Why is the top so interesting?

- Heaviest fundamental particle

\[ M_t(\text{pole}) = 173.1^{+2.0}_{-2.1} \text{ GeV} \]

- Short lifetime: Decays before forming bound states
  - Directly measure top properties from decays
  - Top quark predominantly produced through QCD interactions
  - Dominant decays through weak interactions

- Large coupling to Higgs

\[ Y_t = \frac{\sqrt{2}M_t}{v} \sim 1 \]
The top is a window into EWSB

- Longitudinal W’s ↔ Goldstones
  \[ \Phi = \begin{pmatrix} -iG^+ \\ v + H + iG^0 \end{pmatrix} \]
  \[ \partial^\mu G^+ \leftrightarrow W_L^{\mu+} \]
  \[ \partial^\mu G^0 \leftrightarrow Z_L^{\mu} \]

- Longitudinal gauge interactions with top are enhanced \( t\bar{t}Z_L, \ t\bar{b}W_L \sim \frac{M_t}{v} \)

- Higher dimension interactions can give effects growing with energy
  - Tails of top distributions are sensitive to new physics effects

\[ \sim \frac{(\text{Energy})^2}{\Lambda^2} \]

Deep connection between Higgs and top
Why is the top so interesting?

- Huge statistics
  - Many precision measurements and calculations:
    - $t\bar{t}, t, t\bar{t} \gamma$ production
    - $t\bar{t}H, tH$ measure $Y_t$
    - $t\bar{t}W, t\bar{t}Z, t\bar{t}t\bar{t}$ test EWSB
- Precision QCD/EW calculations tested and SM parameters extracted
  - $\alpha_s, M_t, \Gamma_t, \text{gluon PDFs}, V_{tb}$
- Large background to SM measurements (in particular Higgs production)
- Tool for new physics studies and to precisely verify consistency of SM
The top mass determines the fate of the universe and constrains new physics.
The top is heavy

- Top coupling to Higgs is $O(1)$

\[ \delta M_H^2 \sim \frac{3Y_t^2}{4\pi^2} \Lambda^2 \]

- Motivates connection between Higgs mass and top quark interactions at the TeV scale
- Many possibilities for top partners that would cancel SM top contributions to Higgs mass

\[ \delta M_H^2 \sim \frac{M_H^2}{\Delta} \quad \rightarrow \quad \Lambda \sim \frac{450 \text{ GeV}}{\Delta} \]

[McCullough]

S. Dawson
New physics from top

- **Directly**: Probe on-shell new physics with direct searches
- **Indirectly**: Probing the effect of new physics on SM observables through precision physics

Precision calculations and measurements of SM top properties

Search for new resonances

Progress in all three areas
Top and precision measurements

- Top quark pair production
- NNLO: STRIPPER [Czakon, Heymes, Mitov, '15], $q_t$ subtraction [Catani, Devoto, Grazzini, Kallweit, Mazzitelli, '19]

- Tour de force!
- New tools and new insights into QFT needed
Top quark spin correlation at NNLO

- Spin information of tops carried by leptons
  \[ pp \to t\bar{t} \to b\bar{b}l^+l^-\nu\bar{\nu}X \]
- Fiducial results in good agreement with experiment
- At NNLO consistent theory results
  - Can expand consistently in \( \alpha_s \) (red curves)
  - Blue curves are full result
  - Tension in comparison of data with inclusive measurements

[Czakon, Mitov, Poncelet, ‘20]
Top quark lepton observables at NNLO

- Impressive agreement with data; significantly reduced scale dependence at NNLO

LHC 13 TeV $m_t = 172.5$ GeV
Scale: $H_T/4$ PDF: NNPDF31

0 $\Delta \eta$ 5 $\Delta \eta$
0 $\Delta \phi$ 5 $\Delta \phi$

2008.11133
Top mass sensitivity @NNLO

- Sensitive to $\Delta M_t \sim 1$ GeV

[S. Dawson]
Top quark lepton observables at NNLO

- Reanalysis of CMS fiducial analysis with $\nu$ momentum included in jets
- Excellent agreement
- Black is reanalyzed data
- Grey is original analysis

Note sensitivity to $\Delta M_t$ shift of 1 GeV

[Poncelet]
Differential distributions at NNLO

- Continuing question: Are we measuring pole mass or $\overline{MS}$ mass?

$$M_t = m_t(\mu_m) \left[ 1 + \sum_k \left( \frac{\alpha_s(\mu_m)}{\pi} \right)^k d^k(\mu_m) \right]$$

- Scheme dependence reduced at NNLO

[Catani]

S. Dawson
Differential distributions at NNLO

- Difference between using pole mass or $\overline{MS}$ mass reduced at NNLO

- Good agreement with data
- Threshold uncertainties
Top mass extraction beyond NNLO

- Even including NNLO, NNLL' (soft gluon resummation), QCD x EW, there is theory/experimental discrepancy at low $M_{t\bar{t}}$ (which is region most sensitive to $M_t$)

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Improve by including Coulomb corrections → resum to all orders in $\alpha_s$ using effective field theory techniques

\[ \beta = \sqrt{1 - \frac{4m_t^2}{M^2_t}} \to 0 \]
Top mass extraction

- Include next-to-leading power resummation of Coulomb corrections and combine with NNLO calculations

Resummation moves the extracted mass up by more than a GeV: Closer to world average

[Yang]

S. Dawson
**$ttW$ production**

- $ttW$ is window for new physics, anomalous top couplings, important background for multi-lepton signatures, background to $ttH$
- ATLAS and CMS see excess over SM NLO+NNLL theory

Theory improvements highly motivated!
Theory progress in $t\bar{t}W$

- NLO QCD complete off-shell (resonant and non-resonant diagrams, interferences, finite width) for 3 lepton channel
  \[ pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu \tau^+ \nu_\tau b\bar{b} \]
- 2 independent calculations at 13 TeV

Off-shell effects increase up to 30-50% in tails, well above scale uncertainties

[Bevilacqua]

S. Dawson
Theory progress in $t\bar{t}W$

- NLO corrections to off-shell $t\bar{t}W$
  \[ pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu \tau^+ \nu_\tau b\bar{b} \]

- Large K factors when $t\bar{t}$ recoils against $W + $ light jet at NLO

- Both calculations find that integrated cross section shows excellent agreement with double pole approximation

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[S. Dawson]

[Pelliccioli]

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2007.12089
Theory progress in $t\bar{t}\gamma$ production

- $t\bar{t}\gamma$ at NLO including off-shell effects, resonant and non-resonant interactions, interferences $pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}\gamma$

- NLO correction up to $-43\%$
- Theory uncertainties up to $\pm 56\%$

- NLO correction up to $+8\%$
- Theory uncertainties up to $\pm 7\%$

[Worek]
Improving precision with $t\bar{t}\gamma$

- Can improve precision by taking NLO ratios
  - Fiducial integrated $\sigma_{tt\gamma}$ with dynamical scale theory error of $\pm 6\%$
  - Fiducial differential $d\sigma_{tt\gamma}/dX$ theory error $\pm 10-30\%$
  - $\sigma_{tt\gamma}/\sigma_{tt} \pm (1-3)\%$ theory uncertainty
  - Differential cross section ratios give theory uncertainties of $\pm (1-6)\%$

\[
\left[ \frac{d\sigma_{tt\gamma}/dX}{d\sigma_{tt}/dX} \right]_{NLO}
\]

[Worek]
Connecting theory and experiment

- Progress in including NLO effects in generators
  - $bb4l$ generator in POWHEG box describes top pair production and decay including full offshell and non-resonant contributions exactly at NLO ($Wt$ and $t\bar{t}$ combined straightforwardly)

New generators include QCD corrections also in decays with resonance aware subtractions that preserve virtuality of resonances

[Ferrario-Ravasio]
Generator progress at NLO

- Discrepancy between the $t\bar{t}b\bar{b}$ generators $\rightarrow$ can be reduced by proper scale choice ([Buccioni et al]

[Ferrario-Ravasio]
New techniques with ML

- Need for more efficient event generation at HL-LHC
  - Train generative adversarial networks directly on events to generate more statistics and replace fast detector simulations
  - Significant technical progress on GANs
  - Example: LHC \( t\bar{t} \rightarrow 6\text{jets} \)

![2D correlations](image)

Systematic undershoot in tails

[Butter]
Technical progress with GANs

- Progress using GANs for event subtraction
- Example:
  - Background: $pp \rightarrow e^+e^-$
  - Signal: $pp \rightarrow \gamma \rightarrow e^+e^-$

GANs may be useful for subtracting dipoles from real emission terms

[S. Dawson]
4 top production

- Large sensitivity to BSM effects
- Many possibilities:

CMS: \[ \left| \frac{Y_t}{Y_t,SM} \right| < 1.7 \]

@ 95% CL
4 top production

- Sensitive to EFT effects that grow with energy
- Motivates high energy colliders

\[ L_{EFT} \sim L_{SM} + \frac{C_{\Box}}{\Lambda^2} | \Box H |^2 \]

\[ \hat{H} = C_{\Box} \frac{M_H^2}{\Lambda^2} \]

[McCullough]
4 tops in the future

- Contact interactions probed at FCC-hh and high energy e^+e^-

\[ L \sim \frac{g_s^2}{m_*^2} (t_R \gamma_\mu t_R)(\bar{t}_R \gamma^\mu t_R) \]

- Contribution to t\bar{t}W from 4-fermion top operator?

[Theil]
Top as a window to new physics

- Effective field theory connects contributions from different types of measurements.

- Consider 22 operators involving top quarks and fit to $t\bar{t}$, $t$, $tW$, $tZ$, $t\bar{t}W$, $t\bar{t}Z$, $t$ decay including NLO QCD.

[Westhoff]
Top as a window to new physics

- How to untangle effects of different operators?
- 4-quark vs gluon operators using boosted tops
- Sensitivity to 4-quark operators grows with energy

\[ \sigma_{tt}(s) \sim \sigma_{SM}\left(1 + \frac{m_t v}{\Lambda^2} C_{1G} + \frac{s}{\Lambda^2} C_{tu}^8 + \mathcal{O}\left(\frac{s^2}{\Lambda^4}\right)C_1C_3\right) \]

\[ O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\phi G_{\mu\nu}^{A} \]
\[ O_{tG}^8 = (\bar{t}\gamma_\mu T^A t)(\bar{q}_i\gamma_\mu T^A q_i) \]

- Similarly, charge asymmetries sensitive to chiral structure of operators

\[
\text{charge asymmetry:} \quad A_{|y|} = \frac{\sigma_{SM}^A + \sigma_{AA}(C_{Qq}^1 + C_{Qq}^8)}{\sigma_{tt}}
\]

\[ O_{tq}^8 = (\bar{t}_R\gamma_\mu T^A t_R)(\bar{q}_L\gamma_\mu T^A q_L) \sim RL \]
\[ O_{Qq}^1 = (Q_L\gamma_\mu T^A Q_L)(q_L\gamma_\mu T^A q_L) \sim LL \]

[Westhoff]

Precision QCD calculations crucial for subtracting SM background in tails
EFT and the top

- Fit to $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}\gamma$, $tZq$, $t\gamma q$, $t\bar{b}$, $tW$, $tq$
  production at the LHC, along with $t \rightarrow Wb$, $e^+e^- \rightarrow b\bar{b}$
- NLO QCD effects included in fit
- Effects of inclusion of LEP data apparent in improved fit to $C_{HQ}^3$ (affects $Zb\bar{b}$ and $Zt\bar{t}$ vertices)

Note 2020 improvement

[Miralles]
New physics and the top

- Flavor changing neutral currents in top sector can arise in BSM scenarios
  - Add effective FC top interaction with leptophobich scalar
    \[ L \sim \frac{S}{\Lambda} \bar{t} L Y_{tq} q R \]

- Example of poorly constrained scenario:
  \( pp \to tS, S \to l^+ l^- \)

- Can be probed at LHC with 150 fb\(^{-1}\)

* q is light quark

[Peixoto]
B meson production in top events

- $b \rightarrow B$ at low energy described by non-perturbative fragmentation function
  - Many pieces to get fully NNLO description of B meson production from top

\[
O_B \left( \frac{Q^2}{m^2}, \alpha_s \right) = O_b \left( \frac{Q^2}{m^2}, \alpha_s \right) \times D_{b \rightarrow B}^{NP}(z)
\]

Non-perturbative, fit from data

\[
O_b \left( \frac{Q^2}{m^2}, \alpha_s \right) = \sum_{i,j} C_i \left( \frac{Q^2}{\mu_F^2}, \alpha_s \right) \times E_{i \rightarrow j} \left( \frac{\mu_F^2}{\mu_0^2}, \alpha_s \right) \times D_{j \rightarrow b} \left( \frac{\mu_0^2}{m^2}, \alpha_s \right)
\]

- Goal: fully differential MC calculation of one B-hadron + X at NNLO

[Mitov]
B meson production in top events

B production in decay of unpolarized top quark at NNLO

Grey band is variation of fragmentation function

B production in $t\bar{t}$ production and decay

[Mitov]

S. Dawson
Beyond the usual paradigm

- Quantum information and entanglement with top quarks
- Idea is to detect entanglement at the LHC by characterizing spin correlations of $t\bar{t}$ pairs

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \phi} = \frac{1}{2} (1 - D \cos \phi)$$

- $\phi$ is angle between the lepton directions in the $t$ and $\bar{t}$ rest frames

[Afik]
Thanks

- Thanks to organizers and speakers for such an interesting meeting!
- Apologies for my inadequate coverage of the immense number of interesting results presented here
- I predict many more exciting meetings about the top quark!