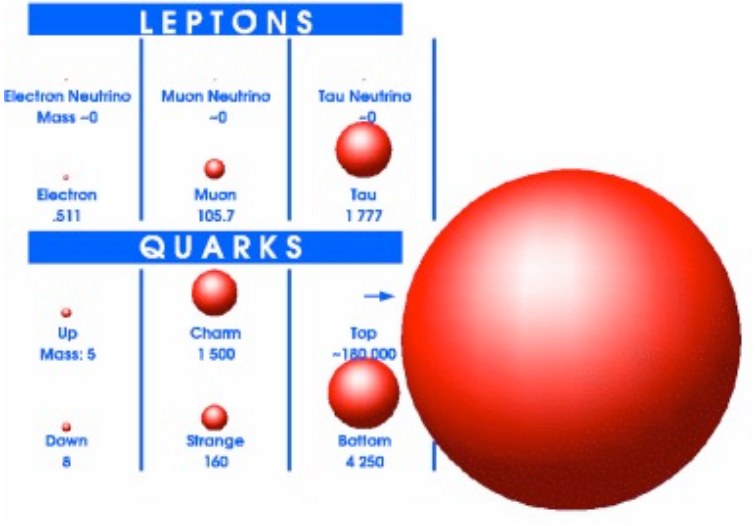
# Top Quark Production

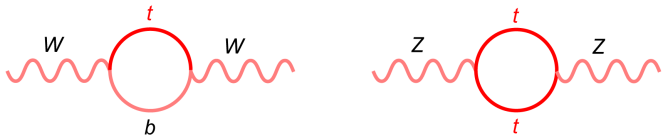
Andreas B. Meyer
PIC, 12 September 2012

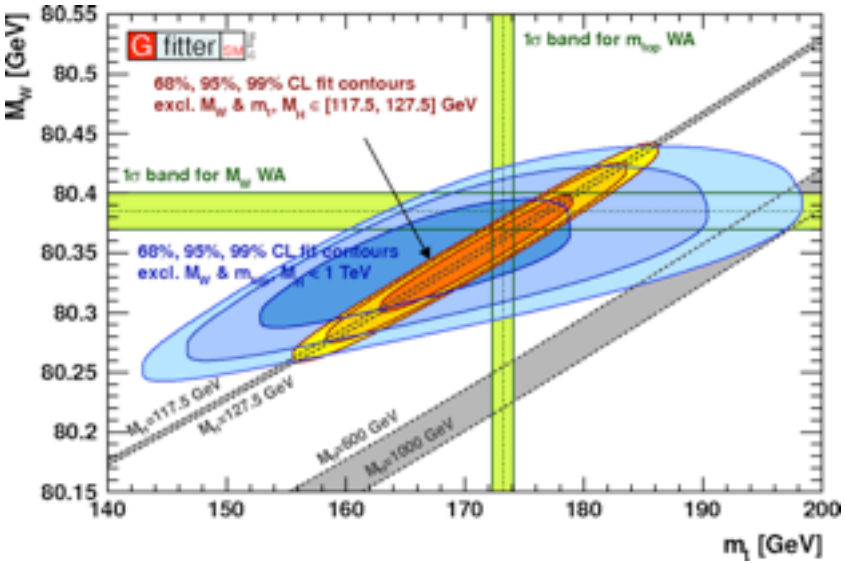
# Motivation

- **Top Quark is special**
  - Heaviest known particle
  - $\tau \sim 5 \times 10^{-25}$ s: decay before hadronization: "bare quark"
  - Maximum sensitivity to Higgs (EWK loops, gg $\longrightarrow$ H)
- **Search for New Physics**
  - New physics might preferentially couple / decay to top
  - Non-standard couplings ?
- **Precision measurements of SM parameters**
  - Total cross sections, differential distributions
  - Properties (mass, spin structure, asymmetries, $V_{tb}$ …)
- **Is the top quark the particle as predicted in the Standard Model ?**

**Precise top quark measurements**
**$\longrightarrow$ sensitivity to QCD, EWK and New Physics**

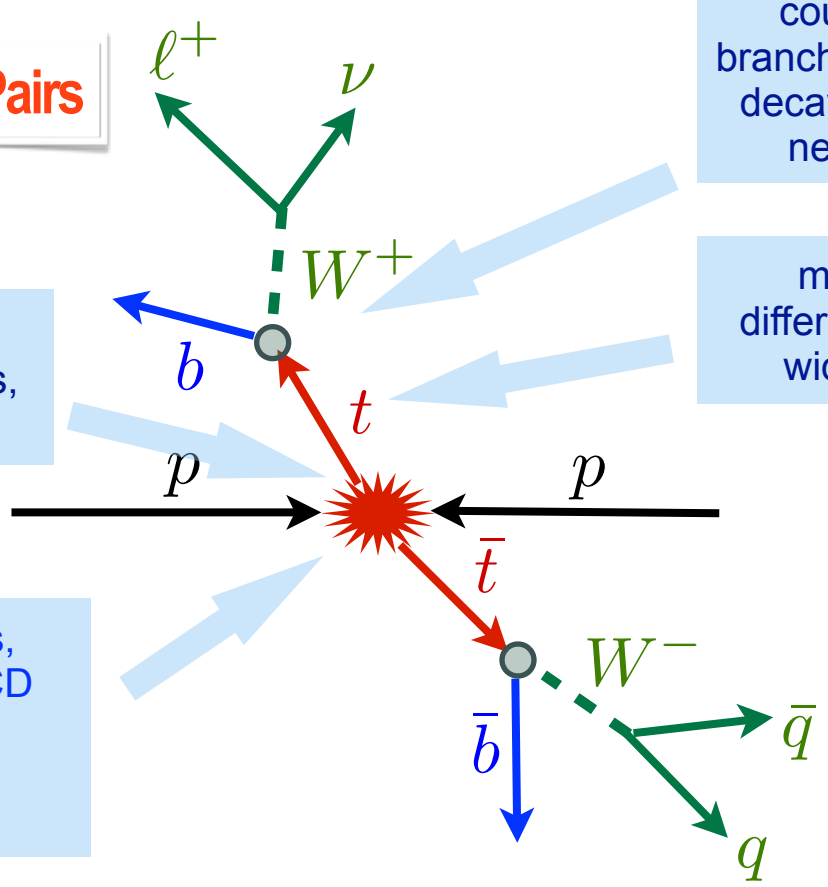


# Top Quark Properties in Production and Decay

**Top Quark Pairs**




couplings, $V_{tb}$, branching ratios, rare decays, W-helicity, new particles

mass, mass difference, charge, width, lifetime

asymmetries, spin correlations, color flow

cross sections, kinematics, QCD parameters, resonances, new particles

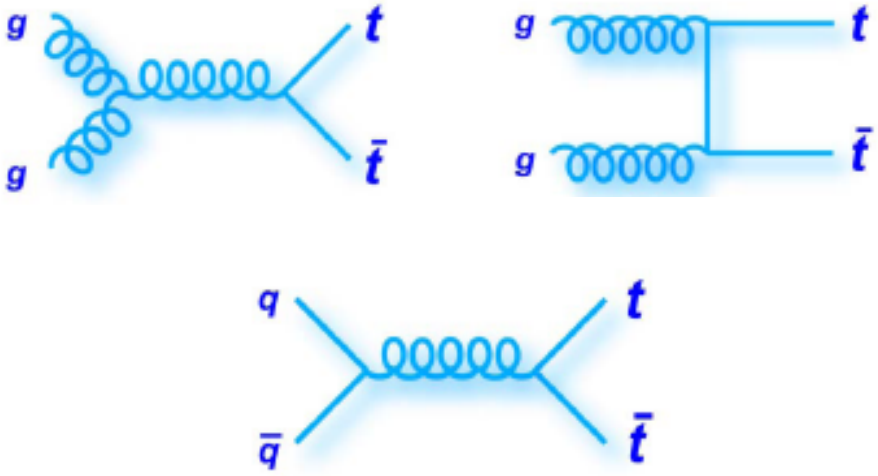
- **three presentations today:**
  - Top Quark Production
  - Charge Asymmetry
  - Top Quark Properties

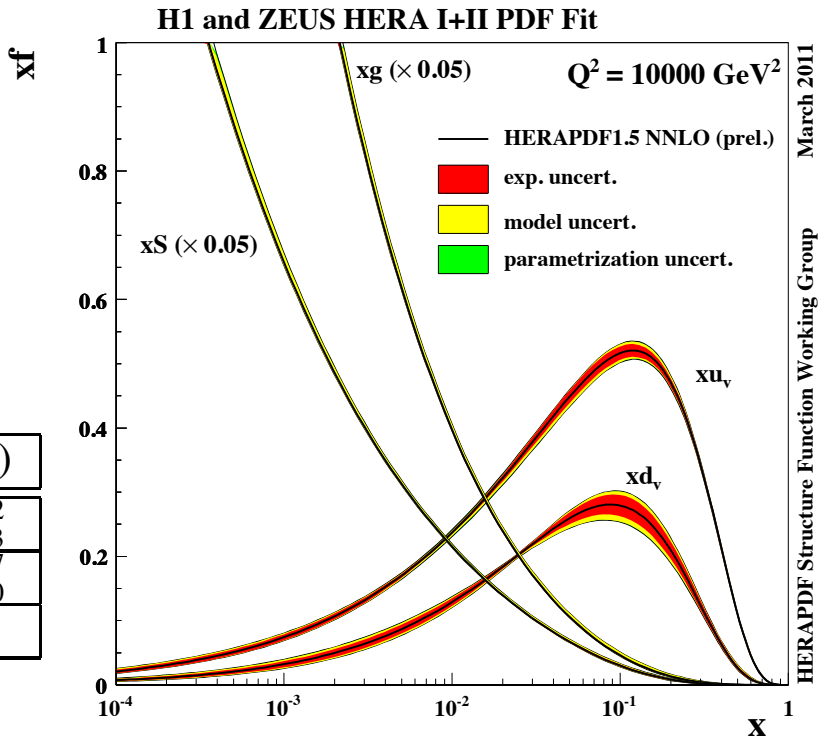
**EWK Single-Top Production**

s,t,tW channel production, properties, couplings

# Top Quark Pair Production

| | LHC (7TeV) | Tevatron |
|---|---|---|
| gg | ~80% | ~15% |
| $q\bar{q}$ | ~20% | ~85% |



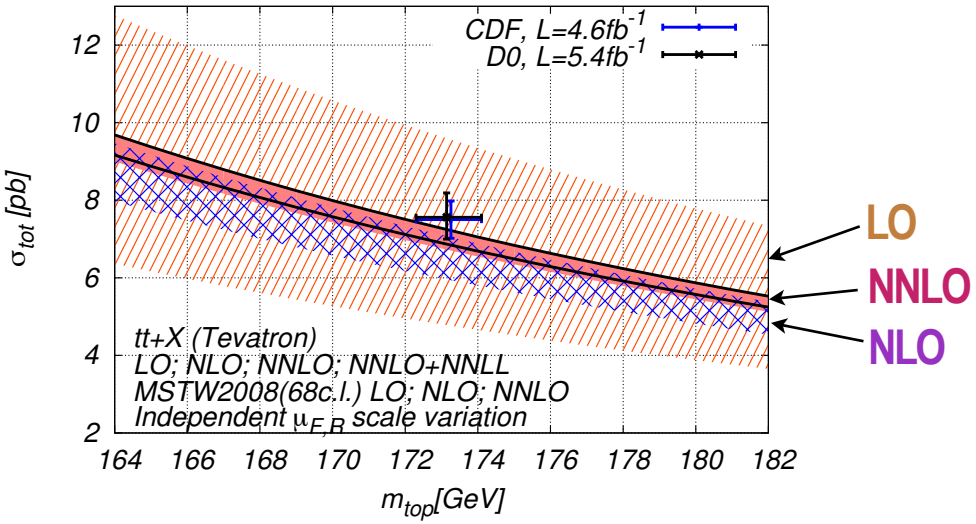

Beneke et al (TOPIXS), arXiv:1208.5578 [hep-ph], 29 Aug 2012

| $\sigma_{tt}$[pb] | Tevatron | LHC (7 TeV) | LHC (8 TeV) |
|---|---|---|---|
| NLO | $6.68^{+0.36+0.23}_{-0.75-0.22}$ | $158.1^{+19.5+6.8}_{-21.2-6.2}$ | $226.2^{+27.8+9.2}_{-29.7-8.3}$ |
| NNLO | $7.00^{+0.21+0.29}_{-0.31-0.25}$ | $160.9^{+11.1+7.2}_{-11.5-6.7}$ | $229.8^{+16.5+9.7}_{-16.7-9.0}$ |
| **NNLL** | $7.15^{+0.21+0.30}_{-0.20-0.25}$ | $162.4^{+6.7+7.3}_{-6.9-6.8}$ | $231.8^{+9.6+9.8}_{-9.9-9.1}$ |

**LHC (gg→tt) complementary to Tevatron (qq→tt)**

# Top Quark Pair Production

Bärnreuther, Czakon, Mitov 1204.5201 [hep-ph]




Beneke et al (TOPIXS), arXiv:1208.5578 [hep-ph], 29 Aug 2012

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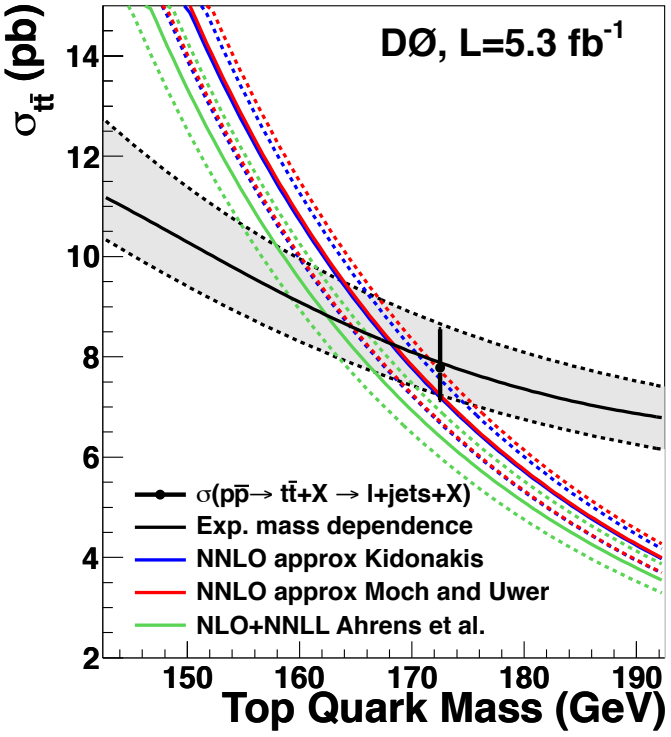
- **Calculations**
  - NLO (+NNLL)
  - approx. NNLO (+NNLL)
  - full NNLO (available for qq)
- **Event generators**
  - NLO+PS
    - MC@NLO
    - POWHEG
  - Tree-level (+ HO) matched PS
    - MADGRAPH
    - ALPGEN
    - COMPHEP
    - SHERPA
    - PYTHIA (LO)
    - LO AcerMC

**full NNLO now available for qq → tt**

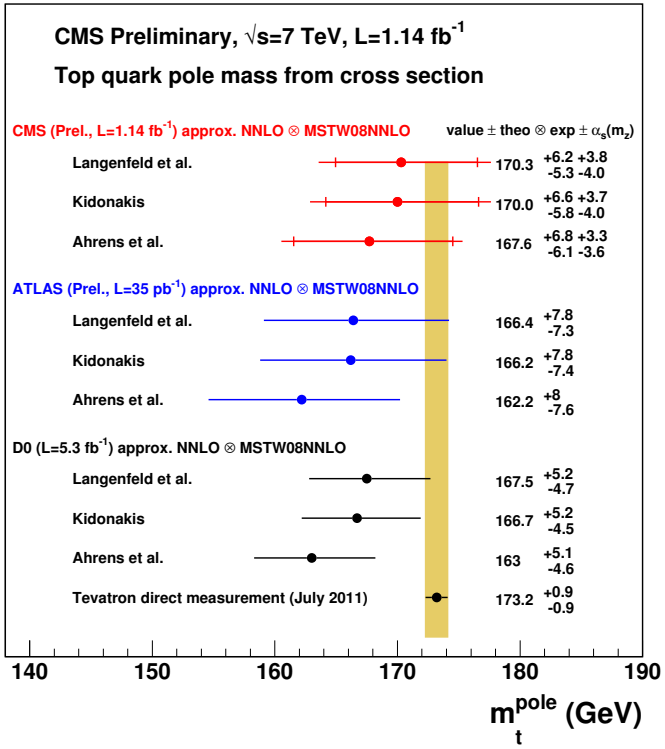
# Top Quark Cross Section and Mass

PRD 84, 012008 (2011)
PLB 703 (2011) 422

5.3 fb$^{-1}$



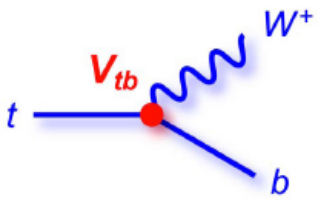

PLB 703 (2011) 422
CMS TOP-11-008
ATLAS-CONF-2011-054




- Most measured cross sections are quoted for a mass of 172.5 GeV
- Extract mass from cross section measurements

**cross section depends on top quark mass (both in measurements and calculations)**

# tt Event Signatures

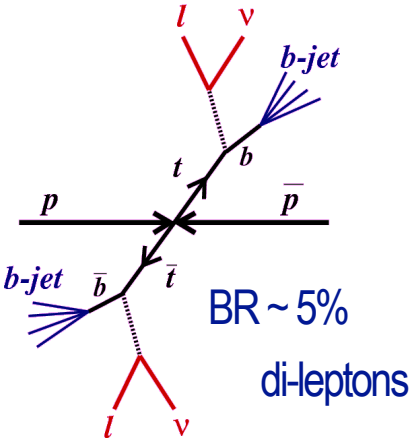



| $W$ decay | $e^+$ | $\mu^+$ | $\tau^+$ | $u\bar{d}$ | $c\bar{s}$ |
|---|---|---|---|---|---|
| $\bar{e}$ | $e\bar{e}$ | $e\mu$ | $e\tau$ | electron+jets | |
| $\bar{\mu}$ | $e\mu$ | $\mu\bar{\mu}$ | $\mu\tau$ | muon+jets | |
| $\bar{\tau}$ | $e\tau$ | $\mu\tau$ | $\tau\bar{\tau}$ | tau+jets | |
| $\bar{u}d$ | electron+jets | muon+jets | tau+jets | all-hadronic | |
| $\bar{c}s$ | | | | | |

dileptons

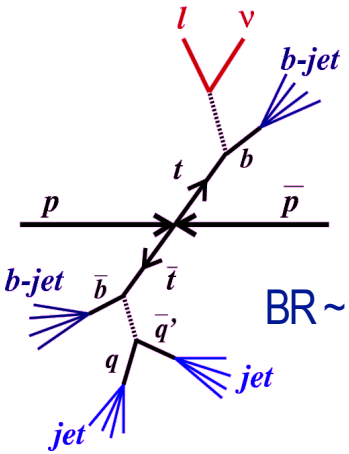
**All experiments have measured tt in all decay channels (except $\tau\tau$)**

Signal:



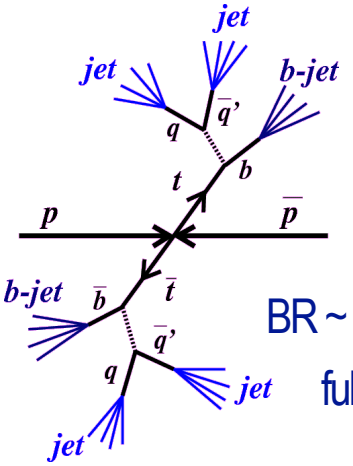

BR ~ 5%

di-leptons




BR ~ 30%

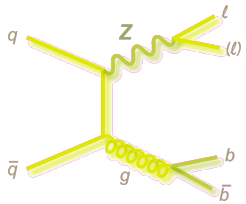
l+jets



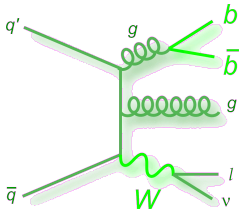

BR ~ 45%

fully hadronic

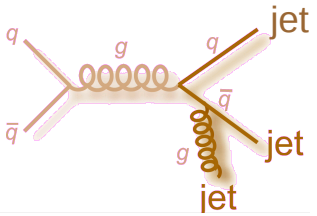
Backgrounds:




Z+jets




W+jets



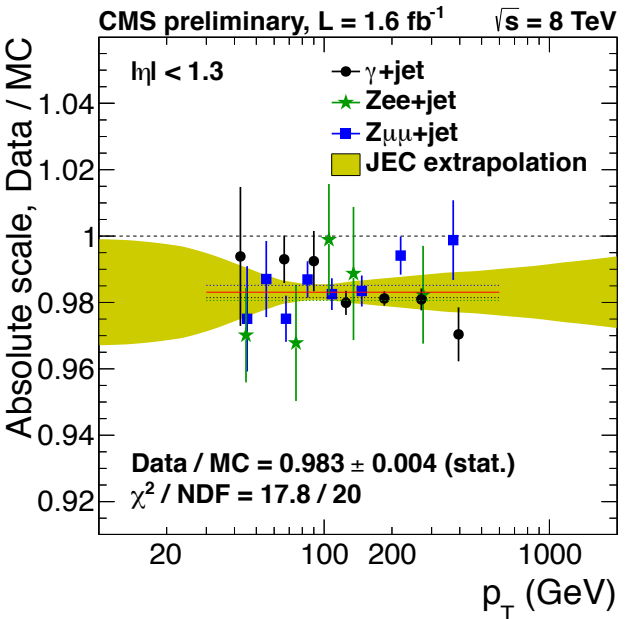

QCD multijets

**Analyses: dominant backgrounds determined from the data (using control regions)**

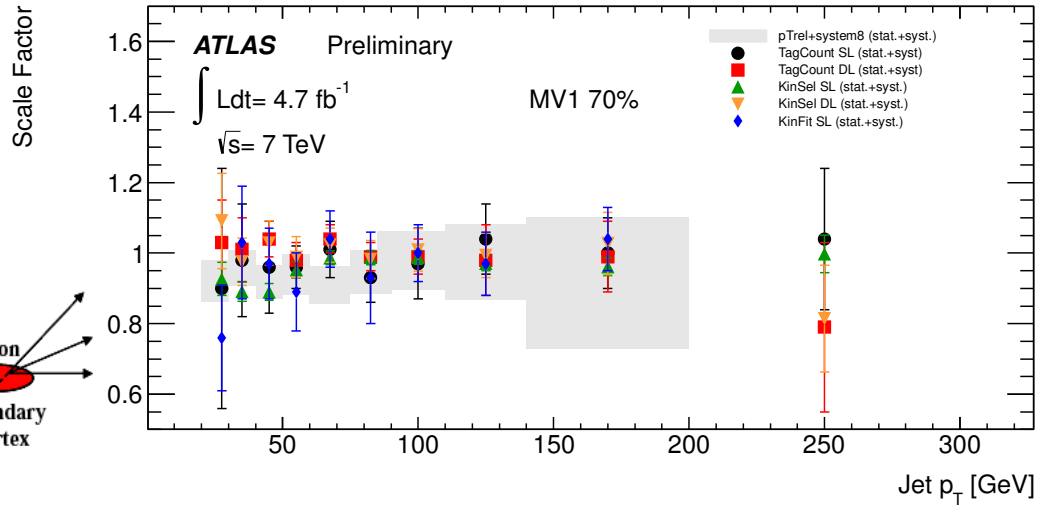
# Experimental Techniques

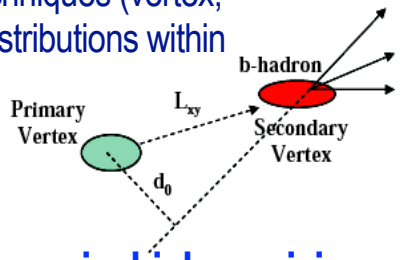
- **Isolated Leptons (e, μ or tau)**
  - isolation cuts against QCD backgrounds
- **Pile-up subtraction**
  - based on charged component
- **Jet (and $E_T^{miss}$)**
  - CMS: particle flow (track/calo combination)
  - ATLAS: topological clusters (e/h weighting) + track corrections.
  - optimal resolution and scale uncertainties,
  - minimal flavour response differences
- **b-tagging**
  - combination of several techniques (vertex, impact parameter, track distributions within jets)

CMS-DP-2012/012




ATLAS-CONF-2012-097

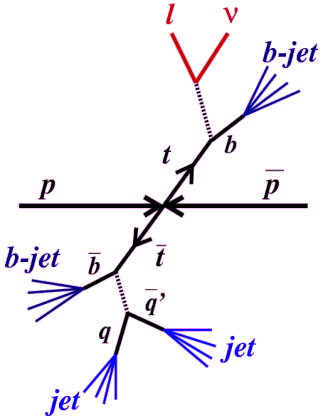


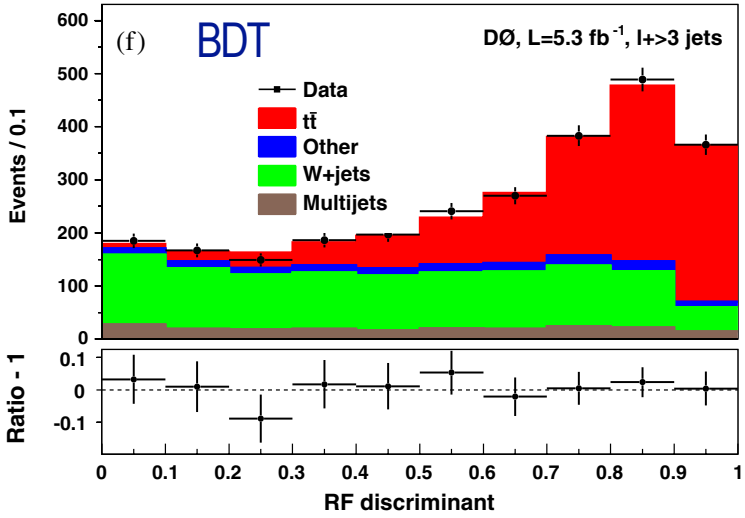

**Top quarks require high precision calibration for leptons, jets and b-tagging**

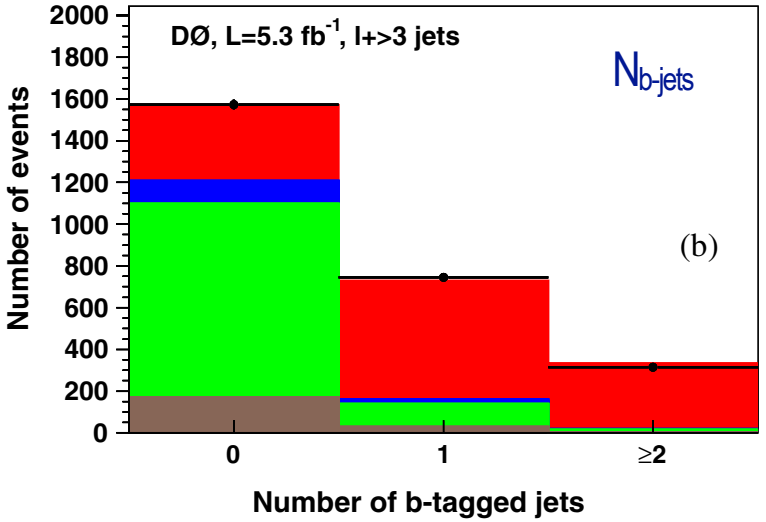
# $\sigma_{tt}$: e/μ+jets

PRD 84, 012008 (2011) 5.3 fb$^{-1}$




- **Signature**
  - 1 isolated e or μ
  - jets, $E_T^{miss}$
- **Three analyses**
  - Event topologies for 2, 3 and >3 jet categories using Boosted Decision Trees
  - 3 b-tag categories for 3 and >3 jets
  - Combination of BDT and b-tag
- **Cross section**
  - Simultaneous fit to all categories
  - Systematics fitted as nuisance parameters
  - W+jets heavy flavour scale factor $f_H$ (correction to ALPGEN prediction) also measured ($f_H$= 1.55 $\pm 0.09_{stat}$ $+0.17-0.19_{syst}$)
- **Dominant Systematics**
  - Luminosity, signal modeling, jet identification, b-tagging

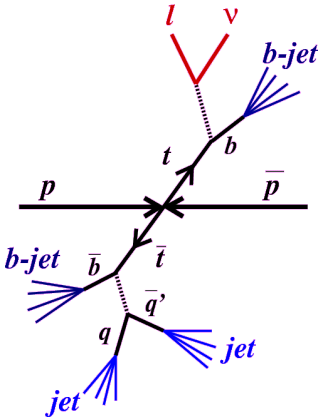



$\sigma_{tt}$ = 7.78 +0.77-0.64$_{stat+sys}$ pb

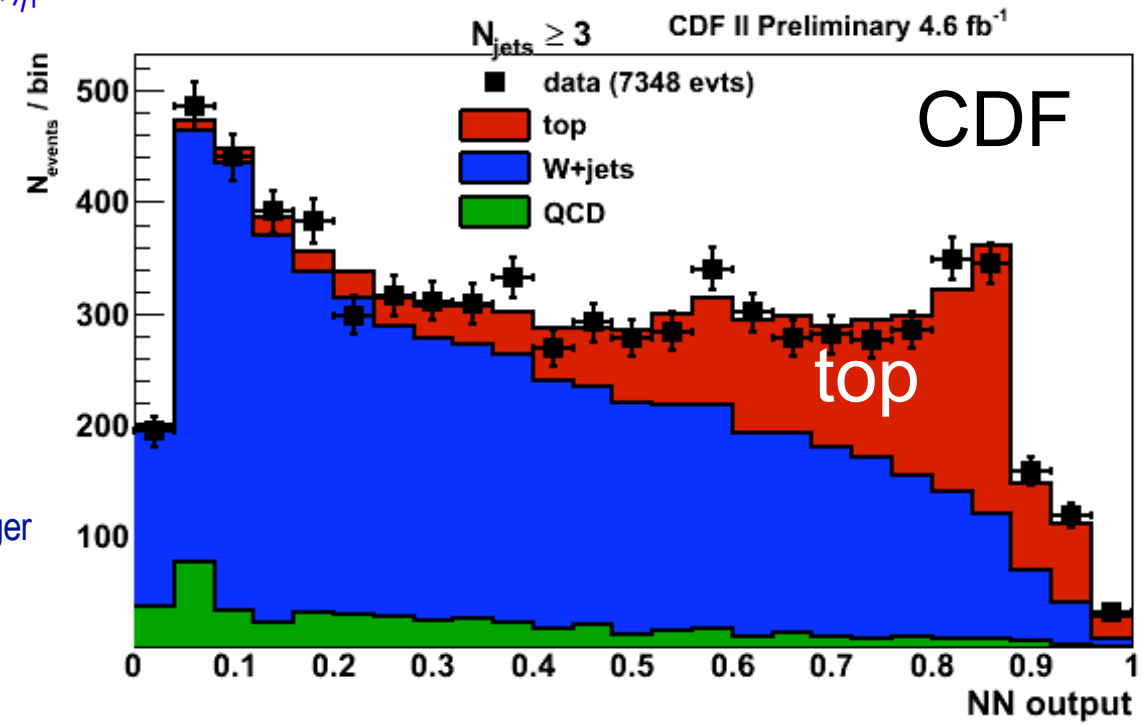
~9%

# $\sigma_{tt}$: e/μ+jets




PRL 105, 012001 (2010) 4.6 fb$^{-1}$

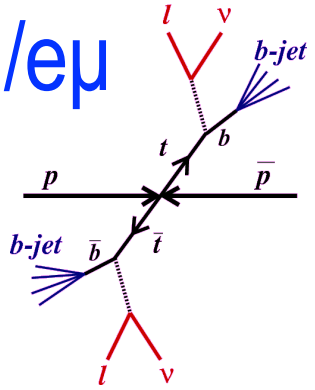
- **Signature**
  - 1 isolated e or μ
  - jets, $E_T^{miss}$
- **Two analyses combined**
  - Event topologies (neural net)
  - b-tagging
  - combination using best linear unbiased estimate (BLUE)
- **Normalize to $Z^0$ cross section**
  - Trade luminosity uncertainty for $Z^0$ theory uncertainty
  - Measure $Z^0$ cross section using same trigger and lepton-ID
- **Dominant Systematics**
  - Jet energy scale, signal modeling, $Z^0$ theory




$\sigma_{tt} = 7.70 \pm 0.52_{stat+sys}$ pb

7% (9% with luminosity unc.)

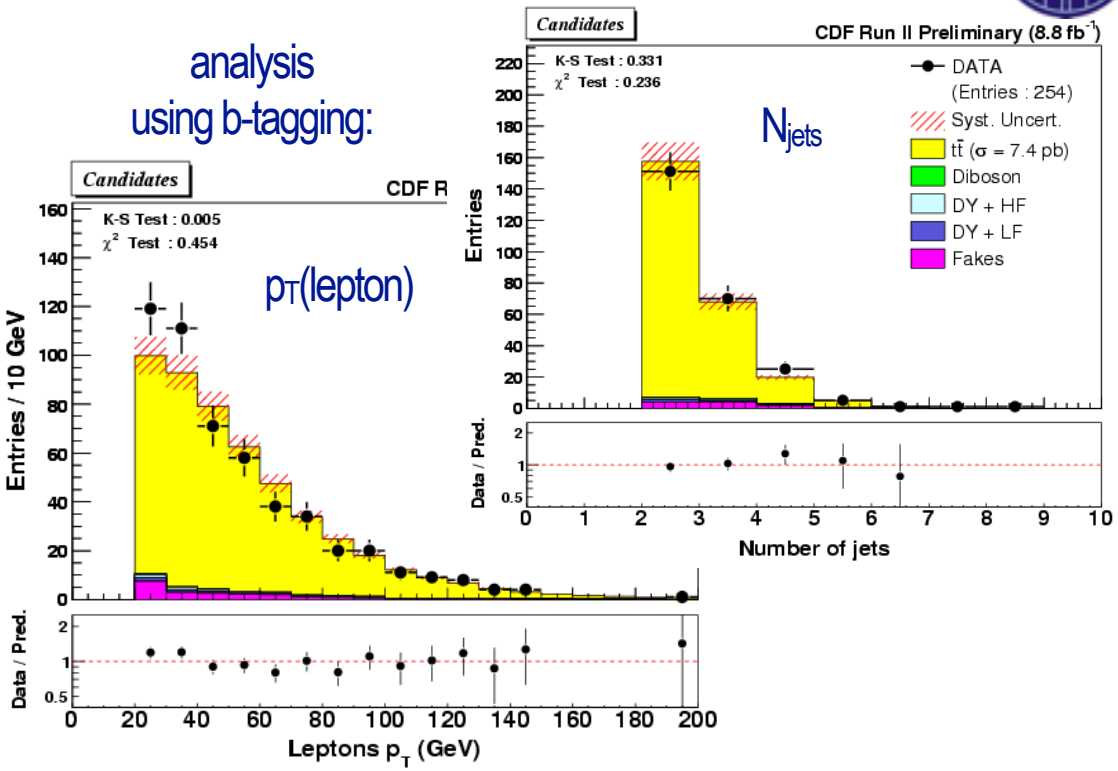
# $\sigma_{tt}$: ee/μμ/eμ




- **Signature**
  - 2 e or μ
  - 2 jets
- **Cut-and-count analysis**
  - with b-tagging
  - w/o b-tagging
- **Dominant Uncertainties**
  - Statistics, lepton-ID, jet energy scale, background modeling / b-tagging

CDF-CONF-10878 (2012) 9 fb$^{-1}$

analysis using b-tagging:




$\sigma_{tt}$ = 7.47 ± 0.50$_{stat}$ ± 0.53$_{syst}$ ± 0.46$_{lumi}$ pb ~11%

analysis w/o b-tagging:

$\sigma_{tt}$ = 7.66 ± 0.46$_{stat}$ ± 0.66$_{syst}$ ± 0.47$_{lumi}$ pb ~12%

PLB 704 (2011) 403 5.4 fb$^{-1}$

- select ee, μμ with 2 jets, eμ with 1 or 2 jets, simultaneous fit to b-tag NN discriminants, systematics as nuisance parameters

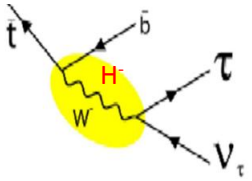
$\sigma_{tt}$ = 7.36 +0.90-0.79$_{stat+syst}$ pb ~11%

# $\sigma_{tt}$: τ+e/μ

http://www-cdf.fnal.gov/physics/new/top/2012/ttbar_taulep_xsec_9invfb/Publicpage.html

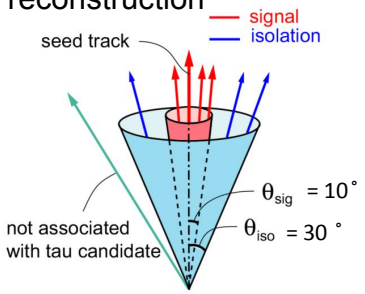
CDF: 9.2 fb$^{-1}$

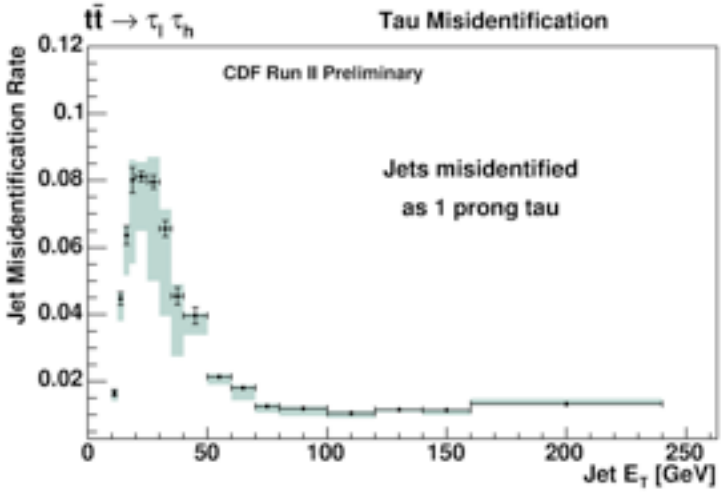
**tau-channel:**
**sensitivity to possible H+**




- **Signature**
  - 1 e or μ
  - 1 tau-candidate (narrow jet)
  - 2 or more jets (at least 1 b-tag)
  - $E_T^{miss}$

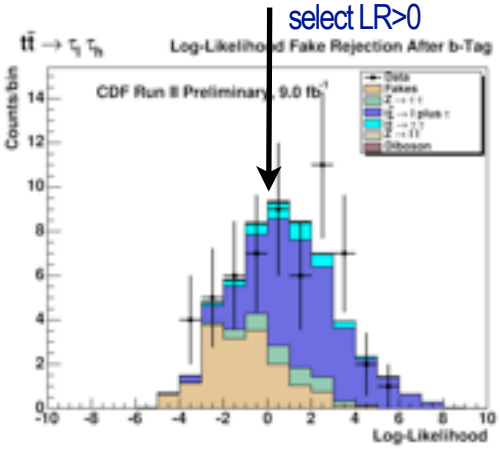
Tau reconstruction

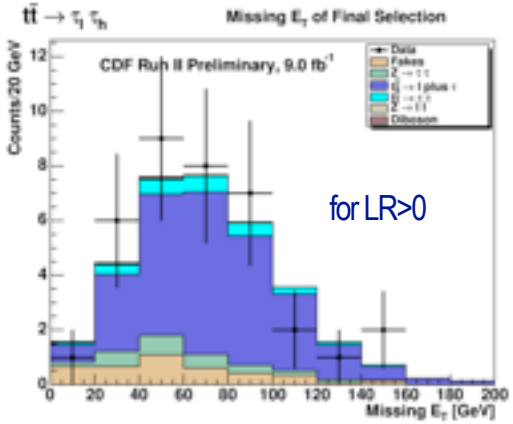



- **Log-likelihood ratio discriminant**
  - tau(E/p), tau(Iso), 3rd-jet $E_T$, $E_T^{miss}$, $M_T$(W)

- **Dominant Uncertainties**
  - Statistics, jet energy scale, b-tagging, luminosity




$\sigma_{tt}$ = 8.2 ± 2.3$_{stat}$ +1.2-1.1$_{syst}$ ± 0.5$_{lumi}$ pb

~32%

# $\sigma_{tt}$: Tevatron

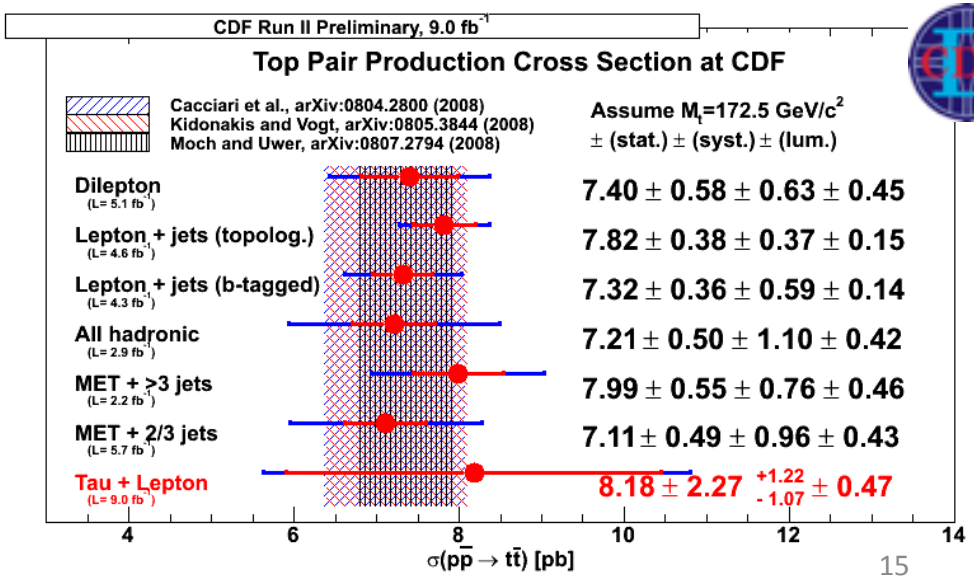
- **CDF**
  - $7.50 \pm 0.48_{stat+sys}$ pb
  - ~6.4%

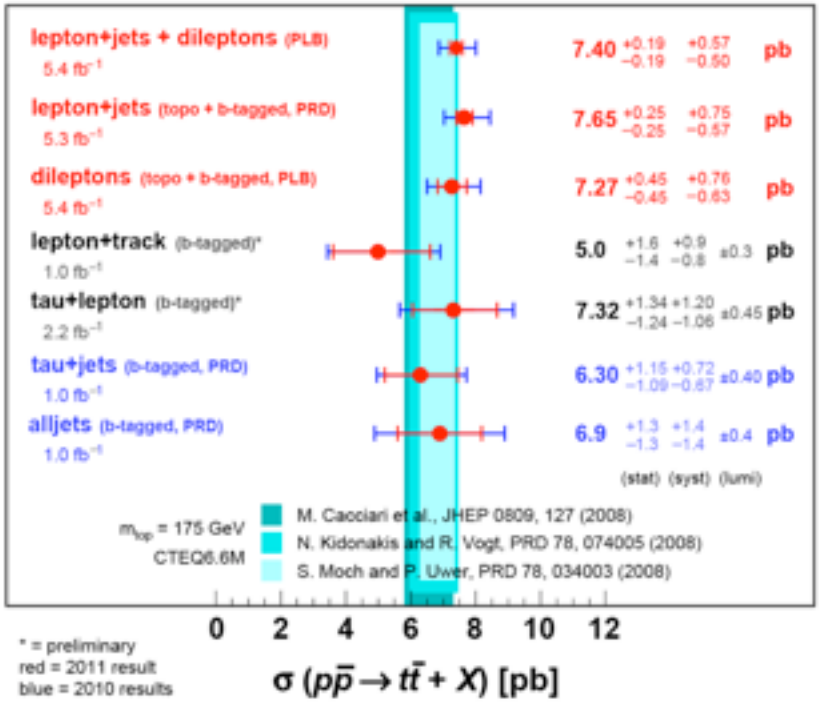
- **D0 (l+jets and dileptons combined)**
  - $7.56 + 0.63\text{-}0.56_{stat+sys}$ pb
  - ~8%

PLB 704 (2011) 403

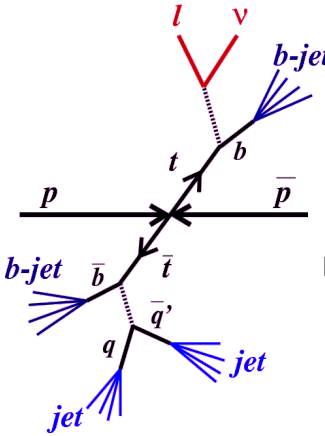
- **Theory**
  - NNLO+NNLL (gg: approx. NNLO+NNLL)
  - $7.07+0.14\text{-}0.23_{scales}+0.19\text{-}0.12_{pdf}$ pb
  - ~4%

Bärnreuther, Czakon, Mitov 1204.5201 [hep-ph]



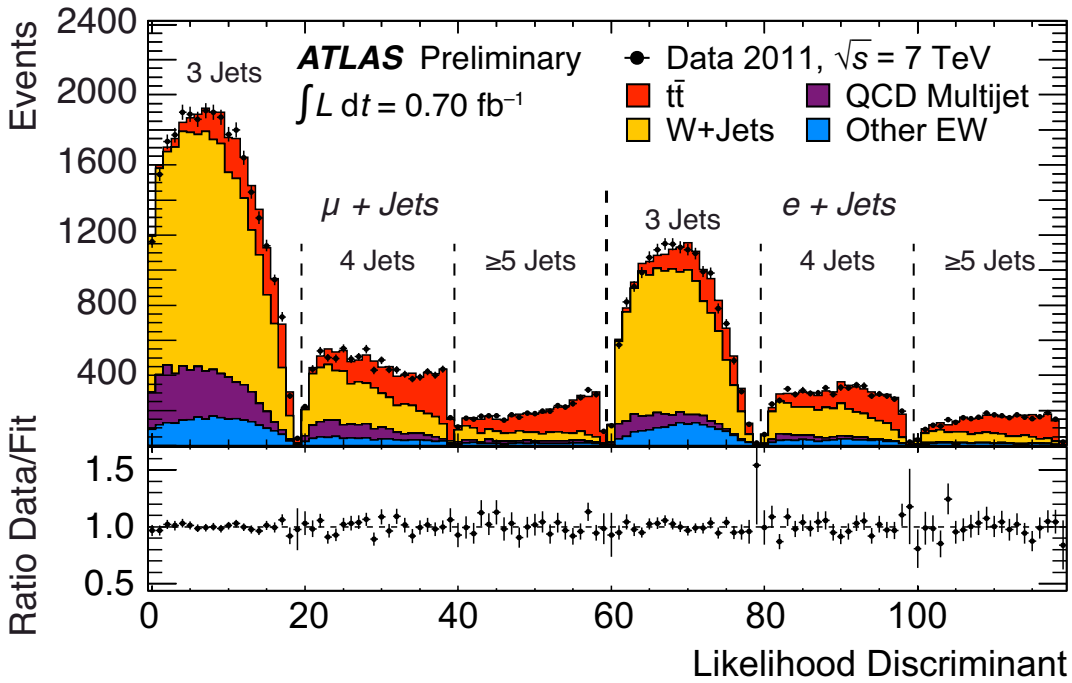



# $\sigma_{tt}$: e/μ+jets




- **Signature**
  - 1 isolated e or μ
  - 3 jets, $E_T^{miss}$
- **Analysis**
  - Likelihood discriminant from η(lepton), $p_T$(jet), aplanarity, $H_{T,3p}$
  - no b-tag
  - W+jets background shape from ALPGEN, normalization fitted with constraint from W-charge asymmetry
  - In-situ fit of systematics
- **Dominant Systematics**
  - signal modeling (MC@NLO vs POWHEG), jet energy scale, lepton-ID
  - Luminosity (not yet using final number)

ATLAS CONF 2011-121 0.70 fb$^{-1}$



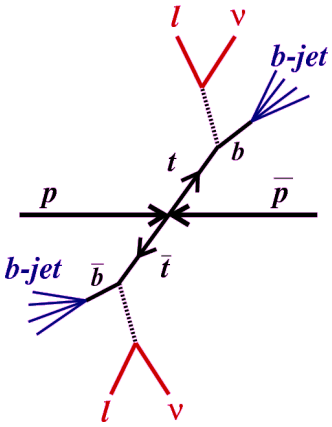

$\sigma_{tt}$ = 179.0 ± 3.9$_{stat}$ ± 9.0$_{syst}$ ± 6.6$_{lumi}$ pb — 6.5%

CMS TOP-11-003 1.1 fb$^{-1}$

- fit to 2ndary vertex mass in bins of jet and b-tag multiplicity, in-situ fit of systematics

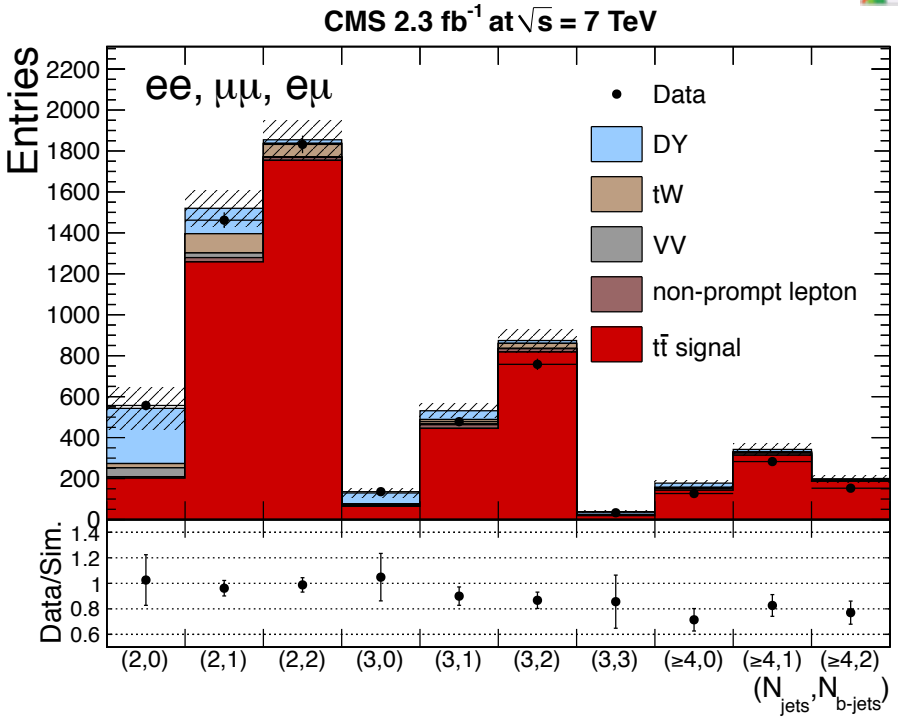
$\sigma_{tt}$ = 164.4 ± 2.8$_{stat}$ ± 11.9$_{syst}$ ± 7.4$_{lumi}$ pb — 9%

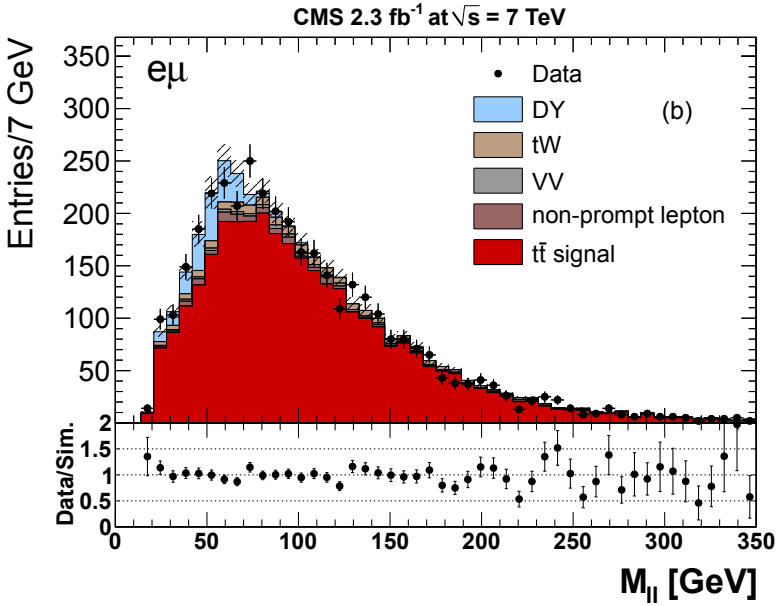
# $\sigma_{tt}$: ee/μμ/eμ




- **Signature**
  - 2 e or μ
  - 2 jets, b-tag
- **Analysis**
  - High purity, high statistics
  - Profile-likelihood fit to N-jets and N-bjets.
- **Dominant Systematics**
  - lepton efficiency, jet energy

CMS arXiv:1208.2671 2.3 fb$^{-1}$




$\sigma_{tt}$ = 161.9 ± 2.5$_{stat}$ ± 5.1$_{syst}$ ± 3.6$_{lumi}$ pb

4.2%

most precise measurement so far

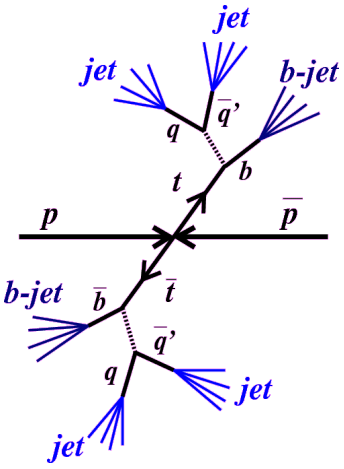
ATLAS JHEP 1205 (2012) 059 0.70 fb$^{-1}$

- combination of cross sections from samples with and w/o b-tag

$\sigma_{tt}$ = 176 ± 5$_{stat}$ +14-11$_{syst}$ ± 8$_{lumi}$ pb

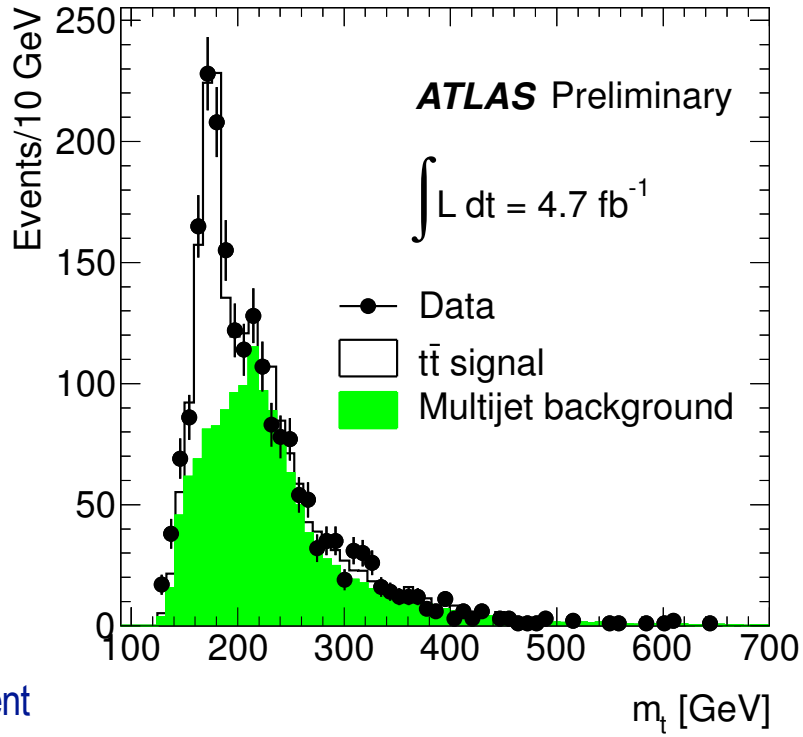
8%

# $\sigma_{tt}$: all jets




- **Signature**
  - 6 or more jets, 2 b-tagged
- **Analysis**
  - kinematic fit ($\chi^2 < 30$) to reconstruct top quark mass
  - Cross section from unbinned likelihood fit to top quark mass
  - Background shape from b-untagged data passing event selection
- **Dominant uncertainties**
  - Jet energy scale, b-tagging, ISR/FSR

ATLAS CONF-2012-031 4.7 fb$^{-1}$




$\sigma_{tt} = 168 \pm 12_{stat} + 60\text{-}57_{syst} \pm 6_{lumi}$ pb

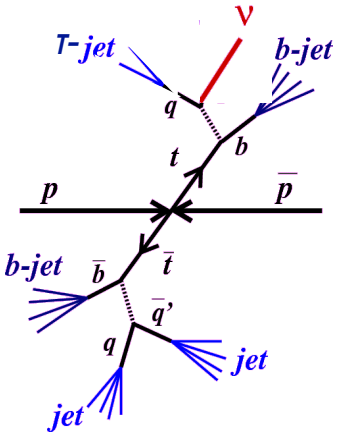
33%

CMS TOP-11-007 1.1 fb$^{-1}$

$\sigma_{tt} = 136 \pm 20_{stat} \pm 40_{syst} \pm 8_{lumi}$ pb

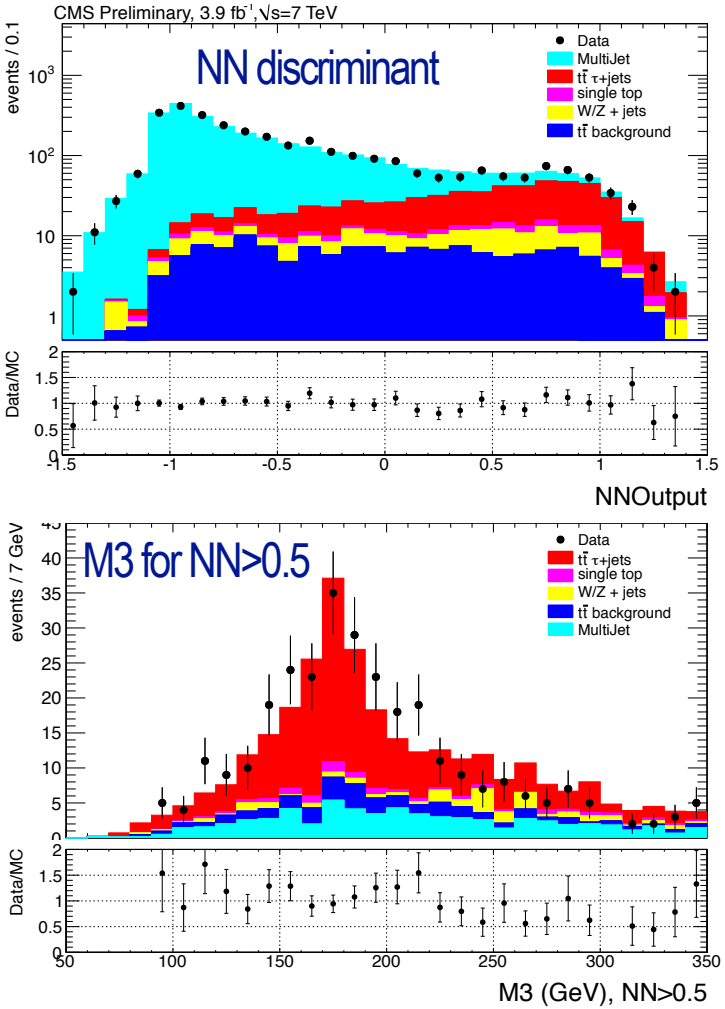
33%

# $\sigma_{tt}$: τ+jets




- **Signature**
  - 1 tau-jet
  - 4 jets, at least 1 b-tag
- **Analysis**
  - tau-identification using HPS algorithm
  - Kinematic fit to identify hadronic top
  - Neural network to separate signal from background: HT, aplanarity, $Q_\tau$, $E_T^{miss}$, $\Delta\varphi(E_T^{miss},\tau)$, M(jets,τ), $\chi^2$(kin)
  - Template fit to NN output
- **Dominant Uncertainties**
  - Statistics, jet energy scale, tau-identification

CMS TOP-11-004 3.9 fb$^{-1}$




ATLAS CONF-2012-032 1.7 fb$^{-1}$

$\sigma_{tt}$ = 200 ± 19$_{stat}$ ± 43$_{syst}$ pb

23%

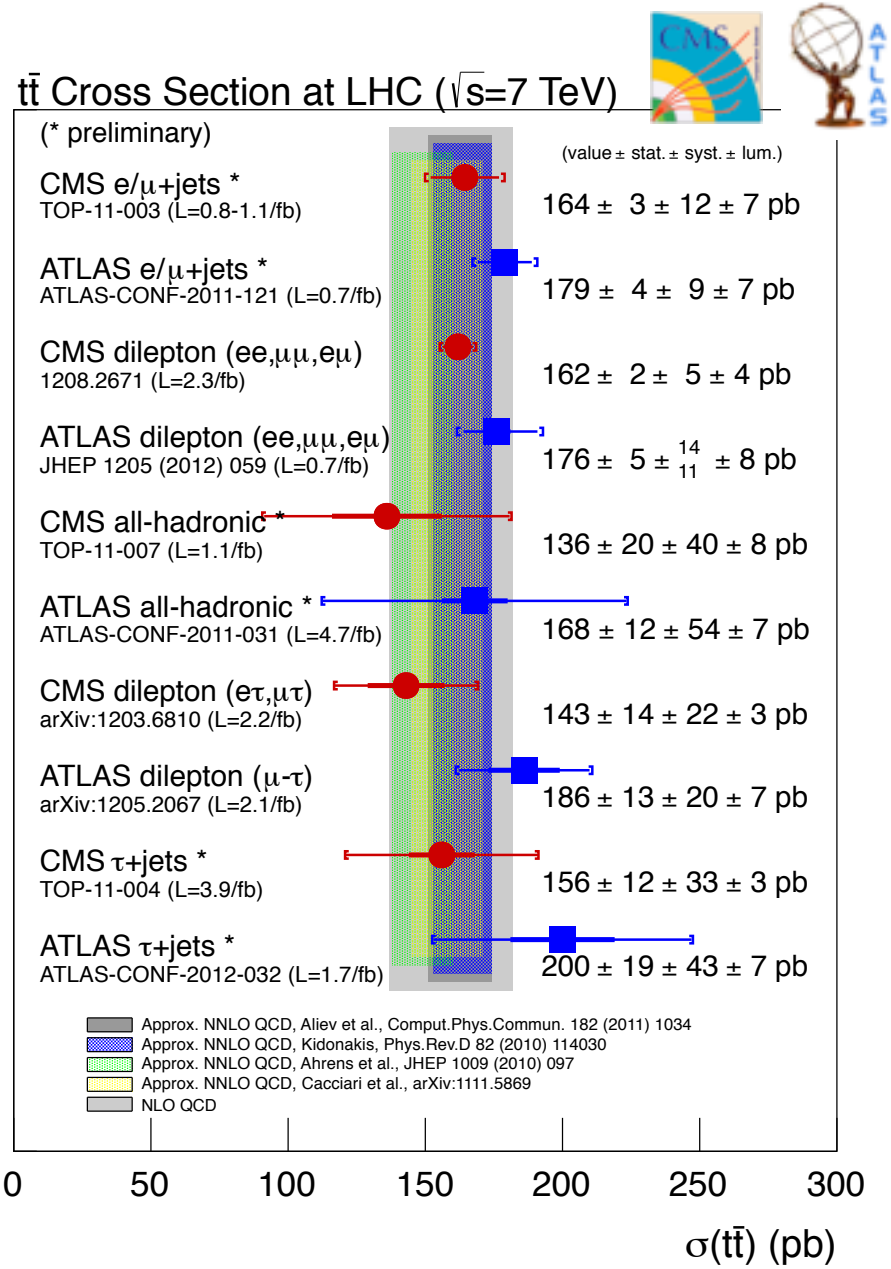
$\sigma_{tt}$ = 156 ± 12$_{stat}$ ± 33$_{syst}$ ± 3$_{lumi}$ pb

22%

# $\sigma_{tt}$: LHC (7 TeV)

- **ATLAS combination** ATLAS CONF-2012-024
  - $\sigma_{tt}$ = 177 ±3 +8-7 ±7 pb (6.2%)
- **CMS dilepton** CMS arXiv:1208.2671
  - $\sigma_{tt}$ = 162 ±2 ±5 ±4 pb (4.2%)

| | σ(tt) (7 TeV) ± scale ± PDF |
|---|---|
| MCFM (NLO QCD) | **160 +20-21 +8-9 pb** |
| Kidonakis | **163 +7-5 ±9 pb** |
| Aliev et al (HATHOR1.2) | **164 +5-9 ±9 pb** |
| Ahrens et al. | **155 +8-9 +8-9 pb** |
| Beneke et al. | **163 +7-8 +15-14 pb** |
| Cacciari et al (TOP++) | **159 +12-14 ±4 pb** |
| Moch et al (HATHOR1.3) | **175 +10-13 ±5 pb** |

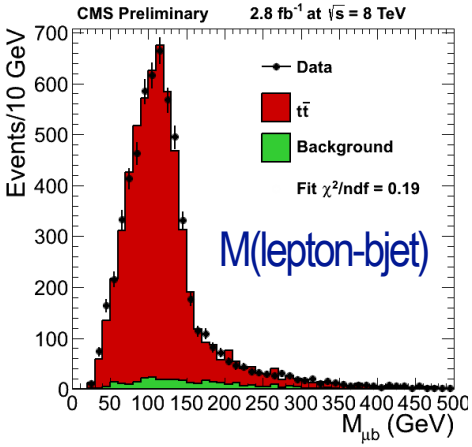


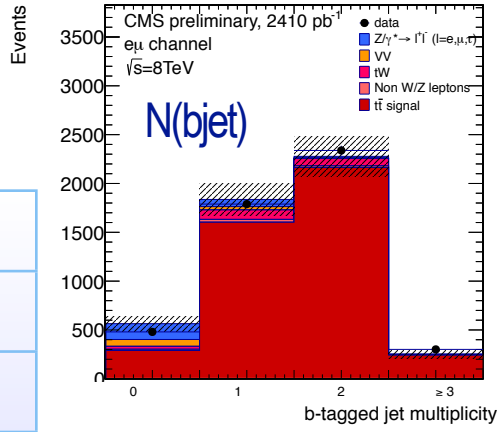

**All measurements compatible within errors -- some tension emerging between ATLAS and CMS (?)**

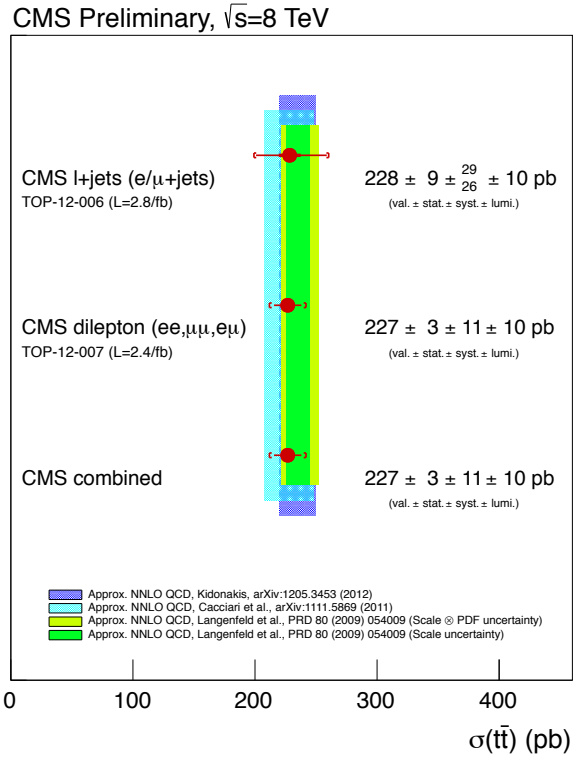
# $\sigma_{tt}$: LHC (8 TeV)

CMS TOP-12-006, TOP-12-007 2.4/2.8 fb$^{-1}$

- **e/μ+jets**
  - Template fit to $M_{lb}$
  - QCD multijet shape from data
  - Dominant systematics: b-tagging, jet-energy scale
- **di-lepton:**
  - Cut-and-count
  - Dominant systematics: lepton-ID, jet energy scale



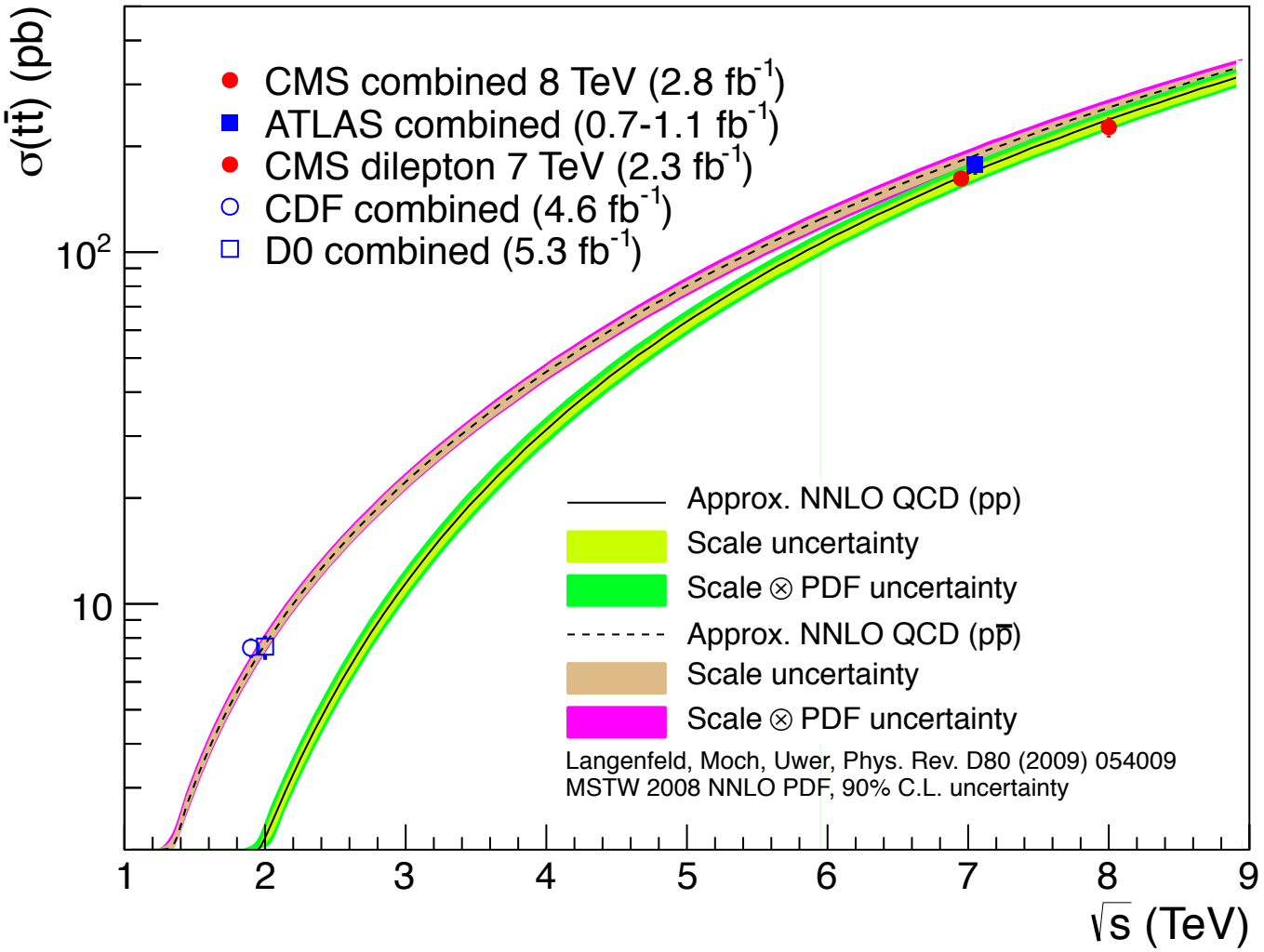

| Author | $\sigma_{tt}$ (8 TeV)±scale±PDF |
|---|---|
| Kidonakis | **234 +10-7 ±12 pb** |
| Ahrens et al. | **225 ±12 +11-12 pb** |
| Beneke et al. | **231 ±10 ±10 pb** |
| Cacciari et al | **229 +18-20 ±6 pb** |
| Moch et al | **250 +14-18 ±6 pb** |

$\sigma_{tt} = 227 \pm 3_{stat} \pm 11_{syst} \pm 10_{lumi}$ pb

6.6%

$$\frac{\sigma_{t\bar{t}}(8\ \mathrm{TeV})}{\sigma_{t\bar{t}}(7\ \mathrm{TeV})} = 1.41 \pm 0.11$$

# Inclusive tt Cross Section $\sigma_{tt}$

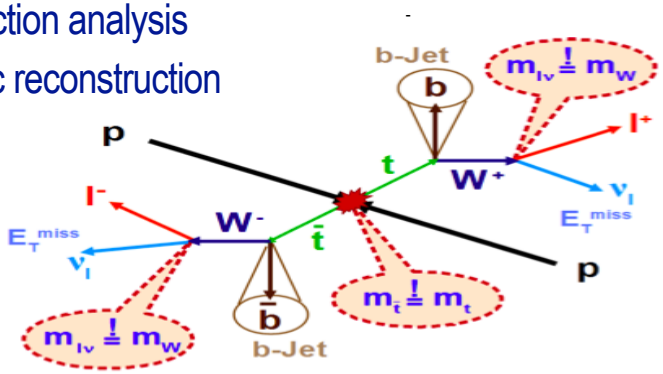



**Tevatron: 6.4%-8%**

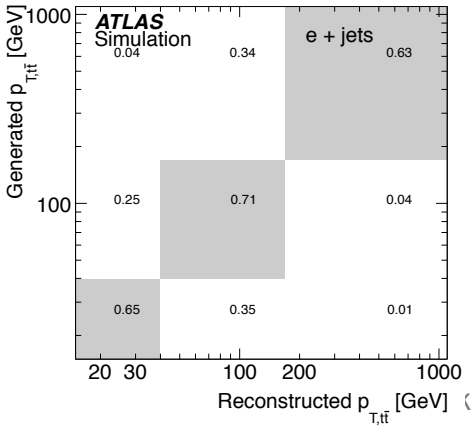
**LHC: 4.2%-6.2%**

# Differential tt Cross Sections

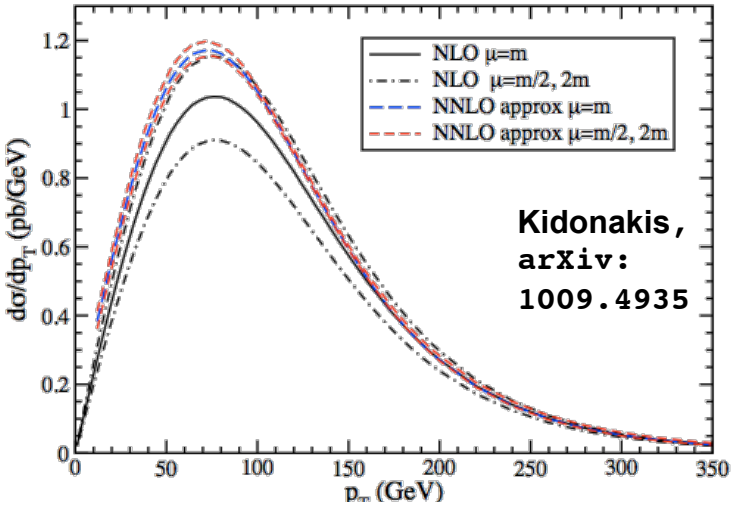
- **Measure top quark kinematic distributions**
  - Test theory predictions and models
  - Ensure that acceptances, efficiencies are correct
  - Enhance sensitivity to new physics
  - Extract / use for PDF-fits (future)
- **Main analysis ingredients:**
  - Cross section analysis
  - Kidonakis, arXiv:1009.4935 [hep-ph]

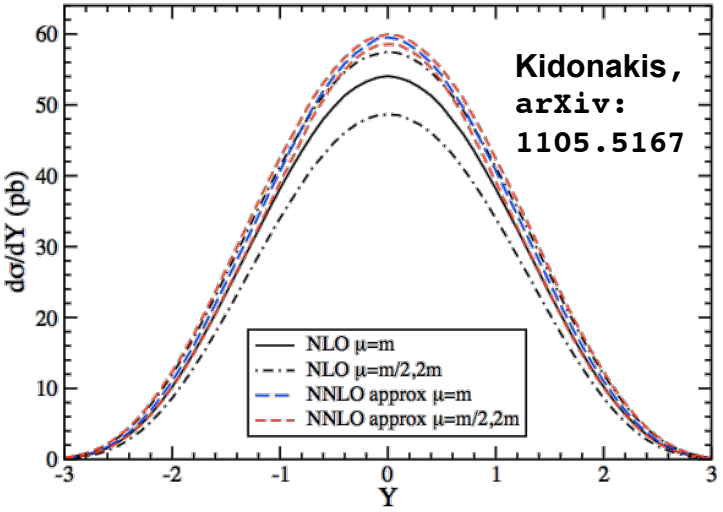



  - Unfolding



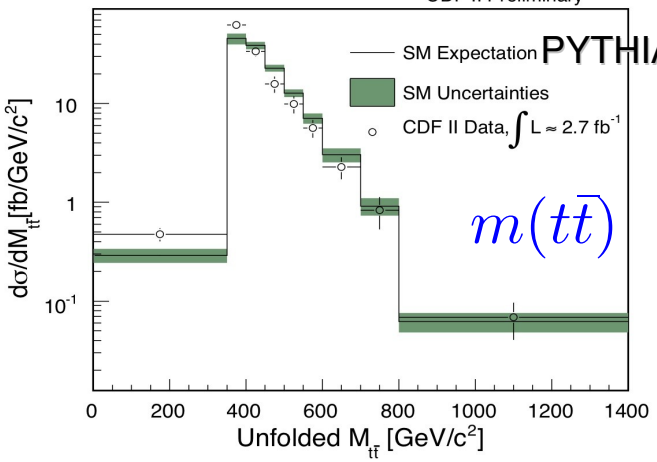

pp -> tt̄ at LHC $S^{1/2}$=7 TeV m=173 GeV



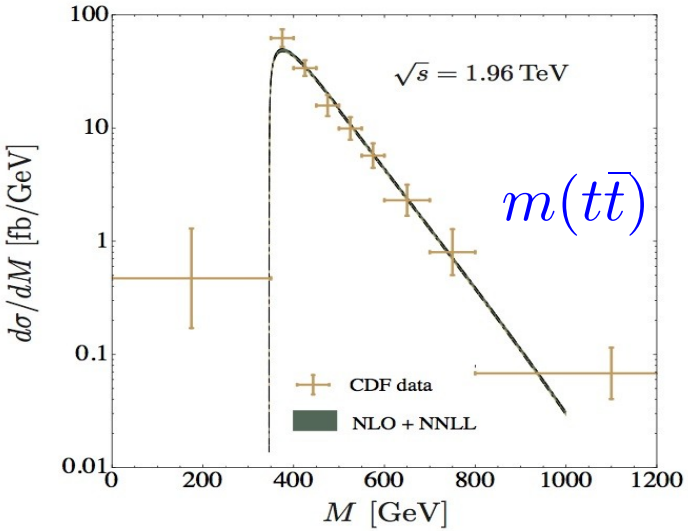



# Tevatron

PRL 102, 222003 (2009) 2.7 fb$^{-1}$

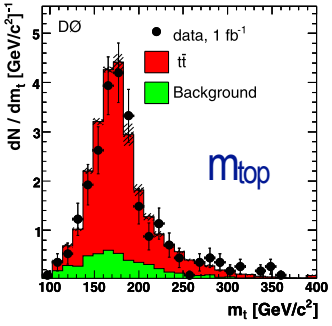


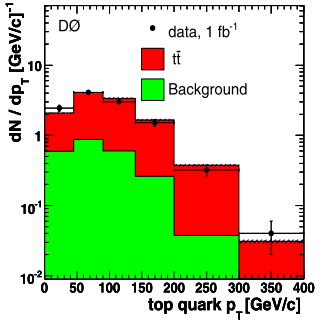

Ahrens, Ferrogia, Neubert, Pecjak, Yang
arXiv:1006.4682 [hep-ph]

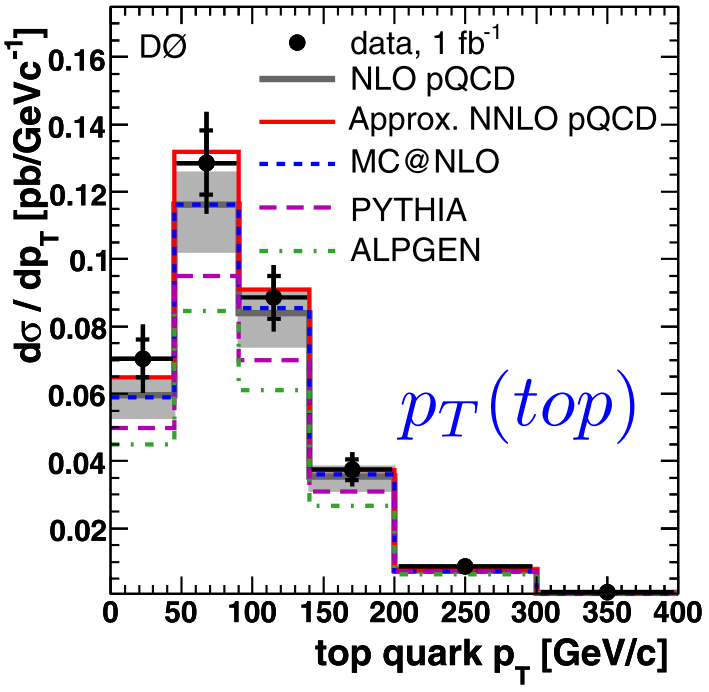



**NLO+NNLL: improved description of shape**

PLB 693, 515 (2010) 1.0 fb$^{-1}$



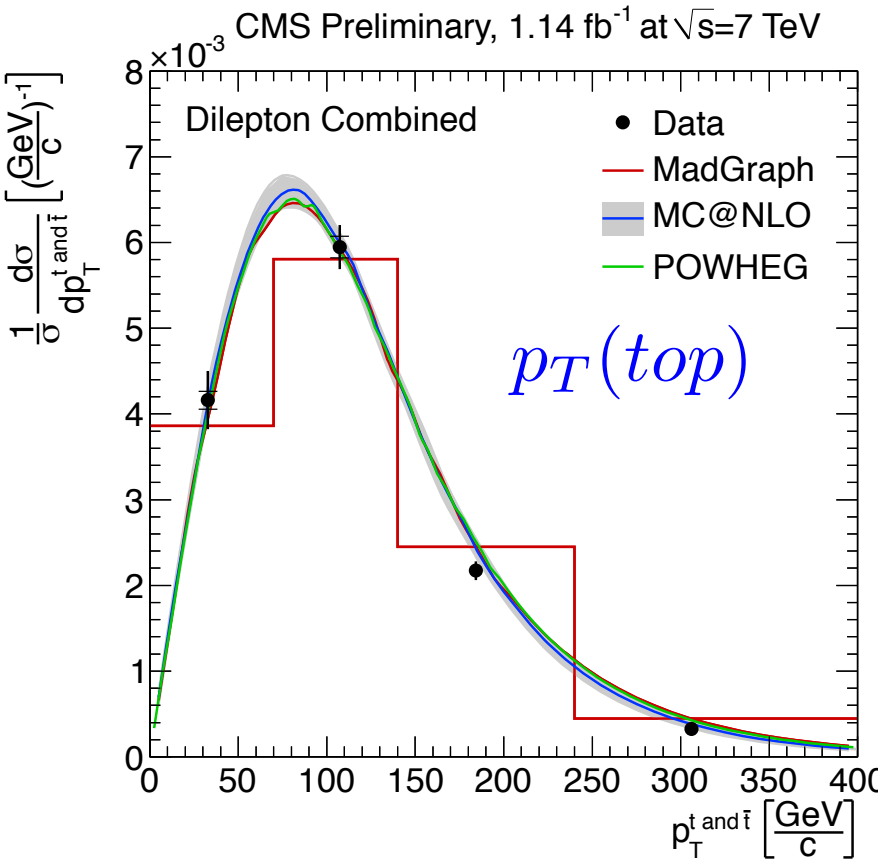



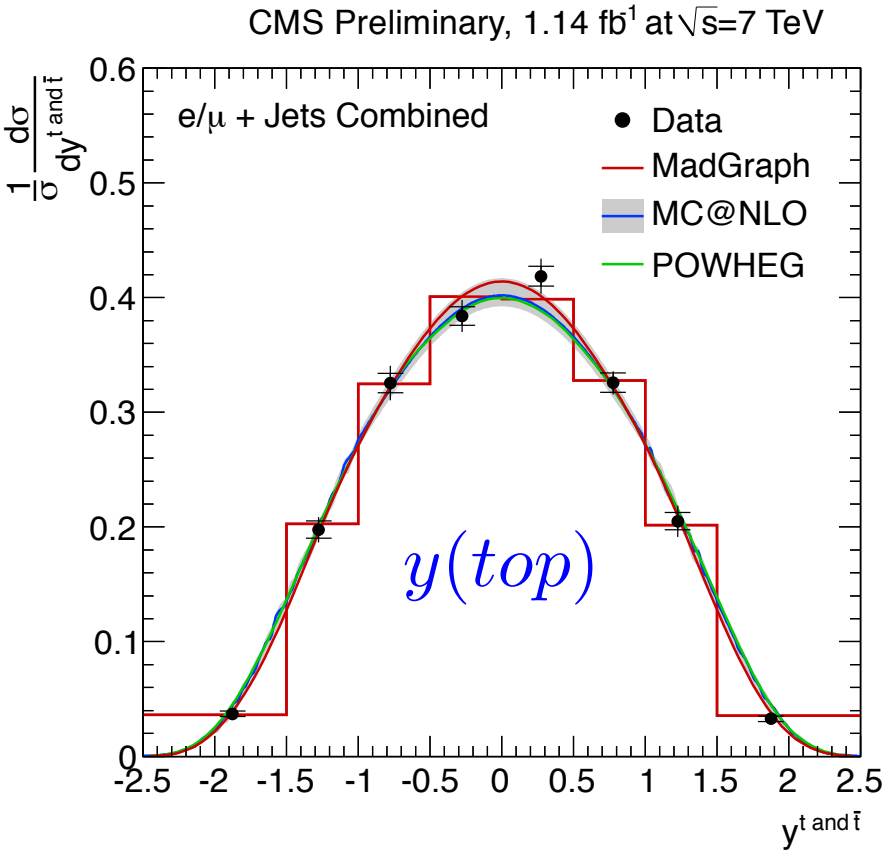




**Need NLO to describe normalization**

# LHC: Top Quark Distributions

CMS TOP-11-013 1.14 fb$^{-1}$



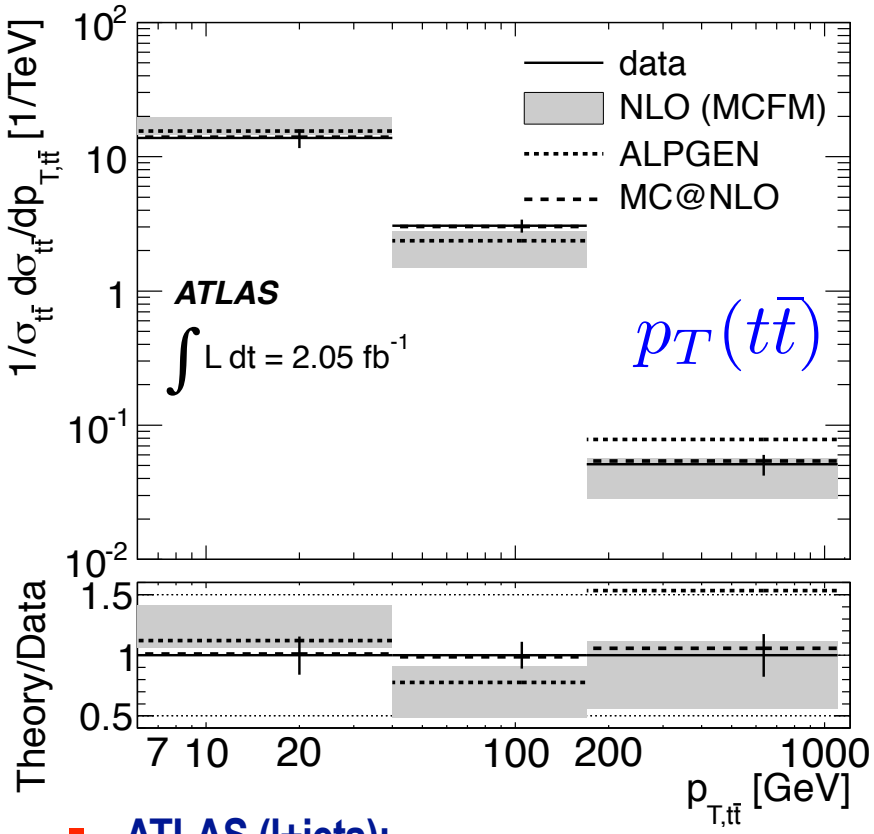




- **CMS (l+jets, dileptons)**
  - 'visible phase space' (region with maximum acceptance)
  - Comparisons: MADGRAPH, POWHEG(PYTHIA), MC@NLO(HERWIG)

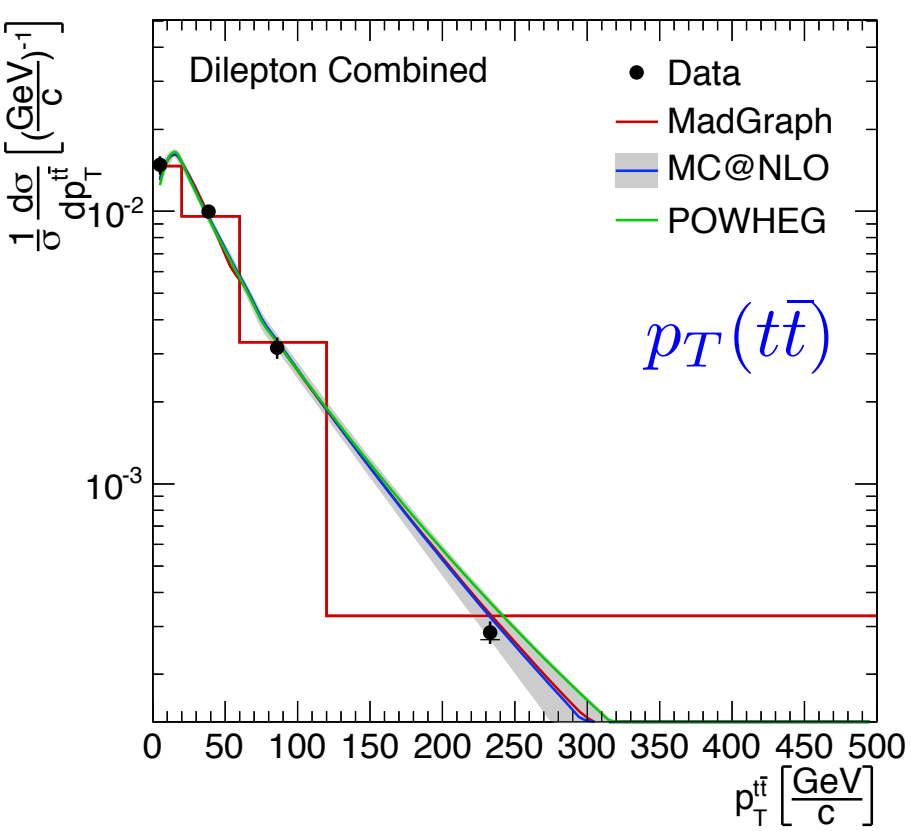
**Good agreement between data and all predictions**

# LHC: Top Quark Pair Distributions: $p_T(t\bar{t})$

arXiv 1207.5644 2.05 fb$^{-1}$




CMS TOP-11-013 1.14 fb$^{-1}$

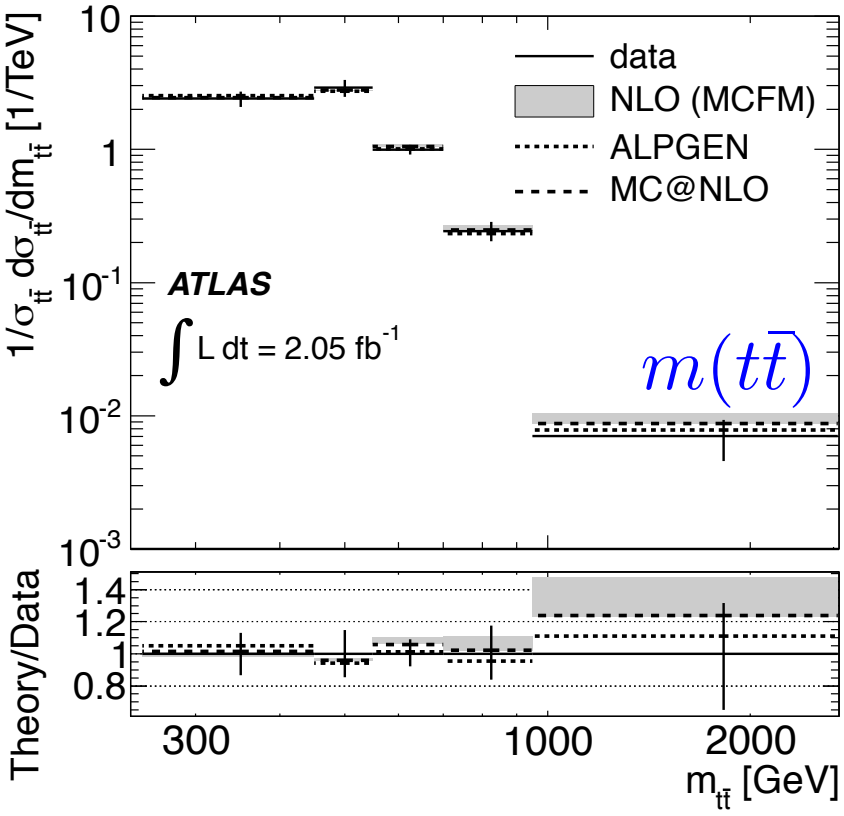



- **ATLAS (l+jets):**
  - Full phase space
  - Comparisons: NLO(MCFM), NLO+NNLL, ALPGEN, MC@NLO

$p_T(t\bar{t})$: **sensitivity to QCD radiation**

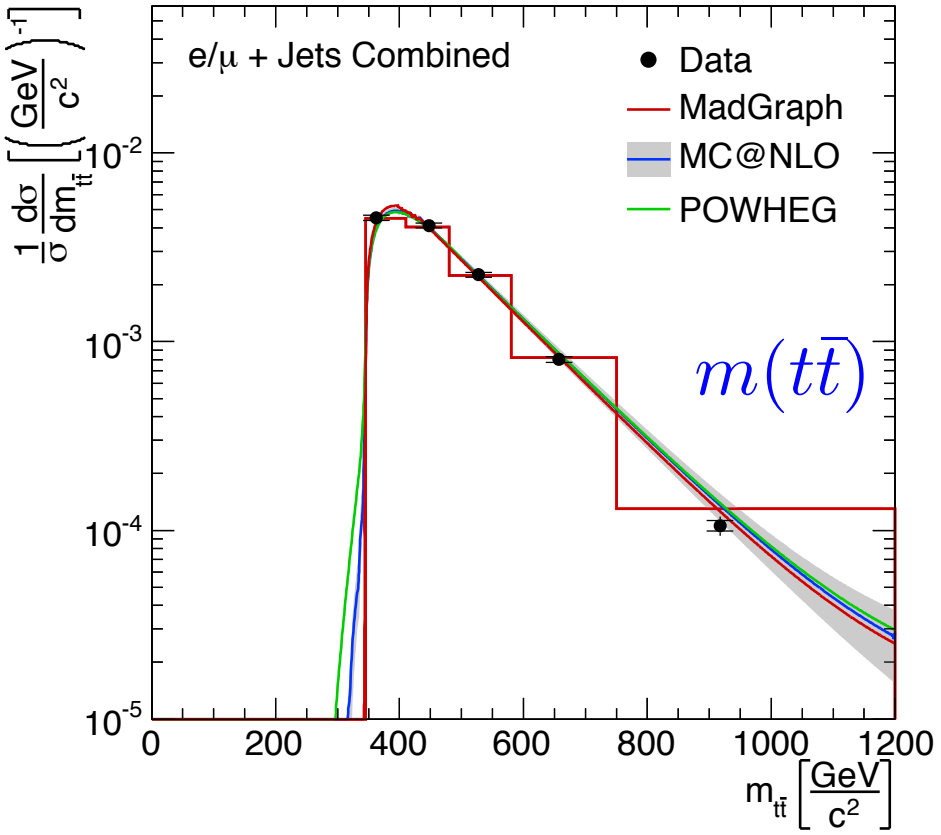
# LHC: Top Quark Pair Distributions: $m(t\bar{t})$

arXiv 1207.5644 2.05 fb$^{-1}$




CMS TOP-11-013 1.14 fb$^{-1}$

CMS Preliminary, 1.14 fb$^{-1}$ at $\sqrt{s}$=7 TeV



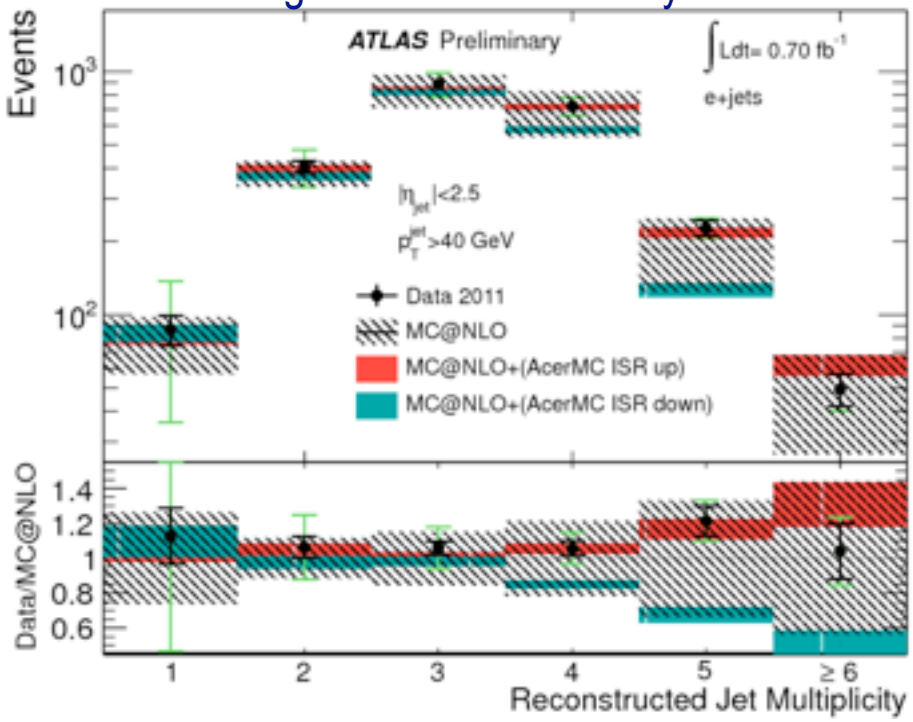

**sensitivity to (resonant or non-resonant) new physics**

**High $m_{tt}$: increasing theory uncertainties due to PDF**

# tt+jets

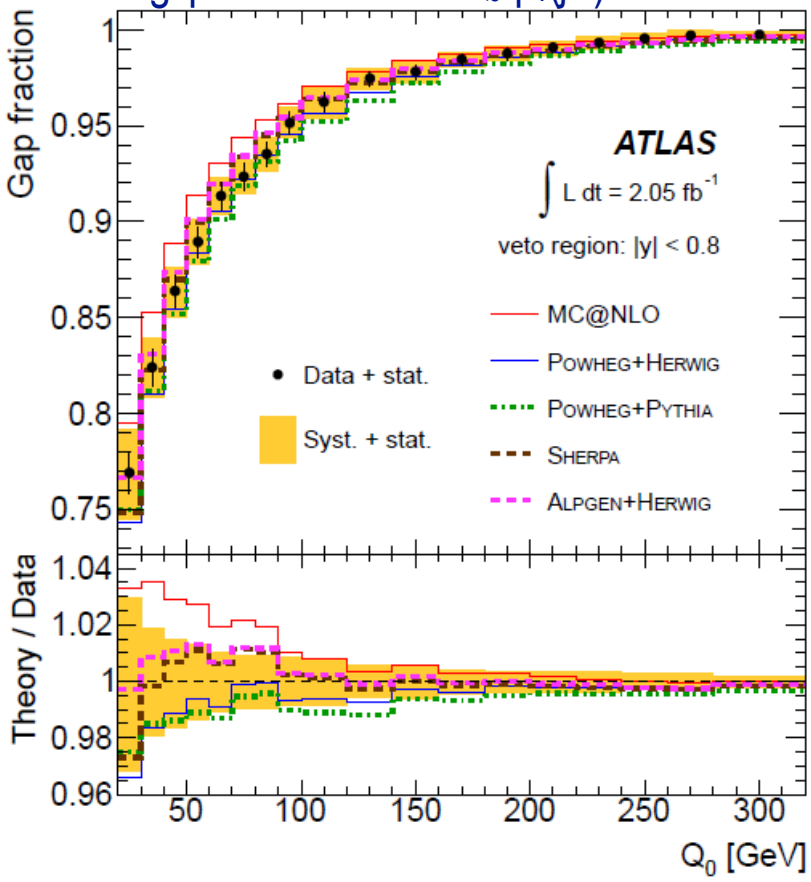
ATLAS-CONF-2011-142 0.70 fb$^{-1}$

background subtracted event yields




EPJ, C72 (2012) 2043 ATLAS 2.05 fb$^{-1}$

gap fraction as fct of $Q_0$=$p_T$(jet) threshold




- Additional jets due to QCD radiation
- tt+>1 jet: test of NLO+PS event generation

**Improve choice of model and scales for future measurements (properties and searches)**

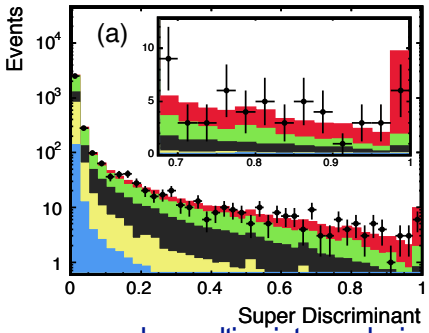
ATLAS-CONF-2012-083 4.7 fb$^{-1}$

$$\frac{\sigma_{t\bar{t}+\text{jets}}}{\sigma_{t\bar{t}}} = 0.54 \pm 0.01(stat.)^{+0.05}_{-0.08}(syst.)$$

# Single Top Production

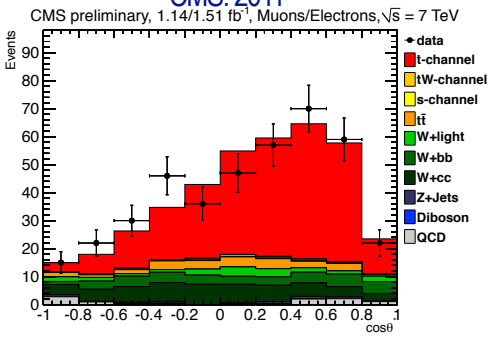
- **Test of EW interactions**
- **Probe for new physics**
  - measure Vtb
  - 4th generation
  - FCNC
- **sensitivity to b-PDF and u/d-PDF**
  - t and Wt channel
- **Main backgrounds**
  - W+jets background
  - top pair production
  - QCD multijet production

CDF: 2009

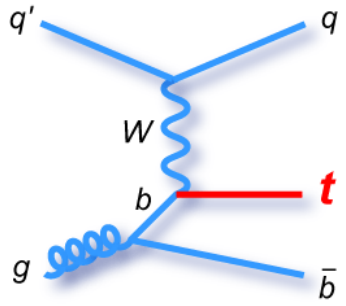


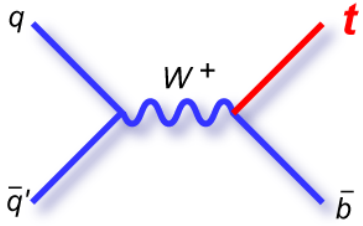

complex multivariate analysis

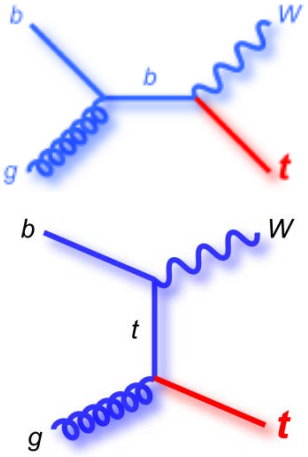
CMS: 2011




simple kinematic analysis



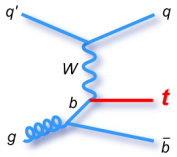




| Predictions | t-channel ($\sigma_{tqb}$) | s-channel ($\sigma_{tb}$) | tW-channel |
|---|---|---|---|
| Tevatron | **2.26 pb** | **1.04 pb** | **0.28 pb** |
| LHC (7 TeV) | **64.6 pb** | **4.6 pb** | **15.7 pb** |

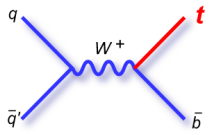
**LHC: much more gluons, leading to very different relative contributions**

# Single Top Event Signatures

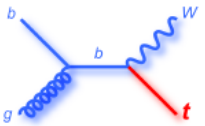
Signal:



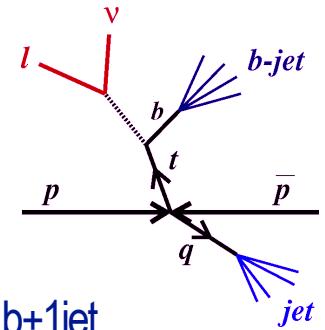

t-channel (tqb)



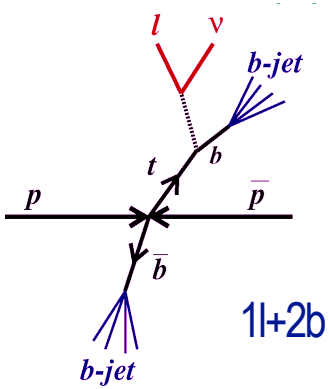

s-channel (tb)



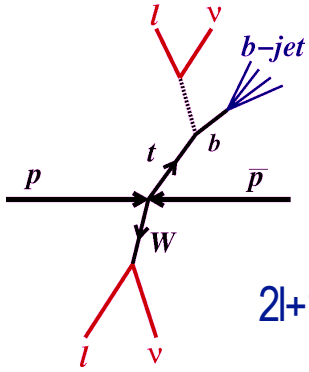

tW-channel




1l+1b+1jet

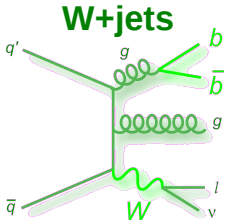



1l+2b

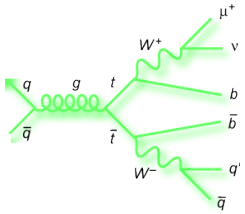


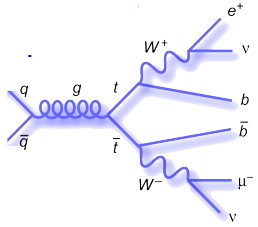

2l+1b

Backgrounds:

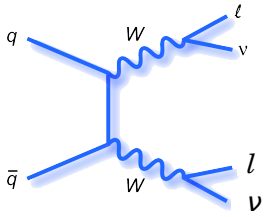


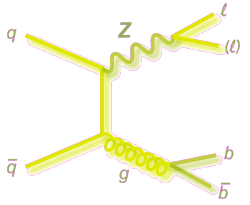

W+jets




top quark pairs

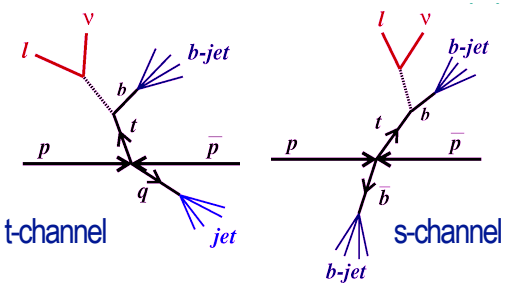


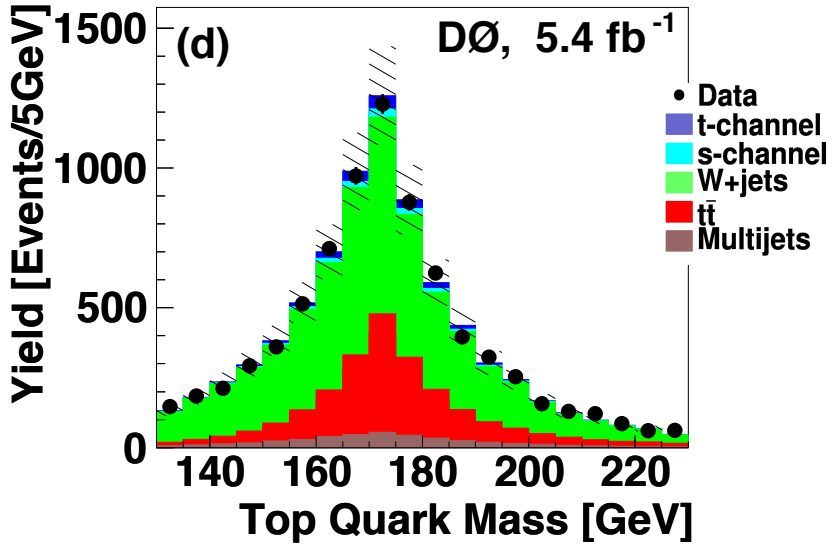

Diboson and Z+jets

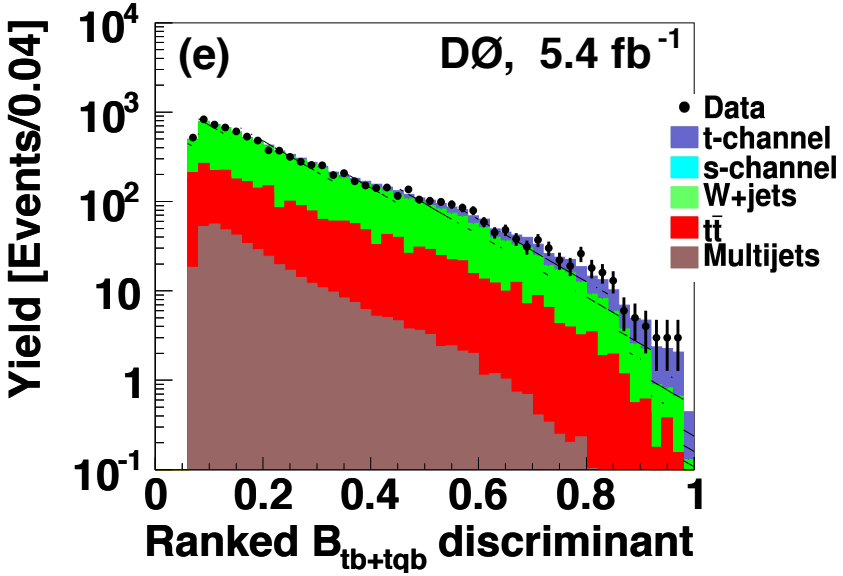
# Tevatron t+s channel

PRD 84, 112001 (2011) 5.4 fb$^{-1}$

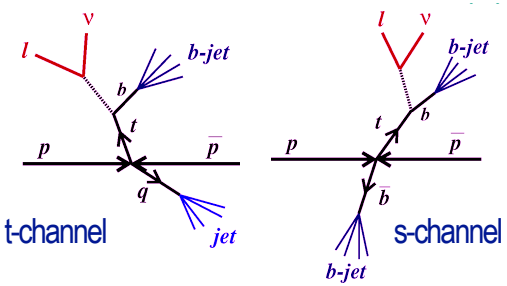



- **Signature**
  - e/μ and $E_T^{miss}$
  - 2,3 or 4 jets with 1 or 2 b-tags
  - $H_T$>120,140,160 GeV
- **Analysis**
  - Combination of three MVA, separately for t, s and t+s
    - Boosted Decision Tree
    - Bayesian Neural Network (BNN)
    - Neuro-evolution of augmented topologies (NEAT)
- **Dominant systematics**
  - Luminosity, jet-energy scale, b-tagging

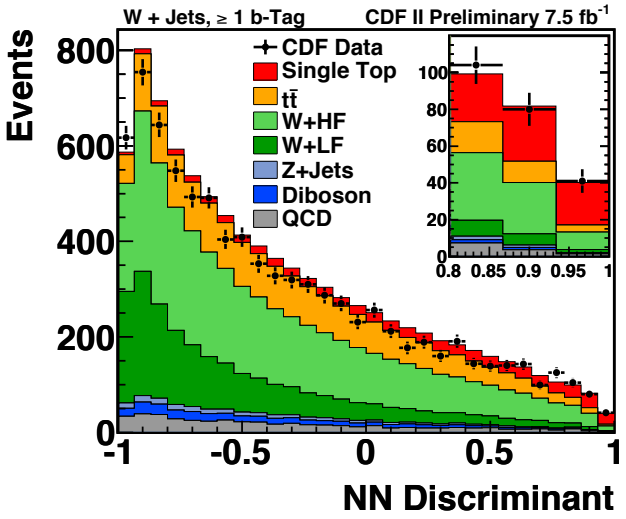


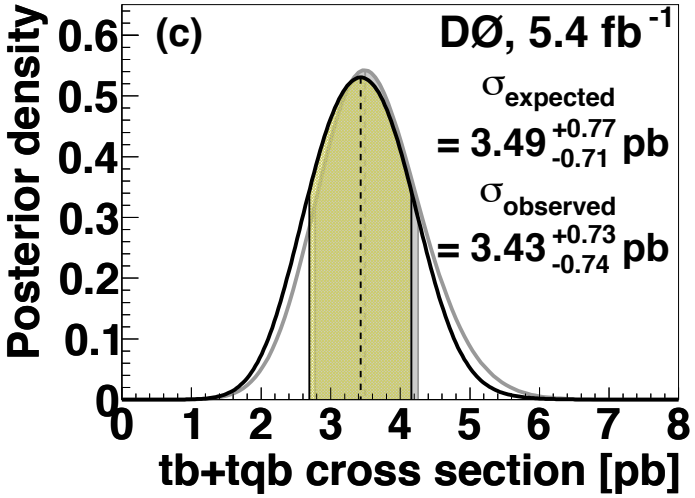
# Tevatron t+s channel

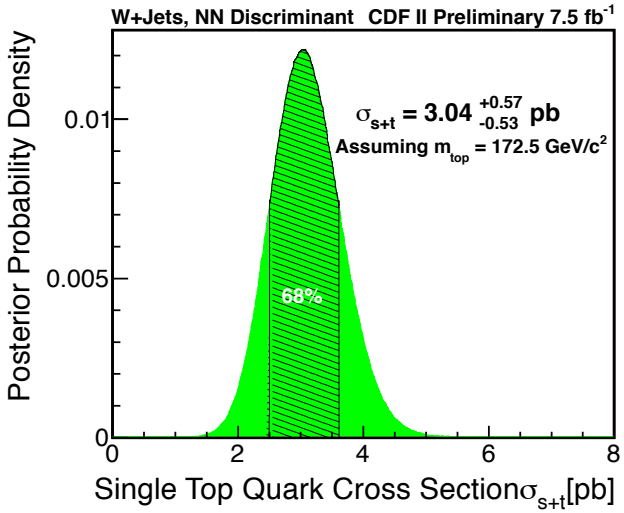



CDF-CONF-10793 7.5 fb$^{-1}$




PRD 84, 112001 (2011) 5.4 fb$^{-1}$



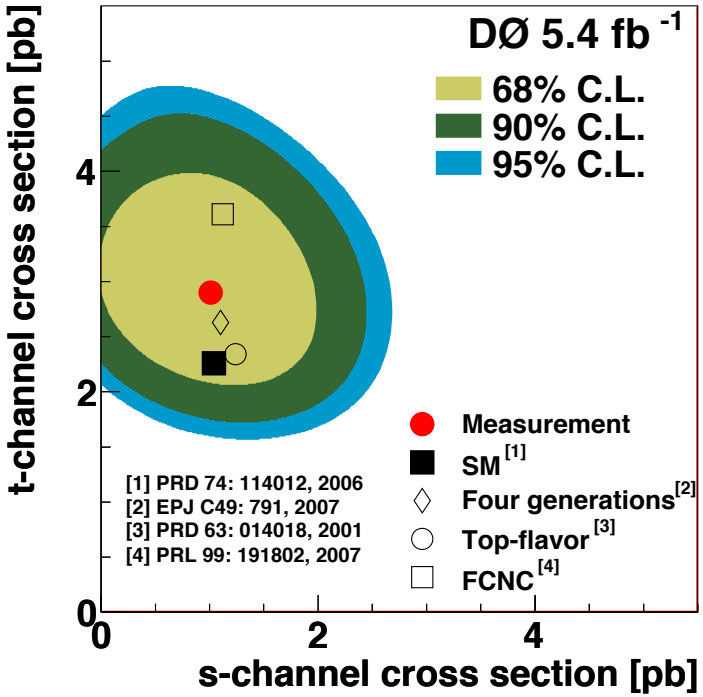




$\sigma_{s+t}$ = 3.43 +0.73-0.74$_{stat+syst}$ pb ~21%

$\sigma_{s+t}$ = 3.04 +0.57-0.53$_{stat+syst}$ pb ~18%

# t and s-channel

PLB 705, 313 (2011) 5.4 fb$^{-1}$

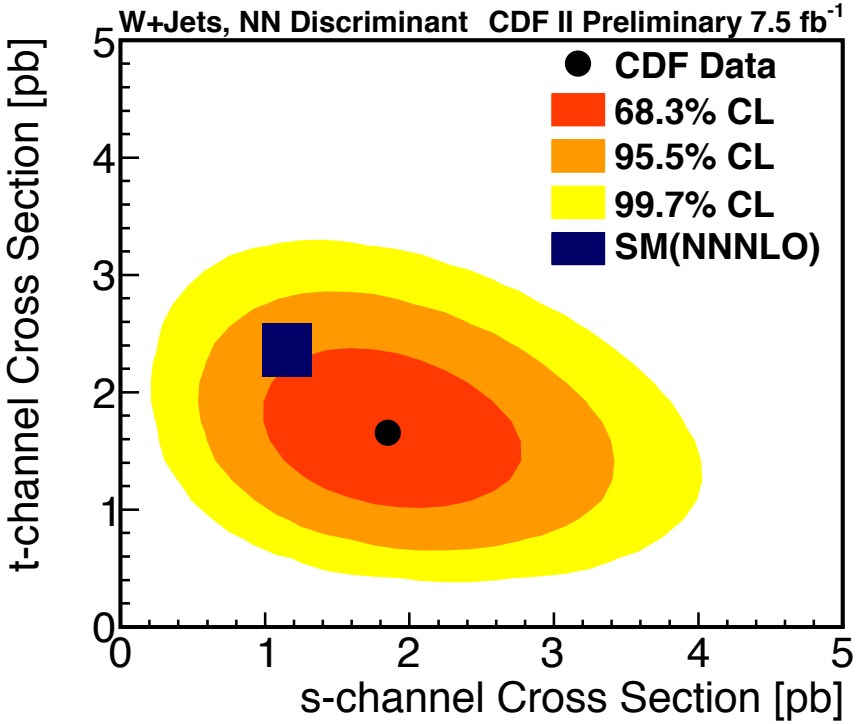



$\sigma_s = 0.98 \pm 0.63_{stat+syst}$ pb

$\sigma_t = 2.90 \pm 0.59_{stat+syst}$ pb

5.5σ

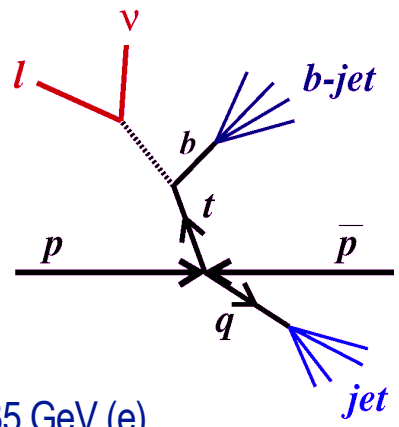
CDF-CONF-10793 7.5 fb$^{-1}$




$\sigma_s = 1.81$ +0.63-0.58$_{stat+syst}$ pb ~35%

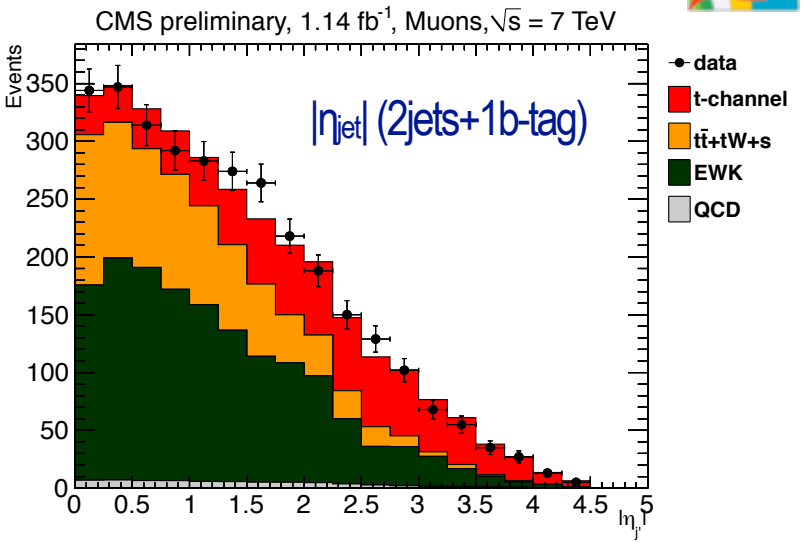
$\sigma_t = 1.49$ +0.47-0.42$_{stat+syst}$ pb ~30%

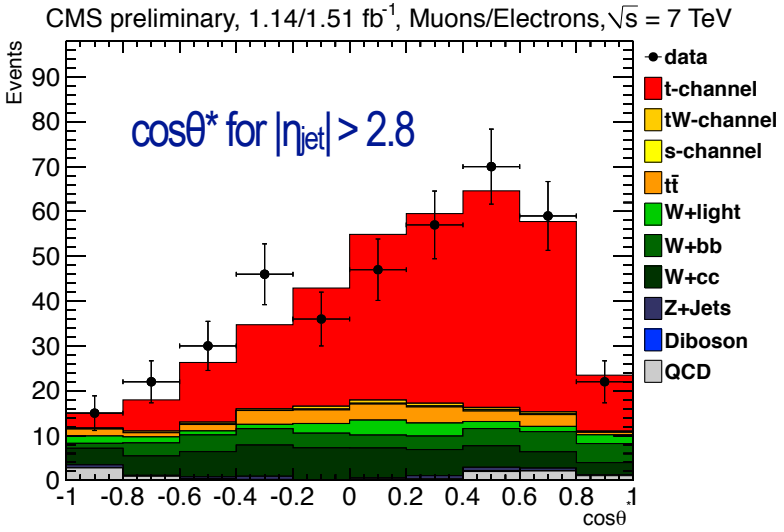
# LHC t-channel




- **Signature**
  - 1 e or μ
  - 2 or 3 jets
  - $m_T(W)>40$ GeV (μ) or $E_T^{miss}>35$ GeV (e)
- **Analysis**
  - Cross section from template fit to $|\eta_{jet}|$ of 2jets+1b-tag sample
  - Background from control samples:
    - 2 jet + 0 b-tag (W+jets)
    - 3 jet + 2 b-tag (tt-enriched)
  - Left-handed top production: cosθ* (angle between lepton and non-b jet in top rest frame) for $|\eta_{jet}|>2.8$
- **Dominant uncertainties**
  - Statistics, W+hq, jet energy scale, b-tagging

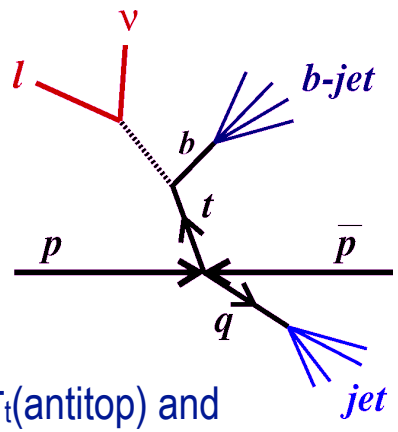
CMS TOP-11-021 1.1(μ)/1.5(e) fb$^{-1}$



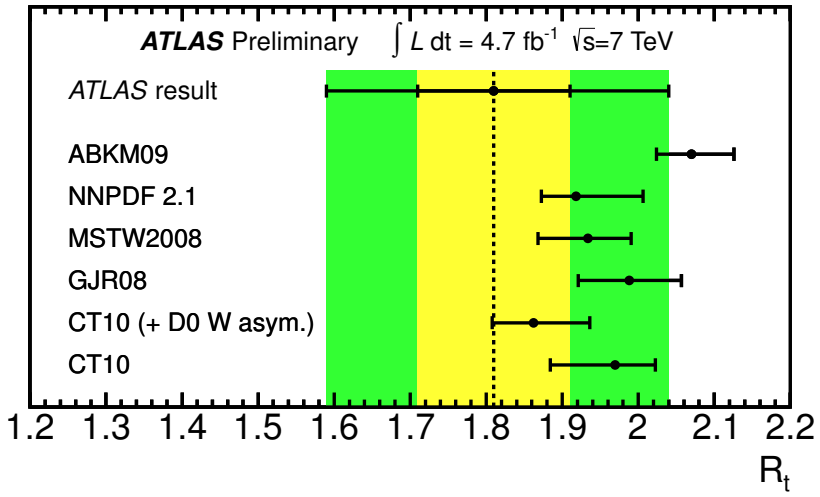

$\sigma_s = 70.2 \pm 5.2_{stat} \pm 10.4_{syst} \pm 3.4_{lumi}$ pb ~17%

# LHC t-channel



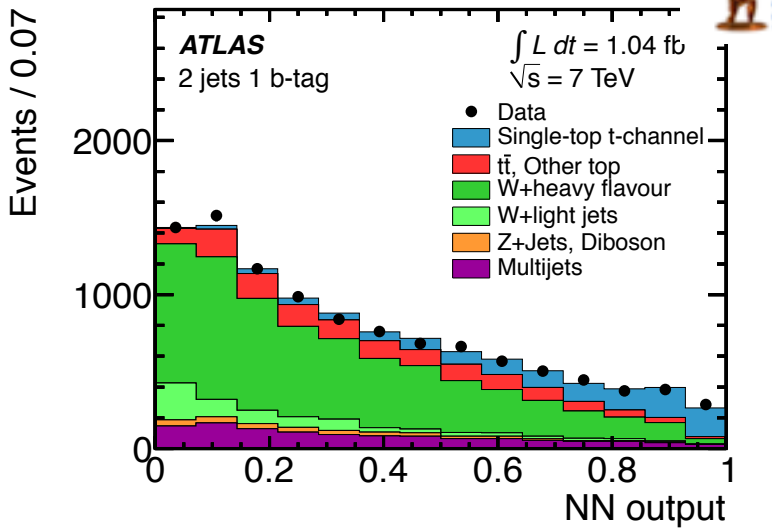

- **Analysis**
  - Neural Network
  - Also determine $\sigma_t$(top) and $\sigma_t$(antitop) and their ratio $R_t$

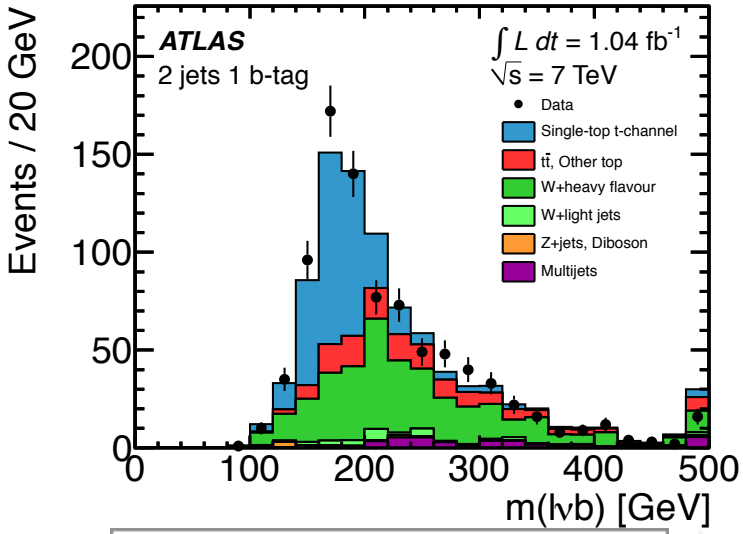
ATLAS-CONF-2012-056 ATLAS 4.7 fb$^{-1}$




$R_t = 1.81 \pm 0.10_{stat} + 0.21\text{-}0.20_{syst}$ ~17%

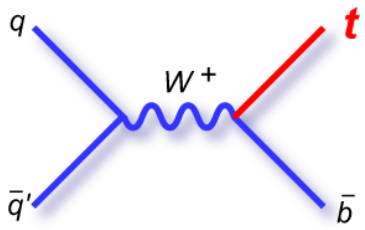
arXiv:1205.3130 ATLAS 1.04 fb$^{-1}$

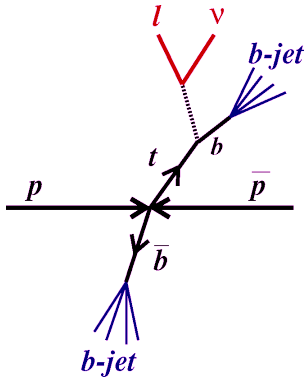



$\sigma_t = 83 \pm 4_{stat} +20\text{-}19_{syst}$ pb ~22%

# LHC s-channel



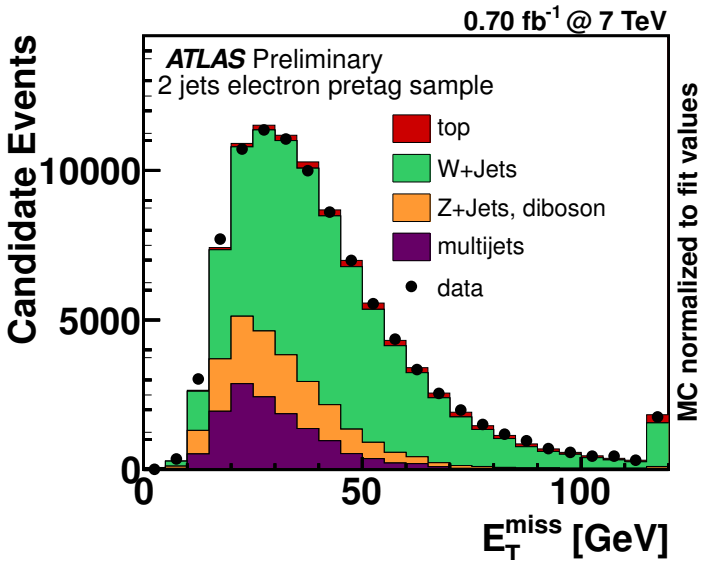



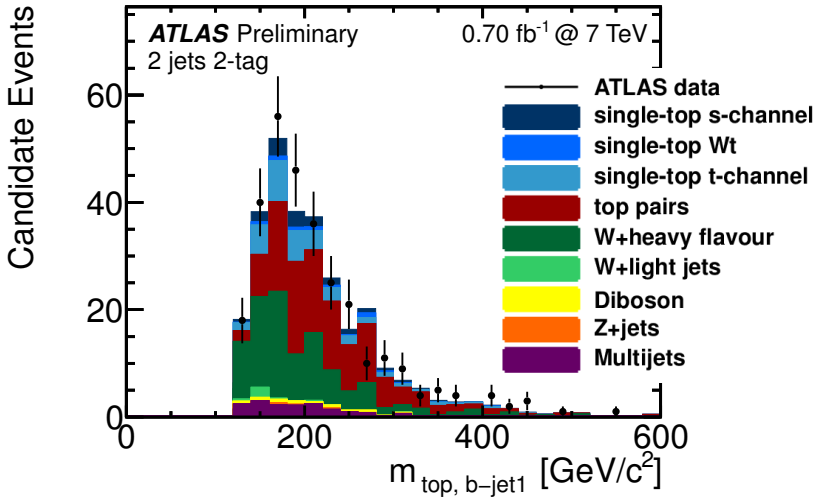

- **Signature**
  - 1 e or μ, 2 b-tagged jets, $E_T^{miss}$
- **Cut-based selection optimized on signal MC**
  - $30 < m_{top,j2} < 247$ GeV/c²
  - $p_T(j_1, j_2) < 189$ GeV/c
  - $m_T(top) < 111$ GeV
  - $0.43 < \Delta R(b - jet_1, b - jet_2) < 3.6$
  - $123 < m_{top,j1} < 788$ GeV/c²
  - $0.74 < \Delta R(b - jet_1, lepton) < 4.68$
- **Determine upper limit:**

$\sigma_s < 26.5$ pb observed (< 20.5 pb expected)

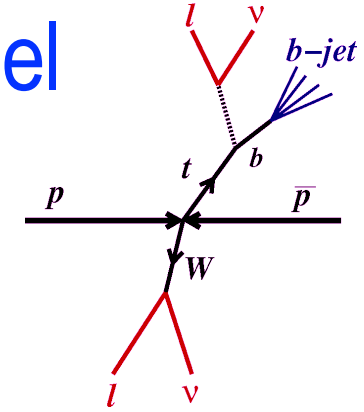
SM prediction: 4.6 pb

ATLAS-CONF-2011-118 0.70 fb$^{-1}$



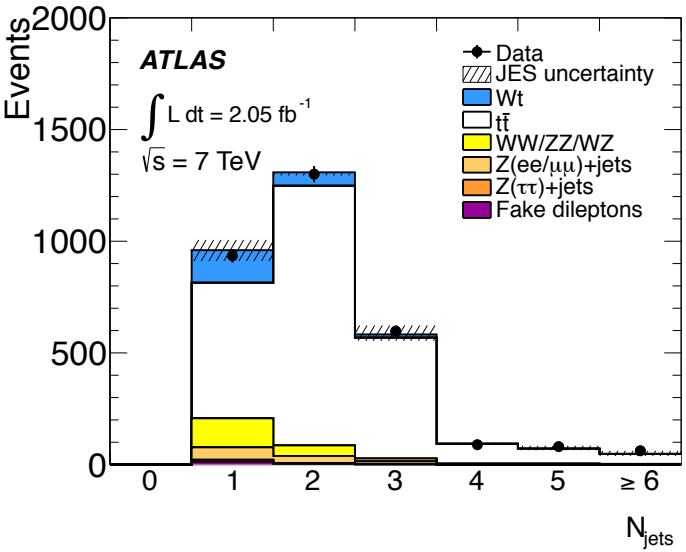



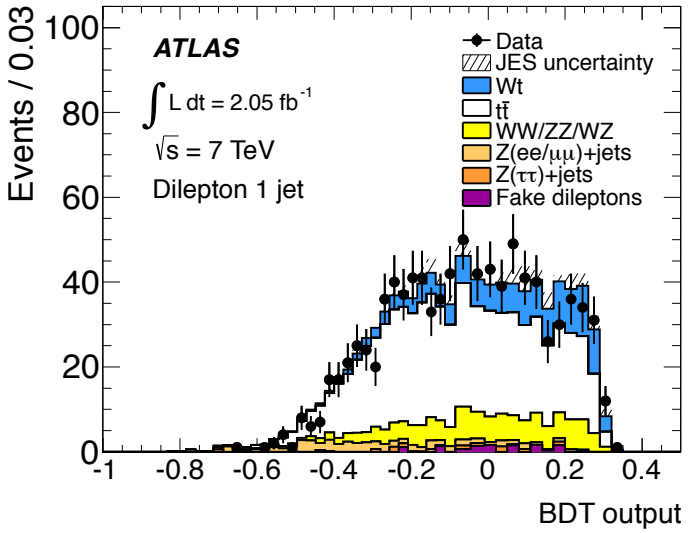
# LHC tW-channel




- **Event Signature**
  - 2 leptons, 1 jet (no b-tag)
  - $E_T^{miss}$
- **Analysis**
  - NLO (>1 jet) interference terms with tt production: take difference between LO and NLO as model uncertainty
  - BDT with 22 variables ($p_{T,sys}$: vect. pT-sum of leading leptons, $E_T^{miss}$, $p_{T,sys}/sqrt(H_{T(leptons)}+sum(E_T))$, …)
  - Cross section from template fit to BDT output
- **Dominant uncertainties:**
  - Statistics, jet energy scale, hadronization (pythia/herwig)
- **First measurement: signal established** 3.3σ

arXiv:1205.5764 ATLAS 2.05 fb$^{-1}$




$\sigma_s = 16.8 \pm 2.9_{stat} \pm 4.9_{syst}$ pb

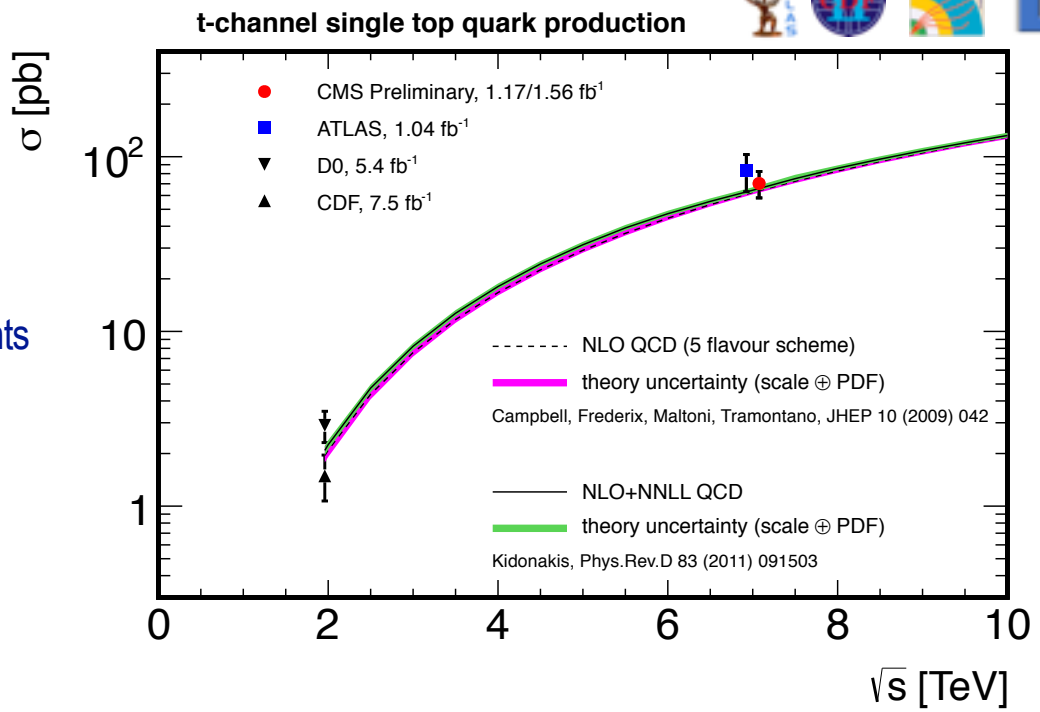
CMS TOP-11-022 2.1 fb$^{-1}$

$\sigma_s = 22\ ^{+9}_{-7}{}_{stat+syst}$ pb

2.7σ

# Summary single-top

- All experiments: t-channel measurements
- LHC s-channel: upper limit
- tW channel:
  - Inaccessible at the Tevatron
  - First measurement at the LHC




| | t-channel ($\sigma_{tqb}$) [pb] | s-channel ($\sigma_{tb}$) [pb] | tW-channel [pb] |
|---|---|---|---|
| expected 1.96TeV | 2.26 | 1.04 | 0.28 |
| CDF | 1.49 $+0.47-0.42_{stat+sys}$ | 1.81 $+0.63-0.58_{stat+sys}$ | - |
| D0 | 2.9 $\pm 0.59_{stat+sys}$ | 0.98 $\pm 0.63_{stat+sys}$ | - |
| expected 7TeV | 64.6 | 4.6 | 15.7 |
| ATLAS | 83 $\pm 4_{stat}$ $+20-19_{syst}$ | < 26 obs. (22 exp.) | 16.8 $\pm 2.9_{stat}$ $\pm 4.9_{sys}$ |
| CMS | 70.2 $\pm 5.2_{stat}$ $\pm 10.4_{syst}$ $\pm 3.4_{lum}$ | - | 22 $+9-7_{stat+sys}$ |

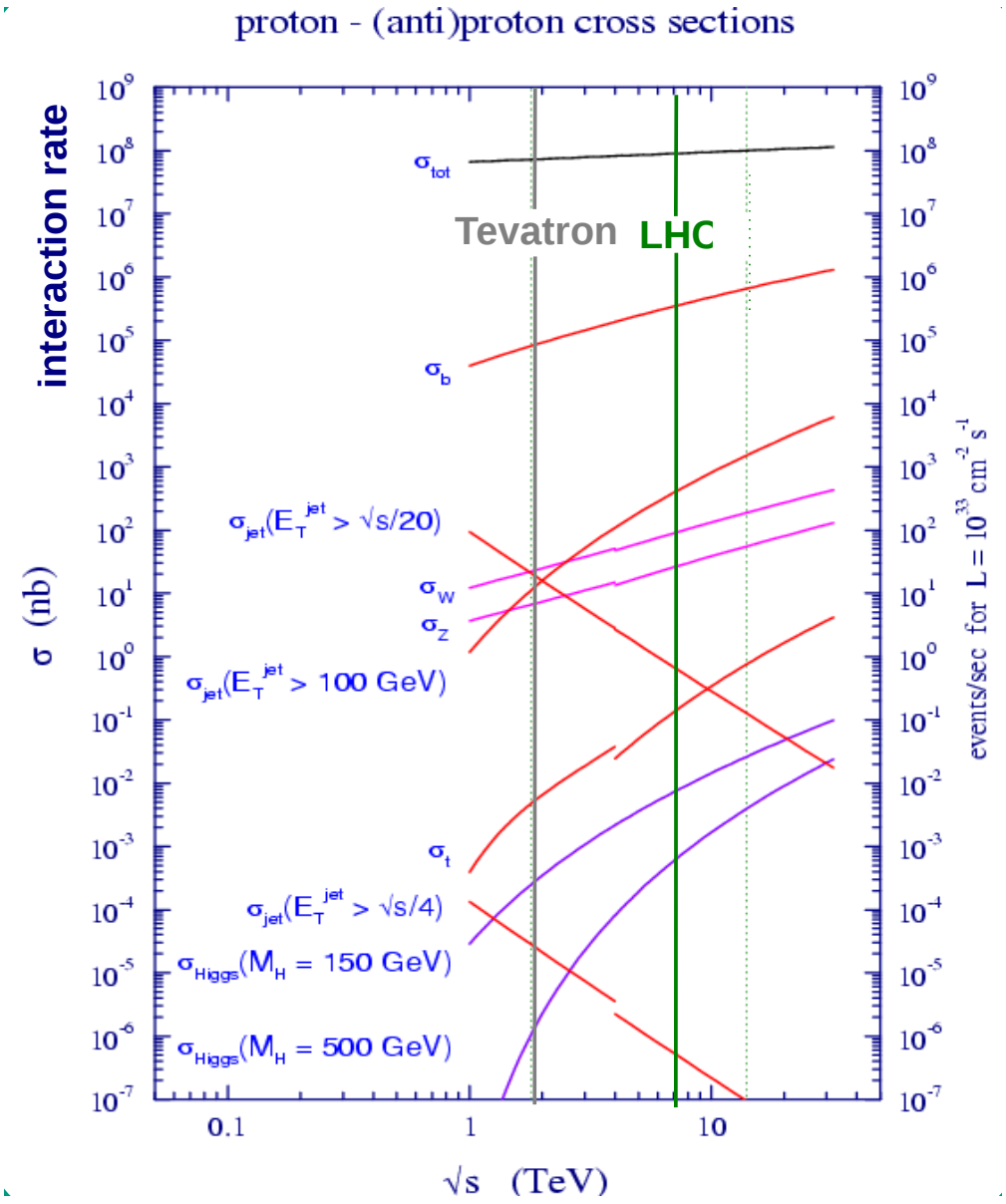
# Conclusions

- **Top Quark Production: Key to QCD, Electro-Weak and New Physics**
- **Tevatron: measurements based on full ~10 $fb^{-1}$ are coming out now**
- **LHC: complementary, entering < 5%-regime of precision → challenging / constraining theory**
- **Recent first LHC measurements: $\sigma_{tt}$(8TeV), $d\sigma_{tt}/dX$(7TeV), single top in tW-channel, ttW/Z**
- **All results so far in good agreement with SM predictions**
- **Many more measurements with improved precision underway (TOP2012 workshop next week)**
- **Statistics → systematics: expect another leap in precision with 2012 data**

# Backup

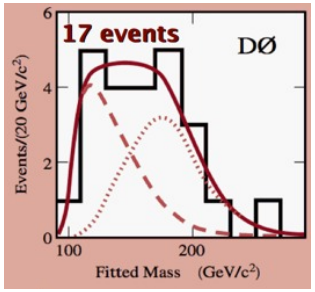
# Outline of this Talk

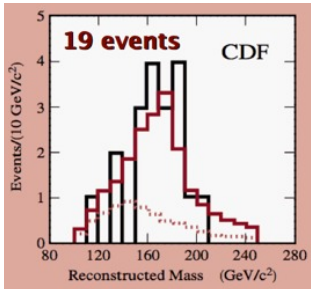
- **Introduction**
- **Inclusive tt Cross Sections**
- **Detailed tt Measurements**
  - Differential cross sections
  - tt+jets
  - tt+W/Z
- **Single Top Cross Sections**
  - t channel
  - s channel
  - tW channel
- **Conclusions**



# Tevatron: Top Discovery

- **Birthplace of the top quark**
  - 1995: top quark pairs

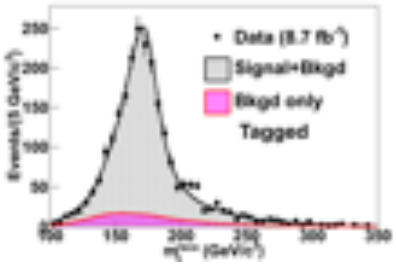


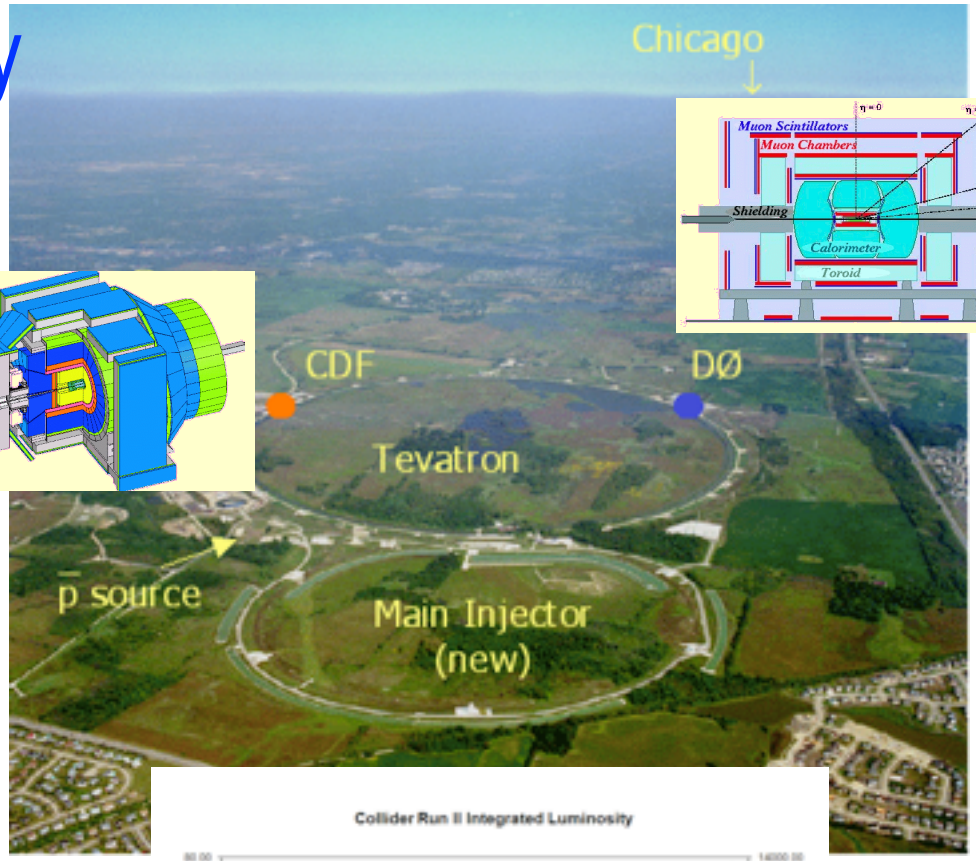



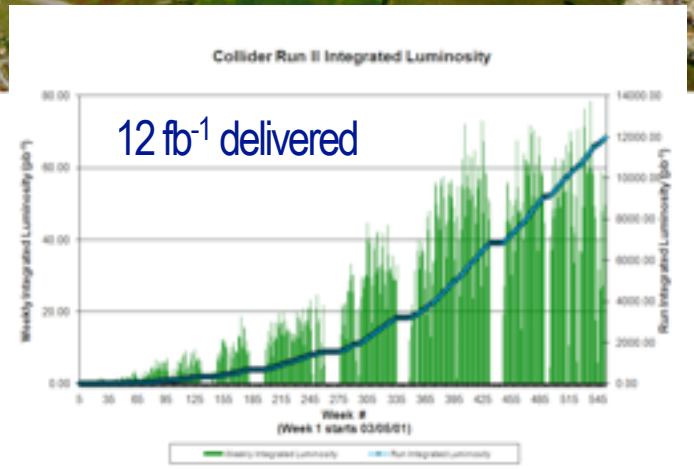

  - 2009: single top

- **Unique $p\bar{p}$ collider**
  - 1.96 TeV, 4.4 x $10^{32}$ $cm^{-2}s^{-1}$
  - 1-2 tt / h ⟶ 70,000 top pairs per experiment

- **A wealth of precision measurements of top quark production, decay and properties**



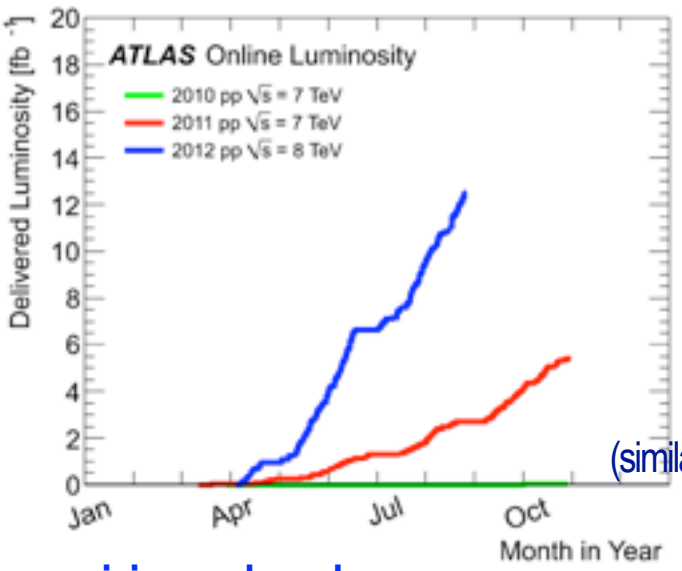




**Tevatron data taking stopped 30 September 2011**

# LHC: Top Factory

- **Datataking started March 30, 2010**
- **pp collider**
  - 7 … 8 … up to 14 TeV
  - max. inst. lum.: 8 x $10^{33}$ $cm^{-2}s^{-1}$
  - ~ 150 tt/ hour
  - > 12 $fb^{-1}$ delivered in 2012 alone
  - 3,000,000 top pairs per experiment
- **Precision measurements of top quark production, decay and properties in full swing**
  - ATLAS+CMS: > 30 journal publications on top quarks alone since 2010

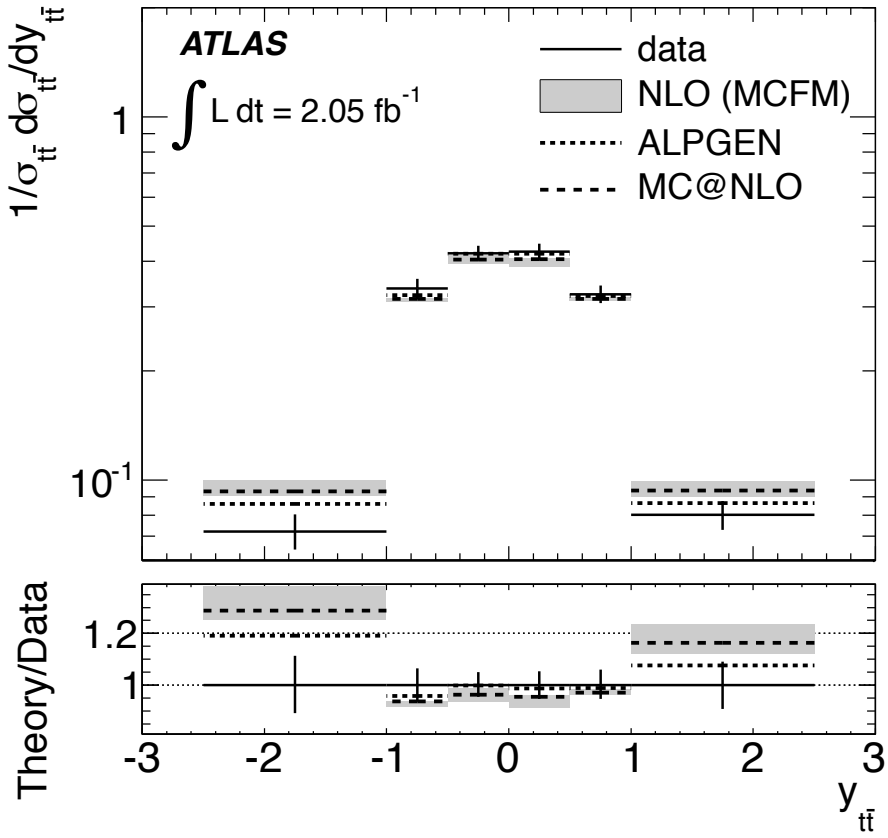



(similar for CMS)

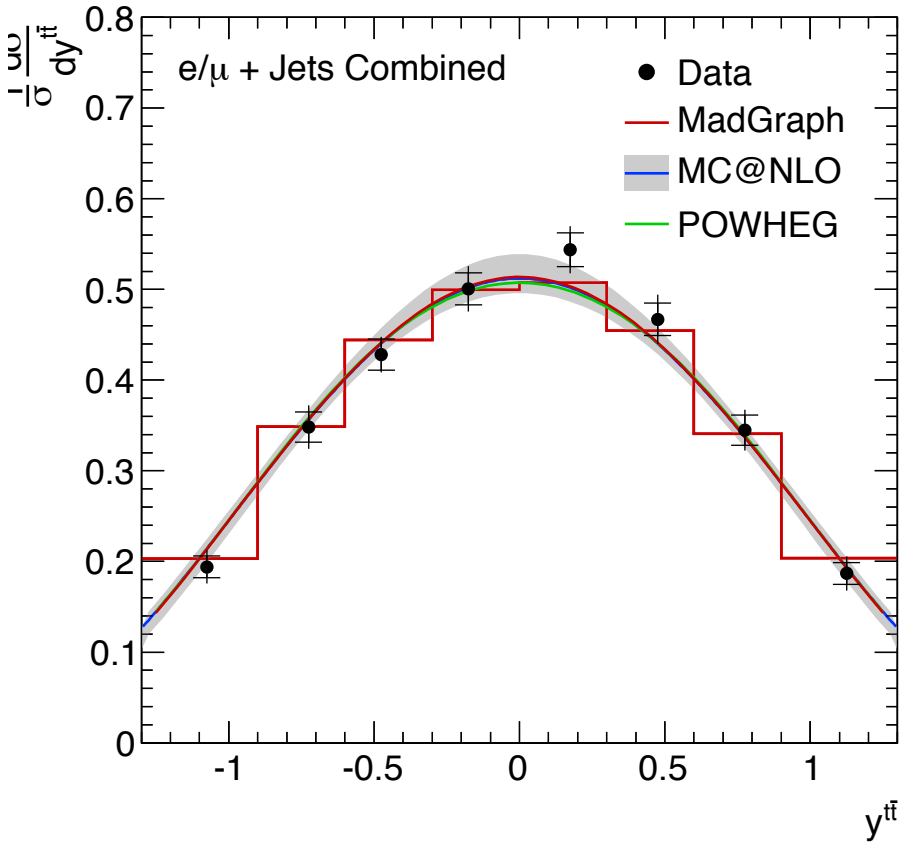
**LHC: built to exceed Tevatron precision and reach**

# LHC: Top Quark Pair Distributions: $y(t\bar{t})$

arXiv 1207.5644 2.1 fb$^{-1}$




CMS TOP-11-013 1.1 fb$^{-1}$



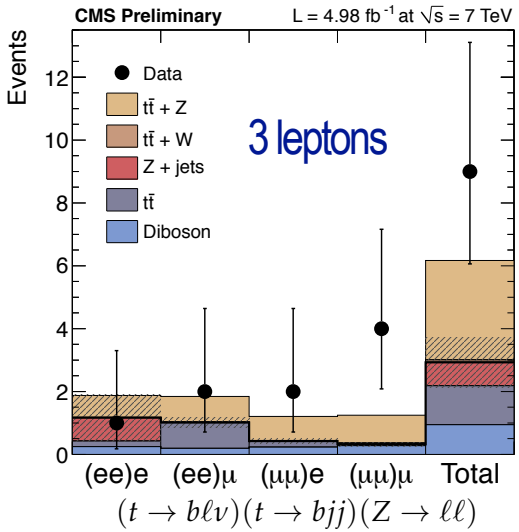

$y(t\bar{t})$

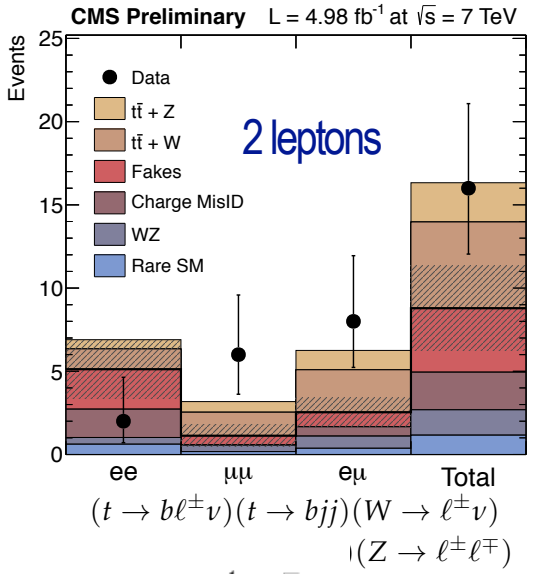
**sensitive to g-PDF at high x**

# tt+W and tt+Z

CMS TOP-12-014 5.0 fb$^{-1}$

- **3-Lepton Analysis**
  - 3 e or μ (pt> 20,20,10)
  - 2 opposite-charge same-flavour
  - 3 jets, 2 b-tags
  - $H_T$>120 GeV
- **2-Lepton Analysis**
  - 2 same-charge e or μ
  - 3 jets, 1 b-tag
  - $H_T$>100 GeV
- **First measurement: signal established** 4.7σ




$\sigma(ttV) = 0.51 + 0.15\text{-}0.13_{stat} + 0.05\text{-}0.04_{syst}$ pb

ATLAS CONF-2012-126 4.7 fb$^{-1}$

- Harder selection: 3 e ($p_T$> 25) or μ ($p_T$>20), 4 jets, $E_T^{miss}$>30 GeV

Limit: σ(ttZ) < 0.71 pb (0.74 pb exp.)