Lomonosov Conference on Elementary Particle Physics

Top quark physics at the CMS experiment

Leonardo Benucci - University of Ghent
On behalf of the CMS Collaboration

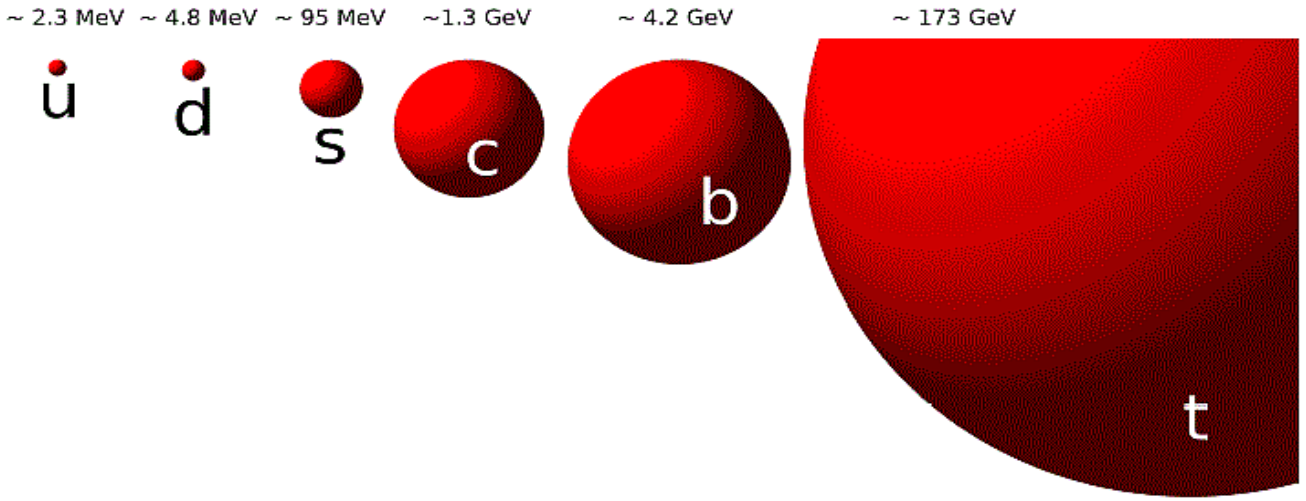
Moscow, August 27th, 2013

The top quark is special

Most massive elementary particle known to date

Special role in many theories beyond the Standard Model

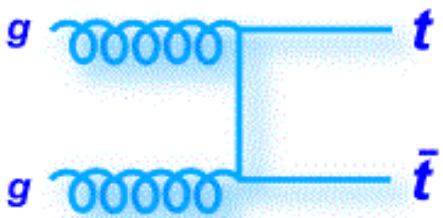
→ Short-lived, so it decays before hadronizing. Possible to study the properties of a bare quark.

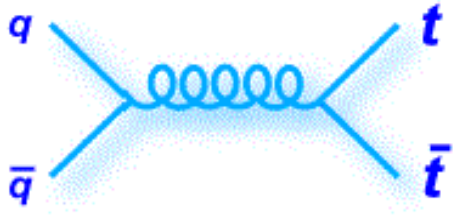


- Precision tests of perturbative QCD
- Possible window to new physics
- Main background in many BSM searches.

How to produce a top quark

- Top pair production (through strong interaction):



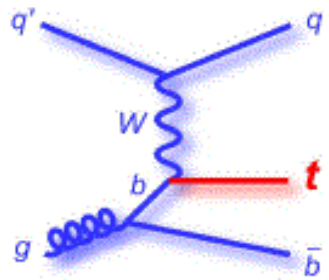


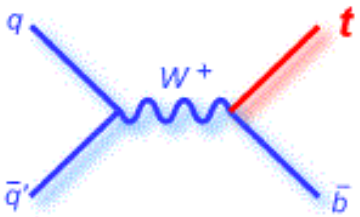
~ 85% at LHC

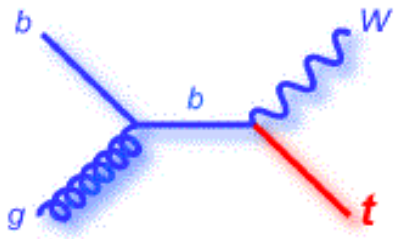
~ 85% at Tevatron

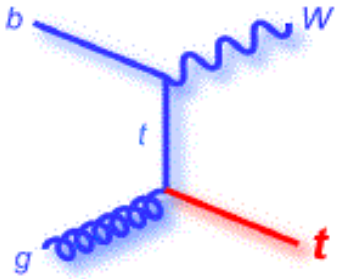
~ 7 pb @Tevatron, ~ 107 pb @LHC 7 TeV, ~ 240 pb @LHC 8 TeV

- Single top production (through electroweak interaction):









t-channel

2 pb @Tevatron
65 pb @LHC 7 TeV
87 pb @LHC 8 TeV

s-channel

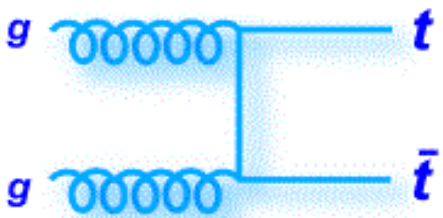
1 pb @Tevatron
5 pb @LHC 7 TeV
6 pb @LHC 8 TeV

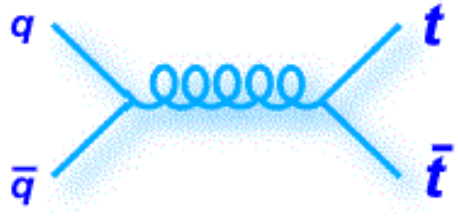
Wt-channel

0.3 pb @Tevatron
16 pb @LHC 7 TeV
22 pb @LHC 8 TeV

How to produce a top quark

- Top pair production (through strong interaction):





~ 85% at LHC

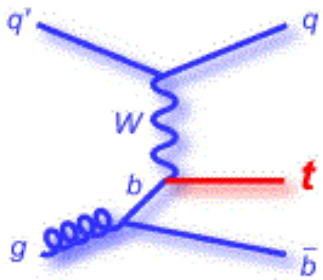
~ 85% at Tevatron

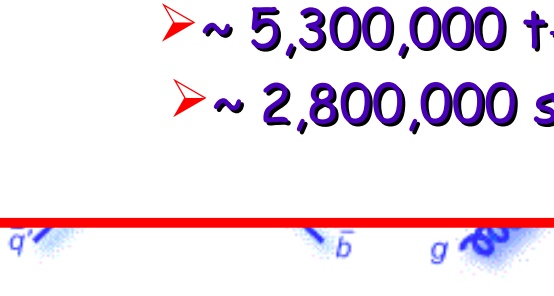
~ 7 pb @

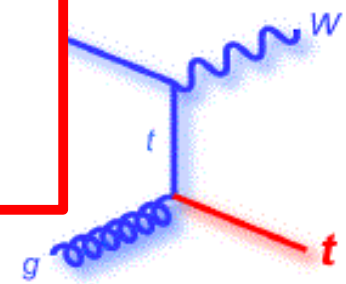
- Single top p ion):

After 2011 and 2012 runs we have :

- ~ 5,300,000 t-t pairs
- ~ 2,800,000 single-t







t-channel

2 pb @Tevatron
65 pb @LHC 7 TeV
87 pb @LHC 8 TeV

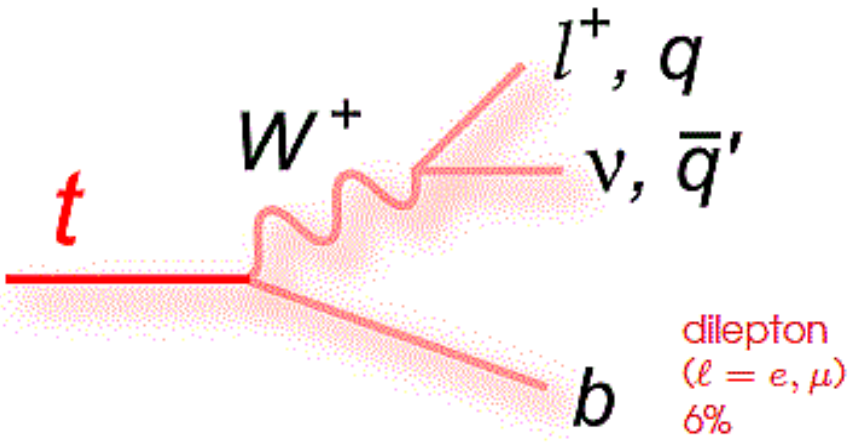
s-channel

1 pb @Tevatron
5 pb @LHC 7 TeV
6 pb @LHC 8 TeV

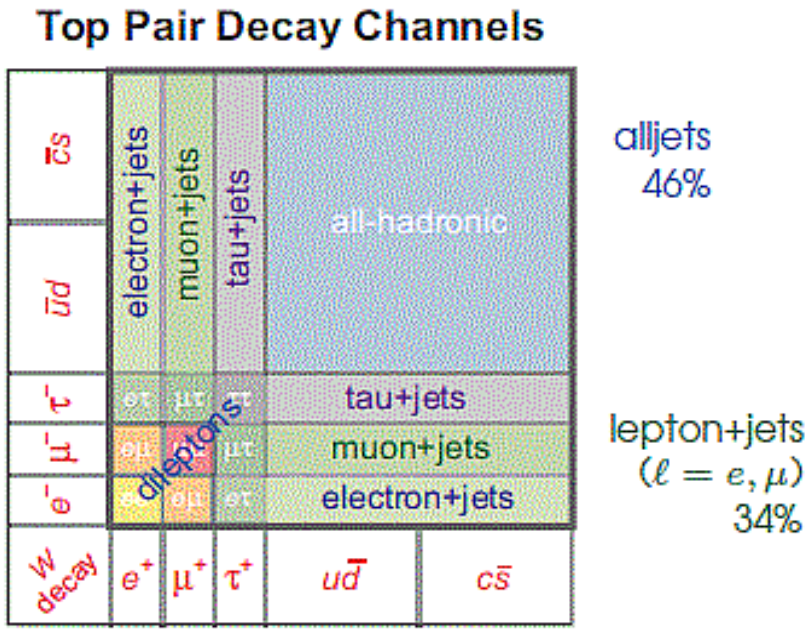
Wt-channel

0.3 pb @Tevatron
16 pb @LHC 7 TeV
22 pb @LHC 8 TeV

How a top quark decays



dilepton
($\ell = e, \mu$)
6%



The top quark decays almost exclusively to a W boson and a b quark

The W boson in turn decays hadronically (BR ~ 70%) or leptonically (BR ~ 30%)

All-jets: largest BR but largest background

Semi-leptonic: large BR and manageable background

Di-leptonic: small BR and small background

What can be measured with the top

- Measurements in Top production:
  - ✓ Pair production cross section $\sigma(tt)$
  - ✓ Single top production cross section: t-channel, s- and Wt-channel
  - ✓ Associated production with Z/W and jets
  - ✓ Differential cross section
  - ✓ production asymmetries

- Measurements in Top properties:
  - ✓ Top mass from final state
  - ✓ Top mass from constraints on $\sigma(tt)$ and α_s
  - ✓ Top mass from decay length of B mesons
  - ✓ Wtb coupling
  - ✓ Spin correlations

- Searches for New Physics:
  - ✓ Limits on FCNC and baryon number violation decays
  - ✓ ...many, mony others!

What can be measured with the top

- Measurements in Top production:
  - ✓ Pair production cross section $\sigma(tt)$
  - ✓ Single top production cross section: t-channel, s- and Wt-channel
  - ✓ Associated production with Z/W and jets
  - ✓ Differential cross section
  - ✓ production asymmetries

Public results on:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

- Measurements in Top properties:
  - ✓ Top mass from final state
  - ✓ Top mass from constraints on $\sigma(tt)$ and α_s
  - ✓ Top mass from decay length of B mesons
  - ✓ Wtb coupling
  - ✓ Spin correlations

- Searches for New Physics:
  - ✓ Limits on FCNC and baryon number violation decays
  - ✓ ...many, mony others!

What can be measured with the top

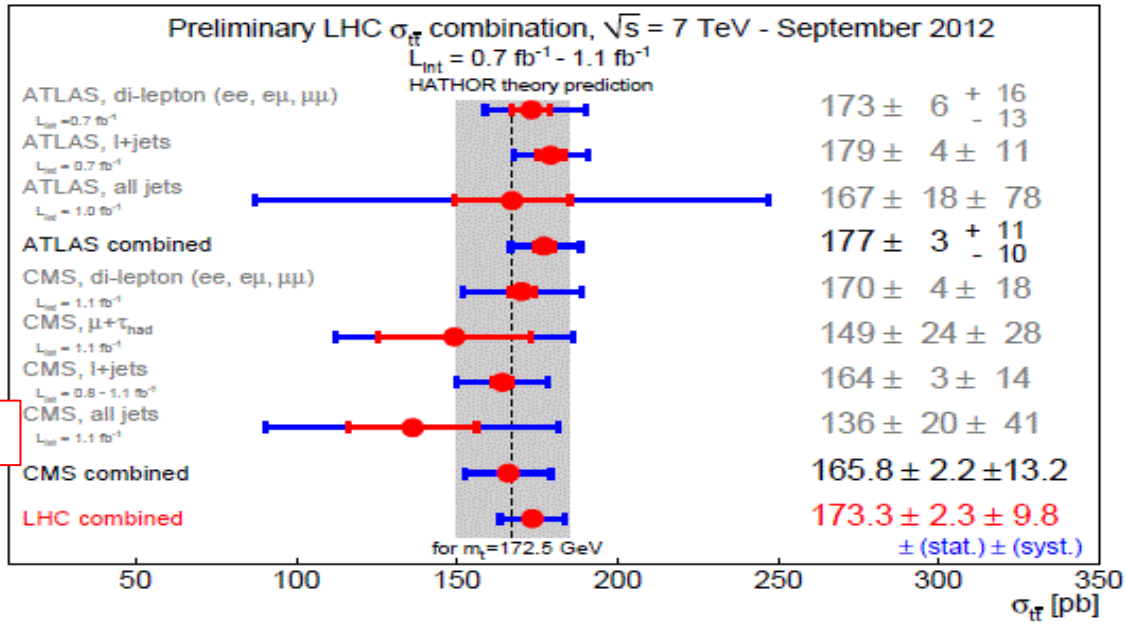
- **Measurements in Top production:**
  - ✓ **Pair production cross section σ(tt)**
  - ✓ **Single top production cross section: t-channel, s- and Wt-channel**
  - ✓ **Associated production with Z/W and jets**
  - ✓ **Differential cross section**
  - ✓ **production asymmetries**

- Measurements in Top properties:
  - ✓ Top mass from final state
  - ✓ Top mass from constraints on σ(tt) and α_s
  - ✓ Top mass from decay length of B mesons
  - ✓ Wtb coupling
  - ✓ Spin correlations

- Searches for New Physics:
  - ✓ Limits on FCNC and baryon number violation decays
  - ✓ ...many, mony others!

Pair-production cross-section

7 TeV results:



Phys. Lett. B 720 (2013) 83

JHEP 1305 (2013) 065

CMS $\ell\ell$: $161.9 \pm 2.5(\text{stat})^{+5.1}_{-5.0}(\text{syst}) \pm 3.6(\text{lumi})$ pb

Total uncertainty (CMS $\ell\ell$): 4.2%

8 TeV results:

CMS $\ell\ell$: $227 \pm 3(\text{stat}) \pm 10(\text{syst}) \pm 10(\text{lumi})$ pb

CMS ℓ+j: $228 \pm 9(\text{stat})^{+29}_{-26}(\text{syst}) \pm 10(\text{lumi})$ pb

Total uncertainty (CMS $\ell\ell$): 6.3%

Pair-production cross-section

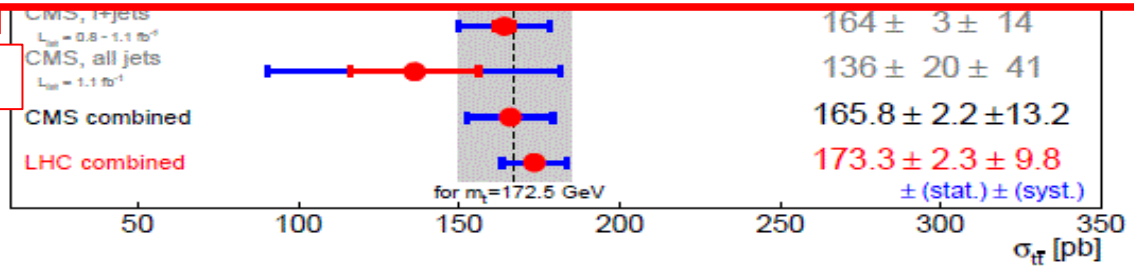
Cross sections consistent both with theory and across channels

- Systematic uncertainties now comparable with statistic.
- Generator modeling uncertainties dominating.

→ *New Physics can be effectively constrained*

σ(tt) now available at full NNLO (Czakon, Fiedler, Mitov arXiv:1303.6254)

JHEP 1305 (2013) 065



CMS $\ell\ell$: $161.9 \pm 2.5(\text{stat})^{+5.1}_{-5.0}(\text{syst}) \pm 3.6(\text{lumi})$ pb

Total uncertainty (CMS $\ell\ell$): 4.2%

8 TeV results:

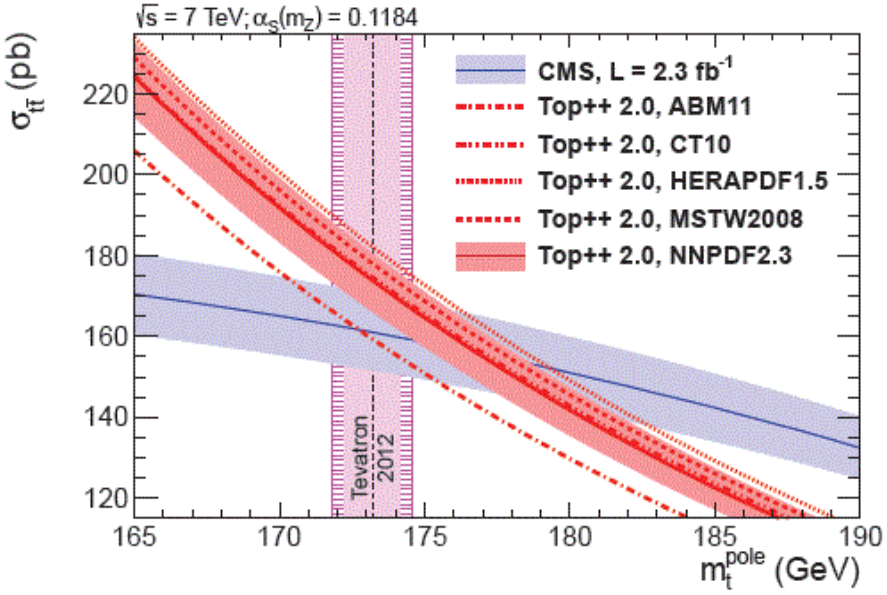
CMS $\ell\ell$: $227 \pm 3(\text{stat}) \pm 10(\text{syst}) \pm 10(\text{lumi})$ pb

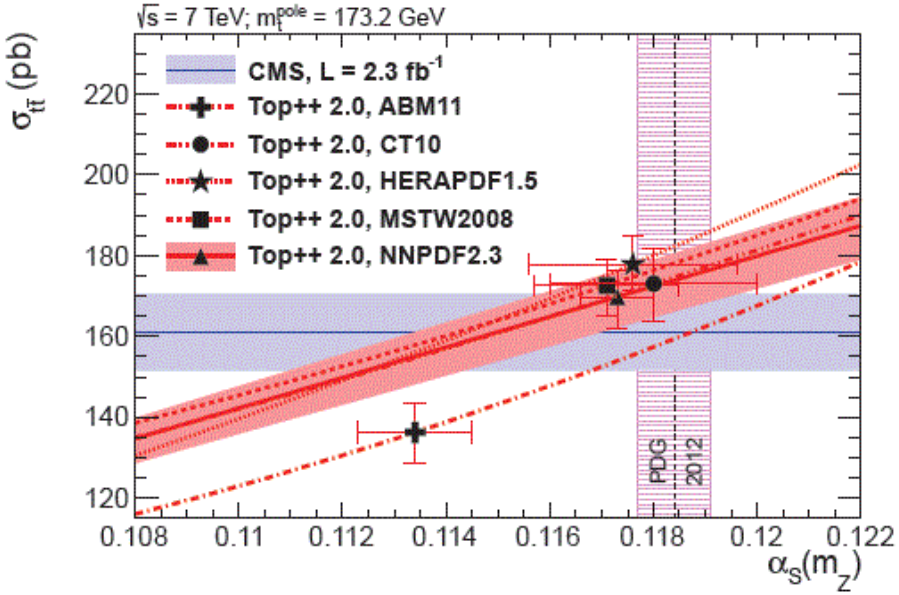
CMS ℓ+j: $228 \pm 9(\text{stat})^{+29}_{-26}(\text{syst}) \pm 10(\text{lumi})$ pb

Total uncertainty (CMS $\ell\ell$): 6.3%

σ(tt) related to α_s and m_t

Cross section dependence on α_s and m_t^{pole} is used to constrain α_s and/or m_t^{pole}





→ **Pole mass determination complementary to direct top mass measurements (different systematics and theoretically well defined).**

CMS: $m_t^{\text{pole}} = 176.7^{+3.8}_{-3.4}$ GeV (NNLO, arXiv:1303.6254)

CMS: $\alpha_s(m_Z) = 0.1151^{+0.0033}_{-0.0032}$ (if m_t^{pole} fixed to measured top quark mass)

arXiv:1307.1907

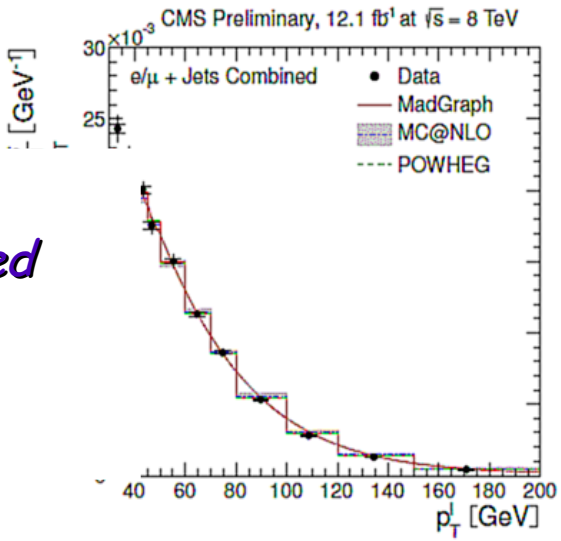
Differential cross-section

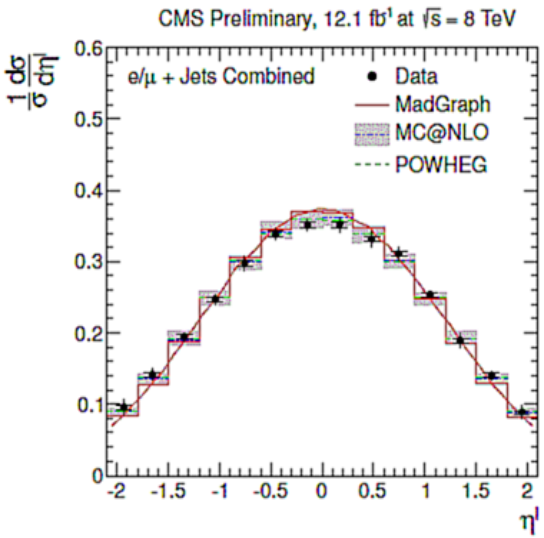
Enough data to make a large set of differential cross-section measurements vs.:

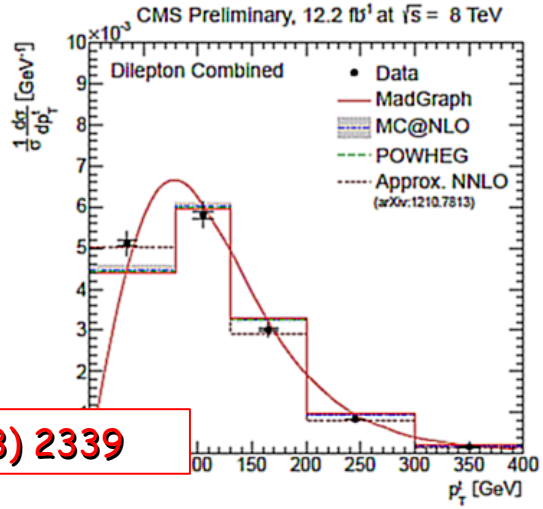
- *kinematics of $t\bar{t}$ system*
- *top quark decay products*

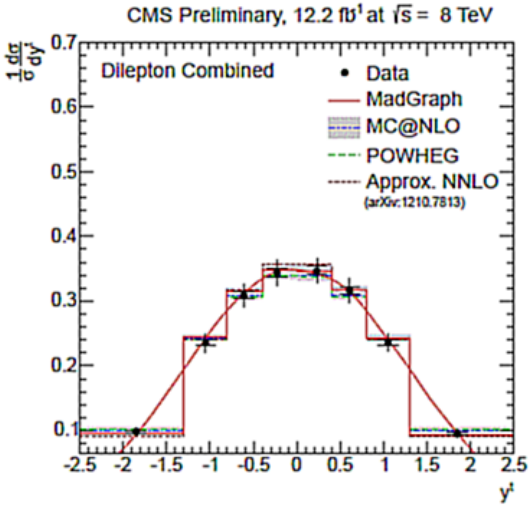
→ *Good agreement with tested generators*

→ *Most bins are systematics limited*







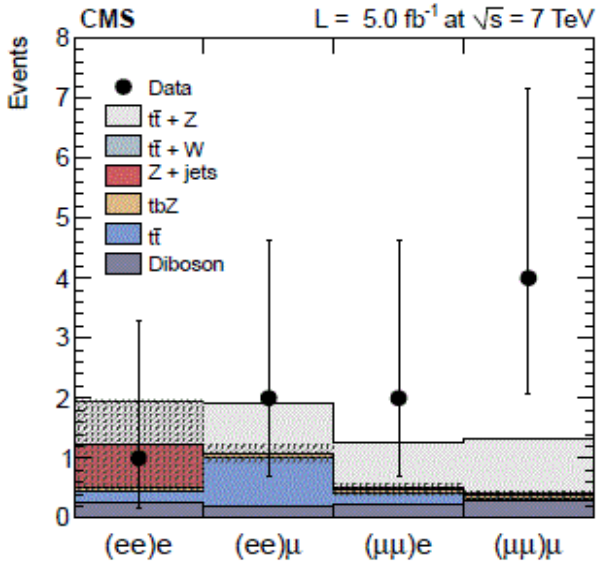


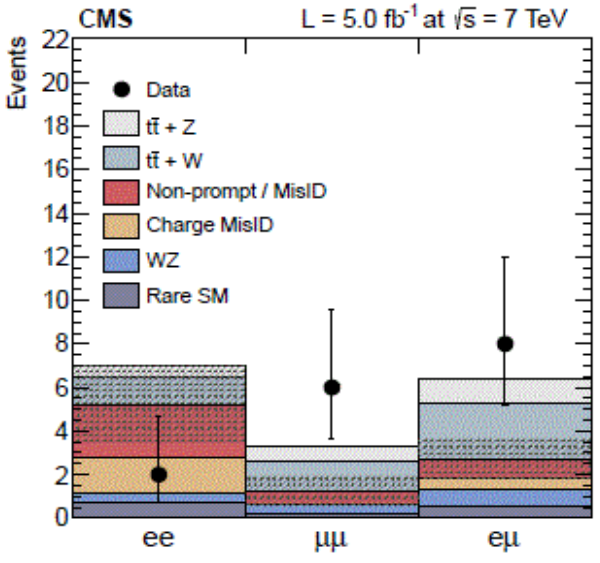
Eur. Phys. J. C73 (2013) 2339

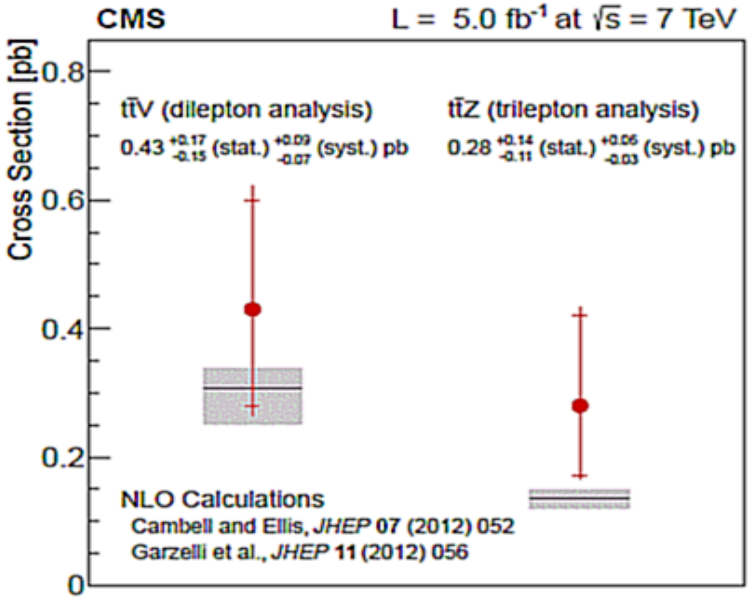
Top pair production with Z,W

- **Dilepton analysis:**
  tt + W/Z

- **Trilepton analysis:**
  tt + Z







Phys. Rev. Lett. 110 (2013) 172002

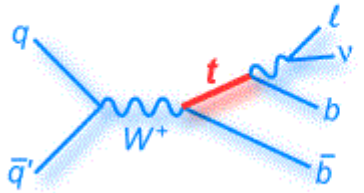
Single-top studies

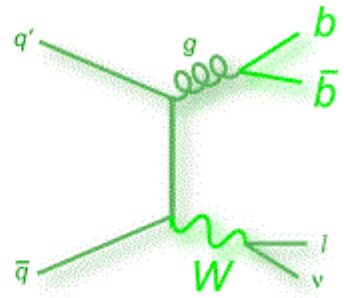
→ *Can directly probe the Wtb coupling and V_{tb} in CKM matrix*

- Challenging, mainly due to the background from W+jets

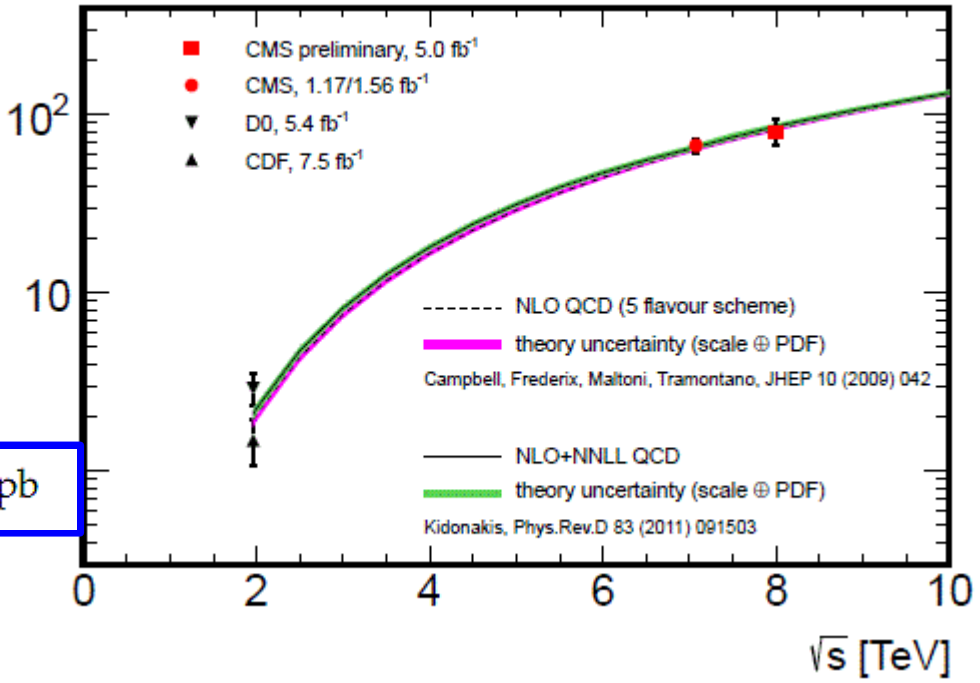
→ *Need MVA techniques*

- s + t-channel production observed at CDF and D0 in 2009
- t-channel observed both at Tevatron and LHC
- Evidence for s-channel production at D0
- Observation of Wt-channel production at CMS
- Evidence by both ATLAS and CMS 2012/2013





t-channel single top quark production

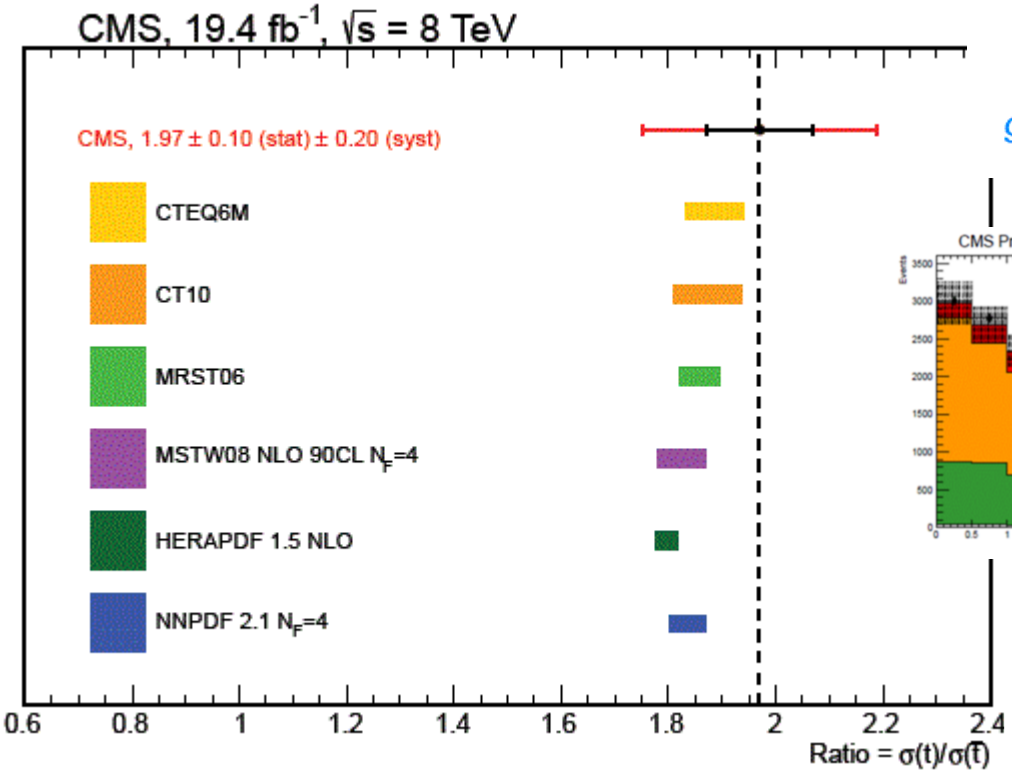


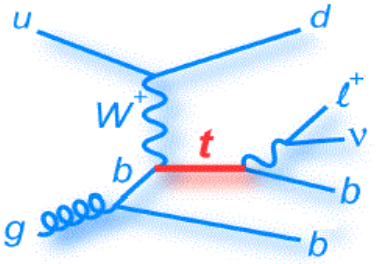
$$\sigma_{t-\mathrm{ch.}} = 80.1 \pm 5.7(\mathrm{stat.}) \pm 11.0(\mathrm{syst.}) \pm 4.0(\mathrm{lumi.})\ \mathrm{pb}$$

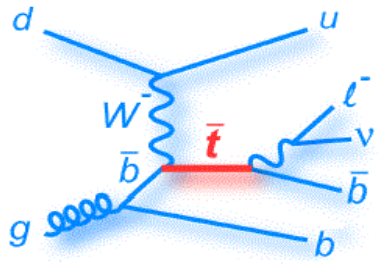
JHEP 12 (2012) 035

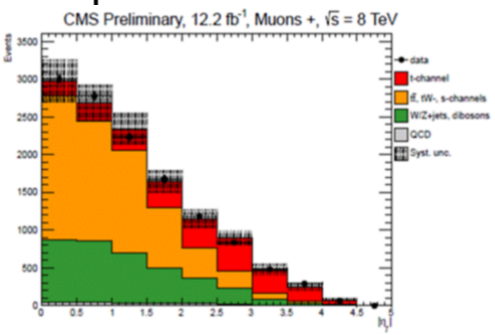
Single-top studies

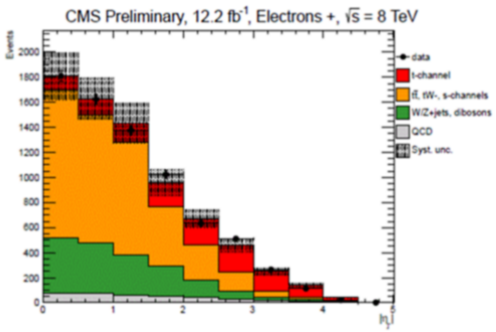
→ Ratio $R_{t\text{-ch.}} = \sigma_{t\text{-ch.,top}} / \sigma_{t\text{-ch.,anti-top}}$ is sensitive to u/d content of proton











The |η(j)| distribution is exploited to extract the signal simultaneously in the events with positively and negatively charged leptons

$$R_t = 1.76 \pm 0.14(\text{stat}) \pm 0.21(\text{syst})$$

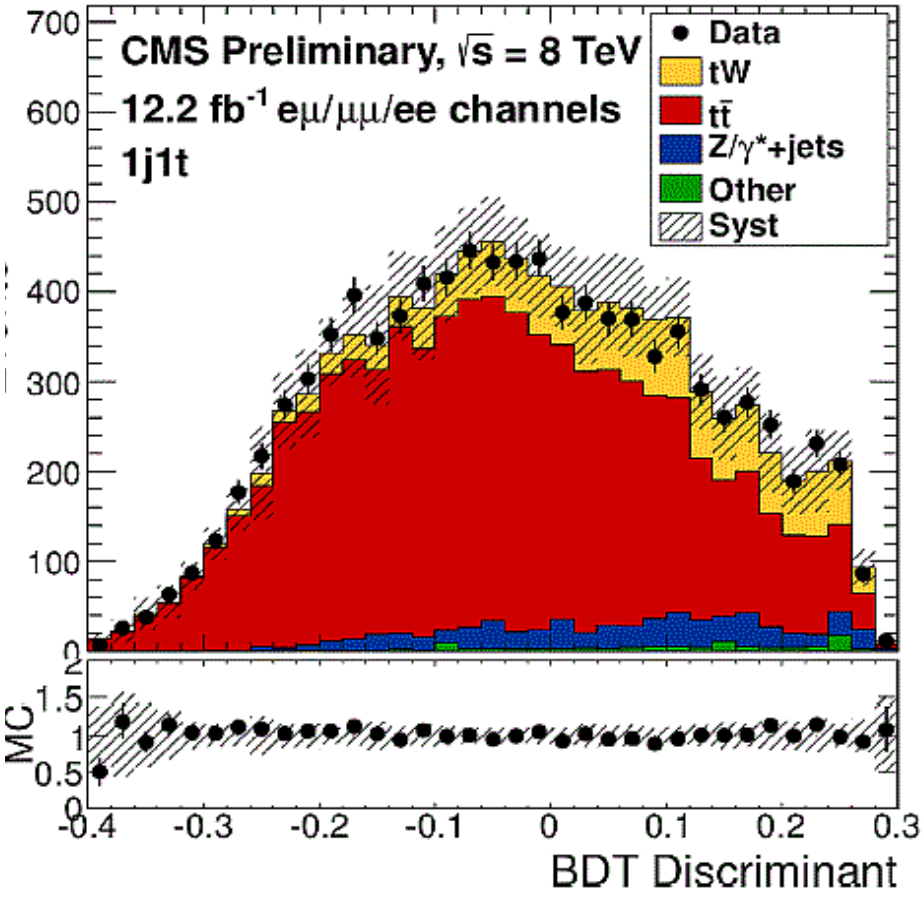
CMS-PAS-TOP-12-038

Observation of Wt production

→ First observation of Wt production by CMS

- The measurement is performed selecting events with two leptons and a jet originated from a b quark
- A multivariate analysis based on kinematic properties is used to separate the signal from the $t\bar{t}$ background.

→ very interesting production mechanism because of its interference with top quark pair production, sensitivity to new physics and role as a background to several SUSY and Higgs searches



$$\sigma = 23.4^{+5.5}_{-5.4}\ \text{pb}$$

6.0σ significance

CMS-PAS-TOP-12-040

What can be measured with the top

- Measurements in Top production:
  - ✓ Pair production cross section σ(tt)
  - ✓ Single top production cross section: t-channel, s- and Wt-channel
  - ✓ Associated production with Z/W and jets
  - ✓ Differential cross section
  - ✓ production asymmetries

- **Measurements in Top properties:**
  - ✓ **Top mass from final state**
  - ✓ **Top mass from constraints on σ(tt) and α_s**
  - ✓ **Top mass from decay length of B mesons**
  - ✓ **Wtb coupling**
  - ✓ **Spin correlations**

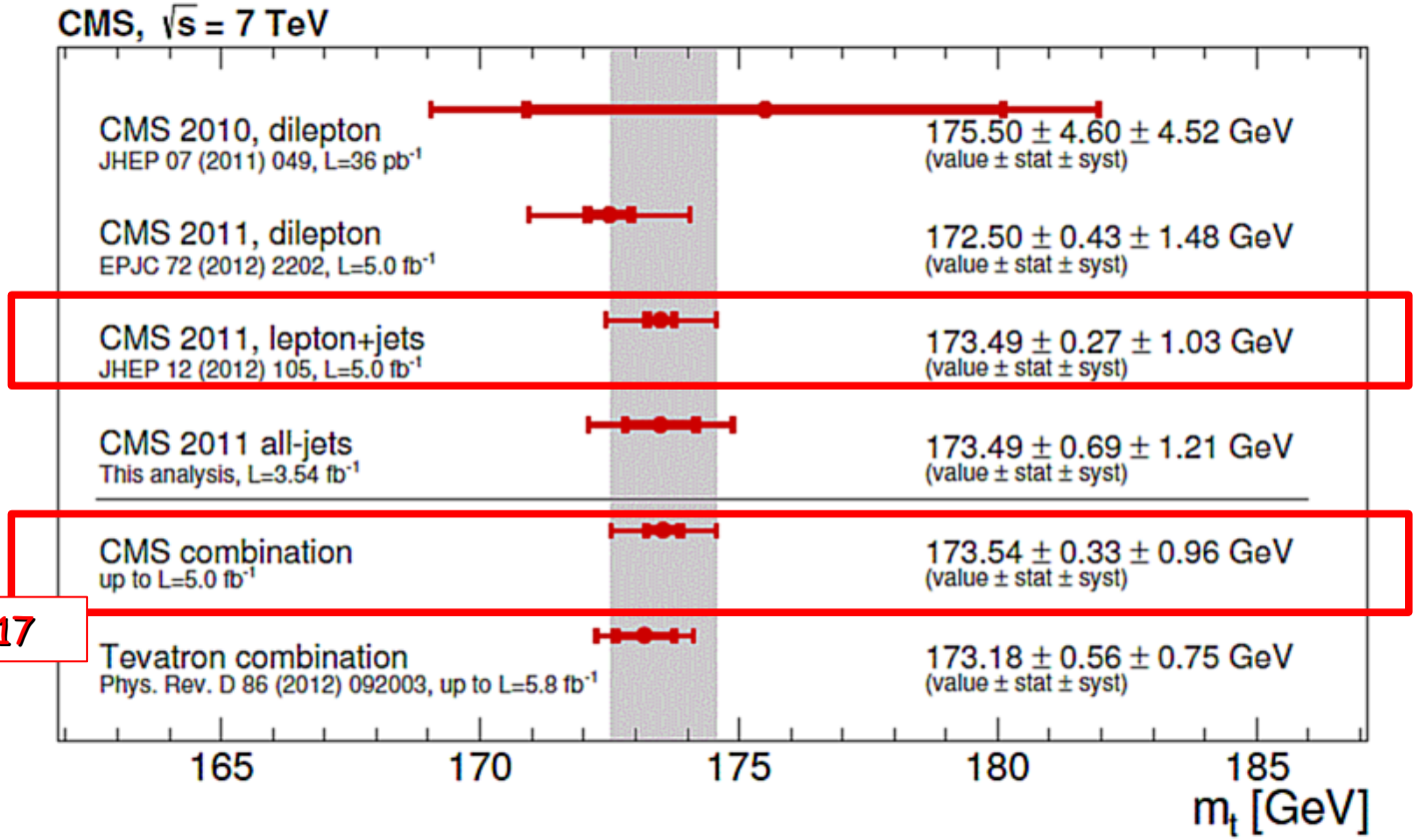
- Searches for New Physics:
  - ✓ Limits on FCNC and baryon number violation decays

Top quark mass

→ Tevatron (CDF-D0 combination) still provides the best mass measurement:

173.20 ± 0.51 ± 0.71 GeV (arXiv:1305.3929)

- Best single LHC measurement from CMS: ±1.06 GeV, i.e. 0.6%
- Best experiment-wide measurement from CMS: ±1.00 GeV
- Updated LHC mass combination in progress (harmonise systematic treatment)



arXiv:1307.4617

Top mass from transverse decay length

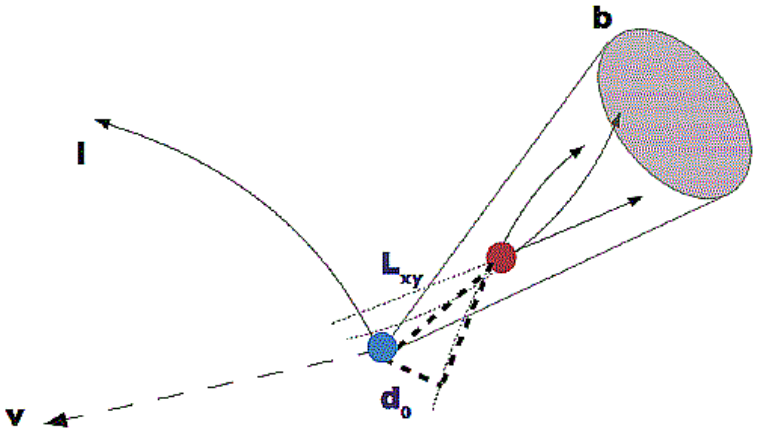
Lifetime-based technique, using

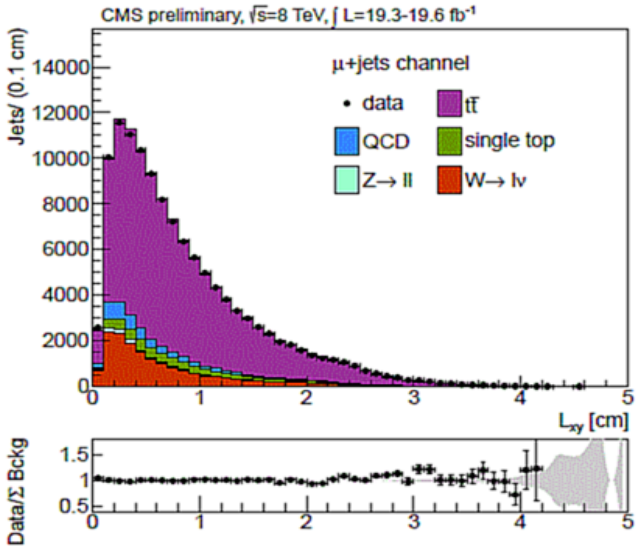
$$L_{xy} = \gamma_b \beta_B \tau_B \approx 0.4 \cdot \frac{m_t}{m_B} \beta_B \tau_B.$$

First used at CDF (Phys. Rev. D75, 071102 (2007))

- Linear mass dependence, Lxy/GeV = 25 – 30 μm/GeV

→ Complementary systematics to traditional measurements, e.g. minimal dependence on jet energy scale





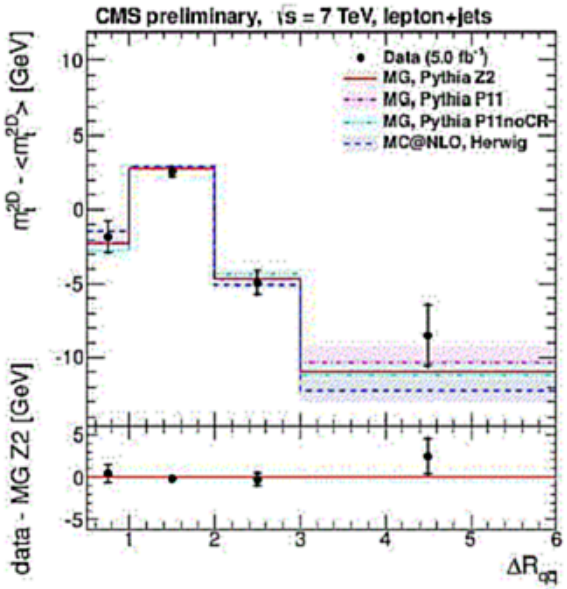
- In each event, select secondary vertex with largest Lxy
- the median of Lxy is used to extract m_t

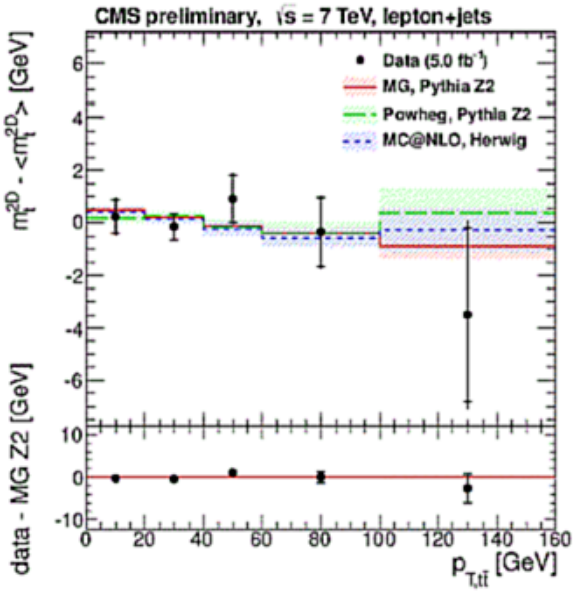
CMS-PAS-TOP-12-030

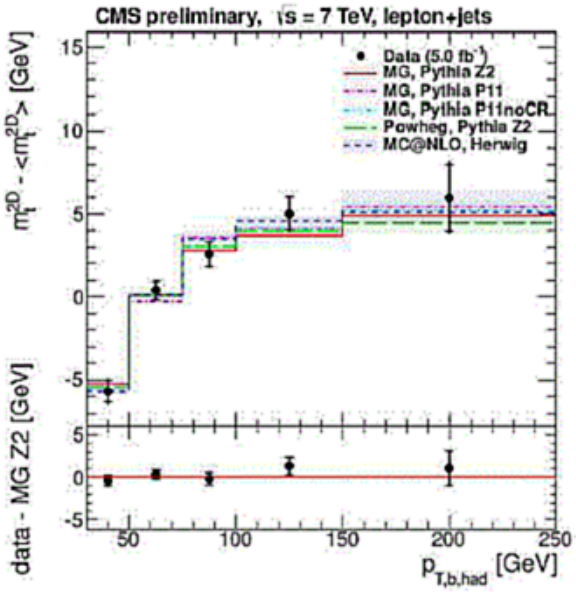
$$m_t = 173.5 \pm 1.5_{stat} \pm 1.3_{syst} \pm 2.6_{p_T(t)} \text{ GeV}$$

Further Mass Measurements

- Differential mass measurements, to probe e.g. color reconnections and initial/final state radiation







CMS-TOP-12-029

- Top-antitop mass difference, to test CPT theorem
  - ✓ Mass reconstructed with the Ideogram Likelihood method
  - ✓ part of (theoretical) systematics cancel out

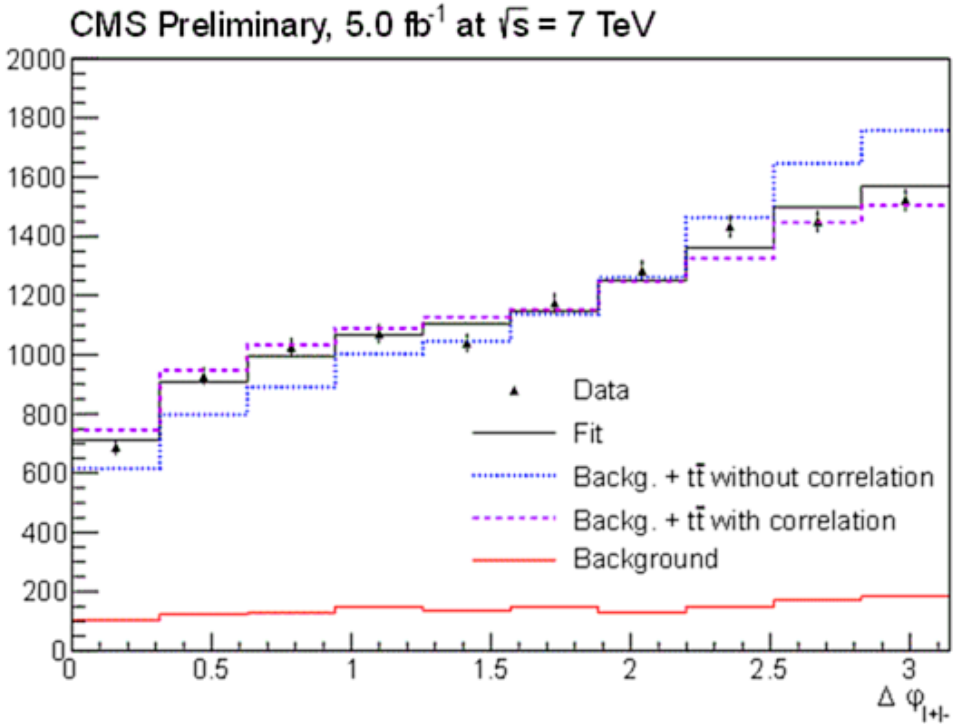
$$\Delta m_t = -272 \pm 196\ (\text{stat.}) \pm 122\ (\text{syst.})\ \text{MeV}.$$

CMS-TOP-12-031

Spin Correlations

Spins of top and anti-top are correlated in SM

→ Short top quark lifetime ($\sim 5 \times 10^{-25}$ s) means spin information is carried on to decay products.



Measure fraction of SM-like events using template fit to $\Delta\phi(\ell\ell)$ distribution

- **f_{SM} = 0 → no correlations.**
- **f_{SM} = 1 → correlations (SM)**

ATLAS: $f^{SM} = 1.30 \pm 0.14^{+0.27}_{-0.22} \rightarrow 5.1\sigma$

Phys. Rev. Lett. 108, 212001 (2012)

CMS: $f^{SM} = 0.74 \pm 0.08(\text{stat}) \pm 0.24(\text{syst})$

CMS-TOP-12-004

D0: $f^{SM} = 0.85 \pm 0.29 \rightarrow 3.1\sigma$

Phys. Rev. Lett. 108, 032004 (2012)

Anomalous Couplings and CP Violation

Effective lagrangian for Wtb vertex:

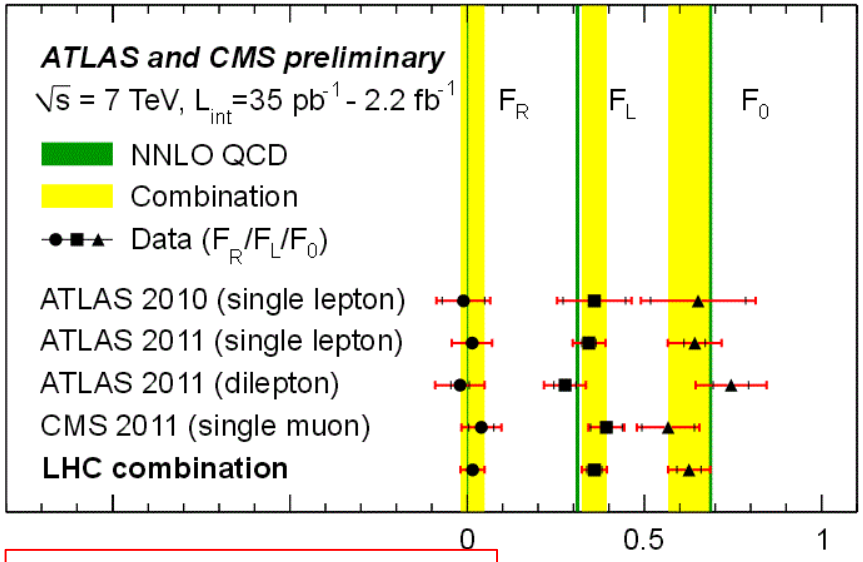
V_R, g_L, g_R anomalous couplings

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + \text{h.c.}$$

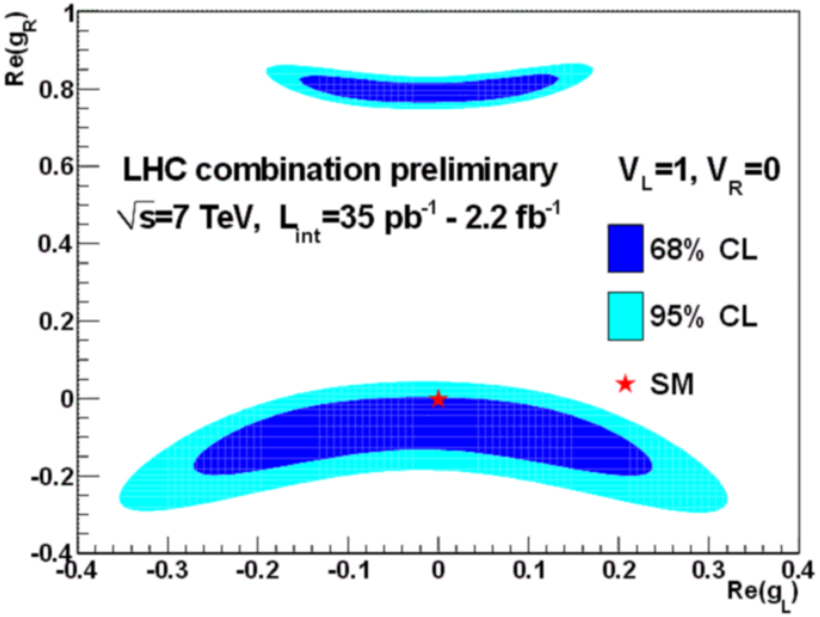
- Interpret F_R, F_L, F_0 in terms of anomalous couplings.
- Assume $V_L = 1, V_R = 0$. Derive limits on g_L and g_R.

- CP violation if $Im(g_R) \neq 0$.
- A_{FB}^{N} in single top t-channel (top $\sim 90\%$ polarized).

$$A_{FB}^{N} = \frac{N(\cos\theta^N > 0) - N(\cos\theta^N < 0)}{N(\cos\theta^N > 0) + N(\cos\theta^N < 0)}$$



CMS-PAS-TOP-12-025



Fwd-Bkwd and Charge Asymmetries

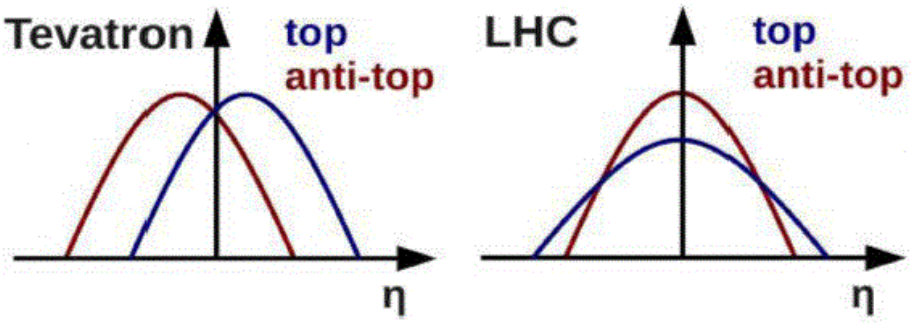
- New physics in top sector can alter angular distributions.
- Study forward-backward and charge asymmetries.

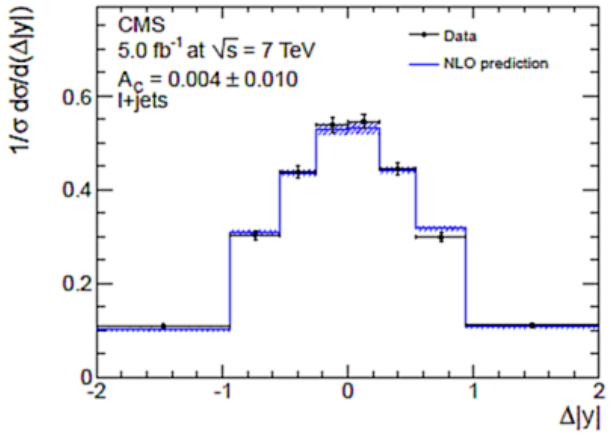
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

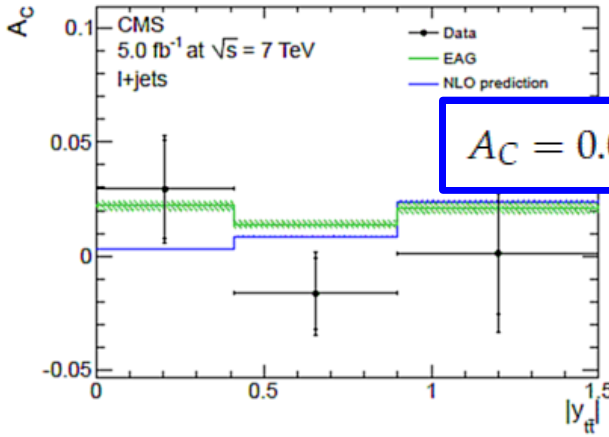
with $\Delta y = y_t - y_{\bar{t}}$

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

with $\Delta|y| = |y_t| - |y_{\bar{t}}|$







$$A_C = 0.004 \pm 0.010\ (\text{stat.}) \pm 0.011\ (\text{syst.})\ .$$

Phys. Lett. B 717, 129 (2012)

- Tevatron $A_{FB}(t\bar{t})$ measurements in tension with SM at ~ 2.5σ
- CMS $A_C(t\bar{t})$ measurements consistent with SM

What can be measured with the top

- Measurements in Top production:
  - ✓ Pair production cross section σ(tt)
  - ✓ Single top production cross section: t-channel, s- and Wt-channel
  - ✓ Associated production with Z/W and jets
  - ✓ Differential cross section
  - ✓ production asymmetries

- Measurements in Top properties:
  - ✓ Top mass from final state
  - ✓ Top mass from constraints on σ(tt) and α_s
  - ✓ Top mass from decay length of B mesons
  - ✓ Wtb coupling
  - ✓ Spin correlations

- **Searches for New Physics:**
  - ✓ **Limits on FCNC and baryon number violation decays**

Flavour Changing Neutral Currents

- The t→Zq decay is highly suppressed in the Standard Model (BR ~10^{-14})
- However,there are several models (R-parity-violating supersymmetric models, top-color-assisted technicolor models etc.) that predict enhancements as large as BR ~10^{-4}

→ *An upper limit to this process can be beneficial to constrain various models beyond SM*

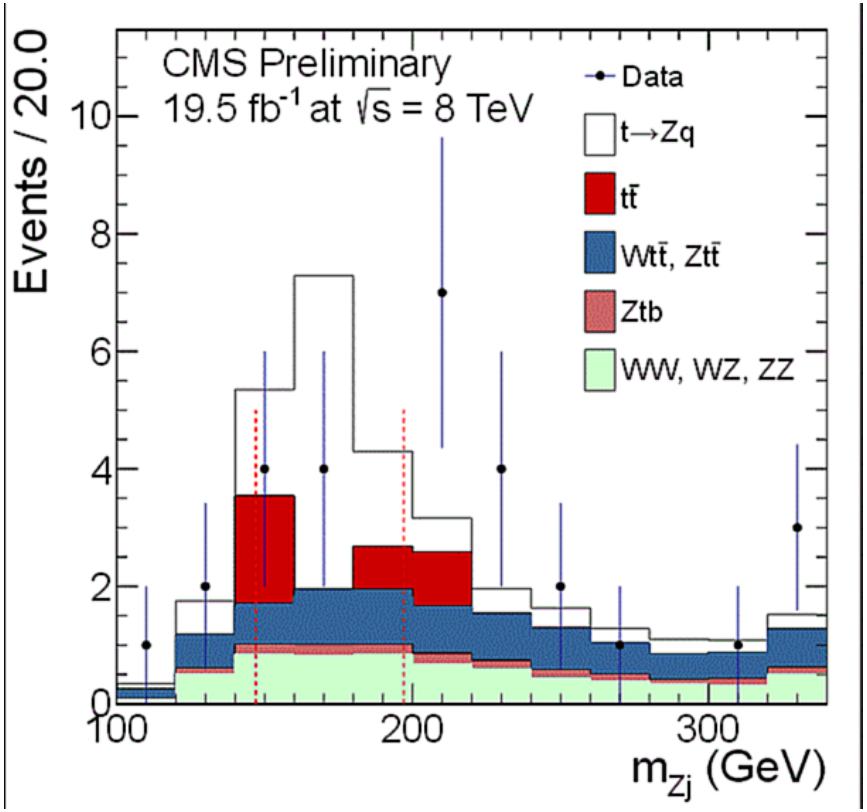
- $t\bar{t} \rightarrow Wb + Zq \rightarrow \ell\nu b + \ell\ell q$

ATLAS: $BR(t \rightarrow Zq) < 0.73\%$ @ 95% C.L. (7 TeV)

CMS: $BR(t \rightarrow Zq) < 0.07\%$ @ 95% C.L. (8 TeV)

JHEP 1209 (2012) 139

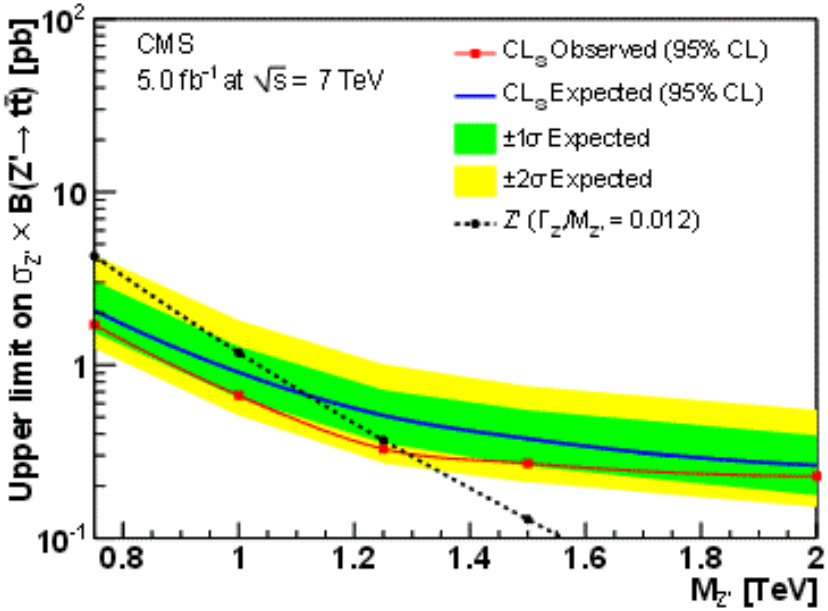
CMS-PAS-TOP-12-037

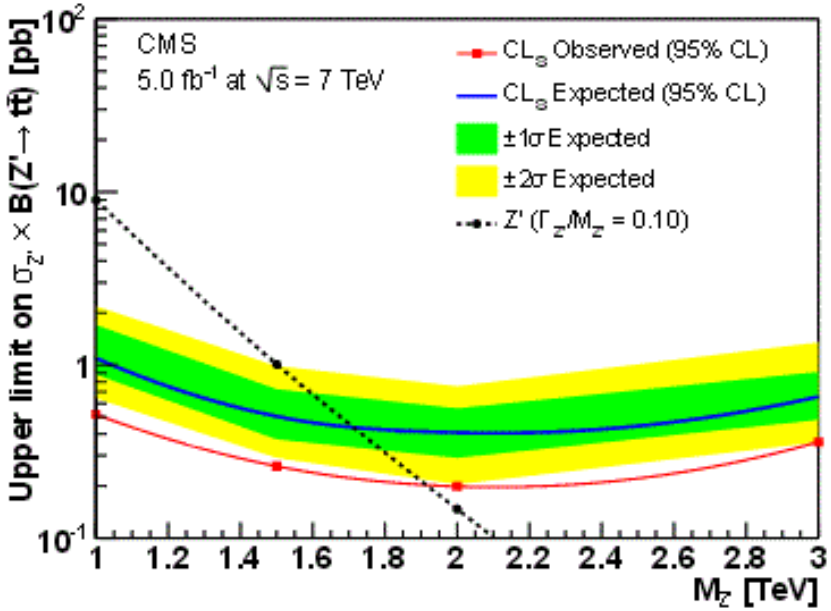


Search for Z' resonances

A search for resonances decaying to top quark-antiquark pairs is performed using a dilepton+jets data sample

- Upper limits for the production of Z' → tt resonances in the 750-3000 GeV range
- existence of a leptophobic topcolor particle Z' excluded at the 95% confidence level for $M_{Z'} < 1.3$ TeV for $\Gamma_{Z'} = 0.012\ M_{Z'}$, and $M_{Z'} < 1.9$ TeV for $\Gamma_{Z'} = 0.10\ M_{Z'}$

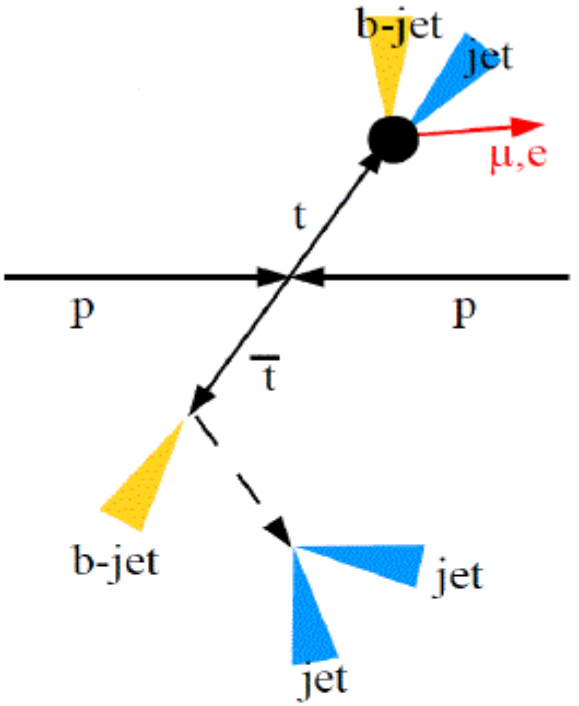


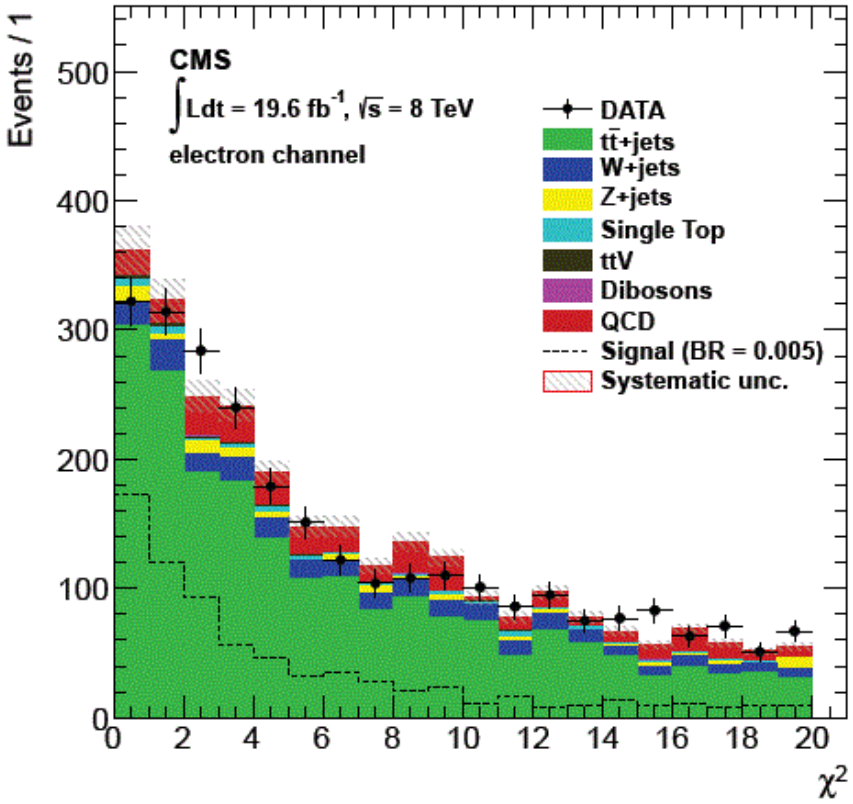


arXiv:1211.3338 [hep-ex]

Baryon Number Violating Decays

- Baryon number violation possible in several BSM scenarios.
- Search for $t\bar{t}$ events in which one top decays through $t \to \bar{b}\bar{c}\mu^+$ or $t \to \bar{b}\bar{u}e^+$.





- No significant excess over expected background.

$$BR(t \to \bar{b}\bar{c}\mu^+) < 0.0016 \text{ @ 95\% C.L.}$$
$$BR(t \to \bar{b}\bar{u}e^+) < 0.0017 \text{ @ 95\% C.L.}$$

CMS-B2G-12-023

Summary

Very rich top physics program at CMS experiments

→ Most analyses are only systematics limited

- Top production:
  - ✓ Pair production cross section with O(4-6%) uncertainty.
  - ✓ Single top t-channel cross section with O(20%) uncertainty.
  - ✓ s- and Wt-channel production observed at 3.7σ and 6σ level.
  - ✓ Associated production ($t\bar{t}V$, $t\bar{t}j$), differential cross section measured

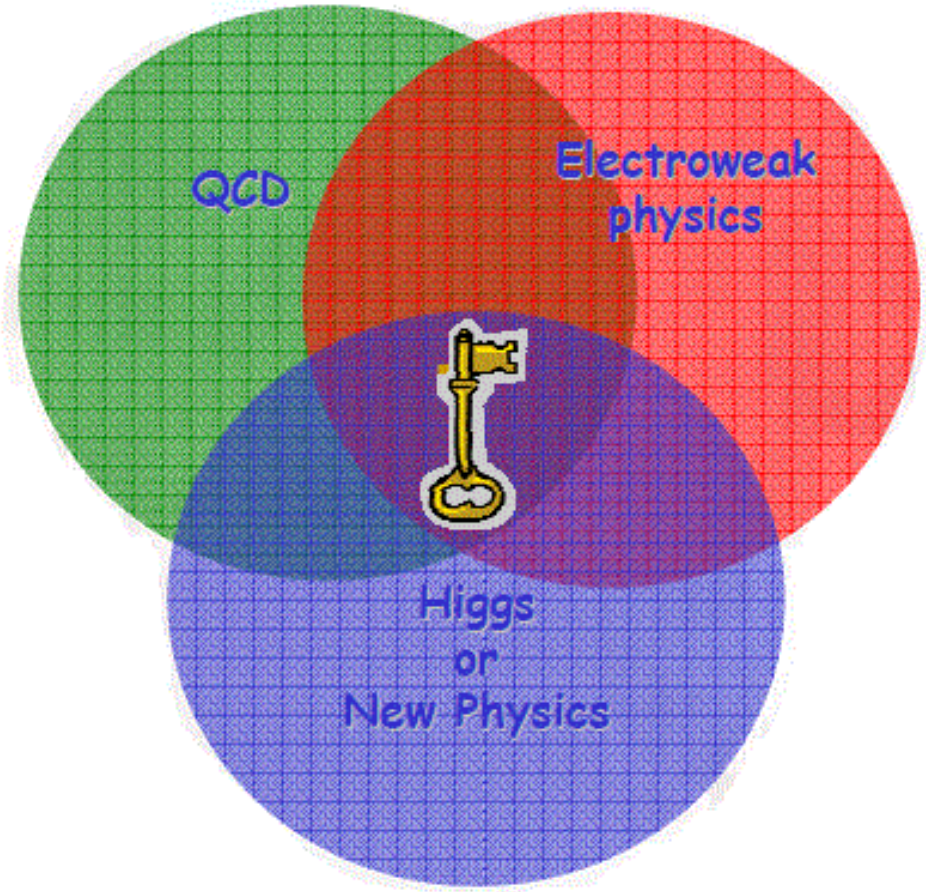
- Top properties:
  - ✓ Top mass uncertainty is currently 0.5% (0.87 GeV).
  - ✓ Polarization, asymmetry and coupling measurements all consistent with SM
  - ✓ Spin correlations observed
  - ✓ Limits on FCNC and baryon number violation decays

- Searches:
  - ✓ Wide range of searches for new phenomena

Summary

What is still hidden in the interplay of QCD, Electroweak and Higgs sector ?

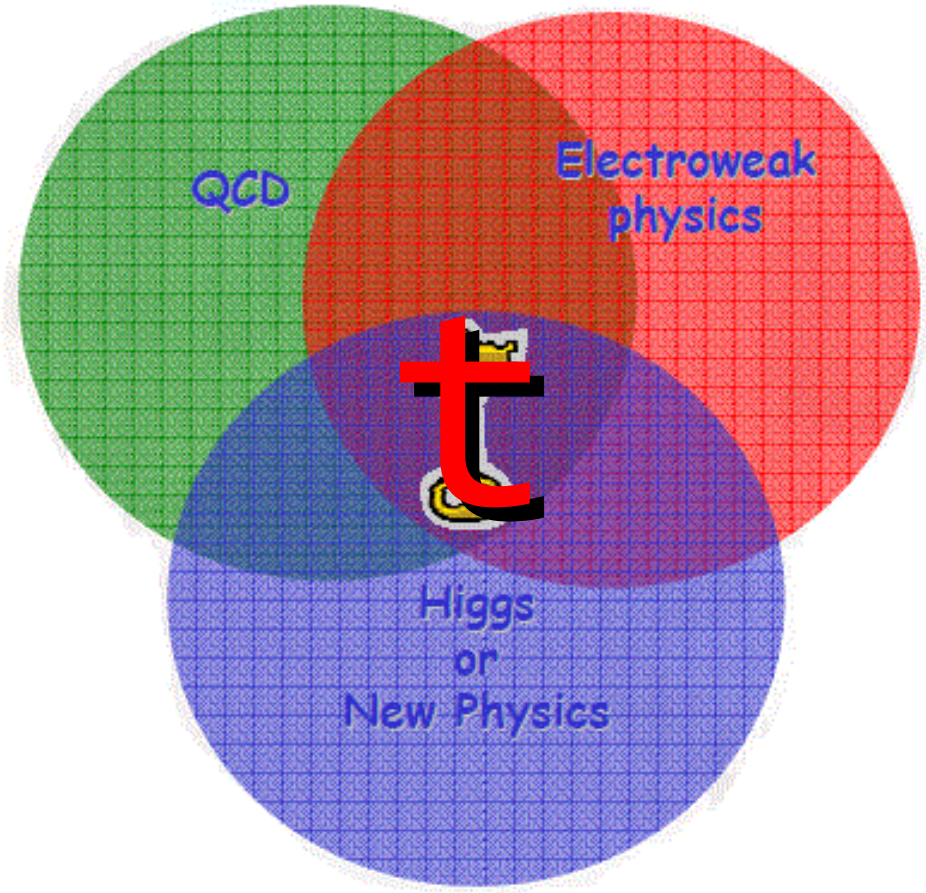
→ Top quark is the THE key to enter this realm



Summary

What is still hidden in the interplay of QCD, Electroweak and Higgs sector ?

→ Top quark is the THE key to enter this realm



Backup

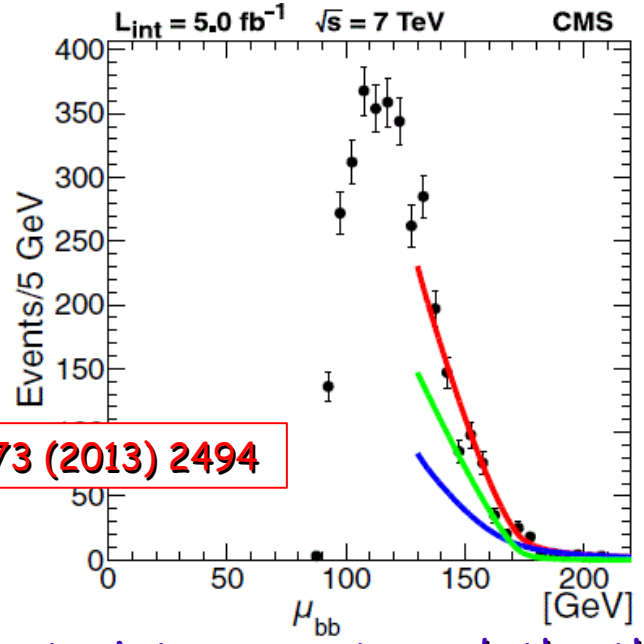
Top mass by kinematic endpoints

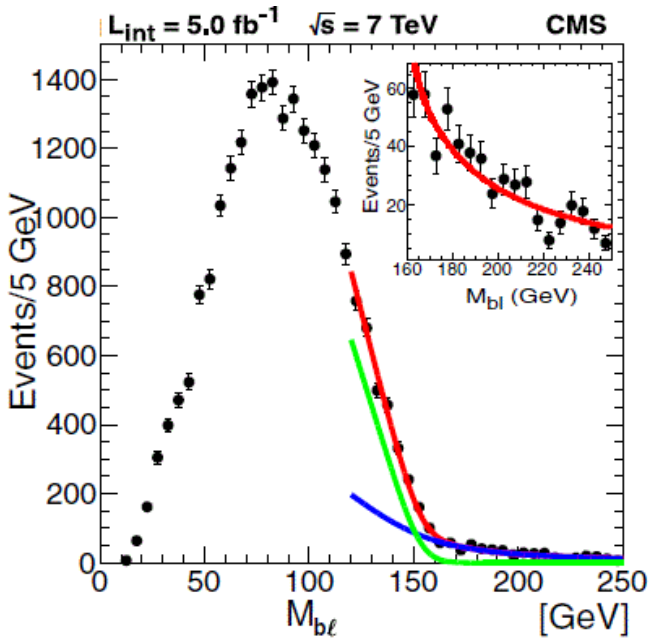
→ A simultaneous measurement of the top-quark, W-boson, and neutrino masses based on endpoint determinations in kinematic distributions

- When the neutrino and W-boson masses are constrained to their world-average:

$$M_t = 173.9 \pm 0.9\,(\text{stat.})^{+1.7}_{-2.1}\,(\text{syst.})\,\text{GeV}.$$

Eur. Phys. J. C73 (2013) 2494

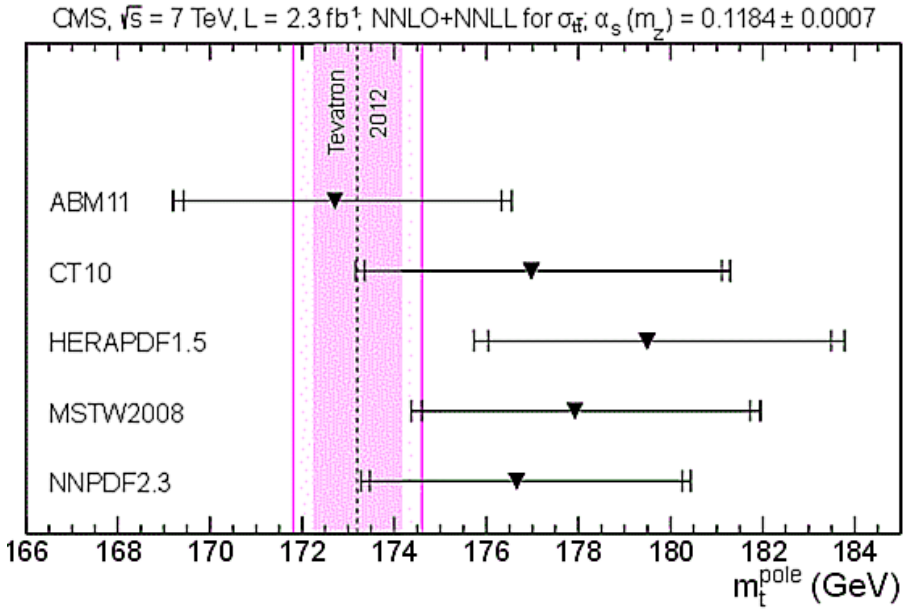


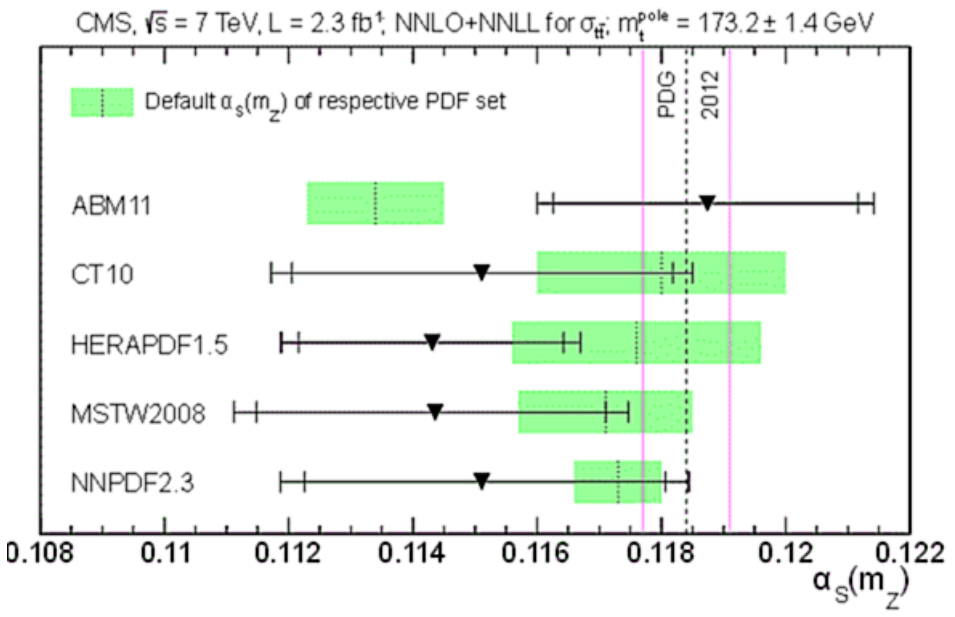


- When constraints are not used, the three particle masses are obtained in a simultaneous fit
- the method may be used to search for unknown masses in BSM physics

σ(tt) related to α_s and m_t

Cross section dependence on α_s and m_t^{pole} is used to constrain α_s and/or m_t^{pole}





→ **Pole mass determination complementary to direct top mass measurements (different systematics and theoretically well defined).**

CMS: $m_t^{\text{pole}} = 176.7^{+3.8}_{-3.4}$ GeV (NNLO, arXiv:1303.6254)

CMS: $\alpha_s(m_Z) = 0.1151^{+0.0033}_{-0.0032}$ (if m_t^{pole} fixed to measured top quark mass)

arXiv:1307.1907