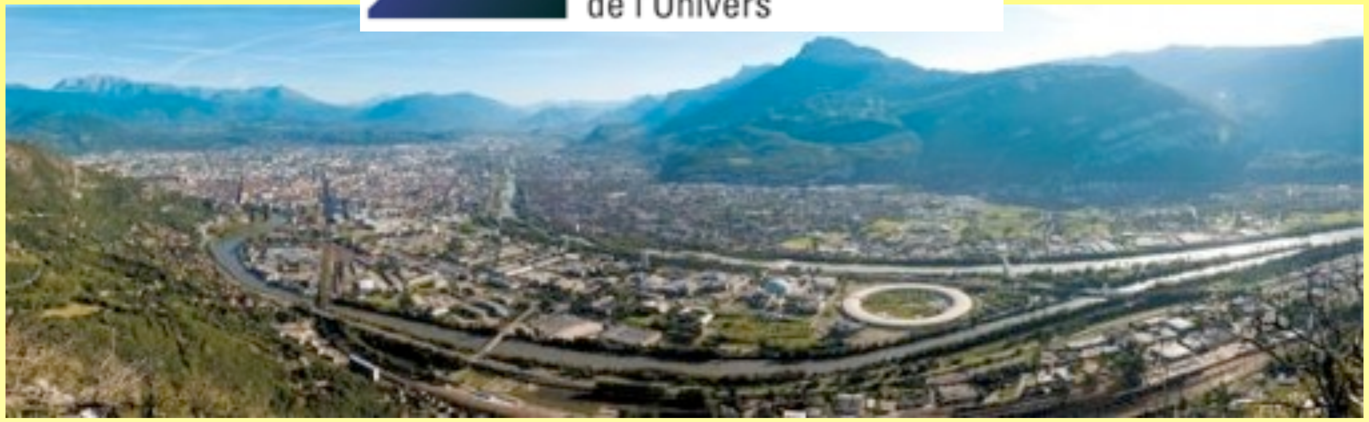

Top Quark Physics

At Hadron Colliders

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CEA-Saclay

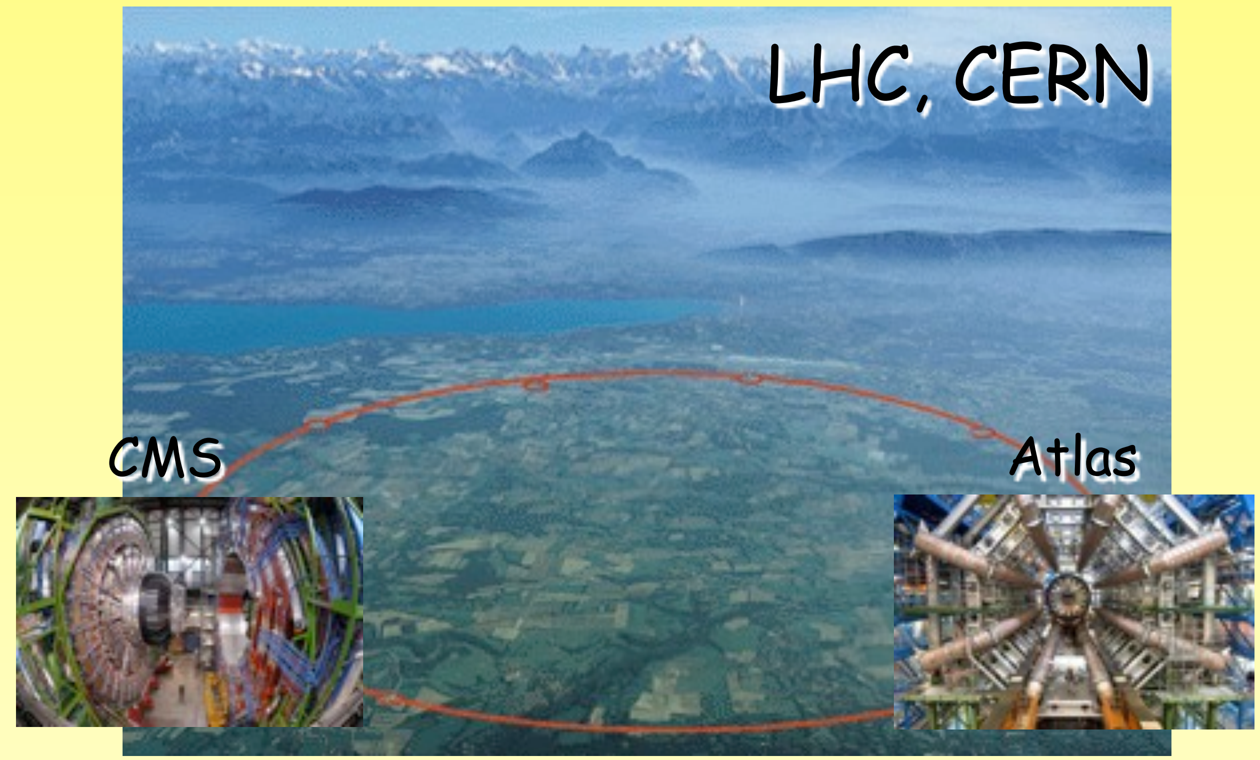
Results from the Atlas, CDF, CMS and D0 collaborations

thanks to R. Chierici, M. Cristinziani, M. Grunewald, F. Margaroli, Y. Peters, F-P. Schilling, C. Schwanenberger, T. Schwartz, B. Tuchming, W. Verkerke

EPS-HEP Conference, Grenoble, 25-July-2011

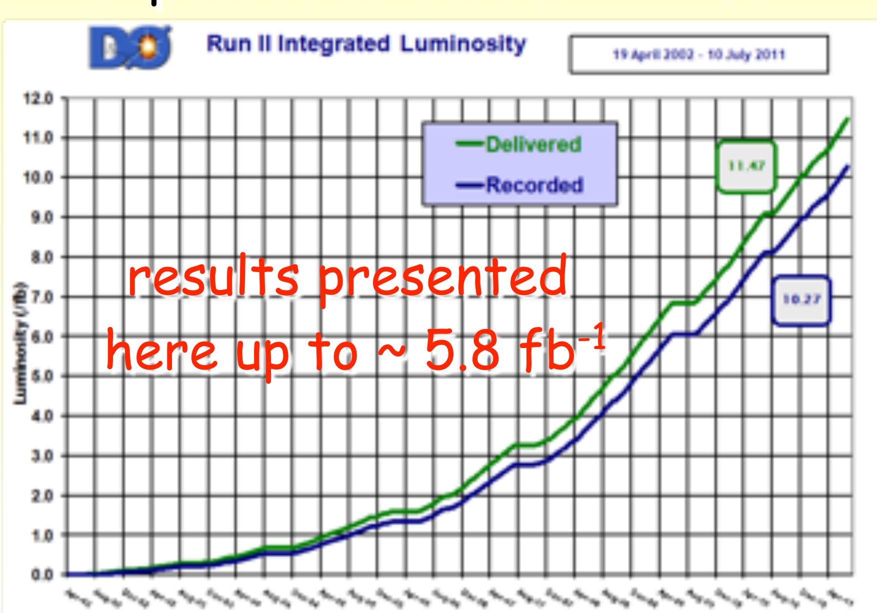
Hadron Colliders

$p\bar{p}$ collider, $\sqrt{s} = 1.96$ TeV

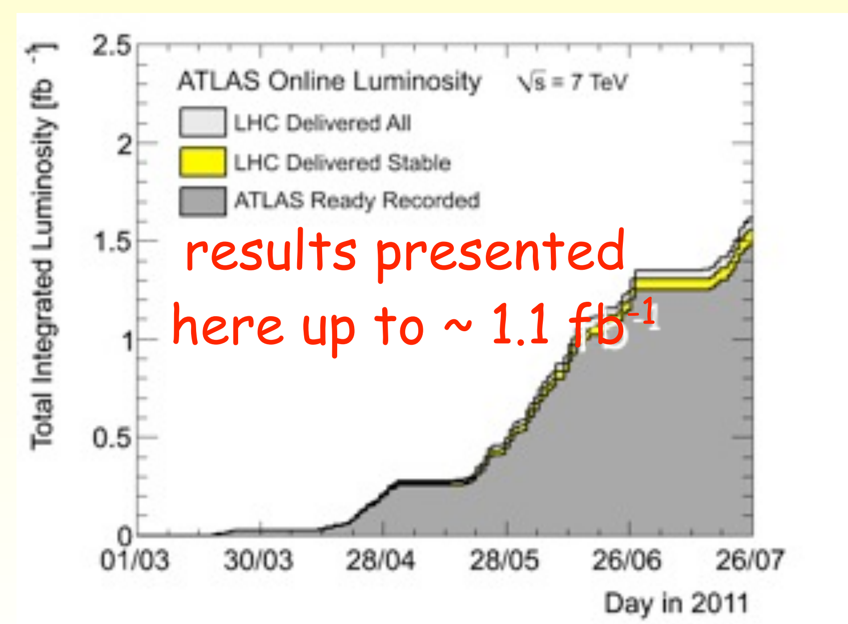


pp collider, $\sqrt{s} = 7$ TeV

Run II started in 2002, will end Sep. 30th 2011
expected to deliver ~ 12 fb^{-1}



started in 2009, 1st phase until end of 2012
expected to deliver 2-5 fb^{-1} at the end of 2011



Why Do We Study the Top Quark ?

- It is the heaviest elementary particle

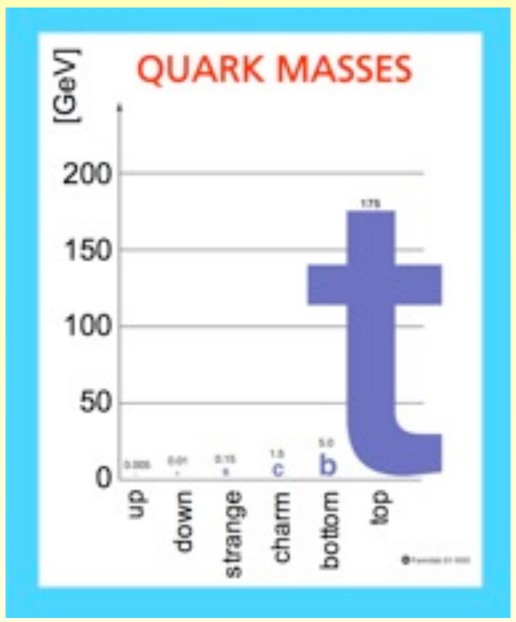
discovered in 1995 by CDF and D0
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

$$\mathcal{L}_{\text{Yukawa}} = -\lambda_t \overline{\psi_{Lt}} \Phi \psi_{Rt}$$

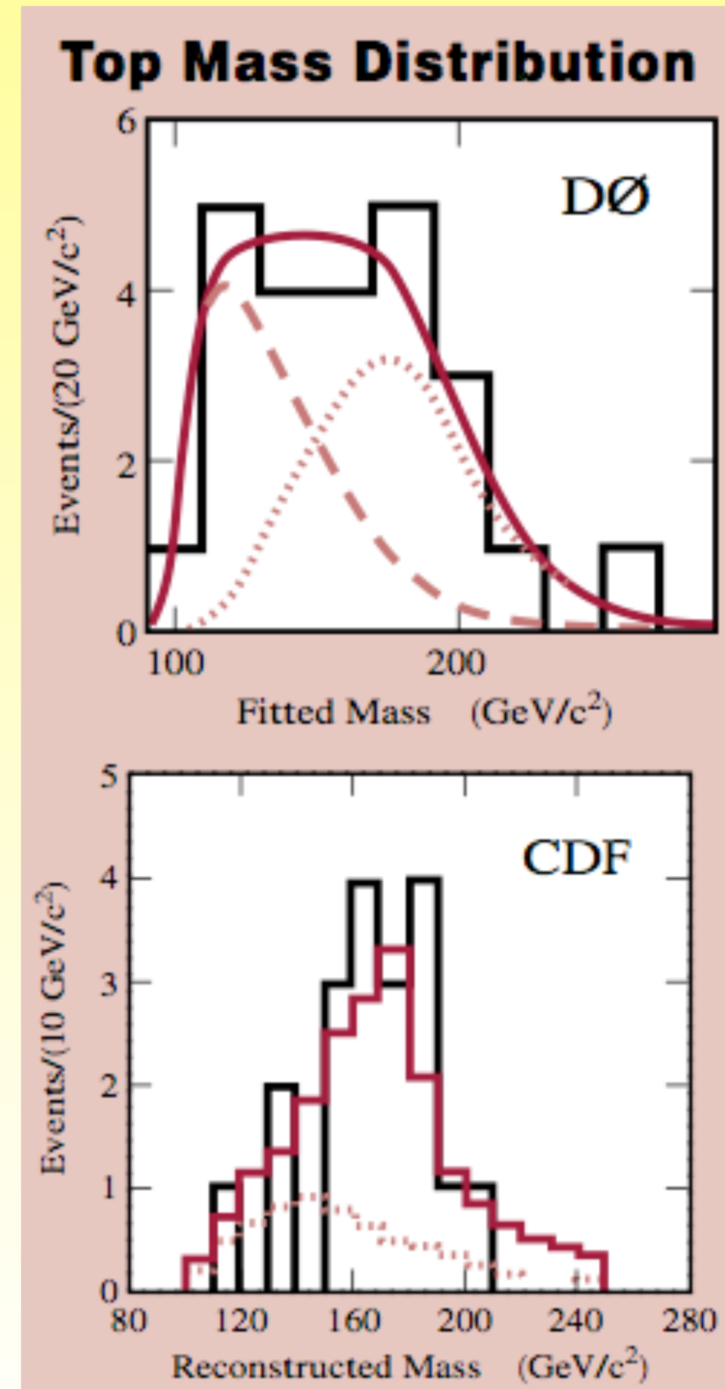
$$\lambda_t \approx 1 \;!!$$

$$m_t >> m_b$$

$$\tau \approx 5.10^{-25}\text{s} << \Lambda_{\text{QCD}}^{-1}$$



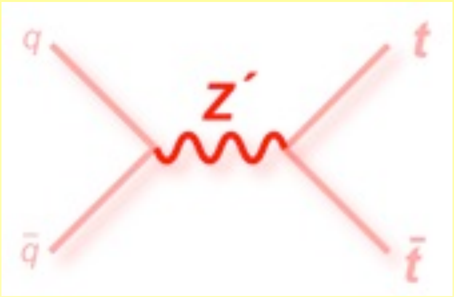
- coupling to the Higgs boson close to 1: special role in the electroweak symmetry breaking ?
- decay before hadronizing: unique way to observe a bare quark



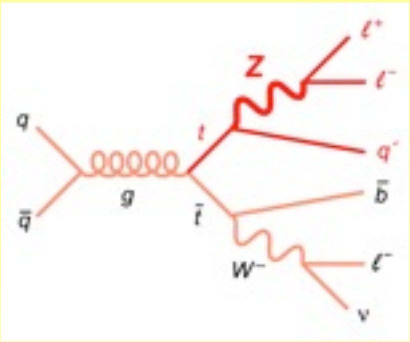
The top quark is a special quark !
Special sector to search for new physics

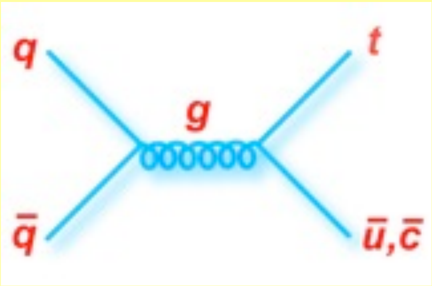
Direct Search For New Physics in the Top Sector

- look for specific new models that involve top signatures or for new particles that decay like tops



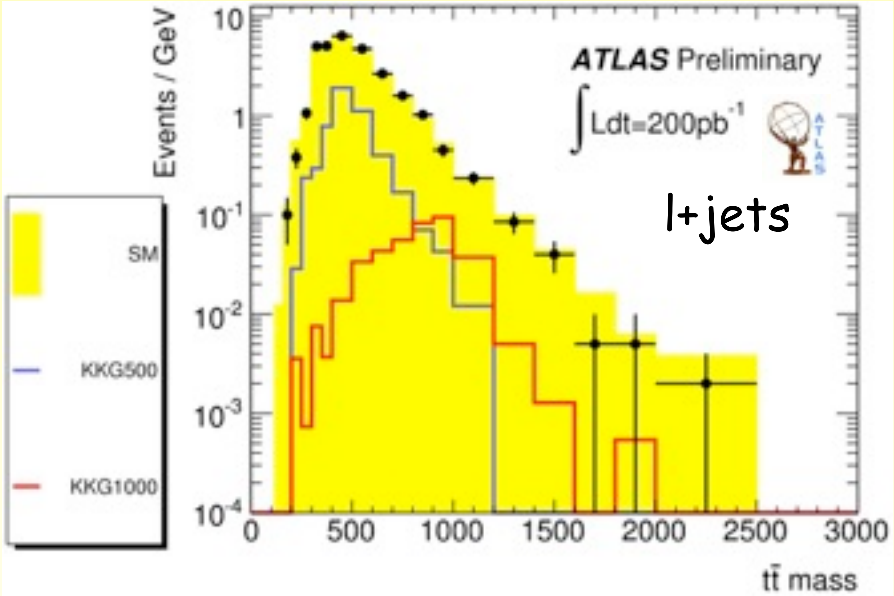
new particle ?

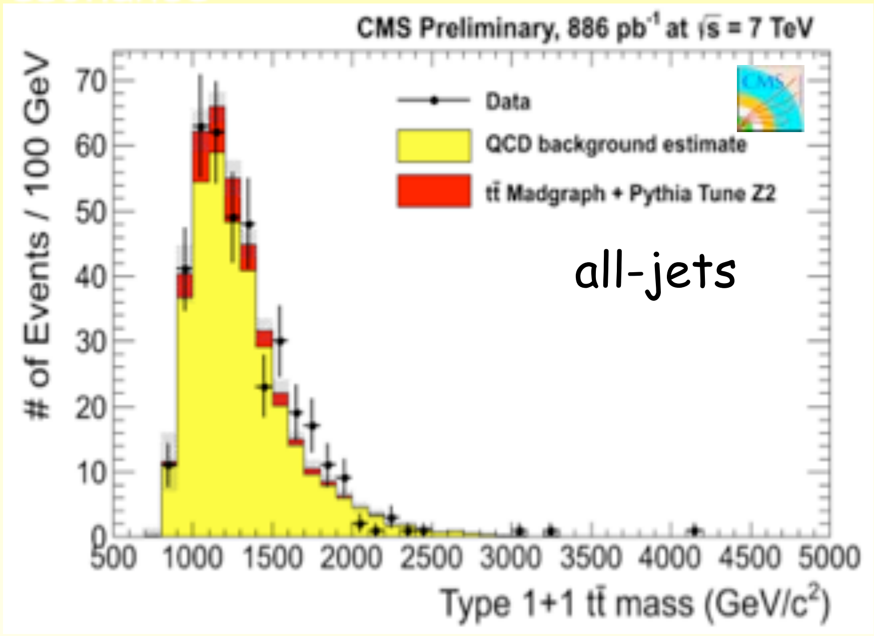




new couplings (FCNC) ?

search for $t\bar{t}$ resonance



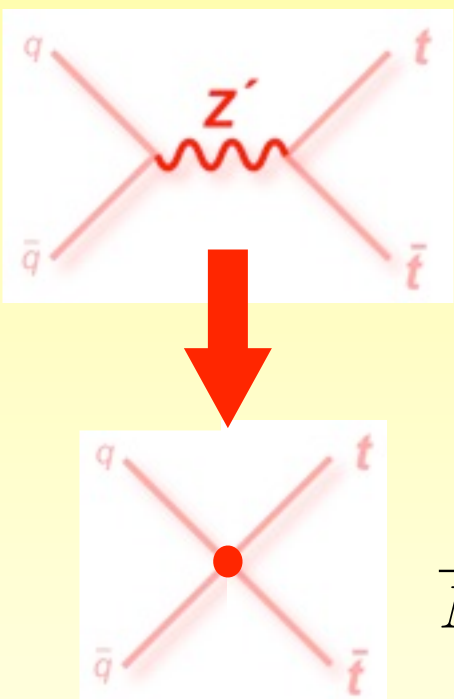


see talks by A. Duperrin (Tevatron), D. Charlton (Atlas), G. Tonelli (CMS) and the parallel session talks

Model Independent Search for New Physics with Tops

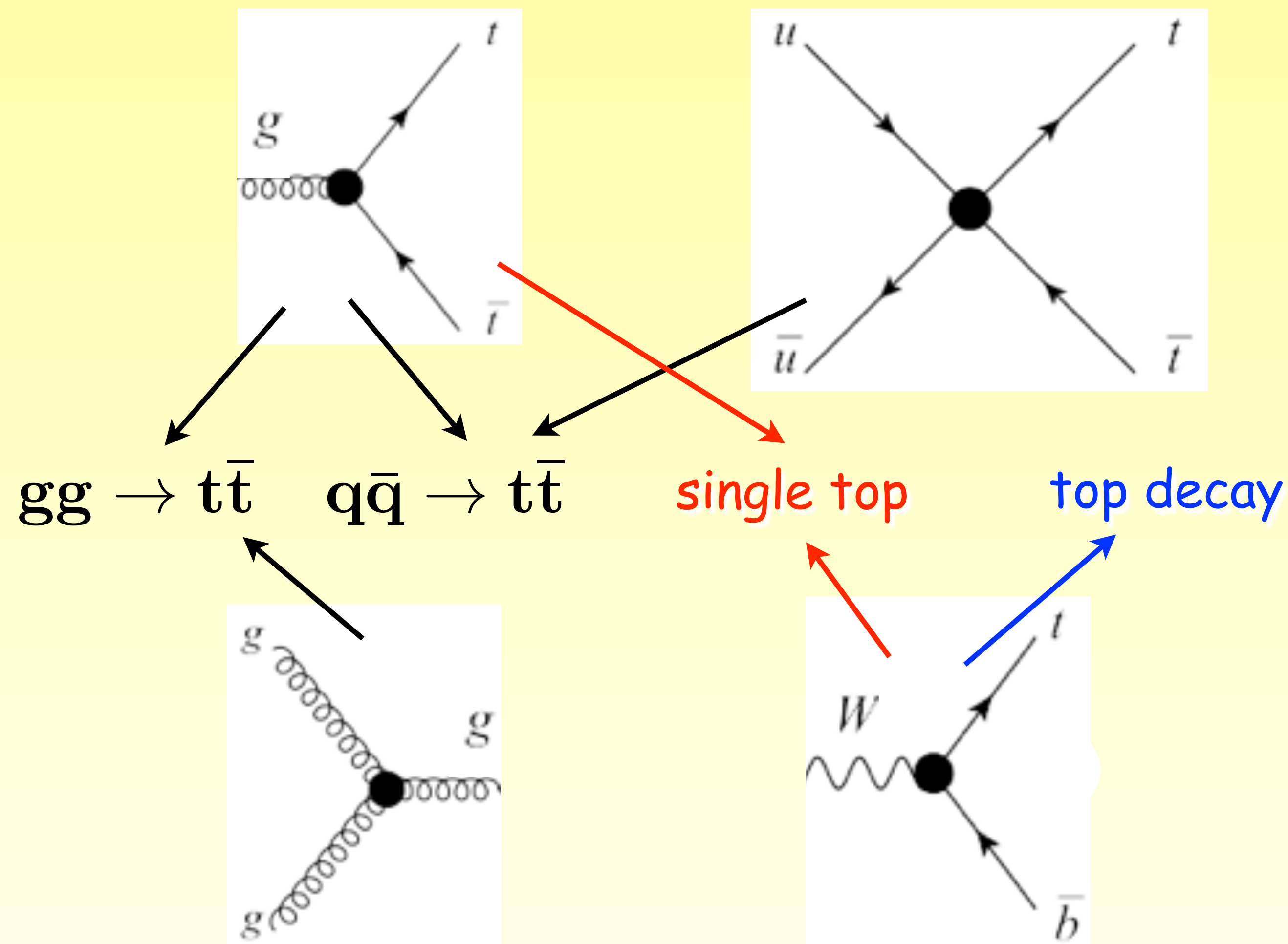
- look for deviations from the Standard Model expectation:
  - precisely measure the top properties
  - new physics effects could be seen as new or anomalous couplings

for example:



$$\frac{g^2}{p^2 - M^2}$$

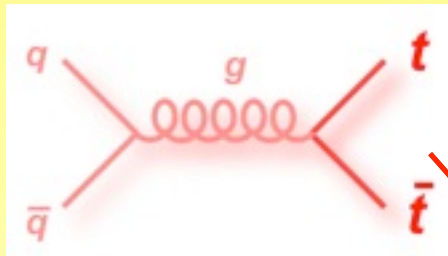
$$\frac{g^2}{M^2} \quad (M = \Lambda)$$

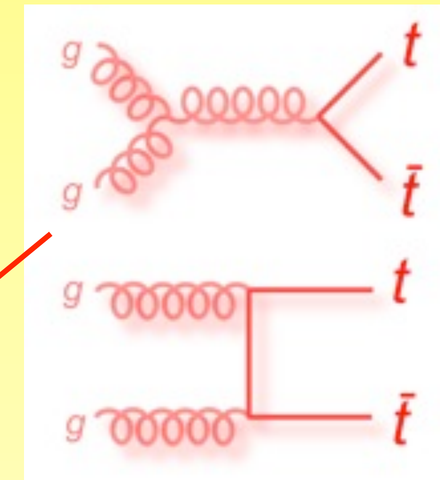


Different top observables can constrain different new physics effects

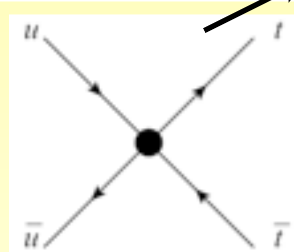
Top Quark Pair Production at Hadron Colliders

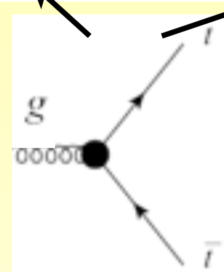
- main production: $t\bar{t}$ pairs via strong interaction

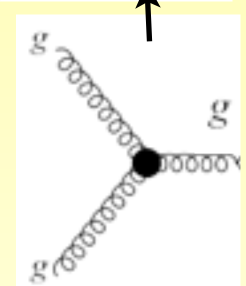




	$q\bar{q}$	gg
$p\bar{p}$ @ 1.96 TeV	85 %	15 %
pp @ 7 TeV	15 %	85 %







The Tevatron is a quark-antiquark annihilation machine

The LHC is a gluon fusion machine

for $m_t = 172.5$ GeV:

$$\sigma(p\bar{p} \to t\bar{t})_{\text{NNLOapprox}} = 7.46^{+0.48}_{-0.67}\ \text{pb}$$

$$\sigma(pp \to t\bar{t})_{\text{NNLOapprox}} = 164.6^{+11.4}_{-15.7}\ \text{pb}$$

Langenfeld et al. PRD 80, 054009 (2009)
Aliev et al., Comput.Phys.Commun. 182, 1034 (2011) *
Kidonakis, Phys.Rev. D82, 114030 (2010)
Ahrens et al., JHEP 1009, 097 (2010), arXiv:1105.5824

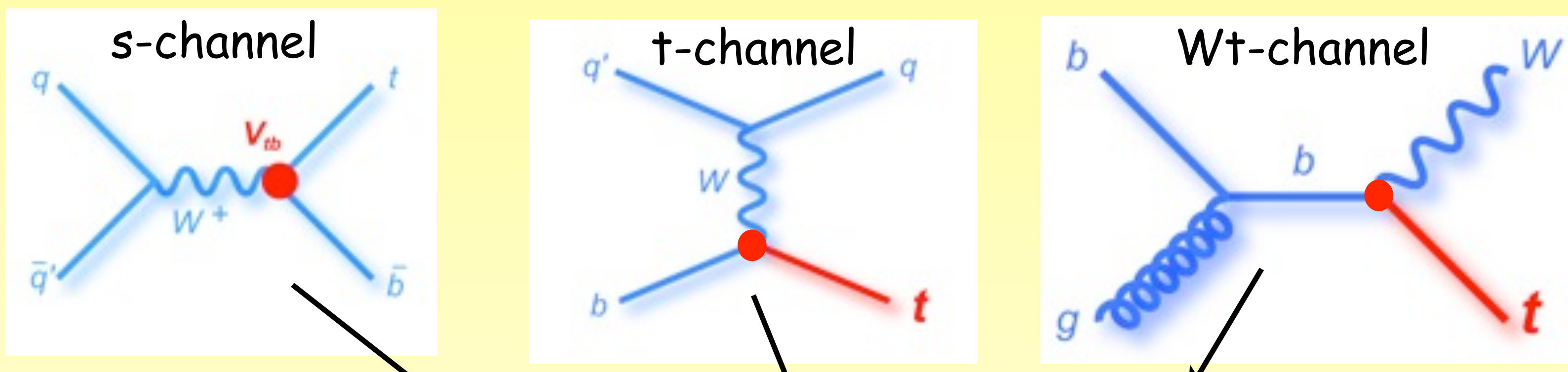
with 1 fb^{-1} at LHC, ~ 4 times more $t\bar{t}$ than at Tevatron with 5 fb^{-1}

Electroweak Top Production At Hadron Colliders

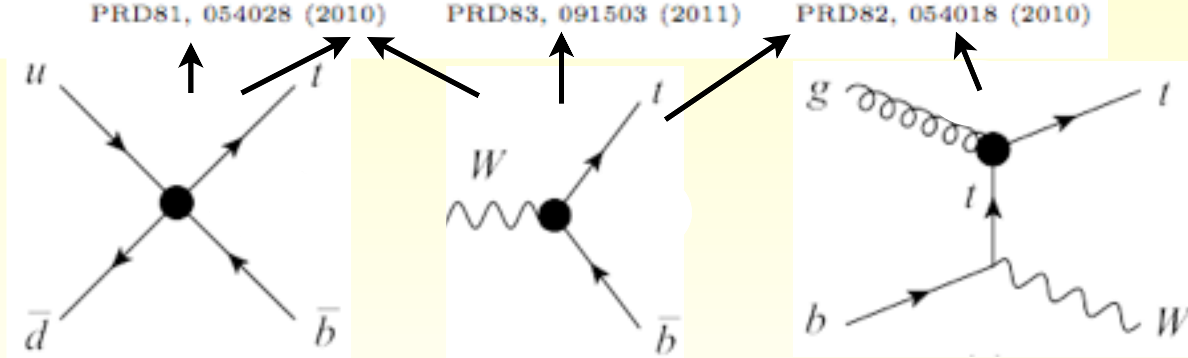
- discovered in 2009 at the Tevatron

  PRL 103, 092001 (2009), PRL 103, 092002 (2009)
- allows to directly measure V_{tb}
- challenging to measure

  - small cross section and background similar signature than signal



for $m_t = 172.5$ GeV: (in pb)	σ_{tb}	σ_{tqb}	σ_{tW}
$p\bar{p}$ @ 1.96 TeV	1.04 ± 0.04	2.26 ± 0.12	0.28 ± 0.06
	PRD 74, 114012 (2006)		
pp @ 7 TeV	4.6 ± 0.3	$64.6^{+3.3}_{-2.6}$	15.7 ± 1.4
	PRD81, 054028 (2010)	PRD83, 091503 (2011)	PRD82, 054018 (2010)

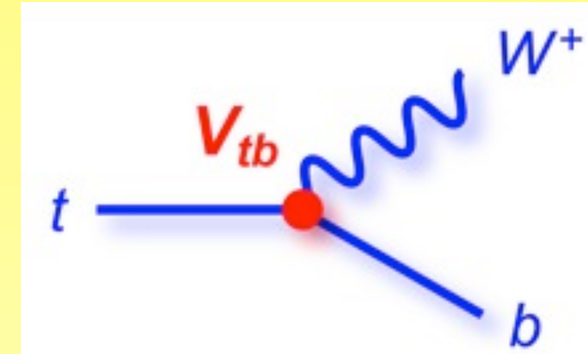


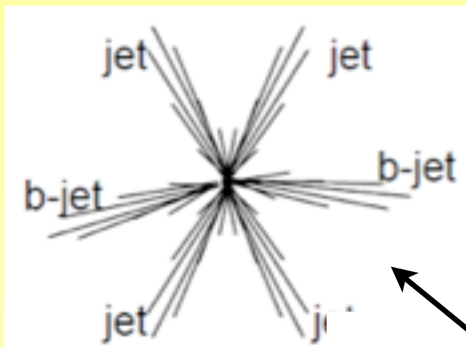
Interesting to measure the 3 processes separately

tW not possible at Tevatron, s-channel very challenging at LHC

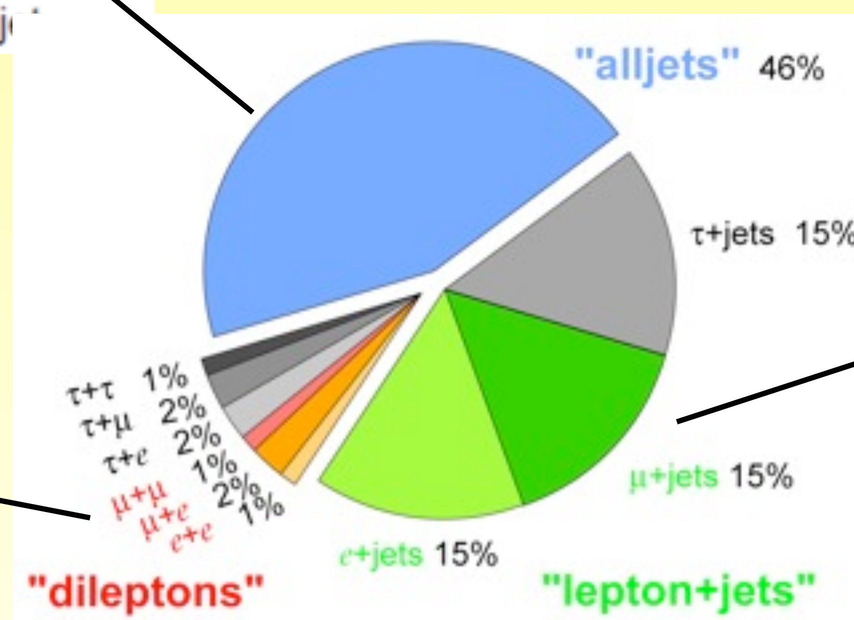
Top Quark Pair Signatures

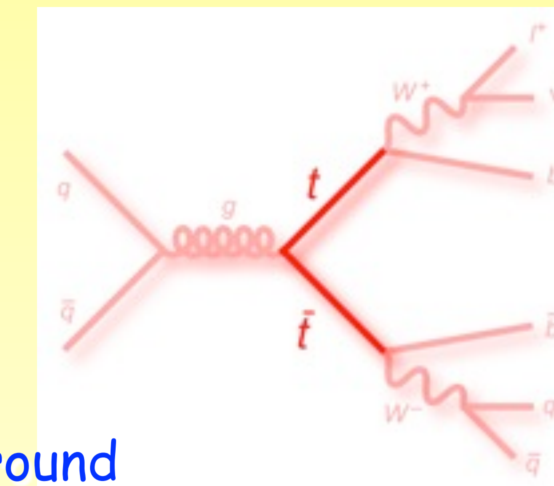
- within the Standard Model: $B(t \to Wb) \approx 1$
  - could be modified by new physics
- top pair signatures classified according to the W decays



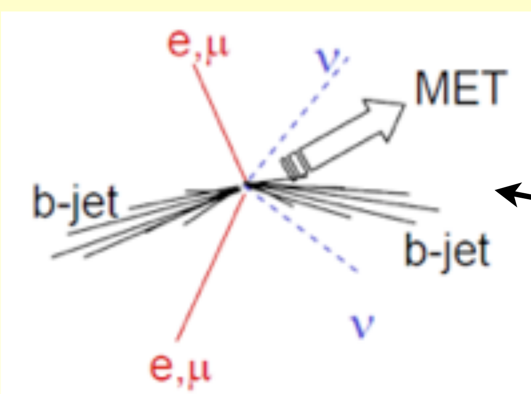


alljets: large rate, large background
main background: multijet
(estimated from data)



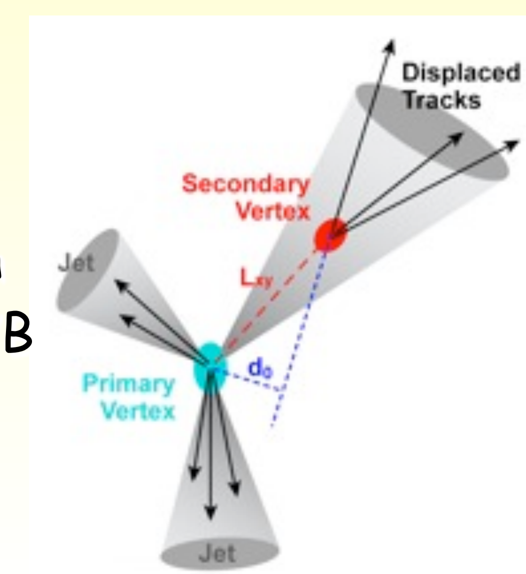


l+jets: good rate,
reasonable background
main backgrounds:
W+jets (shape: MC, normalization: data)
multijet: fake lepton (estimated from data)



dilepton: small rate, small background
main background: Drell-Yan: fake missing Et
(estimated from data)

b-quark jet identification
often used to enhance S/B



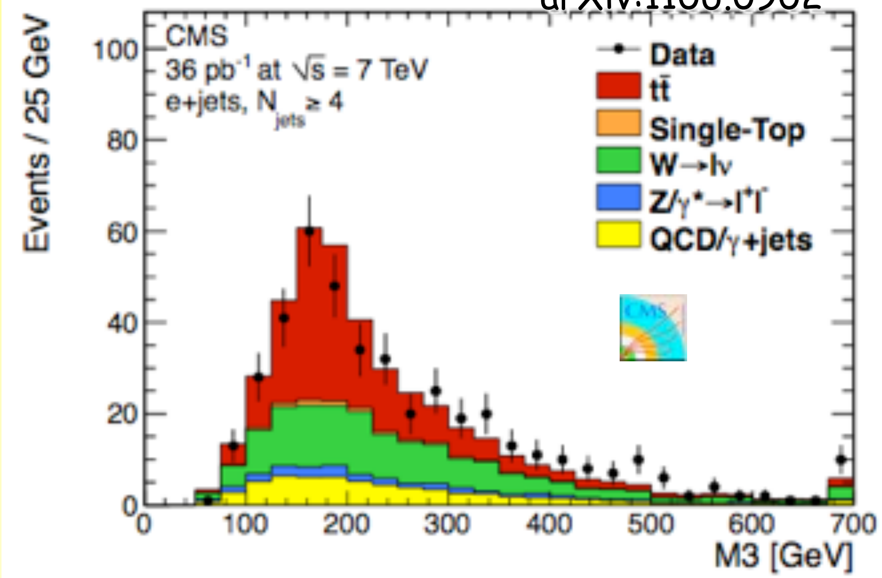
Top Quark Production

Lepton + Jets Top Pair Cross Section

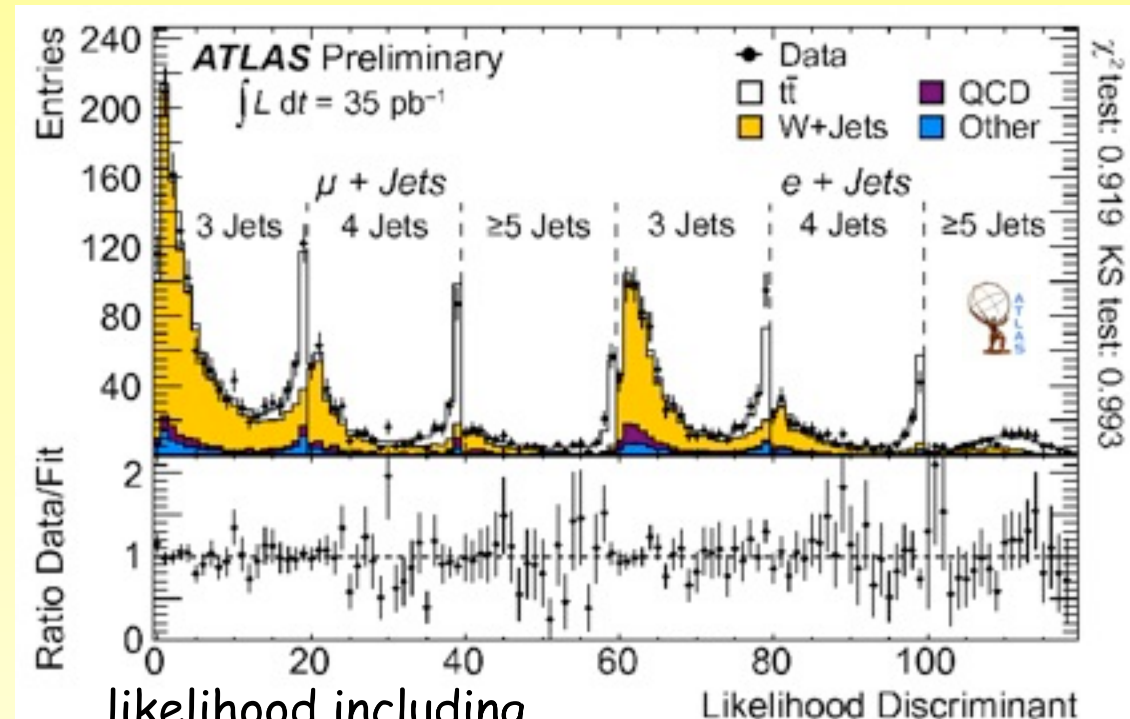
- most precise channel

- measurements with or without b-tagging
- usually fit the number of W+jets together with the number of $t\bar{t}$
- can also fit the systematic uncertainties to reduce them

arXiv:1106.0902



discriminating variables:
Njets=3: MET
Njets ≥ 4: M_3=M_{jjj}



likelihood including
kinematic observables and b-tagging information

ℓ+jets channel
for $m_t = 172.5$ GeV:

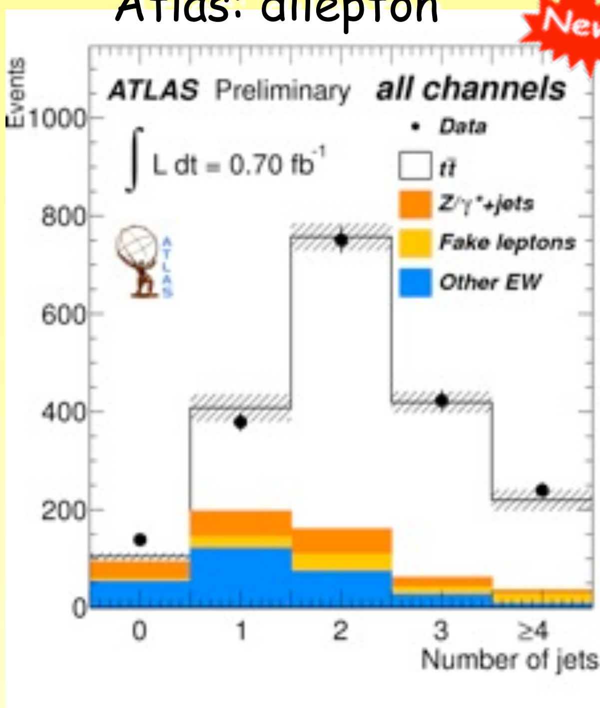
CDF (4.6 fb^{-1}, PRL 105, 012001 (2010))	$\sigma(p\bar{p} \to t\bar{t}) =$	7.70 ± 0.52 (stat + syst + theory) pb
D0 (5.6 fb^{-1}, arXiv:1101.0124)	$\sigma(p\bar{p} \to t\bar{t}) =$	$7.78^{+0.77}_{-0.64}$ (stat + syst + lumi) pb
Atlas (35 pb^{-1})	$\sigma(pp \to t\bar{t}) =$	$186 \pm 10(\text{stat})^{+21}_{-20}(\text{syst}) \pm 6(\text{lumi})$ pb
CMS (36 pb^{-1}, arXiv:1106.0902)	$\sigma(pp \to t\bar{t}) =$	$150 \pm 9(\text{stat}) \pm 17(\text{syst}) \pm 6(\text{lumi})$ pb

dominant systematics:
Jet Energy Scale (JES),
Jet ID, b-tagging,
W+HF fraction

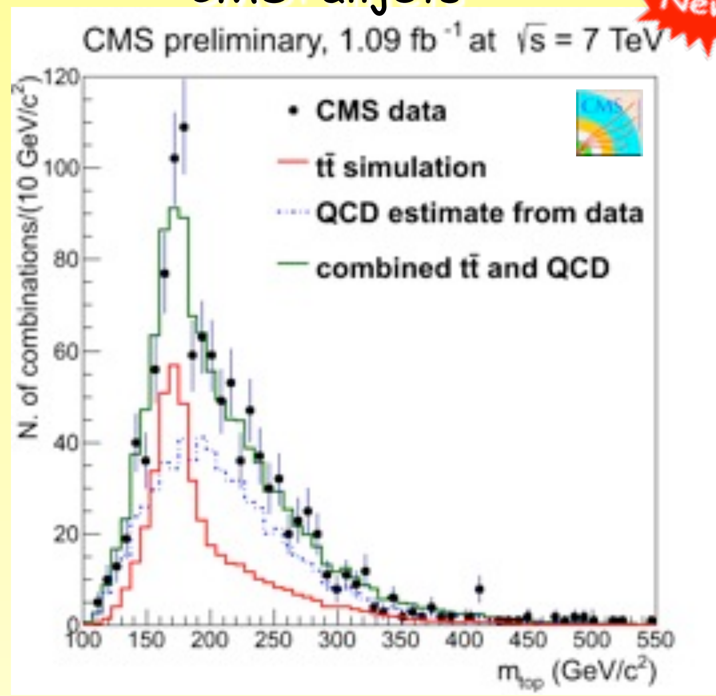
Top Pair Cross Sections In the Other Channels

- interest:
  - measurements in different signal/background environment
  - see if all decay channels give the same cross section

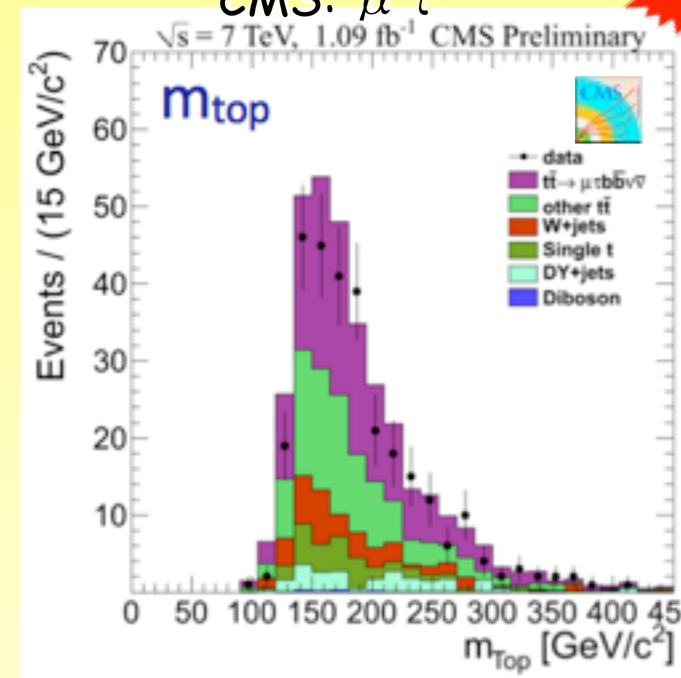
Atlas: dilepton



CMS: alljets



CMS: μ τ



Agreements between the different decay channels

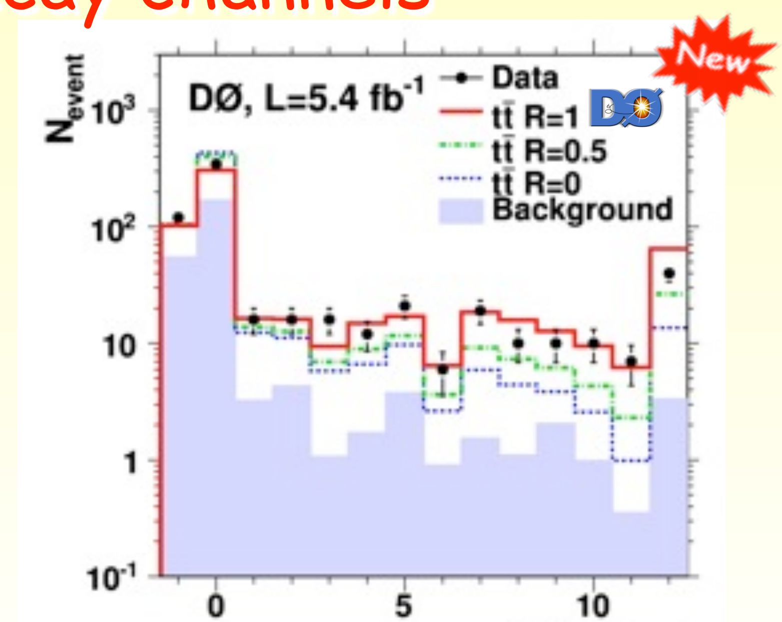
- in addition to the cross section
  - fit together cross section and R:

$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

SM predicts R =1

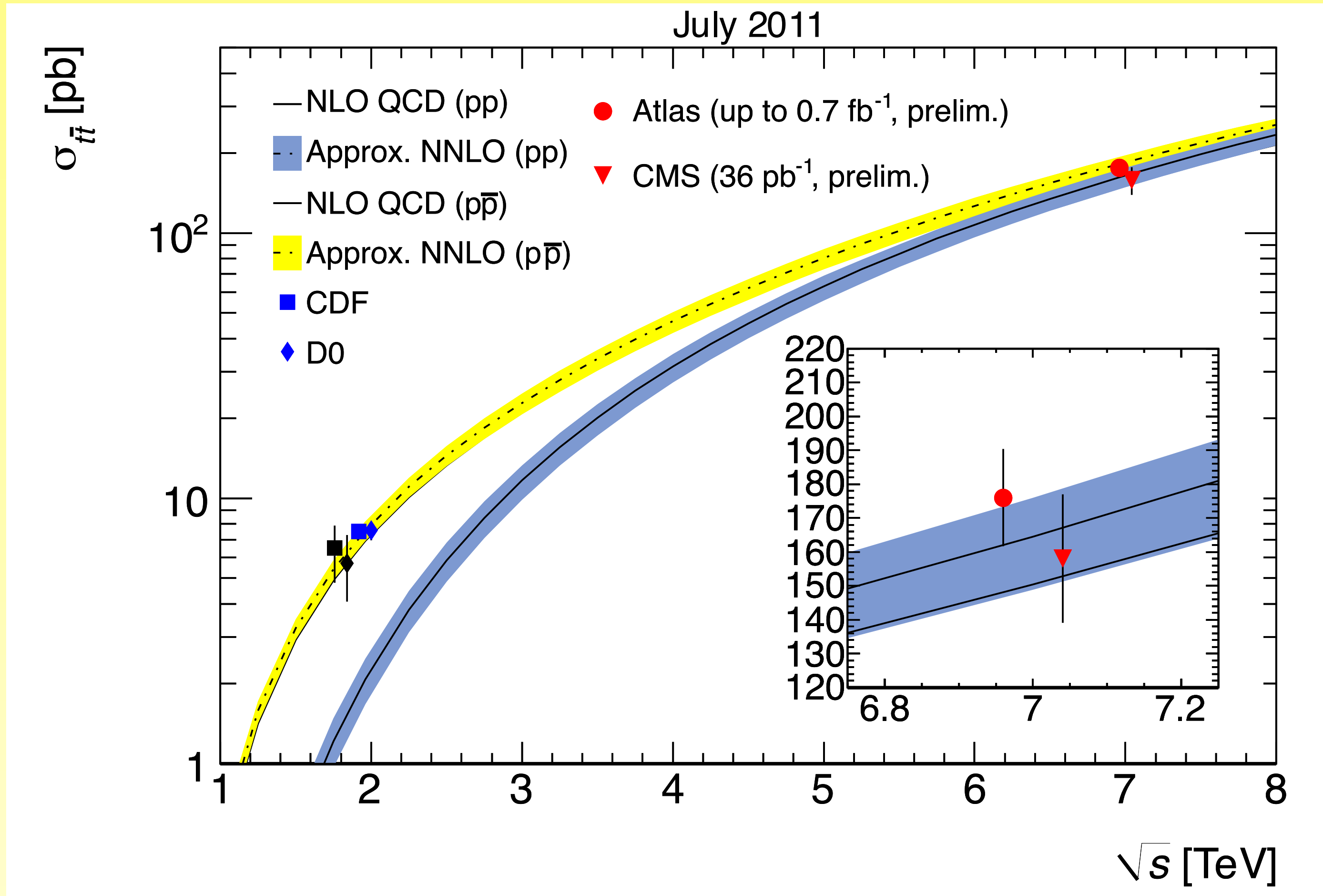
ljets+dilepton: $|V_{tb}| = 0.95 \pm 0.02$ assuming CKM unitarity

(agreement with the SM: 1.6 %)



arXiv:1106.5436

Top Quark Pair Cross Section Summary



decay channel combined
for $m_t = 172.5$ GeV:

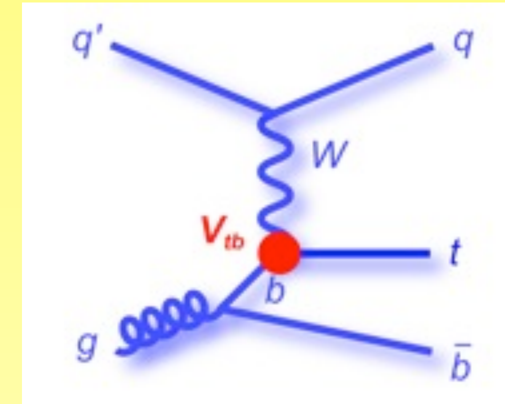
CDF (up to 4.6 fb^{-1})	$\sigma(p\bar{p} \to t\bar{t}) =$	$7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	~ 6.5 %
D0 (5.6 fb^{-1}, arXiv:1105.5384)	$\sigma(p\bar{p} \to t\bar{t}) =$	$7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb	
Atlas (up to 0.7 fb^{-1})	$\sigma(pp \to t\bar{t}) =$	$176 \pm 5(\text{stat})^{+13}_{-10}(\text{syst}) \pm 7(\text{lumi})$ pb	~ 8 %
CMS (36 pb^{-1})	$\sigma(pp \to t\bar{t}) =$	$158 \pm 10(\text{uncor.}) \pm 15(\text{cor.}) \pm 6(\text{lumi})$ pb	

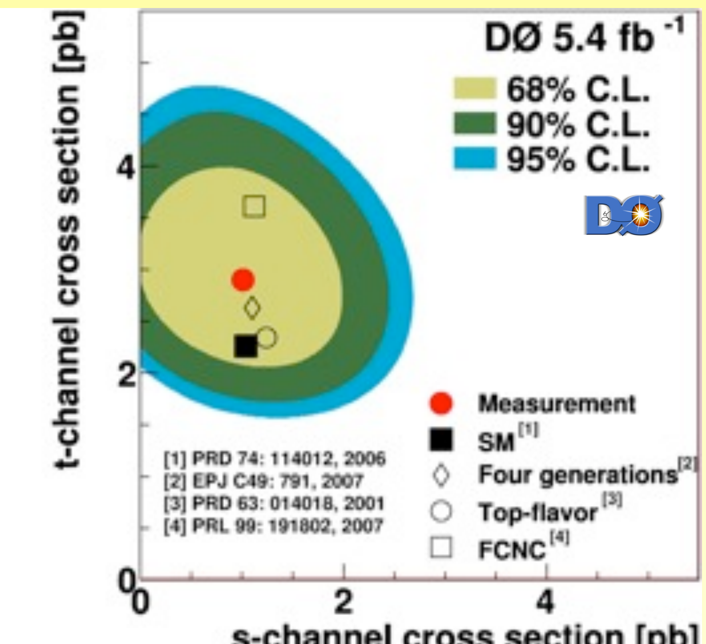
Measurements agree with the QCD predictions

Future measurements will focus on differential cross sections

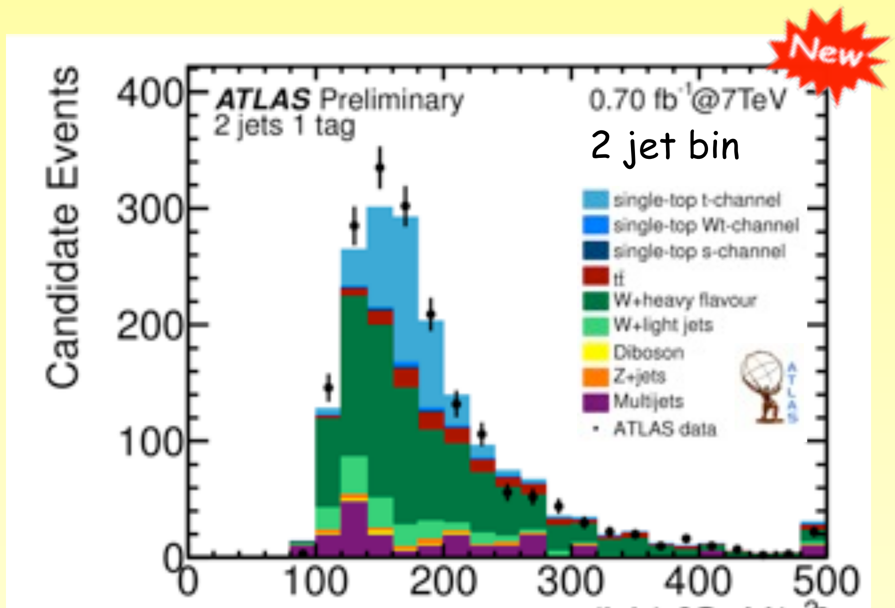
t-Channel Single Top Cross Section

- analysis strategy
  - discriminate signal (t-channel) from background (other single top, W+jets, $t\bar{t}$):
    * Tevatron: multivariate (Neural Networks, Boosted Decision Trees, ...)
    * LHC: cut-based or multivariate



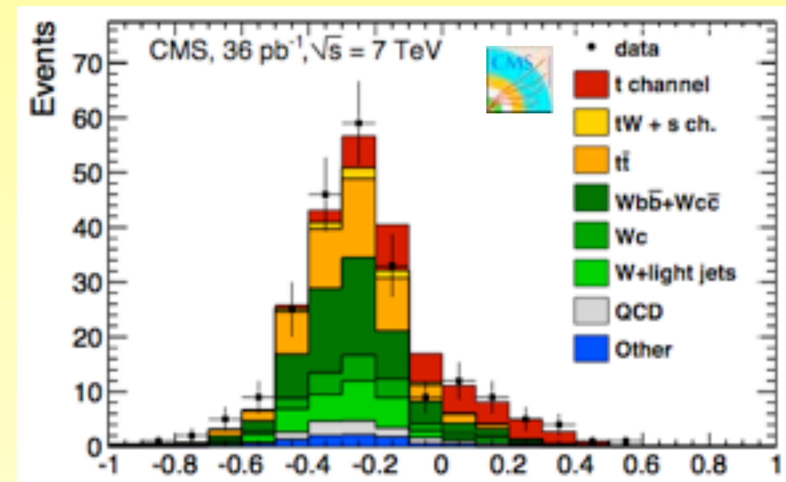


*combination of 3 multivariate discriminants



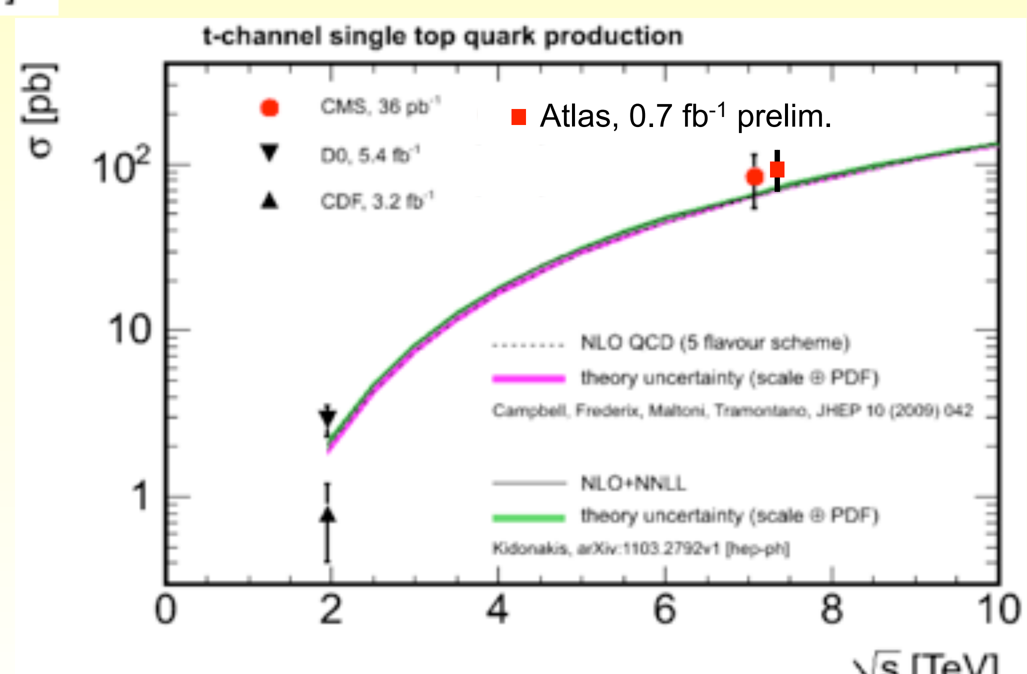
*cut based

* neural network (NN)



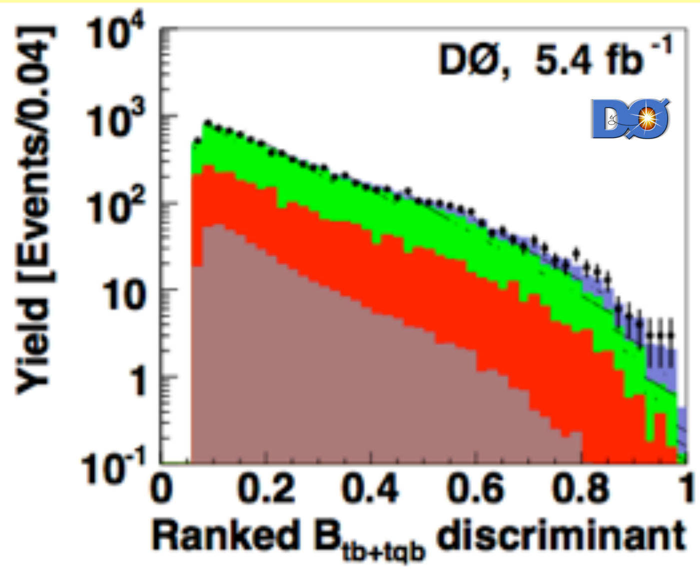
* 2D fit: cos(l,light j)*- η light
* boosted decision tree (BDT)

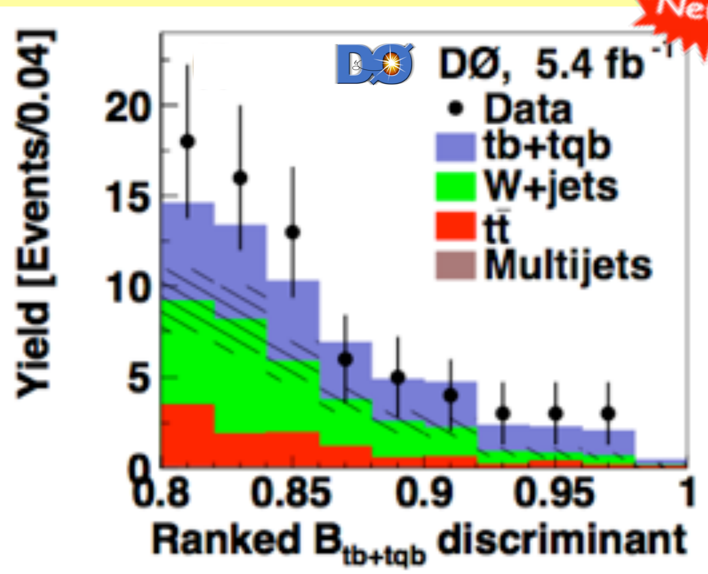
σ_{tqb} (pb) for $m_t = 172.5$ GeV:		
CDF (3.2 fb^{-1})	0.8 ± 0.4	
D0 (5.4 fb^{-1}, arXiv:1105.2788)	2.90 ± 0.59	5.5σ
CMS (36 pb^{-1}, arXiv:1106.3052)	$83.6 \pm 29.8(\mathrm{stat+syst}) \pm 3.3(\mathrm{lumi})$	3.7σ
Atlas (0.7 fb^{-1})	90^{+32}_{-22}	7.6σ



Other Single Top Cross Sections

- inclusive cross section at the Tevatron
  - signal: both t and s-channel





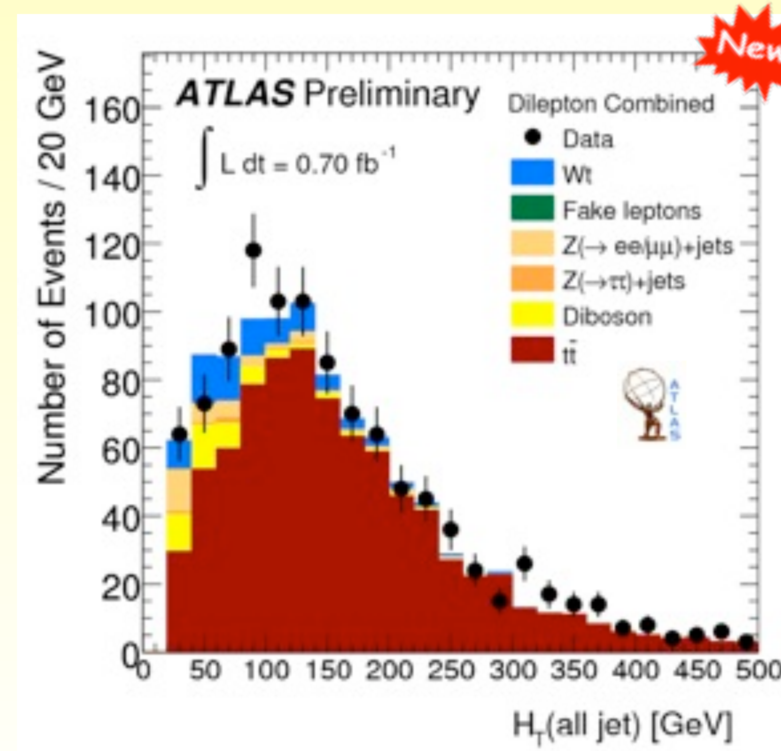
D0 (5.4 fb^{-1}) for $m_t = 172.5$ GeV:	
$\sigma_{\rm tb}$	$0.68^{+0.38}_{-0.35}$ pb
$\sigma_{\rm tb/tqb}$	$3.43^{+0.73}_{-0.74}$ pb

need more statistics for s-channel sensitivity

$|V_{tb}| > 0.79$ at 95% CL for $0 \leq V_{tb} \leq 1$

- search for Wt channel in the dilepton channel
  - cut based
  - main background: $t\bar{t}$

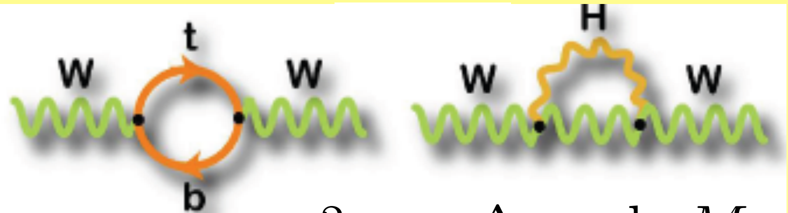
$$\sigma(pp \rightarrow Wt + X) \; < \; 39.1 \text{ pb}$$



Top Quark Properties

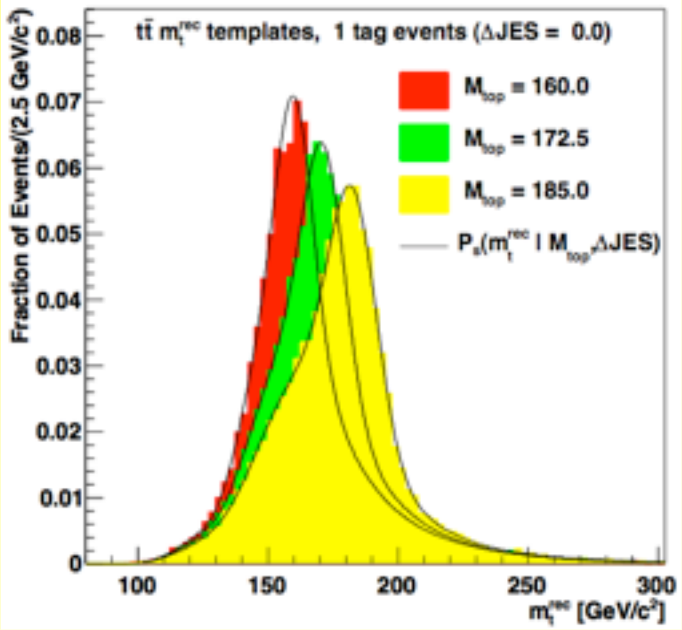
Top Quark Mass

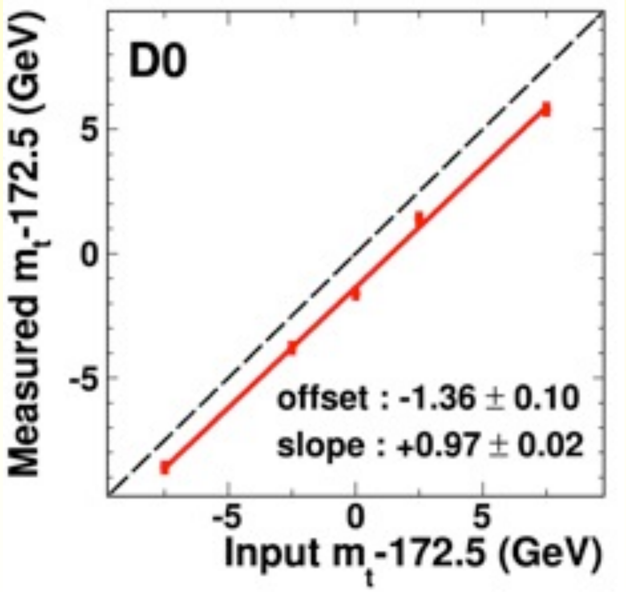
- why measuring the top mass precisely ?
  - free parameter of the SM
  - predict the Higgs boson mass together with the W boson mass
  - consistency of the SM and possibly with the direct Higgs measurements



$\Delta r \propto M_t^2$ $\Delta r \propto \ln M_H$

- how to measure the top mass ?
  - <u>template method</u>:
    * compare an observable in data with MC generated with different masses
  - <u>matrix element method</u>:
    * build an event probability based on the LO $t\bar{t}$ matrix element using the full kinematics of the event
  - <u>ideogram method</u>:
    * event likelihood computed as a convolution of a Gaussian resolution function with a Breit-Wigner (signal)





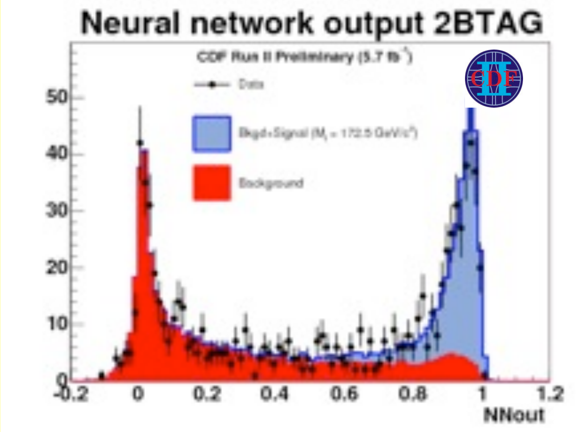
- for channel with at least one W decaying hadronically, can calibrate the jet energy scale (JES) constraining M_{jj} to M_W

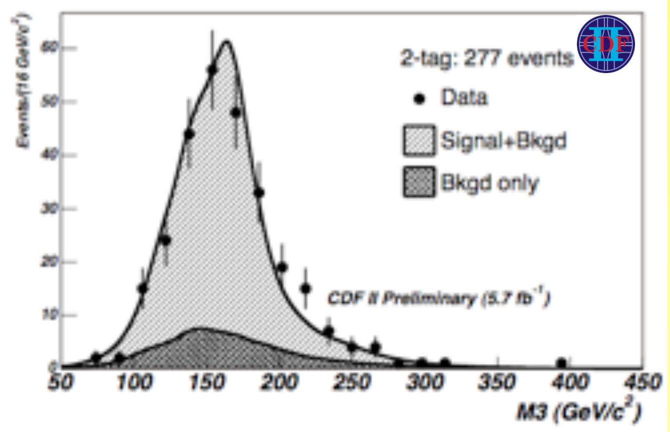
- need to calibrate the method to correct for any potential biases

Top Quark Mass Measurements

- CDF template result using MET+jets events
  - NN selection to extract the signal
  - observables: Mt: $M_3=M_{jjj}$, $M'_3=M_{jjj'}$, JES: $M_2=M_{jj}$

$$M_{top} = 172.3 \pm 2.4 \text{ (stat.} + \text{JES)} \pm 1.0 \text{ (syst.)} \, GeV/c^2$$

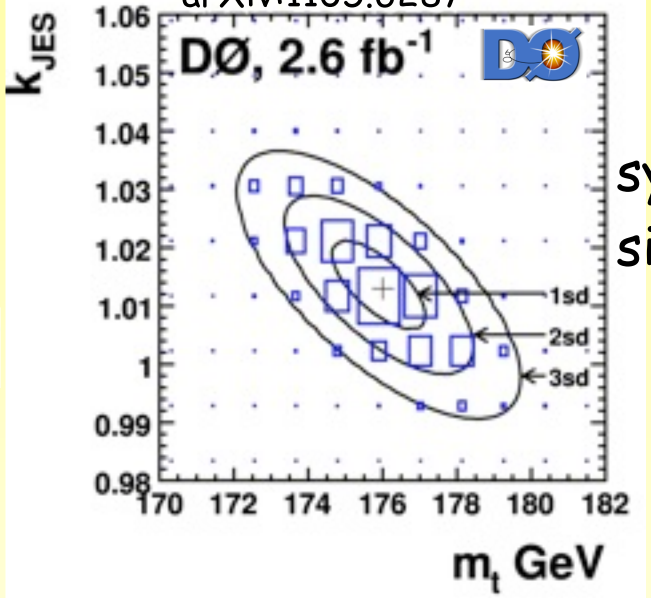




arXiv:1105.6287

- D0 ME result using lepton+jets events
  - new flavor-dependent jet response correction
  - combine with the previous 1 fb^{-1} measurement

$$m_t = 174.94 \pm 0.83(\text{stat}) \pm 0.78(\text{JES}) \pm 0.96(\text{syst}) \text{ GeV}$$

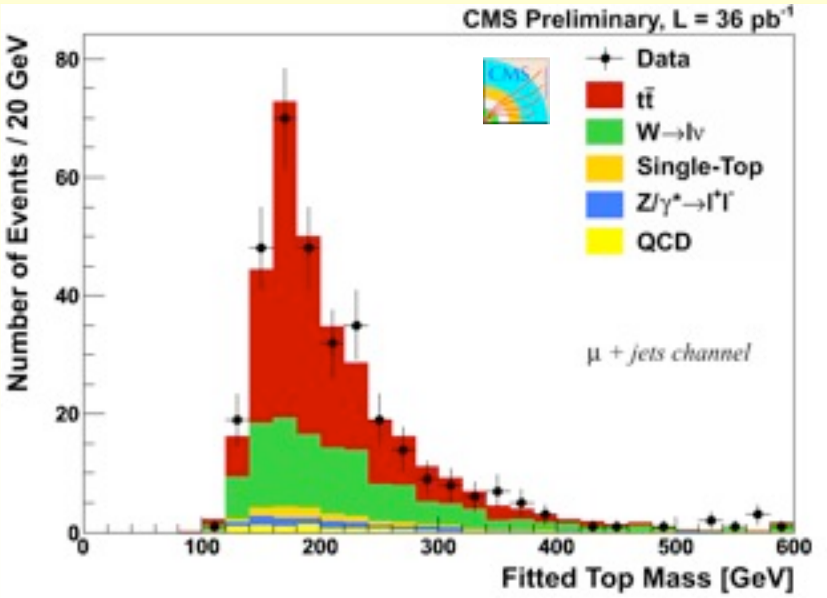


systematically limited:
signal modeling, residual JES

- CMS ideogram result using lepton+jets events

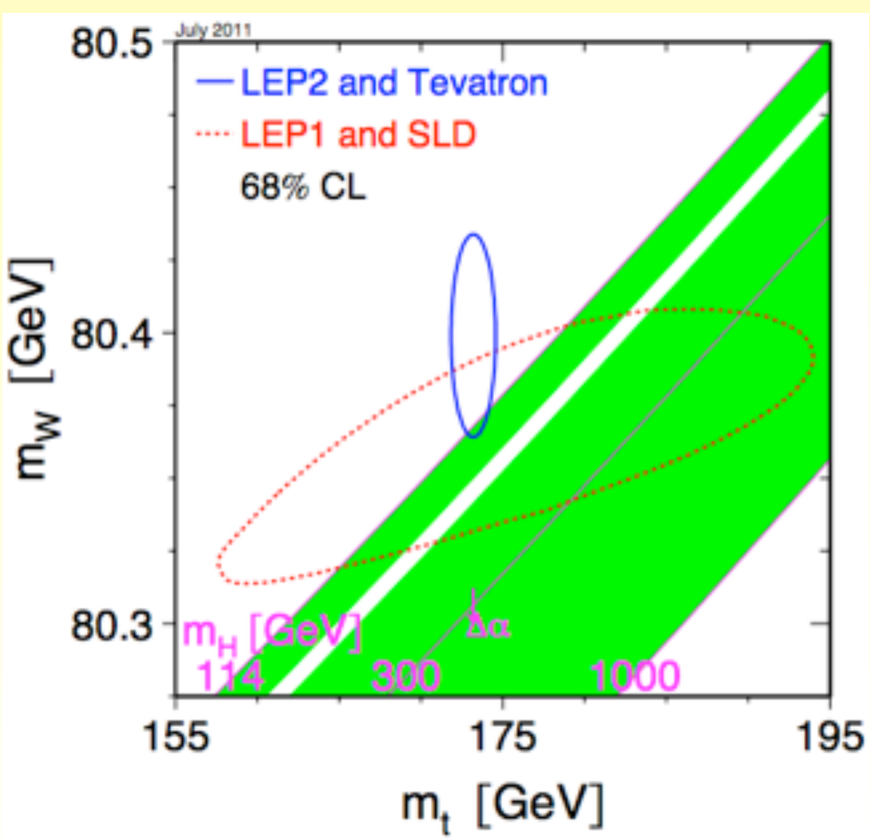
$$m_t = 173.1 \pm 2.1(\text{stat})^{+2.8}_{-2.5}(\text{syst}) \text{ GeV}$$

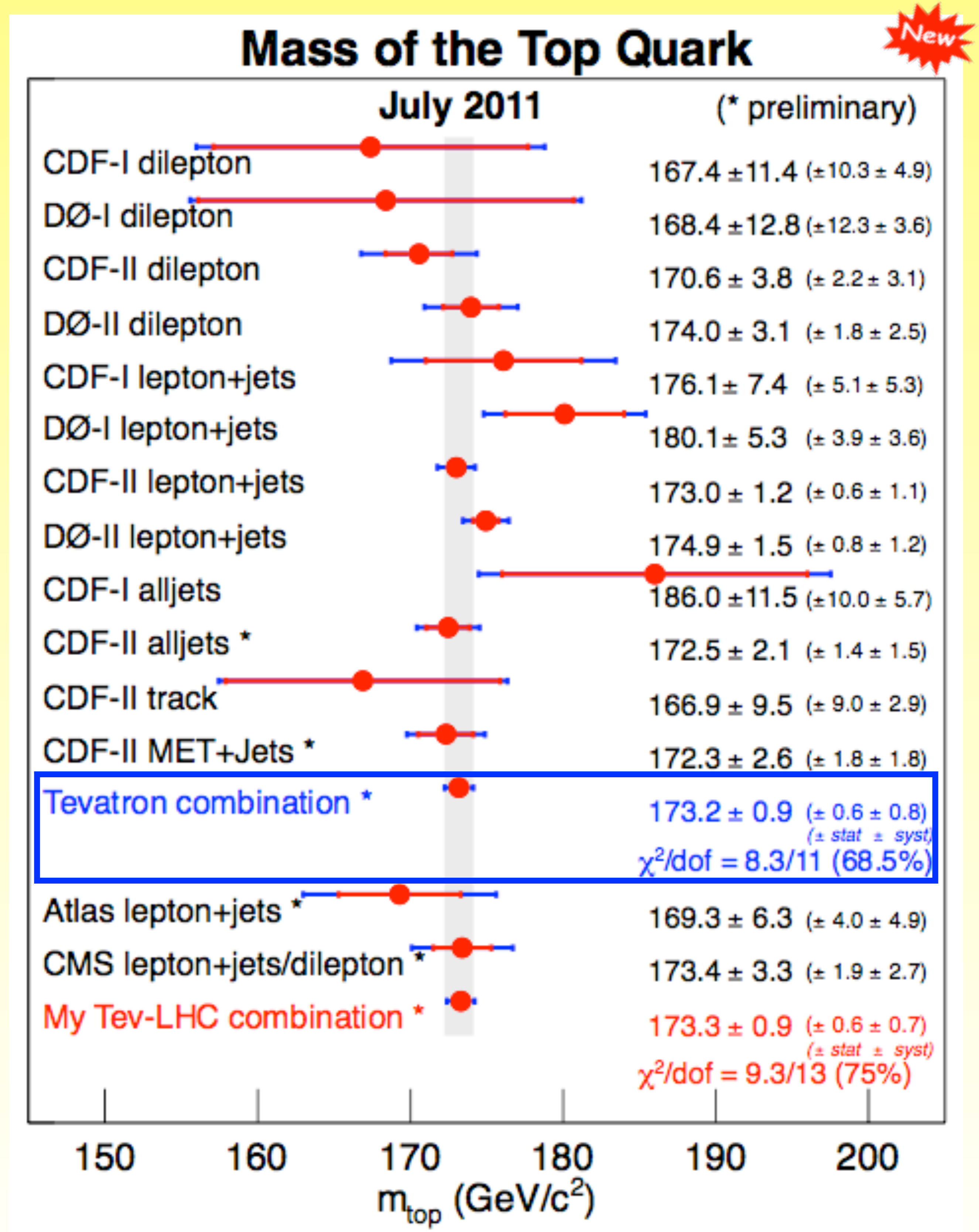
dominant systematics:
JES, factorization scale



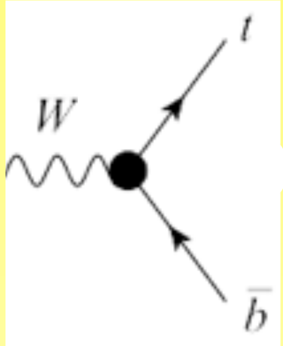
Top Quark Mass Summary

- new Tevatron combination
  - uncertainty below 1 GeV for the first time
  - all channels give consistent results
  - still working on decreasing the systematic uncertainties
- new electroweak fit, constraints on the Higgs boson mass:
  - m_H < 161 GeV at 95% CL (m_H < 185 with LEP limit)
  - $m_H = 92^{+34}_{-26}$ GeV





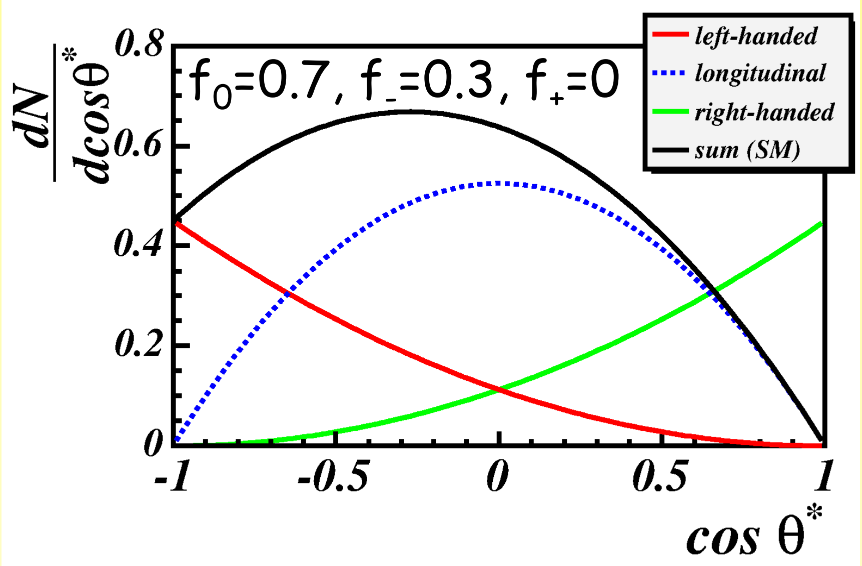
W Boson Helicity In Top Decays



- motivation:
  - test the SM at the electroweak scale
  - new physics could affect the helicity, no right-handed W in the SM

- measurement methods:
  - template fit of the cos θ^* distribution

    (angle between the lepton from the W boson and the top direction in W boson rest frame)
  - matrix element (ME)



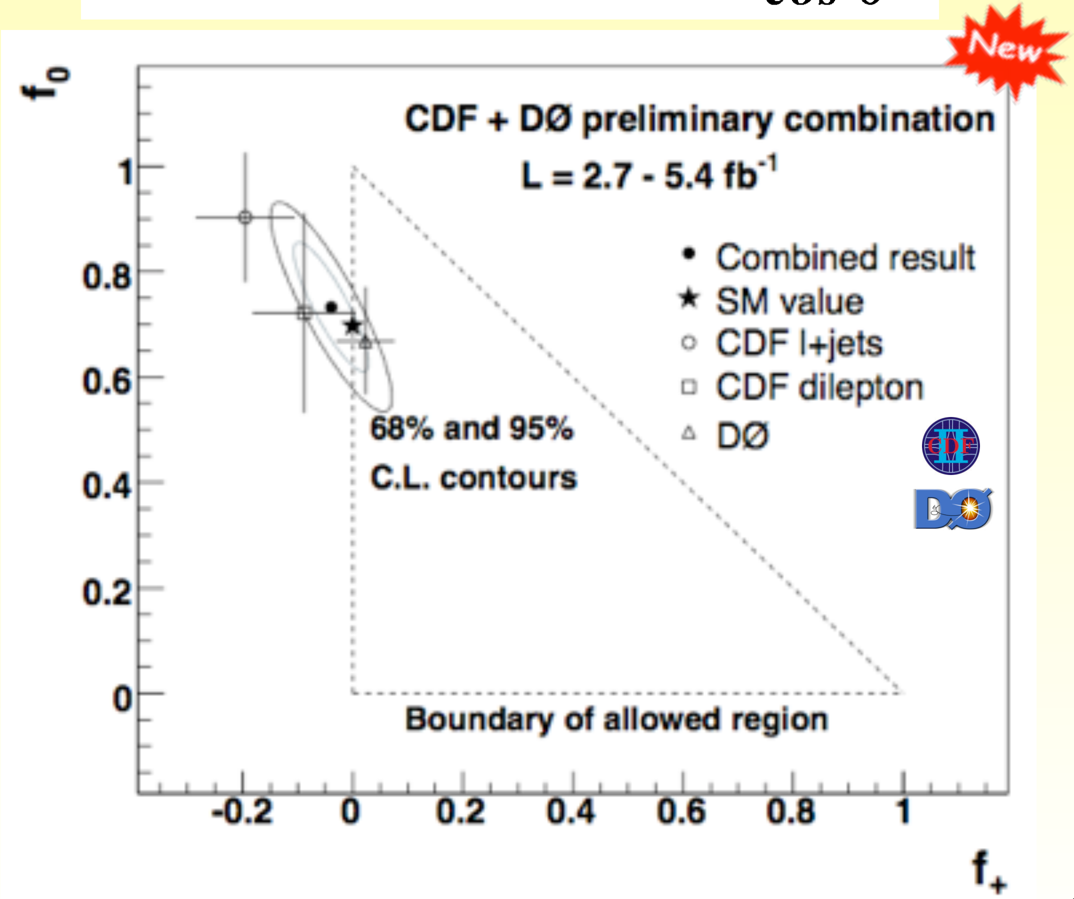
- combination of the latest Tevatron results:
  - taken correlation into account

    both when f_0 and f_+ are floating or only one of them

$$f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$$
$$f_+ = -0.039 \pm 0.034(\text{stat}) \pm 0.030(\text{syst})$$
(2D)

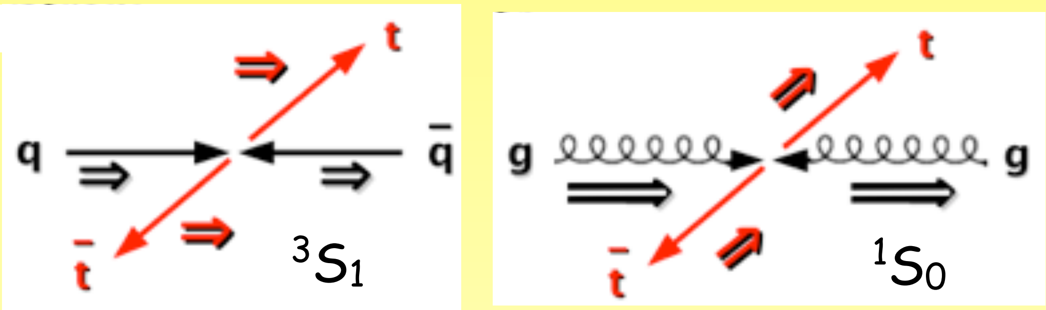
- Atlas result:
  - lepton+jets template (35 pb^{-1})

$$f_0 = 0.59 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$$
$$f_- = 0.41 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$$
(1D)



Top Pair Spin Correlations

- in the SM, the spin of the top and of the antitop are produced correlated
  - correlation preserved in the decay products
  - can be affected by new physics

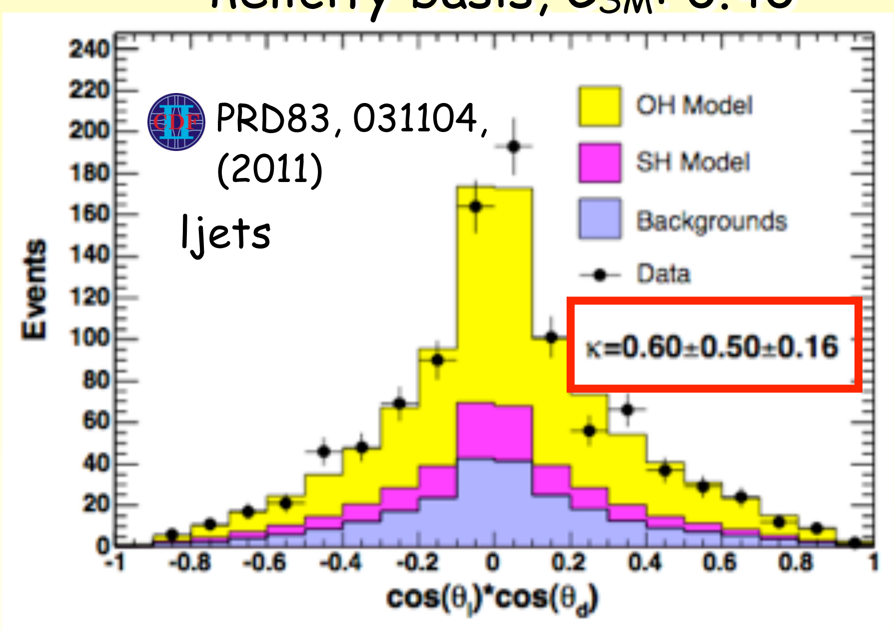


- measurement methods:
  - template fit of the cos θ_1 cos θ_2 distribution

(θ : angle from the down-type fermion wrt spin basis in the top/antitop rest frame)

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2}=\frac{1}{4}(1-C\cos\theta_1\cos\theta_2)$$

helicity basis, C_{SM}: 0.40



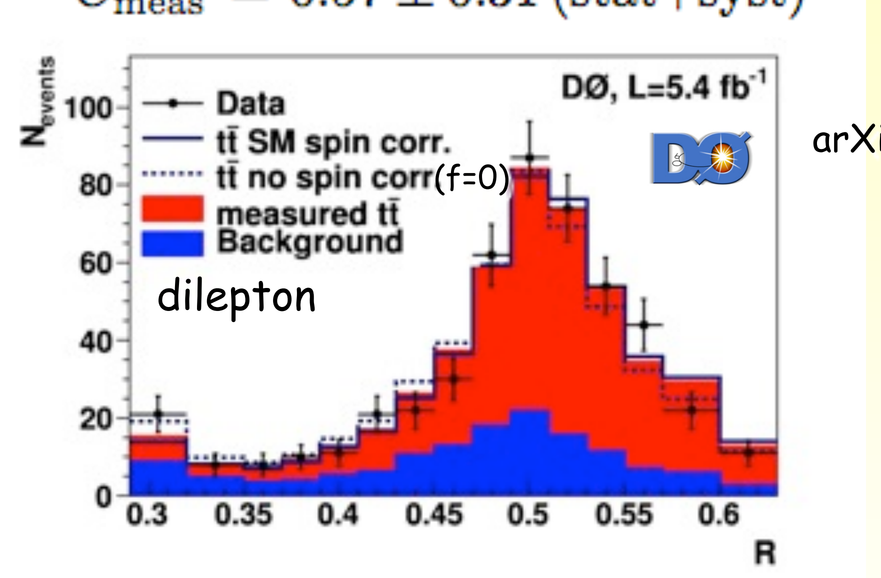
- matrix element: measure f: fraction of events with spin correlation using a template fit of R

$$R=\frac{P_{sgn}(H=c)}{P_{sgn}(H=u)+P_{sgn}(H=c)}$$

using ME without spin corr. using ME with spin corr.

$$f_{meas}=0.74^{+0.40}_{-0.41}\ (\text{stat+syst})$$

$$C_{meas}=0.57\pm0.31\ (\text{stat+syst})$$

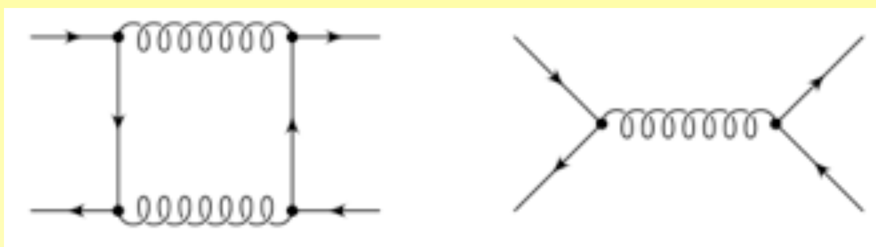


arXiv:1104.5194

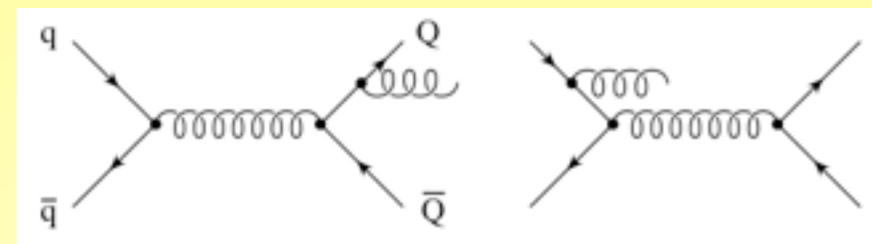
Still statistically limited, close to 3 σ sensitivity

Top-Antitop Charge Asymmetry

- At NLO, QCD predicts an asymmetry for $t\bar{t}$ produced via $q\bar{q}$ initial state
  - the top quark is predicted to be emitted preferably in the direction of the incoming quark
  - the exchange of new particles like Z′ or axigluon could modify it

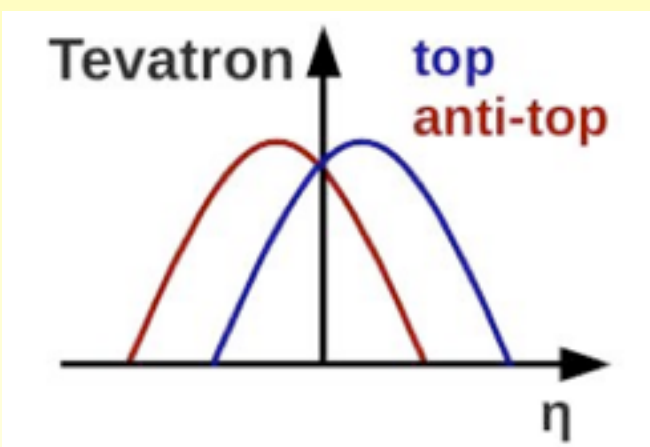


\+



positive asymmetry

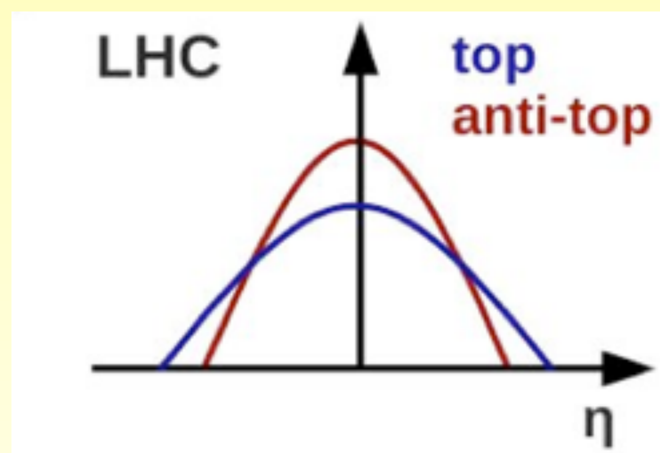
negative asymmetry

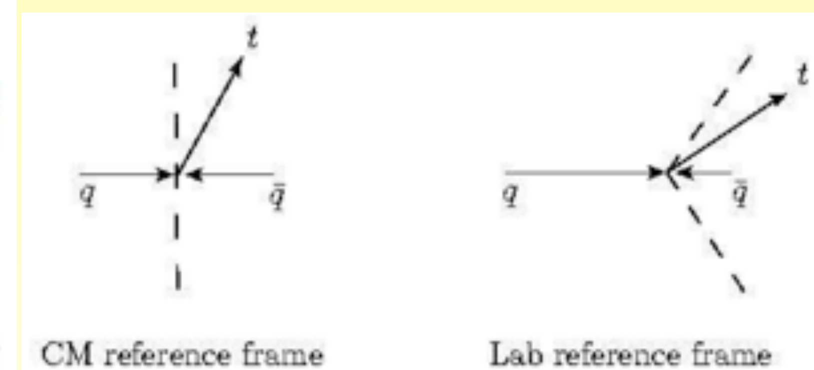


forward-backward asymmetry

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

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





central-forward asymmetry

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

$$\Delta|Y| = |Y_t| - |Y_{\bar{t}}|$$

smaller at LHC since low $q\bar{q}$ fraction

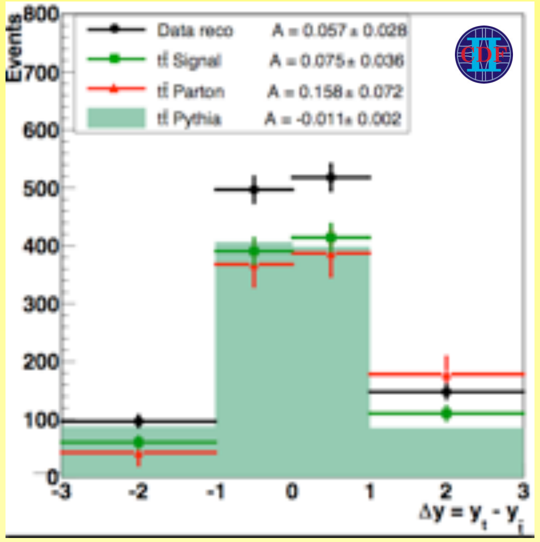
Tevatron Top Charge Asymmetry Results

- CDF measurements

ljets, PRD83, 112003 (2011)

$A_{t\bar{t}}$	ljets	ljets ($M_{t\bar{t}} \geq 450$ GeV)	dilepton
unfolded data	0.158 ± 0.074	0.475 ± 0.114	0.42 ± 0.16
SM prediction (MCFM)	0.058 ± 0.009	0.088 ± 0.013	0.06 ± 0.01

3.4 σ difference



- D0 ljets measurement

- unfold the reconstructed distribution to correct for acceptance and detector effects

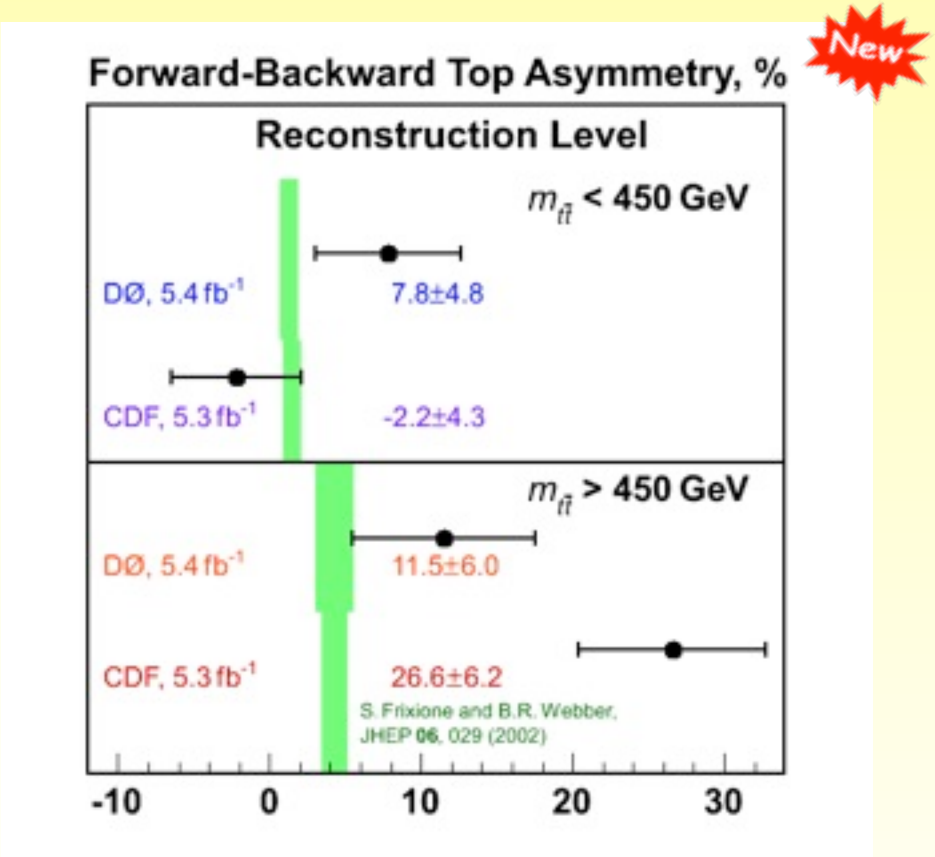
	A_{FB} (%)	
	Reconstruction level	Production level
Data	9.2 ± 3.7	19.6 ± 6.5
MC@NLO	2.4 ± 0.7	5.0 ± 0.1

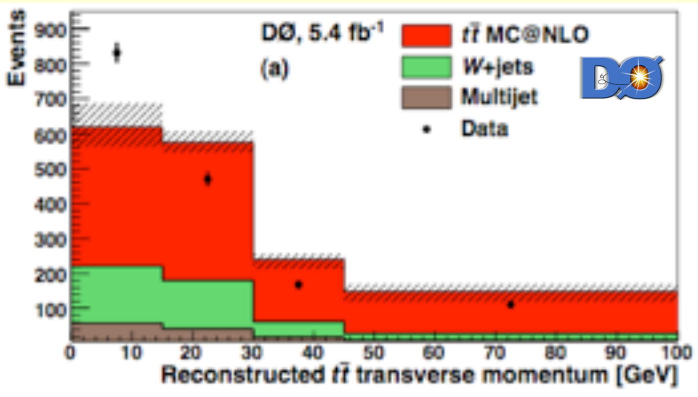
~ 2.4 σ

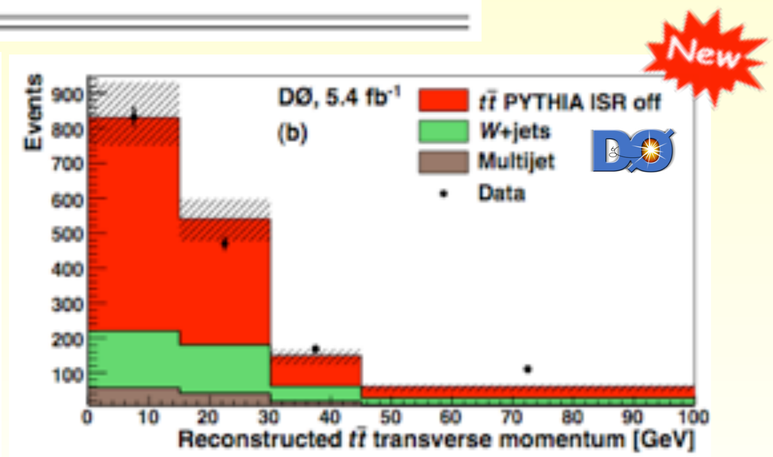
$$A^l_{FB} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

	A^l_{FB} (%)	
	Reconstruction level	Production level
Data	14.2 ± 3.8	15.2 ± 4.0
MC@NLO	0.8 ± 0.6	2.1 ± 0.1

> 3 σ







Statistically limited measurements, need better understanding of the predictions

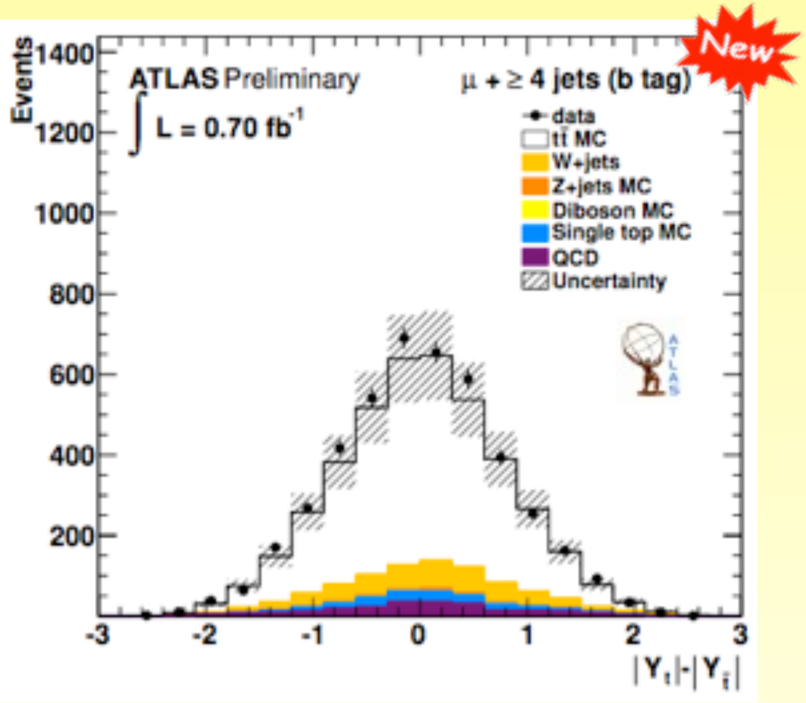
LHC Top Charge Asymmetry Results

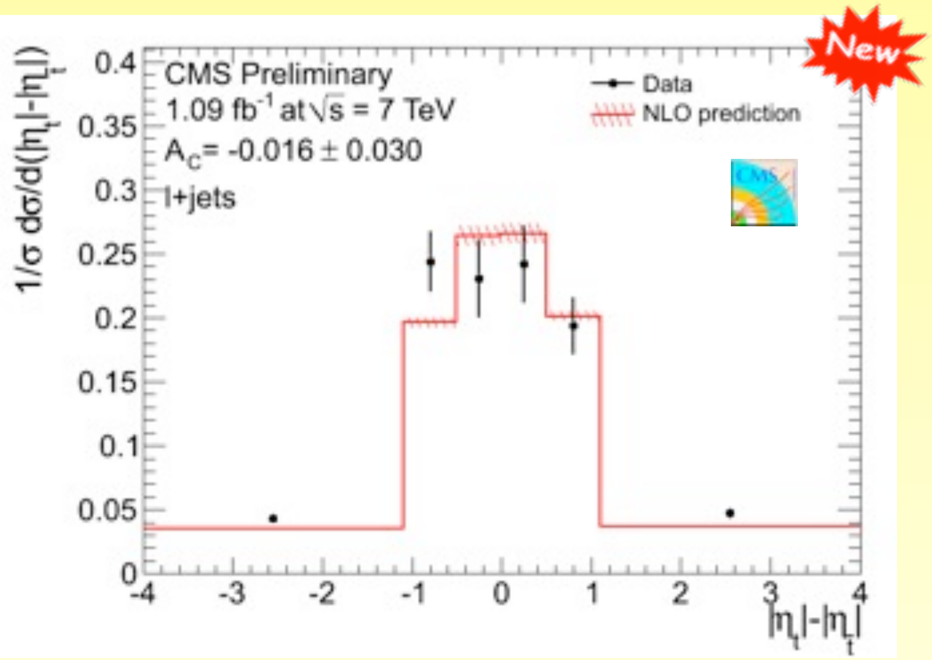
- different observables

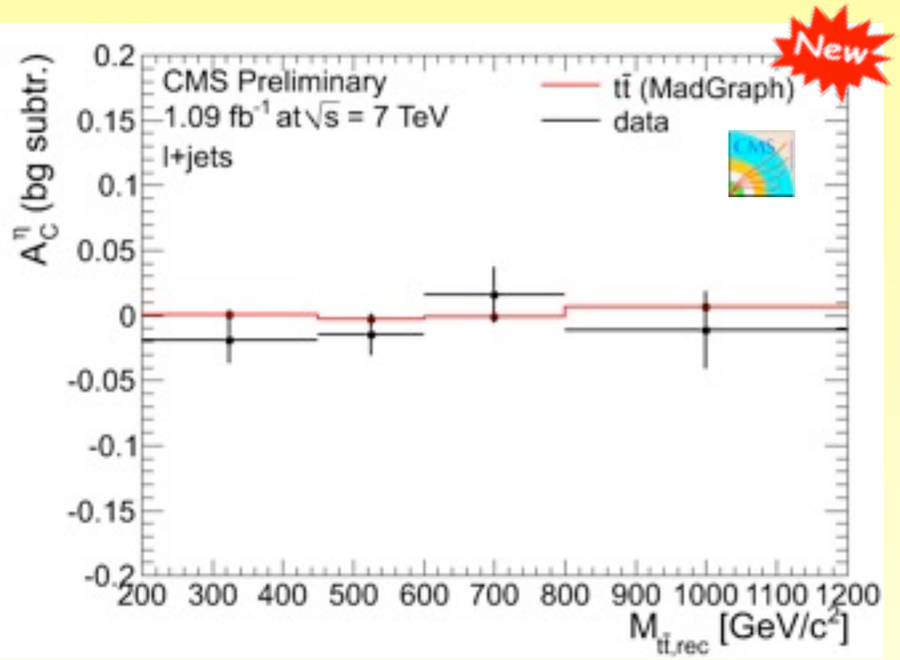
$$A_C = \frac{N(\Delta > 0) - N(\Delta < 0)}{N(\Delta > 0) + N(\Delta < 0)}$$

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

- CMS: $\Delta^\eta = |\eta_t| - |\eta_{\bar{t}}|$ $\Delta^{y^2} = (y_t - y_{\bar{t}})(y_t + y_{\bar{t}})$







	unfolded data	SM prediction
Altas: A_C^y (0.7 fb^{-1})	-0.024 ± 0.016 (stat) ± 0.023 (syst)	0.006 (MC@NLO)
CMS: A_C^η (1.1 fb^{-1})	-0.016 ± 0.030 (stat)$^{+0.010}_{-0.019}$ (syst)	0.0130

Currently no deviation from the predictions

Summary and Conclusion

We are looking forward for exciting discoveries in the top quark sector

Property	Measurement		SM Prediction	Luminosity (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	$p\bar{p} \to t\bar{t}$	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
	$pp \to t\bar{t}$	Atlas: $180 \pm 9(\text{stat}) \pm 15(\text{syst}) \pm 6(\text{lumi})$ pb	$164.6^{+11.4}_{-15.7}$ pb	up to 0.7
		CMS: $158 \pm 10(\text{uncor.}) \pm 15(\text{cor.}) \pm 6(\text{lumi})$ pb		0.036
σ_{tbq} (for $M_t = 172.5$ GeV)	$p\bar{p} \to t\bar{t}$	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
	$pp \to t\bar{t}$	Atlas: 90^{+32}_{-22} pb	$64.6^{+3.3}_{-2.6}$ pb	0.7
		CMS: $83.6 \pm 29.8(\text{stat}+\text{syst}) \pm 3.3(\text{lumi})$ pb		0.035
σ_{tb} (for $M_t = 172.5$ GeV)	$p\bar{p} \to t\bar{t}$	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
σ_{Wt} (for $M_t = 172.5$ GeV)	$pp \to t\bar{t}$	Atlas: < 39.1 pb	15.7 ± 1.4 pb	0.7
$\lvert V_{tb}\rvert$		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
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	$p\bar{p} \to t\bar{t}$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
M_t		Tev: 173.2 ± 0.9 GeV	-	up to 5.8
		Atlas: 169.3 ± 6.3 GeV	-	0.035
		CMS: 173.4 ± 3.3 GeV	-	0.036
$M_t - M_{\bar{t}}$		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
		Atlas: $f_0 = 0.59 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$	0.7	0.035
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
spin correlation	C_{beam}	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
		D0: $0.57 \pm 0.31(\text{stat}+\text{sys})$		5.4
Charge asymmetry	$p\bar{p} \to t\bar{t}$	CDF: 0.158 ± 0.074	0.06	5.3
		D0: 0.196 ± 0.065		5.4
	$pp \to t\bar{t}$	Atlas: $A_C^y = -0.024 \pm 0.016(\text{stat}) \pm 0.023(\text{syst})$	0.006	0.7
		CMS: $A_C^\eta = -0.016 \pm 0.030(\text{stat})^{+0.010}_{-0.019}(\text{syst})$	0.013	1.1

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Backup

The Detectors