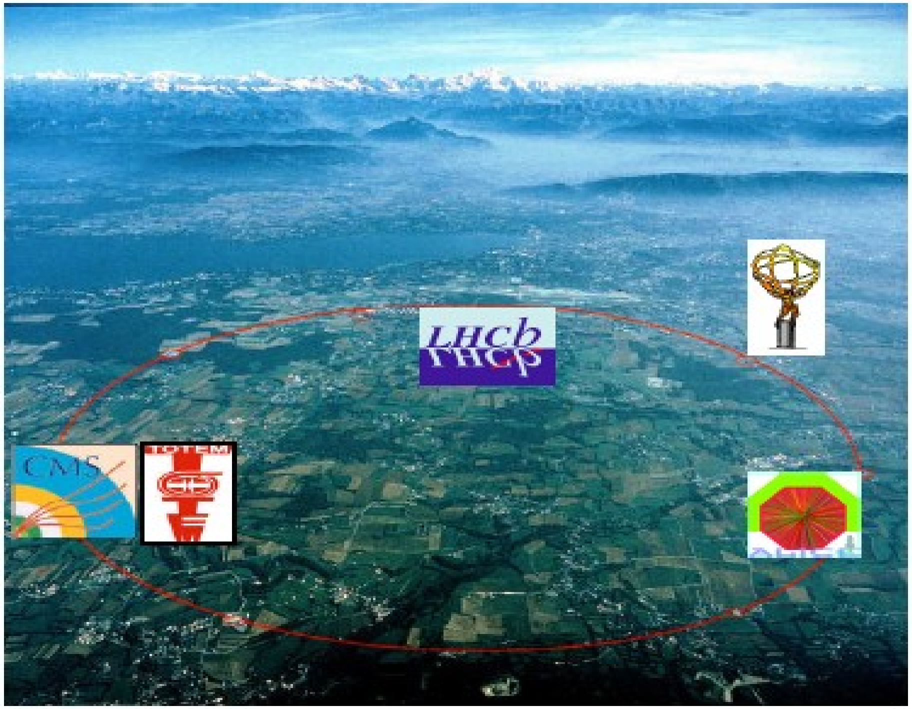
Physics with first fb^{-1}

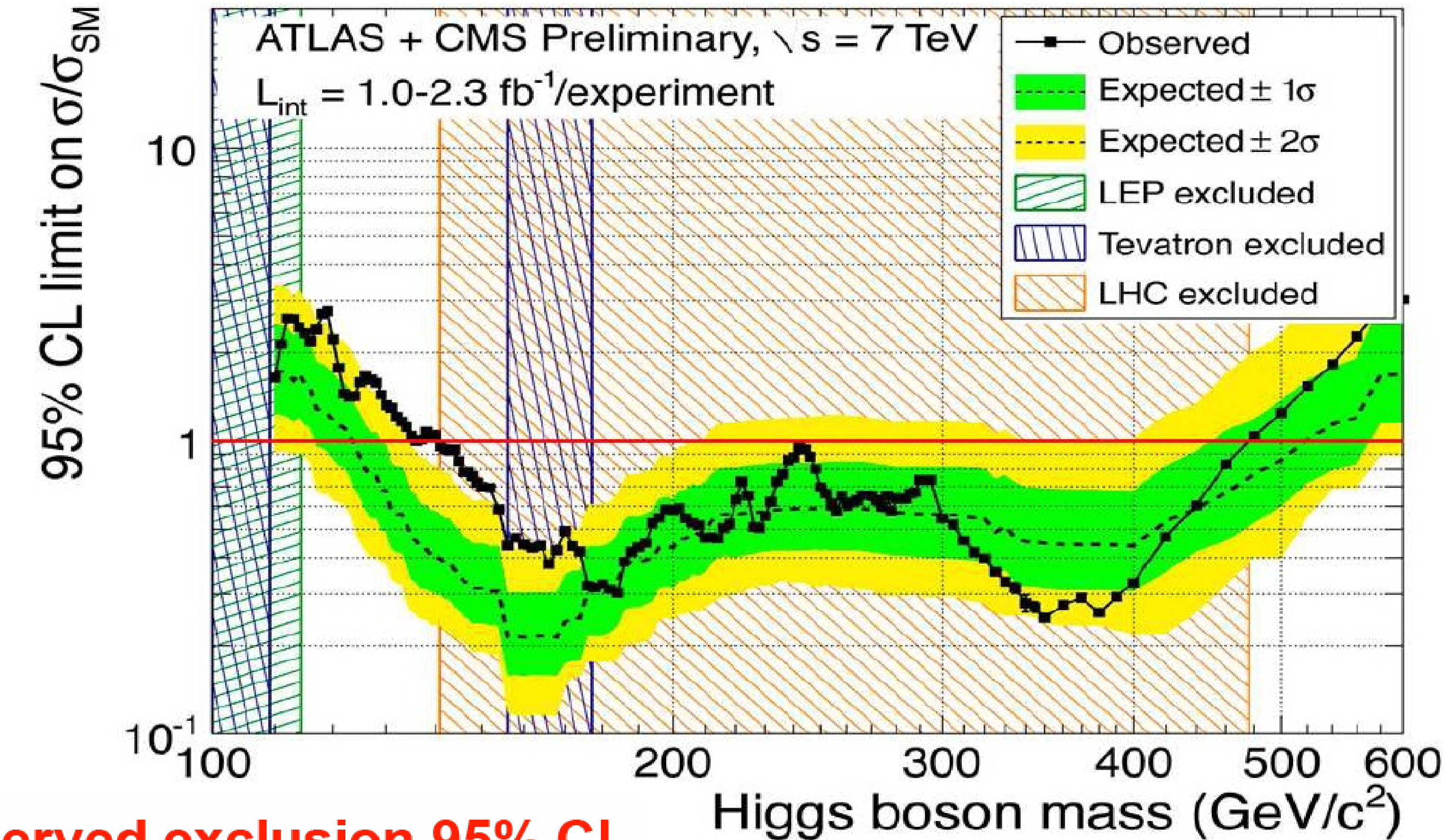
at Large Hadron Collider

Today:

- **Physics with top quarks**



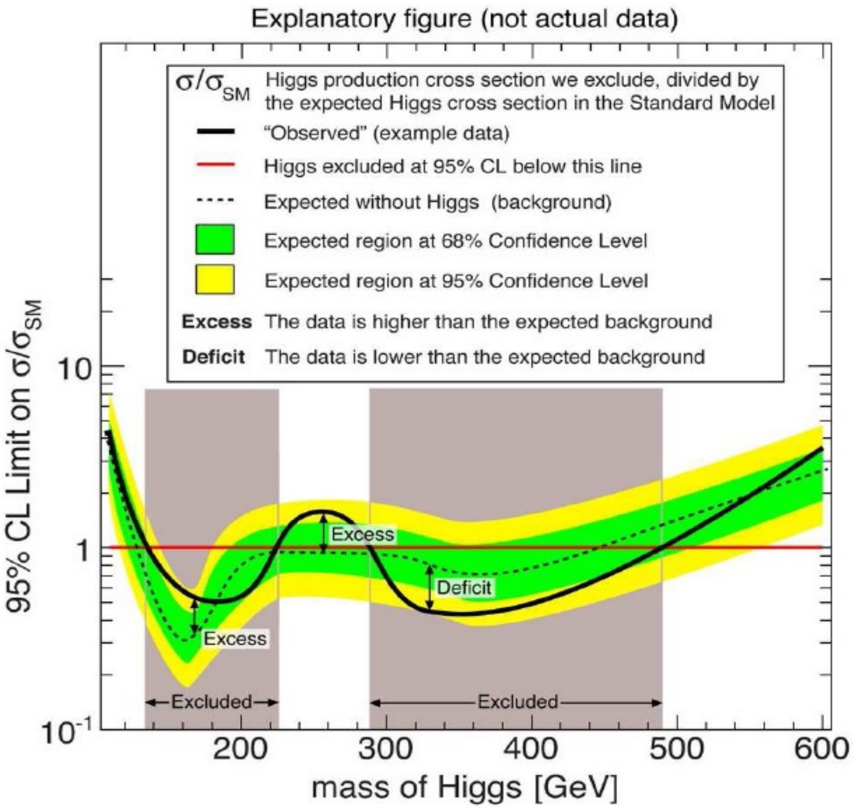
News from HCP (Paris 2011)



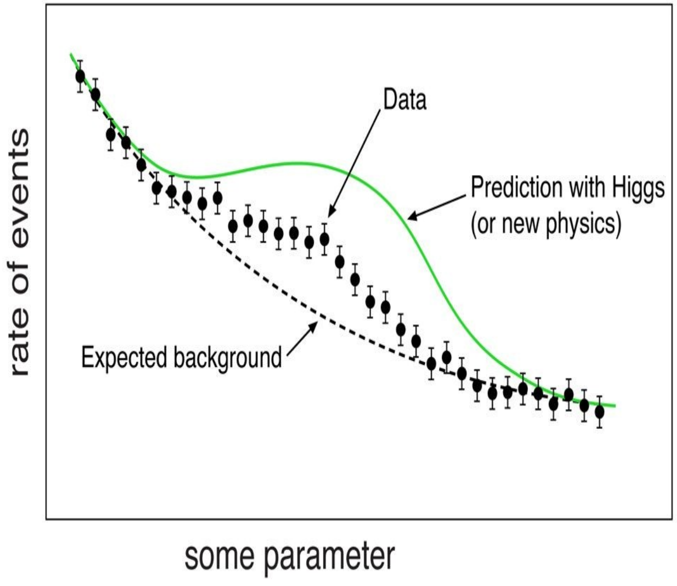
Observed exclusion 95% CL
141-476 GeV

Expected exclusion 95% CL
124-520 GeV

Explanatory figure



Possible excess



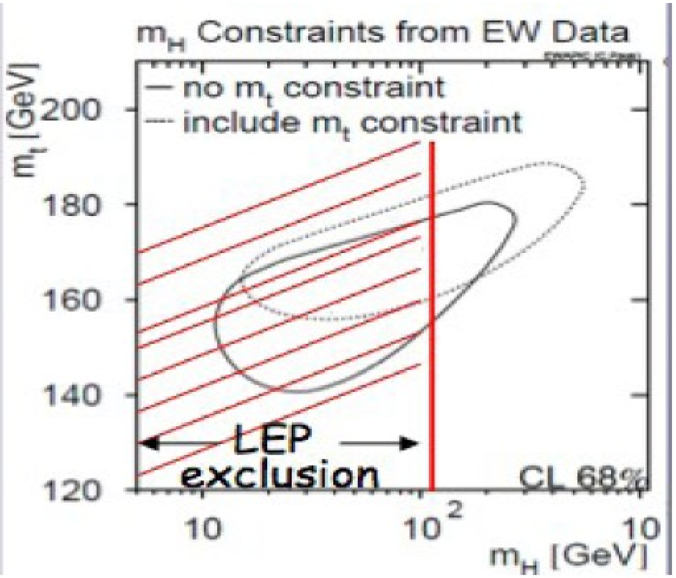
Brief history of the top quark

- 1976: **Discovery of Upsilon** at Fermilab
  - Contains a 5th quark: the **b-quark**
    - Structure of the families **suggested existence of** the 6th quark: **the top**
- From here on the race to find top quark begun
  - Petra (e^+e^-): **m_t > 23.3 GeV** in 1984
  - Tristan (e^+e^-) in Japan: **m_t > 30.2 GeV** in late 80s
  - SPS (p pbar): discovery of W and Z in 1983
  - UA1: **m_t > 44 GeV** in 1988 (after having access in 1984 which they thought was evidence for the top)
  - LEP (e+e-): **m_t > 45.8 GeV** in 1990
  - UA2: **m_t > 69 GeV** which closed down channel
    - $W \rightarrow t\,b$ search closed down

Brief history of the top quark

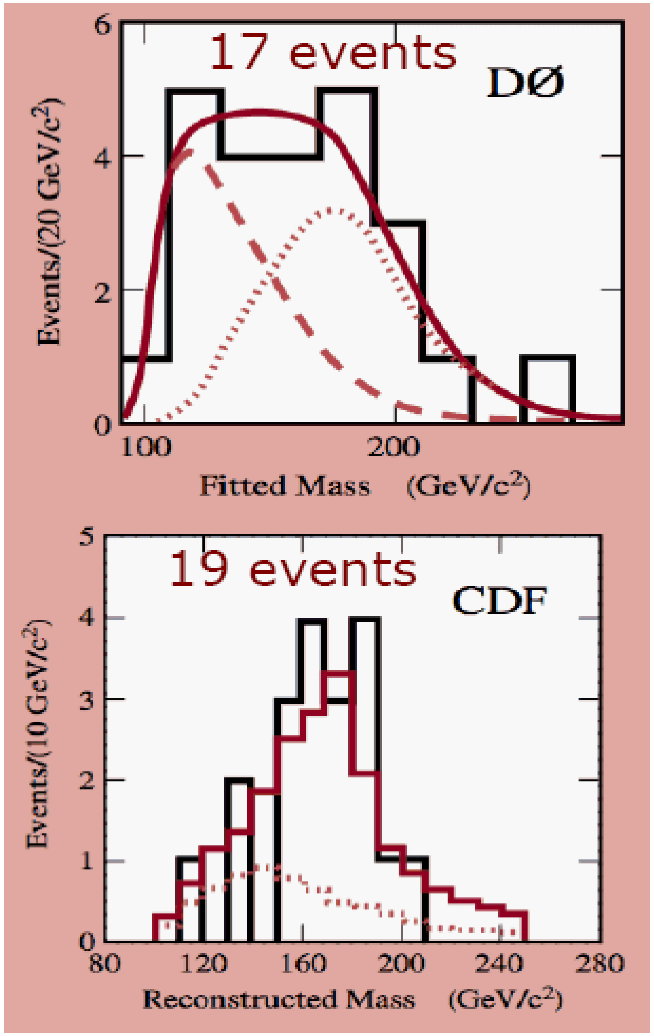
- Searching again for ttbar production with top mass above W boson mass
  - **1992:** first lower limits on top from CDF (**m_t > 91 GeV**)
  - **1994:** first lower limits on top from D0 (**m_t > 131 GeV**)
- Electroweak fits from LEP/SLS/Tevatron data:
  - **155 GeV < m_t < 185 GeV**
- Early **1994**:

  "Evidence for top at CDF"

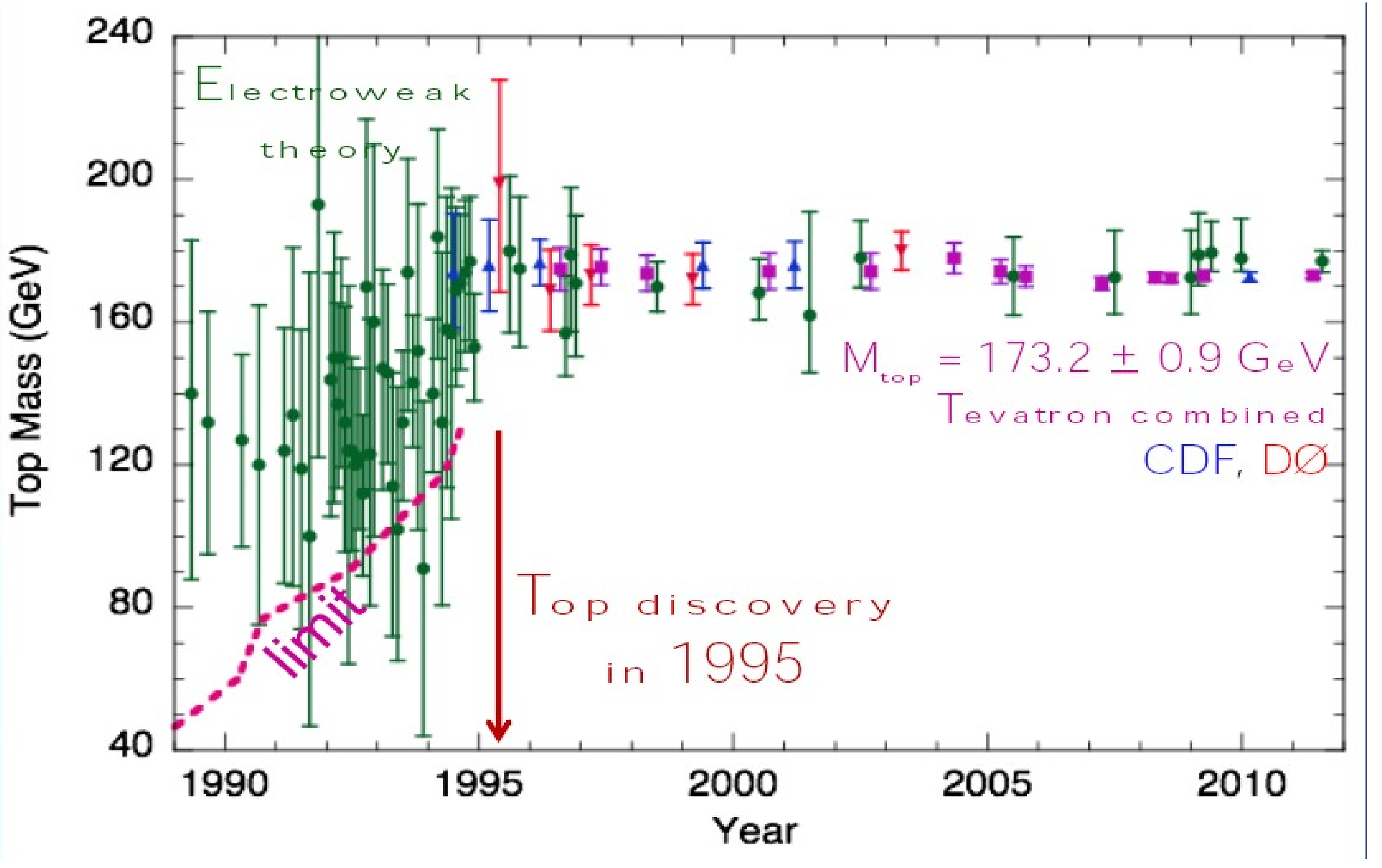


Top-quark discovery

- **February 24th 1995**: Simultaneus submission of **top discovery** papers to PRL by CDF and D0
  - 50 pb^{-1} at D0
    - m_t = 199 ± 30 GeV
    - σ_{tt} = 6.4 ± 2.2 pb
    - Background-only hypothesis rejected at 4.6σ
  - 67 pb^{-1} at CDF
    - m_t = 176 ± 13 GeV
    - $\sigma_{tt} = 6.8^{+3.6}_{-2.4}$ pb
    - Background-only hypothesis rejected at 4.8σ

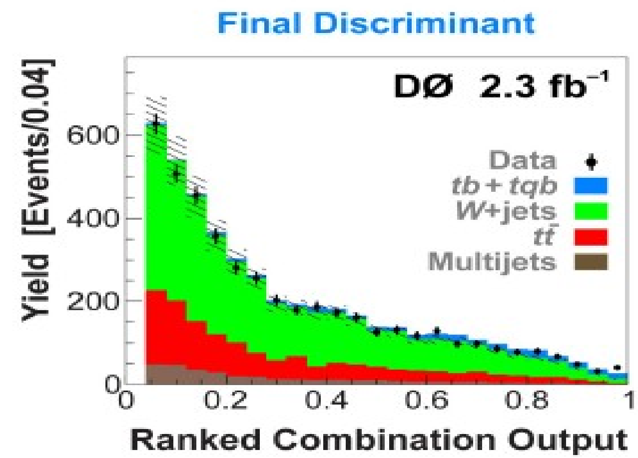


Top quark mass measurement

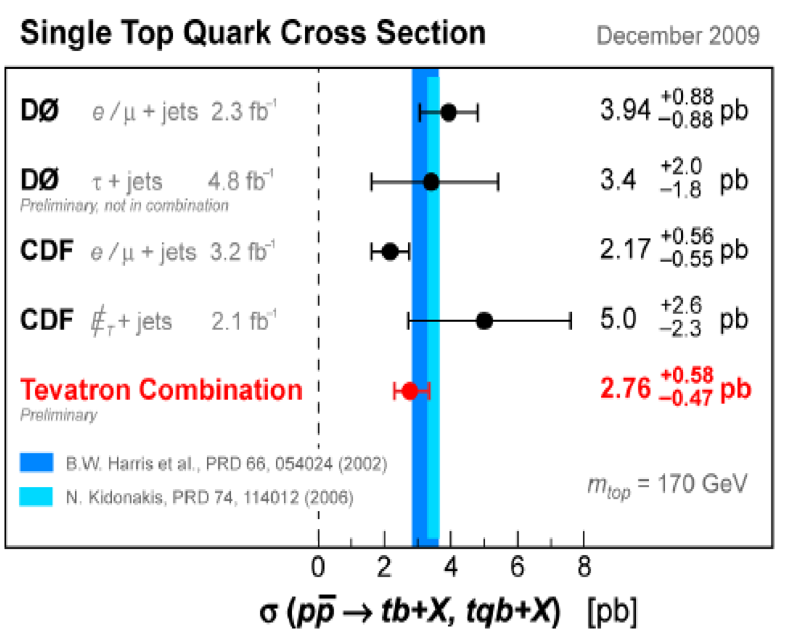


Single top-quark production

- **2009**: Observation of top quarks in single top production
  - **5σ** by CDF & D0!

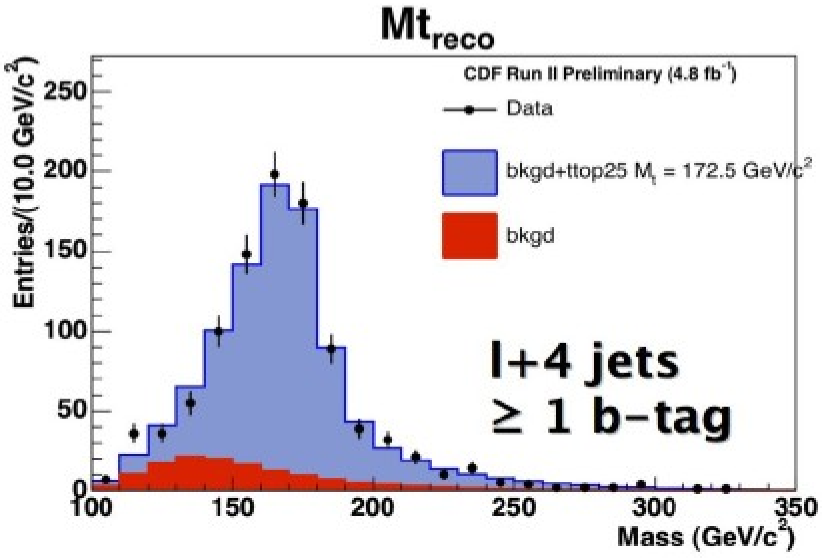


- Single top: very challenging channel
  - Low signal: similar **signature like W+jets!**
  - Counting only: Uncertainty on background larger than expected signal



Where we are today?

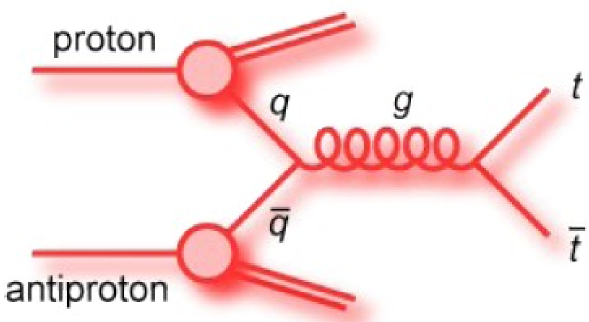
- **Tevatron:**
  - Roughly 1000s of events
  - Precision measurements of production cross-section
  - Observation in single top
  - Precise study of top properties
  - Searches for new physics using top quarks



Top-quark pair production

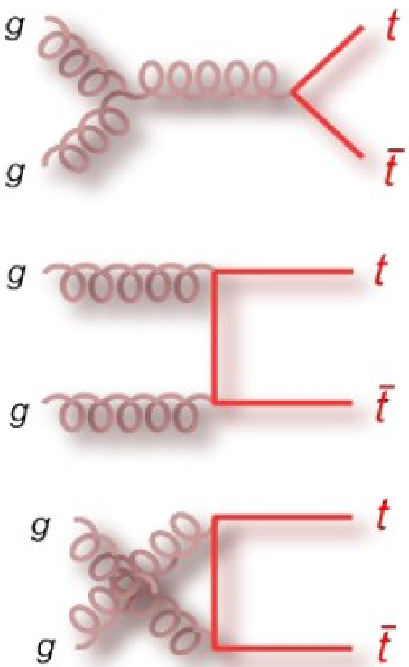
- Most properties measured in $t\bar{t}$ events
- At Tevatron:

  85% + 15%



- At LHC:
  14 TeV: 10% + 90%

  7 TeV: 15% + 85%



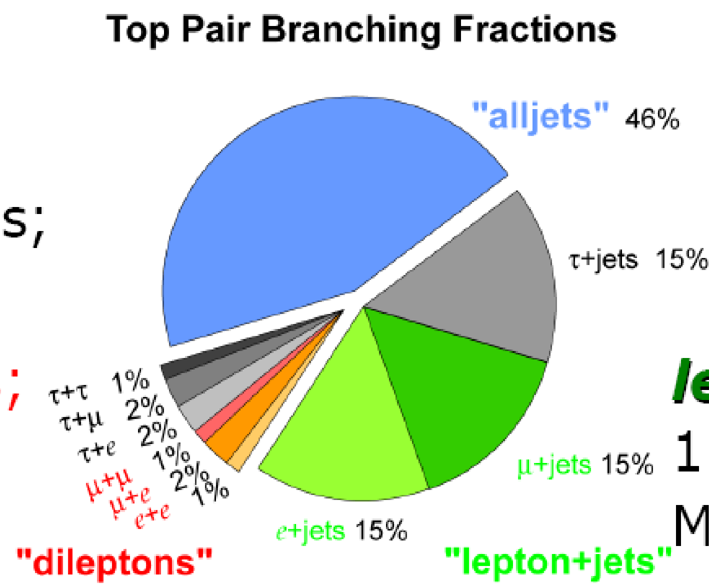
- Production cross section (@Tevatron):
  approximate NNLO: $\sigma = 7.46^{+0.48}_{-0.67}\,pb$ @ m_t=172.5GeV
  - 20 times higher @LHC (7TeV): $\sigma = 164.6^{+11.4}_{-15.7}\,pb$

Final states in ttbar

$t\bar{t} \rightarrow W^+bW^-\bar{b}$: Final states are classified according to W decay

$B(t \rightarrow W^+b) = 100\%$

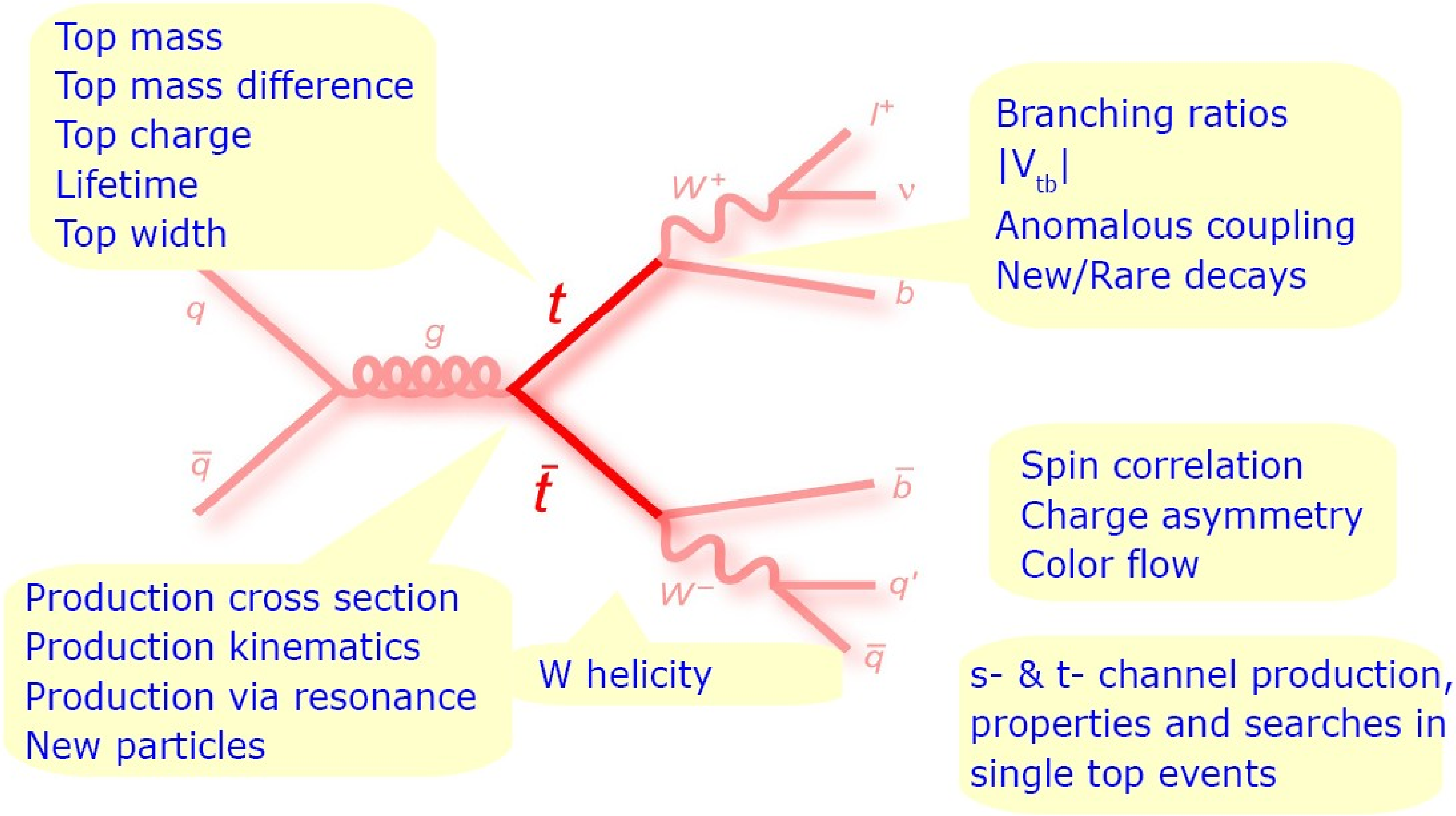
pure hadronic:
≥6 jets (2 b-jets)



dilepton:
2 isolated leptons;
High missing E_T
from 2 neutrinos;
2 b-jets

lepton+jets:
1 isolated lepton;
Missing E_T from neutrino;
≥4 jets (2 b-jets)

What we study about top-quark?



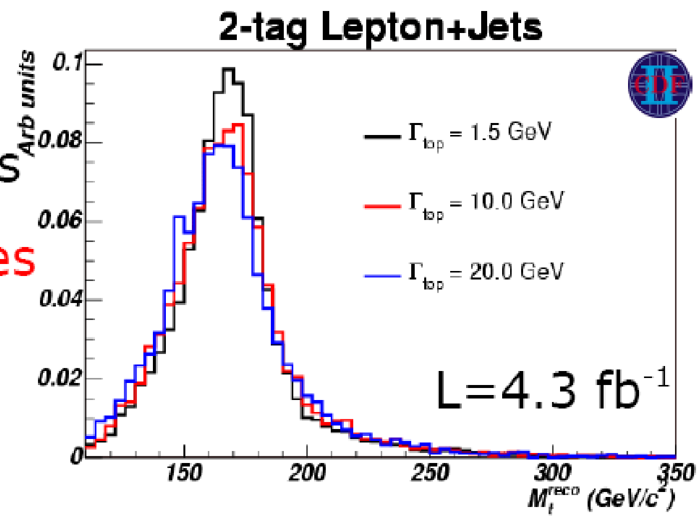
Measurements from Tevatron

Property	Measurement	SM Prediction	Luminosity (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
	D0: 2.90 ± 0.59 pb		5.4
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
	D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	5.3
	D0: 0.196 ± 0.065		5.4
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		5.4
M_t	Tev: 173.2 ± 0.9 GeV	-	up to 5.8
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	6.0
$\lvert V_{tb}\rvert$	CDF: $\lvert V_{tb}\rvert = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	3.2
	D0: $\lvert V_{tb}\rvert = 1.02^{+0.10}_{-0.11}$		5.4
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	0.2
	D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	5.6
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3

Top quark width

- Top lifetime ~5x10^{-25}s
  => Top quark decay width is 1.4 GeV
- Top width determination using l+jets events
- Direct: Reconstruct top mass → fit templates

  0.3<Γ<4.4 GeV @68% CL
  Γ<7.6 GeV @95% CL



PRL 105 232003

- Indirect: Extract partial and total width from combination of R measurement and t-channel cross section
  - Partial width from t-channel cross section

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to Wb)}$$

$$\Gamma_t = 1.99^{+0.69}_{-0.55}\, GeV$$

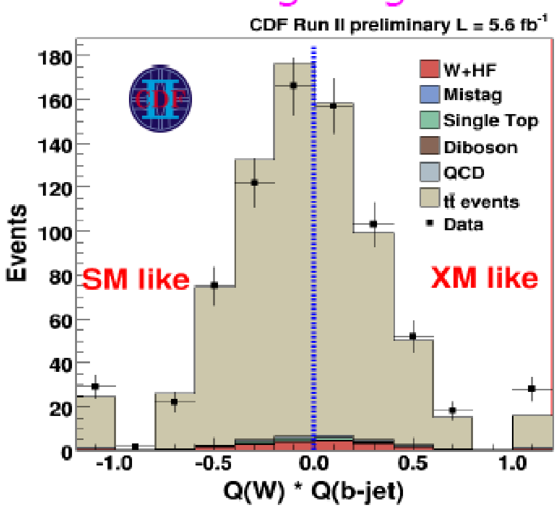
$$\tau_t = \frac{1}{\Gamma_t} = (3.3^{+1.3}_{-0.9}) \times 10^{-25}\, s$$

Most precise determination of top width!

PRL 106, 022001 (2011)

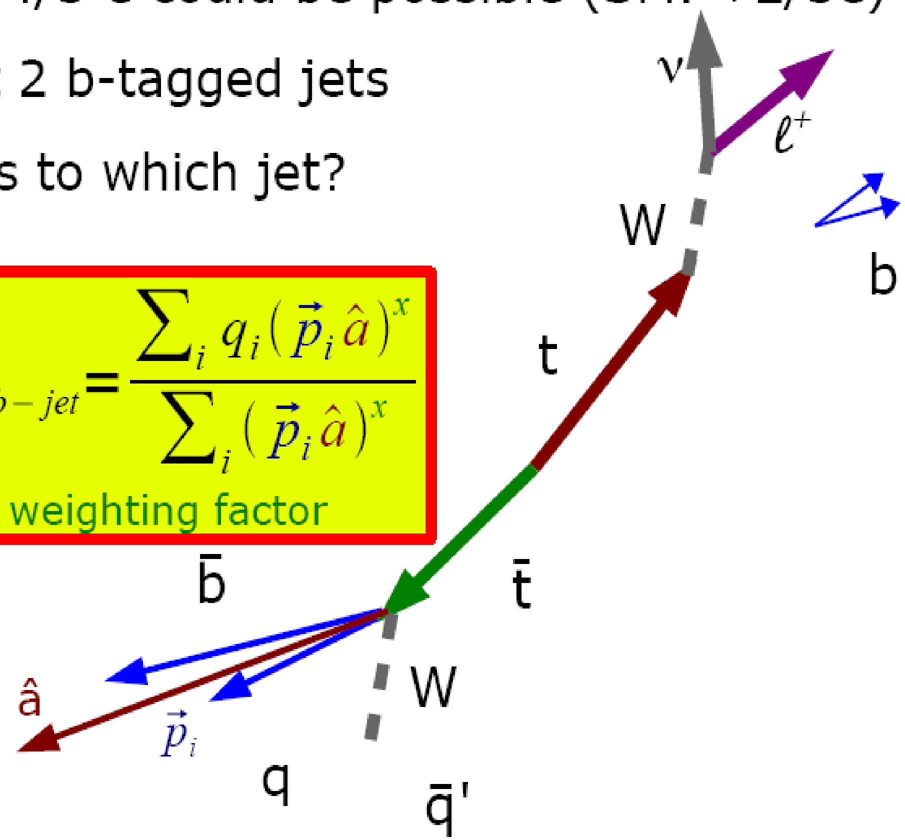
Top quark charge

- Exotic model with top charge -4/3 e could be possible (SM: +2/3e)
- Use l+jets events with at least 2 b-tagged jets
- Kinematic fit: Which W belongs to which jet?
- Determine top charge from
  - Lepton from W
  - Jet charge algorithm



$$Q_{b-jet} = \frac{\sum_i q_i (\vec{p}_i \hat{a})^x}{\sum_i (\vec{p}_i \hat{a})^x}$$

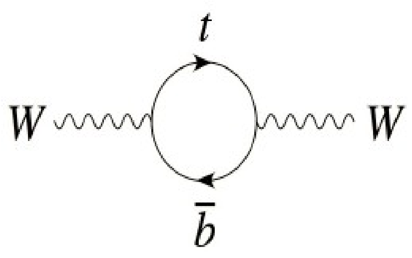
x: weighting factor

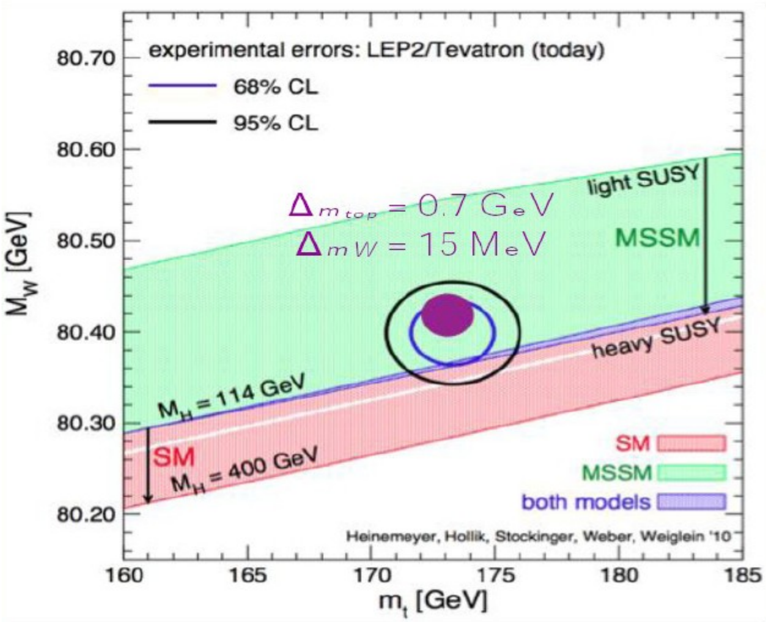


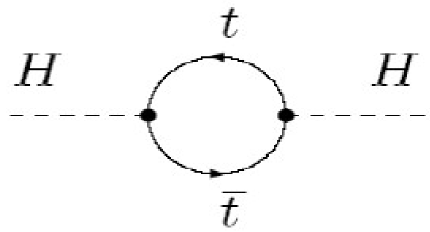
Exclude exotic top charge of -4/3 e at 95% CL!

Top quark mass

- Free parameter of the SM
- Together with W mass: puts constraint on Higgs mass

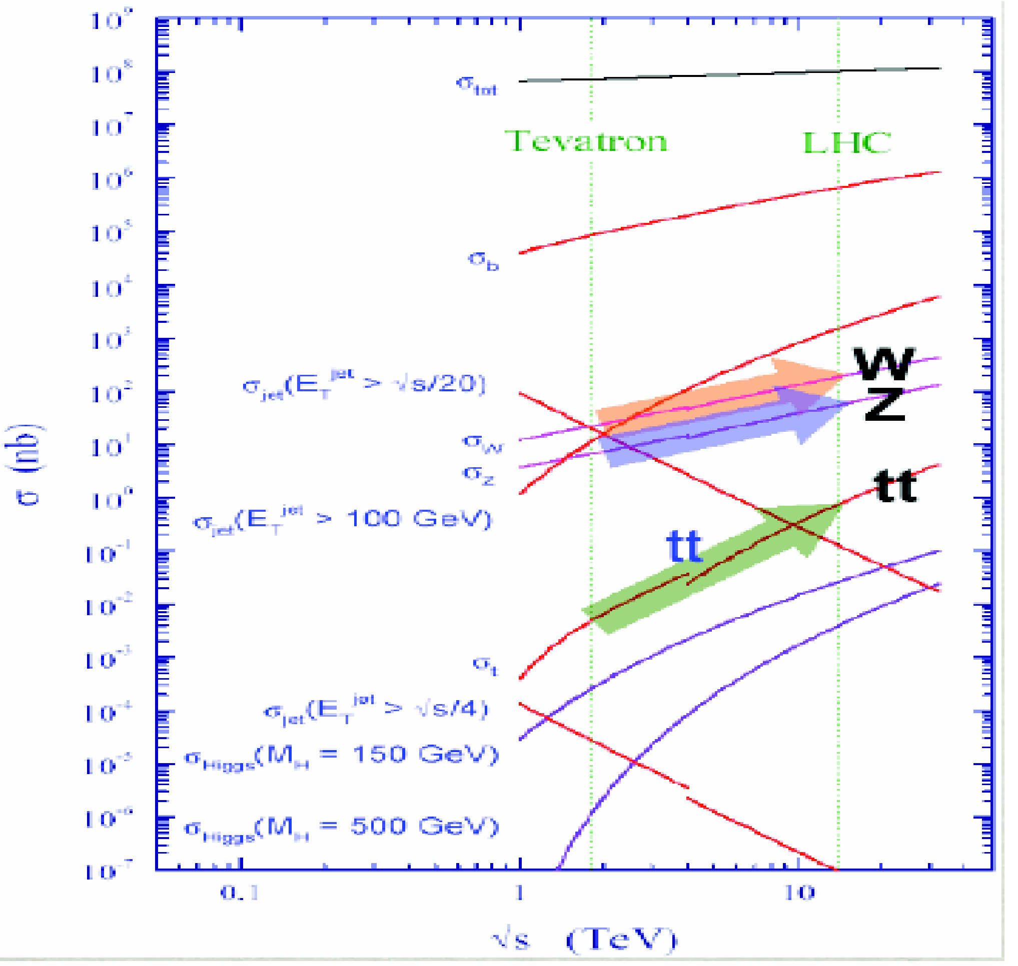






- Measurement done with several methods:
  Template method, ideogram, matrix element, etc.

Top-quarks at LHC



- **LHC:** since 2010 new top factory
  - Already now 10-100ks of events!
  - Already now some measurements limited by systematics

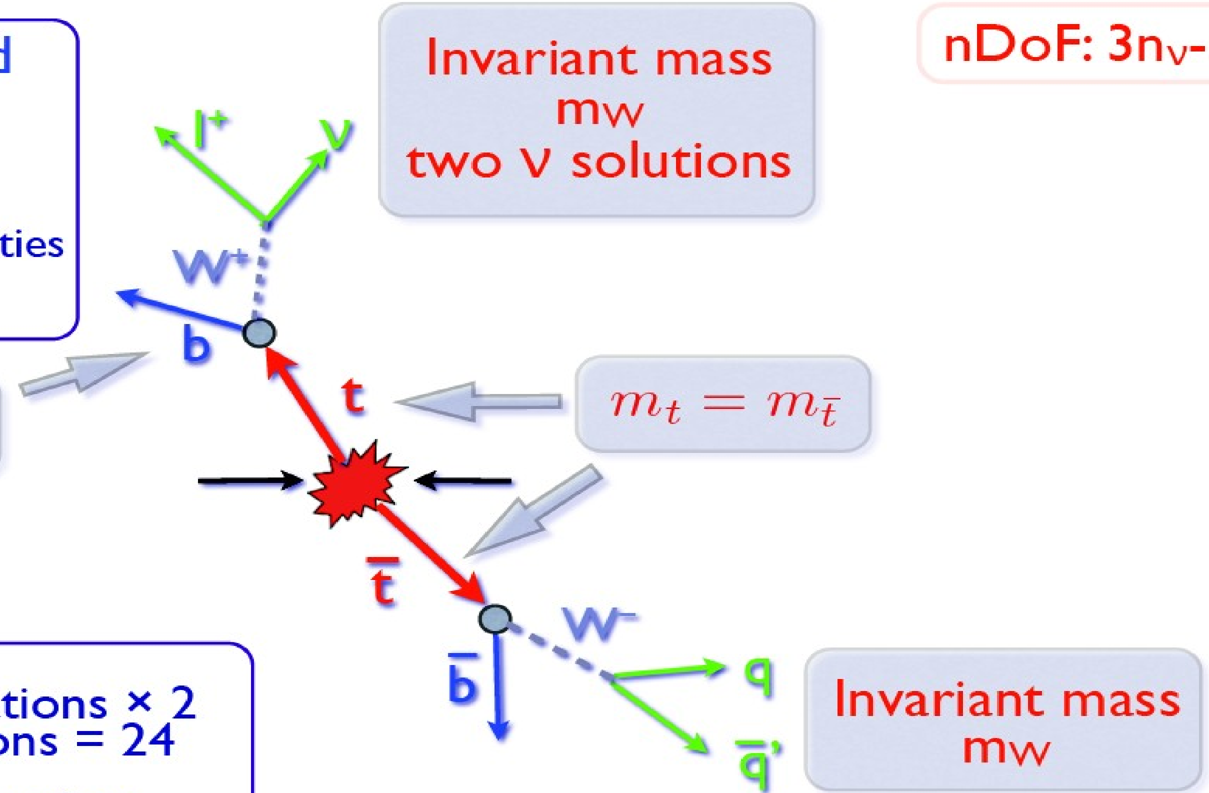
Top event reconstruction l+jets

nDoF: $3n_\nu$-5

Over constrained kinematic (-2)

- 18 variables
- 17 measured quantities
- 3 constraints

b-tag



- 12 jet configurations × 2 neutrino solutions = 24
- b-tag: 12 permutation
- 2 b-tags: 4 permutations

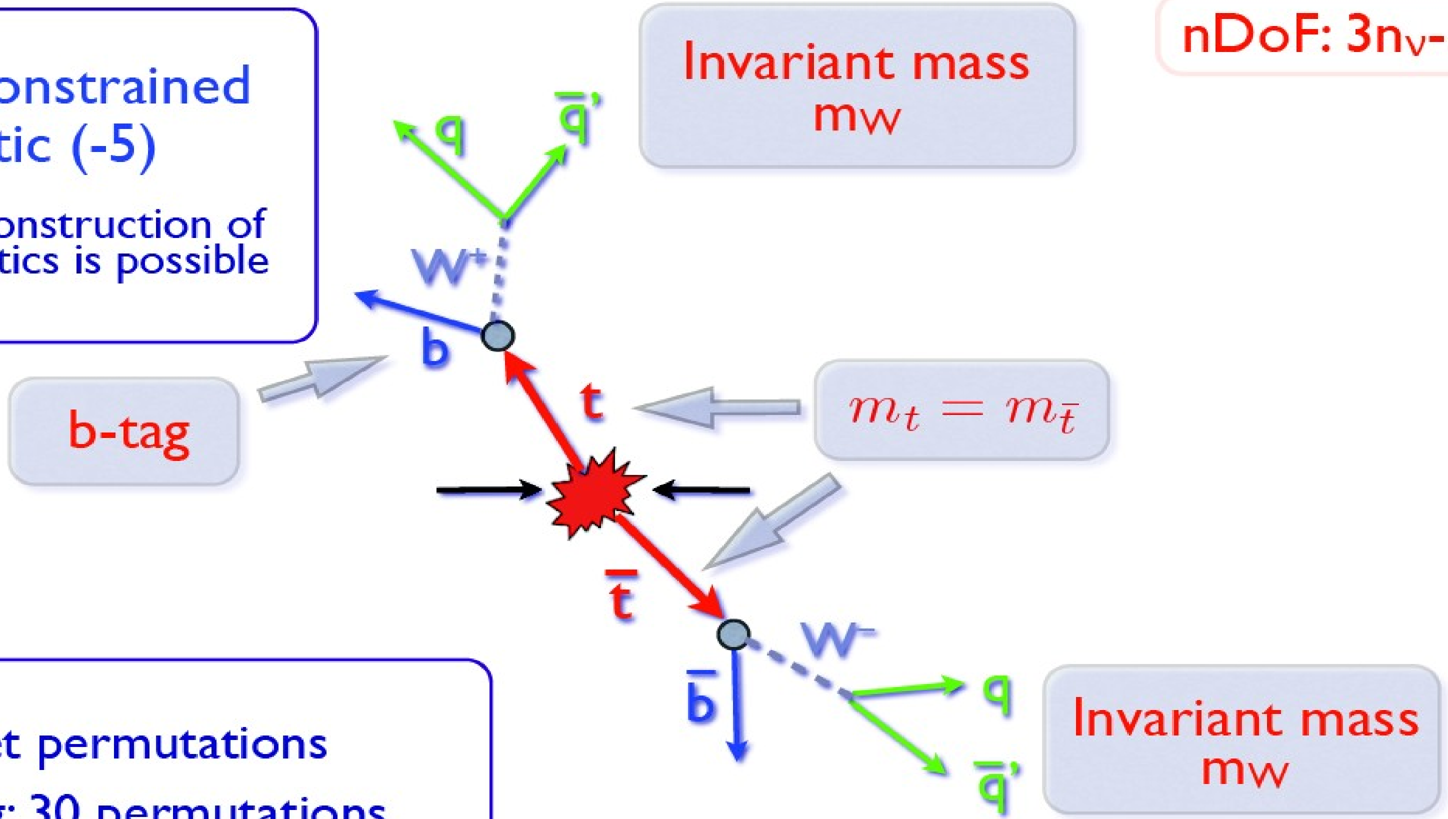
Presence of hadronic W allows to constrain JES

Top event reconstruction: all hadronic

nDoF: $3n_\nu$-5

Over constrained kinematic (-5)

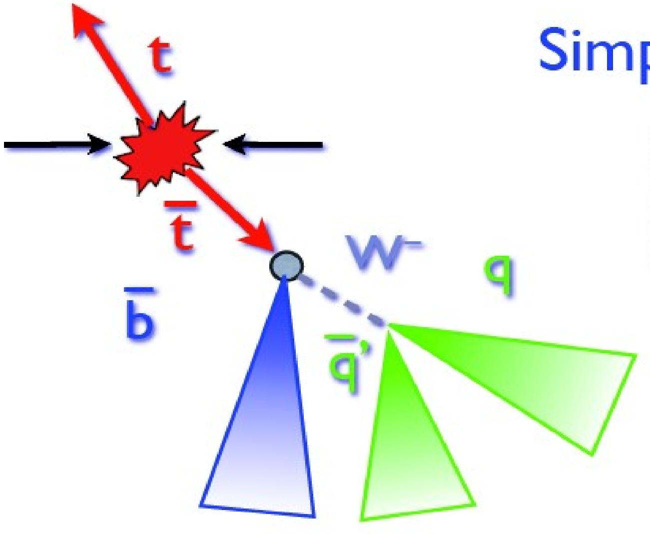
- full reconstruction of kinematics is possible



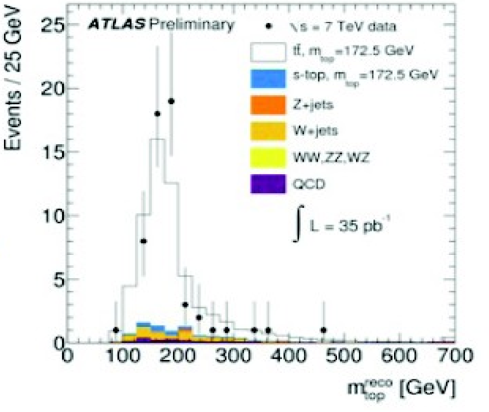
- 90 jet permutations
- b-tag: 30 permutations
- 2 b-tags: 6 permutations

Presence of hadronic W allows to constrain JES

Top event reconstruction l+jets



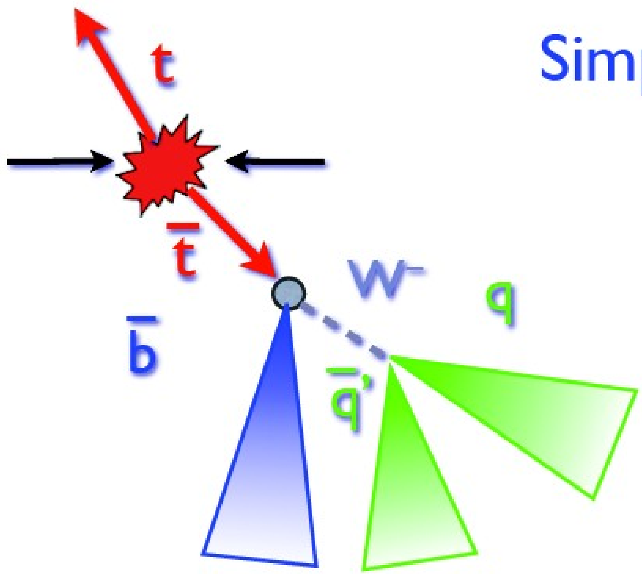
Simple reconstruction - hadronic top



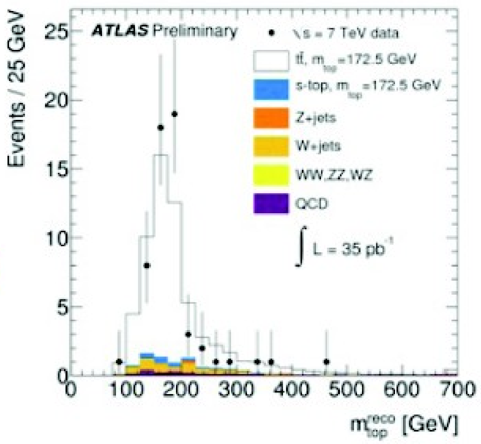
- take three highest p_T jets to build top mass
- if 1 b-tag in triplet take two jets with no b-tag to build W mass
- if 2 b-tags in triplet drop the event
- if no b-tag take two jets with min ΔR

ATLAS-CONF-2011-033

Top event reconstruction l+jets



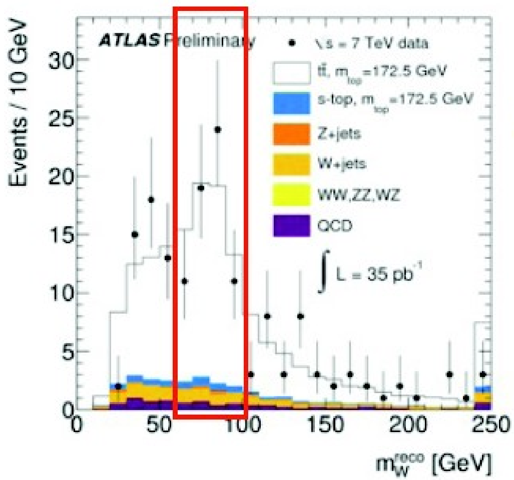
Simple reconstruction - hadronic top



- take three highest p_T jets to build top mass
- W mass window cut: $60 < m_W < 100$ GeV

45%(36%) of correctly reconstructed W(top)

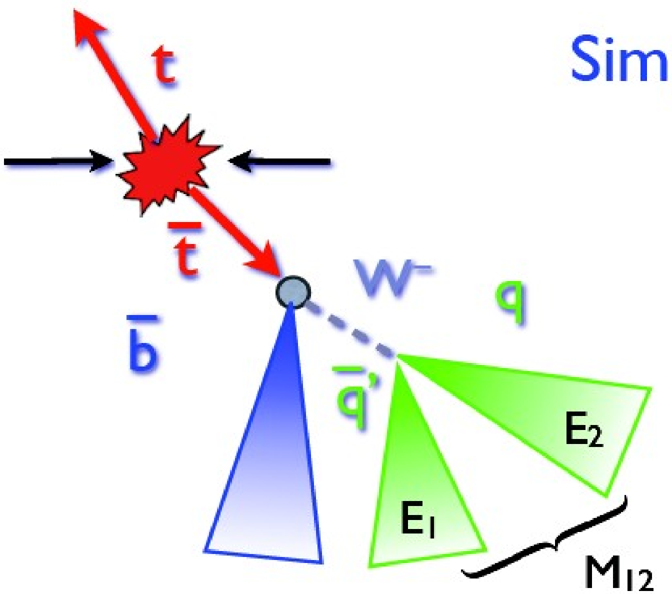
- if 1 b-tag in triplet take two jets with no b-tag to build W mass
- if 2 b-tags in triplet drop the event
- if no b-tag take two jets with min ΔR



- Disadvantages:
  - loss of efficiency
  - jet resolutions are not taken into account

ATLAS-CONF-2011-033

Top event reconstruction l+jets



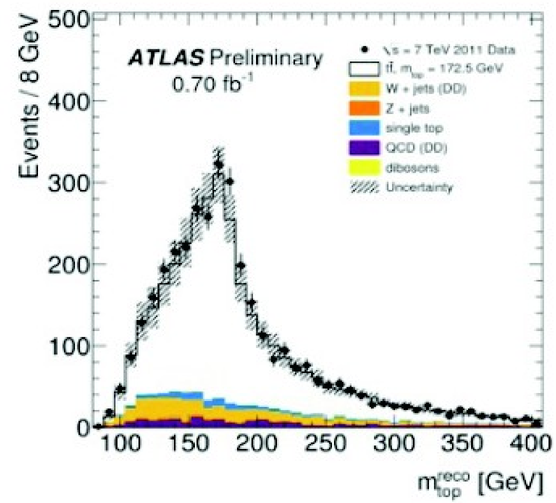
Simple reconstruction - hadronic top

- consider light jets pair with $50<m_W<100$ GeV
- combine with b-tagged jet
- select combination with highest p_T as a top quark candidate
- perform kinematic fit of hadronic W candidate

$$\chi^2(\alpha_1,\alpha_2) = \left[\frac{E_1(1-\alpha_1)}{\sigma_1}\right]^2 + \left[\frac{E_2(1-\alpha_2)}{\sigma_2}\right]^2 + \left[\frac{M_{12}(\alpha_1,\alpha_2)-m_W}{\Gamma_W}\right]^2$$

ATLAS-CONF-2011-120

- determines α_1 and α_2
- recalibrates jet energies
- improves m_t resolution



Top event reconstruction l+jets

- χ^2 minimization
  - takes into account reconstructed objects resolutions in p_T
  - approximates W and top Breit-Wigner lineshapes with Gaussians
  - minimized with respect to all parton level kinematic quantities and m_t^{rec} for each jet-to-parton assignment

$$\chi^2 = \frac{(m_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(m_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jjb} - m_t^{rec})^2}{\Gamma_t^2} + \frac{(m_{\ell\nu b} - m_t^{rec})^2}{\Gamma_t^2}$$

$$+ \sum_{i=\ell,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_{UE^2}}$$

  - definition in all hadronic channel is similar

Top event reconstruction l+jets

- χ^2 minimization
  - takes into account reconstructed objects resolutions in p_T
  - approximates W and top Breit-Wigner lineshapes with Gaussians
  - minimized with respect to all parton level kinematic quantities and m_t^{rec} for each jet-to-parton assignment

$$\chi^2 = \frac{(m_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(m_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jjb} - m_t^{rec})^2}{\Gamma_t^2} + \frac{(m_{\ell\nu b} - m_t^{rec})^2}{\Gamma_t^2}$$
$$+ \sum_{i=\ell,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_{UE^2}}$$

  - definition in all hadronic channel is similar

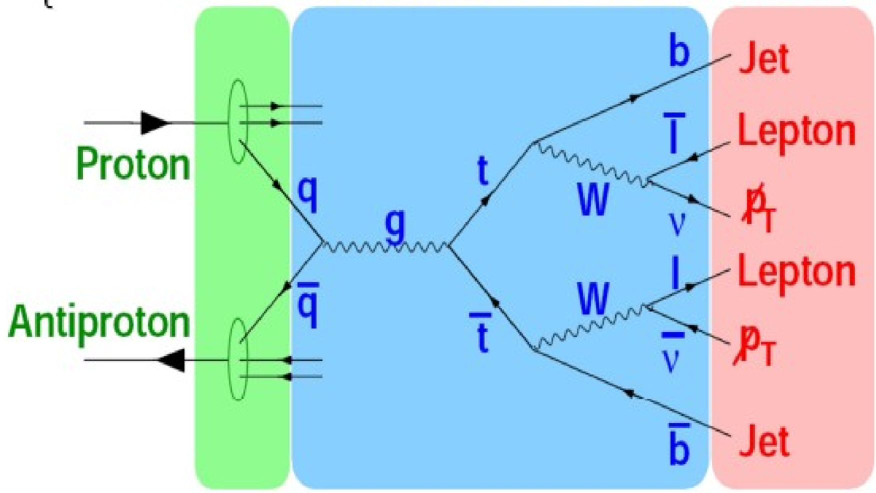
- more sophisticated χ^2 minimization - HitFit
  - uses Transfer Functions to correct reconstructed objects to parton level
  - loose cut on hadronic W mass: 40 GeV<m_W<140 GeV before the fit to reject some permutations

S.Snyder, Ph.D. thesis, SUNY, Stony Brook, 1995

Matrix element method

- Use full event kinematics → most precise method
- For each event calculate probability to belong to certain top mass

  $P_{sig}(x;m_t) \propto \int$ PDF x Matrix element x Transfer function



- Perform likelihood fit of event probabilities
- Probability depends on top mass (& JES for in-situ fit)
- Used in l+jets & dilepton final states

Top event reconstruction l+jets

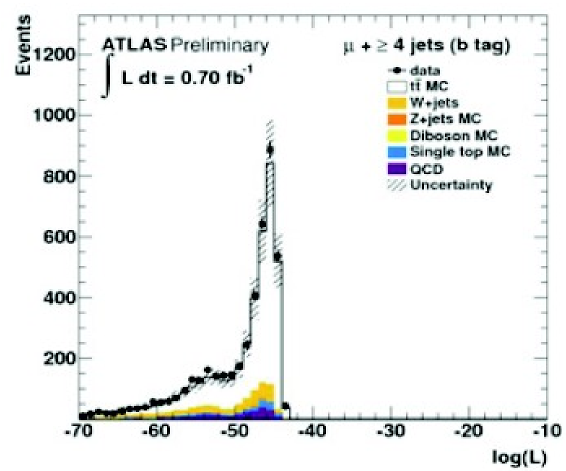
- Kinematic Likelihood fitter (KLfitter)

ATLAS-CONF-2011-033

$$
\begin{aligned}
L \; = \; & BW(\hat{E}_{jet,1}, \hat{E}_{jet,2} | m_W, \Gamma_W) \cdot BW(\hat{E}_{\ell}, \hat{E}_{\nu} | m_W, \Gamma_W) \cdot \\
& BW(\hat{E}_{jet,1}, \hat{E}_{jet,2}, \hat{E}_{jet,3} | m_{top}^{reco}, \Gamma_{top}) \cdot BW(\hat{E}_{\ell}, \hat{E}_{\nu}, \hat{E}_{jet,4} | m_{top}^{reco}, \Gamma_{top}) \cdot \\
& TF(E_x^{miss} | \hat{p}_{x,\nu}) \cdot TF(E_y^{miss} | \hat{p}_{y,\nu}) \cdot TF(E_{\ell} | \hat{E}_{\ell}) \cdot \\
& \prod_{i=1}^{4} TF(E_{jet,i} | \hat{E}_{jet,i}) \cdot \prod_{i=1}^{4} TF(\eta_{jet,i} | \hat{\eta}_{jet,i}) \cdot \prod_{i=1}^{4} TF(\phi_{jet,i} | \hat{\phi}_{jet,i}) \cdot \delta(b\text{-tagged jet} \mid b\text{-quark}).
\end{aligned}
$$

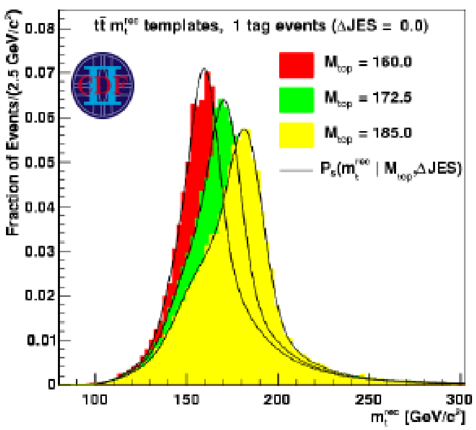
uses Breit-Wigner lineshapes for top and W

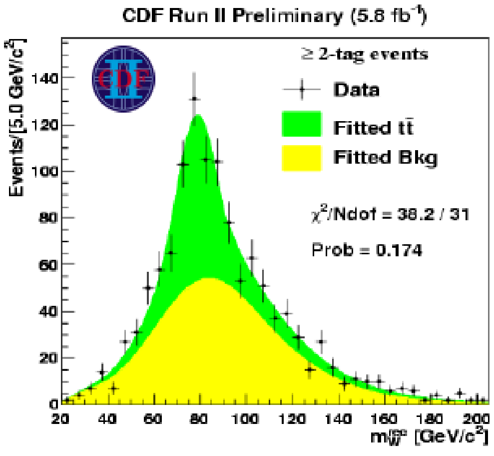
- Transfer Functions to correct reconstructed objects to parton level:
  - energies and angles of light and b-jets
  - the energy of the charged lepton
  - two components of the missing E_T
- b-tagging information can be use as a cut or as a weight

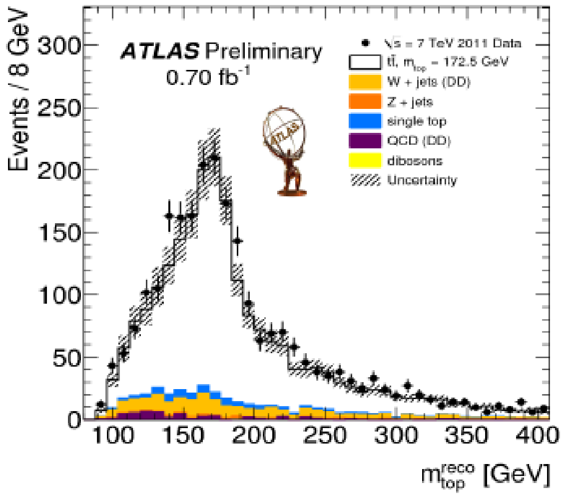


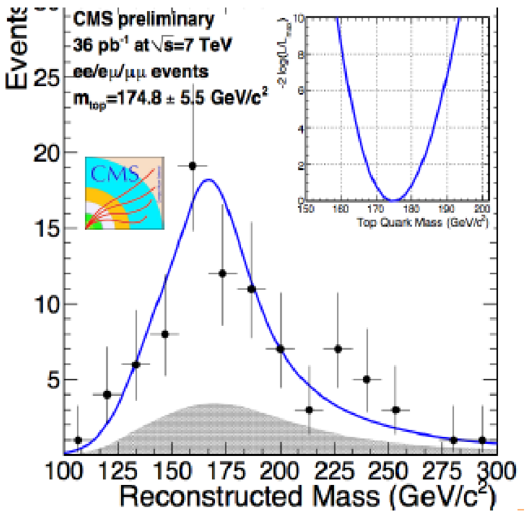
Template method

- Construct mass dependent template, fit to data
- Alljets and l+jets: Take info from hadronically decaying W mass to constrain jet energy scale





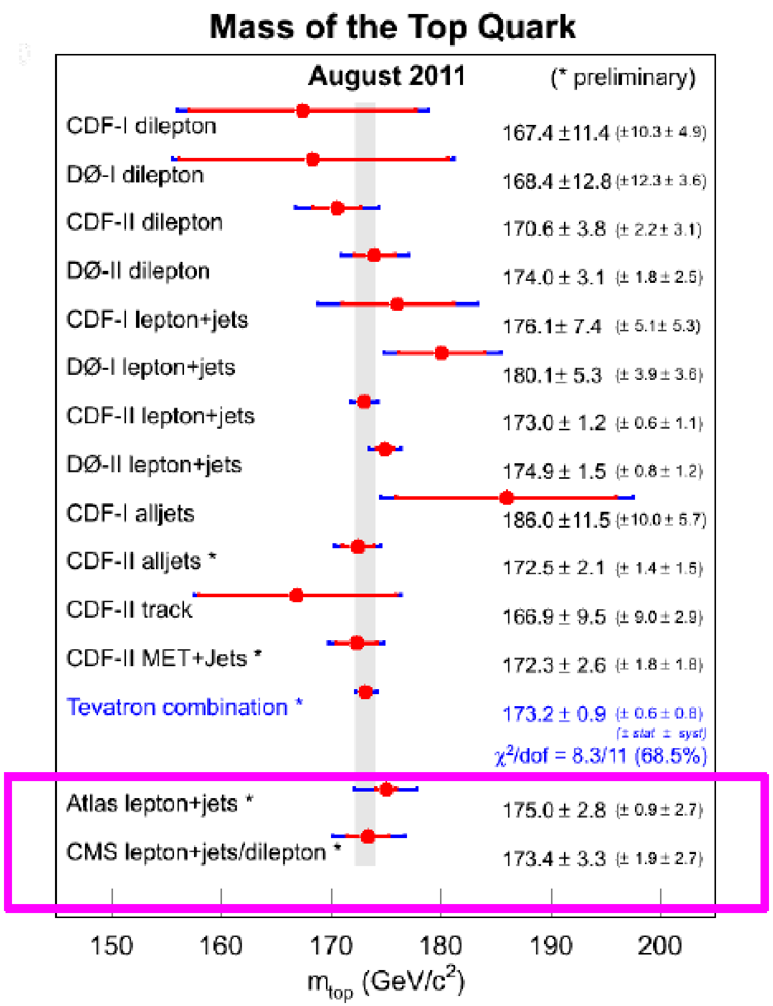




- Dilepton: Construction of templates more complicated due to presence of two neutrinos
  - Neutrino weighting, Matrix Weighting,…

Top-quark mass combinations

PIC2011 status

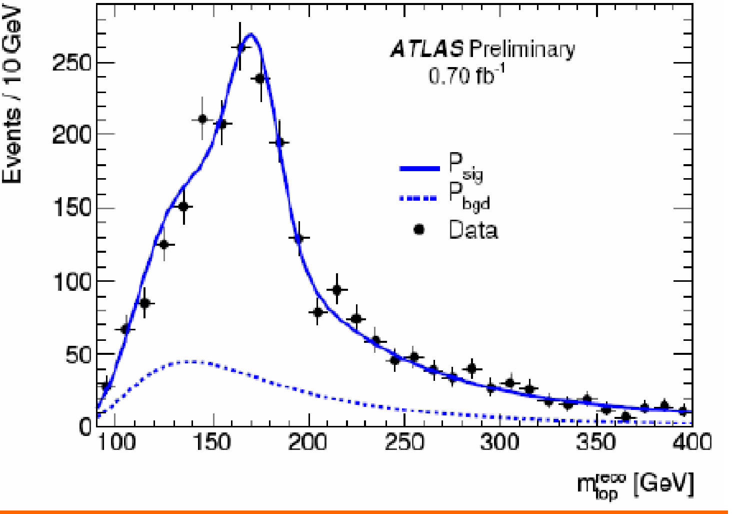


- Systematics limited!
  - Main effort for experiments: detailed understanding of systematics
  - Main systematics at Tevatron: JES-related
  - Main systematics at LHC: JES-related and ISR/FSR
- Tevatron combination: first time uncertainty below 1GeV!

Top mass with ATLAS

- Analysis performed with **0.70 fb^{-1}** in **l+jets** channel,
  - asking the presence of one b-jet
- 3-jet from hadronic top: combination with higher total p_T
- Technique: **m_{top} and JES determined simultaneously**
  - W mass and width used as constraints
- m_{top}^{reco} in data have been compared to signal + backgrounds templates with ≠ JES and m_{top}
  - **m_{top} and JES from a likelihood fit**

- Main systematics:
  - signal modelling
  - JES for light jets and b-jets



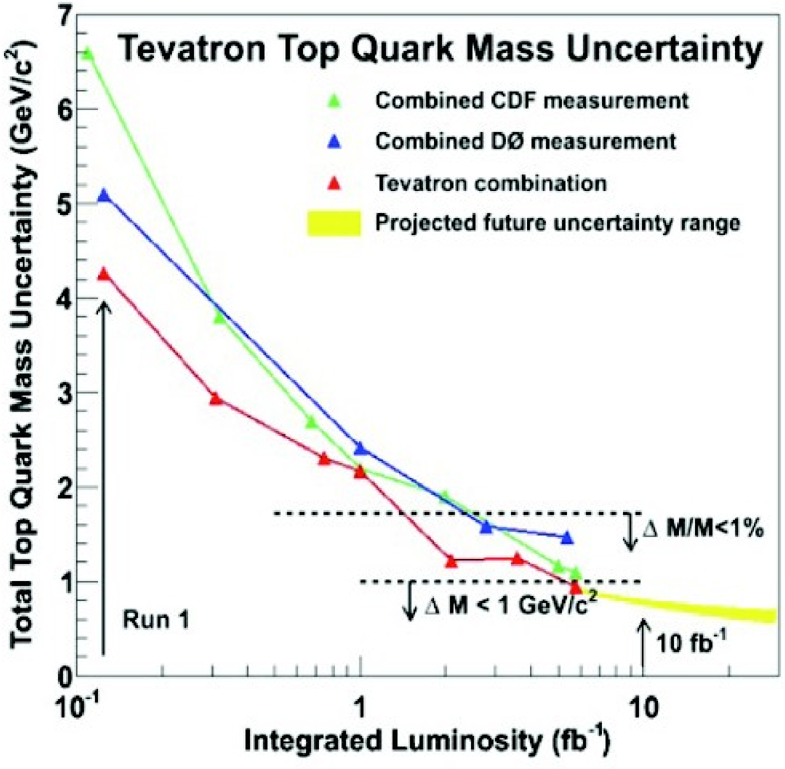
$$m_{top} = \left(175.9 \pm 0.9_{stat} \pm 2.7_{syst}\right) \text{ GeV}$$

Limited by systematics

ATLAS-CONF-2011-120

Future precision: Tevatron

- Each experiment is expected to achieve uncertainty of 0.9-1.0 GeV with the full dataset
- Tevatron combination is expected to have uncertainty of 0.7-0.8 GeV

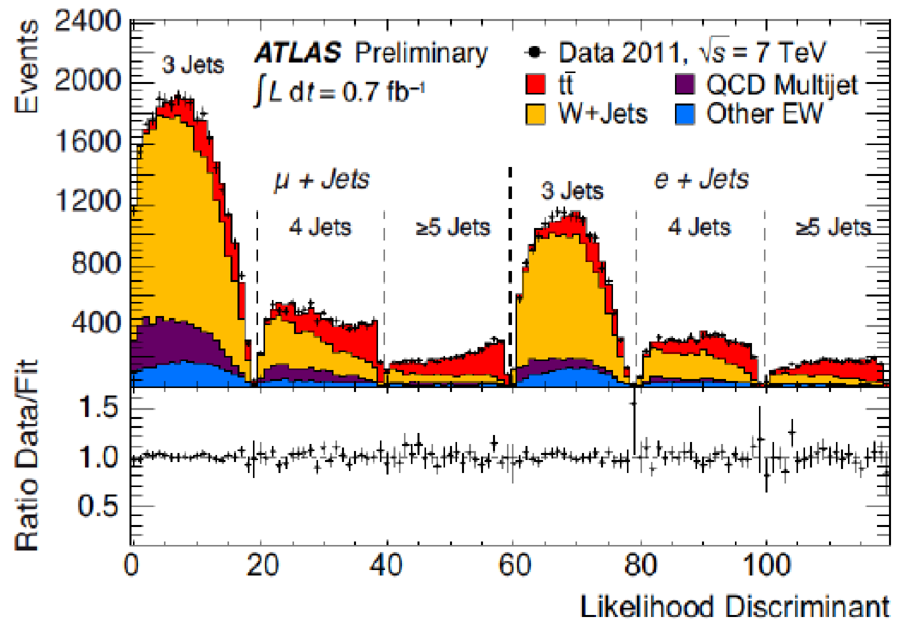


Top quark mass: what we measure?

- What is theoretical interpretation of the measured parameter?
  - We extract top mass based on Monte Carlo → is it the pole mass?
- Alternative method: extract mass form the measured cross-section for ttbar production
  - Assuming MC mass = pole mass or MSbar mass
    - Take difference as systematics
  - Calculate σ_{tt} as function of pole mass; compare to measured σ_{tt} as a function of pole mass
    - Extract pole mass:
      - **$m_t = 167.5^{+5.2}_{-4.7}$ GeV (D0)**
      - **$m_t = 166.4^{+7.8}_{-7.3}$ GeV (ATLAS, 35pb^{-1})**

Inclusive cross-section: l+jets pre-tag

- Analysis with **0.70 fb^{-1}**.
- **No b-tagging** request applied
- Make use of kinematical differences between $t\bar{t}$ and W+jets:
  - **likelihood discriminant** based on 4 variables
    - lepton η, leading jet p_T, event aplanarity and transverse momentum of all jets but the two leading ones
- **Fit in 6 channels**: 3, 4 and >= 5jets in e and μ ch.
- Main systematics:
  - signal modelling (choice of signal MC generator, ISR/FSR) and jet energy scale (JES)



$$\sigma_{t\bar{t}} = 179.0 \pm 3.9\,(\text{stat}) \pm 9.0\,(\text{syst}) \pm 6.6\,(\text{lumi})\ \text{pb}$$

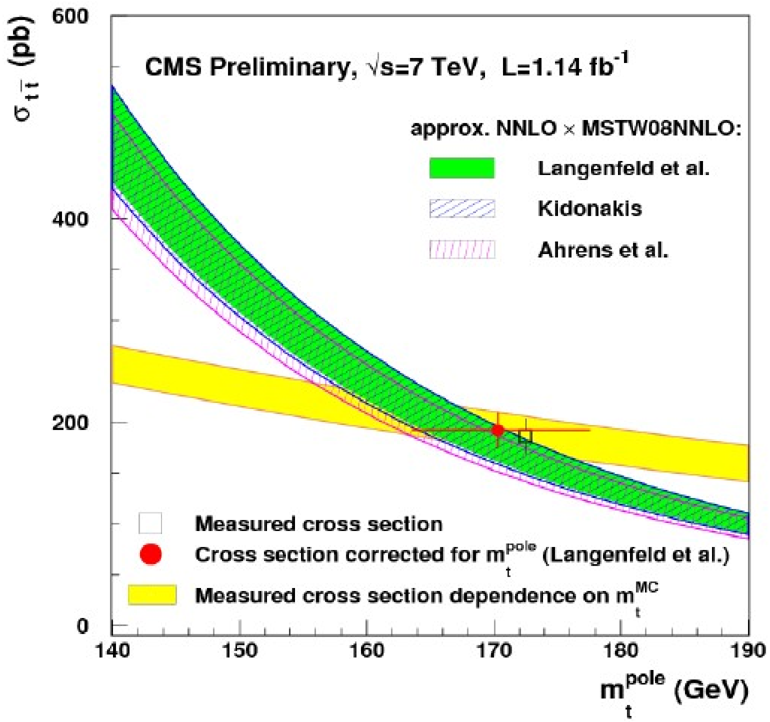
7% uncertainty!

ATLAS-CONF-2011-121

Top mass from cross-section

$1.1\ fb^{-1}$

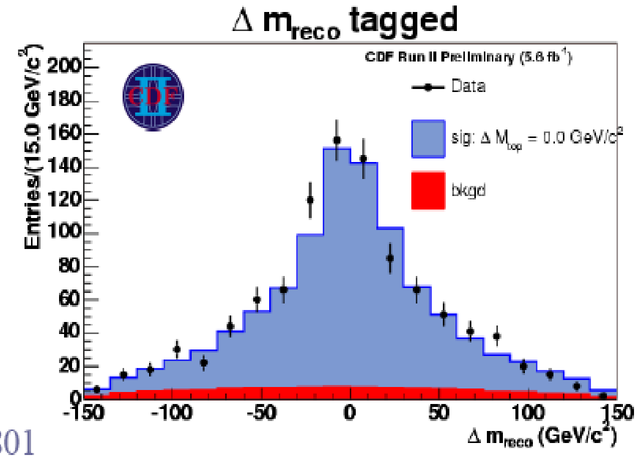
- The result is not competitive in precision but:
  - Provides the top quark mass value in an exact definition of the mass-pole
  - Important cross-check, complementary to direct top mass measurements
- Likelihood fit on the mass dependence
- Uncertainty of the theory includes:
  - Variation of the renormalisation, factorisation scales
  - Error due to experimental uncertainties in the PDFs
  - Variation of the strong coupling constant in the PDF

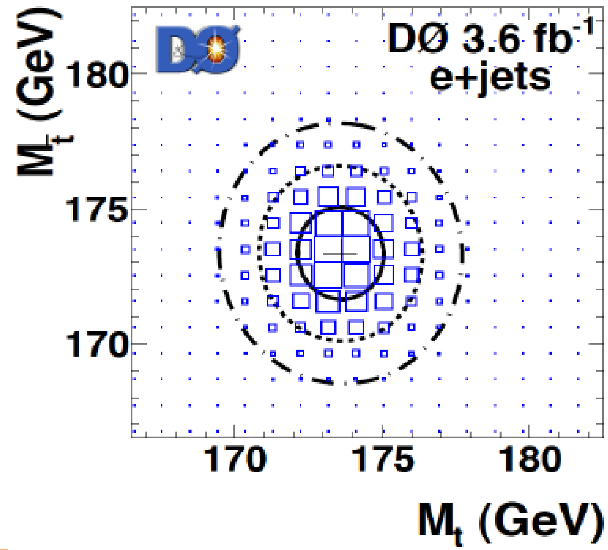


Approx. NNLO × MSTW08NNLO	m_t^{pole} / GeV	$m_t^{\overline{MS}}$ / GeV
Langenfeld et al. [7]	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis [8]	$170.0^{+7.6}_{-7.1}$	–
Ahrens et al. [9]	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$

Top anti-top mass difference

- Do top and anti-top have equal mass?
  - If not: CPT violation!
- Using template technique
  - CDF (Assume average top mass of 172.5GeV)
    $m_t - m_{\bar{t}} = -3.3 \pm 1.7\,\text{GeV}$ ($5.6\,\text{fb}^{-1}$) PRL 106, 161801
- Using Matrix Element technique (DØ)
  - $P_{sig}(x; m_t, m_{\bar{t}})$ instead of $P_{sig}(x; m_t)$
    $m_t - m_{\bar{t}} = 0.8 \pm 1.9\,\text{GeV}$ ($3.6\,\text{fb}^{-1}$) arXiv:1106.2063
- Still statistics limited
- Good agreement with the SM!

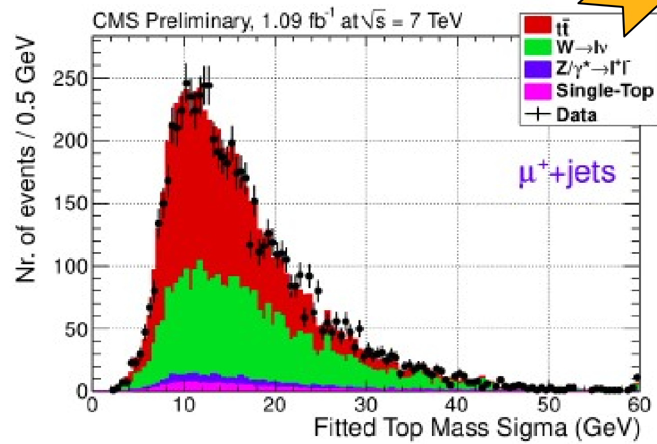


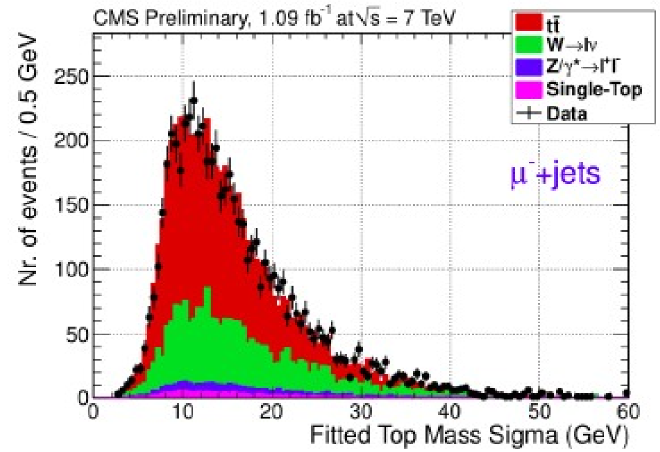


Top anti-top mass difference

1.1fb^{-1}

- Select events with a muon and multi-jet in the final state
- The muon charge allows to split the data sample in two sub-samples, where top or anti-top quarks decay hadronically
- Ideogram (approximate ME) method is used to measure mass of the top quarks.
- Many systematics cancel with the subtraction



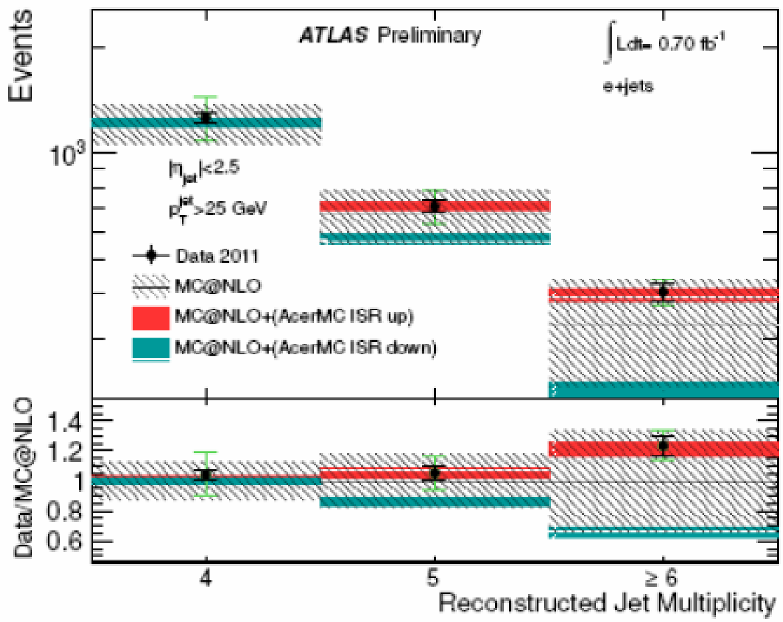


World best limit!

$$\Delta m_t^{\text{measured}} = -1.20 \pm 1.21\ (\text{stat}) \pm 0.47\ (\text{syst})\ \text{GeV}$$

Jets multiplicity in tt events

- Motivation: jet multiplicity measurement gives the **possibility to constrain ISR at m_{top} energy**
- Analysis based on **0.70 fb^{-1}** in **l+jets** channel
- QCD and W+jets backgrounds estimated from data
- Jet multiplicity distribution after background subtraction compared to different MC predictions:
  - **ISR varied within the uncertainty**
- Main uncertainties:
  - at low jet multiplicity (4 jets): QCD and W+jets backgrounds
  - at high jet multiplicity: JES

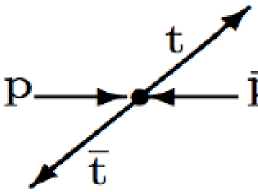


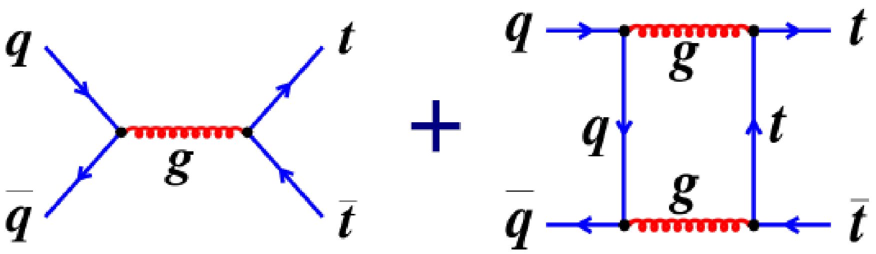
ATLAS-CONF-2011-142

Present uncertainty:
no discrimination is possible

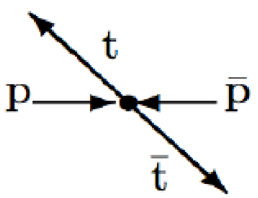
ttbar charge asymmetry: ppbar

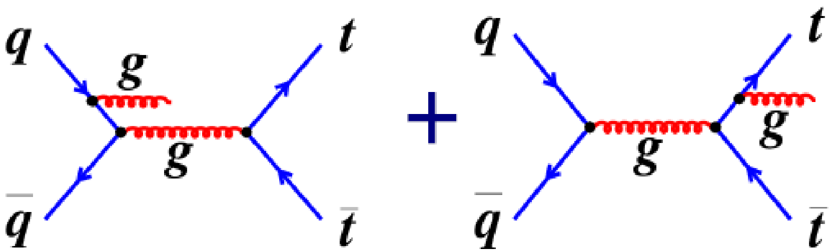
- LO: No charge asymmetry expected
- NLO QCD: Interference between $q\bar{q}$ diagrams
- Tree level and box diagrams:
  - Positive asymmetry





- Initial and final state radiation:
  - Negative asymmetry





- Sensitive to new physics, e. g. Z' & sensitive to theory modeling

ttbar charge asymmetry

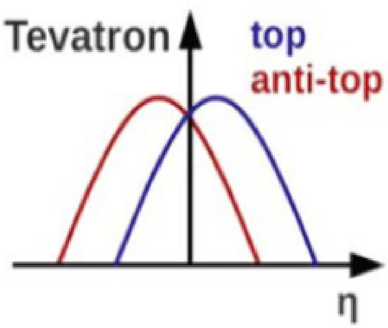
- Tevatron: $p\bar{p}$ is CP eigenstate → pp (LHC) is not
  → different way to measure the effect at Tevatron and LHC

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

Tevatron

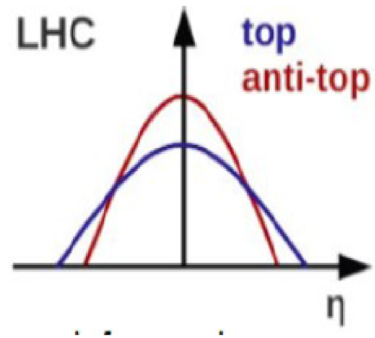
$$A_C = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)}$$

LHC



$$y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right)$$

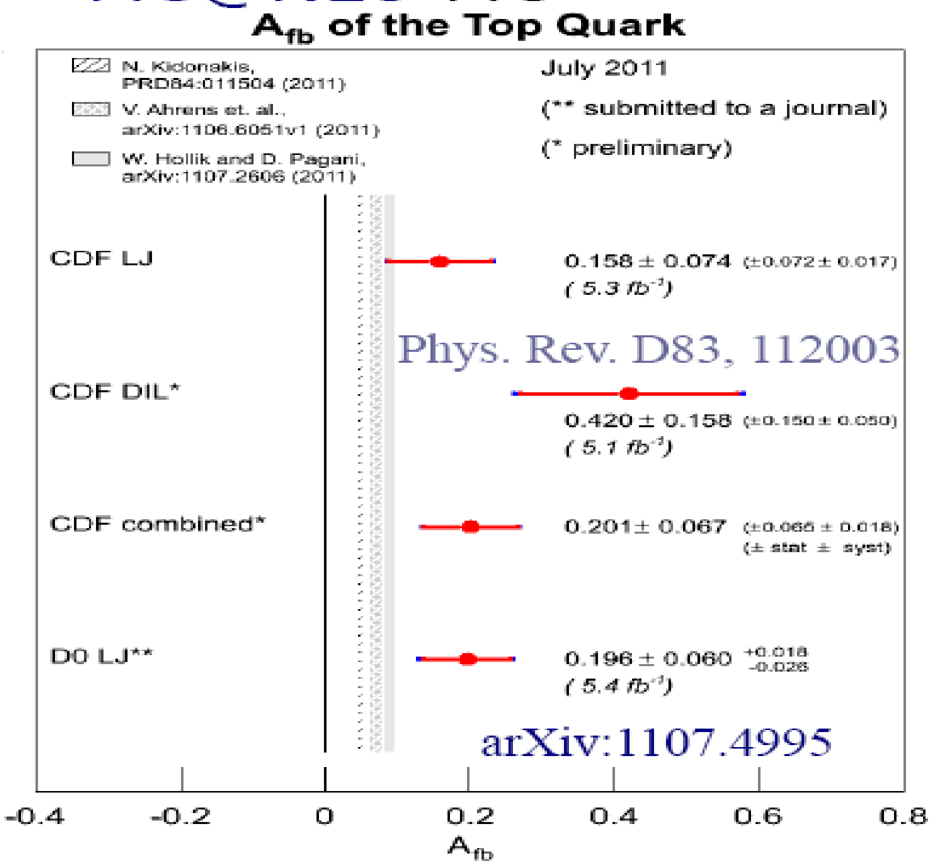
$\Delta y = y_t - y_{\bar{t}}$ $\quad$ $\Delta|y| = |y_t| - |y_{\bar{t}}|$

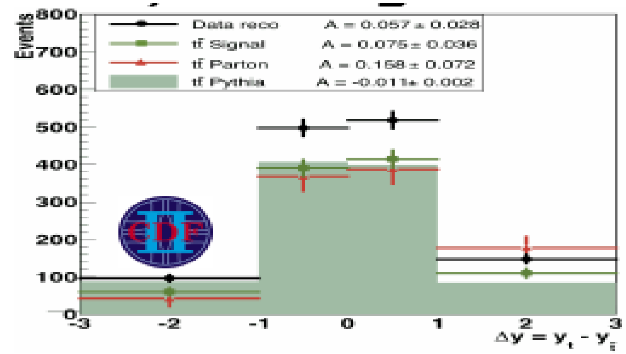


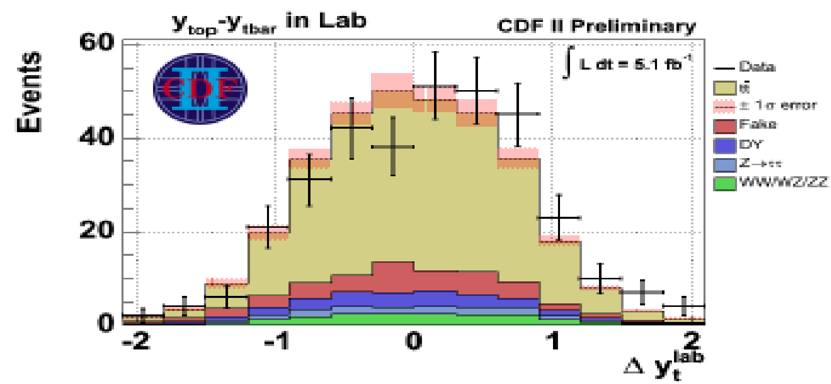
- LHC: $q\bar{q}$ fraction only 15% → asymmetry smaller than at Tevatron
- Requires reconstruction of $t\bar{t}$ system → Kinematic fitter
- All experiments: results in l+jets; CDF: result in dilepton

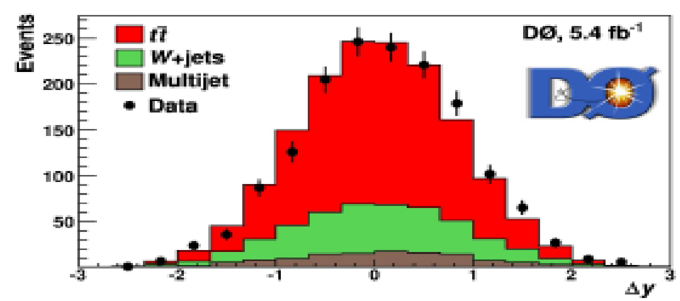
ttbar charge asymmetry: ppbar

- Prediction from MC@NLO MC



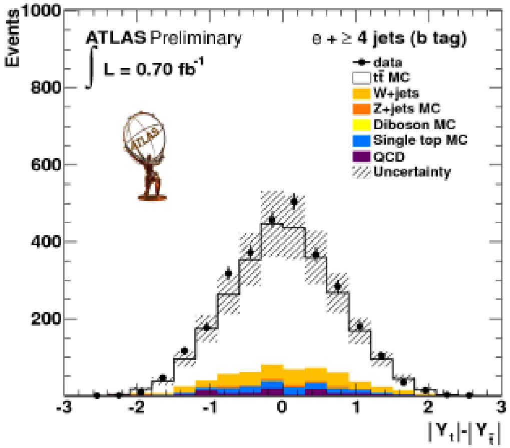


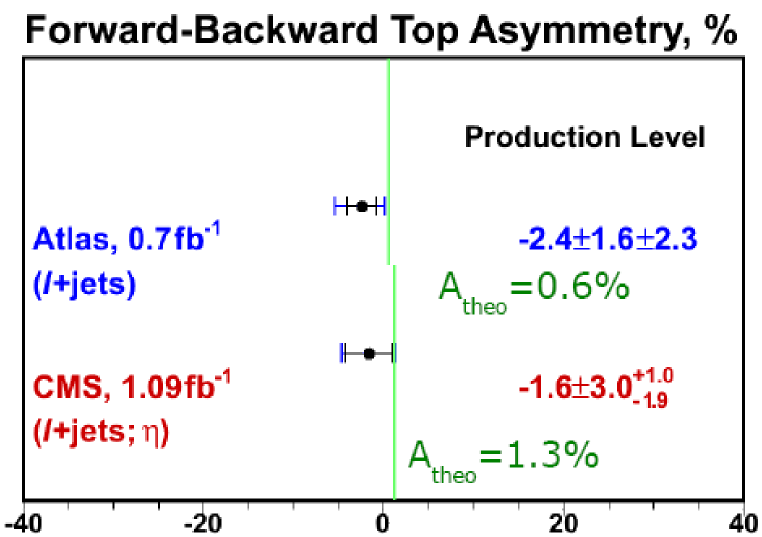


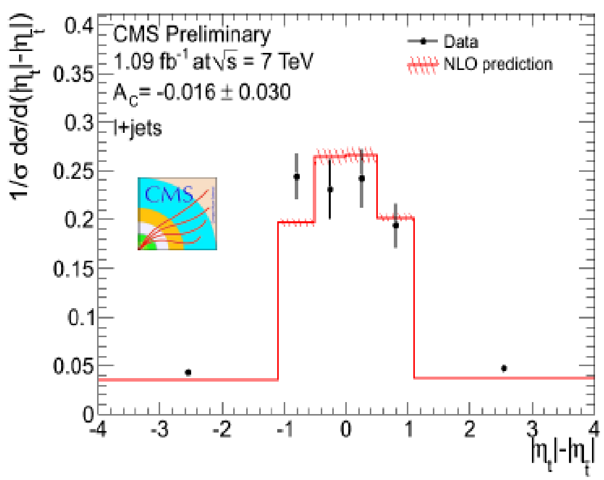


ttbar charge asymmetry: ppbar

- Measurements at LHC already becoming systematics limited
  - Mainly modeling of signal
- CMS: using η instead of y
  - Another measurement done using $\Delta(y^2)$



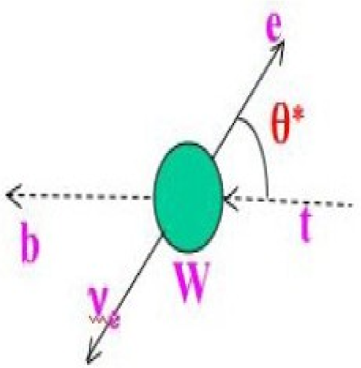




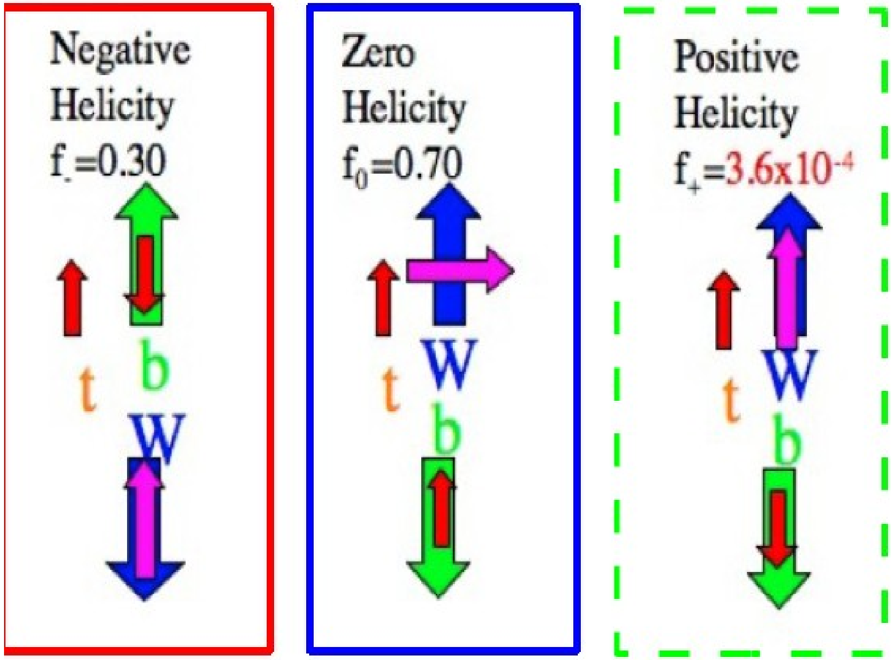
ATLAS-CONF-2011-106

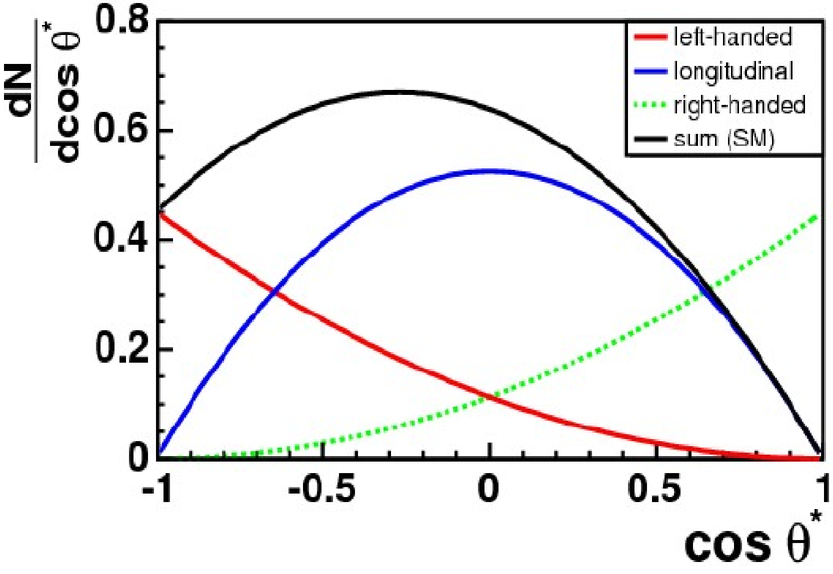
CMS PAS TOP-11-014

W helicity in top quarks decay



- Left-handed coupling of W-boson to fermions:
  Not every combination of spin for W and b-quark is allowed

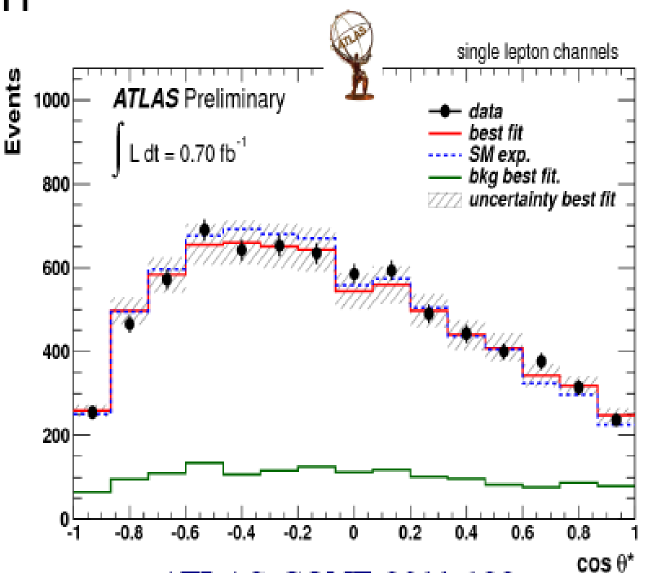




- Measure angle θ* between down-type decay product (lepton, d-, s-quark) of W and top quark in W rest frame

W helicity in top quarks decay

- Template fit of cosθ* in l+jets and dilepton
  - f_-, f_0, f_+; in dilepton f_+ fixed
- Float f_-, f_0, f_+ with $f_- + f_0 + f_+ = 1$ (l+jets):
  $f_0 = 0.57 \pm 0.07(stat) \pm 0.09(syst)$
  $f_+ = 0.09 \pm 0.04(stat) \pm 0.08(syst)$
- Fix $f_+ = 0$; combined dilepton & l+jets:
  $f_0 = 0.75 \pm 0.08(stat+syst)$
- Systematics limited;
  main systematics → modeling of signal & ISR/FSR
- Consistent with SM prediction

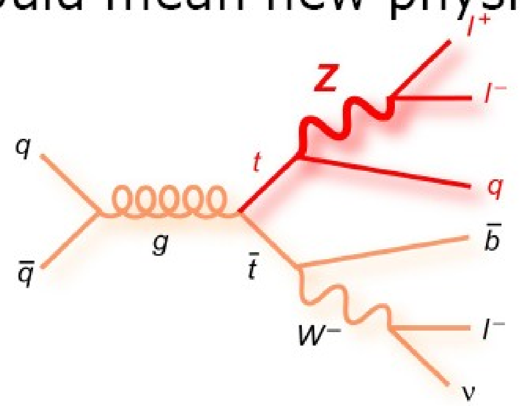


ATLAS-CONF-2011-122

FCNC in top decays

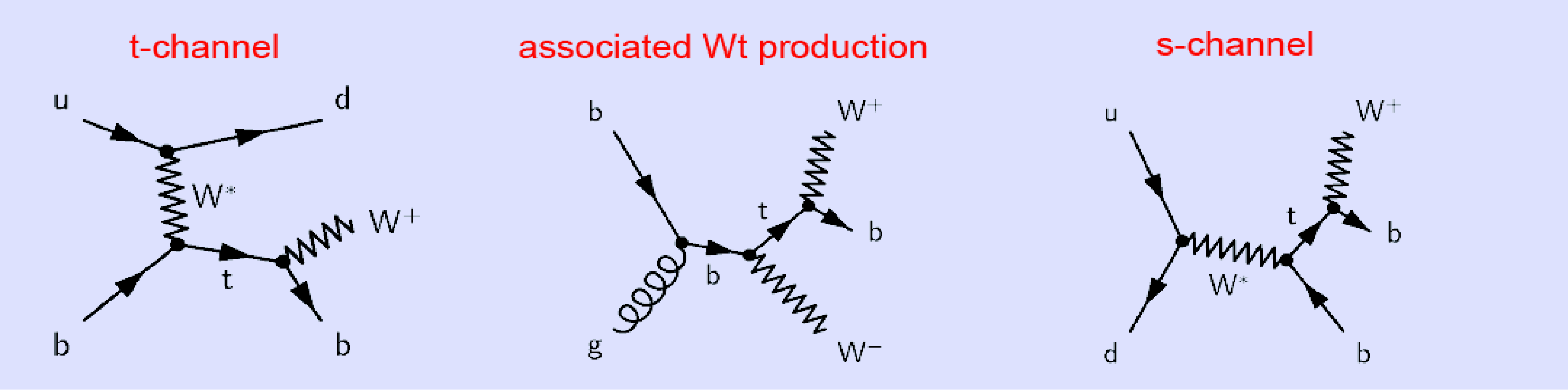
- No FCNC in SM → any indication of FCNC would mean new physics
- Look at events with 3 leptons
  - DØ (4.1fb^{-1}) Limit: B(t→Zq)<3.2%
    - World's best limit

PLB 701, 313 (2011)



Single top production

- Top quark production via weak interactions



cross sections at LHC with $\sqrt{s}$ = 7 TeV (m_t = 173 GeV)

64.2 ± 2.6 pb   15.6 ± 1.3 pb   4.6 ± 0.2 pb

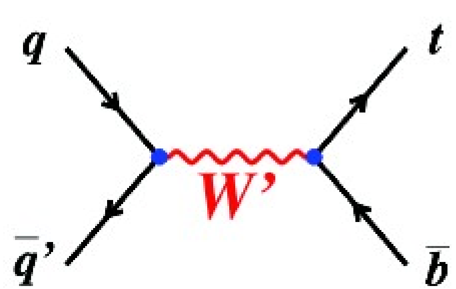
cross sections at the Tevatron with $\sqrt{s}$ = 1.96 TeV (m_t = 173 GeV)

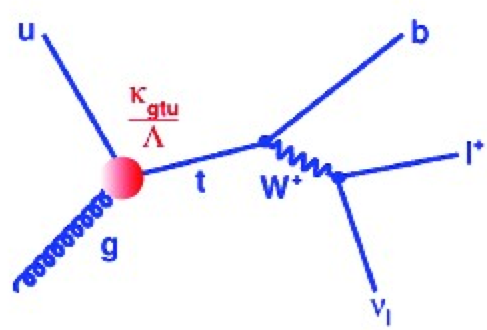
2.1 ± 0.1 pb   0.25 ± 0.03 pb   1.05 ± 0.05 pb

Why look for single top quarks?

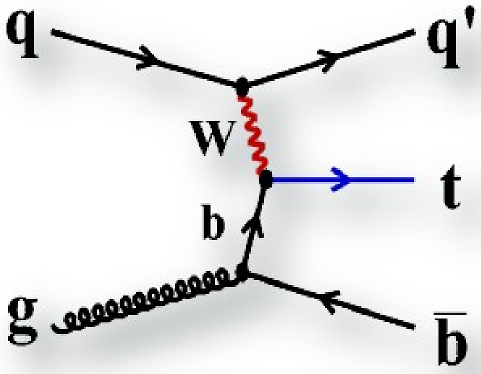
- Test of the SM predictions
  - Does it exist? YES
  - Establish different channels separately
  - Cross-section ~ $|V_{tb}|^2$
    - Test unitarity of the CKM matrix, e.g. hints for existent of the 4-th generation
    - Test of b-quark PDF: DGLAP evolution?
- Search for non-SM phenomena

$$V_{ub}^2 + V_{cb}^2 + V_{tb}^2 \stackrel{?}{=} 1$$





t-channel analyses

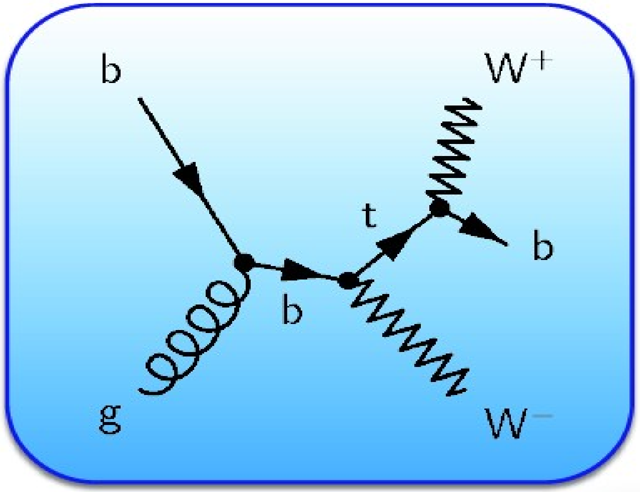


- Largest cross section of single-top processes
- Improved S/B ratio (≈10%) compared to Tevatron (≈7%)

Analysis history at ATLAS

- CONF note (Moriond) with 35 pb^{-1} (1.6 σ), ATLAS-CONF-2011-027
- CONF note (PLHC) with 156 pb^{-1} (6.2 σ), ATLAS-CONF-2011-088
- CONF note (EPS) with 0.70 fb^{-1} (7.6 σ), ATLAS-CONF-2011-101

Wt channel analyses



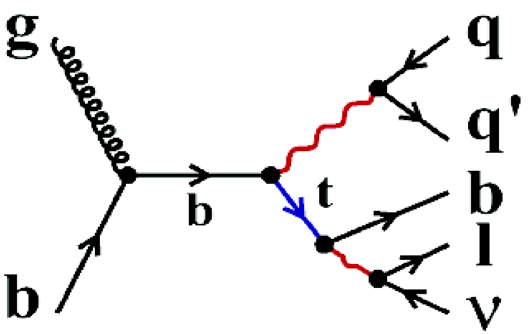
Two channels according to W decay modes:

1) Dilepton channel
   both W: $W \to e\nu$ or $W \to \mu\nu$
   ➔ 2 charged leptons, E_T^{miss}, 1 b-jet

2) Lepton + jets channel
   $W \to e\nu$ or $W \to \mu\nu$ + $W \to q\bar{q}$ (qqbar)
   ➔ 1 charged lepton, E_T^{miss}, 3 jets

- CONF note with 35 pb^{-1} (Moriond)
  ATLAS-CONF-2011-027
- CONF note with 0.70 fb^{-1} (EPS)
  ATLAS-CONF-2011-104
- Physics Analysis Summary (TOP2011)
  CMS PAS TOP-11-022

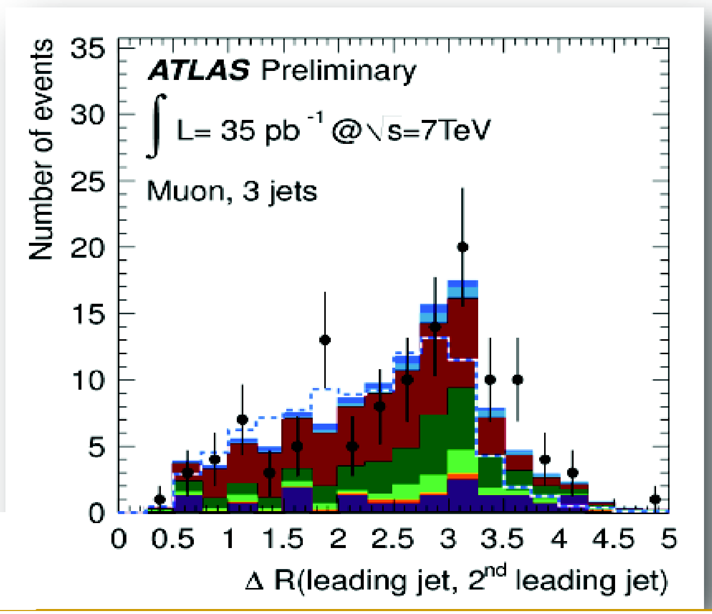
Wt channel: l+jets



Experimental signature:

- Isolated charged lepton
- Missing transverse energy
- Three high-p_T jets

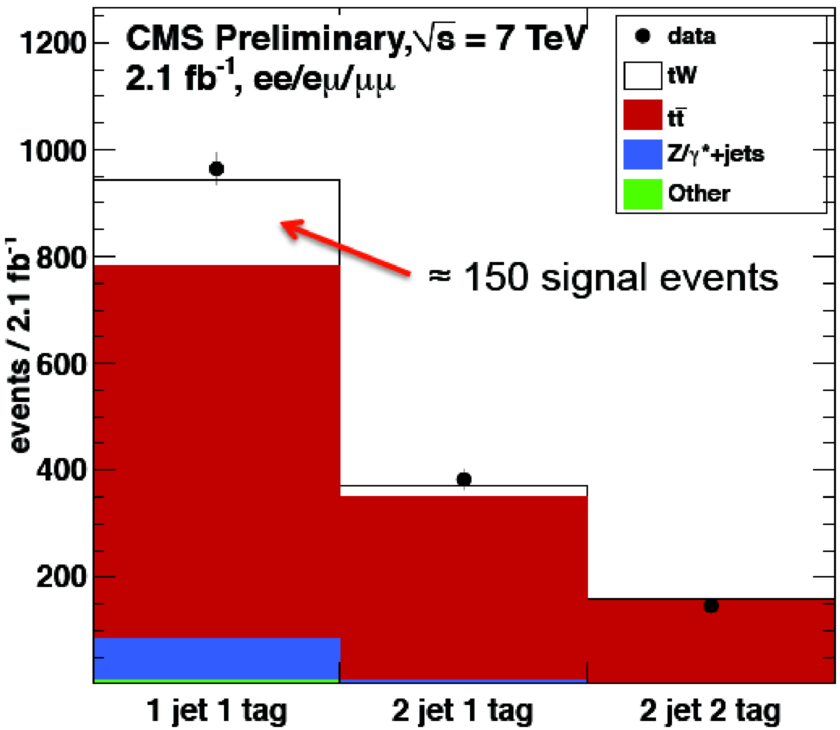
➔ Event selection very similar to t-channel analysis, same background estimation strategy



Analysis of 2010 data with 35 pb^{-1}

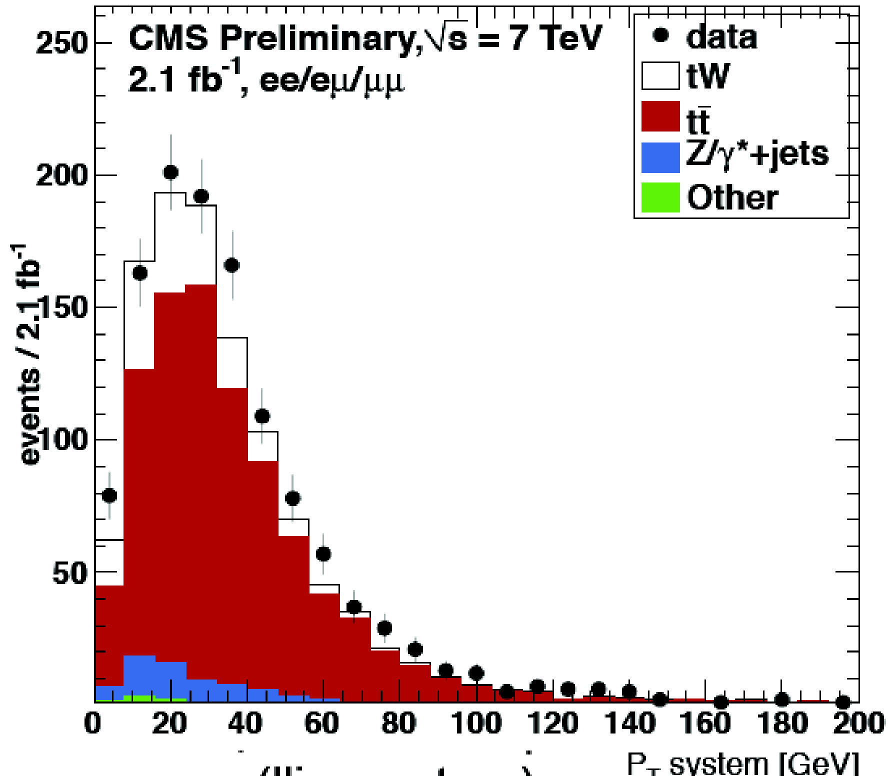
- ATLAS-CONF-2011-27 (Moriond 2011)
- Obtain S/B = 4 – 6%
- Dilepton and lepton+jets channel were combined:
  observed limit at the 95% C.L.:
  σ (Wt) < 158 pb
- Multivariate analyses are in preparation.

Wt channel:dileptons



signal region

top-antitop sideband region
➔ simultaneous fit

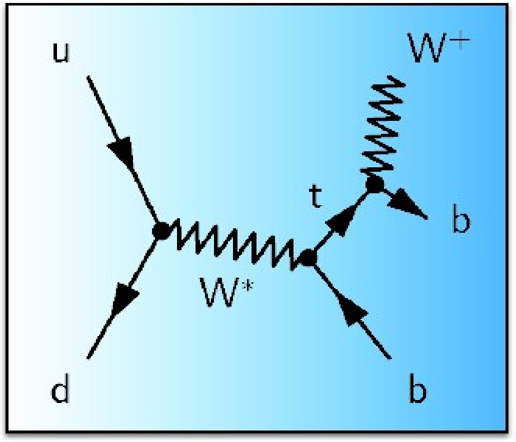


p_T(lljν=system)

(similar technique in ATLAS)

Good agreement with expected jet multiplicity distribution and kinematic distributions.

s-channel analysis



- Smallest cross section of all single-top processes. (antiquarks in the initial state needed)
- Signature similar to t-channel, but:
  - No forward jet.
  - Two central b-quark jets.
  - Jet definition uses: $|\eta| < 2.5$.
  - Use double tagged events.
- First s-channel analysis at ATLAS using 0.70 fb^{-1}.

ATLAS-CONF-2011-118

Cut-based analysis

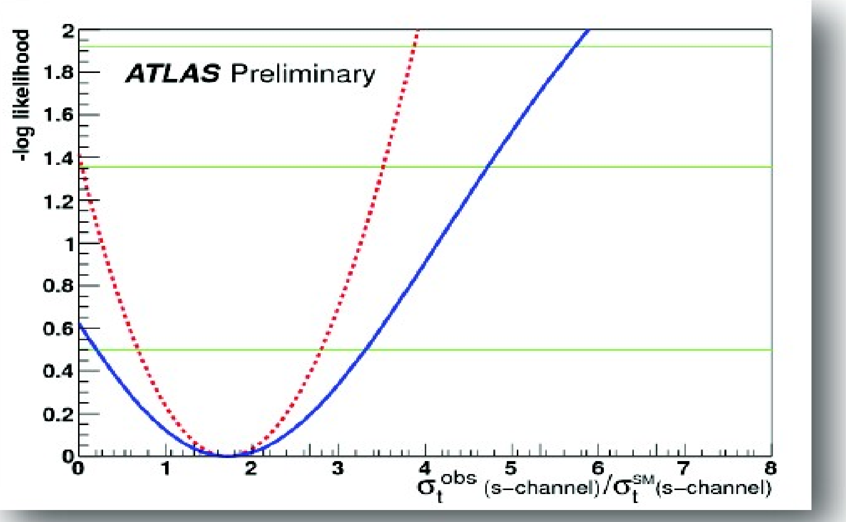
Selection	Signal	Background	$S/\sqrt{B}$
Preselection Only	104	153802	0.26
Number of tagged jets=2	18	415	0.88
$30 < m_{top,jet2} < 247$ GeV/c^2	17	349	0.91
$p_T(jet1, jet2) < 189$ GeV/c	17	346	0.91
$m_T(W) < 111$ GeV/c	17	318	0.95
$0.43 < \Delta R(b-jet1, lepton) < 3.6$	17	308	0.97
$123 < m_{top,jet1} < 788$ GeV/c^2	17	302	0.98
$0.74 < \Delta R(b-jet1, b-jet2) < 4.68$	16	269	0.98

s-channel analysis

Event yield after final selection:

	Final Selection
s-channel	16 ± 6
t-channel	33 ± 13
Wt	5 ± 3
$t\bar{t}$	111 ± 47
W+jets	4 ± 5
Wc+jets	10 ± 8
$Wc\bar{c}$+jets	14 ± 12
$Wb\bar{b}$+jets	70 ± 51
Z+jets	1 ± 1
Diboson	4 ± 1
Multijets	17 ± 10
TOTAL Exp	285 ± 17
$S/\sqrt{B}$	0.98
DATA	296

Statistical analysis: Profile likelihood



Observed limit @ the 95% C.L.:

$\sigma_{s\text{-channel}} < 26.5$ pb

SM: $\sigma_s = 4.6$ pb

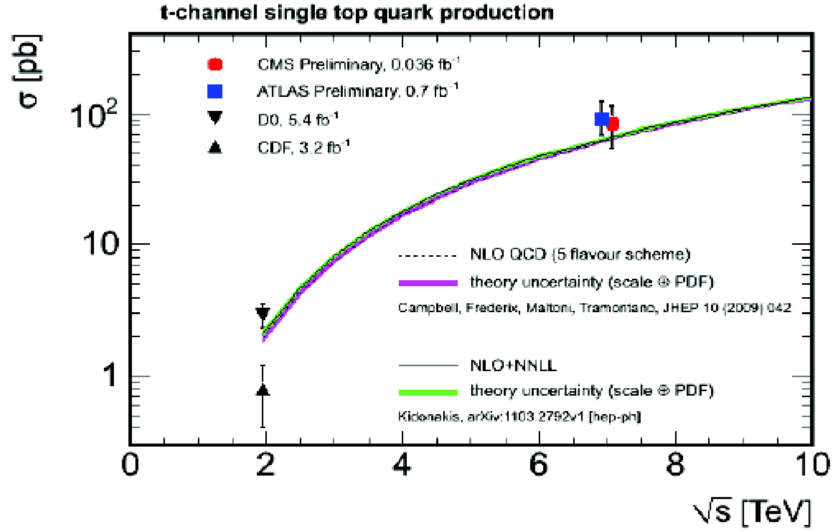
Single top : summary

- Single top t-channel production has been observed at ATLAS (7.6σ @ 0.7 fb^{-1}) and CMS (3.7σ @ 35 pb^{-1}).
- Measured t-channel cross sections are in agreement with the SM (64.2 ± 2.6 pb).

CMS: σ (t-ch.) = 84 ± 30 (stat. + syst.) pb

ATLAS: σ (t-ch.) = 90 ± 9 (stat.) $^{+31}_{-20}$ (syst.) pb

- With 0.70 fb^{-1} (ATLAS) already systematically (~30%) limited (stat. unc. 10%).



- FCNC search (ATLAS):

  σ_{FCNC} < 17.3 pb @ 95% C.L.

First steps to measure subleading single-top processes:

- Wt @ CMS: 2.7σ
  σ (Wt) = 22 $^{+9}_{-7}$ (stat.+ syst.) pb
- σ (Wt) < 39 pb @ 95% C.L.
- σ (s-chan.) < 26.5 pb @ 95% C.L.

Summary

- Almost all what we knew one year ago about top quark came from **Tevatron**
  - Measurements in all possible final states
  - Measurements of numerous top quark properties
  - Pioneer searches and analysis techniques
  - **Still providing legacy measurements**
- ATLAS and CMS have already (within only 2 years!) performed a complete first survey of the phase-space of the top quark mass and properties. The results are:
  - Very competitive with TeVatron in precision
  - Better than TeVatron for limits
  - Systematics limited e.g. in the mass determination
  - In agreement with Standard Model expectations so far
- **Both the searches and precise measurements of its properties tell us that top-quark is a Standard Model particle (asymmetry ?)**

Plan

- Amazing how much could have been done with only 36pb^{-1} data accumulated in 2010: numbers of results are still in the pile-line but already theory is being tested quantitatively.... and is holding its own (unfortunately)

  7.12 Diboson production and TGS couplings

  4.01 Higgs boson... where we are?

  18.01 What's new from New Physics searches?

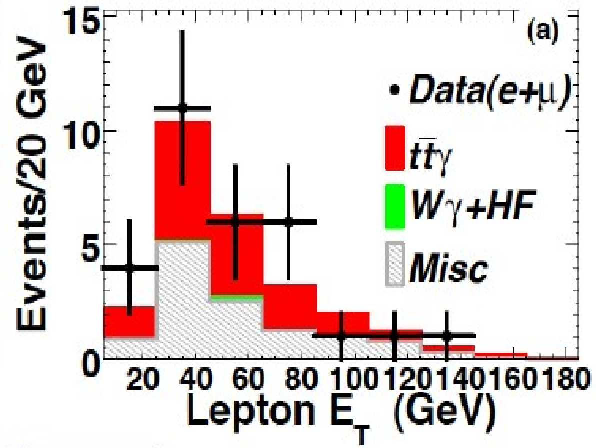
Measurements from Tevatron

Property	Measurement	SM Prediction	Luminosity (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: 7.5 ± 0.31(stat) ± 0.34(syst) ± 0.15(theory) pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
	D0: 2.90 ± 0.59 pb		5.4
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
	D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	5.3
	D0: 0.196 ± 0.065		5.4
spin correlation	CDF: 0.72 ± 0.64(stat) ± 0.26(syst)	$0.777^{+0.027}_{-0.042}$	5.3
	D0: 0.66 ± 0.23(stat + sys)		5.4
M_t	Tev: 173.2 ± 0.9 GeV	-	up to 5.8
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	6.0
$\lvert V_{tb}\rvert$	CDF: $\lvert V_{tb}\rvert = 0.91 \pm 0.11$(stat + sys) ± 0.07(theory)	1	3.2
	D0: $\lvert V_{tb}\rvert = 1.02^{+0.10}_{-0.11}$		5.4
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	0.2
	D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: -3.3 ± 1.4(stat) ± 1.0(syst) GeV	0	5.6
	D0: 0.8 ± 1.8(stat) ± 0.5(syst) GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063$(stat) ± 0.052(syst)	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3

Good agreement with SM

Measurements from Tevatron

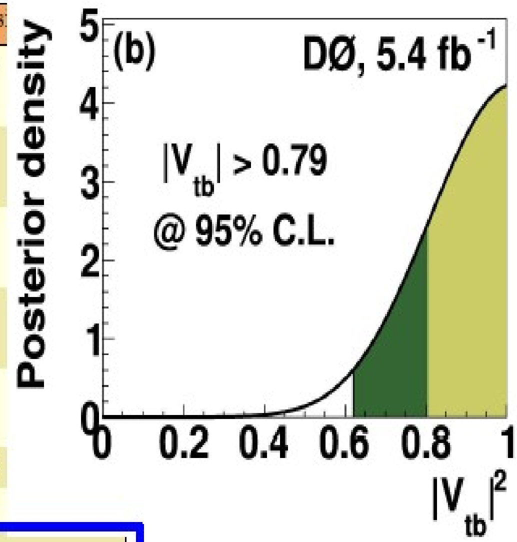
Property	Measurement	SM Prediction	Lum
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
	D0: 2.90 ± 0.59 pb		5.4
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
	D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	5.3
	D0: 0.196 ± 0.065		5.4
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		5.4
M_t	Tev: 173.2 ± 0.9 GeV	-	up to
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	6.0
$\lvert V_{tb} \rvert$	CDF: $\lvert V_{tb} \rvert = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	3.2
	D0: $\lvert V_{tb} \rvert = 1.02^{+0.10}_{-0.11}$		5.4
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	0.2
	D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	5.6
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3



First evidence for $t\bar{t}\gamma$ production!
→ Well in agreement with SM

Measurements from Tevatron

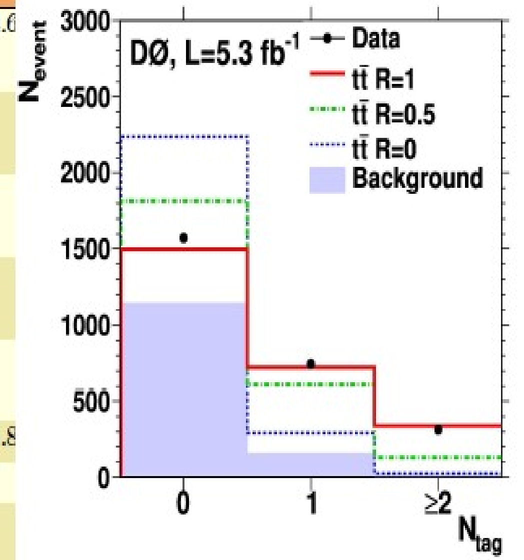
Property	Measurement	SM Prediction	Luminos
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
$\sigma_{\mathbf{tbq}}$ (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
	D0: 2.90 ± 0.59 pb		5.4
$\sigma_{\mathbf{tb}}$ (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
	D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	5.3
	D0: 0.196 ± 0.065		5.4
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		5.4
M_t	Tev: 173.2 ± 0.9 GeV	-	up to 5.8
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	6.0
$\lvert V_{tb}\rvert$	CDF: $\lvert V_{tb}\rvert = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	3.2
	D0: $\lvert V_{tb}\rvert = 1.02^{+0.10}_{-0.11}$		5.4
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	0.2
	D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	5.6
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3



Tight constraints from Tevatron
→ LHC should catch up soon

Measurements from Tevatron

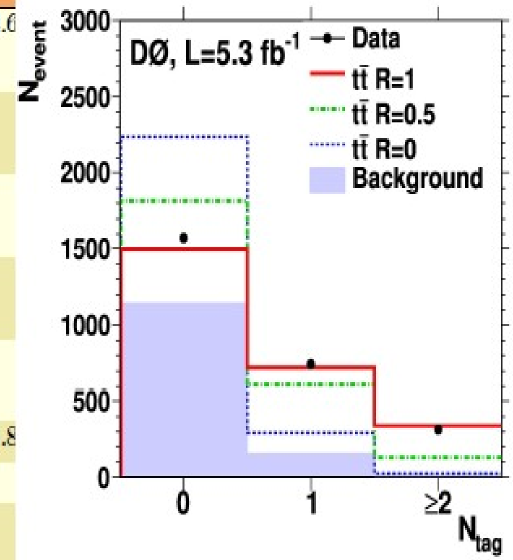
Property	Measurement	SM Prediction	Lumino
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
	D0: 2.90 ± 0.59 pb		5.4
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
	D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	5.3
	D0: 0.196 ± 0.065		5.4
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		5.4
M_t	Tev: 173.2 ± 0.9 GeV	-	up to 5.8
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	6.0
$\|V_{tb}\|$	CDF: $\|V_{tb}\| = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	3.2
	D0: $\|V_{tb}\| = 1.02^{+0.10}_{-0.11}$		5.4
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	0.2
	D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	5.6
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3



World's best measurement of R → limited by systematics

Measurements from Tevatron

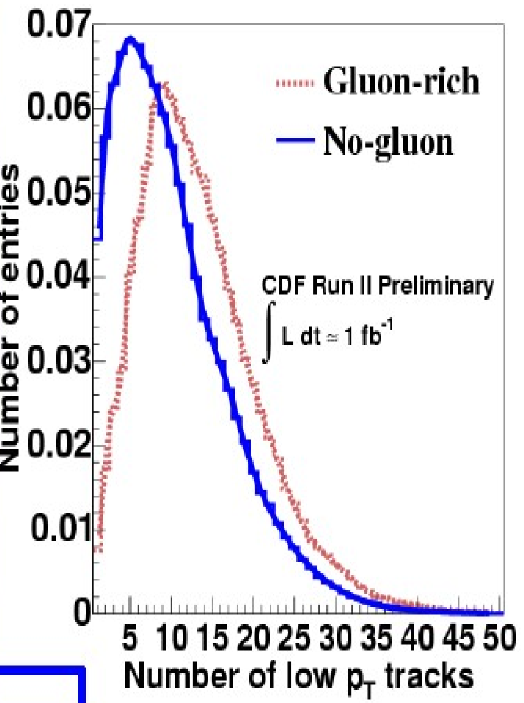
Property	Measurement	SM Prediction	Lumino
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
	D0: 2.90 ± 0.59 pb		5.4
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
	D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	5.3
	D0: 0.196 ± 0.065		5.4
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		5.4
M_t	Tev: 173.2 ± 0.9 GeV	-	up to 5.8
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	6.0
$\lvert V_{tb}\rvert$	CDF: $\lvert V_{tb}\rvert = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	3.2
	D0: $\lvert V_{tb}\rvert = 1.02^{+0.10}_{-0.11}$		5.4
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	0.2
	D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	5.6
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3



World's best measurement of R → limited by systematics

Measurements from Tevatron

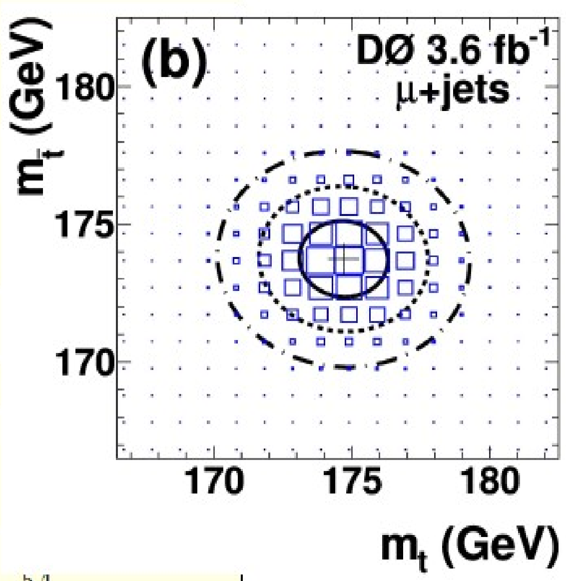
Property	Measurement	SM Prediction	Luminosity
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
	D0: 2.90 ± 0.59 pb		5.4
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
	D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	5.3
	D0: 0.196 ± 0.065		5.4
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		5.4
M_t	Tev: 173.2 ± 0.9 GeV	-	up to 5.8
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	6.0
$\lvert V_{tb} \rvert$	CDF: $\lvert V_{tb} \rvert = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	3.2
	D0: $\lvert V_{tb} \rvert = 1.02^{+0.10}_{-0.11}$		5.4
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	0.2
	D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	5.6
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3



Fraction won't be the same at LHC

Measurements from Tevatron

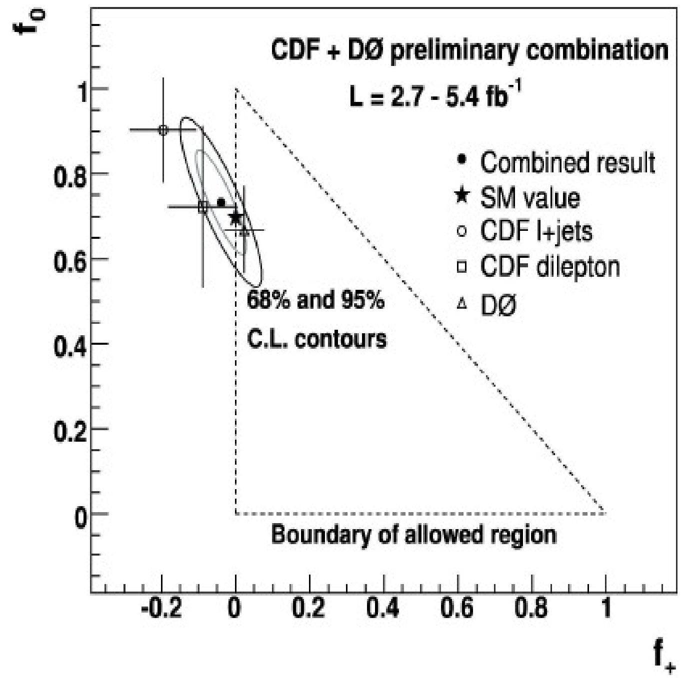
Property	Measurement	SM Prediction	Luminosity (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	
	D0: 2.90 ± 0.59 pb		
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	
	D0: $0.68^{+0.38}_{-0.35}$ pb		
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	
	D0: 0.196 ± 0.065		
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		
M_t	Tev: 173.2 ± 0.9 GeV	-	
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	
$\lvert V_{tb}\rvert$	CDF: $\lvert V_{tb}\rvert = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	
	D0: $\lvert V_{tb}\rvert = 1.02^{+0.10}_{-0.11}$		
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	
	D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	5.6
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3



First time done at Tevatron
→ statistics limited
→ CMS recently released more precise result

Measurements from Tevatron

Property	Measurement		
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb		
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)		
	D0: 2.90 ± 0.59 pb		
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)		
	D0: $0.68^{+0.38}_{-0.35}$ pb		
Charge asymmetry	CDF: 0.158 ± 0.074		
	D0: 0.196 ± 0.065		
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$		
	D0: $0.66 \pm 0.23(\text{stat}+\text{sys})$		
M_t	Tev: 173.2 ± 0.9 GeV		
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb		
$\lvert V_{tb}\rvert$	CDF: $\lvert V_{tb}\rvert = 0.91 \pm 0.11(\text{stat}+\text{sys}) \pm 0.07(\text{theory})$		
	D0: $\lvert V_{tb}\rvert = 1.02^{+0.10}_{-0.11}$		
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL		
	D0: 0.90 ± 0.04		
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$		
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV		
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3

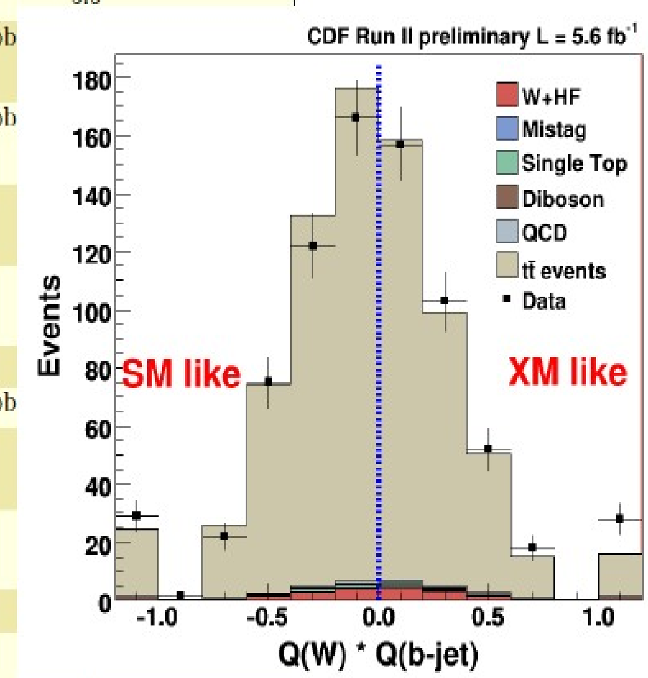


Good agreement with SM

→ Equal statistics and systematics error

Measurements from Tevatron

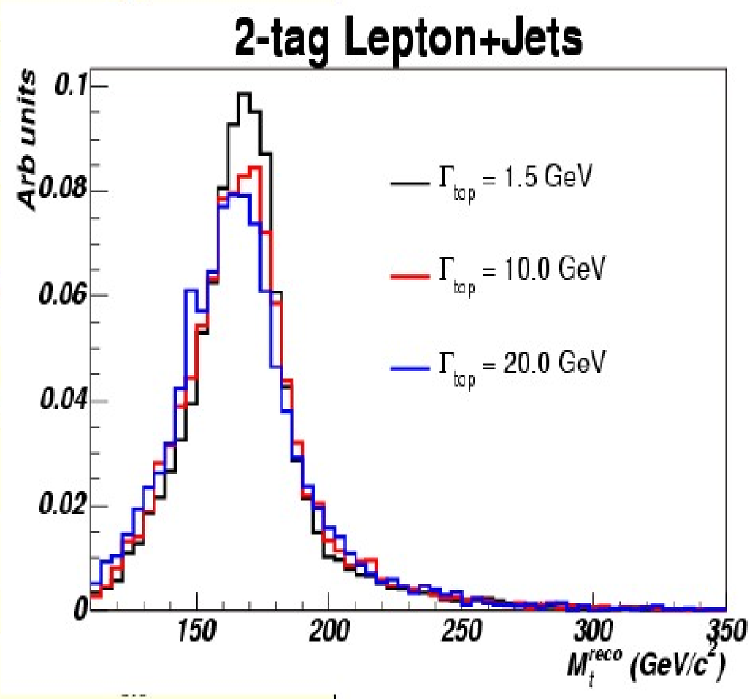
Property	Measurement	SM Prediction	Luminosity (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	
	D0: 2.90 ± 0.59 pb		
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	
	D0: $0.68^{+0.38}_{-0.35}$ pb		
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	
	D0: 0.196 ± 0.065		
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		
M_t	Tev: 173.2 ± 0.9 GeV	-	
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	
$\|V_{tb}\|$	CDF: $\|V_{tb}\| = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	
	D0: $\|V_{tb}\| = 1.02^{+0.10}_{-0.11}$		
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	
	D0: 0.90 ± 0.04		
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		[illegible]
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3



Confirmation of SM charge

Measurements from Tevatron

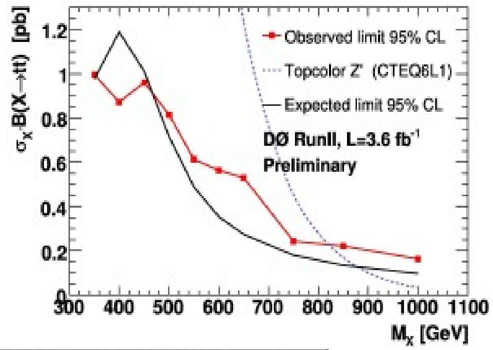
Property	Measurement	SM Prediction	Luminosity (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ±	
	D0: 2.90 ± 0.59 pb		
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ±	
	D0: $0.68^{+0.38}_{-0.35}$ pb		
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	
	D0: 0.196 ± 0.065		
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	0.777^{+0}_{-0}	
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		
M_t	Tev: 173.2 ± 0.9 GeV	-	
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ±	
$\|V_{tb}\|$	CDF: $\|V_{tb}\| = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	
	D0: $\|V_{tb}\| = 1.02^{+0.10}_{-0.11}$		
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	
	D0: 0.90 ± 0.04		
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3

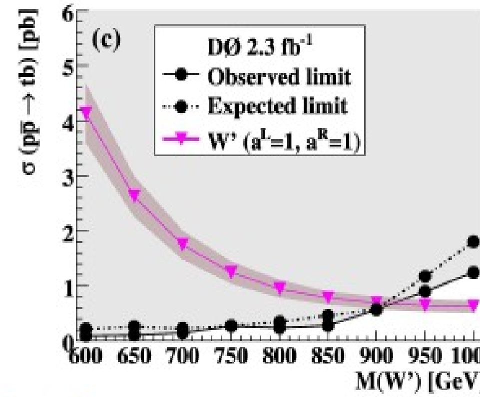


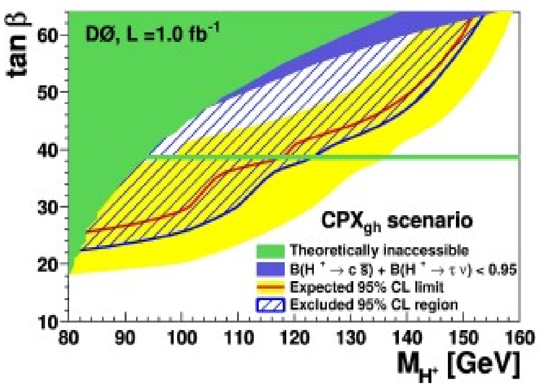
Very precise indirect determination!

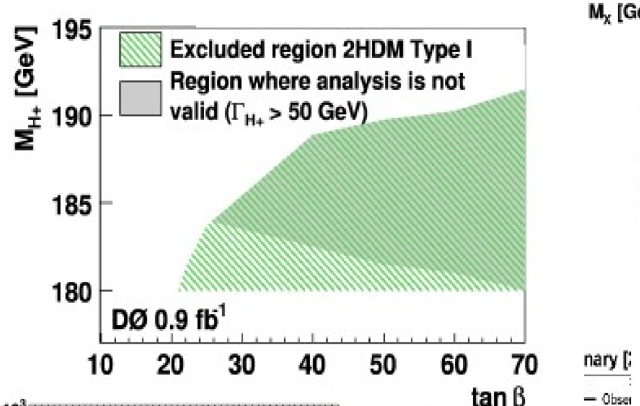
Sensitive searches from Tevatron

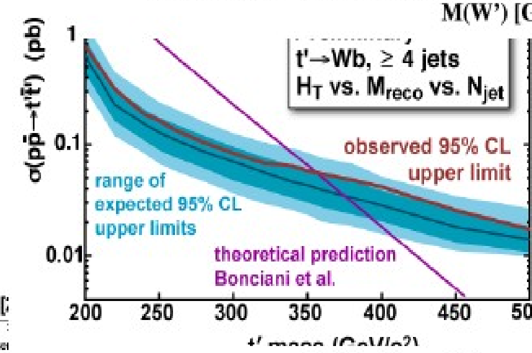
- Many sensitive searches: t', Z', W', H^+, FCNC, boosted top, $t\bar{t}H$,...

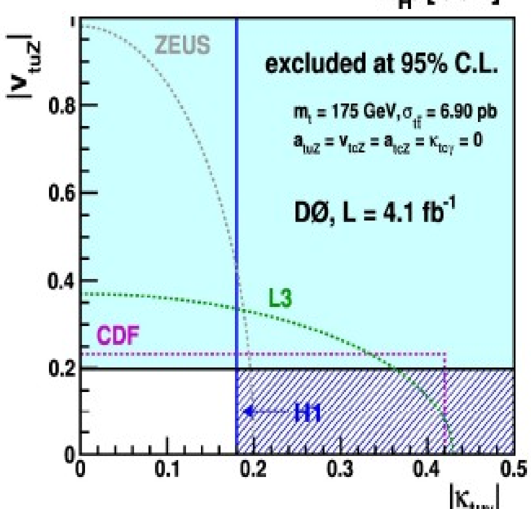


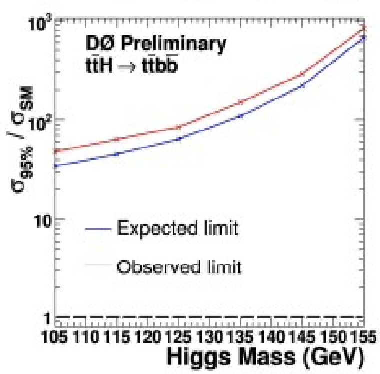


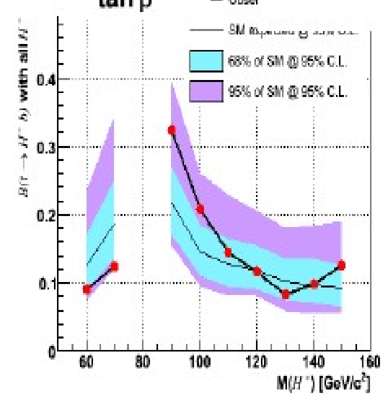


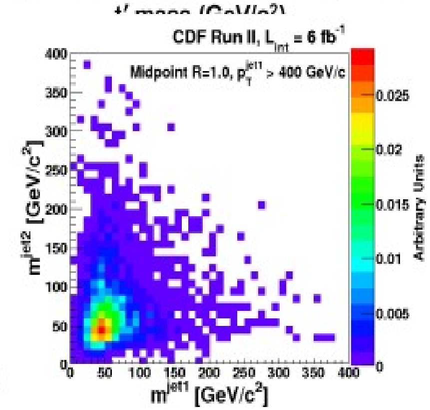












Tevatron inheritance to LHC era

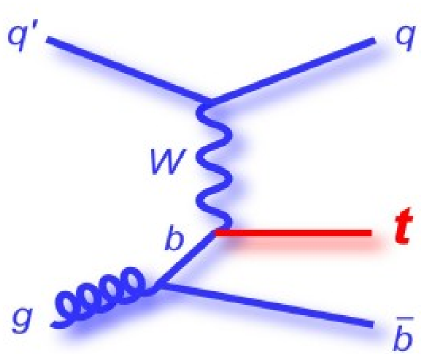
- Which measurements can still compete with the new top factory?
- The secret lies in the differences:

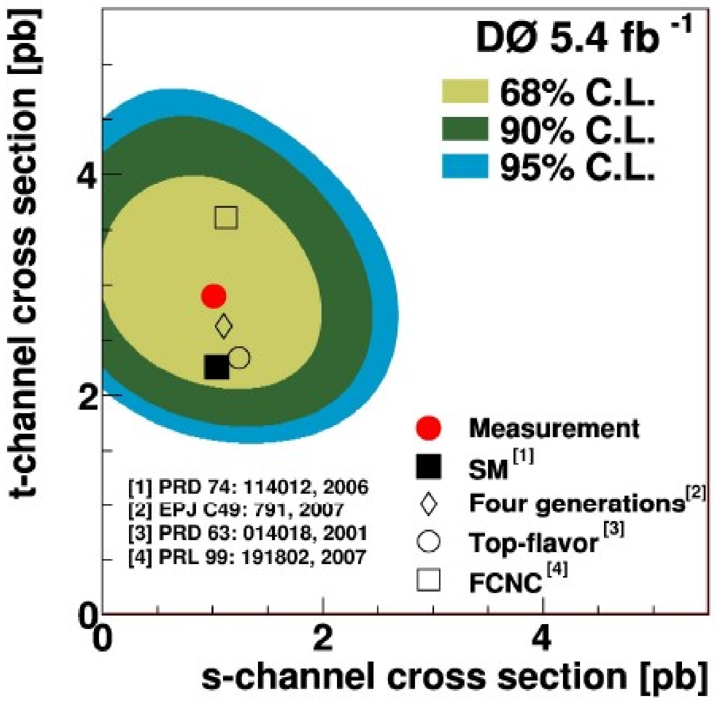
Tevatron:	LHC:
Collision: $p\bar{p} \rightarrow$ CP eigenstate!	Collision: pp
Energy: 1.96 TeV	Energy: 7 TeV
85% $q\bar{q}$ annihilation 15% gluon fusion	15% $q\bar{q}$ annihilation 85% gluon fusion

- Legacy: (Mainly) Analyses that explore the difference!
  - Different energies (& production type): Cross section (differential and total)
  - Different production types: Spin correlation &Forward backward Asymmetry
  - Well understood environment: Mass

Single top: t-channel

- DØ, 2011: Observation of t-channel single top production (5.5 SD significance)
  - $(p\bar{p} \rightarrow tqb + X) = 2.90 \pm 0.59$ pb
  - Limited by systematics
- t-channel:
  - Needs very special selection (high jet η, low p_T for soft b-jet)





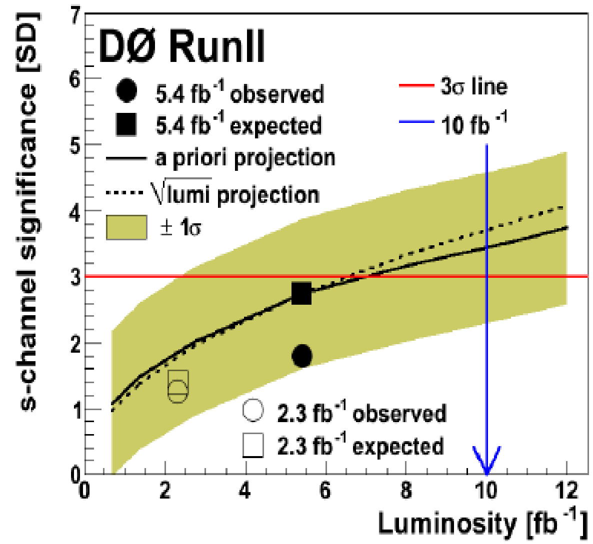
Single top: s-channel

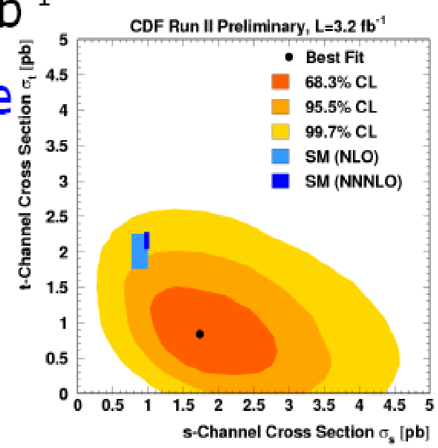
- Legacy with full dataset: s-channel
  - Only 4x higher production rate at LHC (even more background)
- So far:
  - DØ: Expected sensitivity with 5.4fb^{-1} close to 3 sigma
  - CDF: sensitivity not calculated but about 3 sigma with 3.2fb^{-1}

    → With full dataset evidence per experiment doable
- CDF+DØ combination:

  At least evidence!

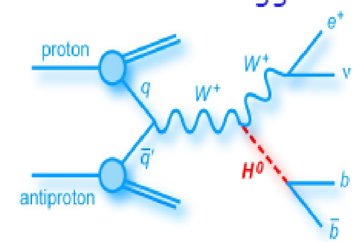
  Maybe observation?





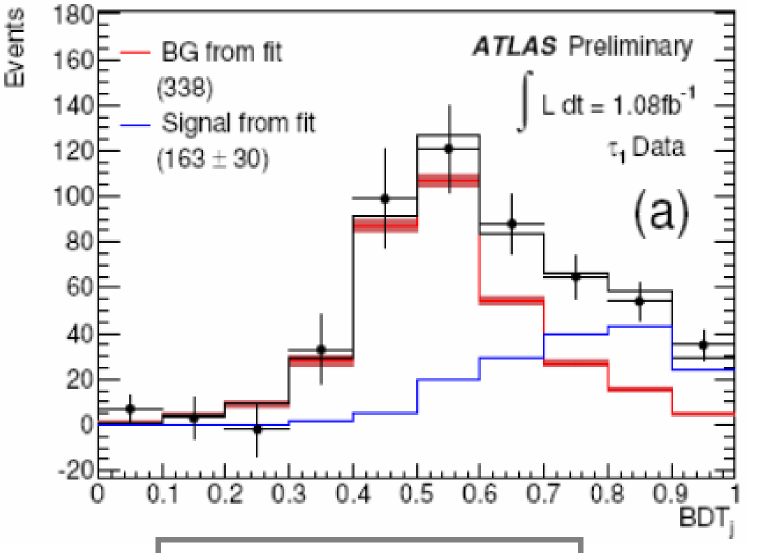
Single top final state looks similar to WH!

Use methods developed in single top search also for Higgs search



Inclusive cross-section: $\mu+\tau$

- <u>Motivation:</u> decays like **$t \to bH^+$** can enhance BR of final states involving τ-leptons
- Analysis on **1.1 fb^{-1}**, with **one μ and one hadronically decaying** τ
  - event selection: 1 μ, 1 τ-jet (with one track τ_1 and with three tracks τ_3) and two other jets, one of them passing b-tagging
- **Boosted decision trees (BDT) used to identify τ's** and reject electrons and jets
- **Signal fractions from a fit on BDT_j**
  - **backgrounds** templates using control samples in data
- Main systematics:
  - τ-identification,
  - ISR/FSR modelling
  - b-tagging



ATLAS-CONF-2010-119

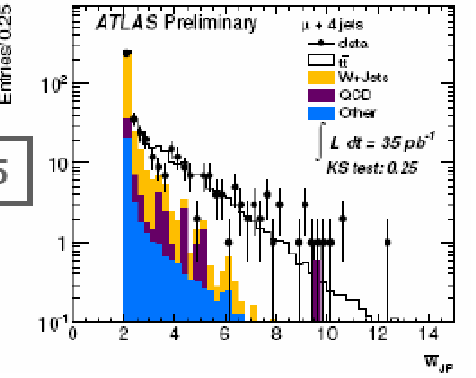
$$\sigma_{t\bar{t}} = 142 \pm 21\ (\text{stat.}) \pm^{20}_{16}\ (\text{syst.}) \pm 5\ (\text{lumi.})\quad \text{pb}$$

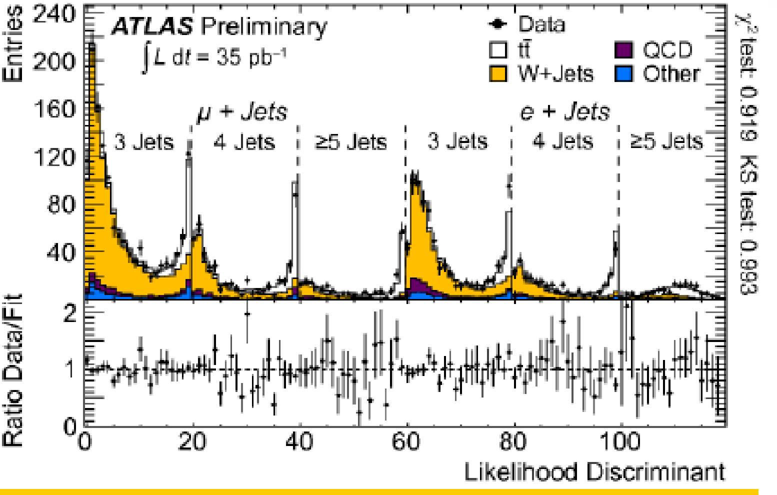
~20% precision

Inclusive cross-section: l+jets tag

- Analysis based on **35 pb^{-1}**:
- **Multivariate technique** to separate signal from background
  - **likelihood discriminant** based on 4 variables
    - lepton η, event aplanarity, transverse momentum of all jets but the two leading ones, average **b-tagging probability** (considering the two jets with the lowest light jet probability)
- **Fit in 6 channels**: 3, 4 and ≥5 jets in e and μ channel
- Main systematics:
  - W+jets heavy flavour fraction
  - b-tagging calibration

ATLAS-CONF-2011-035



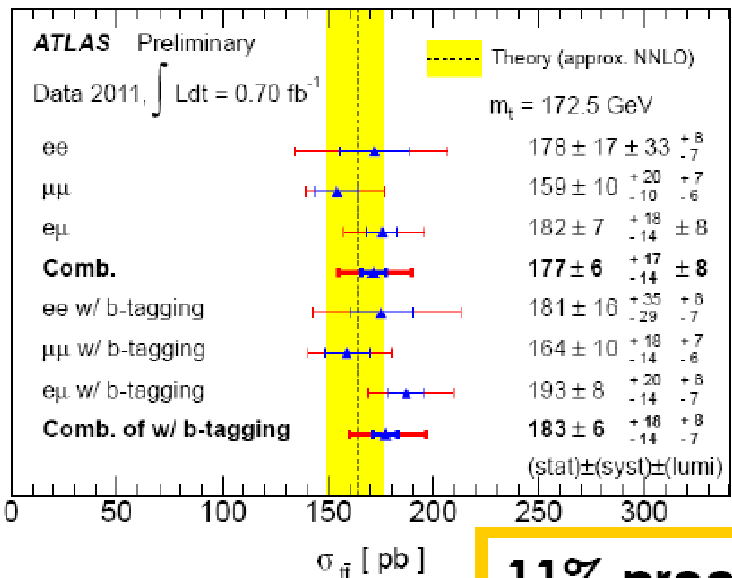


$$\sigma_{t\bar{t}} = 186 \pm 10\,(\mathrm{stat.})^{+21}_{-20}\,(\mathrm{syst.}) \pm 6\,(\mathrm{lumi.})\,\mathrm{pb}$$

13% uncertainty

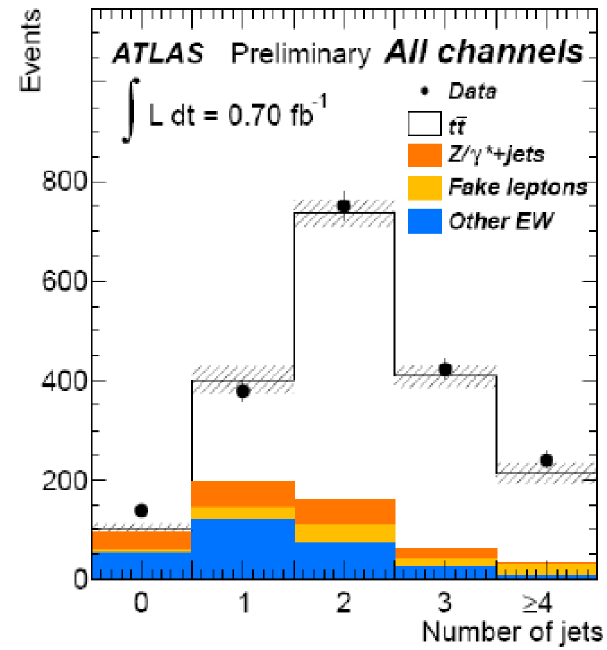
Inclusive cross-section: dilepton

- Data corresponding to **0.70 fb^{-1}**
- Two counting analysis **with/without** the request of a b-tagged jet
- Main backgrounds estimated from data:
  - QCD
  - Z+jets



11% precision

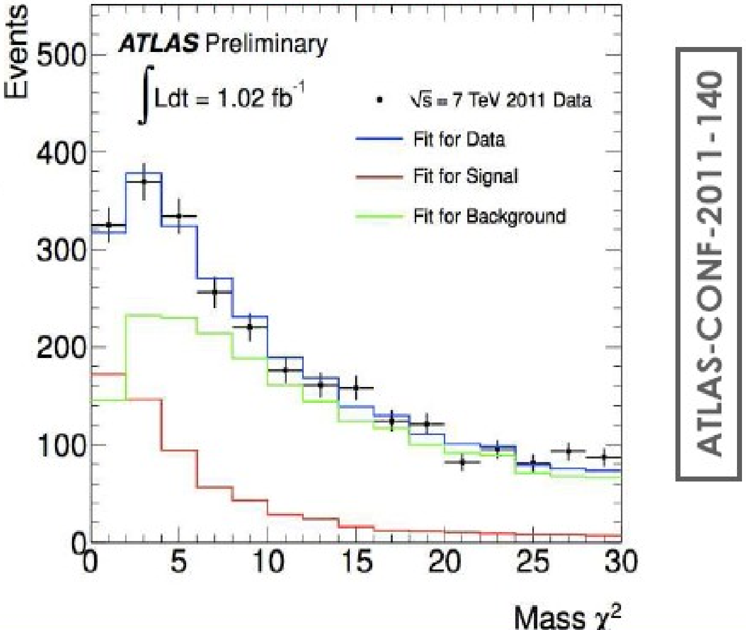
ATLAS-CONF-2011-100



- Main systematics:
  - JES
  - luminosity
  - b-tagging efficiency (tag analysis)

Inclusive cross-section: all hadronic

- Analysis based on **1.02 fb^{-1}**
- Event selection
  - multi-jet trigger
  - at least 6 jets, 2 b-tagged
  - upper cut on **E_T^{miss} significance**: $E_T^{miss}/\sqrt{H_T}$
    - H_T = scalar sum of the transverse momentum of all jets in the event
  - minimal **ΔR separation between the two b-jets**: $\Delta R(b,\bar{b}) > 1.2$
- The signal fraction is extracted from a fit on χ^2 mass distribution using signal+background templates
  - signal: from MC
  - QCD: from data using control samples with exactly 4 or 5 jets
- Main systematics:
  - ISR/FSR modelling
  - JES
  - b-tagging efficiency

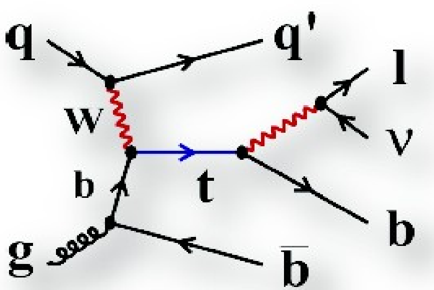


$$\sigma(pp \to t\bar{t}) = 167 \pm 18\ (\text{stat.})\ \pm 78\ (\text{syst.})\ \pm 6\ (\text{lum.})\ \text{pb}$$

48% precision

LHC analyses

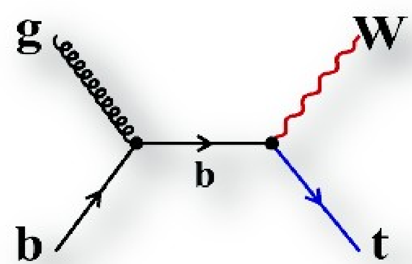
t channel



CMS
- 2D fit
- boosted decision tree

ATLAS
- cut-based
- neural network

Wt channel

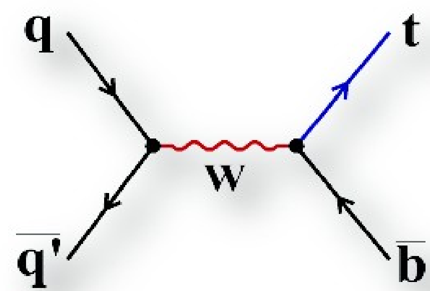


ATLAS: lepton+jets and dilepton channel: cut-based

CMS: dilepton channel

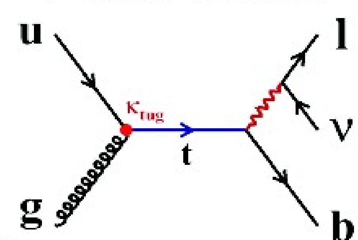
NEW $2.1\ fb^{-1}$

s channel



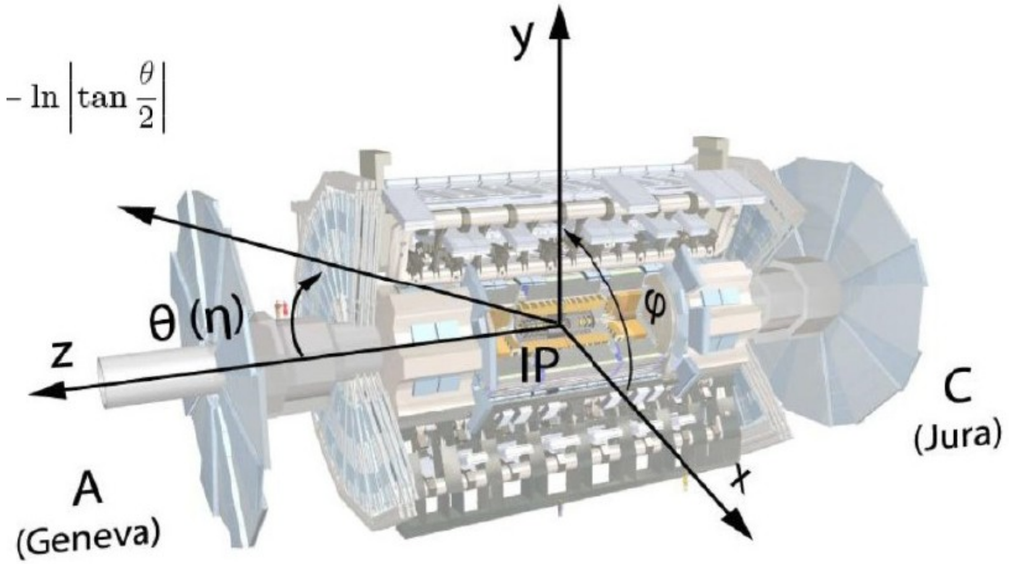
ATLAS: cut-based

FCNC search



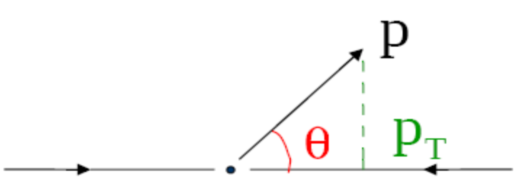
ATLAS: neural network

ATLAS Detector



THE ATLAS DETECTOR IS REALLY BIG!

- Length : $\sim$ 46 m
- Radius : $\sim$ 12 m
- Weight : $\sim$ 7000 tons
- $\sim 10^8$ electronic channels
- 3000 km of cables



Transverse momentum

(in the plane perpendicular to the beam)

$$p_T = p \sin\theta$$

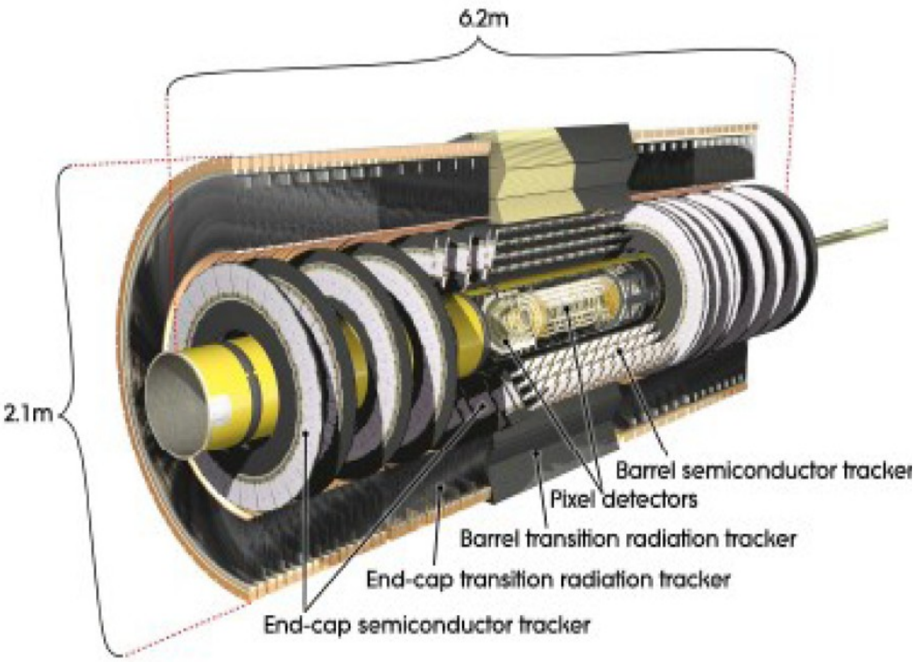
Rapidity: $\eta = -\log(\mathrm{tg}\,\frac{\theta}{2})$

$\theta = 90^\circ \rightarrow \eta = 0$

$\theta = 10^\circ \rightarrow \eta \cong 2.4$

$\theta = 170^\circ \rightarrow \eta \cong -2.4$

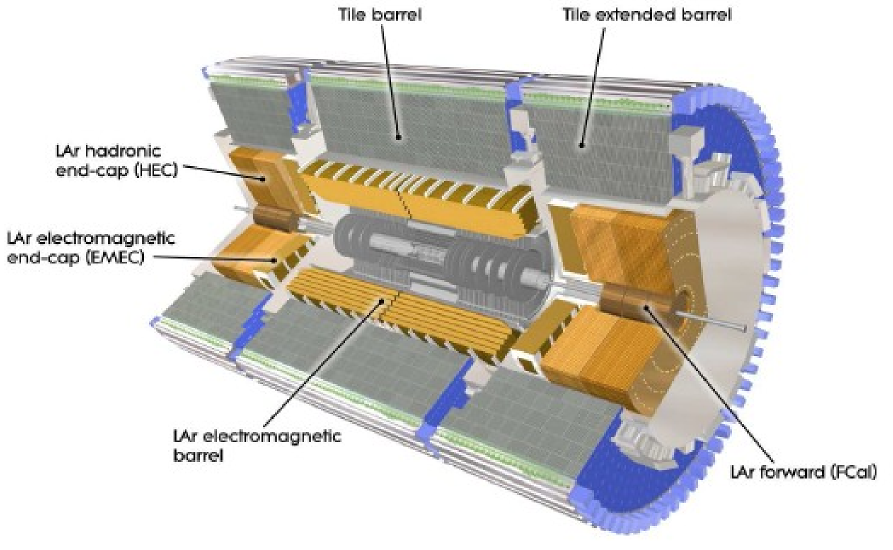
ATLAS Inner Detector



The inner detector $|\eta| < 2.5$ consists of

- Pixel detectors, semi-conductor tracker (SCT), transition radiation tracker
  - $\approx$ 87 million readout channels
  - Immersed in 2T solenoidal magnetic field
- Resolution of $\sigma/p_T = 5 \times 10^{-4} \oplus 0.015$

ATLAS Calorimeters



Electromagnetic and hadronic calorimeters

- Subsystem technology and granularity $\leftrightarrow$ shower characteristics
- Transverse and longitudinal sampling $\approx$ 200000 readout cells up to $|\eta| < 4.9$

Electromagnetic Calorimeters:

- Fine granularity $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ in central region
- Energy resolution $10\%/\sqrt{E}$

Hadronic Calorimeters:

- Granularity $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in central region, less segmented in forward region
- Energy resolution $50\%/\sqrt{E} \oplus 0.03$