Making Jets our friends at the LHC

or

W+b a background for heavy particle searches

Michael Spannowsky

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ITP, University of Karlsruhe
# Outline

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W+b quark physics at the LHC

Eugene

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Michael Spannowsky

09/18/2009
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W+b quark physics at the LHC

Eugene

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MSSM

- Minimal particle content
- Minimal gauge group
- Chiral anomaly among fermions

Two oppositely charged Higgsinos

Superpotential governs interaction among the scalars and their superpartners

- relevant part:

\[ W = \hat{Q}_i Y_{ij}^u \hat{U}_j \hat{H}_u - \hat{Q}_i Y_{ij}^d \hat{D}_j \hat{H}_d + \mu \hat{H}_u \hat{H}_d \]

SUSY has to be broken

No need to assume specific breaking scenario

Explicit breaking by soft terms

Large number of free parameters induced

Relevant soft-breaking Lagrangian:

\[
\mathcal{L}_{\text{soft}} = -\tilde{u}_R^i m_{\tilde{u}_{ij}}^2 \tilde{u}_{Rj} + \tilde{d}_R^i m_{\tilde{d}_{ij}}^2 \tilde{d}_{Rj} - \tilde{u}_L^i m_{\tilde{u}_{ij}}^2 \tilde{u}_{Lj} + \tilde{d}_L^i m_{\tilde{d}_{ij}}^2 \tilde{d}_{Lj} \\
- \left[ \tilde{u}_L A_{ij}^u \tilde{u}_{Rj} H_u^0 - \tilde{d}_L V_{ki} A_{kj}^d \tilde{u}_{Rj} H_u^+ - \tilde{u}_L V_{ik}^* A_{kj}^d \tilde{d}_{Rj} H_d^- + \tilde{d}_L A_{ij}^d \tilde{d}_{Rj} H_d^0 + \text{h.c.} \right]
\]
Often additional symmetry imposed:

**Minimal flavor violation**

**Basic principle of MFV:**
The Yukawa couplings are the only sources of flavor and CP violation
[D‘Ambrosio et al, 2002]

**Motivation of MFV:**
- Success of SM predictions in FCNC processes
- Reduction of free parameters
- Phenomenologically more predictive

But, MFV is more restrictive than present experimental results demand

**Up-squark mass matrix in MFV**

\[
\mathcal{M}_{u_{mfv}}^u = \begin{pmatrix}
(M_u^2)_{LL}^u & 0 & 0 & \Delta_{u,11}^u & 0 & 0 \\
0 & (M_u^2)_{c,LL}^u & 0 & 0 & \Delta_{u,22}^u & 0 \\
0 & 0 & (M_u^2)_{t,LL}^u & 0 & 0 & \Delta_{u,33}^u \\
h.c. & 0 & 0 & (M_u^2)_{RR}^u & 0 & 0 \\
& & & & & \end{pmatrix}
\]
Often additional symmetry imposed:

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**Up-squark mass matrix in NMFV**

\[
M_{nmfv}^u = \begin{pmatrix}
(M_u^2)_{LL}^u & \Delta_{LL,12}^u & \Delta_{LL,13}^u & \Delta_{LR,11}^u & \Delta_{LR,12}^u & \Delta_{LR,13}^u \\
(M_u^2)_{LL}^c & \Delta_{LL,23}^u & \Delta_{LR,21}^u & \Delta_{LR,22}^u & \Delta_{LR,23}^u & \Delta_{LR,23}^u \\
(M_u^2)_{RR}^u & \Delta_{LR,31}^u & \Delta_{LR,32}^u & \Delta_{LR,31}^u & \Delta_{LR,33}^u & \Delta_{LR,33}^u \\
(M_u^2)_{RR}^c & \Delta_{RR,12}^u & \Delta_{RR,13}^u & \Delta_{RR,12}^u & \Delta_{RR,13}^u & \Delta_{RR,23}^u \\
(M_u^2)_{RR}^t & \Delta_{RR,23}^u & \Delta_{RR,23}^u & \Delta_{RR,23}^u & \Delta_{RR,23}^u & \Delta_{RR,23}^u \\
\end{pmatrix}
\]

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Mass Insertion Approximation

In general the squark mass matrix has to be diagonalized

\[ Z^u \mathcal{M}^u Z^{u\dagger} = \text{diag}(m_{\tilde{u}_i}^2) \]

Two 'approximately equivalent' pictures:

<table>
<thead>
<tr>
<th>Mass Matrix</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass eigenstate</td>
<td>( \mathcal{M}<em>I \delta</em>{IJ} )</td>
</tr>
<tr>
<td>flavor eigenstate</td>
<td>( \mathcal{M}_{IJ} )</td>
</tr>
</tbody>
</table>

For MIA \( \delta_{AB,ij} = \Delta_{AB,ij} / \tilde{m}^2 \) has to be small and \( M_{ii}^2 \approx \tilde{m}^2 \)

\[
\mathcal{M} = \begin{pmatrix}
M_{11}^2 & \Delta_{LL,12} & \cdots \\
\Delta_{LL,21} & M_{22}^2 & \cdots \\
\vdots & \vdots & \ddots 
\end{pmatrix} \approx \tilde{m}^2 \left[ 1 + \begin{pmatrix}
0 & \delta_{LL,12} & \cdots \\
\delta_{LL,21} & 0 & \cdots \\
\vdots & \vdots & \ddots 
\end{pmatrix} \right]
\]

\[
Z_{ia} \tilde{q}_a = Z_{aj}^{\dagger} \tilde{q}_j = \tilde{q}_i + \tilde{q}_i \tilde{q}_j + \cdots
\]
Overview of flavor constraints:

\[
M_{nmfv}^u = \begin{pmatrix}
(M_u^2)^u_{LL} & \Delta_{LL,12}^u & \Delta_{LL,13}^u & \Delta_{LR,11}^u & \Delta_{LR,12}^u & \Delta_{LR,13}^u \\
(M_u^2)^c_{LL} & \Delta_{LL,23}^u & \Delta_{LR,21}^u & \Delta_{LR,22}^u & \Delta_{LR,31}^u & \Delta_{LR,32}^u \\
\hfill \text{h.c.} & \Delta_{LR,33}^u & \Delta_{RR,12}^u & \Delta_{RR,13}^u & \Delta_{RR,23}^u & \Delta_{RR,23}^u
\end{pmatrix}
\]

**Red** entries severely constrained by:
- Kaon physics
- \(B_d - B_{\bar{d}}\) and \(B_s - B_{\bar{s}}\) mixing
- \(B \rightarrow X_s \gamma\) and \(B \rightarrow \rho \gamma\)
- \(B \rightarrow X_s ll\) and \(B \rightarrow \pi ll\)
- Corrections to quark masses
- Exp. constraints from direct searches

**Green** entries almost unconstrained

W+b quark physics at the LHC
Overview of flavor constraints:

\[
\mathcal{M}_{nmfv}^u = \begin{pmatrix}
(M^2_u)^{uu}_{LL} & \Delta^u_{LL,12} & \Delta^u_{LL,13} & \Delta^u_{LR,11} & \Delta^u_{LR,12} & \Delta^u_{LR,13} \\
(M^2_u)^{c}_{LL} & \Delta^u_{LL,23} & \Delta^u_{LR,21} & \Delta^u_{LR,22} & \Delta^u_{LR,23} \\
(M^2_u)^{t}_{RR} & \Delta^u_{RR,31} & \Delta^u_{RR,32} & \Delta^u_{RR,12} & \Delta^u_{RR,13} \\
& \text{h.c.} & (M^2_u)^{c}_{RR} & (M^2_u)^{t}_{RR} & (M^2_u)^{t}_{RR} \\
\end{pmatrix}
\]

Red entries severely constrained by:
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- $B_d - B_{\bar{d}}$ and $B_s - B_{\bar{s}}$ mixing
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(M_u^2)_{LR}^c & \Delta_{LR,21}^u & \Delta_{LR,22}^u & \Delta_{RR,12}^u & \Delta_{RR,13}^u \\
(M_u^2)_{LR}^t & \Delta_{LR,23}^u & \Delta_{LR,22}^u & \Delta_{RR,23}^u & \Delta_{RR,23}^u \\
\text{h.c.} & \text{h.c.} & \text{h.c.} & \text{h.c.} & \text{h.c.}
\end{pmatrix}
\]

**Red** entries severely constrained by:
- Kaon physics
- \( B_d - B_{\bar{d}} \) and \( B_s - B_{\bar{s}} \) mixing
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- Corrections to quark masses
- Exp. constraints from direct searches

**Green** entries almost unconstrained

W+b quark physics at the LHC

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Charged Higgs production at the LHC

[Dittmaier, Hiller, Plehn, MS; 2008 Phys.Rev.D77]

Charged Higgs is a clear signal for ‘New Physics’
but difficult to find: no $H^\pm W^\mp Z$ interaction
at tree-level

→ Production in association with heavy
  quarks or Yukawa-coupling suppressed

→ Search strategy: Couple it to a bottom
  quark in the large $\tan \beta$ regime

→ Left with hole for $\tan \beta < 10$

Can charged Higgs production for small $\tan \beta$ be enhanced in NMFV?

[Assamagan, Coadou 2002]
Single charged Higgs production in NMFV

- Direct production without phase-space suppression
- But what about the background?

\[ L_{H^\pm q\bar{q}'} \supset g \left[ -\frac{m_W}{\sqrt{2}} \sin 2\beta + \frac{m_d^2 \tan \beta + m_u^2 \cot \beta}{\sqrt{2}m_W} \right] \tilde{d}_L \tilde{u}_L H^- \\
+ \left[ \frac{g}{\sqrt{2}m_W} (\langle H_1^0 \rangle A^d \tan \beta - m_d\mu) \right] \tilde{d}_R \tilde{u}_L H^- \\
+ \left[ \frac{g}{\sqrt{2}m_W} (\langle H_2^0 \rangle A^u \cot \beta - m_u\mu) \right] \tilde{d}_L \tilde{u}_R H^- \]

- In MFV all contributions suppressed by small Yukawa-couplings
  \[ \ln m_q \to 0 \] amplitude strictly zero
- NMFV circumvents Yukawa-coupling suppression - especially for small \( \tan \beta \)
Points outside rainbow-coded area forbidden:

- **Blue**: Violates radiative and semileptonic decays
- **Green**: Violates rad. and semilep. decays and exp. squark mass bounds
- **Grey**: Negative squark mass square
- **Orange**: Violates BB-Mixing bounds and rad. and semilep. decays
- **Black**: Violates BB-Mixing bounds, rad. and semilep. decays and exp. squark mass bounds
Points outside rainbow-coded area forbidden:

- **Blue**: Violates radiative and semileptonic decays
- **Green**: Violates rad. and semilep. decays and exp. squark mass bounds
- **Grey**: Negative squark mass square
- **Yellow**: Violates exp. squark mass bounds
Results of single $H^\pm$ production

- Flavor-mixing can strongly enhance charged Higgs production cross-section

- Largest contribution from $\delta_{LR,31}^u$

- Tree-Level value for hadronic cross-section with $M_{H^+} = 188\text{GeV}$:
  \[ \sigma_{\text{tree}}(pp \to H^+ + X) = 41\text{fb} \]

- Unfortunately, $\sigma(pp \to W^+ + X) \approx 90\text{nb}$
  
  ![Graph showing the ratio of tree-level to loop cross-section with $M_{H^+} = 188\text{GeV}$ and $\delta_{LR,31}^u$](image)

  ![Graph showing the cross-section $\sigma(pp \to H^+ + X)$ with $M_{H^+} = 188\text{GeV}$ and $\delta_{LR,31}^u = 0.5$](image)

- Bad signal to background ratio
Considered process: $\sigma(pp \rightarrow H^+ + \text{Jet})$

- Even with $m_q \rightarrow 0$ (just D-Terms) and MFV cross-section is finite
- Just SUSY-QCD corrections - expected to cause largest enhancement
- We require a hard jet to handle collinear divergencies $p_{T,j} \geq 100$ GeV
- Background is large: $\sigma(pp \rightarrow W^+ + \text{Jet}) \approx 1.1$ nb

Results:

<table>
<thead>
<tr>
<th>$m_{H^+}$ (GeV)</th>
<th>$\tan\beta$</th>
<th>$\sigma_{2\text{HDM}}$</th>
<th>$\sigma_{2\text{HDM}}^{(m_\tau=0)}$</th>
<th>$\sigma_{\text{SUSY}}$</th>
<th>$\sigma_{\text{SUSY}}^{(m_\tau=0)}$</th>
<th>$\sigma_{\text{SUSY}}^{(m_q=0)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>188</td>
<td>3</td>
<td>$2.5 \cdot 10^{-1}$</td>
<td>$1.9 \cdot 10^{-1}$</td>
<td>$14.3 \cdot 10^{0}$</td>
<td>$14.2 \cdot 10^{0}$</td>
<td>$13.9 \cdot 10^{0}$</td>
</tr>
<tr>
<td>188</td>
<td>7</td>
<td>$9.9 \cdot 10^{-1}$</td>
<td>$6.0 \cdot 10^{-1}$</td>
<td>$4.6 \cdot 10^{0}$</td>
<td>$4.4 \cdot 10^{0}$</td>
<td>$3.0 \cdot 10^{0}$</td>
</tr>
<tr>
<td>400</td>
<td>3</td>
<td>$4.0 \cdot 10^{-2}$</td>
<td>$3.0 \cdot 10^{-2}$</td>
<td>$2.4 \cdot 10^{0}$</td>
<td>$2.4 \cdot 10^{0}$</td>
<td>$2.3 \cdot 10^{0}$</td>
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<tr>
<td>400</td>
<td>7</td>
<td>$1.6 \cdot 10^{-1}$</td>
<td>$1.0 \cdot 10^{-1}$</td>
<td>$7.9 \cdot 10^{-1}$</td>
<td>$7.3 \cdot 10^{-1}$</td>
<td>$5.4 \cdot 10^{-1}$</td>
</tr>
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</table>

- $\sigma_{\text{SUSY}}$ corresponds to $\delta_{LR,31}^u = 0.5$
- NMFFV can enhance cross-section by one order of magnitude for small $\tan\beta$
Direct Top production

[NMFV contributions can induce effective u-g-t coupling sensitive to \( \delta_{LR,31} \)]

Three major backgrounds:

- **miss-tagged b-jet in**
  
  \[ pp \rightarrow Jet \mu^+\nu_\mu \]

- **collinear bottom pair**
  
  \[ pp \rightarrow \bar{b}b\mu^+\nu_\mu \]

- **CKM suppressed**
  
  \[ pp \rightarrow b\mu^+\nu_\mu \]
SPS2 inspired parameter point:
(relevant values at SUSY mass scale)

\[
\begin{align*}
\tan \beta &= 9.6, \\
M_1 &= 125 \text{ GeV}, \\
M_2 &= 233 \text{ GeV}, \\
m_{\tilde{U}_{L,33}} &= 1279 \text{ GeV}, \\
m_{\tilde{U}_{R,11}} &= 1534 \text{ GeV}, \\
m_{\tilde{U}_{R,22}} &= 1534 \text{ GeV}, \\
m_{\tilde{U}_{R,33}} &= 956 \text{ GeV}, \\
m_{\tilde{A}_0} &= 223 \text{ GeV},
\end{align*}
\]

For squark mixing we assume \( A_t = 900 \text{ GeV} \) and \( \delta_{LR,31} = 0.7 \)

\[
\begin{align*}
p_{T_\ell} &> 15 \text{ GeV} \\
p_{T_b} &> 20 \text{ GeV}
\end{align*}
\]

acceptance cuts:
\[
\begin{align*}
|\eta_b|, |\eta_\ell| &< 2.5 \\
\Delta R_{b\ell} &> 0.4
\end{align*}
\]

b-tagging with b-jet efficiency of 0.5 and non b-jet efficiency of 1/100

signal:
\[
\sigma(pp \rightarrow t \rightarrow b\nu_l l^+) \approx 50.0 \text{ fb}
\]

background:
\[
\begin{align*}
\sigma(pp \rightarrow \text{jet } \nu_l l^+) &\approx 12944.4 \text{ fb} \\
\sigma(pp \rightarrow b\nu_l l^+) &\approx 105.9 \text{ fb} \\
\sigma(pp \rightarrow bb\nu_l l^+) &\approx 181.0 \text{ fb}
\end{align*}
\]

DPG-Frühjahrstagung 09  München  14  Michael Spannowsky  12.03.2009
Selected differential distributions for signal and background

Reconstruct $\sqrt{s}$ with $m_{l,\nu_l} = m_W$
and $p_t = p_b + p_l + p_{\nu_l}$

Improved Cuts: 55 GeV < $p_{T_b}$ < 80 GeV
165 GeV < $\sqrt{s_{\text{rec}}}$ < 185 GeV

Cross-sections: $\sigma(pp \rightarrow t \rightarrow b \nu_l l^+) \simeq 13.2$ fb
$\sigma(pp \rightarrow \text{jet} \nu_l l^+) \simeq 496$ fb
$\sigma(pp \rightarrow b \nu_l l^+) \simeq 4.4$ fb

S/B still bad

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Can further Jets help us out?

Simulate further Jet radiation using Merging

~CA

- Top system boosted in direction of incoming gluon
- Radiation off incoming gluon enhanced
- Gluon radiation back-to-back to tagged lepton
- W-Case: Drell-Yan like production with add parton splitting
Correlations for first radiated QCD jet

Cuts: \( p_T > 30, 30, 20 \text{ GeV} \) \( |\eta_j| < 2.5 \)

+ former cuts

\( \Delta \eta_{b_1,j_1} > 1 \) \( \Delta \eta_{e,j_1} > 1 \)

<table>
<thead>
<tr>
<th>( \sigma_S )</th>
<th>( \sigma_{W,j} )</th>
<th>( \sigma_{W,b} )</th>
<th>( S/B )</th>
<th>( S/\sqrt{B} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>after acceptance cuts</td>
<td>50 fb</td>
<td>12944 fb</td>
<td>105 fb</td>
<td>1/260</td>
</tr>
<tr>
<td>after resonance cuts</td>
<td>13.2 fb</td>
<td>496 fb</td>
<td>4.4 fb</td>
<td>1/38</td>
</tr>
<tr>
<td>requiring second jet</td>
<td>7.2 fb</td>
<td>160 fb</td>
<td>1/22</td>
<td>4.4</td>
</tr>
<tr>
<td>after jets cuts</td>
<td>5.0 fb</td>
<td>48 fb</td>
<td>1/9.6</td>
<td>5.6</td>
</tr>
</tbody>
</table>

at \( 60 \text{ fb}^{-1} \)

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At 95% CL
Can we use Jets to distinguish the three channels?

Jet cuts: \( p_{T_j} > 30, 30, 20, 20, 20 \cdots \text{GeV} \) \( |\eta_j| < 2.5 \)

Lepton cuts: \( p_{T_\ell} > 15 \text{ GeV} \) \( |\eta_\ell| < 2.5 \) \( \Delta R_{j\ell} > 0.4 \)

Introduce \( \cos \theta^*(P_1, P_2) \) to distinguish between the channels:
\[ \cos \theta^*(P_1, P_2) \] parameterizes angle between \( \vec{p}_1 \) in rest frame of \( P_1 + P_2 \) and \( (\vec{p}_1 + \vec{p}_2) \) in the lab frame

Extreme case:

\[ \vec{p}_1 \cdot \vec{p}_2 \]

\[ (\vec{p}_1 + \vec{p}_2) \]
What do we expect from the three channels?

**t-channel:**
- One hard central non-b jet balances the top
- Expect second jet from gluon splitting

**s-channel:**
- Second bottom jet from off-shell W decay
- Two competing hard bottom jets of comparable pT, 40-80 GeV

**direct-top:**
- No additional bottom jets
- Mainly jet radiation off the gluon
**tth - using boosted Jets**

[Plehn, Salam, MS]

**Motivation:**
- sizable cross-section
- Higgs discovery contribution in low mass range
- access to t- and b-Yukawa couplings

**What we know from theorists‘ calculations:**

**tth:**
\[
\sigma_{NLO} = 702 \text{ fb} \quad \text{k-factor of 1.2 at } \mu = m_t + M_H/2
\]

[Beenakker et al., PRL 87 2001]

[Reina, Wackeroth, PRD D65 2002]

**ttbb:**
\[
\sigma_{NLO} = 2638(6) \text{ fb} \quad \text{k-factor of 1.7 at } \mu_0 = m_t
\]

[Bredenstein et al., PRL 103 2009]
What we know from experimentalists (ATLAS) side:

[Cammin and Schumacher, ATL-PHYS-2003-024]

<table>
<thead>
<tr>
<th>Preselection cut</th>
<th>( t\bar{t}H (fb) )</th>
<th>( t\bar{t}b (EW) ) (fb)</th>
<th>( t\bar{t}b ) (QCD) (fb)</th>
<th>( t\bar{t}X ) (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton</td>
<td>57. ± 0.2</td>
<td>141 ± 1.0</td>
<td>1356 ± 6</td>
<td>63710 ± 99</td>
</tr>
<tr>
<td>+ ≥ 6 jets</td>
<td>36 ± 0.2</td>
<td>77 ± 0.9</td>
<td>665 ± 4</td>
<td>26214 ± 64</td>
</tr>
<tr>
<td>+ ≥ 4 loose b-tags</td>
<td>16.2 ± 0.2</td>
<td>23 ± 0.7</td>
<td>198 ± 3</td>
<td>2589 ± 25</td>
</tr>
<tr>
<td>+ ≥ 4 tight b-tags</td>
<td>3.8 ± 0.06</td>
<td>4.2 ± 0.2</td>
<td>30 ± 0.8</td>
<td>51 ± 2</td>
</tr>
</tbody>
</table>

Preselection:

- **lepton triggered**
  - \( p_T > 25/20 \) GeV for e/\( \mu \), \(|\eta|\)

- **6 jets**
  - \(|\eta| < 5\)
  - \( p_T > 20 \) GeV

- **b-tags**
  - loose b-tag: \( \varepsilon \sim 85\% \) and light (charm) jet rejection
  - tight b-tag: \( \varepsilon \sim 65\% \) and light (charm) jet rejection

\[ S/B \sim 1/9 \quad \text{and} \quad S/\sqrt{B} \sim 2.2 \quad \text{for} \quad 30 \ \text{fb}^{-1} \]
Bad S/B due to bb combinatorics - can boosted Higgs help?

based on:  [Butterworth et al, PRL 100 2008]

min. selection cuts:

- 2 Jets with \( p_{T,j} \geq 200 \text{ GeV} \)  \( \rightarrow \)  Signal \( \sim 24.4 \text{ fb} \)
- Lepton with \( p_{T,l} \geq 15 \text{ GeV} \)  \( \rightarrow \)  with CA, \( R=1.5 \)

Major backgrounds:

\[
\begin{align*}
    	tt\bar{b}b & - \text{irreducible QCD background} \\
    	tt\bar{b}j\bar{b}j & \\
    	tt\bar{z} & - \text{irreducible Z-peak background} \\
    Wjj & \\
\end{align*}
\]

Our k factors:

\[
\begin{align*}
    	tt\bar{b}b & = 2.2 \\
    	tt\bar{b}j\bar{b}j & = 1.3 \\
    	tt\bar{z} & = 1.4 \\
\end{align*}
\]

We use ME scale choice: central \( m_T^2 \) scale after kT-clustering

corresponds to \( m_T^2 + p_T^2 \) for one 1 P
Kinematic situation - the one we hope for

Only 2 or 3 b in one cone reduces combinatorics
Things we need

I. Working Top-tagger:

• Has to work in busy final-state
• Has to be insensitive against UE
• Based on MW and MT reconstruction

After positive identification of top run Higgs-tagger on remaining jets

II. Working Higgs-tagger (based on WH/ZH study):

• Has to work in busy final-state
• Has to be insensitive against UE
• No Higgs mass should be assumed
Things we need

I. Working Top-tagger:

• Has to work in busy final-state
• Has to be insensitive against UE
• Based on MW and MT reconstruction

After positive identification of top run Higgs-tagger on remaining jets

II. Working Higgs-tagger (based on WH/ZH study):

• Has to work in busy final-state
• Has to be insensitive against UE
• No Higgs mass should be assumed

Work in Progress
**Wjj no killer**

Cross-section drops from 15 nb to 40 pb for staggered 200/300 GeV Jet cuts

After leptonic W branching ratio and two bottom tags down to 3.2 fb

After top and Higgs tag \(\ll 0.1 \text{ fb}\) small enough to be under control
Conclusions

W+b is an important background to BSM processes and new particle searches.

It might be possible to use Jets to improve on these searches.

The intersectional field of flavor and collider physics may give interesting results at the LHC.
Add-ons
Squark mass matrices

\[
M_{\tilde{u}} = \begin{pmatrix}
\frac{v_2}{2} Y_u Y_u^\dagger & (m_Q^2)^T - \frac{\cos 2\beta}{6} (M_Z^2 - 4M_W^2) 1 \\
-\mu \frac{v_1}{\sqrt{2}} Y_u^\dagger & -\mu * \frac{v_1}{\sqrt{2}} Y_u - \frac{v_1}{\sqrt{2}} \tan \beta A_u
\end{pmatrix}
\]

\[
M_{\tilde{d}} = \begin{pmatrix}
\frac{v_2}{2} Y_d Y_d^\dagger & (m_Q^2)^T - \frac{\cos 2\beta}{6} (M_Z^2 + 2M_W^2) 1 \\
\mu \frac{v_1}{\sqrt{2}} \tan \beta Y_d^\dagger & \mu * \frac{v_1}{\sqrt{2}} Y_d + \frac{v_1}{\sqrt{2}} \tan \beta A_d
\end{pmatrix}
\]

In super-CKM basis squarks undergo same rotation as quarks:

\[
u_L \equiv V^u \Psi_{UL}, \quad d_L \equiv V^d \Psi_{DL}, \quad u_R \equiv U^u \Psi_U, \quad d_R \equiv U^d \Psi_D
\]

\[
\tilde{u}_L = V^u \tilde{U}_L, \quad \tilde{d}_L = V^d \tilde{D}_L, \quad \tilde{u}_R = U^u \tilde{U}, \quad \tilde{d}_R = U^d \tilde{D}
\]

CKM matrix

\[ V \equiv V^u V^d^\dagger \]

SU(2) relation

\[
m_{\tilde{D}_L}^2 = V^d m_Q^2 V^d^\dagger \\
m_{\tilde{U}_L}^2 = V^u m_Q^2 V^u^\dagger
\]

Extended flavor structure of MSSM has to reproduce experimental results

\[ m_{\tilde{U}_L}^2 = V \cdot m_{\tilde{D}_L}^2 \cdot V^\dagger \]

‘SUSY flavor problem’

W+b quark physics at the LHC

Eugene 31 Michael Spannowsky 09/18/2009
MLM matching


Use parton shower to choose events

1. Generate multiparton event with cut on jet $p_T^{\text{min}}, \eta_{\text{max}}$ and $\Delta R_{\text{min}}$, and factorization scale = “central scale” (e.g. transverse mass)
2. Cluster event (according to color) and use $d_i \simeq k^2_T$ for $\alpha_s$ scale
3. Shower event (using Pythia or Herwig) starting from fact. scale
4. Collect showered partons in cone jets with same $\Delta R_{\text{min}}$ and $p_T^{\text{cut}} > p_T^{\text{min}}$
5. Keep event only if each jet matched to one parton
6. For highest multiplicity sample, allow extra jets with $p_T < p_T^{\text{parton min}}$

Stolen from J. Alwall’s Talk
CKKW matching


Imitate parton shower procedure for matrix elements

1. Choose a cutoff (jet resolution) scale $d_{\text{ini}}$
2. Generate multiparton event with $d_{\text{min}} = d_{\text{ini}}$ and factorization scale $d_{\text{ini}}$
3. Cluster event with $k_T$ algorithm to find “parton shower history”
4. Use $d_i \sim k^2_T$ in each vertex as scale for $\alpha_s$
5. Weight event with NLL Sudakov factor $\Delta(d_j, d_{\text{ini}})/\Delta(d_i, d_{\text{ini}})$ for each parton line between vertices $i$ and $j$ ($d_j$ can be $d_{\text{ini}}$)
6. Shower event, allowing only emissions with $k_T < d_{\text{ini}}$ (“vetoed showers”)
7. For highest multiplicity sample, use $\min(d_i)$ of event as $d_{\text{ini}}$

Boost-invariant $k_T$ measure:

$$\begin{cases} 
   d_{iB} = p^2_{T,i} \\
   d_{ij} = \min(p^2_{T,i}, p^2_{T,j})F_{ij} \\
   F_{ij} = 2 \{ \cosh(\eta_i - \eta_j) - \cos(\phi_i - \phi_j) \}
\end{cases}$$