Measurement of the top quark mass using single top events

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Motivation

- **Top quark:**
  - Most massive elementary particle in standard model ⇒ largest Yukawa coupling with the Higgs boson
  - Largest contributor among SM particles to one-loop corrections of Higgs self-coupling ⇒ stability of the electroweak vacuum

- Correction in $\lambda$ above is proportional to $m^4$

- **Top quark mass:**
  - Top-quark pair is the largest contributor to this measurement
  - Traditionally, $m_{\text{top}}$ measurements using $t\bar{t}$ events:
    \[ m_t = 172.44 \pm 0.13 \text{ (stat)} \pm 0.47 \text{ (syst)} \text{ GeV} \]
    (overall precision is 0.28%)
  - Jet energy scale and color reconnection are the two dominant sources of systematics

* [https://doi.org/10.1103/PhysRevD.93.072004](https://doi.org/10.1103/PhysRevD.93.072004)
Signal and Background

- The $t$-channel process has at least two jets of which one is b-tagged, coming from the top quark decay.
- There is a light flavor jet recoiling against the top quark in the high pseudorapidity ($\eta$) region.
- We also have an isolated lepton and large missing transverse momentum due to the escaping neutrino.

1. The most significant background arises from top pair where one top quark decays leptonically.
2. W/Z+jets are the next dominant contributor followed by QCD multijet events.

**Diagram:**
- **t-channel process**  $\sigma = 217 \text{ pb} @ 13 \text{ TeV}$
- **top-pair process**  $\sigma = 831 \text{ pb}$
- **W+jets process**  $\sigma = 63 \times 10^3 \text{ pb}$
- **QCD multijet**  $\sigma = 30 \times 10^6 \text{ pb}$

**Measurement of the top quark mass using single top events**
Event selection

1. **Exactly one lepton:**
   - $\mu$: $p_T > 26$ GeV, $|\eta| < 2.4$, passes tight ID, $I_{\text{rel}} < 0.06$ within $\Delta R = 0.4$
   - $e$: $p_T > 35$ GeV, $|\eta| < 2.1$, passes tight ID, barrel-endcap transition gap in ECAL is excluded

2. **Veto events with second lepton:**
   - $p_T > 10$ (15) GeV, $|\eta| < 2.4$ (2.5), loose (veto) ID, $I_{\text{rel}} < 0.2$ for $\mu$ ($e$)

3. **Two jets (reconstructed with the anti-$k_T$ algorithm, radius parameter 0.4):**
   - $p_T > 40$ GeV, $|\eta| < 4.7$, loose ID, $\Delta R(\ell, \text{jets}) > 0.4$

4. **One b-tagged jet with:**
   - $|\eta| < 2.4$

5. **Transverse W mass $m_T^W > 50$ GeV**
   - To rejet the QCD multijet background
Signal and validation regions

**No of jets**
- 2
- 3
- 0
- 1
- 2

**No. of b-tagged jets**
- Signal region
- W/Z + heavy flavor
- tt⁻ control region
- QCD

**Validation of QCD estimation from SB**

**CMS, work in progress**

**Measurement of the top quark mass using single top events**
QCD estimation

- QCD has high cross section but a very low selection efficiency
- Require high MC statistics $\Rightarrow$ time consuming $\Rightarrow$ directly use data to estimate QCD
  - Go to the SB by inverting $I_{\text{rel}}/ID$ $\rightarrow$ subtract nonQCD from it $\Rightarrow$ data-driven QCD template
- Maximum likelihood fit to data in the signal region with

$$F(m_t^W) = N_{QCD} \times Q(m_t^W) + N_{\text{nonQCD}} \times W(m_t^W)$$
Top quark mass reconstruction

- Estimate $p_{z,v}$ from lepton 4-momenta and MET using the W-mass constraint

$$\{p_v + p_\ell\}^2 = P_w^2 = m_w^2$$

- In the case of real solutions:
  - Take the one with smallest absolute value

- In the case of imaginary solutions:
  - Vary $p_{x,v}$ and $p_{y,v}$ keeping W-mass constraint satisfied, and choose $p_{T,v}$ having lowest ΔR with MET

- Reconstruct the 4-momentum of W boson from lepton and $\nu$ four-momenta

- Add b-tagged jet 4-momenta to that of W boson to get the top quark kinematics including mass
**Machine learning to fight backgrounds**

- Design a boosted decision tree (BDT) for each final state to separate signal from backgrounds

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rank $\mu$</th>
<th>Rank $e$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta R_{bj'}$</td>
<td>1</td>
<td>1</td>
<td>Angular separation in $\eta - \phi$ space between the b-tagged and untagged jets</td>
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<td>light jet $</td>
<td>\eta</td>
<td>$</td>
<td>2</td>
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<tr>
<td>$m_{bj'}$</td>
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<td>3</td>
<td>Invariant mass of the system comprising the b-tagged and untagged jets</td>
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<tr>
<td>$\cos \theta^*$</td>
<td>4</td>
<td>4</td>
<td>Cosine of the angle between the lepton and untagged jet in the rest frame of the top quark</td>
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<tr>
<td>$m_T^W$</td>
<td>5</td>
<td>5</td>
<td>Transverse W boson mass</td>
</tr>
<tr>
<td>FW1</td>
<td>-</td>
<td>6</td>
<td>First-order Fox-Wolfram moment (electron final state)</td>
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<tr>
<td>$</td>
<td>\Delta \eta_{lb}</td>
<td>$</td>
<td>6</td>
</tr>
<tr>
<td>$p_T^b + p_T^l$</td>
<td>7</td>
<td>8</td>
<td>Scalar sum of $p_T$ of the b-tagged and untagged jets</td>
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<tr>
<td>$</td>
<td>\eta_l</td>
<td>$</td>
<td>8</td>
</tr>
</tbody>
</table>

**2J1T, $m_T^W > 50$ GeV**

**CMS simulation, work in progress**

- $\mu + \text{jets}$
  - Training Sample (Signal)
  - Test Sample (Signal)
  - Training Sample (Background)
  - Test Sample (Background)
  - $K_{S_{\text{sig}}} : 57.3\%$
  - $K_{S_{\text{bkg}}} : 90.6\%$

- $e + \text{jets}$
  - Training Sample (Signal)
  - Test Sample (Signal)
  - Training Sample (Background)
  - Test Sample (Background)
  - $K_{S_{\text{sig}}} : 75.1\%$
  - $K_{S_{\text{bkg}}} : 93.5\%$
Optimised cut on BDT output

- BDT cut is optimized to get the ensure high signal purity
- For BDT > 0.8 we get ≈ 60% signal purity
Extraction of $m_t$

- Fit performed simultaneously in muon and electron final state

- $F(y = \ln m_t) = f_{t\text{-ch}} \cdot F_{t\text{-ch}}(y_0) + f_{\text{Top}} \cdot F_{\text{Top}}(y_0) + f_{\text{EWK}} \cdot F_{\text{EWK}}(y_0)$

- $y_0$, $f_{t\text{-ch}}$, $f_{\text{Top}}$, and $f_{\text{EWK}}$ are allowed to float during the fit

- Constraints on the normalization added as nuisance parameters to the fit:
  
  $f_{t\text{-ch}} \rightarrow 15\%$, $f_{\text{Top}} \rightarrow 6\%$ and $f_{\text{EWK}} \rightarrow 10\%$

- $F_{t\text{-ch}}(y_0)$:
  - Modeled by an asymmetric Gaussian to model peak plus a Landau function to model tail

- $F_{\text{Top}}(y_0)$:
  - Modeled by Crystal Ball function

- $F_{\text{EWK}}(y_0)$:
  - Modeled by Novosibirsk function

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Measurement of the top quark mass using single top events

DAE-BRNS HIGH ENERGY PHYSICS SYMPOSIUM

CMS Simulation, work in progress
Mass linearity and calibration

- Dedicated samples used for t-ch and tt⁻ with alternate top mass hypotheses
- Fit framework shows a linear behavior

Mass calibration is done using the relationship
between $\Delta m_{\text{offset}} = |m_{\text{True}} - m_{\text{Fit}}|$ vs. $m_{\text{Fit}}$

$\pm 1\sigma$ uncertainty band is shown in the plot
Systematic uncertainty

- Signal and bkg. normalization added as nuisance parameters to the fit
- All other uncertainties are externalized \( \rightarrow \) fit repeated with varied templates
- Uncertainties due to jet energy scale and resolution are evaluated according to the CMS-wide recommendation
- 2.5% uncertainty in luminosity is propagated
- 4.6% uncertainty in \( \sigma_{\text{min. bias}} = 69.2 \) mb propagated as unc. due to pileup
- 50% uncertainty in QCD normalization is propagated
- Dedicated MC samples used for t-ch. and ttbar modeling unc. sources
- Alternate color reconnection tune models and top mass hypotheses are considered for t-ch and ttbar simultaneously
- Uncertainties due to QCD scale, PDF, initial- and final-state-radiation effects are calculated using reweighted templates

Total syst. unc. is estimated to be < 1 GeV (dominated by jet energy scale)
Summary

- Measured the top quark mass using $t$-channel single top quark events in CMS
- Current blind analysis yields
  \[ m_t = 172.48 \pm 0.29 \text{ (stat.+prof.)} \pm < 1 \text{ (syst.) GeV} \]
- Dominant systematic sources: jet energy scale, ISR/FSR for signal, and color reconnection
- Expect to achieve a sub-GeV precision for the first time in this specific channel
- Final results anticipated by the Winter-2021 conference
Thank you
$m_{\text{top}}$ correlation with the BDT response

**e + jets**
- $\rho_{\text{corre}} = -13.01\%$
- CMS simulation, work in progress

**$\mu + jets$**
- $\rho_{\text{corre}} = -13.61\%$
- CMS simulation, work in progress

**Top**
- $\rho_{\text{corre}} = -26.59\%$
- CMS simulation, work in progress

**EWK**
- $\rho_{\text{corre}} = -21.61\%$
- CMS simulation, work in progress

**EWK**
- $\rho_{\text{corre}} = -24.75\%$
- CMS simulation, work in progress

Measurement of the top quark mass using t-channel process
Measurement of the top quark mass using t-channel process

- More symmetric distribution
- Easy to model parametric shape
Optimised cut on BDT output

CMS simulation, work in progress

e + jets

\[ 2J1T, m_T^2 > 50 \text{ GeV} \]

Efficiency vs. BDT response cut

CMS simulation, work in progress

\[ \mu + jets \]

Efficiency vs. BDT response cut
Measurement of the top quark mass using t-channel process

Data-MC comparison after the fit: 2J0T

**e + jets**

**μ + jets**
Studies with pseudoexperiments

- $Y_0$ and corresponding pull obtained from 10000 pseudo experiments
- Pull distribution follows a Gaussian distribution with mean $\approx 0$ and $\sigma \approx 1$

Expected statistical uncertainty from pseudo experiments $\rightarrow \pm 0.29$ GeV
- Describe correlation between jets based on event topology
- When there are two jets in the event, we get

\[ H_1 = \frac{1 + r^2 + 2r P_1 \cos \Omega_{12}}{(1+r)^2} \Rightarrow H_1 = \frac{1 + r^2 + 2r \cos \Omega_{12}}{(1+r)^2} \]

Here \( r = p_T^{j1}/p_T^{j2} \) and \( \Omega_{12} \) is angle between the jets.
### Data and simulated samples

<table>
<thead>
<tr>
<th>Run period</th>
<th>Run range</th>
<th>Dataset name</th>
<th>$L_{int}$ (fb$^{-1}$)</th>
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### Process

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