Search for Weak Scale Supersymmetric Particles in Compressed Scenarios

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Search for Weak Scale Supersymmetric Particles in Compressed Scenarios

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Abstract

This is the abstract

Acknowledgements

Thanks everybody

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Chapter 3

Compressed SUSY Search

Abstract

This chapter summarizes the approach for a compressed susy search and pertinent sensitive kinematic variables that the analysis is based on.

3.1 analysis overview

A compressed system is defined by a sparticle such as a neutralino 2 or stop in which the mass difference with this particle and the lightest supersymmetrical particle is small. The mass difference is considered small when the sparticle decays to intermediate standard model particles like W,Z,t such that the intermediate particle is forced off shell. For example the smallest targeted mass splittings can range between 3 to 10 GeV in neutralino 2 to W/Z decays. The intermediate decays will be difficult to detect or separate from standard model backgrounds. To assist in identifying compressed topologies we look for ISR assisted events. The signature of the event then becomes an ISR jet back to back with sparticle system which consists of mostly missing transverse energy from the LSP and soft SM particles.

3.2 reference frames and kinematic variables

An isr assisted event is divided into multiple reference frames. The CM frame consists of the particles measured in the lab e.g. the isr jet against the met system. The sparticle frame consists two subsystems A and B. THe sparticles are expected to be pair produced if r parity is conserved.

The kinematic variables the form basis of the search is RISR and MPERP. Risr. RISR is process independent and peaks at the ratio of sparticle/lsp masses. mperp is the transverse mass of the sparticle frame with respect to the sparticle frame boost axis.

3.3 signal models

The analysis is generalized to deal with a broad range of signal models but the three targeted compressed signal processes incldue stop, neutralino/chargino, slepton production. the signals include T2tt, T2bW, TChiWZ, TChiWW, TSlepSlep

Chapter 4

The Tag-and-Probe

Abstract

The Tag-and-Probe is a method used to measure the selection efficiencies of an object using data. In the context of this compressed SUSY analysis, the Tag-and-probe measures the efficiencies separately of each light lepton(e/μ) selection critera. The total lepton selection efficiency is then computed by combining factorized efficiency components. The same general method is used for both electrons and muons, however, Muons utilize the J/ψ di-muon trigger which allow more precise efficiency measurements from data at lower p_T.

4.1 Introduction and Methodology

An important element of a lepton based search is properly modeling the efficiency of selected leptons. A purely Monte-Carlo driven approach is inadequate in perfectly describing nuances in data due to imperfections in modeling. Instead of trying to model exactly all physics and detector effects with simulation, the efficiencies can be directly measured from data by using the Tag-and-Probe method.

The Tag-and-Probe method is used to measure a selection criteria by using a well known resonance such as a Z, J/ψ, or Υ and counting the number of probes that pass that criteria. Each counted instance of the Tag-and-Probe consists of two selected leptons. One of the selected leptons is the tag and the other is the probe. The tag passes tight selection requirement to give high confidence that it isn't a fake lepton. Fake leptons fall into two possible categories: reducible and irreducible. A reducible fake lepton is a particle that fakes the signature of a lepton such as a charged pion. An irreducible fake lepton is an actual lepton which coincidentally passes some selection criteria but is not the targeted leptons of interest e.g. an isolated muon from a jet accompanying a leptonic Z decay of interest. The second lepton in the Tag-and-Probe is the probe. The probe is subjected to the selection criteria whose efficiency is being measured. The invariant mass of the pair of leptons is calculated and required to fall within a defined range around the resonance. A particular event may have multiple lepton pairs but the tag and the probe are not allowed to switch positions and be counted twice, as double counting would lead to a bias in the efficiency measurement [7]. To avoid bias, the tag and probe are required to be the opposite charge and same flavor where the tag is randomly selected. If multiple same flavor lepton pairs occur in single event i.e. there are multiple probes to a single tag, the treatment for selecting the pairs differs between electrons and muons. There is no specific study which led to justifying the differing arbitration approaches in flavors, only that the choice reflects the default choices implemented in the existing code bases. For muons, no arbitration is used, all pairs are utilized which means an additional pair not truly from the resonance will then contribute as combinitorial background in a single event. For electrons, only a single probe is selected per event which has the highest p_{T}. The selected probes can either pass or fail their selection which leads to the formation of three distributions, one with a passing probe, one with a failing probe, and one with all probes. An example of all three distributions is shown in Figure 4.1. The probability of observing k passing probes in n Tag-and-Probe pair trials is dependent on the selection efficiency ε and can be expressed as a likelihood from the binomial probabilty density $P(k|\varepsilon, n) = \binom{n}{k}\varepsilon^k(1-\varepsilon)^{n-k}$. The MLE estimator for efficiency is then the fraction of passing probes to the total number of pairs, or $\varepsilon = k/n$. Technical documentation for the Tag-and-Probe in CMS is scarce, but, an early strategy for fitting efficiency is defined in [3]. The legacy code base as of `CMSSW_10_6_X` uses a binned maximum likelihood between the observed passing probes and failing probes where the efficiency extracted is an explicit fit parameter. The two simultaneously fit functions are:

$$N^{\mathrm{Pass}} = N_{\mathrm{Total}}(\varepsilon \cdot f^{\mathrm{sig}}_{\mathrm{All}}) + \varepsilon_{\mathrm{bkg}} \cdot (1 - f^{\mathrm{sig}}_{\mathrm{All}})) \tag{4.1}$$

$$N^{\mathrm{Fail}} = N_{\mathrm{Total}}((1-\varepsilon) \cdot f^{\mathrm{sig}}_{\mathrm{All}} + (1-\varepsilon_{\mathrm{bkg}}) \cdot (1 - f^{\mathrm{sig}}_{\mathrm{All}})) \tag{4.2}$$

$N^{\mathrm{Pass/Fail}}$ is the total number of observed probes that either pass or fail the selection criteria while N_{Total} is the total number of Tag-and-Probe pairs. The binomial estimator for efficiency, ε, enters the fit functions as the first term but is accompanied by a second term that describes the background contribution with its own efficiency $\varepsilon_{\mathrm{bkg}}$. The term $f^{\mathrm{sig}}_{\mathrm{All}}$ is the fraction of background subtracted signal events over the allowed dilepton mass range. $f^{\mathrm{sig}}_{\mathrm{All}}$ depends on the defined signal and background pdfs. The nominal pdfs chosen for reported fits uses a 5 parameter Voigtian+Voigtian signal model which share a common mean but use independent Γ and σ. The signal model is combined with an Exponential background model.

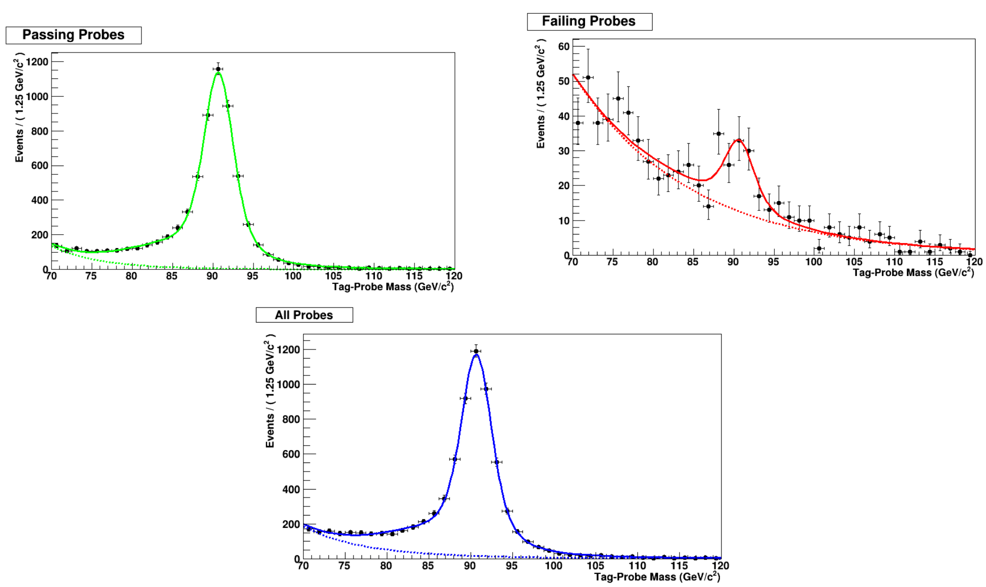

Figure 4.1: Example Tag-and-Probe Z di-muon fits for passing,failing, and all probes with the Medium Id, $|\eta| < 1.2$, and $p_T < 20$ GeV

4.2 Lepton Object Definitions

Leptons are selected according to the minimium requirement "VeryLoose" which depend kinematic and topological quantities which are shown in Table 4.1. The electrons use an additional loose MVA requirement: MVA VLooseFO ID [?]. The set of VeryLoose leptons are further subdivided by quality into three mutually exclusive categories: Gold, Silver, and Bronze. Each category has a measure of three main quantities, the first being the quality of the pre-determined Id. The Id's differ per flavor and are the standard working points defined by the corresponding physics object group. The muons use the Medium Id [4] and electrons use a more strict selection, due to their messy nature, with the Tight Id [8]. The second quantity is the "promptness" or distance of the lepton production point from the primary vertex. Promptness is measured by the significance of the 3D impact parameter (SIP3D) which is defined as the impact parameter normalized by its measured error. A SIP3D > 1 is associated with a secondary particle which is not produced at the primary vertex. The last component is the isolation, a measure of the density of particles in a cone around the lepton. Two similar but complimentary absolute isolations are used: PFIso [5] and MiniIso [2]. Both isolations are an energy sum of neighboring particles inside a cone, but, PFIso has a fixed cone size of $R = 0.4$ cm and miniIso cone sizes varies inversely with lepton p_{T} as shown in 4.3.

$$R_{\mathrm{miniIso}} = \begin{cases} 0.2 & p_{\mathrm{T}}^{\ell} < 50\mathrm{GeV} \\ \frac{10}{p_{\mathrm{T}}^{\ell}} & 50\mathrm{GeV} \leq p_{\mathrm{T}}^{\ell} \leq 200\mathrm{GeV} \\ 0.05 & p_{\mathrm{T}}^{\ell} > 200\mathrm{GeV} \end{cases} \tag{4.3}$$

Mini isolation also includes effective area pile-up corrections provided in a look up table of bins of p_{T} and η in the CMSSW Producer/Ntuplizing stage. The implementation of mini-isolation and their corrections utilize the same IsoValueMap producer as used in NANO AOD as of `CMSSW_10_6_X`.

The explicit flavor independent formulas for Gold, Silver, and Bronze can be generalized by the product of three components which are the measured efficiences of the three previously mentioned quantities. The efficiencies take the form of conditional probabilities to be measured independently in sequence relative to each other:

$$
\begin{aligned}
\epsilon_{\text{Gold}} &= \epsilon_{\text{ID}} \times \epsilon_{\text{Isolated}|\text{ID}} \times \epsilon_{\text{Prompt}|(\text{ID}\cap\text{Isolated})} \\
\epsilon_{\text{Silver}} &= \epsilon_{\text{ID}} \times \epsilon_{\text{Isolated}|\text{ID}} \times \left(1 - \epsilon_{\text{Prompt}|(\text{ID}\cap\text{Isolated})}\right) \\
\epsilon_{\text{Bronze}} &= 1 - \left(\epsilon_{\text{ID}} \times \epsilon_{\text{Isolated}|\text{ID}}\right)
\end{aligned}
\tag{4.4}
$$

The subscript for an efficiency, e.g. $\epsilon_{\text{Prompt}|(\text{ID}\cap\text{Isolated})}$, reads as the efficiency to pass the SIP3D requirement given the lepton passes the Id and Isolation requirements. From equation 4.4 the Gold, Silver, and Bronze effiencies can be read off as Gold passes all criteria, Silver fails only the SIP3D requirement, and Bronze fails either the Id or isolation and is agnostic to SIP3D. While isolation and vertexing requirements are physically uncorrelated, there is an intersection between the two, meaning a lepton can be both prompt and isolated. This intersection then demands the necessity for conditional efficiencies. The order of the conditional efficiencies is also chosen to minimize the number of measured efficiencies by reusing efficiencies across Gold, Silver, and Bronze.

Table 4.1: The criteria that define the minimum requirements for an accepted lepton. The electron and muon requirements are equivalent in terms of pseudorapidity, vertexing, and isolation but vary in p_{T} threshold and the MVA VLooseFO working point. The MVA VLooseFO ID also varies between years.

Criteria	Electron	Muon
p_{T}	≥ 5 GeV	≥ 3 GeV
$\lvert\eta\rvert$	< 2.4	< 2.4
$\text{IP}_{3D}/\sigma_{\text{IP}_{3D}}$	< 8	< 8
$\lvert d_{xy}\rvert$	< 0.05 cm	< 0.05 cm
$\lvert d_z\rvert$	< 0.1 cm	< 0.1 cm
$\text{PFIso}_{\text{abs}}$	$< 20 + (300/p_{\text{T}})$ GeV	$< 20 + (300/p_{\text{T}})$ GeV
MVA VLooseFO ID	✓	–

The advantage of having various lepton quality categories allows for robust sensitivity to a wide range of signal processes. This strategy boosts the overall modeling statistics and provides control regions for multiple scenarios. The populations of different truth selected objects are shown in Figure 4.2 and the overall efficiency for Gold, Silver, and Bronze on truth matched objects are shown in Figure 4.3. The gold region is mainly populated by prompt and isolated leptons that are produced within the primary vertex. This region also coincides with the signature of many targeted electroweakino models. The silver selection accomodates both leptonically decaying taus, providing a ideal region for stau's, and assists in recovering efficiency of isolated b decays in stop production. The bronze selection is rich in fake leptons and provides the best regions to extract overall fake rates for other regions as well as a surplus of events to anchor the fit.

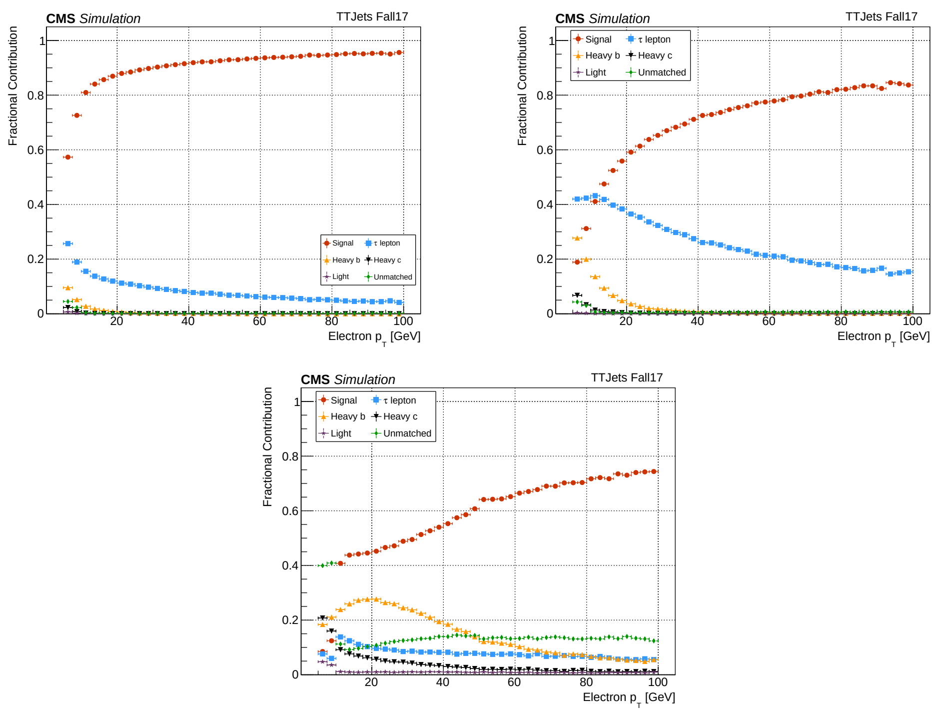

Figure 4.2: Gold (Top-Left), Silver (Top-Right) and Bronze (Bottom) MC truth matching in TTJets sample 2017. Signal is defined here as prompt electrons from a W decay.

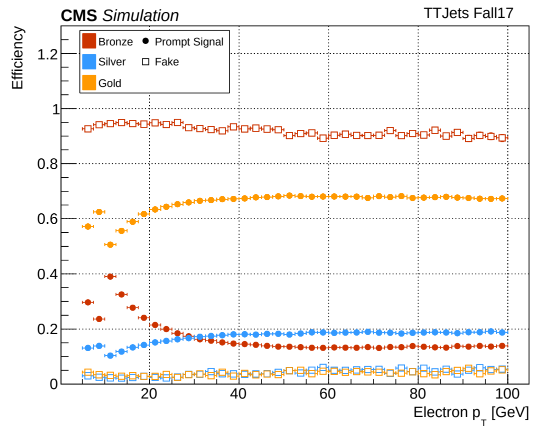

Figure 4.3: Gold, Silver, and Bronze efficiency on truth matched prompt electrons as signal and secondary electons as Fakes.

4.3 Electron Tag-and-Probe

The electron tag and probe is done by using the Z resonance over the entire p_{T} range of selected electrons. The selected binnings follow the p_{T} and η binning conventions from the electron physics object group and are $p_T \in [5, 10, 20, 30, 40, 70, 100]$ and $|\eta| \in [0, 0.6, 1.4, 2.4]$. The electron Tag-and-Probe tools uses a centrally curated CMSSW PhysicsTools in `CMSSW_10_2_X`. The Tag-and-Probe software pipeline consists of two steps, an ntuplizing stage and a fitting stage. The Ntupilizing stage selectsTag-and-Probe pairs along with all potential variables of interest and loads them onto an ntuple using TnPTreeProducer. The samples used in the Ntuplizing stage are listed in Table **??**. In the fitting stage, a random subset of of TnP pairs are sampled with TnPTreeAnalyzer. The TnPTreeAnalyzer performs all of the fitting and efficiency measurements according to the specified selection criteria.

A general selection of electron pairs is applied for TnP candidates to be considered. The basic selection for electrons is different for the tag and probe but both depend on super cluster (SC)

Type	Year	Sample Name
Data	2016	`/SingleElectron/Run2016B-17Jul2018_ver2-v1/MINIAOD`
Data	2017	`/SingleElectron/Run2017C-31Mar2018-v1/MINIAOD`
Data	2018	`/EGamma/Run2018A-PromptReco-v1/MINIAOD`
MC	2016	`/DYJetsToLL_Pt-100To250_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/RunIISummer16MiniAODv3-PUMoriond17_94X_mcRun2_asymptotic_v3_ext5-v2/MINIAODSIM`
MC	2017	`/DYJetsToLL_Pt-100To250_TuneCP5_13TeV-amcatnloFXFX-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM`
MC	2018	`/DYJetsToLL_Pt-100To250_TuneCP5_13TeV-amcatnloFXFX-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM`

kinematics. The super clusters are expected to fall within the calorimeter acceptance and clusters within the ECAL and endcap gaps are vetoed. The invariant mass of the electron of the pair also is required to fall within a specified Z-window.

Tag-and-Probe Electron Candidate Selection Criteria			
Tag	Probe	Super Cluster	Pair
$\lvert\eta_{SC}\rvert \leq 2.1$	$\lvert\eta_{SC}\rvert \leq 2.5$	$\lvert\eta\rvert < 2.5$	50GeV $< m_{ee} <$ 130GeV
veto $1.4442 \leq \lvert\eta_{SC}\rvert \leq 1.566$	$E_{ECAL}\sin(\theta_{SC}) > 5.0$ GeV	$E_T > 5.0$ GeV	
$p_{\mathrm{T}} \geq 30.0$ GeV	x	x	
Passes tightID	x	x	

The triggers selected are HLT electron collections and are grouped by specific paths and filters. The tag electrons are matched to trigger objects in the path/filter combination and passed based on the OR of triggers in the collection. The probes are not subjected to trigger matching. The chosen trigger combinations are the following:

- 2016: `HLT_Ele27_eta2p1_WPTight_Gsf_v*`
- 2017: `HLT_Ele32_WPTight_Gsf_L1DoubleEG_v*`
- 2018: `HLT_Ele32_WPTight_Gsf_v*`

How to calculate gold silver and bronze The gold silver and bronze efficiencies are calculated based one the same prescprtion defined in Equations 4.4

efficiency plots, I'll have to actually make these myself....

The combination of these efficiencies we get the gold silver and bronze efficiencies and scale factors

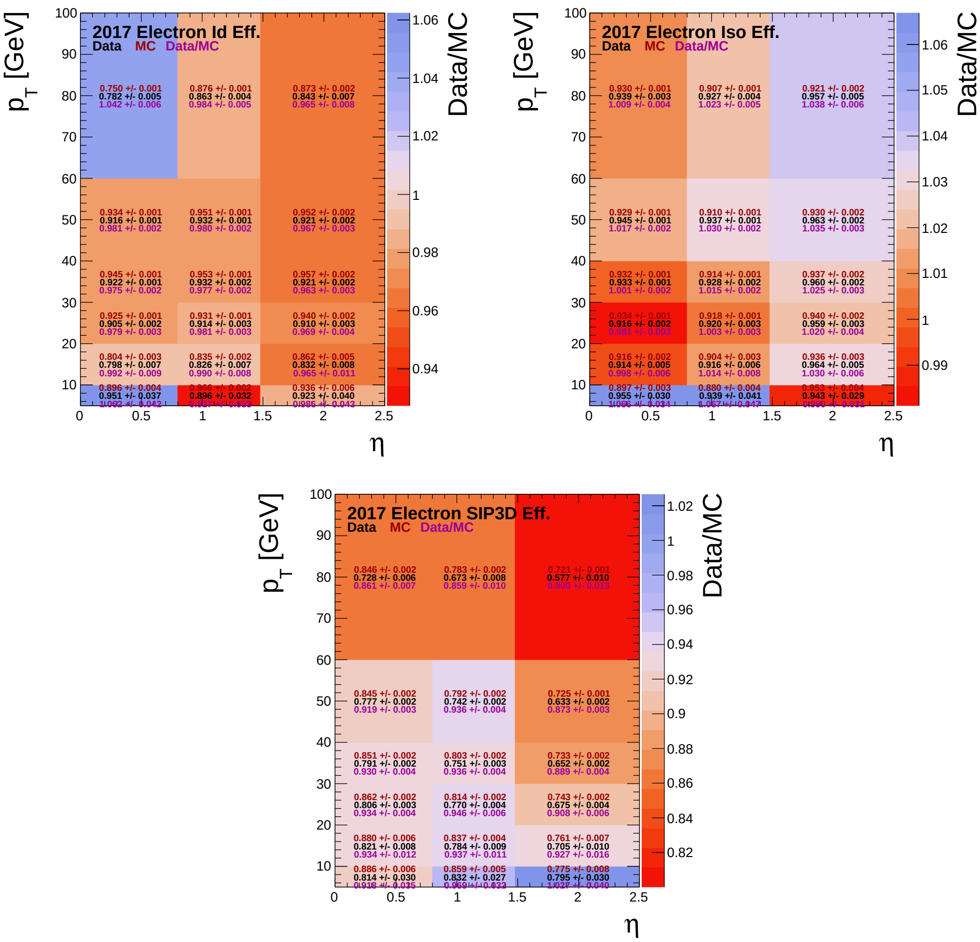

Figure 4.4: fig:el2deff

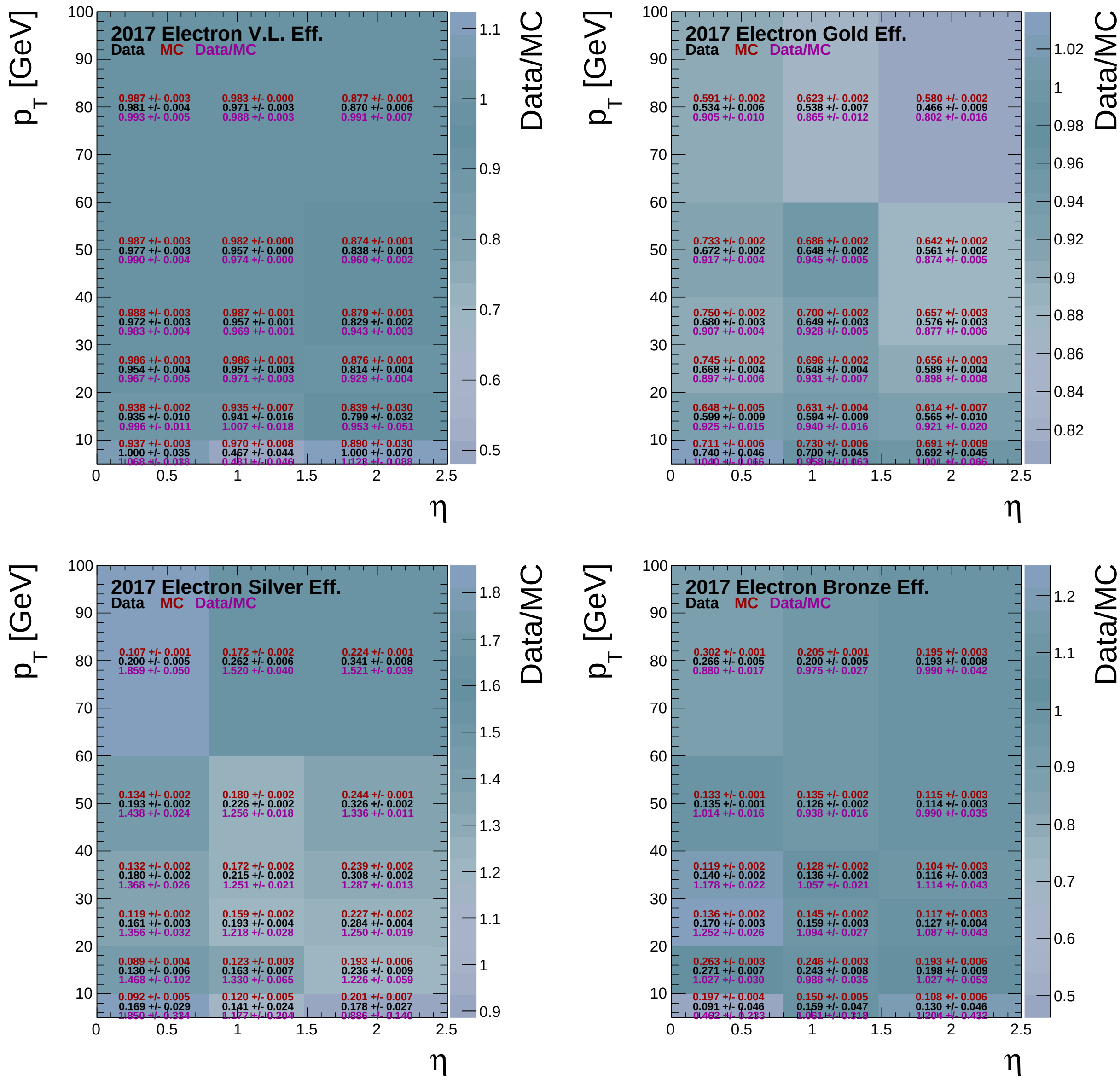

Figure 4.5: 2017 electron GSB efficiency and SF

4.4 Muon Tag-and-Probe

The muon Tag-and-Probe tools also uses a centrally curated CMSSW PhysicsTools in `CMSSW_10_6_X`. The software pipeline is identical to electons in that it consists of an ntuplizing and fitting stage. The code bases are separate but functionally identical. The muon Tag-and-Probe efficiencies are measured above 20 GeV using the Z boson. Muons below 20 GeV benefit from the J/ψ meson for Id measurements only. The η bins are divided into a central and forward regions around the endcaps at $|\eta| = 2.1$. In total there are three sets of binnings: The low p_{T} J/ψ binning J/ψ^L used to measure muon Id below 20 GeV, the high p_{T} Z binning Z^H above 20 GeV, and the low p_{T} Z binning Z^L used to extrapolate isolation and impact parameter efficiencies down to 3 GeV. The explicit bin edges for each range are define as follows:

Muon Binning		
Range	p_T GeV	$\|\eta\|$
J/ψ^L	[3.0, 4.0, 5.0, 6.0, 7.0, 9.0, 14.0, 20.0]	[0, 1.2, 2.4]
Z^H	[10, 20, 30, 40, 60, 100]	[0, 1.2, 2.4]
Z^L	[6,8,10,14,18,22,28,32,38,44,50]	[0, 1.2, 2.4]

Topological dependecies for isolation and impact parameters prevent measurement using the J/ψ. About 30% of prompt J/ψ are produced from higher mass states χ_c and $\Psi(2S)$ thus J/ψ will be produced from a cascade inside jets and likely be unisolated [6]. Similary another 10% of all J/ψ are produced within b-jets and leading to non-prompt unisolated events [1].

The exact criteria chosen for the tag and probe vary between physics processes but are identical across the two Z ranges. The selections follow the standards defined from the centrally produced muon Tag-and-Probe efficiencies.

Data will have an implicit selection due to triggering to reflect this selection in MC tags are required to pass a trigger in the denominator of efficiency for all criteria in addition to matching HLT objects in HLT trigger collections. The triggers available vary from year to

Tag-and-Probe Muon Candidate Selection Criteria		
J/ψ		
Tag	Probe	Pair
isGlobalMuon numberOfMatchedStations>1 $p_{\mathrm{T}} > 5$ GeV Matches hltIterL3MuonCandidates	Matches hltTracksIter OR Maches hltMuTrackJpsiEffCtfTrackCands x	$2.8\text{GeV} < m_{\mu\mu} < 3.4\text{GeV}$ $\lvert z_{\mu_1} - z_{\mu_2}\rvert < 1$ cm x
Z		
passes tightID $\sum p_{\mathrm{T}}^{ch}/p_{\mathrm{T}} < 0.2$ $p_{\mathrm{T}} > 15$ GeV	No requirement x	$m_{\mu\mu} > 60$ GeV $\lvert z_{\mu_1} - z_{\mu_2}\rvert < 4$ cm x

year and are as follows:

- J/ψ 2016,2017,2018: `Mu7p5Tk2`
- Z 2016: `IsoTkMu22`
- Z 2017, 2018: `isoMu24eta2p1`

The Gold/Silver/Bronze efficiency definitions depend p_{T} and reflect the high and low binning separations between Z and J/ψ. The low p_{T} muons include the Id measured by J/ψ as well as the extrapolated efficiencies from SIP3D and isolation fits in Z_L. The high p_{T} muons are composed of all the factors directly measured in Z_H :

$p_{\mathrm{T}} \in [3, 20)$

$$\begin{aligned}
\epsilon_{\text{Gold}} &= \epsilon_{\text{ID}}^{J/\psi} \times \epsilon_{\text{Isolated}|\text{ID}}^{Z_L} \times \epsilon_{\text{Prompt}|(\text{ID}\cap\text{Isolated})}^{Z_L} \\
\epsilon_{\text{Silver}} &= \epsilon_{\text{ID}}^{J/\psi} \times \epsilon_{\text{Isolated}|\text{ID}}^{Z_L} \times (1 - \epsilon_{\text{Prompt}|(\text{ID}\cap\text{Isolated})}^{Z_L}) \\
\epsilon_{\text{Bronze}} &= 1 - (\epsilon_{\text{ID}}^{J/\psi} \times \epsilon_{\text{Isolated}|\text{ID}}^{Z_L})
\end{aligned} \tag{4.5}$$

$p_{\mathrm{T}} \in [20, 100]$

$$\begin{aligned}
\epsilon_{\text{Gold}} &= \epsilon_{\text{ID}}^{Z_H} \times \epsilon_{\text{Isolated}|\text{ID}}^{Z_H} \times \epsilon_{\text{Prompt}|(\text{ID}\cap\text{Isolated})}^{Z_H} \\
\epsilon_{\text{Silver}} &= \epsilon_{\text{ID}}^{Z_H} \times \epsilon_{\text{Isolated}|\text{ID}}^{Z_H} \times (1 - \epsilon_{\text{Prompt}|(\text{ID}\cap\text{Isolated})}^{Z_H}) \\
\epsilon_{\text{Bronze}} &= 1 - (\epsilon_{\text{ID}}^{Z_H} \times \epsilon_{\text{Isolated}|\text{ID}}^{Z_H})
\end{aligned} \tag{4.6}$$

The ID efficiency with statistical errors for both data and MC are shown in Figure 4.6. The other efficiencies for each year for all p_{T} ranges are included in the appendix. The overlapping bins between J/ψ and Z do not all match within statistical uncertainties. However, the average deviation of the efficiency central values are 0.02% for MC and 1% for data.

The extrapolation of the vertexing and isolation efficiencies below 20 GeV is done by fitting a quadratic polynomial to the efficiencies on the Z_L interval. Both data and MC are shown in Figure 4.7. The errors for each bin are the combined statistical and systematic errors from Table **??** and are adjusted before the polynomial fit. Any efficiencies below 20 GeV are then reported from the fit model. The fit errors are the 68% confidence interval combined with the systematic errors. The worst observed P-value is $\approx 2\%$ but most of the fits are high quality.

The very loose and the efficiency components combined into Gold, Silver, and Bronze are summarized in Figure 4.8, the other years are included in the appendix. The tool used to store/calculate efficiencies can be found at `https://github.com/Jphsx/LepTool`. The cumulative efficiency for a muon also includes the efficiency of the VeryLoose selection and is defined as:

$$\epsilon_{\mu} = \epsilon_{\text{VeryLoose}} \times \epsilon_{\text{Gold/Silver/Bronze}} \tag{4.7}$$

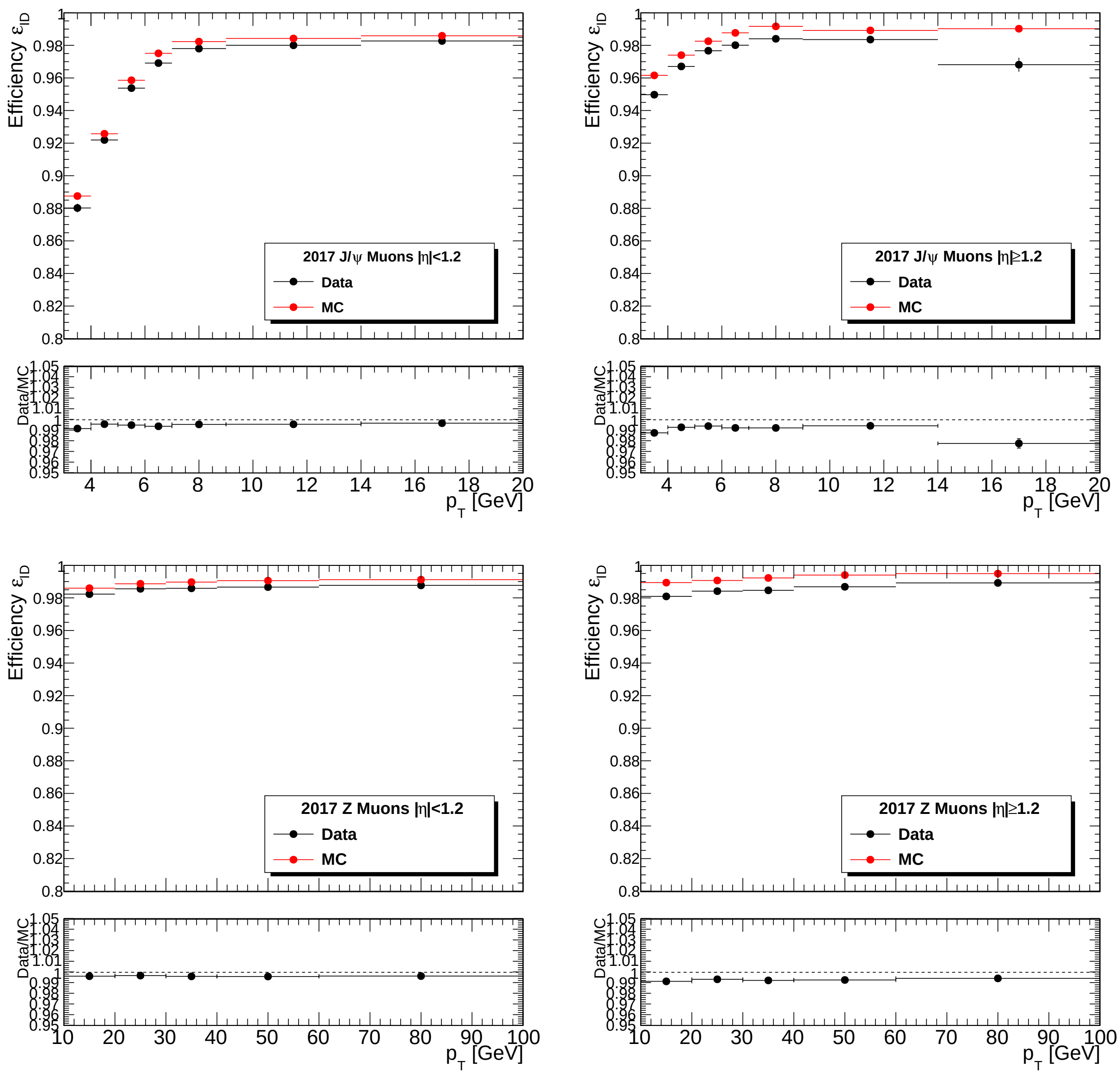

Figure 4.6: Tag-and-Probe efficiencies for the Medium Id in 2017. The left plots show the barrel while the right plots show the endcaps. The top fits use J/ψ resonance while the bottom use the Z resonance.

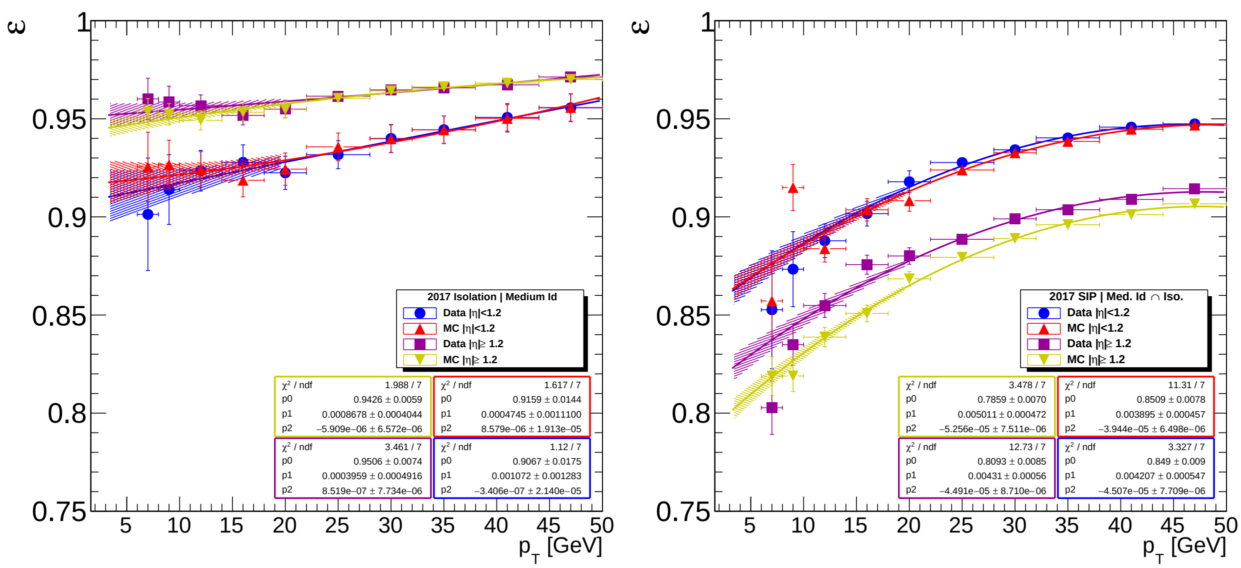

Figure 4.7: The fitted muon isolation and SIP3D efficiencies for 2017. Includes both data and MC which are separated between barrel and endcap.

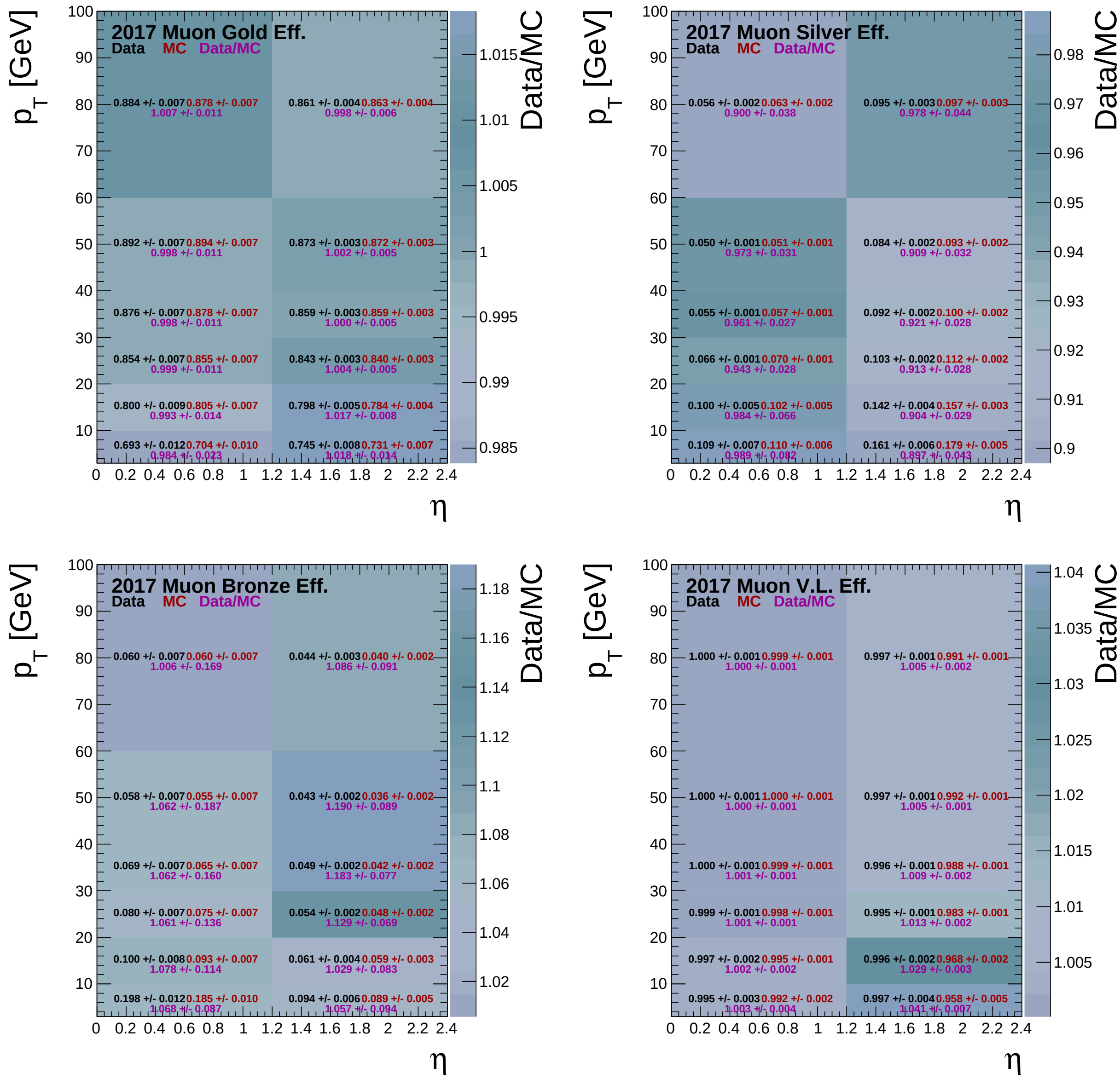

Figure 4.8: The combined efficiency components from equations 4.5 and 4.6 and Very Loose for 2017. The low-p_{T} region (< 20 GeV) includes the contributions from J/ψ as well as the isolation and SIP3D extrapolations. Propagated errors are treated as uncorrelated.

4.5 Lepton Systematics and Scale Factors

The systematic error for the electron and muon efficiencies are derived by varying the Tag-and-Probe signal and background models, slimming and widening the mass window , and increasing and decreasing the number of bins used in the fit. The systematic error is defined as the maximum spread in efficiencies between the modeling variations with an example spread shown in Figure Z. Rather than compute the systematic error for every bin, similarities between neighboring bins motivates using a simplified bin approach which was chosen qualitatively by the background shape. The same η bins are utilized according to lepton flavor, but the p_{T} bins are consolidated into a high and low bin pivoting on 20 GeV. A high and low systematic is derived for each selection criteria per flavor per year and is applied to the efficiencies that fall within the corresponding p_{T} and η range.

Scale factors are derived bin by bin for each criteria per flavor per year by finding the ratio of efficiencies in data to Monte Carlo. The scale factor variance is propagated by combining both the statistical error from the Tag-and-Probe in quadrature with the systematic error. An example set of scale factors for 2017 muon criteria is shown in Figure Z. Additional scale factors are also needed adjusting the differences between samples which are either created with a full simulation or fast simulation. The Fast to Full factor is obtained by extracting the criteria efficiency ratio between full and fast sim ttbar samples.

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Appendix A

My Appendix, Next to my Spleen

There could be lots of stuff here