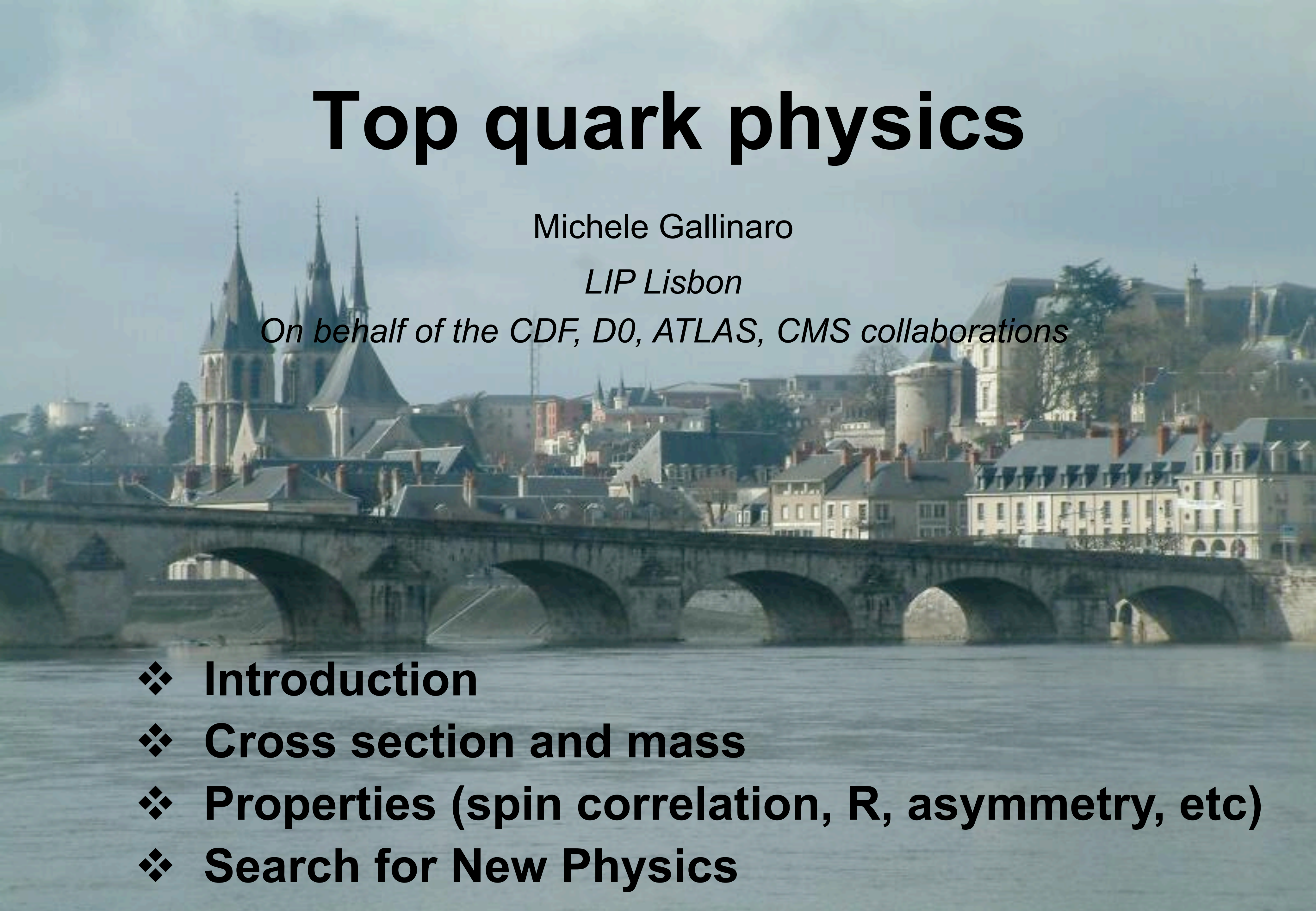


Top quark physics

Michele Gallinaro

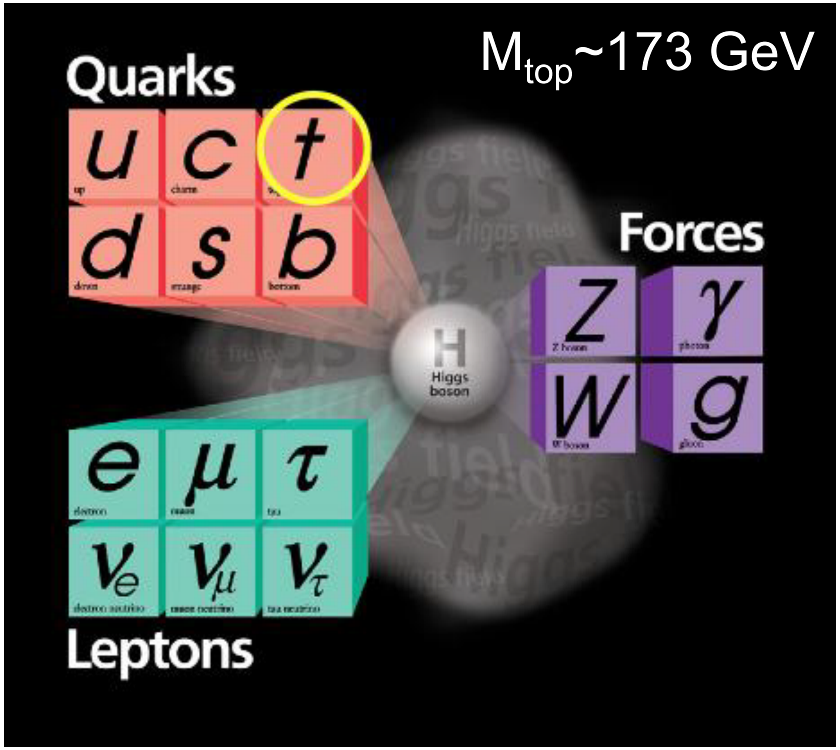
LIP Lisbon

On behalf of the CDF, D0, ATLAS, CMS collaborations

- **Introduction**
- **Cross section and mass**
- **Properties (spin correlation, R, asymmetry, etc)**
- **Search for New Physics**

The top quark

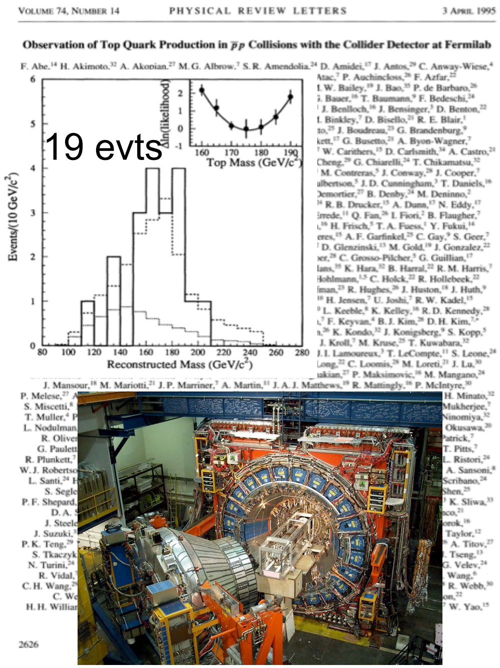
- The heaviest known elementary particle
- Coupling to the Higgs ~1
- For M_{top}=175 GeV⇒Γ=1.4 GeV
  ⇒no hadronization
- Open question: why is Top so massive?
  - Special role in EWK symmetry breaking?
- Large samples of top quarks available
  - even larger in the near future
- Top quarks are main background for many New Physics searches
- Precision measurements may provide insight into physics beyond SM

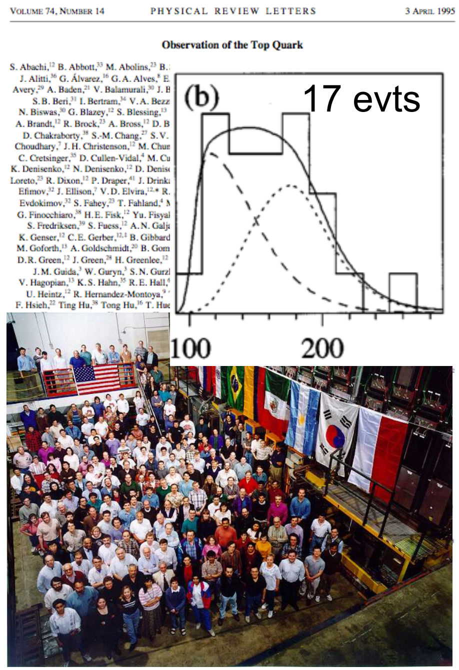


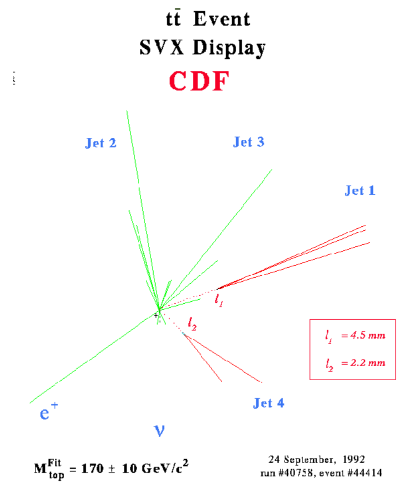
(short) history of the top quark

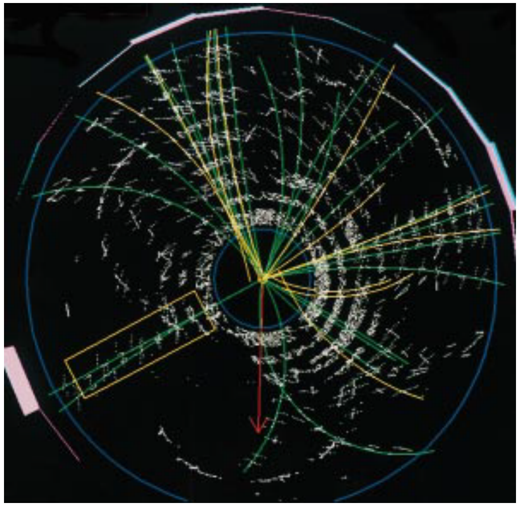
Discovery of the top quark (1995)

Observed excess consistent with: $t\bar{t} \rightarrow W^+W^-b\bar{b}$



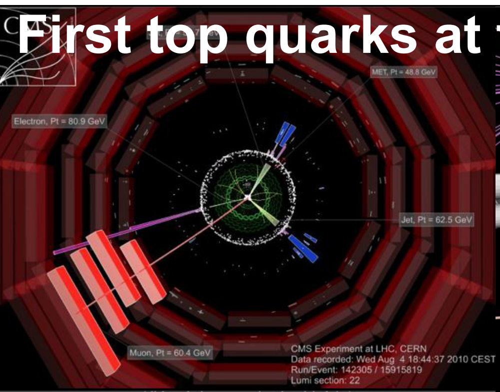


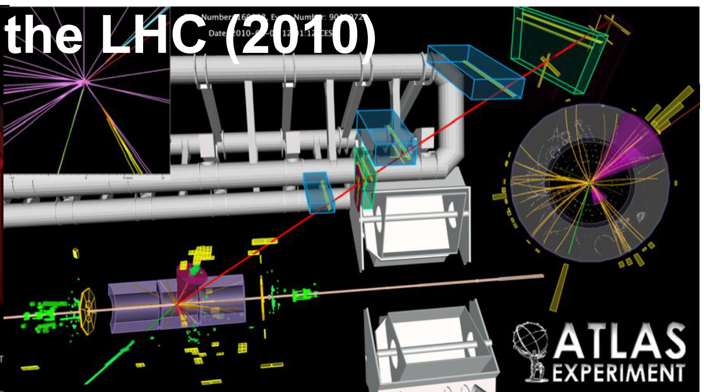


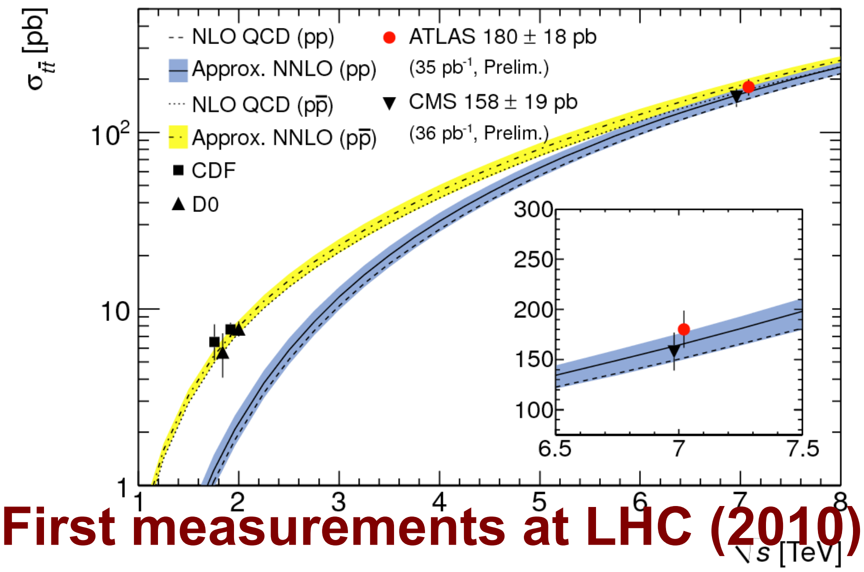


Observation of single top quark (2009)

First top quarks at the LHC (2010)

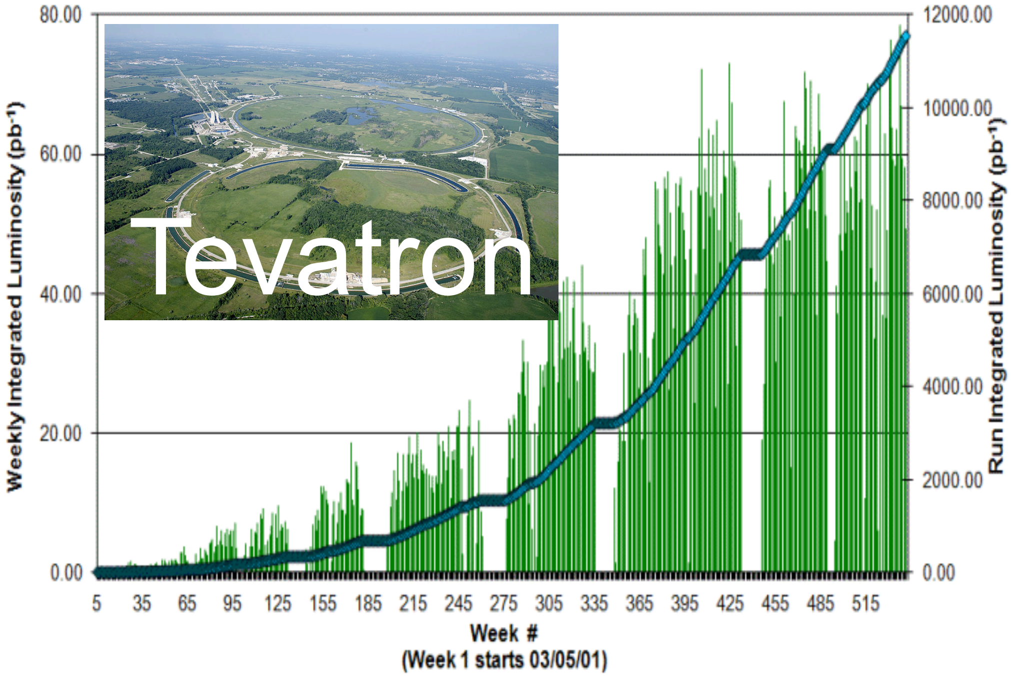


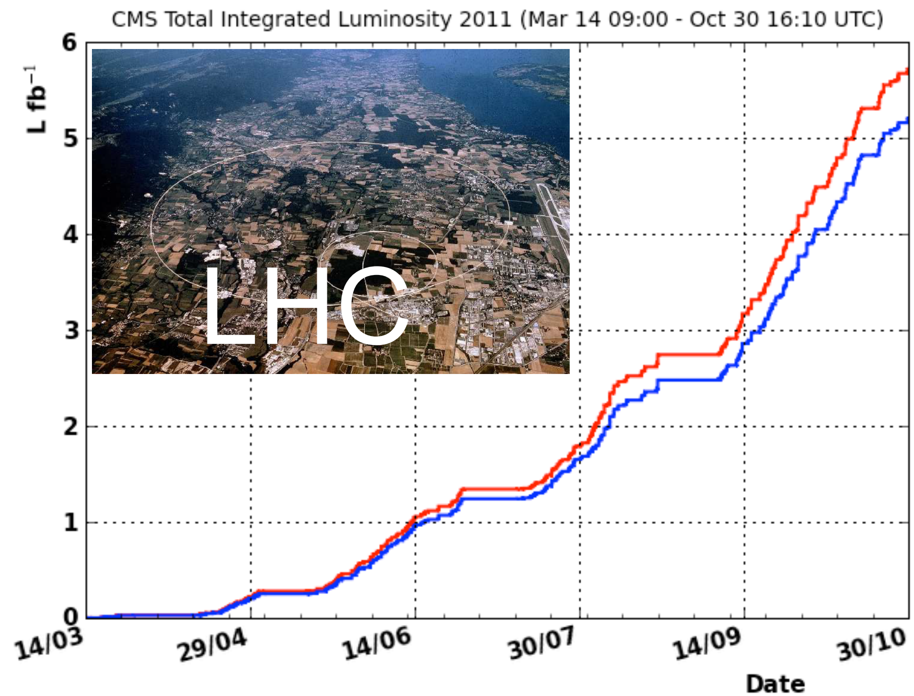




First measurements at LHC (2010)

Tevatron vs LHC





Energy: 1.96 TeV
Int. Luminosity: 12 fb^{-1}
Age: ~25 years
Events/exp (5 fb^{-1})
250 ee eμ μμ
2000 lepton + jets

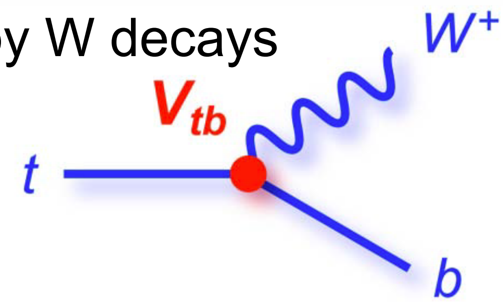
x 50

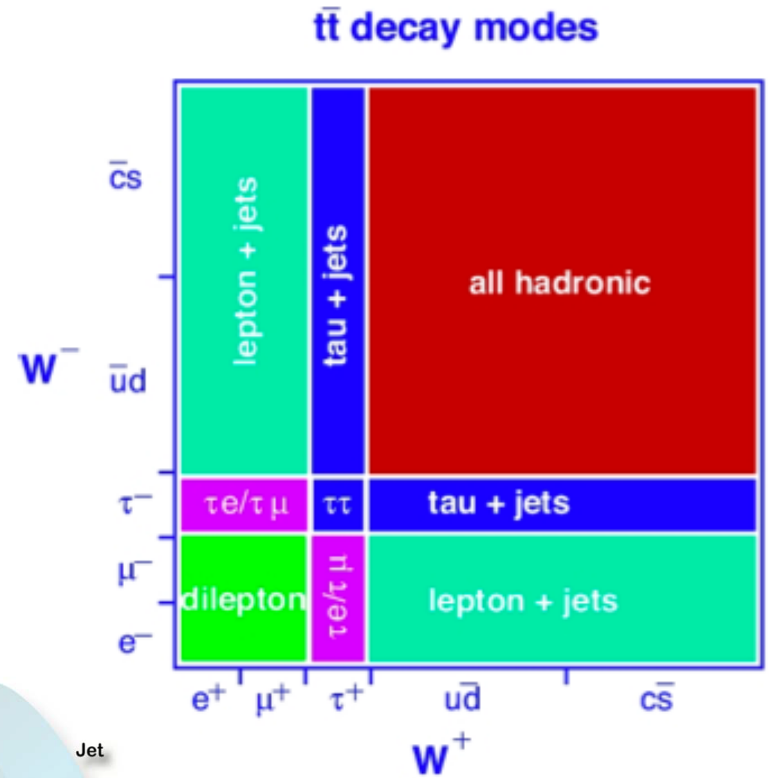
Energy: 7 TeV
Int. Luminosity: 5 fb^{-1}
Age: ~2 years
Events/exp (5 fb^{-1})
12k ee eμ μμ
100k lepton + jets

Top quark decays

Top quarks (mostly) produced in pairs

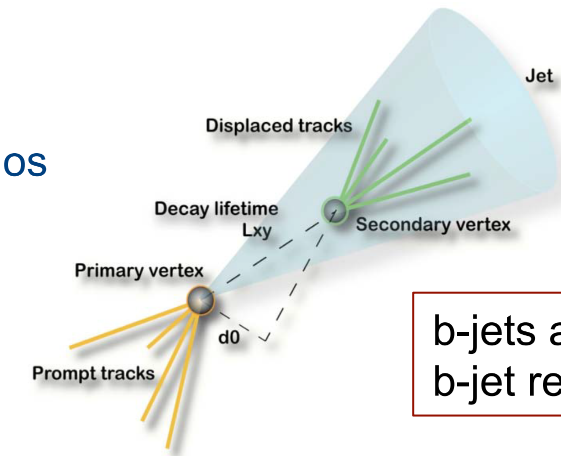
Event topology determined by W decays



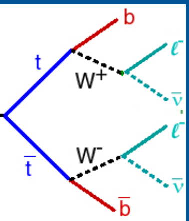


For ttbar pairs:

- Dilepton (ee, μμ, eμ):
  - BR~5%, 2 leptons+2 b-jets + 2 neutrinos
- Lepton (e or μ) + jets
  - BR~30%, one lepton + 4 jets (2 from b) + 1 neutrino
- All hadronic
  - BR~45%, 6 jets (2 from b), no neutrinos
- Tau(had)+X
  - BR~21%



b-jets always present
b-jet reconstruction plays important role



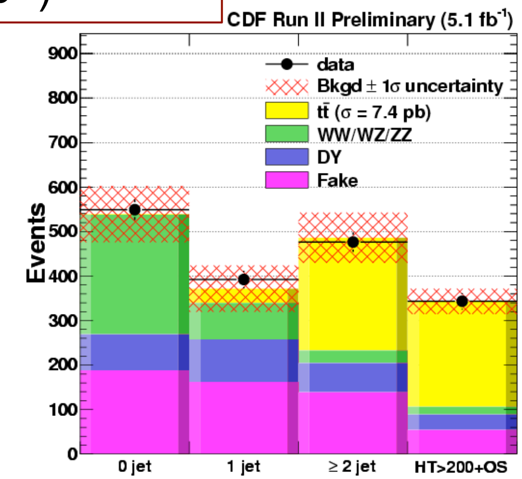
Dilepton channel

Branching Ratio (BR) ~5%
background: small

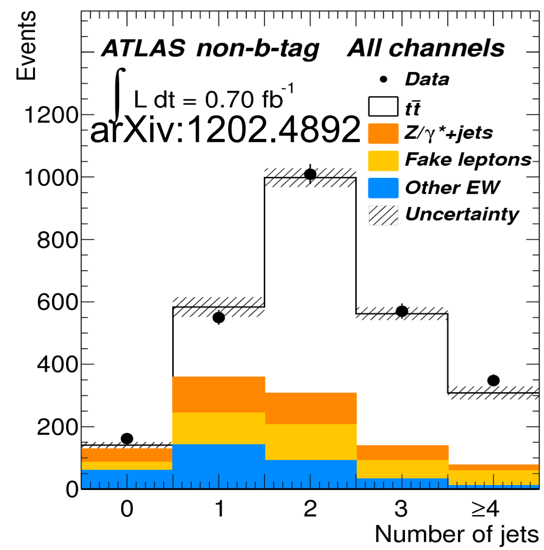
- ➢two leptons + ≥2 jets + MET
- ➢more kinematical variables

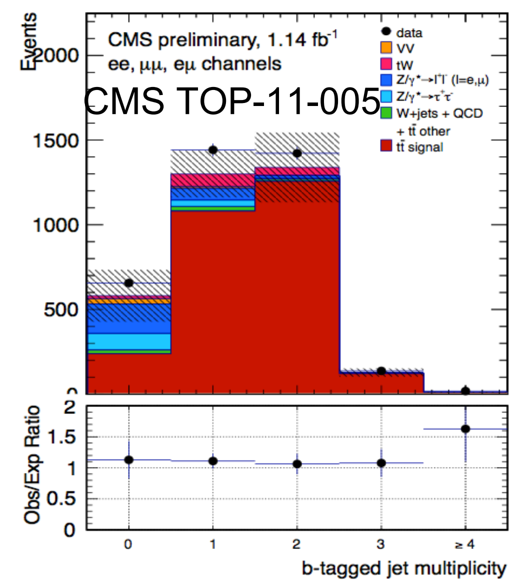
σ_{tt} = 7.4±0.6(stat)±0.6(syst)±0.5(lumi) pb
CDF note 10163 (5.1 fb^{-1})

±13%



- Signal visible w/without b-tagging
- Measure cross section:
  - Profile likelihood
  - Cut and count
- Main systematics: JES, lepton ID, (pileup, b-tag, signal modeling)



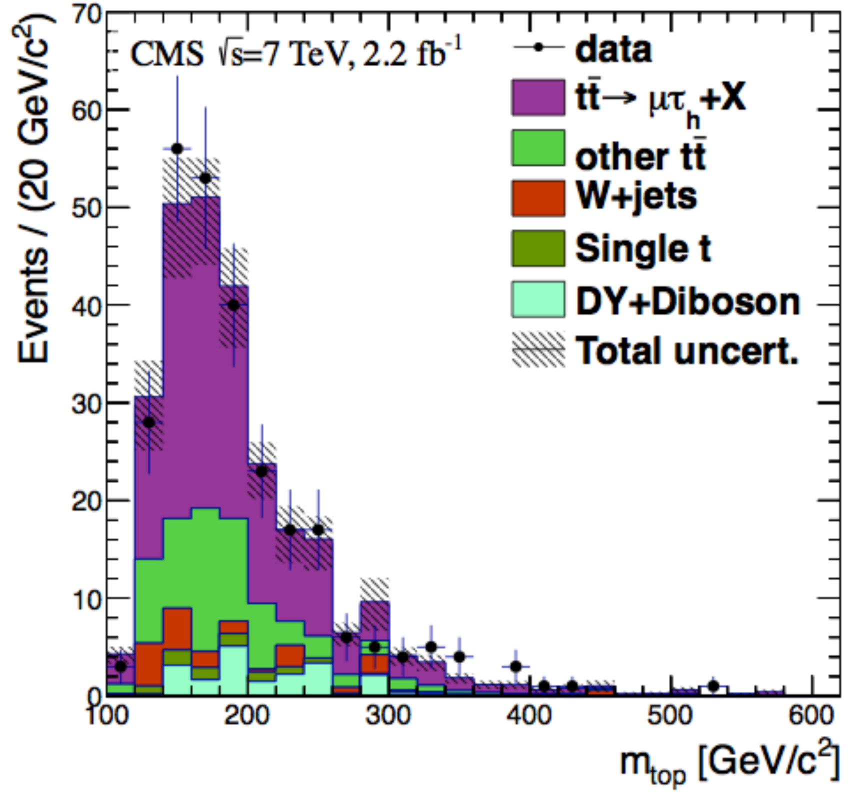


$$\sigma_{t\bar{t}} = 176 \pm 5(\mathrm{stat.})^{+14}_{-11}(\mathrm{syst.}) \pm 8(\mathrm{lum.})\ \mathrm{pb}$$ ATLAS ±10%

$$\sigma_{t\bar{t}} = 169.9 \pm 3.9\ (\mathrm{stat.}) \pm 16.3\ (\mathrm{syst.}) \pm 7.6\ (\mathrm{lumi.})\mathrm{pb}$$ CMS ±11%

Taus

arxiv.org/abs/1203.6810



Dileptons with taus

- First top quark cross section including τ at LHC
- Tau fake leptons determined from data with QCD events

Also τ+jets cross section:

CMS TOP-11-004

$\sigma_{t\bar{t}} = 156 \pm 12\,(\text{stat.}) \pm 33\,(\text{sys.}) \pm 3\,(\text{lumi})\,\text{pb}$

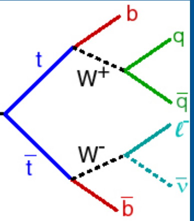
$\sigma_{t\bar{t}} = 200 \pm 19\,(\text{stat.}) \pm 43\,(\text{syst.})\,\text{pb}$

ATLAS-CONF-2012-032

Tau+lepton cross section:

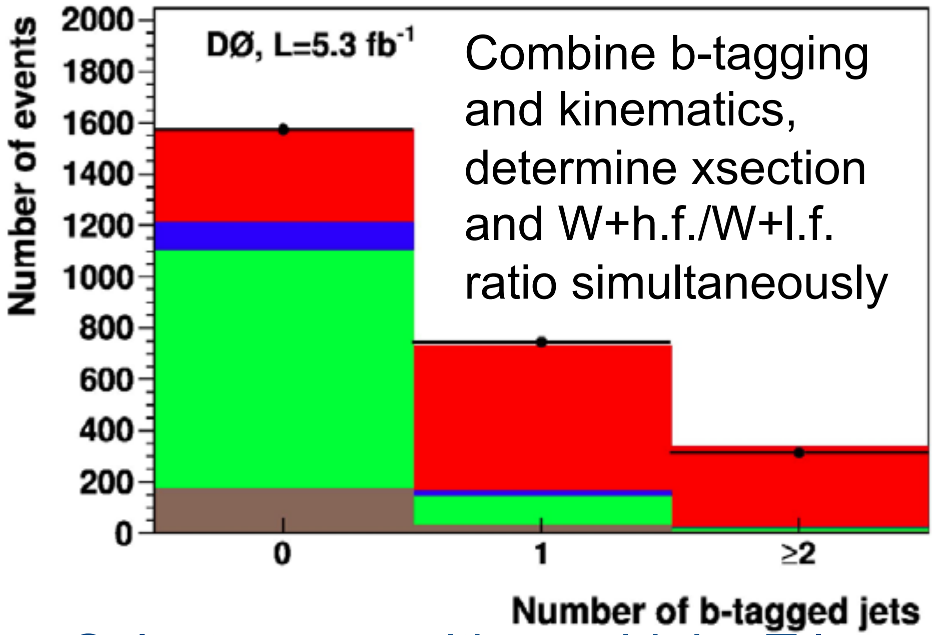
arXiv:1205.2067 $\sigma_{t\bar{t}} = 186 \pm 13\,(\text{stat.}) \pm 20\,(\text{syst.}) \pm 7(\text{lumi.})\,\text{pb}$ ATLAS ±15%

arXiv:1203.6810 $\sigma_{t\bar{t}} = 143 \pm 14(\text{stat.}) \pm 22(\text{syst.}) \pm 3(\text{lumi.})\,\text{pb}$ CMS ±16%

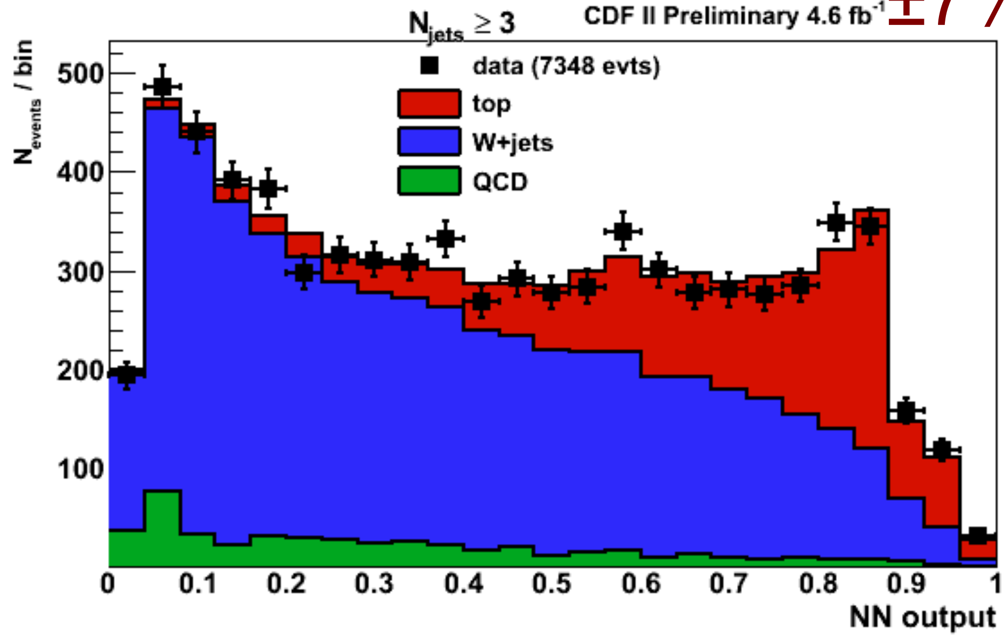


Lepton + jets

±10%



±7%



- Select events with one high pT lepton, MET and jets (including b-tagged)
  - Measure cross section using b-tagging or topological Neural Network
- Largest uncertainty due to luminosity
  - Reduced by normalizing to Z cross section

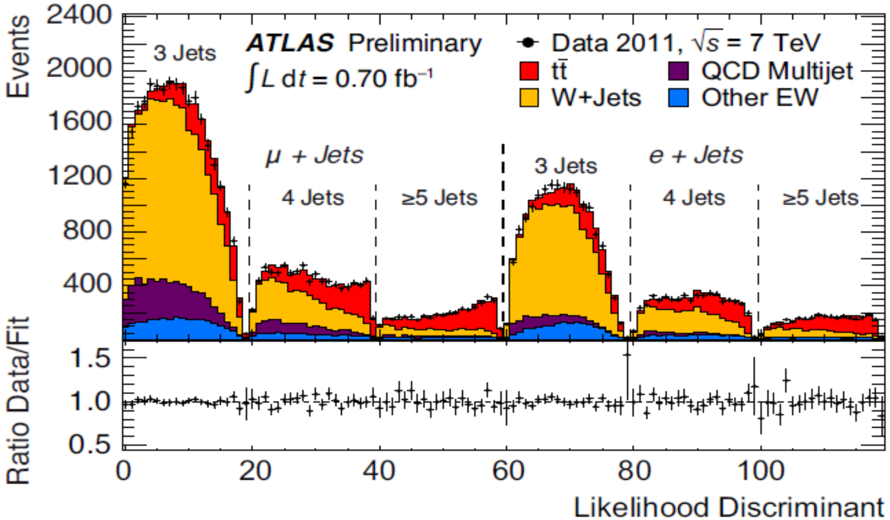
PRD 84 (2011) 012008

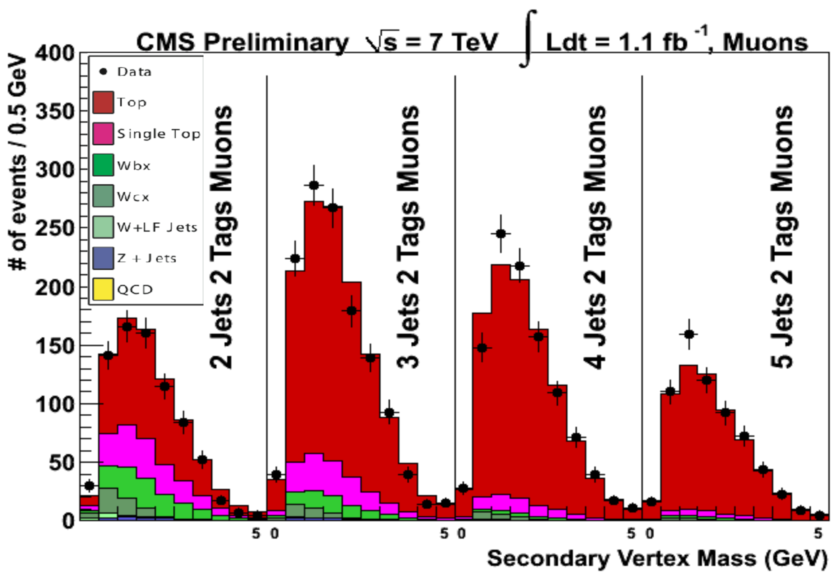
D0 (5.3 fb^{-1}, m_t= 172.5 GeV), b-tagged:
σ_{tt}=7.78±0.25(stat)$^{+0.73}_{-0.59}$ (syst) pb

PRL 105 (2010) 012001

CDF (4.6 fb^{-1}, m_t= 172.5 GeV), topo NN:
σ_{tt}=7.70±0.52(stat+syst) pb

Lepton + jets





Main backgrounds:

- Hadronic multijet: rejected by m_T, MET, controlled from sidebands
- W+jets (heavy flavor)

Use kinematics to select ttbar

- Mass of sec. vertex
- topology

Categorize events and extract σ_{tt} from fit

ATLAS: CONF-2011-100

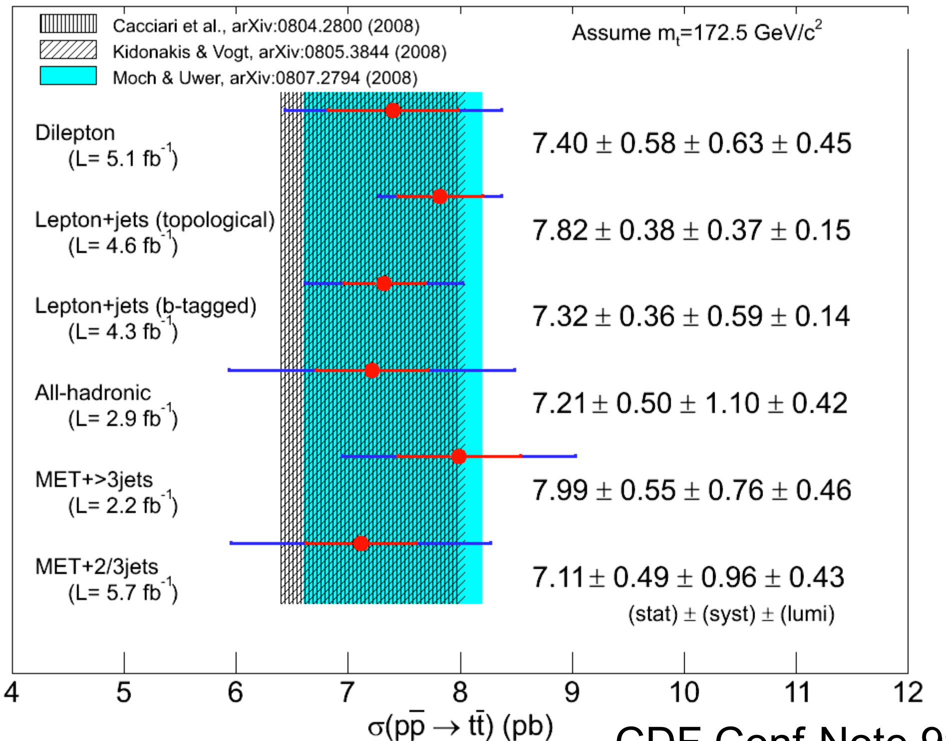
$179.0 \pm 3.9\,(stat) \pm 9.0\,(syst) \pm 6.6\,(lumi)$ pb ±7%

$164.4 \pm 2.8(stat.) \pm 11.9(syst.) \pm 7.4(lum.)$ pb ±9%

CMS: TOP-11-005

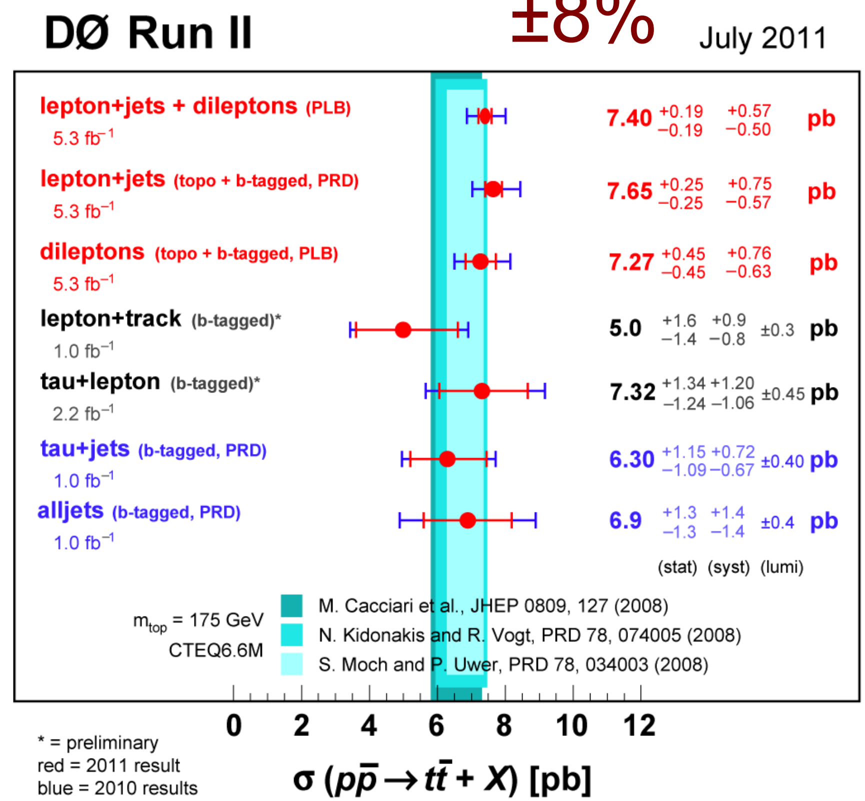
Cross sections at Tevatron

±6%



CDF Conf-Note 9913

±8%



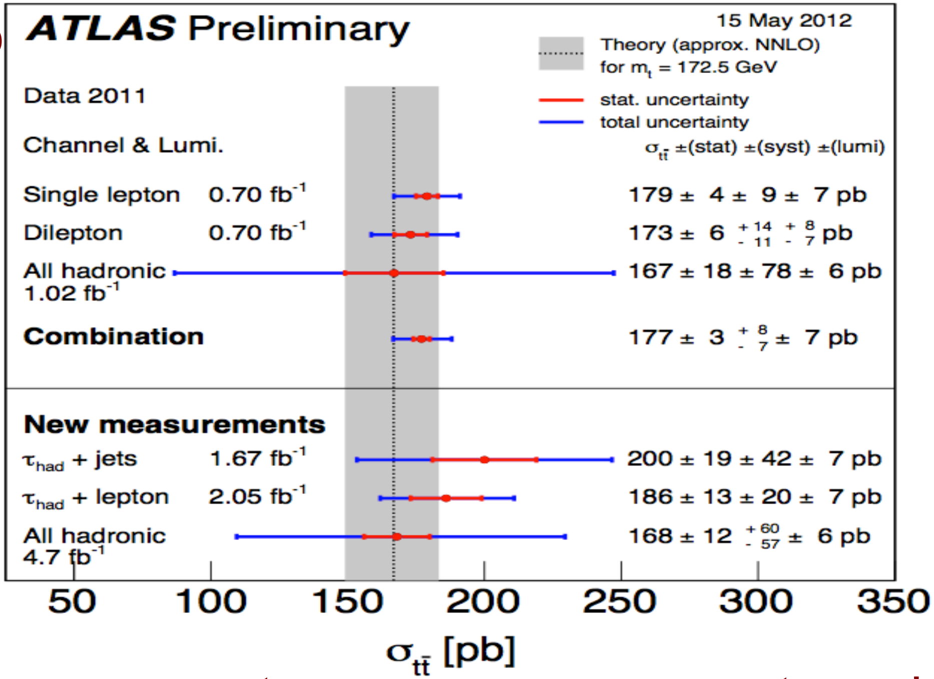
- Good agreement with SM
- Measurements ~limited by systematics

CDF Combined (4.6 fb^{-1}, m_t= 172.5 GeV)
σ_{tt} = 7.5±0.3(stat)±0.3(syst)±0.15(Z_{theo}) pb

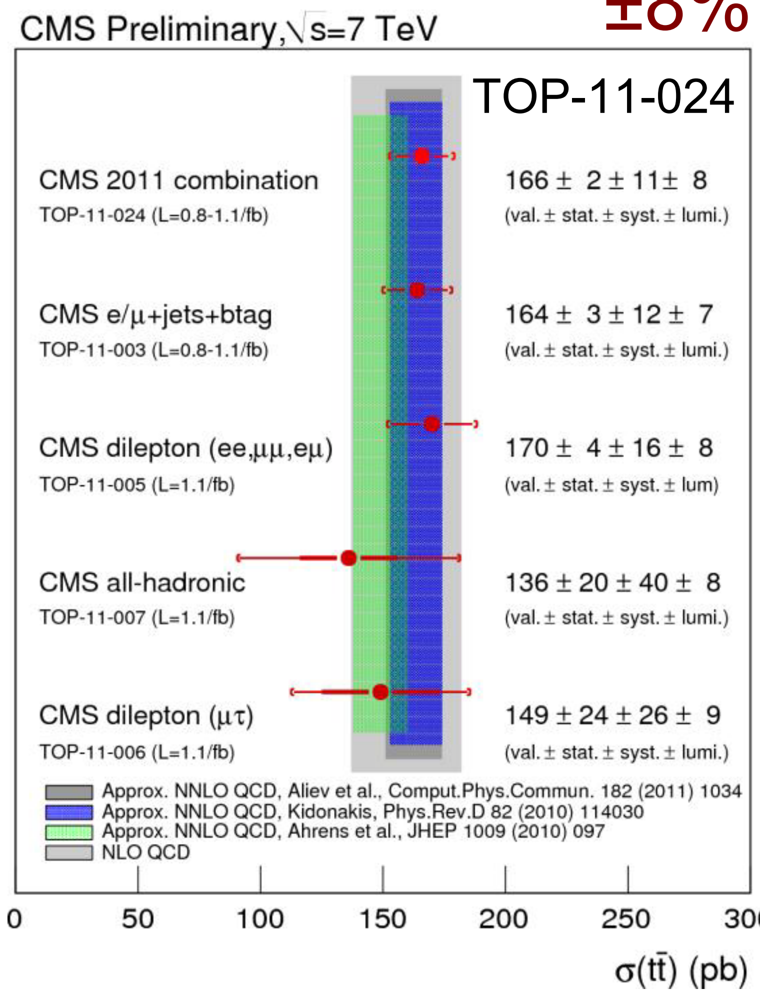
D0 combined (5.3 fb^{-1}, m_t= 170 GeV)
l+jets and dileptons
σ_{tt} = 7.4±0.19 (stat) $^{+0.57}_{-0.50}$ (syst) pb

Cross sections at 7 TeV

±7%



±8%



Good agreement among measurements and predictions for all decay modes

	Tevatron	LHC (7 TeV)
NLO	$6.74^{+0.36+0.37}_{-0.76-0.24}$	160^{+20+8}_{-21-9}
Aliev et. al. [77]	$7.13^{+0.31+0.36}_{-0.39-0.26}$	164^{+3+9}_{-9-9}
Kidonakis [14]	$7.08^{+0.00+0.36}_{-0.24-0.24}$	163^{+7+9}_{-5-9}
Ahrens et. al. [69]	$6.65^{+0.08+0.33}_{-0.41-0.24}$	156^{+8+8}_{-9-9}

⇒measurements are challenging the theory

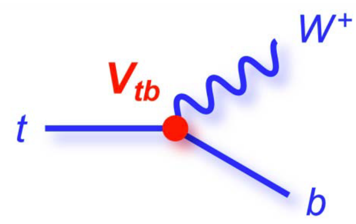
scale unc. ~5%

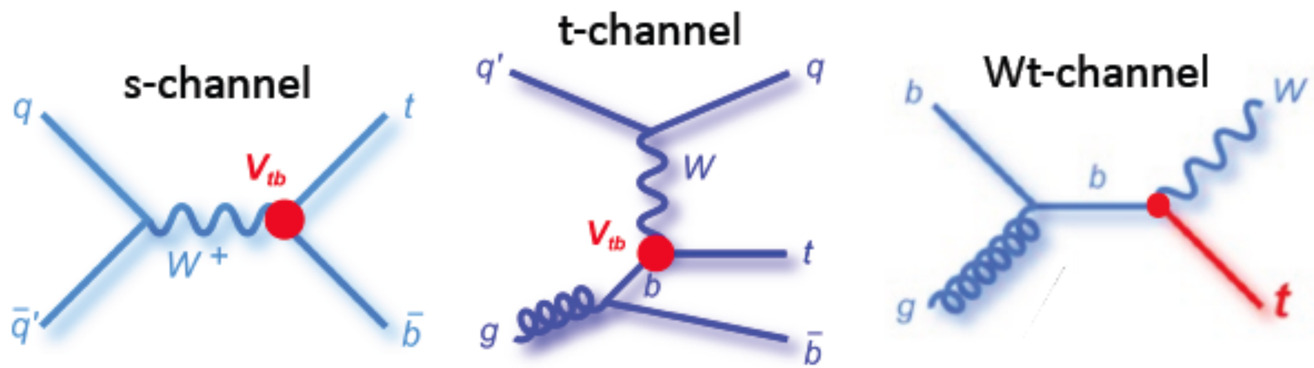
PDF unc. ~5%

Single top

- Test Electroweak production of top
- Challenging measurement (small signal, similar bkg)
- Direct measurement of Vtb (check structure of Wtb vertex)
- Sensitive to New Physics processes (FCNC, W', etc)

$\sigma \sim |V_{tb}|^2$



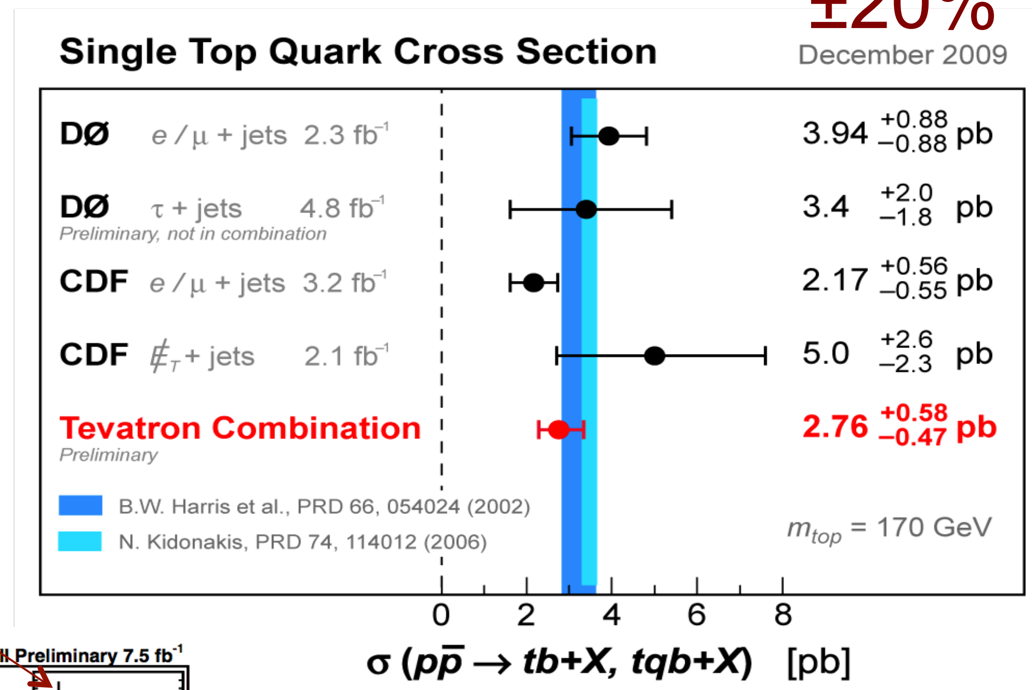


For M_t = 172.5 GeV	σ_{tb}	σ_{tqb}	σ_{tW}
$p\bar{p}$ @ 1.96 TeV	1.04 ± 0.04 pb	2.26 ± 0.12 pb	0.28 ± 0.06 pb
pp @ 7 TeV	4.6 ± 0.3 pb	64.6 +3.3 -2.6 pb	15.7 ± 1.4 pb

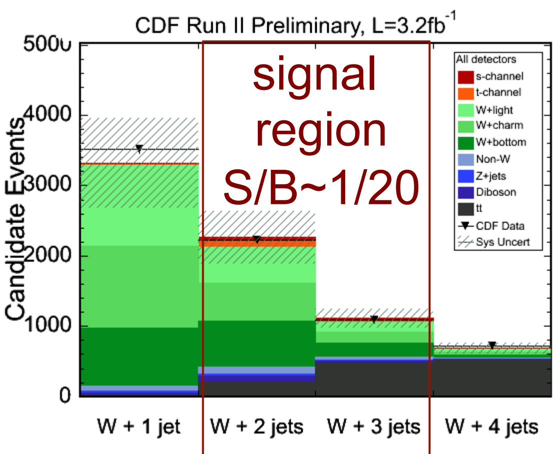
Single top

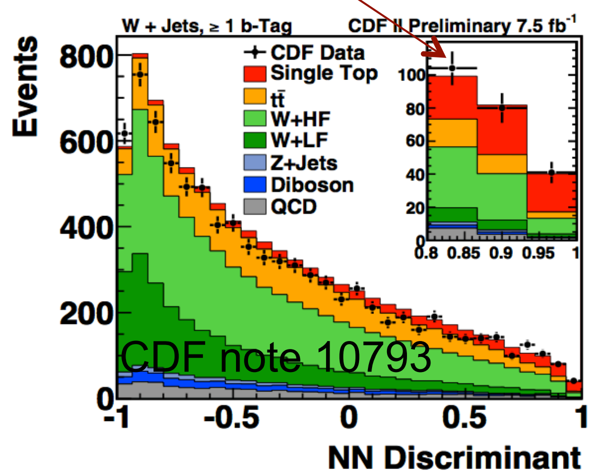
- Difficult measurement
- Observed at Tevatron in 2009
- First evidence at LHC in 2010

±20%



Multivariate techniques to enhance the signal

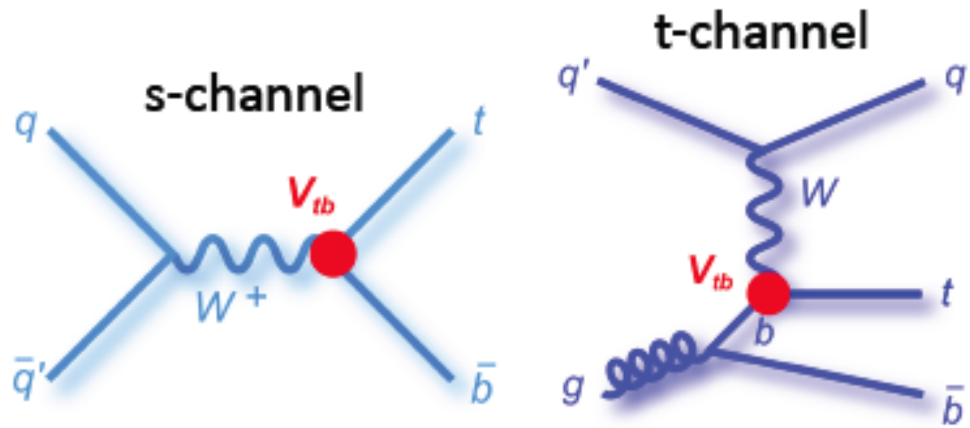


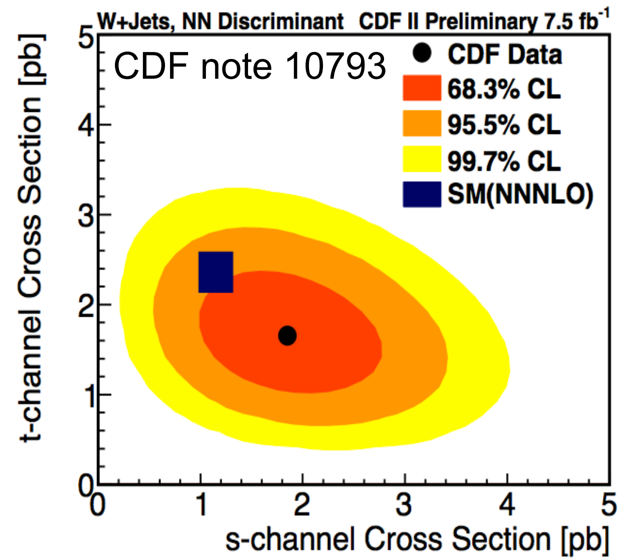


PRL 103, 092001(2009). PRL 103, 092002(2009)

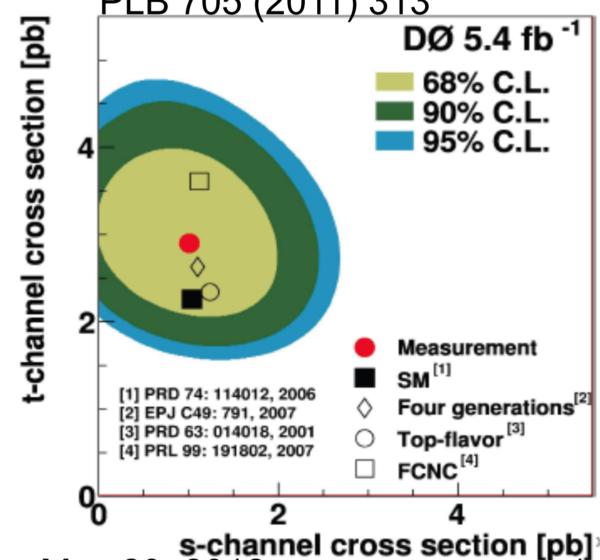
Single top: s- and t-channels

- s- and t-channels sensitive to different BSM processes
- Simultaneous determination of s- and t-channel cross sections
- MVA training (no constraint on relative rates)





PLB 705 (2011) 313



σ(t-ch)=2.90±0.59 pb
σ(s-ch)=0.98±0.63 pb

PLB 705 (2011) 313

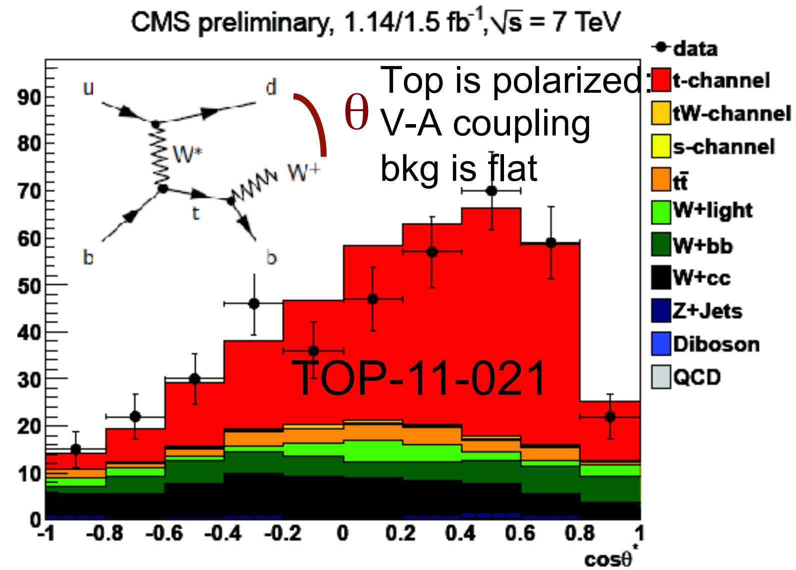
⇒most precise measurement in t-channel at Tev: >5σ significance

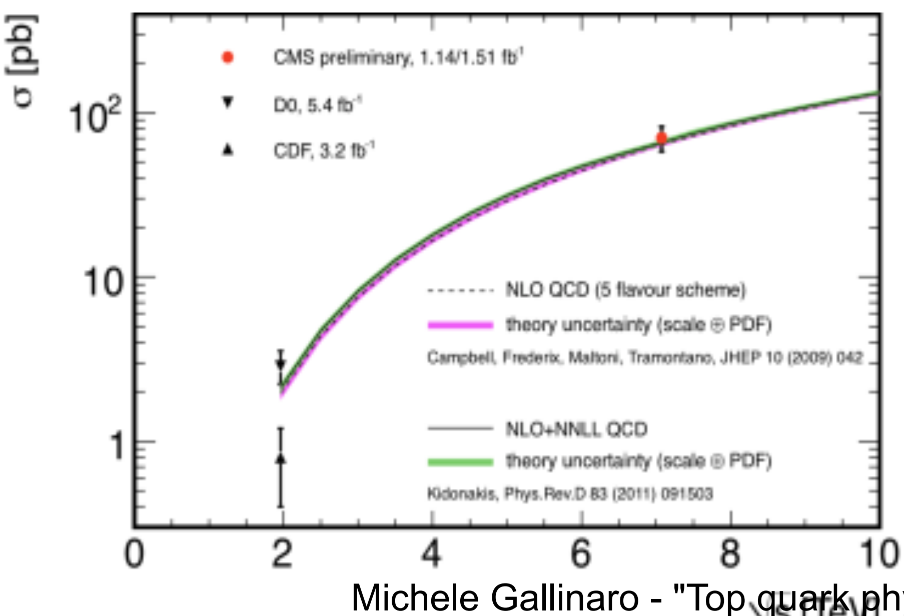
$|V_{tb}|>0.79$ @95%CL with Vtb:[0,1]

D0: PRD84, 112001 (2011)

Single top at LHC: t-channel

- Dominant production is t-channel
  - 1 central/isolated lepton, MET, 1 b-jet, 1 forward recoil jet
- main backgrounds: multijet, W+jets
- Signal-background separation
  - Robust fit to angular variables
  - MVA to exploit signal topology
  - backgrnd rates/shapes taken from control regions in data
- LHC results consistent with SM





t-channel has small theory unc.

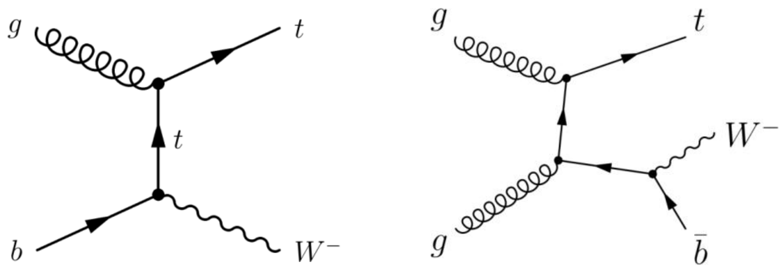
$$\sigma^{th}_{t-ch.} = 64.57^{+2.09}_{-0.71}\,(\text{scale})^{+1.51}_{-1.74}\,(\text{PDF})\ \text{pb} \qquad \pm 4\%$$

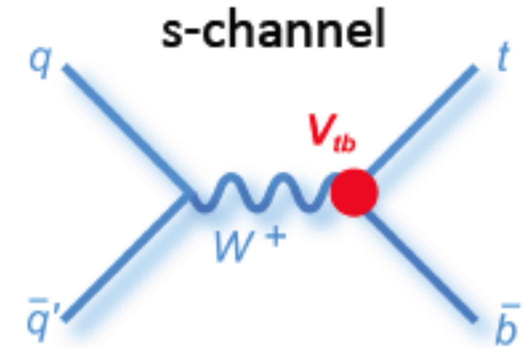
CMS: TOP-11-021
σ_t = 70.2 ± 5.2(stat)±10.4(syst)±3.4 (lum) pb ±18%

σ_t = 83 ± 4 (stat) ± 20 (syst) pb ±31%
ATLAS: arXiv:1205.3130

Single top: tW- and s-channel

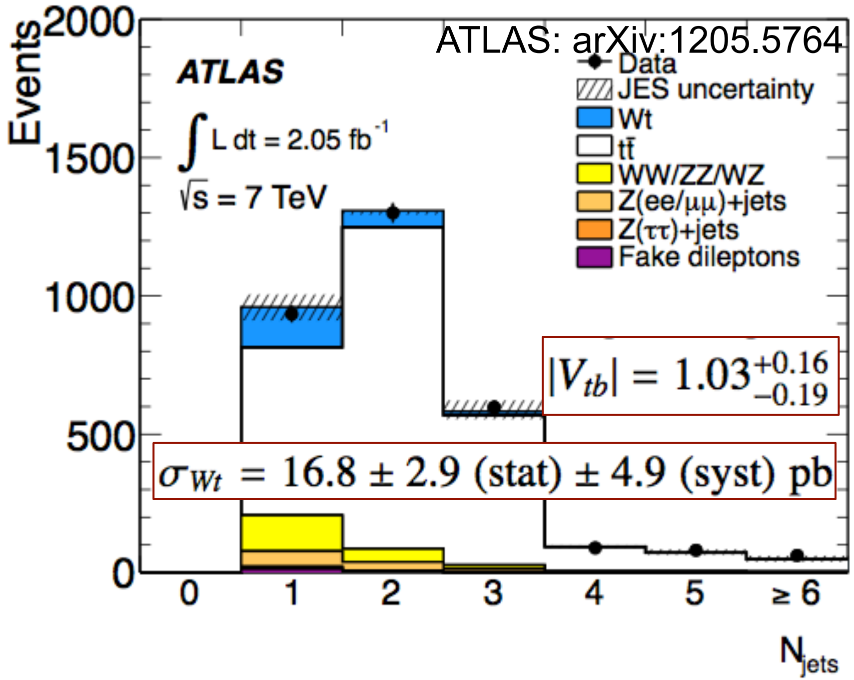
s-channel and associated tW production (lepton+jets, dilepton)





$\sigma_{Wt} = 22^{+9}_{-7}$ (stat ⊕ syst) pb 2.7 σ CMS TOP-11-022

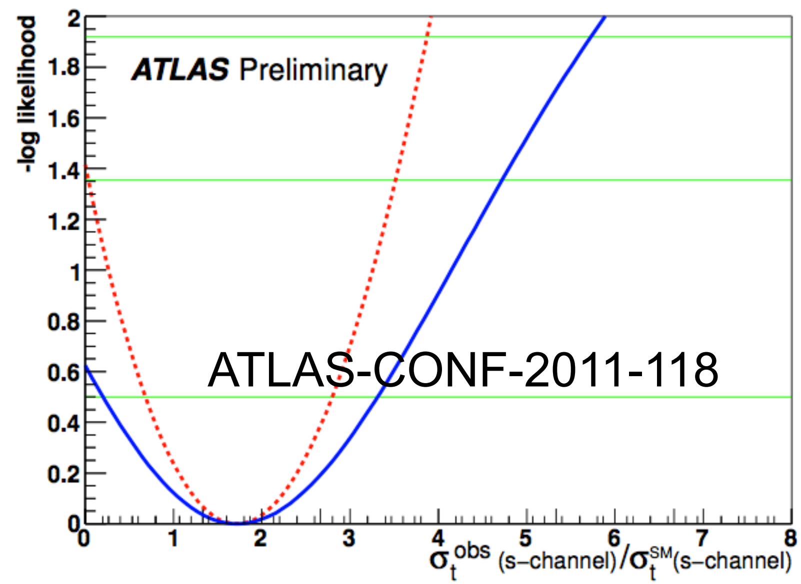
$\sigma_{s\text{-}ch}$ <26.5 pb @95% C.L.



$|V_{tb}| = 1.03^{+0.16}_{-0.19}$

$\sigma_{Wt} = 16.8 \pm 2.9$ (stat) ± 4.9 (syst) pb

±37%

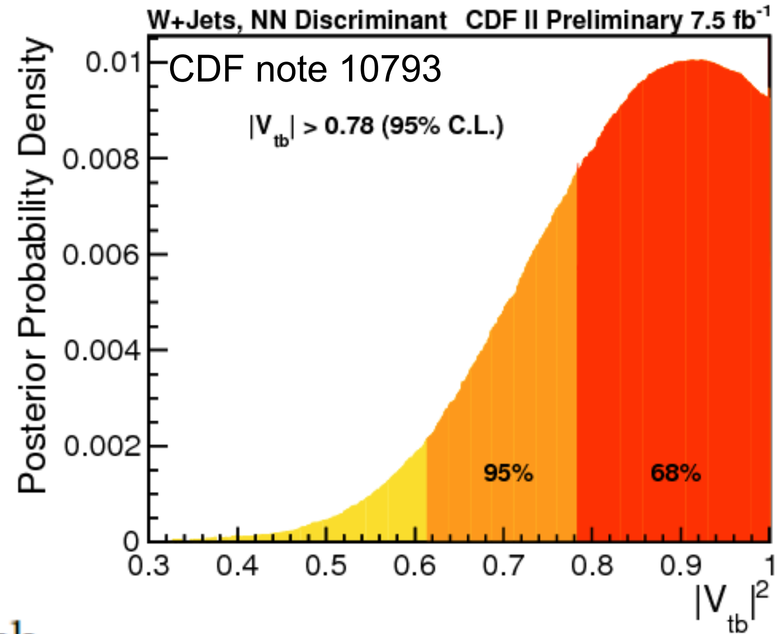


ATLAS-CONF-2011-118

Direct $|V_{tb}|$ measurement

- Use cross section result
- Measurement assumes SM production mechanism, does not assume 3-generation/unitarity

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



$$\sigma_{t-\text{ch.}} = 70.2 \pm 5.2(\text{stat.}) \pm 10.4(\text{syst.}) \pm 3.4(\text{lumi.})\ \text{pb}$$

$|V_{tb}|$=1.04 ± 0.09 (exp) ± 0.02(theo)
CMS: TOP-11-021

$|V_{tb}|$>0.78 @95%CL
CDF: 7.5fb^{-1}

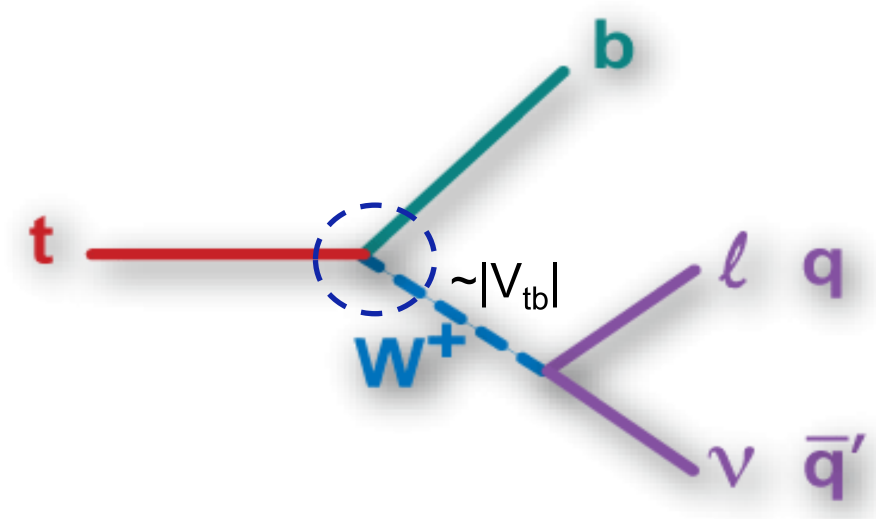
$$\sigma_t = 83 \pm 4\ (\text{stat.})\ ^{+20}_{-19}\ (\text{syst.})\ \text{pb}$$

$|V_{tb}|$>0.75 @95%CL
ATLAS: arXiv:1205.3130

$|V_{tb}|$>0.79 @95%CL
D0: 5.4fb^{-1} PRD84, 112001 (2011)

Is BR(t→Wb)~100% ?

- In the SM, $R \equiv \dfrac{BR(t \to Wb)}{BR(t \to Wq)} \approx |V_{tb}|^2$ (q=b,s,d) 0.9980<R<0.9984
- In SM: R=1 constrained by unitarity. R<1 could indicate New Physics
- Drop assumption R=1
- measure R by comparing the number of ttbar events with 0, 1 and 2 b-tags



Measure R simultaneously with ttbar cross section:

$\sigma_{p\bar{p}\to t\bar{t}}(pb)$	7.4 ± 1.1
R	0.91 ± 0.09
$\lvert V_{tb}\rvert$	0.95 ± 0.05

CDF prelim. 7.5 fb^{-1}
lepton+jets channel

$\sigma_{t\bar{t}} = 7.74^{+0.67}_{-0.57}$ pb
R=0.90±0.04 (stat+syst)
$|V_{tb}|$=0.95±0.02 (stat+syst)
$|V_{tb}|$>0.88 @99.7% C.L.

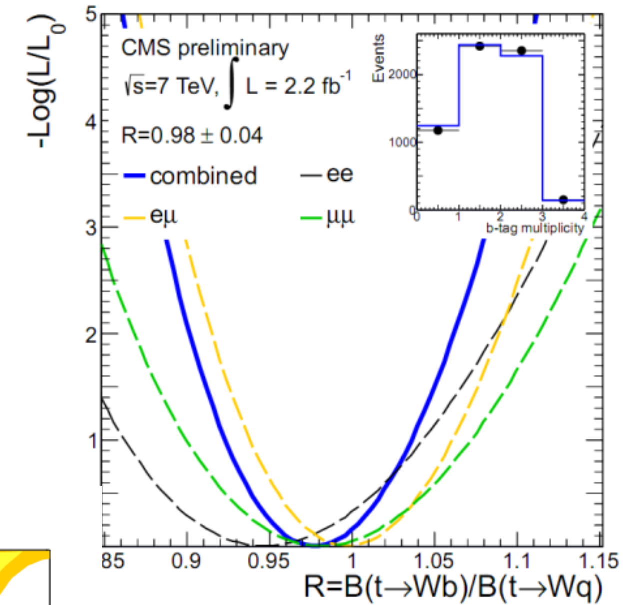
D0 5.4 fb^{-1}
l+jets & dilepton

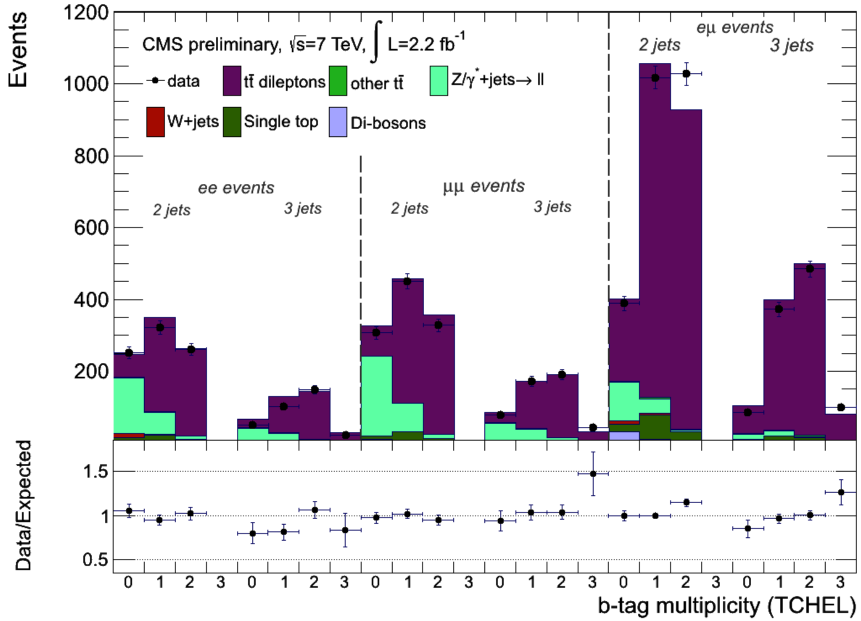
PRL 107, 121802 (2011)

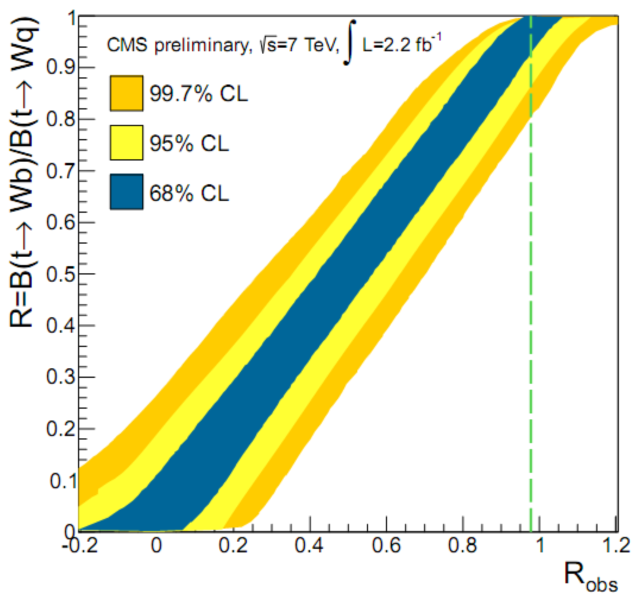
Not yet sensitive to SM

R=B(t→Wb)/B(t→Wq)

- First measurement at the LHC
- Use dilepton events (standard selection)
- Fully "data-driven" background determination
  - Use wrong assignment in Mlb distribution
- b-tagging multiplicity parametrized as function of R, ε_b, ε_q
  - Fit R, using ε_b from inclusive b-jet production





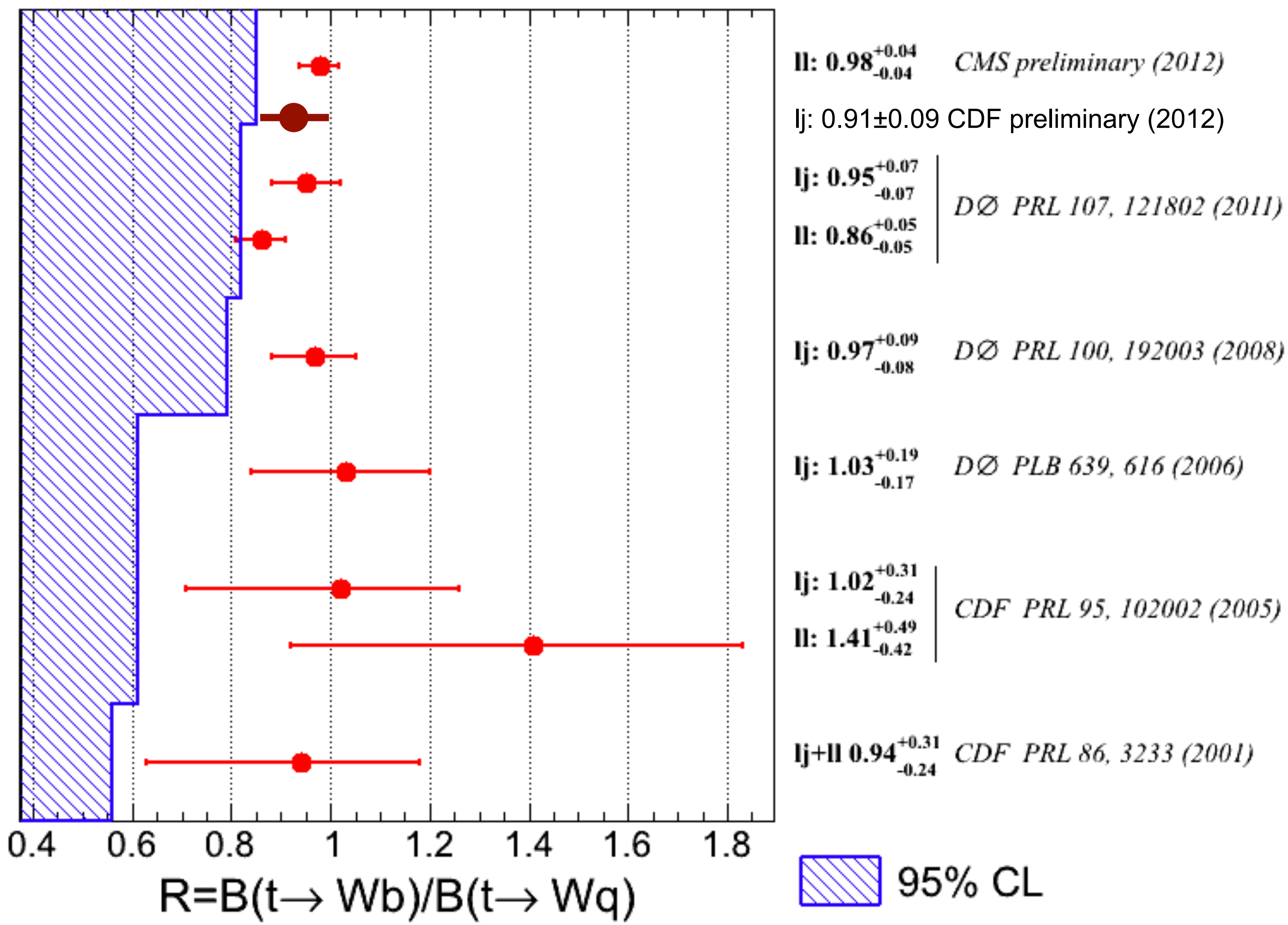


$R = 0.98 \pm 0.04$

$R > 0.85$ at 95% C.L.

CMS TOP-11-029

Summary of R measurements

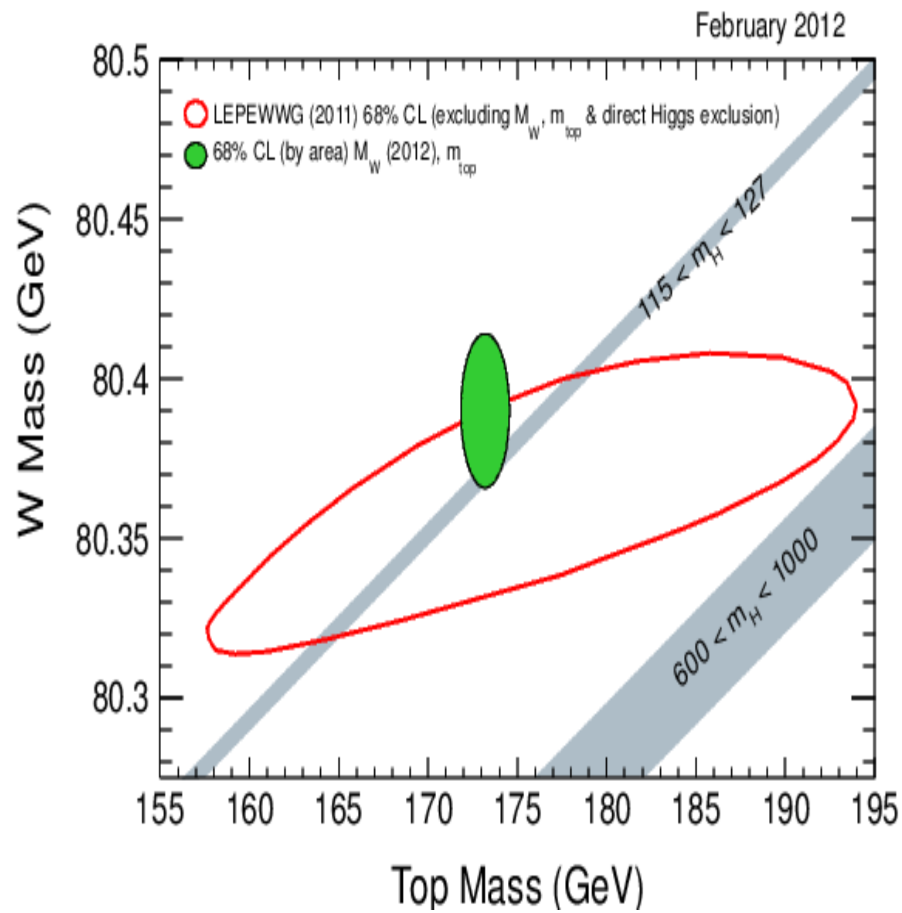


Top quark mass

- Top quark mass is a fundamental parameter of the SM
  - Known with good accuracy from the Tevatron: 173.2±0.9 GeV (arXiv:1107.5255)
  - Indirect constraint on the Higgs boson mass via EW corrections

  ⇒ $m_H=92^{+34}_{-26}$ GeV or <161 GeV

$\delta m_W \propto m_t^2$ $\delta m_W \propto \log m_h$



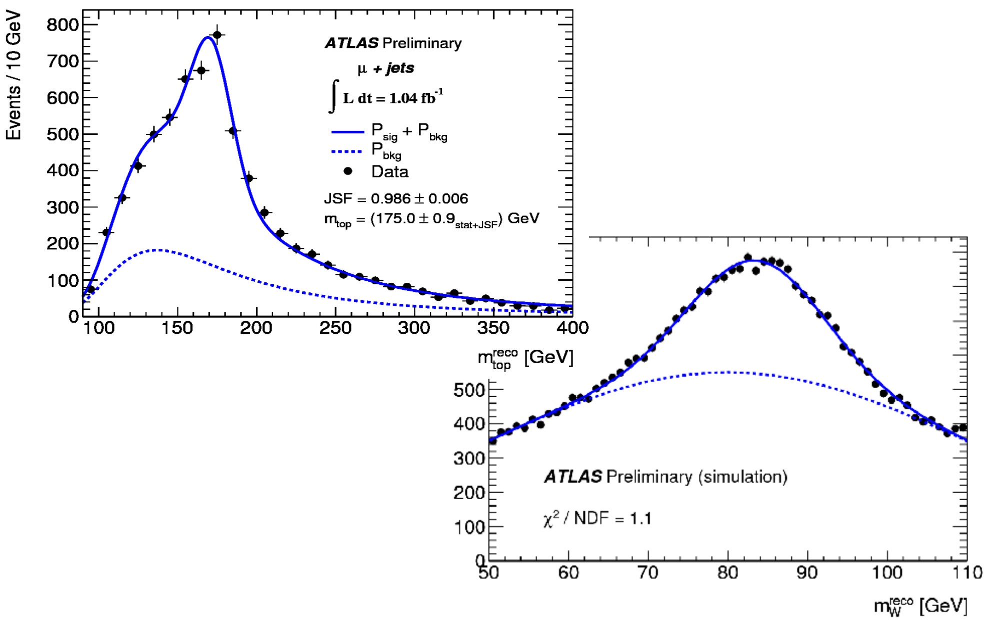
- Top is the only fermion with the mass of the order of EWSB scale
- Measuring precisely m_W and m_{top}
  - Test consistency of SM
  - Search for New Physics

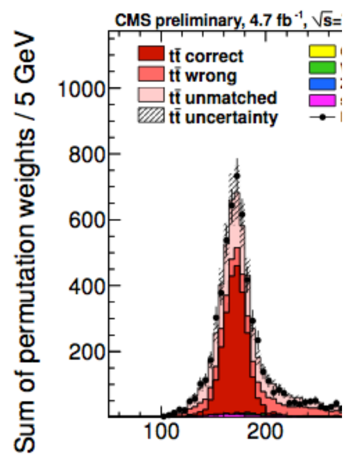
Lepton + jets

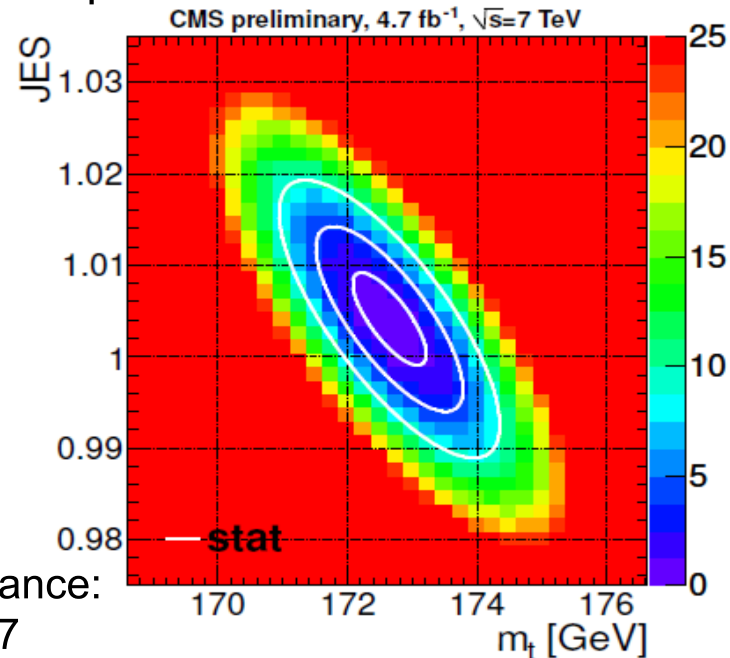
- in-situ calibration of the light quark JES from W→ qq’

ATLAS: template fit as function of JES and top quark mass

CMS: kinematic fit + “ideogram” method combine event-per-event likelihood







Test CPT invariance: arXiv:1204.2807

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

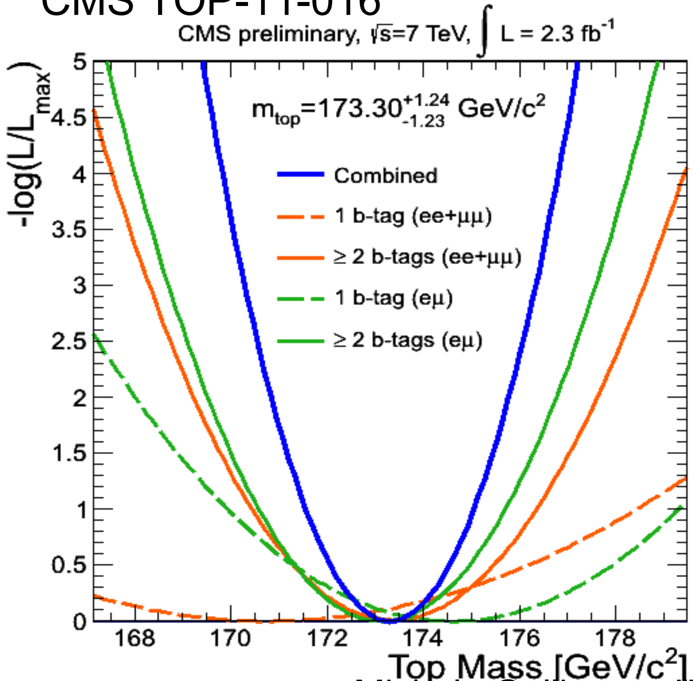
⇨m_{top}=174.4 ± 0.6 (stat) ± 2.3 (syst) GeV	ATLAS: arXiv:1203.5755	±1.4%
172.6 ± 0.6 (stat) ± 1.2 (syst) GeV	CMS TOP-11-015	±0.8%

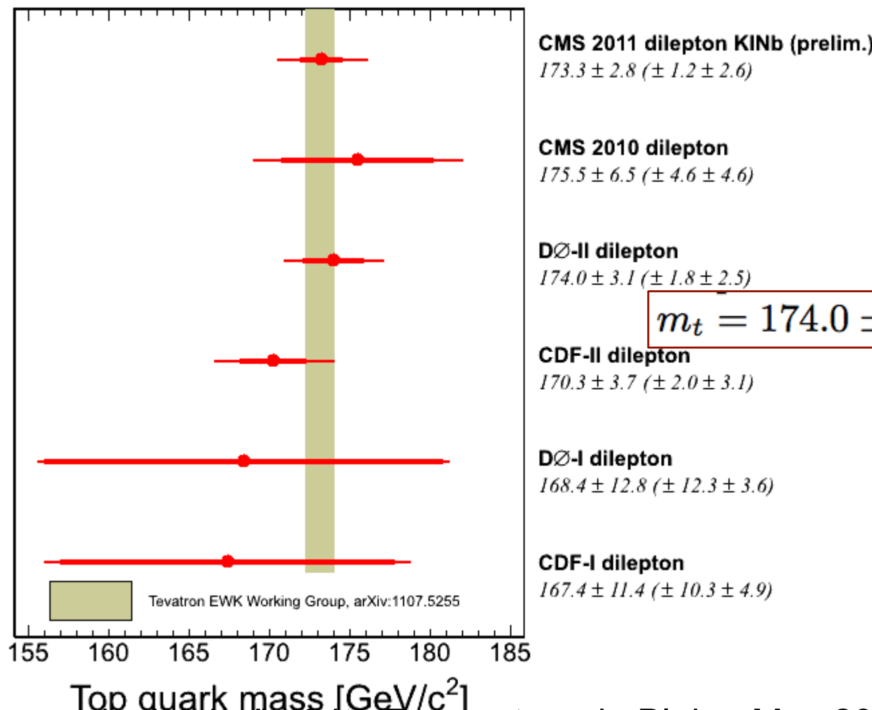
Top mass in dileptons

- Under-constrained system (2 neutrinos)
- Event selection similar to cross section measurement (require MET)
- Reconstruct event kinematics with full event kinematic (KINb method)
- Measurement dominated by JES uncertainty

$$m_{top} = 173.3 \pm 1.2(\text{stat.})^{+2.5}_{-2.6}(\text{syst.})\ \text{GeV}/c^2$$ ±1.7%

CMS TOP-11-016

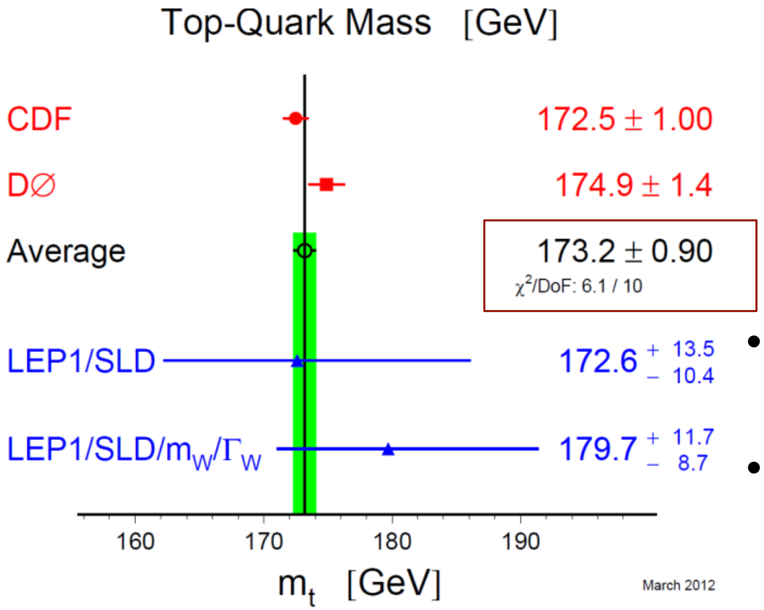




D0: arXiv 1201.5172
JEC from lepton+jets

$$m_t = 174.0 \pm 2.4(\text{stat}) \pm 1.4(\text{syst})\ \text{GeV}$$

Top quark mass

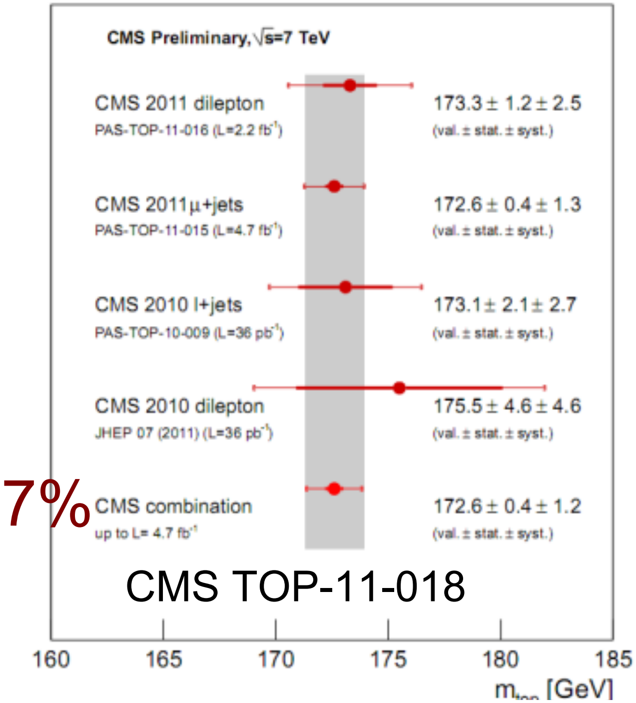


arXiv:1107.5255

±0.5%

- Combination dominated by the l+jet channel
- Towards LHC and global combination

±0.7%

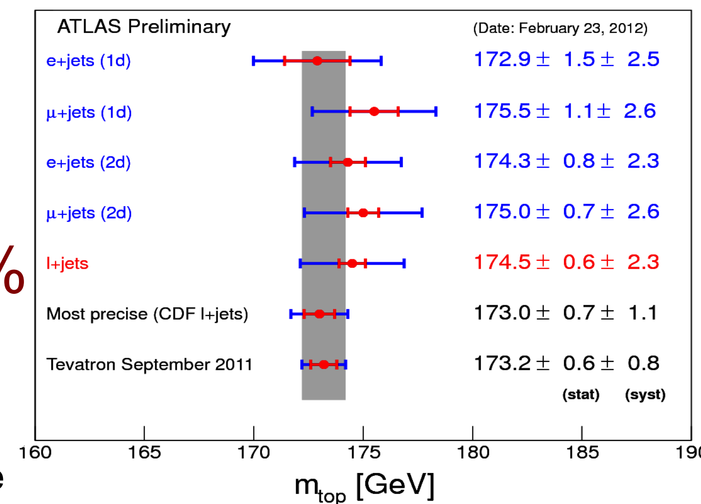


Global EWK fit:

- $M_H = 92^{+34}_{-26}$GeV, or M_H<161GeV
- direct searches: M_H>115.5 GeV, M_H<127 GeV

⇨ fit suggests SM Higgs is light

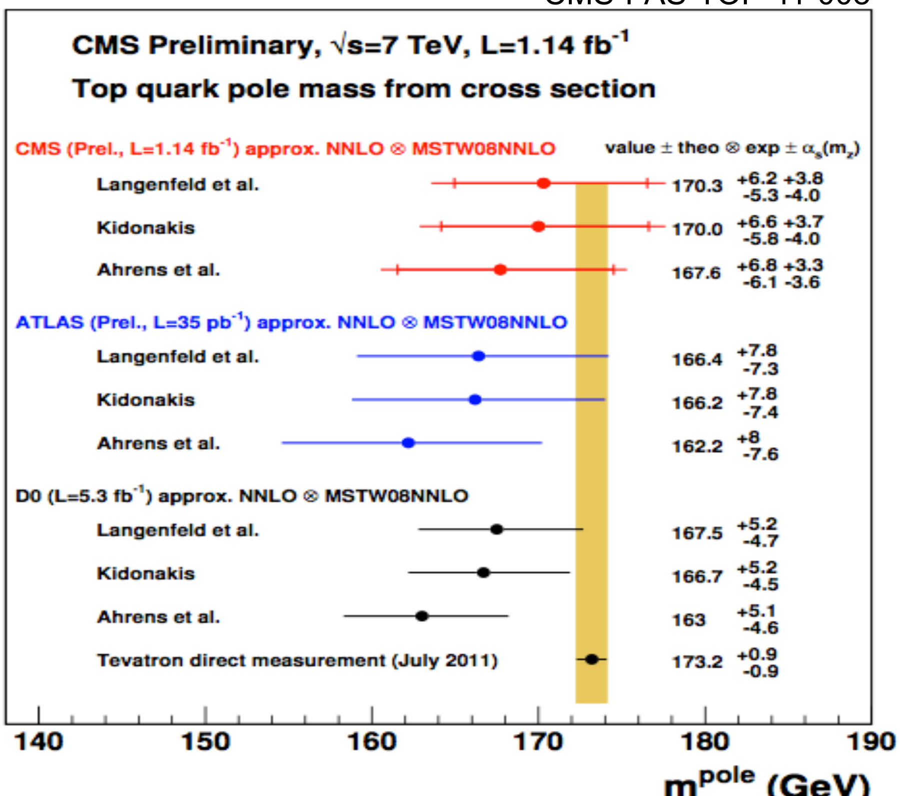
±1.4%

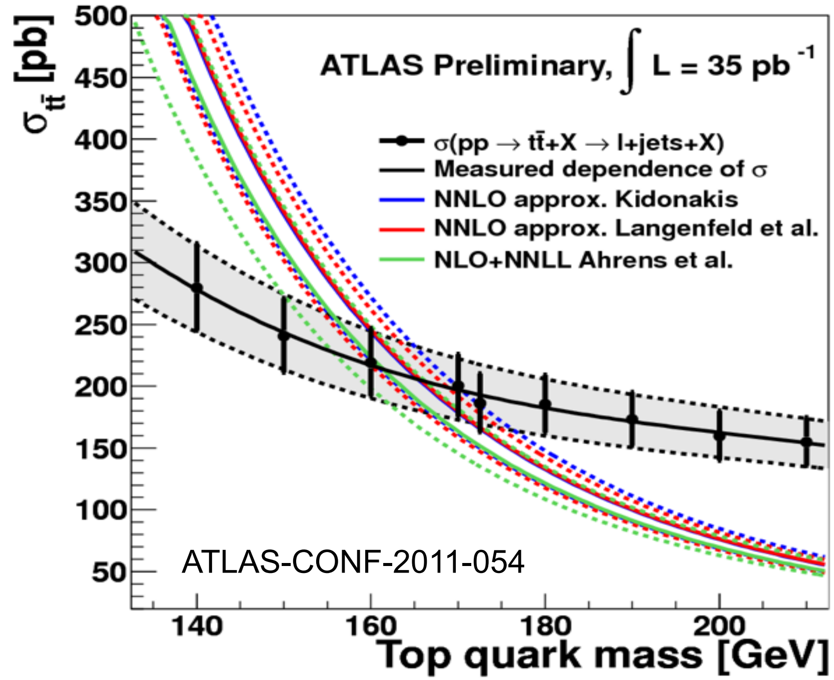


Top mass from cross section

- Direct m_{top} measurements rely on details of kinematics, reconstruction, calibration
- Extract mass from cross section
- determine top quark pole mass using the experimental ttbar production cross section

CMS-PAS-TOP-11-008





Also determine m(MSbar):

CMS-PAS-TOP-11-008

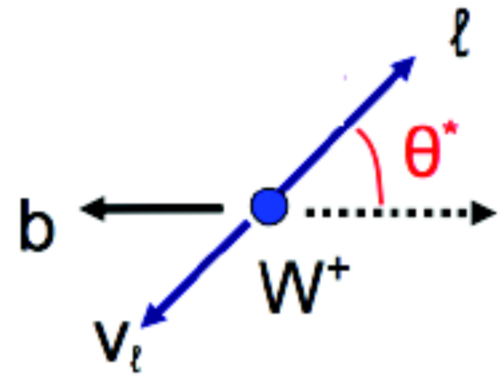
Approx. NNLO × HERAPDF15NNLO	m_t^{pole} / GeV	$m_t^{\overline{MS}}$ / GeV
Langenfeld et al. [7]	$171.7^{+6.8}_{-6.0}$	$164.3^{+6.5}_{-5.7}$
Ahrens et al. [9]	$169.1^{+6.7}_{-5.9}$	$161.0^{+6.8}_{-6.1}$

⇒It works but the uncertainty is large

W helicity

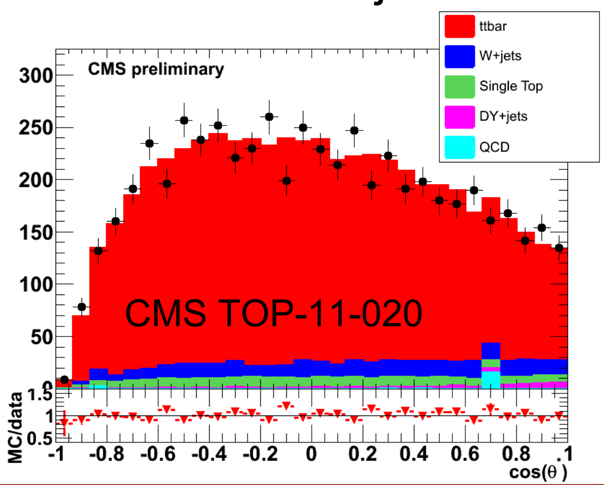
- Top decays before hadronization
  - Spin information is directly transferred to its decay products (t→Wb)
- Sensitive to anomalous tWb coupling

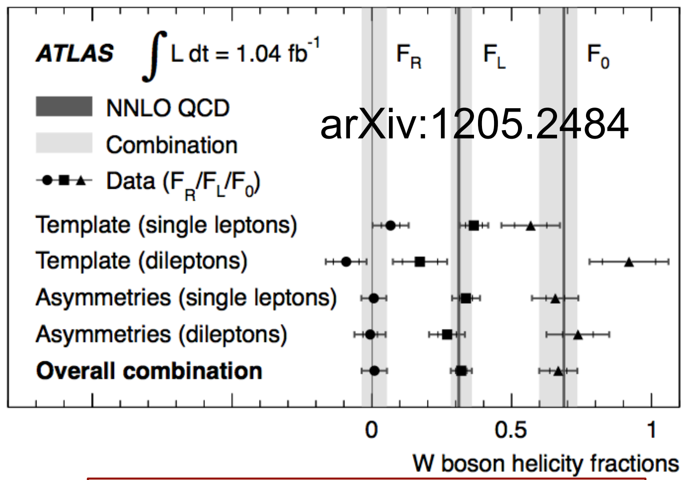
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*_\ell} = \frac{3}{8}(1+\cos\theta^*_\ell)^2 F_R + \frac{3}{8}(1-\cos\theta^*_\ell)^2 F_L + \frac{3}{4}\sin^2\theta^*_\ell F_0$$

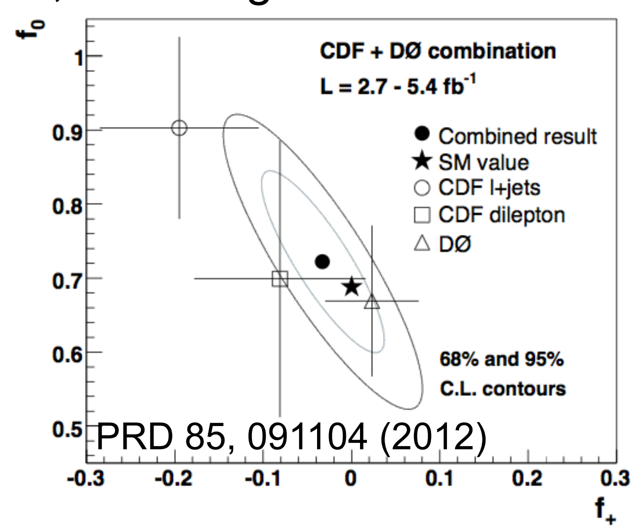


- Measure θ*: angle between lepton and b-jet (in W rest frame)
- 3 possible W polarization modes: $F_0 = 0.698, \quad F_L = 0.301, \quad F_R = 4.1\times 10^{-4}.$

Measurement subject to: detector effects, resolution, acceptance, modeling of uncertainties







$$\begin{aligned} F_0 &= 0.567 \pm 0.074(\text{stat.}) \pm 0.047(\text{syst.}) \\ F_L &= 0.393 \pm 0.045(\text{stat.}) \pm 0.029(\text{syst.}) \\ F_R &= 0.040 \pm 0.035\ (\text{stat.}) \pm 0.044(\text{syst.}) \end{aligned}$$

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

⇒results consistent with SM

Wtb coupling

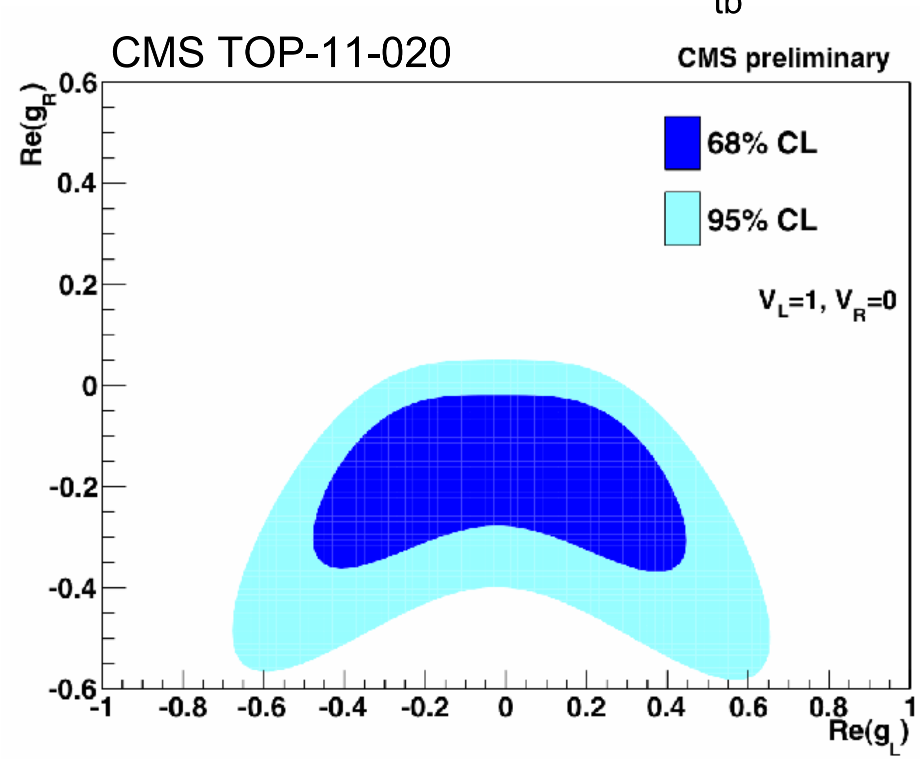
- Helicity fractions constrain anomalous couplings

$$\mathcal{L}_{tWb} = \mathcal{L}_{tWb}^{\rm SM} - \frac{g}{\sqrt{2}}\bar{b}\Big[(V_L P_L + V_R P_R)\gamma^\mu + \frac{i\sigma^{\mu\nu}q_\nu}{m_W}(G_L P_L + G_R P_R)\Big]tW_\mu$$

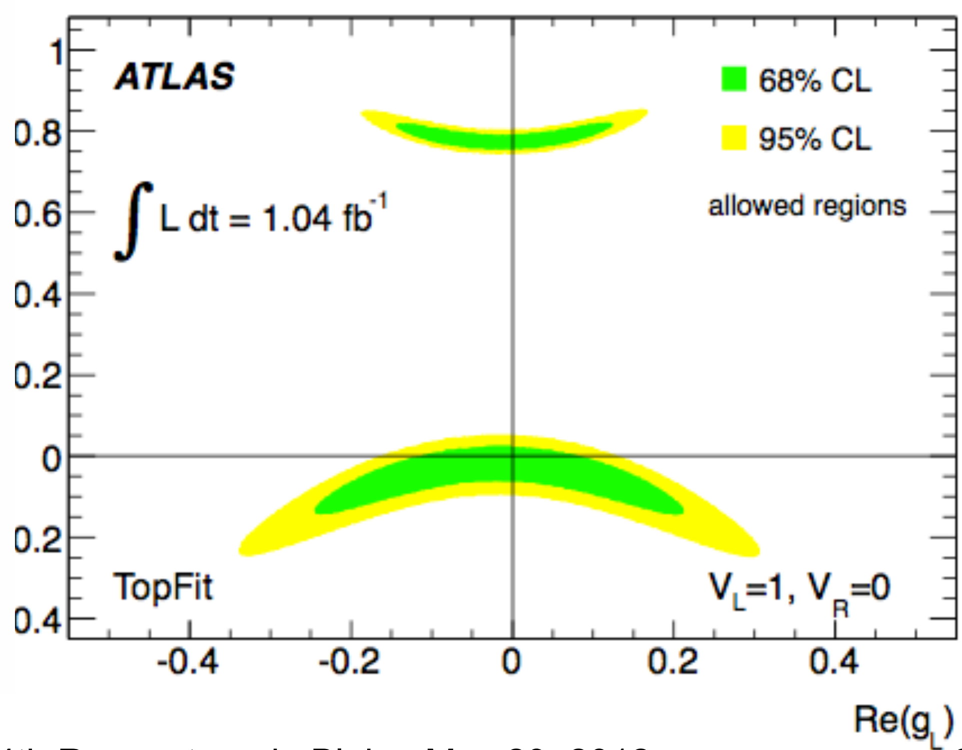
$V_{tb}=1$

In SM: $V_R=g_L=g_R=0$

CMS TOP-11-020

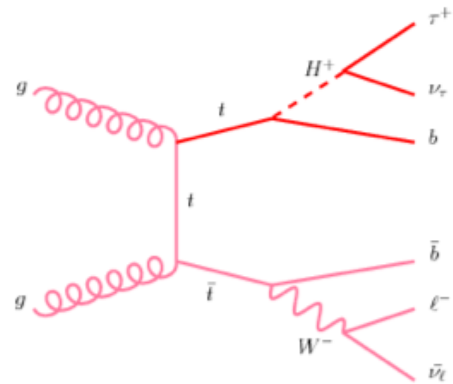


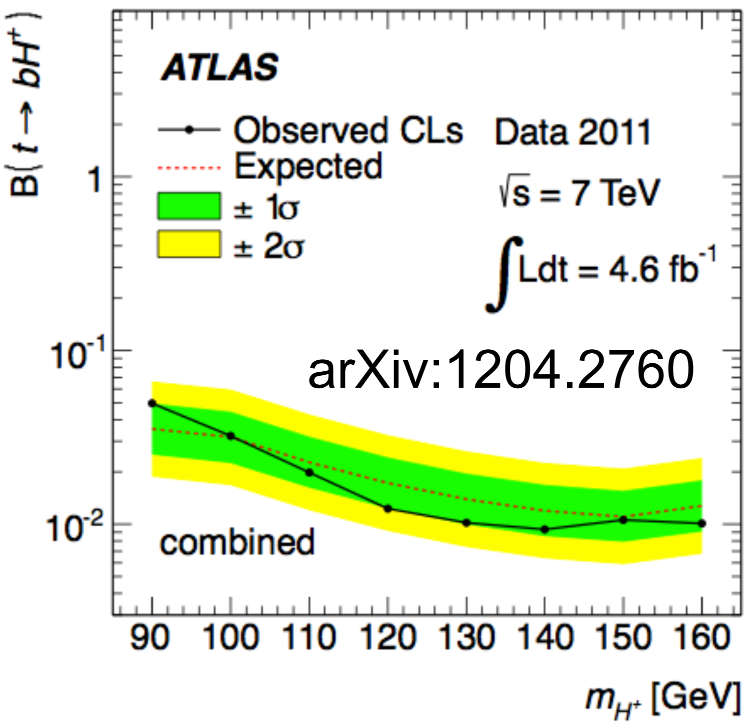
arXiv:1205.2484

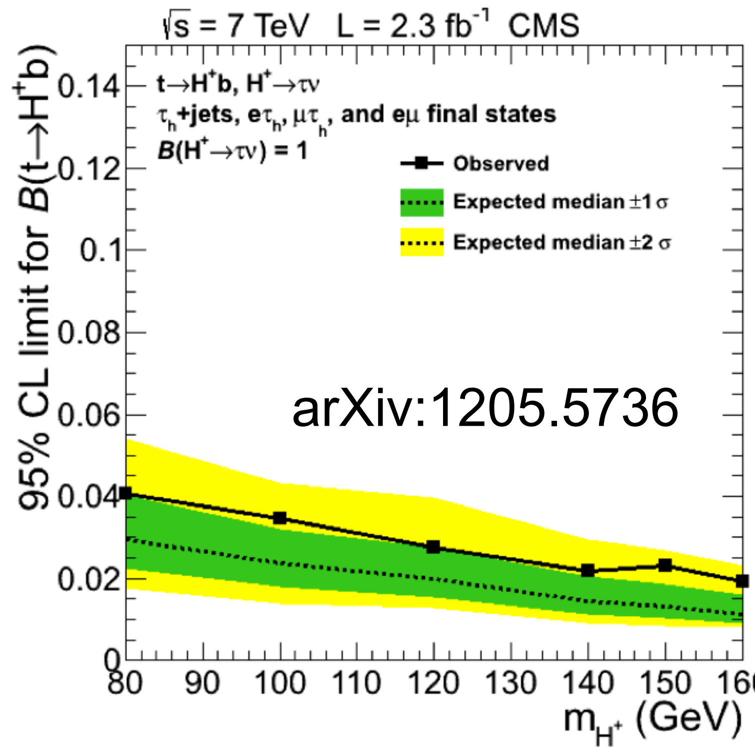


Probing the Wtb vertex

- If top quark plays special role in EWK symmetry breaking, couplings to W may change
- Charged Higgs may alter coupling to W

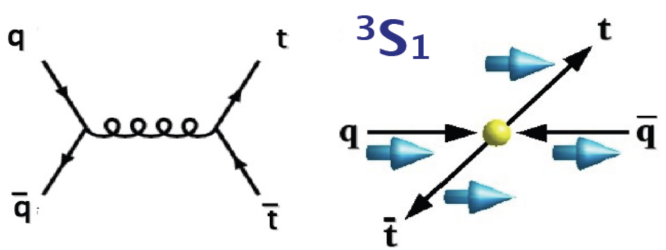






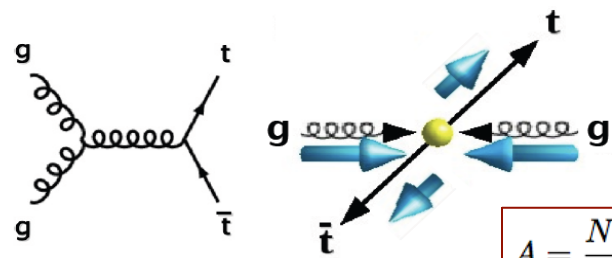
Spin correlation: Tevatron vs LHC

- Top quark decay products retain correlation
  - decays before hadronization ($\tau \sim 10^{-25}$ sec) ⇒ spin information transmitted to decay products ($t \rightarrow Wb$)
- Spin correlation depends on the production mode



Tevatron

- Dominated by qqbar annihilation
- ttbar pairs produced at threshold



LHC

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

- Dominated by gg annihilation
- ttbar pairs produced far from threshold

Bernreuther, Brandenburg, Si, Uwer, Nucl. Phys. B690 (2004) 81

- Analyze spin using angular distributions of decay products
- Spin correlation may differ from what expected in SM
  - charged Higgs $t \rightarrow H^+ b$, or other BSM processes

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 + \kappa \cos\theta_1 \cos\theta_2\right)$$

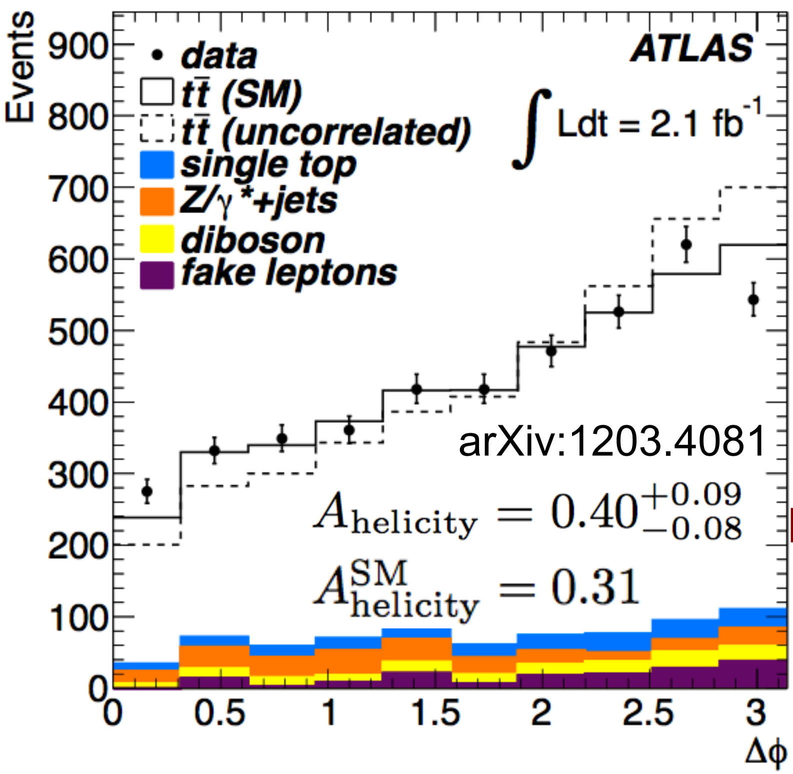
⇒complementarity between Tevatron and LHC

Spin correlation

Access spin information via the angular distributions of its decay products

- Fit to difference in azimuthal angle between leptons $\Delta\phi$
- No need for full top quark event reconstruction
- Main systematics: JES, resolution/efficiency, fake leptons

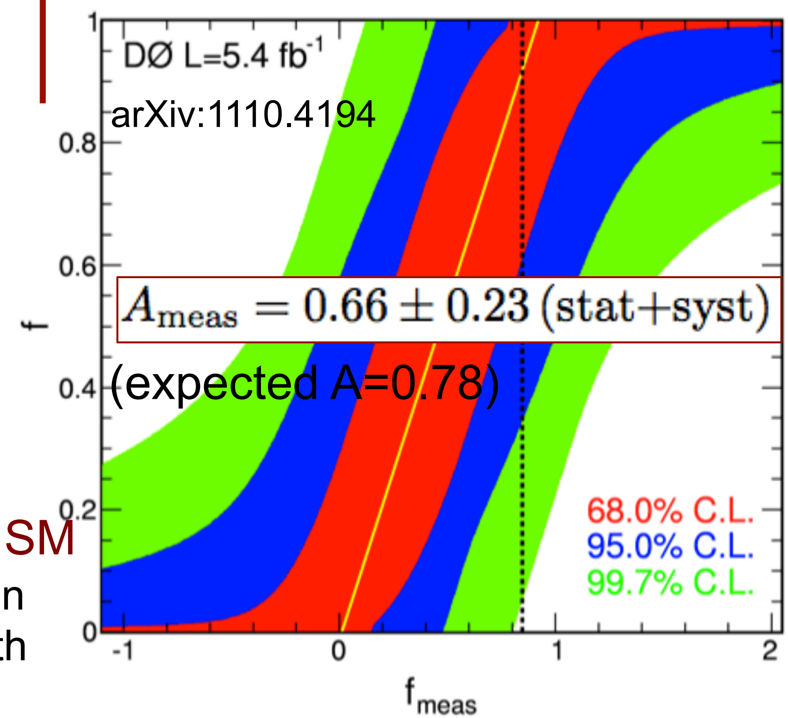
- Use l+jet channel (729 events)
- Matrix element method
- results indicate spin correlation at 3.1σ



$$A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}}$$

Results consistent with SM

inconsistent with zero-spin hypothesis correlation with a significance of 5.1σ



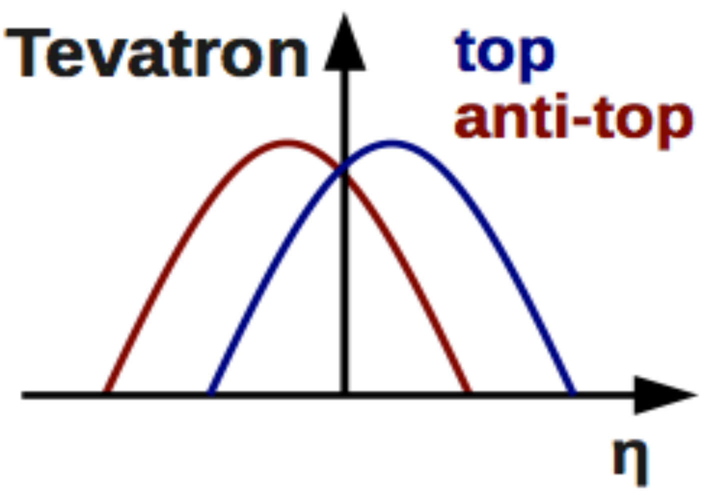
See also, CDF note 10211

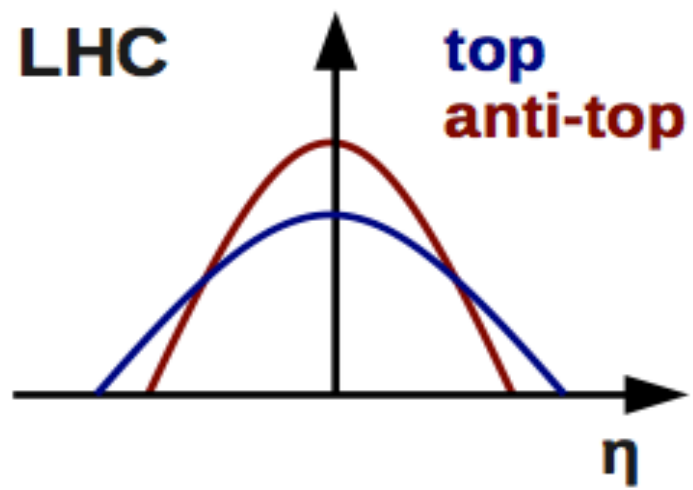
Charge asymmetry

- In qqbar→ttbar (Tevatron): top quarks are emitted in the direction of the incoming quark, anti-top quarks in the direction of the incoming anti-quark
- No asymmetry in gg→ttbar (LHC)

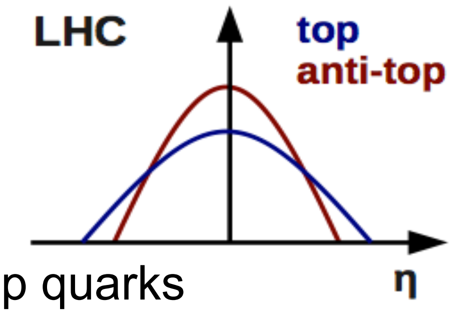
SM: Only small asymmetry due to ISR/FSR

New physics: production mechanisms with new exchange bosons could enhance the charge asymmetry





Charge asymmetry



- Quarks have larger momentum than anti-quarks
- Anti-quarks from sea tend to have lower x
  - larger average momentum fraction of quarks leads to an excess of top quarks produced in the forward directions
- Charge asymmetry transfers boost difference to ttbar final state
- Effects at LHC are smaller due to larger gg→ttbar contribution
- Variables sensitive to the asymmetry are:

$$\Delta|\eta| = |\eta_t| - |\eta_{\bar{t}}| \qquad \Delta|y| = |y_t| - |y_{\bar{t}}| \qquad \Delta y^2 = y_t^2 - y_{\bar{t}}^2$$

- At LHC, asymmetry defined as:

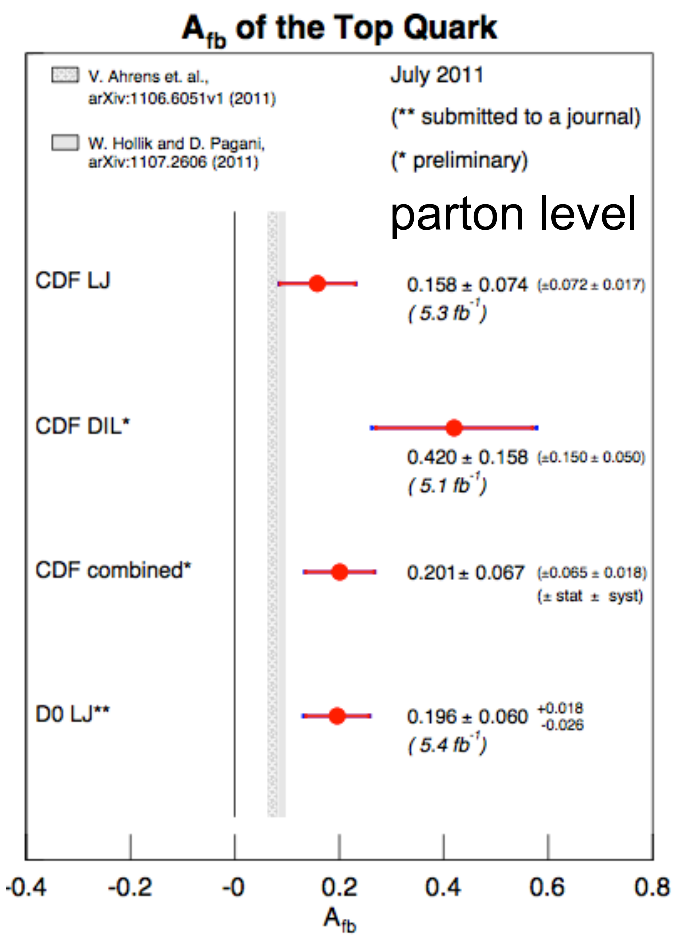
$$A_C = \frac{N^+ - N^-}{N^+ + N^-}$$

$N^+(N^-)$: number of events with positive and negative values in the sensitive variable

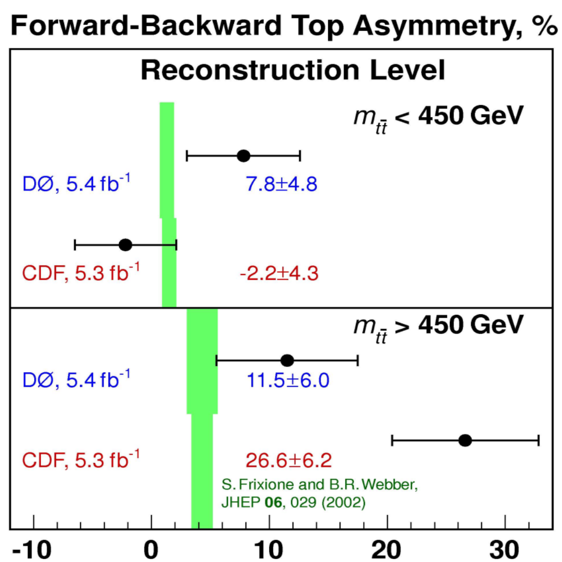
Charge asymmetry anomaly?

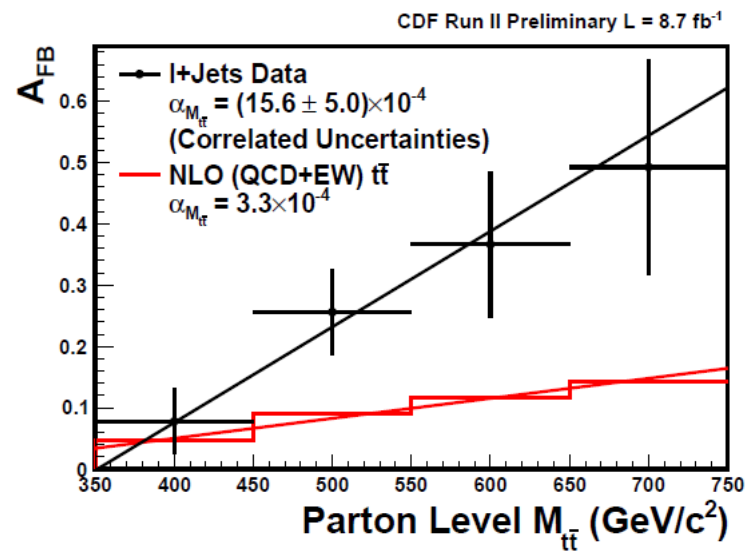
- Tevatron experiments observe a differential dependency on charge asymmetry
  - Sign of new physics?

arXiv:1101.0034
arXiv:0712.0851
CDF Note 10807



- At high mass, a 3σ discrepancy
- Study asymmetry vs mass of ttbar system

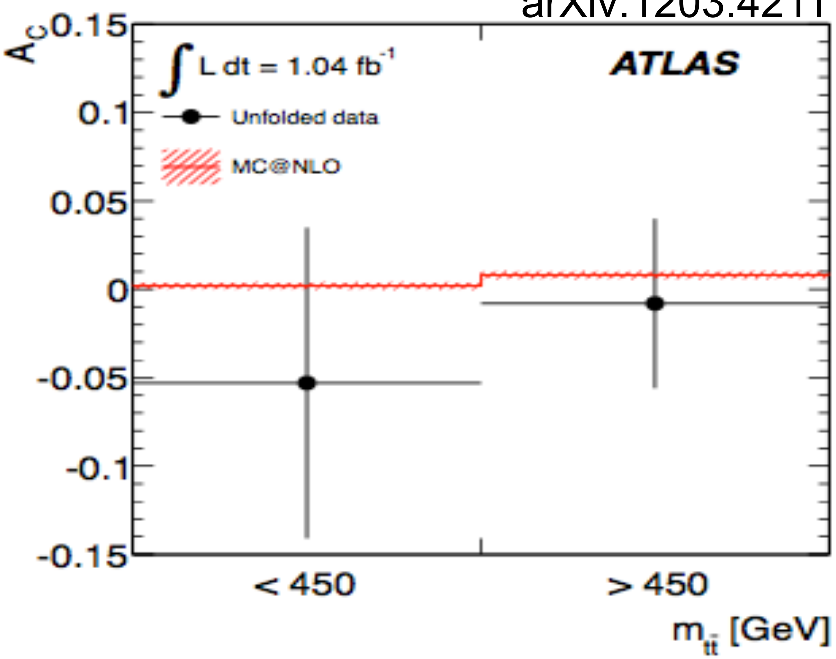




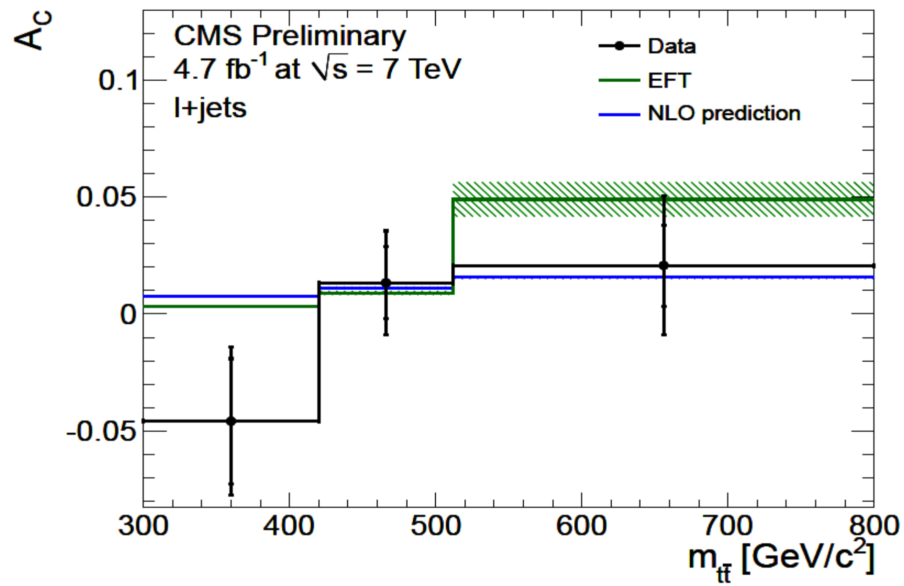
Differential charge asymmetry

- Charge asymmetry depends on phase space
  - High mass/p_T enhance quark annihilation (initial state)
- Asymmetry measured in p_T, y or invariant mass of the top pair system
- Good agreement found between data and SM expectations within uncertainties

arXiv:1203.4211



CMS TOP-11-030

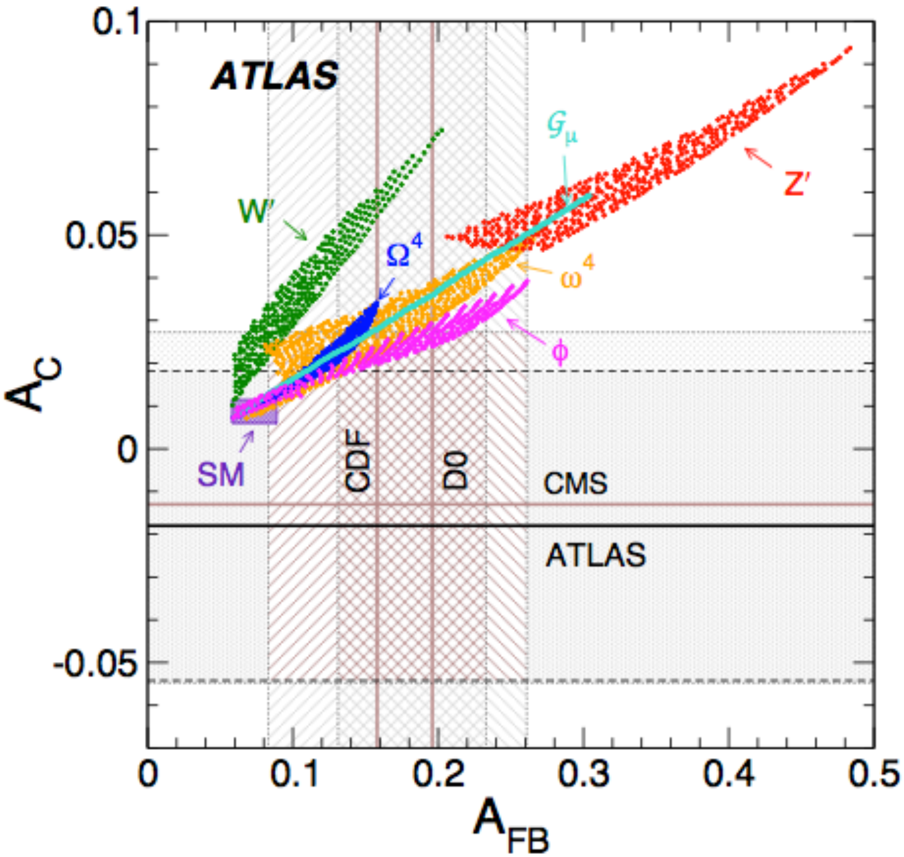


Anomalous axial-vector coupling of gluons to quarks could explain the Tevatron anomaly [PRD84:054017,2011]

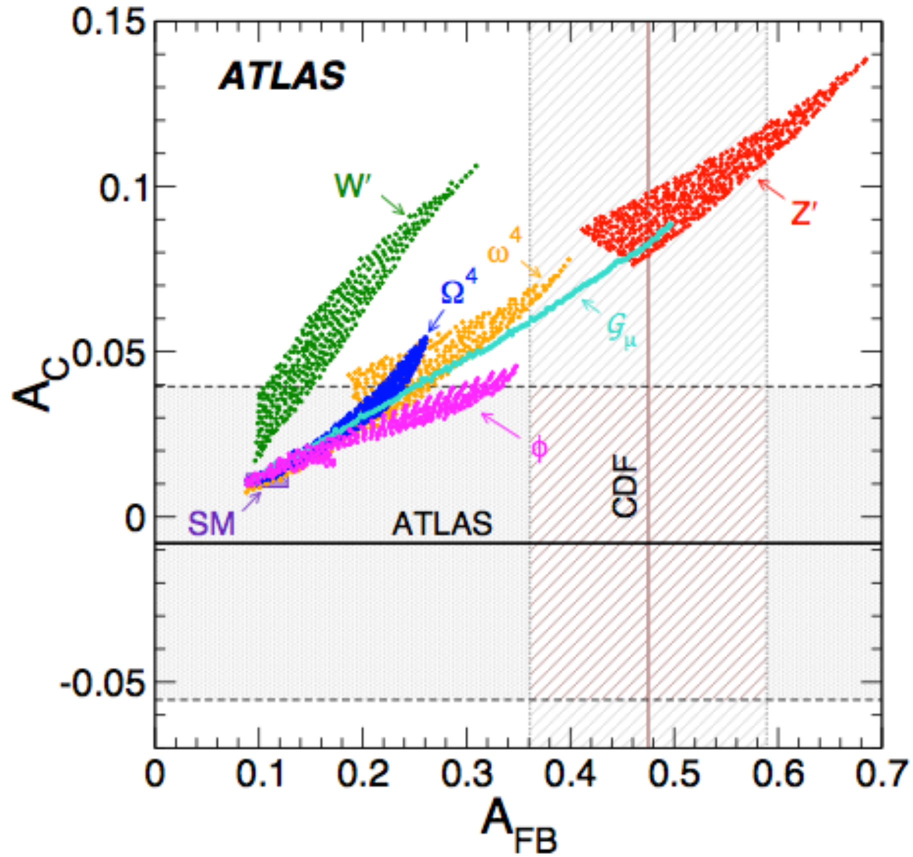
Constraints on New Physics

arXiv:1203.4211

Inclusive

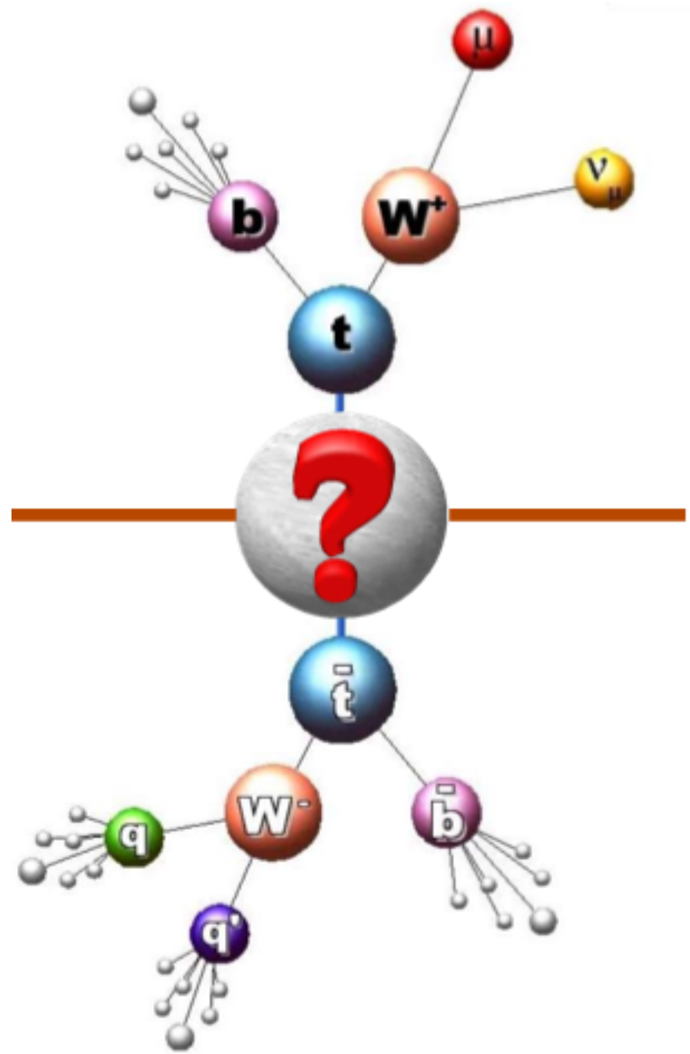


m_{tt}>450 GeV



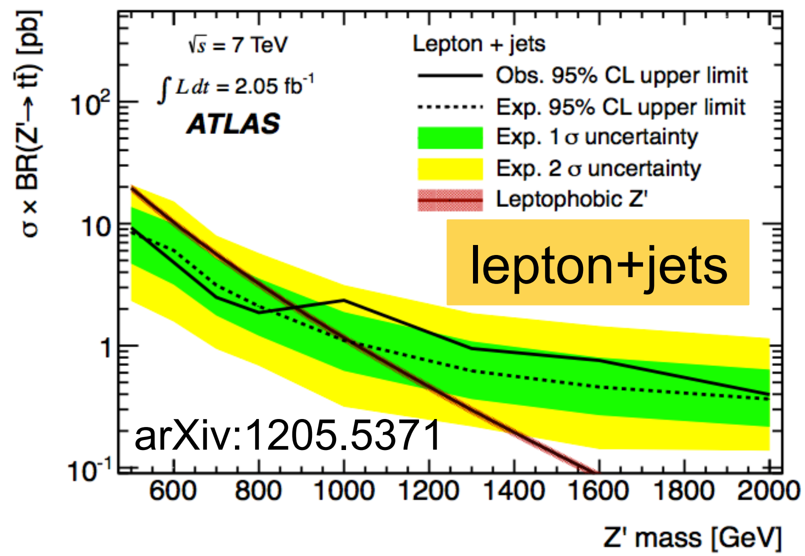
Top quark pair resonance

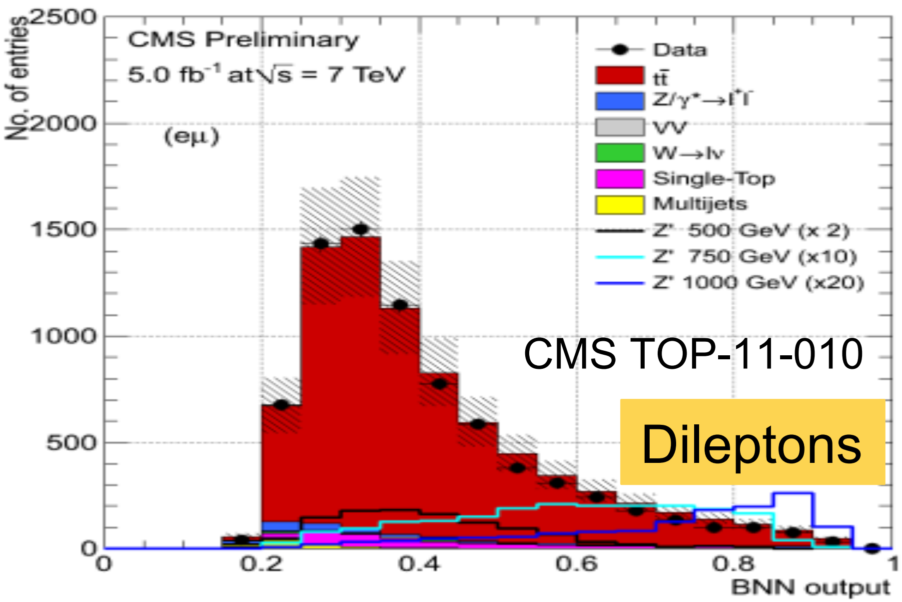
- No resonance expected in SM
- Why is Top so heavy?
  - new physics?
  - is third generation ‘special’?
- Experimental check
  - search for a bump in the invariant mass spectrum
  - Progressive loss in reconstruction ability due to jet merging

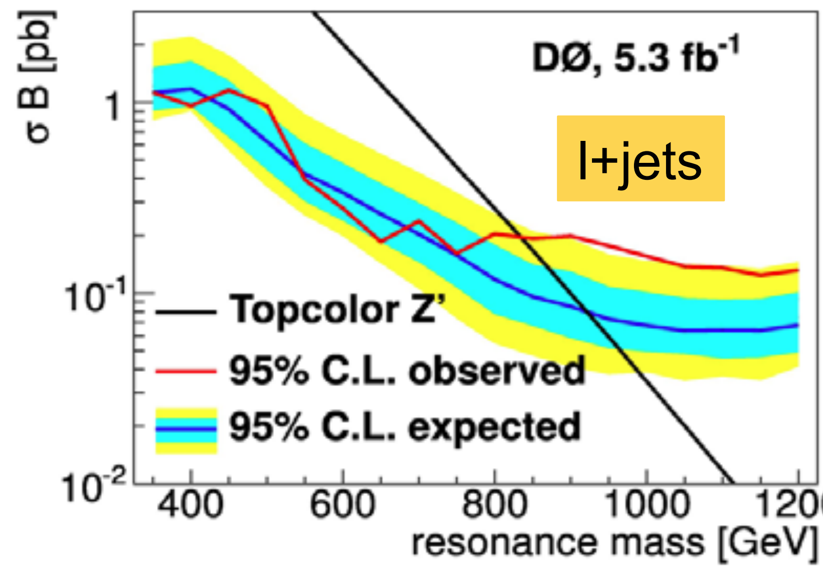


Search for heavy resonances

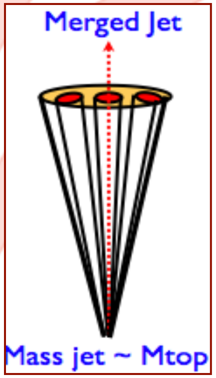
- search for massive neutral bosons decaying via a ttbar quark pair
- use dilepton/lepton+jet final states (electron and muon)
  - Reconstruct M_{ttbar} in different categories (e/μ, *n*-jets, *n* b-tags)
  - l+jet events: full event reconstruction
  - Dileptons: use NN approach to improve S-B separation
- systematics include shape (JES, b-tag, theory model) and rates (eff. bkg yields)

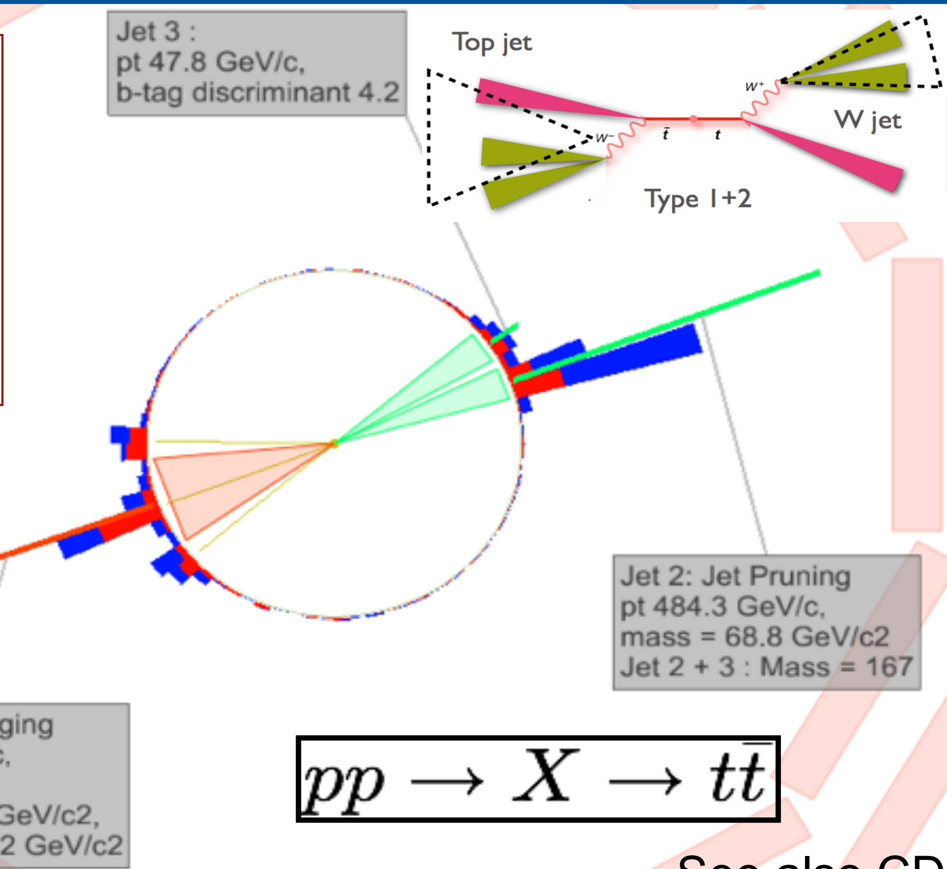




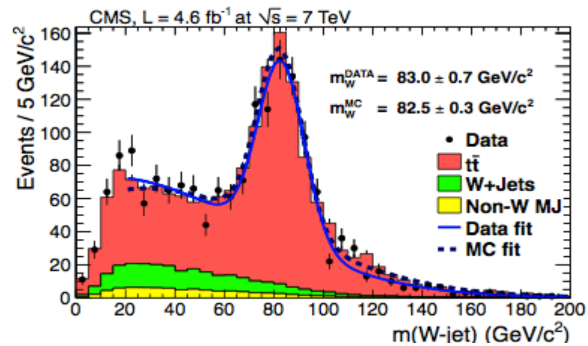


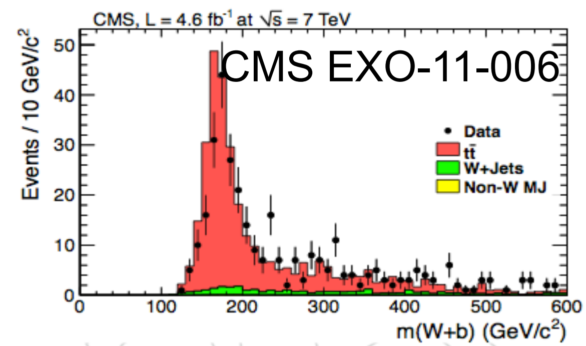
Boosted jet topology

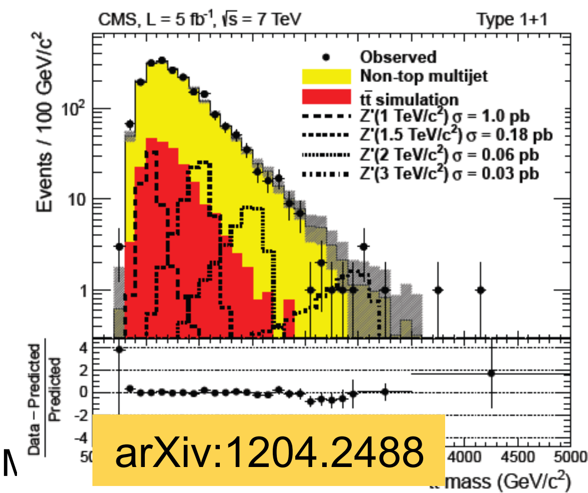




$$pp \rightarrow X \rightarrow t\bar{t}$$

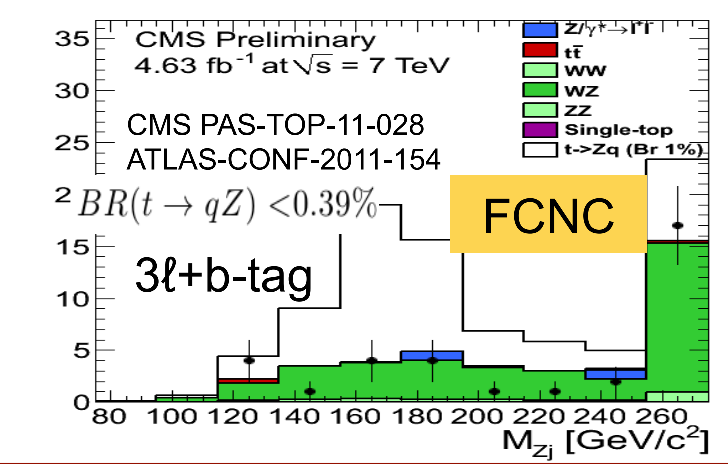


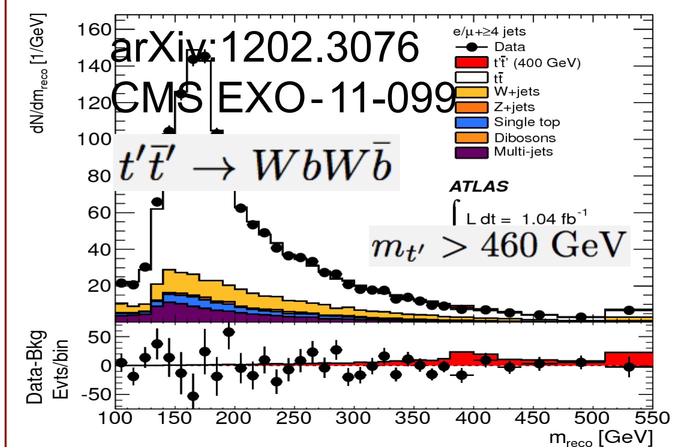


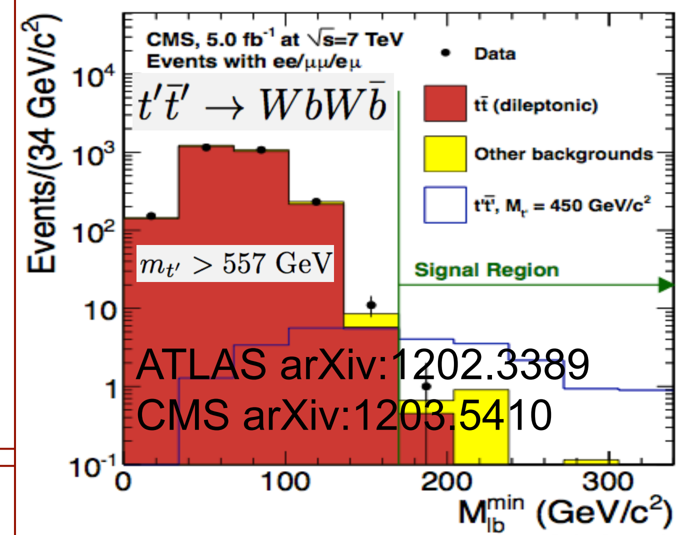


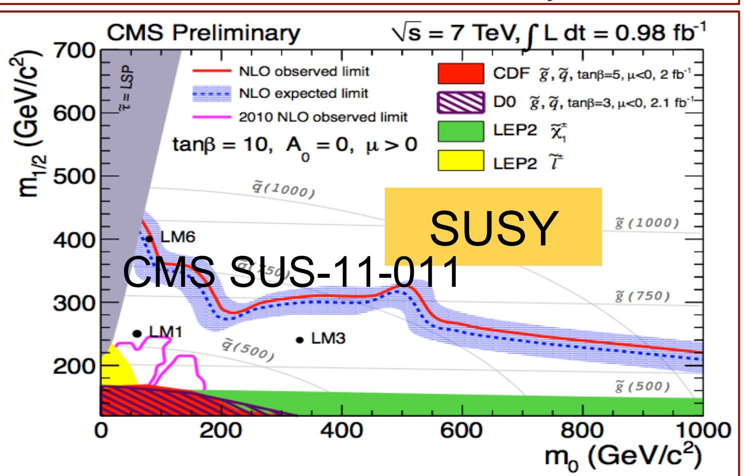
See also CDF note 10234

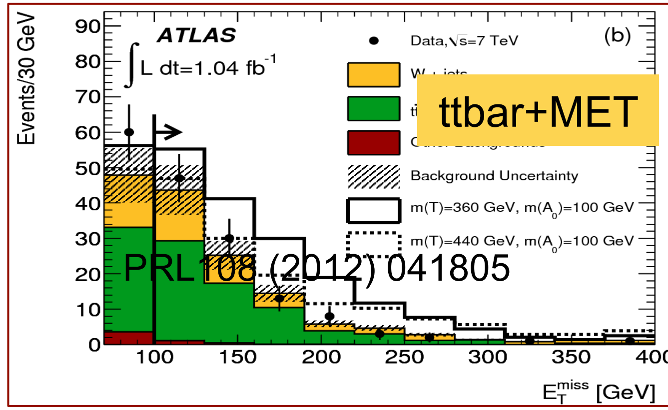
- At LHC energy, EWK scale particles produced beyond threshold
- Jets are highly collimated
- Jet-parton matching breaks down
- Decay products and FSR collected in a fat jet

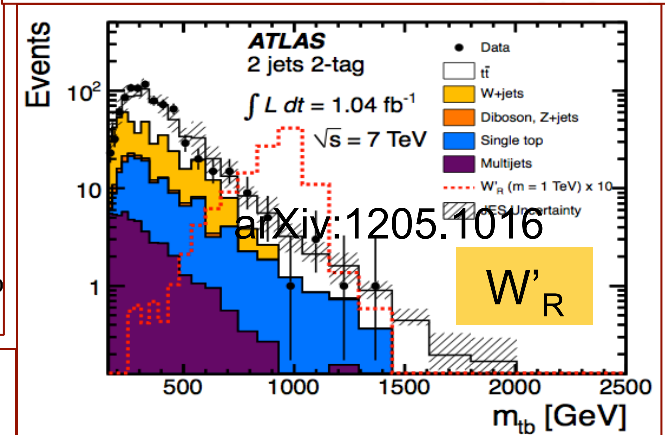

CMS Preliminary
4.63 fb^{-1} at $\sqrt{s}$ = 7 TeV
CMS PAS-TOP-11-028
ATLAS-CONF-2011-154
$BR(t \to qZ) < 0.39\%$
3ℓ+b-tag
FCNC
Z/γ*→l+l-
tt̄
WW
WZ
ZZ
Single-top
t->Zq (Br 1%)
M_{Zj} [GeV/c^2]

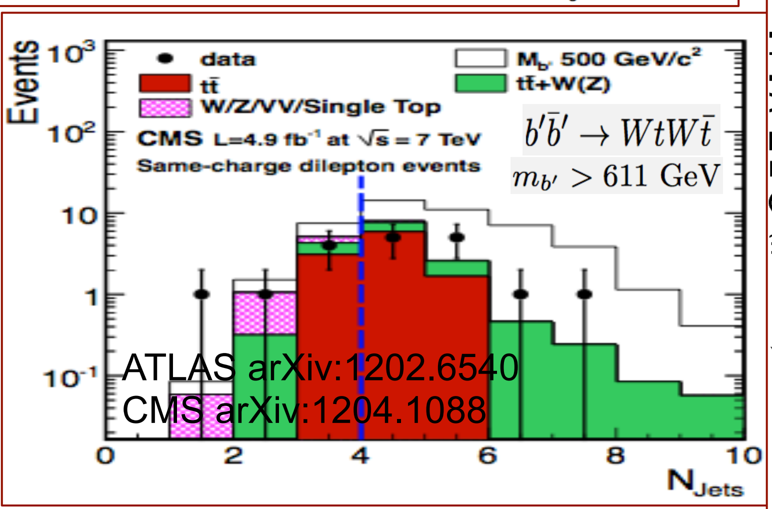

arXiv:1202.3076
CMS EXO-11-099
$t'\bar{t}' \to WbW\bar{b}$
$m_{t'} > 460$ GeV
ATLAS
∫ L dt = 1.04 fb^{-1}
e/μ+≥4 jets
Data
Z+jets
Single top
Dibosons
Multi-jets
W+jets
dN/dm$_{reco}$ [1/GeV]
Data-Bkg Evts/bin
m$_{reco}$ [GeV]

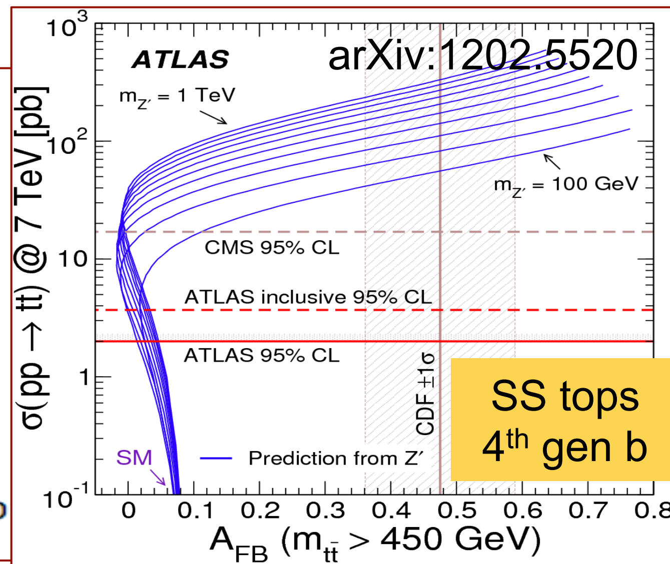

CMS, 5.0 fb^{-1} at $\sqrt{s}$=7 TeV
Events with ee/μμ/eμ
$t'\bar{t}' \to WbW\bar{b}$
$m_{t'} > 557$ GeV
Data
tt̄ (dileptonic)
Other backgrounds
Signal Region
ATLAS arXiv:1202.3389
CMS arXiv:1203.5410
Events/(34 GeV/c^2)
M_{lb}^{min} (GeV/c^2)

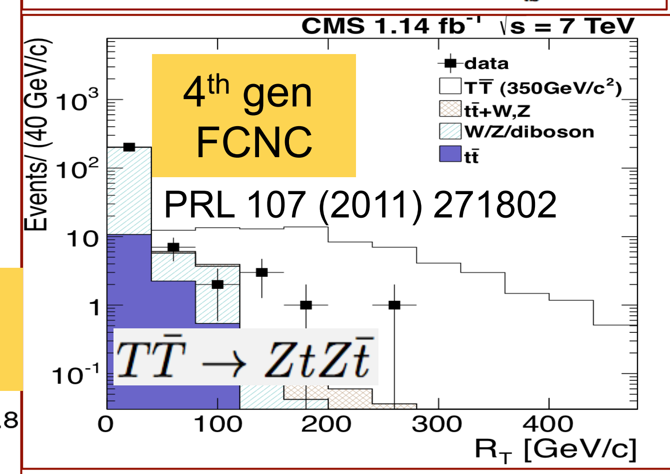

CMS Preliminary
$\sqrt{s}$ = 7 TeV, ∫ L dt = 0.98 fb^{-1}
NLO observed limit
NLO expected limit
2010 NLO observed limit
tanβ = 10, A$_0$ = 0, μ > 0
LEP2
SUSY
CMS SUS-11-011
LM6
LM1
LM3
$m_{1/2}$ (GeV/c^2)
m_0 (GeV/c^2)


ATLAS
∫ L dt=1.04 fb^{-1}
Data,$\sqrt{s}$=7 TeV
ttbar+MET
Background Uncertainty
m(T)=360 GeV, m(A$_0$)=100 GeV
m(T)=440 GeV, m(A$_0$)=100 GeV
PRL 108 (2012) 041805
Events/30 GeV
E_T^{miss} [GeV]


ATLAS
2 jets 2-tag
∫ L dt = 1.04 fb^{-1}
$\sqrt{s}$ = 7 TeV
Data
W+jets
Diboson, Z+jets
Single top
Multijets
arXiv:1205.1016
W'$_R$
Events
m_{tb} [GeV]


data
tt̄
W/Z/VV/Single Top
M$_{b'}$ 500 GeV/c^2
tt̄+W(Z)
CMS L=4.9 fb^{-1} at $\sqrt{s}$ = 7 TeV
Same-charge dilepton events
$b'\bar{b}' \to WtW\bar{t}$
$m_{b'} > 611$ GeV
ATLAS arXiv:1202.6540
CMS arXiv:1204.1088
Events
N$_{Jets}$


ATLAS
arXiv:1202.5520
$m_{Z'}$ = 1 TeV
$m_{Z'}$ = 100 GeV
CMS 95% CL
ATLAS inclusive 95% CL
ATLAS 95% CL
CDF ±1σ
SM
Prediction from Z'
SS tops
4th gen b
σ(pp → tt) @ 7 TeV [pb]
A_{FB} ($m_{t\bar{t}}$ > 450 GeV)


CMS 1.14 fb^{-1} $\sqrt{s}$ = 7 TeV
4th gen FCNC
data
TT̄ (350GeV/c^2)
tt̄+W,Z
W/Z/diboson
tt̄
PRL 107 (2011) 271802
$T\bar{T} \to ZtZ\bar{t}$
Events/ (40 GeV/c)
R$_T$ [GeV/c]

Summary

- A lot of progress in understanding top quark properties
- From a few events up to detailed studies
- Top quarks can be used for testing deviation from SM
- Main background for New Physics searches
- This year 8 TeV collisions at LHC with plenty of top quark events

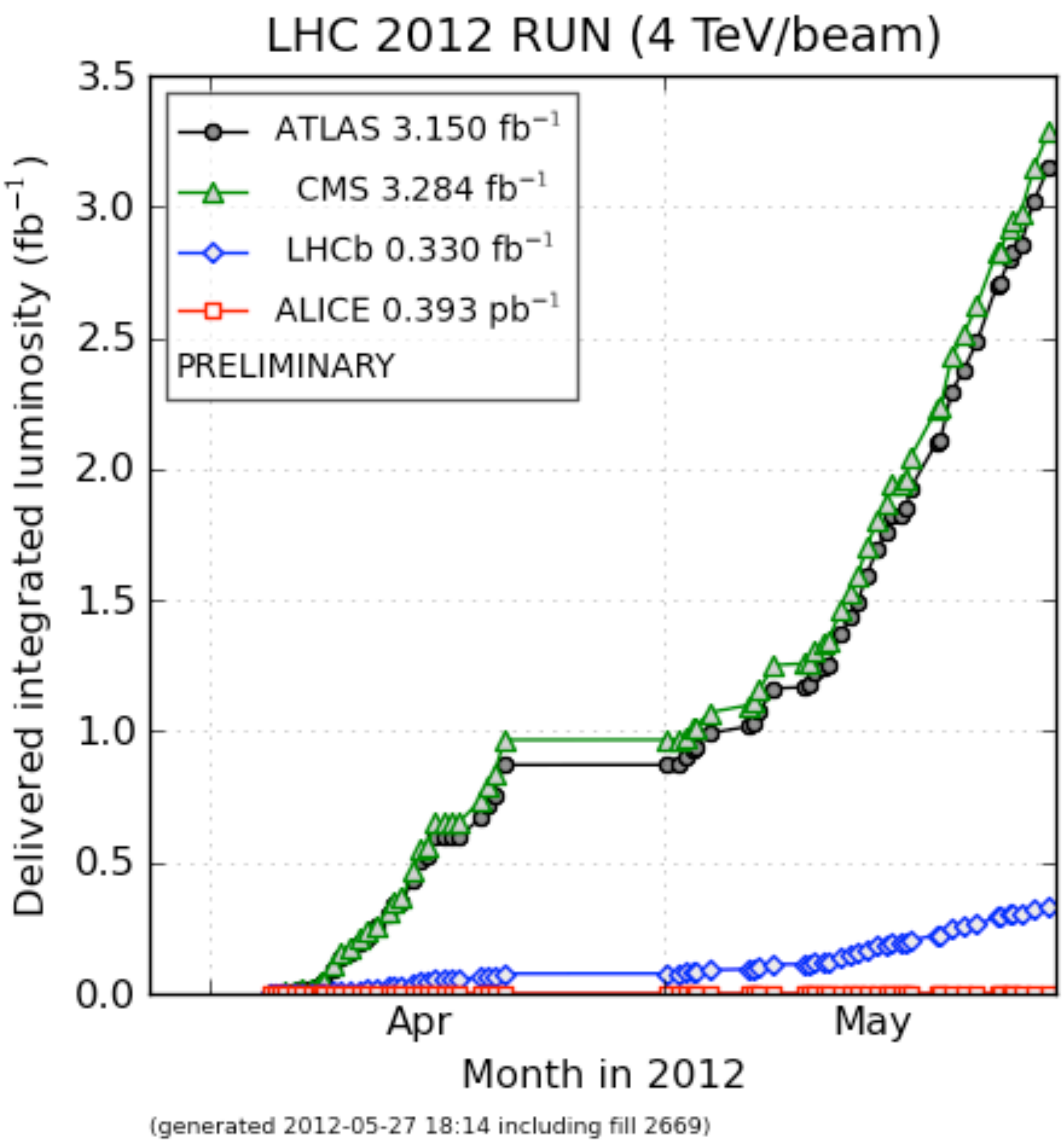
- No hints for New Physics yet

Thank you

Many thanks to the Tevatron and LHC collaborations, friends and colleagues

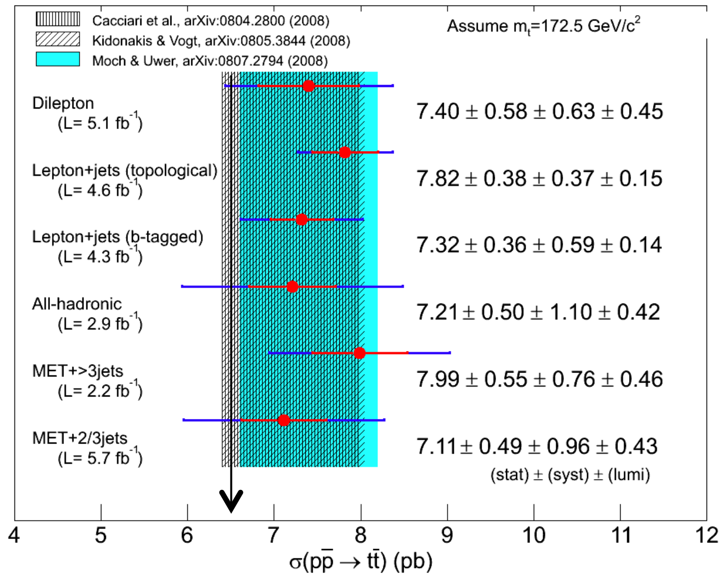
backup

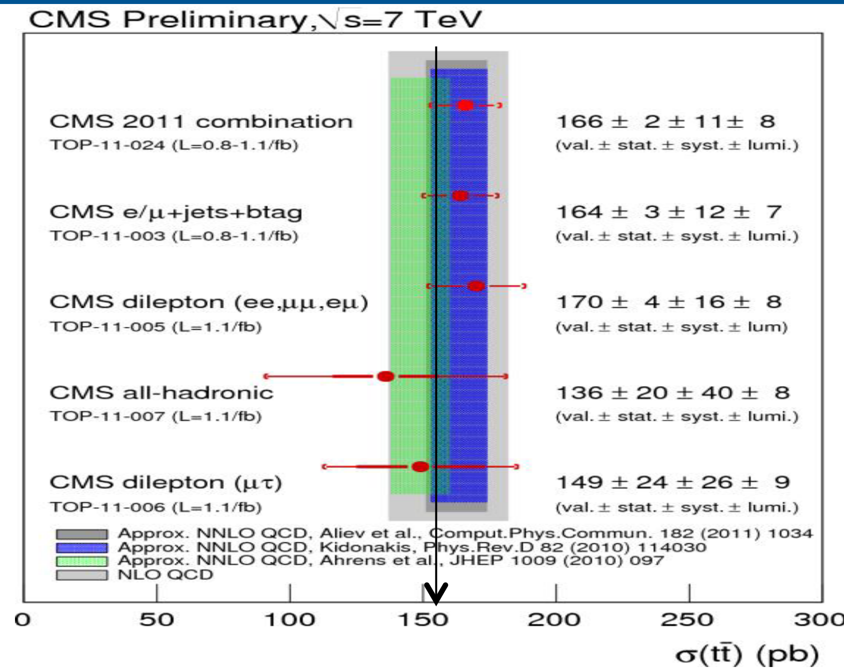
2012



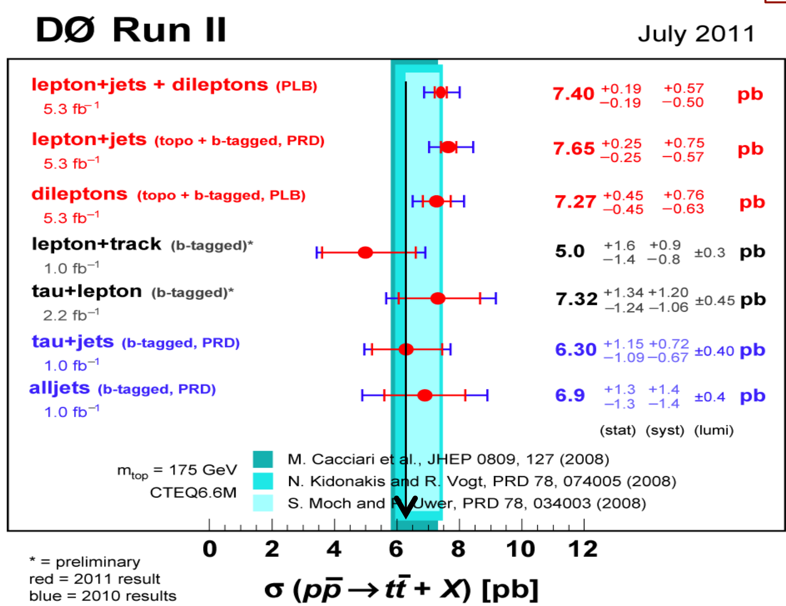
LHC 2012 RUN (4 TeV/beam)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Delivered integrated luminosity (fb^{-1})
ATLAS 3.150 fb^{-1}
CMS 3.284 fb^{-1}
LHCb 0.330 fb^{-1}
ALICE 0.393 pb^{-1}
PRELIMINARY
Apr
May
Month in 2012
(generated 2012-05-27 18:14 including fill 2669)

Cross section measurements



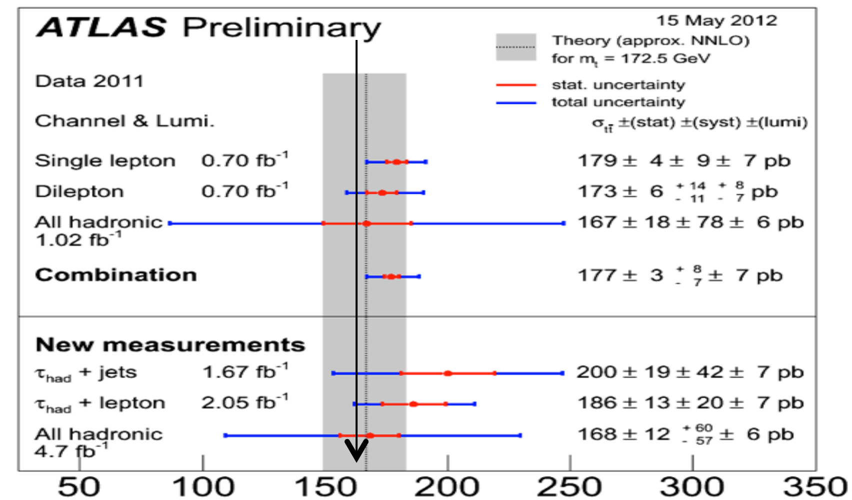


Ahrens et al. (1105.5824) predict lower cross section



Hint for NP?

⇒not yet

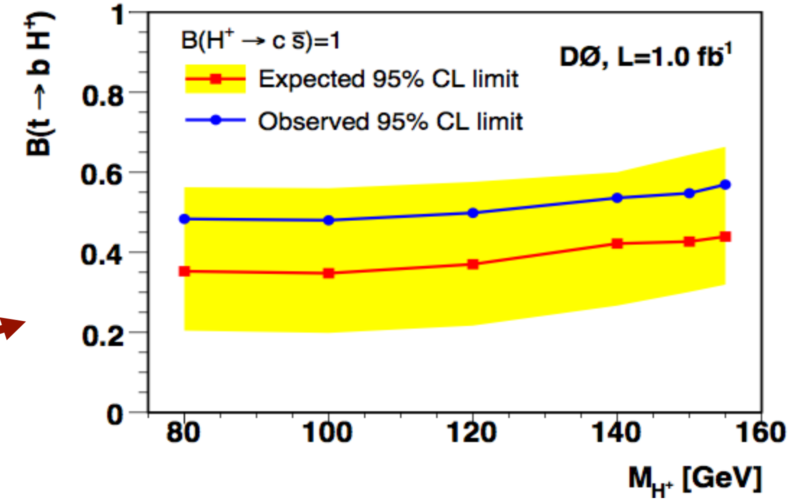


Cross section ratios: example

- Measurements tend to be dominated by syst. uncert.
- Ratios could provide extra handle to reduce them
- Cross section may change with light charged Higgs
- use cross section ratios

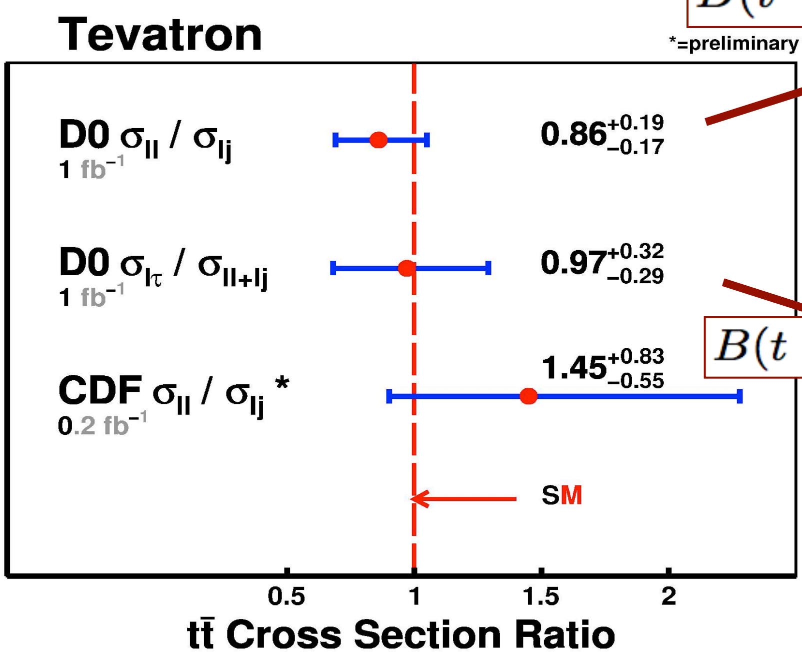
⇨improve sensitivity to BSM

arXiv:0903.5525



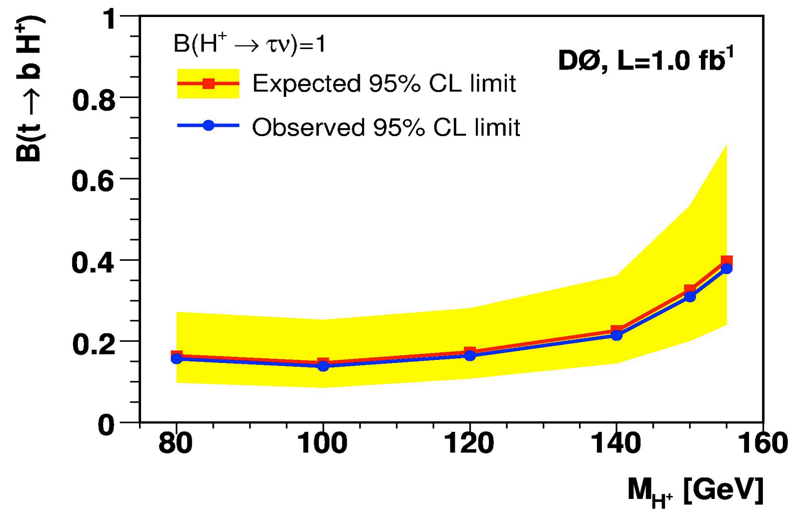
$B(t \to H^+ b \to c\bar{s}b)$

lept.+jets



$B(t \to H^+ b \to \tau^+ \nu b)$

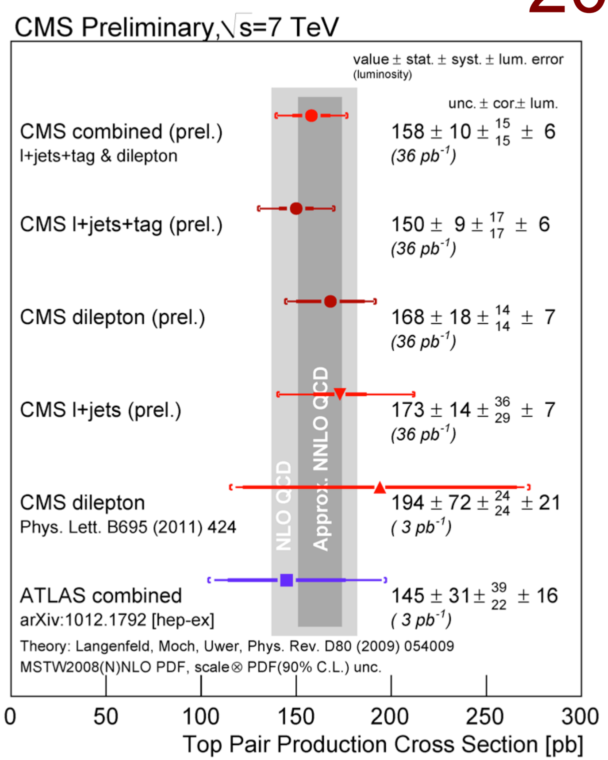
tau leptons



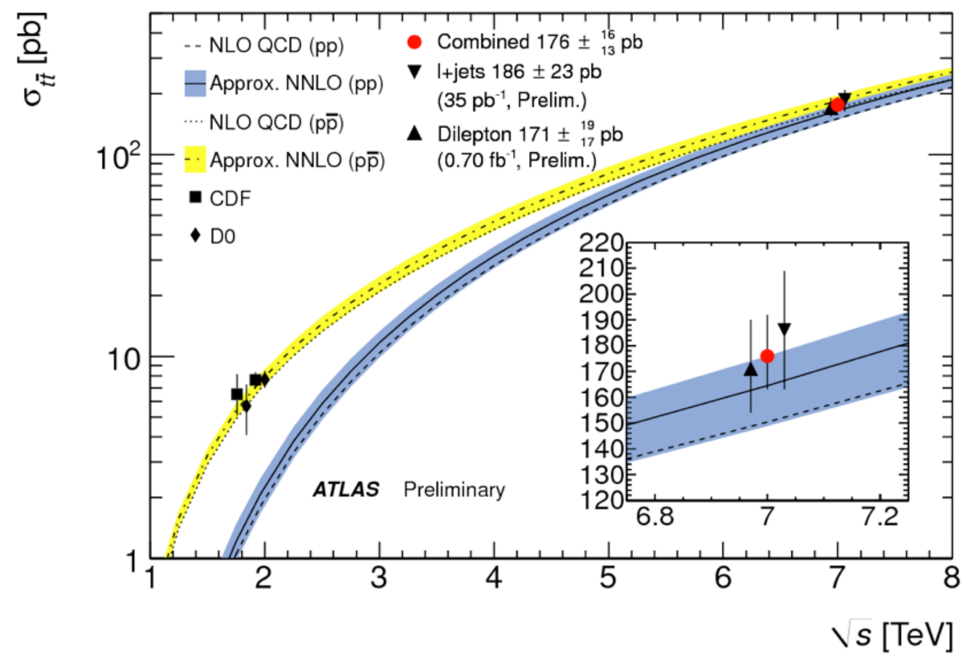
Cross section

- Cross section measurements provide a test of perturbative QCD predictions
- Comparison in different channels may provide constraints on BSM physics
- ttbar is a dominant background for New Physics searches

2010



2010

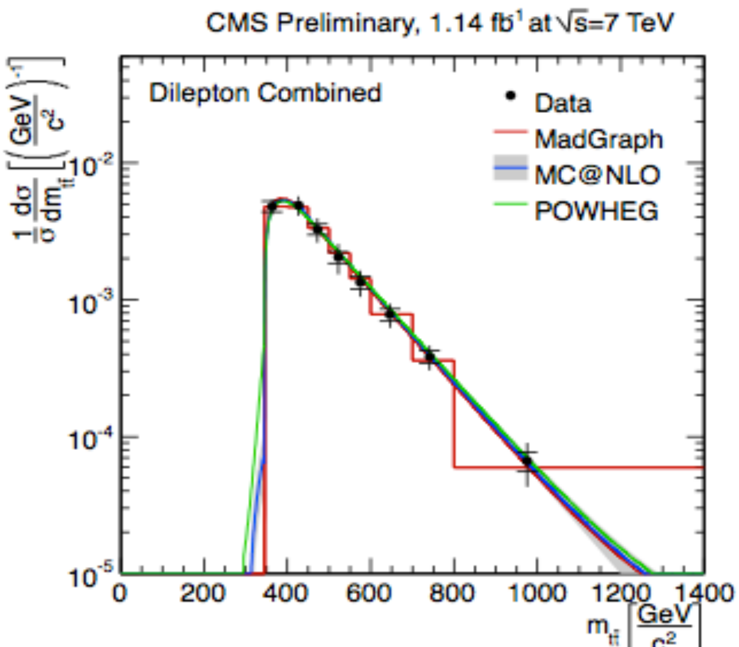


Differential cross section

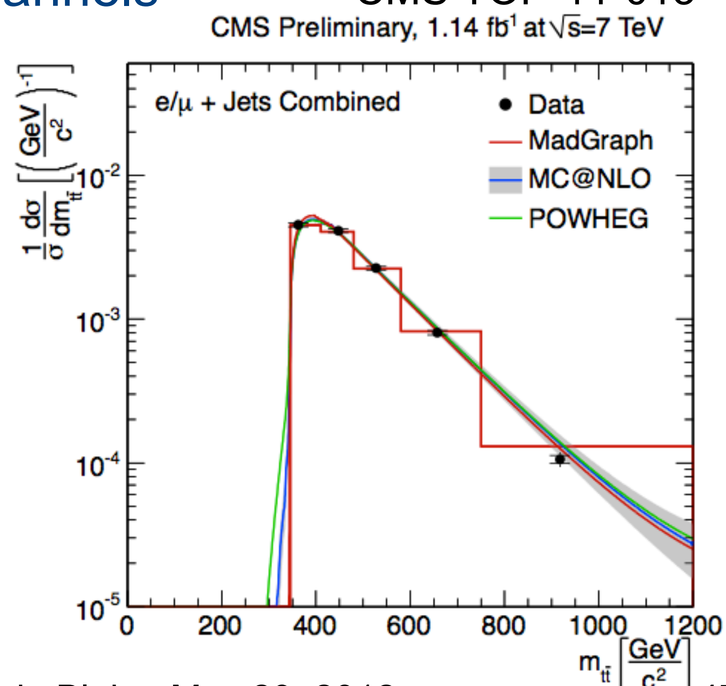
- Measure differential cross section
  - Test perturbative QCD
  - Test BSM scenarios (Z' decays, etc) with narrow resonance
- Reconstruct event kinematic properties
- Cross sections measured as a function of p_T, η, invariant mass of the final state leptons, the top quarks, and the tt system
- Good agreement found in dilepton and lepton+jet channels

$$\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma_{t\bar{t}}}{dX}$$

CMS TOP-11-013



top quark pair invariant mass



Differential cross section

- Measure differential cross section
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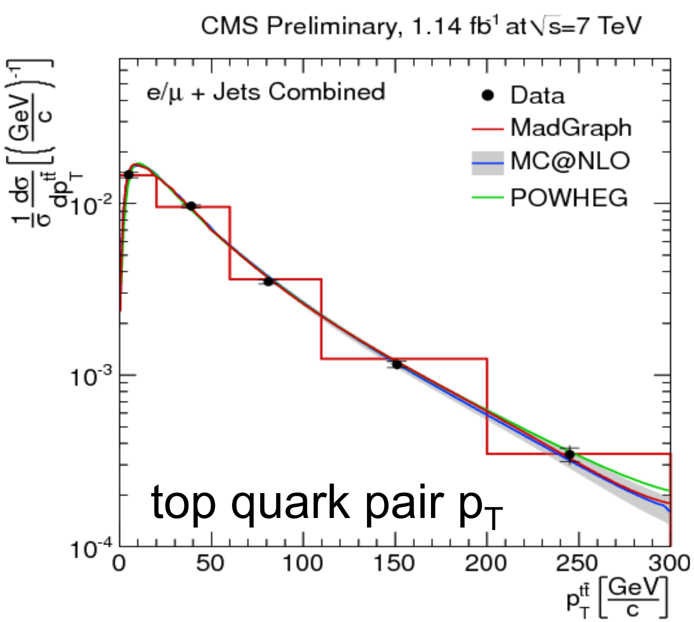
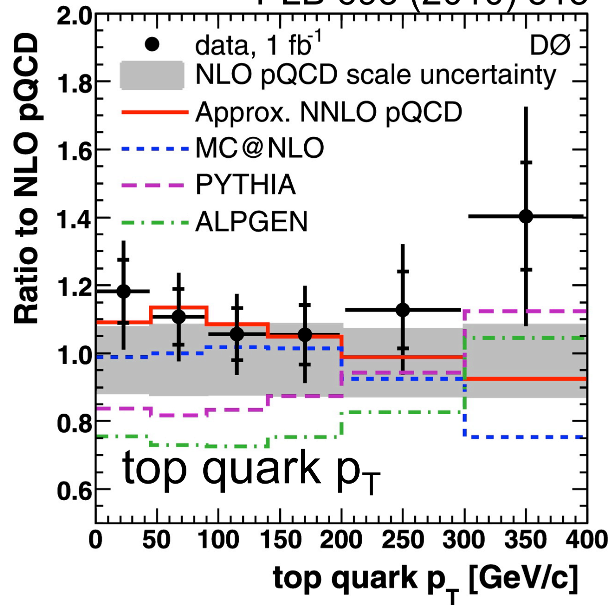
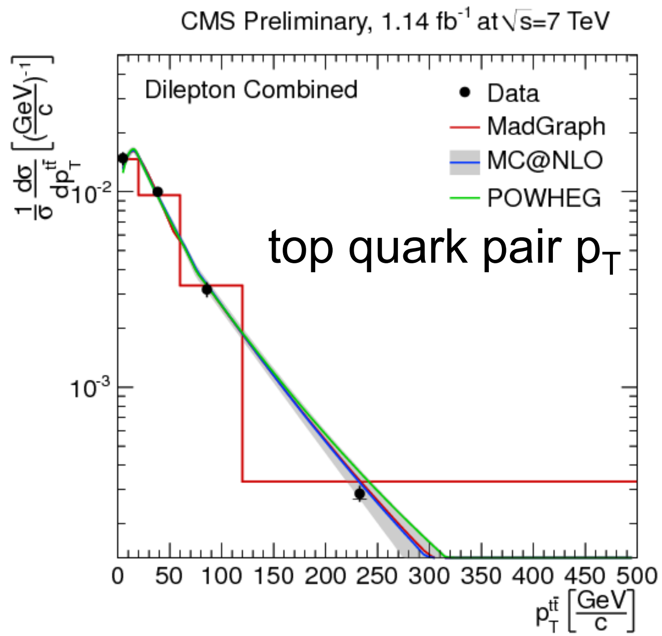


PLB 693 (2010) 515

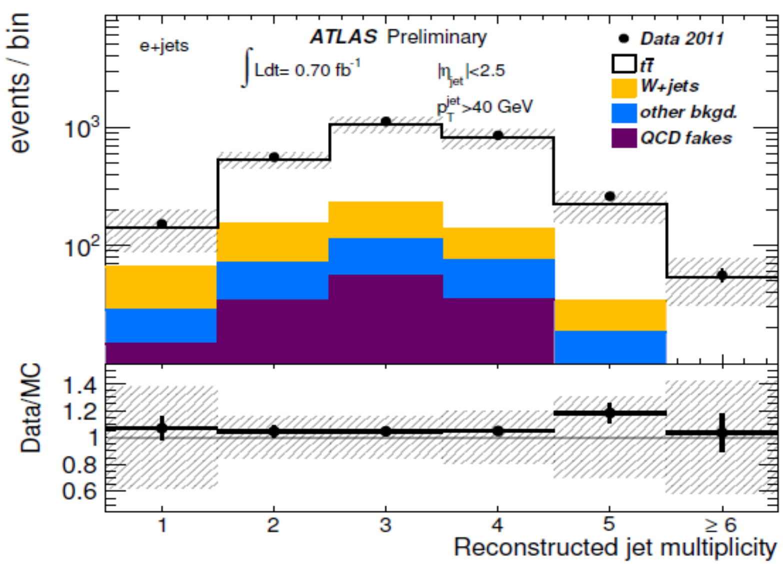




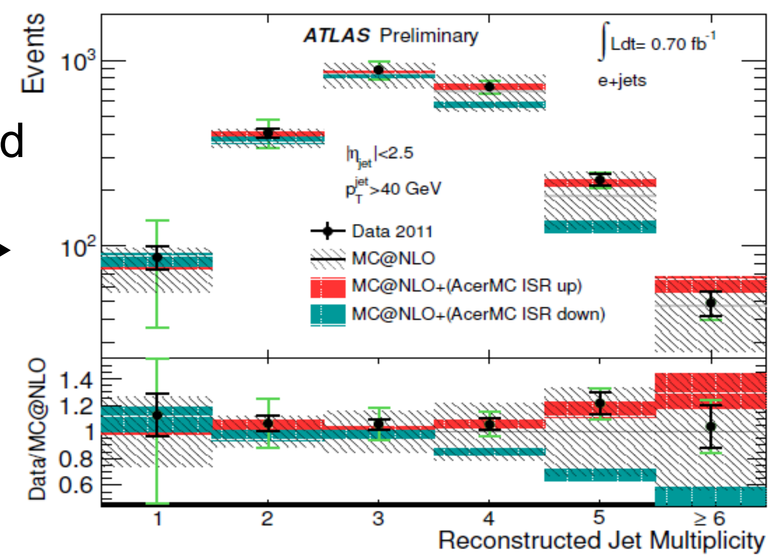
Jet multiplicities: test of pQCD

- Jet scaling tests QCD: PDF evolution and running α_s
  - useful to constrain initial state radiation (ISR) at the scale of the top quark mass
  - provides a test of perturbative QCD in a new energy regime
- Study multiplicity distribution of reconstructed jets
  - Analysis performed in the single lepton channel
- data in agreement with signal ttbar MC distributions
- Comparison with different ISR MC samples
- Uncertainties dominated by JES

ATLAS-CONF-2011-142

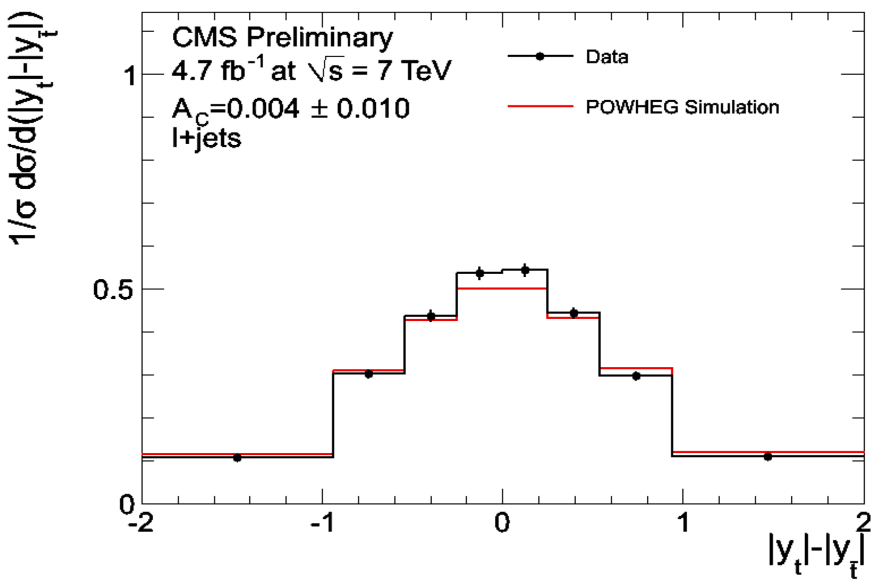


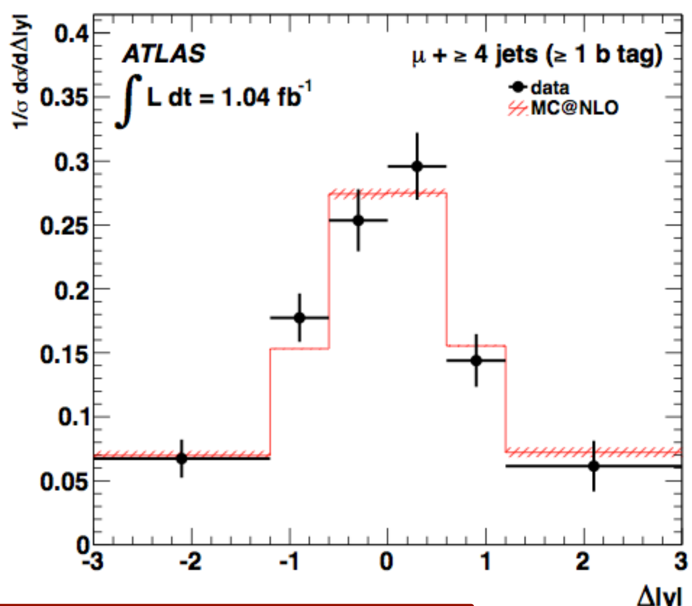
After background subtraction

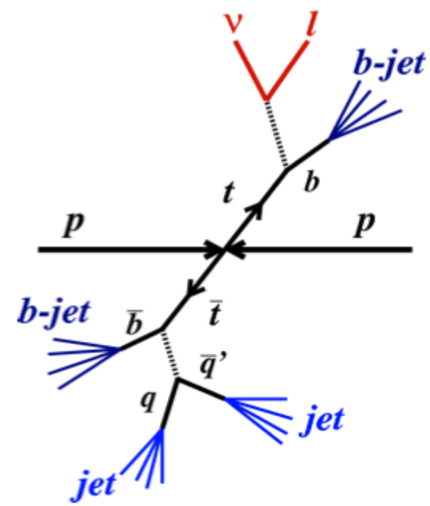


Charge asymmetry

- Use lepton+jet final state
- Measurement is based on the fully reconstructed 4 momenta of top and anti-top in each event
- Top charge correlated with lepton





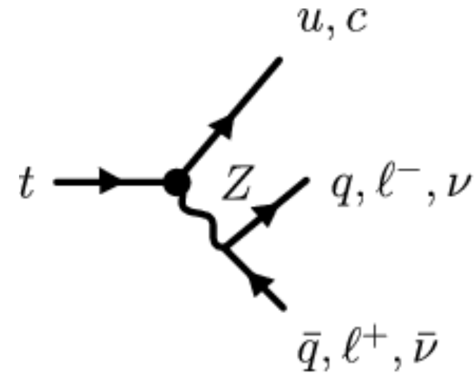


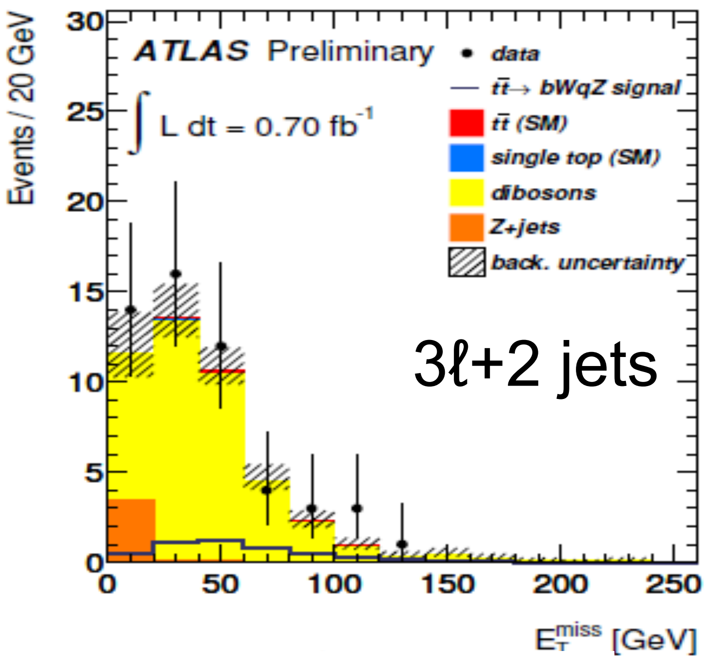
ATLAS: arXiv:1203.4211
CMS: arXiv:1112.5100
CMS TOP-11-030

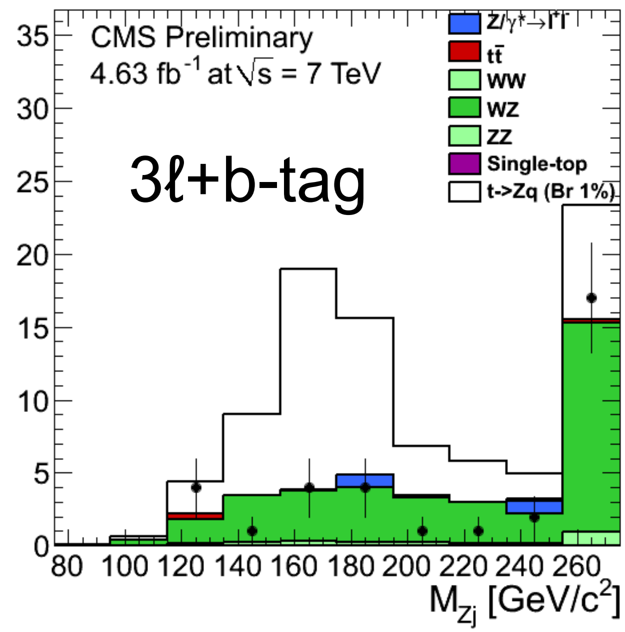
ATLAS: arXiv:1203.4211	-0.018 ± 0.028 (stat.) ± 0.023 (syst.)
CMS: TOP-11-030	0.004 ± 0.010 (stat.) ± 0.012 (syst.)
Theory prediction (SM)	0.0115 ± 0.0006

Rare decays: FCNC

- At LO, FCNC is highly suppressed: BR($t\rightarrow qZ$)<10^{-14} (NLO)
  - BSM can enhance BR by factor of 10^{10}
- Search for $t\rightarrow qZ\rightarrow q\ell^+\ell^-$
  - 3 leptons+2jets, very clean signature
- Top mass can be used as a candle for Z+jet decay







ATLAS: $BR(t\rightarrow qZ) < 1.3\%$

CMS: $BR(t\rightarrow qZ) < 0.39\%$

CMS PAS-TOP-11-028
ATLAS-CONF-2011-154

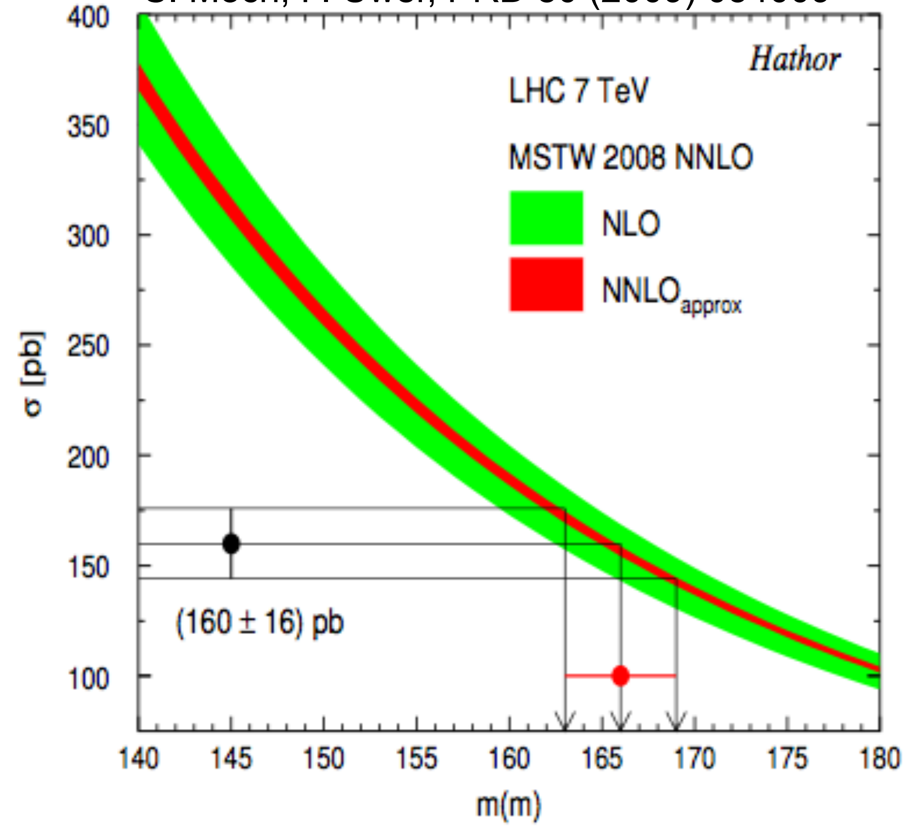
Top mass from cross section

- Direct m_{top} measurements rely on details of kinematics, reconstruction, calibration
- Extraction of mass from xsection
  – compare the measured cross section with fully inclusive higher-order perturbative QCD computations where top quark mass parameter is un-ambiguously defined as the pole mass
- Experimental measurement has small uncertainty: ~0.5%
- What mass is measured?
  – Could be interpreted as pole mass

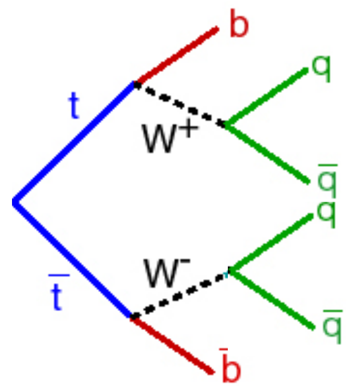
(A=4-5)

- Compare theory prediction (measured) cross section vs pole mass (=m_{top})
- Exploit relation of cross section and mass:
  – $\Delta\sigma/\sigma = -A \cdot \Delta m/m$

S. Moch, P. Uwer, PRD 80 (2009) 054009

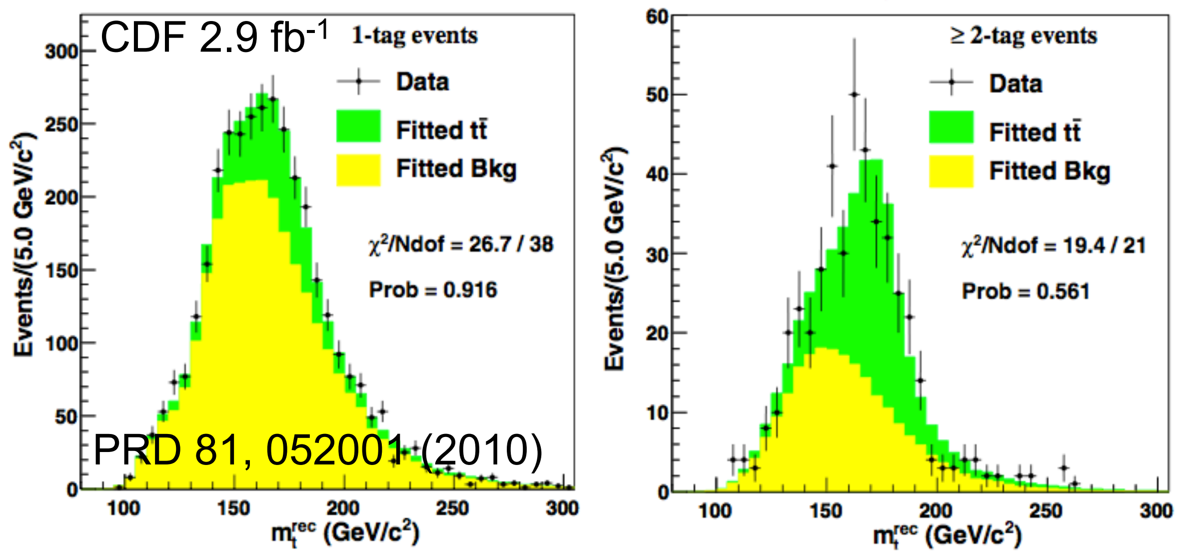


All hadronic



BR ~44%
background: large

Top reconstructed invariant mass with 1 b-tag and ≥2 b-tags



The measurement of the ttbar production cross section is performed through a likelihood fit:

$$\mathcal{L} = \mathcal{L}_{1\,tag} \times \mathcal{L}_{\geq 2\,tags} \times \mathcal{L}_{L}$$

lumi

$$\mathcal{L}_{1,\geq 2\,tags} = \mathcal{L}_{n_s} \times \mathcal{L}_{\epsilon}$$

signal yield   signal efficiency

$$\mathcal{L}(\sigma_{t\bar{t}}) = e^{-(\sigma_{t\bar{t}}\cdot\epsilon\cdot L - n_s)^2/2\sigma^2_{n_s}}$$

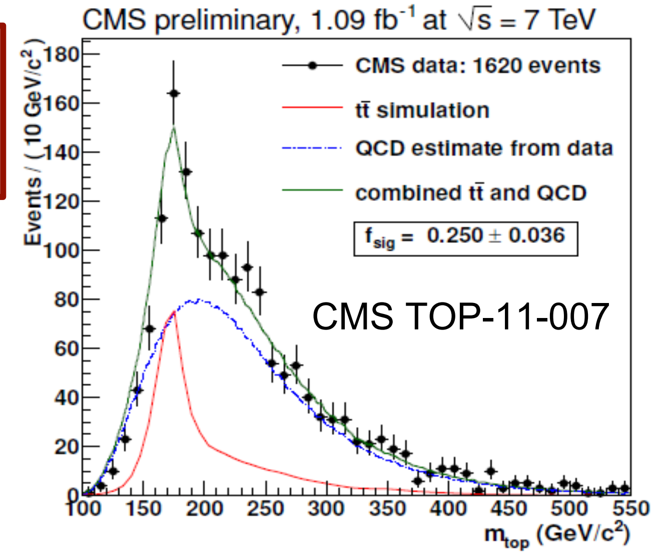
$$\sigma_{t\bar{t}} = 7.2 \pm 0.5(\mathrm{stat}) \pm 1.0(\mathrm{syst}) \pm 0.4(\mathrm{lum})\ \mathrm{pb}$$

±16%

All hadronic

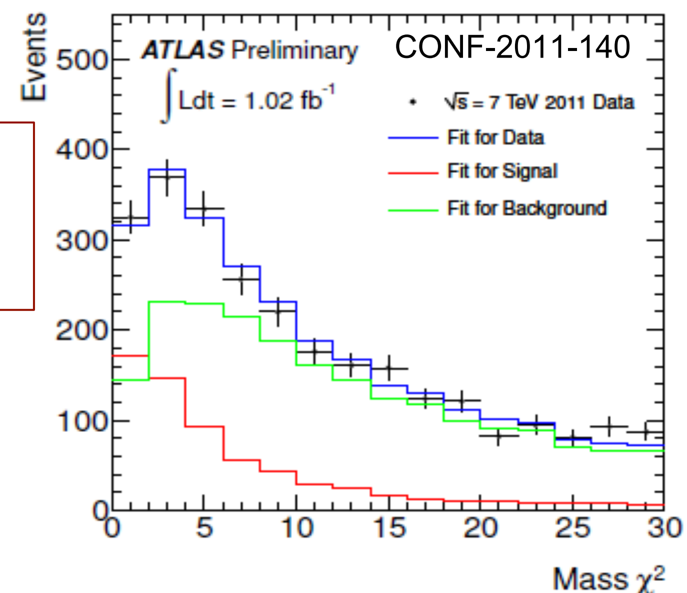
- Large BR, but large bkg
- Select at least 6 jets
  - b-tagging reduces combinatorics
- Top cross section from unbinned maximum likelihood to the reconstructed top mass
- Multijet QCD is main background (determ. from data)
  - Use events with 4-5 jets
  - Re-weigh mass spectrum from anti-tagged sample

Selection step	Events	Signal fraction
At least 6 jets	248 109	2%
At least two b-tags	6 905	17%
Kinematic fit	1 620	32%



- Results:

Fit χ^2 or top mass
(signal from generator, background data-driven)



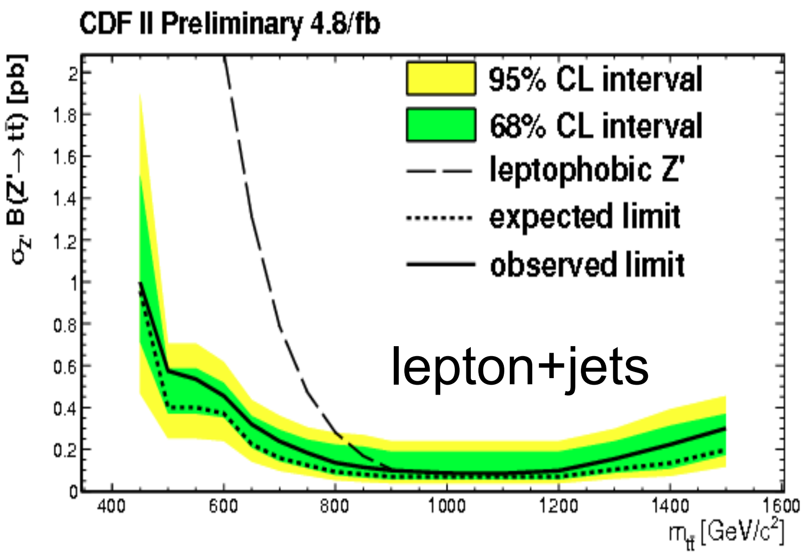
ATLAS ±48%

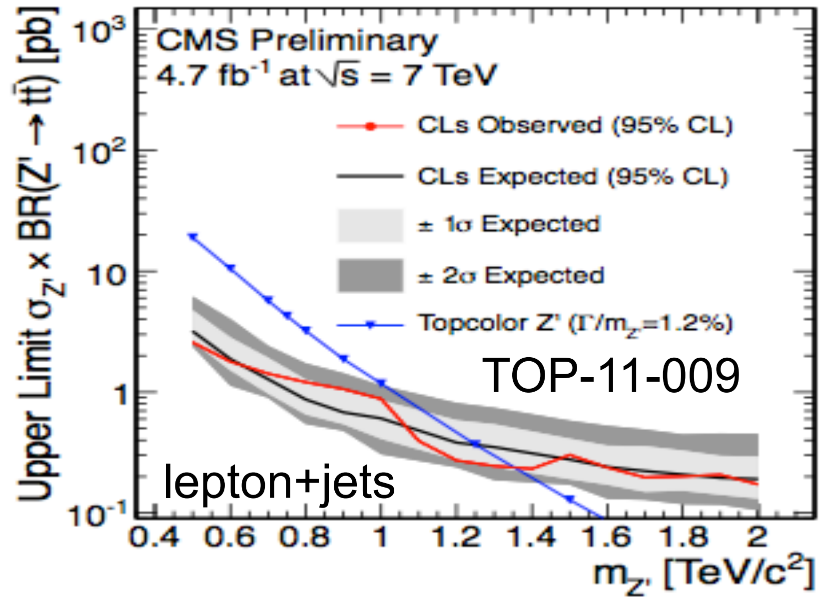
$$\sigma(pp \to t\bar{t}) = 167 \pm 18\ (\text{stat.})\ \pm 78\ (\text{syst.})\ \pm 6\ (\text{lum.})\ \text{pb}$$

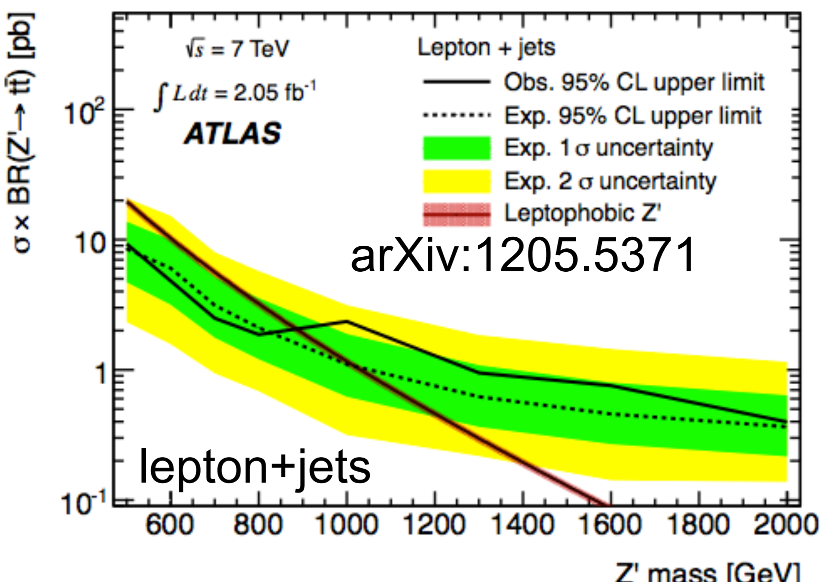
$$136 \pm 20\ (\text{stat.}) \pm 40\ (\text{sys.}) \pm 8\ (\text{lumi.})\ \text{pb}$$

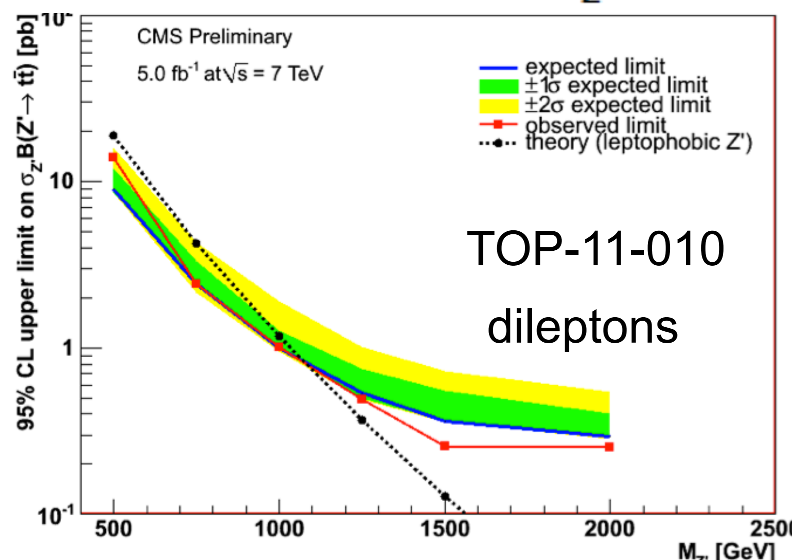
CMS ±33%

Heavy ttbar resonances



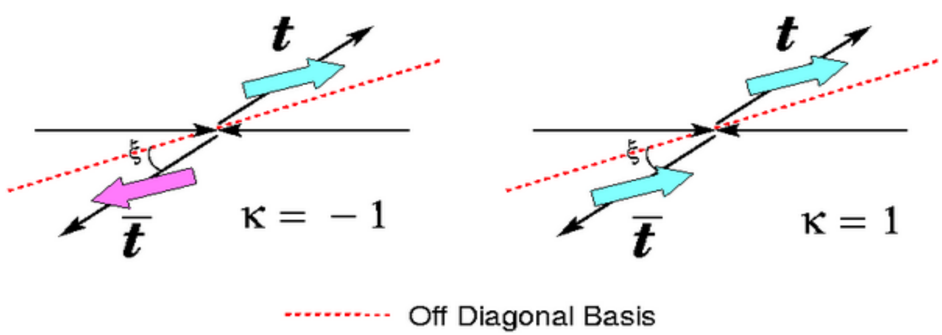






Spin correlation

- Top quarks are not polarized but their spins are correlated
- Top quark decay products retain correlation
  - decays before hadronization ($\tau \sim 10^{-25}$ sec) $\Rightarrow$ spin information transmitted to decay products ($t \rightarrow Wb$)
- Spin correlation depends on the production mode



$$\kappa = \frac{n_{\pm\pm} - n_{\pm\mp}}{n_{\pm\pm} + n_{\pm\mp}}$$

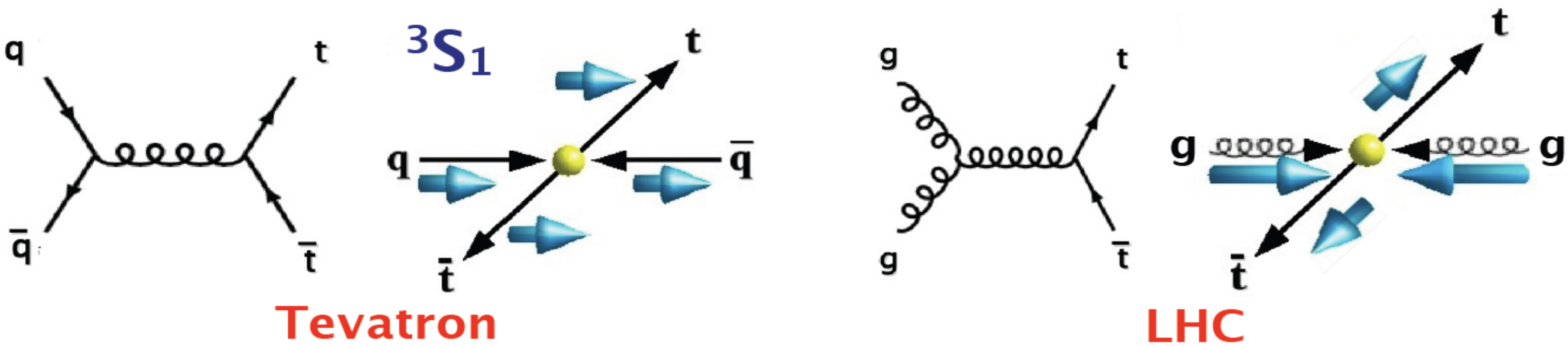
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 + \kappa\cos\theta_1\cos\theta_2\right)$$

correlation strength

- Analyze spin using angular distributions of decay products
  - θ_1 and θ_2 are the angles of decay products wrt a “quantization axis”
  - value of κ depends on spin basis (for example, off-diagonal vs maximal)
- Spin correlation may differ from what expected in SM
  - charged Higgs $t \rightarrow H^+ b$, or other BSM processes

Spin correlation: Tevatron vs LHC

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



- Dominated by qqbar annihilation
- ttbar pairs produced at threshold
- “beam axis” as spin quantization axis

- Dominated by gg annihilation
- ttbar pairs produced far from threshold
- “helicity basis” and “maximal basis”

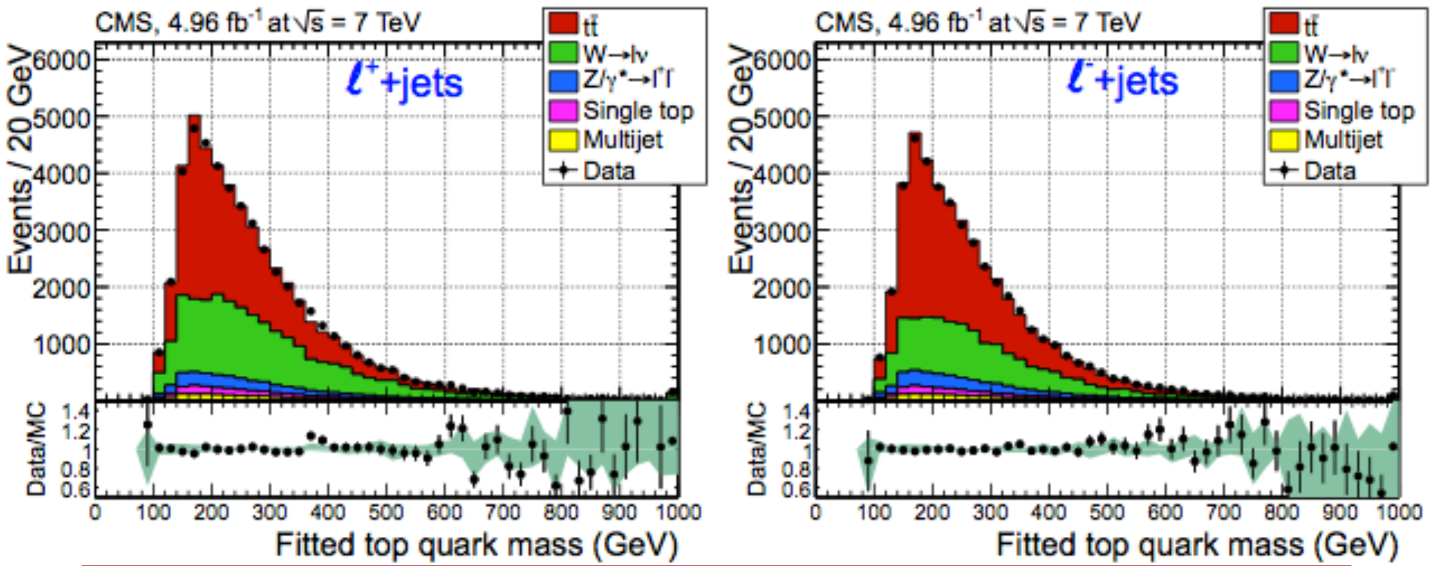
Bernreuther, Brandenburg, Si, Uwer, Nucl. Phys. B690 (2004) 81

⇒complementarity between Tevatron and LHC

Top-antiTop mass difference

- Test of CPT invariance: particle and anti-particle have same mass
  - If masses are different →CPT violation
  - Top quark is unique because it decays before hadronizing
- use μ+jet ttbar events: positive/negative muons (L=5.0/fb)
  - Compare mass measured from μ^+/μ^- +jets
  - Use hadronic side

arXiv:1204.2807



CDF:
PRL 106 (2011) 132001
$\Delta m = -3.3 \pm 1.7$ GeV

D0:
PRD 84 (2011) 052005
$\Delta m = 0.84 \pm 1.87$ GeV

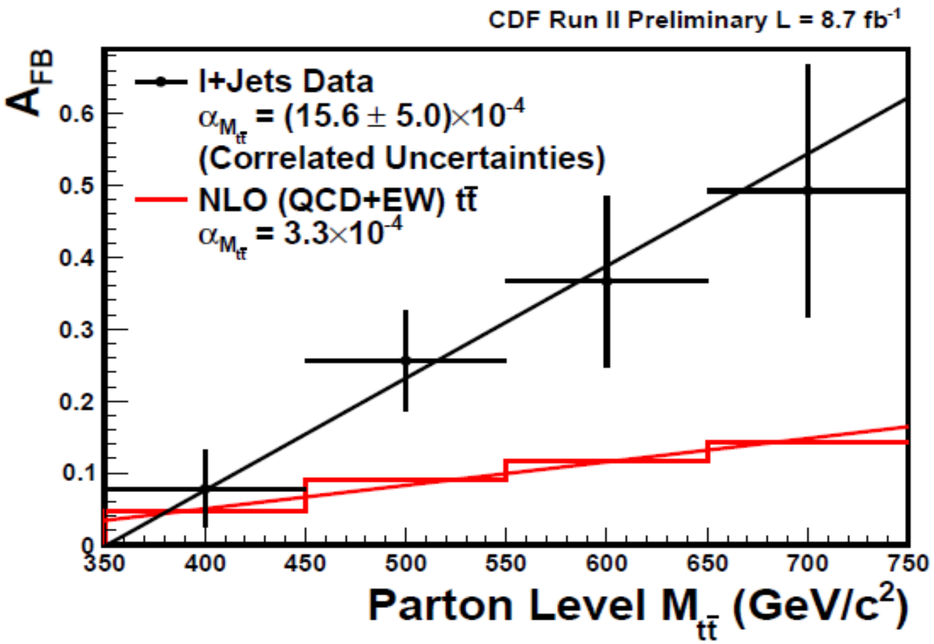
$$\Delta m_t = -0.44 \pm 0.46\ (\text{stat.}) \pm 0.27\ (\text{syst.})\ \text{GeV}$$

Most precise top quark mass difference (statistically limited)

Same sign top production

- Measurements of forward-backward asymmetry A_{FB} in ttbar production at the Tevatron inconsistent (?) with SM
- A_{FB} increases with invariant mass of ttbar system
  - at high (>450 GeV) invariant mass: A_{FB}=0.30±0.07
- Many attempts to explain A_{FB} invoke FCNC mediated by massive Z' boson
- Z' exchange would create a high inv. mass asymmetry at the Tevatron

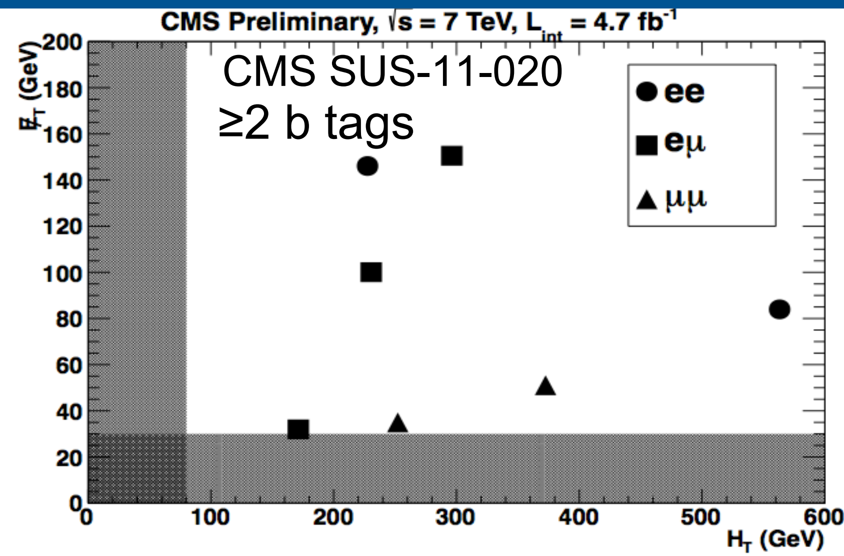
⇒ Search for same sign tops in data
  - Berger et al. (arXiv:1101.5625)

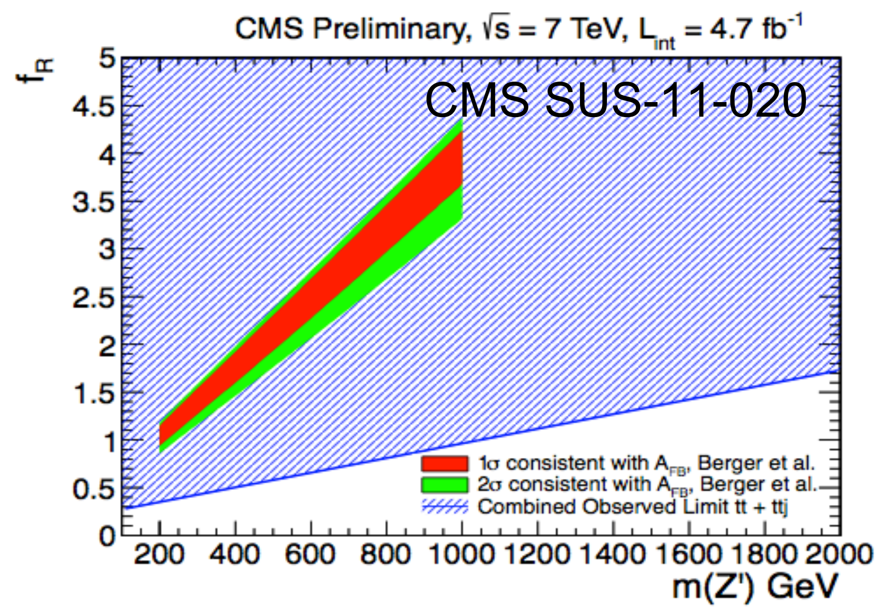


Same sign events

CMS EXO-11-065, SUS-11-020

- Similar event selection as in ttbar, except same-sign leptons
- Use sum of jet p_T (H_T) and MET
- 7 events are selected in the data
- All main backgrounds data-driven
  - Background dominated by jets faking leptons
  - ttbar lepton+jets with one fake lepton
  - Mis-measured charge in dilepton (DY/ttbar)
- Set exclusion limits
- This FCNC Z' production limit inconsistent with Tevatron FB asymmetry
- provide constraints on several models in a topology with 2 like-sign leptons, MET, b-jets
  - like-sign top quarks production in Z′ model
  - production of two sbottom quarks

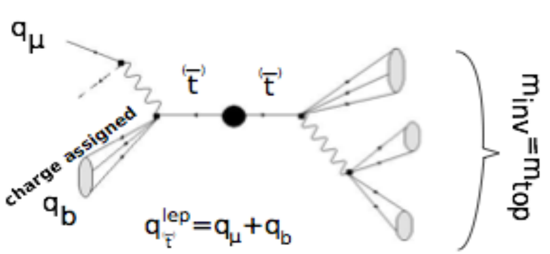




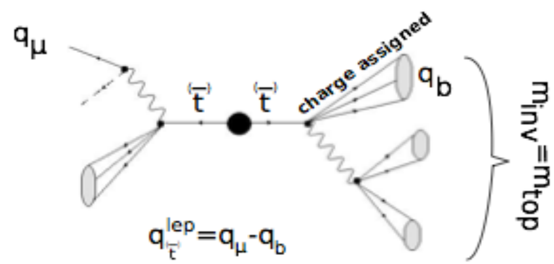
Top quark charge

- top quark is the electroweak isospin partner of the bottom quark and is expected to have a charge of +2/3 e
- Use lepton+jets final state
- Measure charges of W and b quark
  - assign charge from semi-leptonic b-decays
  - Establish correlation between charge of the b-quark and a weighted sum of the electric charges of the particles belonging to the b-jet
  - Dilution: B-oscillations and presence of semi-leptonic c-quark decays
- Define two categories: +2/3e and -4/3e
- Pair b-jet to top quark charge

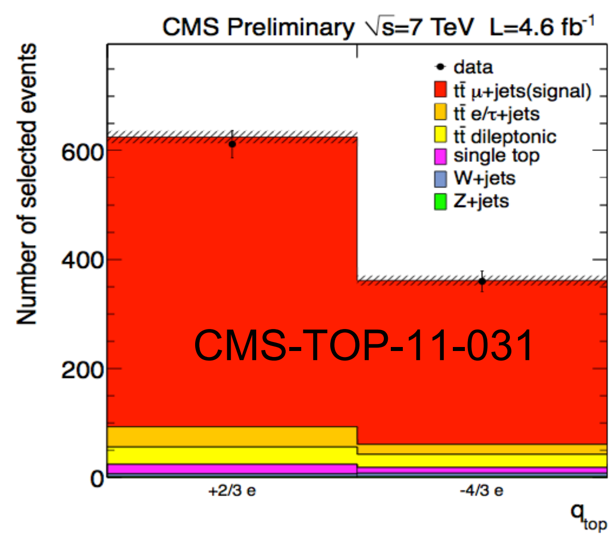
$$Q_{b\,jet} = \frac{\sum_i q_i |\vec{j}\cdot\vec{p}_i|^\kappa}{\sum_i |\vec{j}\cdot\vec{p}_i|^\kappa}$$



(a)



(b)



Top quark charge

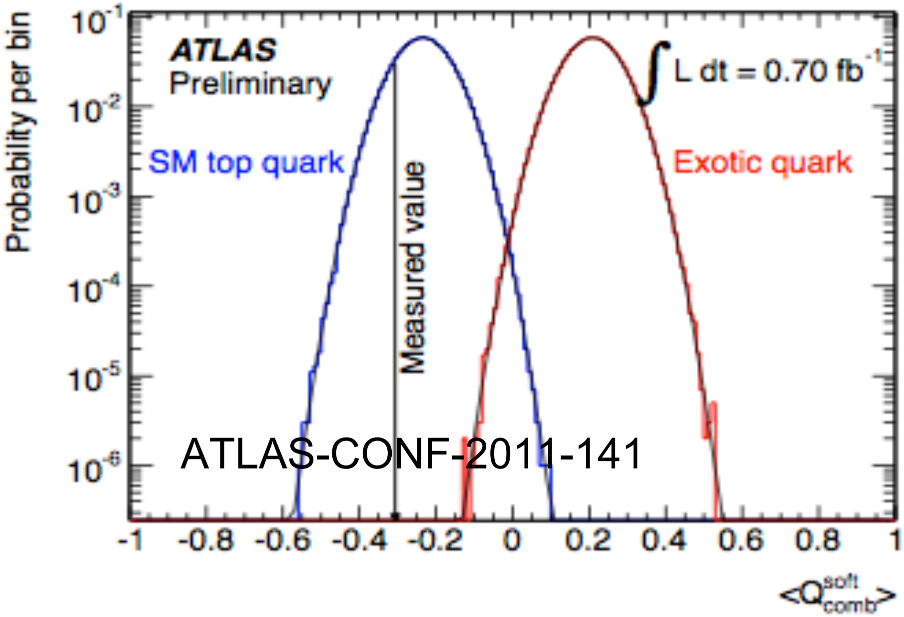
- Scenario with exotic top of charge −4/3 e would correspond to an asymmetry between the two categories of *A* = −1

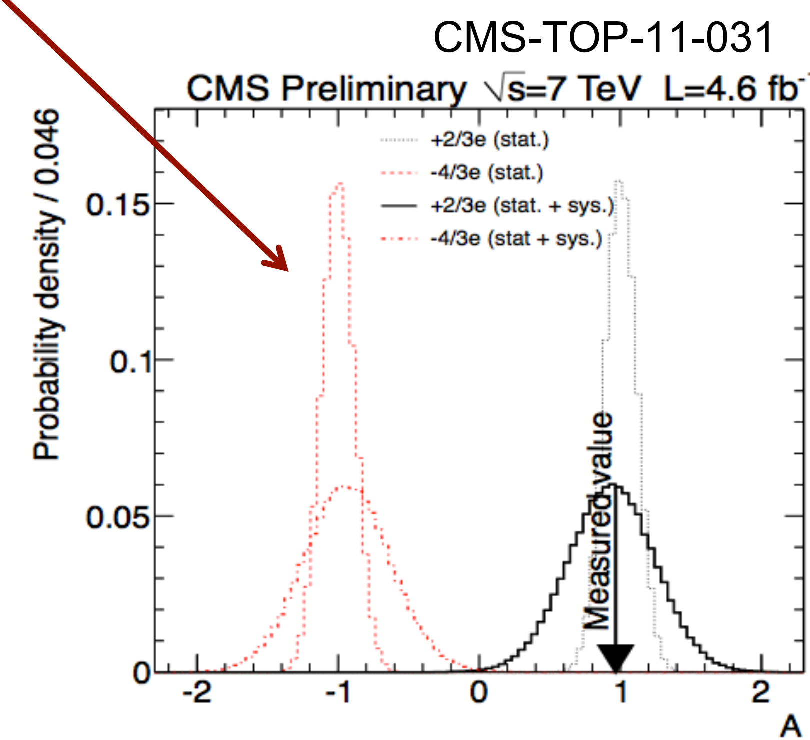
$$A = \frac{1}{D_S}\frac{N_{SM} - N_{XM} - \langle N_{BG} \rangle D_B}{N_{SM} + N_{XM} - \langle N_{BG} \rangle}$$

- Measure:

$$A_{meas} = 0.97 \pm 0.12(\text{stat.}) \pm 0.31(\text{sys.})$$

- Exclude exotic quark with charge -4/3 e





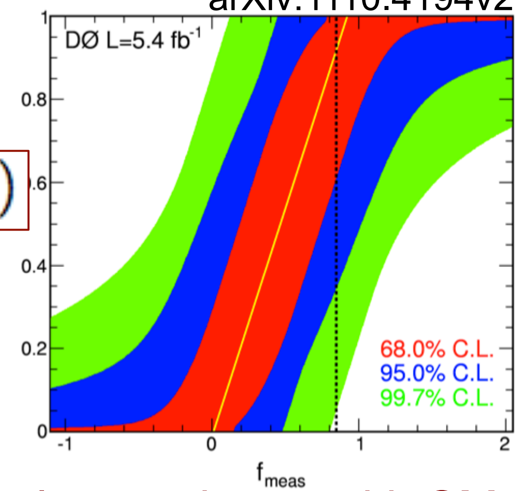
⇒Both experiments exclude exotic scenario at >5σ

Spin correlation

- Spin correlation may differ from that expected in the SM
  - top quark decays into a charged Higgs boson and a b quark ($t \rightarrow H^+ b$)
  - Other BSM scenarios

$$f_{\text{meas}} = 0.85 \pm 0.29(\text{stat} + \text{syst})$$

arXiv:1110.4194v2



$$A_{\text{meas}} = 0.66 \pm 0.23\,(\text{stat+syst})$$

(expected A=0.78)

- Measure ratio of ttbar events with correlated spins to the total number of ttbar events
- Use l+jet channel (729 events)
- Matrix element method
- results indicate spin correlation at 3.1σ

Results consistent with SM

Spin correlation

$$A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}}$$

- Access spin information via the angular distributions of its decay products
  - Most sensitive probes are leptons and d-type quarks
- Fit to difference in azimuthal angle between leptons $\Delta\phi$
- No need for full top quark event reconstruction
  - Strategy: fit $\Delta\phi$ dilepton distribution with binned likelihood
  - Translate result to maximal/helicity basis
- Main systematics: JES, resolution/efficiency, fake leptons
- Results in agreement with SM
  - inconsistent with zero-spin hypothesis correlation with a significance of 5.1σ