ATLAS+CMS top program at HL-LHC

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Outline

• Perspectives of top physics at HL-LHC
• Top quark identification
• Review of recent studies of top physics at HL-LHC
  – Flavor changing neutral currents
  – J/ψ reconstruction in top decays
  – tt resonances
• More top physics at HL-LHC
• Summary
Top at HL-LHC

- With projected 3000/fb of integrated luminosity, the number of top quarks produced at HL-LHC is huge
- Plenty of topics for SM physics studies:
  - Precision measurement of top production (kinematic properties, differential cross sections) and properties (mass)
  - Verification of theoretical models
  - Top couplings
  - Associated top production: \(tt(V/\gamma/H)\)
  - Rare decays
- Physics beyond SM:
  - Resonances decaying into top quarks
  - Asymmetries, chromomagnetic moments
  - Top quarks arising in BSM processes (SUSY, charged Higgs,..)
HL-LHC challenge

• Challenging experimental environment
  – Need to find the ways to mitigate the pileup: $<\mu>=140$ at $L=5\times10^{34}/\text{cm}^2\text{s}$, 200 at $L=7.5\times10^{34}/\text{cm}^2\text{s}$
  – Top quark reconstruction is particularly complex, relies on all detector components

• Challenge to physics studies
  – Object performance: can’t afford full simulation for all analyses, use parameterized performance functions
  – Extrapolation of analyses with background derived on real data is tricky
  – Need to figure the way to evaluate the evolution of various systematic uncertainties
    • Zero approximation: assume systematic uncertainties as in Run 2
    • Many systematic uncertainties are expected to be reduced with statistics (e.g. background production cross sections), both due to lower stat. uncertainty and ability to go to tighter operating points
    • Difficult to evaluate without dedicated studies, $\sqrt{L}$ scaling seems like a good estimate
Top quark identification

- Top quarks decay right after they are born, need to be reconstructed
- $\text{Br}(t \rightarrow Wb) \sim 100\%$ unless we are looking for rare decays
- Two options: $t \rightarrow Wb \rightarrow l\nu b$ or $t \rightarrow Wb \rightarrow jjb$
  - Leptonic top: (isolated) $e/\mu + b$-jet + MET
  - Hadronic top, resolved: three jets, one of them $b$-jet
  - Hadronic top, boosted: a large $R$ jet with substructure
- Identification of jets coming from $b$-quarks ($b$-tagging) is key for top reconstruction
b-tagging performance (1)

- Current b-tagging algorithms at both ATLAS and CMS are based on track impact parameters and reconstruction of secondary vertices
- Information related to IP and SV is combined into a single discriminating variable (tag weight) using multivariate analysis techniques
  - CMS: cMVAv2 (BDT, central region), DeepCSV (deep neural network, forward region)
  - ATLAS: MV2 (BDT), DL1 (deep learning – not currently used for upgrade studies)
- Questions to address at HL-LHC:
  - algorithm sensitivity to high pileup environment up to \(<\mu>=200\)
  - performance in the very forward region: both experiments intend to extend the b-tagging \(|\eta|\) coverage up to 3.5—4
b-tagging at high luminosity remains solid
  – b-tagging efficiency at fixed mistag rate is a function of pileup density, not $<\mu>$

Performance in the very forward region is a problem
  – Existing algorithms are not optimized for large $|\eta|$, tracking is losing lever arm
Jet substructure

- Jet substructure: way to identify highly boosted tops (and W,Z,H)
  - mass drop: ratio of masses of highest subjet and the large-R jet
  - Nsubjettiness $\tau_N$: $p_T$ weighted $\Delta R$ distance between each jet constituent and its nearest subjet axis under assumption that the jet has N subjets
- With the upgraded CMS tracker, highly granular jet substructure reconstruction is available at higher jet momenta than achieved with the Phase-1 tracker
  - improved large R jet mass resolution
  - gain in identification of boosted objects

CMS-TDR-014
Flavor changing neutral currents (1)

- Flavor changing neutral currents: golden analysis for top physics
  - SM: not allowed at the tree level, highly suppressed in loops
  - Enhanced in BSM: RPV SUSY, technicolor

<table>
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<th>BR</th>
<th>SM</th>
<th>2HDM</th>
<th>MSSM</th>
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<td>$t \rightarrow cg$</td>
<td>$5 \times 10^{-12}$</td>
<td>$10^{-8}-10^{-4}$</td>
<td>$10^{-7}-10^{-6}$</td>
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<td>$t \rightarrow cZ$</td>
<td>$1 \times 10^{-14}$</td>
<td>$10^{-10}-10^{-6}$</td>
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<td>$t \rightarrow c\gamma$</td>
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<td>$10^{-9}-10^{-8}$</td>
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<td>$t \rightarrow cH$</td>
<td>$3 \times 10^{-15}$</td>
<td>$10^{-5}-10^{-3}$</td>
<td>$10^{-9}-10^{-5}$</td>
</tr>
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</table>
Flavor changing neutral currents (2)

- $tt \rightarrow (l\nu b)(Zq) \rightarrow 3l+(\geq 1\ b\text{-jet})+(\geq 1\ jet)$
  - Strategy: kinematic reconstruction via $\chi^2$
  - Dominant uncertainties: data driven fakes and tV/ttV backgrounds

- $tt \rightarrow (l\nu b)(Hq) \rightarrow l+(2,3\ b\text{-jets})$
  - Strategy: discriminant built from PDFs for each jet permutation
  - Dominant uncertainties: tt+HF normalization, flavor tagging

BR limits (depending on systematic extrapolation scenario):
- $t \rightarrow Zu$: $(1-2) \times 10^{-4}$
- $t \rightarrow Zc$: $(2-4) \times 10^{-4}$
- $t \rightarrow Hq$: $\sim 2 \times 10^{-4}$
Flavor changing neutral currents (3)

- \( tt \rightarrow (\mu b)(\gamma q) \rightarrow \mu + \gamma + (\geq 1 \text{ b-jet}) \)
  - Strategy: cut-and-count
  - Dominant systematic uncertainties: instrumental (fake photons), \( tV+jets, VV \gamma \)
J/ψ reconstruction in top decays

- Look at $t \rightarrow Wb \rightarrow (\mu\nu)(J/\psi+X) \rightarrow 3\mu+X$
- Alternative measurement of top mass that does not suffer from uncertainties due to b-jet reconstruction
- An opportunity to perform a dedicated tuning of the b fragmentation

Expected number of events in the J/ψ peak at 3000/fb: $6 \times 10^5$

Expected $m_t$ precision:
- $\pm 0.24$ GeV (stat)
- $\pm 0.53$ GeV (syst)

CMS-TDR-014

CMS-TDR-016
Heavy tt resonances

- Many theories predict heavy (TeV scale) particles decaying into top pairs
- Produced tops are highly boosted, leading to dense tracking environment
- Benchmark: leptophobic $Z'$ from topcolor-assisted technicolor
  - $\text{Br}(Z' \to tt) = 1/3$, width $<<$ experimental resolution
  - ATLAS exclusion limit ($3.2/\text{fb}$, $\sqrt{s}=13$ TeV): 2.0 TeV
- Current analysis: $Z' \to tt \to l\nu qq \to (e/\mu) + b + \text{large-R-jet+MET (boosted)}$ or $Z' \to tt \to l\nu qq \to (e/\mu) + b + \geq 3j + \text{MET (resolved)}$
- Obtained $Z'$ mass reach: 4 TeV
More top physics at HL-LHC

- 4top production
  - new physics (resonances, top compositeness, 4t vertices,..)
  - sensitivity to Higgs width
  - $\sigma_{SM} = 6$ fb at $\sqrt{s} = 13$ TeV, need HL-LHC to discover
- Wtb couplings
  - see previous talk
- $V_{ts}/V_{td}$ measurements
  - can be improved measuring single top production vs rapidity (arXiv:1002.4718)
- $ttZ$, $tt\gamma$, $ttg$ couplings
- Charge asymmetry in top-antitop production
  - may learn a lot from comparison of $tt$ and $ttW$ (arXiv:1406.3262)
Summary

- Top quark studies at HL-LHC open possibilities to improve our understanding of the SM and search for BSM physics in channels that depend on statistics
  - rare decays, multidimensional differential cross sections, couplings, ..
- Top quark reconstruction is complex, relies on all detector components and accurate Monte Carlo modeling
  - many current measurements are systematics driven
- Other physics analyses depend on good understanding of top production
  - top is background to most processes with heavy flavor in the final state: SM and BSM Higgs, SUSY, ..
  - calibration of detector performance, particularly b-tagging algorithms
- The top studies for HL-LHC are at their beginning
  - more studies will show more potential