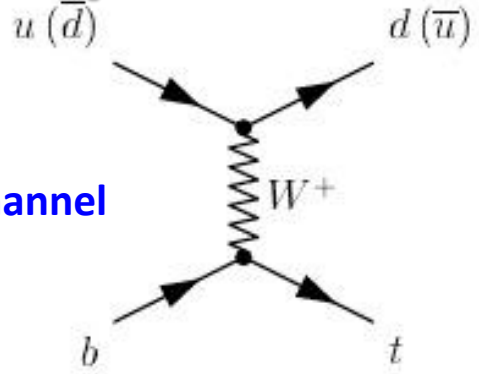
Top Quark Couplings: Experiment

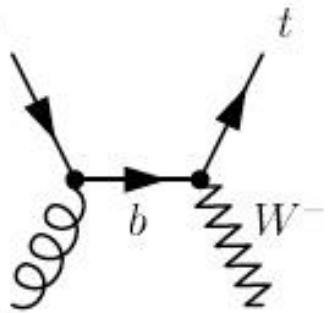
LHC and Tevatron

- Tevatron = **Top discovery** machine
  - 1.96 TeV proton-antiproton machine
  - In some of the results presented Tevatron still holds the first place
- LHC = **Top factory**
  - **7, 8 and beyond (design energy 14) TeV**
  - In 7 and 8 TeV operation delivered **~2** orders of magnitude more top quarks than at the Tevatron
    - Sensitive to some of the top couplings already, and need more energy / data to get more
- Reference document for the presentation
  - http://www.snowmass2013.org/tiki-download_file.php?fileId=40

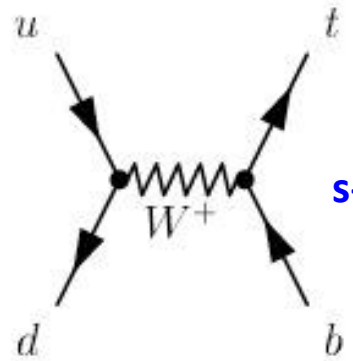
Top Quark Weak Interaction Measurements



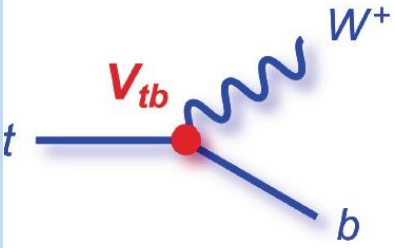
t-channel



Wt production



s-channel

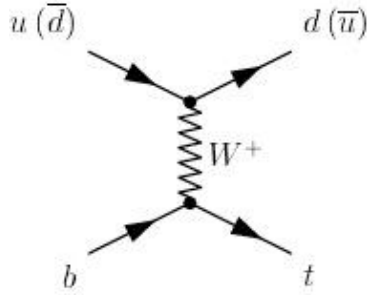


E_{CM} [TeV]	t-channel	Wt-channel	s-channel
1.96	2.10 ± 0.19 pb	0.22 ± 0.08 pb	1.05 ± 0.07 pb
7	$64.57^{+3.32}_{-2.62}$ pb	$15.74^{+1.34}_{-1.36}$ pb	$4.63^{+0.29}_{-0.27}$ pb
8	87.8 ± 3.4 pb	22.4 ± 1.5 pb	5.6 ± 0.3 pb

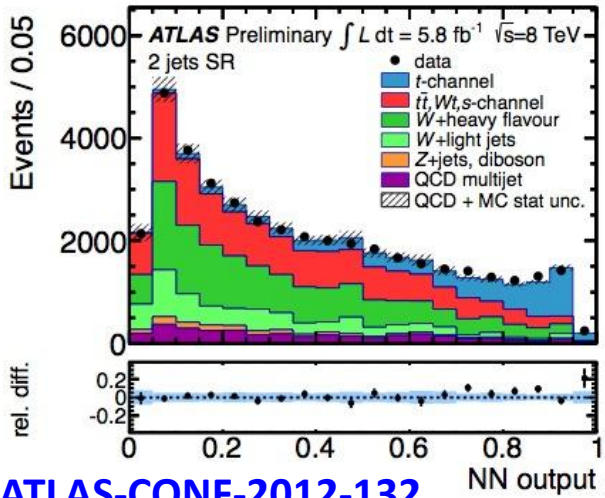
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- The top-quark can be produced singly by an electroweak **Wtb**-vertex
- Motivation
  - Complementary information on top-quark properties
  - Direct measurement of the CKM matrix element $\mathbf{V_{tb}}$
  - Sensitive to many models of new physics
  - Information on the **b-quark PDF**

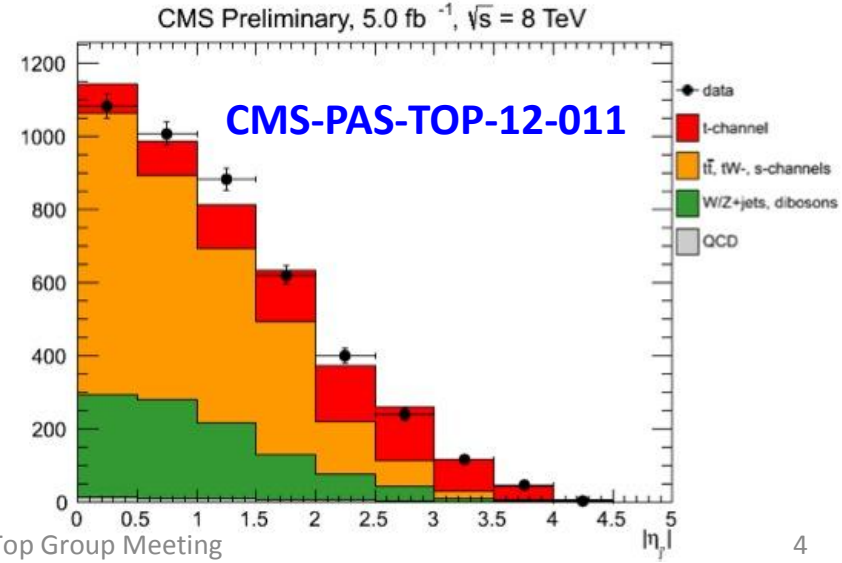
Single top: t-channel



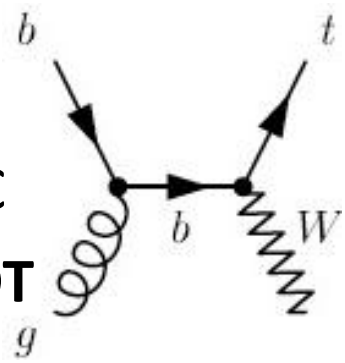
- Method
  - **ATLAS**: binned maximum likelihood fit to the NN output distribution
  - **CMS**: eta distribution of the recoil jet
- Measurement
  - **ATLAS**: **95 ± 18 pb, V_{tb} = 1.04 +0.10/-0.11**
  - **CMS**: **80.1 ± 5.7(stat) ± 11.0(syst) ± 4.0(lumi) pb, V_{tb} > 0.81 @ 95% CL**
- Dominant Systematics
  - **ATLAS**: Jet Energy Scale (**JES**), **b-tagging**, and **ISR/FSR**
  - **CMS**: **statistical**, **JES**, **t-chan generator**



ATLAS-CONF-2012-132

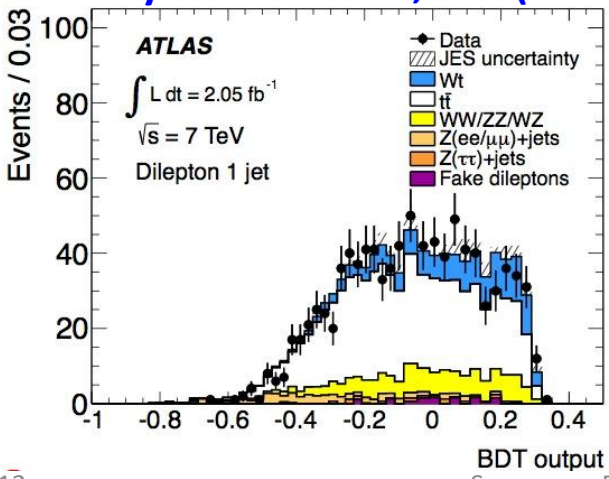


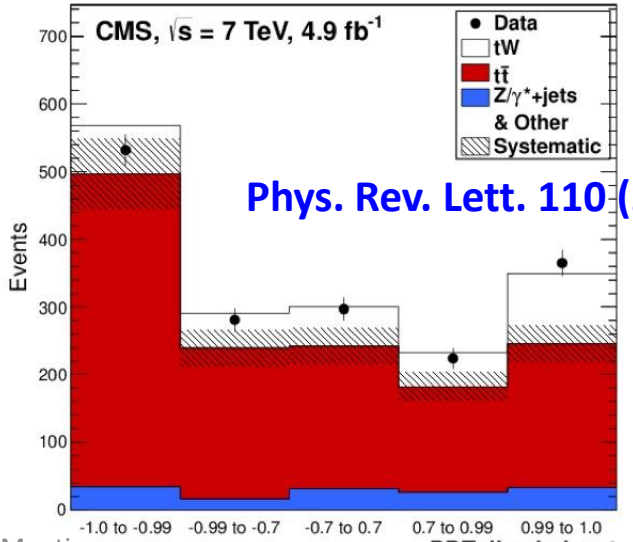
Single top: Wt-channel



- Negligible @ Tevatron, 2nd highest single top xsec @ LHC
- **Evidence** for **Wt** @ **7** TeV (both used **Template fit to a BDT output)**
  - **ATLAS**: **3.3** sigma, 16.8 **± 2.9(stat) ± 4.9(syst) pb**
  - **CMS**: **4.0** sigma, **16.4 +5/-4 pb**
- Dominant Systematics
  - **ATLAS**: Jet Energy Scale (**JES**), **statistics**, and **ISR/FSR**
  - **CMS**: **JES**, **statistics, factorization/renormalization scale**

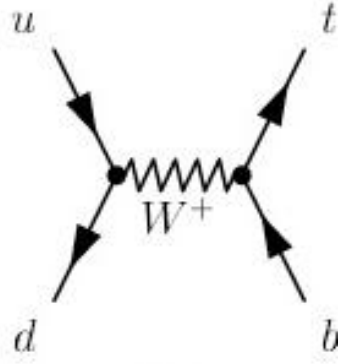
Phys. Lett. B. 716, 142 (2012)





Phys. Rev. Lett. 110 (2013)

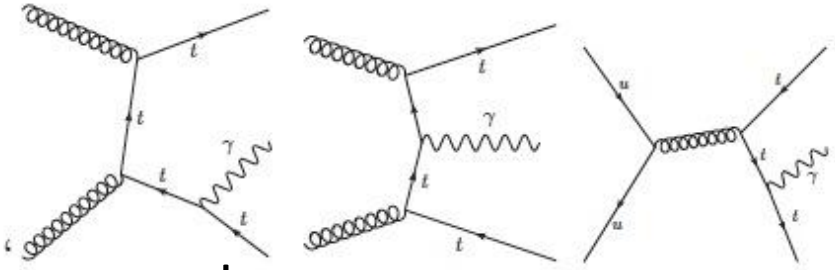
Single top: s-channel



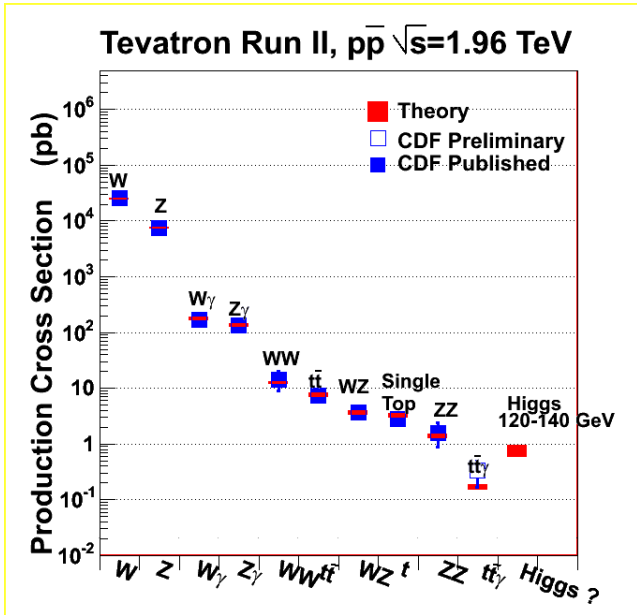
- Negligible @ LHC, 2nd highest single top xsec @ Tevatron
- Measurements from CDF and Dzero
  - Measure xsec for t-channel and s-channel together, then extract the components
  - **CDF**: **1.81 +0.63/0.58 pb, CDF Note 10793**

  http://www-cdf.fnal.gov/physics/new/top/confNotes/cdf10793 SingleTop 7.5 public.pdf
  - **DZERO**: **0.68 +0.38/-0.35 pb, Phys.Rev. D84 (2011) 112001**
- Dominant Systematics
  - **CDF**: background normalization
  - **DZero**: **JES**, JER, corrections to b-tagging efficiencies, and the correction for jet-flavor composition in W+jets events

ttbar + Photon



- Sensitive to top charge and to top-photon couplings
  - Need to identify photons coming from top
    - Suppress photons from W, leptons, jets (gg fusion ttbar production dominates @LHC => less ISR QED)
- Control sample / Background to ttbar + Higgs, Higgs to diphoton
- For now can only measure the cross section
  - **CDF**: first evidence of ttbar + photon production (using **6 fb^{-1}** of data)
    - Dominated by stat. uncertainty
  - **ATLAS**: preliminary measurement with **1 fb^{-1}** (but still below 3 sigma significance)
    - Dominated by systematics: photon ID, ISR/FSR, jet energy scale

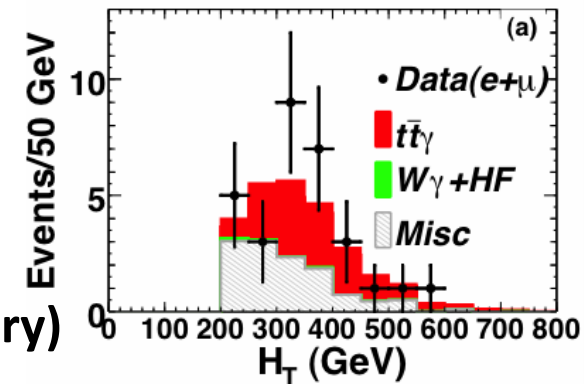


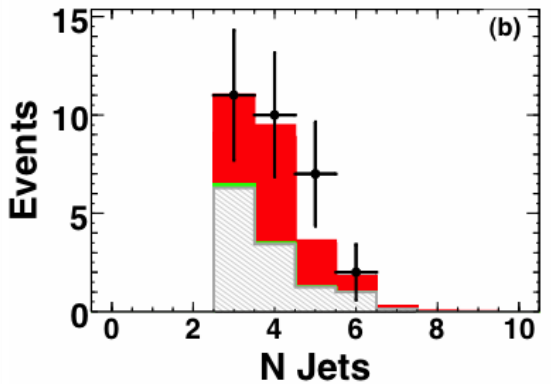
ttbar + Photon: Results

CDF, **Phys.Rev.D84:031104,2011**

$$\sigma_{t\bar{t}\gamma} = 0.18 \pm 0.08 \text{ pb}$$

$$\sigma^{total}_{t\bar{t}\gamma} = 0.17 \pm 0.03 \text{ pb}$$ **(Theory)**

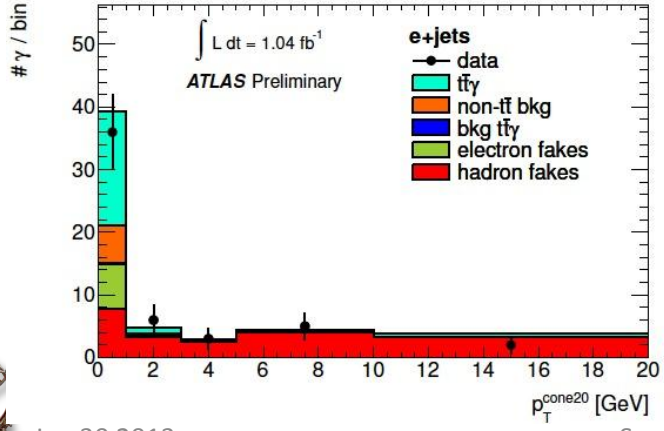


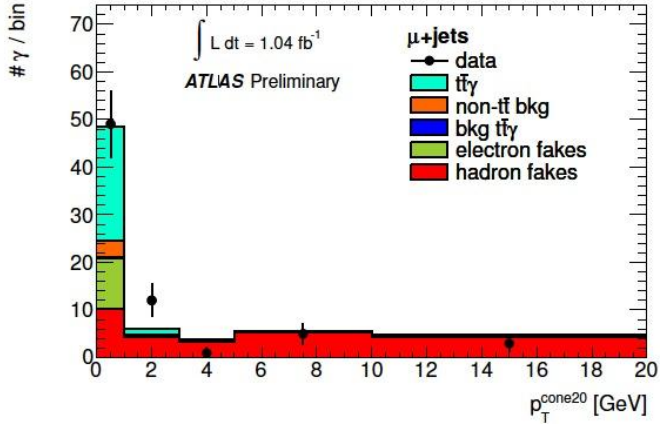


ATLAS, **ATLAS-CONF-2011-153**

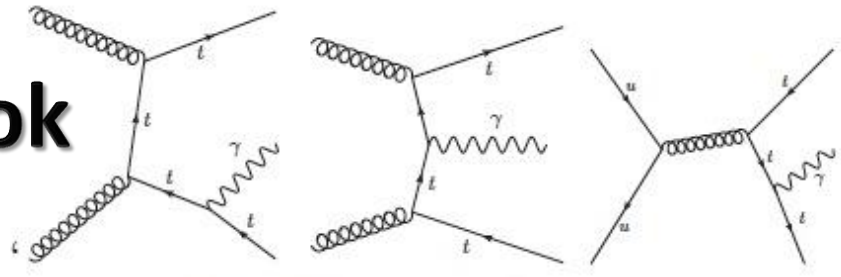
$$\sigma_{t\bar{t}\gamma} = 2.0 \pm 0.5\,(stat.) \pm 0.7\,(syst.) \pm 0.08\,(lumi.) \text{ pb}$$

$$2.1 \pm 0.4 \text{ pb}$$ **(Theory)**



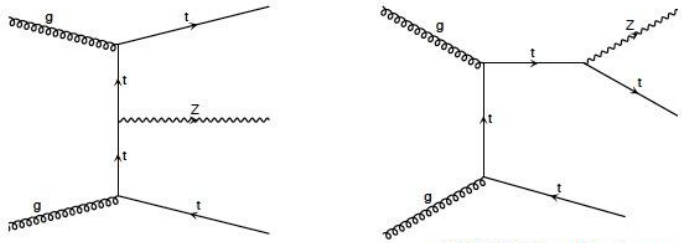


ttbar + Photon: Outlook



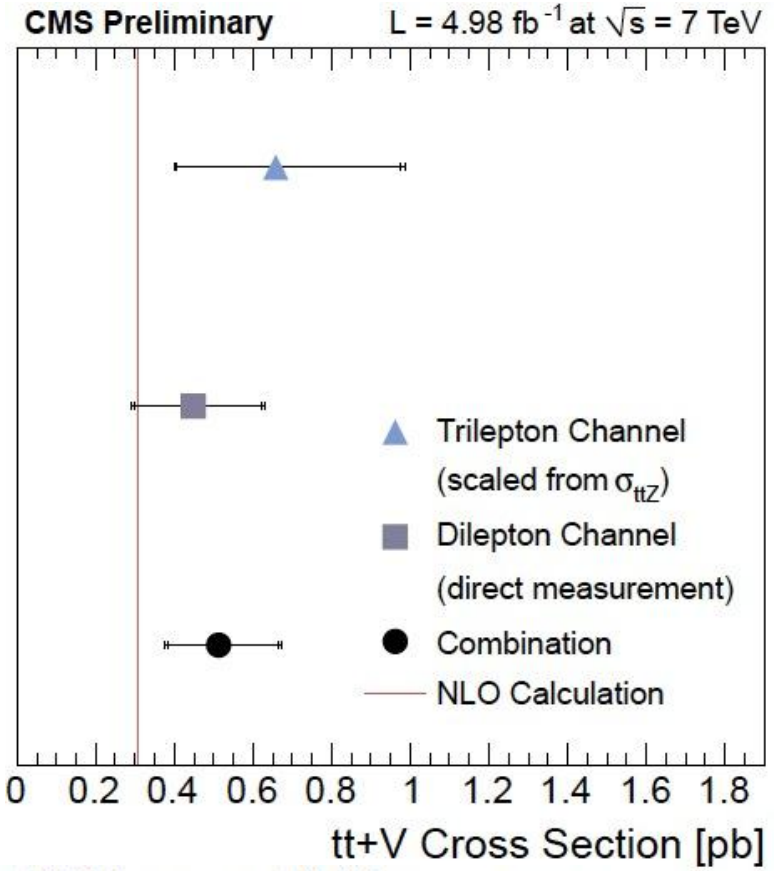
- With current 2011 / 2012 data
  - Should be able to measure ttbar + photon cross section with 5+ sigma significance
  - Can play around with ΔR (photon, X) cuts to isolate photons coming from top, **Phys.Rev. D71 (2005) 054013**
- **7** -> **14** TeV: LO cross section increases by a factor of **5** **(MadGraph,** photon p_T > **20** GeV**)**
  - **300 fb^{-1}**: few thousands events expected => can go for couplings measurement, **Phys.Rev. D71 (2005) 054013**
    - In both lepton + jets and dilepton channels
  - **3000 fb^{-1}**: differential measurements (couplings as a function of photon p_T etc)

ttbar + Z



CMS-PAS-TOP-12-014

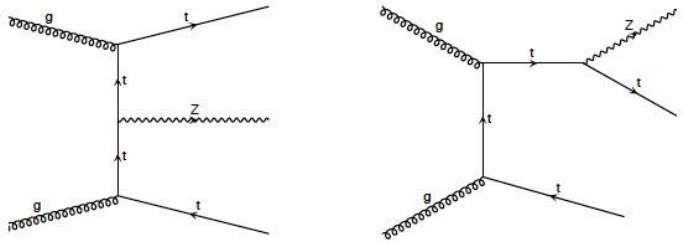
- ttbar + Z production is directly sensitive to ttZ couplings
- For now can only measure the cross section
  - **CMS**: first evidence of ttbar + Z production as well as ttbar + V cross section measurement
    - **Dominated by stat. uncertainty**
  - **ATLAS**: generic ttbar + Z selection, hence not sensitive. Set a limit for the production **xsec < 0.71 pb**
    ATLAS-CONF-2012-126



$$\sigma_{t\bar{t}Z} = 0.30^{+0.14}_{-0.11}(stat)^{+0.04}_{-0.02}(syst)\ \text{pb}$$

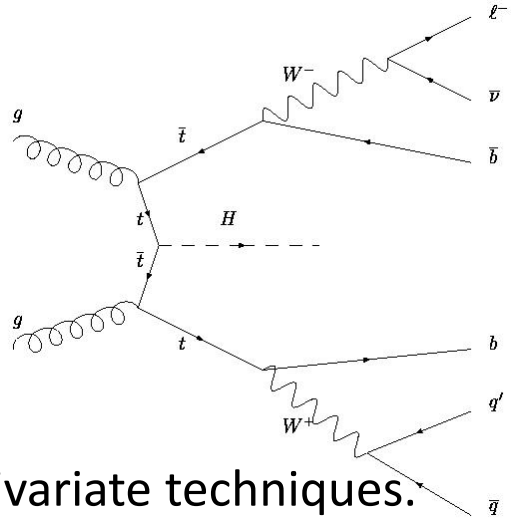
$$\sigma_{t\bar{t}V} = 0.51^{+0.15}_{-0.13}(stat)^{+0.05}_{-0.04}(syst)\ \text{pb}$$

ttbar + Z: Outlook



- With current 2011 / 2012 data
  - **7** -> **8** TeV: ttZ LO cross section increases by a factor of **1.4** (**MadGraph**)
    - Stat. uncertainty will decrease by a factor of **2.5**
    - Still **limited by statistics**
- **7** -> **14** TeV: LO cross section increases by a factor of **10** (**MadGraph**)
  - **300 fb^{-1}**: ttZ axial (vector) couplings can be determined with an uncertainty **45-85%** (**15-20%**), **Phys.Rev. D71 (2005) 054013**
  - **3000 fb^{-1}**: a factor of **3** better

ttbar + Higgs



- ttbar + Higgs => square of top Yukawa coupling
  - One of the key points of Higgs physics program
- **Tevatron (CDF)**
  - Searches in lepton + jets and all-hadronic channel. Multivariate techniques.
  - **Lepton+jets**: Observed (expected) limit = **20.5 (12.6) x SM**

    Phys.Rev.Lett. 109 (2012) 181802
  - **0-lepton**: Observed (expected) limit = **36.2 (26.2) x SM**

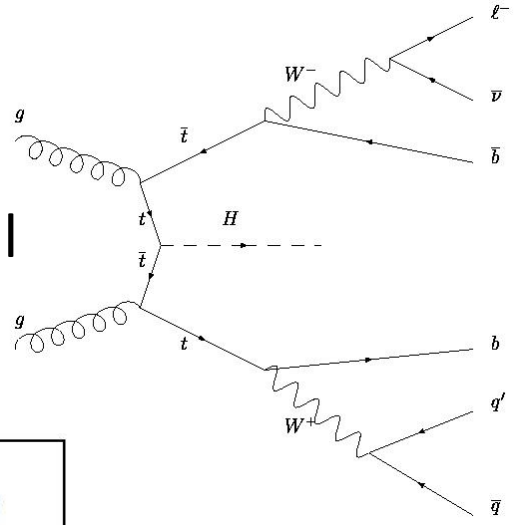
    CDF note 10582

    http://www-cdf.fnal.gov/physics/new/hdg/Results_files/results/tthNoLepton_110708/
- **LHC**
  - **CMS**: analyzed both **dilepton** and **lepton + jets** channels:

    observed (expected) limit **4.6 (3.8) x SM, CMS-PAS-HIG-12-025**
  - **ATLAS**: analyzed **lepton + jets** channel:

    observed (expected) limit = **13.1 (10.5) x SM, ATLAS-CONF-2012-135**

ttbar + Higgs: Outlook



- Will profit from increased energy, statistics, as well as better understanding of backgrounds: ttbar + bbbar, ttbar + (di)photon

$gg \to H$
$qq \to qqH$
$gg \to t\bar{t}H$
$qq' \to VH$

$\longleftrightarrow$ $g_{HXX} = g^{SM}_{HXX}\ (1 + \Delta_X)$ $\longleftrightarrow$

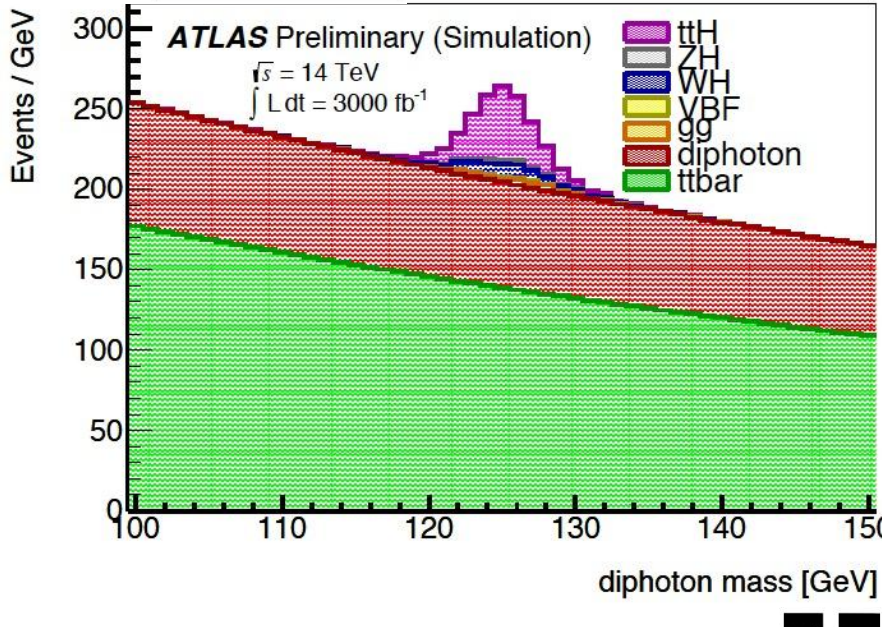
$H \to ZZ$
$H \to WW$
$H \to b\bar{b}$
$H \to \tau^+\tau^-$
$H \to \gamma\gamma$

- ATLAS:

  Higgs partial widths ratio (Γt/Γg) measurement precision to better than **55**% (**25**%) with **300** (**3000**) **fb^{-1}**,

  ATL-PHYS-PUB-2012-004

  – ttbar+Higgs, Higgs -> **diphoton/dimuon**



Jet Multiplicity in Top Pair Events

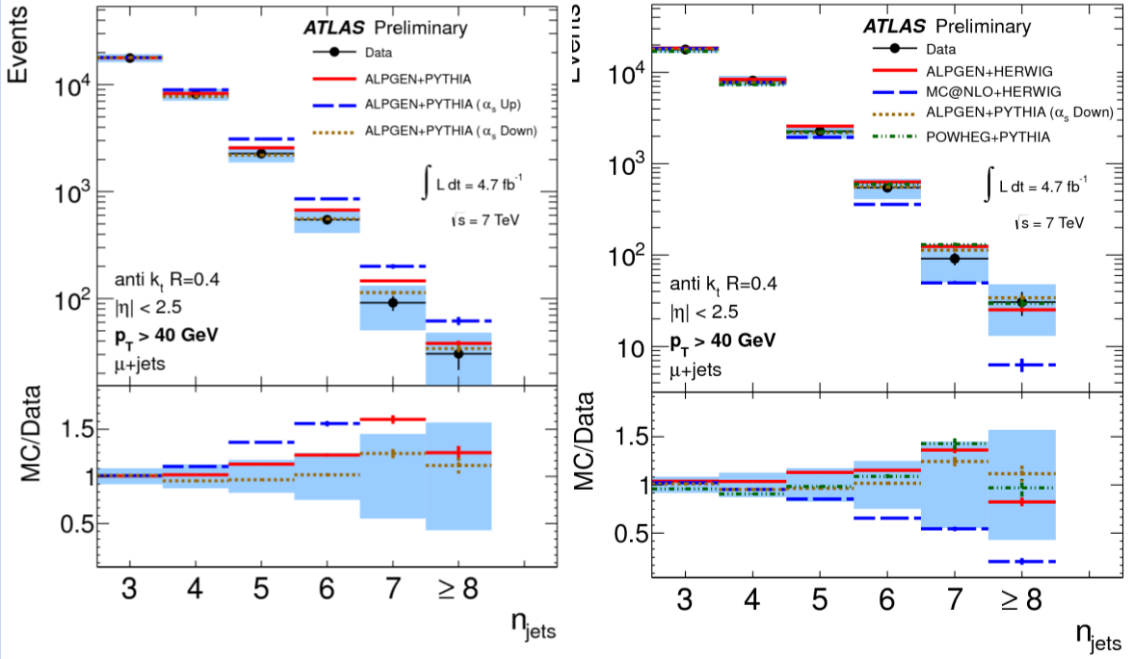
- Motivation
  - **Constrain** ISR/FSR models at the scale of the top quark mass
  - **Test** perturbative QCD in the LHC energy regime
- Lepton + Jets channel (ATLAS), Dilepton channel (CMS)
  - Jet multiplicities as a function of jet p_T thresholds:
    - **ATLAS: 25**, **40**, **60** and **80** GeV, **ATLAS-CONF-2012-155**
    - **CMS: 30** and **60** GeV, **CMS-PAS-TOP-12-023**
  - Subtract backgrounds and **unfold to particle level**
    - Account for detector efficiencies, resolution effects and biases
  - **Dominated by systematics in all regions**
  - **Compare** to various Monte Carlo simulation models
    - ALPGEN+HERWIG
    - ALPGEN+PYTHIA (α_s-down and α_s-up variations)
    - MC@NLO+HERWIG
    - POWHEG+PYTHIA
    - MadGraph + PYTHIA

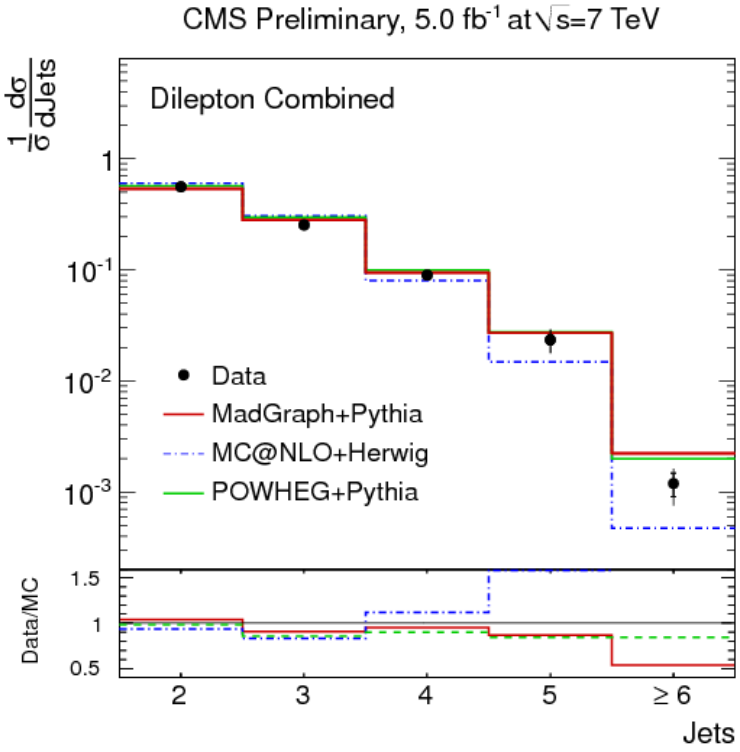
Jet Multiplicity in Top Pair Events: Unfolded

ATLAS-CONF-2012-155

ATLAS Disfavored:

- **MC@NLO + Herwig**
- **ALGPEN+Pythia with α_s-up variation**





CMS-PAS-TOP-12-023

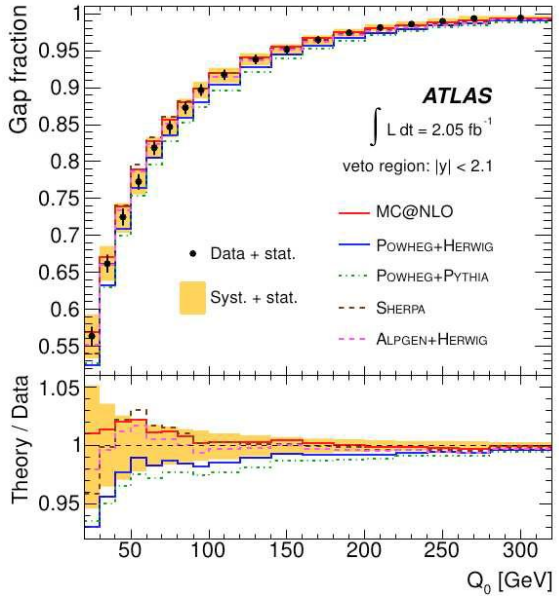
CMS Disfavored:

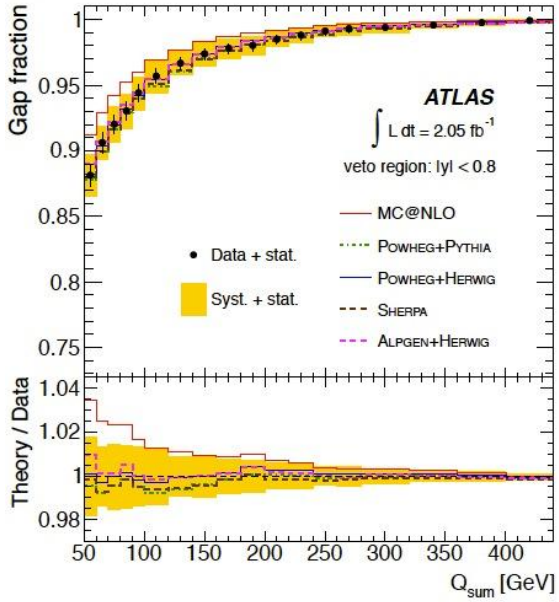
- **MC@NLO + Herwig**

arXiv:1203.5015

ttbar with Jet Veto: ATLAS

- **Gap fraction** f(x) = n(x)/N
  - **N** is the **total number** of selected ttbar events
  - **n(x)** is the **N (ttbar events with additional jet veto)**
    - **x = Q_0**: no additional jets with $p_T > Q_0$ in a rapidity interval (CMS calls the variable p_T)
    - **x = Q_{sum}**: the scalar sum of the additional jets' p_T in the rapidity interval < Q_{sum} (CMS calls the variable H_T)
- Senstive to
  - ISR / FSR
  - Effects of different shower models
  - Higher order effects of different generators
- Conclusions (ATLAS, **lepton + jets** channel)
  - **MC@NLO underestimates** the data in the central region |y| < 0.8
  - All models describe data in the full |y|<2.1 veto interval, but **tend to predict too much jet activity**

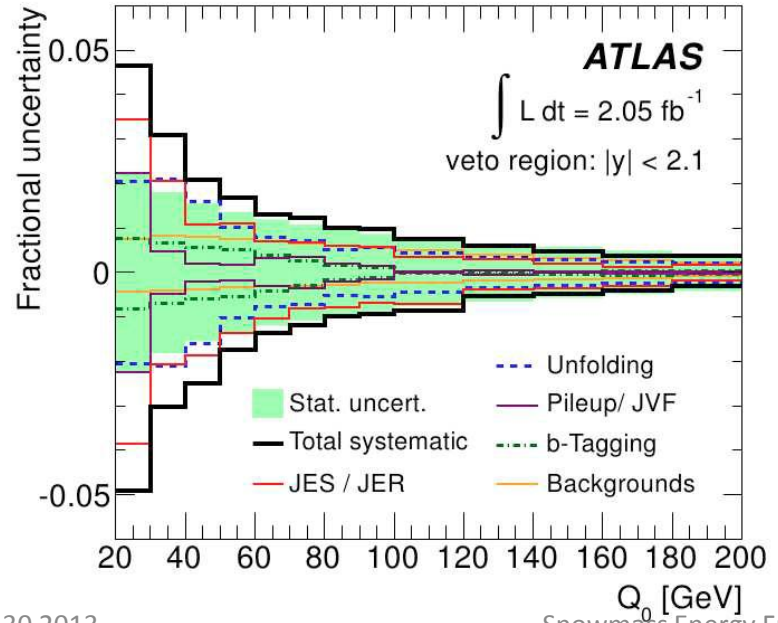


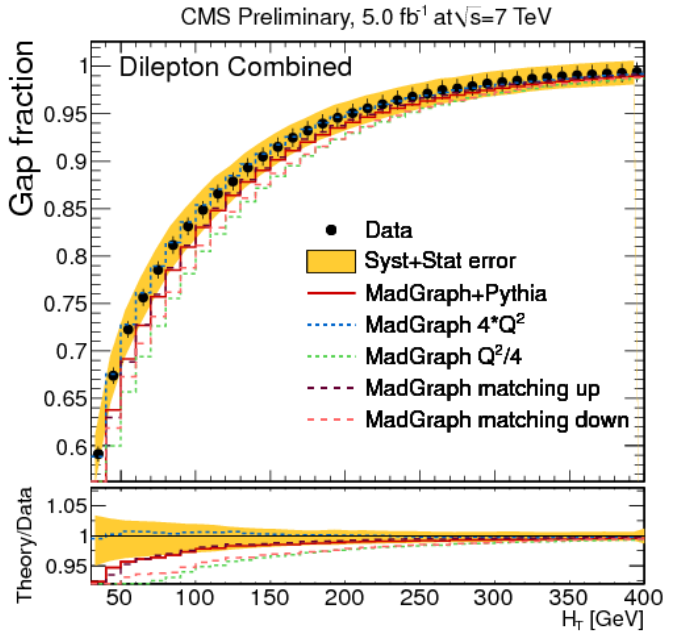


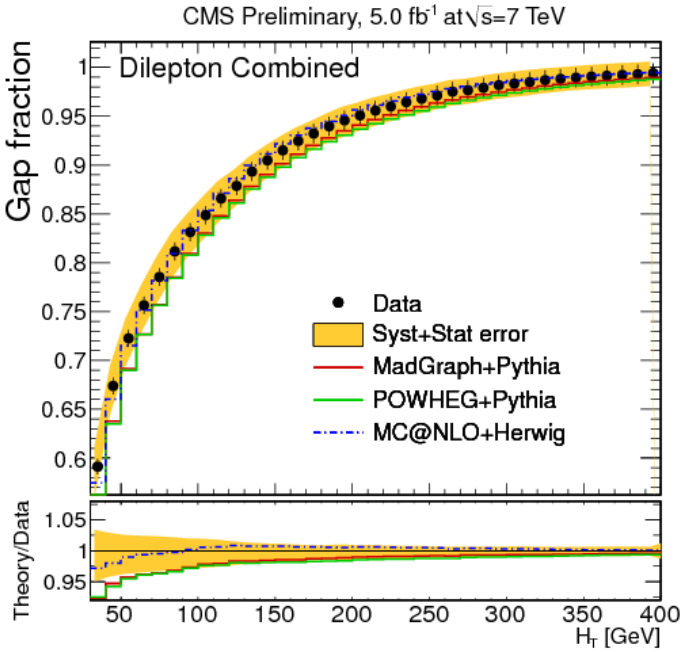
CMS-PAS-TOP-12-023

ttbar with Jet Veto: CMS

- Conclusions (CMS, **dilepton** channel)
  - **MC@NLO** gives the **best prediction**
  - **Increasing Q^2 scale in MadGraph** improves the data/MC agreement
- Overall comment
  - Already **dominated by systematics** both for ATLAS and CMS
  - With more data can go into more details

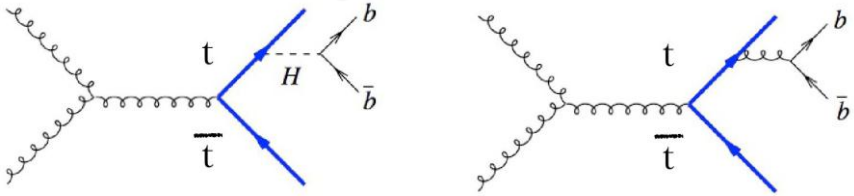


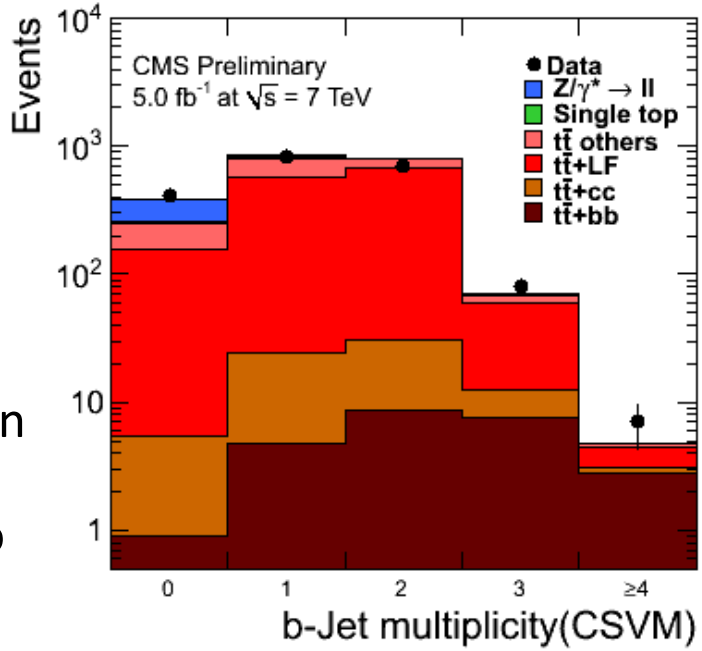




CMS-PAS-TOP-12-024

ttbar+jets HF Composition: CMS





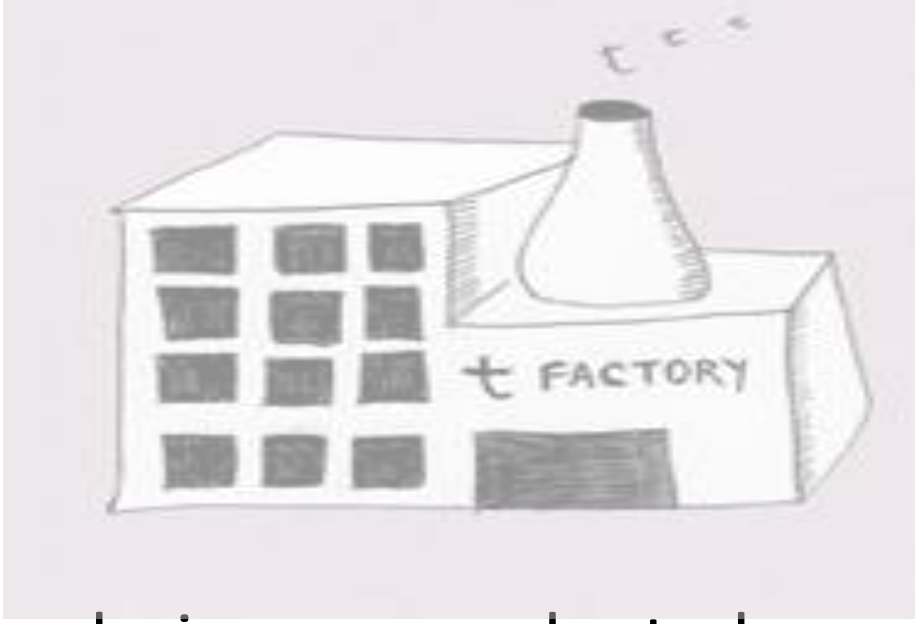
- **Motivation:**
  - ttbar+Higgs is important channel for measurement of top quark to Higgs boson coupling
  - Irreducible background from ttbar in association with bbbar as predicted by higher order QCD
  - Measure cross section ratio for uncertainties to cancel, e.g. luminosity, jet and lepton efficiencies
- **Method:**
  - Fit to the b-tagged jet multiplicity distribution
- **Dominant Systematic Uncertainties:**
  - b-tag scale factor (**18%**), Q2 scale (**6%**), MC (**3%**)

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 3.6 \pm 1.1(stat.) \pm 0.9(sys.)\%$$

Top quark + jets: Outlook

- More statistics / more energy
  - Detailed understanding of top pair production with jets
    - Reduce systematics – report ratios of multiplicites
    - Finer binning (as stat.uncertainty is not an issue)
  - Feedback to theory community
  - Better precision SM predictions for beyond-the-SM searches
- For rare processes (ttbar + Heavy Flavor)
  - More statistics will help
  - Can measure ccbar and bbbar separately
  - Expect input from theory community
    - NLO calculation is challenging…

Summary / Outlook



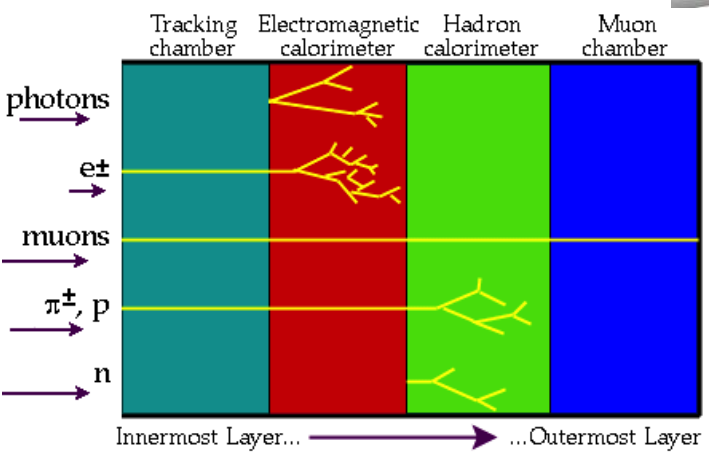
- **LHC** keeps providing top quarks in unprecedented quantities
- **Precision** measurements, **detailed** studies, improving of **understanding** of the heaviest known particle and its properties
- We will learn a lot in the years to come…
  - …if we better plan it, we will learn even more ;)

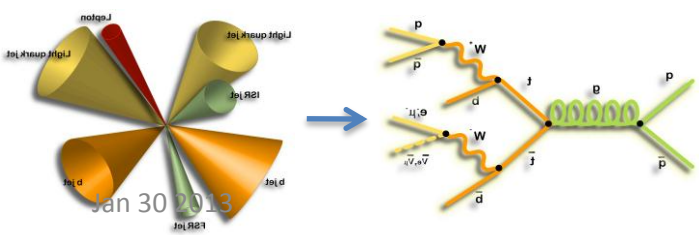
Top pair production at ATLAS

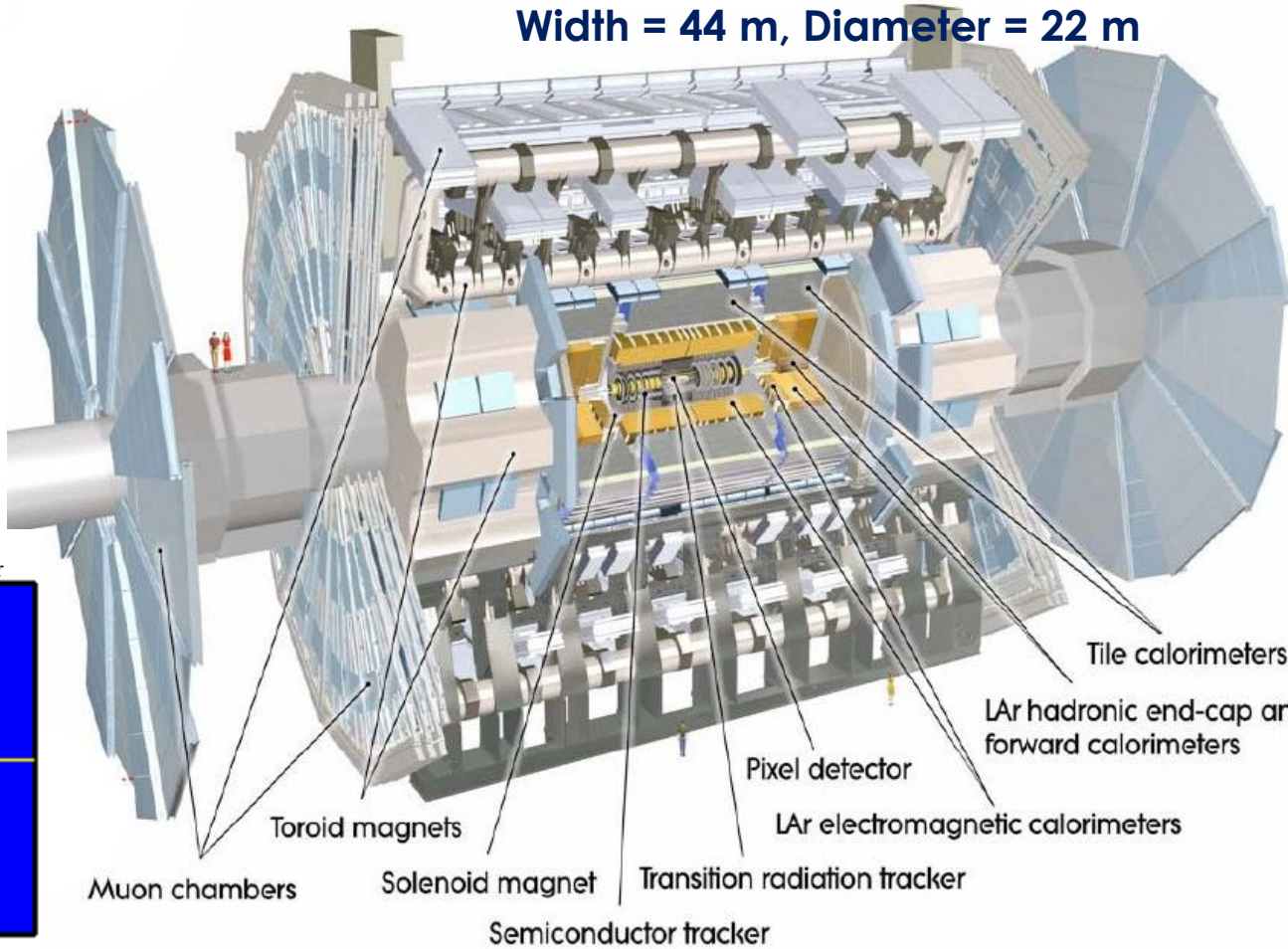
LHC / ATLAS

Large HaΔRon Collider

- p-p collider
- Center of mass energy
  - √s = 7 TeV @ 2010-11
  - √s = 8 TeV @ 2012
  - √s = 13-14 TeV @ 2014+
- Multi-purpose experiments:
  ATLAS and CMS



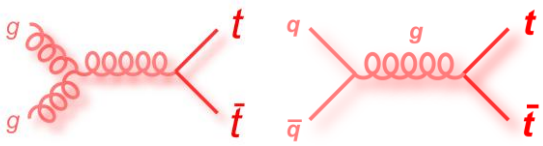




Subdetectors and identified objects:

- Trackers:electrons, muons, jets, taus, photons
- Calorimeters:electrons, muons, jets, taus, photons
- Muon Detectors: muons

Introduction



165^{+11}_{-16} pb

Approx.NNLO, m_{top}=172.5 GeV, 7 TeV pp collisions

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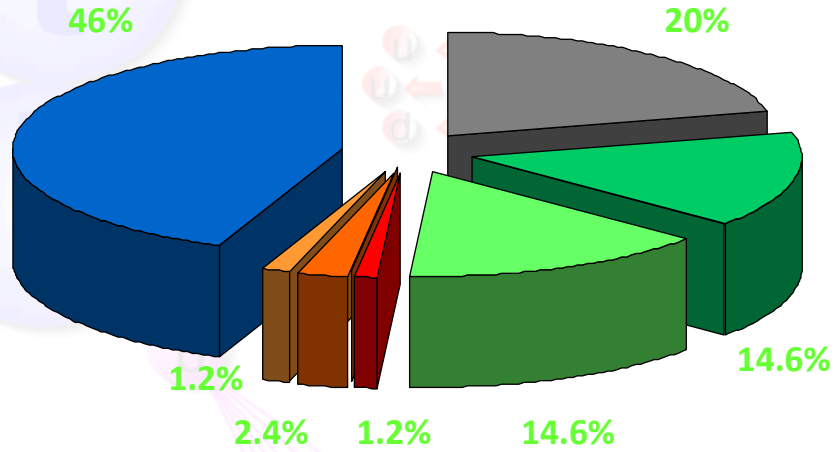
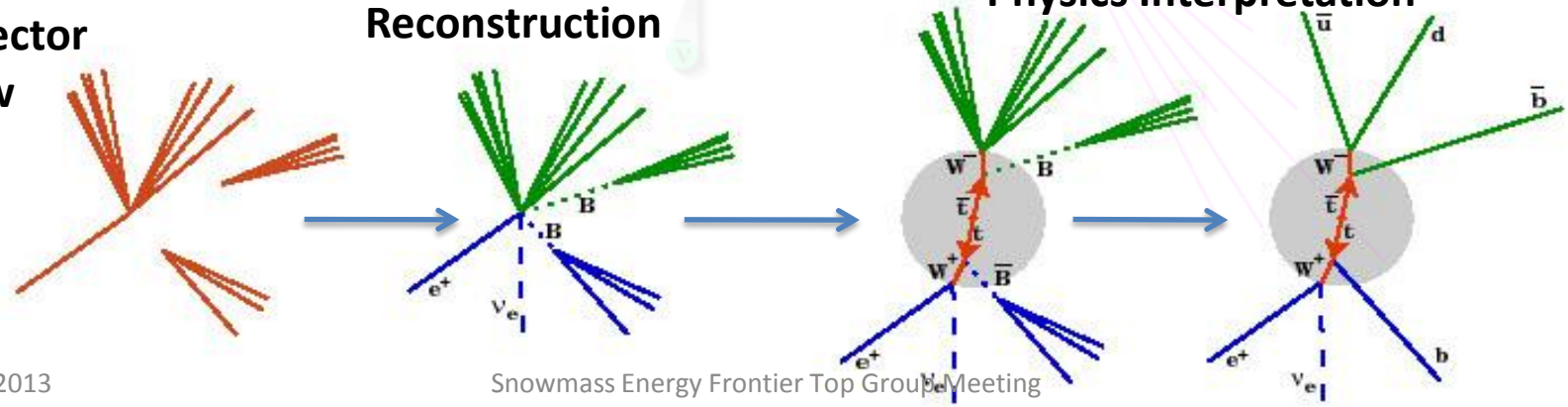
- Top pair production at the LHC through gg (**80**%) and qq̄ (**20**%)
- Top pair decay modes
  - The more jets, the more challenging the systematics get (Jet energy scale, ISR/FSR etc)



Detector View

Reconstruction

Physics Interpretation

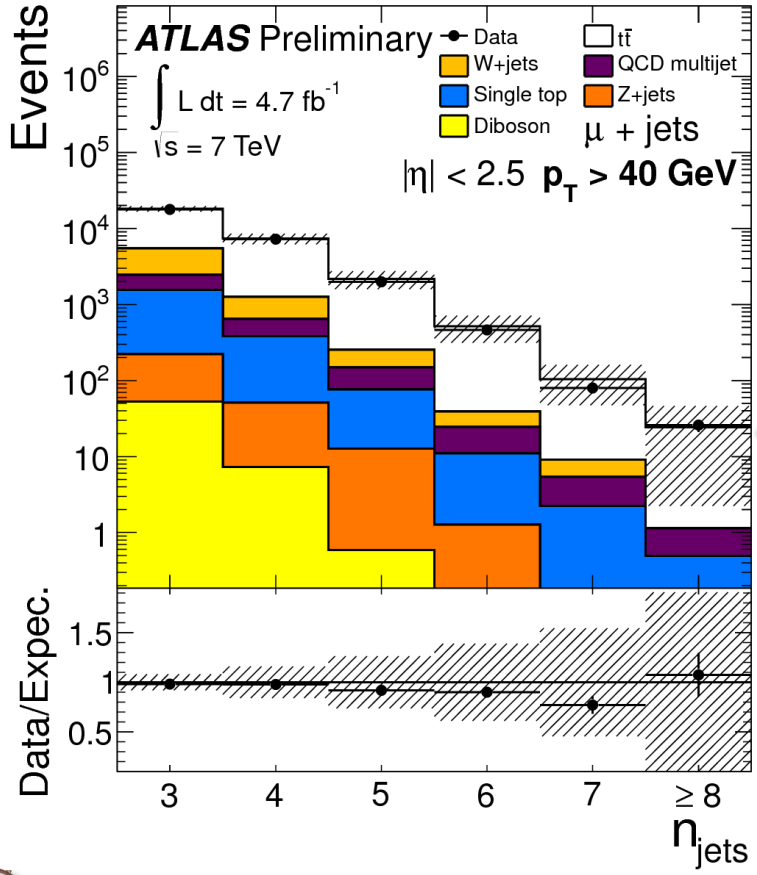


Jet Multiplicity in Top Pair Events: Unfolded

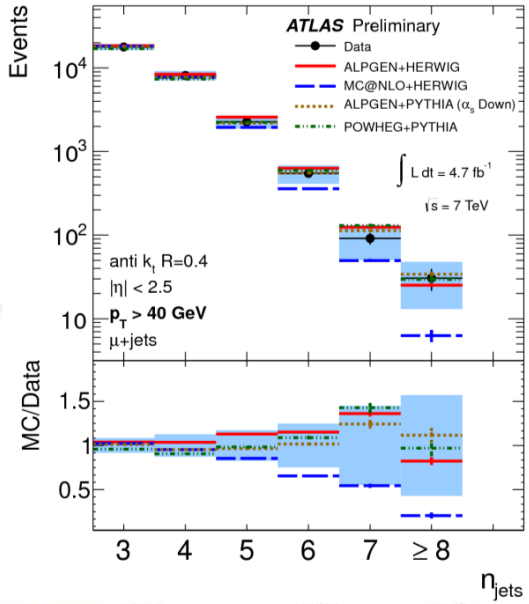
NEW

Disfavored:

- MC@NLO + Herwig
- ALGPEN+Pythia with α_s-up variation



unfold



$$\vec{N}_{\text{part}} = \vec{f}_{\text{part!reco}} \cdot \mathbf{M}^{\text{reco}}_{\text{part}} \cdot \vec{f}_{\text{reco!part}} \cdot \vec{f}_{\text{accpt}} \cdot (\vec{N}_{\text{reco}} - \vec{f}_{\text{bgnd}})$$

unfold