Top Quark Physics at LHC
Denis Gelé, IPHC (Strasbourg, France)
On behalf of the ATLAS and CMS Collaborations
DIS 2009
ATLAS and CMS at LHC

Multipurpose complexe detectors dedicated to particles properties measurements:
good muon identification and momentum resolution, good electromagnetic identification
and $\gamma/e$ energy resolution, performant calorimetry for hadrons, precise and efficient
inner tracking (inc. vertex capabilities), good jet and Miss$E_T$ resolution

$pp$ collisions at LHC. Goal: $\sqrt{s} = 14$ TeV, $L = 10^{34}$ cm$^{-2}$s$^{-1}$

2009-2010: $\sqrt{s} = 10$ TeV, $L = 10^{31} - 10^{32}$ cm$^{-2}$s$^{-1}$, $\int$Ldt $\approx$ 200 pb$^{-1}$

Detector commissionning with cosmics events
O(100M) events ->
Tests of reco/analysis chain, tracker operation
and alignement, muon detector resolution and
efficiency

\[ \geq 95\% \text{ pixel detector operational} \]

ALL results presented from simulations at $\sqrt{s} = 14$ TeV
Top Quark production and decay at LHC

Strong interaction: tt pair

- Full hadronic: 6jets (2b) ~ 400K events
- Semileptonic: lν+4jets (2b) ~ 270K events
- Dileptonic:2l2ν+ 2b ~ 68K events

\[ \text{BR}(t\to Wb) \sim 100\%, \text{no top hadronization (SM)} \]

\[ \sigma_{\text{NLO}} \sim 900\text{pb} \]

\[ \Delta \text{Th/Th} : \sim 6\text{-}9\% \]

Weak interaction: single t / \( t^- \)

- t-channel: lν+2jets (1b) ~ 50K events
- tW: lν+3jets (1b) ~ 20K events
- s-channel: lν + 2jets (2b) ~ 2K events

\[ \sigma_{\text{NLO}} \sim 11\text{pb} \]

\[ \sigma_{\text{NLO}} \sim 246\text{pb} \]

\[ \sigma_{\text{NLO}} \sim 66\text{pb} \]

\[ \Delta \text{Th/Th} : \sim 5\text{-}10\% \]

\[ \sigma(t) \neq \sigma(t^-) \]

LHC=Top factory: High \( P_T \) lepton(s)+MissE_{T}+multijets (with\( \geq 1b \)}
Motivations for top quark physics at the LHC

1/ Measurements
- **Xsections**
  - Rediscovering (O(10pb⁻¹), basic (O(100pb⁻¹), precise (≥1fb⁻¹)
  - Main bckg for searches beyond SM
- **Top mass determination**
  - fundamental parameter (highest mass in SM)
  - Higgs mass constraint
- **Top properties**
  - charge,spin pol., decays, couplings, rare/FCNC decays

2/ Top=Tool for understanding/calibration of the detector
- Jet energy scale, B-tagging

Start at $\sqrt{s} = 10$ TeV instead of $\sqrt{s} = 14$ TeV
  - $tt$ Xsec reduced by a factor $\sim 2$
  - $Z/W$+jets down by $\sim 25\%$, (Higgs(200GeV)$\sim 50\%$)
Remarkable topology: t and t central, back to back in transverse plane

**Dilepton selection** (ee, μμ, eμ incl. τ -> lepton):
2 isolated high $P_T$ (>20GeV) leptons, loose elId
2 central jets ($E_T$>30GeV)
Miss$E_T$>20GeV (eμ), 30GeV (ee, μμ)
Bckgd = Z+jets, tt semil(+fake), W+jets

**Semileptonic (μ) selection:**
1 central isolated high $P_T$ (>30GeV) μ
≥ 4 central high $P_T$ jets (>40GeV, $E_T^{lead,jet}$>65GeV)
Isolation cuts ($E_{cone}^{Calo/Tracker}$, ΔR(μ, closest jet))
Bckgd = W+jets, tt(other decay channels), QCD

NO B-tagging, Data-driven methods to control bckgd being investigated

Robust counting method: $\sigma . BR = (N_{data} - N_{bckgd}) / \epsilon \int L$ (bckgd subtraction)

$N_{sig} = 128$

$S/B = 7$

$\epsilon = 10.3\%$

$\Delta \sigma / \sigma$ (stat) = 9%

$S/B = 1.7$
Top pairs (measurement with ≥100pb⁻¹-1fb⁻¹)

Dilepton final states

Selection similar to O(10pb⁻¹): 2 isolated high \( P_T \) \( l^+l^- \) (\( l=e,\mu \), e\( l_d \), \( \text{MissE}_T \), \( M_Z \) veto)

Xsection extraction from:
- Robust counting method:
  - ATLAS: \( \Delta \sigma/\sigma(100\text{pb}^{-1}) = 4(\text{stat})-2+5(\text{sys})\pm2(\text{pdf})\% \)
  - CMS(+B-tag): 8(\text{stat})\%, Bckgd~0
  - CMS(+B-tag, \( M_W \) constraint, 10fb⁻¹): 0.9(stat)±11%
- 2D binned llhood fit in (\( \text{MissE}_T, N_{\text{jets}} \)) space (ATLAS): \( \Delta \sigma/\sigma(100\text{pb}^{-1}) = 4(\text{stat})\pm4(\text{sys})\pm2(\text{pdf})\% \)
- Llhood fit to angular variables (\(|\Delta\phi(\text{lepton1, MissE}_T)|\)) (ATLAS): \( \Delta \sigma/\sigma(100\text{pb}^{-1}) = 5(\text{stat})-5+8(\text{sys})\pm0.2(\text{pdf})\% \)
  + Lumi error = 5%
Top pairs (measurement with $\geq 100\text{pb}^{-1}-1\text{fb}^{-1}$)

Semileptonic final states

- 1 isolated high $P_T (>20\text{GeV})$ e/$\mu$, $\geq 4$ jets ($P_T>20-40\text{GeV}$), hadronic top mass reconstruction

**Event reconstruction (tt compatibility):**

- **ATLAS:** $\times E_T>20\text{GeV}$, purification with $M_{jjj}=M_{\text{TopHad}}$,
  $\{jjj\}=3$ jets combination with highest transverse sum.
  Additional constraint: at least one $M_{jj}=\text{consistent with } M_W$
  (1 or 2 additional b-tags possible)

- **CMS:** 2 b-tagged jets, convergence requirement of a kine fit with $M_{jj}=M_W$ constraint

**Xsection determination:** Counting method, llhood fit to $M_{jjj}$ shape

**ATLAS:** $\Delta \sigma/\sigma(100\text{pb}^{-1}, \text{no b-tag})=3(\text{stat})\pm 16(\text{sys})\pm 3(\text{pdf})\%$ (counting) $7\pm 15\pm 3(\text{llhood})$, $+\text{lumi}=5\%$

**CMS:** $\Delta \sigma/\sigma(1000\text{pb}^{-1}, \text{b-tag, } \mu \text{ channel})=1.2(\text{stat})\pm 13.6(\text{sys+lumi})\%$ (counting)

main sys = B-tagging
Single top production (1)

$\sigma(t) \sim 300 \text{pb} \sim 1/3 \ \sigma(tt)$, important bckgd -> more complexe to select/reconstruct/extract -> Multivariate statistical analyses (boosted decision trees, genetic algorithm, multiple llhood)

**t-channel**

$q_l \nu b(b)$, 1 light jet in forward/backward direction, low $P_T$ additional $b$

Selection with sequential cuts on lepton, $b$-jet, $\text{MissE}_T$, forward jet and top mass

CMS ($\mu$, optimization with genetic algo. + counting method):

$\Delta \sigma/\sigma(10\text{fb}^{-1}) = 2.7(\text{stat})\pm 9.4(\text{sys})\%$

ATLAS ($e^+ \mu$): Additional rejection of bckgd ($tt, W+jets$) by applying BDT (10 kinematic variables not too sensitive to JES) -> reduce sys. by a half:

$\Delta \sigma/\sigma(10\text{fb}^{-1}) = 1.8(\text{stat})\pm 10(\text{sys})\%$

Need bckgd control (data-driven methods for $tt$, $W+jets$, QCD)

AND excellent knowledge of detector performance ($\text{JES and b-tagging} \leq 5\%$ uncertainty level)
Single top production (2)

**tW-channel**

\[ qql, l\nu b \ (close \ to \ tt \ with \ only \ 1 \ b\text{-}jet) \]

Selection with sequential cuts on kinematic variables (lepton \( P_T \),..., b-tagging)

CMS: Additional sophisticated \( b\text{-}W \) pairing (Fisher discriminant)

\( \rightarrow \ S/B = 0.37 \ (0.18) \) for dileptonic (semileptonic) channel \((10\text{fb}^{-1})\) \( \Rightarrow \) Significance \( = S/(S+B)^{1/2} \)

\( = 6 \) (dilep.+semil.), \( tt \) dominant bkg

ATLAS: Several Boosted Decision Trees built from 25 variables \( \rightarrow \) reduce sys. by a half:

3\( \sigma \) evidence with \( O(1\text{fb}^{-1}) \), \( \Delta\sigma/\sigma(10\text{fb}^{-1}) \sim 20\% \)

Main sys. = JES, B-tagging

**s-channel**

\( = l\nu bb \) The most difficult, a challenge

CMS: \( \Delta\sigma/\sigma(10\text{fb}^{-1}) = 18(\text{stat})\pm31(\text{sys})\% \)

ATLAS: 3\( \sigma \) evidence with 30 fb\(^{-1} \)

---

**DIS 2009**

Denis Gelé - IPHC, Strasbourg
Top mass measurements (1)

\[ M_{\text{Top}} = 173.1 \pm 1.2 \text{ GeV} \ (CDF+D0, \ arXiv:0903.2503) \]

Direct measurement: the Lepton+jet “golden” channel

Event selection: mainly semil. selection for Xsec (e+\(\mu\) for ATLAS, \(\mu\) for CMS) with 2 b-tagged jets (optional relaxed procedure studied (0/1 b-tagged jet for ATLAS)), then

Several steps (ATLAS≠CMS):

- Hadronic W mass reconstruction \(M_{jj}\) (j=light) from 2 methods:
  - with \(\chi^2\) minimization event by event (\(M_W\) constraint +
    in-situ jet energy calibration)
  - geometric method: closest jet pair in space
- Top quark reconstruction
  - choose the closest b to \{jj\}
- Top quark mass measurement from \(\chi^2\) kinematic fit (incl. \({l\nu}\) reconstruction) \(\rightarrow \Delta M_{\text{Top}}(\text{stat}) \leq 0.4\text{GeV} \text{ for } 1 \text{ fb}^{-1}\)

dominated by systematics (mostly (b)JES): 1-3.5 GeV if \(\Delta\text{JES}/\text{JES} \sim 1-5\%\)
Hadronic Top quark reconstruction
- Pair of anti b-tagged jets combined with b-tagged jets according to largest llhood -> purity ~ 82%

3 Top quark mass estimator investigated:
- Simple gaussian fit on reconstructed mass spectrum
- Convolution of the theoretical expected pdf $P(M_t|\hat{M}_t^{true})$ with gaussian resolution function:
  $$R \sim \exp \left( -\frac{1}{2} \left( \frac{M_t - M_t^{fit}}{\sigma_{M_t^{fit}}} \right)^2 \right)$$
- Convolution with a full parametrization (incl. Breit-Wigner shape, combinatorial, residual bckgd)

=> A llhood variable $L$ is reconstructed reflecting the signal probability: $\text{Max}(L) = M_{Top}$

<table>
<thead>
<tr>
<th>$\Delta M_{Top}$ (GeV)</th>
<th>Total Systematical uncertainty</th>
<th>Statistical Uncertainty (10 fb$^{-1}$)</th>
<th>Total Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.21</td>
<td>0.32</td>
<td>3.23</td>
</tr>
<tr>
<td></td>
<td>1.27</td>
<td>0.36</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>1.13</td>
<td>0.21</td>
<td>1.15</td>
</tr>
</tbody>
</table>

<1.2GeV if $\Delta\text{JES/JES} \sim 1.5\%$
Top mass measurements (3)

Other methods

- Other W decay channels:
  - Dilepton: $\Delta M_{\text{Top}} \sim 2.9\text{GeV}$ for $\leq 10\text{fb}^{-1}$ CMS, (b-JES dominates)
  - Fully hadronic: challenging! $\Delta M_{\text{Top}} \sim 4.2\text{GeV}$ ($1\text{fb}^{-1}$) limited by QCD, JES

- From $t \rightarrow$ lepton+J/ψ + X decays, with $J/\psi \rightarrow \mu^+\mu^-$

Easy to identify (clean samples) but BR(overall in tt)$\sim 5.3 \times 10^{-5}$ -> O(1000) signal events for $100\text{fb}^{-1}$ after selection

Systematics dominated by theoretical modeling of the events, negligible JES

$\Delta M_{\text{Top}} < 2\text{ GeV}$ for $20\text{fb}^{-1}$
Top properties

Top: Large mass, large width => unique to top quark properties: tests of the V-A structure of top decays; top spin; |V_{tb}|; charge; couplings; rare decays

Semileptonic W decay -> distribution of ψ = angle(lepton/W-restframe, W_{top-restframe})

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

polarized W -> longitudinal lefthanded righthanded

Events (normalized)

ATLAS

F_L = 0.29±0.02±0.03  F_0 = 0.70±0.04±0.02  F_R = 0.01±0.02±0.02

SM: 0.304 0.695 0.001

Top spin correlations in tt decays: accessible via an asymmetry measurement

\[ A = \frac{N(t\bar{t}, same helicity) - N(t\bar{t}, opp. helicity)}{N(t\bar{t}, same helicity) + N(t\bar{t}, opp. helicity)} \]

ATLAS precision \( \sim O(50\%) \) (730pb\(^{-1}\))

CMS precision \( \sim O(20\%) \) (10fb\(^{-1}\))
Anomalous top production and rare top decays

Large Yukawa coupling (~1) => Significant potential to discover new physics (top resonances, Z', Kaluza-Klein modes, Susy)

Resonance Z' -> tt
- -> lνqqbb

ATLAS: 5σ discovery with 1fb^{-1} for 700GeV Z'
(σ.BR(Z'→tt) = 11pb)

FCNC rare decays (t→(Z,γ,g)q) can be investigated

BR(t→γq)=5.7\times10^{-4} (w/o sys.)
BR(t→Zq)=11.4\times10^{-4}
B-tagging

$\tt$ events used to isolate a highly enriched $b$-jet sample $\rightarrow$ exploited to calibrate jet algorithm and extract $b$-tagging efficiency $\varepsilon_b$ for energetic jet

Selection of lepton+jets or dileptons final states:

- Counting method $(0,1,\geq2$ b-tagged jets) $\rightarrow$ $\Delta \varepsilon_b / \varepsilon_b \sim 4-5\%$ (semil. - dilep. resp., ATLAS, 100pb$^{-1}$)

- From an enriched sample (topological/kinematic selection), $\varepsilon_b = (F_{\text{tag}} - \varepsilon_b (1-P_b))/P_b$, $F_{\text{tag}} =$ measured fraction of jet tagged, $P_b =$ $b$ purity $\rightarrow$ get $\varepsilon_b$ versus $E_T$ and $\eta$ of the jet

$\rightarrow$ CMS: $\Delta \varepsilon_b / \varepsilon_b \sim 6/10\%$ (barrel/endcap) for 1fb$^{-1}$

Main sys = ISR/FSR, event selection and purity

$\rightarrow$ ATLAS: $\Delta \varepsilon_b / \varepsilon_b \sim 8\%$ for 200pb$^{-1}$ of semil. events
Jet Energy Scale (JES)

Selection of tt-> lνbjjb final states and identification of hadronic top system {jjb}; Use of the B-tagging

- ATLAS: 2 complementary methods
  - χ² fit of Mjj mass with template distributions(light JES,JEResolution) -> Precision of 2% for bare JES (all P_T) with 50pb⁻¹, no sys. error source > 0.5% identified
  - Iterative rescaling of Mjj with scale factor derived from M^{PDG}_W/ M^{FITTER}_jj constraint in bins of E_Tjet, η_{jet} (for the selected sample, P_Tjet >40GeV) -> 2% on light JES (E,η) with 1fb⁻¹

- CMS:
  - Rescale each jet with relative shifts {ΔE(light-jet),ΔE(b-jet)}, remake/refit W had. Mass and had. top (bW) mass spectra, solve the equation M(top,W;{ΔE})=M(top,W)^{PDG} -> best estimate of {ΔE}
  - ~1% on b-JES and light-JES with 100pb⁻¹
Conclusion

Top quark physics plays an essential role in the LHC program:

- unique laboratory: large amount of quark top production (for both $\sqrt{s} = 14$ TeV and 10 TeV) $\Rightarrow$ measurement limitations from systematics. Complete tool for testing lepton, jet (incl. B), MissE$_T$.

At $\sqrt{s} = 14$ TeV and low integrated luminosity, ATLAS and CMS can:

- Rediscover the top at the start-up ($\sim$ O(10 pb$^{-1}$))
- Provide basic measurements with O(100 pb$^{-1}$): tt pair production via strong interaction ($\sim$ 10-20%); B-tagging efficiency ($\sim$ 5-10%);

Need to develop data-driven methods to calibrate, control backgrounds

Beyond (O(1- 10 fb$^{-1}$)),

- access to precise measurements: $M_{\text{TOP}}$ ($\sim$1-3 GeV), single top production (10-20%), Jet Energy Scale

Hint for new physics can be found through top signature (rare decays, resonances, backgrounds for SUSY searches ...)

DIS 2009
Denis Gelé – IPHC, Strasbourg
Backup slides
To people of ATLAS & CMS Top Groups (and others) for their help/comments
Main references:

- Others (not exhaustive!):
# ATLAS/CMS

<table>
<thead>
<tr>
<th>MAGNET (S)</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets</td>
<td></td>
<td>Solenoid Calorimeters inside field 1 magnet</td>
</tr>
<tr>
<td>TRACKER</td>
<td>Si pixels+ strips</td>
<td>Si pixels + strips</td>
</tr>
<tr>
<td></td>
<td>TRD → particle identification</td>
<td>No particle identification</td>
</tr>
<tr>
<td></td>
<td>B=2T</td>
<td>B=4T</td>
</tr>
<tr>
<td></td>
<td>σ/p_T \sim 5x10^{-4} p_T $\oplus$ 0.01</td>
<td>σ/p_T \sim 1.5x10^{-4} p_T $\oplus$ 0.005</td>
</tr>
<tr>
<td>EM CALO</td>
<td>Pb-liquid argon</td>
<td>PbWO_4 crystals</td>
</tr>
<tr>
<td></td>
<td>σ/E \sim 10%/\sqrt{E} uniform longitudinal segmentation</td>
<td>σ/E \sim 2-5%/\sqrt{E}</td>
</tr>
<tr>
<td>HAD CALO</td>
<td>Fe-scint. + Cu-liquid argon (10 λ)</td>
<td>Brass-scint. (&gt; 5.8 λ +catcher)</td>
</tr>
<tr>
<td></td>
<td>σ/E \sim 50%/\sqrt{E} $\oplus$ 0.03</td>
<td>σ/E \sim 100%/\sqrt{E} $\oplus$ 0.05</td>
</tr>
<tr>
<td>MUON</td>
<td>Air → σ/p_T &lt; 10 % at 1 TeV standalone; larger acceptance</td>
<td>Fe → σ/p_T \sim 5% at 1 TeV combining with tracker</td>
</tr>
</tbody>
</table>
SM parameter measurements will be dominated by systematics errors:
- from instrumental effects, luminosity
- from MonteCarlo: ISR/FSR, PDF, 

<table>
<thead>
<tr>
<th>SM Process</th>
<th>$\sigma$(pb)</th>
<th>Evts/1fb$^{-1}$ for 14TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum bias</td>
<td>$10^{11}$</td>
<td>$\sim 10^{14}$</td>
</tr>
<tr>
<td>bb</td>
<td>$5 \times 10^8$</td>
<td>$\sim 10^{12}$</td>
</tr>
<tr>
<td>tt</td>
<td>414 908</td>
<td>$\sim 9 \times 10^5$</td>
</tr>
<tr>
<td>single t</td>
<td>164 323</td>
<td>$\sim 3 \times 10^5$</td>
</tr>
<tr>
<td>W$\rightarrow$lv</td>
<td>46 $10^3$ 68 $10^3$</td>
<td>$\sim 70 \times 10^6$</td>
</tr>
<tr>
<td>Z$\rightarrow$ll</td>
<td>4200 8000</td>
<td>$\sim 8 \times 10^6$</td>
</tr>
</tbody>
</table>

10TeV 14TeV
The preferred scenario:

Start the LHC as soon as possible and run for one year.

End September 09
End October

tt: Competing with Tevatron with ~ 100pb⁻¹ @ √s = 10 TeV
Details of sys. errors for singletop t-channel →

<table>
<thead>
<tr>
<th>Source</th>
<th>Analysis of 10 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Variation</td>
</tr>
<tr>
<td>Data Statistics</td>
<td></td>
</tr>
<tr>
<td>MC Statistics</td>
<td>2.0%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3%</td>
</tr>
<tr>
<td>b-tagging</td>
<td>3%</td>
</tr>
<tr>
<td>JES</td>
<td>1%</td>
</tr>
<tr>
<td>Lepton ID</td>
<td>0.2%</td>
</tr>
<tr>
<td>Trigger</td>
<td>1.0%</td>
</tr>
<tr>
<td>Bkg x-section</td>
<td>6.9%</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>+2.2 %   -3.2%</td>
</tr>
<tr>
<td>PDF</td>
<td>+1.38 %   -1.07%</td>
</tr>
<tr>
<td>MC Model</td>
<td>4.2%</td>
</tr>
<tr>
<td>Total</td>
<td>4.2%</td>
</tr>
</tbody>
</table>
Top mass reconstruction, systematics

Semileptonic channel (for 1-10fb⁻¹)

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>$\chi^2$ minimization method</th>
<th>geometric method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light jet energy scale</td>
<td>0.2 GeV/%</td>
<td>0.2 GeV/%</td>
</tr>
<tr>
<td><strong>b jet energy scale</strong></td>
<td>0.7 GeV/%</td>
<td>0.7 GeV/%</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>$\simeq 0.3$ GeV</td>
<td>$\simeq 0.4$ GeV</td>
</tr>
<tr>
<td>b quark fragmentation</td>
<td>$\leq 0.1$ GeV</td>
<td>$\leq 0.1$ GeV</td>
</tr>
<tr>
<td>Background</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>Method</td>
<td>0.1 to 0.2 GeV</td>
<td>0.1 to 0.2 GeV</td>
</tr>
</tbody>
</table>

**ATLAS:**

**CMS:**
Anomalous couplings

General effective Lagrangian for the $tbW$ vertex:

$$L = -\frac{g}{\sqrt{2}} b \gamma^\mu (V_L P_L + V_R P_R) t W^- \mu - \frac{g}{\sqrt{2}} \frac{i \sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W^- \mu (+h.c.)$$

where $P_{R/L} = (1 \pm \gamma^5)/2$ : usual right and left handed projector, vector-like $V_{R/L}$ and tensor-like $g_{R/L}$ are top couplings. In SM: $V_L = V_{tb}$, others are anomalous.

The W polarization is sensitive to V and g couplings associated to $tbW$ vertex $\Rightarrow$ helicity fractions ($F_L, F_0, F_R$) as well as helicity ratios $F_{R,L}/F_0$ are sensitive to them.

Can extract $tbW$ vertex info from angular asymmetries involving angle $\psi$ (between charged lepton in W rest-frame and W direction in the top rest frame), ex: forward-backward asymmetry $A_{FB} = \frac{3}{4}(F_R - F_L)$ ($=-0.223$ in SM). (No need to fit an angular distribution)
Top itself is expected to be produced essentially unpolarized but there are correlations between the spins of the 2 tops in the same events (close to the threshold, in gluon gluon fusion, top pairs are produced in a $^1S_0$ state).

Spin correlations accessible via double differential angular distributions: angle $\theta_1$ between $t$ decay product 1 in the $t$ rest frame and the $t$ in the $tt$ rest frame, same $\theta_2$ for $t$.

\[ \Theta_1 = \theta_{l-t}, \Theta_2 = \theta_{b-t} \]

\[ \Theta_1 = \theta_{l-t}, \Theta_2 = \theta_{q-t} \]
Appears in $H^\pm$ searches (H$^\pm$ boson in MSSM, non-minimal Higgs models):

In MSSM: if $M_H < M_{top}$: $t \rightarrow H^\pm b$, $H^\pm \rightarrow \tau \nu$ (dominant decay) => signature = $(Hb)(Wb)$

For example ($\tau \rightarrow$ had.)$\nu$Wbb decays that can be directly searched (or indirectly (decrease of the number of SM tt decays)):

High $P_T$ isolated leptons vetoed

5$\sigma$ significance discovery contour

95% CL exclusion contour

if $M_H > M_{top}$: $gb \rightarrow tH^\pm$, $H^\pm \rightarrow tb$ (dominant decay)
Top beyond SM (single top & heavy top)


LHC SM

3σ theory

FCNC Z-t-c

4th quark \( V_{ts} = 0.55 \)

Top-flavor \( M_{Z'} = 1 \text{ TeV} \)

Top-pion \( M_\pi = 450 \text{ GeV} \)

CMS, minimum Xsection required for a 5σ discovery

Xsection values for 2 cases, \( \lambda = \text{Yukawa couplings/gauge groups} \)

Heavy Top \( T \rightarrow tZ^0 (Z^0 \rightarrow l^+l^-, W \rightarrow l\nu, l = e, \mu) \) for \( M_t = 1 \text{ TeV/c}^2 \)

\( \lambda_1 = 2 \lambda_2 \)

\( \lambda_1 = \lambda_2 \)