Experimental summary

Reinhard Schwienhorst, Michigan State
Top is a Millennial

- Discovered 1995 - 25 year anniversary!
- Experienced Internet boom, 9/11 and the Great Recession

Fermilab CDF and D0 top-quark discovery

- Only a handful of events
- Already clear top mass peak at 175 GeV
- Based on 0.05 fb\(^{-1}\)
LHC collisions recorded

- Run 1
  $\sqrt{s} = 7-8$ TeV
  20 fb$^{-1}$ per experiment

- Long Shutdown 1

- Run 2
  $\sqrt{s} = 13$ TeV
  Almost 150 fb$^{-1}$ per experiment

- About a million times more top-quarks than in top discovery
Introduction

• Too many results to show them all, apologies if I skipped your favorite result
• Many new results over the past year, most channels now have measurements from both ATLAS and CMS
  - First LHC\textsubscript{top}WG plot at 13 TeV now public
• Measurements from previous $n$ years are still valuable
  - Persistence - many measurements will not be updated for a long time
  - Full Run-2 data results will be continue to be published for the next 3-5 years
• Virtual top-quark conference format works
  - No common meals, no excursion, no late-nite student sessions
  - But no travel, more access, more opportunities for creativity
  - Plenty of questions and discussion after talks and for posters
  - I counted 150/120/80/70/90 people connected each day
  - Thanks a lot to the organizers!
Theme: Precision measurements and their challenges

- Top pair modeling and uncertainties (Simone Amoroso)
  - PW+PY, Matching, Parton Shower, what next?
  - b-fragmentation, strange and charm in top events (Juan Gonzalez)
- Bottlenecks (Valentina Vecchio)
  - Profiling of uncertainties, unfolding
- Inclusive cross-sections (Olga Bessidskaia Bylund)
  - Top pair and single top
  - Elastic top production virtual poster by Jay Howarth
- Differential distributions (Otto Hindrichs)
  - State-of-the-art unfolding
  - CMS t-channel poster by Matthias Komm
  - CMS tW poster by Victor Bouza
  - YSF talk on ATLAS differential all-hadronic by Riccardo Poggi
- Interpretations (Matteo Defranchis)
  - Top mass, PDFs
  - YSF talk on CMS Yukawa coupling from ttbar XS by Evan Ranken
MC generators and their uncertainties

- ATLAS and CMS both use Powheg+Pythia as the main top-pair generator
  - Different tunes/shower settings
  - Outstanding agreement with data, well beyond expectations for an NLOPS generator (thanks to years of tuning)
  - But also plenty of regions with large mismodellings
- Differences also in systematic uncertainty treatment
  - NLO subtraction, PS, top pT, color reconnection
- Ambiguities in MC predictions likely to dominate top measurements also in the future

Development of better models is essential

Need high accuracy predictions, and well-defined uncertainties (as small as possible too)
B-fragmentation

- New ATLAS analysis
- Isolate charged particles from $b$-decay from those from PV
  - Unfold to particle level and compare generators and tunes

\[ z_{T,b}^{ch} = \frac{p_{T,b}^{ch}}{p_{T,jet}^{ch}} \]

\[ \rho = \frac{2p_{T,b}^{ch}}{p_T^e + p_T^\mu} \]
Profiling

- Many analyses now rely on profiling of nuisance parameters in signal and control regions to correct for mis-modeling and reduce uncertainties
  - Important to prevent unphysical constraints and pulls of NPs
  - Challenging to use these results in global fits and combinations
    - “Uncertainties are a matter of trust”
- Still need a more unified approach in presenting profiled results

Inclusive $tt$ cross-section

- Dilepton channel most precise
  - ATLAS uncertainty 2.4%
    - 2l requirement, then fit ratio of 1-tag and 2-tag
  - CMS uncertainty 4% - profile likelihood fit to many distributions
- ATLAS lepton+jets uncertainty 4.6% - profile likelihood fit

ATLAS l+jets

CMS $ll$
Inclusive single top cross-section

- CMS t-channel at 13 TeV
  - Profile only experimental and background uncertainties
  - Uncertainty 15%
  - Basis for differential measurements and interpretations

- ATLAS tW l\bar{j} at 8 TeV
  - Not as sensitive as dilepton, but reconstruction of both W bosons
  - Uncertainty 27%
Unfolded differential cross sections

- Differential distributions are the pillars of top-quark physics
- Introduction in Otto’s talk, and important issues in Valentina’s
- Important unfolding checks:
  - Bottomline test - chi2 at detector level should be similar to unfolded level (CMS)
  - Stress test - unfolding reweighted MC should reproduce reweighting function (ATLAS)
- Thousands of bins in 1d, 2d, 3d
  - Including correlations and uncertainties
  - Assumptions and special treatments need to be clear
    - Profile likelihood or fully Bayesian unfolding
Unfolding with profiling of uncertainties

• Provide auxiliary distributions to constrain uncertainties
• ATLAS: eg ttbb, include distribution of b-tag discriminant in likelihood
• CMS: $M(t\bar{t}b\bar{t})$ distribution (CMS)
  - Include $N_b$, $m_{lb}$, jet $p_T$ in likelihood
Unfolded differential cross sections

• New unfolded results: CMS boosted all-hadronic
ATLAS all-hadronic resolved final state

- Slope in top-quark $p_T$ persists
- More visible for second-leading top quark
Differential cross sections - interpretation

- 3d cross-sections provide detailed physics information
  - PDF fits, generator tuning
- Ratios cancel many uncertainties
Top mass

- Top mass from inclusive XS
  - Compare to NNLO prediction
  - Limited by theory uncertainties
- Running of the top mass from differential XS
  - $M(t\bar{t})$
  - Sensitive to threshold effects

ATLAS
- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- $m_t^{\text{pole}} = 173.1^{+2.0}_{-2.1}$ GeV

CMS
- ABMP16_5_nlo PDF set
- $\mu_{\text{ref}} = 476$ GeV
- $\mu_0 = \mu_{\text{ref}}$
- NLO extraction from differential $\sigma_{t\bar{t}}$
- One-loop RGE, $n_f = 5$, $\alpha_s(m_Z) = 0.1191$
Yukawa coupling from tt dilepton

- Develop multiplicative EW correction for signal sample
- Profile likelihood fit to 2d $m_{bbll}$ and $y_{bbll}$

CMS

$137 \text{ fb}^{-1} (13 \text{ TeV})$

- $Y_t < 1.54$ at 95% CL
- Slightly better than 4-top

$Y_t = 1.16^{+0.07}_{-0.08} (\text{stat})^{+0.17}_{-0.27} (\text{syst})$
Theme: Top+X

- Top-pair plus boson production (Rustem Ospanov)
  - Inclusive and differential $tt + \gamma, W, Z$
  - YSF talk on ATLAS $ttZ$ by Florian Fisher
- TtH and tH and 4-top (Korbinian Schweiger)
  - And ATLAS 4-top joker talk by Erich Varnes
- Tt+HF (Sebastien Wertz)
  - And CMS $ttcc$ joker talk by Seth Moortgat
**tt+V**

- New measurements of $tt+W, Z, \gamma$
  - Lepton isolation is key to $ttW$ and $ttZ$
**ttV differential**

- **ATLAS ttγ** inclusive and differential in $e\mu$ final state with full Run 2 data
  - Not (yet) in new summary plot

- **CMS ttZ differential**
ATLAS ttZ

- Inclusive and differential ttZ measurement with 139 fb$^{-1}$
ttH and tH

- 6 measurements with full Run 2 dataset
- ATLAS combination in $\kappa$-framework
  - Exclude negative $\kappa_t$ at $2.9\sigma$
- CMS multilepton analysis
  - 35x3 distributions
4-top

- No narrow resonances, many final-state jets, small XS
- Multilepton final states most sensitive
  - Build on ttH multilepton experience
  - ATLAS analysis based on full Run 2 data, obs (exp) sig 4.3 (2.4)σ
  - CMS analysis based on full Run 2 dataset and search for new scalar or vector particle
**tt+bb**

- Top+HF is an important background
  - For ttH(bb), 4-top
  - Test of ISR flavor composition at high scale
- B-tagging is key
- lepton+jets, dilepton and now also all-hadronic final state
Theme: EFT, asymmetries, CEDM, ee

- Flavor-Changing Neutral Currents and EFT (Mohammad Kareem)
- CMS EFT interpretations (Nicolas Tonon)
- Charge asymmetry, lepton universality (Nello Bruscino)
  - ATLAS first evidence for charge asymmetry
  - ATLAS lepton universality measurement in W boson decays
- Other interpretations
  - YSF talk on CMS CEDM limit by Seungkyu Ha
  - YSF talk on top mass in ee→tt+γ by Angelika Widl
EFT

- ATLAS and CMS have started to publish papers top EFT operators in Warsaw basis - document produced for LHCTopWG

Interpreting top-quark LHC measurements in the standard-model effective field theory


- Using data for EFT interpretations
  - Inclusive cross-section and other parameter measurements
  - Unfolded differential measurements
  - Impact of EFT on acceptance, background?

- Combinations are a challenge
  - Correlations of uncertainties between measurements, experiments
  - Modeling of modified signals, backgrounds
  - Which information to make available publicly?

- LHCTopWG open meeting in middle of October
EFT

- $W$ helicity combination of ATLAS and CMS measurements
  - And interpretation in terms of EFT coefficients
- Spin correlation LHCTopWG summary plot
CMS EFT

- Use multiple approaches
  - EFT from cross-section
  - EFT from unfolded distributions
  - EFT from likelihood fits to detector-level data
  - Hybrid approach
  - Summary plots to summarize current status

![Graph showing 95% CL limits of top quark - scalar boson operators](attachment:image.png)

**CMS Preliminary**

EFT from top quark production \( \sqrt{s} = 13 \text{ TeV} \)

**Top quark - scalar boson operators**

- Marginalized
- Individual

**MFV basis adopted from arXiv:1802.07237**

- Dimension 6 operators (\( \Lambda = 1 \text{ TeV} \))

<table>
<thead>
<tr>
<th>Operator</th>
<th>Marginalized</th>
<th>Individual</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{C}_i \equiv C_i / \Lambda^2 )</td>
<td>( \tilde{C}_3 )</td>
<td>( \tilde{C}_3 )</td>
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<tr>
<td>( C_{\phi \bar{Q}} )</td>
<td>( 10 \times )</td>
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<td>( C_{\phi Q} )</td>
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<tr>
<td>( C_{\phi \bar{t}b} )</td>
<td>( 10 \times )</td>
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<td>( C_{\phi t} )</td>
<td>( 10 \times )</td>
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<td>( C_{t \phi} )</td>
<td>( 10 \times )</td>
<td>( 10 \times )</td>
</tr>
</tbody>
</table>

**September 2020**

  - TOP-19-001
    - 35.9 fb\(^{-1}\)
    - 41.5 fb\(^{-1}\)
  - TOP-19-001
    - 41.5 fb\(^{-1}\)
  - JHEP 03 (2020) 056
    - 77.5 fb\(^{-1}\)
  - TOP-19-001
    - 41.5 fb\(^{-1}\)
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Flavor-Changing Neutral Currents

ATLAS+CMS Preliminary
LHCTopWG

September 2020

Each limit assumes that all other processes are zero

95% CL upper limits

ATLAS  CMS
[9] CMS-PAS-TOP-17-017
[10] JHEP 07 (2017) 003

Theory predictions from arXiv:1311.2028

Branching ratio

NEW

NEW
ATLAS charged lepton flavor universality

- Top quarks provide a pure sample of W bosons
- Resolve puzzle from LEP
- Separate $W \to \tau$ and $W W \to e,\mu$ decays

![Graph showing charged lepton flavor universality data from ATLAS](image-url)
CMS top Charged Electric Dipole Moment

Search for CP violating anomalous top quark coupling in proton-proton collisions at $\sqrt{s} = 13$ TeV

Seungkyu Ha$^{1,2}$
on behalf of the CMS Collaboration
Sep. 16, 2020

Korea University$^1$, Yonsei University$^2$

CEDM leads to CP violation

Energy-based asymmetry discriminant
Set 95% CL limit
Top mass from radiative events at lepton collider

- Precision top mass measurement at ee collider without top mass scan
  - Can measure mass with 150 MeV accuracy at 500 GeV
- Can measure running top mass

\[
e^{+}e^{-} \rightarrow t\bar{t}\gamma, \sqrt{s}=380 \text{ GeV}
\]

\[
\frac{d\sigma}{d\sqrt{s'}} \text{ [fb/1 GeV]}
\]

[Boronat, Fullana, Fuster, Gomis, Hoang, Mateu, Vos, AW 2019]
Theme: Machine learning is everywhere

- Overview of ML use by ATLAS and CMS (Ben Nachman)
  - Active area of developments
  - Wide range of application
- Jet substructure with latent algorithms (Jernej Kamenik)
  - Reveal physics of the algorithm
- Top mass and BSM and resolving it with ML (Bryan Ostdiek)
  - SUSY stop contamination in top mass measurements
Modern machine learning


- Classifiers perform well when they are fully optimized on all of the available information
  - Image pixels (clusters, tracks, not high-level variables)
  - Sub-structure, flavor information
It’s not all in the ROC curves

- Experimental challenges include hard-to-model backgrounds (e.g., multijet) and large systematic uncertainties
- Adapt learning approach to underlying physics problem

**Fun fact: this plot required training 10k NNs**

**Deep learning + weak supervision + anomaly detection leading to real physics output!**

\[ \sqrt{s} = 13 \text{ TeV}, \ 139 \text{ fb}^{-1} \]
\[ \varepsilon = 0.1, m_A = 3000 \text{ GeV} \]

- Observed
- Expected
- \( \pm 1 \sigma \)
- \( \pm 2 \sigma \)

**Inclusive search**

**Dedicated (80,80) search**

**\( (m_B, m_C) \) [GeV]**

B = top, C = BSM? See J. Kim et al., JHEP 04 (2020) 30
Latent algorithms

- “Where is the physics?” - ask the boosted-top ML algorithm directly
- 2 examples:
  - Variational Autoencoder
  - Latent Dirichlet Allocation - selects 2 themes
  - Both trained on a mixed sample: $B$: QCD (light quark & gluon) dijets
    \[ S: pp \rightarrow t\bar{t} \rightarrow W^+W^-b\bar{b}, \quad S/B = 1 \]
Top mass, BSM, DCTR

- SUSY top noise under top mass peak
- Could affect top mass measurements in template fits
- DCTR: Deep neural networks using Classification for Tuning and Reweighting
- DNN: Series of deep neural networks
- DNN reduces mass uncertainties more than W-based JES calibration
Theme: Jokers

- CMS ttcc (*Seth Moortgat*)
- CMS EFT fit to tt+X (*Brent Yates*)
- ATLAS 4-top (*Erich Varnes*)
• Top + HF is an important background
  - For ttH, 4-top, searches
  - ttbb has been studied already by ATLAS and CMS, not yet ttcc
• ML for particle ID, b-tagging, charm tagging, event reconstruction, final template fit
EFT interpretation of tt+X with CMS

- $\text{ttll, ttlv, tllq, ttH, tHq}$
- 16 EFT operators, consider one-at-a-time
- Quadratic model for yields in each bin based on MC

(graphic and data points)
**Challenges:**
- modelling of backgrounds, tt+ W+jets
- up to 9 jets

4.3 s.d. from 0 (2.4 s.d. expected) Evidence for $t\bar{t}t\bar{t}$ production
Theme: posters

• Poster session had 9 posters (same # as last year)
  - All high-quality
  - If you haven’t made a video yet, make one, then upload to youtube!

• Appetizers and drinks at home
Posters

- Elastic top production virtual poster (Jay Howarth)
  https://www.youtube.com/watch?v=9VB4nFd7LRo

- Single top at CMS
  - T-channel (incl, diff, R) by Matthias Komm
  - tW by Victor Bouza
Posters

- Re-analysis of D0 JES and its impact on D0 top mass (Hannu Siikonen)
  - Tevatron top mass measurements are still important
  - Statement from D0 at
    https://www-d0.fnal.gov/Run2Physics/WWW/results/final/TOP/T14E/D0_statement_top_mass.pdf
  - “We do not confirm the conclusions”
  - Some differences in event selection, details of correction factors
  - Some cuts were hard-coded and not documented in each analysis internal note
  - JES plot that was used had work-in-progress central values
Posters

- ttW studies at ATLAS by Marcos Miralles Lopez
- Search for hidden stop with CMS by Andrea Fernandez
Top to the Extreme

- Top as a background in high-mass searches, Leonid Serkin
  - Top pT reweighting
  - Treat tt background uncorrelated bin-by-bin

- Searches with highly boosted tops, Titas Roy
  - B* search to tW all-hadronic
Conclusions

• Virtual top-quark workshop was a big success, over 150 people connected, lively discussions
  - Thanks for turning on video when talking and asking questions
  - Which of this year’s features should we keep in future years?
• New ATLAS and CMS results, most with full Run 2 dataset
  - Still expect many more results with full Run 2 dataset
• Interpretations of measurements are just starting
  - By ATLAS and CMS, in global fits
  - EFT, BSM, SM parameters, PDFs, generator tuning, others
• Run 3 and HL-LHC are coming
  - Planning for future colliders (ee and hh)
  - Snowmass 21 EF03 https://snowmass21.org/energy/heavy_flavour
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  - Snowmass 21.

This is the golden age of top quark physics.
Additional material
Flavor-changing neutral currents
Modern machine learning

Classifiers perform well when they are fully optimized on all of the available information
- All calorimeter cells (pixels)
- Sub-structure information
CMS EFT

- Use multiple approaches
  - EFT from cross-section
  - EFT from unfolded distributions
  - EFT from likelihood fits to detector-level data
  - Hybrid

Hybrid dilepton
Top pair and tW
LHC collisions future

3,000 fb⁻¹ by 2035
HL-LHC

Twenty times the current dataset in 15 years

300 fb⁻¹ by 2025
Top to the Extreme

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- Searches with highly boosted tops, Titas Roy

Top $p_T$ reweighting to data

Treat top in each bin independently