τ粒子へ崩壊するHiggs粒子の探索

津野 総司（高エネ研）
What’s ingredient?

Focusing on new physics searches at LHC

**Experimentalist:**
- Limited proofs ($\sigma$, $m$, ratio, angles...)
  - Model independent searches (SUSY)
  - Extension of SM measurements (Higgs)

**Theorist:**
- Many models (A...X,Y,Z)MSSM,GDM...
  - Interpretation of experimental data (New physics)
  - Perturbative expansion (Higher order BSM/QCD)

In term of Higgs searches,

**How do experimentalists collaborate with theorist?**
- SM, MSSM Higgs ($\rightarrow \tau \tau$) is a pretty tight theory.
- Many theoretical uncertainties in SM background prediction.

@MoriondEW2008

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Contents

1) Briefly summarize current baseline analysis.

2) Topics toward “discovery”. (experimentalist)
   -- SM DY \( Z \rightarrow \tau\tau \) measurement. (MSSM, Z’ searches)
   -- Jet Veto study.
   -- Missing \( p_T \) and Forward jets.
   -- ELWK Z measurement.

3) Discussion toward “discovery” (theorist)
   -- Analysis for “exclusion”.
   -- SM background prediction.
Higgs粒子探索
Tevatronから間接的にlow mass Higgsが好まれる。

LHCでのSM Higgs生成素過程は、

**Gluon fusion**    **Vector Boson Fusion (VBF)**

Gluon fusion ～ 10-50pb (~10,000 evts at 1fb⁻¹)
VBF production ～ 2-8pb (~2000 evts at 1fb⁻¹)

VBFは2番目に大きな断面積

VBF productionは、前後方にジェットを生み出すのが特徴。
H → ττ analysis

質量再構成できる数少ないチャンネル。

- H → γγ (σ_{MH}~1.7 GeV)
- H → ZZ → 4l (σ_{MH}~2.3 GeV)
- H → ττ (σ_{MH}~9 GeV)

- (H → bb (σ_{MH}~20 GeV))
- (H → μμ (σ_{MH} < natural width))

解析はバックグラウンドとの戦い。

High bkg. rejection ... VBF Higgs
Large cross section ... MSSM H → ττ
High Mass resolution ... MSSM H → μμ

Analysis for “Discovery”
Expecting ~100% uncertainty.

Target ~20 “signal” events
(cut-based analysis)
VBF $H \rightarrow \tau\tau$

110GeV ~ 130GeVで最も感度が高い。

解析モード:

ll-channel : Br.~12%, Trig.Acc~ 9.1%(e), 9.9%(μ)
lh-channel : Br.~46%, Trig.Acc~ 9.1%(e), 9.9%(μ)
   (High $p_T$ lepton, e $p_T>$25GeV, μ $p_T>$20GeV)
hh-channel : Br.~42%, Trig.Acc~ 3.7%
   (Hadronic $\tau(p_T>$35GeV, MET>40GeV)

解析に必要な事: 広範囲に渡って、日本groupがcontribute

Tau ID : Likelihood, NN (KEK/東大)
Forward jet : Efficiency/Calibration (東大)
Missing Et : Resolution (寺師氏、next talk)
Trigger : Combined Trigger
Central Jet veto : 鈴木氏、next talk
   (b-jet veto) : 廣瀬氏、next talk
MSSM Higgs Associated $bbh \rightarrow \tau\tau/\mu\mu$

Promising channel in large $\tan\beta$

Associate production with $b$-quark

Large coupling or narrow peak (experimental)

$(H \rightarrow \tau\tau)$  $(H \rightarrow \mu\mu)$

CMS Physics TDR 2006

SN-ATLAS-2007-063

10$fb^{-1}$

significance for $h \rightarrow \mu\mu$ search
Mass reconstruction

Collinear Approximation

$H \rightarrow \tau \tau$ mass reconstruction

\[ \tau_1 \quad \text{missing } p_T \quad \tau_2 \]

Collinear Mass

$\tau$ decay products

\[ M_{\tau\tau} = \sqrt{2(E_h + E_{\nu h})(E_l + E_{\nu l})(1 - \cos \theta_{\tau\tau})}. \]

\[ M_{\tau\tau} = \frac{M_{ll}}{\sqrt{x_{\tau l} x_{\tau h}}} \quad \text{for } x_{\tau} > 0 \]

where,

\[ x_{\tau h} = \frac{E_h}{E_h + E_{\nu h}} = \frac{h_x l_y - h_y l_x}{D_h}, \]

\[ x_{\tau l} = \frac{E_l}{E_l + E_{\nu l}} = \frac{h_x l_y - h_y l_x}{D_l}, \]

\[ x_{\tau \nu} = \frac{E_{\nu h}}{E_h + E_{\nu h}} = \frac{h_x l_y - h_y l_x}{D_{\nu h}}. \]

Jacobian

\[ J = \frac{\Delta M_{\tau\tau}}{\Delta \rho y} = \sqrt{\left( \frac{\partial M_{\mu\tau}}{\partial \rho x} \right)^2 + \left( \frac{\partial M_{\mu\tau}}{\partial \rho y} \right)^2}. \]

\[ J = \frac{1}{2} \frac{M_{ll}}{\sqrt{x_{\tau l} x_{\tau h}}} \sqrt{(x_{\tau l} h_x D_h^2 - x_{\tau h} l_x D_l^2)^2 + (x_{\tau l} h_x D_l^2 - x_{\tau h} l_x D_h^2)^2}. \]

Asymmetric: due to $m_\parallel < m_{\tau\tau}$

Mis-calibrated MET causes “mass shift”.

Understanding of MET is crucial.

Still asymmetric. (MET mis-calibration)
Forward Jet tagging

\[
\begin{align*}
\text{Leading jet } p_T &> 40 \text{GeV} \\
\text{Jet } p_T &> 20 \text{GeV, } |\eta| < 4.8
\end{align*}
\]

Forward jet reco. $\varepsilon$

\[
\begin{align*}
\text{Leading jet } \eta
\end{align*}
\]

\[
\begin{align*}
\text{Di-jet separation } \eta
\end{align*}
\]

\[
\begin{align*}
\text{Di-jet mass}
\end{align*}
\]

\[
\begin{align*}
\text{Opposite hemisphere ( } \eta_1 \times \eta_2 < 0 \text{ )} \\
\Delta \eta_{jj} > 4.4, \ m_{jj} > 700 \text{GeV} \\
\text{no 3rd jet}
\end{align*}
\]

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Central Jet Veto (CJV)

no color connection between final state partons.

less hadron activity in central

high density

less (color-string) density

Jet veto

Forward jet

ISR parton

hadron activity

high density

Big uncertainty in "Theory".

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optimization
Acceptance (VBF H)

<table>
<thead>
<tr>
<th>Detector oriented selection</th>
<th>Kinematics oriented selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control sample</td>
<td></td>
</tr>
</tbody>
</table>

**Remarks:**
- Irreducible background: $Z\tau\tau+$jets
- Reducible background: $t\bar{t}$bar/W+jets etc. ($t\bar{t}$bar is complicated object.)
  - (5% $ll$-mode, 45% real-tau mode, 50% $l+$jets mode)
- Kinematics-oriented selection: factor $\sim$4 for signal, $\sim$400 for backgrounds.

**Overall rejection** $\sim10^{7-8}$ rejection for reducible backgrounds.
Summary of background (VBF H)

lh-channel

<table>
<thead>
<tr>
<th></th>
<th>$Z \to \tau^+\tau^- + \text{jets}(\geq 1)$</th>
<th>$tt$</th>
<th>$Z \to l^+l^- + n \text{jets}$</th>
<th>$W \to \ell\nu + n \text{jets}$</th>
<th>diboson</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD</td>
<td>$172.5 \times 10^3$</td>
<td>$833 \times 10^3$</td>
<td>$787.2 \times 10^3$</td>
<td>$8649 \times 10^3$</td>
<td>$174.1 \times 10^3$</td>
</tr>
<tr>
<td>ELWK</td>
<td>1693</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full</td>
<td>$52.7(1) \times 10^3$</td>
<td>$209.8(2) \times 10^3$</td>
<td>$649.1(4) \times 10^3$</td>
<td>$4411(13) \times 10^3$</td>
<td>$32.0(1) \times 10^3$</td>
</tr>
<tr>
<td>Fast</td>
<td>$43.7(1) \times 10^3$</td>
<td>$179.1(2) \times 10^3$</td>
<td>$602.2(4) \times 10^3$</td>
<td>$3815(12) \times 10^3$</td>
<td>$28.0(1) \times 10^3$</td>
</tr>
<tr>
<td>Lep</td>
<td>$39.3(1) \times 10^3$</td>
<td>$156.4(2) \times 10^3$</td>
<td>$221.7(4) \times 10^3$</td>
<td>$3811(12) \times 10^3$</td>
<td>$23.7(1) \times 10^3$</td>
</tr>
<tr>
<td>Hadr</td>
<td>$3137(43)$</td>
<td>$5224(56)$</td>
<td>$20740(159)$</td>
<td>$32537(1012)$</td>
<td>$704(30)$</td>
</tr>
<tr>
<td>Missing $p_T$</td>
<td>$871(20)$</td>
<td>$4251(59)$</td>
<td>$479(27)$</td>
<td>$21001(801)$</td>
<td>$474(26)$</td>
</tr>
<tr>
<td>Collinear</td>
<td>$526(15)$</td>
<td>$56(19)$</td>
<td>$17(3)$</td>
<td>$324(46)$</td>
<td>$32(6)$</td>
</tr>
<tr>
<td>Approx.</td>
<td>$78(2)$</td>
<td>$606(19)$</td>
<td>$17(3)$</td>
<td>$324(46)$</td>
<td>$32(6)$</td>
</tr>
<tr>
<td>Transverse mass</td>
<td>$425(14)$</td>
<td>$176(10)$</td>
<td>$11(2)$</td>
<td>$67(18)$</td>
<td>$14(3)$</td>
</tr>
<tr>
<td>$N$ jets $\geq 2$</td>
<td>$241(7)$</td>
<td>$162(9)$</td>
<td>$8(1)$</td>
<td>$49(11)$</td>
<td>$7(1)$</td>
</tr>
<tr>
<td>Forward jet</td>
<td>$41(3)$</td>
<td>$32(4)$</td>
<td>$1.3(6)$</td>
<td>$\geq 2.9(3)^*$</td>
<td>$3(1)$</td>
</tr>
<tr>
<td>Jet kinematics</td>
<td>$2.8(1)$</td>
<td>$2.2(2)^*$</td>
<td>$3.0(1)^*$</td>
<td>$0.57(8)^*$</td>
<td>$0.05(2)^*$</td>
</tr>
<tr>
<td>Central jet veto</td>
<td>$1.2(1)$</td>
<td>$0.32(7)^*$</td>
<td>$0.27(4)$</td>
<td>$0.051(7)^*$</td>
<td>$0.03(5)^*$</td>
</tr>
<tr>
<td>Mass window</td>
<td>$0.11(2)$</td>
<td>$0.04(1)$</td>
<td>$\leq 0.04$</td>
<td>$0.008(1)^*$</td>
<td>$0.02(1)^*$</td>
</tr>
</tbody>
</table>

Note: QCD Z/W+jets : Alpgen, k-factor w.r.t. NNLO inclusive Z prod. is applied. ELWK Z+jets : Sherpa, ttbar /di-boson : MC@NLO

Signal (H120) : 0.61 fb
Irreducible Z+jets : 0.15 fb
Reducible backgrounds (ttbar/W+jets etc.) : < 0.08
Background estimation (1)

real dataを使って、バックグラウンドを評価。

Shape and acceptance estimation by DATA.

control data  manipulated sample

1) Replace muon to tau.
2) Re-run TAUOLA.
3) Re-simulation again.

- Missing Et is modeled by DATA.
  Important for tail structure.
- Acceptance is also handled correctly.
Background estimation (II)

real dataを使って、バックグラウンドを評価。

Overall QCD fake estimation (at Control region)

Track multiplicity fit:
- count the track outside tau core region.
- fit the n-tracks by likelihood.

\[
L = \prod_i^n \text{Pois}(n_{\text{exp}}^{\text{tot}} \times (r_{\text{tau}} f_{\text{tau}} + r_{\text{lcp}} f_{\text{lcp}} + (1 - r_{\text{tau}} - r_{\text{lcp}}) f_{\text{jet}}), N_{\text{obs}}^{\text{tot}}) \\
\times \text{Gaus}(n_{\text{exp}}^{\text{tot}}, N_{\text{obs}}^{\text{tot}}) \\
( \times \text{Gaus}(n_{\text{exp}}^{\text{tot}} f_{\text{lcp}}, N_{\text{lcp}}^{\text{measured}}))
\]

(fit the ratio)

- shape (pdf) are modeled by real-data.
  (ex. QCD jet shape by JET triggered data)

expected error of “ratio of tau” in the events
Shape signal parameterization

Signal / irreducible Z+jets:

Make use of Jacobian to handle “non-gaussian tail”.

Divide three regions, then fix the fraction in each component.

Fit with three gaussian but fixed ratio and widths given by Jacobian.

\[
L_{H/Z}(M_{\ell\ell}|m, \sigma_{H/Z}) = \mathcal{N} \left[ \frac{1}{2} + \frac{1}{2} \text{erf} \left( \frac{M_{\ell\ell} - \langle M_{\text{vis}} \rangle}{\sqrt{2}\sigma_{\text{vis}}} \right) \right] \times \sum_{i=1}^{3} N_i \text{Gaus}(M_{\ell\ell}|m + \delta_i, \sigma_{H/Z}(\langle J \rangle_i))
\]

**Note:** fitting parameters \((m, \sigma)\) (2-parameters)
Shape QCD parameterization

Because of lack of MC statistics, we put 50% shape uncertainty. So that all reducible background shape are categorized as “QCD”.

Parameterization:

\[ L_{QCD}(M_{\tau\tau}|a_0, a_1, a_2, a_3) = \mathcal{N} \left( \frac{a_0}{M_{\tau\tau} + a_1} \right)^{a_2} (M_{\tau\tau})^{a_3} \]

4 fitting parameters
Likelihood fitting

Likelihood function

\[ L(data|\mu, M_H, \nu) = L_{track}(track\, multiplicity|r_{QCD}) \times L_Z(Z + jets\, control|\sigma_Z) \times L_{QCD}(QCD\, control|a_0, a_1, a_2, a_3) \times L_{s+b}(signal\, candidates|\mu, M_H, \sigma_H, \sigma_Z, r_{QCD}, a_0, a_1, a_2, a_3), \]

Overall constrain

- Fit at once in “control region”.
- Fit in signal region w/ Higgs event.
- Fit background shape again.

Shape uncertainty is correctly handled.

Simultaneous fit\footnote{unbined}

- Signal Region (S: 21 evts, B: 70 evts at 30 fb\(^{-1}\) )
- Control Region (bkg. domain, 12,000 evts at 30 fb\(^{-1}\) )
- Large stat.
- Small stat.

10k Pseudo-experiment

pull width

pull/width

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Signal sensitivity

LLR(mass fit)によるsignificance。

Background shape systematics:
- Z+jets: 10%
- QCD (ttbar/W+jets): 50%
Systematic uncertainty

Dominant source of systematics:
- Jet Energy Scale (20%)
- Central Jet Veto (Theory) (30%)

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty</th>
<th>Effect on signal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity</td>
<td>±3%</td>
<td>±3%</td>
</tr>
<tr>
<td>muon energy scale</td>
<td>±1%</td>
<td>±1%</td>
</tr>
<tr>
<td>muon energy resolution</td>
<td>$\sigma(p_T) \oplus 0.011p_T \oplus 1.7 \times 10^{-4}p_T^2$</td>
<td>±0.5%</td>
</tr>
<tr>
<td>muon ID efficiency</td>
<td>±1%</td>
<td>±2%</td>
</tr>
<tr>
<td>electron energy scale</td>
<td>±0.5%</td>
<td>±0.4%</td>
</tr>
<tr>
<td>electron energy resolution</td>
<td>$\sigma(E_T) \oplus 7.3 \times 10^{-3}E_T$</td>
<td>±0.3%</td>
</tr>
<tr>
<td>electron ID efficiency</td>
<td>±0.2%</td>
<td>±0.4%</td>
</tr>
<tr>
<td>tau energy scale</td>
<td>±5%</td>
<td>±5%</td>
</tr>
<tr>
<td>tau energy resolution</td>
<td>$\sigma(E_T) \oplus 0.45\sqrt{E_T}$</td>
<td>±%</td>
</tr>
<tr>
<td>tau ID efficiency</td>
<td>±5%</td>
<td>±5%</td>
</tr>
<tr>
<td>jet energy scale</td>
<td>±7% (</td>
<td>$\eta$</td>
</tr>
<tr>
<td>jet energy resolution</td>
<td>$\sigma(E_T) \oplus 0.45\sqrt{E_T}$ (</td>
<td>$\eta$</td>
</tr>
<tr>
<td>$b$-tagging efficiency</td>
<td>±5%</td>
<td>±5%</td>
</tr>
<tr>
<td>forward tagging efficiency</td>
<td>±14%</td>
<td>±2%</td>
</tr>
<tr>
<td>central jet veto efficiency</td>
<td>±11%</td>
<td>±2%</td>
</tr>
<tr>
<td>total summed in quadrature</td>
<td>±18%</td>
<td></td>
</tr>
</tbody>
</table>

PDF uncertainties               | ±3.5%                | ±3.5%                       |
| scale dependence on cross-section | ±3%                 | ±3%                         |
| scale dependence CTV efficiency | ±1%                  | ±1%                         |
| parton-shower and underlying event | ±<10%               | ±<10%                       |
| total summed in quadrature     |                      | ±<10%                       |

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Summary

新しい事:

発見のためのBaseline Analysis の確立。

  -- 基本的にすべてFull simulation
  -- Background estimationは、Data-driven analysis
  -- Mass Fitter の開発。
  -- 一つの解析チャンネルをグループとして解析。
    （Author list 47人、12 グループ）

発見のためのロードマップの確立。

  -- 実験が始まるまでに必要な研究課題の把握。
  -- 実験開始から発見までに必要な研究課題の把握。

詳しくは、「LHCが切り開く物理」研究会で。
Early physics to discovery
Study plan

The first part of event selection is exactly same as

- SM DY $Z \rightarrow \tau\tau$ measurement
- MSSM $H$ and $Z'$ searches

VBF specific study（並行して）

- ELWK $Z$ measurement
- Central Jet Veto
- Fitter, MET, jets etc...

Detector oriented selection

control sample

 Kinematics oriented selection

基本的に全く同じ解析

+ Jet kinematical cut

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>120</th>
</tr>
</thead>
</table>
| Cross section (fb) | 309.1 (100%)
| Trigger | 57.2(1) (18.5%)
| Trigger lepton | 49.5(1) (86.5%)
| Di-lepton veto | 43.4(1) (87.9%)
| Hadronic $\tau$ | 8.02(7) (18.4%)
| Missing $E_T \geq 30$ GeV | 4.96(5) (61.9%)
| Collinear Approx. | 3.34(5) (67.4%)
| Transverse mass | 2.46(4) (78.3%)
| $N$ jets $\geq 2$ | 2.02(4) (82.3%)
| Forward jet | 1.52(3) (75.1%)
| Jet kinematics | 0.82(2) (53.9%)
| Central jet veto | 0.72(2) (87.5%)
| Mass window | 0.61(2) (85.2%)

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$Z \rightarrow \tau\tau(lh)$ measurement in early data

Soshi Tsuno and Junichi Tanaka
Univ. of Tokyo
Brief analysis procedure:

1) Make n track distribution just before requiring the 1- or 3- prong events.
2) QCD jets (fake) likely distributes higher track multiplicity region.
3) Fit the signal and (modeled) background shape by likelihood. (need more points and factorized bkg.)
4) Then, obtain the overall number of signal and background.

Problem:

- TauRec likelihood is optimized up to 3 tracks.  
  (The track multiplicity is part of likelihood variables.)

- 1P3P is the algorithm for few track objects.  
  (1-prong and 3-prong + a few addition)

- After all, the track multiplicity is suppressed in the algorithm level.
Track re-counting method

Two Track Correlation Method:
- Count the tracks in wider region (0.2<\(\Delta R\)<0.7).
- To obtain the good separation to fake-tau (jet), make use of the two track momentum fraction weighted by the separation angle.

\[
\frac{p_T^i}{(p_T^{\tau \text{ trk}} \Delta R)} > \text{const., count it.}
\]

It also works further QCD rejection.
Summary of tau identification

Reco+id efficiency:
- Cut-based TauRec ($Z\to\tau^+\tau^-$)
- Cut-based TauRec ($W\to l\nu$)
- Likelihood-based TauRec ($Z\to\tau^+\tau^-$)
- Likelihood-based TauRec ($W\to l\nu$)

Fake rate (TopoC4):
- Cut-based TauRec ($J1-J4$)
- Likelihood-based TauRec ($J1-J4$)
- Cut-based Tau1P3P ($J1-J4$)

<table>
<thead>
<tr>
<th>cut-based TauRec (Tokyo2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tau id: 1-prong tau:</td>
</tr>
<tr>
<td>$r_{EM} &lt; 0.1$</td>
</tr>
<tr>
<td>$f_{iso} &lt; 0.2$</td>
</tr>
<tr>
<td>$d_{width}/d_{width} &lt; 0.02$</td>
</tr>
<tr>
<td>$N\text{stripoll} &lt; 30$</td>
</tr>
<tr>
<td>e-veto:</td>
</tr>
<tr>
<td>trk.$N_{hit}^{TRT}/N_{hit}^{TRT} &lt; 0.2$</td>
</tr>
<tr>
<td>if $</td>
</tr>
<tr>
<td>crack removal ($1.45 &lt;</td>
</tr>
<tr>
<td>$E_{T}^{HAD}/p_T &lt; 0.002$</td>
</tr>
<tr>
<td>in matched e/gamma object</td>
</tr>
<tr>
<td>track re-calculation:</td>
</tr>
<tr>
<td>$D &gt; 0.4$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>cut-based Tau1P3P</th>
</tr>
</thead>
<tbody>
<tr>
<td>tau id: 1-prong tau:</td>
</tr>
<tr>
<td>$r_{EM} &lt; 0.1$</td>
</tr>
<tr>
<td>$f_{iso} &lt; 0.2$</td>
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<td>$d_{width}/d_{width} &lt; 0.02$</td>
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<tr>
<td>in matched e/gamma object</td>
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<tr>
<td>track re-calculation:</td>
</tr>
<tr>
<td>$D &gt; 0.4$</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>likelihood-based TauRec</th>
</tr>
</thead>
<tbody>
<tr>
<td>tau id: 1-prong tau:</td>
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<tr>
<td>likelihood &gt; 4</td>
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<td>e-veto:</td>
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<tr>
<td>trk.$N_{hit}^{TRT}/N_{hit}^{TRT} &lt; 0.2$</td>
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<tr>
<td>if $</td>
</tr>
<tr>
<td>crack removal ($1.45 &lt;</td>
</tr>
<tr>
<td>$E_{T}^{HAD}/p_T &lt; 0.002$</td>
</tr>
<tr>
<td>in matched e/gamma object</td>
</tr>
<tr>
<td>track re-calculation:</td>
</tr>
<tr>
<td>$D &gt; 0.4$</td>
</tr>
</tbody>
</table>

| 3-prong tau: |
| $r_{EM} < 0.1$ |
| $f_{iso} < 0.2$ |
| $d_{width}/d_{width} < 0.02$ |
| $N\text{stripoll} < 30$ |
| e-veto: |
| minimum trk.$N_{hit}^{TRT}/N_{hit}^{TRT} < 0.2$ |
| if $|\eta| < 1.9$ |
| crack removal ($1.45 < |\eta_{trk}| < 1.52$) |
| $E_{T}^{HAD}/p_T < 0.002$ |
| in matched e/gamma object |
| track re-calculation: |
| $D > 0.4$ |
Event selection

Table 3. Identification parameters for electron and muon.

- **Electron ID**: Medium
  - Isolation $E_{T\text{cone}}/p_T < 0.1$
  - $p_T > 25$ GeV for trigger electron (e25i)
  - $p_T > 15$ GeV for the other electron

- **Muon ID**: Medium
  - $\chi^2/\nu \text{dof} < 5$, combined $\chi^2 < 20$
  - onlyHighpT==true, isCombined==false.
  - Overlap removal with the same muons with $\Delta R < 0.1$
  - $p_T > 20$ GeV for trigger muon (mu20i)
  - $p_T > 10$ GeV for the other muon

Electron reco+id efficiency:

- Medium
- ~75%

Event selection:

- **Trigger**: e25i or mu20i
- **Trigger Lepton**: $p_T > 25$ GeV for electron
  - $p_T > 20$ GeV for muon
- **Di-lepton veto**: veto if $N_{\text{lep}} \geq 2$
- **Missing $E_T$**: $H_T > 20$ GeV, $\Delta\phi_{\text{lep},H_T} < 2.8$
- **Transverse Mass**: $M_T < 30$ GeV
- **$\tau$-tagging**: One tight tau before track re-calculation
  - $p_T > 25$ GeV, $\Delta\phi_{\text{lep},\tau} < 2.8$
  - Opposite charge to the trigger lepton
- **$\tau$-identification**: 1-prong or 3-prong for recalculated tracks

Table 4: Summary of the event selection.
Cut flow

<table>
<thead>
<tr>
<th>Process</th>
<th>$Z \rightarrow \tau^+\tau^-$</th>
<th>$Z \rightarrow e^+e^-/\mu^+\mu^-$</th>
<th>$tt$</th>
<th>$W \rightarrow l\nu$</th>
<th>$WW/ZZ/WZ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Section(pb)</td>
<td>246.0 ± 0.5</td>
<td>2931 ± 3</td>
<td>461.1 ± 0.7</td>
<td>22767 ± 29</td>
<td>34.4 ± 0.1</td>
</tr>
<tr>
<td>Trigger</td>
<td>40.3 ± 0.2</td>
<td>2028 ± 2</td>
<td>225.7 ± 0.5</td>
<td>12417 ± 21</td>
<td>20.32 ± 0.08</td>
</tr>
<tr>
<td>Trigger lepton</td>
<td>31.1 ± 0.1</td>
<td>1827 ± 2</td>
<td>177.0 ± 0.4</td>
<td>10465 ± 19</td>
<td>17.12 ± 0.08</td>
</tr>
<tr>
<td>Di-Lepton Veto</td>
<td>26.5 ± 0.1</td>
<td>952 ± 1</td>
<td>156.6 ± 0.4</td>
<td>10461 ± 19</td>
<td>14.58 ± 0.07</td>
</tr>
<tr>
<td>Missing $E_T$</td>
<td>13.7 ± 0.1</td>
<td>192.7 ± 0.7</td>
<td>134.1 ± 0.3</td>
<td>3884 ± 11</td>
<td>9.73 ± 0.06</td>
</tr>
<tr>
<td>Transverse Mass</td>
<td>9.9 ± 0.1</td>
<td>43.2 ± 0.3</td>
<td>22.2 ± 0.1</td>
<td>167 ± 2</td>
<td>1.08 ± 0.02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cut-based TauRec (Tokyo2007)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$-tagging</td>
<td>2.23 ± 0.05</td>
<td>2.17 ± 0.08</td>
<td>2.28 ± 0.05</td>
<td>6.3 ± 0.4</td>
<td>0.081 ± 0.005</td>
</tr>
<tr>
<td>$\tau$-id</td>
<td>1.77 ± 0.04</td>
<td>1.52 ± 0.06</td>
<td>0.83 ± 0.03</td>
<td>2.4 ± 0.2</td>
<td>0.037 ± 0.004</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cut-based Tau1P3P</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$-tagging</td>
<td>1.71 ± 0.04</td>
<td>1.14 ± 0.06</td>
<td>0.96 ± 0.03</td>
<td>2.1 ± 0.2</td>
<td>0.039 ± 0.004</td>
</tr>
<tr>
<td>$\tau$-id</td>
<td>1.51 ± 0.04</td>
<td>0.98 ± 0.05</td>
<td>0.51 ± 0.02</td>
<td>0.8 ± 0.1</td>
<td>0.024 ± 0.003</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Likelihood-based TauRec</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$-tagging</td>
<td>2.34 ± 0.05</td>
<td>1.77 ± 0.07</td>
<td>1.08 ± 0.03</td>
<td>2.2 ± 0.2</td>
<td>0.049 ± 0.004</td>
</tr>
<tr>
<td>$\tau$-id</td>
<td>2.05 ± 0.05</td>
<td>1.47 ± 0.06</td>
<td>0.62 ± 0.02</td>
<td>1.2 ± 0.2</td>
<td>0.031 ± 0.003</td>
</tr>
</tbody>
</table>

Table 5: Cut flow table of the events for various processes. The events are normalized by the cross sections in pb unit. The error is the statistical error by the Monte Carlo, not by the given luminosity.

Note that
- These numbers are used as the input of the fitting. (not a final number)
- The contribution form QCD jet is unknown. Should be estimated by fit.
Track multiplicity fit

Extended likelihood function:

\[ L = \prod_i^N \text{Pois}(n_{\text{exp}}^{\text{tot}} \times (r_{\text{tau}} f_{\text{tau}} + r_{\text{lep}} f_{\text{lep}} + (1 - r_{\text{tau}} - r_{\text{lep}}) f_{\text{jet}}), N_{\text{obs}}^i) \times \text{Gaus}(n_{\text{exp}}^{\text{tot}}, N_{\text{obs}}^{\text{tot}}) \times \text{Gaus}(n_{\text{exp}}^{\text{tot}} r_{\text{lep}} N_{\text{lep}}^{\text{measured}}) \]

Fitting parameters:

- \( n_{\text{exp}} \): number of events expected by fit,
- \( r_{\text{tau}} \): event fraction of tau contribution wrt \( n_{\text{exp}} \),
- \( r_{\text{lep}} \): event fraction of lepton contribution wrt \( n_{\text{exp}} \).

Observables:

- \( N_{\text{obs}} \): number of observed events.
- \( N_{\text{lep}}^{\text{measured}} \): number of estimated events from the another measurements.

Probability function:

- \( f_{\text{tau}} \): probability function of the track multiplicity for tau candidates,
- \( f_{\text{lep}} \): probability function of the track multiplicity for lepton candidates,
- \( f_{\text{jet}} \): probability function of the track multiplicity for QCD jet candidates.
Probability function

Cut-based TauRec:

Cut-based Tau1P3P:

Likelihood-based TauRec:

Modeling:
- tau signal from MC
- lepton(electron) from DATA
- QCD jet from DATA
Systematics

Model uncertainty:

- low pT jet v.s. high pT jet shape (high pT jet becomes narrow.)
- cut-bias (before/after MET cut)

Note that we should consider more systematics.
Pseudo-experiment

Purpose:

- Check our fitting procedure is correct or not.
- Estimate correct statistical error.

Make "pseudo-DATA".

Suppose: QCD jets contribute twice larger from the estimation by the cut-flow table.

Pseudo-DATA is produced by the template histograms of the track multiplicity distribution.

After 2000 pseudo-experiments,

Outcome from fitter should be correct statistical error.

Should be normal gaussian.
Results

Measurement accuracy as a function of luminosity.

Scenario (A):
No constrain in the fit.

Scenario (B):
Constrain in the lepton normalization.

The absolute cross section can be determined with
~35% accuracy w/o constrain
~10% accuracy w/ constrain
at 200 pb⁻¹.
Update of Track-based Jet Veto Study for VBF Higgs analysis

S. Tsuno, Univ. of Tokyo

Previous talk was given in July.19.2006 at Higgs Meeting.
Introduction

- Naïve jet veto with “Calorimeter-based Jet Veto” (currently used) will have large systematics by the multiple interaction and pile-up events.
- On the other hand, the signal sensitivity gets worse with higher threshold of the jet energy for the veto.
- Basically, jet is weak to correlate between characteristics for the jet veto in VBF process and multiple-interactions.

The “calorimeter-based jet” is not good quantity to avoid the multiple/pile-up events.

Rome sample

Different pile-up sample, 0, 2.3, 4.6.

Jet Multiplicity $E_T > 20$ GeV

Now, we cut 3rd jet contribution.
**Track-based Jet Veto**

Using track information, we can specify where this track comes from.

**Procedure:**
- Count the number of tracks associated with “event vertex”.
- Apply the cut for this track numbers.

Signal(VBF) : less track multiplicity, Background : larger multiplicity.
Central Jet Veto:

Less activity in the central region

It is not necessary it can be a “jet”.

High precision
Only charged particles

Calorimeter cluster
Many clusters
Quality cuts
Use timing info.

Track
Many tracks
Quality cuts
Use vertex info.

Calorimeter jet
Traditional approach

Track jet
A bunch of tracks
pointing primary vertex

Worse energy resolution

Maybe, energy flow-like approach may be better(??)

Pile-up and theoretical uncertainties are serious.
**Event Vertex**

Definition depends on the search channels.

For simplicity, this study (VBF H to $\tau\tau(lh)$) uses "z position of triggered high $p_T$ lepton".

Counts the tracks associated with the event vertex within $\Delta z < 0.46$ cm.

**Graph**: Mean: 0.0019
Sigma: 0.236

**Diagram**: 0.46 cm
0.92 cm

Then,

Not count

$Z$
Track multiplicity

Tracks associated with the event vertex. Achieve similar performance with “calor-based” Jet Veto w/o pile-up effect.

Relative $\eta^*$

$$\eta^* = \eta_{\text{trks}} - \frac{\eta_{j1} + \eta_{j2}}{2}$$

Absolute detector $\eta$

- $\Delta \eta^* < 1.0$
- $\Delta \eta_{\text{det}} < 2.4$

VBF $H \rightarrow \tau^+\tau^-$
**Luminosity dependence**

Inst. Luminosity \( \propto \) Number of vertices

Can be controlled \( \pm 1\sim2 \) track level.

Scaling linearly.
Trigger Study for di-tau events

Soshi Tsuno (KEK)
Trigger study for ll- and lh-channel

- Trigger Hypothesis on AOD w/ several configuration.
  Increase the pT threshold at Level.2.
  (TrigL2CaloHypo for electron, Mufast/Mucomb for muon)

- Single lepton trigger efficiency :
  Signal : M_\text{H} = 120\text{GeV} w/ and w/o pileup are used.
  QCD di-jets rate (Hz) is considered.
  Real signal from Min.Bias events is excluded in the rate calculation,
  J0-J4 samples are used for di-jets fake rate calculation.

- Efficiency definition :
  \[ \varepsilon_{\text{TRIG}} = \frac{\text{identified lepton w/ Trigger decision}}{\text{identified lepton}} \] (event-by-event basis)
  \[ \varepsilon_{\text{1D}} = \frac{\text{identified lepton matched w/ truth (}\Delta R < 0.2\text{)}}{\text{truth lepton}} \]
Single electron efficiency:

Electron ID: $p_T > 15\text{GeV}$, Class:Medium ($\text{IsEM}&0x3FF$) Cal.Isolation EtCone02/$p_T < 0.1$

ID efficiency: $\sim 70\%$
TRIG efficiency: $\sim 90\%$
Overall efficiency for single electron event: $\sim 65\%$

No sample dependence is observed at Trigger level.

Detector paper (rel.13)
Single muon efficiency:

Muon ID: \( p_T > 10 \text{GeV} \), Staco: \( \text{isCombined}=1 \)
Cal. Isolation \( \text{EtCone02}/p_T < 0.1 \)

ID efficiency: \( \sim 90\% \)
TRIG efficiency: \( \sim 80\% \)
Overall efficiency for single electron event: \( \sim 75\% \)

No sample dependence is observed at Trigger level.
Many “tau trigger” events are overlap with “electron trigger”. Di-lepton channel is “inclusive” for both e- and mu- triggers.

<table>
<thead>
<tr>
<th>Trigger name</th>
<th>Trigger acceptance for signal (w/ pileup) (%)</th>
<th>lh-channel cross section after cuts (w/ pileup) (fb)</th>
<th>lh-channel cross section after cuts (w/ pileup) (fb)</th>
<th>Di-jet trigger rate J0-J4 (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>no trigger</td>
<td>EF = 46.9 (46.9)</td>
<td>0.27 ± 0.01 (0.14 ± 0.01)</td>
<td>0.23 ± 0.01 (0.21 ± 0.01)</td>
<td>91 ± 15 (7 ± 12)</td>
</tr>
<tr>
<td>e25i</td>
<td>9.08 ± 0.03 (6.79 ± 0.06)</td>
<td>0.21 ± 0.01 (0.10 ± 0.01)</td>
<td>0.19 ± 0.01 (0.18 ± 0.01)</td>
<td>14 ± 3 (14 ± 3)</td>
</tr>
<tr>
<td>e35i</td>
<td>6.24 ± 0.03 (6.04 ± 0.06)</td>
<td>0.21 ± 0.01 (0.10 ± 0.01)</td>
<td>0.19 ± 0.01 (0.18 ± 0.01)</td>
<td>7 ± 3 (7 ± 3)</td>
</tr>
<tr>
<td>e25i+xe30</td>
<td>5.08 ± 0.03 (5.36 ± 0.05)</td>
<td>0.25 ± 0.01 (0.15 ± 0.01)</td>
<td>0.24 ± 0.01 (0.22 ± 0.01)</td>
<td>4 ± 3 (4 ± 3)</td>
</tr>
<tr>
<td>e35i+xe30</td>
<td>3.50 ± 0.02 (3.68 ± 0.03)</td>
<td>0.17 ± 0.01 (0.10 ± 0.01)</td>
<td>0.17 ± 0.00 (0.17 ± 0.01)</td>
<td>1.1 ± 0.4 (1.1 ± 0.4)</td>
</tr>
<tr>
<td>mu20i</td>
<td>9.88 ± 0.04 (8.84 ± 0.06)</td>
<td>0.37 ± 0.01 (0.18 ± 0.01)</td>
<td>0.30 ± 0.01 (0.20 ± 0.01)</td>
<td>11 ± 14 (9 ± 12)</td>
</tr>
<tr>
<td>mu25i</td>
<td>8.01 ± 0.03 (7.16 ± 0.05)</td>
<td>0.26 ± 0.01 (0.17 ± 0.01)</td>
<td>0.26 ± 0.01 (0.17 ± 0.01)</td>
<td>50 ± 8 (50 ± 8)</td>
</tr>
<tr>
<td>mu20i+tau25i</td>
<td>2.49 ± 0.02 (2.11 ± 0.03)</td>
<td>0.092 ± 0.007 (0.06 ± 0.01)</td>
<td>1.2 ± 0.4 (1.2 ± 0.4)</td>
<td>1.6 ± 0.2 (0.6 ± 0.2)</td>
</tr>
<tr>
<td>mu25i+tau25i</td>
<td>1.96 ± 0.02 (1.67 ± 0.02)</td>
<td>0.077 ± 0.006 (0.049 ± 0.009)</td>
<td>0.6 ± 0.2 (0.6 ± 0.2)</td>
<td>31 ± 7 (7 ± 5)</td>
</tr>
<tr>
<td>mu6+tau30i</td>
<td>4.00 ± 0.02 (3.47 ± 0.04)</td>
<td>0.123 ± 0.008 (0.10 ± 0.01)</td>
<td>0.12 ± 0.00 (0.10 ± 0.01)</td>
<td>16 ± 5 (12 ± 3)</td>
</tr>
<tr>
<td>mu10+tau25i</td>
<td>4.42 ± 0.02 (3.75 ± 0.04)</td>
<td>0.157 ± 0.009 (0.11 ± 0.01)</td>
<td>1.6 ± 0.2 (1.6 ± 0.2)</td>
<td>16 ± 6 (11 ± 3)</td>
</tr>
<tr>
<td>mu10+tau35i</td>
<td>3.29 ± 0.02 (2.85 ± 0.03)</td>
<td>0.119 ± 0.008 (0.09 ± 0.01)</td>
<td>1.3 ± 0.6 (8 ± 3)</td>
<td>13 ± 6 (8 ± 3)</td>
</tr>
<tr>
<td>mu20+xe30</td>
<td>8.34 ± 0.03 (7.59 ± 0.05)</td>
<td>0.30 ± 0.01 (0.20 ± 0.01)</td>
<td>0.30 ± 0.01 (0.20 ± 0.01)</td>
<td>20 ± 4 (15 ± 1)</td>
</tr>
<tr>
<td>mu25+xe30</td>
<td>6.93 ± 0.03 (6.27 ± 0.05)</td>
<td>0.26 ± 0.01 (0.17 ± 0.01)</td>
<td>0.26 ± 0.01 (0.17 ± 0.01)</td>
<td>10 ± 1 (10 ± 1)</td>
</tr>
<tr>
<td>2e15i</td>
<td>0.49 ± 0.01 (0.45 ± 0.01)</td>
<td>0.003 ± 0.001 (0.003 ± 0.002)</td>
<td>0.070 ± 0.006 (0.055 ± 0.009)</td>
<td>1890 ± 69 (1667 ± 61)</td>
</tr>
<tr>
<td>e10–mu6</td>
<td>16.35 ± 0.04 (15.00 ± 0.07)</td>
<td>0.02 ± 0.02 (0.34 ± 0.02)</td>
<td>0.36 ± 0.01 (0.26 ± 0.02)</td>
<td>205 ± 20 (184 ± 18)</td>
</tr>
<tr>
<td>e15+mu10</td>
<td>10.53 ± 0.04 (9.48 ± 0.06)</td>
<td>0.57 ± 0.01 (0.48 ± 0.06)</td>
<td>0.32 ± 0.01 (0.22 ± 0.01)</td>
<td>1890 ± 69 (1667 ± 61)</td>
</tr>
</tbody>
</table>

Table 1: VBF $H \rightarrow \tau \tau$ ($m_H=120$GeV) in lh- and ll-channels. 12.0.6 Trigger Hypothesis on AOD. Di-jet trigger rate (Hz) is calculated at $L=10^{33}$cm$^{-2}$s$^{-1}$. 

L=$10^{33}$cm$^{-2}$s$^{-1}$
Many things to do...

Missing pT, pileup study, forward jets, new fitter, mass reconstruction, fast-simulation etc...

誰か手伝ってもらえませんか？
Exclusion and Yukawa coupling

H → ττは、Yukawa couplingを直接検証できる。
もしDATAがSM consistentであるとすると、
もし、このモードで、Higgsが見つからなければ、
tanβ < 1
See-saw ??
\[ \frac{y_1^2}{M_1} + \frac{y_2^2}{M_2} + \frac{y_3^2}{M_3} = 0 \]
Lepton-flavor violation:

exclusionで議論できるphysicsはありませんか？
Central Jet Veto uncertainty

- jet-veto has no impact at LO (no partons in final state)
- jet-veto at NLO corresponds to cut on Higgs transverse momentum
- K-factors ($\sigma^{(N)\text{NLO}}/\sigma^{\text{LO}}$) depend heavily on cut-value!
  - inclusive K-factors would fail to describe the picture reliably
At parton shower

まだまだ、怪しい。

何とかならないでしょうか？ 理論の方。

Martch.28th.2008 LHC Kenkyukai, S. Tsuno
Backup
Physics strategy

最初の2, 3年で、Higgs粒子、SUSY粒子発見。

2008(summer)/09: first 10/14 TeV physics run, initial $L \sim 10^{31}$ cm$^{-2}$s$^{-1}$, $L_{\text{int}} \sim 1$ fb$^{-1}$
Detector commissioning: alignment, in-situ calibration / trigger menu
First SM measurements: W/Z/top & min.bias/jets & PDF $\sim 100$ pb$^{-1}$

2009/10: low luminosity run, instantaneous $L \sim 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$, $L_{\text{int}} \sim 10$ fb$^{-1}$
First B rare decay searches,
First searches: high mass DY(Z’), ADD, BH, SUSY $\sim 1$ fb$^{-1}$
First Higgs discovery: $H \rightarrow 4$ leptons, WW, $\gamma \gamma$ & MSSM Higgs

2010/11: low luminosity run, inst.$L \sim 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$, $L_{\text{int}} \sim 10$ fb$^{-1}$/yr
Light Higgs searches, SUSY measurements (model specific), …

2012~: high luminosity run, inst.$L \sim 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$, $L \sim 100$ fb$^{-1}$/yr
many, many … toward SLHC…
ATLAS detector

Tevatronにはない広い $\eta$ の範囲をカバー。

- Muon standalone tracking
- Inner tracker coverage $|\eta|\sim 2.7$
- Calorimeter coverage $|\eta|\sim 5.0$
Analysis model

Control room

Run operation

DAQ

Trigger

DATA

trigger

FDR

User analysis

Full Dress Rehearsal (FDR)

Load tests with cosmic (200MB/s vs 1GB/s at LHC)

Average throughput (MB/s) from Tier-0 to Tiers-1

~300 MB/s

end of run

Tier-0 (CERN)

Grid throughout

Data quality

monitoring
Demonstration: simplest Likelihood function

Naïve construction:

\[
L_{\text{shape}} = \frac{e^{-(n_s+n_{b1}+n_{b2})}}{N_{\text{obs}}!} \left( n_s + n_{b1} + n_{b2} + \cdots \right)^{N_{\text{obs}}} \prod_{i}^{N_{\text{obs}}} n_{s} f_{s} (m_H | \nu) + n_{b1} f_{b1} (m_H | \nu) + \cdots \frac{n_s + n_{b1} + n_{b2} + \cdots}{n_s + n_{b1} + n_{b2} + \cdots}
\]

We would like to include “constraint term from the (independent) external measurements”.
Following CDF top mass measurement,

\[
L_{\text{bkg}} = \text{Gauss}(n_{b1}, N_{b1}^{\text{exp}}, \sigma_{b1}^{\text{exp}}) \times \text{Gauss}(n_{b2}, N_{b2}^{\text{exp}}, \sigma_{b2}^{\text{exp}}) \cdots
\]

The likelihood function is formed as

\[
L = L_{\text{shape}} \times L_{\text{bkg}}
\]

The combined likelihood function is formed as

\[
L_{\text{combined}} = L_{\text{lh-channel}} \times L_{\text{ll-channel}} \times L_{\text{hh-channel}}
\]
Impact on the generator difference

Matthias Roder, Nov. 21. 2007

Predicts 41% systematics as the maximum fluctuation.

\begin{itemize}
\item Different event selection,
\item No collinear mass reconstruction,
\item Atlfast
\end{itemize}

CSC Full simulation

While predicts 29% difference as the systematics.

Those difference have to be investigated again.

Martch.28th.2008

LHC Kenkyukai, S. Tsuno
Good Track definition

Follows tracking/tau group recommendation.

<table>
<thead>
<tr>
<th>Hits</th>
<th>Pixel</th>
<th>SCT</th>
<th>TRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 &lt;</td>
<td>η</td>
<td>&lt; 0.6</td>
<td>1</td>
</tr>
<tr>
<td>0.6 &lt;</td>
<td>η</td>
<td>&lt; 1.4</td>
<td>1</td>
</tr>
<tr>
<td>1.4 &lt;</td>
<td>η</td>
<td>&lt; 2.0</td>
<td>1</td>
</tr>
<tr>
<td>2.0 &lt;</td>
<td>η</td>
<td>&lt;</td>
<td>1</td>
</tr>
</tbody>
</table>

- Track $p_T > 1$ GeV
- No $z_0$, $d_0$, $\chi^2$ cut applied at the moment.
Jet Shape

Jet shape is one of the most well-tuned variable in showering MC.

The track multiplicity distribution is a good variable for signal and background modeling.

(QCD Jets are modeled by DATA.)

From Mario’s study, Phys.Rev.D71(2005)112002
### Data set

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section (pb)</th>
<th>Generator</th>
<th>Data set</th>
<th>Task id</th>
<th>events</th>
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<td>246.0</td>
<td>Herwig</td>
<td>5188</td>
<td>8566</td>
<td>194k</td>
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<td>5144</td>
<td>7539</td>
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<tr>
<td>$Z \rightarrow \mu^+\mu^-$</td>
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<td>454k</td>
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<td>6045</td>
<td>573k</td>
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<td>$t\bar{t}$ (no hadronic mode)</td>
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<td>MC@NLO</td>
<td>5200</td>
<td>8037</td>
<td>$536k^2$</td>
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</tbody>
</table>

1mm G4 signal includes filter efficiency.
**Tau identification**

Three tau identifications:

- cut-based TauRec ID (Tokyo2007),
- cut-based Tau1P3P ID \( \text{discrCut} = 1 \),
- likelihood-based TauRec ID ... *used as reference*

**Cut-based TauRec (Tokyo2007):**

![Diagram of TauRec algorithm variables](image-url)

*Figure 1: Variables in TauRec algorithm used in the cut-based \( \tau \) identification. (a) EM radius, (b) isolation fraction (c) squared strip width for 1-prong tau candidates, and (d), (e), and (f) are their corresponding variables for 3-prong tau candidates.*