: Event Weights by Z-Boost

Z-Boost Bin	Weight
1: 0-50 GeV	1.1192 ± 0.0250
2: 50-100 GeV	1.1034 ± 0.0133
3: 100-150 GeV	1.0675 ± 0.0116
4: 150-200 GeV	1.0637 ± 0.0126
5: 200-300 GeV	1.0242 ± 0.0132
6: 300-400 GeV	0.9453 ± 0.0184
7: 400-600 GeV	0.8579 ± 0.0277
8: 600-1000 GeV	0.7822 ± 0.1130

Reported uncertainties here are statistical for each weight.

- The bottom right figure shows Data/MC agreement within accepted ranges for jet resolution at CMS→no further corrections for jet energy resolution are necessary.
- **The distributions nicely model the data after correcting simulation with the boost weights.**



$$\vec{r}_T = -\left(\vec{E}_T^{\,\mathrm{miss}} + \vec{Z}_T\right)$$ projected along $\vec{Z}_T$

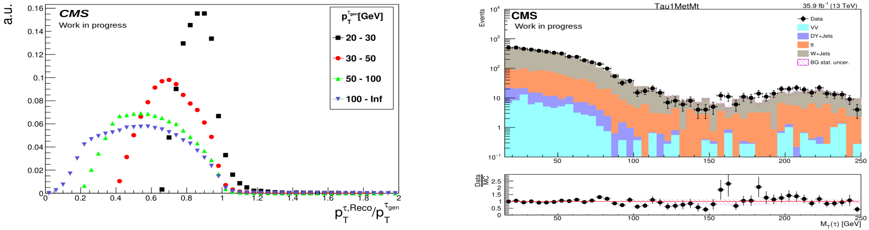
no-weigths (top) and weights (bottom)

Background: $\mu \rightarrow \tau_h$ emulation in W+Jets

Lepton universality:

- For additional confidence in our BG estimates, we follow a second methodology: select muon control sample in data, and then replace muon by τs using response templates. $p_T^{\tau gen}$ is the p_T before the τ decays.

  $\sigma(p_T^{\mu}) < 2\% \rightarrow p_T^{\mu} \approx p_T^{\tau gen}$ $\quad$ $Response = R(p_T^{\tau gen}) = p_T^{\tau_h, RECO} / p_T^{\tau gen}$
- Take p_T^{μ} in data, we assume it's $\approx p_T^{\tau gen}$, and generate random $p_T^{\tau_h, RECO}$ using the response templates from MC (left side).
- Weights are applied to correct for reconstruction and identification efficiencies.
- Perform closure tests in both MC and data. Data closure test (right side) are performed in a sample orthogonal to the SR, containing small signal contamination, such that, signal-like cuts except require $40 < p_T^{\tau_h, RECO} < 60$ GeV.



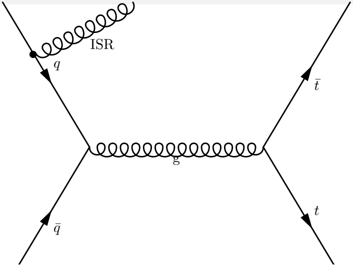
Defining the $t\bar{t}$ Control Region

$$N_{\rm SR} = \sigma \cdot L_{\rm int} \cdot \epsilon_{\tau_h} \cdot \epsilon_{E_{\rm T}^{\rm miss}} \cdot \epsilon_{\rm ISR} \cdot \boxed{\epsilon_{\rm b-jet}}$$

Cuts for the $t\bar{t}$ CR
ID(τ_h): Tight/VTight
$N(\mathrm{b-jets}) = 1/2$
$N(\mathrm{prongs}) = 1/1\mathrm{or}2\mathrm{or}3$
Others: SR

We use LO HT-binned MG samples for W/Z+jets and correct with NLO k-factor (see backup).

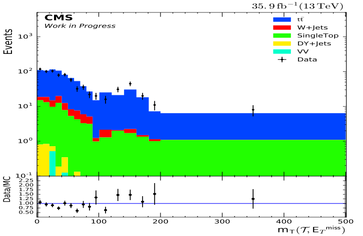
- Trigger: HLT_PFMETNoMu120_PFMHTNoMu120_IDTight
- Tau Discriminator: Tight



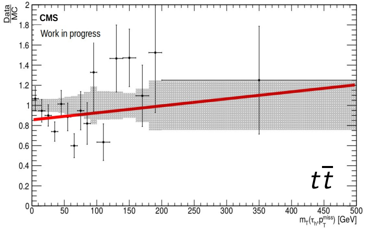
Region	$N(\mathrm{b-jet})$	τ ID	$N(\mathrm{prongs})$
Signal	$== 0$	Tight	1
CR 1	$== 1$	Tight	1, 2, or 3
CR 2	$== 2$	Tight	1, 2, or 3
CR 3	$== 1$	VTight	1
CR 4	$== 2$	VTight	1

- We develop four $t\bar{t}$ CRs to identify and minimize QCD multijet BGs.

Results of the $t\bar{t}$ Control Region



$m_T(\tau, E_T^{miss})$ for $t\bar{t}$ CR 4 (2b, VTight, 1hps)



Data/MC ratio, as a function of m_T, in the $t\bar{t}$ control region

- The measured data-to-MC ratio for $t\bar{t}$ is:

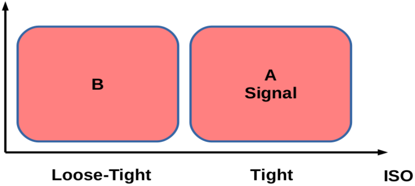
$$SF_{t\bar{t}} = 0.94 \pm 0.05$$

therefore, the $t\bar{t}$ prediction in the SR is estimated by correcting the MC prediction with this SF.

- Since m_T shapes are consistent between data and MC, we are confident in taking the $t\bar{t}$ shape in the SR directly from MC.

QCD estimation: Fully Data Driven

- We use the ABCD method to estimate QCD contribution in the SR.
- **The shape of QCD events is obtained by requiring the same criteria as in the SR, but selecting events that pass the loose τ_h isolation working point and fail the tight (Loose minus Tight events). This CR is referred to as CR_B.**
- CR_B has high purity of QCD events. The contamination from other BGs in CR_B is subtracted from data, using the MC prediction.
- **In order to estimate the rate of QCD events in the signal region, a transfer factor to extrapolate from CR_B to the SR is needed.**
- The transfer factor is obtained using two additional CRs, obtained using $Z(\to \mu\mu) + \tau_h$ and $W(\to \mu\nu) + \tau_h$ events. The τ_h results from a jet misidentified as a τ_h and it will be referred to as τ_h^{fake} (see next slides)

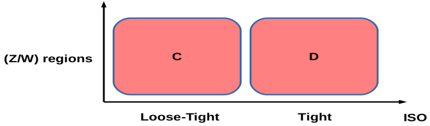


QCD estimation estrategy: Measuring the Tight to Loose ratio.

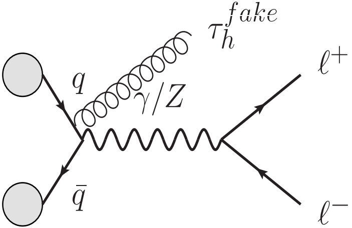
- Selected $Z(\to \mu\mu) + \tau_h^{fake}$ events, where the τ_h^{fake} passes the loose isolation criterion but fails the tight are referred to as CRC.
- Selected $W(\to \mu\nu) + \tau_h^{fake}$ events, where the τ_h^{fake} passes the nominal tight isolation criterion are referred to as CRD.
- The transfer factor is then defined as

$$TF = \frac{N^{Data}(CRD) - N^{MC}_{Non-QCD}}{N^{Data}(CRC) - N^{MC}_{Non-QCD}}$$

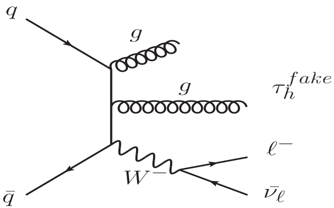
- From now on, this transfer factor will be referred to as the tight-to-loose ratio: $TF = R^{Tight}_{Loose}$.



$(Z \to \mu\mu)\tau_h^{fake}$



$(W \to \mu\nu)\tau_h^{fake}$



$Z(\rightarrow \mu\mu) + \tau_h^{fake}$ yields

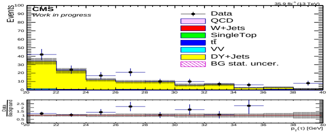
- The R_{Loose}^{Tight} is measured vs $p_T(\tau_h)$.

Central Selections	
Trigger	HLT−IsoMu24−
$N(\mu)$	2
$p_T(\mu_1)$	> 30 GeV
$p_T(\mu_2)$	< 10 GeV
$\lvert\eta(\mu)\rvert$	< 2.1
$N(\tau_h)$	1
$p_T(\tau_h)$	$> 20\& < 40$ GeV
$\lvert\eta(\tau_h)\rvert$	< 2.1
$Q(\mu_1) \times Q(\mu_2)$	-1
E_T^{miss}	> 30 GeV
$m(\mu, \mu)$	> 70 & $< 110.$ GeV

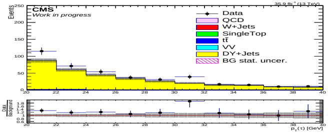
$p_T(\tau_h)[GeV]$	$Ratio_{Loose}^{Tight}$
[20, 22.5]	0.37 ± 0.06
[22.5, 25]	0.36 ± 0.08
[25, 27.5]	0.38 ± 0.10
[27.5, 30]	0.36 ± 0.10
[30, 32.5]	0.29 ± 0.09
[32.5, 35]	0.34 ± 0.13
[35, 37.5]	0.25 ± 0.19
[37.5, 40]	0.42 ± 0.22

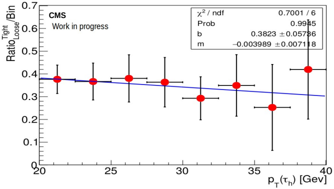
We use the linear fit instead of the bin-by-bin Tight-to-Loose ratio in order to reduce the uncertainty in the QCD BG estimation.

Pass Tight ISO



Pass Loose Fails Tight





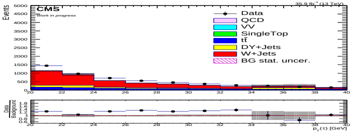
$W(\to \mu\nu) + \tau_h^{fake}$ yields

- The R_{Loose}^{Tight} is also measured as function of $p_T(\tau_h)$ using $W \to \mu\nu + \tau_h^{fake}$ events.

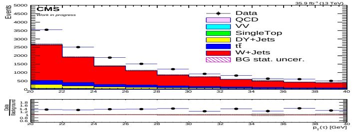
Central Selections	
Trigger	HLT−IsoMu24−
$N(\mu)$	$== 1$
$p_T(\mu)$	> 30 GeV
$\lvert\eta(\mu)\rvert$	< 2.1
$N(\tau_h)$	1
$N(e)$ & $N(b-jets)$	$== 0$
$p_T(\tau_h)$	$> 20\& < 40$ GeV
$\lvert\eta(\tau_h)\rvert$	< 2.1
E_T^{miss}	> 30 GeV
$m_T(\mu, E_T^{miss})$	$> 50\ \& < 120.$ GeV

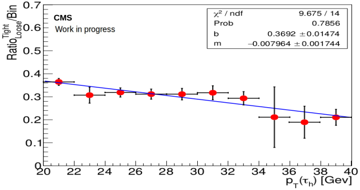
$p_T(\tau_h)[GeV]$	$Ratio_{Loose}^{Tight}$
[20, 22.5]	0.36 ± 0.01
[22.5, 25]	0.34 ± 0.02
[25, 27.5]	0.29 ± 0.01
[27.5, 30]	0.32 ± 0.01
[30, 32.5]	0.26 ± 0.01
[32.5, 35]	0.26 ± 0.02
[35, 37.5]	0.27 ± 0.02
[37.5, 40]	0.27 ± 0.03

Pass Tight ISO



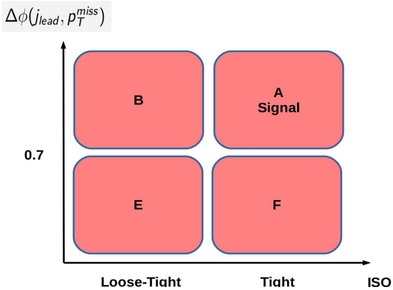
Pass Loose and Fails Tight





Closure Test inverting $\Delta\phi(j_{lead,p_T^{miss}})$ cut

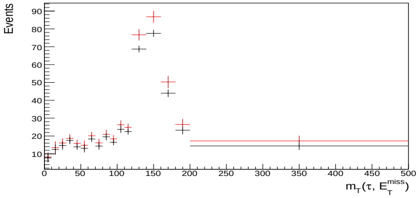
- **To validate the extraction of the shape from the non-isolated events and the $p_T(\tau_h)$ dependent R_{Loose}^{Tight} ratios, two additional CRs are used.**
- The CRs are obtained by inverting the $\Delta\phi_{min}(jet, p_T^{miss})$ requirement. In the inverted $\Delta\phi_{min}(jet, p_T^{miss})$ CR, isolation sidebands are also defined, as shown in the sketch below.
- The shape for QCD events in CRF is obtained from CRE and the normalization is obtained using the R_{Loose}^{Tight} ratios.

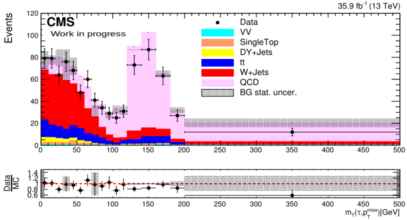


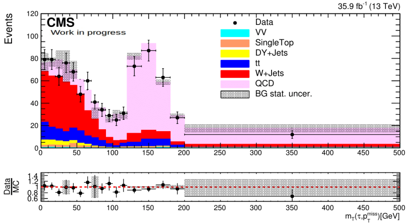
QCD Multijets estimation: Obtaining the final shape through (Z/W) CR weights

CRD (Tight ISO) data driven (DD) QCD	
Data	896
VV	3.6 ± 1.1
DY+Jets	25.7 ± 0.9
$t\bar{t}$	117.6 ± 6.6
W+Jets	343.0 ± 5.6
$N^{QCD}(DD_Z)$	471.6 ± 19.1
$N^{QCD}(DD_W)$	421.4 ± 17.3
Total Backround	897.4 ± 36.5

Shape obtained from Z weights (Red) and from W weights (Black)





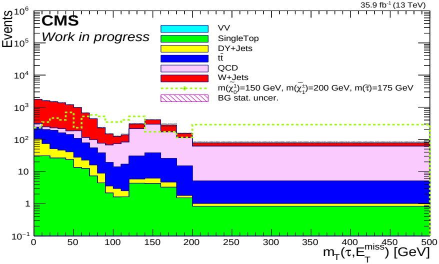


With the $Z(W)$ $p_T(\tau_h)$-dependent. The ratio is shown Above(Below)

Background estimation in the SR

- $Z/W/t\bar{t}/\text{QCD}$ estimations done for 2016 data.

Central Selections	Yield	Fraction
VV	149.9 ± 7.2	1.2%
SingleTop	202.1 ± 5.7	1.7%
DY	232.0 ± 5.0	2.0%
tt	1002.2 ± 19.3	8.6%
QCD	1359.9 ± 18.6	11.7%
W+Jets	8596.1 ± 60.5	74.4%
Total Back	11542 ± 67.0	
SignalLSP150 $\times$ 10X	6398.6 ± 603.9	



Summary and Conclusions

- CMS initiated SUSY search in $\widetilde{\tau} - \widetilde{\chi}_1^0$ coanaihilation scenarios using ISR jet.
- Studies on Z$(\rightarrow \mu^+\mu^-) + \mathrm{ISR}$ resulted in the boson boost weights for 2016 data.
  - The efficiency ϵ_{ISR} is well-understood.
  - After further study into jet resolution, ϵ_{MET} is also well-understood.
- Those boson weights (and modeling of the p_T^{miss}) were validated on a region of W$(\rightarrow \mu\nu) + \mathrm{ISR}$ for 2016 data.
- Z$(\rightarrow \tau^+\tau^-) + \mathrm{ISR}$ CR shows that $\epsilon_{\tau\mathrm{ID}}$ is well-understood.
- Contributions of W+Jets, Z+Jets and $t\bar{t}$ backgrounds to the SR are well-understood (2016).
- The Full Data Driven method seems to be the best strategy to estimate the QCD Multijets contribution in the SR. The shape is extracted from CRB and it will be reweighted using the 2D histogram and the corresponding $p_T(\tau_h)$ weights.
- We expect to exclude $\tilde{\chi}_2^0/\tilde{\chi}_1^{\pm}$ with masses below 330 GeV Pheno study

$m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0) = 50$ GeV and $m(\tilde{\tau}) = \frac{1}{2}m(\tilde{\chi}_1^{\pm}) + \frac{1}{2}m(\tilde{\chi}_1^0)$ GeV.

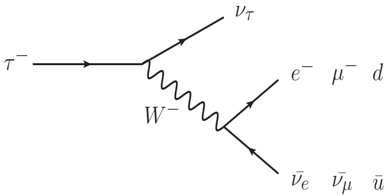
Thanks

BACKUP SLIDES

Particle Algorithm and τ properties

Particle Flow Algorithm

- The algorithm reconstructs the stable visible particle individually in each sub-detector.
- The information recollected by all sub-detectors is combined.
- The visible particles are divided in groups: Photons, electrons, neutral and charge hadrons and muons.
- This information is used to reconstruct high level objects as: The Jets, E_T^{miss} and τs



Feynman diagram for τ decay modes

General Properties

- $m_\tau = 1.777$ GeV
- $t_{lifetime}(\tau) = 290.6$ fs
- $c\tau = 87\mu m$

Leptonic Decay

$\tau^\pm \to e^\pm \nu_e \nu_\tau$	17.8%
$\tau^\pm \to \mu^\pm \nu_\mu \nu_\tau$	17.4%

Hadronic Decay

$\tau^\pm \to h^\pm \nu_\tau$	11.5%
$\tau^\pm \to h^\pm \pi^0 \nu_\tau$	26.0%
$\tau^\pm \to h^\pm \pi^0 \pi^0 \nu_\tau$	10.8%
$\tau^\pm \to h^\pm h^\pm h^\mp \nu_\tau$	9.8%
$\tau^\pm \to h^\pm h^\pm h^\mp \pi^0 \nu_\tau$	4.8%

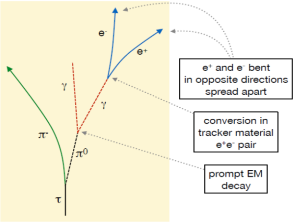
- In the leptonic decay the τ decays too fast, in general, it is no possible to distinguish the e/μ that come from the other collision. On the other hand, in the hadronic decay the signature is similar to the QCD multijet background. Therefore, an algorithm for τ identification is needed.

τ reconstruction

Hadron plus strips Algorithm (HPS)

- This Algorithm takes the Jet as a input and reconstruct the individual decay mode, the three decay modes are shown in the following table:

Decay Mode	
1-prong	$\tau^{\pm} \rightarrow h^{\pm}\nu_{\tau}$
1-prong+$n\pi^0$	$\tau^{\pm} \rightarrow h^{\pm}\pi^0\nu_{\tau}$
	$\tau^{\pm} \rightarrow h^{\pm}\pi^0\pi^0\nu_{\tau}$
3-prong	$\tau^{\pm} \rightarrow h^{\pm}h^{\pm}h^{\mp}\nu_{\tau}$



- The π^0 decays into $\gamma\gamma$, these photons probably can be produce a electron-positron pairs, therefore, these objects are clustered in the ECAL strip in the plane (η, ϕ)
- The τ candidate is reconstructed using the clustered strip in the ECAL and the charge particles tracks coming from the Jets.

Possible Fake Candidates:

- QCD jets: Compose by charge (≈ 65 %) and neutral (≈ 20 %) hadrons and photons (≈ 15 %)
- Electrons: Could be misidentified as $h^{\pm}$ or $h^{\pm}\pi^0$ decay modes of the τ.
- Muons: Could be misidentified as $h^{\pm}$ decay mode of the τ.

In order to distinguish the different physics objects, there are discriminants dedicated to tag correctly the τ

τ isolation discriminators

MVA-based Isolation discriminators

- The QCD jets have a larger multiplicity of particles that the τ jets
- The τ jets in general, have a narrower cones that the QCD jets.
- Depends on the strong of the selection, there are different working points. For example, the Tight isolation has a identification efficiency of $\approx$ 60% and a fake rate of 4.4×10^{-3}

Against electron discriminators

- Base on the amount of Bremsstrahlung associated to the leading track and the multiplicity of particles.
- The Loose isolation has a identification efficiency of $\approx$ 83% and a fake rate of 4.4×10^{-2}

Against muon discriminators

- Base on the hits in the muon chambers and low deposits of energy in the ECAL and HCAL.
- The Tight isolation has a identification efficiency of $\approx$ 99% and a fake rate of 1.4×10^{-3}