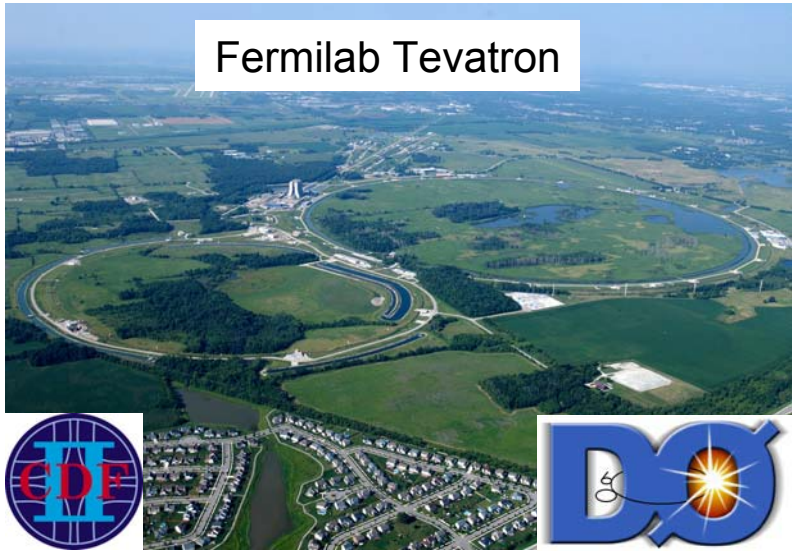
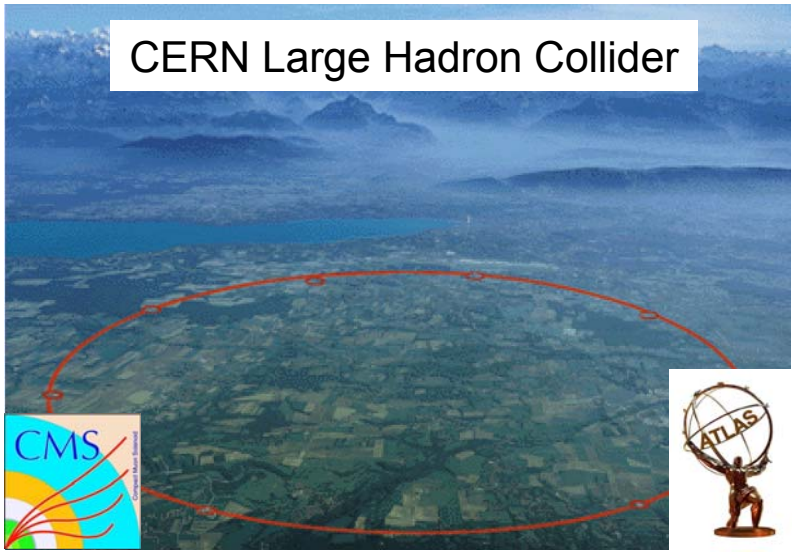
NEW RESULTS FROM THE TOP QUARK

Thomas Muller, Institut für Experimentelle Kernphysik, KIT



Tevatron:

- Run 1: $\sqrt{s}$ = 1.8 TeV (1992-1996)
  Top quark discovery in 1995 with 65pb^{-1} (around 20 events each experiment)
- Run 2: $\sqrt{s}$ = 1.96 TeV (2001-2011)
  12 fb^{-1} delivered, on tape 10 fb^{-1}
  8.7 fb^{-1} being analysed so far

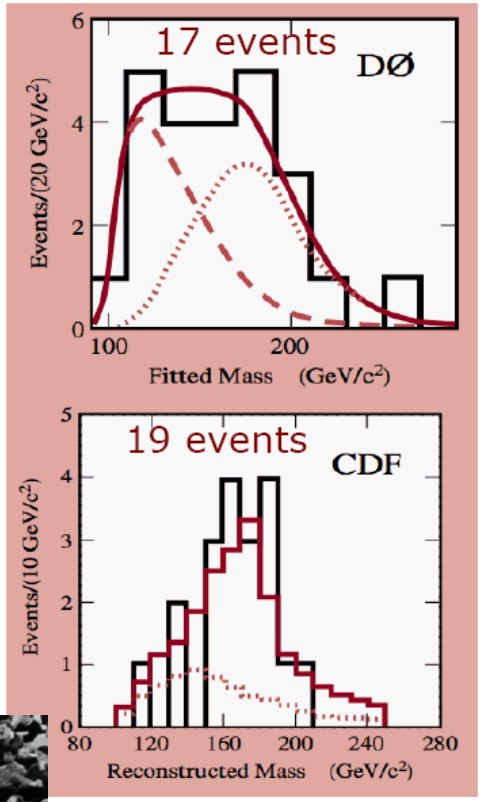


LHC:

- $\sqrt{s}$ = 7 TeV (2010-2011)
  5.7 fb^{-1} delivered, on tape 5 fb^{-1}
  Around 1M $t\bar{t}$ pairs produced per exp.
- Results in ~60k reconstructed $t\bar{t}$ events in e/μ+jets or in dilepton final state

- $\sqrt{s}$ = 8 TeV (2012 ongoing)
  More than 1M $t\bar{t}$ pairs produced
  2.8 fb^{-1} being analysed so far

- February 24th 1995: Simultaneous submission of Top Discovery papers to PRL, by CDF and DØ
- 50 pb^{-1} at DØ
  - m_t = 199±30 GeV
  - $\sigma_{t\bar{t}}$ = 6.4±2.2 pb
  - Background-only hypothesis rejected at 4.6σ
- 67 pb^{-1} at CDF
  - m_t = 176±13 GeV
  - $\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ pb
  - Background-only hypothesis rejected at 4.8σ

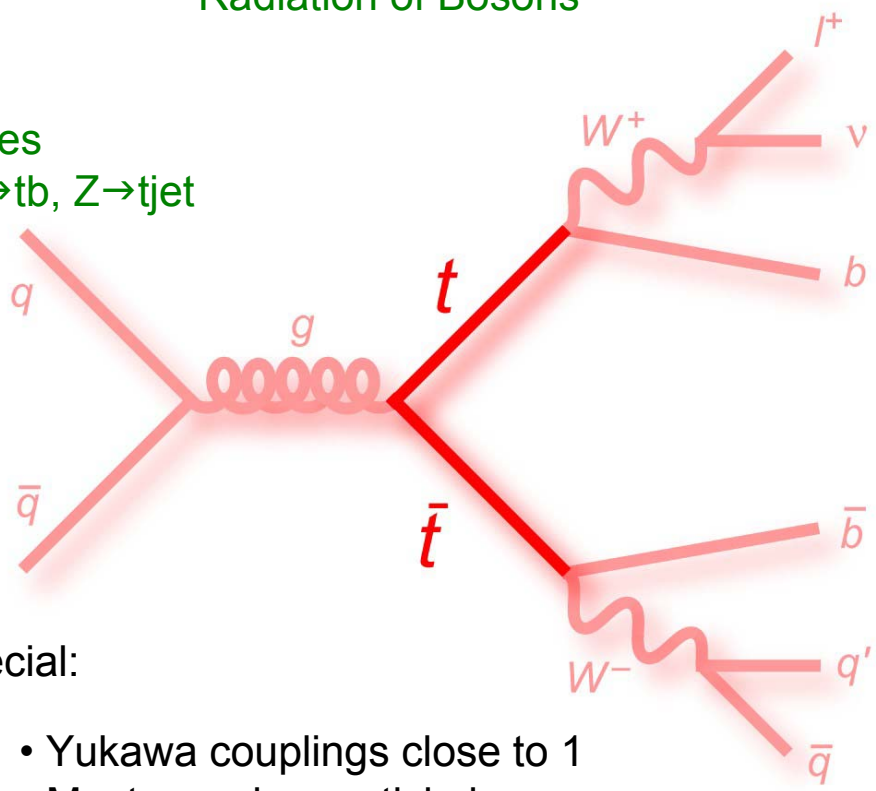


All Around the Top

THE PARTICLE
- Mass (matter vs. anti-matter)
- Life-time / width
- Charge
- Radiation of Bosons

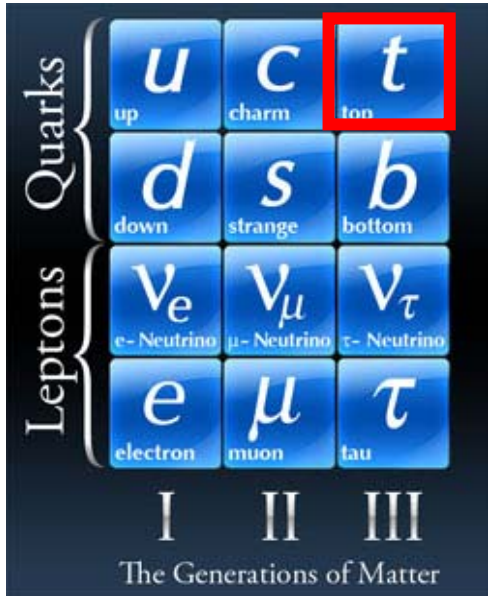
TOP PRODUCTION
- Cross sections
- Top polarisation
- Spin-correlations
- Production asymmetries
- Resonances X→tt, Y→tb, Z→tjet
- Fourth generation t'

TOP DECAY
- Charged Higgs
- W helicity
- Anomalous couplings
- CKM matrix elements



The top quark is very special:

- Yukawa couplings close to 1
- Most massive particle known
- The only „free“ quark
- Appears as signal, background and maybe decay product of new states



Top Quark Cross Sections (Th.)

Cross sections (pb) [m_{top} = 173 GeV]	s-channel	t-channel	tW channel	top pair
Tevatron: ppbar@1.96TeV	$1.046^{+0.002}_{-0.01}{}^{+0.06}_{-0.056}$	$2.08^{+0.00}_{-0.04} \pm 0.12$	0.22 ± 0.08	$7.08^{+0.00}_{-0.24}{}^{+0.36}_{-0.27}$
LHC: pp @ 7 TeV	$4.56 \pm 0.07^{+0.18}_{-0.17}$	$65.9^{+2.1}_{-0.7}{}^{+1.5}_{-1.7}$	$15.6 \pm 0.4^{+1.0}_{-1.2}$	$163^{+7}_{-5} \pm 9$
LHC: pp @ 8 TeV	$5.55 \pm 0.08 \pm 0.21$	$87.2^{+2.8}_{-1.0}{}^{+2.0}_{-2.2}$	$22.2 \pm 0.6 \pm 1.4$	$234^{+10}_{-7} \pm 12$

N. Kidonakis
arxiv.org/pdf/1205.3453v1 (2012)

Top Contributions at ICHEP

TR4 - Top Quark Physics - Roo 216 (09:00-18:00)

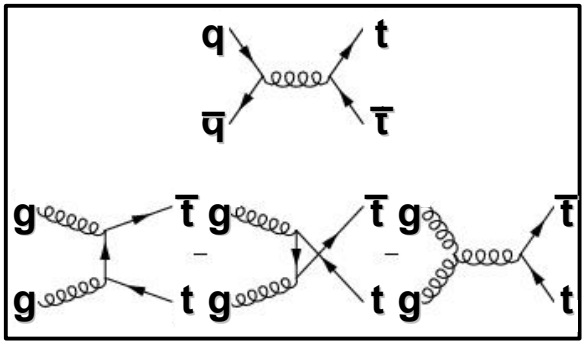
time	[id] title	presenter
09:00	[185] Inclusive top quark pair production cross - section (ATLAS)	Mr. DERUE, Frederic
09:15	[582] Top quark pair production cross section at CMS	Dr. RODRIGUEZ MARRERO, Ana
09:30	[186] Differential top quark pair production (ATLAS)	Dr. CHILDERS, Taylor
09:45	[586] Differential cross sections in top pair events at CMS	Dr. ALDAYA MARTIN, Maria
10:00	[689] Cross section measurements of top quark production at CDF	Mr. CORBO, Matteo
10:15	[83] NRQCD matching coefficient at next-to-next-to-next-to-leading order	Dr. MARQUARD, Peter
10:30	Refreshment Break	
11:00	[534] Measurements of the inclusive cross section and of differential distributions in top quark pair production (D0)	Prof. SCHWANENBERGER, Christian
11:15	[187] Measurements of single top quark production (ATLAS)	Mr. STURM, Philipp
11:30	[594] Single top production in CMS	Dr. BENELLI, Gabriele
11:45	[538] Measurements of single top quark production cross sections and |Vtb| in ppbar collisions at sqrt(s)=1.96 TeV (D0 and CDF)	Dr. PETERS, Yvonne
12:00	[189] Measurement of the top quark mass (ATLAS)	Dr. SALAMANNA, Giuseppe
12:15	[588] Measurements of the top quark mass (CMS)	Dr. STADIE, Hartmut
12:30	[590] Measurement of the top-antitop mass difference (CMS)	Mr. VAN ONSEM, Gerrit
12:45	Lunch Break	
14:00	[693] Top quark mass measurements at CDF	Dr. LEE, Hyun Su
14:15	[543] Measurement of the top quark mass in ppbar collisions using events with two leptons (D0)	Dr. BRANDT, Oleg
14:30	[536] Tevatron and LHC top mass combinations	Dr. DELIOT, Frederic
14:45	[424] Top Precision Studies at Linear Colliders	Dr. VOS, Marcel
15:00	[852] Spin correlation and W helicity in top quark events with ATLAS	Dr. JÜNGST, Markus
15:15	[592] Spin correlations and W helicity in top events with CMS	Dr. SUMOWIDAGDO, Suharyo
15:30	Refreshment Break	
16:00	[541] Spin correlation in ttbar production (D0)	Dr. PETERS, Yvonne
16:15	[533] Measurement of top quark properties - electric charge and width (D0)	Prof. SCHWANENBERGER, Christian
16:30	[545] Combination of CDF and D0 measurements of the W boson helicity in top quark decays	VARNES, Assoc. Prof. Erich Ward
16:45	[190] Other top quark properties in ATLAS	Dr. LIMOSANI, Antonio
17:00	[601] Other top quark properties in CMS	Ms. KÜSSEL, Yvonne
17:15	[690] Top quark properties at CDF	Dr. OH, Youngdo
17:30	[60] TTbar Spin Correlations at Hadron Colliders	Dr. PARKE, Stephen
17:47	[867] .	

TR4 - Top Quark Physics and TR11 - Particle Astrophysics & Cosmology - Room 216 (09:00-18:00)

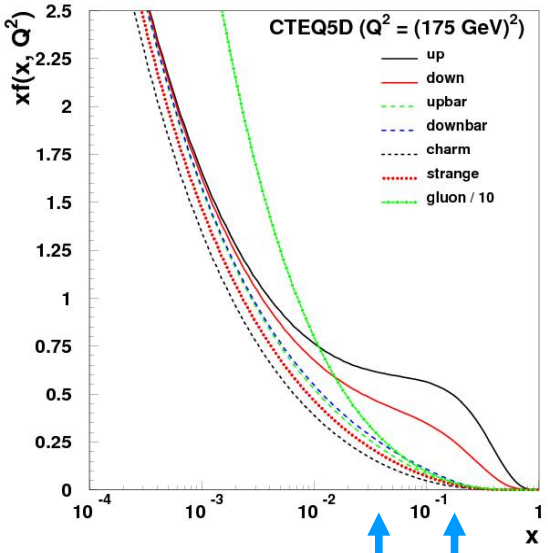
time	[id] title	presenter
09:00	[191] Charge asymmetry in top pairs at ATLAS	Dr. GIORDANI, Mario
09:15	[587] Measurement of the charge asymmetry in top quark pair production in pp collisions (CMS)	Dr. CHWALEK, Thorsten
09:30	[684] Asymmetry measurements in t-tbar at CDF	Dr. HAYS, Chris
09:45	[532] Measurement of the forward-backward charge asymmetry in top quark pair production (D0)	Dr. GROHSJEAN, Alexander Josef
10:00	[474] Top quark forward-backward asymmetry from gauged flavor symmetry	Prof. BABU, Kaladi S.
10:17	[318] Dynamical Origin of the Correlation between the Top Quark Production Asymmetries A_{FB}^t and A_{FB}^{ℓ}	Dr. BERGER, Edmond
10:34	Refreshment Break	
11:00	[513] Diagnosing top-quark Forward-Backward Asymmetry	Dr. GUPTA, Sudhir Kumar
11:15	[188] Searches in s-channel single top quark production at ATLAS	Dr. ALVAREZ GONZALEZ, Barbara
11:30	[853] FCNC in top quark production and decay at ATLAS	Dr. CRISTINZIANI, Markus
11:45	[599] Search for FCNC in top pair events in pp collisions (CMS)	Dr. CHAO, Yuan
12:00	[52] CP violation in top-quark physics	Prof. VALENCIA, German
12:15	[495] Search for a Narrow ttbar Resonance in ppbar Collisions at sqrt(s) = 1.96 TeV (Combined D0, CDF)	ASSOC. PROF. VARNES, Erich
12:32	Lunch Break	
14:00	[585] Measurement of the top pair invariant mass distribution and search for New Physics (CMS)	Prof. BLEKMAN, Freya
14:15	[192] Searches for ttbar resonances (ATLAS)	Dr. VOS, Marcel
14:30	[76] Z' signals in polarised top-antitop final states	Mr. MIMASU, Ken
14:45	[443] A charged Z' to explain the apparent disagreement in top-antitop asymmetires between Tevatron and LHC	Ms. COLUCCIO LESKOW, Estefania
15:00	[46] Top Decays with Flavor Changing Neutral Higgs Interactions at the LHC	Prof. KAO, Chung
15:15	[540] Search for anomalous Wtb couplings in ppbar collisions at sqrt(s) = 1.96 TeV (D0)	Prof. BLOOM, Kenneth

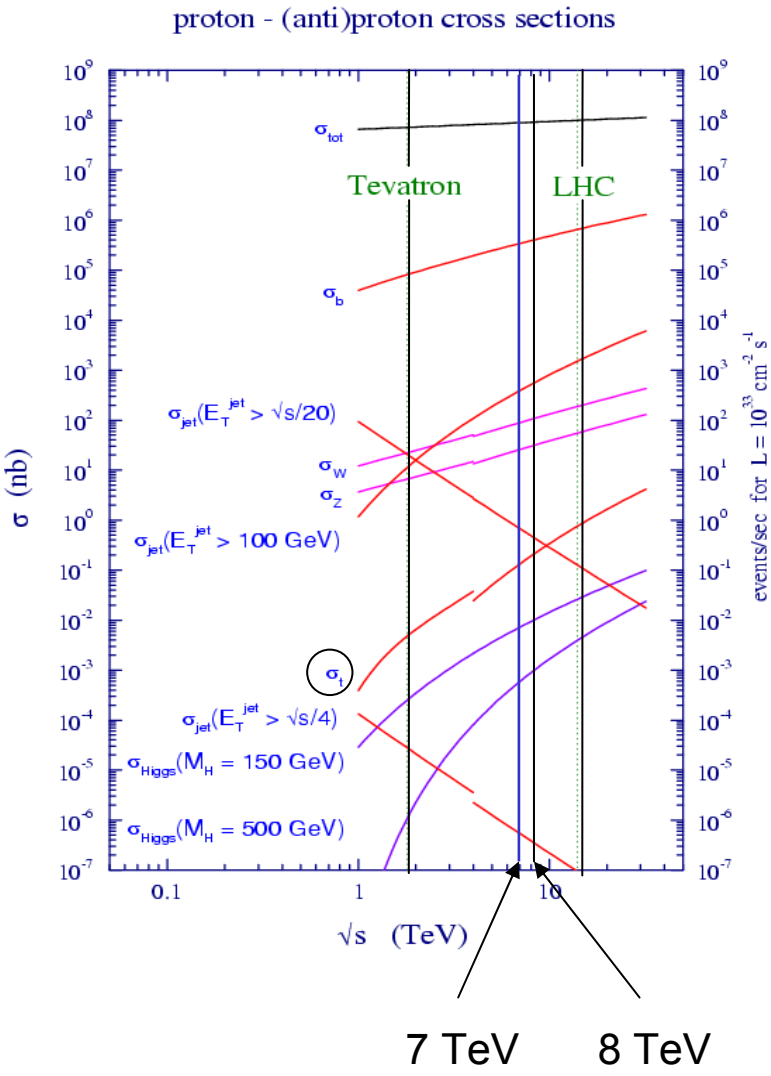
Apologies for not mentioning all results

1. PAIR PRODUCTION OF TOP QUARKS



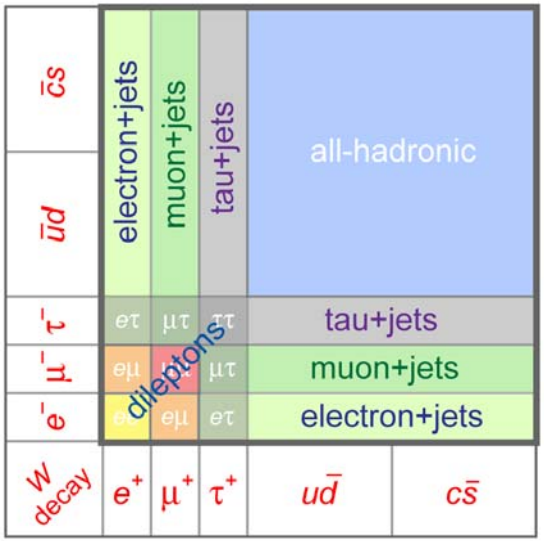
	TEV	LHC
←	~85%	~15%
←	~15%	~85%



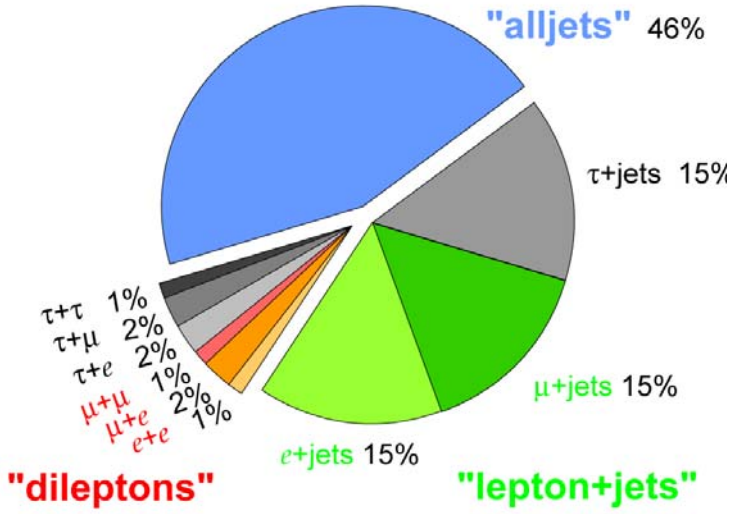


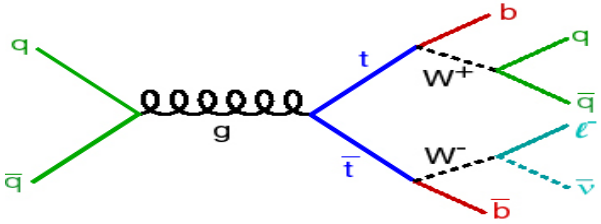
Decay Channals

Top Pair Decay Channels

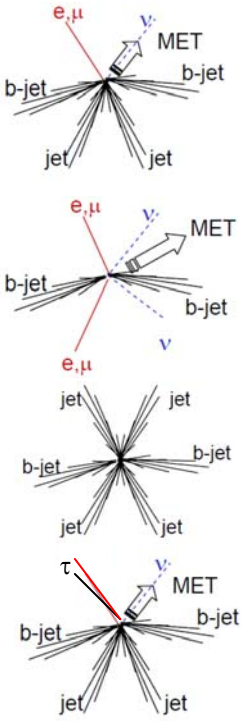


Top Pair Branching Fractions

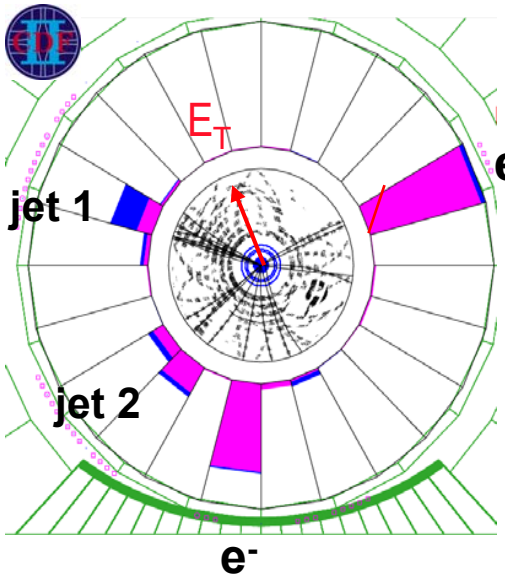




- **$t \rightarrow Wb$**
  Events classified by W decay
  - "Lepton [e,μ] + jets" (34%)
    $tt \rightarrow bl\nu bqq'$
  - "Dilepton [e,μ]" (6%)
    $tt \rightarrow bl\nu bl\nu$
  - "All jets" (46%)
    $tt \rightarrow bqq'bqq'$
  - "Tau + jets" (15%)
    $tt \rightarrow b\tau\nu bqq'$



1.1 Cross Section Measurements of $t\bar{t}$ Production



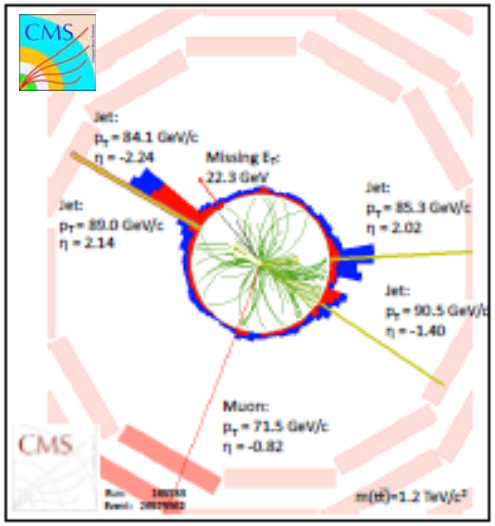
Finding the top:

Signal:

- Triggering on lepton
- High missing transverse energy ($\not{E}_T$)
- High E_T jets, central and spherical
- Two b-jets (displaced vertex)

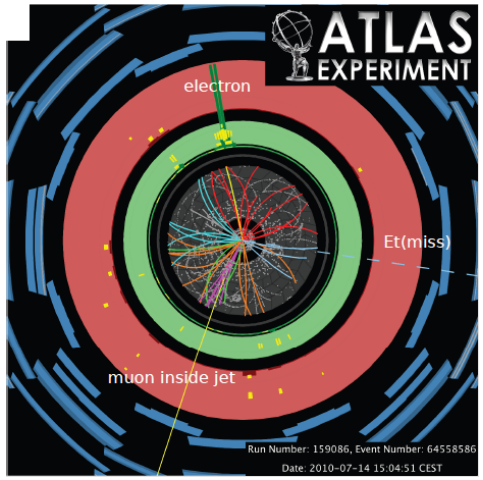
Background:

- Dilepton: Z+Jets, Single Top (tW), QCD, W+Jets
- Lepton+Jets: W+Jets, Single Top
- All Hadronic: QCD multi jet events



Determination of the cross section

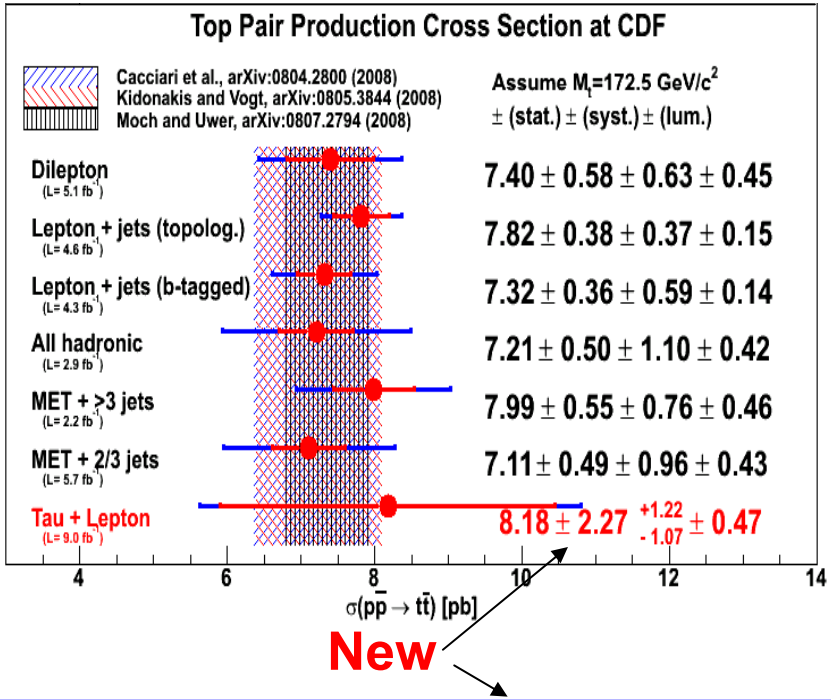
$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int Ldt}$$



Measurements at the Tevatron

CDF Run II

Conf. Note 10878



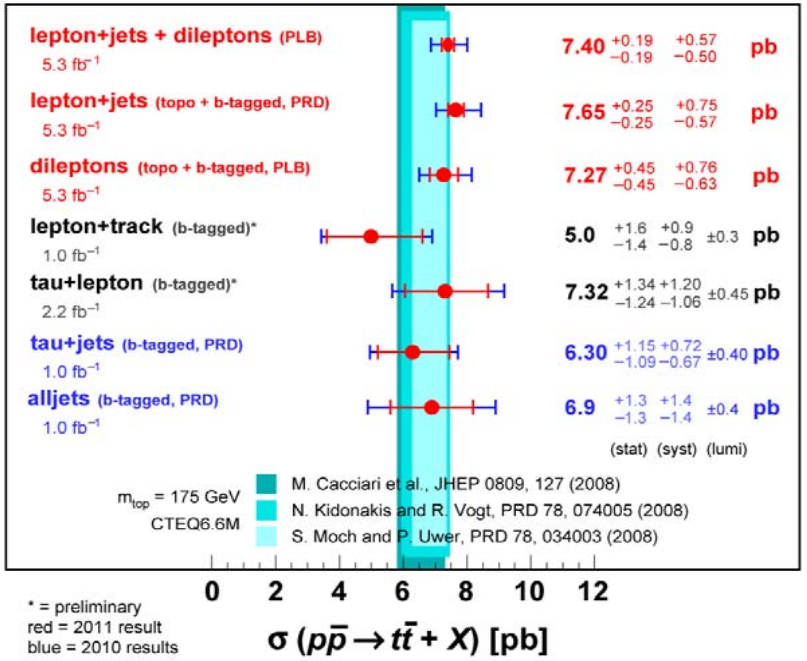
New

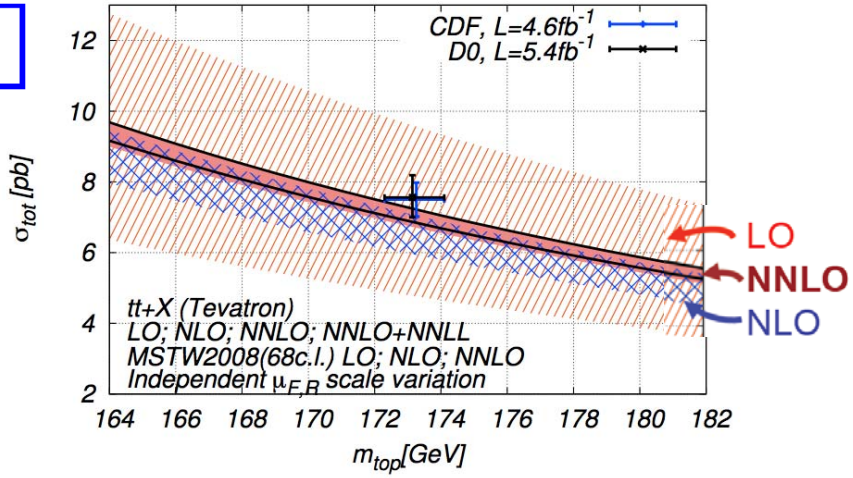
$$\sigma_{btag} = 7.47 \pm 0.50_{stat} \pm 0.53_{syst} \pm 0.46_{lumi}\ pb$$

- Consitency amongst various channels
- Limitation from systematic uncertainties (JES, b-tab, W+jets)
- Sensitive to NNLO predictions (Bernreuter, Czakon, Mitov, arXiv:1204.5201)

D0 Run II

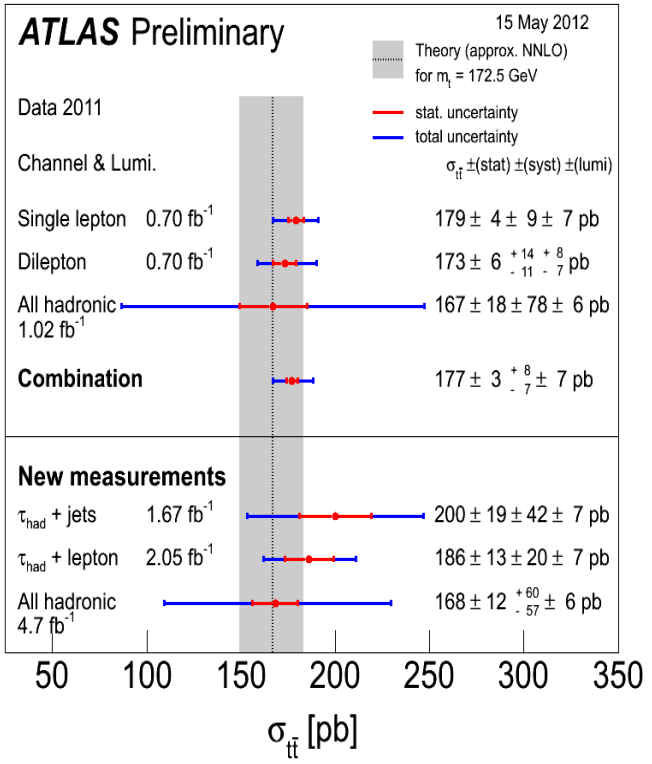
arXiv:1105.5834

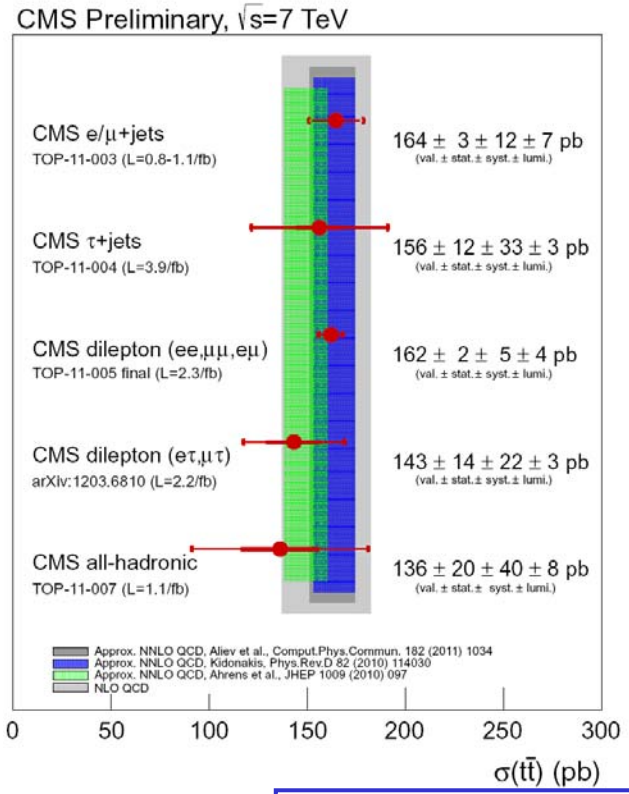




ATLAS (ATLAS-CONF-2012-024)

- Combination done as product of the individual likelihoods of each channel
- $\sigma = 177 \pm 3\,(\text{stat}) \pm 7\,(\text{syst.}) \pm 7\,(\text{lum.})\ \text{pb}$





CMS (CMS-PAS-TOP-11-024)

- Combination done using a binned maximum likelihood fit
- $\sigma = 165.8 \pm 2.2(\text{stat}) \pm 10.6(\text{syst.}) \pm 7.8(\text{lum.})\text{pb}$

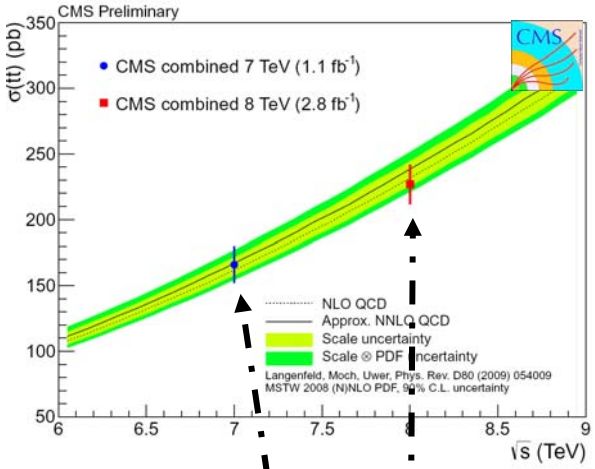
Results are compatible with NNLO calculations

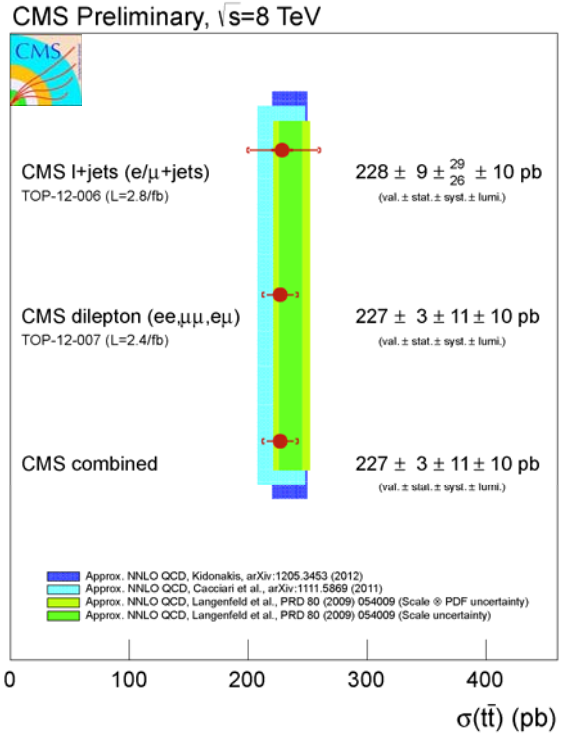
Top-Antitop Production Cross Sections

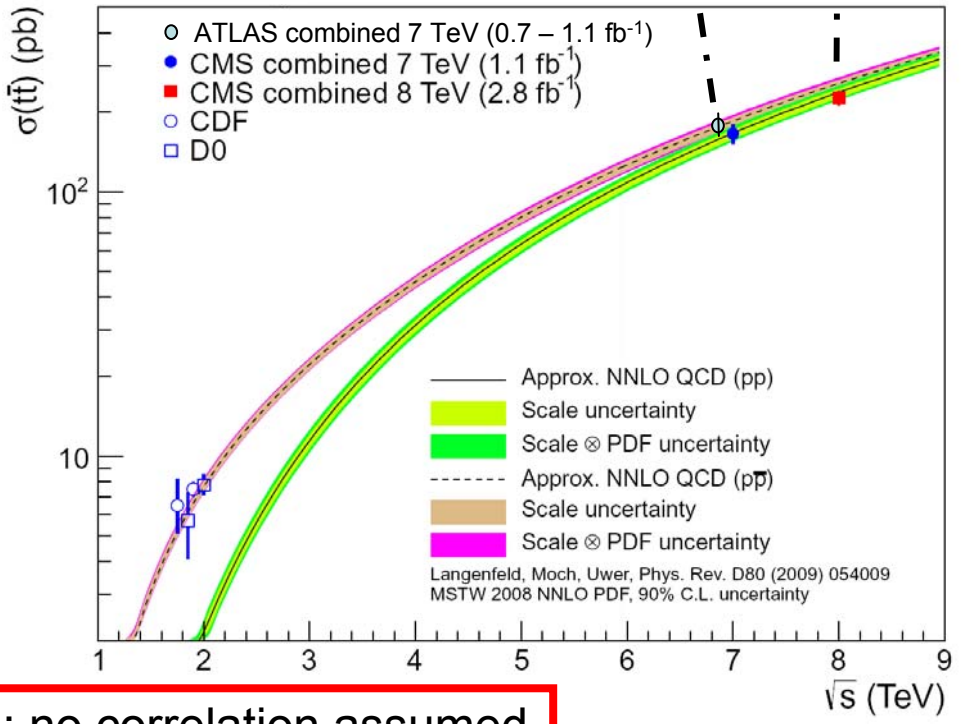
CMS (CMS-PAS-TOP-12-006/7)

- **New measurement at 8 TeV !**
- Lepton + jets and di-lepton channals combined:

$$\sigma = 227 \pm 3\ (\text{stat}) \pm 11\ (\text{syst.}) \pm 10\ (\text{lum.})\ \text{pb}$$





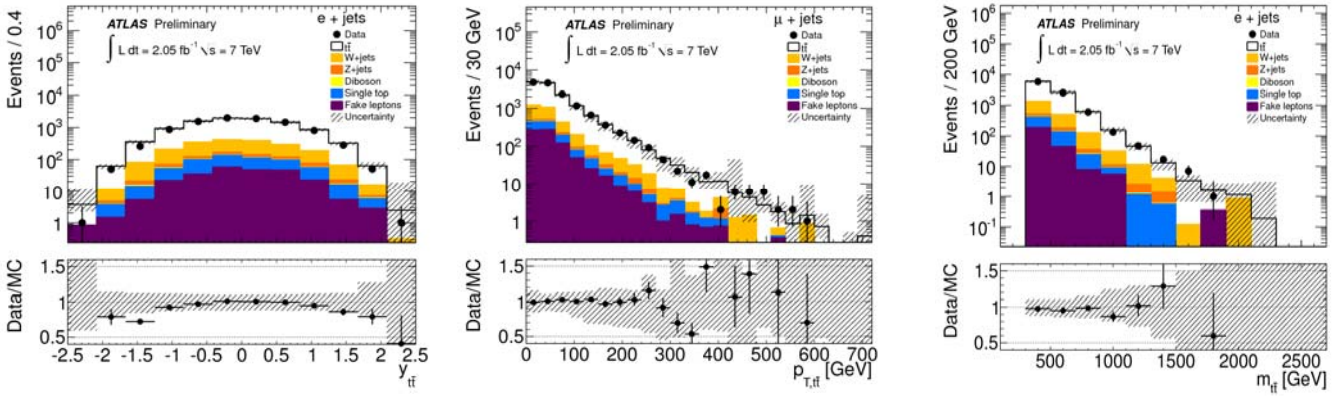


CMS $\sigma(8\text{TeV})/\sigma(7\text{TeV}) = 1.41 \pm 0.11$; no correlation assumed

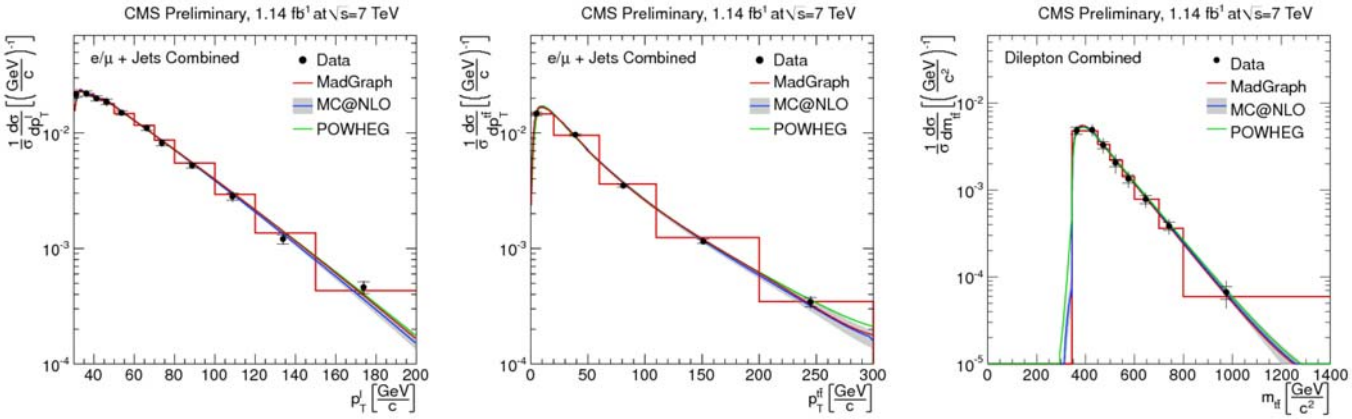
Top-Antitop Differential Cross Sections

- Measure differential cross sections in the lepton+jet channel
- Important test of QCD
- Event selections similar to the cross section analyses
- Bin-to-bin unfolding to parton level at CMS

$$\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\sigma}\frac{N^i_{data} - N^i_{bkg}}{\epsilon \cdot \mathcal{L}}$$



ATLAS
Paper in Prep.



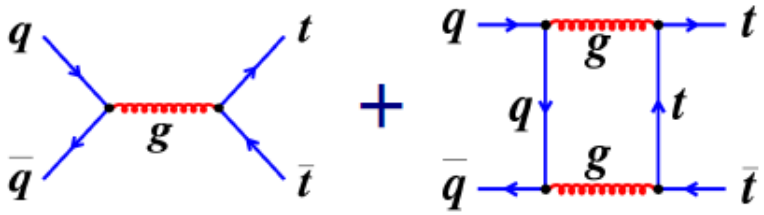
CMS
PAS-TOP-11-013

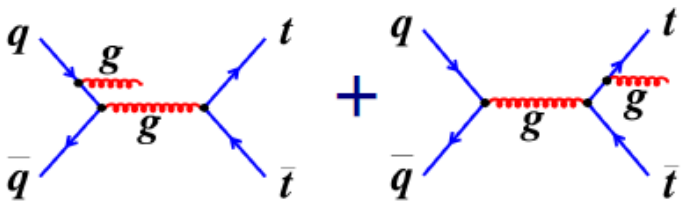
In conclusion, $t\bar{t}$ production is well described by SM calculations

1.2 Top-Antitop Charge Asymmetry

NLO QCD: interference of higher order diagrams leads to asymmetry for $t\bar{t}$ produced through $q\bar{q}$ annihilation:

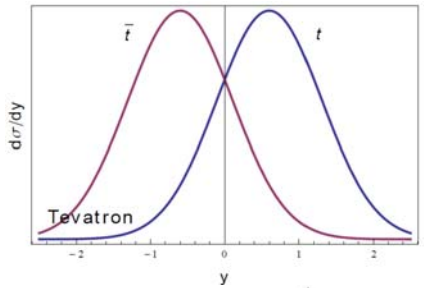
- Top quark is emitted preferentially in direction of the incoming quark
- Antitop quark opposite
- Production through new processes may lead to different asymmetries





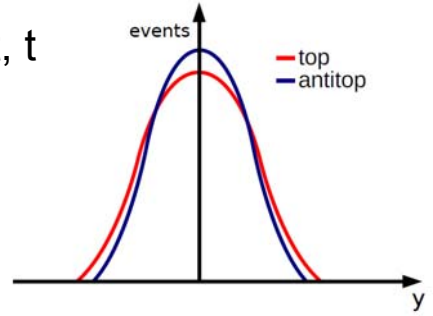
- At Tevatron: define forward-backward asymmetry

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

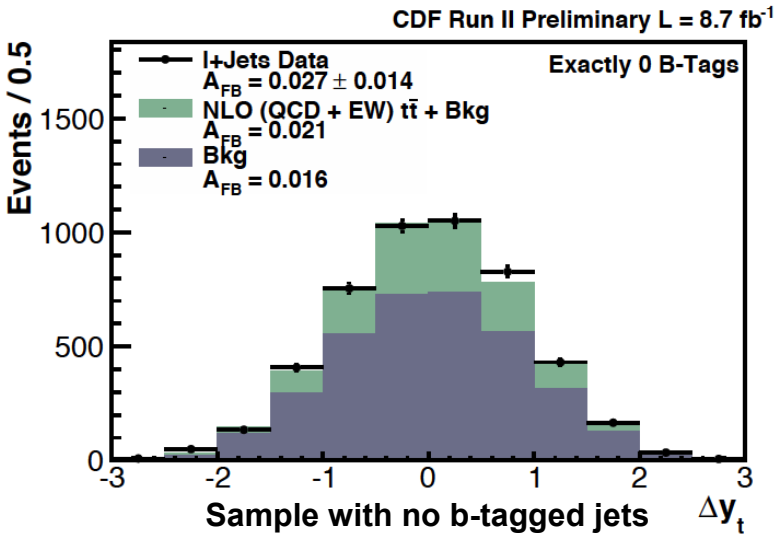


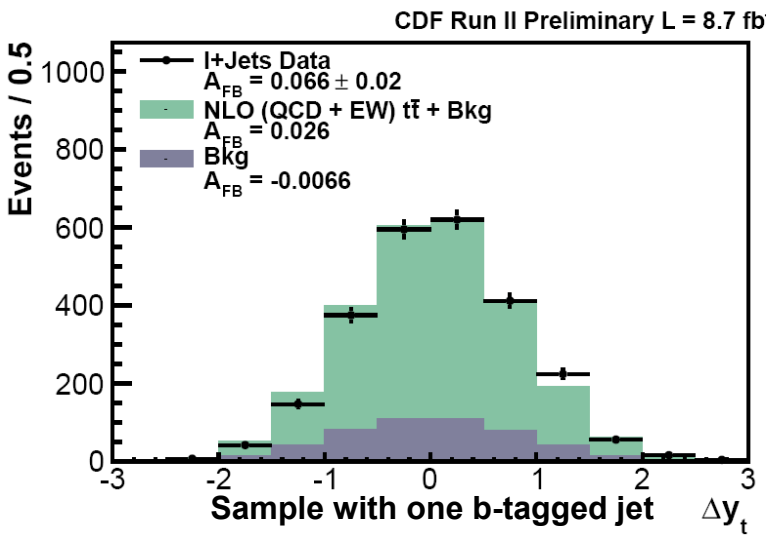
- At LHC: define asymmetry in the widths of rapidity distributions of t, t̄

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \qquad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

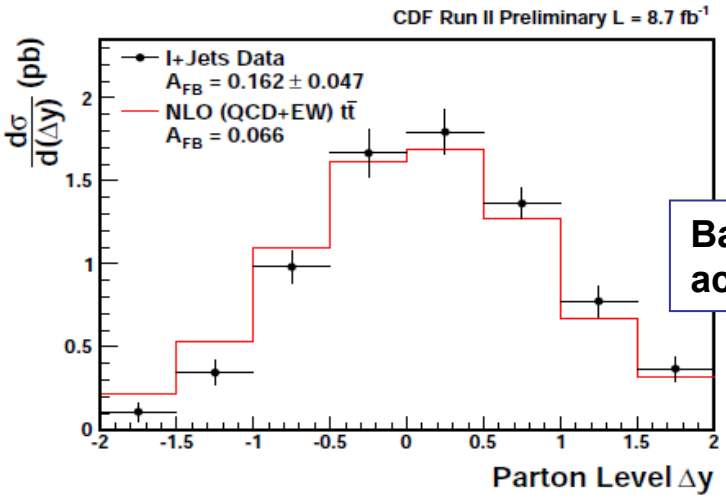


Asymmetries at the Tevatron

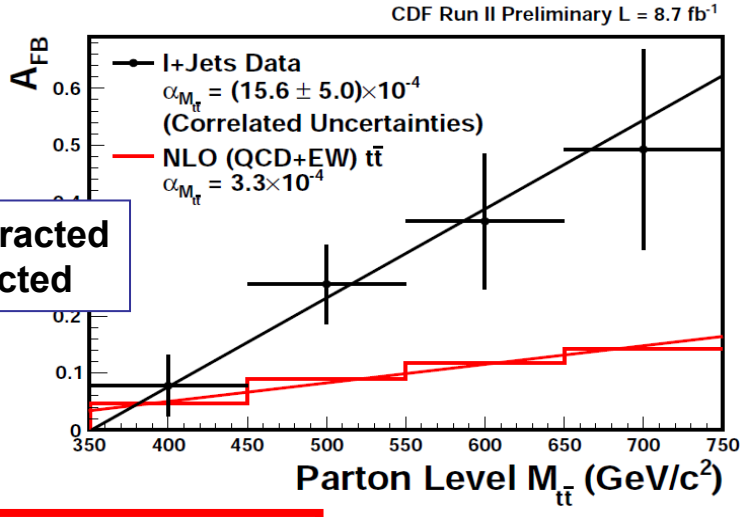




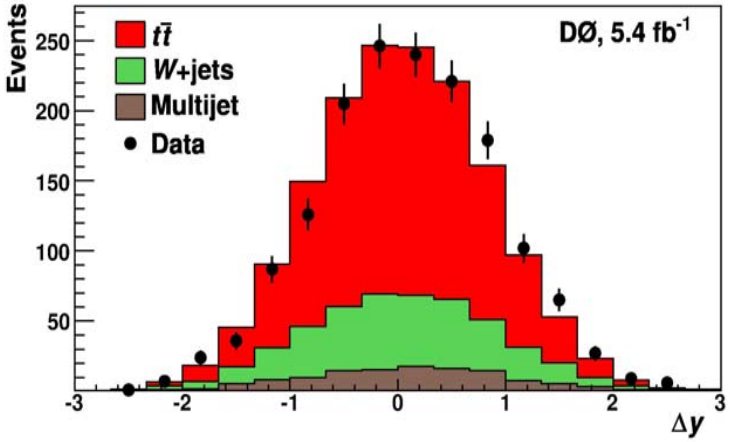
CDF-Note 10807



Background-subtracted acceptance corrected



$A_{FB} = 0.162 \pm 0.041(stat) \pm 0.022\ (syst)$



Δy in the lepton-jets channel

Measured asymmetry on detector level after bkg subtraction:

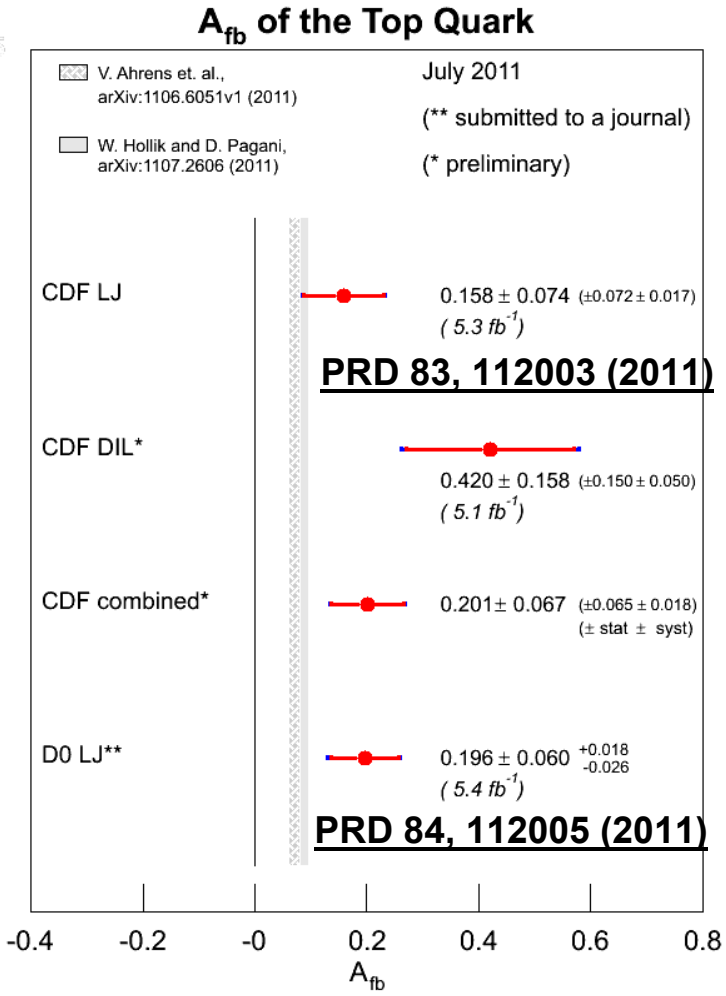
A_{FB} det = 0.092 ± 0.037 (stat+syst)

MC@NLO: A_{FB} det = 0.024 ± 0.007

Measured asymmetry on parton level:

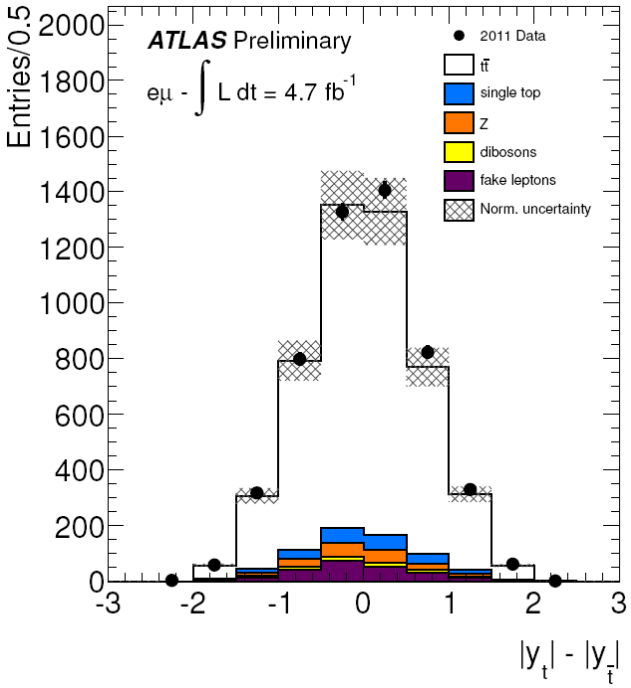
A_{FB} = 0.196 ± 0.065 (stat+syst)

Summary:

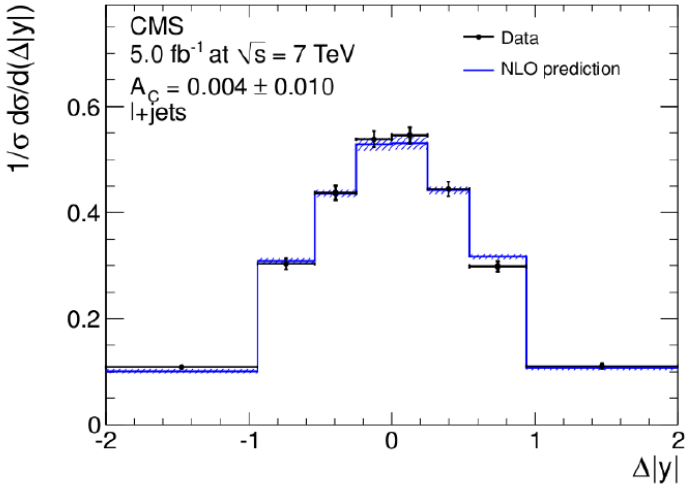


Both CDF and D0 see significant asymmetry in $t\bar{t}$ production in all channels with strong dependence on m_{tt}, in conflict with the SM

Asymmetries at the LHC



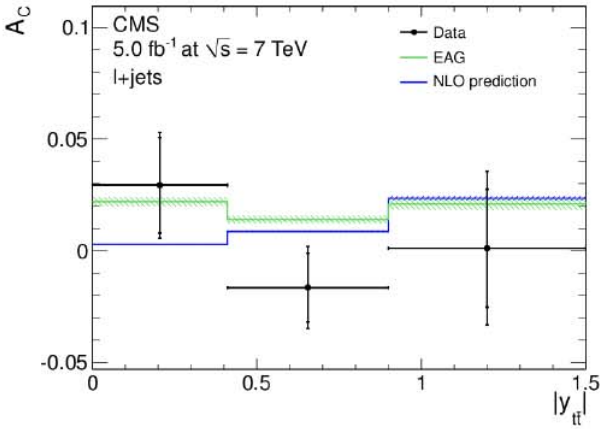
ATLAS-CONF-2012-057

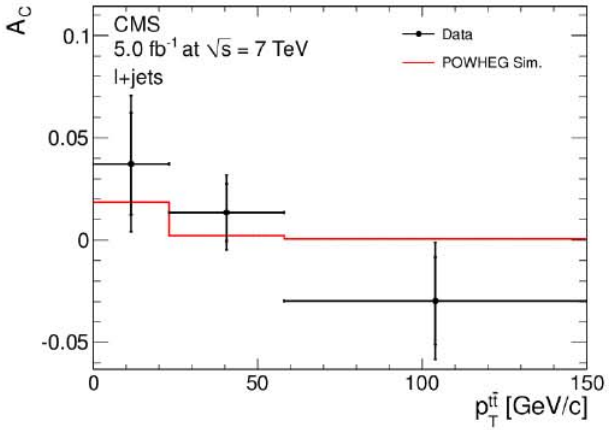


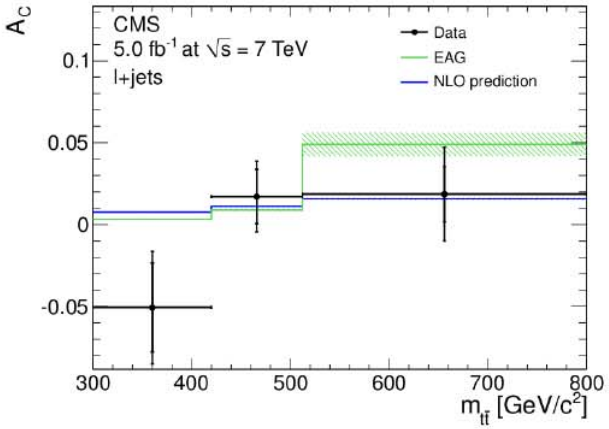
CMS PAPER TOP-11-030

- ATLAS: A_C = 0.029 +- 0.018 (stat.) +- 0.014 (syst.)
- CMS: Corrected: A_C = 0.004 +- 0.010 (stat.) +- 0.011 (syst.)
- Theory (Kühn, Rodrigo): A_C = 0.0115 +- 0.0006

Differential asymmetries at the LHC







Asymmetry measured in pT, y or invariant mass of the top pair system

Measured asymmetries are compared to

- SM prediction at NLO [1]
- SM simulation at NLO (POWHEG)
- BSM prediction with an effective axial-vector coupling of the gluon at the one-loop level (EAG) [2]; can explain the strong dependence of AFB on m(tt) as seen by CDF

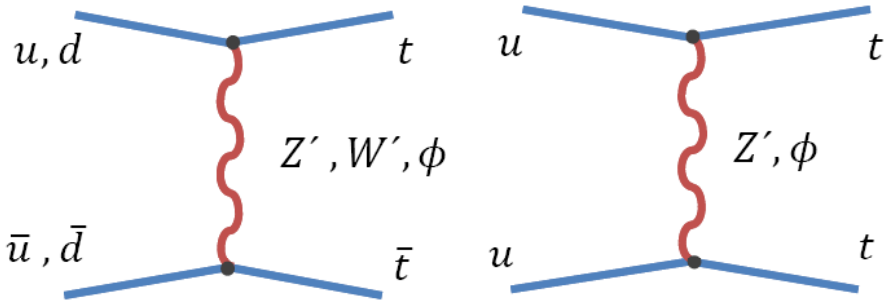
[1] Kühn, Rodrigo - arXiv:1109.6830 [2] Gabrielli, Racioppi, Raidal - PRD 85 (2012) 074021, arXiv:1112.5885; arXiv:1203.1488

At LHC data are compatible with SM and with BSM prediction. Tevatron results display much larger asymmetry than SM

An LHC run at low energies would be helpful (once we explored the energy frontier.

New physics in the t-channel

[Jung, Murayama, Pierce, Wells / Cheung, Keung,Yuan / Cao, Heng,Wu,Yang / Barger, Keung, Yu / Cao, McKeen, Rosner, Saughnessy, Wagner / Berger, Cao, Chen, Li, Zhang / Bhattacherjee, Biswal, Ghosh/ Zhou, Wang, Zhu / Aguilar-Saavedra, Perez-Victoria/ Buckley, Hooper, Kopp, Neil / Rajaraman, Surujon, Tait/ Duraisamy, Rashed, Datta, …]
[Shu,Tait,Wang / Cao,Heng,Wu,Yang / Dorsner, Faifer, Kamenik, Kosnik / Jung,Ko,Lee,Nam. Aguilar-Saavedra, Perez-Victoria / Patel, Sharma / Ligeti, Marques Tavares, Schmalz, …]



- Because of color algebra a Z' (SM Z) in the s-channel do not interfere with the LO QCD amplitude
- (coloured) scalars do not generate an asymmetry in the s-channel

- A sizeable charge asymmetry requires **large flavour violating couplings** [Jung,Murayama,Pierce,Wells]
- Relatively light Z´ and/or W´: O(200-700 GeV), or O(1TeV) colored scalars
- **like sign $tt + \bar{t}\bar{t}$**, very constrained at Tevatron, and the LHC

1.3 Top Quark Polarisation

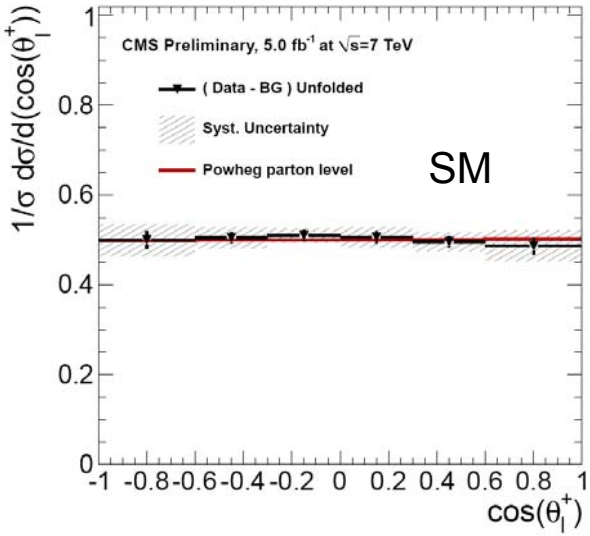
In BSM possibility of top polarisation, for instance through axi-gluon or W‘ couplings.

D. Krohn, T. Liu, J. Shelton et al., Phys.Rev. D84 (2011) 074034

Angular distribution of charged leptons sensitive to polarisation:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{i,n}} = \frac{1}{2}\left(1 + 2\mathcal{P}_n\kappa_i\cos\theta_{i,n}\right)$$

n direction of the top in the $t\bar{t}$ rest frame
κ_i = 1 for leptons



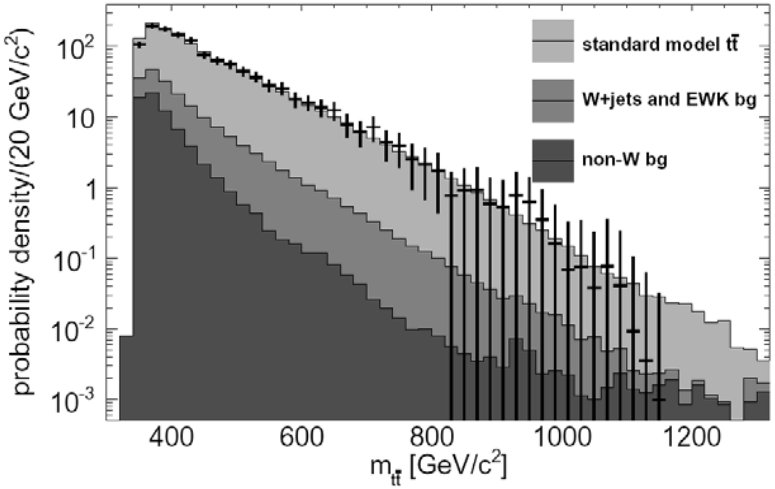
CMS PAS TOP-12-016

$$P_n = -0.009 \pm 0.029 \pm 0.041$$

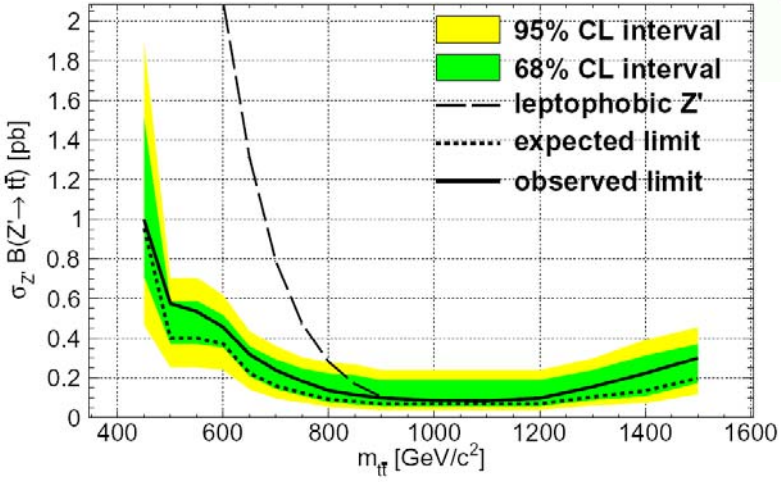
Consistent with Standard Model

1.4 Search for $t\bar{t}$ Resonances

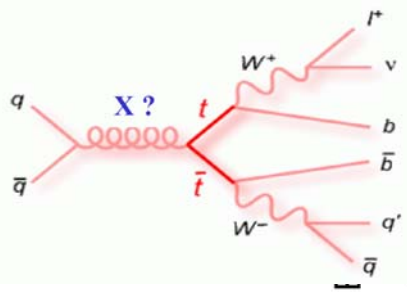
CDF: lepton+jets selection, no b-tagging requirements



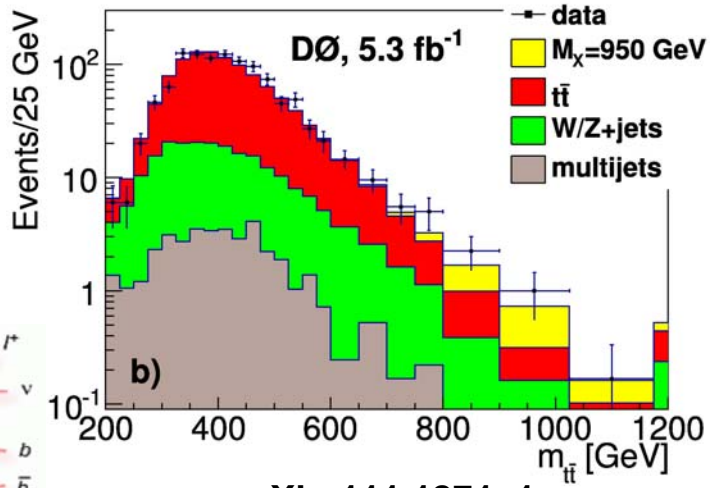
Phys. Rev. D 84, 072004 (2011)



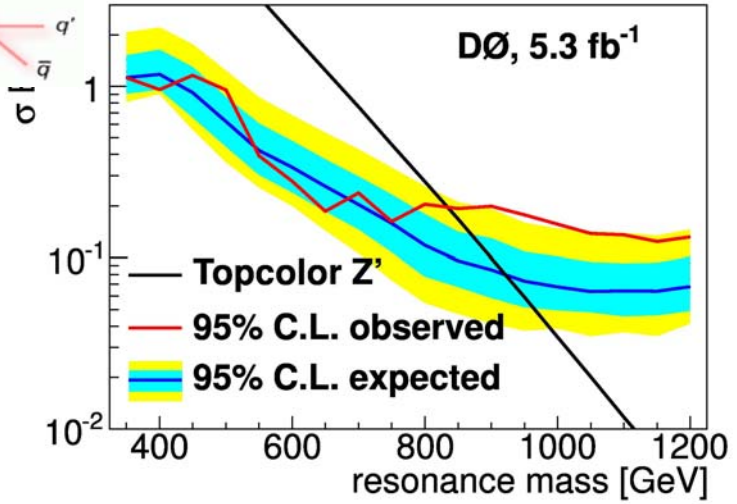
M_X>900 GeV @95% C.L.



DØ: lepton+jets selection, at least one b-tagged jet



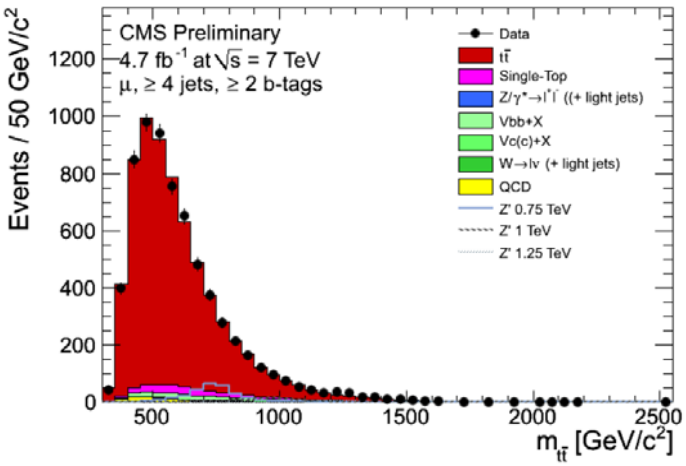
arXiv:111.1271v1



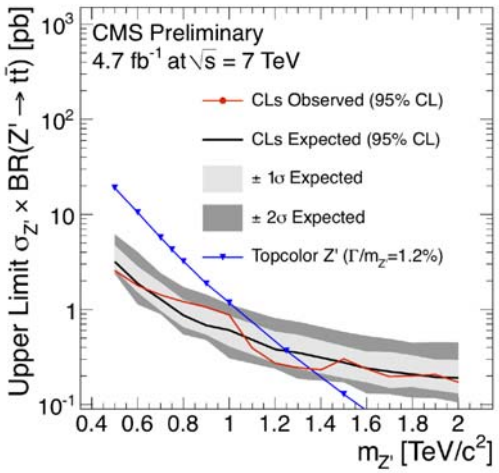
M_X>835 GeV @95% C.L.

Searches at the LHC

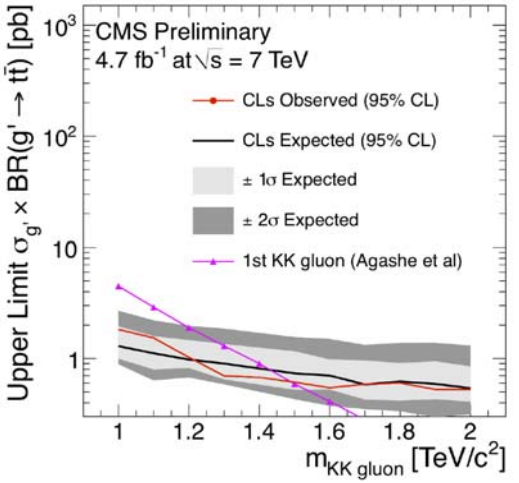
CMS TOP-11-009/010, EXO-11-006/093



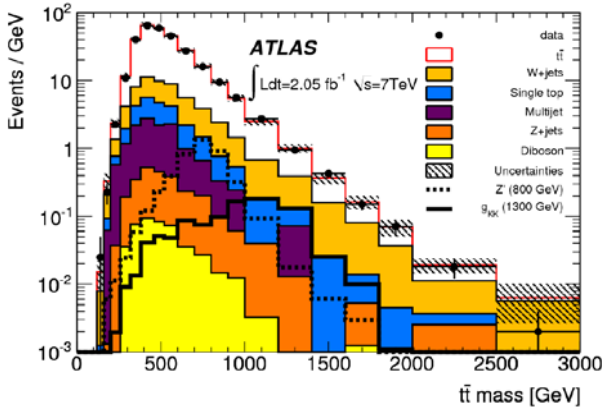
Topcolor Z'

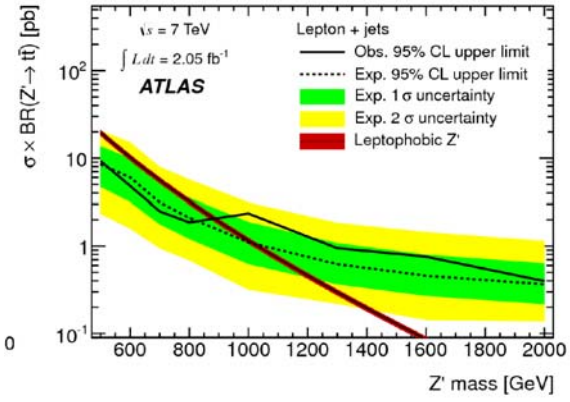


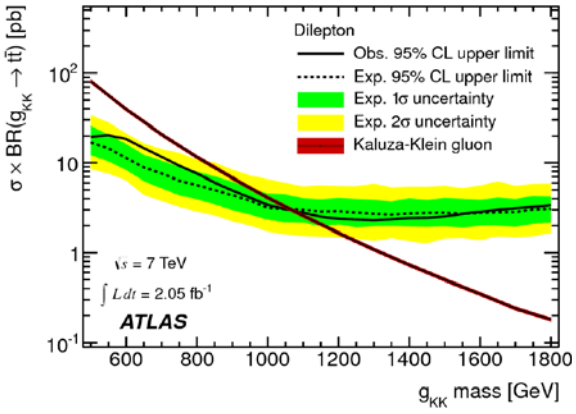
Extra-dimensions



arXiv:1205.5371







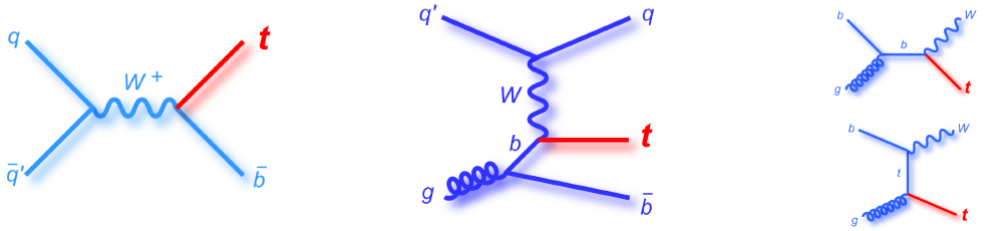
So far data compatible with SM up to 1…1.6 TeV

2. SINGLE TOP PRODUCTION

Observation of single top production:

- cross section $\propto V_{tb}^2$
- study top-polarization and EWK top interaction

s-channel **t-channel** **Wt-channel**



Test of non-SM phenomena:

- 4th generation
- FCNC couplings
- W' , $H^{\pm}$
- anomalous W_{tb} couplings

Main backgrounds:

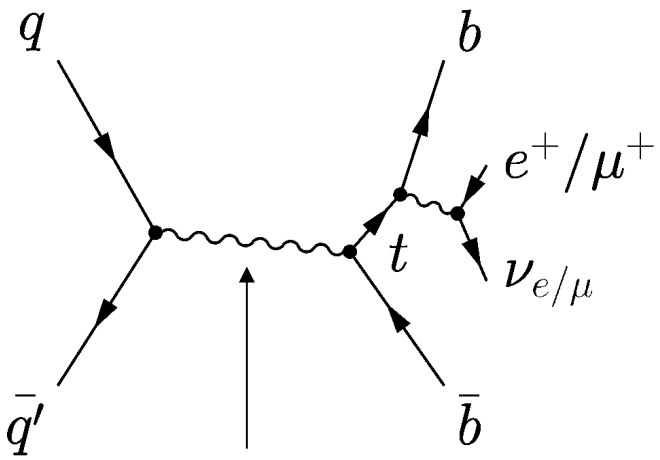
- s-channel: Top pair, W + (HF) jets, QCD
- t-channel: Top pair, W + (HF) jets, QCD
- Wt-channel: Top pair, Z + (HF) jets, QCD

Signal – background discrimination:

- Tevatron: multivariate methods (neural networks, boosted decision trees, matrix element method)
- LHC: cut-based or multivariate method

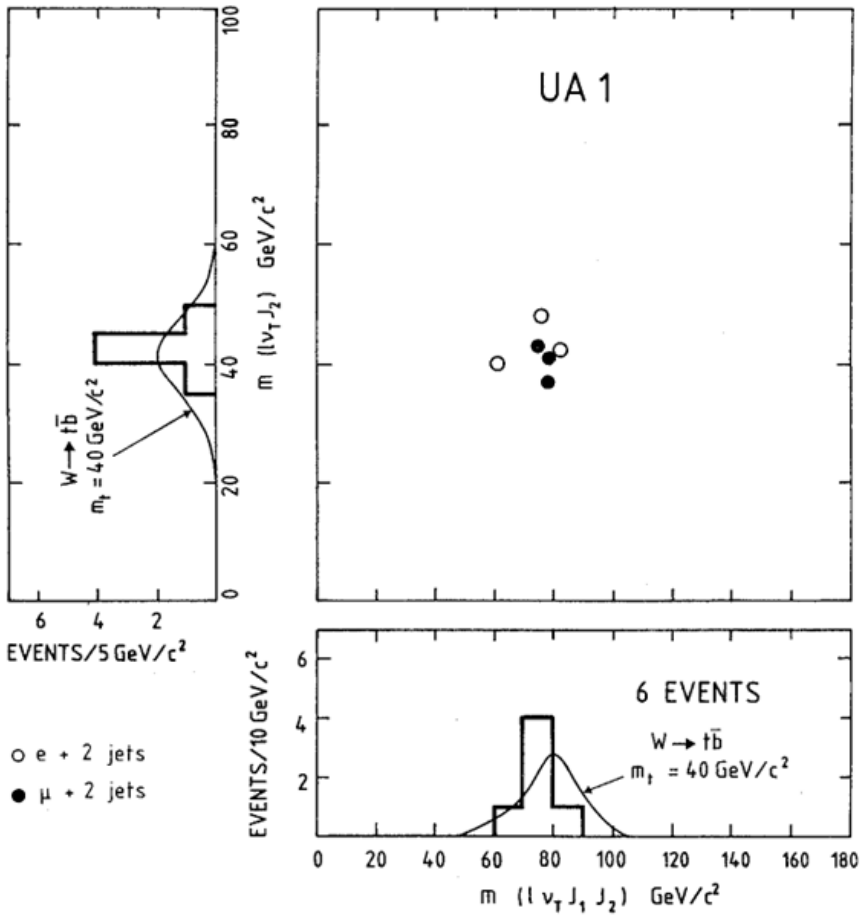
Collider	s-channel: σ_{tb}	t-channel: σ_{tqb}	Wt-channel: σ_{tW}
Tevatron: $p\bar{p}$ (1.96 TeV)	1.05 pb	2.08 pb	0.22 pb
LHC: pp (7 TeV)	4.6 pb	66 pb	15.7 pb

First “Observation” of Single Top



on-shell W boson

… by UA1 at CERN Sp$\bar{p}$S

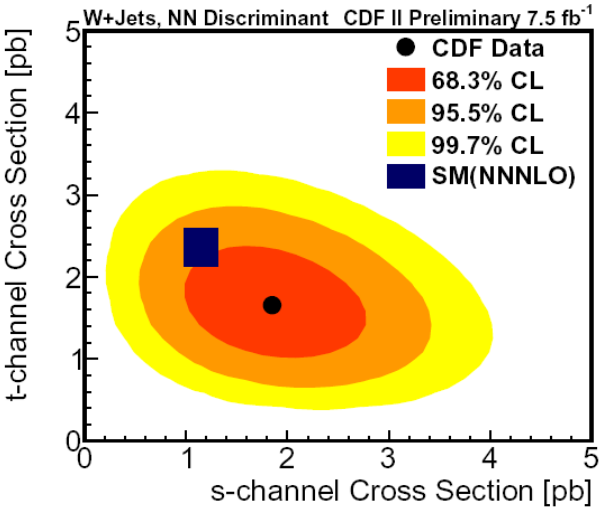


- excess in $M_{l\nu b}$ vs. $M_{l\nu bb}$ scatter plot
- compatible with $m_t = 40 \pm 10$ GeV
- later improved background estimate

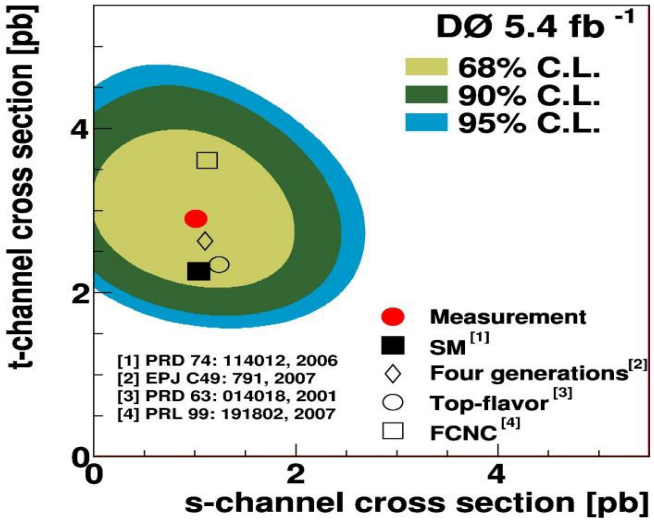
Phys. Lett. B 147, 493 (1984)

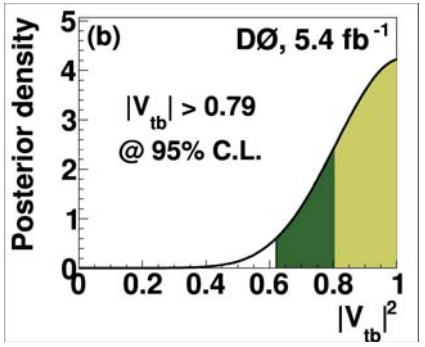
2.1 Single Top at the Tevatron

CDF Note 10878



PLB 705, 313 (2011)





$\sigma_s = 1.81^{+0.63}_{-0.58}$ pb
$\sigma_t = 1.49^{+0.47}_{-0.42}$ pb

$V_{tb} > 0.78$ @ 95% C.L.

$\sigma_s = 0.98 \pm 0.63$ pb
$\sigma_t = 2.90 \pm 0.59$ pb

$V_{tb} > 0.79$ @ 95% C.L.

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$

- No assumption about number of generations
- Assumption: $|V_{ts}|^2 + |V_{td}|^2 << |V_{tb}|^2$

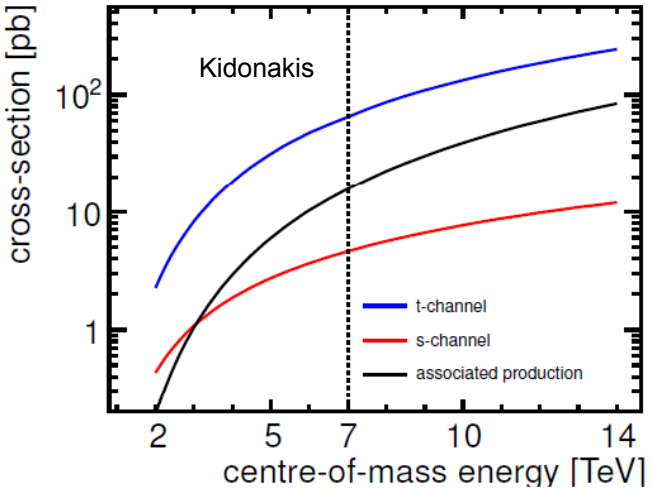
2.2 Single Top at the LHC

ATLAS: σ = 83 ± 4 (stat.) ± 20-19(syst.) pb

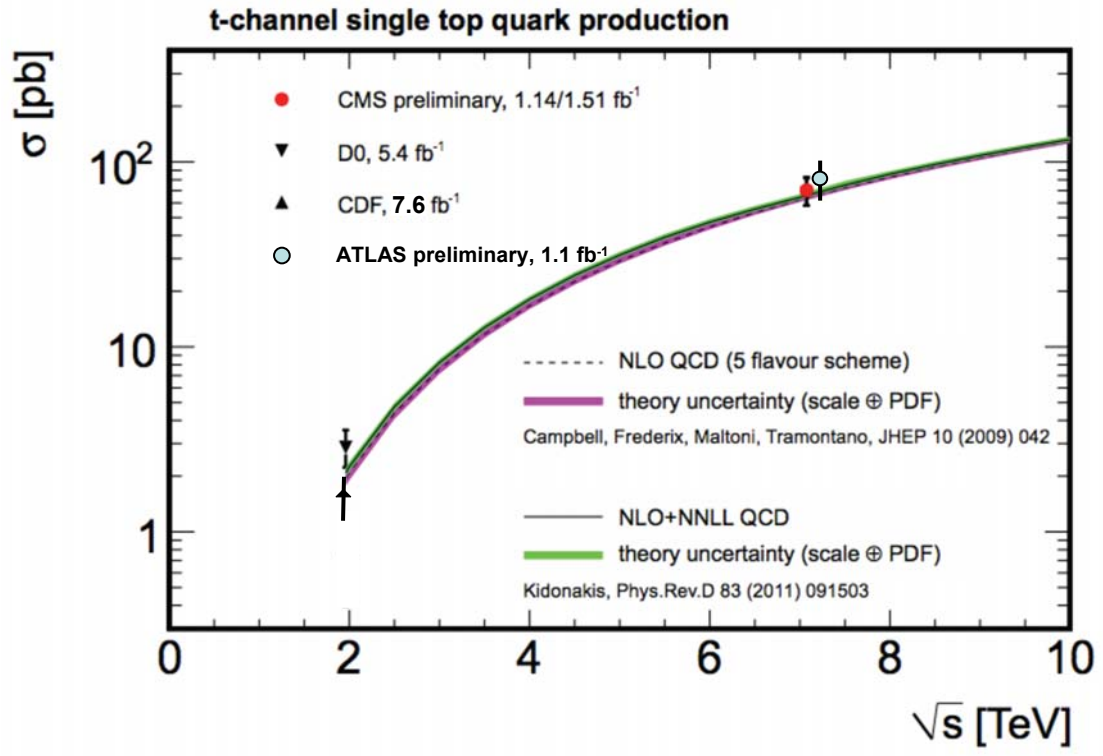
ATLAS-CONF-1205.3130

CMS: s = 70.2 ± 5.2 (stat.) ± 10.4(syst.) ± 3.4(lumi.) pb

CMS-PAS-TOP-11-021

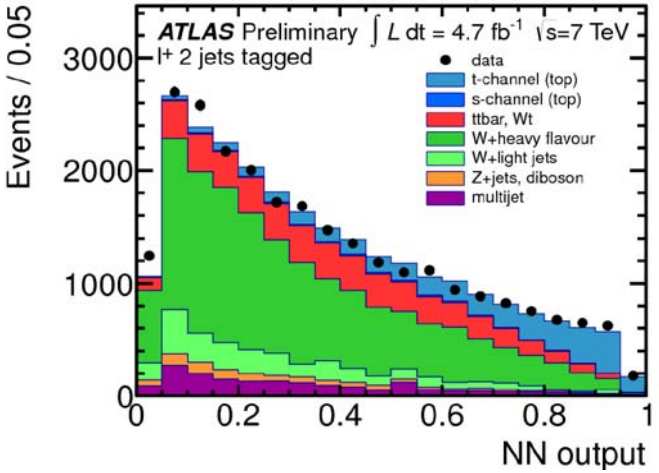


Summary



Ratio $R_t = \sigma_t/\sigma_{\bar{t}}$

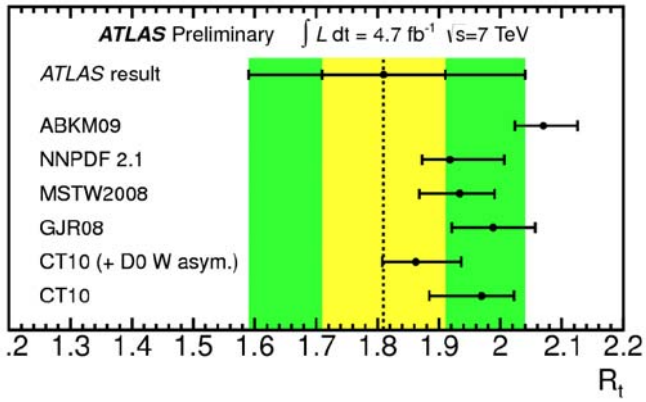
- R_t is sensitive to the u/d PDFs; naïve expectation $R_t = 2$
- Measurement of σ_t using binned max. likelihood fit to NN output in 2-jets and 3-jets data split according to charge of lepton



$\sigma_t = 53.2 \pm 10.8$ pb

$\sigma_{\bar{t}} = 29.5^{+7.4}_{-7.5}$ pb

$R_t = 1.81^{+0.23}_{-0.22}$



ATLAS-CONF-2012-056

Correlations between the individual cross section measurements are taken into account, leading to a reduction of the uncertainty

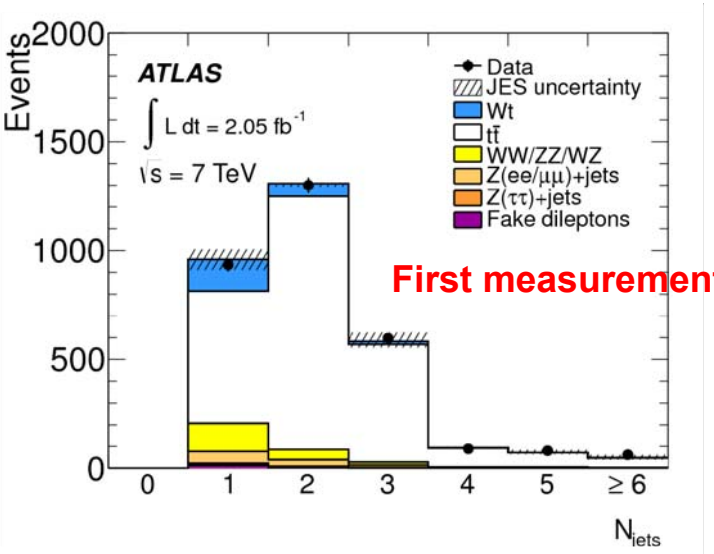
The measurement is in agreement with the predictions based on various global PDF sets that range from 1.86 to 2.07.

2.3 Single Top: tW-channel

Final state: 2 isolated leptons, 1 b-tagged jet and MET (as dilepton top pair but with 1 b jet less)

ATLAS (arXiv:1205.5764)

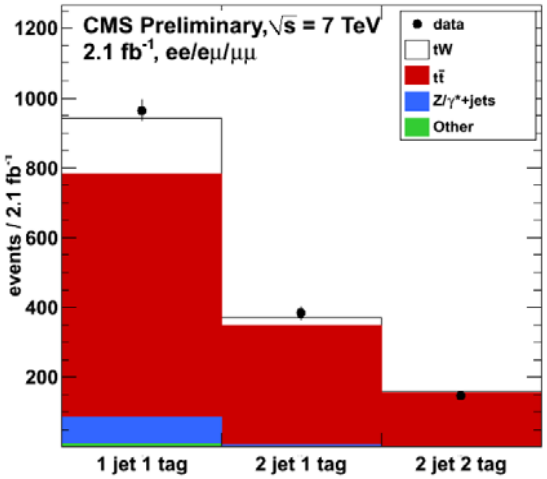
- Isolated lepton p_T> 25 GeV/c
- $\not{E}_T$ > 50 GeV
- No b tagging requirement
- MVA (BDT) based analysis



First measurement !

CMS (CMS-PAS-TOP-11-022)

- Isolated lepton p_T>20 GeV/c
- $\not{E}_T$>30GeV
- 2nd b-jet veto is applied for signal region
- Cut based analysis

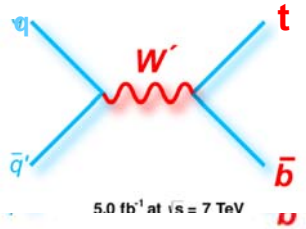


ATLAS: σ = 16.8 $\pm$ 2.9 (stat.) $\pm$ 4.9 (syst.) pb

CMS: $\sigma = 22\ ^{+9}_{-7}$ (stat. + syst.) pb

2.4 Search for tb Resonances

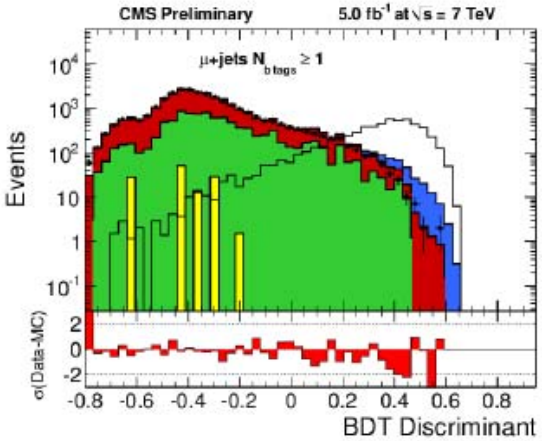
- Right-handed W'_R with SM-like couplings chosen as benchmark model
- Similar signature as single top s-channel (1 lepton, MET, 2 jets and at least 1 *b* tag)

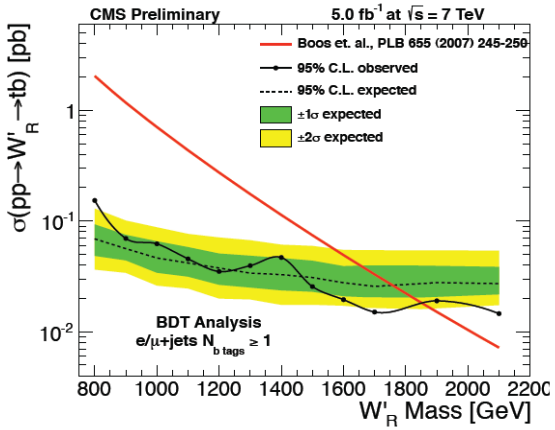


CMS-PAS-EXO-12-001

CMS

- BDT used to discriminate signal from background

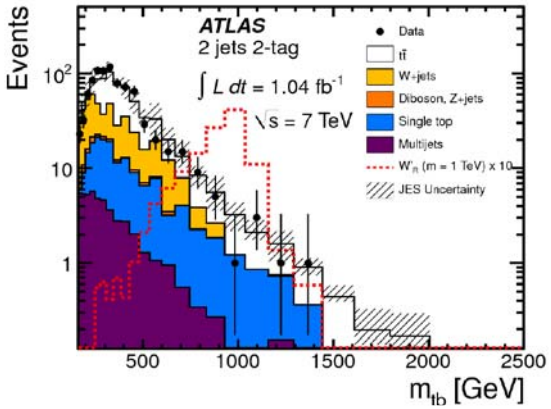


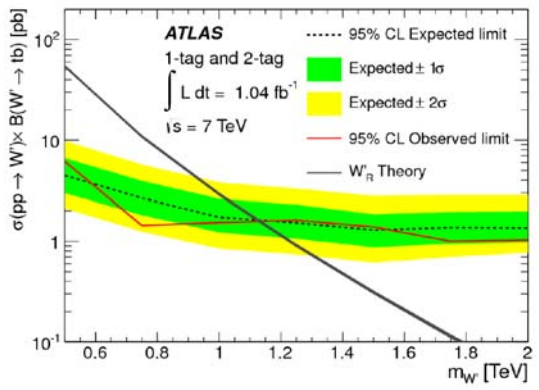


http://arxiv.org/abs/1205.1016

ATLAS

- Invariant mass of *tb* system used as discriminating variable



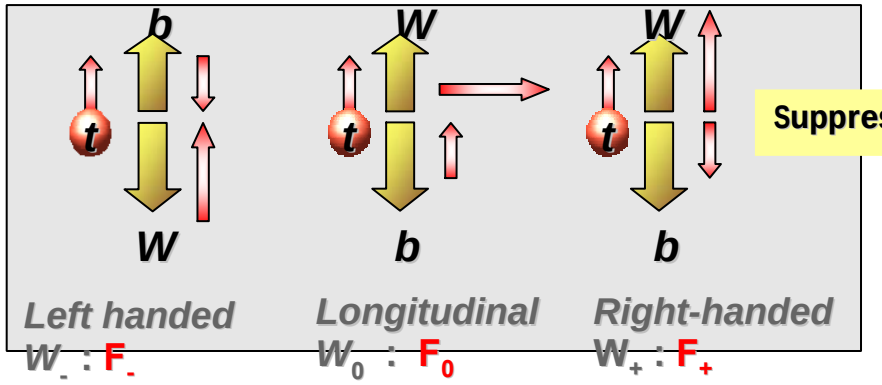


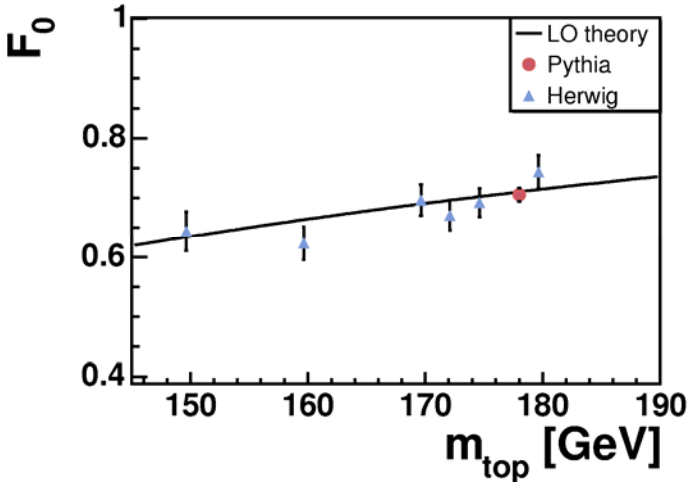
Observed limits (ATLAS, CMS): $m_{W'R} > 1.13 / 1.85$ TeV

3. DECAY PHYSICS: W HELICITY

3.1 W Helicity

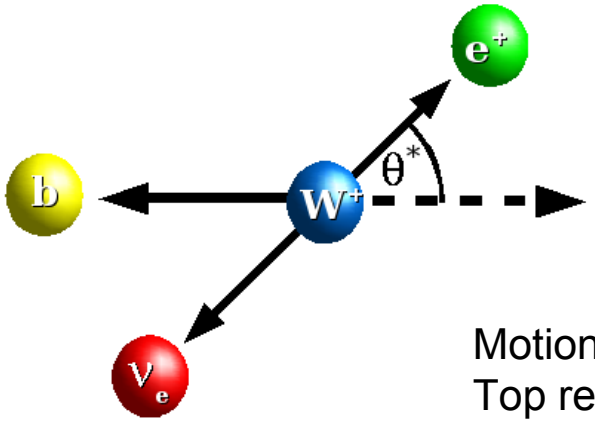
Three possible helicities:





$$F_0 = \frac{m_t^2}{2M_W^2 + m_t^2}$$

Distribution of Angle θ* between charged lepton in W system and W-Boson in Top-Quark system:



Motion of W in Top rest system

$$\frac{dN_{h_W=-1}}{d(\cos\theta^*)} \sim \frac{3}{8}(1-\cos\theta^*)^2$$

SM: $F_- = 0.31$

$$\frac{dN_{h_W=0}}{d(\cos\theta^*)} \sim \frac{3}{4}(1-\cos^2\theta^*)$$

$F_0 = 0.69$

$$\frac{dN_{h_W=+1}}{d(\cos\theta^*)} \sim \frac{3}{8}(1+\cos\theta^*)^2$$

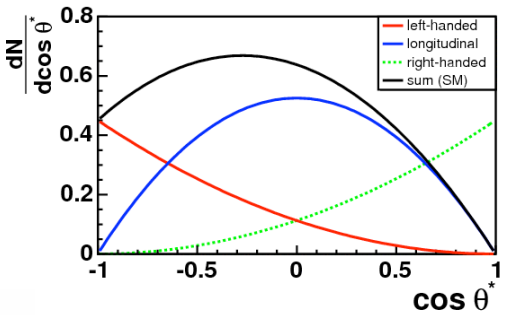
$F_+ = 0.001$

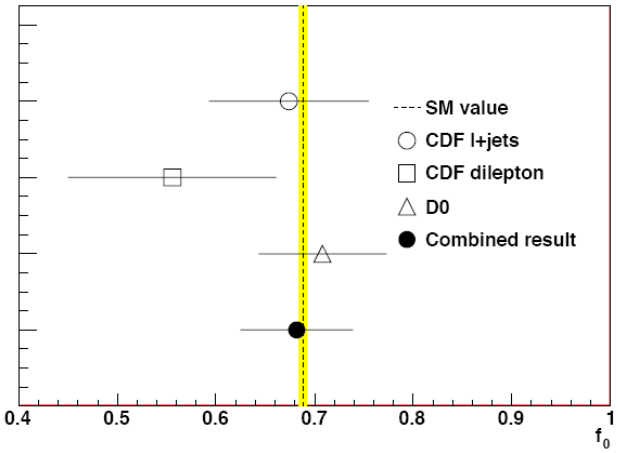
A. Czarnecki, J. G. Körner, J. H. Piclum, Phys. Rev. D 81, 111503 (2010)

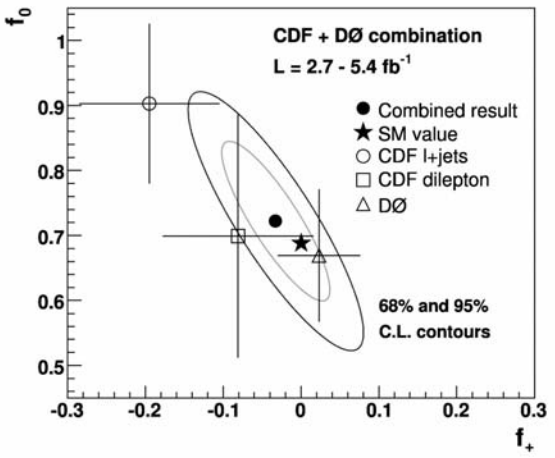
Tevatron Results on W Helicity

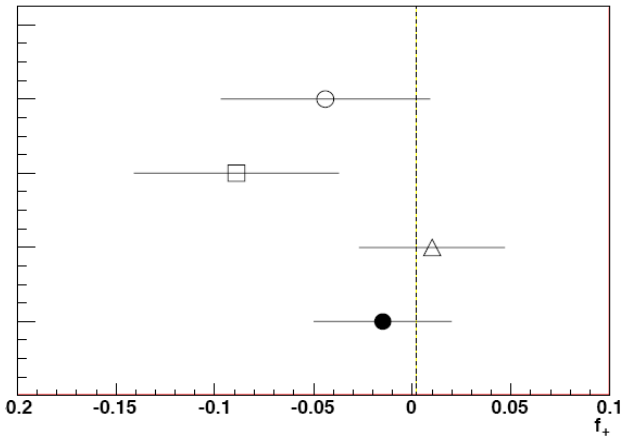
With three helicity fractions, there are two independent quantities to measure (3rd fraction is fixed since $\Sigma f = 1$)

- We choose to measure f_0 and f_+
- Can either measure both fractions simultaneously (2D fit)
- or fix one fraction to its SM value and measure the other (1D fit)







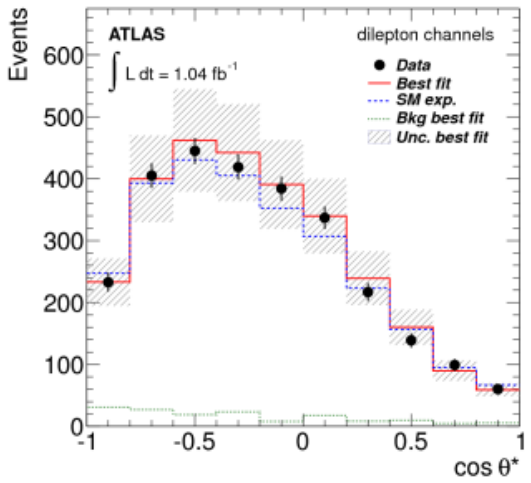


Tevatron Combo

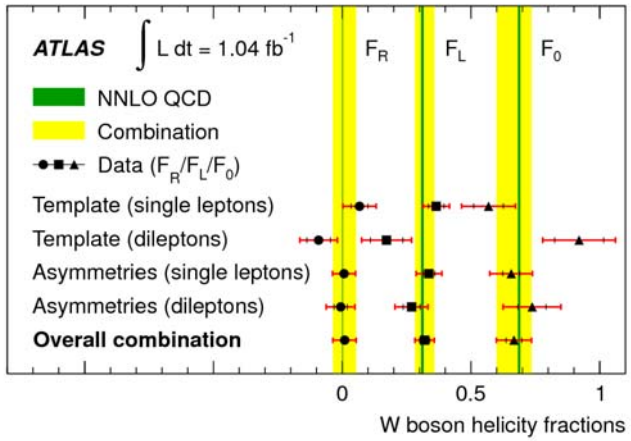
$$2\text{D: } f_0 = 0.722 \pm 0.062 \pm 0.052$$
$$f_+ = -0.033 \pm 0.034 \pm 0.031$$
$$1\text{D: } f_0 = 0.682 \pm 0.035 \pm 0.046$$
$$f_+ = -0.015 \pm 0.018 \pm 0.030$$

PRD85, 071106 (2012)

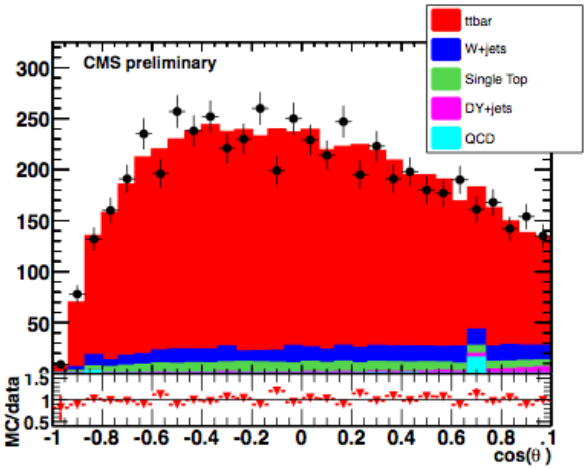
LHC Results



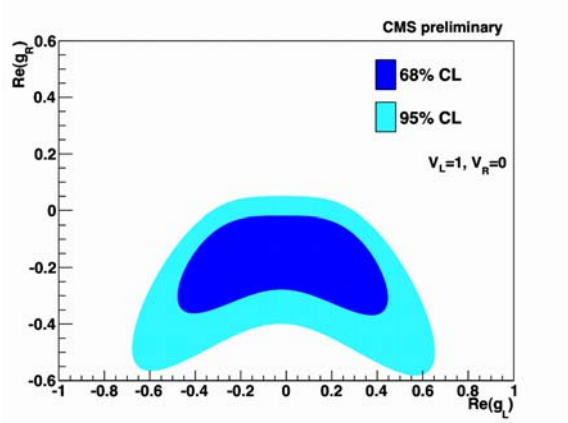
Combine l+jets and dilepton



$$F_0 = 0.67 \pm 0.03\ (\text{stat.}) \pm 0.06\ (\text{syst.}),$$
$$F_L = 0.32 \pm 0.02\ (\text{stat.}) \pm 0.03\ (\text{syst.}),$$
$$F_R = 0.01 \pm 0.01\ (\text{stat.}) \pm 0.04\ (\text{syst.}).$$

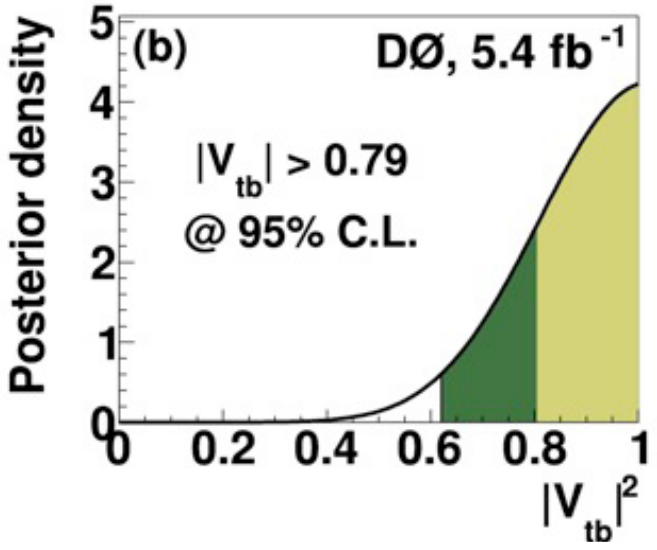


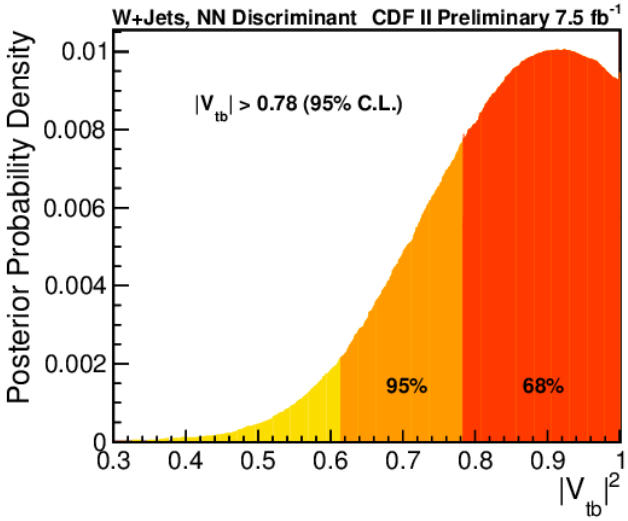
CMS: l+jets



$$F_0 = 0.567 \pm 0.074(\text{stat.}) \pm 0.047(\text{syst.})$$
$$F_L = 0.393 \pm 0.045(\text{stat.}) \pm 0.029(\text{syst.}),$$

3.2 Top couplings from production



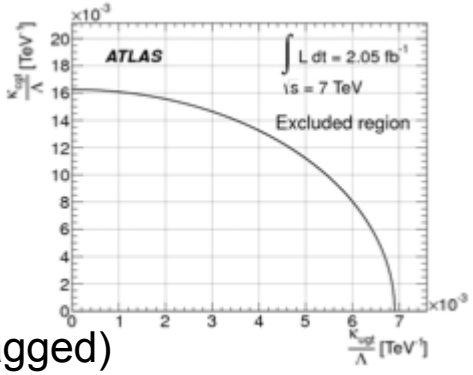


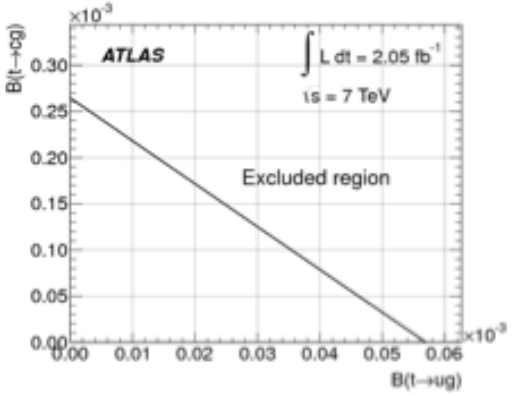
$|Vtb| = 0.92\ ^{+0.10}_{-0.08}$ (stat.+sys.) ± 0.05(theory)

Other single top studies: FCNC single top quark production

Search for:

$qg \to t \to W(\to \ell\nu)b$





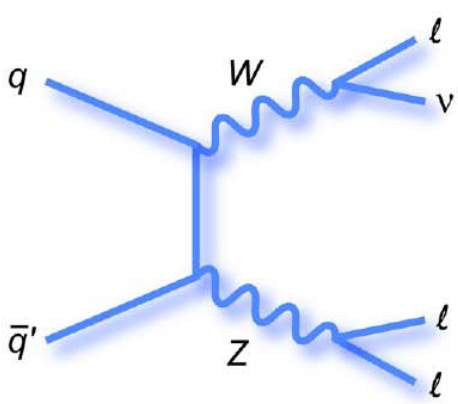
mT+ETmiss>60 GeV
Require only 1 jet (b-tagged)

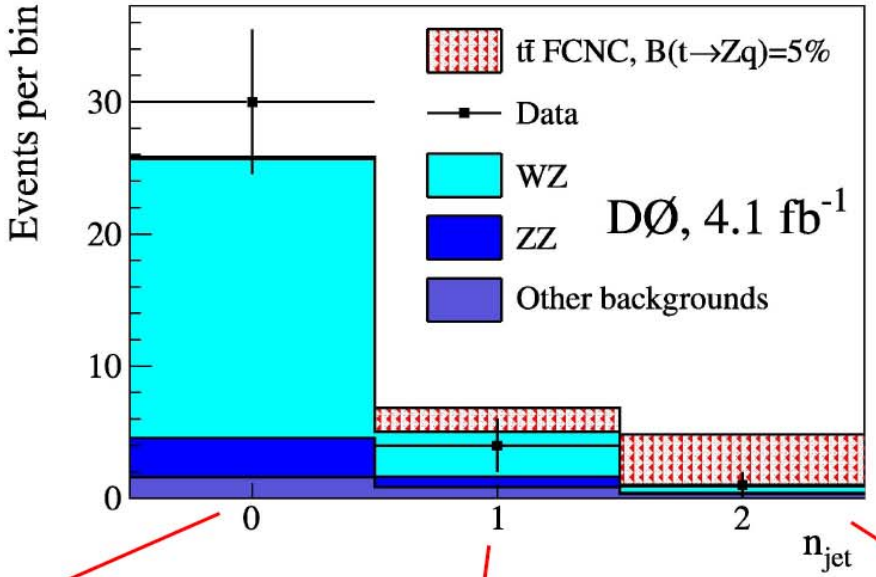
$\sigma(qg \to t) \cdot B(t \to Wb) < 3.9$ pb (95% CL)

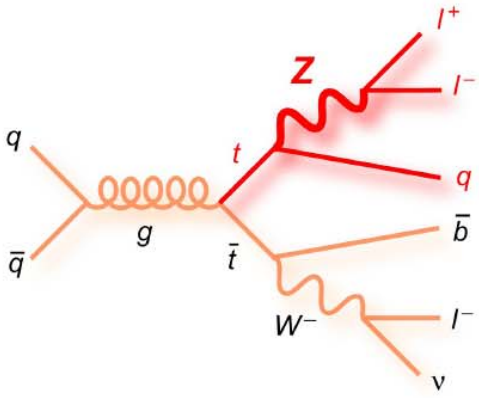
$B(t \to ug) < 5.7 \cdot 10^{-5}, B(t \to cg) < 2.7 \cdot 10^{-4}$

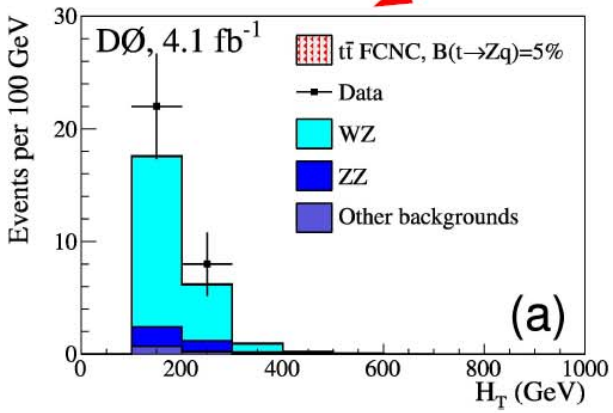
CMS-TOP-11-028 is 0.34%,

3.3 Search for anomalous couplings

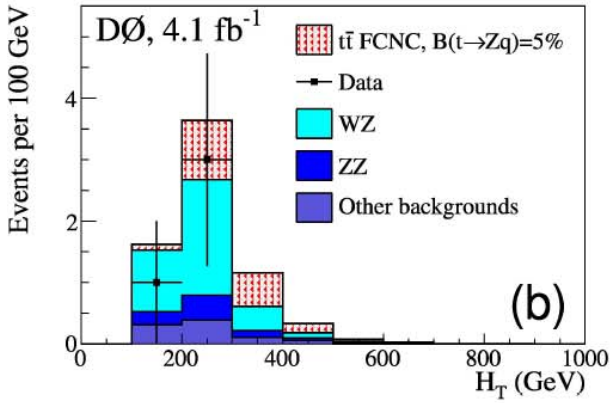




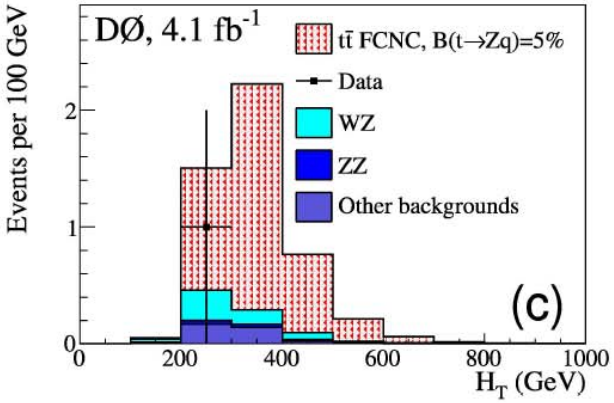




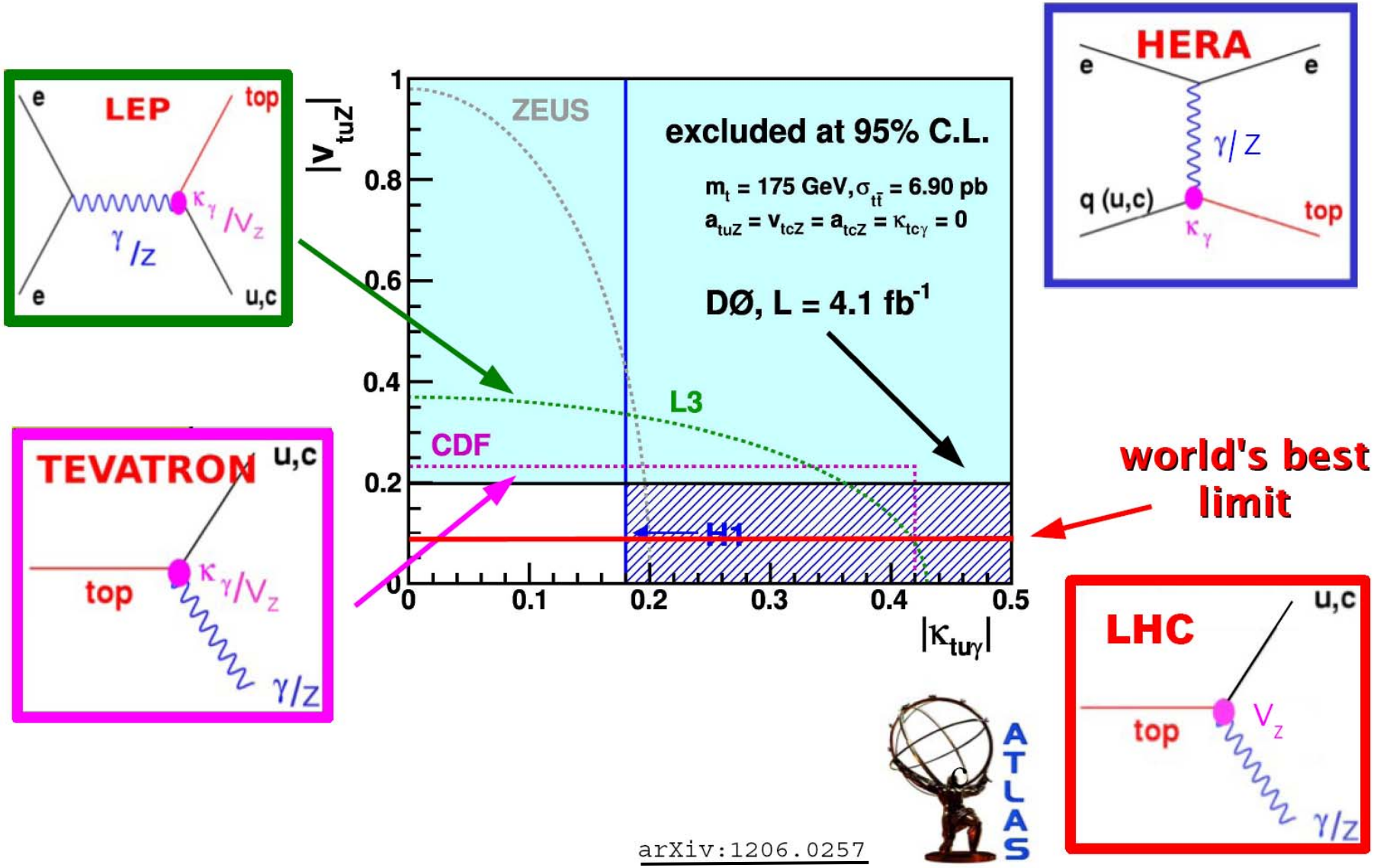
3 leptons + 0 jets



3 leptons + 1 jet



3 leptons + ≥2 jets



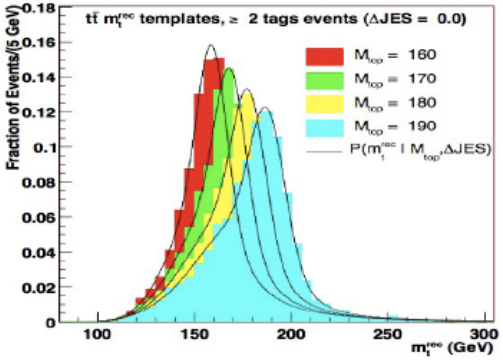
Christian Schwanenberger

4. TOP QUARK PROPERTIES

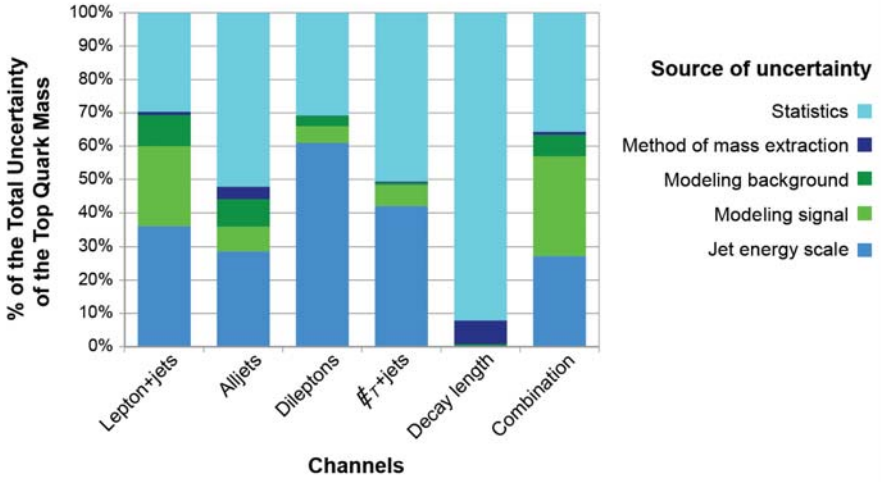
4.1 Top Mass Measurements

Measurement of the top quark mass:

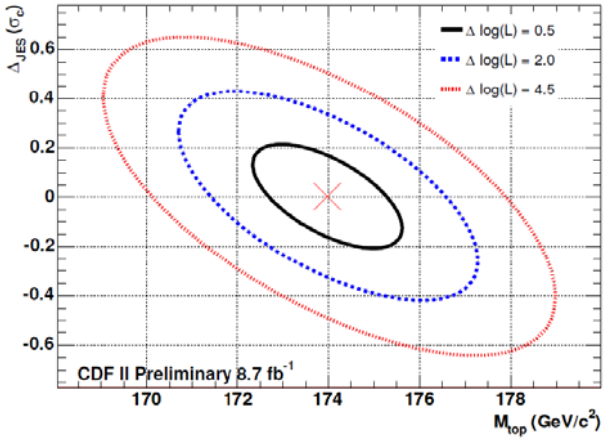
- Template method:
  fit MC generated distributions assuming
  different Mtop to data
- Matrix element method:
  probability based on LO tt matrix element
  using full kinematics of the event
- Ideogram method
  event likelihood computed as a convolution of a
  Gaussian resolution function with a Breit-Wigner (signal)
- Calibration curve method
  di-lepton channel using mt2

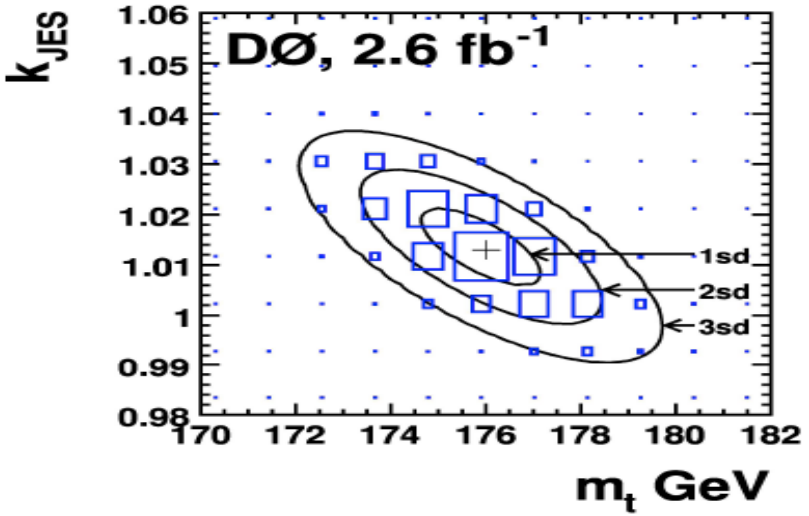


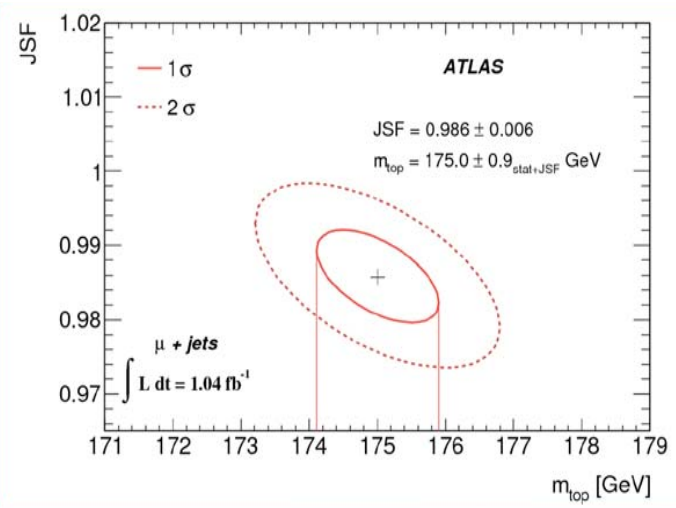
Sources of uncertainties
at Tevatron

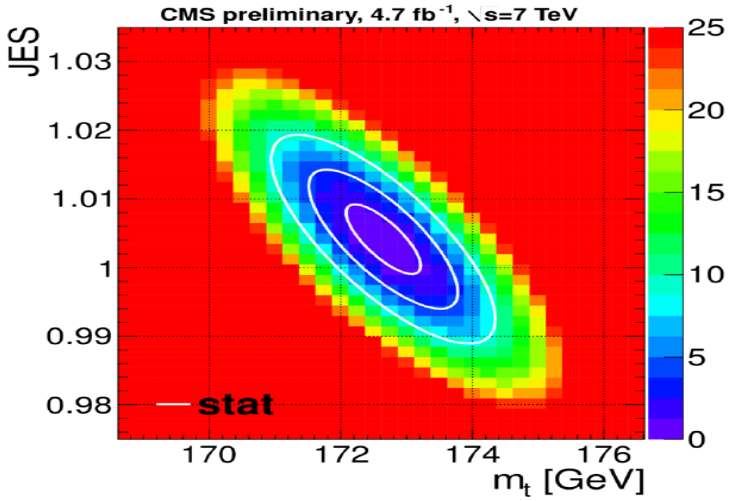


JES vs M_{top} in all four experiments



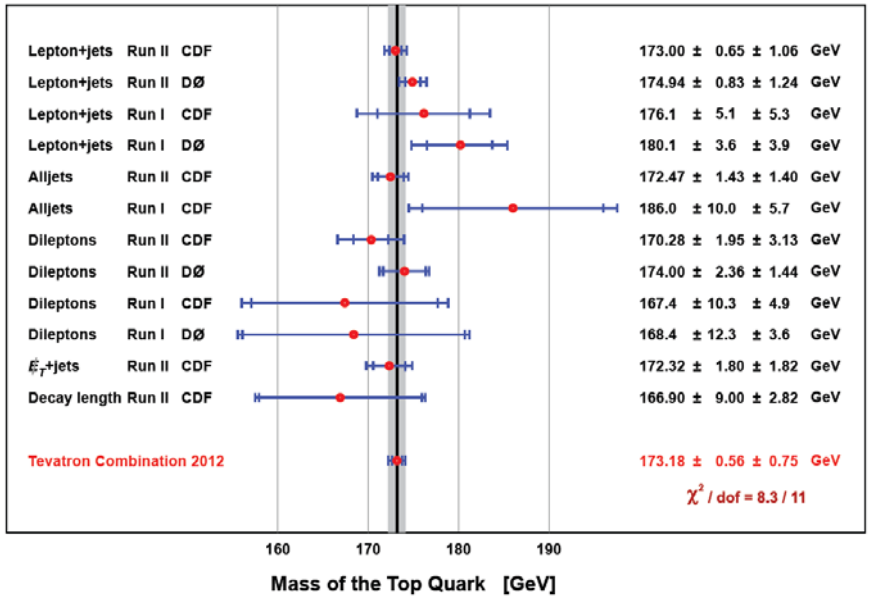


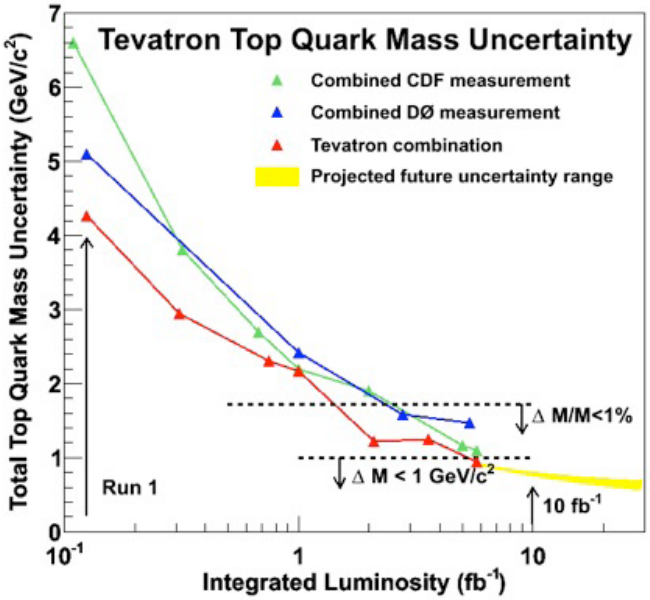




Top Quark Mass Combinations

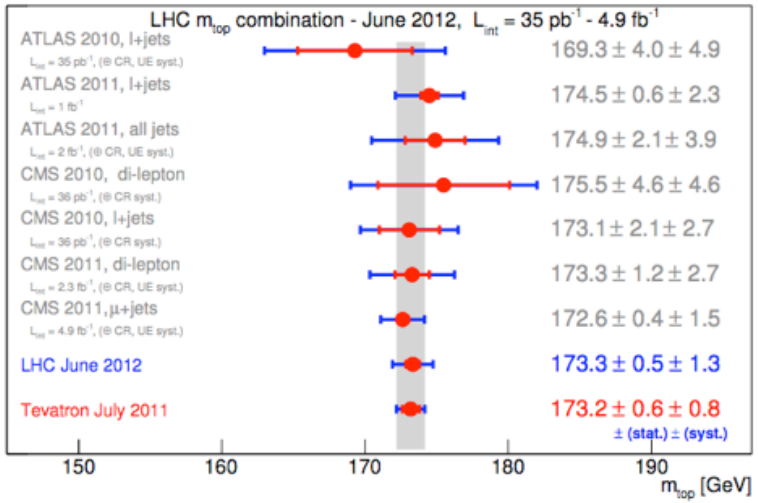
– Tevatron combination and perspectives





Expect to reach precision of 0.7-0.8 GeV

– LHC combination and perspectives



TeV: $m_t^{\text{comb}} = 173.18 \pm 0.56\,(\text{stat}) \pm 0.75\,(\text{syst})$ GeV
$= 173.18 \pm 0.94$ GeV

LHC: $m_{\text{top}} = 173.3 \pm 0.5\,(\text{stat}) \pm 1.3\,(\text{syst})$ GeV
= 173.3 ± 1.4 GeV

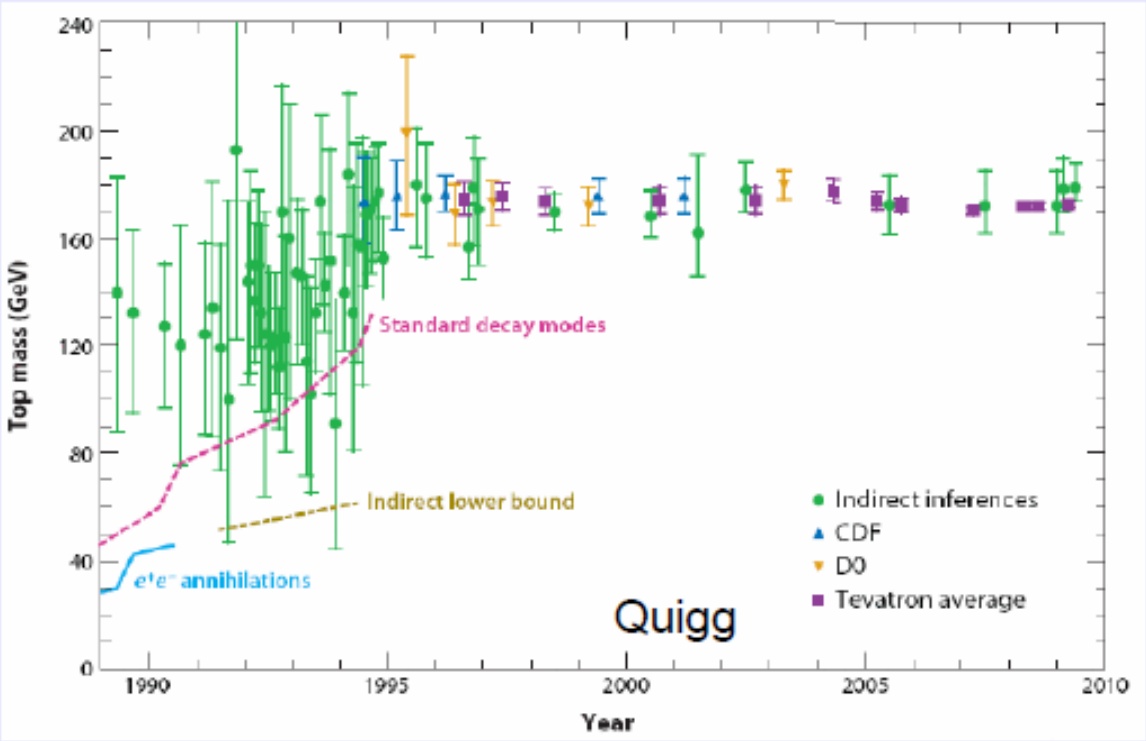
ATLAS-CONF-2012-095

CMS PAS TOP-12-001

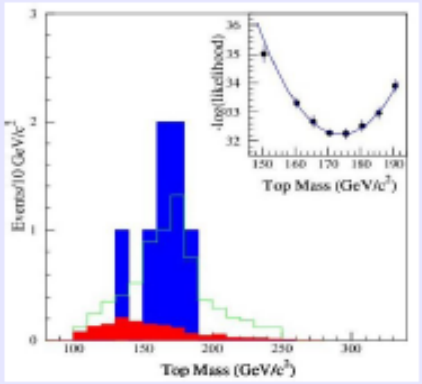
Evolution of Top Quark Mass Determination

Measurement uncertainty on M_T has improved since 1994, but mass value has not changed much

$M_{top} = 173.2 \pm 0.9$ GeV/c²



First measurement
7 events (1.4 background)
CDF, PRD **50**, 2966 (1994)

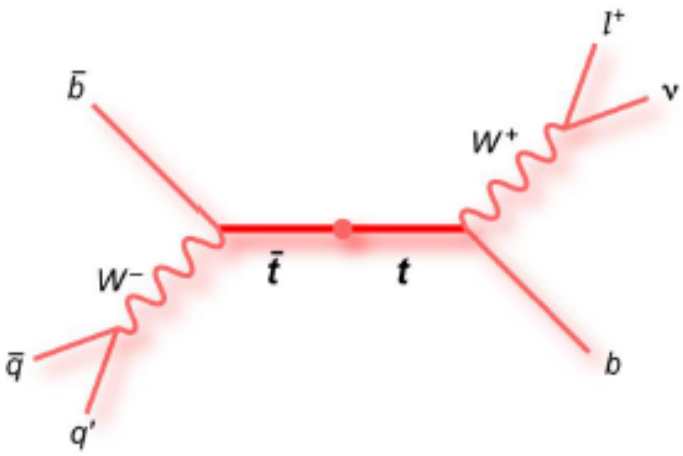


$M_{top} = 174 \pm 10\ ^{+13}_{-12}$ GeV

4.2 $t\bar{t}$ Mass Difference

- CPT theorem predicts masses of particles and antiparticles to be equal
  - Top-quark only particle with color charge to test this invariance

- Analysis Principle:



Leptonic branch:
Using lepton charge to tag top- or antitop-quark

Hadronic branch:
Reconstruct top-quark to determine mass

- Analysis of μ+jets events
  - 1 isolated muon, 4 high-p_T jets
  - Kinematic event reconstruction of 12 permutations
  - Measurement of top- and antitop-quark masses with Ideogram method
    - Taking b-tagging information into account to reduce background events (mainly W+jets)

Test CPT invariance in the top sector

$$\Delta M_t = M_{top} - M_{\overline{top}}$$

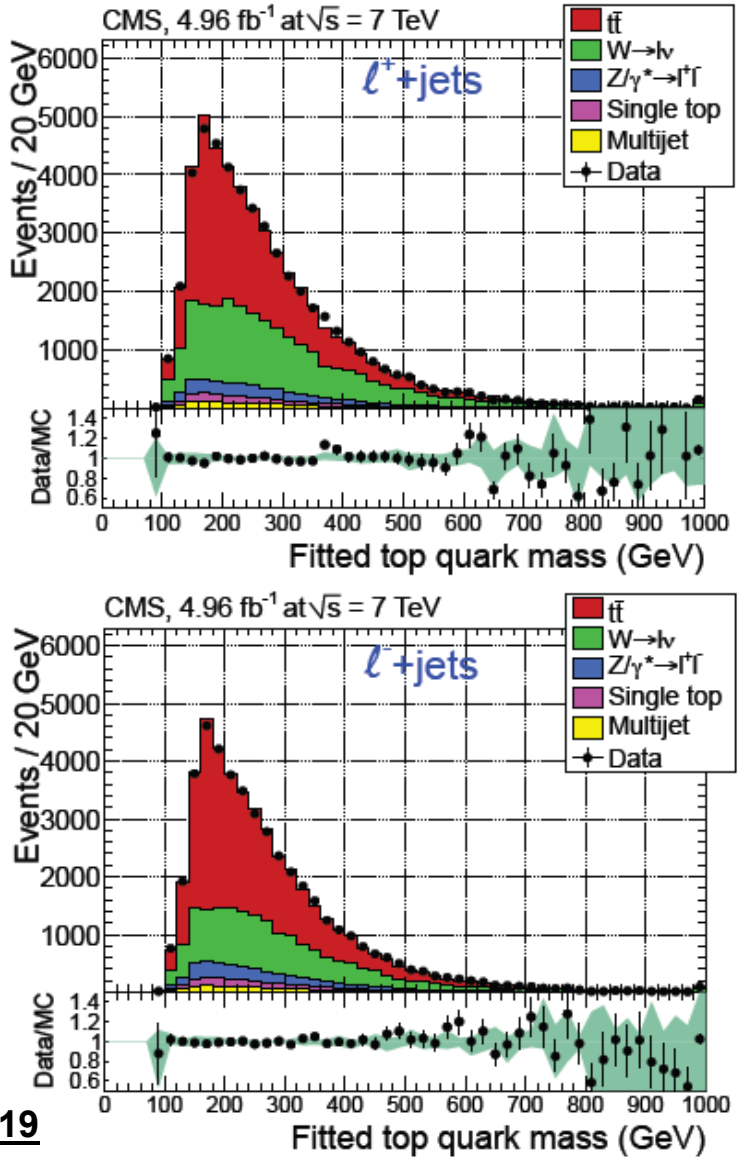
- Reconstruction of the hadronic side: compare ℓ^++jets and ℓ^-+jets events
- Use kinematic fit, and event-per-event likelihood for ℓ^- and ℓ^+ separately

$$\Delta m_t = -0.44 \pm 0.46\ (\text{stat.}) \pm 0.27\ (\text{syst.})\ \text{GeV}$$

Most systematic effects cancel out !
→ the measurement is stat. limited

World's best so far

Consistent with SM,
Consistent between e and μ



CMS-TOP-11-019

4.3 Width of the Top Quark

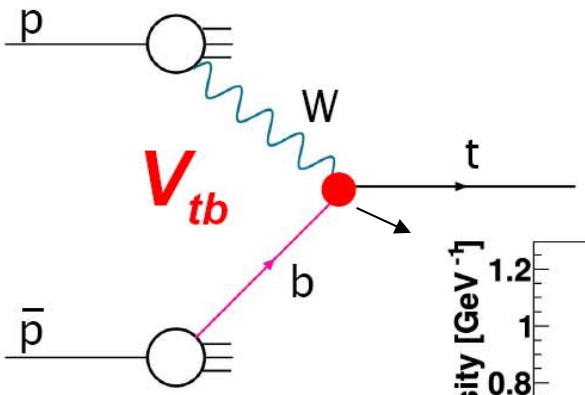
t-channel cross section:

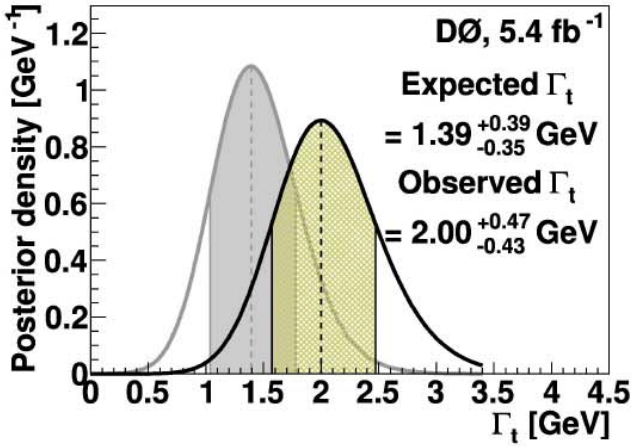
$$\sigma(p\bar{p} \to tqb + X) = 2.90 \pm 0.59 \text{ pb}$$

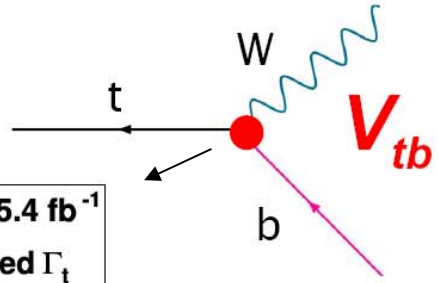
m_t =172.5 GeV

partial decay width:

R= 0.90±0.04 (stat+syst)







$$\tau_{\text{top}} \propto \left(\frac{M_W}{M_{\text{top}}}\right)^3$$

$$\tau_{\text{top}} \approx 4.7 \cdot 10^{-25} \text{ s}$$

Phys. Rev. D84 012008 (2011)

$$\Gamma_t = 2.00^{+0.47}_{-0.43} \text{ GeV}$$

$$\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25} \text{ s}$$

$\Longrightarrow$ **most precise determination**

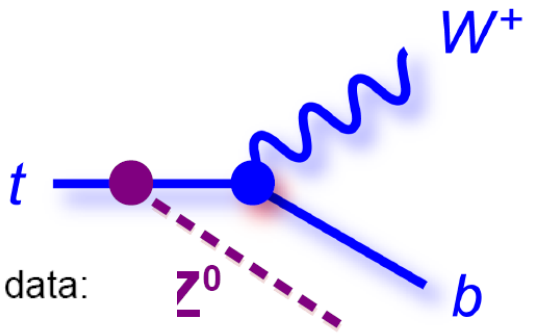
Phys. Rev. D 85, 091104(2012)

4.4 $t\bar{t}$+V Production

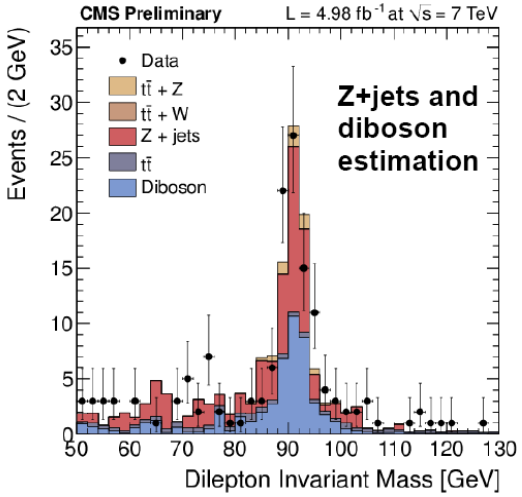
Trilepton channel: $\sigma(t\bar{t}Z \to l + \text{jets} + (Z \to l\,l))$

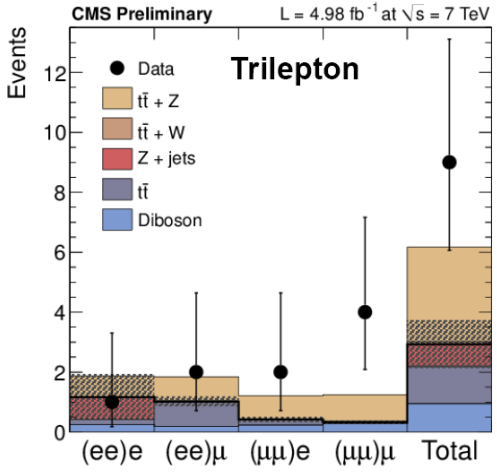
Same-sign dilepton channel: $\sigma(t\bar{t}V \to l + \text{jets} + (W \to l\,\nu) \text{ or } (Z \to l\,l))$

with $l = e$ or μ



- Selection:
  - ➔ 3 leptons: 2 opposite-charge and same-flavor leptons (Z^{cand})
  - ➔ 3 jets (2 *b* tagged), H_T > 120 GeV
- Background estimation from data:
  - ➔ $t\bar{t}$: cross-flavor dilepton events
  - ➔ *Z*+jets and diboson: trilepton, no *b* tag events





CMS-TOP-12-014

First measurement of *ttV*:

- Result combining all 7 channels:

$$\sigma(t\bar{t}V) = 0.51^{+0.15}_{-0.13}(\text{stat.})^{+0.04}_{-0.02}(\text{syst.})\ \text{pb}$$

  - ➔ Significance of 4.67 σ

CONCLUSIONS

Seventeen years after its discovery, top quark physics is ever increasing in fascination.

The Tevatron will leave a legacy in precision measurements, analysis methods and searches at the energy frontier.

The LHC has had a phantastic start and has been taking over from the Tevatron. The LHC has become a top factory.

Theory has been accompanying us in this exciting programme, being a match in terms of precision and paving the way in predicting new phenomena.

So far, agreement with SM predicitions is astounding except for one mystery which seems to solidify. We need to get hold of the asymmetry in all possible ways.

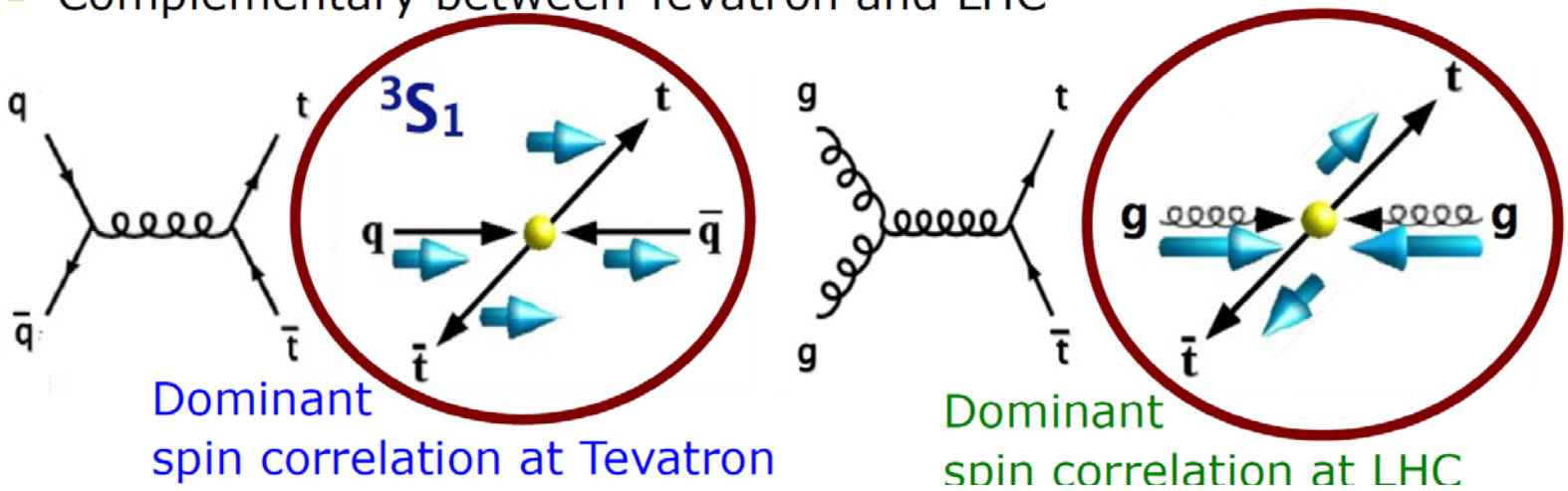
Exciting times are awaiting us !

Supported by the State of Baden-Württemberg, HGF, the DFG and the BMBF

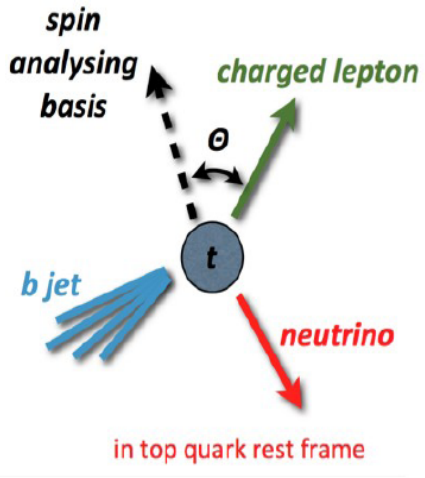
1.4 Spin Correlations

- Spins of t and $\bar{t}$ are predicted to be correlated in SM
- Top decay before hadronization allows to measure top spin from its decay products
- At LHC at low m($t\bar{t}$) ttbar production dominated by like-helicity gluon pairs → like-helicity ttbar pairs.
- In dilepton final states this results in correlations between the leptons in the azimuthal angle Δφ in the lab frame (Mahlon & Parke)

- Complementary between Tevatron and LHC



- Use the angles between decay products and beam axis to analyse spin
  - Dilepton: Angle of (anti)lepton wrt. beam axis in (anti)top rest-frame
  - Spin analysing power of charged lepton and down-type quark is 1 (in LO)

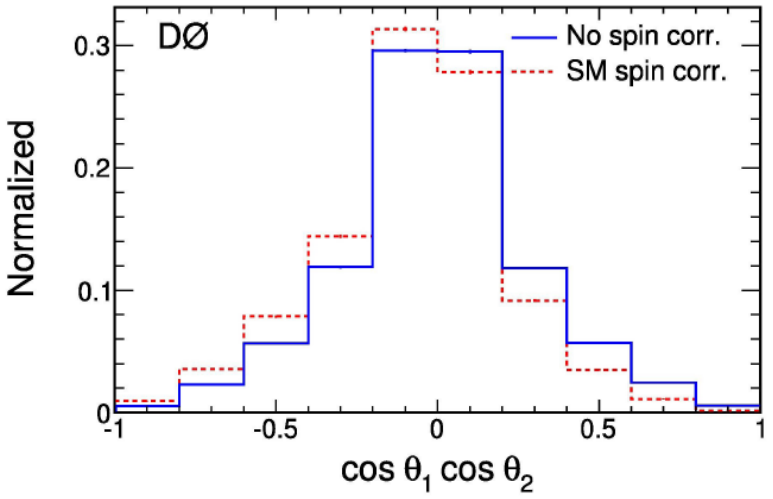


- Differential cross section:

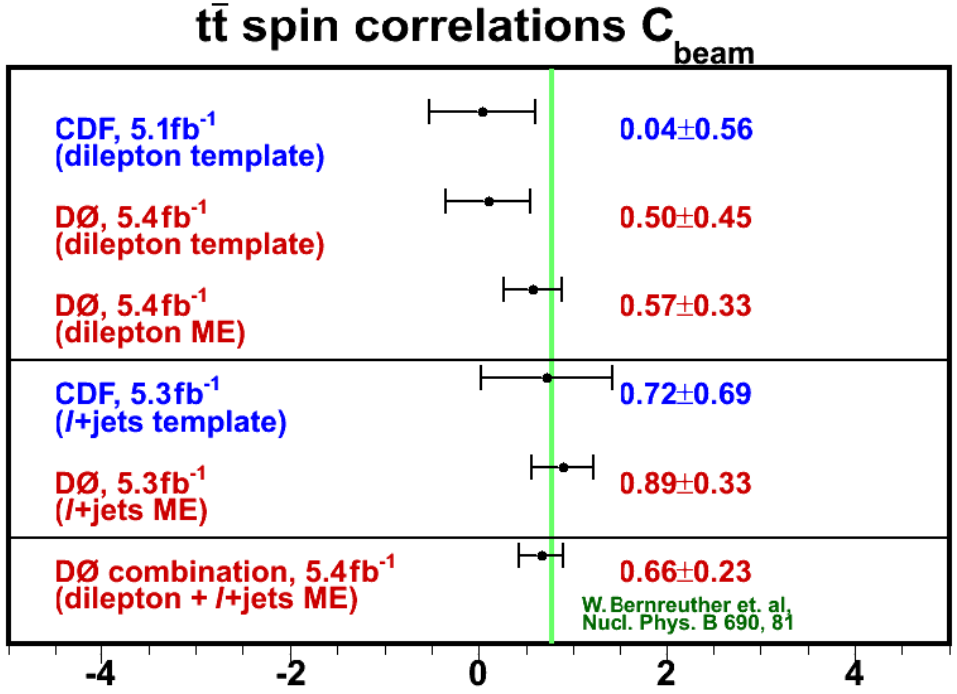
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 \, d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

  - C: spin correlation strength
  - NLO SM: C≈0.78 (beam axis)

$$C = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

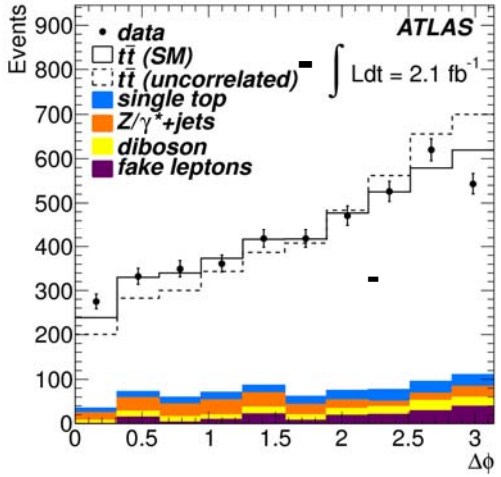


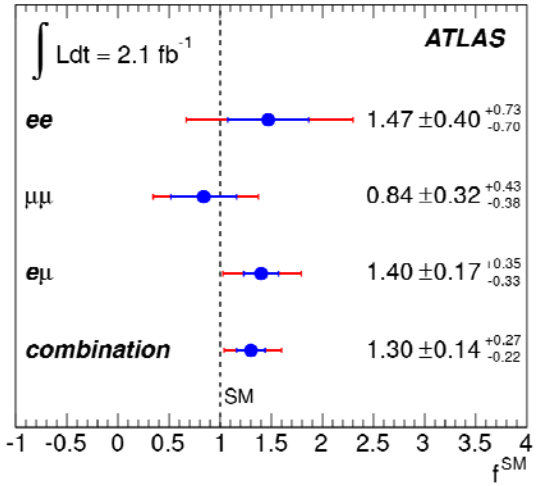
Spin correlations at the Tevatron



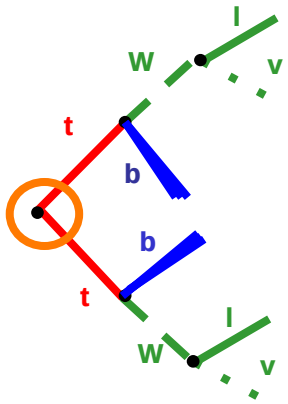
Correlation values in agreement with SM assumptions

Spin correlation at the LHC





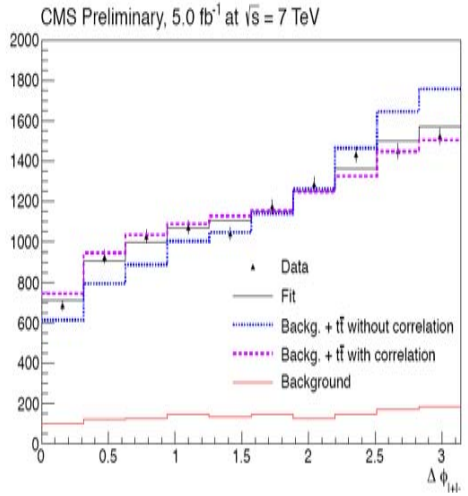
Phys. Rev. Lett. 108 212001 (2012)



$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}.$$

f = 1.06 ± 0.21 (stat.) + 0.40 - 0.27 (syst.)
A = 0.34 ± 0.07 (stat.)+ 0.13 - 0.09 (syst.)

SM: f = 1.0, A = 0.31



f = 0.74 ± 0.08 (stat) ± 0.24 (syst),
A = 0.24 ± 0.02 (stat) ± 0.08 (syst)

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