Top Quark Physics at CMS

Andreas B. Meyer
LHC 2010-2012: Top Quark Factory

- peak inst. luminosity: $8 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
  - $7000$ top quark pairs per hour (8 TeV)
- $> 25 \text{ fb}^{-1}$ recorded
  - $> 5,000,000$ top each CMS and ATLAS

CMS Experiment

- Total Weight 14000 t
- Diameter 15 m
- Magnetic Field 3.8 T
- Silicon Pixel and Strip Trackers
- Crystal ECAL, Brass HCAL
- Muon Chambers, DT, RPC, CSC
- Trigger L1: 100kHz, ~500 Hz to tape
Top Quarks

- The top quark is the heaviest known particle
  - Maximum sensitivity to Higgs (EWK loops, gg → H)
  - $\tau \sim 5 \times 10^{-26}$ s: decay before hadronization: "bare quark"
  - Direct access to spin and charge

- Search for New Physics
  - New physics might preferentially couple / decay to top
  - Measure standard (and non-standard) couplings

- Precision measurement of SM parameters
  - Total cross sections, differential distributions
  - Properties (mass, spin structure, asymmetries, $V_{tb}$ …)

Precise top quark measurements
→ tighten constraints on standard model parameters
→ sensitivity to New Physics

68% and 95% CL contours
- fit w/o $M_W$ and $m_t$ measurements
- fit w/o $M_W$, $m_t$ and $M_H$ measurements
- direct $M_W$ and $m_t$ measurements

$M_W$ world comb. $\equiv 1$
$M_W = 80.385 \pm 0.015$ GeV

$M_t$ world comb. $\equiv 1$
$M_t = 173.34$ GeV
$\delta m_W \propto m_t^2$
$\delta m_W \propto \ln(m_H)$

ArXiv:1407.3792
Contributions to the error on the extracted constant and to be reasonably

Expanding Eq. 5 around the limit

FIG. 2: Partonic cross-section times averaged constant

Close to threshold, the color singlet and color octet

The constant

As explained in Ref. [25], the estimate (14) for

we take the one-loop result (see [17, 25]):































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































Top Quark Pair Production

Contributions to the following we take this error to be 50%. Has to be used with caution and a sizable uncertainty.

Our fits return the value \( R_{gg} = 0.4912 \) for each value of \( \Phi \). For \( gg \) the color singlet and color octet contributions contribute only at the percent level, since they are suppressed by an additional factor of 10. Nonetheless it contributes at NNLO with the constant \( C_{gg} = 3.38 \). We parameterize the second, unknown, which has the advantage of being normalization independent.

Expanding Eq. 5 around the limit \( \mu \rightarrow \mu_{soft} \) used to derive an estimate for the so-far unknown coefficients \( C_{gg} \), \( C_{l} \), and \( C_{H} \). The double real corrections are computed in Ref. [11]. The finite part of the one-loop amplitude is computed with Ref. [31]. The hard matching is related to the hard matching by additional 50%. We observe that as a result of this rather conservative variation, the dependence is computed in a standard way; see Refs. [13, 14].

The PDF sets using the HATHOR parametrization are determined in Ref. [35]. The reason for switching between various colliders and c.m. energies.

The NLO QCD calculations are done using the following PDF sets:

- **HERAPDF1.5**
- **MSTW2008**
- **NNPDF2.1**
- **ABKM09**

For \( \alpha_s \) of the total cross section as function of \( Q^2 \), values (around 0.114) are determined through NLO. Nonetheless it contributes at NNLO.

| Collider     | \( \sigma_{tot} \) [pb] | scales [pb]          | pdf [pb]          |
|--------------|-------------------------|----------------------|-------------------|
| Tevatron     | 7.164                   | +0.110(1.5%)         | +0.169(2.4%)      |
| LHC 7 TeV    | 172.0                   | +4.4(2.6%)           | +4.7(2.7%)        |
| LHC 8 TeV    | 245.8                   | +6.2(2.5%)           | +6.2(2.5%)        |
| LHC 14 TeV   | 953.6                   | +22.7(2.4%)          | +16.2(1.7%)       |

\[ \sigma_{tot} = \sigma_{\text{LO}} + \sigma_{\text{NLO}} + \sigma_{\text{NNLO}} \]

\[ \sigma_{\text{LO}} = 7.164 \text{ pb} \]

\[ \sigma_{\text{NLO}} = 172.0 \text{ pb} \]

\[ \sigma_{\text{NNLO}} = 245.8 \text{ pb} \]

\[ \sigma_{\text{NNLO}} = 953.6 \text{ pb} \]

Full NNLO available since early 2013 - scale and PDF uncertainties 2-3%
Experimental Ingredients

- **Particle Flow**
  - Holistic view of all detector information
  - Combination of tracker and calorimeter to obtain list of identified particles

- **Isolated Leptons (e, μ or τ)**
  - Isolation (including PU subtraction)
  - Calibrations and efficiencies from dilepton resonances (Z, Υ, J/ψ)

- **Jet (and E_T^{miss})**
  - Optimal resolution and scale
  - Pile-up subtraction based on charged component

- **b-tagging**
  - Combination of several techniques (vertex, impact parameter, track distributions within jets)

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Top quark physics: require high-precision leptons, jets and b-tagging

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Andreas B. Meyer

Top Quark Physics at CMS

HQL2014, Mainz, 28 August 2014
### Physics from Top Quark Production and Decay

#### Top Quark Pairs
- Asymmetries, spin correlations, color flow
- Cross sections, kinematics, QCD parameters, resonances, new particles

#### EWK Single-Top Production
- s,t,tW channel production, properties, couplings

#### Menu:
- Production
- Properties
- Couplings
- Mass
- Outlook
**Inclusive $\bar{t}t$ Cross Sections (8 TeV)**

- **dilepton channel: 1e+1$\mu$+2jets (1b-tag)**
  - Almost background-free, remaining backgrounds estimated from data
  - Systematics: $Q^2$, matching, jet energy scale

![Graph showing cross sections and invariant mass distributions for dilepton channels](image)

- $\sigma_{\bar{t}t} = 239 \pm 2_{\text{stat}} \pm 11_{\text{syst}} \pm 6_{\text{lumi}} \text{ pb}$

- First LHC cross section measurement at 8 TeV, still room for improvement

**Acknowledgments**

- The measurement is obtained through an event-counting analysis based on a data sample from statistical, systematic and integrated luminosity components, respectively.
- The results are given for the individual sources of background, $t\overline{t}$ production cross sections, and various leptonic channels.

**Figure 3:** Distributions of (upper left) the dilepton invariant-mass, (upper right) the mass of the two selected leptons ($\ell^+\ell^-$), and (lower left) the $b$-jet multiplicity distribution. The expected distributions for the $t\overline{t}$ signal, in this case, are normalised to the overflow events. The observed distributions are shown as the black circles, with the hatched bands corresponding to the total uncertainty in the predictions. The ratios of data to predictions are shown in the lower right graph. The $t\overline{t}$ production cross section is measured to be $239 \pm 2_{\text{stat}} \pm 11_{\text{syst}} \pm 6_{\text{lumi}} \text{ pb}$ at a center-of-mass energy of 8 TeV, with 5.3 fb$^{-1}$ of data. The CMS collaboration reports that the first LHC cross section measurement at 8 TeV is still room for improvement, and they update the CMS Run1.
Inclusive $\bar{t}t$ Cross Sections (8 TeV)

- e/$\mu$-tau channel: 1e or $\mu + 1$ $\tau$-lepton (1b-tag)
  - Dominant systematics: tau-ID and tau-mis-ID

$\sigma_{\bar{t}t} = 257 \pm 3_{\text{stat}} \pm 24_{\text{syst}} \pm 7_{\text{lumi}}$ pb

9.5%

Precision dominated by tau-ID
ATLAS and CMS have measured the inclusive $t\bar{t}$ cross section in all decay channels (except $\tau\tau$)
Differential $tt$ Cross Sections

- **Measure top quark kinematic distributions**
  - Scrutinize theory predictions and models
  - Ensure that acceptances, efficiencies are correct
  - Enhance sensitivity to new physics
  - Extract / use for PDF-fits (future)

- **Main analysis ingredients:**
  - Kinematic reconstruction
  - Bin-wise cross section analysis
  - Regularized unfolding

CMS results for 7 and 8 TeV for both $l+$jets and dileptons
Differential $t\bar{t}$ Cross Sections

**$\eta(\ell)$**

**$p_T^b$**

**$p_T(t\bar{t})$**

**$m(t\bar{t})$**

**$p_t(top)$**

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**pt(top): Approx. NNLO better than MC - Narrow Z' resonance excluded up to 2 TeV**
tt + jets, tt+bb, tt+tt

NLO QCD: Interference between q → t

Probing radiation and parton shower modelling

ttbb: important background to ttH

σ(ttbb)/σ(ttjj) = 2.2 ± 0.4 stat ± 0.5 syst %

Boosted decision tree

σ(ttt) < 63 fb at 95% CL (obs), 42+18-13 fb (exp)
\( \bar{t} + W, Z, \gamma \)

**Figure 2:** Binned template fit to charged hadron isolation: The real and fake photon templates.

**3.3 Estimation of the photon mis-identification rate**

A background expectation of this value is taken as a systematic uncertainty. Systematic contributions from signal and background processes are shown, and their predictions of the signal efficiencies by 13%, and the contribution from events containing a SM Higgs boson, is measured to be 13 events.

**4.2 Same-sign dilepton results**

The expected contribution from semileptonic double-parton scattering. Yields from these processes are imposed with a grey hashed band. For the trilepton channel, events passing the trilepton selection are characterized by a pair of same-flavour, opposite-sign leptons (\( e \) and \( \mu \)). In the top-quark pair sample, the statistical uncertainty of the signal events, \( (tt+Z) (tt+W) \) combined, is available in the Supplemental Material.

**CMS preliminary** \( L = 19.5 \text{ fb}^{-1} \) at \( \sqrt{s} = 8 \text{ TeV} \)

\( 1\ell + 1\gamma \)

\( \sigma_{tt+\gamma} = 2.4 \pm 0.2 \text{ stat} \pm 0.6 \text{ syst pb} \)

Consistent with SM

Uncertainties statistically limited

→ CMS Run 2

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Top Quark Physics at CMS

HQL2014, Mainz, 28 August 2014
Charge/FB-Asymmetry

- LO: No charge asymmetry expected
- NLO: Interferences between q̄q diagrams
  - diluted at LHC due to large gg and unknown quark direction

Available asymmetry calculations are effectively leading order

\[ A_{FB}^{t\bar{t}} = \frac{N (\Delta y > 0) - N (\Delta y < 0)}{N (\Delta y > 0) + N (\Delta y < 0)} \]

\[ A_{C} = \frac{N (\Delta |y| > 0) - N (\Delta |y| < 0)}{N (\Delta |y| > 0) + N (\Delta |y| < 0)} \]

Tevatron

\[ A_{FB} \]

\[ \eta \]

top

anti-top

LHC

\[ A_{C} \]

\[ |y_{\bar{t}}| \]

top

anti-top
Charge-Asymmetry

**QM: \( A_{C,{\text{top}}} = 1.23 \pm 0.05 \% \)**  

**QCD: \( A_{C,{\text{top}}} = 0.4 \pm 1.0_{\text{stat}} \pm 1.1_{\text{syst}} \% \)**  

**AC,top = 0.4 \pm 1.0_{\text{stat}} \pm 1.1_{\text{syst}} \%**  

**AC,top = 0.5 \pm 0.7_{\text{stat}} \pm 0.6_{\text{syst}} \%**  

**Top Quark Physics at CMS**  

HQL2014, Mainz, 28 August 2014

**NNLO prediction underway**  

**Differential distributions give additional sensitivity**
Spin Correlations

\[ A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}} \]

**CMS, 5.0 fb\(^{-1}\) at \( \sqrt{s} = 7 \) TeV**

\[ A_{\Delta\phi} = \frac{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) - N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) + N(\Delta\phi_{\ell^+\ell^-} < \pi/2)} \]

**Helicity**

\[ A_{\text{helicity}} = 0.113 \pm 0.010_{\text{stat}} \pm 0.007_{\text{syst}} \pm 0.012_{\text{syst}} \]

**SM**

\[ A_{\text{SM}} = 0.115 \pm 0.015 \]

**Uncorrected**

\[ A_{\text{uncorr}} = 0.210 \]

\[ \Rightarrow f_{\text{CMS}} \sim 1.02 \]

Search for chromomagnetic dipole-moments

\[ \mathcal{L}_{\text{eff}} = -\frac{\mu}{2} i\sigma^{\mu\nu} T^a t G^a_{\mu\nu} - \frac{\tilde{\mu}}{2} i\sigma^{\mu\nu} \gamma_5 T^a t G^a_{\mu\nu} \]

\[ -0.043 < \text{Re}(\mu) < 0.117 \text{ at } 95\% \text{ CL} \]

Limited by scale uncertainties

Andreas B. Meyer

Top Quark Physics at CMS
The number of expected events is given by:

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8} (1 - \cos\theta^*)^2 F_L + \frac{3}{8} (1 + \cos\theta^*)^2 F_R + \frac{3}{4} (\sin\theta^*)^2 F_0 \]

- Also available from CMS: dileptons (7 TeV) and single-top topologies (7 and 8 TeV)
- All measurements consistent with left-handed charged currents
  Used to set limits on anomalous couplings
Single Top Production

- Test of EW interactions
- $V_{tb}$ / 4th generation / FCNC
- Sensitivity to b-PDF and u/d-PDF

|                  | $t$ ch. | $tW$ ch. | $s$ ch. | $tt^-$   |
|------------------|---------|----------|---------|----------|
| Tevatron ($pp^-$)| 2 TeV   | 2.08pb   | 0.25pb  | 1.05pb   | 7.08pb   |
|                  | 7 TeV   | 64.6pb   | 15.6pb  | 4.59pb   | 172pb    |
| LHC ($pp$)       | 8 TeV   | 87.6pb   | 22.2pb  | 5.55pb   | 249pb    |
|                  | 14 TeV  | 248pb    | 84.8pb  | 11.9pb   | 954pb    |

LHC: much more gluons, leading to very different relative contributions
t-Channel

- Cut-based analysis
- One e or \( \mu \), 2jets-1b-tag events in reco’d top mass window
- Backgrounds determined from fit to \( \eta \) distribution
- Total cross-section

\[
\sigma_t (8 \text{ TeV}): \quad 83.6 \pm 2.3_{\text{stat}} \pm 7.4_{\text{syst}} \text{ pb}
\]

\( V_{td}, V_{ts} \ll V_{tb} \), unconstrained: \( 0.979 \pm 0.045 \) (exp.) \( \pm 0.016 \) (theo)

constrained < 1 @ 95% CL: \( > 0.92 \)

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Large program of detailed studies (diff. distributions, properties, couplings, QCD studies)
t-Channel: PDF from $\sigma_t/\sigma_{\bar{t}}$

- In pp collisions expect: $u$-density $\sim 2 \times d$-density
- Simultaneous fit to $\eta'$-distributions of positive and negative leptons

CMS, $\sqrt{s} = 8$ TeV, $L = 19.7$ fb$^{-1}$

- CMS
- 1.95 ± 0.10 (stat.) ± 0.19 (syst.)
- ABM11
- CT10
- CT10w
- HERAPDF
- MSTW2008
- NNPDF 2.3

Consistent with expectation - errors still large
**tW-Channel**

- **Event Signature**
  - 2 e or µ, 1 jet (b-tagged)
- **Analysis**
  - Binned likelihood fit to BDT
- **Dominant uncertainties:**
  - statistics, b-tagging, tt bg-model

**Observation! Agrees with SM**

$\sigma_{tW}(8\text{ TeV})$: \(23.4 + 5.5 - 5.4_{\text{stat+syst}}\) pb

$V_{td}, V_{ts} < V_{tb}$, unconstrained: \(1.03 \pm 0.12\) (exp.) $\pm 0.04$ (theo)

Constrained < 1 @ 95% CL: \(> 0.78\)

6.1σ obs. (5.4σ exp.)
\[ R_B = \frac{\text{BR} \left( \text{tWb} \right)}{\text{BR} \left( \text{tWq} \right)} \]

- 2 leptons, 2 jets, MET
- \( R_B \) from fit to b-tag multiplicity
  - data-driven determination of correct jet-assignment fraction, b-tag efficiency and misidentification
- Dominant systematics: b-tag and \( m_{\text{top}} \)
- \(|V_{tb}| \) from \( R_B \) assuming unitary CKM
- Total width \( \Gamma_{\text{top}} \) from \( R_B \) and t-channel single top cross section

Measured t-channel (7 TeV)

\[
\Gamma_t = \frac{\sigma_{t-\text{ch.}}}{B(t \rightarrow Wb)} \cdot \frac{\Gamma(t \rightarrow Wb)}{\sigma_{t-\text{ch.}}} \frac{\Gamma(t \rightarrow Wb)}{\sigma_{t-\text{ch.}}}
\]

| \( R \) |
|---|
| unconstrained |

\[
1.014 \pm 0.003 \pm 0.032
\]

| \( |V_{tb}| \) |
|----------------|
| constrained < 1 @ 95% CL |

\[
> 0.972
\]

| \( \Gamma_{\text{top}} \) |
|----------------|

\[
1.36 \pm 0.02_{\text{stat}} + 0.14_{\text{syst}} - 0.11_{\text{syst}} \text{ GeV}
\]

Most precise direct measurement of \( |V_{tb}| \)
Wtb-Couplings: $|V_{tb}|$ Summary

\[ \mathcal{L} = -\frac{g}{\sqrt{2}} b \gamma^\mu \left( f^L_V P_L + f^R_V P_R \right) t W^-_\mu - \frac{g}{\sqrt{2}} i \sigma^{\mu\nu} \partial_\nu W^-_\mu \left( f^L_T P_L + f^R_T P_R \right) t + h.c. \]

**Vector operators**

\[ |V_{td}|, |V_{ts}| \ll |V_{tb}|, Br \equiv 1 \rightarrow f^L_V V_{tb} = \sqrt{\frac{\sigma_{t-ch.}}{\sigma_{t-ch.}^{sm}}} \]

**Tensor operators**

SM: $f^L_V = V_{tb}$, $f^R_V = f^L_T = f^R_T = 0$ (at tree level)

**CMS Preliminary IV_{tb} Summary August 2014**

- **tW (7 TeV)**: $1.01 \pm 0.16 \pm 0.13_{exp} + 0.03 - 0.04_{theo}$
- **tW (8 TeV)**: $1.03 \pm 0.12_{exp} \pm 0.04_{theo}$
- **t (7 TeV)**: $1.020 \pm 0.046_{exp} \pm 0.017_{theo}$
- **t (8 TeV)**: $0.979 \pm 0.045_{exp} \pm 0.016_{theo}$
- **t (7+8 TeV)**: $0.998 \pm 0.038_{exp} \pm 0.016_{theo}$
- **R**: $1.007 \pm 0.016 \text{ (stat+syst.)}$
Anomalous Wtb-Couplings

$$\mathcal{L} = -\frac{g}{\sqrt{2}} b\gamma^\mu \left( f^L_V P_L + f^R_V P_R \right) t W^-_\mu - \frac{g}{\sqrt{2}} b \frac{i\sigma^{\mu\nu} \partial_\nu W^-_\mu}{M_W} \left( f^L_T P_L + f^R_T P_R \right) t + h.c.$$
Rare Top decays: FCNC

\[ t \rightarrow W^+ c, u \]

\[ t \rightarrow b, s, d \]

\[ \gamma/Z \]

\[ t \rightarrow u, c \]

\[ Z, \gamma, g, H \]

| Process       | SM       | 2HDM(FV) | 2HDM(FC) | MSSM  |
|---------------|----------|----------|----------|-------|
| \( t \rightarrow Zu \) | \( 7 \times 10^{-17} \) | -        | -        | \( \leq 10^{-7} \) |
| \( t \rightarrow Zc \) | \( 1 \times 10^{-14} \) | \( \leq 10^{-6} \) | \( \leq 10^{-10} \) | \( \leq 10^{-7} \) |
| \( t \rightarrow gu \) | \( 4 \times 10^{-14} \) | -        | -        | \( \leq 10^{-7} \) |
| \( t \rightarrow gc \) | \( 5 \times 10^{-12} \) | \( \leq 10^{-4} \) | \( \leq 10^{-8} \) | \( \leq 10^{-7} \) |
| \( t \rightarrow \gamma u \) | \( 4 \times 10^{-16} \) | -        | -        | \( \leq 10^{-8} \) |
| \( t \rightarrow \gamma c \) | \( 5 \times 10^{-14} \) | \( \leq 10^{-7} \) | \( \leq 10^{-9} \) | \( \leq 10^{-8} \) |
| \( t \rightarrow hu \) | \( 2 \times 10^{-17} \) | \( 6 \times 10^{-6} \) | -        | \( \leq 10^{-5} \) |
| \( t \rightarrow hc \) | \( 3 \times 10^{-15} \) | \( 2 \times 10^{-3} \) | \( \leq 10^{-5} \) | \( \leq 10^{-5} \) |

FCNC couplings can be probed in production (single top) and decay of top quarks.
Rare Top decays: FCNC

- **tqZ**: select 3-lepton events and look for Zj-resonance in top-mass window

- **tqγ**: Use BDT to separate ty from Wy (and other backgrounds)
Top-Quark Mass

- Not an observable, i.e. scheme-dependent
  - Pole-mass: viewing top quark as a free parton
  - $\overline{\text{MS}}$ scheme ('running mass'):
    \[ m^{\text{pole}} = m(\mu) \left\{ 1 + \frac{\alpha_s(\mu)}{4\pi} \left( \frac{4}{3} + \ln \left( \frac{\mu^2}{m(\mu)^2} \right) \right) \right\} + \ldots \]
  - 'MC mass': (N)LO+PS yet different from pole or $\overline{\text{MS}}$ mass

- MC mass believed to be close to pole mass within 0.5 GeV

- Experimental uncertainties due to final state modeling
  - Hadronization
  - Fragmentation
  - Colour Reconnection
  - Flavour-dependent jet energy response
Top-Quark Mass in \( l + \text{jets} \) channel

- **Signature**
  - e/\( \mu \) + 4 jets, 2 b-tags (high purity selection)

- **Analysis ('2D-Ideogram')**
  - Reconstruct top mass from \( \text{kin.fit} \) \( (P_{\text{gof}} > 0.2) \)
  - 2D-fit of mass and jet energy scale (JES) using W-mass constraint
  - Weight each fit solution by \( P_{\text{gof}} \)
  - Measurement from max.likelihood in mass-JES plane

- **Dominant Uncertainties**
  - Jet energy resolution: 0.26 GeV
  - Pile-up: 0.27 GeV
  - Flavour-dependent jet energy scale, includes hadronization (PYTHIA vs HERWIG) 0.41 GeV
  - ME-generator: 0.23 GeV

\[ m_{\text{rec}} = 172.04 \pm 0.19_{\text{stat+JES}} \pm 0.75_{\text{syst}} \text{ GeV} \]
**Top-Quark Mass in fully hadronic channel**

- **Signature**
  - 6 jets, 2 b-tags (high purity selection)

- **Analysis ('2D-Ideogram')**
  - Reconstruct top mass from kin.fit \( (P_{\text{gof}} > 0.1) \)
  - 2D-fit of mass and jet energy scale (JES) using W-mass constraint
  - Weight each fit solution by \( P_{\text{gof}} \)
  - Measurement from max. likelihood in mass-JES plane

- **Dominant Uncertainties**
  - \( p_T \) and \( \eta \)-dependent JES: 0.28 GeV
  - Pile-up: 0.31 GeV
  - Flavour-dependent jet energy scale, includes hadronization (PYTHIA vs HERWIG) 0.36 GeV
  - ME-generator: 0.21 GeV

As precise as World Average

\[ m_{\text{top}} = 172.08 \pm 0.36_{\text{stat+JES}} \pm 0.83_{\text{syst}} \text{ GeV} \]
Top Mass: Kinematic Dependence

- Investigate modelling issues: various (non-)perturbative corrections are different in their kinematic dependence
- Investigate distributions with sensitivity to
  - Color reconnection
  - ISR/FSR
  - b-quark kinematics
- Figures: $m_{\text{top}} - \langle m_{\text{top}} \rangle$

| Observable                  | $m_{1D}^{\Delta}$ | JSF $\chi^2$ | $m_{2D}^{\Delta}$ | Ndf |
|-----------------------------|-------------------|--------------|-------------------|-----|
| $\Delta R_{q\ell}$          | 2.87              | 3.66         | 0.83              | 3   |
| $p_{T,t,\text{had}}$        | 0.89              | 12.03        | 5.76              | 4   |
| $|\eta_{t,\text{had}}|$     | 5.56              | 1.22         | 1.14              | 3   |
| $H_{t}^{2}$                 | 6.19              | 9.18         | 7.54              | 4   |
| $m_{t}$                     | 2.16              | 4.69         | 4.22              | 5   |
| Jet multiplicity            | 4.24              | 0.10         | 1.16              | 2   |
| $p_{T,t}$                   | 1.02              | 2.12         | 1.33              | 4   |
| $|\eta_{t,\text{had}}|$     | 1.15              | 0.08         | 0.72              | 2   |
| $\Delta R_{b\bar{b}}$      | 0.37              | 1.63         | 1.77              | 3   |
| $p_{T,b,\text{had}}$        | 2.57              | 5.80         | 2.17              | 4   |
| $|\eta_{b,\text{had}}|$     | 1.15              | 0.08         | 0.72              | 2   |
| $|\eta_{b,\text{had}}|$     | 1.15              | 0.08         | 0.72              | 2   |
| $p_{T,L,W,\text{had}}$      | 1.59              | 8.06         | 1.60              | 4   |
| $|\eta_{L,W,\text{had}}|$   | 1.41              | 1.09         | 1.35              | 3   |
| Total                       | 37.43             | 60.94        | 37.15             | 47  |

No significant deviations between data and various models w.r.t their kinematic dependence
Top Quark Mass Summary

CMS Preliminary

- CMS 2010, dilepton
  - JHEP 07 (2011) 049, 36 pb⁻¹
  - 175.5 ± 4.6 ± 4.6 GeV
    (value ± stat ± syst)

- CMS 2010, lepton+jets
  - PAS TOP-10-009, 36 pb⁻¹
  - 173.1 ± 2.1 ± 2.6 GeV
    (value ± stat ± syst)

- CMS 2011, dilepton
  - EPJC 72 (2012) 2202, 5.0 fb⁻¹
  - 172.5 ± 0.4 ± 1.4 GeV
    (value ± stat ± syst)

- CMS 2011, lepton+jets
  - JHEP 12 (2012) 105, 5.0 fb⁻¹
  - 173.5 ± 0.4 ± 1.0 GeV
    (value ± stat ± syst)

- CMS 2011, all-hadronic
  - arXiv:1307.4617, 3.5 fb⁻¹
  - 173.5 ± 0.7 ± 1.2 GeV
    (value ± stat ± syst)

- CMS 2012, lepton+jets
  - PAS TOP-14-001, 19.7 fb⁻¹
  - 172.0 ± 0.2 ± 0.8 GeV
    (value ± stat ± syst)

- CMS combination
  - March 2014
  - 172.2 ± 0.1 ± 0.7 GeV
    (value ± stat ± syst)

- CMS 2012, all-hadronic
  - PAS TOP-14-002, 19.7 fb⁻¹
  - 172.1 ± 0.4 ± 0.8 GeV
    (value ± stat ± syst)

- Tevatron combination (2014)
  - arXiv:1407.2682
  - 174.3 ± 0.4 ± 0.5 GeV
    (value ± stat ± syst)

- World combination 2014
  - ATLAS, CDF, CMS, D0
  - 173.3 ± 0.3 ± 0.7 GeV
    (value ± stat ± syst)

Results using alternative methods not included in this summary
m(top), \( \alpha_S \) and PDF from \( \text{tt} \) Cross Section

- NNLO calculation: precise relation between cross section, pole mass, \( \alpha_S \) and PDF

- Compare to most precise CMS-cross section measurement: dilepton at 7 TeV

- Blue band: \( m_{\text{MC}}(\text{top}) = m_{\text{pole}}(\text{top}) \pm 1 \text{ GeV} \)

\[
m_t = 176.7^{+3.0}_{-2.8} \text{ GeV}
\]

for fixed \( \alpha_S = 0.1151 \) and NNPDF2.3

\[
\alpha_S(m_Z) = 0.1151^{+0.0028}_{-0.0027}
\]

for fixed \( m_{\text{top}} = 173.2 \pm 1.4 \text{ GeV} \) and NNPDF2.3
Outlook: Top at 13 TeV

Top pair and single top cross sections with and without accompanying Z

13/8 TeV $tt$ and single top cross sections: factors ~4 and ~2.5 resp.

300 fb$^{-1}$: 3$\sigma$-evidence if $B(t \rightarrow Zq)>0.03\%$

$\sqrt{s}$ [TeV] vs $\sigma$ [fb]

- $tt/Z$
- $t\bar{t}$ (t-channel)
- $\bar{t}t$ (t-channel)
- $tt+Z$
- $t+Z$ (t-channel)
- $\bar{t}+Z$ (t-channel)

10 Hz (at $10^{34}$)
2 Hz (at $10^{34}$)
0.01 Hz (at $10^{34}$)

| 14/8 Ratio | $\Delta R_{\text{NNPDF}}$ | $\delta_{\text{PDF}}$ (%) |
|------------|--------------------------|---------------------------|
| $tt/Z$     | 2.12                     | 1.3                       |
| $t\bar{t}$ | 3.90                     | 1.1                       |
| $Z$        | 1.84                     | 0.7                       |
| $W^+$      | 1.75                     | 0.7                       |
| $W^-$      | 1.86                     | 0.6                       |
| $W^+/W^-$  | 0.94                     | 0.3                       |
| $W/Z$      | 0.98                     | 0.1                       |
| $ggH$      | 2.56                     | 0.6                       |
| $t\bar{t}(M_{tt} \geq 1 \text{ TeV})$ | 8.18 | 2.5 |
| $t\bar{t}(M_{tt} \geq 2 \text{ TeV})$ | 24.9 | 6.3 |
| $\sigma_{\text{jet}}(p_T \geq 1 \text{ TeV})$ | 15.1 | 2.1 |
| $\sigma_{\text{jet}}(p_T \geq 2 \text{ TeV})$ | 181.6 | 7.7 |

1402.3856

Campbell, Ellis, Roentsch

FTR-13-016

Mangano, Rojo arXiv:1206.3557

Table 6: Same as Table 4 but for cross section ratios between 14 and 8 TeV.
Conclusions

- Top quark physics: Key to QCD, electro-weak and New Physics

- Precision regime: $\sigma_{tt} < 5\%, m(\text{top}) \lesssim 1 \text{ GeV}, \ldots$

- Inclusive cross section prediction available up to full NNLO, same precision as data

- Top Top-Topics:
  - $tt$ and single-top production including differential distributions, $tt+$jets, $ttbb$, $tttt$
  - $tt+W,Z,\gamma$, charge-asymmetry, spin-correlations, $W$-helicity, $Vtb$, FCNC
  - mass, $\alpha_s$, PDF

- All results so far in agreement with SM predictions

- Run-1: CMS working on Run-1 Legacy measurements
- Run-2: A new regime of precision measurements and searches with top quarks
Backup
Systematics Top-Quark Mass

| Channel                              | $\delta m_t$ (GeV) | $\delta$JSF | $\delta m_t$ (GeV) | $\delta$JSF |
|--------------------------------------|--------------------|-------------|--------------------|-------------|
|                                      | $\ell$+jets        |             | All jets           |             |
| **Experimental uncertainties**       |                    |             |                    |             |
| Fit calibration                      | 0.10               | 0.001       | 0.06               | <0.001      |
| $p_T$- and $\eta$-dependent JES      | 0.18               | 0.007       | 0.28               | 0.006       |
| Lepton energy scale                  | 0.03               | <0.001      |                    |             |
| Missing transverse energy            | 0.09               | 0.001       |                    |             |
| Jet energy resolution                | 0.26               | 0.004       | 0.10               | <0.001      |
| b-tagging                            | 0.02               | <0.001      | 0.02               | <0.001      |
| Pileup                               | 0.27               | 0.005       | 0.31               | 0.001       |
| Trigger                              |                    |             | 0.18               | 0.003       |
| Background                           | 0.11               | 0.001       | 0.22               | 0.002       |
| **Hadronization model**              |                    |             |                    |             |
| Flavor-dependent JSF                 | 0.41               | 0.004       | 0.36               | 0.004       |
| b-fragmentation                      | 0.06               | 0.001       | 0.07               | 0.001       |
| Semi-leptonic B hadron decays        | 0.16               | <0.001      | 0.12               | <0.001      |
| **Hard scattering process model**    |                    |             |                    |             |
| PDF                                  | 0.09               | 0.001       | 0.02               | <0.001      |
| Renormalization/factorization scales | 0.12±0.13          | 0.004±0.001 | 0.19±0.19          | 0.004±0.002 |
| ME-PS matching threshold             | 0.15±0.13          | 0.003±0.001 | 0.20±0.19          | 0.002±0.002 |
| ME generator                         | 0.23±0.14          | 0.003±0.001 | 0.09±0.21          | 0.003±0.002 |
| **Non-perturbative QCD model**       |                    |             |                    |             |
| Underlying event                     | 0.14±0.17          | 0.002±0.002 | 0.13±0.28          | 0.000±0.002 |
| Colour reconnection                  | 0.08±0.15          | 0.002±0.001 | 0.00±0.25          | 0.000±0.002 |
| Total                                | 0.75               | 0.012       | 0.83               | 0.011       |

- Similar treatment as for 7 TeV but larger statistics (data + MC) help refining syst. assessments
- JES uncertainty component due to pileup + $\Delta\sigma_{\text{min.bias}}$
- Signal modelling is added
  - Madgraph vs Powheg +
  - modeling of top $p_T$ estimated after re-weighting simulation to observed top $p_T$
- Hadronization is the dominant uncertainty
  - Pythia-based JES extrapolation: from calibrated jet flavour to other flavours
  - Pythia vs Herwig differences are evaluated separately for light, gluon and b-jets
  - b-fragmentation: default vs LEP
  - Semi-leptonic B rates: from PDG
Systematics Top-Quark Mass

**Radiation effects**

- $p_T(t\bar{t})$
- $H_T$
- $m_{t\bar{t}}$
- $p_T,t\bar{t}$
- Jet multiplicity

**b-quark kinematics**

- $\eta_{b,\text{had}}$
- $p_T,b,\text{had}$
- $\Delta R_{b\bar{b}}$
- $\Delta \phi_{b\bar{b}}$

**Colour reconnection**

- $\Delta R(q,q')$
- $p_T,t,\text{had}$
- $\eta_{t,\text{had}}$

We rely on MC-based models of the top production and decay chain, particularly models for underlying event (UE), colour reconnection (CR) are taken into account. Do these tools describe our data in the different phase space regions? Is our assessment of systematic uncertainties mined by casual cancellations? Can we find sensitivity to different components in top quark $p_T$, $b$-quark rapidity, charge, etc.? Choose representative observables which can potentiate particular effects. Radiation effects and b-quark kinematics. HQL2014, Mainz, 28 August 2014
\[ R = \frac{\text{BR}(tW_b)}{\text{BR}(tW_q)} \]

**Chronological summary of measurements of \( R_B \) performed so far**

| Measurement | Value | Reference |
|-------------|-------|-----------|
| \( R \) | 1.014^{+0.032}_{-0.032} | CMS TOP-12-035 (2014) |
| \( R \) | 0.87±0.07 | CDF arXiv:1404.3392 |
| \( R \) | 0.94^{+0.09}_{-0.09} | CDF PRD 87, 111101 (2014) |
| \( R \) | 0.95^{+0.07}_{-0.07} | DØ PRL 107, 121802 (2011) |
| \( R \) | 0.86^{+0.05}_{-0.05} | |
| \( R \) | 0.97^{+0.09}_{-0.08} | DØ PRL 100, 192003 (2008) |
| \( R \) | 1.03^{+0.19}_{-0.17} | DØ PLB 639, 616 (2006) |
| \( R \) | 1.02^{+0.31}_{-0.24} | CDF PRL 95, 102002 (2005) |
| \( R \) | 1.41^{+0.49}_{-0.42} | |
| \( R \) | 0.94^{+0.31}_{-0.24} | CDF PRL 86, 3233 (2001) |