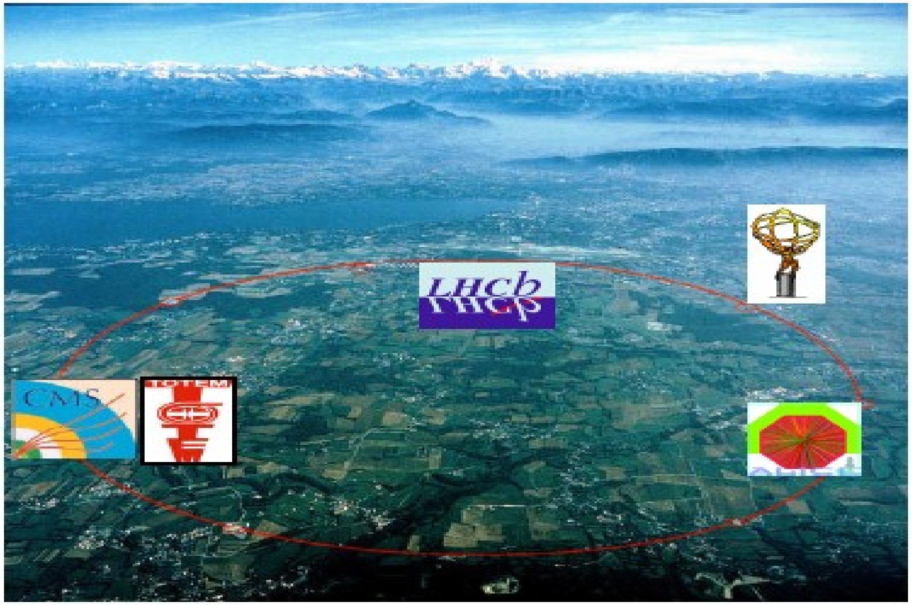
Physics Program

of the experiments at

Large Hadron Collider



Physics with top quarks

21 November 2012

Elzbieta Richter-Was

Latest news

Hadron Collider Physics Symposium 2012
HCP2012
The Hadron Collider Physics Symposium 2012 will be hosted by Kyoto University, in Kyoto, Japan.
The 23rd conference in this series, this meeting will showcase the latest results from the LHC, Tevatron, RHIC and HERA.
November 12 - 16, 2012
Kyoto University
Kyoto, Japan
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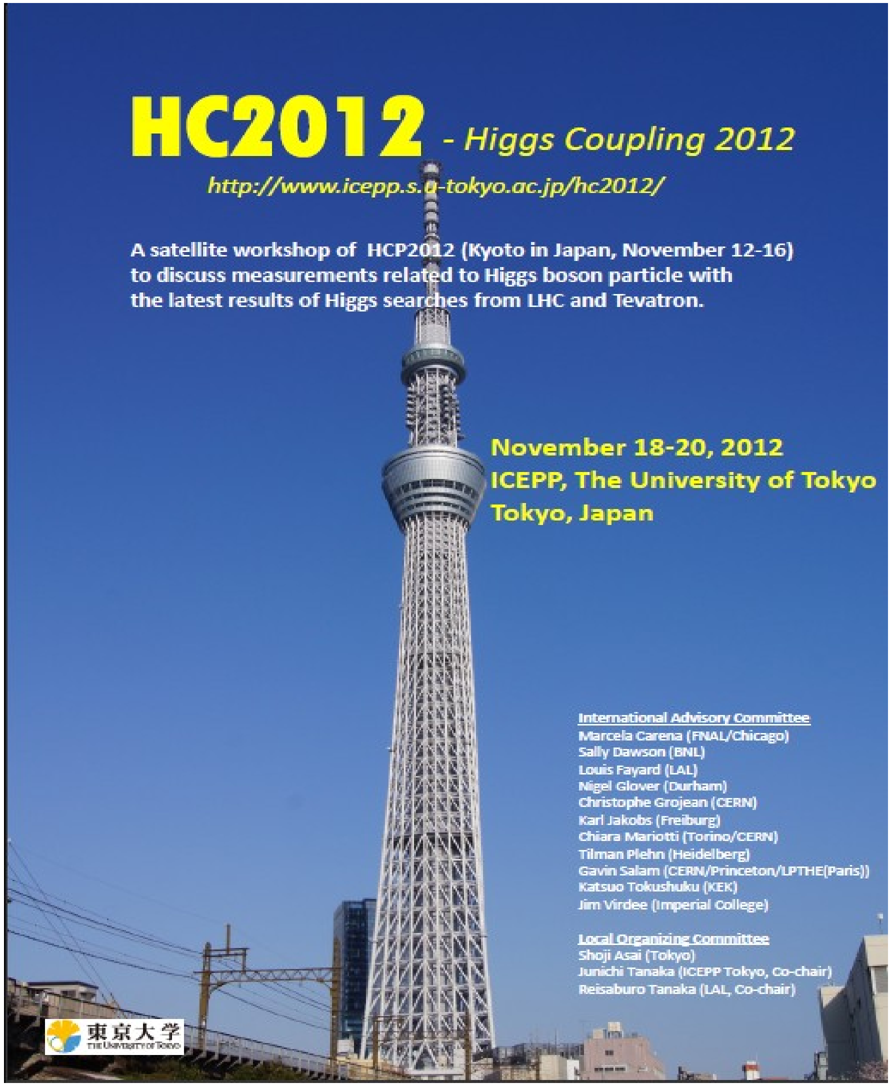

HC2012 - Higgs Coupling 2012
http://www.icepp.s.u-tokyo.ac.jp/hc2012/
A satellite workshop of HCP2012 (Kyoto in Japan, November 12-16)
to discuss measurements related to Higgs boson particle with
the latest results of Higgs searches from LHC and Tevatron.
November 18-20, 2012
ICEPP, The University of Tokyo
Tokyo, Japan
International Advisory Committee
Marcela Carena (FNAL/Chicago)
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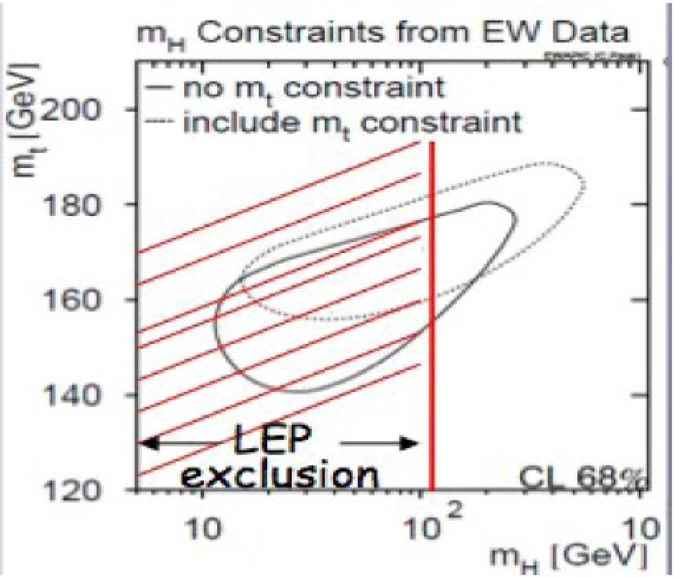
Brief history of the top quark

- 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^-): $\mathbf{m_t > 23.3}$ **GeV** in 1984
  - Tristan (e^+e^-) in Japan: $\mathbf{m_t > 30.2}$ **GeV** in late 80s
  - SPS (p pbar): discovery of W and Z in 1983
  - UA1: $\mathbf{m_t > 44}$ **GeV** in 1988 (after having access in 1984 which they thought was evidence for the top)
  - LEP (e+e-): $\mathbf{m_t > 45.8}$ **GeV** in 1990
  - UA2: $\mathbf{m_t > 69}$ **GeV** which closed down channel
    - $W \rightarrow t\, b$ search closed down

Brief history of the top quark

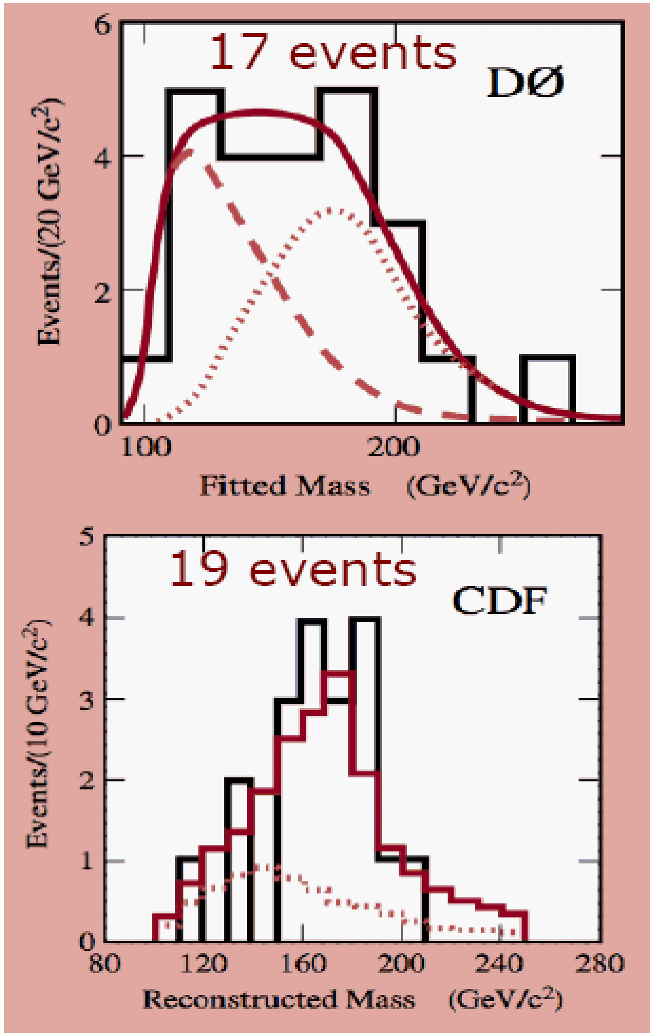
- Searching again for ttbar production with top mass above W boson mass
  - **1992: first lower limits** on top from **CDF** (**m_t > 91 GeV**)
  - **1994: first lower limits** on top from **D0** (**m_t > 131 GeV**)
- Electroweak fits from LEP/SLS/Tevatron data:
  - **155 GeV < m_t < 185 GeV**
- Early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

  “Evidence for top at CDF”

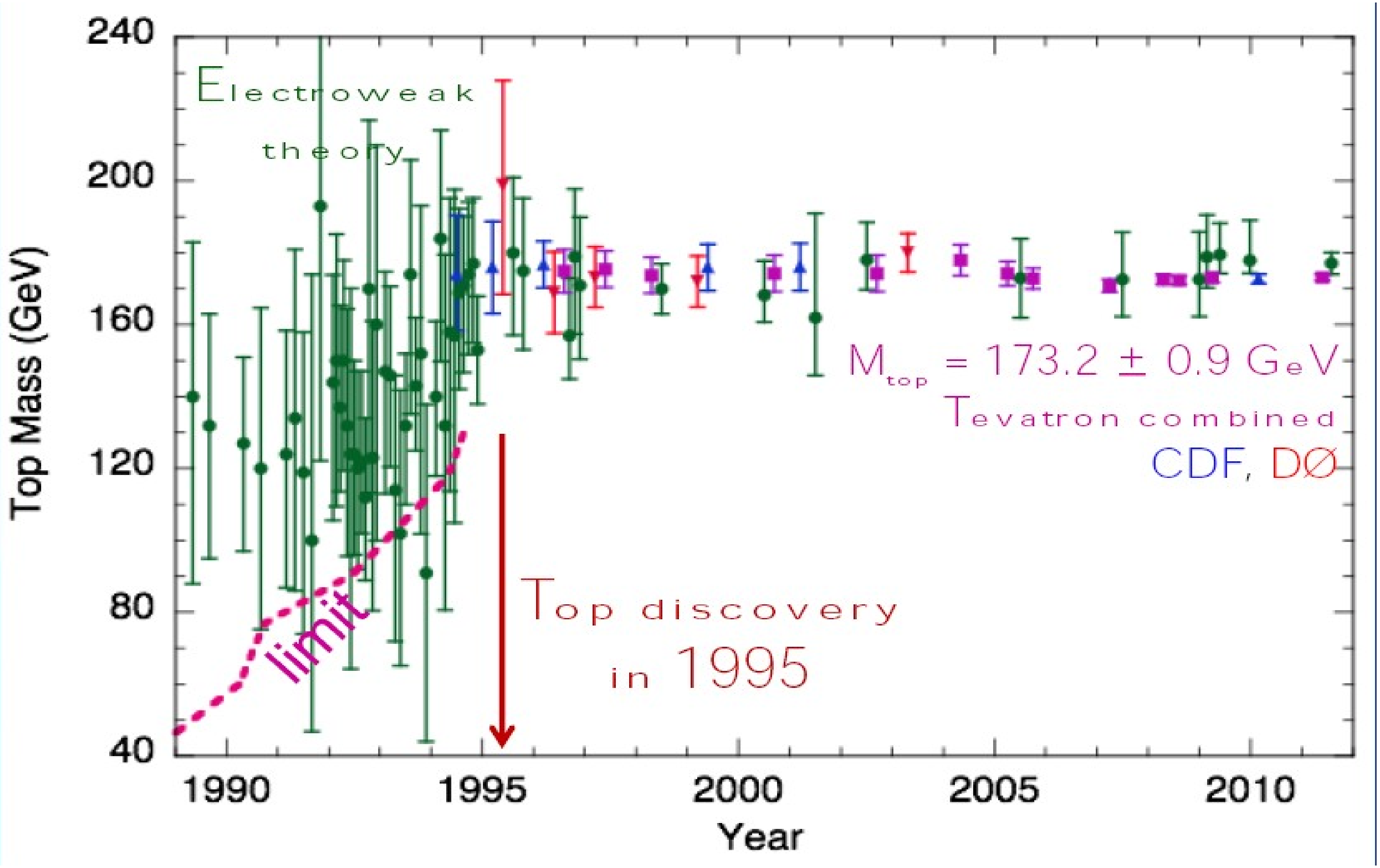


Top-quark discovery

- **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

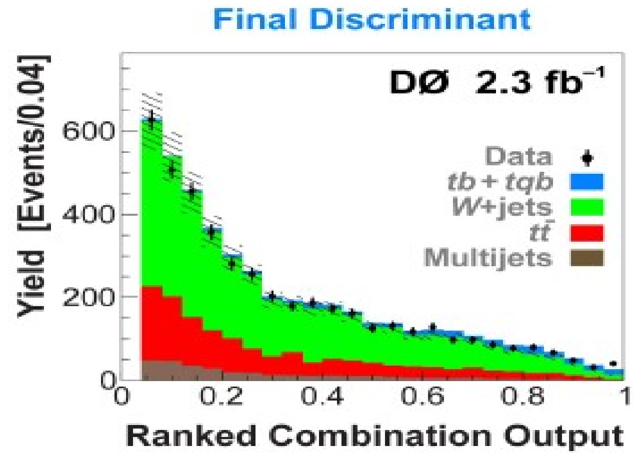


Top quark mass measurement

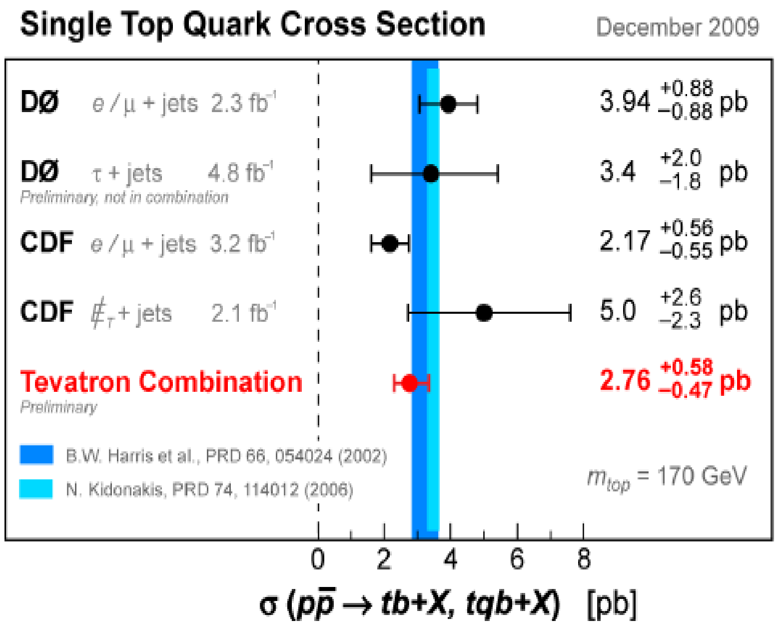


Single top-quark production

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



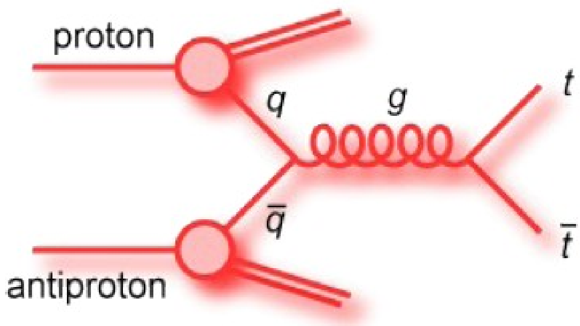
- Single top: very challenging channel
  - Low signal: similar **signature like W+jets!**
  - Counting only: Uncertainty on background larger than expected signal



Top-quark pair production

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

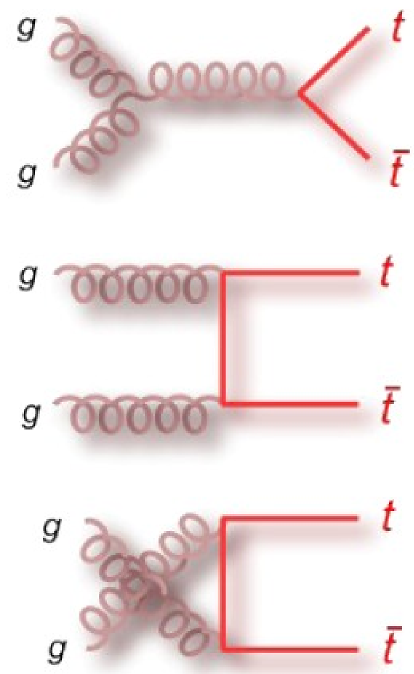
  85%



  + 15%

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

  7 TeV: 15% + 85%



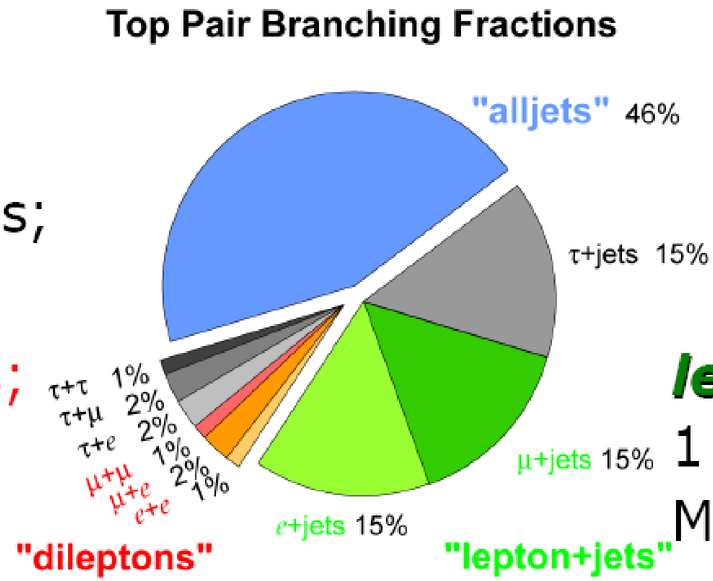
- Production cross section (@Tevatron):
  approximate NNLO: $\sigma = 7.46^{+0.48}_{-0.67}\,pb$ @ m_t=172.5GeV
  - 20 times higher @LHC (7TeV): $\sigma = 164.6^{+11.4}_{-15.7}\,pb$

Final states in ttbar

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

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

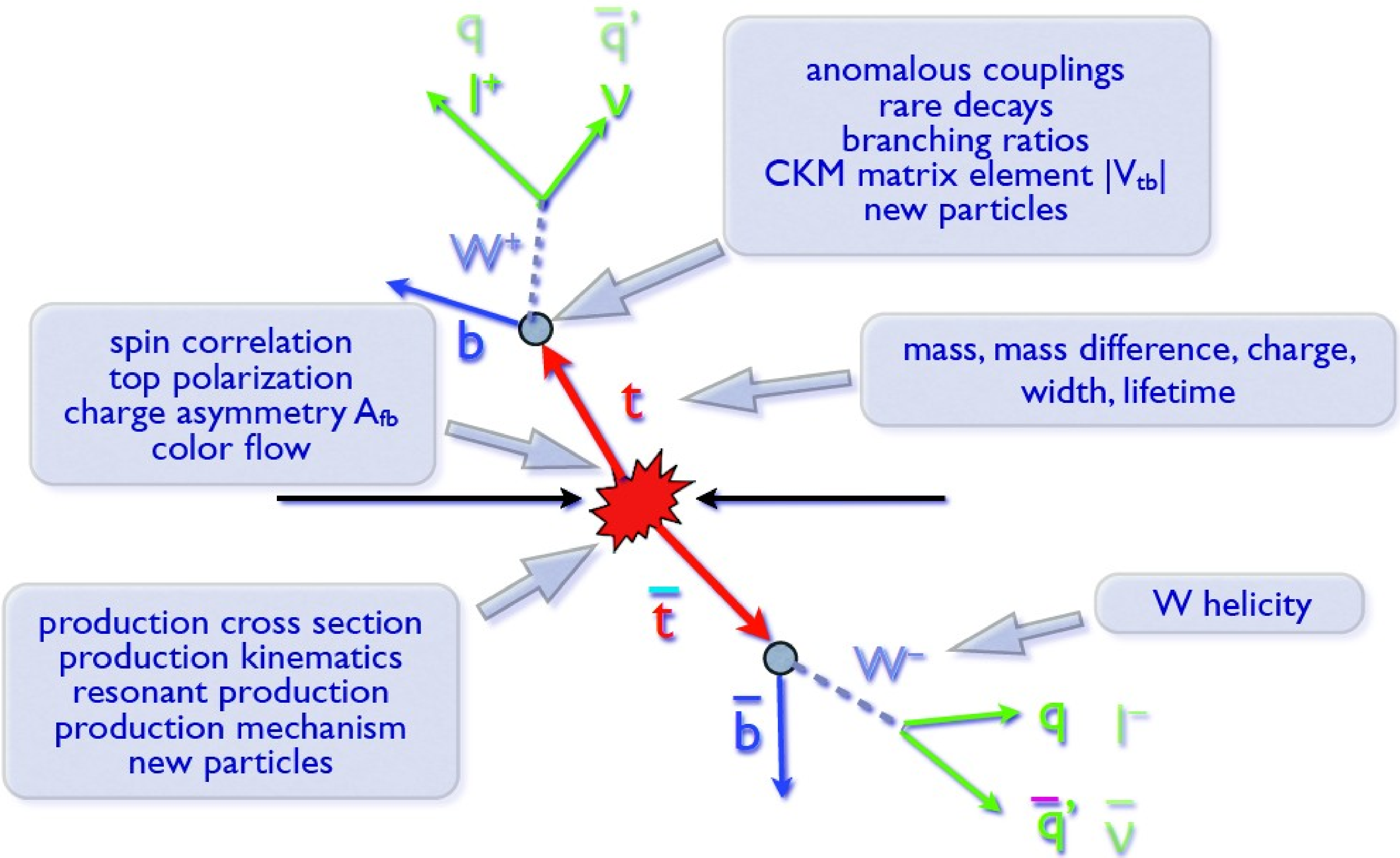
pure hadronic:
≥6 jets (2 b-jets)



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)

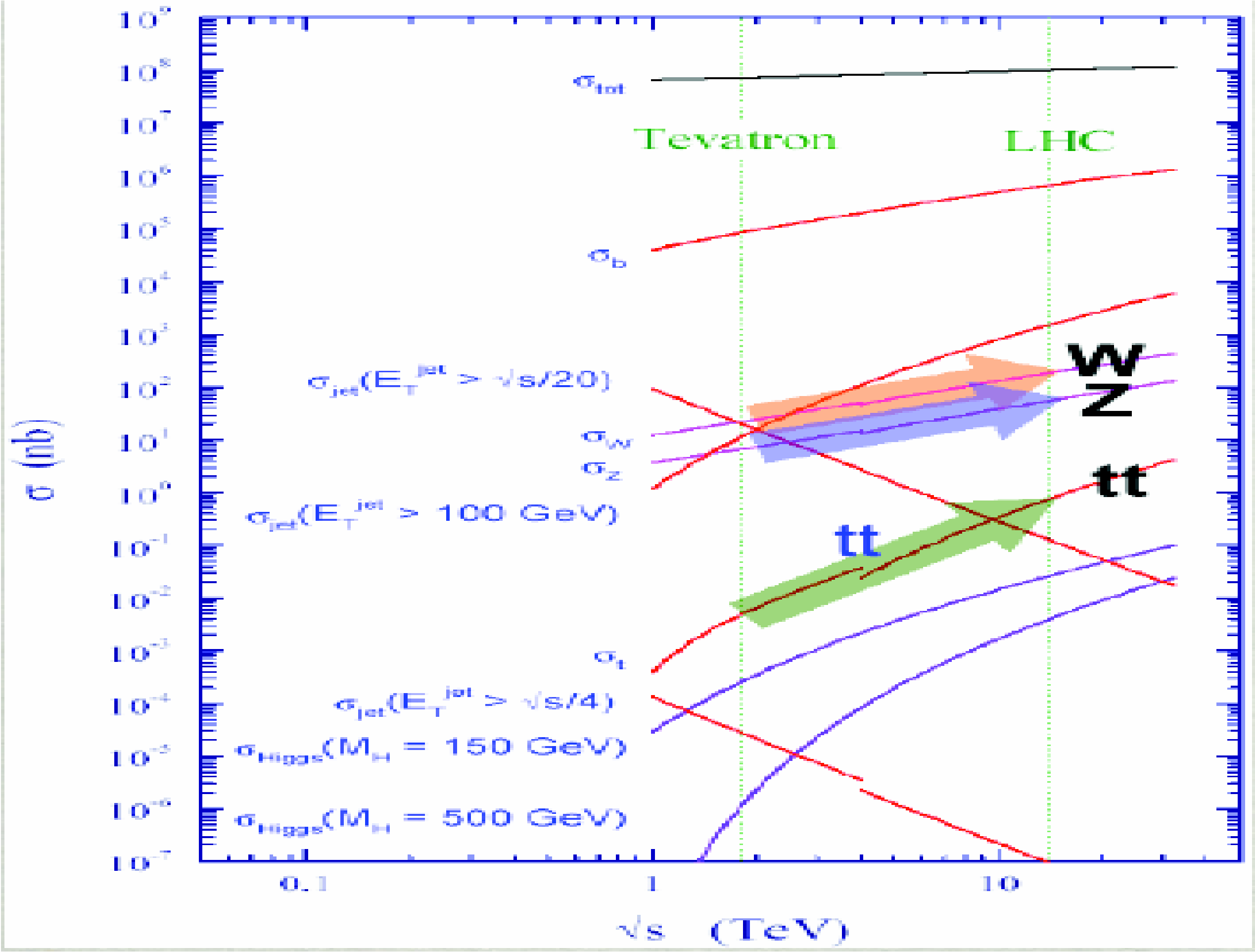
What we study about top-quark?



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-quarks at LHC

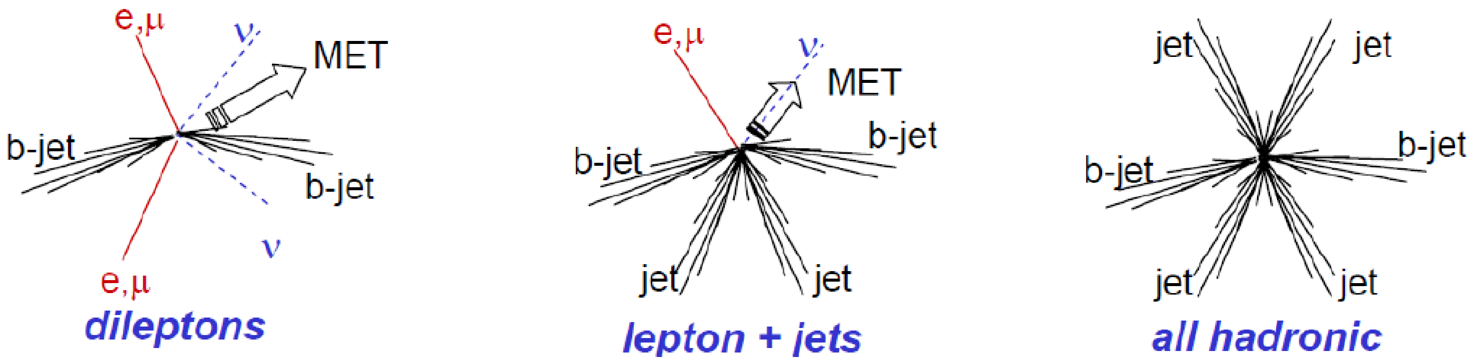


Top mass measurement

- Measurements done according to the decay channel

Decay channel	**CMS**	**ATLAS**	**CDF**	**DØ**
Dilepton	5.0 fb^{-1}	4.7 fb^{-1}	2.0 fb^{-1}	4.3 fb^{-1}
Lepton + Jets	5.0 fb^{-1}	1.0 fb^{-1}	8.7 fb^{-1}	3.6 fb^{-1}
All hadronic	3.5 fb^{-1}	2.0 fb^{-1}	5.8 fb^{-1}	—

- Experimental signature



	Dilepton	**Lepton+jets**	**All hadronic**
Branching Ratio	Low	Medium	High
Background	Tiny (mainly Z+Jets)	Moderate (mainly W+Jets)	High (mainly QCD)
Kinematics	Underconstrained	Constrained	Constrained

Top event reconstruction l+jets

Over constrained kinematic (-2)

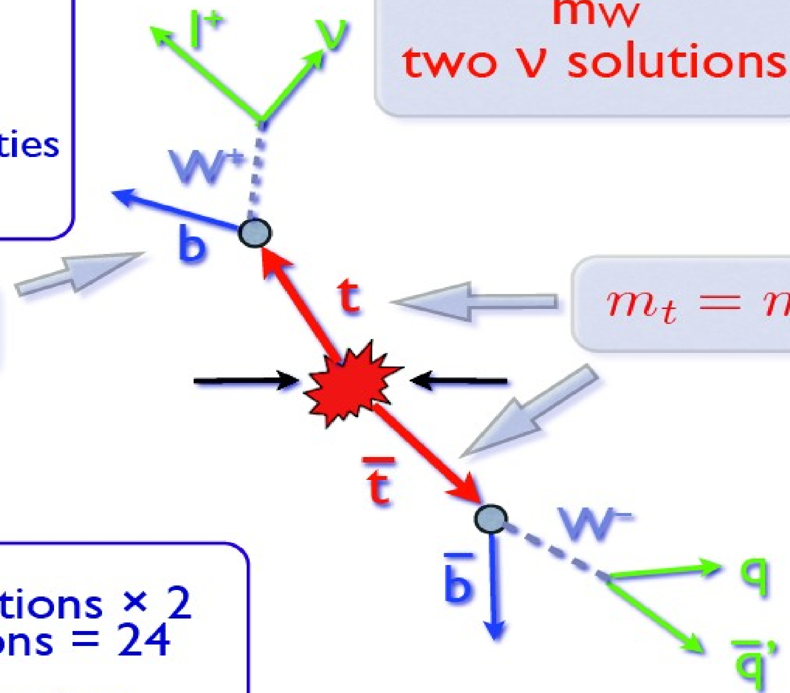
- 18 variables
- 17 measured quantities
- 3 constraints

nDoF: $3n_\nu$-5

Invariant mass m_W
two ν solutions

b-tag

$m_t = m_{\bar{t}}$



Invariant mass m_W

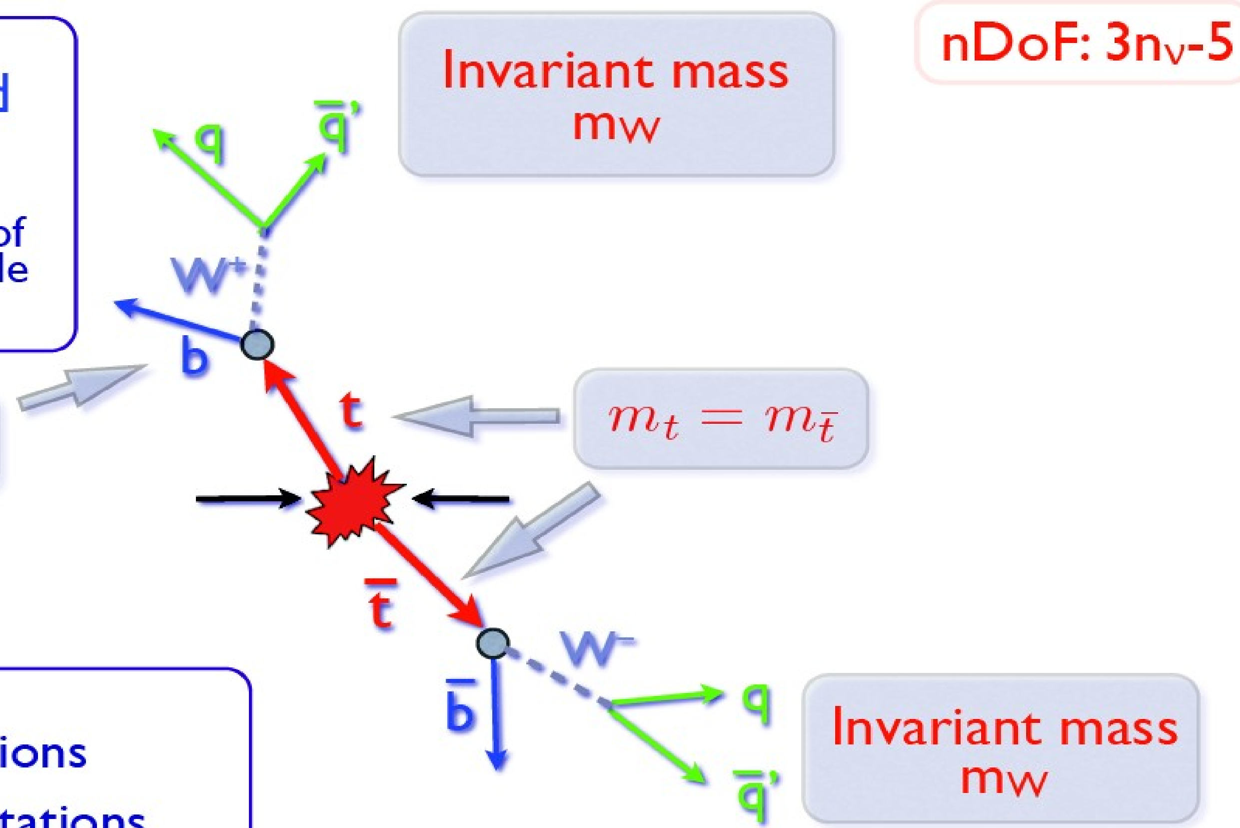
- 12 jet configurations × 2 neutrino solutions = 24
- b-tag: 12 permutation
- 2 b-tags: 4 permutations

Presence of hadronic W allows to constrain JES

Top event reconstruction: all hadronic

Over constrained kinematic (-5)

- full reconstruction of kinematics is possible



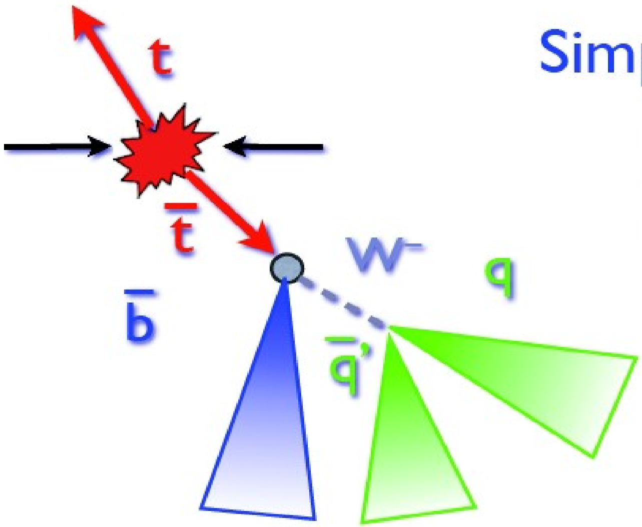
b-tag

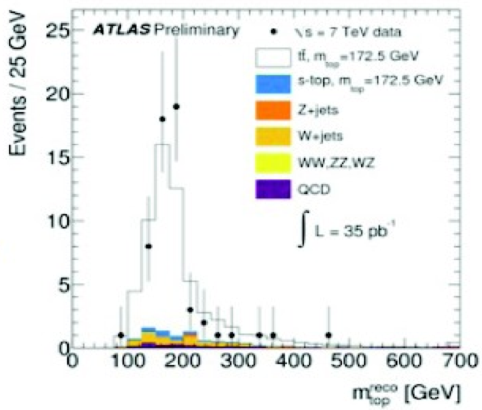
- 90 jet permutations
- b-tag: 30 permutations
- 2 b-tags: 6 permutations

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

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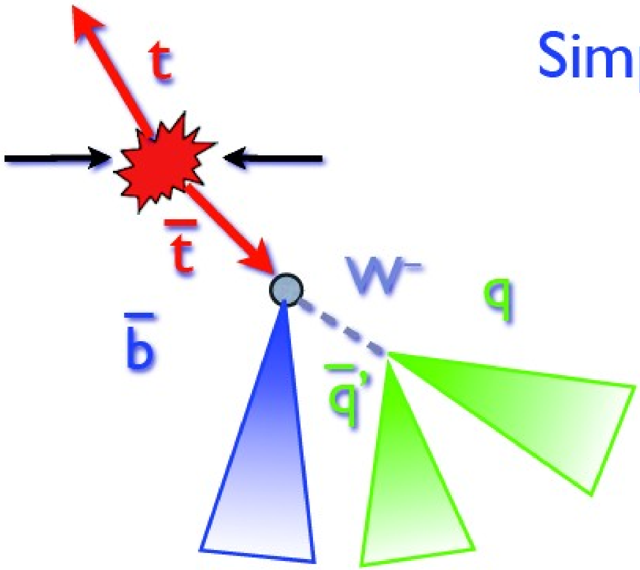
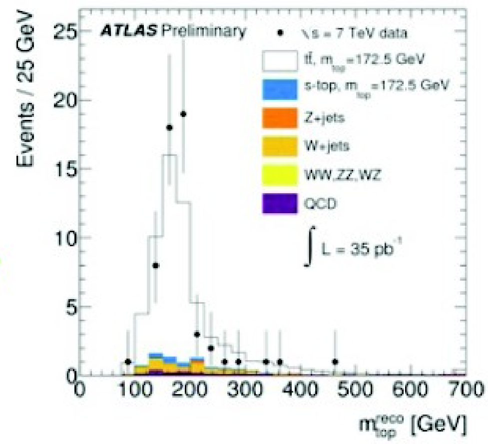
Top event reconstruction l+jets



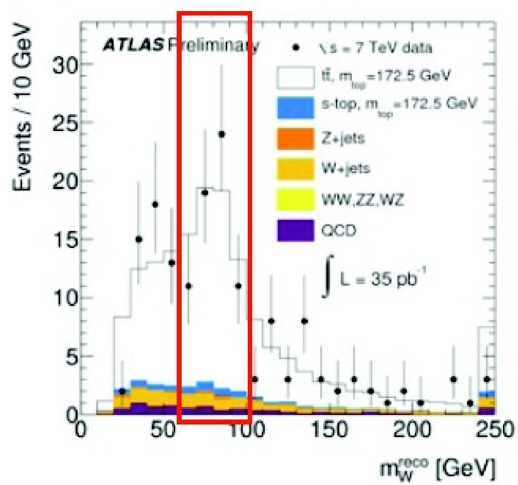
Simple reconstruction - hadronic top



- 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

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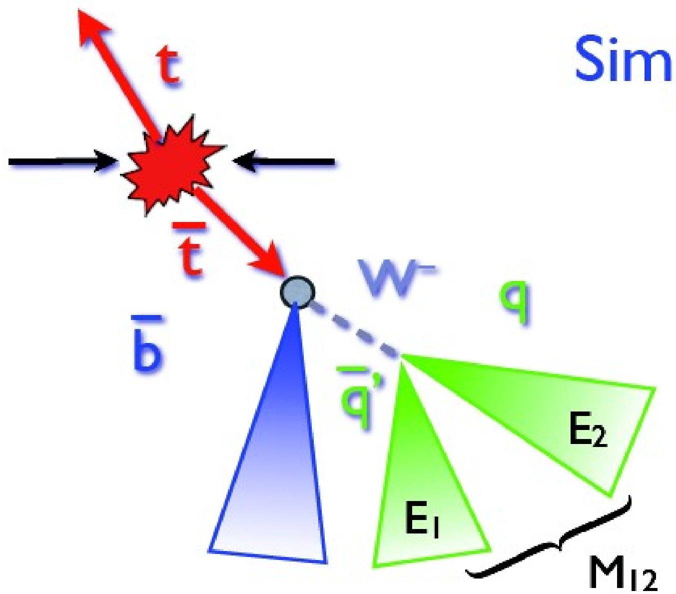
Top event reconstruction l+jets



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

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

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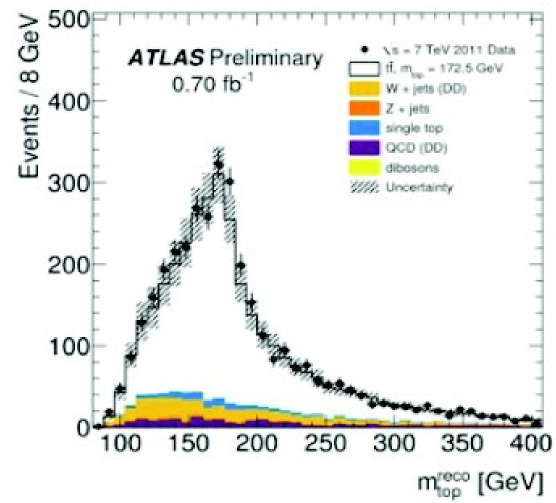
- determines α_1 and α_2
- recalibrates jet energies
- improves m_t resolution



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

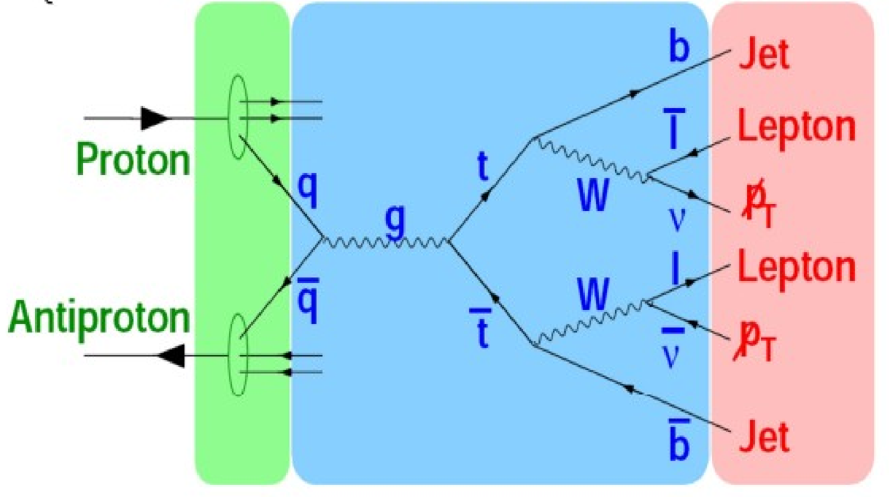
- more sophisticated χ^2 minimization - HitFit
  - uses Transfer Functions to correct reconstructed objects to parton level
  - loose cut on hadronic W mass: 40 GeV<m_W<140 GeV before the fit to reject some permutations

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)

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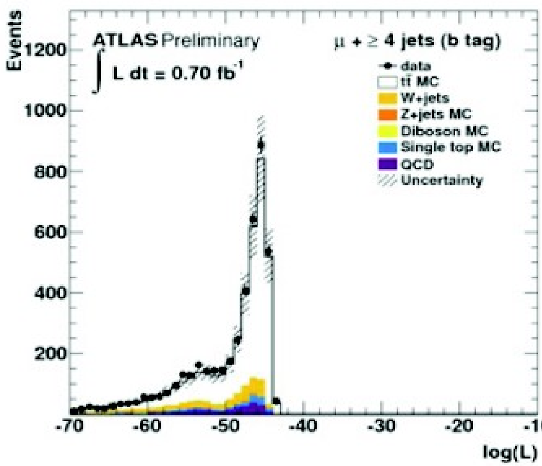
$$L = BW(\hat{E}_{jet,1}, \hat{E}_{jet,2}|m_W, \Gamma_W) \cdot BW(\hat{E}_\ell, \hat{E}_\nu|m_W, \Gamma_W) \cdot BW(\hat{E}_{jet,1}, \hat{E}_{jet,2}, \hat{E}_{jet,3}|m_{top}^{reco}, \Gamma_{top}) \cdot BW(\hat{E}_\ell, \hat{E}_\nu, \hat{E}_{jet,4}|m_{top}^{reco}, \Gamma_{top}) \cdot$$

$$TF(E_x^{miss}|\hat{p}_{x,\nu}) \cdot TF(E_y^{miss}|\hat{p}_{y,\nu}) \cdot TF(E_\ell|\hat{E}_\ell) \cdot \prod_{i=1}^{4} TF(E_{jet,i}|\hat{E}_{jet,i}) \cdot \prod_{i=1}^{4} TF(\eta_{jet,i}|\hat{\eta}_{jet,i}) \cdot \prod_{i=1}^{4} TF(\phi_{jet,i}|\hat{\phi}_{jet,i}) \cdot \delta(b\text{-tagged jet} \mid b\text{-quark}).$$

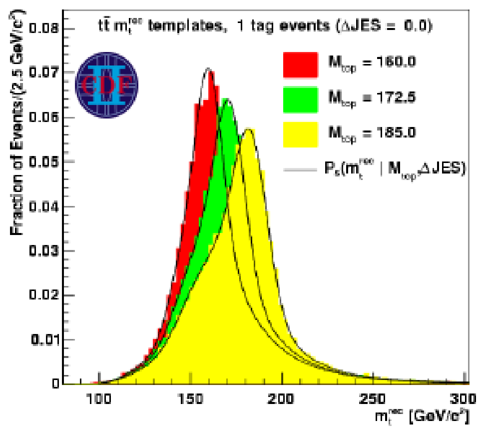
uses Breit-Wigner lineshapes for top and W

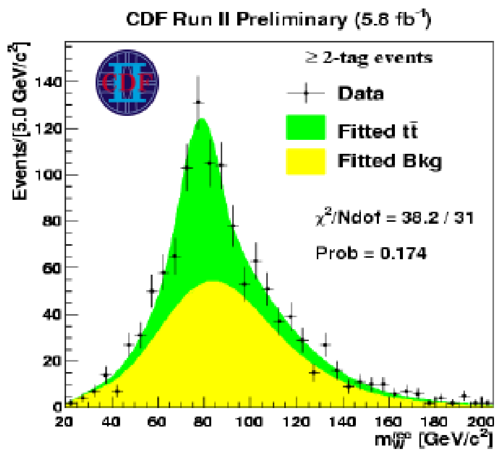
- Transfer Functions to correct reconstructed objects to parton level:
  - energies and angles of light and b-jets
  - the energy of the charged lepton
  - two components of the missing E_T
- b-tagging information can be use as a cut or as a weight

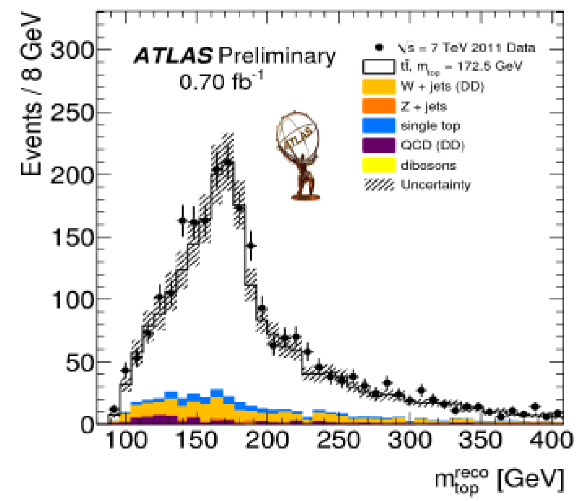


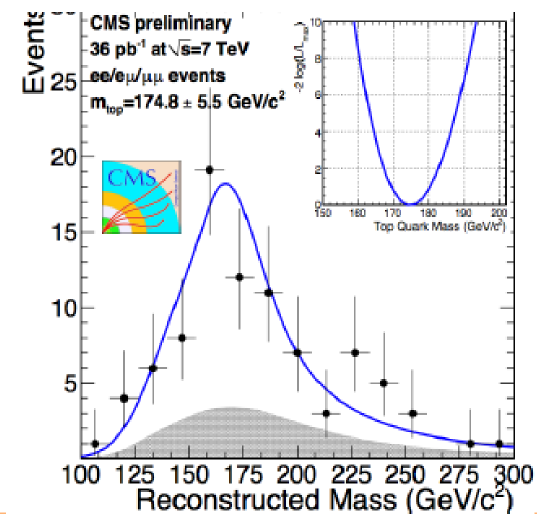
Template method

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







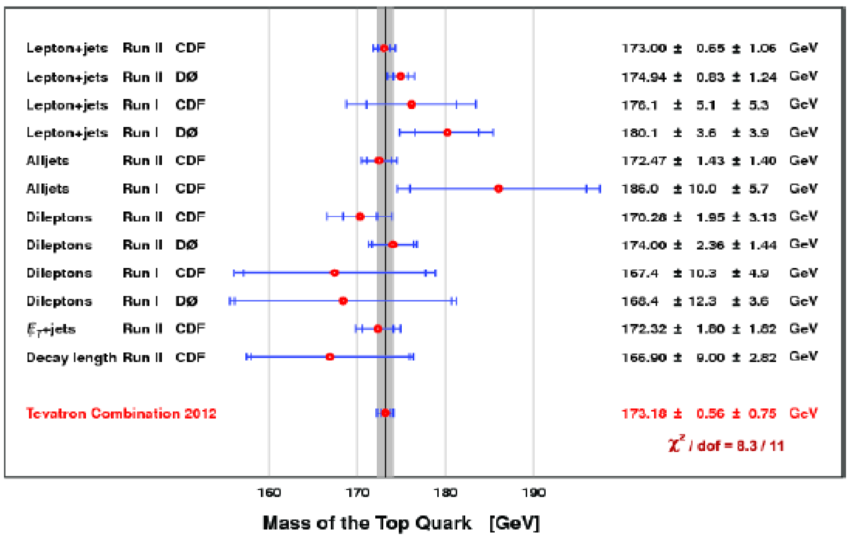


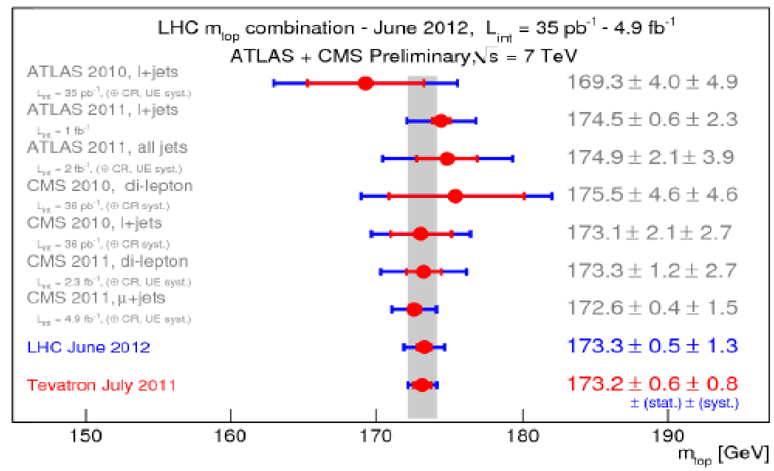
- Dilepton: Construction of templates more complicated due to presence of two neutrinos
  - Neutrino weighting, Matrix Weighting,…

Top-quark mass combinations

- Each experiment combines their own results
- CMS-ATLAS and CDF-DØ also combine

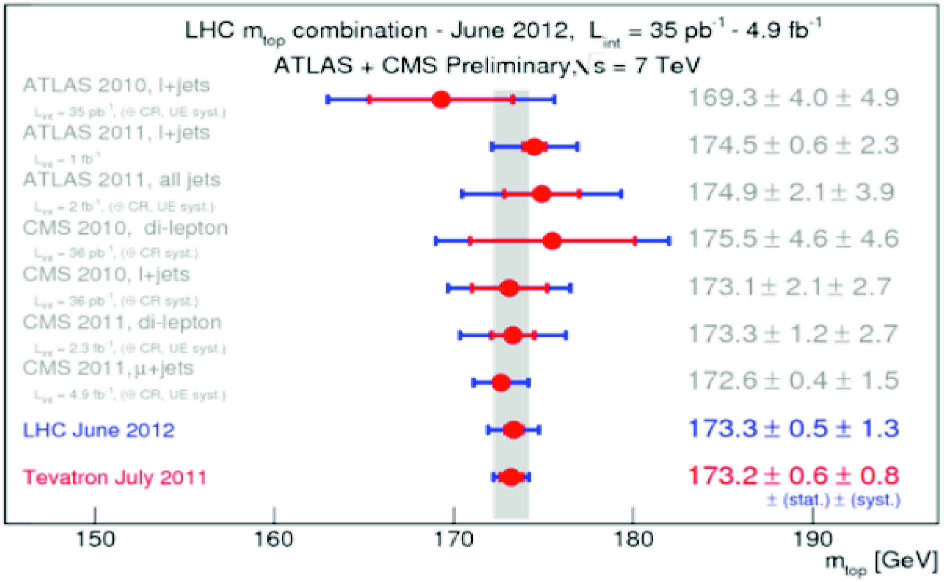
	Top Mass (GeV)
Tevatron	$173.2 \pm 0.6 \pm 0.8$
LHC	$173.3 \pm 0.5 \pm 1.3$





- Measurements from different experiments with different methods agree well with each other
- LHC-Tevatron combination under discussion

LHC top mass combination results



m_t = 173.3±0.5(stat)±1.3(syst) GeV

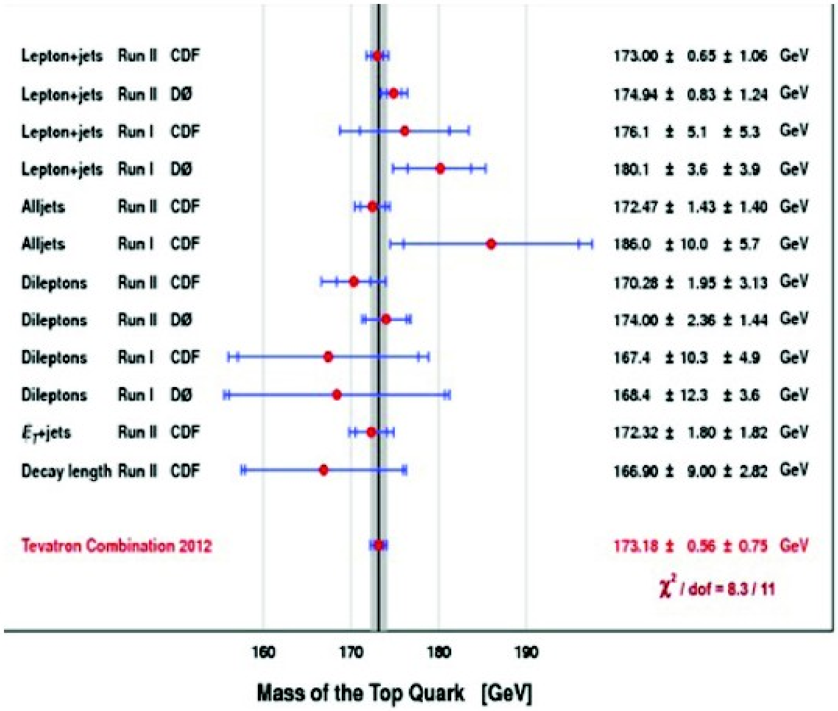
χ^2/NDF = 2.5/6

χ^2 probability = 87%

Combined result is 9% more precise than the best measurement

Uncertainty source	δm_{top} (GeV)
in-situ JES	0.38
rJES (CMS)	0.06
light-jet response (2)	0.07
model of b-jets	0.68
detector model	0.19
underlying event	0.47
radiation	0.69
color reconnection	0.55
MHI	0.25
lepton model	0.01
background data	0.16
background MC	0.01
method calibration	0.13
statistical	0.47
Total	1.40

Tevatron top mass combination results



$m_t = 173.18 \pm 0.56(stat) \pm 0.75(syst)$ GeV
χ^2/NDF = 8.3/11
χ^2 probability = 69%

Combined result is 25% more precise than the best measurement

Uncertainty source	δm_{top} (GeV)
in-situ JES	0.39
light-jet response (1)	0.12
light-jet response (2)	0.19
model of b-jets	0.15
response to b/q/g jets	0.12
out-of-cone correction	0.04
Total JES	0.49
signal model	0.51
jet model	0.11
lepton model	0.10
background data	0.11
background MC	0.14
method calibration	0.09
statistical	0.56
Total	0.94

Top quark mass: what we measure?

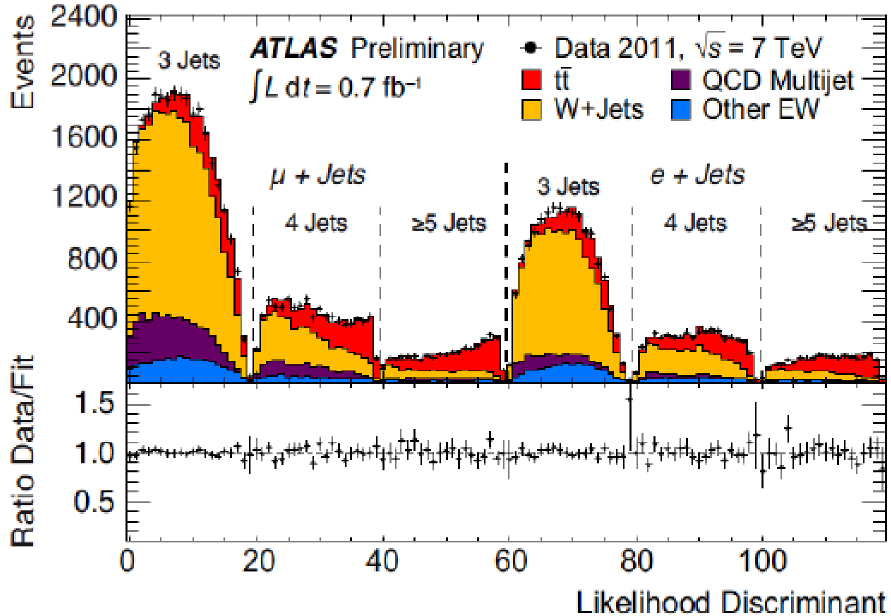
- What is theoretical interpretation of the measured parameter?
  - We extract top mass based on Monte Carlo → is it the pole mass?
- Alternative method: extract mass form the measured cross-section for ttbar production
  - Assuming MC mass = pole mass or MSbar mass
    - Take difference as systematics
  - 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!

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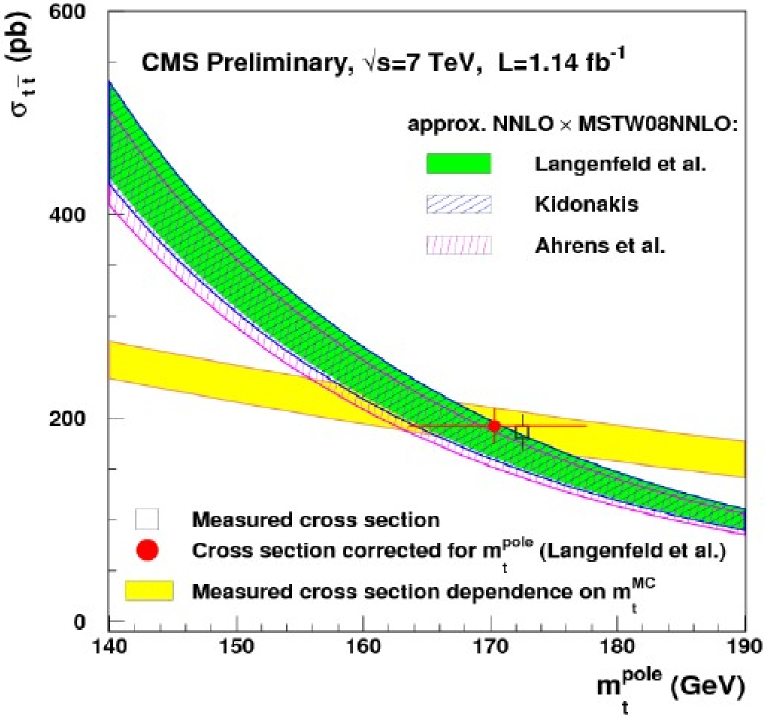
Top mass from cross-section

1.1 fb^{-1}

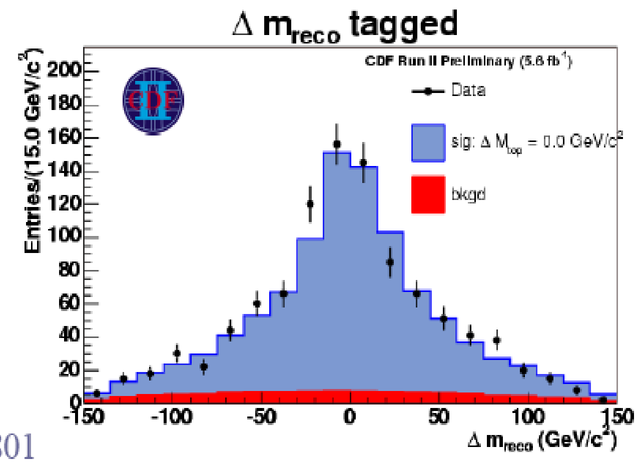
- The result is not competitive in precision but:
  - Provides the top quark mass value in an exact definition of the mass-pole
  - Important cross-check, complementary to direct top mass measurements
- Likelihood fit on the mass dependence
- Uncertainty of the theory includes:
  - Variation of the renormalisation,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

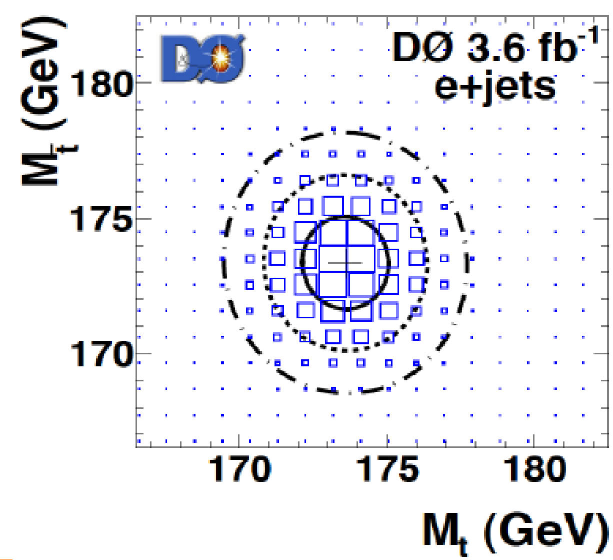


Approx. NNLO × MSTW08NNLO	m_t^{pole} / GeV	$m_t^{\overline{MS}}$ / GeV
Langenfeld et al. [7]	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis [8]	$170.0^{+7.6}_{-7.1}$	–
Ahrens et al. [9]	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$

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)
    $m_t - m_{\bar{t}} = -3.3 \pm 1.7$GeV (5.6fb^{-1}) PRL 106, 161801
- Using Matrix Element technique (DØ)
  - $P_{sig}(x; m_t, m_{\bar{t}})$ instead of $P_{sig}(x; m_t)$
    $m_t - m_{\bar{t}} = 0.8 \pm 1.9$GeV (3.6fb^{-1}) arXiv:1106.2063
- Still statistics limited
- Good agreement with the SM!

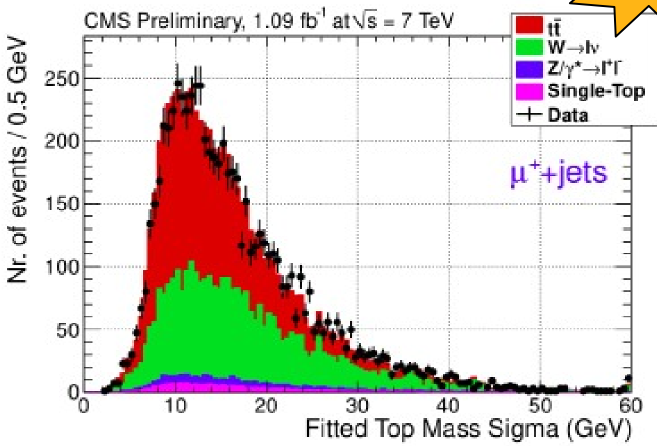


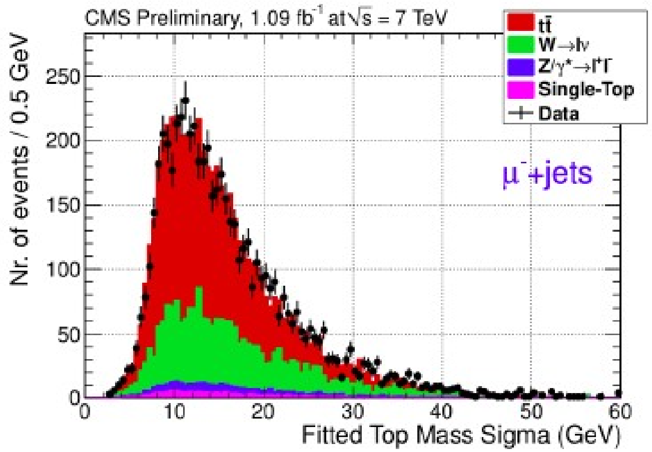


Top anti-top mass difference

$1.1 fb^{-1}$

- 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





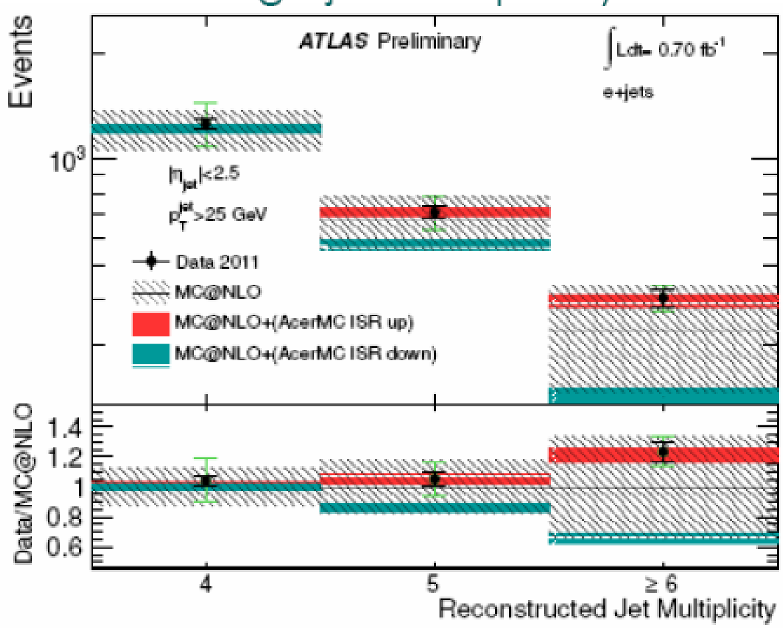
World best limit!

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

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



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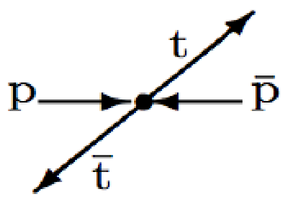
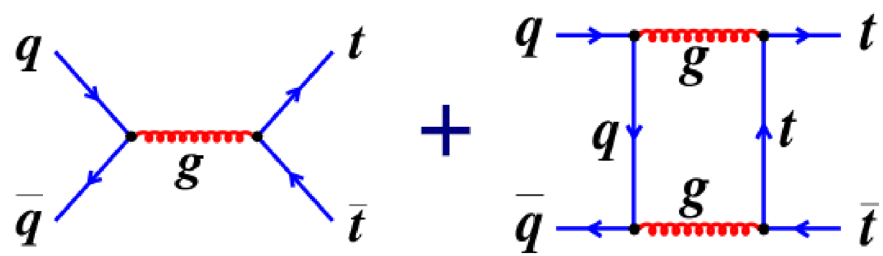
Present uncertainty:
no discrimination is possible

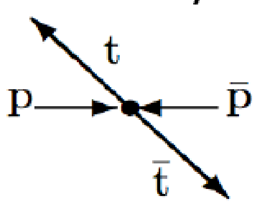
ttbar charge asymmetry: ppbar

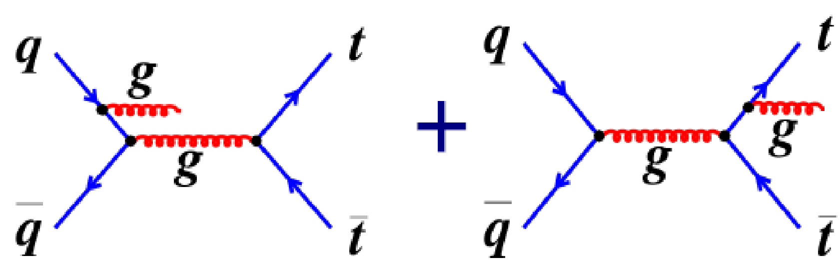
- LO: No charge asymmetry expected
- NLO QCD: Interference between $q\bar{q}$ diagrams
- Tree level and box diagrams:
  - Positive asymmetry





- Initial and final state radiation:
  - Negative asymmetry





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

ttbar charge asymmetry

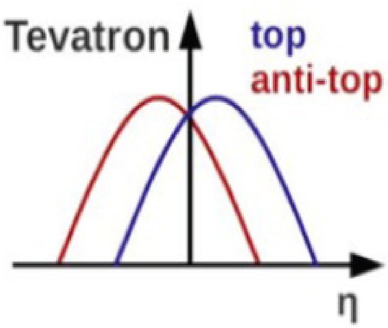
- Tevatron: $p\bar{p}$ is CP eigenstate → pp (LHC) is not
  → different way to measure the effect at Tevatron and LHC

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

Tevatron

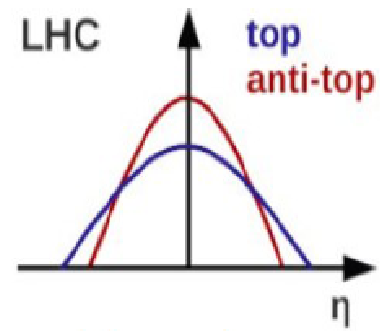
$$A_C = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)}$$

LHC



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

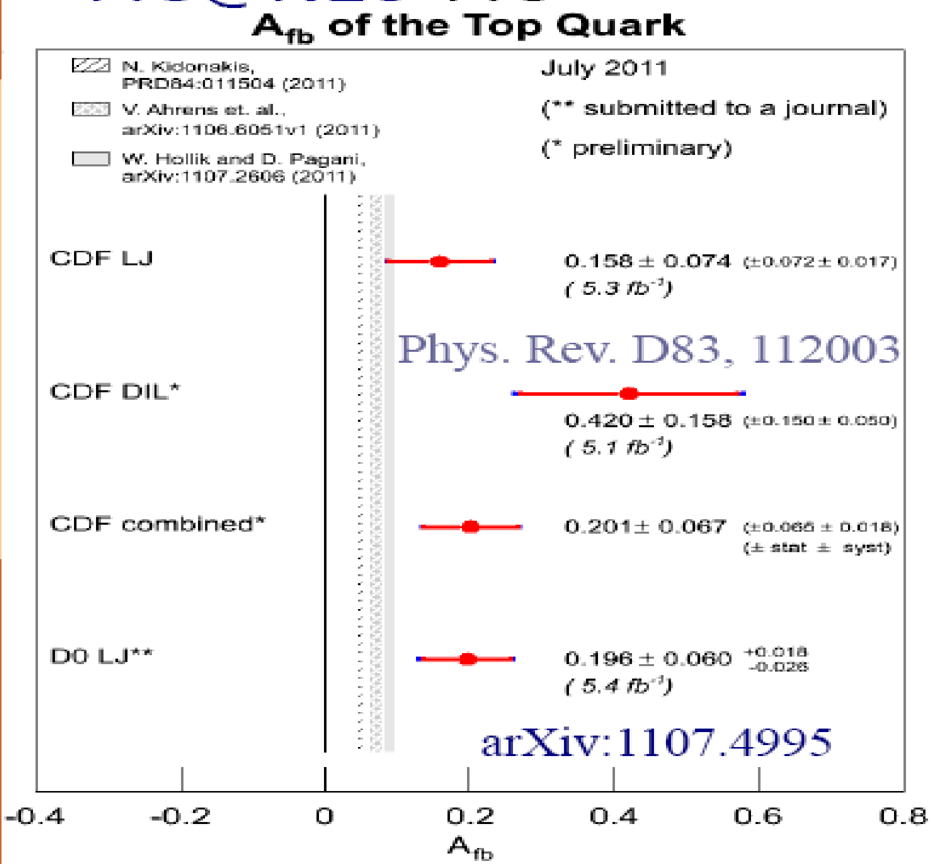
$\Delta y = y_t - y_{\bar{t}}$ $\Delta|y| = |y_t| - |y_{\bar{t}}|$

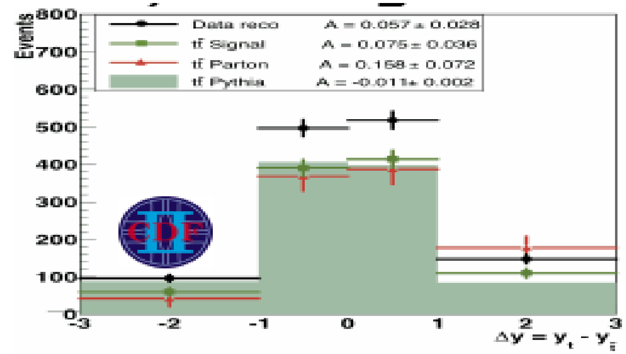


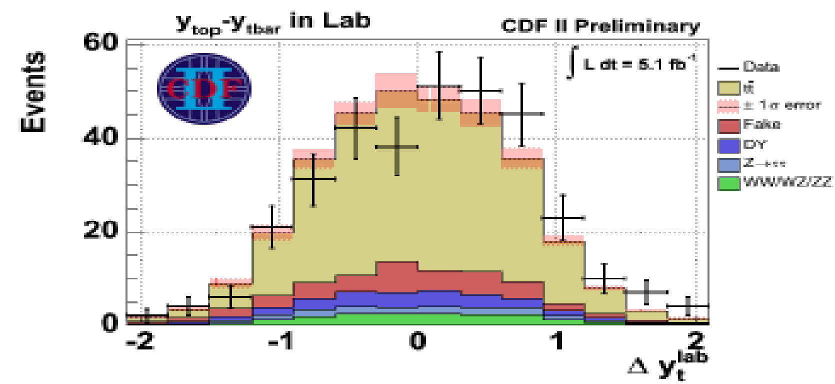
- LHC: $q\bar{q}$ fraction only 15% → asymmetry smaller than at Tevatron
- Requires reconstruction of $t\bar{t}$ system → Kinematic fitter
- All experiments: results in l+jets; CDF: result in dilepton

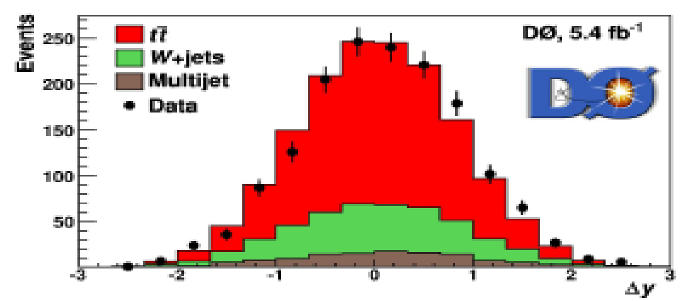
ttbar charge asymmetry: ppbar

- Prediction from MC@NLO MC



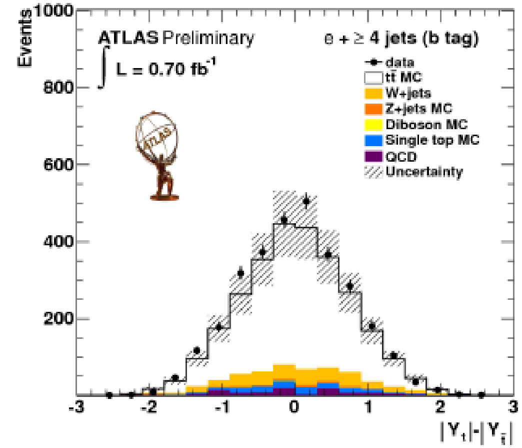


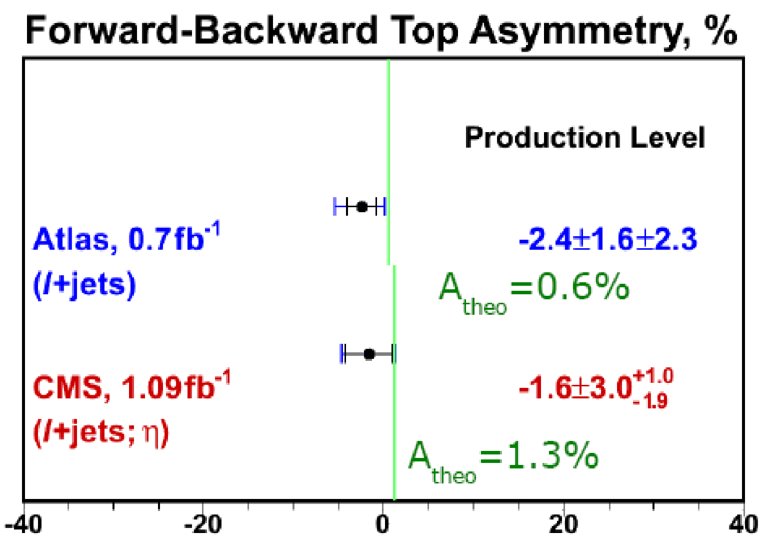


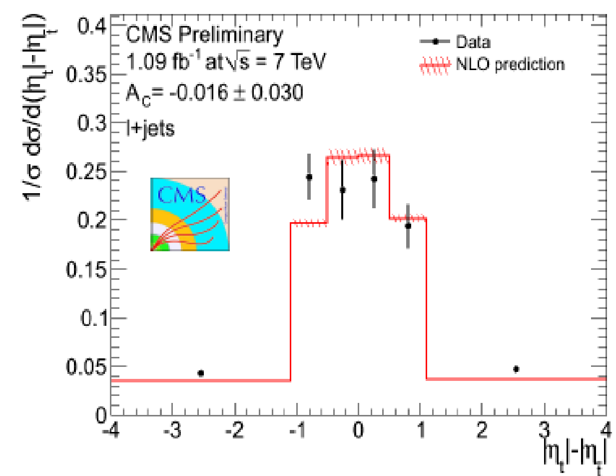


ttbar charge asymmetry: ppbar

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







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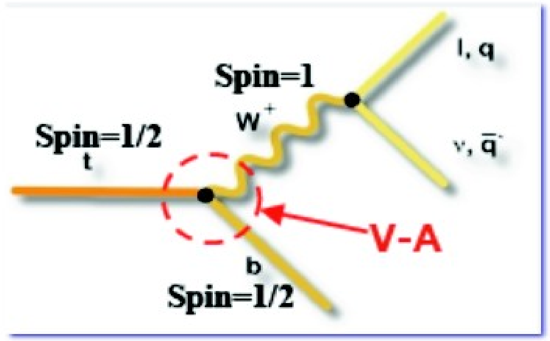
CMS PAS TOP-11-014

W helicity in top quarks decay



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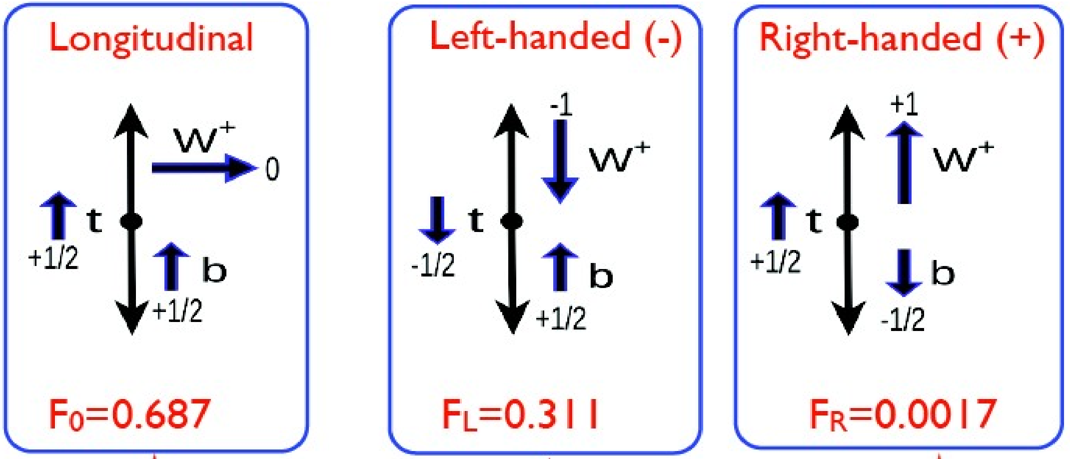
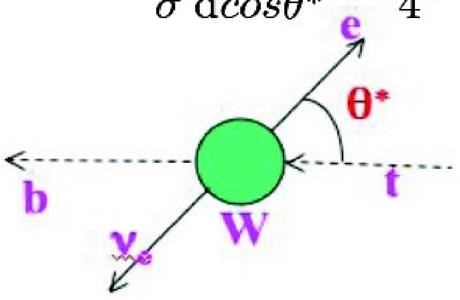
NNLO

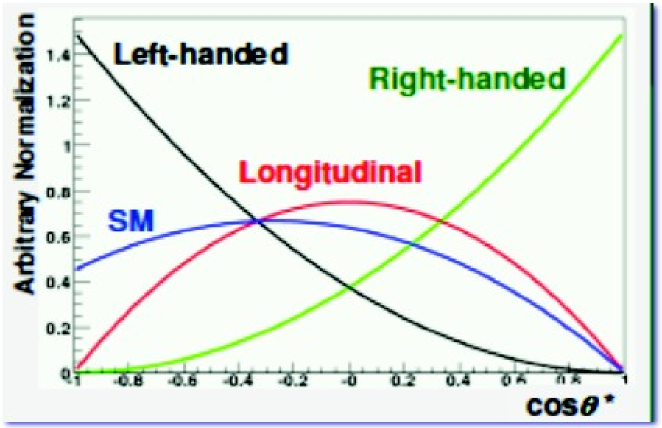


$$\frac{1}{\sigma}\frac{d\sigma}{d cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)F_0 + \frac{3}{8}(1-\cos\,\theta^*)^2 F_{\rm L} + \frac{3}{8}(1+\cos\,\theta^*)^2 F_{\rm R}$$

$F_0 + F_L + F_R = 1$

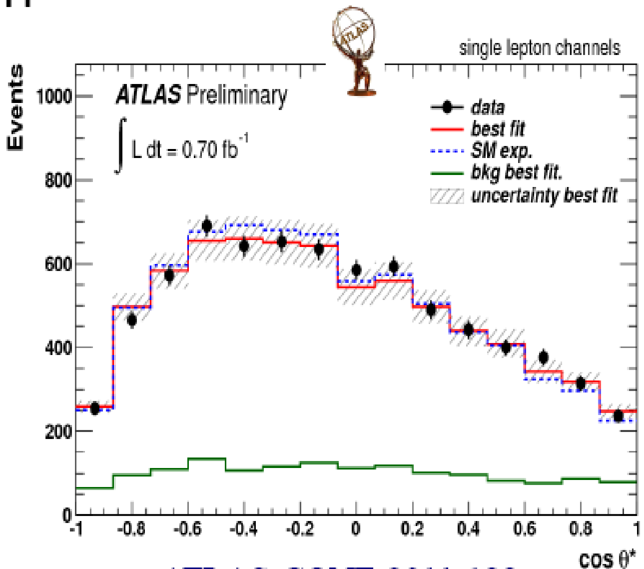


Angle between the momenta of d-type decay product of W (lepton, d-, s-quark) and reversed b-quark momentum in W boson rest frame



W helicity in top quarks decay

- Template fit of $\cos\theta^*$ 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):
  $f_0=0.57\pm0.07(stat)\pm0.09(syst)$
  $f_+=0.09\pm0.04(stat)\pm0.08(syst)$
- Fix $f_+=0$; combined dilepton & l+jets:
  $f_0=0.75\pm0.08(stat+syst)$



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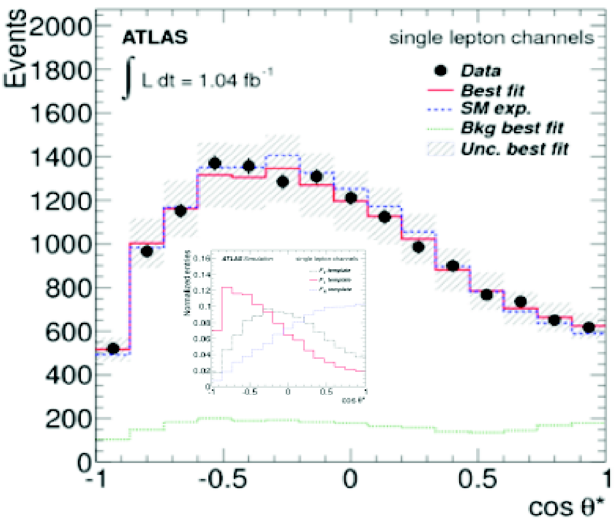
- Systematics limited;
  main systematics → modeling of signal & ISR/FSR
- Consistent with SM prediction

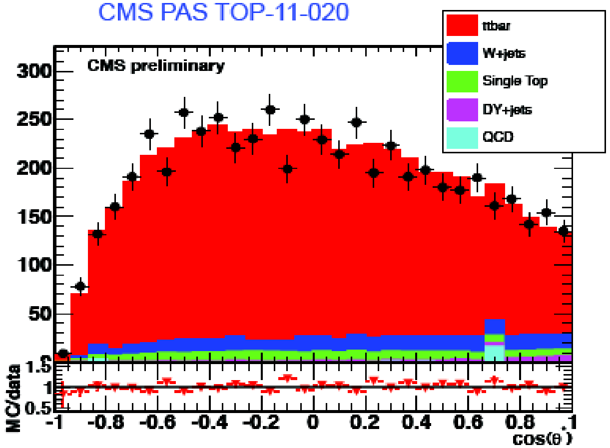
W helicity in top quarks decay

- $1.0\ fb^{-1}$ l+jets and dilepton channels
  - 12,100 candidate events
  - create $\cos\theta^*$ signal templates for $F_0 = 1$, $F_L = 1$ and $F_R = 1$ (Protos MC) and background template
- $2.2\ fb^{-1}$ μ+jets channel
  - 4,570 candidate events
  - different helicity configurations are created by event-by-event reweighting that uses generated $\cos\theta^*$ value
- Fits to data performed
  - with F_0, F_L as free parameters, $F_R = 1-F_0-F_L$
  - with $F_R=0$

JHEP 1206 (2012) 088



CMS PAS TOP-11-020

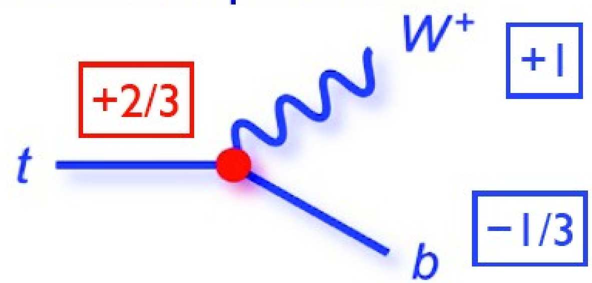


Results of the model independent fit

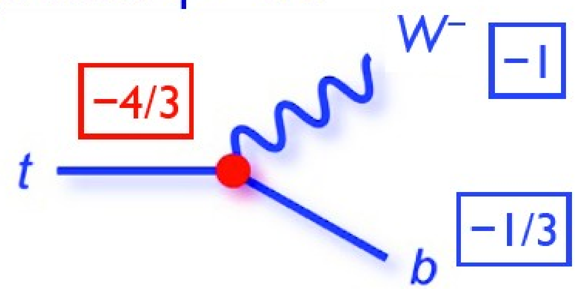
	F_0	F_L
ATLAS	0.66 ±0.06 ±0.07	0.33 ±0.03 ±0.03
CMS	0.567 ±0.074 ±0.047	0.393 ±0.045 ±0.029

Top quark charge

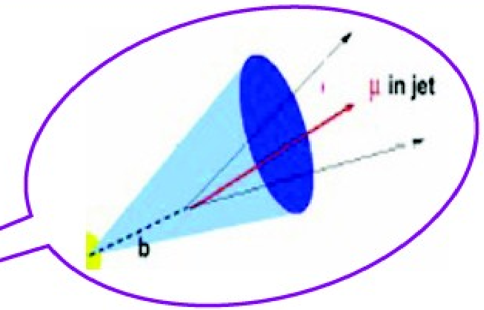
- SM predicts that top quark as a fermion with q=+2/3



- Exotic top-like quark models predict q=−4/3



- Measure top charge by studying its decay products
- Discriminate $t \to W^+ b$ vs $t \to W^- b$
  - determine W charge (based on charge of lepton from W decay)
  - determine b-flavor
    - presence of a soft muon in a jet
    - weighted charge of tracks within a jet
  - perform W-b pairing
    - kinematic reconstruction

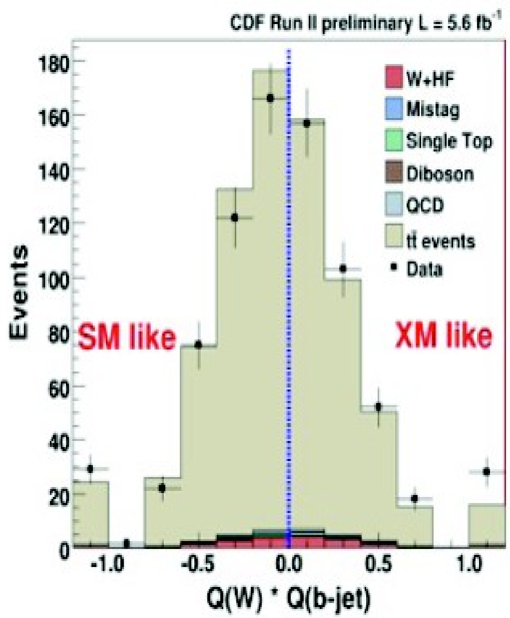


$$Q_{b-jet} = \frac{\sum_i q_i \cdot (\vec{p}_i \cdot \hat{a})^x}{\sum_i (\vec{p}_i \cdot \hat{a})^x}$$

x = weighting factor
$\hat{a}$ = jet axis
$\vec{p}_i$ = track momentum

Top quark charge

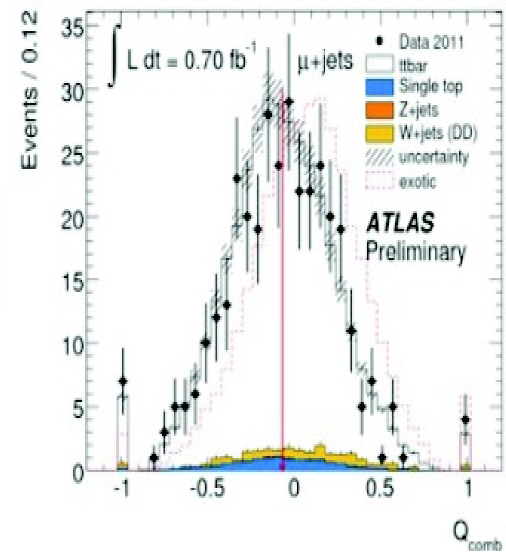
- 670 candidate double tagged l+jets channel, 5.6 fb^{-1}



$f_+ = 0.83$
data strongly favor SM over XM

The exotic model is excluded at 99% CL

- 2,100 candidate l+jets events, 0.7 fb^{-1}



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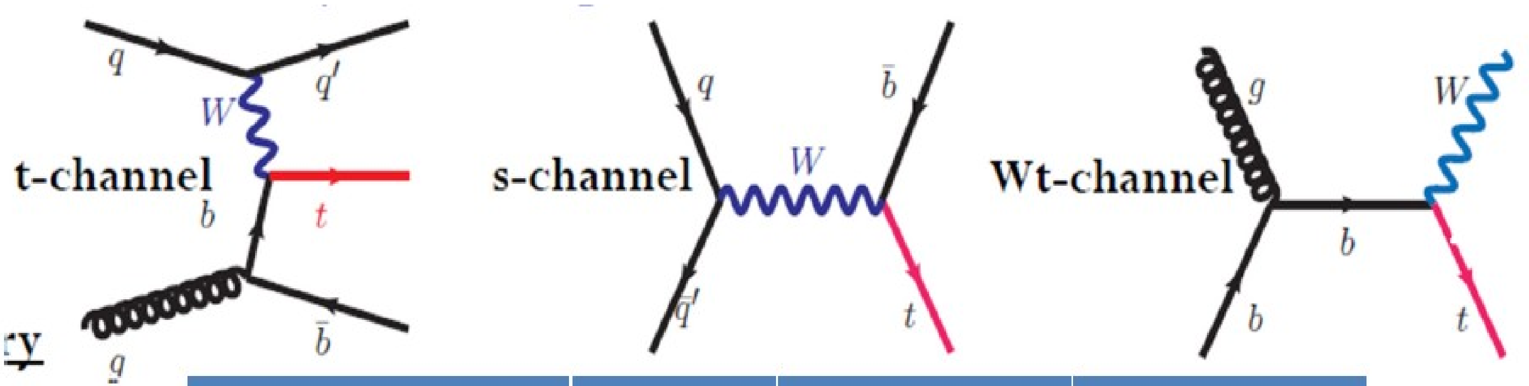
Exotic hypothesis is excluded at 99.9% CL by CMS, >5σ by ATLAS

Electroweak production of top quark

For the first time evidence at Tevatron in 2010 (s+t channel)

It is challenging even for LHC, in particular s-channel observation is a long shot (background)

All diagrams have V_{tb} vertex



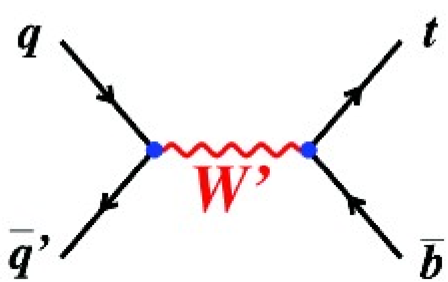
	t channel	s channel	Wt
Tevatron (1.96 T eV)	2.26±0.2	1.04±0.1	0.3±0.06
LHC (7 TeV)	64.2±2.4	4.6±0.2	15.7±1.1
LHC (8 TeV)	87.8±3.4	5.6±0.3	22.4±1.5

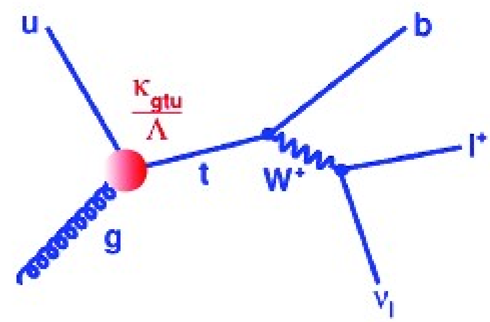
x-sec in pb

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

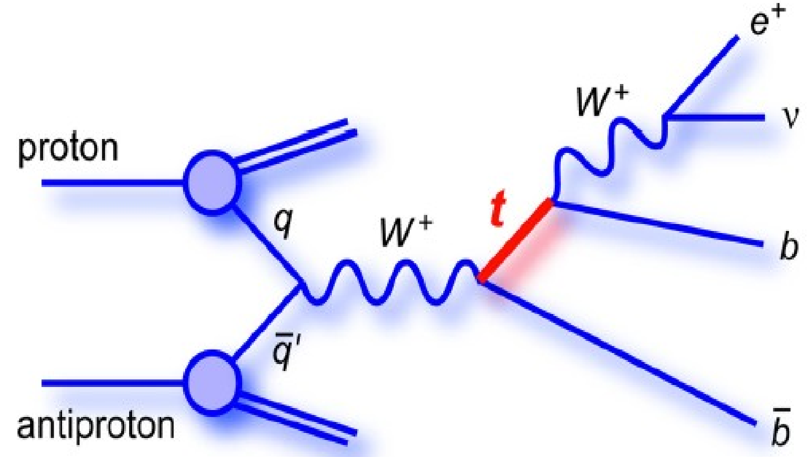
$$V_{ub}^2 + V_{cb}^2 + V_{tb}^2 \stackrel{?}{=} 1$$

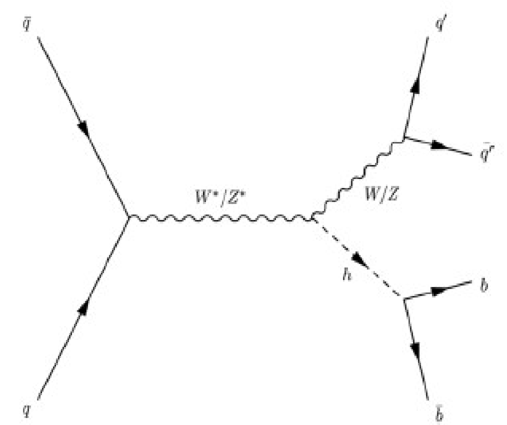




Final state

- Final state is characterized by
  - W + 2-3jets
    - t channel: 2-3 jets (1 forward), 1 b jet
    - s channel: 2 b jets
  - 2W+1 b jet (Wt channel)
- Single top in s and t channel has a final state topology resembling WH
  - Important for Higgs searches in associate production
  - W*, H+





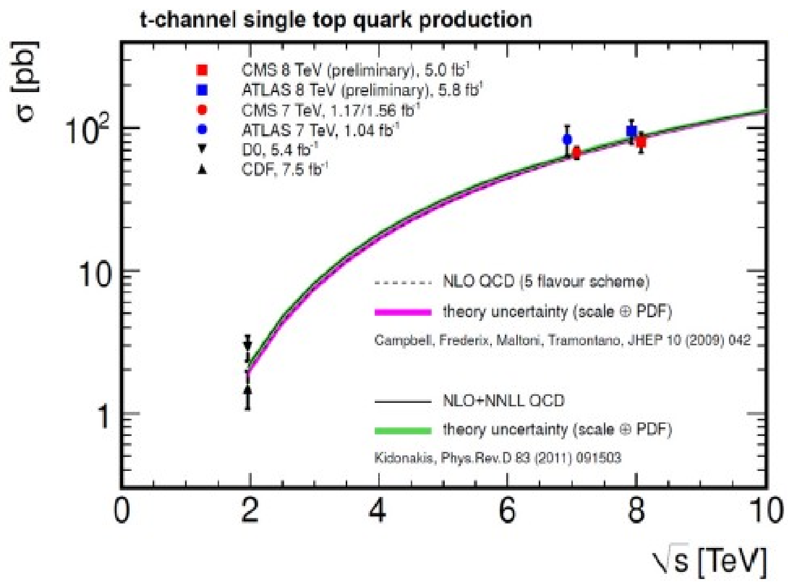
Finding the needle in the haystack

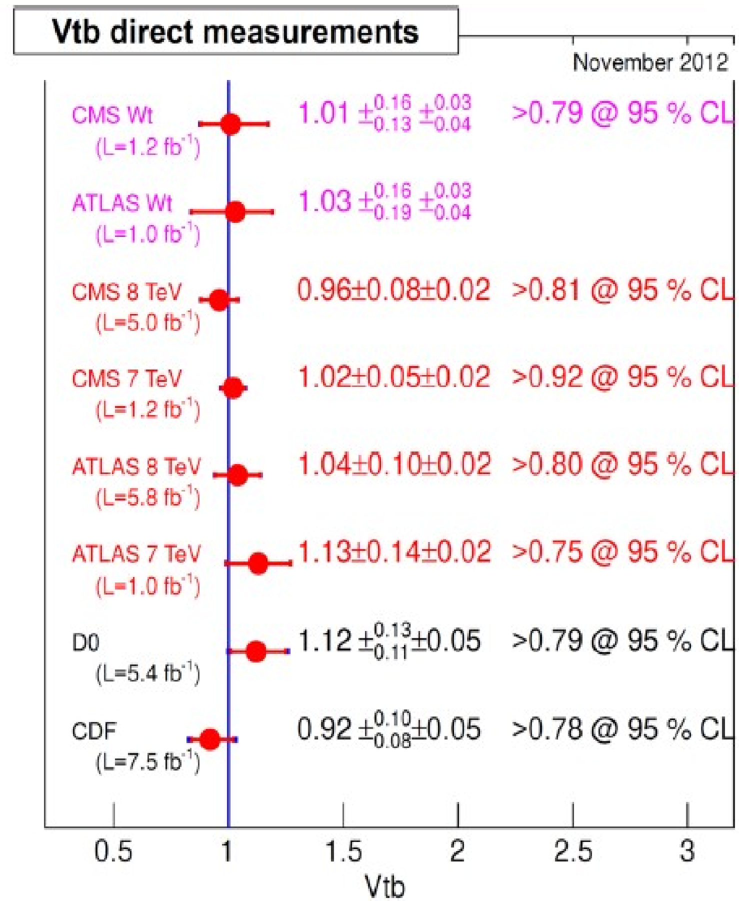
low $S/\sqrt{B}$ → use MVA

- This was done by CDF and D0 at the Tevatron
  - Detailed studies of large number of variables
- ATLAS and CMS:
  - both cut-based and MVA analyses
    - Signal extraction easier for t-channel
    - MVAs are an additional tool

	2-jet		3-jet	
variable	1-tag	2-tag	1-tag	2-tag
$M_{\ell\nu b}$	✓	✓	✓	
$M_{\ell\nu bb}$		✓		✓
$M_{\mathrm{t}}^{\ell\nu b}$	✓	✓	✓	✓
M_{jj}	✓	✓	✓	✓
M_{t}^{w}	✓	✓		
$E_{\mathrm{t}}^{b_{\mathrm{top}}}$		✓	✓	
$E_{\mathrm{t}}^{b_{\mathrm{other}}}$				✓
$\sum e_{\mathrm{t}}^{jj}$			✓	✓
$E_{\mathrm{t}}^{\mathrm{light}}$	✓			✓
p_{t}^{ℓ}	✓			
$p_{\mathrm{t}}^{\ell\nu jj}$			✓	✓
H_{t}	✓		✓	
$\not{E}_T$		✓		
$\not{E}_{T\,\mathrm{sig}}$			✓	
$\cos\theta_{\ell j}$	✓		✓	✓
$\cos\theta_{\ell w}^{w}$	✓			
$\cos\theta_{\ell w}^{t}$	✓			
$\cos\theta_{jj}^{t}$		✓		✓
$Q\times\eta$	✓		✓	✓
η_{ℓ}		✓		
η_{w}	✓	✓		
$\sum\eta_j$	✓		✓	
$\Delta\eta_{jj}$			✓	✓
$\Delta\eta_{t,\mathrm{light}}$			✓	
$\sqrt{\hat{s}}$				✓
Centrality				✓
Jet flavor separator	✓	✓	✓	

Electroweak production of top quark





s channel (Tevatron only)

$\mathrm{CDF} = 1.81^{+0.63}_{-0.58}$ pb

D0=0.98±0.63 pb

Wt (LHC only, 7 TeV)

ATLAS 16.8±5.7 pb

CMS 16^{+5}_{-4} pb

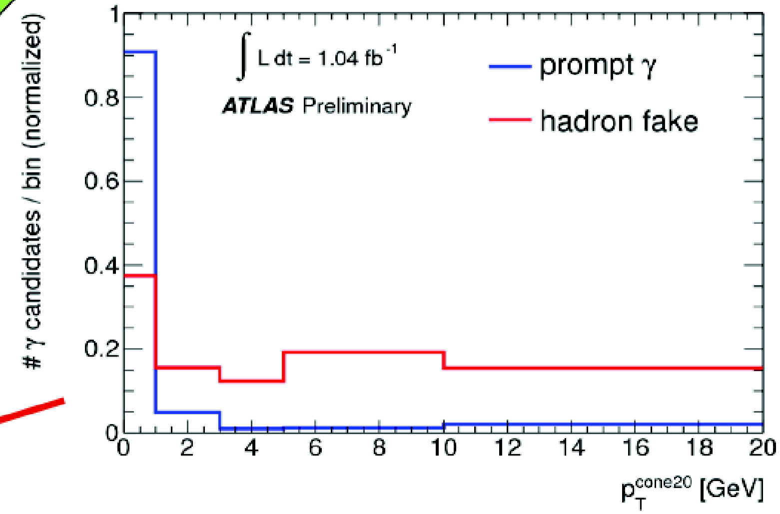
V_{tb} might stay at 10% precision for some time

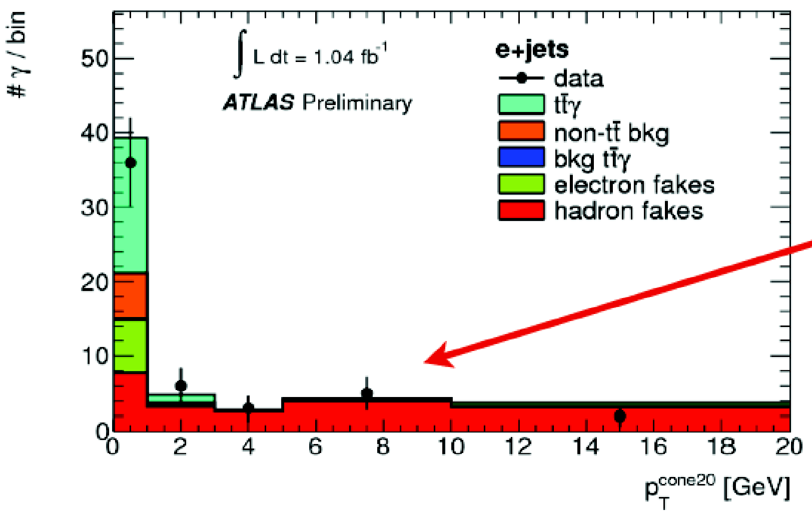
ttγ cross section

1.04 fb^{-1}

ATLAS-CONF-2011-153

- Search for $t\bar{t}$ + prompt photon
- Distinguish prompt from hadron fakes
  - Isolation (p_T^{cone20})
  - Photons E_T > 15 GeV





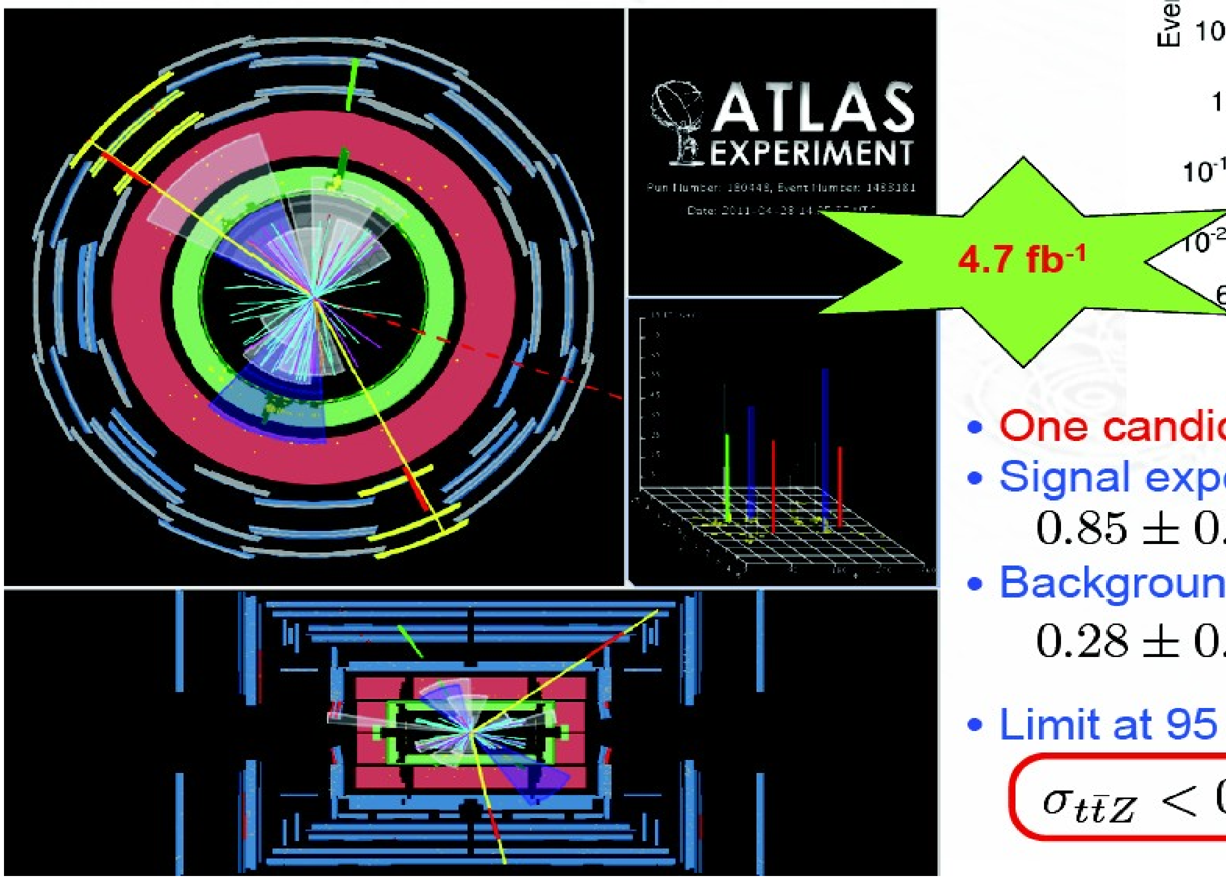
- Background data driven estimation
- Largest uncertainties: JES, ISR/FSR and photon ID efficiency

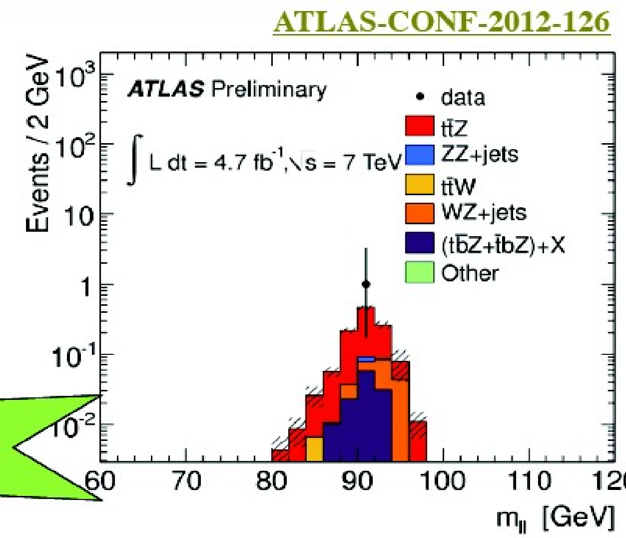
$$\sigma_{t\bar{t}\gamma} = 2.0 \pm 0.50\ (\mathrm{stat.}) \pm 0.70\ (\mathrm{syst.}) \pm 0.08\ (\mathrm{lumi.})\ \mathrm{pb}$$

- **Significance: 2.7 σ**
- Photons p_T > 8 GeV

Search for ttZ production

- Search for $t\bar{t}Z$ events
- Three leptons in final state
  - One from leptonic W and two from Z





- One candidate event found
- Signal expectation of:

$$0.85 \pm 0.04\ (\text{stat.}) \pm 0.14\ (\text{syst.})$$

- Background expectation of:

$$0.28 \pm 0.05\ (\text{stat.}) \pm 0.14\ (\text{syst.})$$

- Limit at 95 % C.L.:

$$\sigma_{t\bar{t}Z} < 0.71\ \text{pb}\ (\text{SM} : 0.14\ \text{pb})$$

Summary

The SM top quark

- Top mass measurements from LHC comparable to Tevatron - precision ~1 GeV
- Cross sections
  - ttbar more precise (dilepton 5%), almost compable to theory
  - Single top 10%
- Differential cross section: keep them coming
  - Already being used in improving signal modeling uncertainties
- Many measurements of other properties are now systematically limited: W helicity, top polarization, spin correlations

Next topics

- 28.11 – Dibosons and anomalous couplings
- 5.12, 12.12 - **Higgs**
- 19.12 – **SUSY**
- 9.1 – other searches for New Physics
- 16.1 - B-physics programme
- 23.1 – heavy ion programme

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

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: $7.56^{+0.63}_{-0.56}$ $(\text{stat} + \text{syst} + \text{lumi})$ 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
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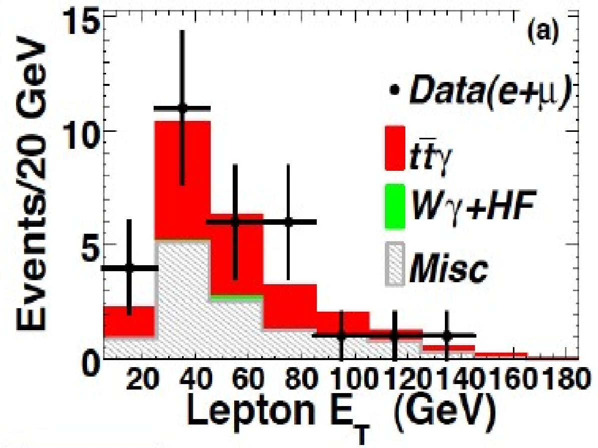
	D0: 0.196 ± 0.065		5.4
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		5.4
M_t	Tev: 173.2 ± 0.9 GeV	-	up to [illegible]
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	6.0
$\lvert V_{tb} \rvert$	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
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	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
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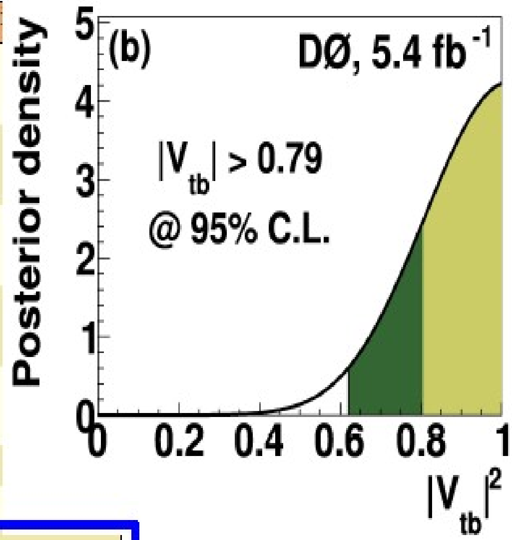
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ 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 ± 0.31(stat) ± 0.34(syst) ± 0.15(theory) pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
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spin correlation	CDF: 0.72 ± 0.64(stat) ± 0.26(syst)	$0.777^{+0.027}_{-0.042}$	5.3
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M_t	Tev: 173.2 ± 0.9 GeV	-	up to 5.8
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	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
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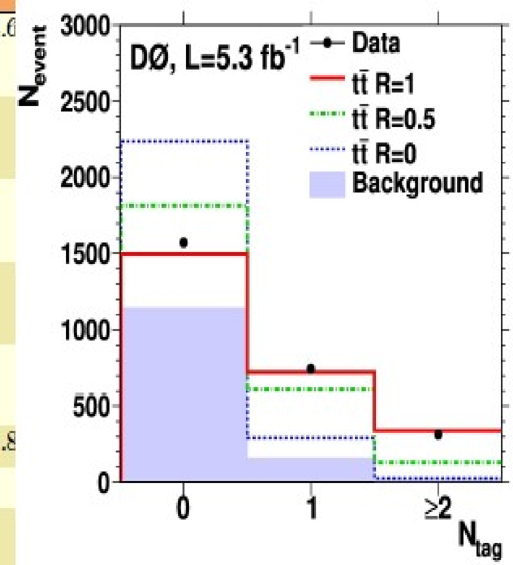

World's best measurement of R → limited by systematics

Measurements from Tevatron

Property	Measurement	SM Prediction	Lumino
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$\sigma_{t\bar{t}\gamma}$	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
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	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
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Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
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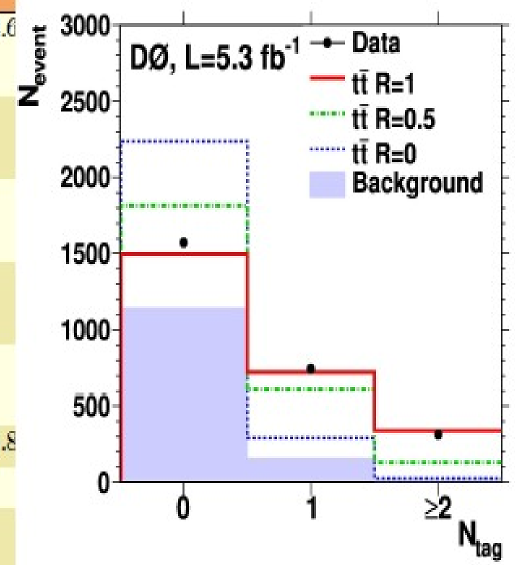

World's best measurement of R → limited by systematics

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
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$\lvert V_{tb} \rvert$	CDF: $\lvert V_{tb} \rvert = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	3.2
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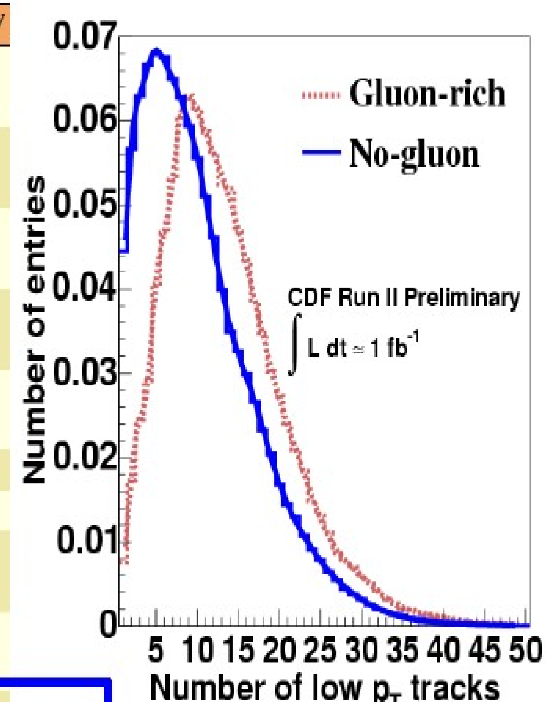
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3



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 ± 0.31(stat) ± 0.34(syst) ± 0.15(theory) pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
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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 ± 0.64(stat) ± 0.26(syst)	$0.777^{+0.027}_{-0.042}$	
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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: $\lvert V_{tb}\rvert = 0.91 \pm 0.11$(stat + sys) ± 0.07(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	
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Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
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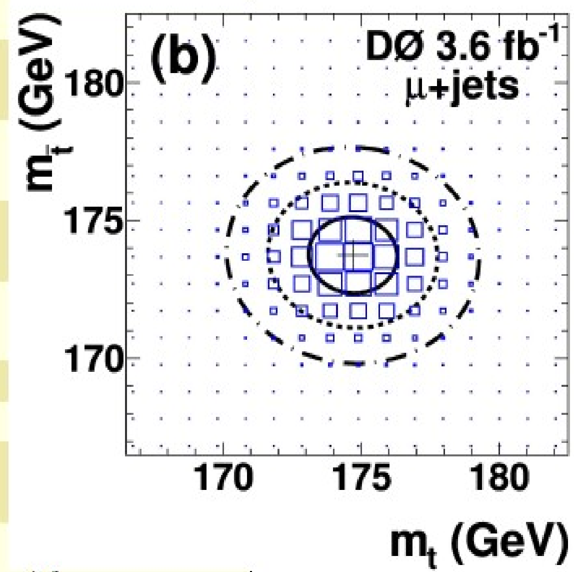
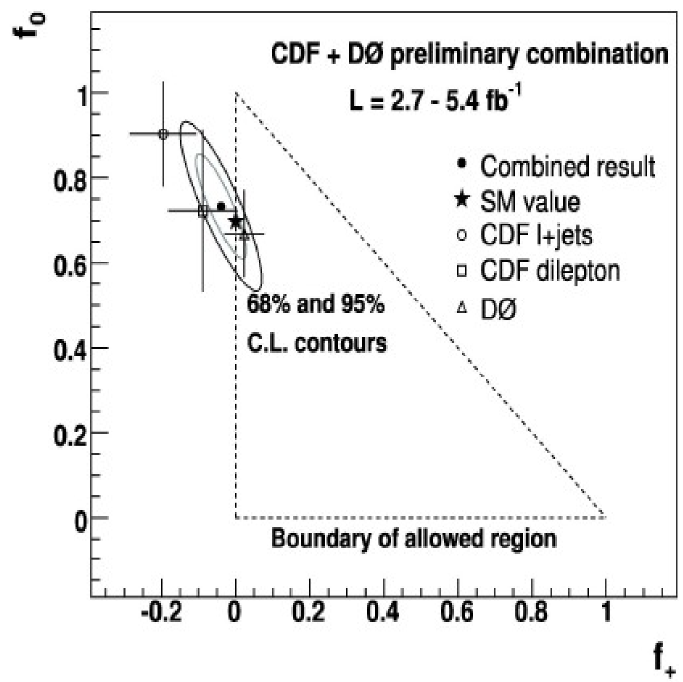


First time done at Tevatron
→ statistics limited
→ CMS recently released more precise result

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		3.0
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

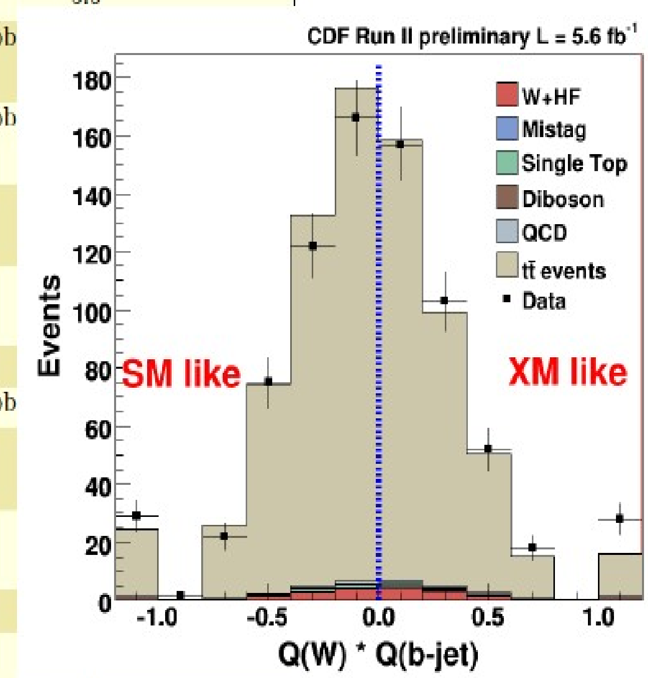


Good agreement with SM

→ Equal statistics and systematics error

Measurements from Tevatron

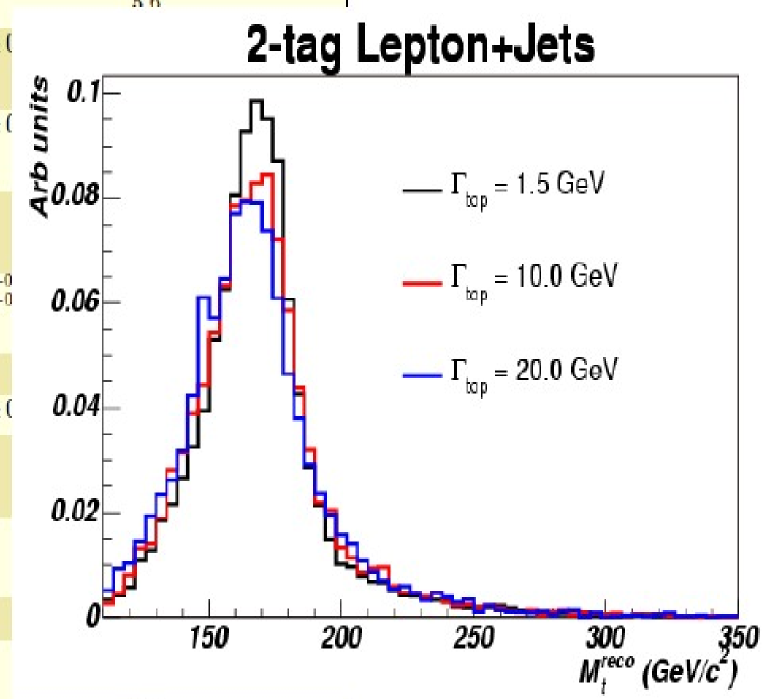
Property	Measurement	SM Prediction	Luminosity (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ 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		
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 ± 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 ±	
	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 ± 0.64(stat) ± 0.26(syst)	0.777	
	D0: 0.66 ± 0.23(stat + sys)		
M_t	Tev: 173.2 ± 0.9 GeV	-	
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ±	
$\lvert V_{tb} \rvert$	CDF: $\lvert V_{tb} \rvert = 0.91 \pm 0.11$(stat + sys) ± 0.07(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		
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	
$M_t - M_{\bar{t}}$	CDF: -3.3 ± 1.4(stat) ± 1.0(syst) GeV	0	
	D0: 0.8 ± 1.8(stat) ± 0.5(syst) GeV		
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



Very precise indirect determination!

Top mass