Top Jets & Boosted QCD Jets @ the LHC

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Outline

✦ Introduction
✦ Emergence of high $p_T$ top ($W,Z,h$) jets at the LHC
✦ Jet mass: Signal & QCD BG (theory+MC)
✦ Jet substructure, massive jet event shapes
✦ Top polarization
✦ Summary
Introduction

In the SM (& beyond) top is unique: only ultra heavy quark, $m_t \sim \langle H \rangle$ induce most severe fine tuning; controls flavor & custodial violation; linked to EW breaking in natural models.
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- In the SM (& beyond) top is unique: only ultra heavy quark, $m_t \sim \langle H \rangle$
  induce most severe fine tuning;
  controls flavor & custodial violation;
  linked to EW breaking in natural models.

- Direct info’ is limited (Tevatron)

- At the LHC: $10^7$ top/yr

- SM: more than $10^4$ top/yr with $\gamma_t \geq 5$. 
The challenge of highly boosted tops

- First, let’s consider NP particle $X$, whose dominant decay channel is $t\bar{t}b\bar{b}$: $X$ might be heavy.
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First, let’s consider NP particle $X$, whose dominant decay channel is $t\bar{t}$: $X$ might be heavy.

Alas, above a TeV, top becomes similar to a light jet, signal is lost!
The challenge of highly boosted tops

First, let’s consider a new particle whose dominant decay channel is $t\bar{t}$.

New object emerges, top jet!
 Resolution problem \w boosted tops 

- The hadronic calorimeters cannot go below $R \sim 0.4$

\[ R^2 = \Delta \eta^2 + \Delta \phi^2 \]
The hadronic calorimeters cannot go below $R \approx 0.4$

$$R^2 = \Delta \eta^2 + \Delta \phi^2$$

**Why:** Hadronic granularity is $R \approx 0.1 \times 0.1$

$$m^2 = (p_1 + p_2)^2 \sim 2p^2 \left[ 1 - (1 - R^2/2) \right] = p^2 R^2$$

pure geometrical mass: $m \sim R p$

(say with $R, p = 0.2, 500, \ m \sim 100\text{GeV}$)
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Pure geometrical mass: $m \sim R p$

(say with $R, p = 0.2, 500, m \sim 100\text{GeV}$)

If $R$ between decay products of top is smaller than 0.4, you cannot resolve the top into daughter jets. (top jet = single jet)
Boosted top (w/z/h) jets & collimation

Partonic Level

Highly Boosted Tops: High Collimations!

$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$
Boosted top (w/z/h) jets & collimation

At final state jets level:
- Define collimation rate as the fraction of top quark which reconstruct to a jet having $140 \text{ GeV} < m_J < 210 \text{ GeV}$.
Top jets at the LHC
Top jets at the LHC

(i) Jet mass.
(ii) Jet substructure.
Top-jets @ the LHC

Are they different from high $p_T$ light jets?

$S/B \sim 1/140$, for $p_T(j) > 1000$ GeV, $R=0.4$

($\sim 20$ pb for jj+X, $\sim 140$ fb for ttbar+X)

top-jet: call for theory, analysis & techniques

Most (naive) direct attempt - mass tagging

Skiba & Tucker-Smith, PRD(07); Holdom, JHEP (07); Frederix & Maltoni (0712.2355); Ellis, Huston, Hatakeyama, Loch & Tonnesmann, PPNP (08); Agashe et. al. PRD(07).
Rejection based on jet mass

✦ Jet cone mass - sum of "massless" momenta in h-cal inside the cone: \( m_J^2 = \left( \sum_{i \in R} P_i \right)^2, P_i^2 = 0 \)

✦ Jet cone mass is non-trivial both for S & B

✦ Understand S&B distributions from 1st principles & compare to MC "data"

✦ Add detector effects
Cone top-jet mass distribution

Naively the signal is $J \propto \delta(m_J - m_t)$

In practice: $m_J^t \sim m_t + \delta m_{QCD} + \delta m_{EW}$

+ detector smearing.

$$J^t(m_J, m_t, R, p_T) \sim \int dm_{QCD} dm_{EW} dm_0 \delta(m_0 - m_t) \delta(m_J - m_{QCD} - m_{EW}) \times J^t_{QCD}(m_{QCD}, R, p_T) \times J^t_{EW}(m_{EW}, m_t/(p_T R)).$$
Cone top-jet mass distribution

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In practice: $m_J^t \sim m_t + \delta m_{QCD} + \delta m_{EW} + \text{detector smearing.}$

Can understood perturbatively fast & small~10GeV
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In practice: $m_J^t \sim m_t + \delta m_{QCD} + \delta m_{EW} + \text{detector smearing.}$

Can understood perturbatively fast & small $\sim 10 \text{GeV}$

Pure kinematical $bW(qq)$ dist’ in/out cone much longer
Cone top-jet mass distribution

Preliminary (Transfer function “Full Simulation”)

Jet Mass Distribution (C4 \( P_T^{MIN} > 1000 \text{ GeV} \))

Sherpa => Full Simulation (CKKW)
QCD cone jet mass distribution

We are interested in the following processes:

\[ H_a(p_a) + H_b(p_b) \rightarrow J_1(m^2_{J_1}, p_{1,T}, R) + X \]

\[ H_a(p_a) + H_b(p_b) \rightarrow J_1(m^2_{J_1}, p_{1,T}, R) + J_2(m^2_{J_2}, p_{2,T}, R) + X \]
QCD cone jet mass distribution

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\[ H_a(p_a) + H_b(p_b) \rightarrow J_1(m_{J_1}^2, p_{1T}, R) + J_2(m_{J_2}^2, p_{2T}, R) + X \]

Factorized hadronic cross section:

\[
\frac{d\sigma_{H_a H_b \rightarrow J_1 X(R)}}{d^2p_T dm_J d\eta} = \sum_{abc} \int dx_a \, dx_b \, \phi_a(x_a) \phi_b(x_b) \frac{d\hat{\sigma}_{ab \rightarrow c X}}{d^2p_T dm_J d\eta}(x_a, x_b, p_T, \eta, m_J, R)
\]

PDF
QCD cone jet mass distribution

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PDF

\[
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\]

Hard cross-section

Jet function

At the leading order
QCD cone jet mass distribution

Boosted QCD Jet via factorization:

\[
\int dm_J J_c = 1 \quad \Rightarrow \quad \frac{d\sigma(R)}{dp_T dm_J} = \sum_c J_c(m_J, p_T, R) \frac{d\hat{\sigma}_c(R)}{dp_T},
\]

where \( c \) represents the flavour of the jet, and where

\[
\frac{d\hat{\sigma}_c(R)}{dp_T} = \sum_{ab} \int dx_a dx_b \phi_a \phi_b \int d\eta \int dm_J \frac{d\hat{\sigma}_{ab\rightarrow cX}(R)}{dp_T dm_J d\eta}.
\]
QCD cone jet mass distribution

Boosted QCD Jet via factorization:

\[ \int d\phi J^c = 1 \]

\[ \frac{d\sigma(R)}{dp_T dm_J} = \sum_c J^c(m_J, p_T, R) \frac{d\hat{\sigma}^c(R)}{dp_T} , \]

where \( c \) represents the flavour of the jet, and where

\[ \frac{d\hat{\sigma}^c(R)}{dp_T} = \sum_{ab} \int dx_a dx_b \phi_a \phi_b \int d\eta \int dm_J \frac{d\hat{\sigma}_{ab \rightarrow cX}(R)}{dp_T dm_J d\eta} . \]

Contact with Data (MC):

\[ \frac{d\sigma_{\text{pred}}(R)}{dp_T dm_J} = \sum_c J^c(m_J, p_T, R) \left( \frac{d\sigma^c(R)}{dp_T} \right)_{MC} \]
QCD cone jet mass distribution

Boosted QCD Jet via factorization:

\[ \int dm_J J^c = 1 \]

\[ \frac{d\sigma(R)}{dp_T dm_J} = \sum J^c(m_J, p_T, R) \frac{d\hat{\sigma}^c(R)}{dp_T}, \]

where, and where

\[ \phi_a \phi_b \int d\eta \int dm_J \frac{d\hat{\sigma}_{ab\to cX}(R)}{dp_T dm_J d\eta}. \]

For large jet mass & small R, no large logs => \( J^i \) can be calculated via perturbative QCD!
Main idea: calculating mass due to two-body QCD bremsstrahlung:

\[
J^{(eik),c}(m_J, p_T, R) = \alpha_s(p_T) \frac{4 C_c}{\pi m_J} \log \left( \frac{1}{z} \tan \left( \frac{R}{2} \right) \sqrt{4 - z^2} \right)
\]

\[
\approx \alpha_s(p_T) \frac{4 C_c}{\pi m_J} \log \left( \frac{R p_T}{m_J} \right),
\]

\[z = \frac{m_J}{p_T}.\]
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\[ z = \frac{m_J}{p_T}, \]

\[ C \begin{cases} 
\text{quark jets:} & C_{(q)} = C_F = \frac{4}{3} \\
\text{gluon jets:} & C_{(g)} = C_A = 3 
\end{cases} \]
Main idea: calculating mass due to two-body QCD bremsstrahlung:

QCD Jet mass distribution, Q+G

\[ C(q) = \frac{4}{3} \]

\[ C(g) = C_A = 3 \]

Q\_1, G\_2, P\_1, P\_2

---

QCD Jet mass distribution, Q+G

(a)

(b)

(c)

(d)

(e)

(f)
Main idea: calculating mass due to two-body QCD bremsstrahlung:

\[
J_{i}^{(1)}(m_{J}, p_{0}, J_{i}, R) = \frac{C_{F} \beta_{i}}{4m_{J_{i}}^{2}} \int_{\cos(R)}^{eta_{i}} \frac{d \cos \theta_{S}}{\pi} \frac{\alpha_{S}(k_{0}) z^{4}}{(2(1 - \beta_{i} \cos \theta_{S}) - z^{2})(1 - \beta_{i} \cos \theta_{S})} \left\{ \begin{array}{l}
\frac{z^{2} (1 + \cos \theta_{S})^{2}}{(1 - \beta_{i} \cos \theta_{S}) (2(1 + \beta_{i})(1 - \beta_{i} \cos \theta_{S}) - z^{2}(1 + \cos \theta_{S})) + \\
\frac{3(1 + \beta_{i})}{z^{2}} + \frac{1}{z^{4}} \frac{(2(1 + \beta_{i})(1 - \beta_{i} \cos \theta_{S}) - z^{2}(1 + \cos \theta_{S}))^{2}}{(1 + \cos \theta_{S})(1 - \beta_{i} \cos \theta_{S})} \end{array} \right\},
\]

\[
\beta_{i} = \sqrt{1 - m_{J_{i}}^{2}/p_{0,J_{i}}^{2}} \quad z = \frac{m_{J}}{p_{0,J_{i}}}, \quad p_{0,J_{i}} = \sqrt{m_{J_{i}}^{2} + p_{T}^{2}}, \text{ and } k_{0} = \frac{p_{0,J_{i}}}{2} \frac{z^{2}}{1 - \beta_{i} \cos \theta_{S}}.
\]

\[
J_{i}^{(1)}(m_{J}, p_{0}, J_{i}, R) = \frac{C_{A} \beta_{i}}{16m_{J_{i}}^{2}} \int_{\cos(R)}^{eta_{i}} \frac{d \cos \theta_{S}}{\pi} \frac{\alpha_{S}(k_{0})}{(1 - \beta \cos \theta_{S})^{2}(1 - \cos^{2} \theta_{S})^{2}(2(1 + \beta_{i}) - z^{2})} \times \left(z^{4}(1 + \cos \theta_{S})^{2} + z^{2}(1 - \cos^{2} \theta_{S})(2(1 + \beta_{i}) - z^{2}) + (1 - \cos \theta_{S})^{2}(2(1 + \beta_{i}) - z^{2})^{2} \right)^{2}
\]
QCD Jet mass distribution, Q+G

$$J^g = \frac{1}{\sigma} \frac{d\sigma}{dM_J}$$ (Gluon Jet Functions, \(P_T = 1\) TeV, \(R=0.4\))

- Running coupling
- Fixed coupling
- Eikonal (no-recoil, fixed coupling)
- \(1/M_J\)
Jet mass distribution theory vs. MC

Revisiting our prediction:

$$\frac{d\sigma_{\text{pred}}(R)}{dp_T dm_J} = \sum_c J^c (m_J, p_T, R) \left( \frac{d\sigma^c (R)}{dp_T} \right)_{\text{MC}}$$
Jet mass distribution theory vs. MC

Revisiting our prediction:

\[
\frac{d\sigma_{\text{pred}}(R)}{dp_T dm_J} = \sum_c J^c (m_J, p_T, R) \left( \frac{d\sigma^c(R)}{dp_T} \right)_{MC}
\]

But, in practice, cannot distinguish partonic origin of a jet: can only give bounds:

\[
J^g > J^q
\]
Jet mass distribution theory vs. MC

\[ \frac{\Delta \sigma}{\Delta P_T} \] (QCD R=0.4 Jets)

- Sherpa
- MadGraph
- Pythia
Jet mass distribution theory vs. MC

Sherpa, jet function convolved
Jet mass distribution theory vs. MC

C7 Jet Mass ($P_T = 1000$ GeV)

- Sherpa
- Pythia
- MadGraph
- Gluon Hypothesis
- Quark Hypothesis

Top Mass Window
QCD jet mass dist’ under control!

Sherpa (CKKW)
With Full Detector Simulation

\[ \frac{d\sigma}{dM_J}(P_T > 1000 \text{ GeV}) \]

Can Calculate Rejection Rate (for jet mass)
QCD jet mass dist’ under control!

**Rejection Ratio**: $(\#\text{ of events for } m_t-\Delta < m_J < m_t+\Delta) / (\text{total # of events})$

- Can use our jet function to calculate it:

\[
\sigma(R)_{\text{upper bound}} = \int_{p_T^{\text{min}}}^{\infty} dp_T \sum_c \left( \frac{d\sigma^c(R)}{dp_T} \right)_{MC} \int_{140\,GeV}^{210\,GeV} J^g(m_J, p_T, R) dm_J
\]

\[
\sigma(R)_{\text{lower bound}} = \int_{p_T^{\text{min}}}^{\infty} dp_T \sum_c \left( \frac{d\sigma^c(R)}{dp_T} \right)_{MC} \int_{140\,GeV}^{210\,GeV} J^g(m_J, p_T, R) dm_J
\]

- Matches well with MC simulation (within 10%)

- For QCD dijet background, double mass tagging will reduce the background (typically, $\epsilon_r \sim 15\%$)
QCD jet mass dist’ under control!

\[ R = 0.4 \text{ Fractional Fake Rate vs } P_{T}^{\text{LEAD}} \]
## Cross Section Uncertainty

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>PDF</th>
<th>Matching</th>
<th>Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow tt(j)$</td>
<td>SHERPA 1.0.9</td>
<td>CTEQ6M</td>
<td>CKKW</td>
<td>141 fb</td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t}(j)$</td>
<td>SHERPA 1.1.2</td>
<td>CTEQ6M</td>
<td>CKKW</td>
<td>149 fb</td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t}(j)$</td>
<td>SHERPA 1.1.2</td>
<td>CTEQ6L</td>
<td>CKKW</td>
<td>281 fb</td>
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<tr>
<td>$pp \rightarrow t\bar{t}(j)$</td>
<td>MG/ME 4</td>
<td>CTEQ6M</td>
<td>MLM</td>
<td>68 fb</td>
</tr>
<tr>
<td>$pp \rightarrow tt$</td>
<td>Pythia 6</td>
<td>CTEQ6L</td>
<td>-</td>
<td>157 fb</td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t}$</td>
<td>Pythia 8</td>
<td>CTEQ6M</td>
<td>-</td>
<td>174 fb</td>
</tr>
<tr>
<td>$pp \rightarrow jj(j)$</td>
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<td>CTEQ6M</td>
<td>CKKW</td>
<td>10.2 pb</td>
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<td>$pp \rightarrow jj(j)$</td>
<td>SHERPA 1.1.2</td>
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<td>CKKW</td>
<td>21.3 pb</td>
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<td>8.54 pb</td>
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Table 1: Cross sections for producing final state $R = 0.4$ leading cone jets with $p_T \geq 1$ TeV and $|\eta| \leq 2$. Generation level cuts were imposed as follows. Final state partons from the hard scatter were required to have $p_T \geq 20$ GeV. For MG/ME, final state partons have $|\eta| \leq 4.5$. Processes with a trailing ($j$) suffix indicate that $2 \rightarrow 2$ and $2 \rightarrow 3$ processes are represented.
Ex. SM ttbar vs. di-jet background!

With transfer-functions ("full simulation")
Ex. SM $ttbar$ vs. di-jet background!

<table>
<thead>
<tr>
<th>$p_T^{lead}$ cut</th>
<th>Cone</th>
<th>$S$ (0% JES)</th>
<th>$\Delta_0$</th>
<th>+5% JES</th>
<th>$\Delta_5$</th>
<th>-5% JES</th>
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<tr>
<td>1000 GeV</td>
<td>C4</td>
<td>293</td>
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<td>2475</td>
<td>5.8%</td>
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<td>1919</td>
<td>-18.0%</td>
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<tr>
<td>1000 GeV</td>
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<td>6272</td>
<td>7.2%</td>
<td>8190</td>
<td>40.0%</td>
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Double mass tagging at 25 fb$^{-1}$ with detector resolution and Jet Energy Scale (JES) look hopeless without high b-tagging efficiency!

$$\Delta_{JES} = \frac{N_{JES} - N_{TRUTH}}{N_{TRUTH}}$$

$S/B \sim 0.11$
Ex. SM ttbar vs. di-jet background!

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<th>$\Delta_-5$</th>
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</thead>
<tbody>
<tr>
<td>1000 GeV</td>
<td>C4</td>
<td>2475</td>
<td>5.8%</td>
<td>2914</td>
<td>24.5%</td>
<td>1919</td>
<td>-18.0%</td>
</tr>
<tr>
<td>1000 GeV</td>
<td>C7</td>
<td>6272</td>
<td>7.2%</td>
<td>8190</td>
<td>40.0%</td>
<td>4894</td>
<td>-16.3%</td>
</tr>
<tr>
<td>1500 GeV</td>
<td>C4</td>
<td>294</td>
<td>16.7%</td>
<td>380</td>
<td>50.8%</td>
<td>196</td>
<td>-22.2%</td>
</tr>
<tr>
<td>1500 GeV</td>
<td>C7</td>
<td>496</td>
<td>23.4%</td>
<td>732</td>
<td>82.1%</td>
<td>330</td>
<td>-17.9%</td>
</tr>
</tbody>
</table>

Double mass tagging at 25 fb$^{-1}$ with detector resolution and Jet Energy Scale (JES) look hopeless without high b-tagging efficiency!

$$\Delta_{JES} = \frac{N_{JES} - N_{TRUTH}}{N_{TRUTH}}$$

S/B ~ 0.11
Ex. SM ttbar vs. di-jet background!
Ex. SM ttbar vs. di-jet background!
Ex. SM ttbar vs. di-jet background!
Ex. SM ttbar vs. di-jet background!

Jet Mass

<table>
<thead>
<tr>
<th>jet_mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean x</td>
</tr>
<tr>
<td>Mean y</td>
</tr>
<tr>
<td>RMS x</td>
</tr>
<tr>
<td>RMS y</td>
</tr>
</tbody>
</table>
Ex. SM ttbar vs. di-jet background!

Need Extra Handles to distinguish Signal from Background!
Pseudo-rapidity independence

QCD Jet Mass ($P_T > 1$ TeV)

Arbitrary Units vs. $M_J$ (GeV)

- C7 Lead Jet ($|\eta| < 1$)
- C7 Lead Jet ($1.0 < |\eta| < 2.5$)
Average Jet Mass (IR Mass cut needed)

\[ \langle M_J \rangle \propto P_T, R \]
Jet sub-structure
Why jets? What else?

- QCD amplitudes have soft-collinear singularity
- Observable: IR safe, smooth function of E flow
  
  *Sterman & Weinberg, PRL (77)*

- Jet is a very inclusive object, defined via direction + $p_T$ ( + mass)

- Even $R=0.4$ contains $O(100)$ had-cells => huge amount of info’ is lost
Jet-shapes

✦ “Jet-shapes” = inclusive observables dependent on energy flow within individual jets
✦ Once jet mass is fixed at a high scale
  ➡ Large class of jet-shapes become perturbatively calculable
  ➡ IR safe jet-shapes combined with IR safe jet algorithm provide a bridge between

Direct theory prediction ↔ Data/MC output
Jet-shapes

“Inclusive observables depend on energy flow within individual jets.”

Once jet mass is fixed at a high scale, a large class of jet-shapes become perturbatively calculable. IR safe jet-shapes combined with an IR safe jet algorithm provide a bridge between Direct theory prediction and Data/MC output.

Can analyze a single event by a variety of jet shapes => the resolution associated with each one need not be dramatic!
IR-safe jet-shapes which know top from QCD jets?

- Successes in high jet mass $\Rightarrow$ jet function is well described by single gluon radiation

- QCD, top: linear, planar E-deposition in the cone
  
  Almeida, SJL, Perez, Sterman, Sung, & Virzi, arXiv:0807.0234
  
  c.f. Wang, Thale: similar event shape, "sphericity tensor"
  arXiv:0806.0023

- IR-safe E-flow tensor:

$$I_{w}^{kl} = \frac{1}{m_J} \sum_{i} w_i \frac{p_{i,k}}{w_i} \frac{p_{i,l}}{w_i}$$

- Planar flow:

$$P_f = \frac{4 \det(I_w)}{\text{tr}(I_w)^2} = \frac{4\lambda_1 \lambda_2}{(\lambda_1 + \lambda_2)^2}$$
Planar flow (Pf), QCD vs top jets

♦ LO: Pf ~ 0 for QCD (2-body decay)

\[ \frac{1}{J} \left( \frac{dJ}{dPf} \right)_{2\text{body}} = \delta(Pf) \]

O(1) for top: smooth
(for isotropic ≥ 3-body decay, Pf~1)

♦ NLO (due to large m): O(\(\alpha_s\)) for QCD
nominal for top
Planar flow (Pf), QCD vs top jets

LO: Pf ~ 0 for QCD (2-body decay) O(1) for top: smooth
(for isotropic ≥ 3-body decay, Pf~1)

NLO (due to large m): O(αs) for QCD nominal for top
Planar flow (Pf), QCD vs top jets

LO: Pf ~ 0 for QCD (2-body decay) O(1) for top jets: smooth (for 3-body decay, Pf~1)

NLO (due to large m): O(αs) for QCD nominal for top jets

Planar flow, Pf (P = 1 TeV, R = 0.4, "no mass cuts")

Graph showing the comparison between QCD jets and Top jets for planar flow (Pf) with the following settings: P = 1 TeV, R = 0.4, and "no mass cuts".

The graph displays the distribution of planar flow with markers for QCD jets and Top jets.
What about 2 body jet, $Z/W/h$

Berger, K´ucs and Sterman (03): introduced for $e^+e^-$ annihilation

Angularities on a cone: Almeida, SJL, Perez, Sterman, Sung, & Virzi, arXiv:0807.0234

\[
\tilde{\tau}_a(R, p_T) = \frac{1}{m_J} \sum_{i \in \text{jet}} \omega_i \sin^a \left( \frac{\pi \theta_i}{2R} \right) \left[ 1 - \cos \left( \frac{\pi \theta_i}{2R} \right) \right]^{1-a}
\]

\[
P^x(\theta_s) = \frac{dJ^x}{d\theta_s} / J^x \Rightarrow P^x(\tilde{\tau}_a)
\]

\[
R(\tilde{\tau}_a) = \frac{P_{\text{sig}}(\tilde{\tau}_a)}{P_{\text{QCD}}(\tilde{\tau}_a)}
\]
Theory: angularity, QCD vs Z

$R^{\tau^{-2}}$ vs. $\tau_{-2}$ for $z=0.05$

- Long.
- $h=\pm 1$
Madgraph: angularity, QCD vs Z

Angularity, $\tau_a$ (a = -2, z = 0.05, R = 0.4)

- Z_{Long.} jets
- QCD jets
Daughter particles remember top polarization

For Urel’ top: **helicity = chirality**

Can do polarization analysis like it was done for the tau

Want to use $P_T$ to probe top polarization: $P_T$ is a directly measured quantity (c.f. For polarization method, need to use derived quantities with biases, like center of mass boost etc.)

- Different from spin-spin correlation where you expand in $s$ wave (for non-relativistic top)
Figure 1: Sketches of angular momentum conservation in $\not{t} \rightarrow t^+b$ decay in the top rest frame. Simple (open) arrows denote particle direction of motion ($spin$). As a massless $b$-quark must be left-handed, the rightmost plot is forbidden in the SM at tree level. Resulting angular lepton distributions are therefore very distinct for each $W$ helicity state.

As it is necessary to know the weak isospin of the $W$ spin analyzer, the charged lepton is the best choice since $u$-like jets cannot be distinguished experimentally from $d$-like jets. Consequently, the $W$ polarization is better measured in dileptonic and semileptonic $t\bar{t}$ channels through the distribution of the $\not{t}$ angle between the charged lepton direction in the $W$ rest frame and the $W$ direction in the top quark rest frame. The $\not{t}$ angular distribution is given by the following expression [6]:

$$
\frac{dN}{d\cos \theta} = \frac{3}{2} \sum_{i=L,R} F_i (\sin \theta \sqrt{2})^2 + (1 - \cos \theta)^2 + (1 + \cos \theta)^2
$$

(2)

Its SM expectation is shown in Figure 3. It reflects the superposition of the three terms of Equation (2), corresponding to the longitudinal ($\sin \theta$), left-handed ($1 - \cos \theta$) and right-handed ($1 + \cos \theta$) $W$ helicity states. Each term is weighted by the fraction $F_0$, $F_L$ or $F_R$ given in Equation (1).
Top Polarization

Figure 1: Sketches of angular momentum conservation in $\text{W} \rightarrow b$ decay in the top rest frame.

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\frac{dN}{d\cos \theta} = \frac{3}{2} \left[ F_0 \left( \sin \theta \sqrt{2} \right)^2 + F_L \left( 1 - \cos \theta \right)^2 + F_R \left( 1 + \cos \theta \right)^2 \right].
$$

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Top Polarization

$\sim 70\%$

$\sim 30\%$

Left-Handed $\text{W}$

Longitudinal $\text{W}$
Top Polarization

✧ b quark:
  - back-warded (soft $P_T$) for $t_R$
  - forwarded (hard $P_T$) for $t_L$

✧ For SM, parity even ($P_T$ distribution will be flat) → look for new Physics where parity is violated

Figure 1: Sketches of angular momentum conservation in $t \rightarrow W^+b$ decay in the top rest frame. Simple (open) arrows denote particle direction of motion (spin). As a massless b-quark must be left-handed, the rightmost plot is forbidden in the SM at tree level. Resulting angular lepton distributions are therefore very distinct for each $W$ helicity state.

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Top Polarization

- lepton: \textit{forwarded} for $t_R$
- \textit{back-warded} for $t_L$

\begin{align*}
\text{~30\%} & \quad \text{~70\%} \\
\end{align*}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{top_polarization_diagram}
\caption{Sketches of the different polarization modes in $W \rightarrow t \nu$ decay and resulting lepton directions. Simple (open) arrows denote particle direction of motion (spin). For $W^-$, left- and right-handed components are inverted.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{angular_distribution}
\caption{Angular distribution of Equation (2) in the SM. The predicted contributions from longitudinal ($0$) and left-handed ($L$) helicity states are shown separately with dashed lines. The right-handed contribution is null in the SM. The sum ($0+L+R$) is depicted with a full line.}
\end{figure}
Top Polarization

- **lepton:** *forwarded for* $t_R$
  - *back-warded for* $t_L$

For Boosted Longitudinal $W$: lepton is *forwarded*
$p_T^{\text{top}} > 1\text{TeV}$

$P_T(b)$ distribution

$P_T(b)$ is limited by W boson mass

**Hadronic Top**

$b$ quark as a spin analyzer
For example with the KK gluon, you'll see suddenly only leptons/bs that follows the RH curves.

Leptonic Top

charged lepton as a spin analyzer
Example: KK gluon

Lepton PT is harder near the KK gluon plateau.
Example: KK gluon

lepton PT is harder near the KK gluon plateau

Also relevant for SUSY: heavy stop decaying into top and wino, etc...
Example: KK gluon

b-quark PT is harder near the KK gluon bump.
$M_{tt}$ vs. $<p_T(b)>$ for $M_{KKG}=3$TeV

Also relevant for SUSY: heavy stop decaying into top and wino, etc...

Example: KK gluon

b-quark PT is harder near the KK gluon bump
Summary

- LHC => new era, precision top physics
- Theory+technique to tag t/W/Z/h jets
- Understand jet mass, but it’s not enough
- Introduce Jet-shapes: very useful, but more to do (exp’+analyses+theory)
Backup: Top Polarization

- Polarization: daughter particles of top still remembers the information

- b is forwarding for $t_L$

- lepton is back-warded for $t_L$

- lepton is in general better spin analyzer compared to b-quark, but b can be used for the hadronic top
Backup: 30% B-tagging efficiency & 1% light jet