Probing the SM: Top quarks and beyond

Michele Gallinaro
LIP Lisbon
March 27, 2017

✓ Top quarks as window to New Physics
✓ Top-Higgs associated production
✓ Top quark signatures in SUSY
✓ Higgs and Dark Matter
SM confirmed by the data

Excellent agreement with all experimental results

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### Standard model of elementary particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (GeV/c²)</th>
<th>Charge</th>
<th>Spin</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up quark</td>
<td>0.24</td>
<td>2/3</td>
<td>1/2</td>
<td>u</td>
</tr>
<tr>
<td>Charm quark</td>
<td>1.77</td>
<td>2/3</td>
<td>1/2</td>
<td>c</td>
</tr>
<tr>
<td>Top quark</td>
<td>171.2</td>
<td>0</td>
<td>1/2</td>
<td>t</td>
</tr>
<tr>
<td>Photon</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>γ</td>
</tr>
<tr>
<td>Higgs boson</td>
<td>125.0</td>
<td>0</td>
<td>0</td>
<td>H</td>
</tr>
</tbody>
</table>

### Quarks

- **Up quark** (u) with mass ≤ 2.2 eV/c²
- **Charmed quark** (c) with mass ≤ 1.77 GeV/c²
- **Top quark** (t) with mass ≤ 104 GeV/c²
- **Down quark** (d) with mass ≤ 4.8 MeV/c²
- **Strange quark** (s) with mass ≤ 104 MeV/c²
- **Bottom quark** (b) with mass ≤ 4.2 GeV/c²
- **Gluon** (g) with mass ≤ 91.2 GeV/c²

### Leptons

- **Electron neutrino** (νₑ) with mass ≤ 0.511 MeV/c²
- **Muon neutrino** (νₘ) with mass ≤ 0.17 MeV/c²
- **Tau neutrino** (νₜ) with mass ≤ 15.5 GeV/c²
- **Electron** (e) with mass ≤ 0.511 MeV/c²
- **Muon** (μ) with mass ≤ 105.7 MeV/c²
- **Tau** (τ) with mass ≤ 1.777 GeV/c²

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M. Gallinaro - "Probing the SM: Top quark properties and beyond" - March 27, 2017
Top quarks as window to BSM physics

Top quark affects stability of Higgs mass

![Diagram](image)

Contributions grow with $\Lambda$:

$$m^2 = m_0^2 + g^2 \Lambda^2$$

Cancellation?

Solutions:

- **Naturalness**: There is no problem
- **Weakly-coupled model at TeV scale**
  - New particles to cancel SM divergences
  - Top partners: new scalar/vectors coupled to top, exotic top decays
- **Strongly-coupled model at TeV scale**
  - ttbar resonances, bound states, 4-top production, etc.
- **New space-time structure**
  - Introduce extra space dimensions to lower Planck scale cutoff to $\sim 1$TeV
  - KK excitations

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The top quark

- The heaviest known elementary particle
- Large coupling to the Higgs: ~1
- Short lifetime
  - for $m_{\text{top}}=175$ GeV $\Rightarrow \Gamma=1.4$ GeV $\Rightarrow$ no hadronization
  - large contributions to EWK corrections $\sim G_F m_{\text{top}}^2$
  - very short lifetime $\Rightarrow$ bound states are not formed
  $\Rightarrow$ opportunity to study a free quark

- Large samples of top quarks available
- Top quarks are main background for many New Physics searches
- Precision measurements may provide insight into physics beyond SM

\[ \tau = 0.4 \times 10^{-24} \text{ sec} \]
Role of top quark physics

- Top quark physics after the Higgs discovery
  - Heavy particle, preferential coupling?
  - Special role in EWSB mechanism?
  - Does it play a role in non-SM physics?
  - Are the couplings affected?
  - Main background for many NP searches

- Monitoring of production mechanism
- Is there any sign of NP in top production/decay?
Role of top quark physics

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"core" $t\bar{t}$ region, e.g., $e\mu + \text{MET} + 2\text{ b-tags}$

event selection region

Drawing by C. Campagnari
Regions hard to explore

up here? compressed

hiding here?

or here?
Top quark decays

Top quarks (mostly) produced in pairs

- Dilepton (ee, μμ, eμ): BR~5%, 2 leptons+2 b-jets+2 neutrinos
- Lepton (e or μ) + jets: BR~30%, one lepton+4jets (2 from b)+1 neutrino
- All hadronic: BR~44%, 6 jets (2 from b), no neutrinos

b-jets always present
b-jet reconstruction plays important role
Cross section: multi-dimensional fit

- Lepton+jet final state
- Keep selection as inclusive as possible
- Categorize events according to (b-)jet multiplicity
  - high-purity vs background dominated
  - Constrain systematics (JES, ISR/FSR, modeling, etc)
- Combined fit of $M_{lb}$ to signal and backgrounds
- Precise cross section measurement

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Probing the Wtb vertex

Dileptons with taus

- cross section measurement including $\tau$s
- Includes only 3rd generation quarks/leptons
- Syst unc: tauld, fakes

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signature</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton(e/$\mu$)</td>
<td>$e\mu, \mu\mu, e\mu + 2b$-jets</td>
<td>4/81</td>
</tr>
<tr>
<td>Single lepton</td>
<td>$e, \mu + \text{jets} + 2b$-jets</td>
<td>24/81</td>
</tr>
<tr>
<td>All-hadronic</td>
<td>$\text{jets} + 2b$-jets</td>
<td>36/81</td>
</tr>
<tr>
<td>Tau dilepton</td>
<td>$e\tau, \mu\tau + 2$ b-jets</td>
<td>4/81</td>
</tr>
<tr>
<td>Tau+jets</td>
<td>$\tau + \text{jets} + 2b$-jets</td>
<td>12/81</td>
</tr>
</tbody>
</table>

- If top quark plays special role in EWK symmetry breaking, couplings to W may change
- Charged Higgs may alter coupling to W
- Search for final states with taus: charged Higgs
How does a top quark decay?

- almost always $t \rightarrow Wb$ (i.e. $V_{tb} \sim 1$)
- lifetime is short, and it decays before hadronizing
- the $W$ is real:
  - can decay $W \rightarrow l\nu$ ($l=e,\mu,\tau$), BR$\sim 1/9$ per lepton
  - can decay $W \rightarrow qq$, BR$\sim 2/3$
Measure $R$ in dilepton channel

- Probe heavy flavor content of ttbar events
- Use ttbar dilepton final state
  - small background
- Measure:

  \[ R \equiv \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)} \]

- Selection:
  - 2 leptons+ $\geq$2 jets + MET
  - no b-tagging in preselection
- Goals:
  - measure $\varepsilon(b)$ and $R$
Data-driven determination of background

- Reconstruct lepton-jet invariant mass
  - Correct assignment
  - Wrong assignment

- Use tail to model background in signal region
Signal vs. background

Scale shape to match spectrum observed with $M_{l_j} > 180$ GeV

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

Lepton-jet pairs / GeV

Lepton-jet invariant mass [GeV]

after background subtraction
Heavy flavor content

- **Measurement**
  - b-tagging multiplicity parametrized as function of $R \epsilon_b, \epsilon_q$, top contribution
  - Number of reconstructed $t \rightarrow Wq$ is estimated from lepton-jet invariant mass

- **$R=1.01\pm0.03$ (stat.$^\oplus$ syst.)**
  - Lower boundary with confidence interval @95%CL after requiring $R \leq 1 \Rightarrow R > 0.955 @95\%\text{CL}$
Variation of the likelihood used to measure R from data
Fit different categories
Summary of R results

Most accurate measurement
Why top quark properties?

- Top quark mass is a fundamental parameter of the SM

\[ \delta m_W \propto m_t^2 \]

\[ \delta m_W \propto \log m_h \]

- Precise measurement needed for checking consistency of the SM

- Top is the only fermion with the mass of the order of EWSB scale

- Discovered Higgs boson fits well with precise determinations of \( m_W \) and \( m_{\text{top}} \)

- Other properties (EWK coupling, production asymmetries, etc.) are predicted by SM

- Precise measurements could reveal breakdown of SM
Precise mass measurement

- Select lepton+jet final state
  - Best channel to measure $m_{\text{top}}$
  - Well defined final state (1 lepton, 1 $\nu$, 2b $W_{qq'}$)
- Select ttbar events: hadronic decays ($m_{\text{top}}, m_W$)
- Kinematic fit: constrain $W$ mass, top-antitop masses
  - In-situ JES calibration
- Measure $m_{\text{top}}$ and JSF

\[ m_t = 172.44 \pm 0.13 \text{ (stat+JSF)} \pm 0.47 \text{ (syst)} \text{ GeV} \]
Top quark mass results

- accurate (~0.3%) measurement
W boson polarization

- W bosons can be produced with left-handed, right-handed, or longitudinal polarization
- Top decay vertex in the SM is characterized by V-A structure
  - Fractions of polarization states are well predicted
- Can probe by measuring the angular distributions of the W boson decay products
- New physics could alter the polarization

\[ F_0 \approx 0.7; \ F_L \approx 0.3; \ \ F_R \approx 0 \]
Spin correlation

• Important tool for precise studies
• Top quark produced are not polarized
  – …but spins between quark and anti-quark are correlated
• Top quark decays before spins decorrelate
  – It decays before hadronization \((\tau \sim 10^{-25} \text{ s})\) ⇒ spin information transmitted to decay products
  – No need to reconstruct full ttbar system
• Spin correlation depends on production mode
• It may differ from SM expectations
  – Decays to charged Higgs and b quark \((t \rightarrow H^+b)\)
  – Other BSM scenarios
How else is Top produced?

- Single top quark production

\[ \sigma(13\text{TeV}) = 217 \text{ pb} \]

\[ \sigma = 10 \text{ pb} \]

\[ \sigma = 72 \text{ pb} \]

Probing top quark production

• Differential measurements
  – Testing QCD, measuring properties, searching for new physics, …
  – Function of kinematics, global variables, associated production

• Increased sensitivity: top quark pairs produced at rest
  – \( \sigma (M_{tt}>1 \text{ TeV at 13 TeV}) = 8 \times \sigma (M_{tt}>1 \text{ at 8 TeV}) \)

\[ \Rightarrow \text{Unique opportunity to probe boosted production at 13 TeV} \]
Boosted topology

- At high energy, particles produced beyond threshold
- All-hadronic topology
  - Top $p_T$ boosted, jets are collimated
  - Decay products and FSR collected in a “fat” jet
- Look at jet substructure
- Measure mass (no neutrinos)

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• In many models there is high potential to discover new physics in the top sector in search for heavy resonances

\[ pp \rightarrow X \rightarrow t\bar{t} \]

• Simple approach to merge neighboring jets

• At LHC energy, EWK scale particles produced beyond threshold
• Jets are highly collimated
• Decay products and FSR collected in a fat jet
Jet/Event selection

- Locate hadronic energy deposit in detector by choosing initial jet finding algorithm
- Impose jet selection cuts on fat jet
  - Recombine jet constituents with new algorithm
  - Filtering: recombine n sub-jets min \( d(i,j) \)
  - Trimming: recombine sub-jets with min \( p_T \)
- Minimum distance between jets is \( R \)
**Boosted topology: Top**

- **Highly boosted top:** three hadronic decays of the top are merged in one top jet.

- **Moderately boosted top:** three hadronic decays of the top are merged in one $W$ jet plus and one $b$ jet candidates.
Top quark pair resonance

- No resonance expected in SM
- Why is top so heavy?
  - new physics?
  - is third generation ‘special’?
- Search for massive neutral bosons decaying via a ttbar quark pair
- Experimental check
  - search for bump in the inv. mass spectrum
  - progressive loss in reconstruction ability due to jet merging
  - reconstruct $M_{ttbar}$ in different categories ($e/\mu$, $n$-jets, $n$ b-tags)
  - $l$+jet events: full event reconstruction
ttbar+Higgs

• ttbar produced in association with H
  – ttbar is a “clean” tag
• direct measurement of Higgs couplings

Cross section for ttH at the LHC:
- 0.13 pb (8 TeV)
- 0.61 pb (14 TeV)

M(H) = 125 GeV

ttH ~1% of total Higgs cross section
ttbar+heavy flavour

- Study rate of ttbb: $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$
- Anomalous tt+jets could signal BSM final states
- First direct measurement of typical bkg to top-Higgs coupling
  - Irreducible non-resonant bkg from ttbb
- Improved theoretical understanding of ttH(bb) crucial to ttH and NP searches

$$\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}} = 0.022 \pm 0.003 \text{ (stat)} \pm 0.005 \text{ (syst)}$$

- In Run1 measured value higher but compatible ($1.6\sigma$) with NLO calculation

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• Direct study of top Yukawa coupling
• Explore all accessible Higgs decay modes
  – $H \rightarrow bb, WW, ZZ$ with multilepton final states

Run1 best fit:
$\mu = 2.80 \pm 1.00$
ttH: multi-leptons, $\tau\tau$

- Multi-leptons: SS, 3L and 4L
- ttH with $H \rightarrow \tau\tau$

$\Rightarrow$ categories per charge, flavor
ttH: multi-leptons, $\tau\tau$

- Multi-leptons: SS, 3L and 4L
- ttH with $H \rightarrow \tau\tau$

⇒ categories per charge, flavor
ttV production ($V=\gamma, W, Z$)

- Large datasets give access to rare tt+W and tt+Z processes
- ttZ: direct probe of top-Z coupling (new physics?)
- ttW: important background to NP searches

- Use multi-lepton final states
  - 2 same-sign charge leptons, 3 or 4 lepton final states
• Measurements will give access to EW couplings of the top

\[ ttV \] production \( (V=\gamma, W, Z) \)

Consistent with theoretical predictions

\[ \sigma_{tt\gamma} = 2.4 \pm 0.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)} \text{ pb} \]
Flavor Changing Neutral Currents

- Expect small signal from SM
- …but signal may be large in BSM models

Final states:
- $Wb$

Couplings:
- $t \rightarrow ug$
- $t \rightarrow cg$
- $t \rightarrow uH$
- $t \rightarrow cH$

ATLAS

CMS

- SM: $tZq$

$\sigma_{qg} \rightarrow t \times B(t \rightarrow Wb) < 3.4 \text{pb}$
$\sigma_{qg} \rightarrow t \times B(t \rightarrow W b) < 2.9 \text{pb}$

$B(t \rightarrow Hc) < 0.40\%$
$B(t \rightarrow Hu) < 0.55\%$

$B(t \rightarrow Zu) < 0.022\%$
$B(t \rightarrow Zc) < 0.049\%$

$\text{SM } \sigma(tZq) = 10^{+8.7}_{-7.8} \text{ fb}$
Scalar top quark

• SUSY is one plausible extension of the SM
• due to the heavy top quark, mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$ can be large, such that the lighter stop $\tilde{t}_1$ can be even lighter than the top quark
• Decays dictated by mass spectrum of other SUSY particles

• Light stop:
  \[ m_{\tilde{t}_1} \lesssim m_t \]
  \[ \tilde{t} \rightarrow b\tilde{\chi}^+ \rightarrow bW\tilde{\chi}_1^0 \]

• Heavy stop:
  \[ \tilde{t} \rightarrow t\tilde{\chi}_1^0 \rightarrow bW\tilde{\chi}_1^0 \]
If SUSY exists and is responsible for solution of hierarchy problem, naturalness arguments suggest that SUSY partners of top quark (*stop*) may have mass close to $m_{\text{top}}$ to cancel top quark loop contributions to Higgs mass.

\[
\tilde{t} \rightarrow t\tilde{\chi}_1^0 \rightarrow bW\tilde{\chi}_1^0 \quad \text{“heavy”}
\]

\[
\tilde{t} \rightarrow b\tilde{\chi}_1^+ \rightarrow bW\tilde{\chi}_1^0 \quad \text{“light”}
\]

- Small predicted cross section
  - for 175GeV: 40pb@8TeV
- Stop pair production: $t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$
  - similar to ttbar lepton+jet and dilepton ch.
  - Additional MET from neutralinos
- change in ttbar cross section
Top cross section: dileptons

- Indirect searches
- SUSY models could produce final states very similar (with additional MET)
- For ex. in dilepton channel
Multi-top production

• Production of 4 tops is an attractive scenario in a number of new physics models
• The SM cross section is 9fb@13TeV

• Use lepton+jets final state
• Combination of kinematical variables and multivariate techniques
• Data are consistent with bkg expectations
• Set upper limit cross section 69fb @95%CL

• Search for same-sign dileptons
• Several models considered
• Consider multiple search regions defined by MET, hadronic energy, number of (b-) jets, and $p_T$ of the leptons in the events
Searches for new particles

**ATLAS Exotics Searches** - 95% CL Exclusion
Status: August 2016

### Model
<table>
<thead>
<tr>
<th>$\delta, \gamma$</th>
<th>Jets</th>
<th>$E_{\text{miss}}^{\text{T}}$</th>
<th>$L \Delta t$ [fb$^{-1}$]</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD $g \rightarrow t \bar{t}$</td>
<td>-</td>
<td>$\geq 1$</td>
<td>Yes</td>
<td>3.2</td>
</tr>
<tr>
<td>ADD non-resonant $t \bar{t}$</td>
<td>$2, 4\mu$</td>
<td>-</td>
<td>20.3</td>
<td></td>
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<tr>
<td>ADD QED $\rightarrow t \bar{t}$</td>
<td>$1, \gamma$</td>
<td>-</td>
<td>20.3</td>
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<tr>
<td>ADD $Q$H</td>
<td>-</td>
<td>$\geq 2$</td>
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<td>3.2</td>
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<tr>
<td>ADD $Q$H multiplet</td>
<td>-</td>
<td>$\geq 3$</td>
<td>3.6</td>
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<td>RS1 $g \rightarrow t \bar{t}$</td>
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<td>RS2 $g \rightarrow t \bar{t}$</td>
<td>$1, \gamma$</td>
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<td>Bulk $R$S $g \rightarrow WW \rightarrow q\overline{q}$</td>
<td>$1, \gamma$</td>
<td>-</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>Bulk $R$S $g \rightarrow HH \rightarrow b\bar{b}b\bar{b}$</td>
<td>-</td>
<td>4 $b$</td>
<td>13.2</td>
<td></td>
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<tr>
<td>Bulk $R$S $g \rightarrow tt$</td>
<td>$1, \gamma$</td>
<td>$\geq 1b, \geq 1j, 2\nu$</td>
<td>20.3</td>
<td></td>
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<tr>
<td>2UED / RPP</td>
<td>$1, \mu$</td>
<td>$\geq 2, \geq 1j, 2\nu$</td>
<td>3.2</td>
<td></td>
</tr>
</tbody>
</table>

### Gauge Bosons
<table>
<thead>
<tr>
<th>$\delta, \gamma$</th>
<th>Jets</th>
<th>$E_{\text{miss}}^{\text{T}}$</th>
<th>$L \Delta t$ [fb$^{-1}$]</th>
<th>Limit</th>
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<tbody>
<tr>
<td>SM $Z \rightarrow \ell\ell$</td>
<td>-</td>
<td>$\tau \tau$</td>
<td>13.3</td>
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<tr>
<td>SM $Z \rightarrow b\bar{b}$</td>
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<td>$2 b$</td>
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<td>Leptoquark $Z \rightarrow b\bar{b}$</td>
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<td>$\tau \tau$</td>
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<tr>
<td>SM $W \rightarrow \tau\nu$</td>
<td>$1, \gamma$</td>
<td>-</td>
<td>13.3</td>
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<tr>
<td>HVT $W \rightarrow ZZ \rightarrow 4\ell$</td>
<td>$0, 4\ell$</td>
<td>-</td>
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<td>HVT $W \rightarrow WH$</td>
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<td>HVT $W \rightarrow WW$</td>
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<td>15.5</td>
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<tr>
<td>LRRSM $W_{L} \rightarrow b\bar{b}$</td>
<td>$1, \gamma$</td>
<td>$b, b, 1j$</td>
<td>20.3</td>
<td></td>
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<tr>
<td>LRRSM $W_{L} \rightarrow W\nu$</td>
<td>$0, b, b, j$</td>
<td>$\geq 1b, \geq 1j$</td>
<td>20.3</td>
<td></td>
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</tbody>
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### C
<table>
<thead>
<tr>
<th>$\delta, \gamma$</th>
<th>Jets</th>
<th>$E_{\text{miss}}^{\text{T}}$</th>
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<th>Limit</th>
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<tbody>
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<td>CL $\nu \nu$</td>
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<td>$\geq 1 j$</td>
<td>Yes</td>
<td>3.2</td>
</tr>
<tr>
<td>CL $\nu \nu$</td>
<td>$2 \mu$</td>
<td>-</td>
<td>3.2</td>
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<td>$2 \mu, 2 \nu$</td>
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### DM
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<tbody>
<tr>
<td>Axial-vector mediator (Dirac DM)</td>
<td>$0, 1 \ell$</td>
<td>$\geq 1$</td>
<td>Yes</td>
<td>3.2</td>
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<td>$0, 2 \ell, 1 \ell$</td>
<td>$\geq 1b, \geq 1j$</td>
<td>20.3</td>
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### LO
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<tbody>
<tr>
<td>Scalar $\Delta Z$ 1$^*$</td>
<td>$2 \mu$</td>
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<td>Scalar $\Delta Z$ 2$^*$</td>
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<td>$2 \mu$</td>
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### Excited

### Higgs
<table>
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<th>$\delta, \gamma$</th>
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<tbody>
<tr>
<td>Strongly coupled scalar Higgs</td>
<td>$1, \gamma$</td>
<td>-</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Higgses</td>
<td>$1, \gamma$</td>
<td>-</td>
<td>13.7</td>
<td></td>
</tr>
</tbody>
</table>

**Mass scale (TeV)**

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

1 Small-radius (large-radius) jets are denoted by the letter $j$ (J).

M. Gallinaro - "Probing the SM: Top quark properties and beyond" - March 27, 2017
“Well known” processes, don’t need to keep all of them ...

New Physics!!
This is where to look
Increased reach at 13 TeV

### Predicted cross-section ratios

<table>
<thead>
<tr>
<th>Process</th>
<th>Ratio (13 TeV)</th>
<th>Ratio (8 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ</td>
<td>2.04</td>
<td>2.04</td>
</tr>
<tr>
<td>ZZ</td>
<td>2.04</td>
<td>2.04</td>
</tr>
<tr>
<td>Single t (s-ch.)</td>
<td>1.97</td>
<td></td>
</tr>
<tr>
<td>Single t (t-ch.)</td>
<td>2.56</td>
<td></td>
</tr>
<tr>
<td>tW</td>
<td>3.21</td>
<td></td>
</tr>
<tr>
<td>tt</td>
<td>3.29</td>
<td></td>
</tr>
<tr>
<td>ggH</td>
<td>2.28</td>
<td></td>
</tr>
<tr>
<td>VBF</td>
<td>2.38</td>
<td></td>
</tr>
<tr>
<td>VH</td>
<td>2.01</td>
<td></td>
</tr>
<tr>
<td>ttH</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>tt (0.7 TeV)</td>
<td>8.4</td>
<td></td>
</tr>
<tr>
<td>tt (0.9 TeV)</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>gg (1.0 TeV)</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>gg (1.5 TeV)</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>gg (2.5 TeV)</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>Z' ssM (2.0 TeV)</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>G* (3.0 TeV)</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>HSCP ~ g (2.0 TeV)</td>
<td>6.7</td>
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</tr>
<tr>
<td>W→tb (2.0 TeV)</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>X5/3 X5/3 (1.0 TeV)</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>X5/3 X5/3 (1.5 TeV)</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

13 TeV with 2.2 fb⁻¹ potentially more sensitive than 8 TeV (19.8 fb⁻¹)
Summary

• Top quarks are valuable probes of SM
• Excellent consistency but SM is incomplete
  – Extensions foresee existence of additional bosons
  – Searches for BSM bosons ongoing
• Dominant background for New Physics searches
• Due to large mass, top quarks may couple to heavy objects
• Deviations from SM may indicate New Physics
• More data will enhance the sensitivity
  – Higgs, multi-top, boosted objects, SUSY, Dark matter, etc.