Top Quark cross section measurements in CMS

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- Introduction on Top Physics
- Top production at LHC
- Top pair cross section measurement
- Single top cross section measurement
- Charge asymmetry
  Conclusion

PLHC 2012

4-9 June 2012 Vancouver.

Motivation to study top quark physics

The Top physics is one of the main pillars of the physics program at the LHC:

Main interests are :

- **<u>Test of the Standard Model</u> (SM) at the LHC energies:**
  *precision measurement of the top production (ttbar, single top production)

  ↓

  test of perturbative QCD

  *top properties (top mass, top charge, decay branching ratios)

- **<u>Important for the physics Beyond Standard Model</u> (BSM)**:
  1) one of the main backgrounds for many BSM signatures:
  precision measurement of cross sections
  2) deviations of top production cross sections from SM predictions
  can **suggest the presence of new physics**.
  For example:
  *__According to SUSY__, the **top** quarks **can also decay** in $\mathbf{H^+}$ +b, and H^+ mainly in tau.
  *__The cross section production of single top (t-channel)__ is sensitive to possibily contribution of a **4th quark generation (t'/b')**
  *The **charge asymmetry** sensitive to possible new production ways due to **exchanging of unknown heavy particles (Z')**.

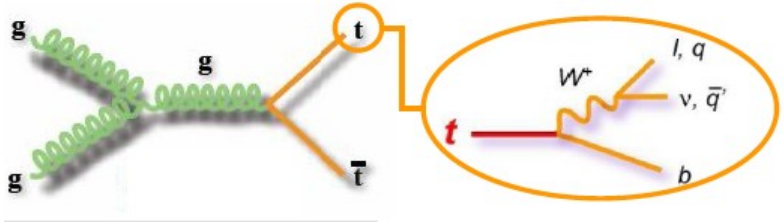
- **Top as a calibration tool**: jet energy scale, b-tagging efficiency

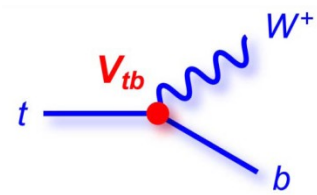
*<u>All CMS public results: **https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults**</u>*

Top Production at LHC

The LHC is a top factory!

Top pair production: 67% by gluon gluon fusion at 7TeV.

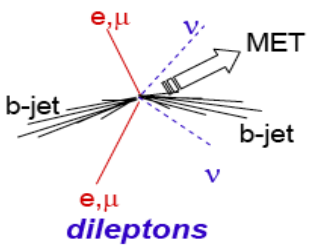


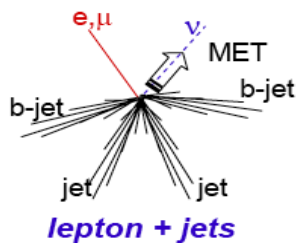


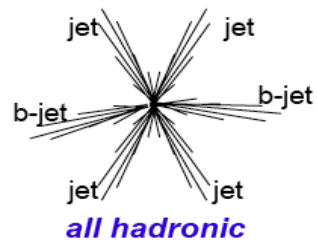
Vtb~1

σ_{tt} = (164 ± 10) pb at 7 TeV (NNLO), 20 times higher than Tevatron!

Kidonakis, PRD 82 (2010) 114030 Langenfeld, Moch, Uwer, PRD80 (2009) 054009

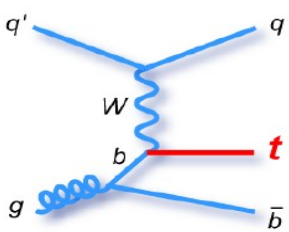




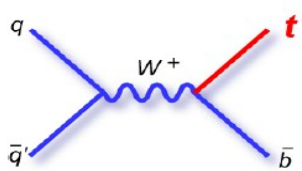


di-leptonic channel (e/μ/tau) :
BR= 9% but clear signature
semi-leptonic channel :
BR= 45%
More events but higher
W+jets and QCD bkg
hadronic channel :
46% of total,
high multi-jet background.

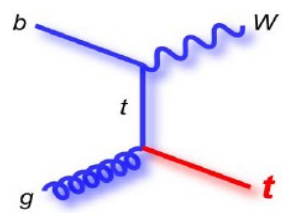
Single Top production: EWK production via three main contribution



t-channel



s-channel



tW-channel

allows a **direct measurement of the Vtb coupling**

σ(7 TeV)~64 pb σ(7 TeV)~4.6 pb σ(7 TeV)~15.6 pb

Measurements of the top pairs production cross section

CROSS SECTION: Lepton (e, μ)+jets channel

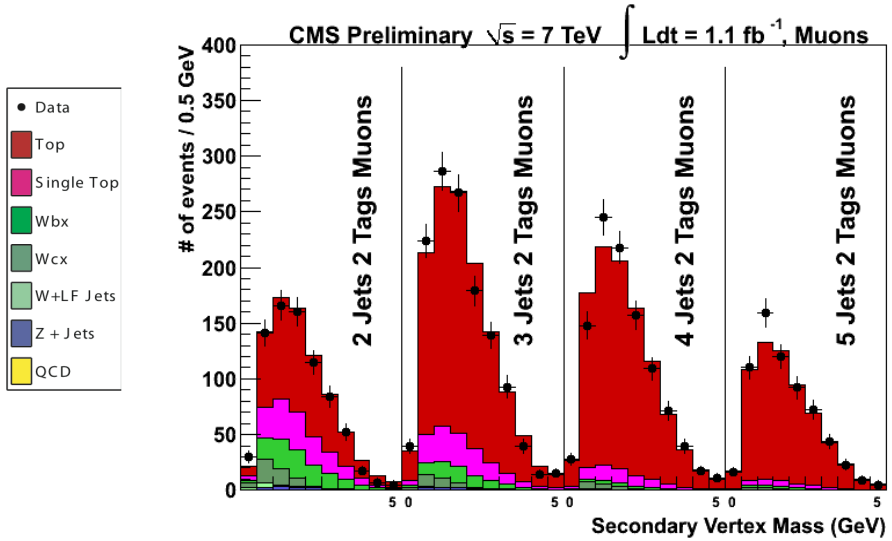
Lepton (e -, μ -) + jets: *Tirgger: Single Lepton trigger (p_T >27, (30) GeV for e- (μ-)).

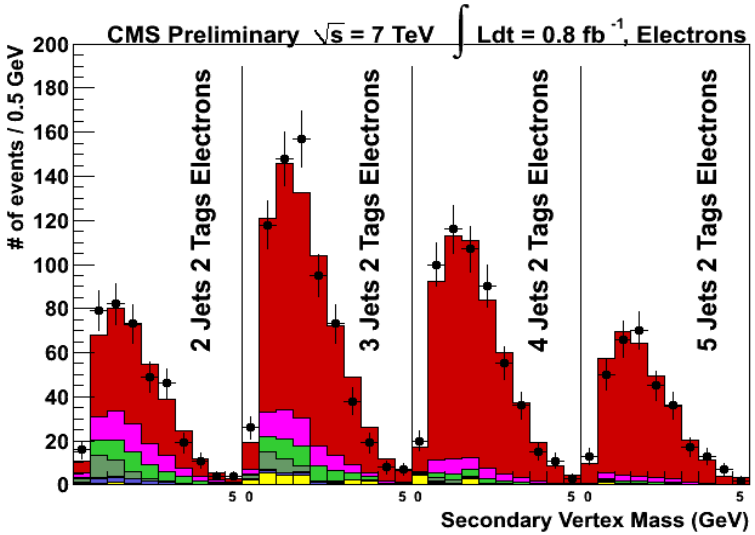
*Offline selection: only 1 lepton compatible with Primary Vertex and properly isolated, at least 1 b-tagged jet, and MET>20/30 for μ-(e-).

*Analysis strategy: **binned maximum likelihood fit** to the secondary vertex mass, in subsamples defined by lepton flavor, Njets, Nbtag. Background (bkg) templates taken from simulation except for the QCD events (normalization derived from a fit to the MET distribution).

TOP-11-003

$$\sigma_{t\bar{t}} = 164.4 \pm 2.8(\text{stat.}) \pm 11.9(\text{syst}) \pm 7.4(\text{lum.})\ \text{pb}$$





- **Systematic errors are treated as nuisance parameters** (radiation parameters (2%), JES (4%), b-tag eff (3%),...).

CROSS SECTION: (hadronic) tau + jets channel

NEW

Hadronic tau + jets:

- Trigger: multijet + tau id trigger, p_T> 45 GeV for all objects.
- Offline selection: 3 pfJet p_T>45 GeV, 4th pfJet p_T> 20GeV, at least 1 b-tagged jet, 1Tau p_T>45GeV, MET>20 GeV
- Analysis strategy: Multivariate analysis (Neural Network NN) to improve the ratio signal/bkg.
  Signal extracted from a template fit of the NN output distribution.
  Main multijet bkg modeled on data vetoing on b-tagged jet events (Jet Probability algorithm has been used).

- Mainly systematic uncertainties are due to the JEC (12%), Tau ID (9%), b-tag (3%) and are estimated by re-iterating the fit procedure.

$$\sigma_{t\bar{t}} = 156 \pm 12\,(\text{stat.}) \pm 33\,(\text{sys.}) \pm 3\,(\text{lumi})\,\text{pb}$$

M3: invariant mass of the 3-jet system with the highest transverse momentum

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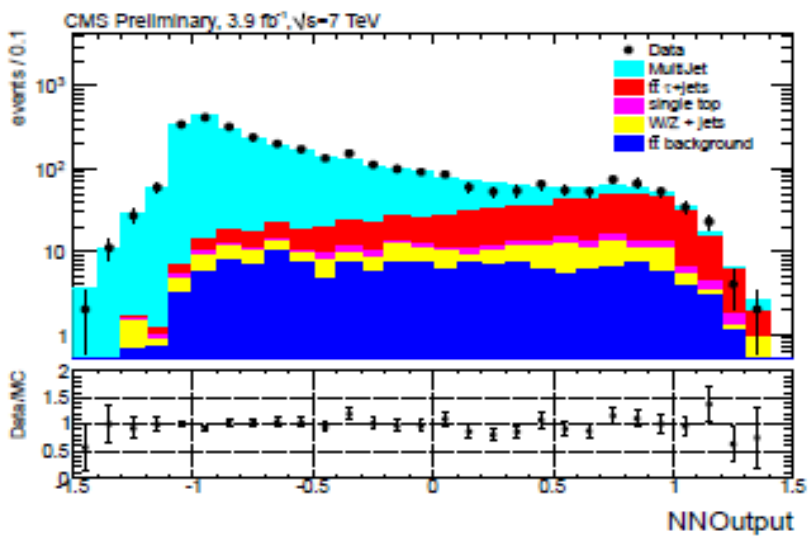

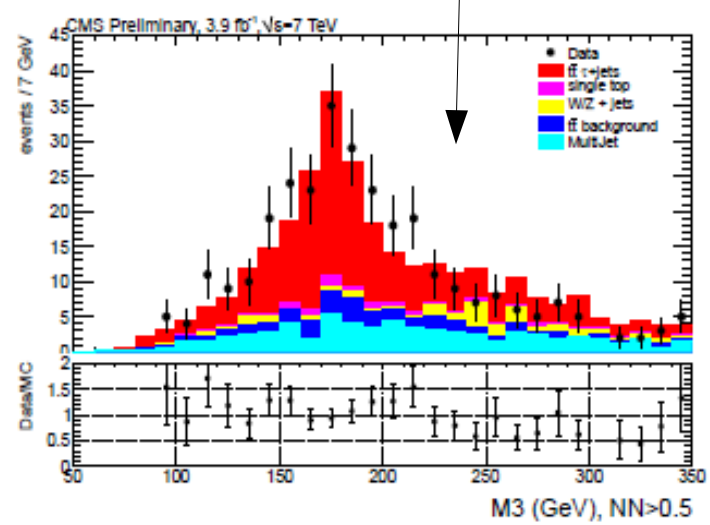

CROSS SECTION: Fully hadronic channel

Fully hadronic channel: *Trigger: multijet trigger + btag Id,
*Offline selection: at least 6 jets and where 2 of them have to be b-tagged. For each possible jet permutation a kinematic fit is performed. The permutation which has the best compatibility with ttbar events is retained.
*Analysis strategy: **template fit to m(top)**. Main QCD bkg modeled on data vetoing on btagged jets.

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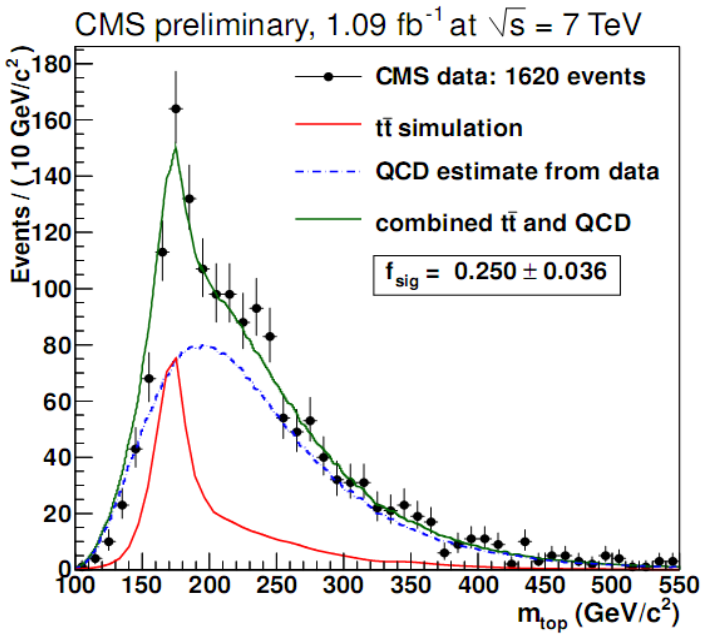
$$\sigma_{t\bar{t}} = 136 \pm 20\ (\text{stat.}) \pm 40\ (\text{sys.}) \pm 8\ (\text{lumi.})\ \text{pb}$$



- Systematic uncertainty coming from b-tagging (16%) JES(14%), and background estimation (12%)

Cross section: di-leptonic channels

TOP-11-005

Di-lepton (e, μ)

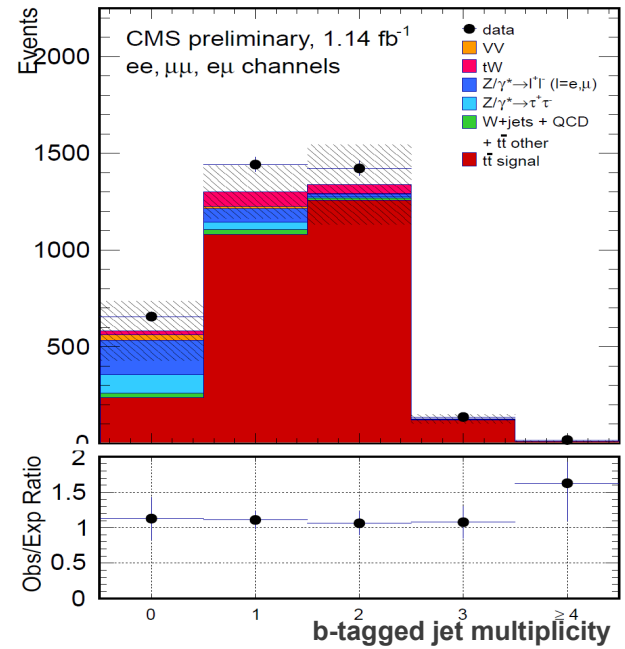
*Trigger: Double Lepton trigger.

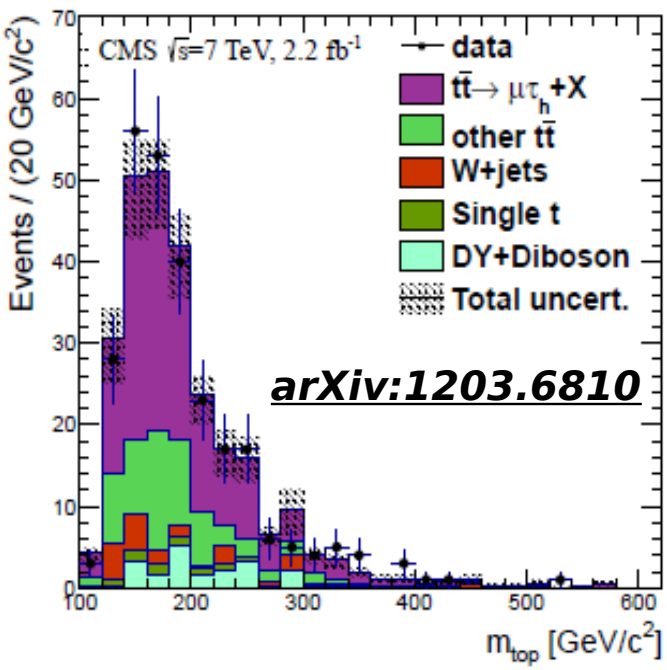
*Offline selection: 2 high p_T central leptons, 2 high p_T jets at least 1 has to be b-tagged, missing E_T >30 GeV.

*Analysis strategy: **counting experiment**.
data driven estimation of Z+jets, W+jets and QCD background.

Systematic uncertainty: b-tagging(5%) leptons sel. efficiency (4%), JES (2%).

$$\sigma_{t\bar{t}} = 169.9 \pm 3.9\ (\text{stat.}) \pm 16.3\ (\text{syst.}) \pm 7.6\ (\text{lumi.})\text{pb}$$





Di-lepton with τ:

*Trigger: Single Muon/electron trigger.

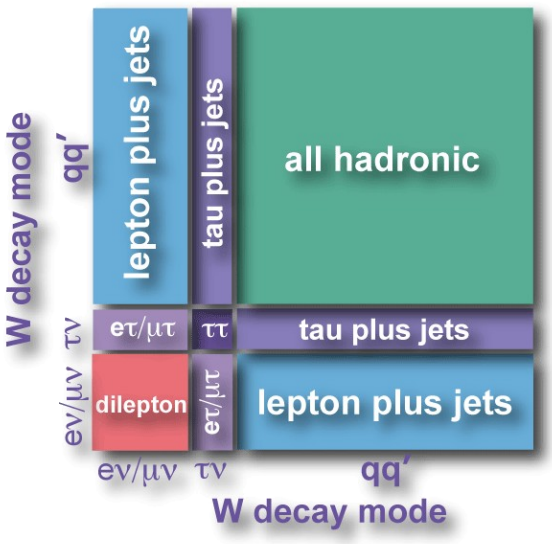
*Offline selection: 1 high p_T, central muon/electron.
1 high p_T, central hadronic tau. At least 3 high p_T central jets. At least 1 of them has to be b-tagged. High missing E_T >40 GeV.

*Analysis strategy: **Signal extracted from the fit to the top mass** (Kinb method).
Data driven estimation of τ-fake background.

Systematic uncertainty from JES (4%), b-tagging(5.5%), background estimation(13%), tau Id (7%)

$$\sigma_{t\bar{t}} = 143 \pm 14(\text{stat.}) \pm 22(\text{syst.}) \pm 3(\text{lumi.})\ \text{pb},$$

Cross section combination



- **Almost all top pair final states have been analyzed:** ℓ(e,μ, tau)+jets, ℓℓ and fully hadronic final states
- The **hadronic tau + jets final state is not yet included in the combination.**

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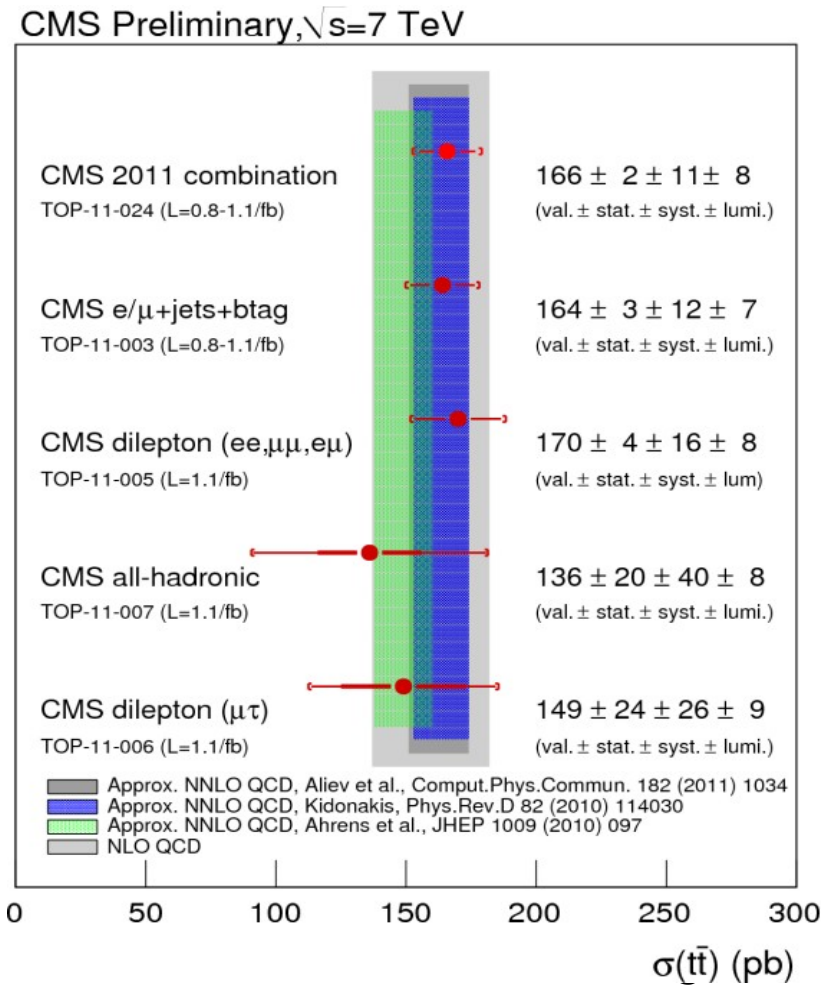

- The **combination** is **performed using a binned maximum likelihood fit**
  - **Experimental uncertainty close to 8%,** compatible to the precision of the approximate NNLO theory. ***excellent agreement of prediction with data.***

Top pair differential cross sections (1)

- Thanks to the high statistic at LHC it was possible the **first measurement of normalized differential cross-sections** in top pair production at 7TeV.

*Important test of pQCD
*Sensitive to new physics

- **Measurement performed in dilepton (eμ, ee, μμ) and lepton+jets channel**. Cross section is measured as function of p_T, rapidity, dilepton invariant mass.

- The **differential cross section is measured by counting the number of events in each bin *"i"* of the interested variable *"X"* and scaled to the integrated luminosity *"L"*.** Hence it is correct for acceptance and efficiencies ***"ε^i "***.

$$\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\sigma}\frac{N^i_{\mathrm{Data}} - N^i_{\mathrm{BG}}}{\Delta^i_{\mathrm{X}}\,\epsilon^i\,L}$$

- **Shape measurement:** differential cross sections normalized to the total cross section as determined in the corresponding inclusive analysis. **Systematics affecting the absolute normalization of the cross section cancel out.**

- A **bin-by-bin unfolding method is used to correct possible migration between bins** due to the trigger and detector efficiencies and resolutions.

Top pair differential cross sections (2)

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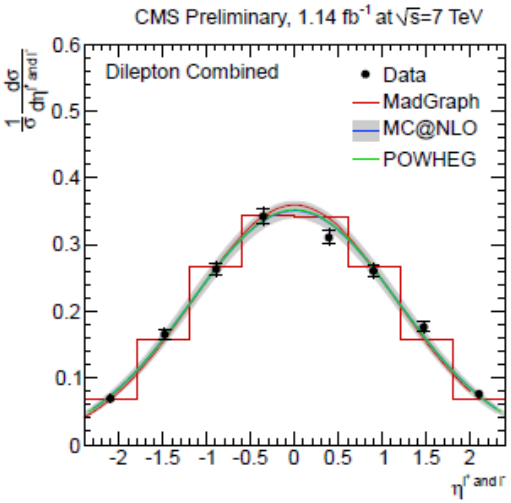
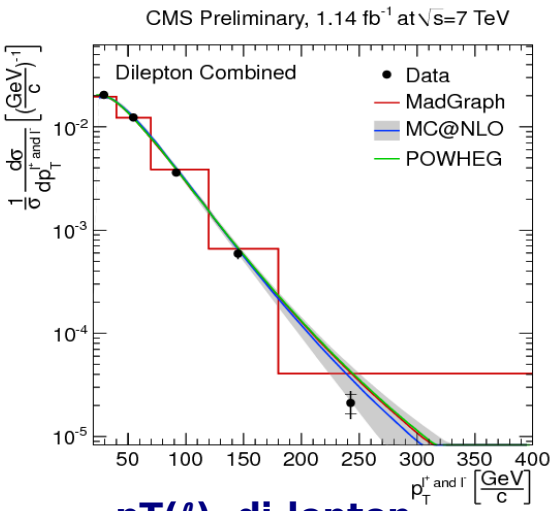
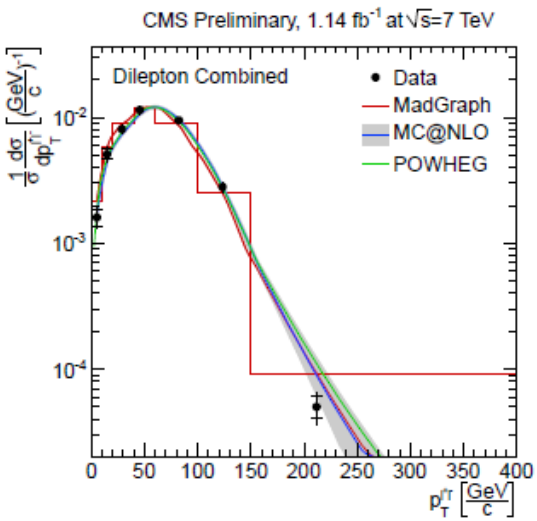


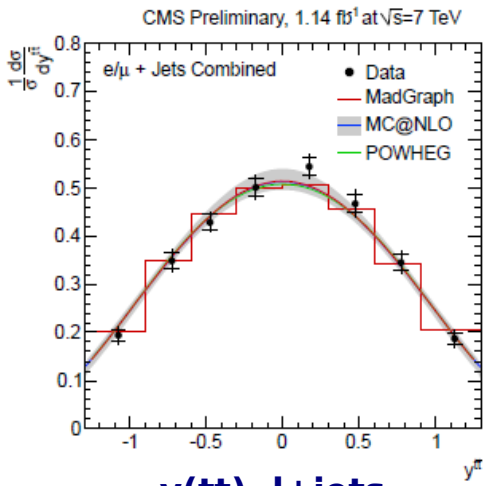
η(l), di-lepton



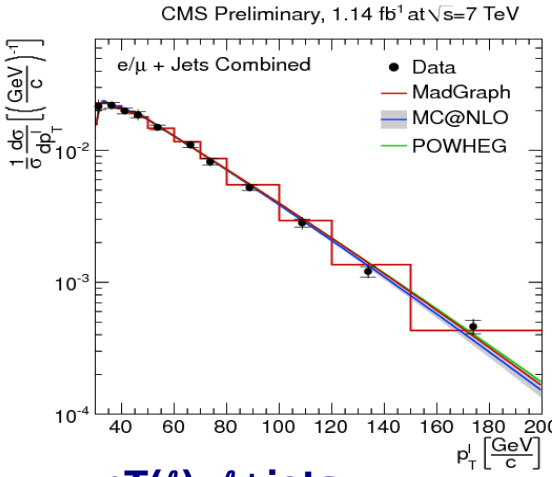
pT(ℓ), di-lepton



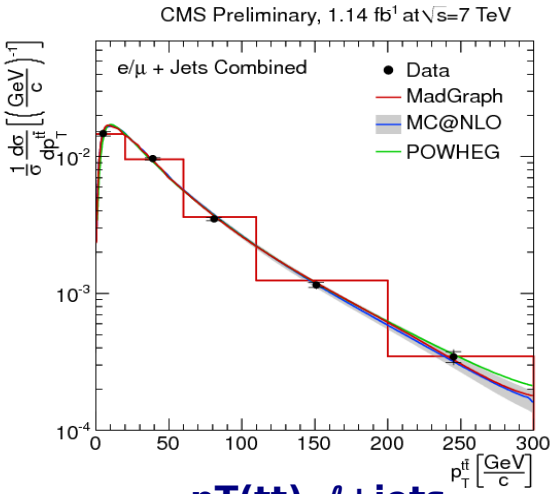
pT(ℓℓ), di-lepton



y(tt), l+jets



pT(ℓ), ℓ+jets



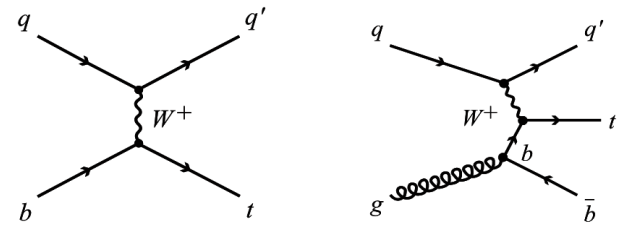
pT(tt), ℓ+jets

- ***Excellent agreement with predictions**
- *Main Systematic uncertainties due to: (JES), lepton selection, b-tagging, model uncertainties due to the MC generation.

Single top cross section measurement

Single top - t-channel

The t-channel has the highest cross section at the LHC. σ(t)~60 pb.



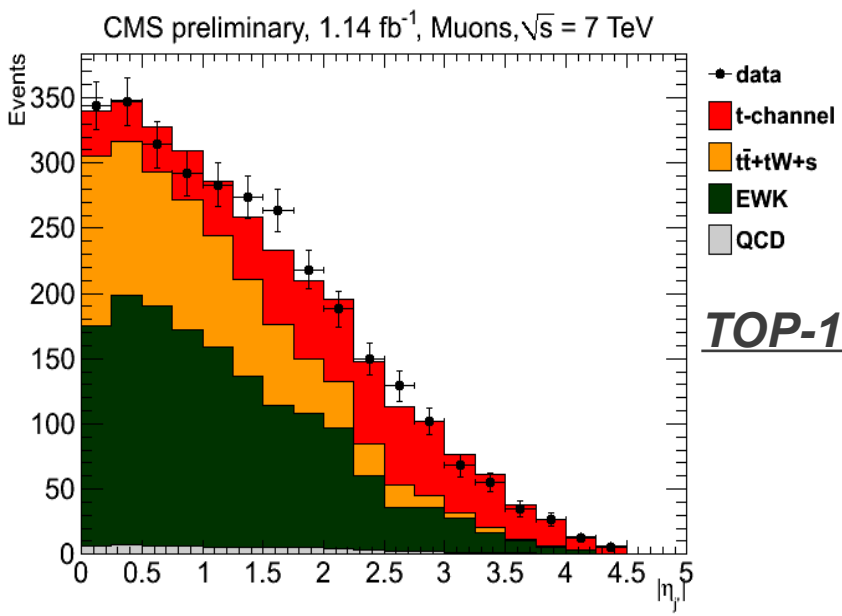
*Trigger: single muon (p_T>17) or an electron (p_T>27) plus a b-jet.

*Offline selection: Signal region defined requiring 1 high p_T, isolated lepton, 2 high p_T jets (at least 1 of them b-tagged).

*Analysis strategy: **Maximum Likelihood fit to the η of the light jet**. Templates for QCD and W+HF events are extracted from data, while template for signal is taken from MC.

$$\sigma_{t-\mathrm{ch.}} = 70.2 \pm 5.2(\mathrm{stat.}) \pm 10.4(\mathrm{syst.}) \pm 3.4(\mathrm{lumi.})\ \mathrm{pb}$$

Systematic uncertainty mainly due to the W+HF extraction (7%), b-tagging 4%, JES (7%)



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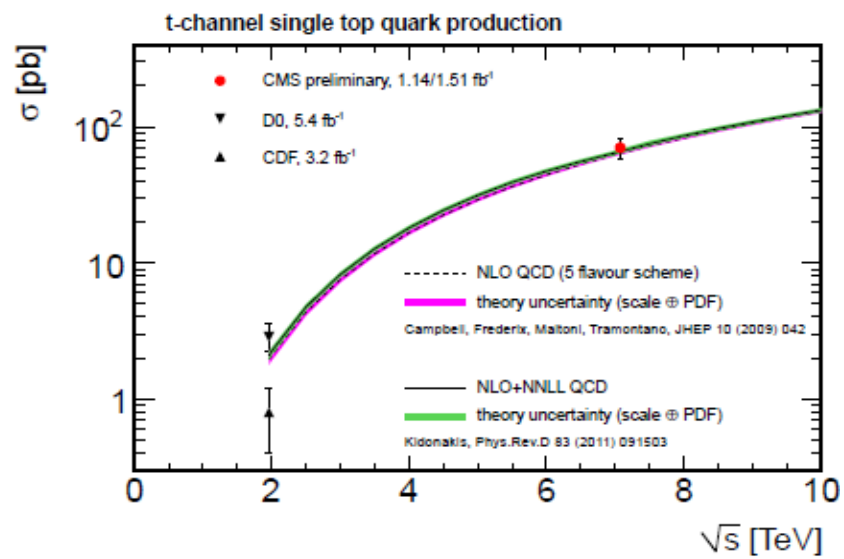
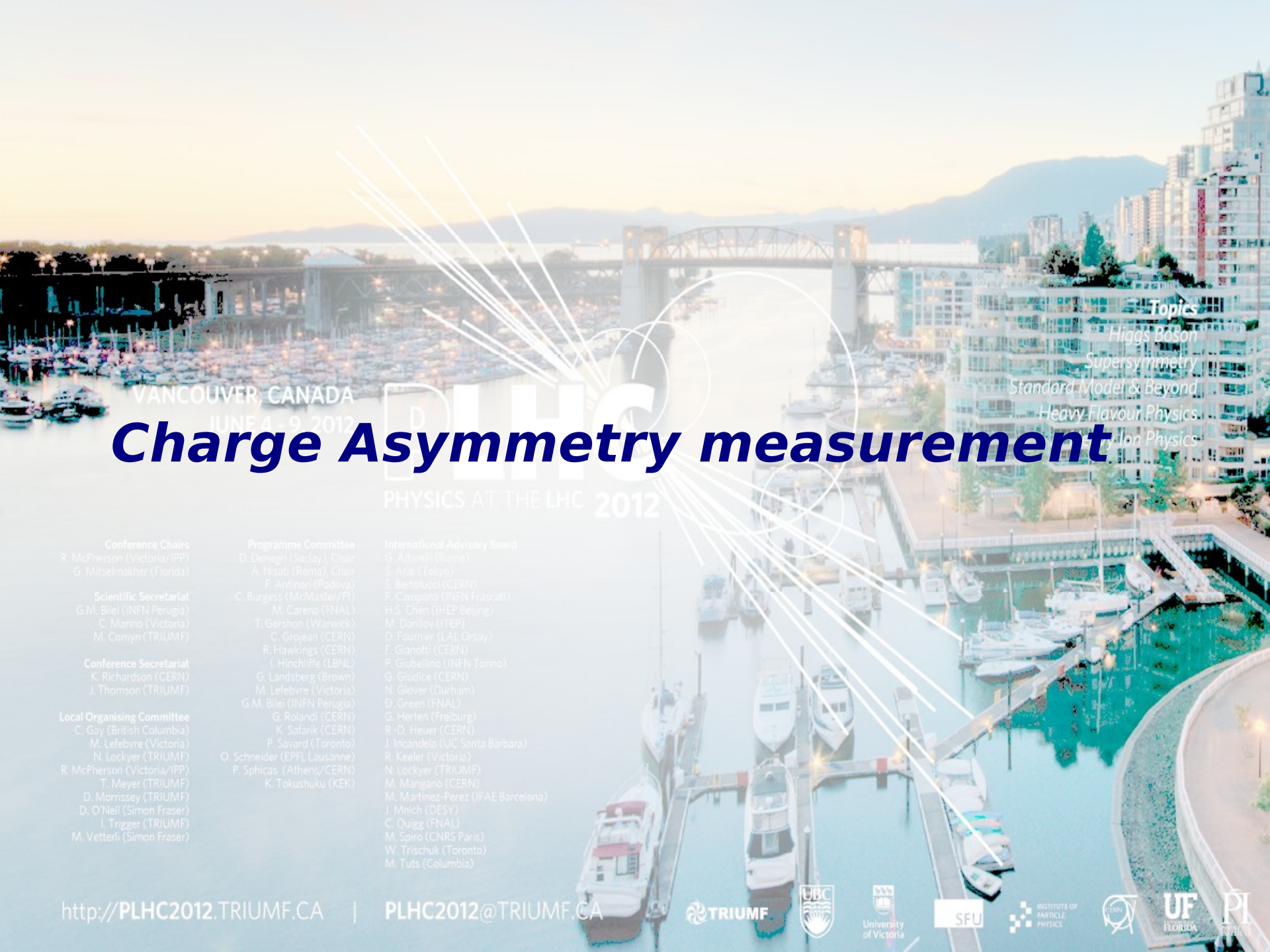
|Vtb| can be derived by assuming $|V_{td}|, |V_{ts}| << |V_{tb}|$

$$|V_{\mathrm{tb}}| = \sqrt{\frac{\sigma_{t-\mathrm{ch.}}}{\sigma^{\mathrm{th}}_{t-\mathrm{ch.}}}} = 1.04 \pm 0.09\,(\mathrm{exp.}) \pm 0.02\,(\mathrm{th.})$$

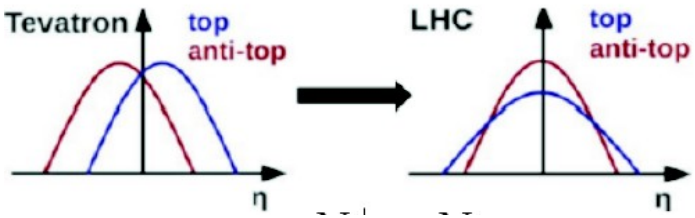


Charge Asymmetry measurement



Charge asymmetry (1)

- **Ac = Difference in angular distribution between top quarks and antiquarks.** Is expected to be small at LHC.

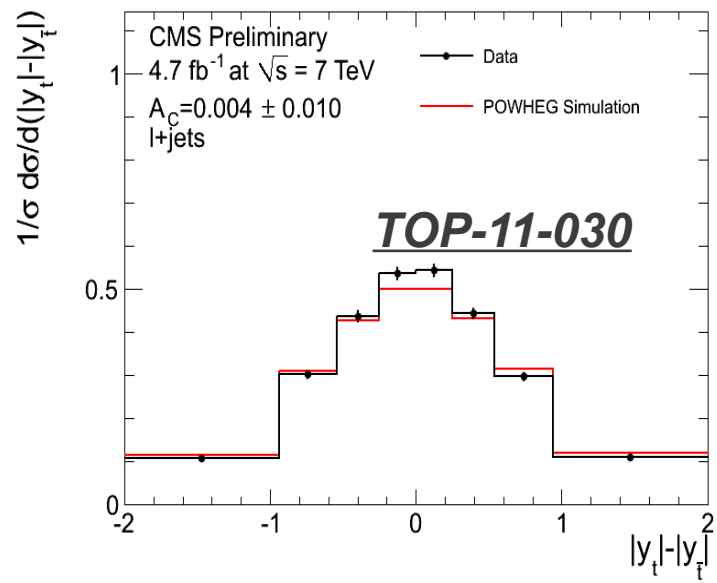


$$\frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$\Delta y = |y_t| - |y_{tbar}|$

- Use ℓ+jets events.
- **The measurement is based on the full reconstruction of the four momentum of the top quarks** in each events used to obtain the inclusive and differential distribution of Δy.
- **Data driven technique in used to estimate the multijet BKG** (discriminating power of M3 and MET are exploited), while the other BKGs are taken from simulation.
- **Results are unfolded for acceptance, efficiencies, BKG contributions** in order to be able to compare the results with the theoretical prediction.

Uncorrected	0.003 ± 0.004 (stat.)
BG-subtracted	0.001 ± 0.005 (stat.)
Final corrected	0.004 ± 0.010 (stat.) ± 0.012 (syst.)
Theory prediction (SM)	0.0115 ± 0.0006



Unfolded inclusive Δy distribution

Charge Asymmetry (2)

- In many new physics scenarios **the charge asymmetry depends on phase space**
- Measurerement of **differential AC as a function of pT, rapidity or invariant mass** of the top pair system.

- As for the inclusive measure we count the number of events with $\Delta y>0$ and $\Delta y<0$, but f**or differential measurements asymmetries are calculated separately for the different bins** in the differentiating variable Vd.

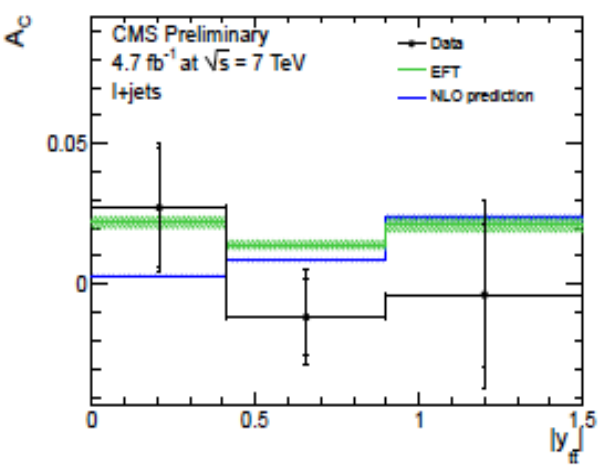
- **Results unfolded like for the inclusive measure**. Here the migration matrix keep in to account also migration between bins of Vd.

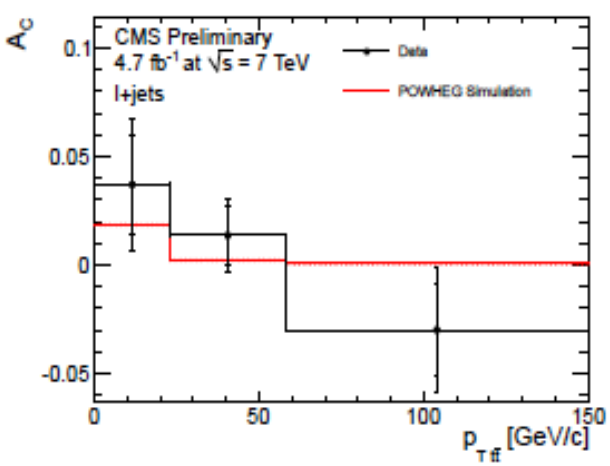
- **Good agreement found between data and SM expectations within uncertainties**

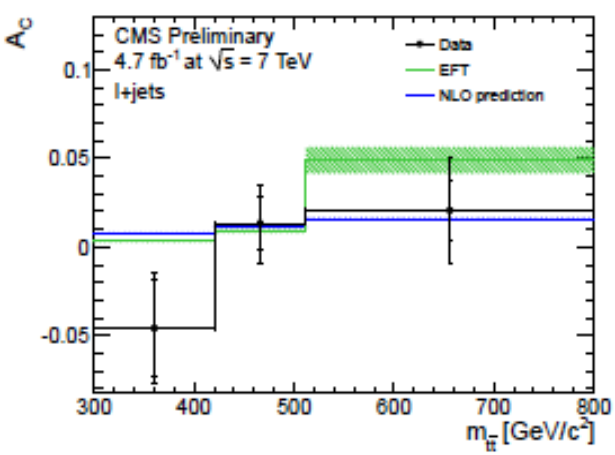
- Main systematics errors are given by the unfolding itself and lepton ID efficiency

- Results also compared with EFT predictions which are able to explain the results from Tevatron.

TOP-11-030







Conclusions

- Thanks to the excellent performance of the LHC and of CMS, top-antitop production cross section has been measured in almost all decay channels.

- The results have already reached a precision comparable with the theoretical predictions.

- The differential cross section in dilepton and lepton + jets channels have been measured for the first time at 7 TeV, showing agreement with theoretical predictions with present statistics

- No hints of new physics yet...Ready to jump on the 8 TeV data to search for evidence for new physics.

Needed ingredient to reconstruct the Top final states

All physics objects are essential for top physics:

Jet and particles are reconstructed with Particle Flow in CMS:

Lepton Id: (e,μ,τ)

*Muon p_T resolution for top is 1-2%

*ECAL resolution ~1% for top

*Excellent ID capabilities: use redundancy of sub- detectors for muons and Shower shapes, H/E, conversion vetoes for electrons.

*HPS algorithm for Tau ~45% efficienct.

B-tagging: Jets defined with anti-kT algorithm with R=0.5

*JEC uncertainty via γ/Z+jets, ≤2% for most of the pT range

*JER about 10%

b-tagging is optionally applied

*Uses secondary vertices and/or IP information

*Efficiencies and fake rates are calibrated by using data

MET reconstruction:

*Resolution vastly improved by the Particle Flow