The Top quark

Michele Gallinaro
LIP Lisbon
March 23, 2020

- Introduction
- Discovery of the Top quark
- Decay and production
- Cross section measurements
Introduction

• Pre-discovery
• Motivation: theory and experiment
• First top quark events in the LHC data
• First measurements
1974

With the discovery of the $J/\Psi$:

**quarks**

\[
\begin{pmatrix}
u \\
d \\
\end{pmatrix}
\begin{pmatrix}
c \\
\end{pmatrix}
\]

**leptons**

\[
\begin{pmatrix}
\nu_e \\
e \\
\end{pmatrix}
\begin{pmatrix}
\nu_{\mu} \\
\mu \\
\end{pmatrix}
\]
1975-1977

- Tau ($\tau$) lepton in Mark I data ($\nu_\tau$ from the decay kinematics)
- Discovery of the Y at Fermilab

\[
\begin{pmatrix}
u_e \\ e
\end{pmatrix}
\begin{pmatrix}
u_\mu \\ \mu
\end{pmatrix}
\begin{pmatrix}
u_\tau \\ \tau
\end{pmatrix}
\begin{pmatrix}u \\ d
\end{pmatrix}
\begin{pmatrix}c \\ s
\end{pmatrix}
\begin{pmatrix}b
\end{pmatrix}
\]

- b: non SM? iso-singlet? SM iso-doublet?
- 1984: DESY measurement of $e^+e^-\rightarrow b\bar{b}$ FB asymmetry: $(22.5 \pm 6.5)\%$
  - cf. 25.2\% SM iso-doublet, 0\% iso-singlet
- If SM is correct there must be a iso-doublet partner, the top quark
- Mass? b/c/s 4.5/1.5/0.5: Mass=15 GeV?
The theory: Why?

- The SM is not a “renormalizable” gauge theory in the absence of the top quark
- Renormalizability is a crucial feature, enabling the SM to be theoretically consistent and be usable as a tool to compute the rate of subnuclear processes between quarks, leptons, and gauge bosons
- Diagrams containing so-called “triangle anomalies” (right), cancel their contributions, thus avoid breaking the renormalizability of the SM, only if the sum of electric charges of all fermions circulating in the triangular loop is zero:

\[ \Sigma Q = -1 + 3 \times [2/3 + (-1/3)] = 0 \]

lepton electric charge quark (up/down) charge
Searches at $e^+e^-$ colliders

- **PETRA** (DESY) could reach ~20 GeV (late ‘70s)
  - Search for narrow resonance
  - Look for increase in $R = (\# \text{ of hadron events})/(\# \text{ of } \mu\mu \text{ events})$
  - Global event characteristics: look for spherical component
  - Negative results. Set limits: $M_t > 23$ GeV

- **TRISTAN** (Japan) built to study the top quark (early ‘80s)
  - Similar search technique:
  - Could reach ~30 GeV: $M_t > 30$ GeV

- **SLC/LEP** (SLAC)
  - Look for $Z \rightarrow t\bar{t}$
  - $M_t > 45$ GeV

- **Reached kinematic limit for direct searches at $e^+e^-$ colliders**
Indirect searches from $e^+e^-$ colliders

- In the SM, various EWK observables depend on the mass of the top quark
- Precision measurements of the EWK parameters, allow to measure virtual corrections with sufficient precision to put constraints on $M_{\text{top}}$
  - Prediction upper limit $< 200-220$ GeV
Early searches at hadron colliders

CERN SppS ($\sqrt{s}=540$ GeV) built to observe $W,Z$
- Access to much higher energies
- Large backgrounds, low event rates
- Difficult reconstruction: jets

1984: UA1
- $W \rightarrow tb \rightarrow l \nu bb$
- Isolated high-$p_T$ lepton
- 2 or 3 hadronic jets
- Observe 5 events ($e^+ \geq 2$ jets), 4 events ($\mu^+ \geq 2$ jets)
- Expected background: 0.2 events
  - Fake leptons dominate; bbar/ccbar negligible
- Result consistent with $M_{top}=40 \pm 10$ GeV
- Stop before claiming discovery…
  $\Rightarrow W+\text{jet background was underestimated}$
The top quark

$w$ 

$\bar{t}b$

$m_{w}$

$\mu$ + 2 jets

o e + 2 jets

$W \rightarrow t\bar{b}$

$m_{t} = 40 \text{ GeV/c}^{2}$

6 EVENTS

EVENTS/5 GeV/c^{2}

EVENTS/10 GeV/c^{2}

m (l \nu_{T} J_{1} J_{2}) GeV/c^{2}

UA 1

$w$ 

$\bar{t}b$

$m_{w}$

$\mu$ + 2 jets

o e + 2 jets

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6 EVENTS

EVENTS/5 GeV/c^{2}

EVENTS/10 GeV/c^{2}

m (l \nu_{T} J_{1} J_{2}) GeV/c^{2}
Searches at hadron colliders

- 1988 UA1
- Larger data sample (x6, total of 600nb\(^{-1}\))
- Improved understanding of the backgrounds
- Fake leptons, W+jets, DY, J/\(\Psi\), bbar/ccbar

<table>
<thead>
<tr>
<th>channel</th>
<th>observed</th>
<th>expected background</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu + \geq 2) jets</td>
<td>10 events</td>
<td>11.5 ± 1.5 events</td>
</tr>
<tr>
<td>(e + \geq 1) jets</td>
<td>26 events</td>
<td>23.4 ± 2.8 events</td>
</tr>
</tbody>
</table>

( + 23 expected if \(M_{\text{top}} = 40\) GeV)

⇒ conclude \(M_{\text{top}} > 44\) GeV
Fermilab joins the hunt

• 1988-89: at CERN, UA2 remains after the upgrades
• \( \sqrt{1.8 \text{ TeV}} \) @Fermilab vs. \( \sqrt{0.63 \text{ TeV}} \) @CERN
• Much better reach for larger mass (only 75 GeV@UA2)
• At Tevatron, pair production dominates: \( \bar{t}t \rightarrow Wb \bar{W}b \)

<table>
<thead>
<tr>
<th>%</th>
<th>ev</th>
<th>( \mu \nu )</th>
<th>( \tau \nu )</th>
<th>( q\bar{q} )</th>
</tr>
</thead>
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<tr>
<td>ev</td>
<td>1.2</td>
<td>2.5</td>
<td>2.5</td>
<td>14.8</td>
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<td></td>
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<td>44.4</td>
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Tevatron

Proton-antiproton collision at 1.8-2.0 TeV
12 countries, 62 institutions
767 physicists
eµ channel
- Event rate lower: 2xBR(W→eν)
- Background small (no W+jets, no DY)
- Dominant background is Z→ττ→eµX (expect 1 evt)
- Observe 1 event (expect 7 evts for M_{top}=70 GeV)

ev+ ≥2 jets
- Dominant background: W+jets
- Discriminant: eν transverse mass
  - Background: W on-shell
  - Signal: W off-shell for M_{top}=40-80 GeV

⇒M_{top}>77 GeV

• UA2 uses similar technique: M_{top}>69 GeV
Change of strategy: $M_{\text{top}} > M_b + M_W$

- Top quark decays to on-shell $W$s: no $M_T(l\nu)$ discriminant
- Main differences:
  - background: $W+$jets (largely quarks and gluons)
  - signal: $W+$jets (2 jets are $b$-jets)
- CDF publication on 88-89 data:
  - Dilepton: include $ee$, $\mu\mu$, $e\mu$ (require missing ET, Z-veto)
  - Single lepton: require low $p_T$ muon (semi-leptonic $b$-decays)

$\Rightarrow M_{\text{top}} > 91$ GeV
D0 joins the hunt
1992-1995
• Tevatron with higher luminosity
• D0: excellent calorimetry, large solid angle and coverage
• CDF: precision vertex detector, good tracker, magnetic spectrometer

Run 1A:
• D0: optimized search for $M_{\text{top}}=100$ GeV
  – $e\mu+\geq 1\text{jet}+\text{MET}$ \hspace{1cm} 1 evt \hspace{0.5cm} (1.1 bkg)
  – $ee+\geq 1\text{jet}+\text{MET}$ \hspace{1cm} 1 \hspace{0.5cm} (0.5)
  – $e+\geq 4\text{jets}+\text{MET}$ \hspace{1cm} 1 \hspace{0.5cm} (2.7)
  – $\mu+\geq 4\text{jets}+\text{MET}$ \hspace{1cm} 0 \hspace{0.5cm} (1.6)

$\Rightarrow M_{\text{top}}>131$ GeV@95%CL
Detecting the top quark at CDF

Strategy
- dilepton: +2 jets
- single lepton: b-tagging
  1) soft e/μ: semi-leptonic b-decay
  2) secondary vertex

New: CDF vertex detector (SVX)
(40 µm impact parameter resolution)
powerful discriminant against background

e + 4 jet event
40758_44414
24-September, 1992
TWO jets tagged by SVX
fit top mass is 170 ± 10 GeV
e^+, Missing E_T, jet #4 from top
jets 1,2,3 from top (2&3 from W)
Tagging b-jets

- Top events contain B hadrons
- Only 1-2% of dominant W+jets background contains heavy flavor

B hadrons are long-lived

Vertex displaced tracks

Semileptonic B hadron decay

Soft Lepton Tagging

- $b \rightarrow \ell v c$ (BR ~ 20%)
- $b \rightarrow c \rightarrow \ell \nu s$ (BR ~ 20%)

Top Event Tagging Efficiency

55%

False Tag Rate (QCD jets)

0.5%

15%

3.6%
Coll. Meeting, Aug. 1993:

- Status report from each group (dilepton, single lepton)
- Small, not significant excess in all channels

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<tr>
<td>DIL</td>
<td>2 events</td>
<td>0.56 ± 0.25</td>
</tr>
<tr>
<td>SVX</td>
<td>6 tags</td>
<td>2.3 ± 0.3</td>
</tr>
<tr>
<td>SLT</td>
<td>7 tags</td>
<td>3.1 ± 0.3</td>
</tr>
<tr>
<td>total</td>
<td>12 events</td>
<td>---</td>
</tr>
</tbody>
</table>

- In total, an excess of events
- Background fluctuation probability: 2.8σ
- Skepticism, additional studies, cross-checks
- Additional 8 months before making the results public

3 events in common
Final steps: CDF and D0

CDF: counting experiment yields 2.8σ
- Few checks: no major discrepancy
- Other checks consistent with presence of signal
- Mass distribution looked good

• There were also other analyses at CDF
  - Difference of jet $E_T$ spectra for signal and bkg
  - Separate two component for signal and bkg
  - CDF chose not to use those for first publication

• Use “counting” experiment

D0: added more data and re-optimized for heavy top (single and dilepton)

• Observed 7 events (expect 4-6 from bkg)
• No independent evidence
Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb$^{-1}$. We find 12 events consistent with either two $W$ bosons, or a $W$ boson and at least one $b$ jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10 \pm 3$ GeV/c$^2$. The $t\bar{t}$ production cross section is measured to be $13.9 \pm 3\%$ pb.
Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

We establish the existence of the top quark using a $67 \text{ pb}^{-1}$ data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8 \text{ TeV}$ collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by $4.8\sigma$. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be $176 \pm 8(\text{stat}) \pm 10(\text{syst}) \text{ GeV}/c^2$, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4} \text{ pb}$. 

M. Gallinaro - "The top quark" - Physics@LHC - March 23, 2020
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$$\sigma_{tt} = 6.8^{+3.6}_{-2.4} \text{ pb}$$

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$$M_{\text{top}} = 176 \pm 8(\text{stat}) \pm 10(\text{syst}) \text{ GeV}$$

CDF and D0 papers submitted simultaneously
Excellent agreement with all experimental results
• Built to explore new energy frontiers
  – First colliding beams in 2009
  – started with “low” luminosity in 2010
  – ~5 fb$^{-1}$@7TeV delivered in 2011
  – ~20 fb$^{-1}$@8TeV in 2012
  – >150fb$^{-1}$@13 TeV in 2015-2018

• re-establish SM measurements
• access to new physics processes

⇒ Top quarks give access to SM and BSM (?)
Tevatron vs LHC

Run II integrated luminosity

Energy: 1.96 TeV
Int. Luminosity: 12 fb⁻¹
Age: ~25 years
Events/exp (1 fb⁻¹)
350 ee eμ, μμ
2k lepton + jets

Energy: 7/8/(13) TeV
Int. Luminosity: 5/20/(150) fb⁻¹
Age: ~9 years
Events/exp (1 fb⁻¹)
40k ee eμ, μμ
250k lepton + jets
The top quark

- The heaviest known elementary particle
- Large coupling to the Higgs: $\sim 1$
- Short lifetime
  - for $m_{\text{top}} = 175 \text{ GeV}$ $\Rightarrow \Gamma = 1.4 \text{ GeV}$ $\Rightarrow$ 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
How is the top quark produced?

Predicted cross sections:

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<tr>
<td>Tevatron</td>
<td>7.164</td>
<td>$+0.110(1.5%)$</td>
<td>$+0.169(2.4%)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-0.200(2.8%)$</td>
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<td>LHC 7 TeV</td>
<td>172.0</td>
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Czakon et al. PRL 110, 252004 (2013)
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~1/9 per lepton
  - can decay $W \rightarrow qq$, BR~2/3
Selection of top quark events

• Trigger:
  – single or double (isolated) lepton

• Leptons:
  – e/μ, \( p_T > 20/30 \) GeV, \(|\eta| < 2.5\)
  – Identification/reconstruction
  – Tracker/calorimeter isolation

• Jets:
  – at least 2 jets, \( p_T > 30 \) GeV, \(|\eta| < 2.5\)
  – anti-kT algorithm, with cone 0.4-0.5
  – b-tagging is optional

• Missing transverse energy:
  – Typically require 30-40 GeV
Particle Flow event reconstruction

- Particle Flow (PF) combines information from all subdetectors to reconstruct particles produced in the collision
  - charged hadrons, neutral hadrons, photons, muons, electrons
  - use complementary info. from separate detectors to improve performance
  - tracks to improve calorimeter measurements

- From list of particles, can construct higher-level objects
  - Jets, b-jets, taus, isolated leptons and photons, MET, etc.
...in a challenging environment

136 vertices!
Challenge: b-tagging

- Lifetime: \( \tau_b \approx 1-2 \text{ psec} \)
- Reduction of background obtained by identifying jets from b-quarks
- Two methods:
  - Secondary vertex tagging
  - Semileptonic decays of b-hadrons in jets \( (b \to l \nu_l X) \)
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
Interesting physics with Top quark

PRODUCTION
- Cross section
- Resonances $X \rightarrow tt$
- Fourth generation $t'$
- Spin-correlations
- New physics (SUSY)
- Flavour physics (FCNC)
...

PROPERTIES
- Mass
- Kinematics
- Charge
- Lifetime and width
- $W$ helicity
- Spin
...

DECAY
- Branching ratios
- Charged Higgs (non-SM)
- Anomalous couplings
- Rare decays
- CKM matrix elements
- Calibration sample @LHC
...

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Top quark events

- LHC@13TeV cross section ~100 times larger than Tevatron
- select ttbar events at LHC:
  - understand/calibrate detector
  - measure properties
- event selection includes SM control events
- ttbar final state is complex (ie not mass peak)
- Top quarks and new physics:
  - ttbar sample may contain new physics
  - look at jet multiplicity bins (since ttbar is background e.g. for SUSY), or other variables
Theory cross sections: TeV vs LHC

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Including NNLO+NNLL approximations
PRL 110, 252004 (2013) (M. Czakon et al.)
Top cross section at 7/8 vs 13 TeV

- LHC collisions started at 7/8 TeV
- LHC design is at 14 TeV
- Top cross section drops faster than background processes at lower $\sqrt{s}$
  - top $\sigma(7\text{TeV}) = 172 \text{ pb}$
  - top $\sigma(8\text{TeV}) = 246 \text{ pb}$
  - top $\sigma(13\text{TeV}) = 832 \text{ pb}$
- Background is more “flat”
Cross section measurement

\[ \sigma_{\bar{t}t} = \frac{N_{\text{obs}} - N_{\text{bgd}}}{\mathcal{E}_{\bar{t}t} \cdot \int Ldt} \]

- Number of observed events
- Number of background events (from data, calculated from theory)
- Acceptance (experimental: detector, efficiencies)
- Luminosity (determined by amount of data, accelerator, triggers, etc)
Dilepton channel

- Branching ratio (BR) ~5%
- Background: small

- Clean final state
  - two leptons + ≥2 jets + MET
  - kinematic variables

- Signal visible w/without b-tagging
- Main systematics: JES, lepton ID, (pileup, b-tag, signal modeling)
Lepton + jets

- BR ~30%
- Background: moderate

- Selection:
  - one lepton + ≥3 jets + MET
  - may require b-tag

- Main backgrounds:
  - hadronic multi-jet, W+jets
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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Cross section: multi-dimensional fit

- Dilepton final state
- Simultaneous fit in $(N_{\text{additional jet}}, N_{b\text{-jet}})$ categories
- Fit of $\sigma_{t\bar{t}}$ and $m(\text{top})$

\[ \sigma_{t\bar{t}} = 803 \pm 2 \text{ (stat)} \pm 25 \text{ (syst)} \pm 20 \text{ (lumi)} \text{ pb} \]
\[ m_t^{\text{MC}} = 172.33 \pm 0.14 \text{ (stat)} ^{+0.66}_{-0.72} \text{ (syst)} \text{ GeV} \]
All hadronic

- BR \( \sim 46\% \)
- Background: large

- Selection:
  - \( \geq 6 \) jets + kinematical selection
  - require b-tag
- Main backgrounds:
  - hadronic multi-jet
• BR ~46%
• Background: large

• Selection:
  – ≥6 jets + kinematical selection
  – require b-tag

• Main backgrounds:
  – hadronic multi-jet
  – same selection without b-tag
Cross sections

± 4%

ATLAS+CMS Preliminary
LHCr-top WG

σ_{tt} summary, \( \sqrt{s} = 13 \text{ TeV} \)

- Total uncertainty
- Scale uncertainty
- Scale @ PDF @ α_s uncertainty

- ATLAS, dilepton \( \mu \mu \)
  - PLB 761 (2016) 136, \( L_{\text{int}} = 3.2 \text{ fb}^{-1} \)
  - ATLAS-CONF-2015-049, \( L_{\text{int}} = 85 \text{ pb}^{-1} \)

- ATLAS, \( l+jets \)
  - ATLAS-CONF-2015-049, \( L_{\text{int}} = 85 \text{ pb}^{-1} \)

- CMS, dilepton \( \mu \mu \)
  - PRL 115 (2015) 052002, \( L_{\text{int}} = 43 \text{ pb}^{-1}, 50 \text{ ns} \)

- CMS, dilepton \( \mu \mu \)
  - EPJC 77 (2017) 172, \( L_{\text{int}} = 2.2 \text{ fb}^{-1}, 25 \text{ ns} \)

- CMS, \( l+jets \)
  - CMS-PAS TOP-17-001, \( L_{\text{int}} = 35.9 \text{ fb}^{-1}, 25 \text{ ns} \)

- CMS, all-jets
  - JHEP 09 (2017) 091, \( L_{\text{int}} = 2.2 \text{ fb}^{-1} \)

- CMS-PAS TOP-16-013, \( L_{\text{int}} = 2.53 \text{ fb}^{-1} \)

- NNPDF3.0, JHEP 04 (2015) 040
- MMHT14, EPJC 75 (2015) 5
- CT14, PRD 93 (2016) 033006
- ABM12, PRD 99 (2015) 054028

* Preliminary

⇒ measurements challenging theory

\[ \text{σ}_{\text{tot}} \] [pb] \begin{tabular}{|c|c|c|c|}
\hline
Collider & \text{σ}_{\text{tot}} \text{ [pb]} & scales \text{ [pb]} & pdf \text{ [pb]} \\
\hline
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\%) \\
\hline
\end{tabular}

\( \pm 3-5\% \)
• Measure differential cross section
  – Test perturbative QCD
  – Test BSM scenarios (Z' decays, etc)

• Cross sections measured as a function of $p_T$, $\eta$, invariant mass of the final state leptons, top quarks, ttbar system, etc.

• Good agreement with expectations
• Correct for detector effects and acceptances
• Softer top $p_T$ (CMS), agreement in ATLAS at high $p_T$
  – Due to momentum reshuffling, P.Nason, cern.ch/event/301787
  – FSR shower changes mass of final state partons. light partons can build sizeable mass, and $t\bar{t}$ do not radiate
  – short term solution: consider difference as uncertainty
• Impact on $ttH$/SUSY/etc searches, tails of $ttbar$ events
• Measure $ttbar$ invariant mass
  – Rate/shape reproduced within uncertainties
Summary

• Introduction on top quark
• Basic concepts on production and decays
• Cross section measurements and relevance to BSM searches

• Next lecture: "Top quarks as probe to New Physics"