$Z \to \tau\tau \to \mu\tau_h$

ATLAS Tau Workshop
Niels Bohr Institute, Copenhagen

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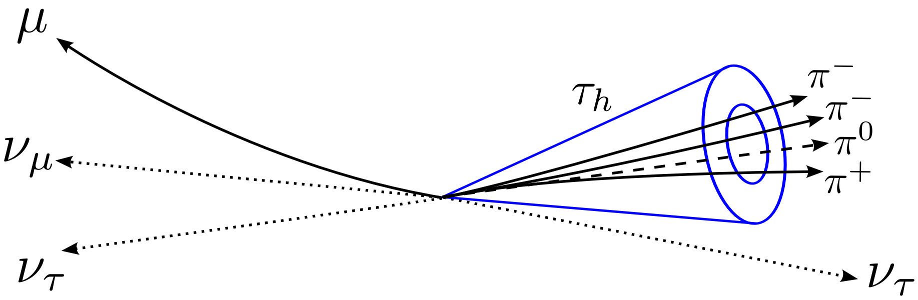
April 16, 2009

Outline

Introduction and Selection



μ
ν_μ
ν_τ
τ_h
π^-
π^-
π^0
π^+
ν_τ

Preface

- Goal: to select $Z \to \tau\tau \to \mu\tau_h$ in early data (10-100 pb^{-1}), to select a control sample of hadronic taus.
- Use only fully simulated `mc08` samples.
- Severe selection criteria to get a relatively pure sample.
- We show $b\bar{b}$ production is a dominant **QCD background**.
- We use a **fake-rate scaling technique** for getting shape and normalization of the $b\bar{b}$ background.
- Very **tight muon isolation** to beat QCD
- We purpose a **new W/Z separating cut** based on $\Delta\phi$.
- Do not use the collinear approximation to reconstruct the Z mass to increase acceptance by avoiding $\cos(\phi_\mu - \phi_\tau) > -0.9$ cut.
- **No cut on the magnitude of MET**
- **New**: S/B improved from $5 \to 6.7$ by extending overlap removal to low p_T muons.

Preselection

All

- $|\eta| < 2.5$

Muons

- `StacoMuonCollection`
- `bestMatch`
- $\chi^2_{\mathrm{fit}}/\mathrm{DOF} < 40$

Electrons

- `ElectronAODCollection`
- `isEM & 0x37f7ff3 == 0` (tight)
- only selected for overlap removal

Tau-jets

- `TauRecContainer`

- Remove overlap between Tau-jets and muons in $\Delta R < 0.4$.
- Require $N(e) = 0$.

Post-selection ID

Muons

- $\chi^2_{\rm fit}/\mathrm{DOF} < 4$
- $\chi^2_{\rm match}/\mathrm{DOF} < 8$
- $p_{\rm T} > 15\,\mathrm{GeV}$

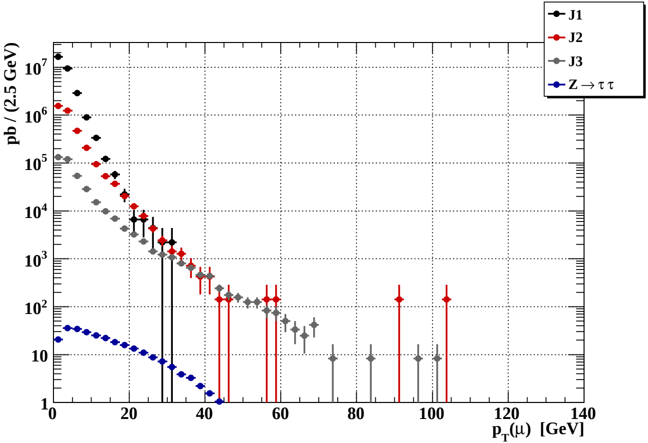
Tau-jets

- $E_{\rm T} > 15\,\mathrm{GeV}$
- $\mathrm{Likelihood} > 4$
- e/μ flags
- 1 or 3 prong
- $|\mathrm{charge}(\tau_h)| = 1$

In the case of multiple tau candidates in a single event, the candidates are sorted by Likelihood, and the candidate with the largest Likelihood above 4 is chosen to do the mass combination with a muon.

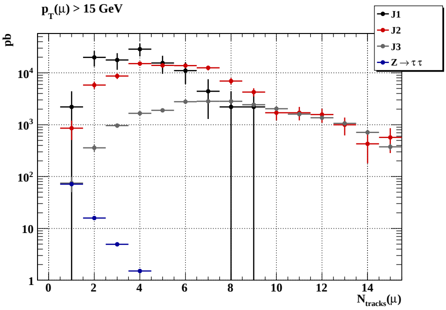
Dijet Background

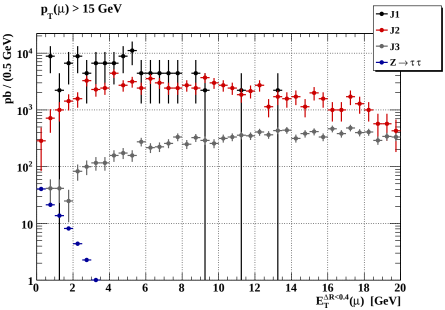
p_{T} of Muons



Muons from dijets are steeply falling in p_{T}. This is the main reason for requiring $p_{\mathrm{T}}(\mu) > 15\,\mathrm{GeV}$.

Two Muon Isolation Variables

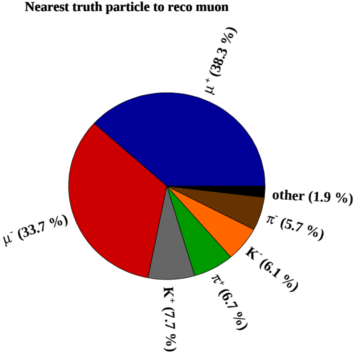


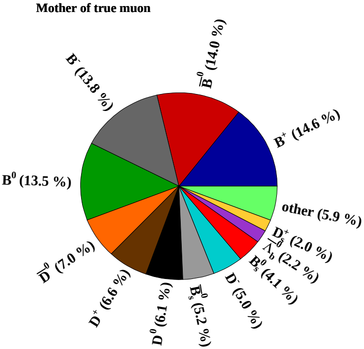


- $N_{\text{tracks}}(\mu; \Delta R < 0.4, p_{\text{T}} > 1\,\text{GeV}) = 1$
- $E_{\text{T}}^{\Delta R<0.4}(\mu) < 2\,\text{GeV}$

After these cuts, there are not enough events left to require tau ID. And to scale to 1 pb^{-1} requires large scale factors. Need a more exclusive sample. Where are these muons coming from? Answer:

Sources of Muons in J2 Dijets





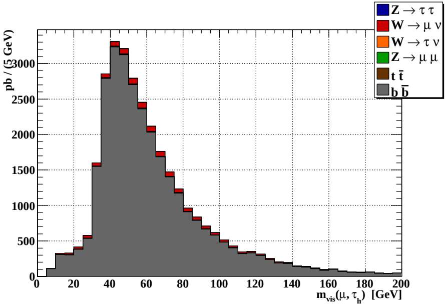
$\Rightarrow$ **Need to look at b-jets.** $\Rightarrow$ $b\bar{b} \to \mu + \text{jets}$

- Using a $b\bar{b}$ sample leaves out the $c\bar{c}$ (D-mesons) contribution.
- We also miss contamination due to muons from π/K decay in flight. **How can this be modeled?**

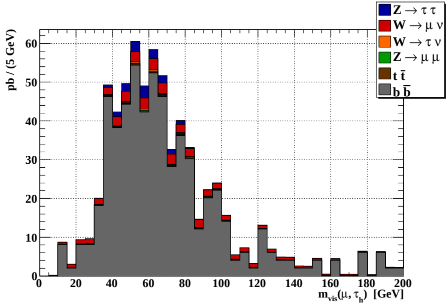
$b\bar{b}$ Background

$b\bar{b}$ Background Dwarfs Others

Before tau ID

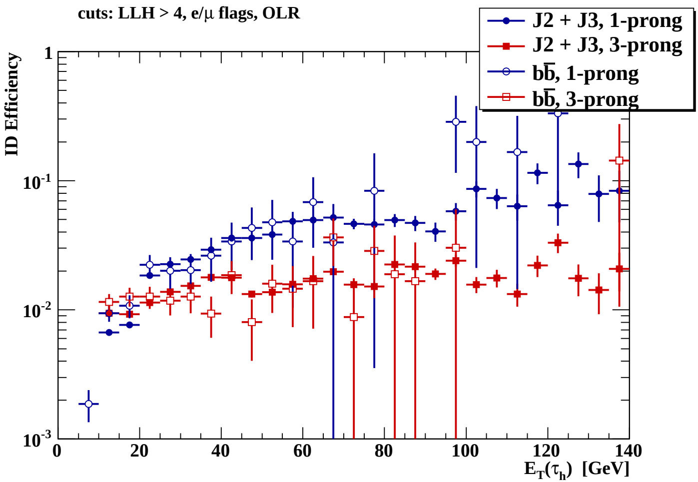


LLH > 4, e/μ flags



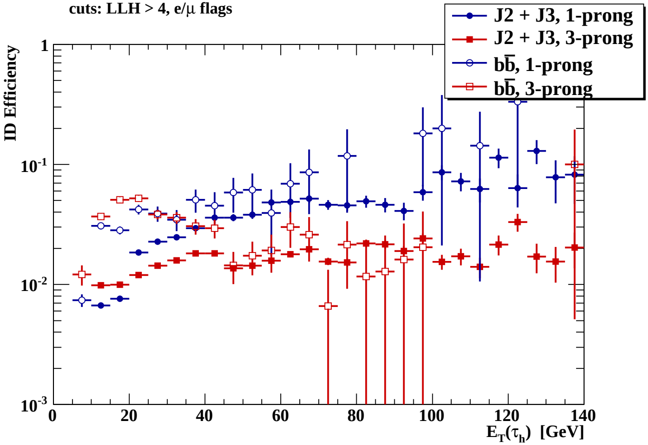
- $b\bar{b}$ sample filtered for a muon with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$
- only has 44 k events $\sim$ 0.5 pb^{-1}
- no events would survive the entire cut flow
- we artificially inflate the sample by **not** requiring tau ID and instead, **scale by the fake-rate** parameterized by E_{T} and n-prongs.
- scale tau candidate–by–candidate
- increases sample size by a factor $\sim$ 100

Jet Fake-rate



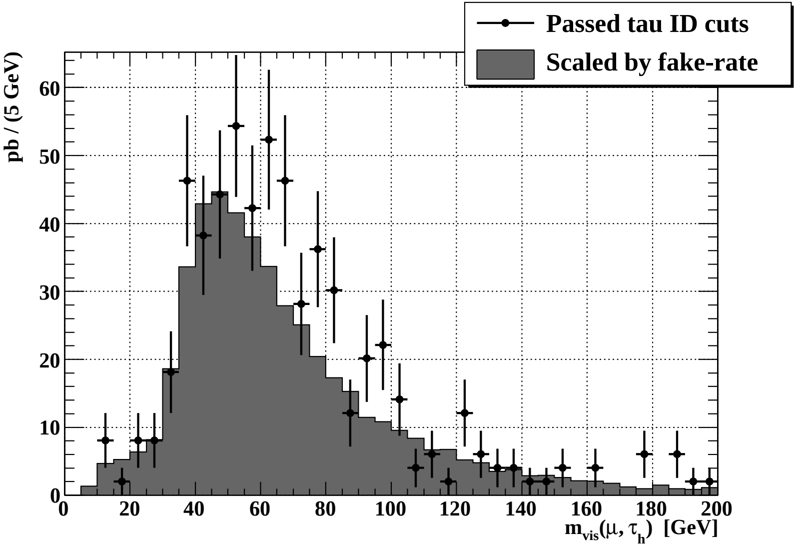
The b-jet fake-rate is within statistical agreement with the inclusive dijet fake-rate. Therefore, we use the more precisely measured dijet fake-rate.

Jet Fake-rate without e/μ overlap removal



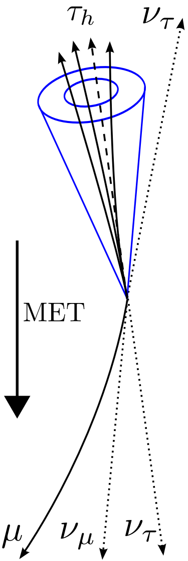
- b-jet fake-rate is significantly different from the inclusive jet fake-rate when one does *not* remove overlap with leptons.
- can e/μ flags be improved?
- veto track instead of whole candidate?

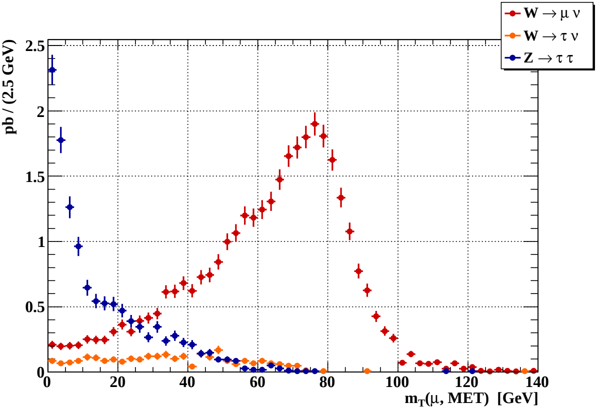
Evaluating the Scaling



W + jets Background

Transverse Mass



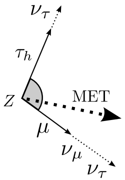


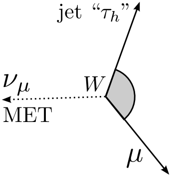
Transverse mass is small when $\Delta\phi$ is small.

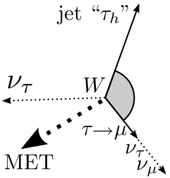
$$m_{\mathrm{T}}(\mu, \mathrm{MET}) = \sqrt{2\, p_{\mathrm{T}}(\mu) \cdot \mathrm{MET} \cdot (1 - \cos \Delta\phi)}$$

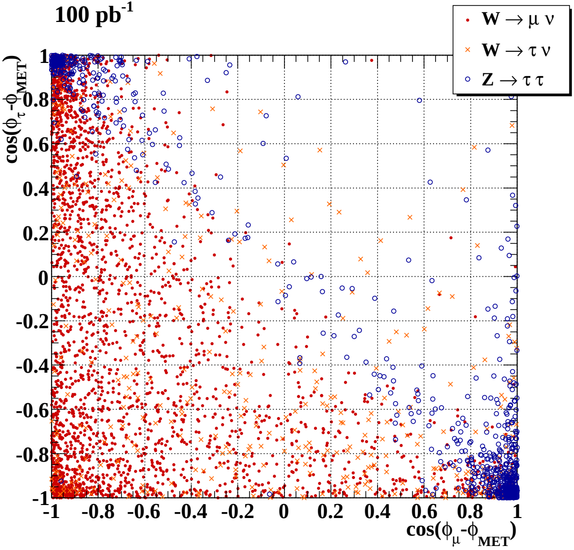
There is a better separating variable...

Angular Correlations



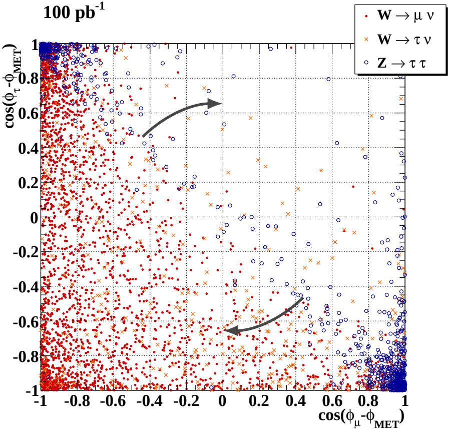






Angular Correlations

One could just cut along the diagonal, but since the cut is a straight line, we can rotate this space clockwise and project down.



$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos(\phi_\mu - \phi_{\rm MET}) \\ \cos(\phi_\tau - \phi_{\rm MET}) \end{pmatrix}$$

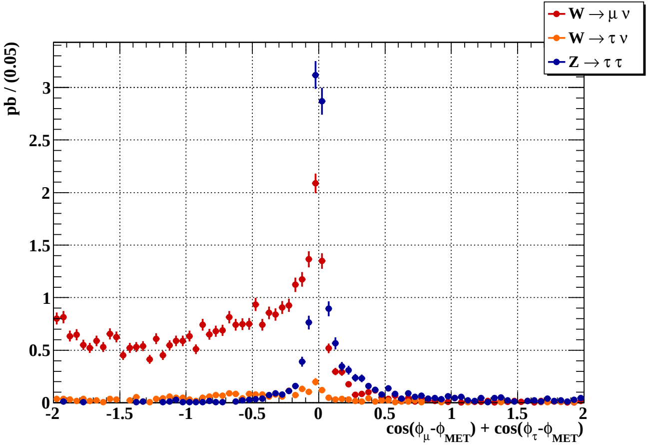
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$\theta = -\pi/4$$

$$\Rightarrow \quad x' = \left[\cos(\phi_\mu - \phi_{\rm MET}) + \cos(\phi_\tau - \phi_{\rm MET})\right] / \sqrt{2}$$

Angular Correlations

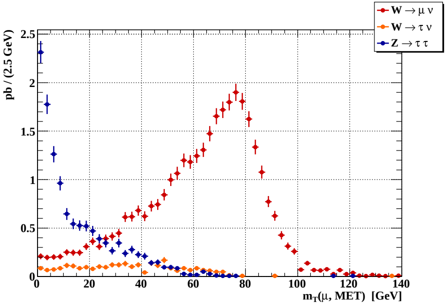
A variable that is remarkably characteristic for the signal!



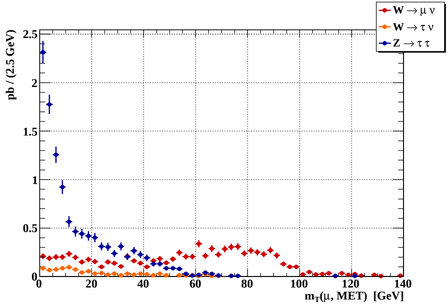
cut: $\cos(\phi_\mu - \phi_{\mathrm{MET}}) + \cos(\phi_\tau - \phi_{\mathrm{MET}}) > -0.15$

Angular Correlations

Before



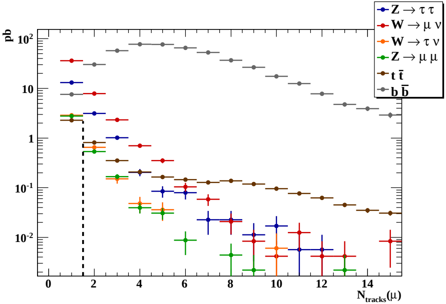
After

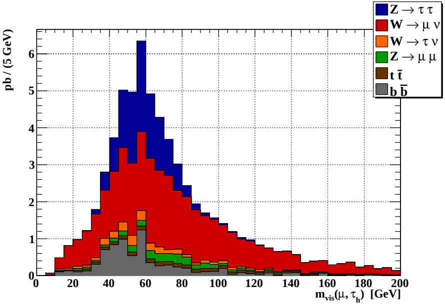


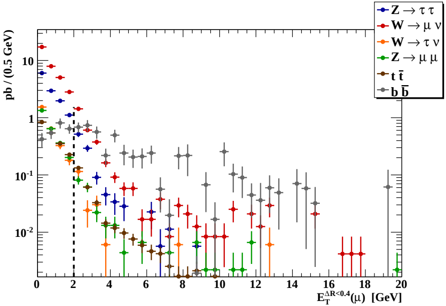
- This cut on the $\sum \cos \Delta\phi$ and $m_{\mathrm{T}} < 50\,\mathrm{GeV}$ accepts **10% more signal** and **increases S/B by 17%** compared to just $m_{\mathrm{T}} < 30\,\mathrm{GeV}$.
- Accepts kinematic phase space where neutrino from τ_h is hard and MET does not align with the muon.
- **Not dependent on MET** scale or magnitude. Only dependent on ϕ measurements of objects and MET. **Smaller systematic error**.

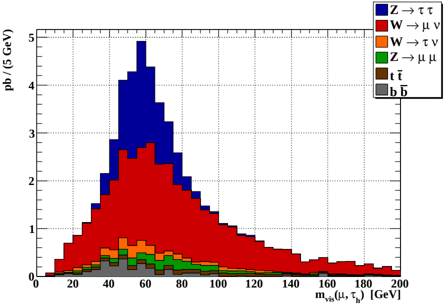
Cut Flow and Results

Muon Isolation

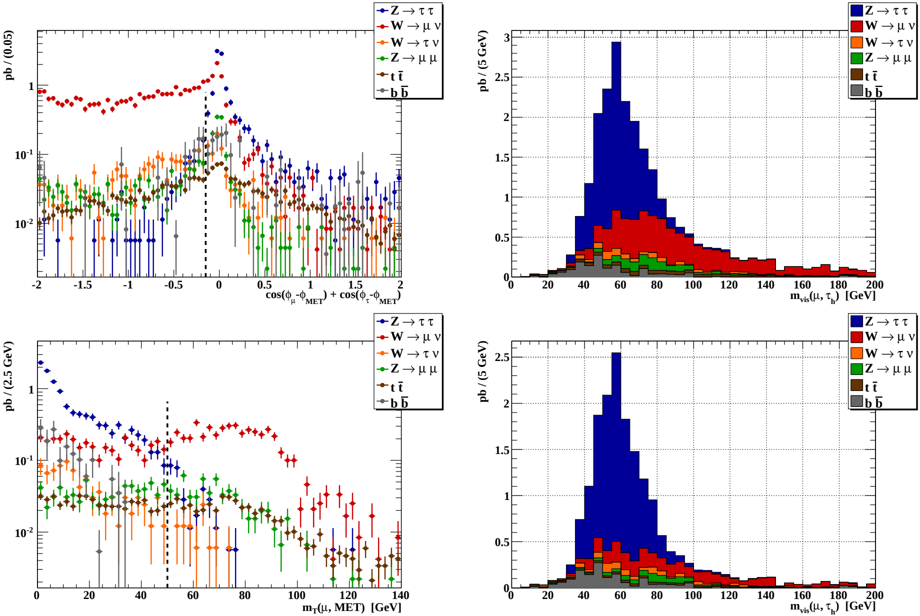




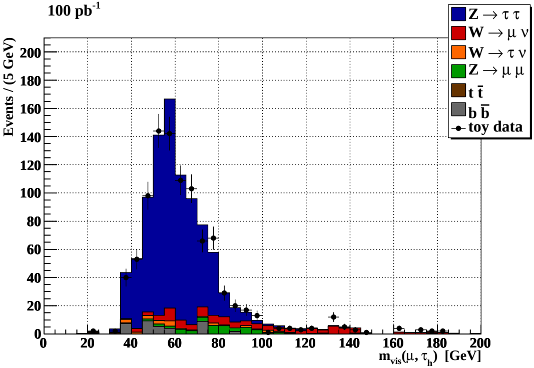




W vs Z Separation



Final Visible Mass Plot



736 signal events in $100\ \mathrm{pb}^{-1}$

- 40% more yield than CSC note with μ channel alone
- no MET cut $\Rightarrow$ tighter μ isolation
- $\sum \cos \Delta\phi$ cut

To demonstrate what the statistical significance will be with $100\ \mathrm{pb}^{-1}$of real data, the “data points” are randomly drawn from Poisson distributions with means equal to the sum of the Monte Carlo in each bin.

Cut Flow

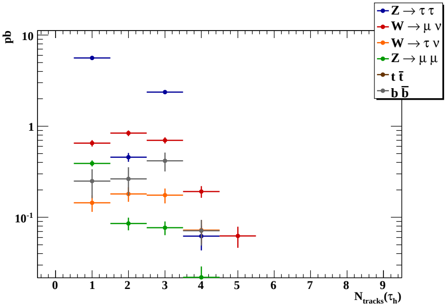
	$Z \to \tau\tau$	$W \to \mu\nu$	$W \to \tau\nu$	$Z \to \mu\mu$	$t\bar{t}$	$b\bar{b}$
generated	1130	10400	3600	1100	205	88500
$N(\mu) = 1$	222	7780	1210	440	83.8	72900
$N(\tau_h) > 0$	192	4420	820	260	83.8	72300
$\Delta R(\mu, \tau_h) > 0.4$	175	3390	542	183	83.8	65100
$p_{\mathrm{T}}(\mu) > 15$ GeV	67.3	3060	219	159	50.5	62500
$\chi^2_{\mathrm{fit}}(\mu)/\mathrm{DOF} < 4$	66.5	3030	217	157	50.1	61900
$\chi^2_{\mathrm{match}}(\mu)/\mathrm{DOF} < 8$	64.5	2960	211	153	48.8	60500
$E_{\mathrm{T}}(\tau_h) = 15 - 140$ GeV	46.7	1260	95.6	65.4	37.7	35500
$N(e) = 0$	42.2	1260	95.1	65.1	31.0	34700
$1 - 5$ prong	40.4	1150	86.8	59.5	28.8	30300
`Likelihood` > 4, e/μ flags	17.7	47.7	3.77	3.57	4.75	†485
$N_{\mathrm{tracks}}(\mu) = 1$	13.1	36.2	2.87	2.78	2.27	7.56
$E_{\mathrm{T}}^{\Delta R<0.4}(\mu) < 2$ GeV	12.1	33.1	2.68	2.55	1.97	2.42
$\sum \cos \Delta\phi > -0.15$	11.3	8.22	0.941	1.31	1.05	1.50
$m_{\mathrm{T}}(\mu, \mathrm{MET}) < 50$ GeV	11.0	3.30	0.857	0.719	0.512	1.50
$N(\tau_h) \leq 2$	8.48	2.45	0.579	0.576	0.0131	1.01
1 or 3 prong	7.96	1.35	0.32	0.468	0.0114	0.666
$\lvert\mathrm{charge}(\tau_h)\rvert = 1$	7.96	1.34	0.32	0.466	0.011	0.645
OS	7.82	0.994	0.241	0.396	0.0097	0.365
$m_{\mathrm{vis}}(\mu, \tau_h) = 35 - 80$ GeV	7.36(20)	0.40(4)	0.16(3)	0.19(2)	0.003(1)	0.35(10)

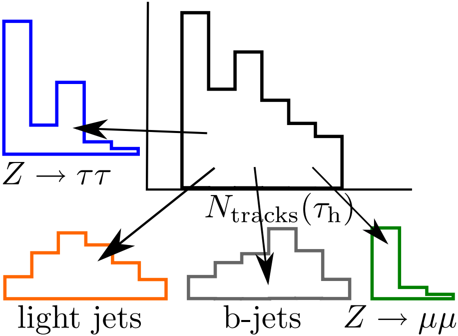
cross sections in pb. $S/B = 6.7$

† denotes the beginning of tau ID scaling

Fit N_{tracks}

Once we have this control sample, we can fit the $N_{\text{tracks}}(\tau_{\text{h}})$ to determine tau ID efficiency.





- each shape should be able to be determined from data
- can bin in E_{T}, η, etc. as statistics allow
- currently working on Monte Carlo proof of concept
- hope to collaborate with Justin, Soshi, *et al.*

Summary

- We estimate a dominant part of the QCD background from $b\bar{b}$ using tau ID fake-rate scaling to artificially inflate the sample size.
- Taming the QCD background will require much more severe isolation cuts than those in the CSC note.
- We introduce a novel way of separating Z from $W + \text{jets}$ by noting angular correlations and cutting on $\cos(\phi_\mu - \phi_\text{MET}) + \cos(\phi_\tau - \phi_\text{MET})$ in addition to the transverse mass.
- $Z \rightarrow \tau\tau \rightarrow \mu\tau_\text{h}$ can be selected with $S/B \approx 6$–7, neglecting the background from light-flavor dijets with π/K decays in flight.
- The lepton filtered JX samples should take into consideration the both c and b-flavor dijets, but we still need to figure out the background from π/K decay in flight.
- This analysis expects ~ 740 signal events in $100\ \text{pb}^{-1}$.
- Forthcoming COM note documenting this analysis.

Final Remarks on Common Benchmark Analysis

- due to combinatoric issues, not best to create DPD with derived quantities
- as long as `TauDPDMaker` is doing some reasonable skimming, no need to make more data redundancy
- having a common validated analysis toolset is a great idea
- selectors and user data calculators
- hasn't PAT already made some recommendations?
- Serban's `TauJetSelector`
- *e.g.* `MilanoElectronSelector`, `PennIsolatedMuonSelector`, `CollinearMassCalculator`
- put in `TauTools`?

Back Up Slides

Raw Cut Flow

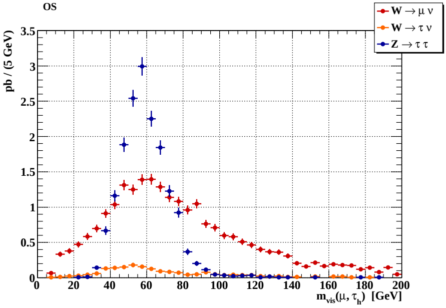
	$Z \to \tau\tau$	$W \to \mu\nu$	$W \to \tau\nu$	$Z \to \mu\mu$	$t\bar{t}$	$b\bar{b}$
generated	199434	2479717	598401	499689	487286	43960
$N(\mu) = 1$	39310	1873201	200511	200210	198626	36230
$N(\tau_h) > 0$	33980	1062371	135822	118182	198577	35891
$\Delta R(\mu, \tau_h) > 0.4$	30890	813982	89929	83416	198489	32337
$p_{\mathrm{T}}(\mu) > 15$ GeV	11892	734696	36301	72289	119794	31019
$\chi^2_{\mathrm{fit}}(\mu)/\mathrm{DOF} < 4$	11757	728068	35951	71532	118784	30758
$\chi^2_{\mathrm{match}}(\mu)/\mathrm{DOF} < 8$	11394	711033	35035	69751	115754	30052
$E_T(\tau_h) = 15 - 140$ GeV	8250	302860	15848	29775	89506	17640
$N(e) = 0$	7464	301430	15769	29632	73558	17227
$1 - 5$ prong	7143	276197	14390	27098	68230	15061
`Likelihood` > 4	3419	12242	670	1796	13217	15061
e flag	3137	11420	625	1626	11275	15061
μ flag	3135	11417	625	1623	11274	20828
$N_{\mathrm{tracks}}(\mu) = 1$	2320	8678	476	1264	5385	357
$E_T^{\Delta R<0.4}(\mu) < 2$ GeV	2132	7933	445	1159	4660	121
$\sum \cos\Delta\phi > -0.15$	1994	1968	156	596	2487	79
$m_{\mathrm{T}}(\mu, \mathrm{MET}) < 50$ GeV	1937	790	142	327	1213	79
$N(\tau_h) \leq 2$	1499	586	96	262	31	54
1 or 3 prong	1407	324	53	213	27	30
$\lvert\mathrm{charge}(\tau_h)\rvert = 1$	1406	320	53	212	26	29
OS	1382	238	40	180	23	17
$m_{\mathrm{vis}}(\mu, \tau_h) = 35 - 80$ GeV	1300	96	26	88	8	16

unscaled number of events

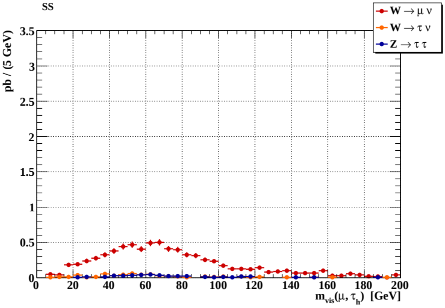
OS vs SS

$W \to \mu\nu$ + jets and $W \to \tau\nu \to \mu\nu\nu$ + jets are the dominant EW backgrounds, the jets faking tau ID.

Opposite Sign



Same Sign



W backgrounds are OS biased.

Datasets

Dataset	Events	Cross Section [pb]	$\int dt\, \mathcal{L}$ [pb^{-1}]	1pb^{-1} scale factor
$Z \to \tau\tau$	199 k	1.13×10^3	177	5.66×10^{-3}
$W \to \mu\nu$	2480 k	10.4×10^3	240	4.17×10^{-3}
$W \to \tau\nu$	598 k	3.61×10^3	166	6.03×10^{-3}
$Z \to \mu\mu$	500 k	1.10×10^3	455	2.20×10^{-3}
$t\bar{t}$	487 k	205	2.37×10^3	422×10^{-6}
$b\bar{b}$	44 k	88.5×10^3	0.497	2.01
J1	390 k	864×10^6	452×10^{-6}	2.21×10^3
J2	393 k	56.0×10^6	7.02×10^{-3}	142
J3	396 k	3.29×10^6	0.12	8.30

The $W \to \tau\nu$ dataset was filtered at the generator for an electron or a muon.

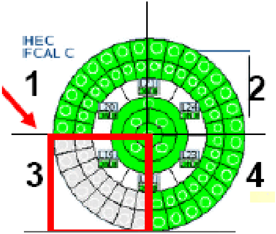
Dataset File Names

```
mc08.106052.PythiaZtautau.recon.AOD.e347_s462_r541
mc08.106021.PythiaWmunu_1Lepton.recon.AOD.e352_s462_r541
mc08.106022.PythiaWtaunu_1Lepton.recon.AOD.e352_s462_r541
mc08.106051.PythiaZmumu_1Lepton.recon.AOD.e347_s462_r541
mc08.105200.T1_McAtNlo_Jimmy.recon.AOD.e357_s462_r541
mc08.108405.PythiaB_bbmu15X.recon.AOD.e347_s462_r541
mc08.105010.J1_pythia_jetjet.recon.AOD.e344_s479_r541
mc08.105011.J2_pythia_jetjet.recon.AOD.e344_s479_r541
mc08.105012.J3_pythia_jetjet.recon.AOD.e344_s479_r541
```

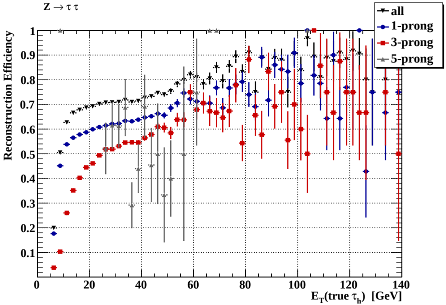
- all reconstructed with Athena 14.2.20.3
- `r541: 14.2.20.3, OFLCOND-00-00-03`

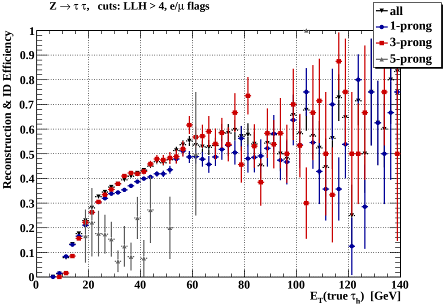
<u>Issues</u>

1. HEC off: $-3.5 < \eta < -1.5$ and $-\pi/2 < \phi < 0$
2. Muon etcone variables mis-filled in AOD. etcone40 $\rightarrow$ etcone30. This means that my muon calo isolation cut is actually on $\Delta R < 0.3$ and not $\Delta R < 0.4$.



Tau-jet Efficiency



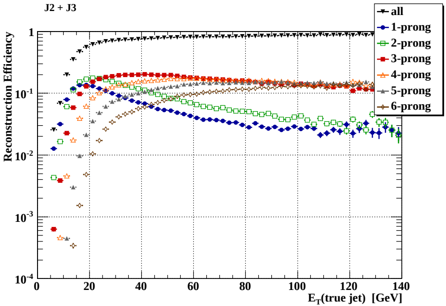


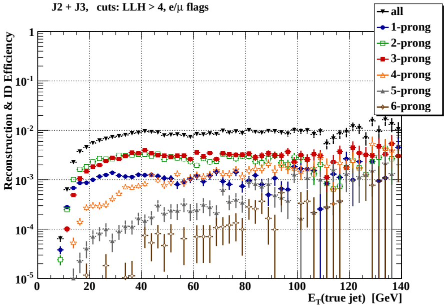
$$\varepsilon = \frac{\text{n-prong candidates (passing ID cuts), matched to a true n-prong } \tau_h}{\text{true n-prong } \tau_h\text{s}}$$

tools to get true τ_h:

`EVTruthTauDecayCompositeCreator`, `EVUDTruthTauVisible`

Jet Fake-rate

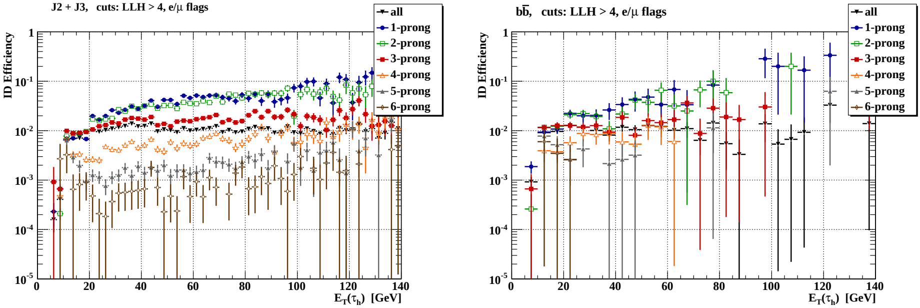




$$\varepsilon = \frac{\text{n-prong candidates (passing ID cuts), matched to a true jet}}{\text{all true jets}}$$

true jets = `Cone4TruthJets`

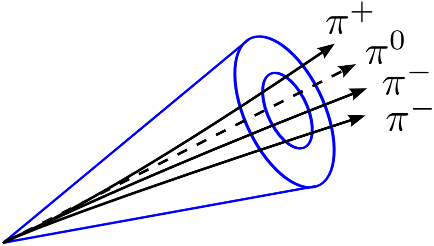
Jet Fake-rate



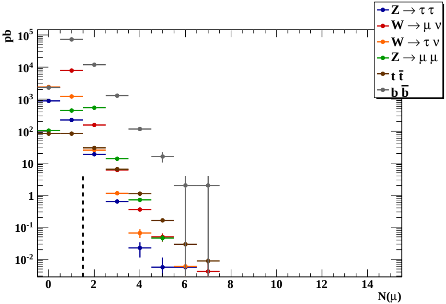
$$\varepsilon = \frac{\text{n-prong candidates passing ID cuts}}{\text{n-prong candidates}}$$

Tau Branching Fractions

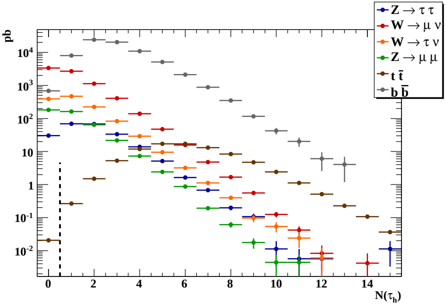
$\tau^- \to$	$e^- \, \bar{\nu}_e \, \nu_\tau$	17.8%	leptonic 35%
	$\mu^- \, \bar{\nu}_\mu \, \nu_\tau$	17.4%	
	$\pi^- \, \pi^0 \, \nu_\tau$	25.5%	1 prong 50%
	$\pi^- \, \nu_\tau$	10.9%	
	$\pi^- \, 2\pi^0 \, \nu_\tau$	9.3%	
	$K^- \, N\pi^0 \, NK^0 \, \nu_\tau$	1.5%	
	$\pi^- \, 3\pi^0 \, \nu_\tau$	1.0%	
	$\pi^- \, \pi^- \, \pi^+ \, \nu_\tau$	9.0%	3 prong 15%
	$\pi^- \, \pi^- \, \pi^+ \, \pi^0 \, \nu_\tau$	4.6%	



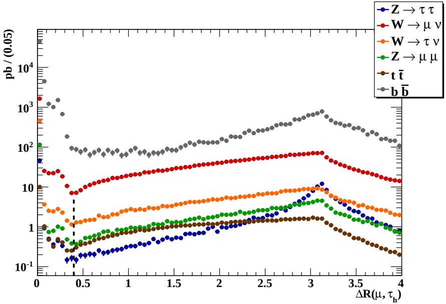
Entire Cut Flow



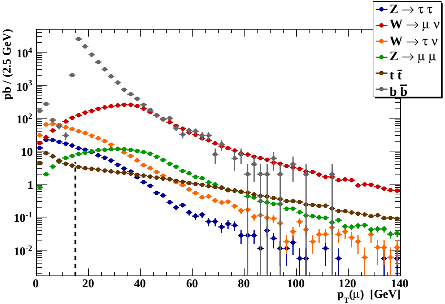
Z → τ τ
W → μ ν
W → τ ν
Z → μ μ
t t̄
b b̄
pb
N(μ)



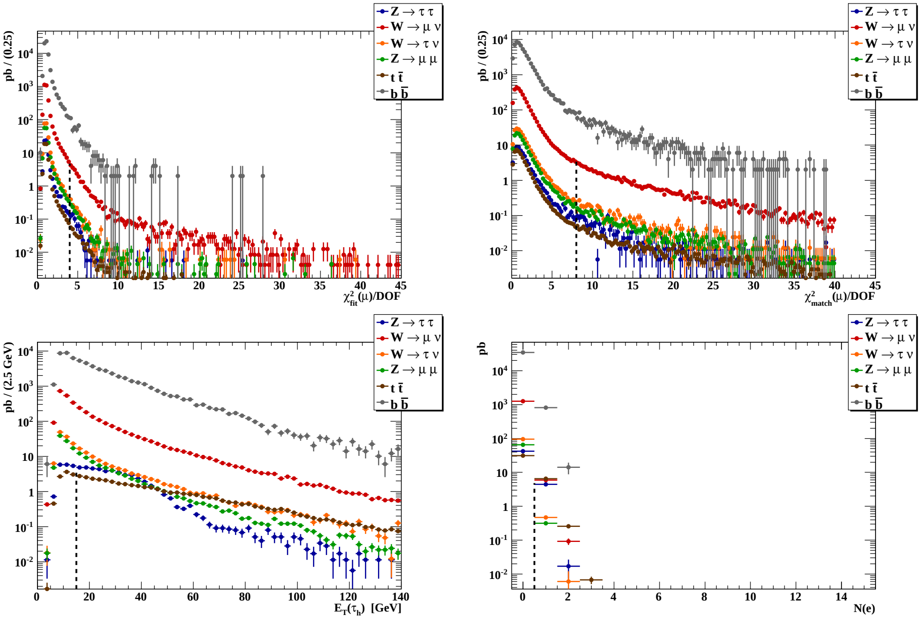
Z → τ τ
W → μ ν
W → τ ν
Z → μ μ
t t̄
b b̄
pb
N(τ_h)

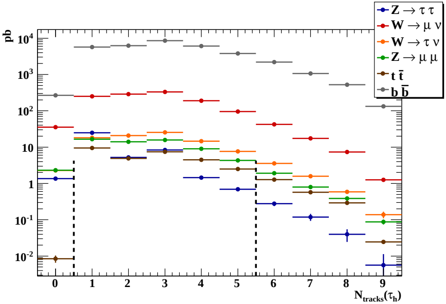


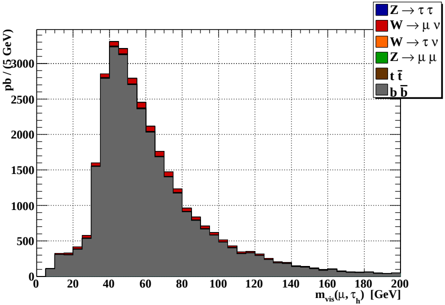
Z → τ τ
W → μ ν
W → τ ν
Z → μ μ
t t̄
b b̄
pb / (0.05)
ΔR(μ, τ_h)

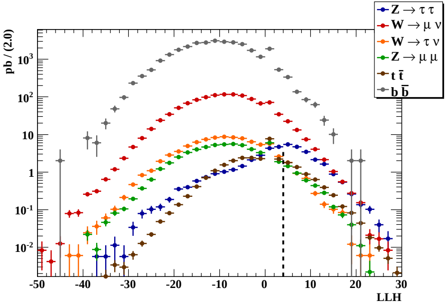


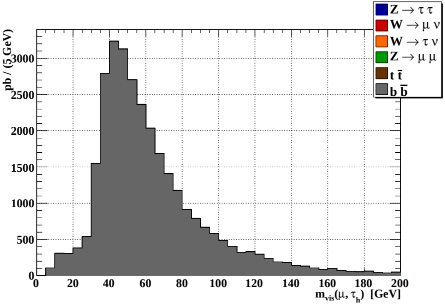
Z → τ τ
W → μ ν
W → τ ν
Z → μ μ
t t̄
b b̄
pb / (2.5 GeV)
p_T(μ) [GeV]

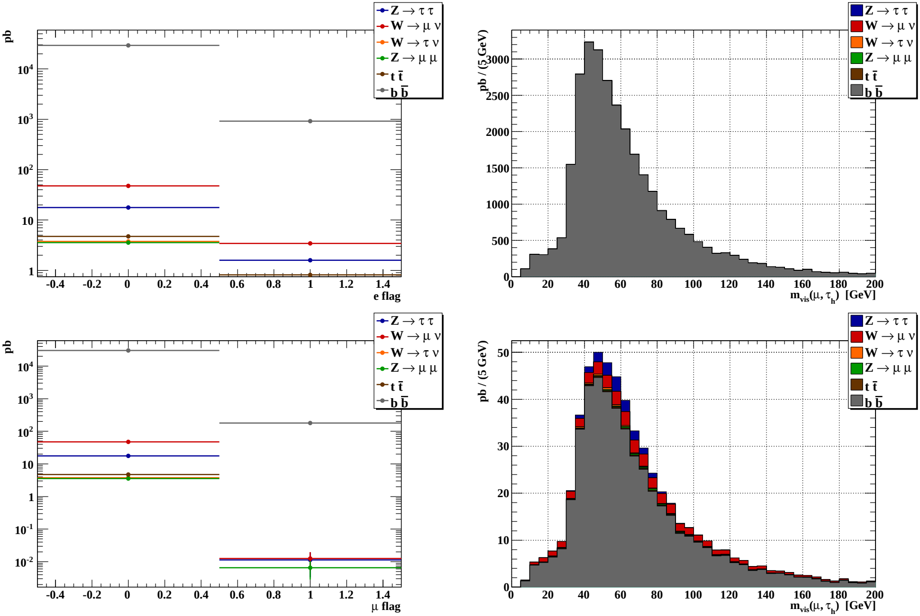

Z → τ τ
W → μ ν
W → τ ν
Z → μ μ
t t̄
b b̄
pb / (0.25)
χ²fit(μ)/DOF
χ²match(μ)/DOF
pb / (2.5 GeV)
ET(τh) [GeV]
pb
N(e)


$Z \to \tau\tau$
$W \to \mu\nu$
$W \to \tau\nu$
$Z \to \mu\mu$
$t\bar{t}$
$b\bar{b}$
pb
$N_{tracks}(\tau_h)$

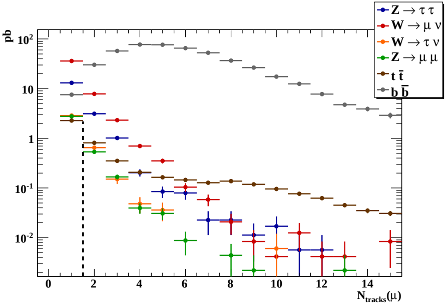

$Z \to \tau\tau$
$W \to \mu\nu$
$W \to \tau\nu$
$Z \to \mu\mu$
$t\bar{t}$
$b\bar{b}$
pb / (5 GeV)
$m_{vis}(\mu, \tau_h)$ [GeV]


$Z \to \tau\tau$
$W \to \mu\nu$
$W \to \tau\nu$
$Z \to \mu\mu$
$t\bar{t}$
$b\bar{b}$
pb / (2.0)
LLH

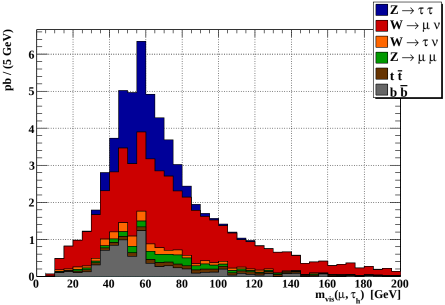

$Z \to \tau\tau$
$W \to \mu\nu$
$W \to \tau\nu$
$Z \to \mu\mu$
$t\bar{t}$
$b\bar{b}$
pb / (5 GeV)
$m_{vis}(\mu, \tau_h)$ [GeV]



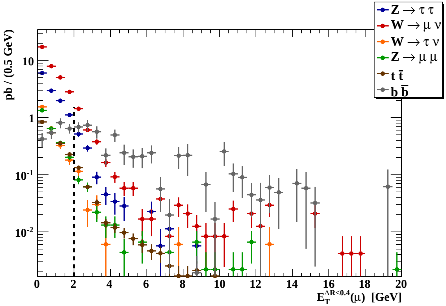
pb
e flag
pb / (5 GeV)
$m_{vis}(\mu, \tau_h)$ [GeV]
pb
μ flag
pb / (5 GeV)
$m_{vis}(\mu, \tau_h)$ [GeV]
Z → τ τ
W → μ ν
W → τ ν
Z → μ μ
t t̄
b b̄



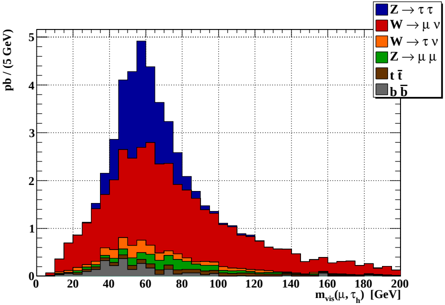
pb
10^2
10
1
10^{-1}
10^{-2}
0
2
4
6
8
10
12
14
$N_{tracks}(\mu)$
$Z \to \tau\tau$
$W \to \mu\nu$
$W \to \tau\nu$
$Z \to \mu\mu$
$t\bar{t}$
$b\bar{b}$



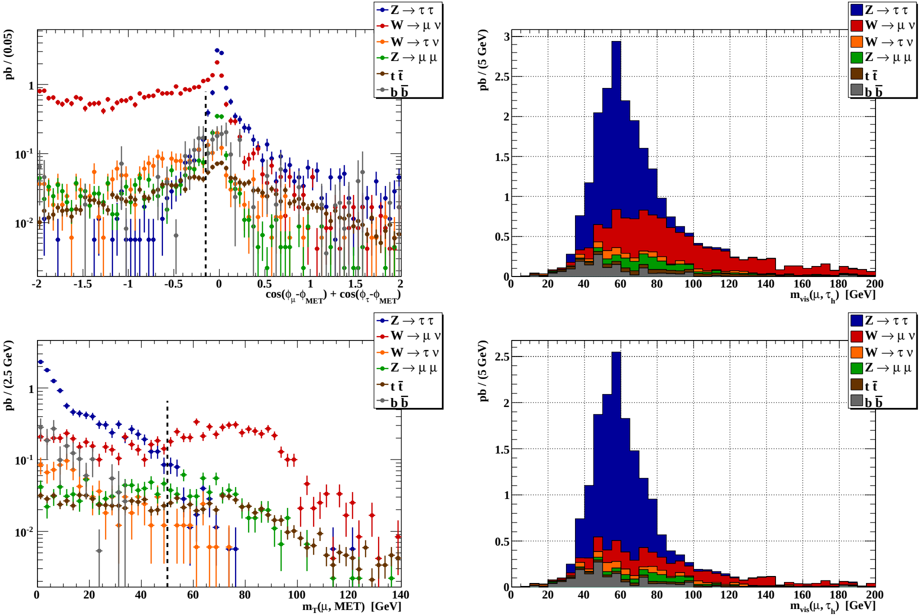
pb / (5 GeV)
0
1
2
3
4
5
6
0
20
40
60
80
100
120
140
160
180
200
$m_{vis}(\mu, \tau_h)$ [GeV]
$Z \to \tau\tau$
$W \to \mu\nu$
$W \to \tau\nu$
$Z \to \mu\mu$
$t\bar{t}$
$b\bar{b}$

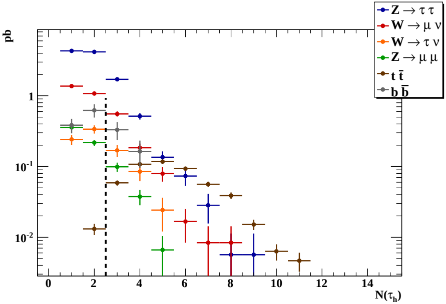


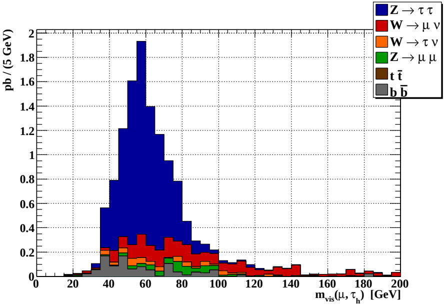
pb / (0.5 GeV)
10
1
10^{-1}
10^{-2}
0
2
4
6
8
10
12
14
16
18
20
$E_T^{\Delta R<0.4}(\mu)$ [GeV]
$Z \to \tau\tau$
$W \to \mu\nu$
$W \to \tau\nu$
$Z \to \mu\mu$
$t\bar{t}$
$b\bar{b}$

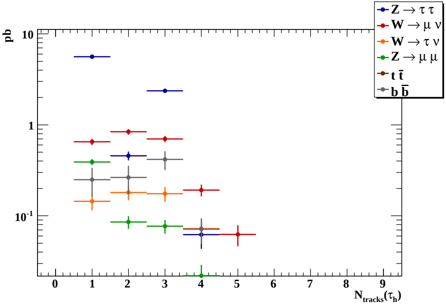


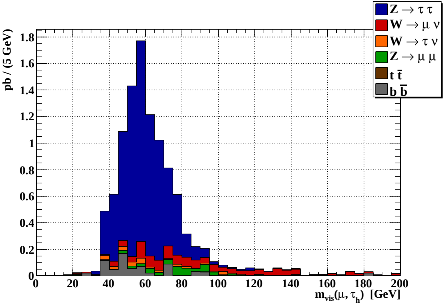
pb / (5 GeV)
0
1
2
3
4
5
0
20
40
60
80
100
120
140
160
180
200
$m_{vis}(\mu, \tau_h)$ [GeV]
$Z \to \tau\tau$
$W \to \mu\nu$
$W \to \tau\nu$
$Z \to \mu\mu$
$t\bar{t}$
$b\bar{b}$

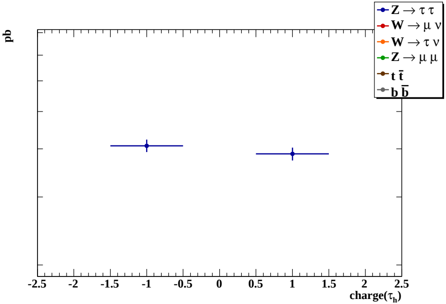

pb / (0.05)
cos(φ_μ-φ_MET) + cos(φ_τ-φ_MET)
pb / (5 GeV)
m_vis(μ, τ_h) [GeV]
pb / (2.5 GeV)
m_T(μ, MET) [GeV]
Z → τ τ
W → μ ν
W → τ ν
Z → μ μ
t t̄
b b̄

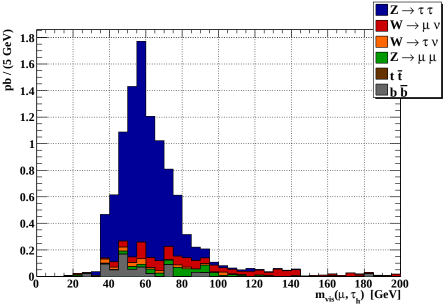

pb
Z → τ τ
W → μ ν
W → τ ν
Z → μ μ
t t̄
b b̄
N(τ_h)

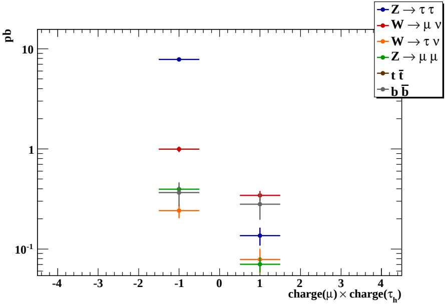

pb / (5 GeV)
Z → τ τ
W → μ ν
W → τ ν
Z → μ μ
t t̄
b b̄
m_vis(μ, τ_h) [GeV]

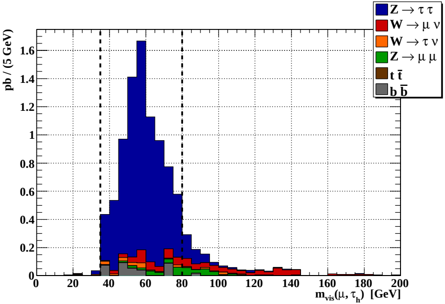

pb
Z → τ τ
W → μ ν
W → τ ν
Z → μ μ
t t̄
b b̄
N_tracks(τ_h)


pb / (5 GeV)
Z → τ τ
W → μ ν
W → τ ν
Z → μ μ
t t̄
b b̄
m_vis(μ, τ_h) [GeV]


pb
charge(τ_h)
$Z \to \tau\tau$
$W \to \mu\nu$
$W \to \tau\nu$
$Z \to \mu\mu$
$t\bar{t}$
$b\bar{b}$


pb / (5 GeV)
$m_{vis}(\mu, \tau_h)$ [GeV]
$Z \to \tau\tau$
$W \to \mu\nu$
$W \to \tau\nu$
$Z \to \mu\mu$
$t\bar{t}$
$b\bar{b}$


pb
charge(μ) $\times$ charge(τ_h)
$Z \to \tau\tau$
$W \to \mu\nu$
$W \to \tau\nu$
$Z \to \mu\mu$
$t\bar{t}$
$b\bar{b}$


pb / (5 GeV)
$m_{vis}(\mu, \tau_h)$ [GeV]
$Z \to \tau\tau$
$W \to \mu\nu$
$W \to \tau\nu$
$Z \to \mu\mu$
$t\bar{t}$
$b\bar{b}$