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Experimental Top Quark Results

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14th November 2013

ATLAS DØ CDF CMS

Outline

- As the time available is limited …
- The focus of this talk is on measurements of top quark properties
  - I will not talk about BSM-specific results, although some are included at the end of the talk
- The talk is also biased towards CMS and ATLAS, although Tevatron results are included where possible

The Top Quark

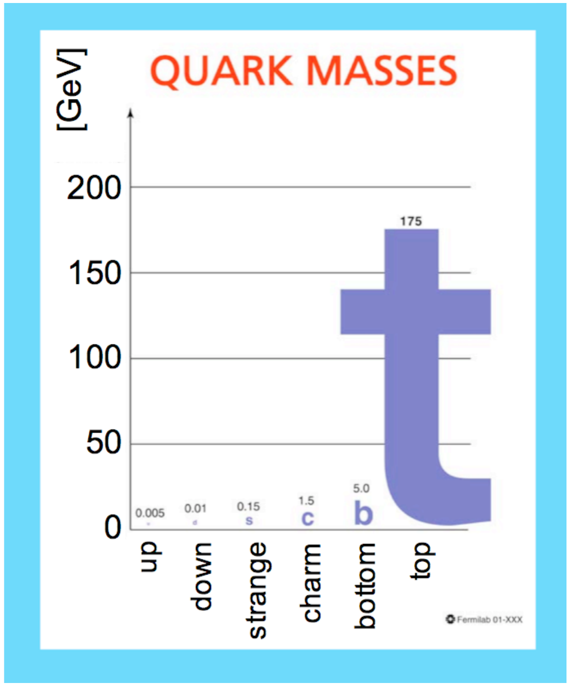
- Top is the $Q = +\frac{2}{3}e$, $T_3 = +\frac{1}{2}$ weak isospin partner of the b-quark in the third generation

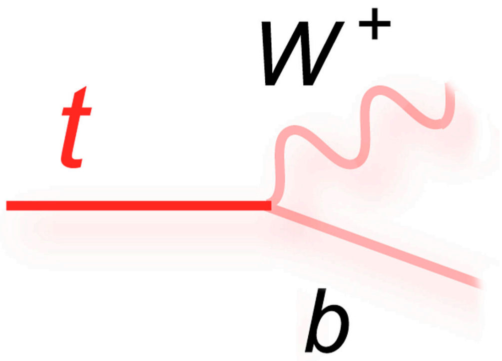
- Top mass: $m_t = 173.07 \pm 0.52 \pm 0.72$ GeV

  (PDG value based on Tevatron measurements)
  - Mass comparable to Rhenium atom (Z =75)

- Top decays to Wb ~100% of the time
  - Implies $|V_{tb}|$ close to unity

- Lifetime ~ 0.5×10^{-24} s
  - Top decays before it can hadronize
  - We can study the properties of the bare quark





Why is the top quark important?

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- Top quark plays an important role in EW symmetry breaking
  - Large mass ⇒ Large Yukawa coupling

$$Y_D \approx (10^{-5}, 0.0005, 0.026)$$

Andreas Weiler – TOP2013

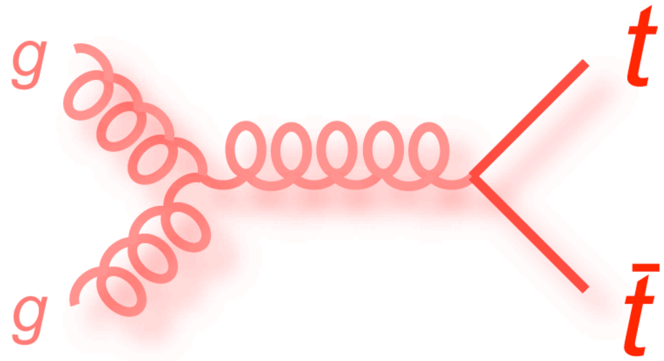
$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007 + 0.004i \\ 10^{-6} & 0.007 & -0.04 + 0.0008i \\ 10^{-8} + 10^{-7}i & 0.0003 & 0.92 \end{pmatrix}$$

- Plays an important role in many BSM scenarios:
  - Resonant tt production
  - Extra decay modes, eg. t → H^{+}b, FCNC t → qZ, light Stop decays
  - Same sign top quark pairs

Production of Top Quark Pairs

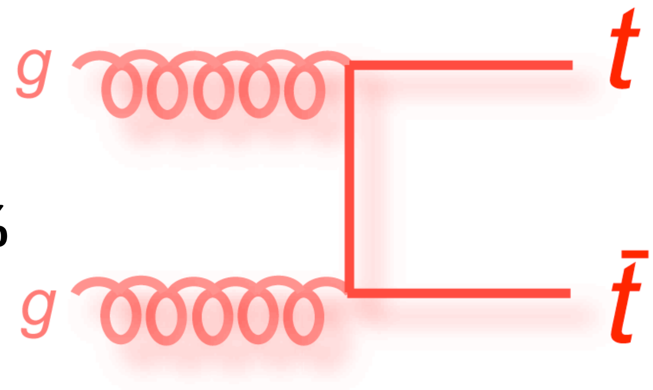
Production Mechanisms

- Dominant production mechanism via pQCD:

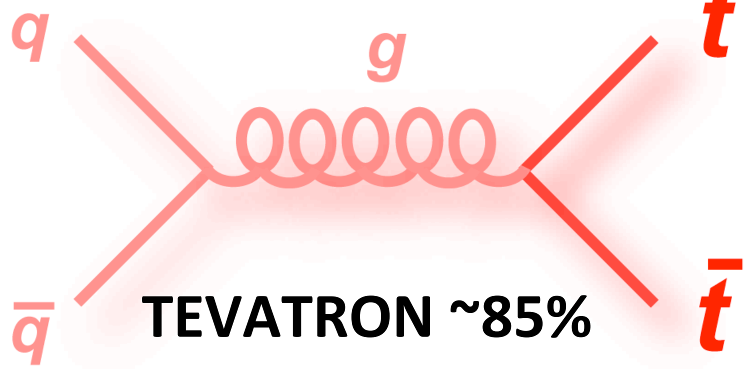


LHC ~80%

TEVATRON ~15%



LHC ~20%

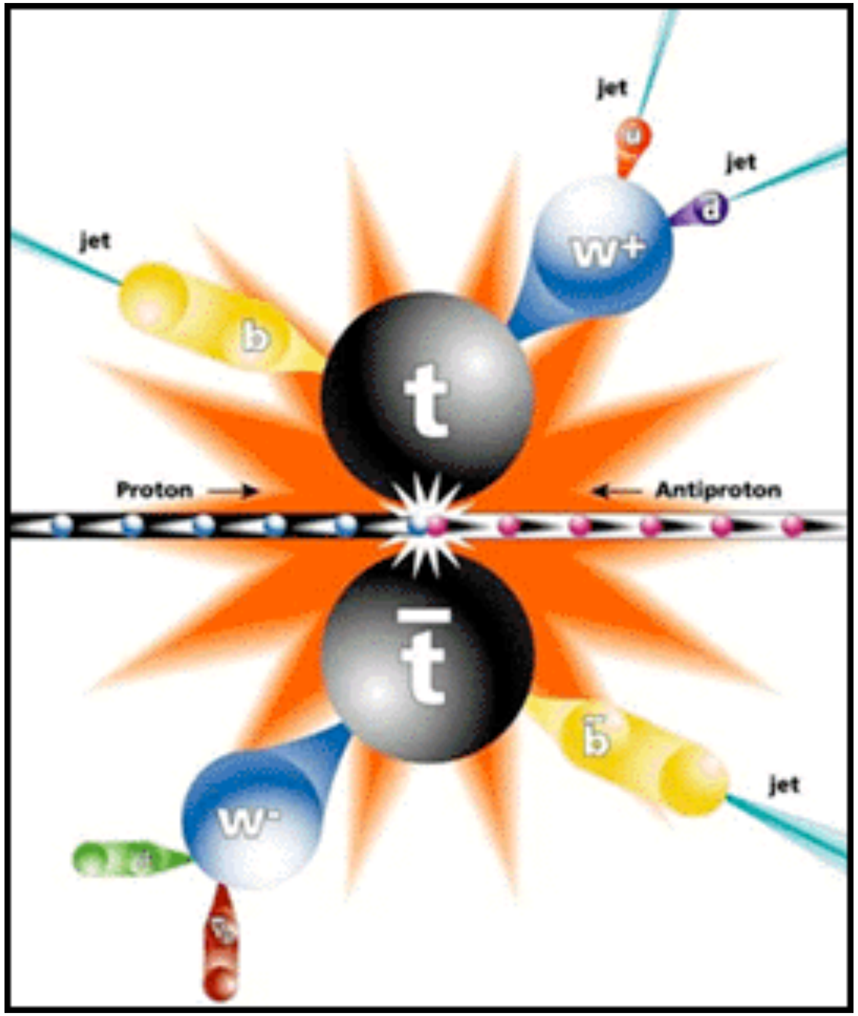


TEVATRON ~85%

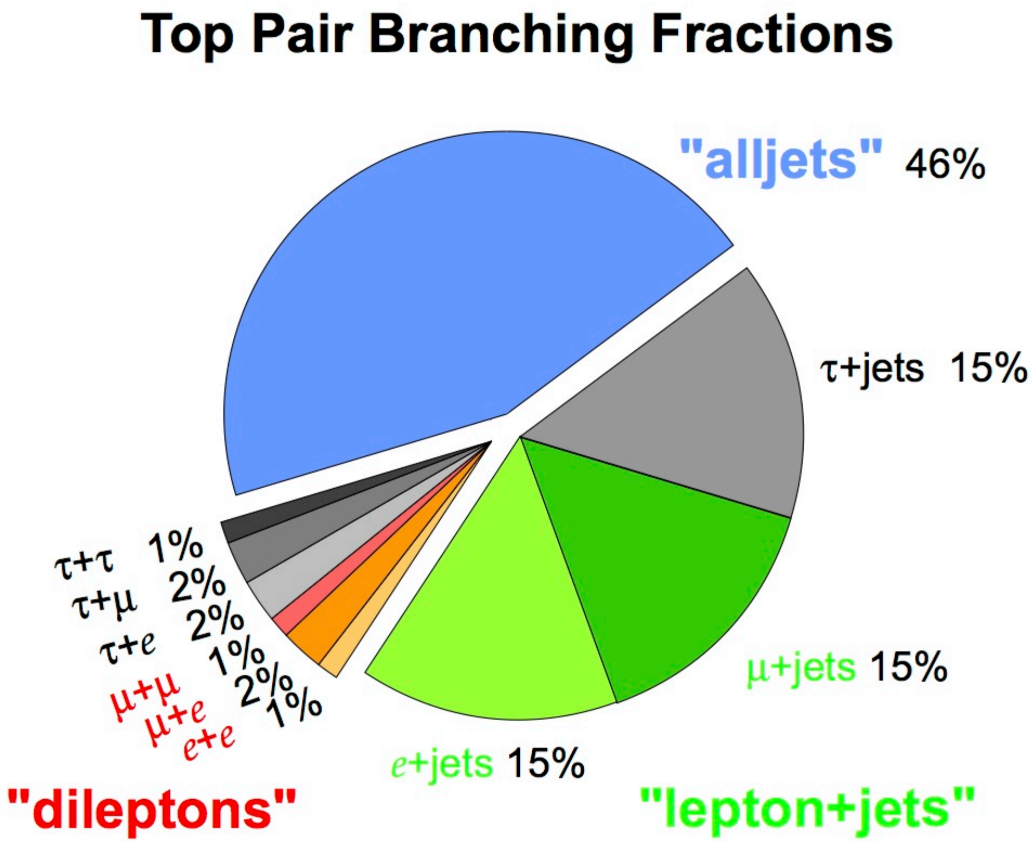
- Driven by gluon PDF at LHC

$$x = \frac{2m_t}{\sqrt{s}} \sim 0.05 \text{ at } \sqrt{s} = 7\text{TeV}$$

Top quark pair decays



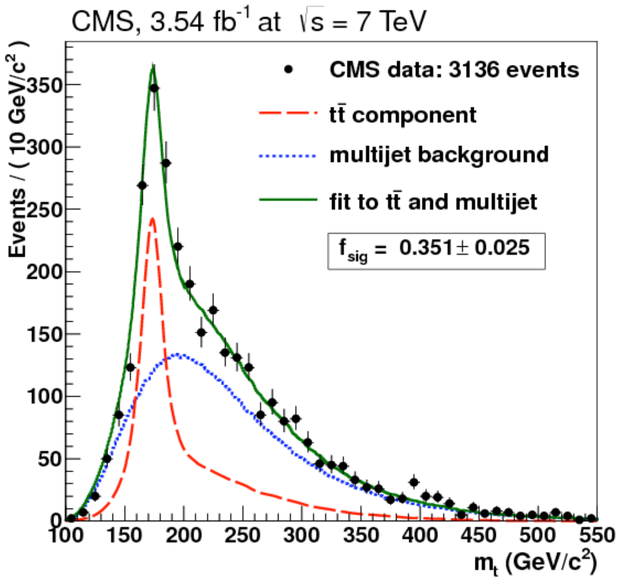
Classify decays according to how the W bosons decay:



Backgrounds

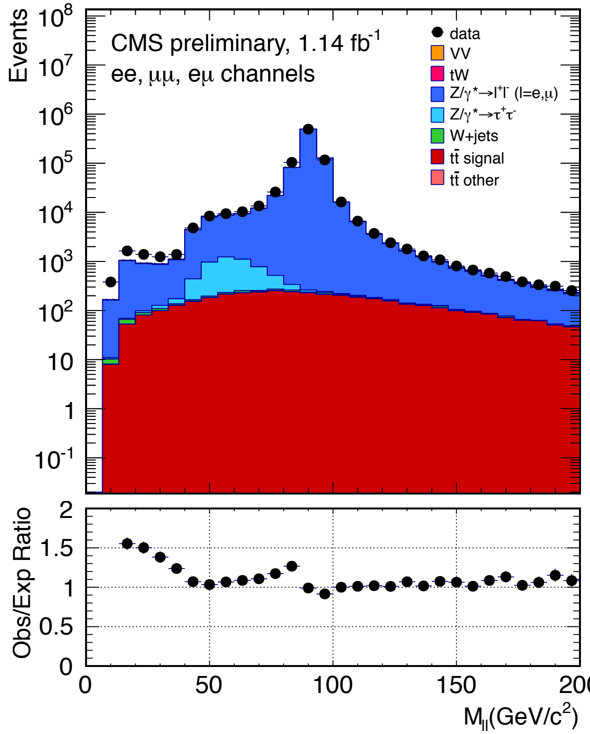
QCD background

Particular problem for all-jets decay: Model using event mixing and fitting



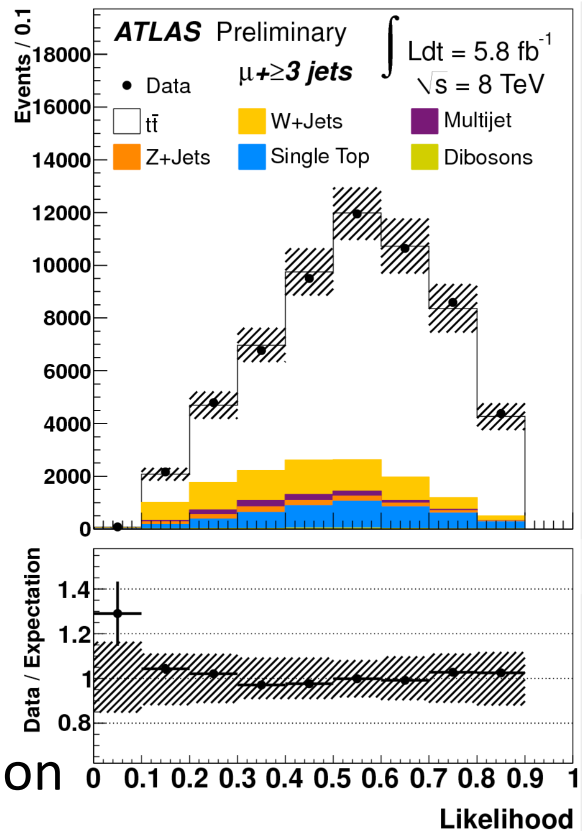
Z + jets

Particular problem for di-lepton decay: Model using Z-peak data



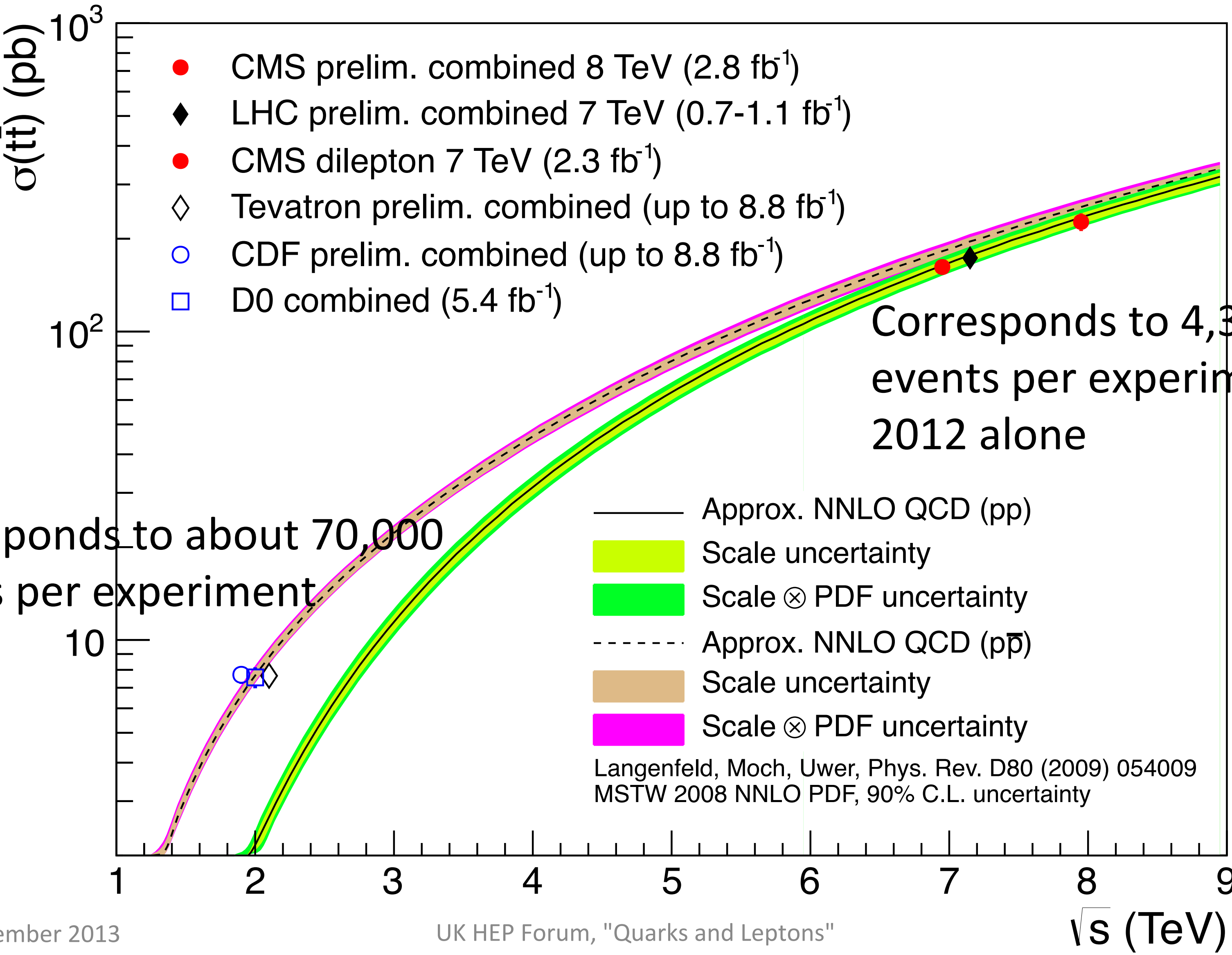
W + jets

Particular problem for l + jets decay: Handled using template fit



Others: Single top, WW, ZZ … Estimated using simulation

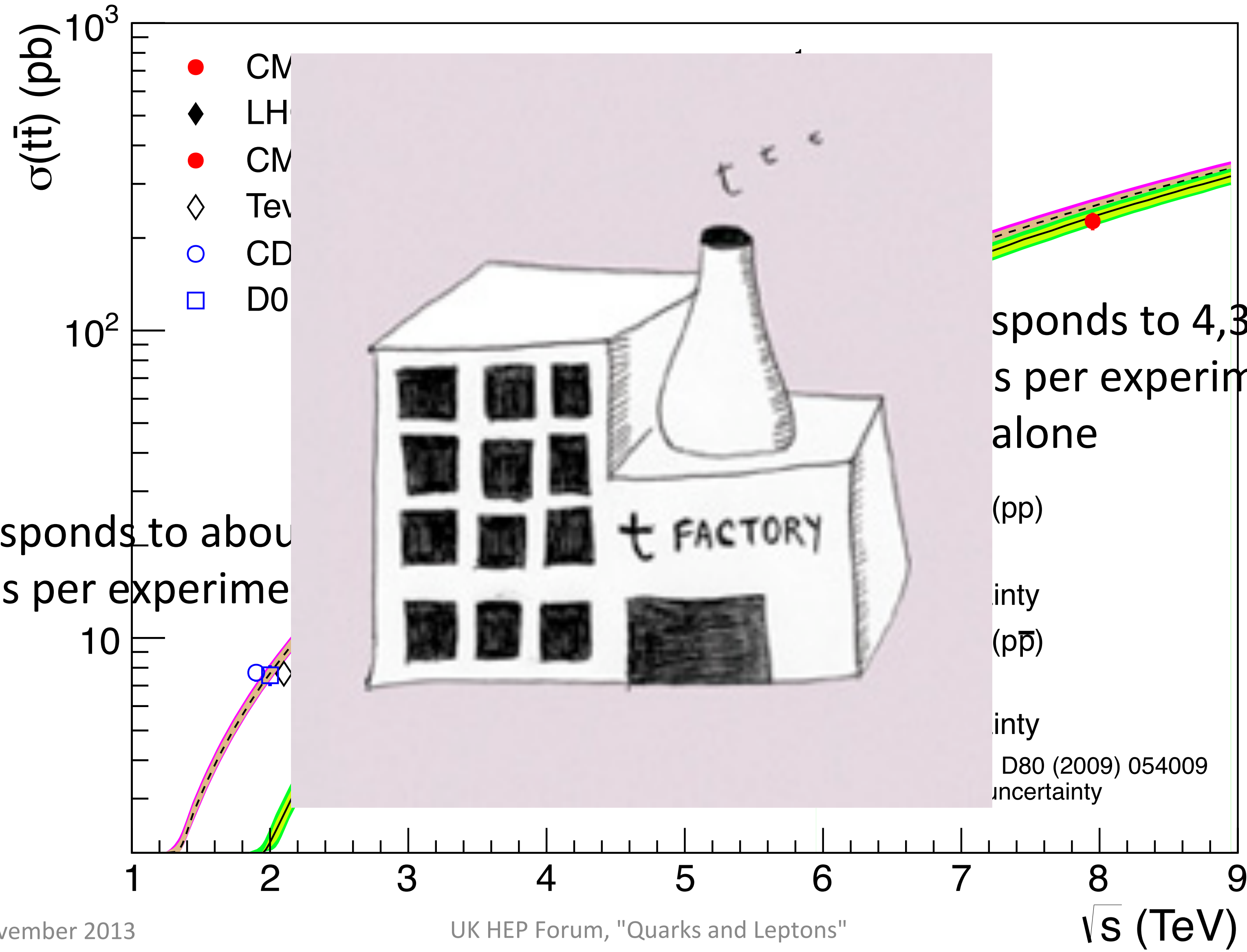
Production cross section: Top pairs



Corresponds to 4,358,000 events per experiment in 2012 alone

Corresponds to about 70,000 events per experiment

Production cross section: Top pairs



sponds to 4,358,000
s per experiment in
alone

Corresponds to abou
events per experime

Top Pair Cross Section @ √s = 7 TeV

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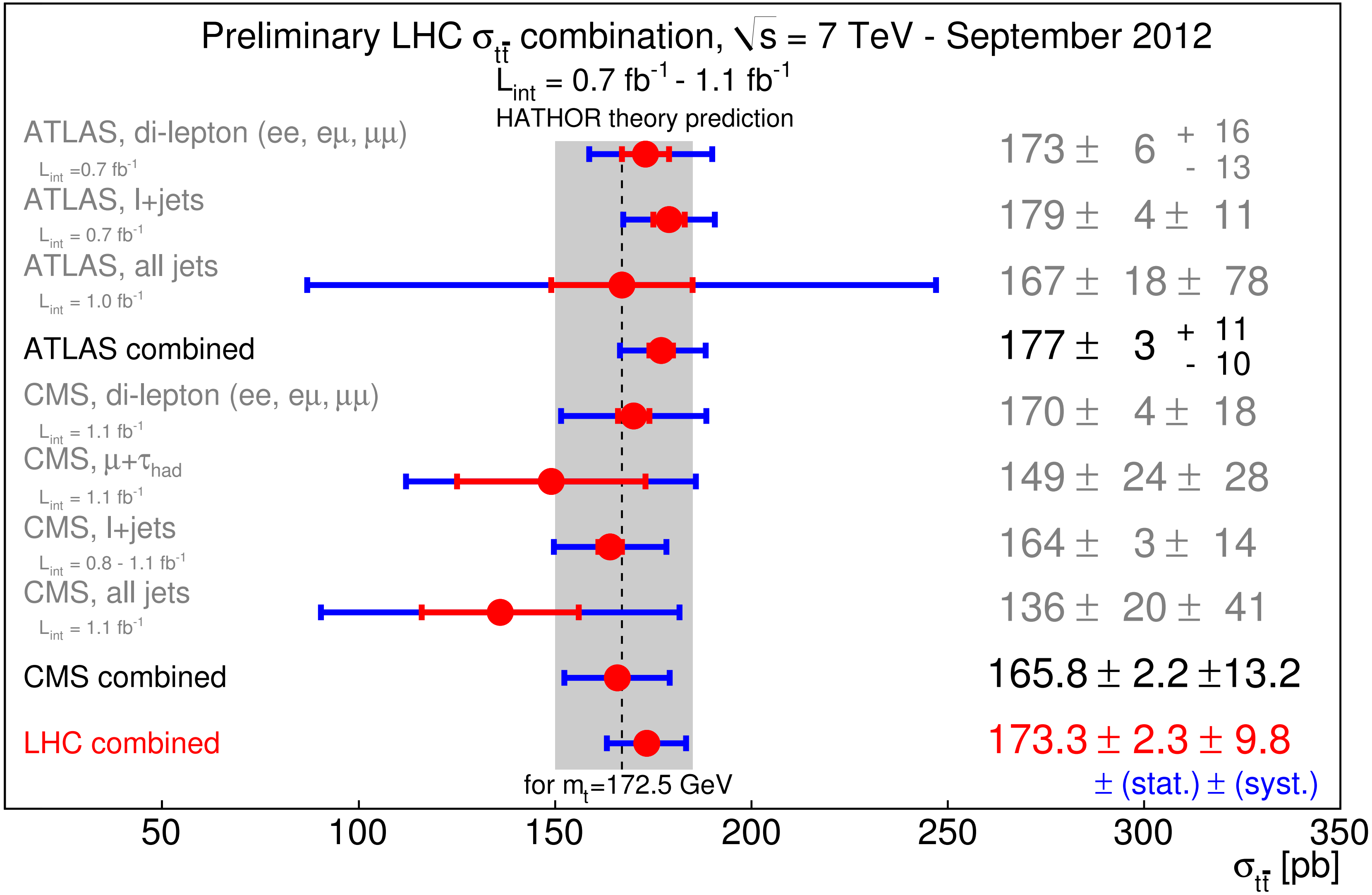
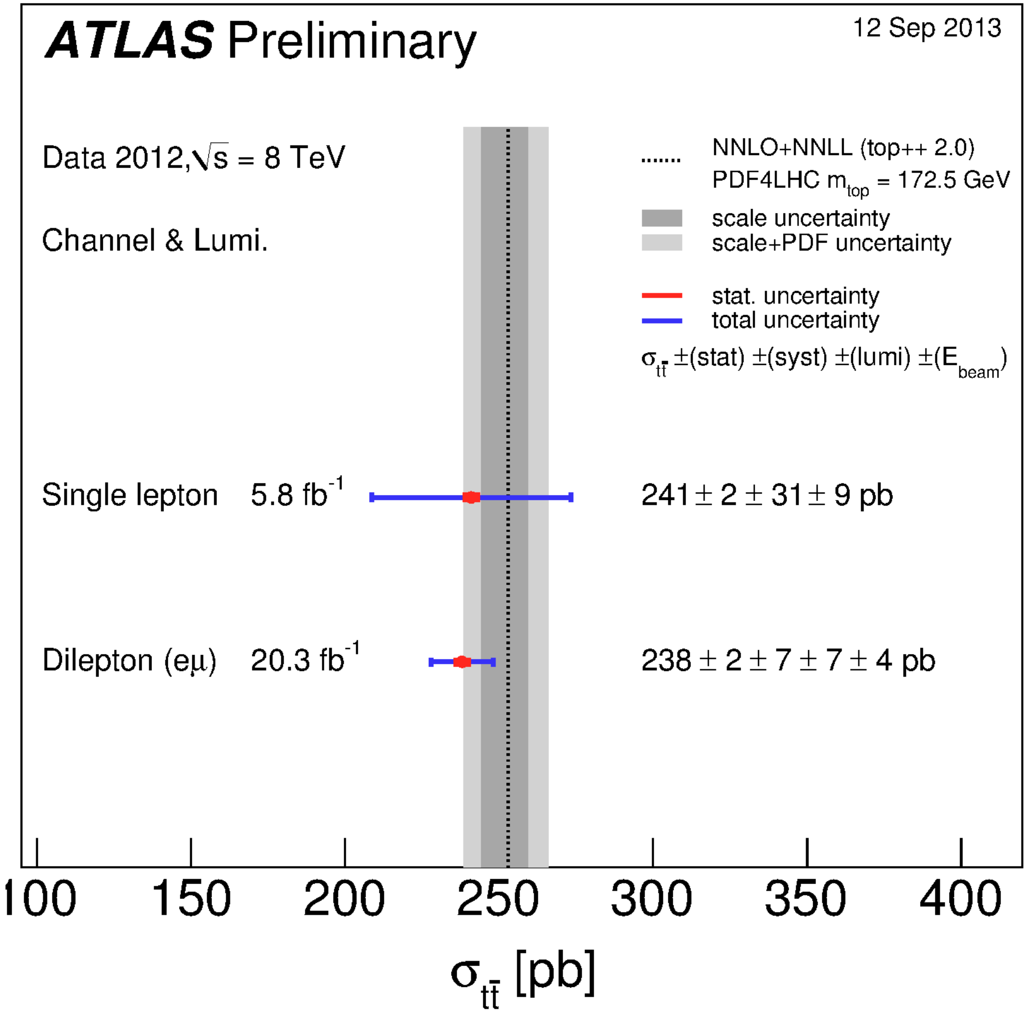
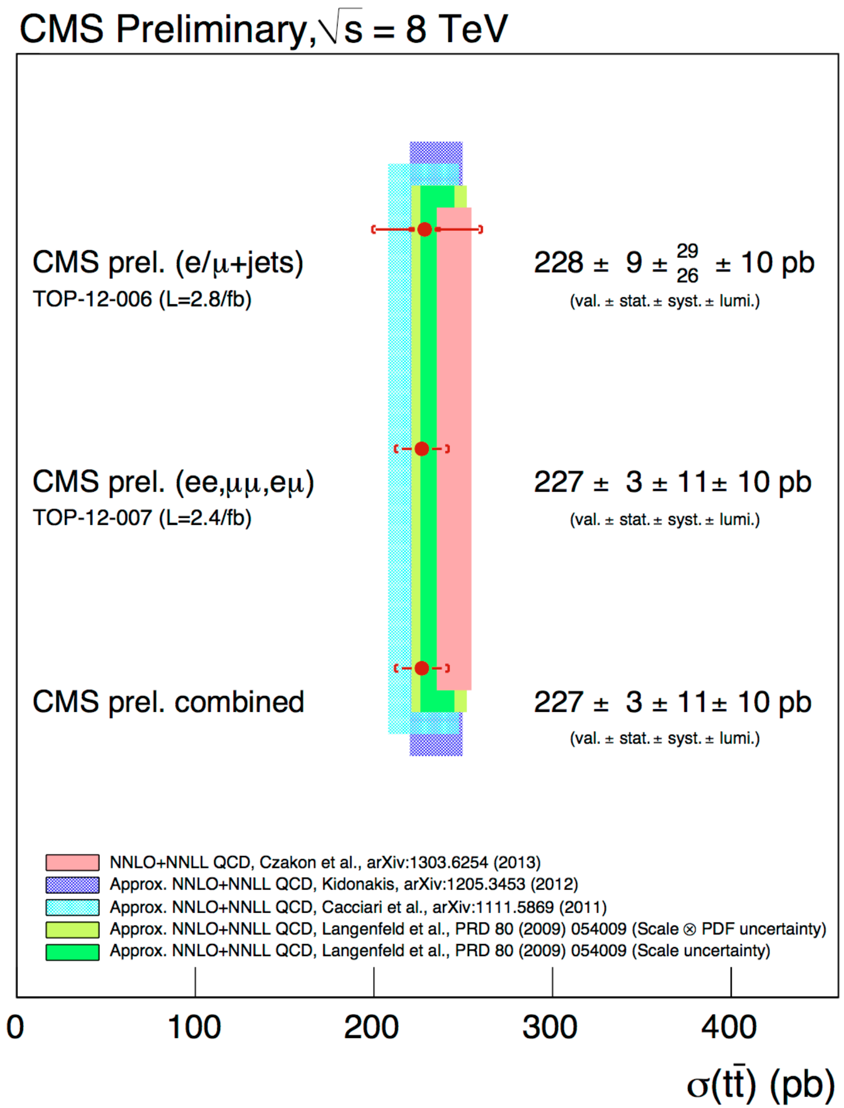


Top Pair Cross Section @ √s = 8 TeV





Cross Section: Energy Dependence

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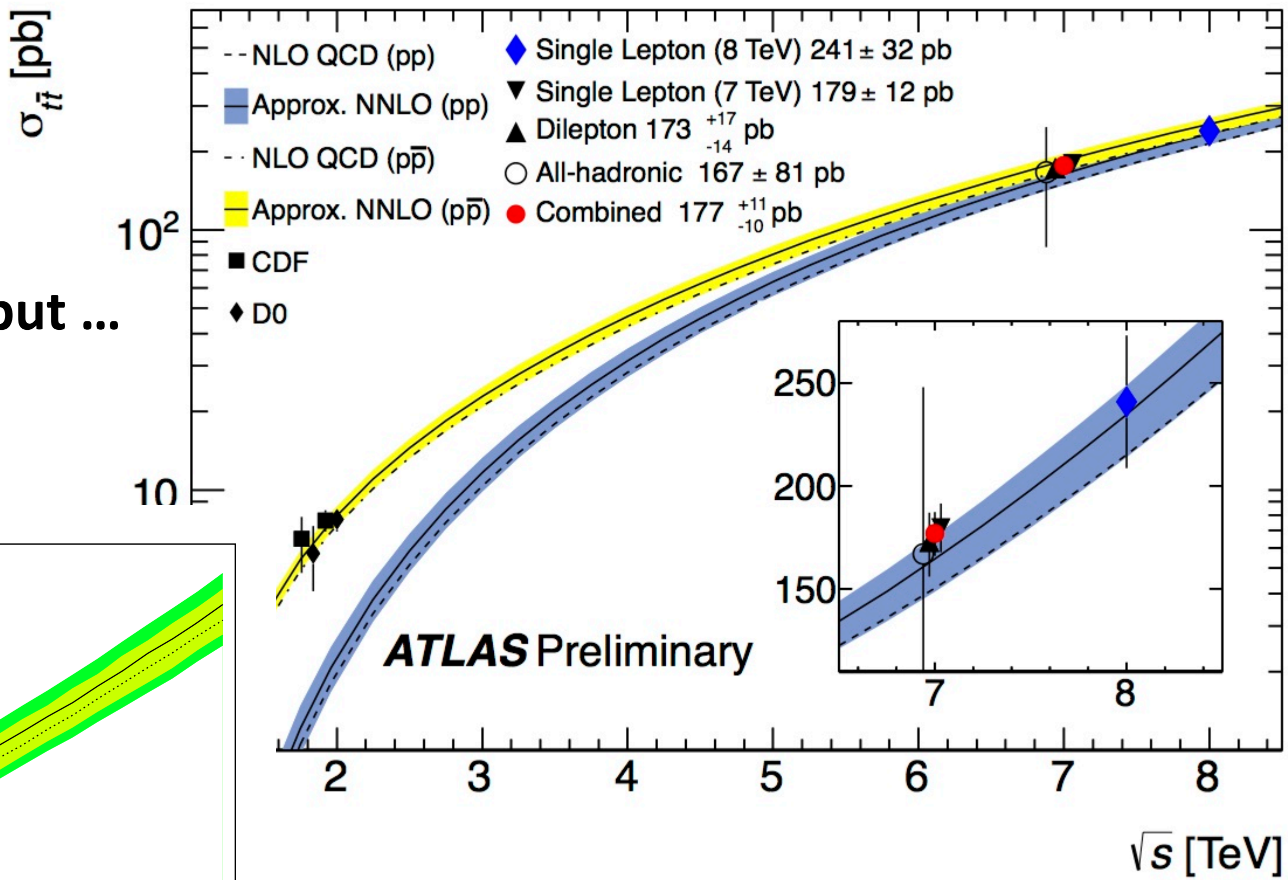
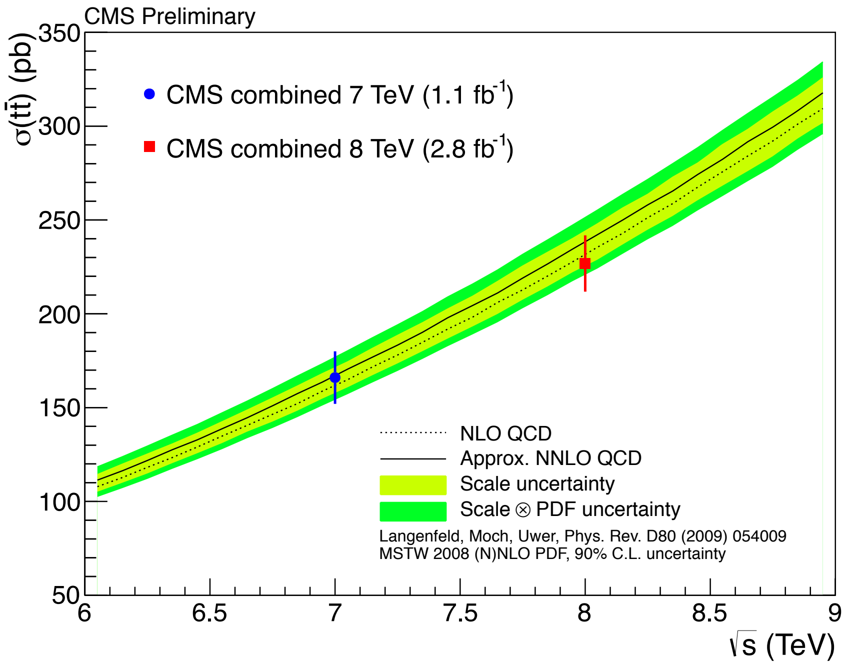
NOT the latest results, but …

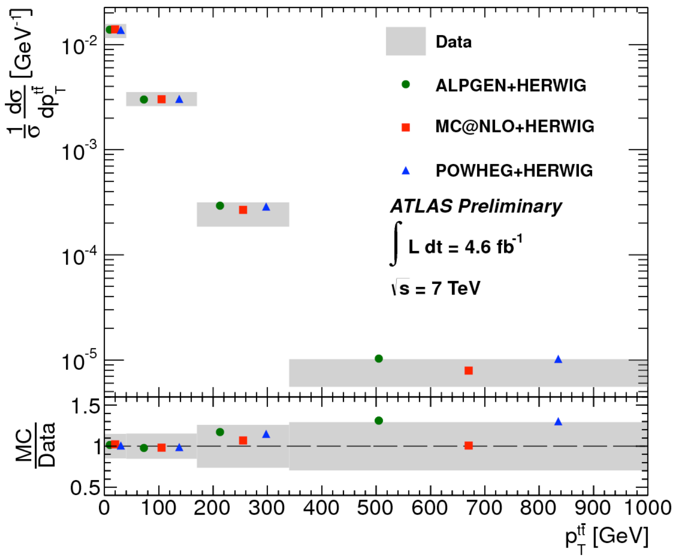


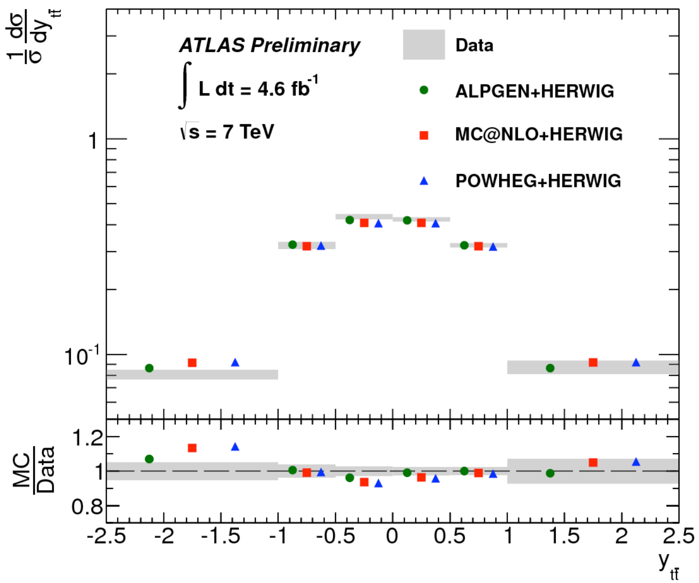


Everything appears consistent with NNLO QCD

Differential cross sections

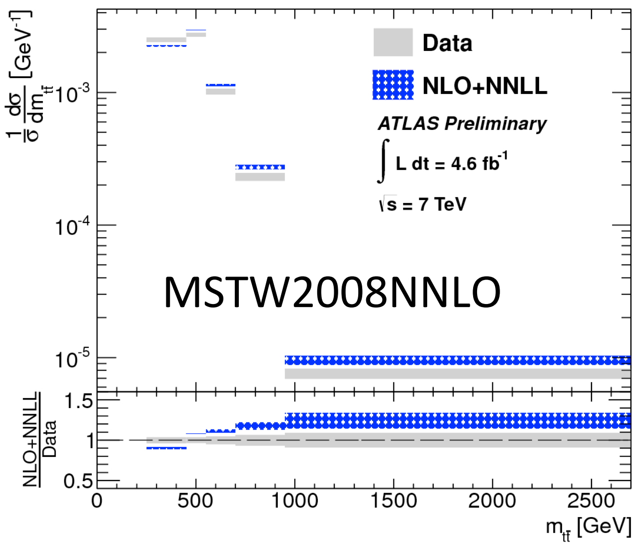
ATLAS-CONF-2013-099: Lepton + Jets





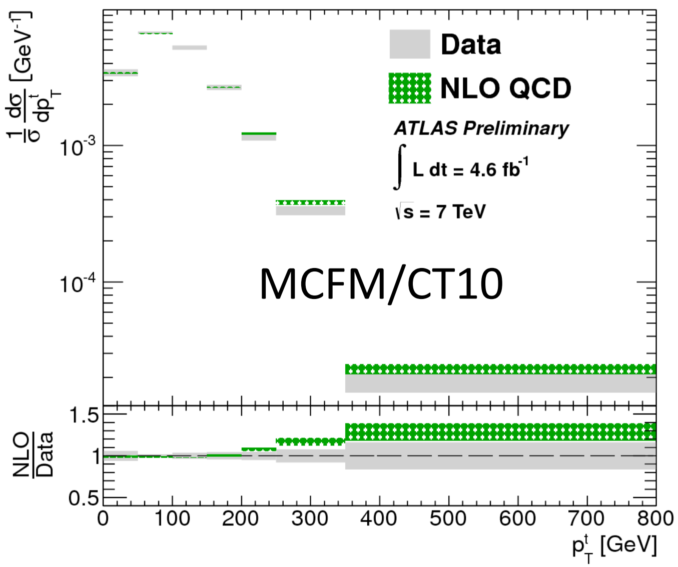
Generally good description by simulation, but p_T(top) too soft above 200 GeV

ALPGEN gives best description of y_{tt}



NLO and NLO/NNLL do not include parton showering

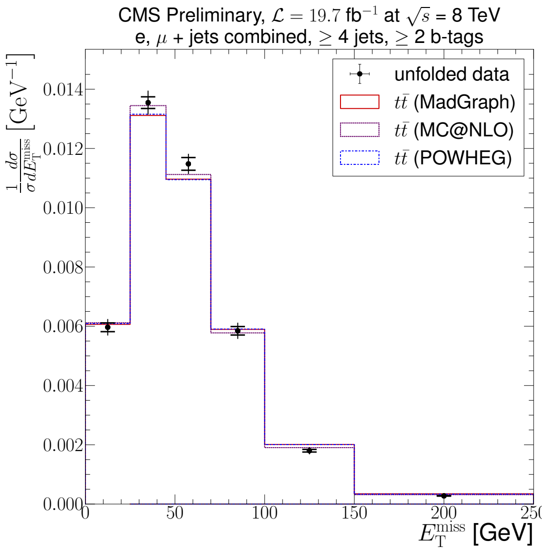
Precise comparison not possible

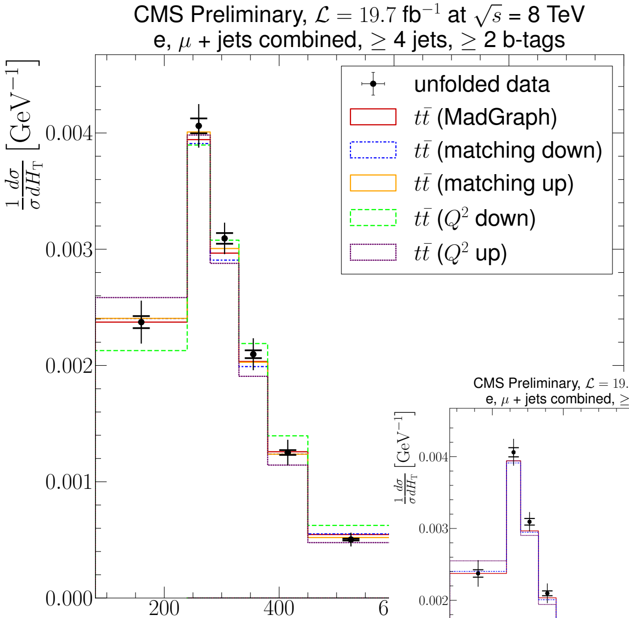


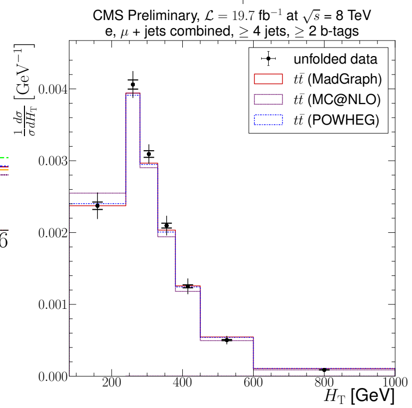
Differential cross sections

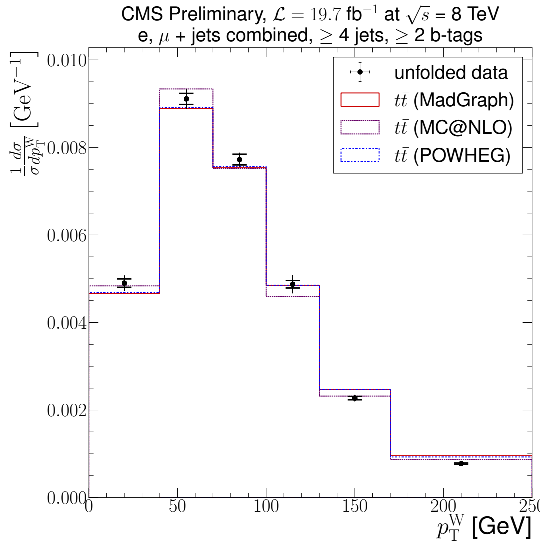
CMS-PAS-TOP-12-042: Lepton + Jets

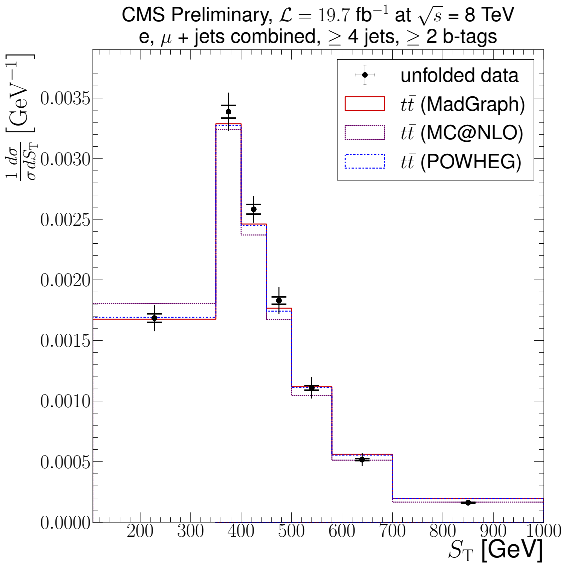
CMS-PAS-TOP-12-028: Dileptons



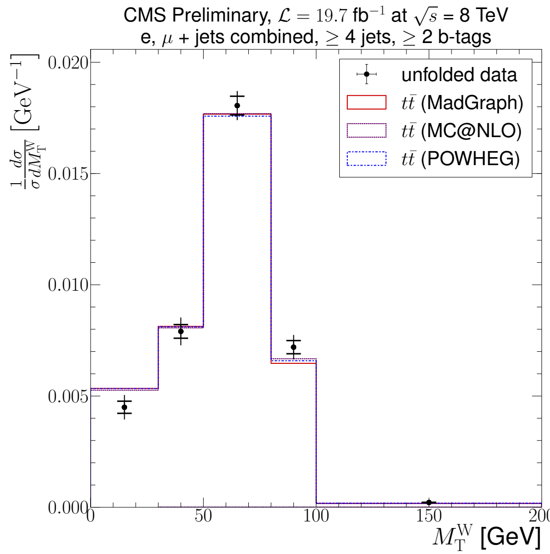








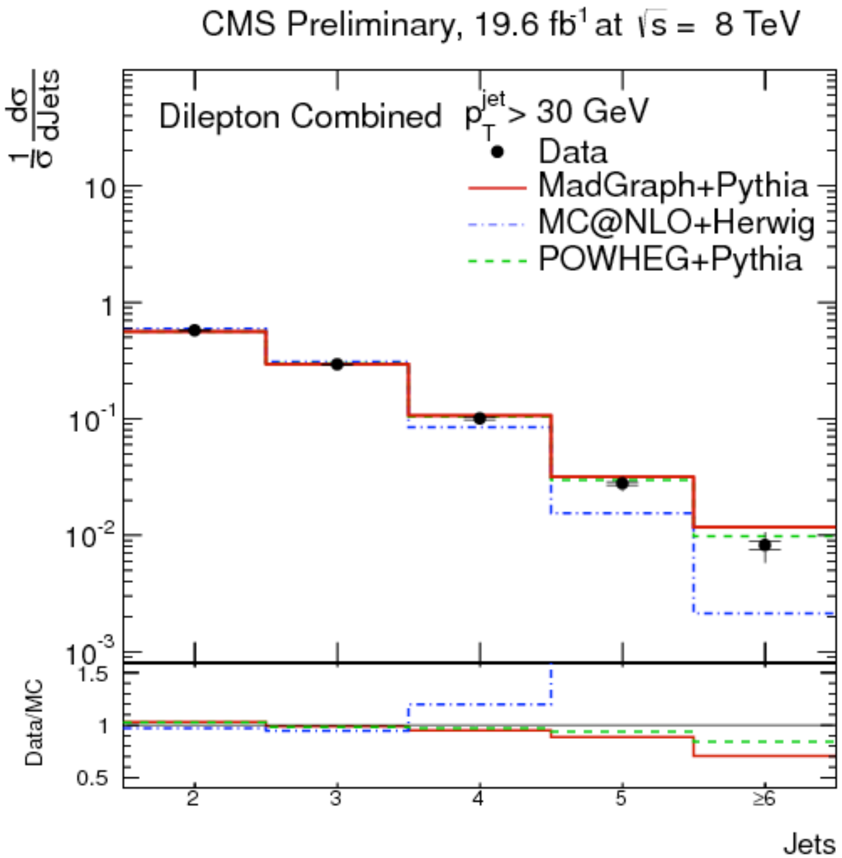
Comparison to simulation only
Everything appears well described
by simulation in both decay modes

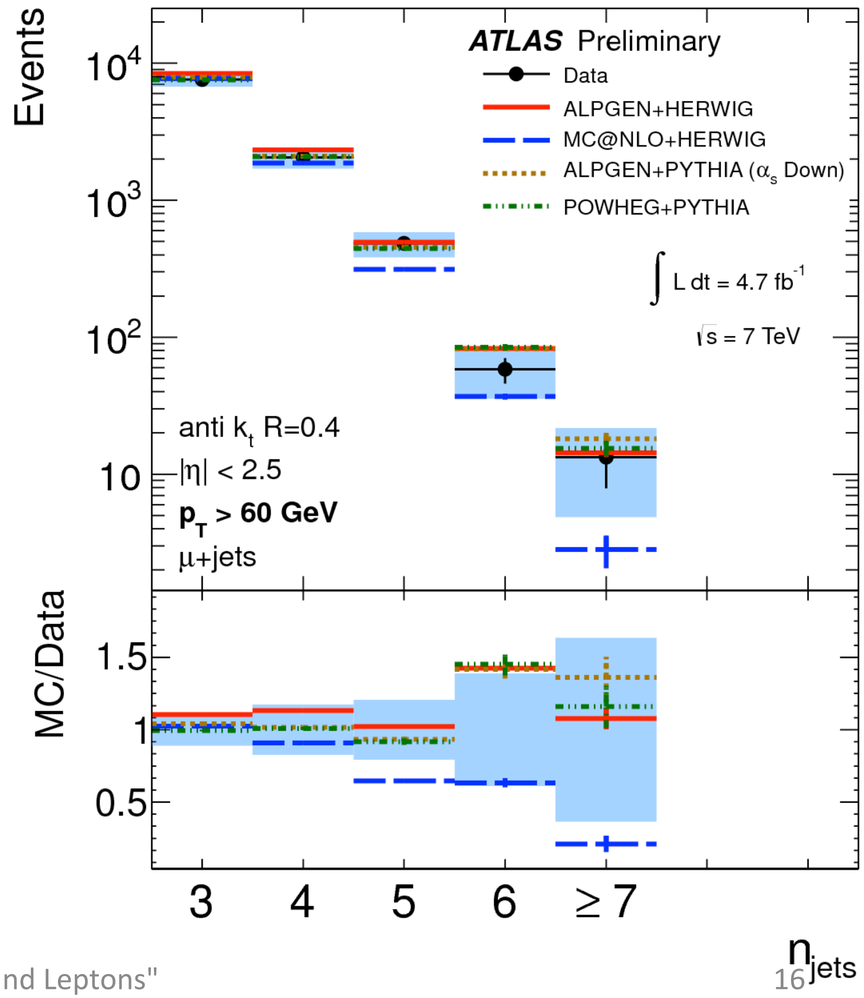


Cross section versus Jet Multiplicity

- Top pair cross section in the presence of additional jets
  - Helps constrain ISR, as well as testing pQCD

CMS-PAS-TOP-12-014
ATLAS-CONF-2012-155

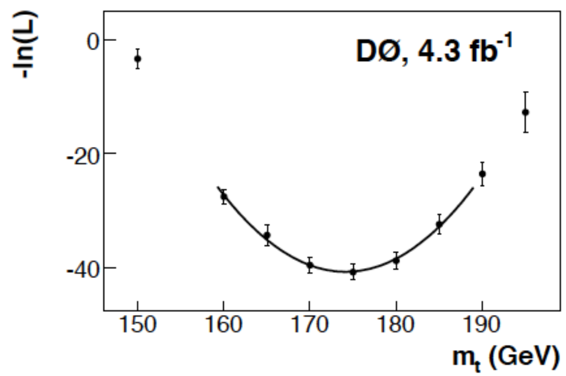


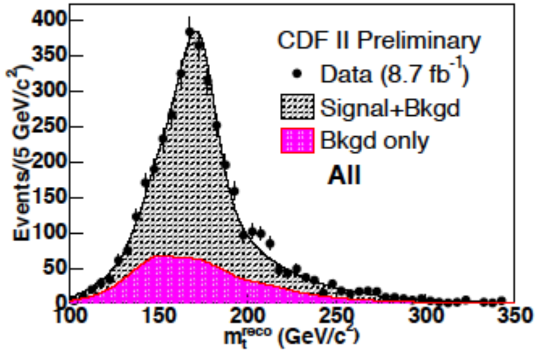


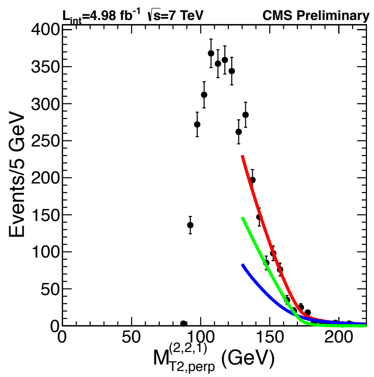
Data disfavour MC@NLO+HERWIG

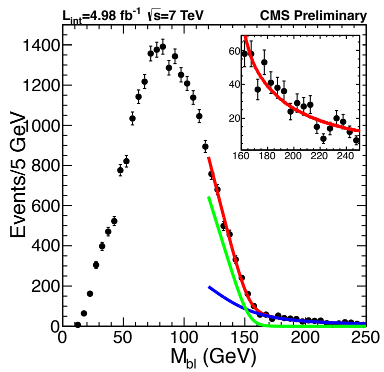
Top Mass Measurements

- Matrix Element method
  - Use MEs for processes contributing to final state to evaluate event-by-event probability densities. Likelihood fit.
- Neutrino weighting method
  - Dileptons – two neutrinos cannot be separated
  - Expect Gaussian distribution for νη (width ∝ m_t)
- Ideogram/Template fits
  - Fit reconstructed masses or other kinematic variables
- Extraction from cross section measurements
- B-hadron lifetime technique
  - Parametrise L_{XY} in terms of m_t
- Extraction from kinematic endpoints
  - 3-body decay constraints on various forms of transverse mass

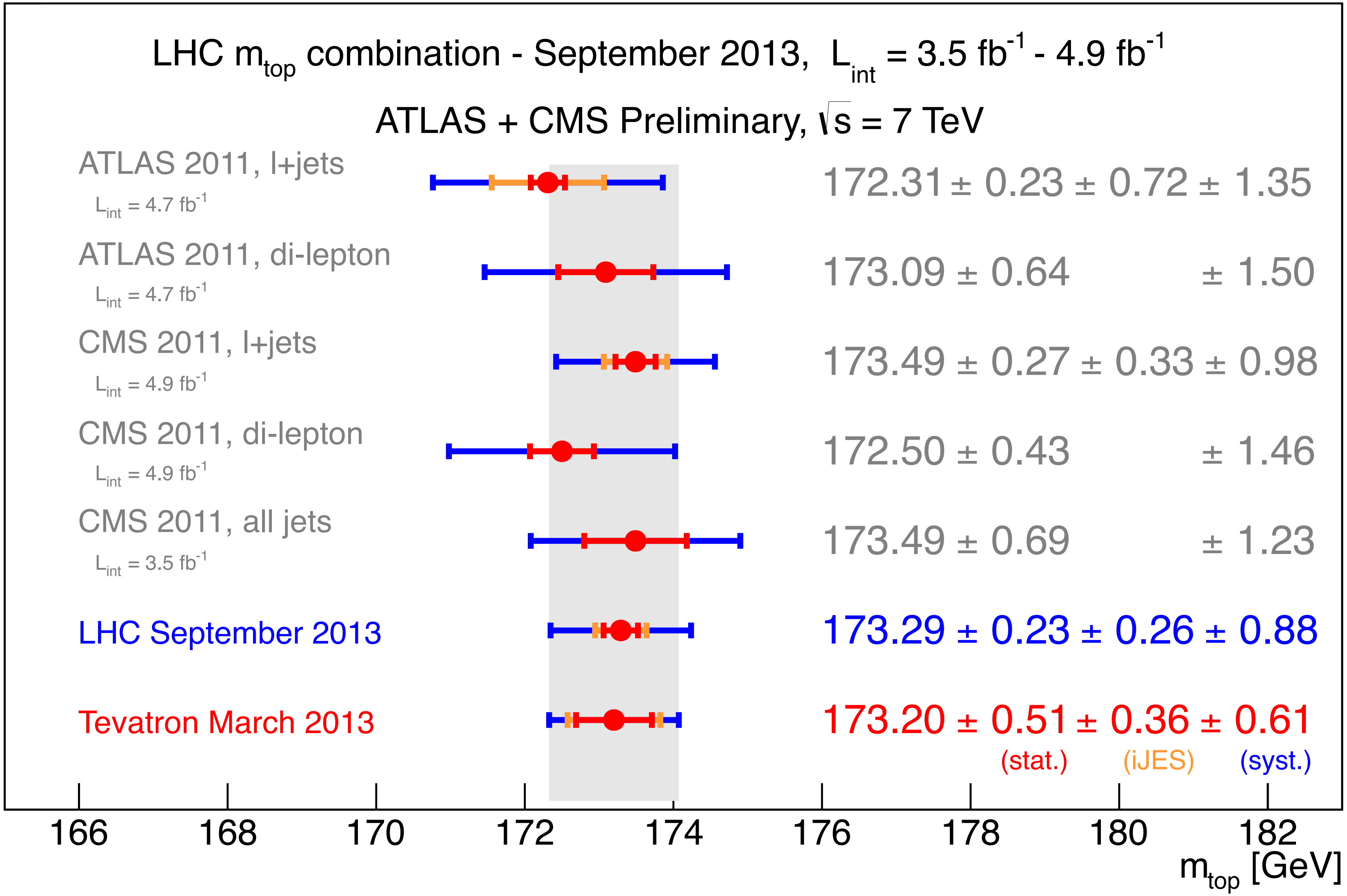








Top Mass Measurements



Top Mass: Related Issues & Measurements

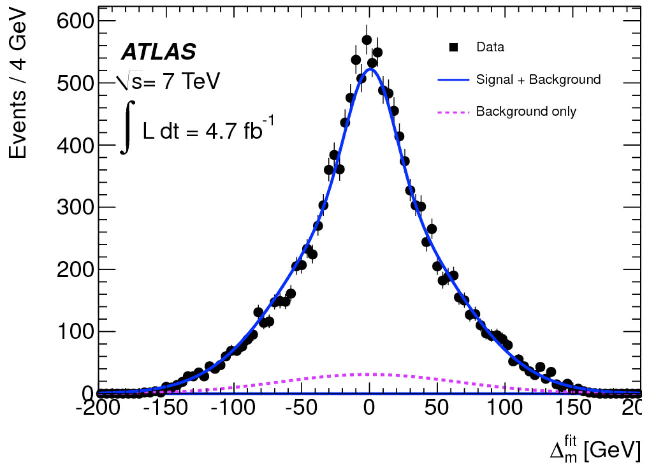
- What mass are we measuring?
  - Extraction from measured cross section: $\overline{MS}$ scheme
  - Other methods: Effectively measuring "MC" m_t
  - m_t (MC) – m_t (pole) ≈ uncertainty on mass measurement

(cf. hep-ph/1101.2599)

CMS-PAS-TOP-12-031
ATLAS: hep-ex/1310.6527

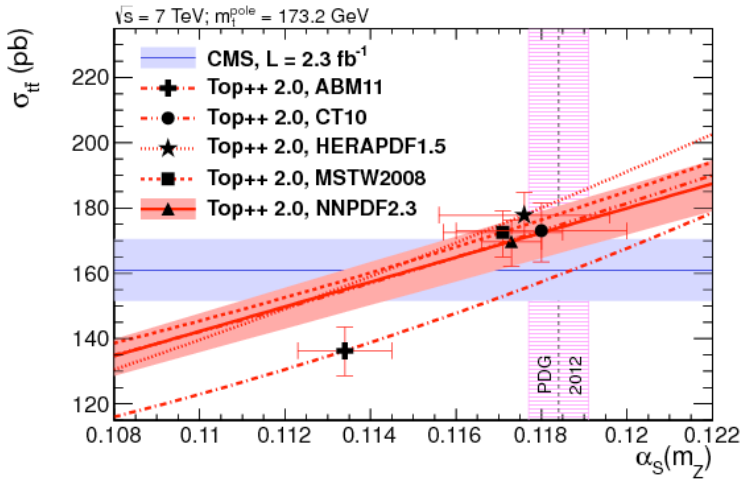
- Mass difference

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



No mass difference observed!

CMS: hep-ex/1307.1907



- Extraction of α_S from cross section

$$m_t(\text{pole}) = 176.7^{+3.6}_{-3.4}\,\text{GeV} \quad \text{(CMS)}$$

$$\alpha_S(m_Z) = 0.1151^{+0.0033}_{-0.0032}$$

$B(t \to Wb)/B(t \to Wq)$

- Decay rate of t → Wq (q = d, s, b) is proportional to $|V_{tq}|^2$
- Assuming that the CKM is a 3 × 3 unitary matrix highly constrains $|V_{tb}|$ to be close to unity

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

- Allows the study of $|V_{tq}|$

CMS-PAS-TOP-12-035
CDF CONF NOTE 11048
D0: PRL 107 (2011) 121802

$$R(D0) = 0.90 \pm 0.04(stat + syst)$$

$$R(CDF) = 0.94 \pm 0.09(stat + syst)$$

$$R(CMS) = 1.023^{+0.036}_{-0.034}(stat + syst)$$

$$R(SM) = 0.99830^{+0.00006}_{-0.00009}$$

Good consistency between experiments and with SM expectations

Top Charge Asymmetry

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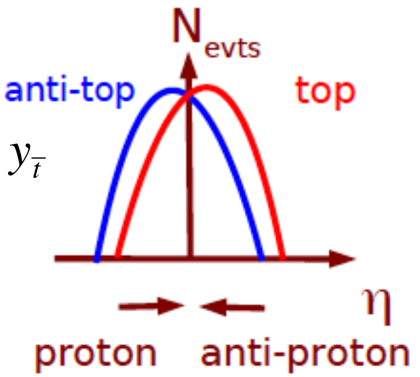
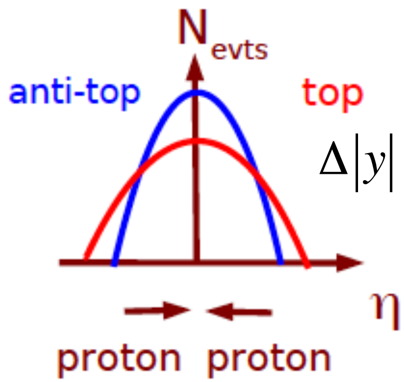
$$\Delta y = y_t - y_{\bar{t}}$$



← TEVATRON

LHC →

V. Shary, Top 2013



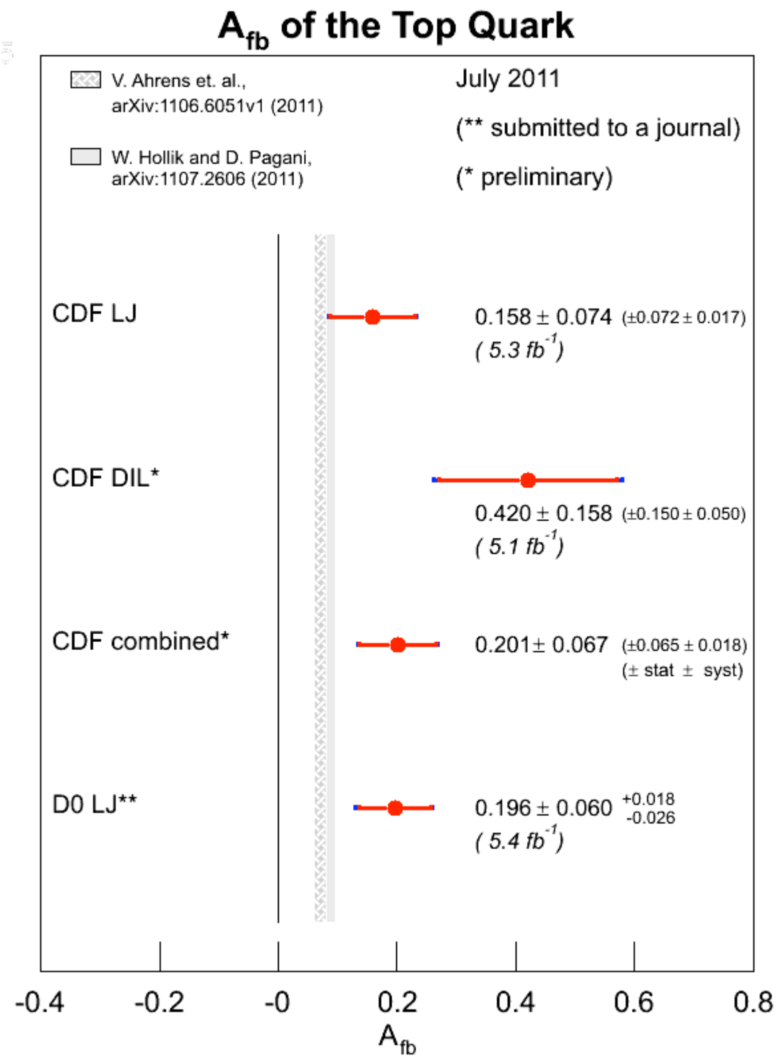
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

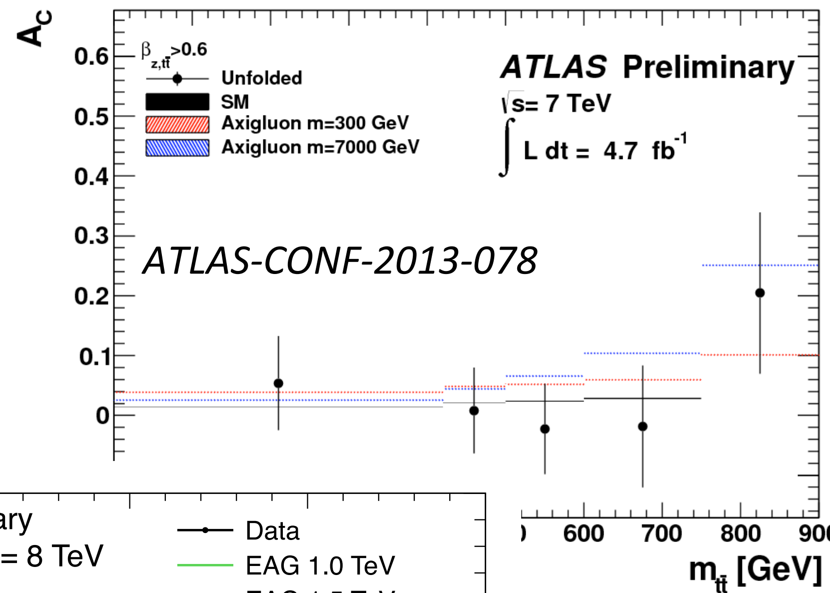
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

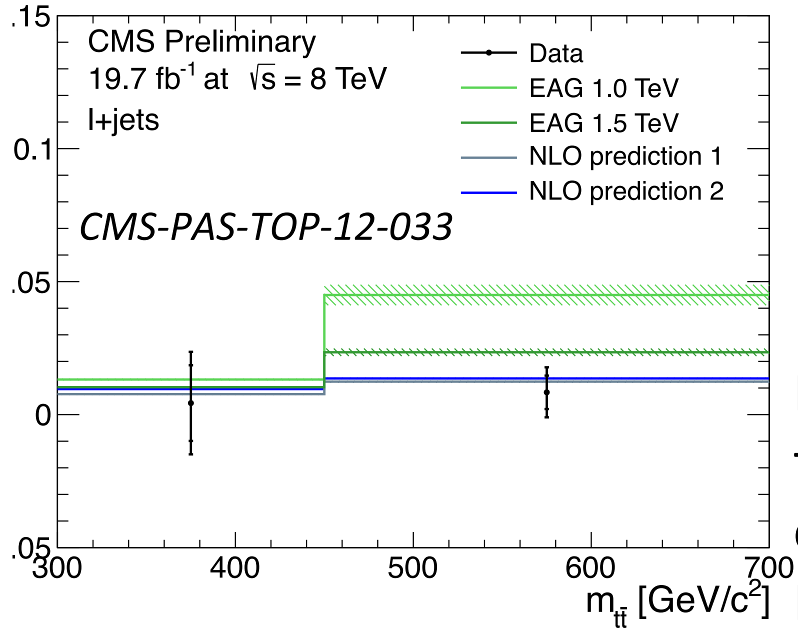
$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

- Difference expected from QCD in angular distributions for top and anti-top quarks
  - Known as the ***charge asymmetry***
  - @ LHC expect ~1% effect
- Expect different behaviour at Tevatron vs. LHC
  - Tevatron results deviate from SM expectations at 2-3σ level
    - Interesting enhancement observed at large m_{tt}

Top Charge Asymmetry







No deviation from SM observed in LHC results

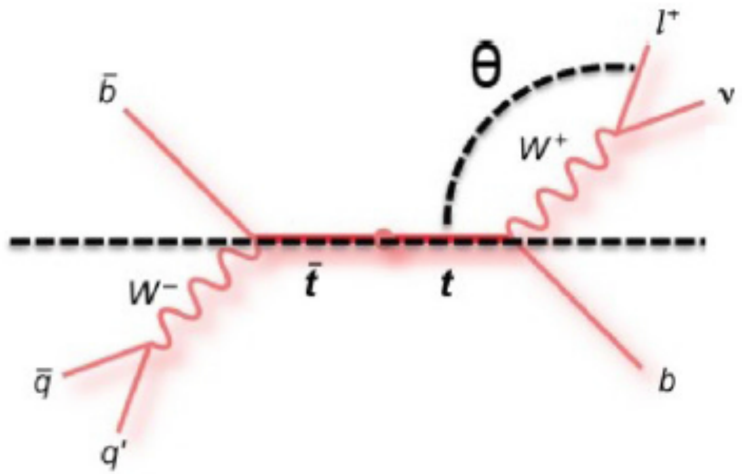
Spin Correlations

- Very short top lifetime → spin information (correlations & polarization) passed to decay products
- Expect negligible top-quark polarization and finite spin correlation in SM

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos(\theta_i)\,d\cos(\theta_j)} = \frac{1}{4}\left(1 + B_i\cos(\theta_i) + B_j\cos(\theta_j) + C\cos(\theta_i)\cos(\theta_j)\right)$$

Top-quark polarization — Antitop-quark polarization — Spin correlation

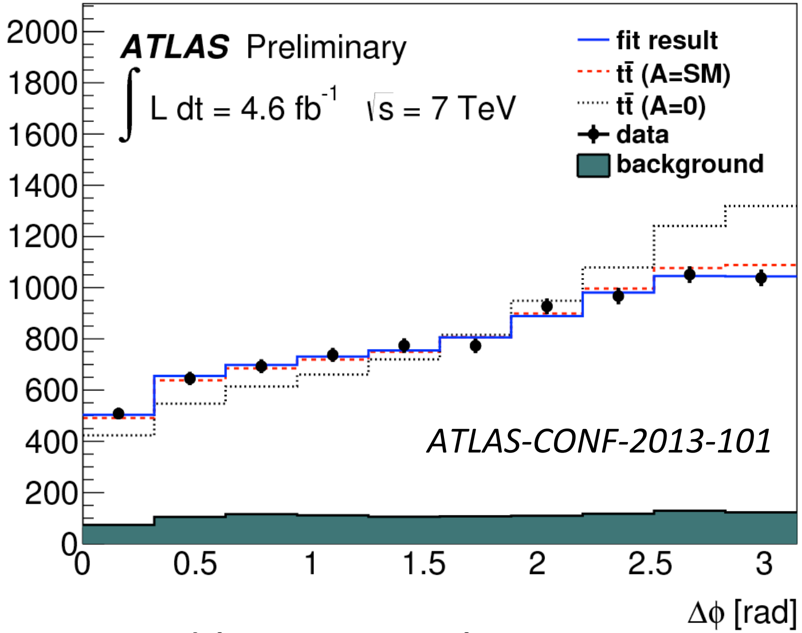
K. Kröninger, Top 2013



Angle θ_i between momentum direction of particle i in the (anti-)top rest frame and a reference axis:

- Beam (Tevatron)
- Helicity axis (LHC)

Spin Correlations



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

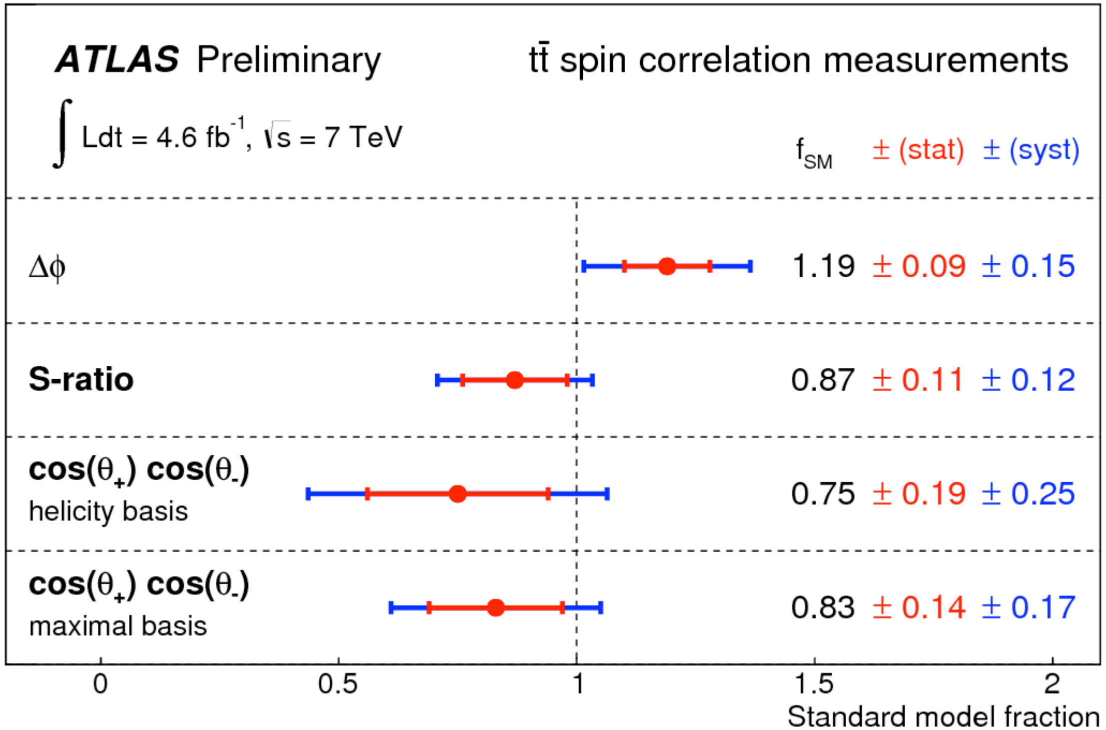
C ≈ A in dilepton case

$$f_{SM} = \frac{N_{A=SM}}{N_{A=SM} + N_{A=0}}$$

CMS dilepton result:

$$f = 0.74 \pm 0.08\ (\mathrm{stat}) \pm 0.24\ (\mathrm{syst})$$

CMS-PAS-TOP-12-004



Tevatron & LHC measurements
Consistent with SM expectations

Top Quark Polarization

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ATLAS results:

$$\alpha_l P_{CPC} = -0.035 \pm 0.014 \text{ (stat)} \pm 0.037 \text{ (syst)}$$
$$\alpha_l P_{CPV} = 0.020 \pm 0.016 \text{ (stat)}^{+0.013}_{-0.017} \text{ (syst)}$$

hep-ex/1307.6511

CPC = top and anti-top have same polarization
CPV = top and anti-top have opposite polarization

Results are consistent with SM expectations and earlier CMS measurement (note factor of 2)

$$P = -0.009 \pm 0.029 \text{ (stat)} \pm 0.041 \text{ (syst)}$$

CMS-PAS-TOP-12-016

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos(\theta_i)} = \frac{1}{2}\left(1 + (2)\alpha_i P \cos(\theta_i)\right)$$

$$B_i \equiv \alpha_i P$$

P = the degree of polarisation
α_i = spin analyzing power of the final-state particle (LHC uses charged leptons α = 1.0)

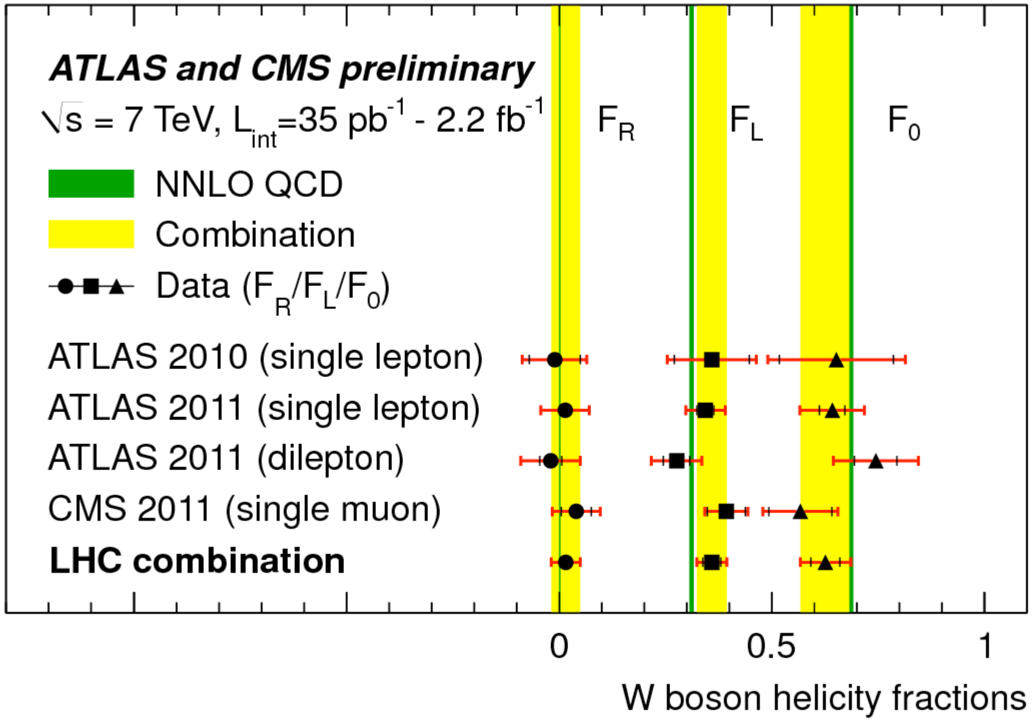
SM P ≈ 0.003 (arXiv:1305.2066)

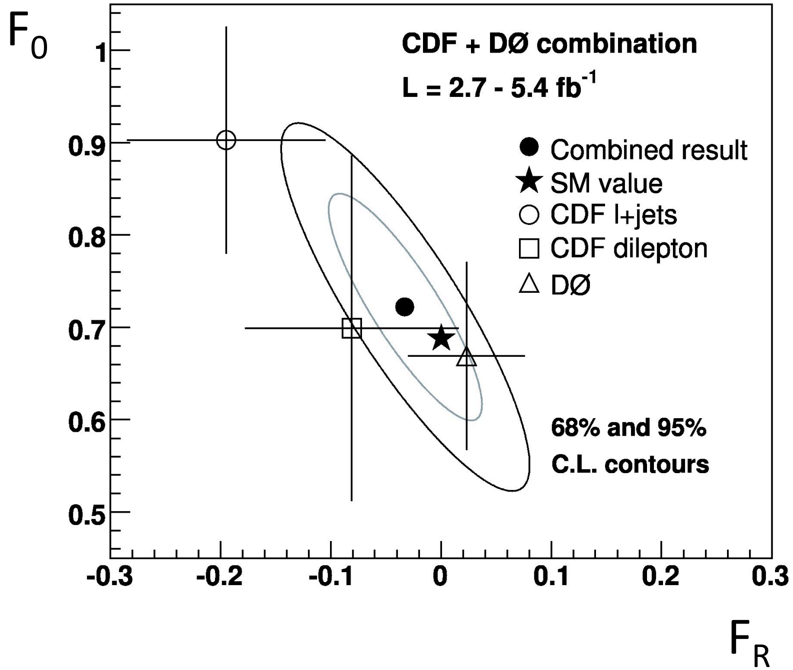
$$P = \frac{N(\cos(\theta^+) > 0) - N(\cos(\theta^+) < 0)}{N(\cos(\theta^+) > 0) + N(\cos(\theta^+) < 0)}$$

W Boson Polarization

- Massive spin-1 W boson has three polarization (helicity) states
  - SM predictions for helicity fractions: F_0, F_L and F_R
  - Extracted from angular distributions of W decay products

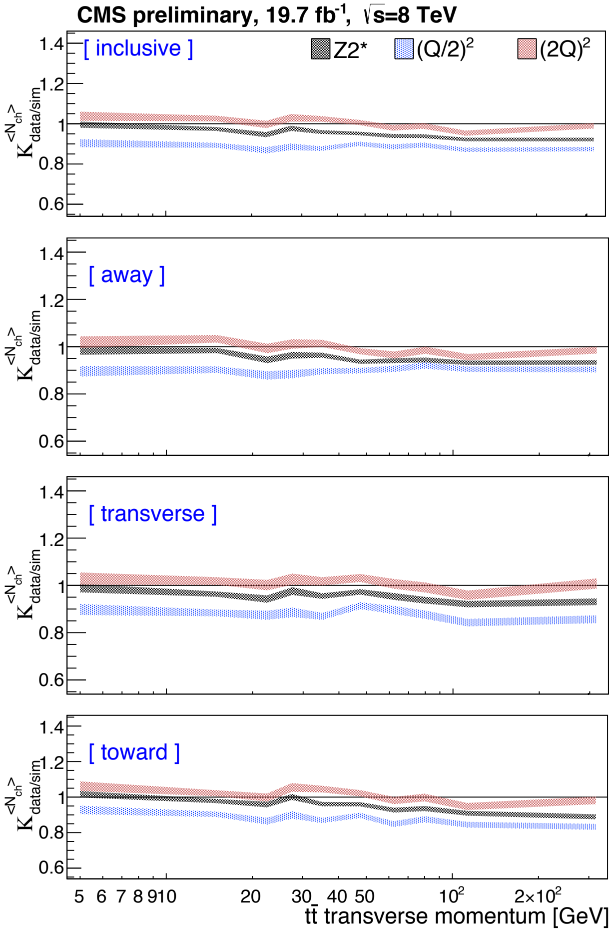
hep-ex/1202.5272





√s = 8 TeV updates from CMS remain consistent with the SM

Modeling of Top Quark Events

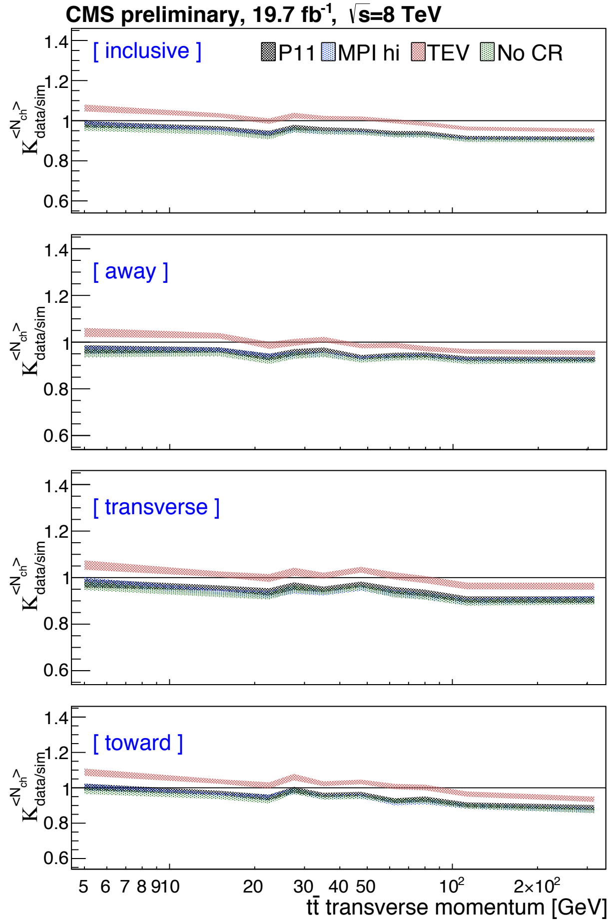


Ratio data-to-MC for N_{ch}

← Comparison to MADGRAPH + PYTHIA6 tune Z2*

Generally reasonable agreement with data

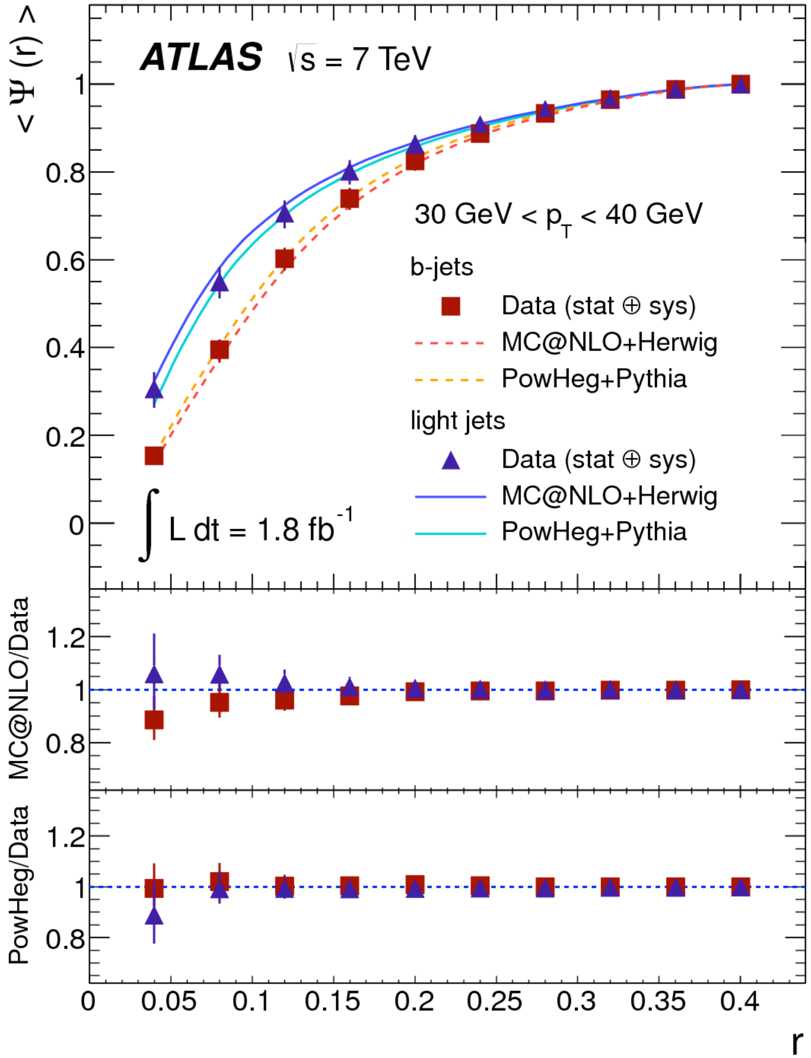
Comparison to Perugia11 tunes →



CMS-PAS-TOP-13-007

- Perugia11 tunes could be further constrained – especially for the case where colour reconnection effects are excluded
- b-quark fragmentation and hadronization also studied

Modeling of Top Quark Events



Integrated jet shape:

$$\Psi(r) = \frac{p_T(0,r)}{p_R(0,R)}; \quad r \leq R$$

hep-ex/1307.5749

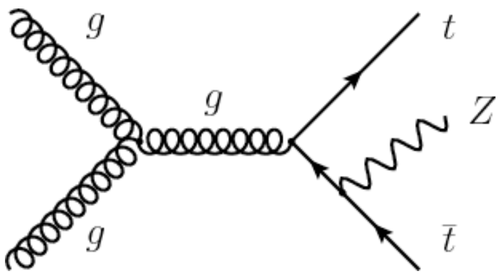
- Observations support earlier CDF measurements: b-jets expected to be broader than light-quark jets
- Behaviour consistent with pQCD
- Perugia11 tunes slightly disfavoured by jet shapes data
- Help improve modeling of jets in MC

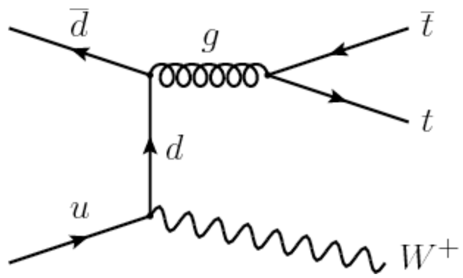
ttV production

Top quark couplings need to be tested:

- Test Wtb coupling via single top production

- Test coupling to γ/Z via tt+γ/Z
  - ttγ measured at Tevatron & LHC
  - ttZ cross section too low for observation at the Tevatron





CDF ttγ result:

$$\sigma_{t\bar{t}\gamma} = 0.18 \pm 0.07(stat) \pm 0.04(syst) \pm 0.01(lumi)\text{pb}$$

$$\sigma_{t\bar{t}\gamma}^{NLO} = 0.17 \pm 0.03\text{pb}$$

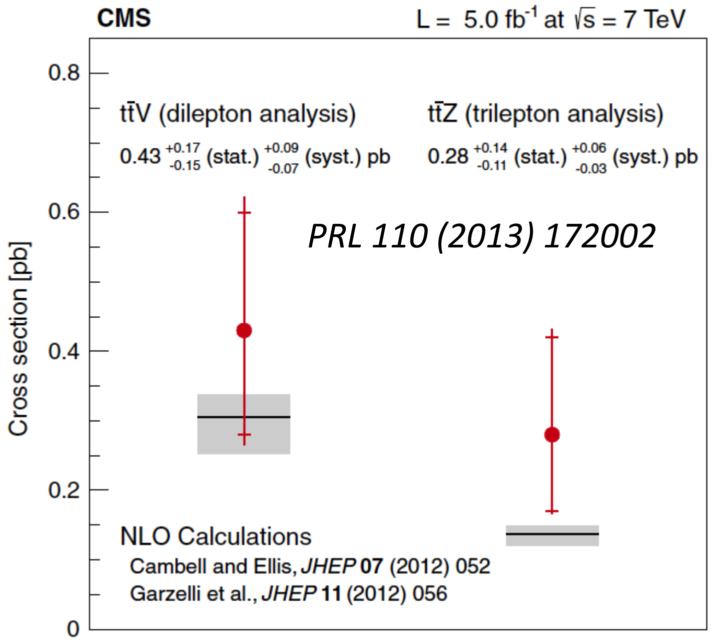
PRD 84 031104

ATLAS ttγ result:

$$\sigma_{t\bar{t}\gamma} \cdot BR = 2.0 \pm 0.5(stat) \pm 0.7(syst) \pm 0.08(lumi)\text{pb}$$

$$\sigma_{t\bar{t}\gamma}^{SM} \cdot BR = 2.1 \pm 0.4\text{pb}$$

ATLAS-CONF-2011/153



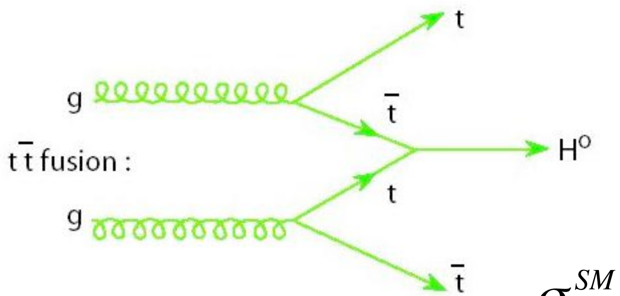
ATLAS upper limit: $\sigma_{t\bar{t}Z} < 0.71\text{pb}$

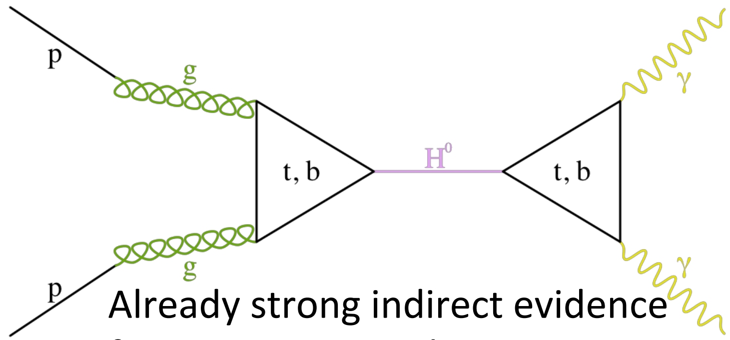
ATLAS-CONF-2012-126 95% credibility

ttH production

Large top Yukawa coupling ➔ special role for top in EW symmetry breaking?

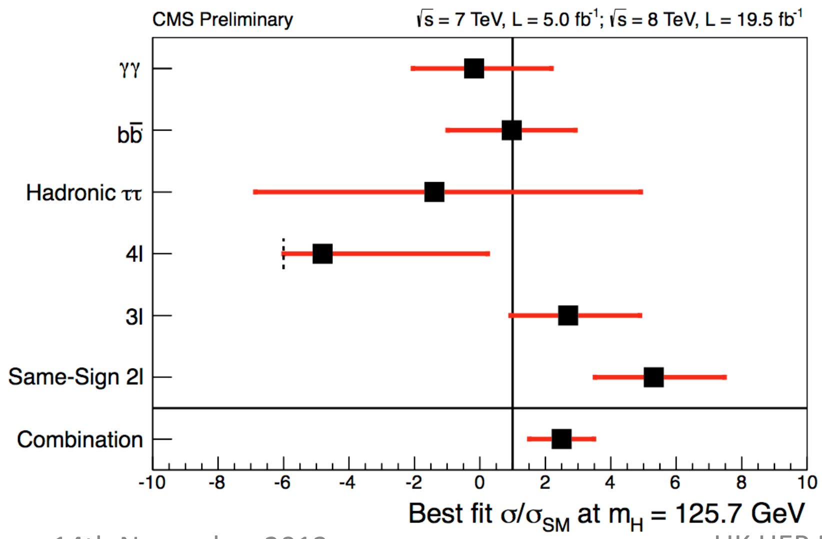
Direct observation of ttH vertex therefore important measurement to make!



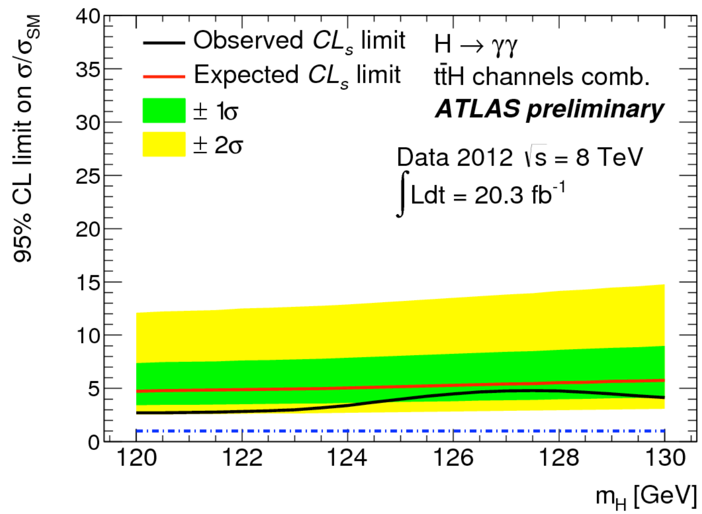


Already strong indirect evidence for top-Higgs coupling

$$\sigma^{SM}_{t\bar{t}H} \sim 0.13\text{pb} \ @ \ \sqrt{s} = 8\text{TeV}$$



No observation yet, but so far all appears consistent with the SM



Single Top Production

Production mechanisms

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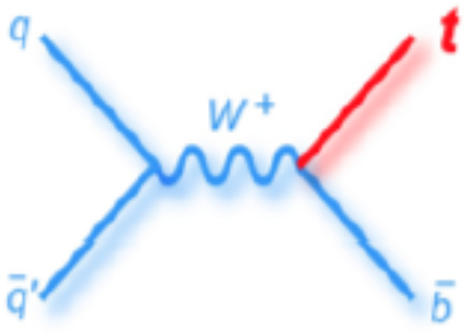
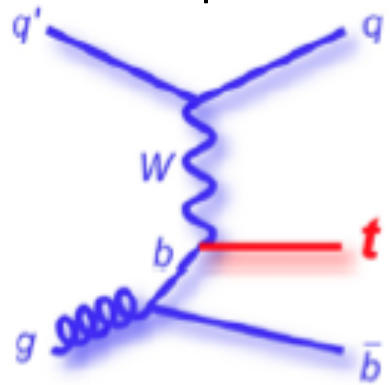
s-channel production



$$\sigma^{Tevatron} = 1.05 \pm 0.05\text{pb}$$

$$\sigma^{LHC} = 4.56 \pm 0.07^{+0.18}_{-0.17}\text{pb}$$

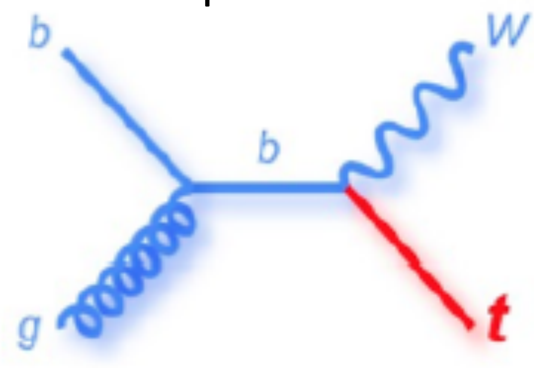
t-channel production



$$\sigma^{Tevatron} = 2.08 \pm 0.08\text{pb}$$

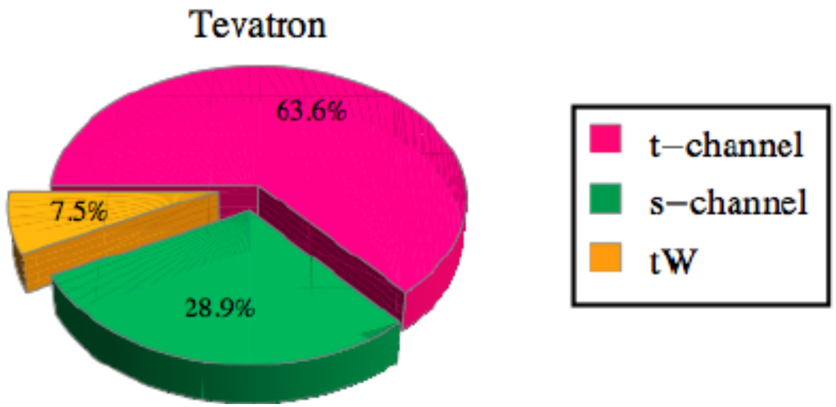
$$\sigma^{LHC} = 87.2^{+2.8+2.0}_{-1.0-2.2}\text{pb}$$

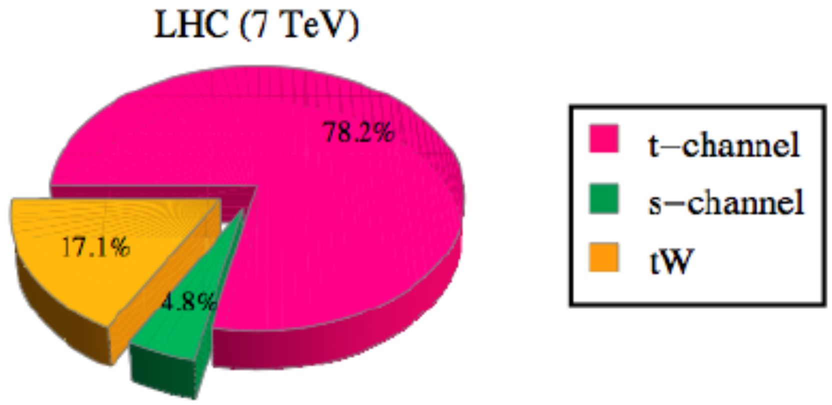
tW production



$$\sigma^{Tevatron} = 0.25 \pm 0.03\text{pb}$$

$$\sigma^{LHC} = 22.2 \pm 0.6 \pm 1.4\text{pb}$$



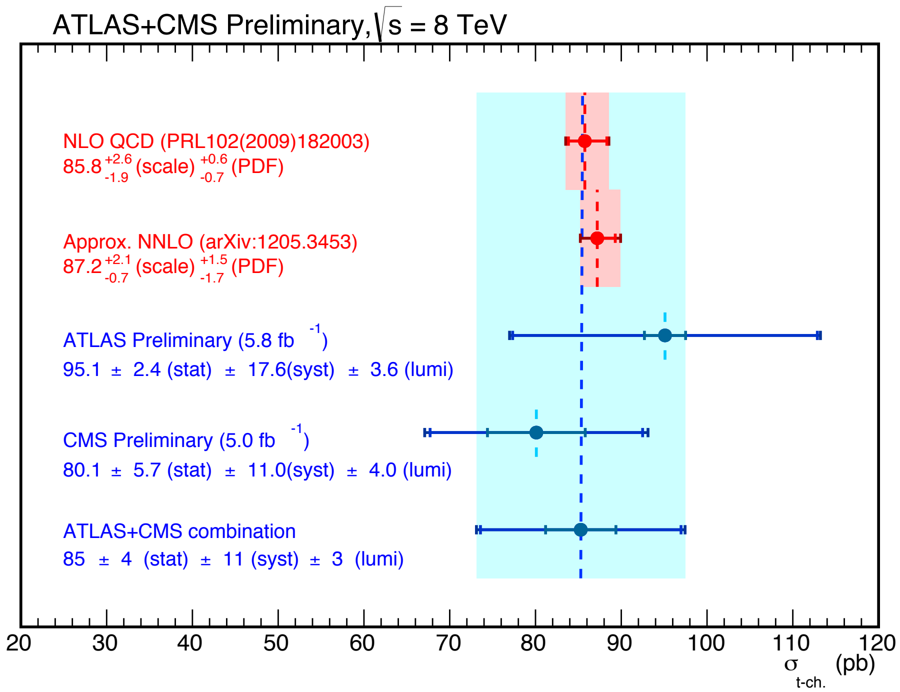


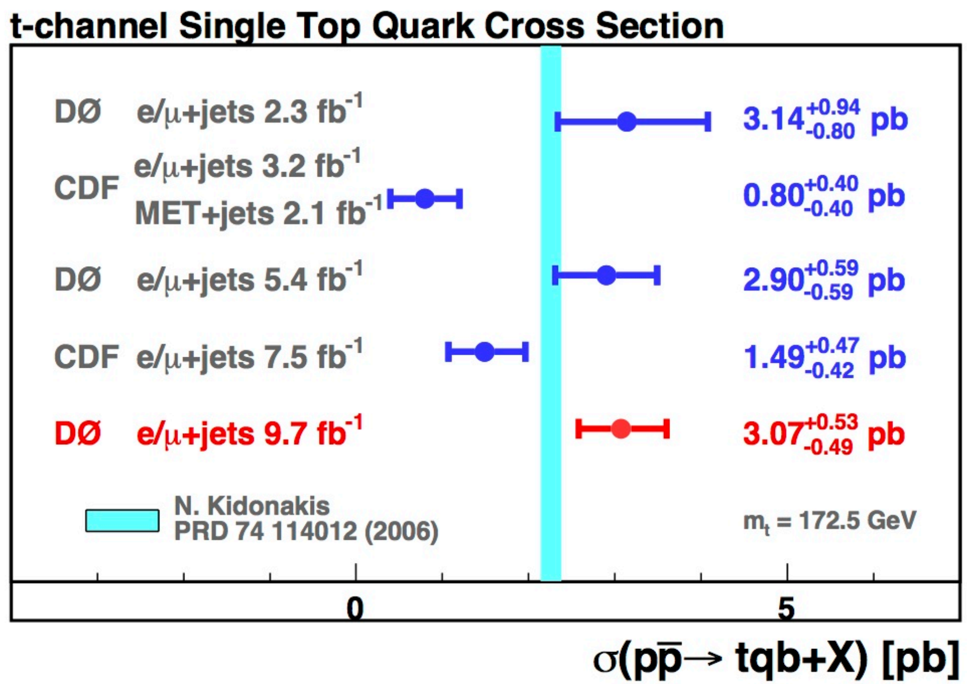
Theoretical cross section calculations: N. Kidonakis

Electroweak top quark production – all involve a Wtb vertex in the production mechanism

t-channel production

- Dominant production mechanism for LHC and Tevatron





Consistent results between experiments and with SM predictions

t-channel production

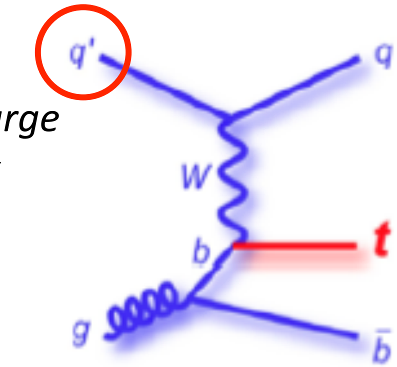
- At LHC, expect asymmetry in production of top and anti-top quarks:

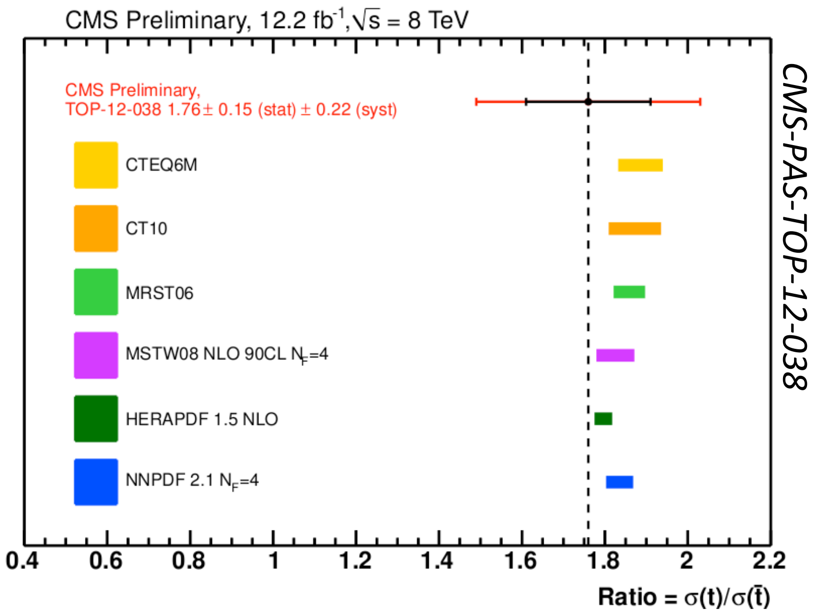
$$\sigma_{top} = 56.4^{+2.1}_{-0.3}(scale) \pm 1.1(PDF)\text{pb}$$

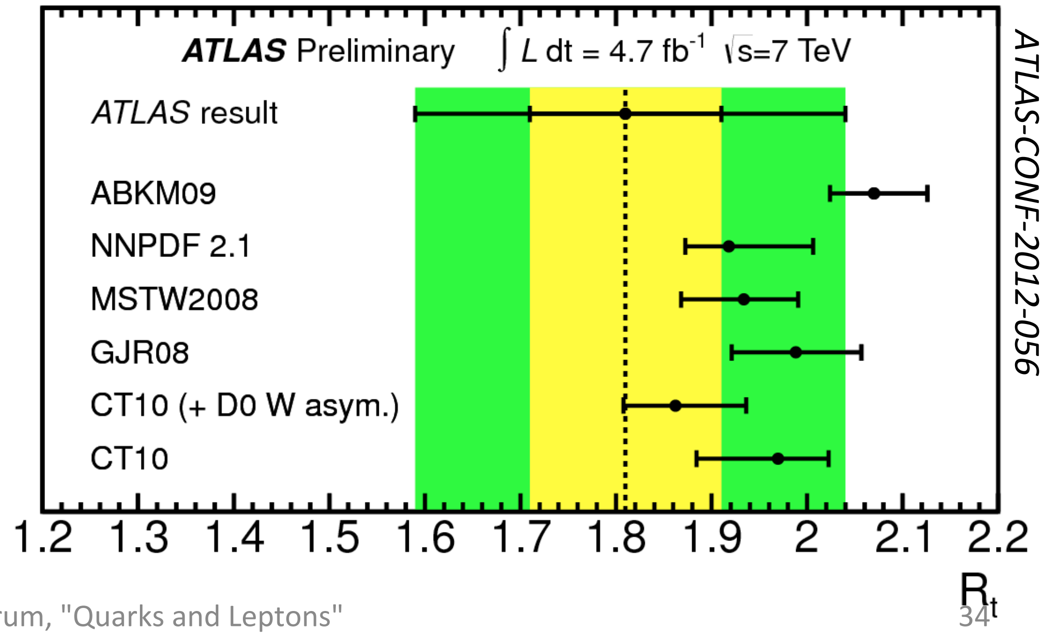
$$\sigma_{anti-top} = 30.7 \pm 0.7(scale)^{+0.9}_{-1.1}(PDF)\text{pb}$$

$$R = \frac{\sigma_{top}}{\sigma_{anti-top}} = 1.84$$

Controls the charge of the top quark

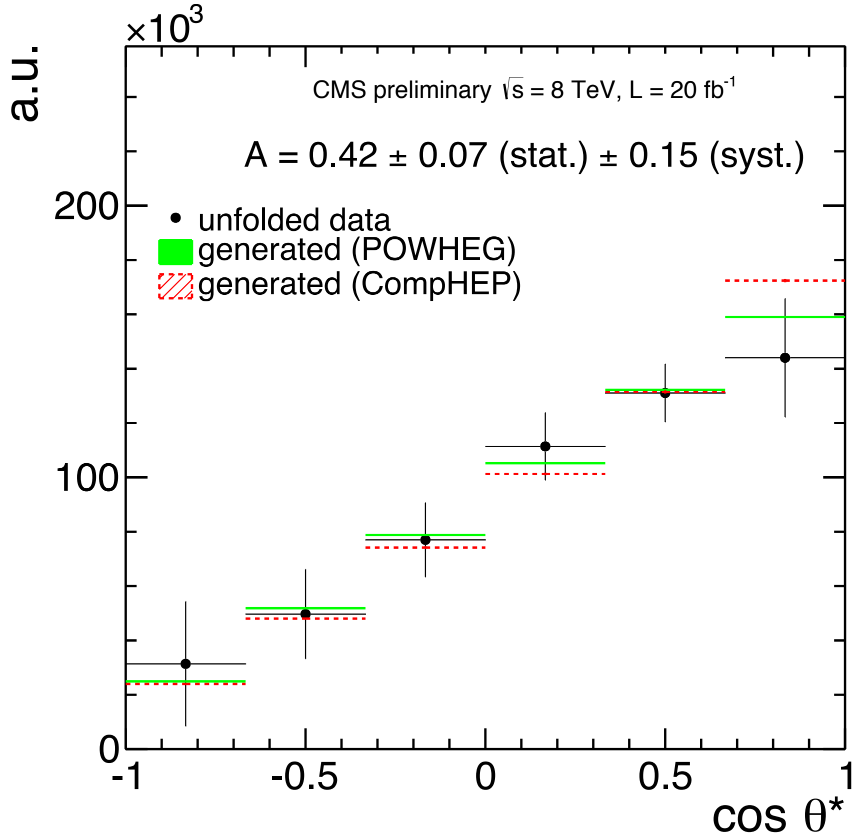






Top Polarization: t-channel measurement

- Expect top quarks to be ≈ 100% polarized
  - Examine the V-A coupling structure of the Wtb vertex



CMS-PAS-TOP-2013-001

$$A_l = \frac{1}{2} P_t \alpha_l = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

α_l = 1.0 in SM for charged leptons

CMS Results

$$A_l = 0.41 \pm 0.17$$

$$\Rightarrow P_t = 0.82 \pm 0.34$$

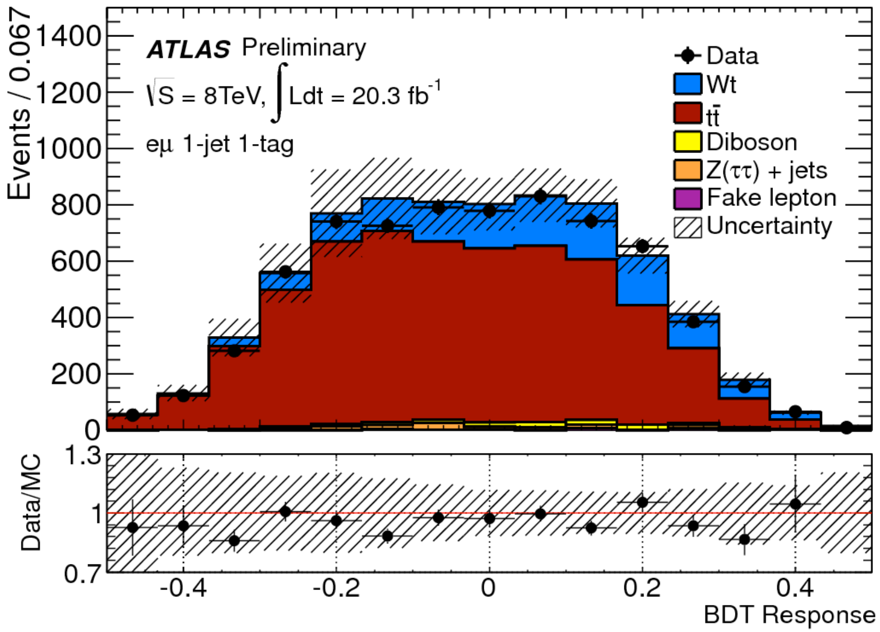
CDF Result

$$P_t = -1^{+0.5}_{-0}$$

Cannot exclude opposite polarization or unpolarized production

tW production

- Second largest production mechanism at LHC; negligible at Tevatron
  - Evidence for existence from √s = 7 TeV data

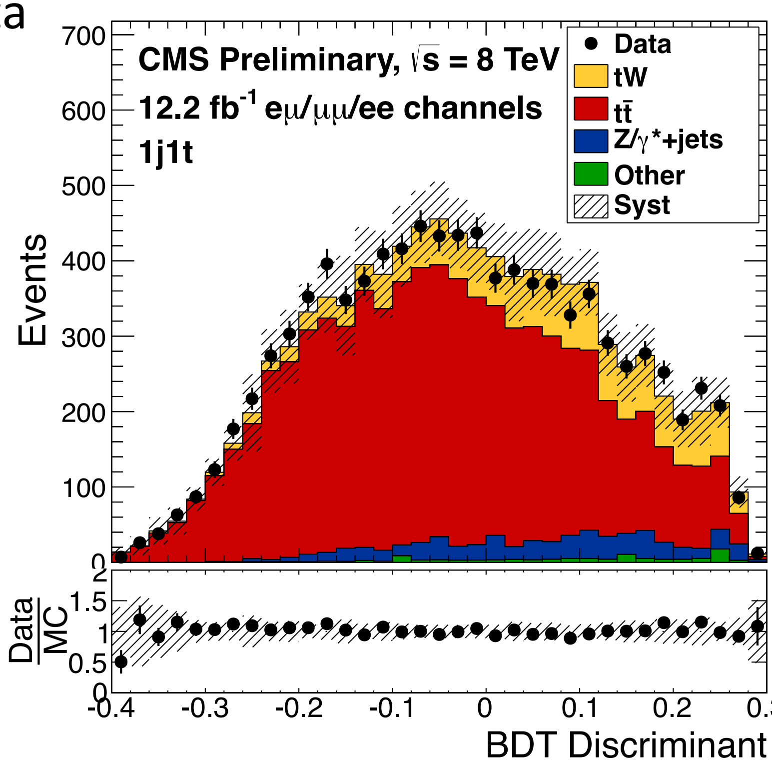


$$\sigma(pp \to Wt + X) = 27.2 \pm 2.8(stat) \pm 5.4(syst)\text{pb}$$

$$|V_{tb}| = 1.10 \pm 0.12(\exp) \pm 0.03(theory)$$

4.0σ significance

First observation of tW production



$$\sigma(pp \to Wt + X) = 23.4^{+5.5}_{-5.4}\text{pb}$$

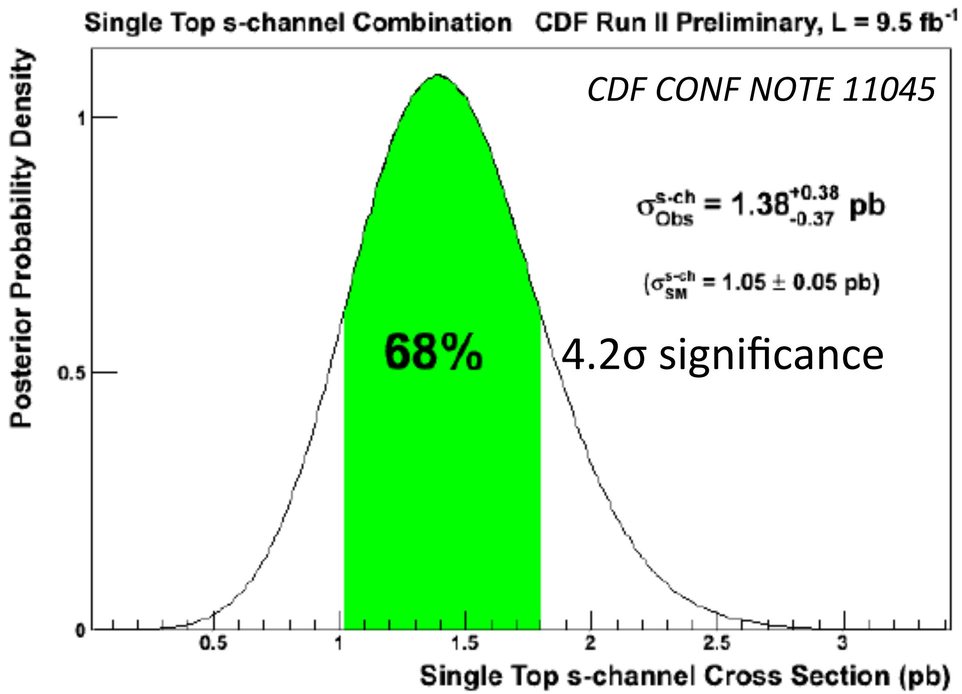
$$|V_{tb}| = 1.03 \pm 0.12(\exp) \pm 0.04(theory)$$

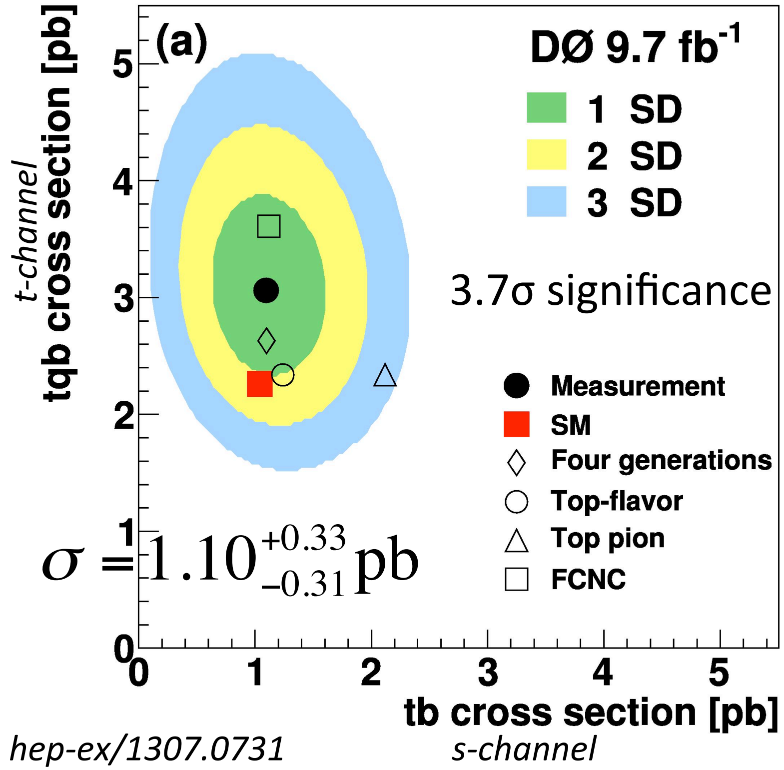
6.0σ significance

CMS-PAS-TOP-12-040
ATLAS-CONF-2013-100

s-channel production

- Not yet observed at Tevatron or LHC





ATLAS s-channel measurement from √s = 7 TeV

σ < 26.5 pb @ 95% CL

ATLAS-CONF-2011-118

So far only evidence for s-channel production from Tevatron

Summary & Prospects

- At $\sqrt{s}$ = 13-14 TeV and 300 fb^{-1}, expect 250M tt pairs and 100M single top events
  - Expect some substantial improvements to top-related measurements, plus some new ones

- Exploit different top mass extraction techniques eg. $t \to b \to J/\psi \to \mu^+\mu^-$
- Improved ttV (V = W, Z) measurements, plus first measurement of tZ
  - Constraint of top couplings to both Z and photon
- Top Yukawa coupling
- Improvement of systematics on existing measurement techniques

- Lots of new and exciting physics to come!

Extra Material

Top-Anti-Top Resonances

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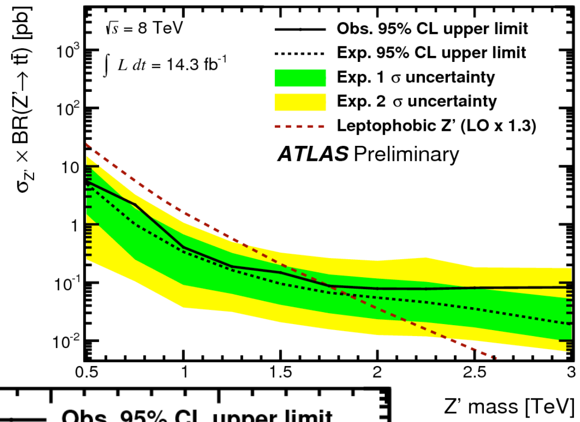
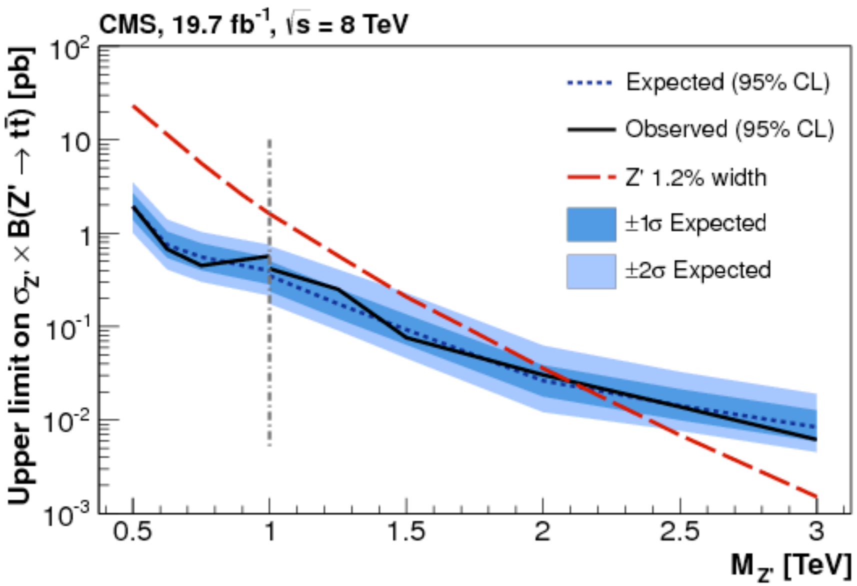
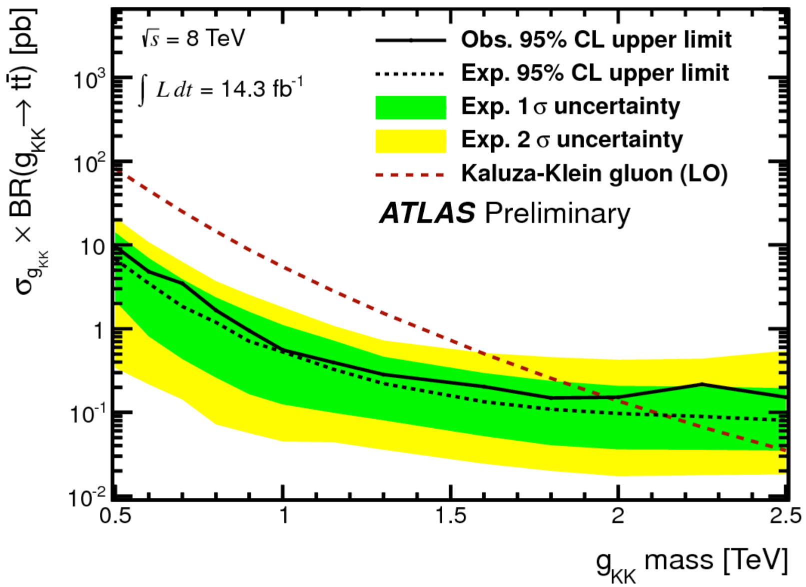
- A number of BSM theories allow for resonant top pair production:
  - Benchmark theories:
    - Leptophobic top-colour Z' (narrow resonances)
    - KK gluons from RS models (broad resonances)
- Tops tend to be highly boosted
  - Use jet substructure observables to identify them







Top Quarks & Supersymmetry

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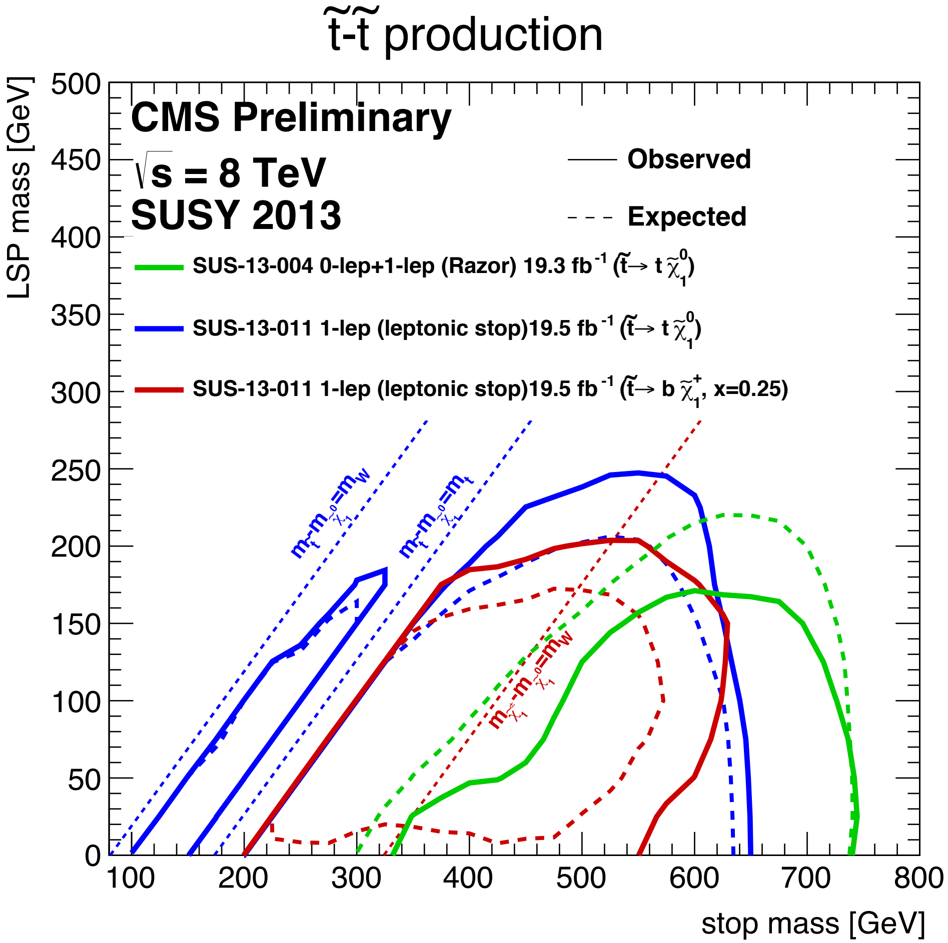
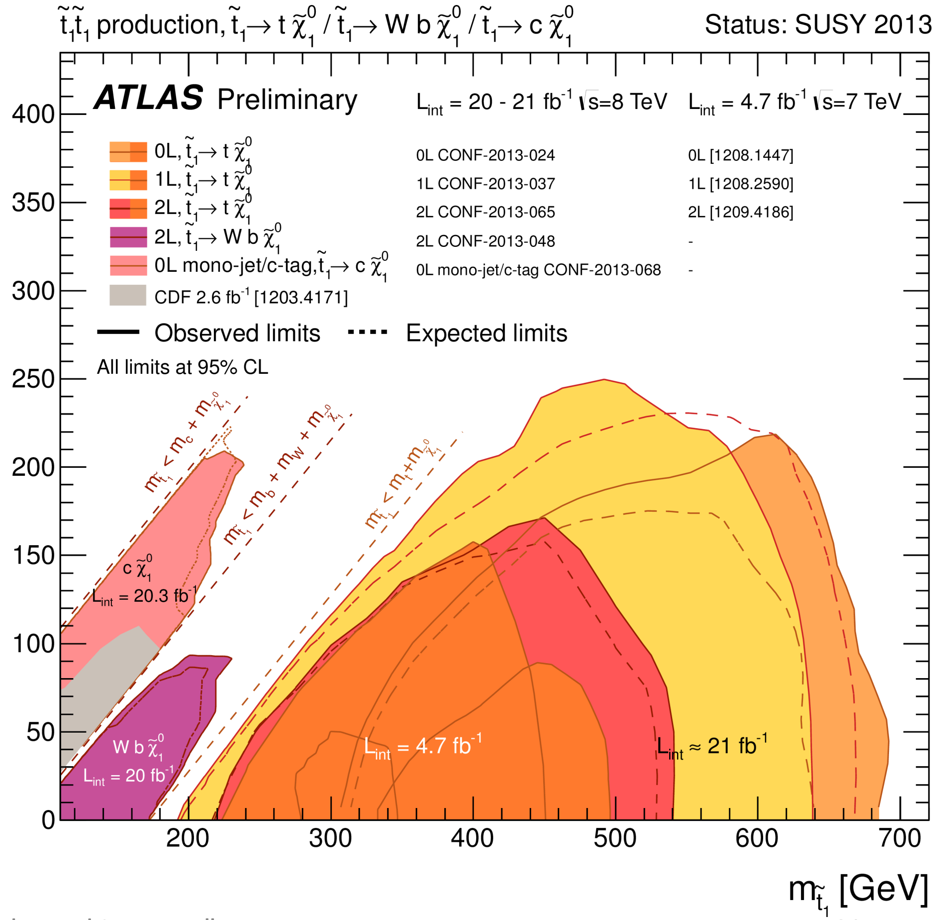
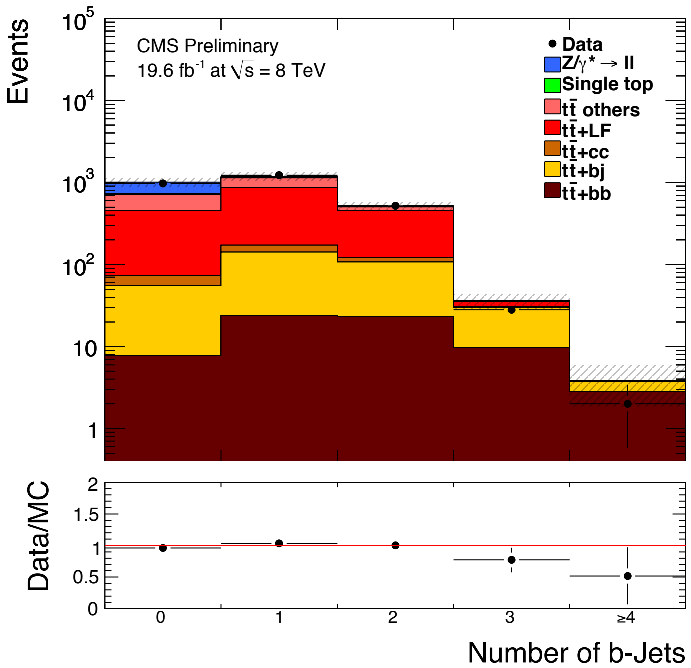
Stop pair production decaying to either top plus neutralino or botton plus chargino

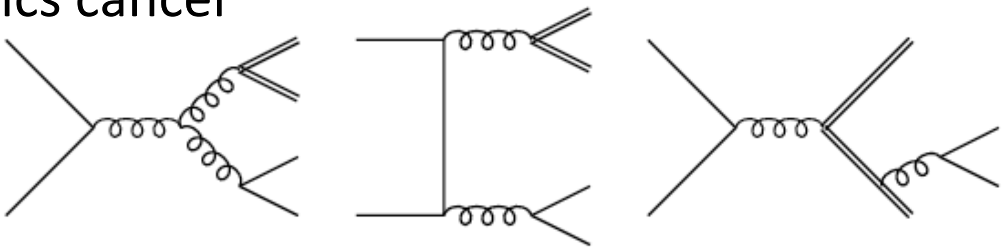




Ratio of σ(ttbb) to σ(ttqq)

- Irreducible background to ttH measurement
- Measure ratio as many systematics cancel





Examples of LO ttbb production diagrams

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.023 \pm 0.003(stat) \pm 0.005(syst)$$

Jet p_T > 20 GeV/c

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.022 \pm 0.004(stat) \pm 0.005(syst)$$

Jet p_T > 40 GeV/c

MADGRAPH: 0.016 ± 0.002, 0.013 ± 0.002
POWHEG: 0.017 ± 0.002, 0.014 ± 0.002

Results appear reasonably consistent with MC predictions