Top Quark Physics with CMS

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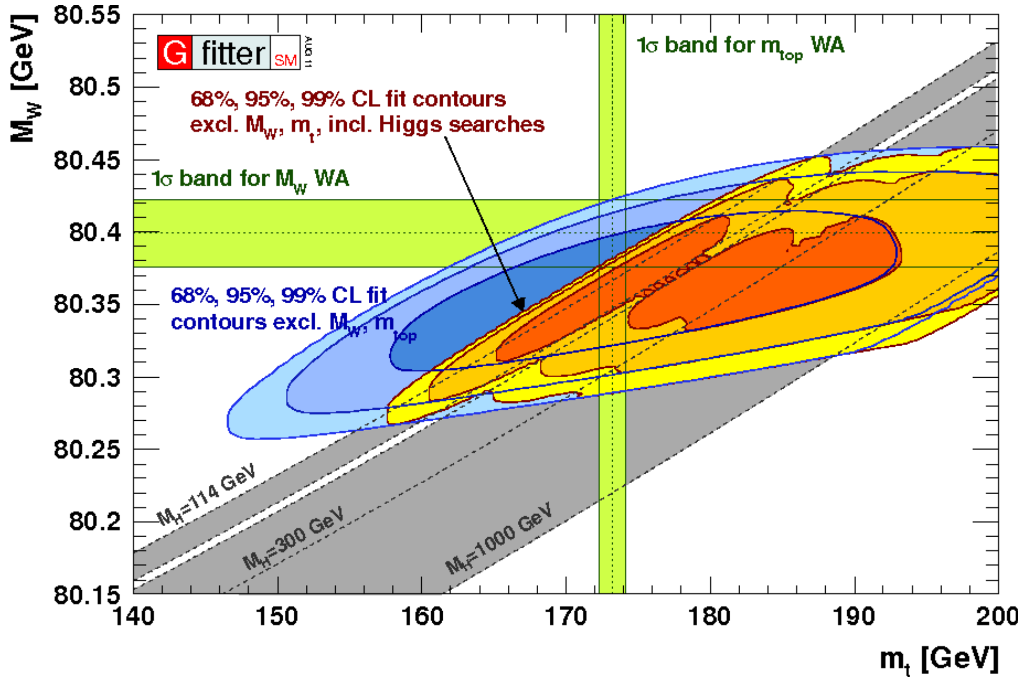
Outline

- Motivation & Introduction
- Physics Objects for Top
- MC Simulation
- Measurements performed so far:
  - Top pair cross section
  - Top mass and top-antitop mass difference
  - Single top cross section (t and tW channel)
  - Search for resonances in top pair invariant mass
  - Charge Asymmetry & search for same-sign top pairs

- 6 journal papers, many preliminary results (PAS notes)
- All CMS public results available from
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Why is Top Physics interesting?

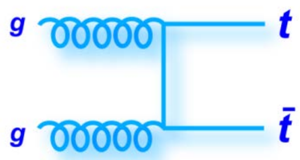
- Heaviest SM particle
  - o m(top)=173.2+/-0.9 GeV (0.5%)
- Special role in EWK symmetry breaking?
- Sensitive to Higgs mass through EWK loop corrections
  - o Low Higgs mass peferred



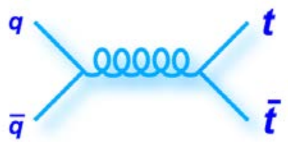
- New physics may couple preferentially to top
  - o e.g. search for new particles decaying into top (pairs) ➔ M(ttbar)
- The top quark may be special
  - o New physics may be hidden in e.g. spin structure
- Top production may be background to SUSY and other NP

Top quark pair production

- Gluon fusion (dominant at LHC)

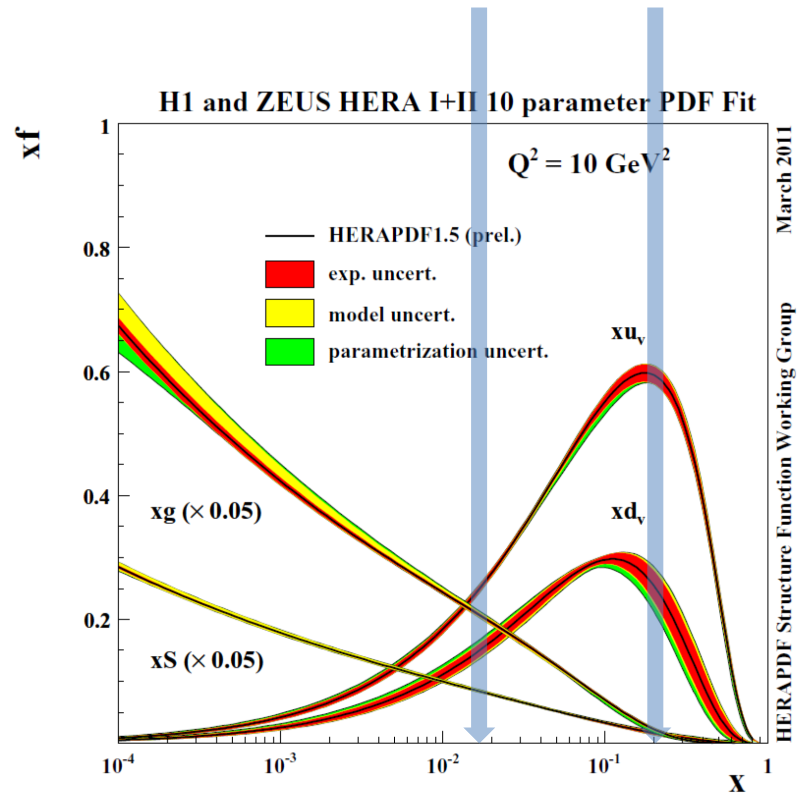


- Quark-antiquark annihilation



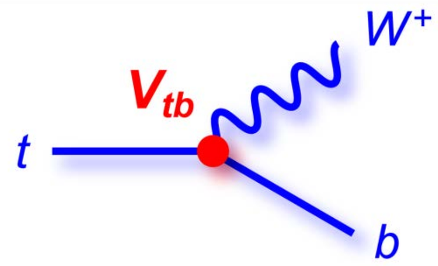
	LHC	Tevatron
gg	~85%	~10%
qq	~15%	~90%

- Total cross section at 7 TeV:
  - NLO (MCFM) $\sigma_{t\bar{t}}^{\mathrm{NLO}} = 158^{+23}_{-24}$ pb
  - approximate NNLO
    - Kidonakis, PRD 82 (2010) 114030
      $$\sigma_{t\bar{t}} = 163^{+11}_{-10} \text{ pb}$$
    - Langenfeld, Moch, Uwer, PRD80 (2009) 054009
      $$\sigma_{t\bar{t}} = 164^{+10}_{-13} \text{ pb}$$
    - Ahrens et al., JHEP 1009 (2010) 097
      $$\sigma_{t\bar{t}} = 149 \pm 11 \text{ pb}$$
    - Cacciari et al, arXiv:1111.5869
      $$\sigma_{t\bar{t}} = 159^{+12}_{-14} \text{ pb}$$

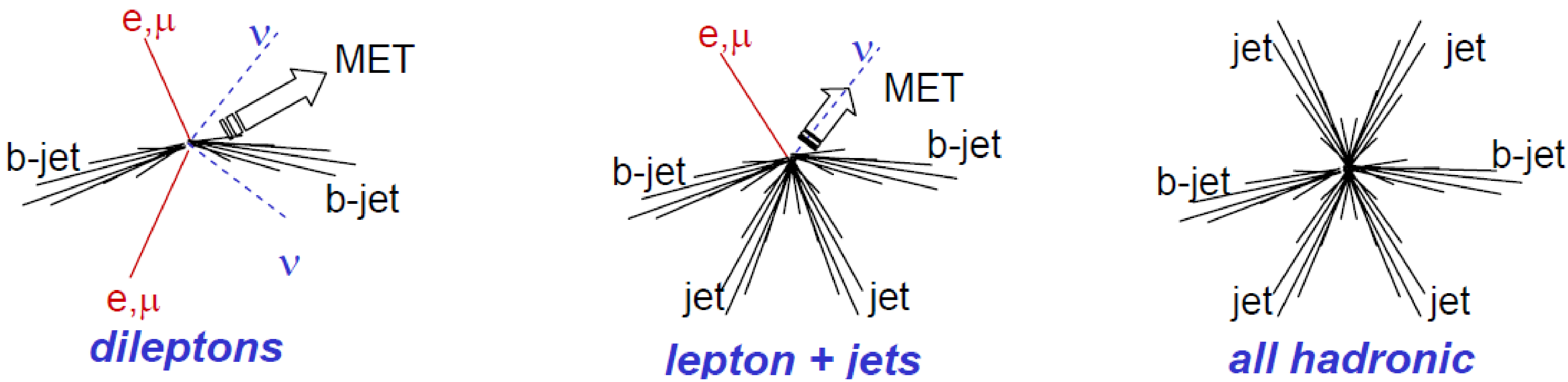


Top quark decays

- Top decays before it can hadronize
  - o almost exclusively t->Wb



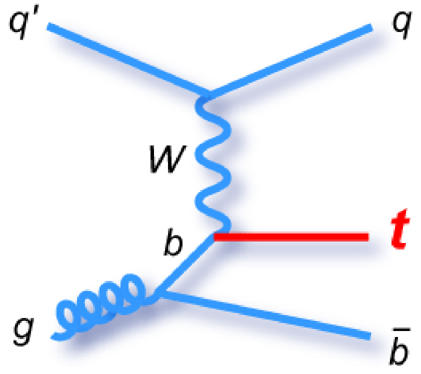
- Top pair event classification according to W decays

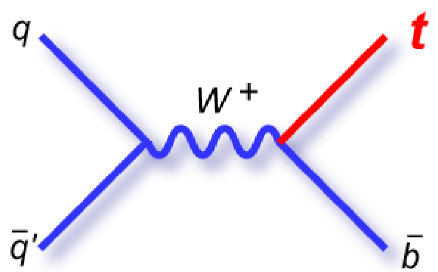


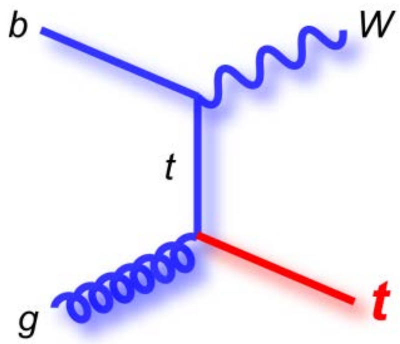
Branching ratio:	~5%	~30%	~46%
Backgrounds:	few (mainly Z+jets)	moderate (mainly W+jets)	huge (mainly QCD)

Single Top Production

- Single top quarks are produced through electroweak interaction







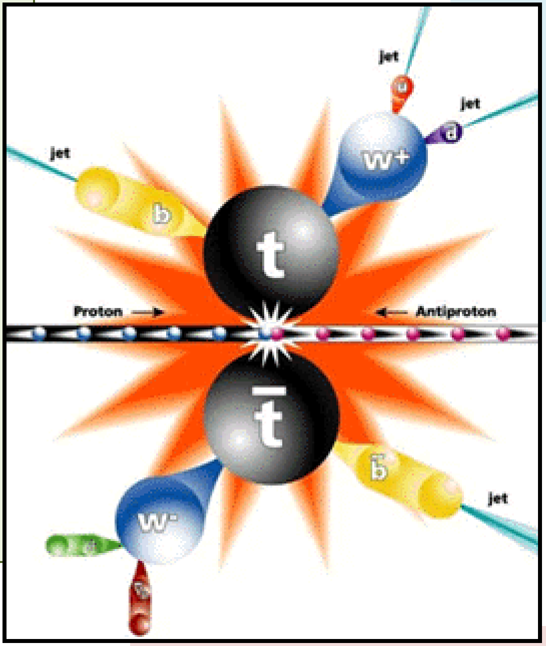
	t-channel	s-channel	tW-channel (associated production)
Cross section:	~64 pb	~4.6 pb	~15.6 pb

Kidonakis, NLO+NNLL:
t-channel: PRD 83 (2011) 091503
s-channel: PRD 81 (2010) 054028
tW-channel: PRD 82 (2010) 054018

Difficult signature (fewer jets)
Large backgrounds from ttbar, V+jets
tW-channel interfers with ttbar at higher orders

LHC Top Physics Program

- Production
  - o Pair cross section (QCD)
  - o Single top cross section (EWK)
  - o Differential cross sections
    - Compare with theory
    - Validate ME+PS models
  - o Charge asymmetry
  - o Spin correlations



- Decay
  - o Branching ratios
  - o t->Wb / t->Wq
  - o W-helicity in top decays (W->tb coupling)

- Intrinsic Properties
  - o Mass (difference)
  - o Charge
  - o Lifetime

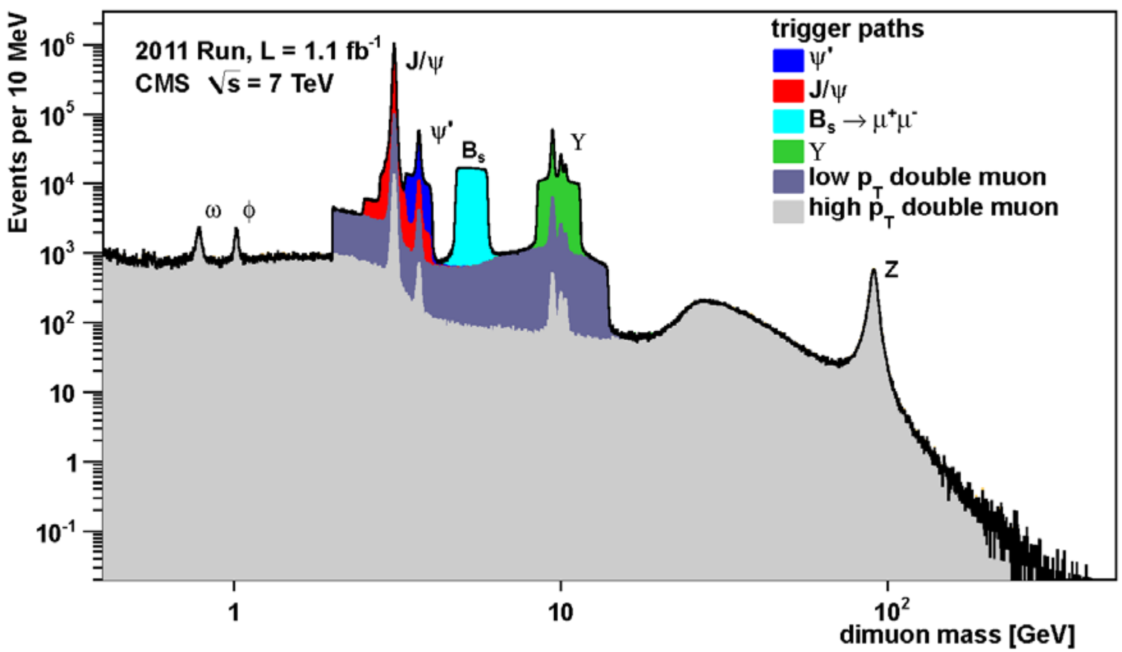
- New physics
  - o New particles decaying to top
  - o BSM top decays
  - o New physics with top-like signature

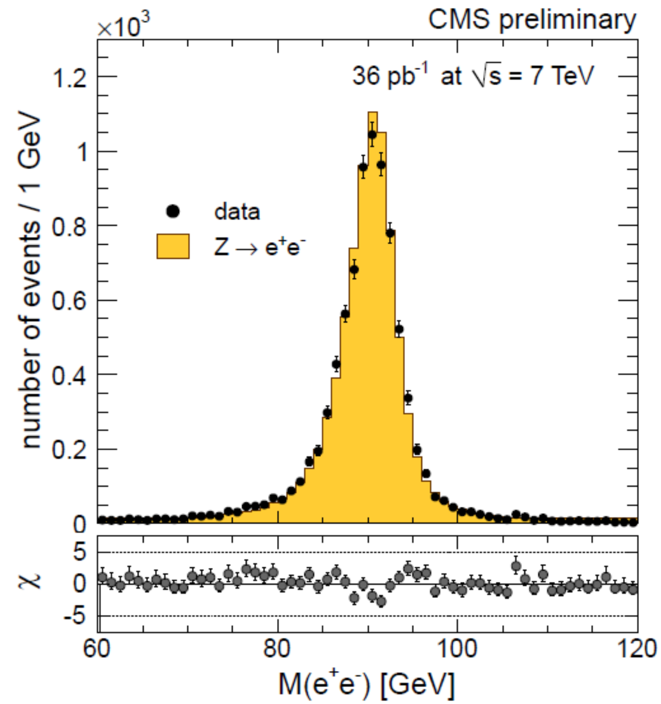
Physics Objects for Top Physics

- Electrons and muons (also taus)
  - o Identification with high efficiency & low fake rate
  - o Precise momentum measurement
  - o Isolation (identify leptons from W-decays, suppress QCD)
  - o Key for triggering top events
- Jets
  - o Precise measurement with small jet energy scale uncertainty
- Missing transverse energy (MET)
  - o Reconstruct transverse neutrino momentum
  - o Reject QCD, Z+jets background
- b-jet identification
  - o High efficiency (and low failure rate) to tag jets from b-quarks
  - o Helps with jet pairing (e.g. for top mass)

Top physics needs ~all physics objects well understood!

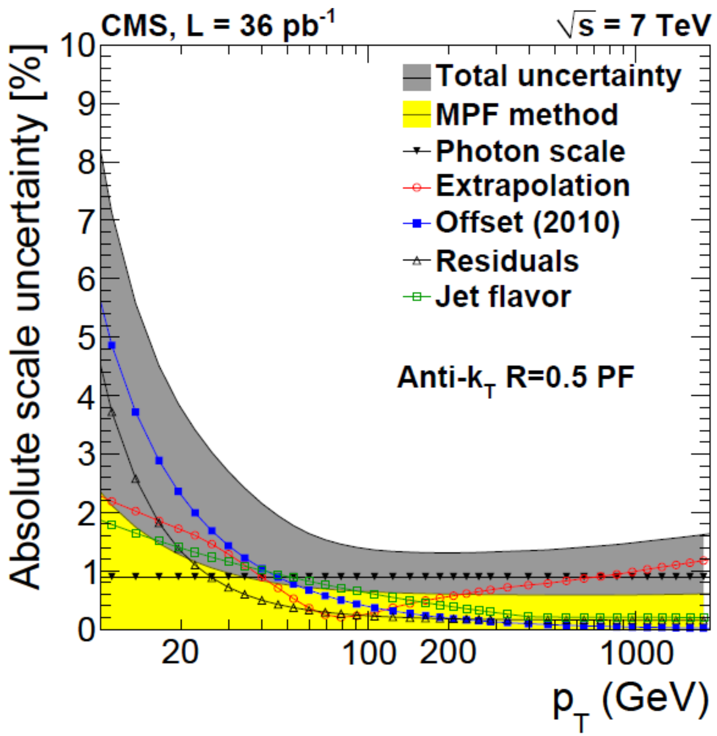
Muons and Electrons

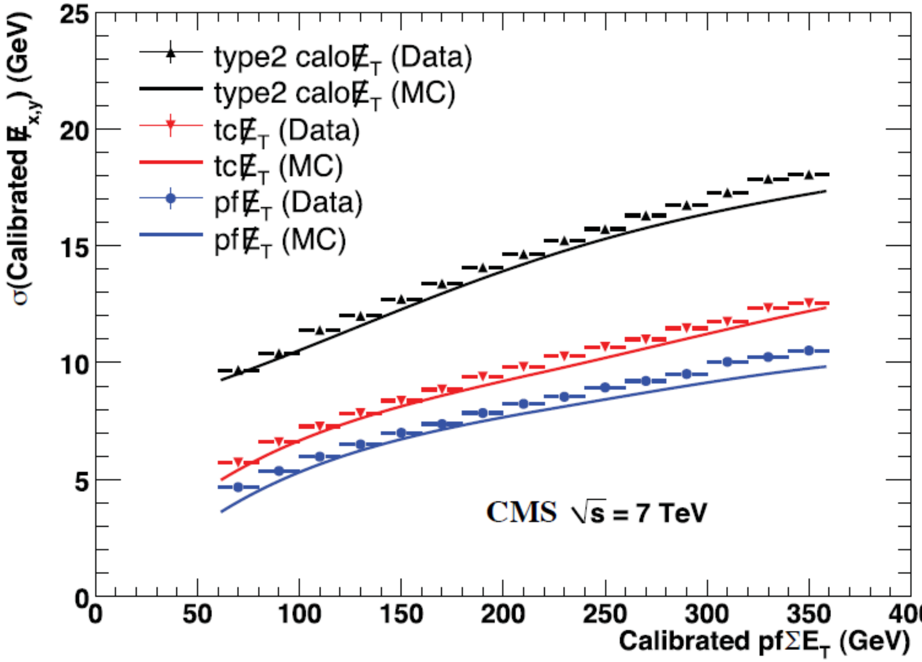




- Muon Pt resolution for Top 1-2% (tracker dominated)
- Good trigger and ID capabilities using redundant subdetectors
- Excellent ECAL resolution (~1% for TOP)
- Good track matching (fit accounting for Bremsstrahlung)
- ID based on shower shape, H/E, etc.

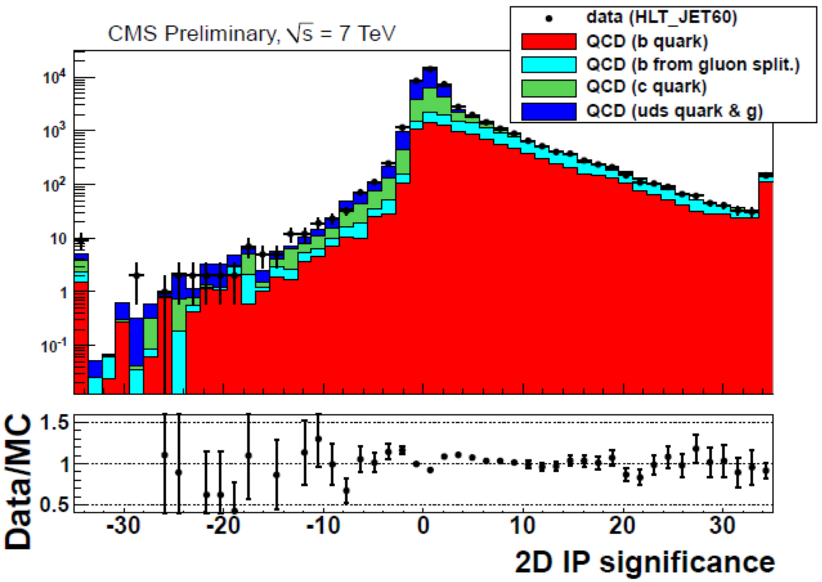
Jets and Missing Transverse Energy

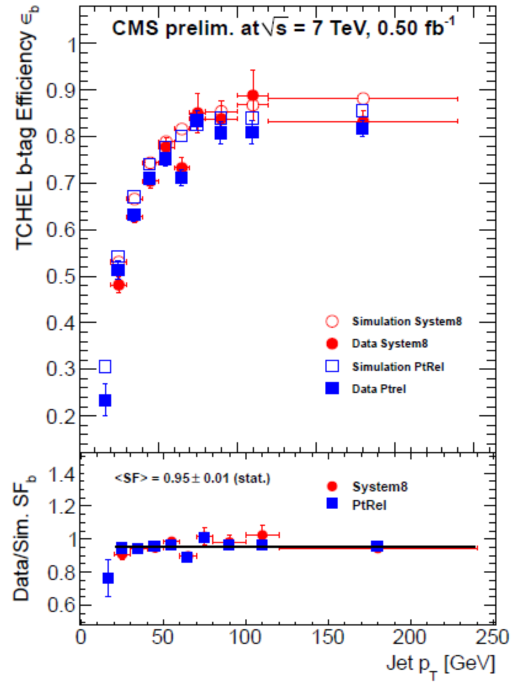


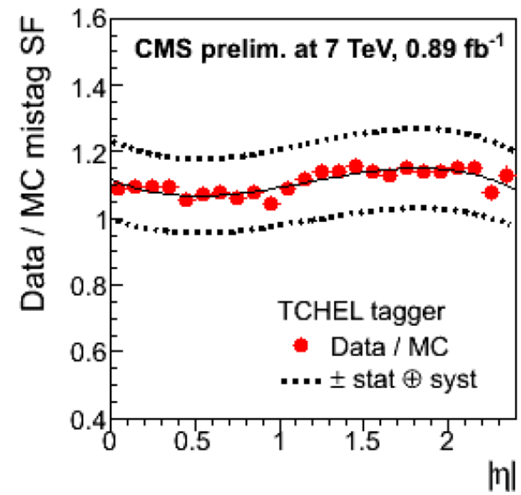


- Particle Flow (“PF”, calo&tracking&muons combined)
- Jets defined using anti-kT algo (dR=0.5)
- Jet energy scale uncertainty <2% for Pt>40 GeV
- Jet Pt resolution 10-15%
- MET resolution vastly improved with PF
- Remove PU component by vertex assoc. (ch.) / jet area method (neutr.)

b-jet Identification







- Crucial ingredient: great tracker performance and alignment
- Top analyses so far mostly use
  - Count tracks with large IP
  - Secondary vertex reconstruction
- Complex algos commissioned

- Data-driven efficiency & mistag rate determination
- SF(Data/MC) close to unity
  - known to ~10% for b-eff
  - known to ~10…20% for mistag rate

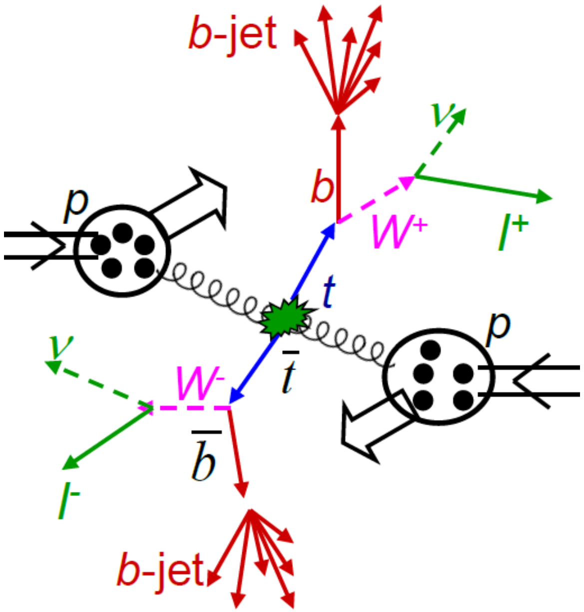
MC Simulation and Theory Uncertainties

- Use MADGRAPH to simulate top signal and most important backgrounds (W/Z+jets)
  - o Matrix elements with up to 3 (tt) or 4 (W/Z) extra jets
  - o ME+PS matching using MLM prescription
  - o Scales set as $Q^2 = M^2_{t,W,Z} + \sum P^2_{T,jets}$
  - o Cross sections rescaled to inclusive (N)NLO values
- Dedicated samples to estimate modelling uncertainties, varying e.g.
  - o scale Q by factors 2.0 and 0.5
  - o amount of ISR/FSR radiation
  - o ME-PS matching scale by factors 2.0 and 0.5
  - o MC@NLO, POWHEG as alternate signal generators
  - o NB new TOPLHCWG started to assess these issues with ATLAS+TH
- Use data-driven backgrounds where possible

Outline

- Top pair cross section
- Top mass (difference)
- Single top cross section
- Top pair invariant mass distribution
- Charge asymmetry & same-sign tops

Dilepton channel: Event selection



- Inclusive double lepton triggers
  - di-muons (Pt>7/7…13/8 GeV)
  - di-electrons (Pt>17/8 GeV)
  - muon-electron (Pt>17/8+8/17 GeV)
- Two isolated, opposite charge leptons (ee,mumu,emu)
  - Pt>20 GeV, |eta|<2.4(mu),2.5(e)
  - Good ID, conversion rejection for electrons
  - Rel. isolation< 0.15 (0.17)

$$\text{Rel.isol.} = \frac{\sum_{R<0.3} p_T^{\text{track}} + \sum_{R<0.3} p_T^{\text{ECAL}} + \sum_{R<0.3} p_T^{\text{HCAL}}}{p_T(\text{lepton})}$$

- Z-boson veto (ee,mumu)
  - |M(ll)-M(Z)|>15 GeV
- Missing Et (MET)
  - MET>30 GeV (only for ee,mumu)

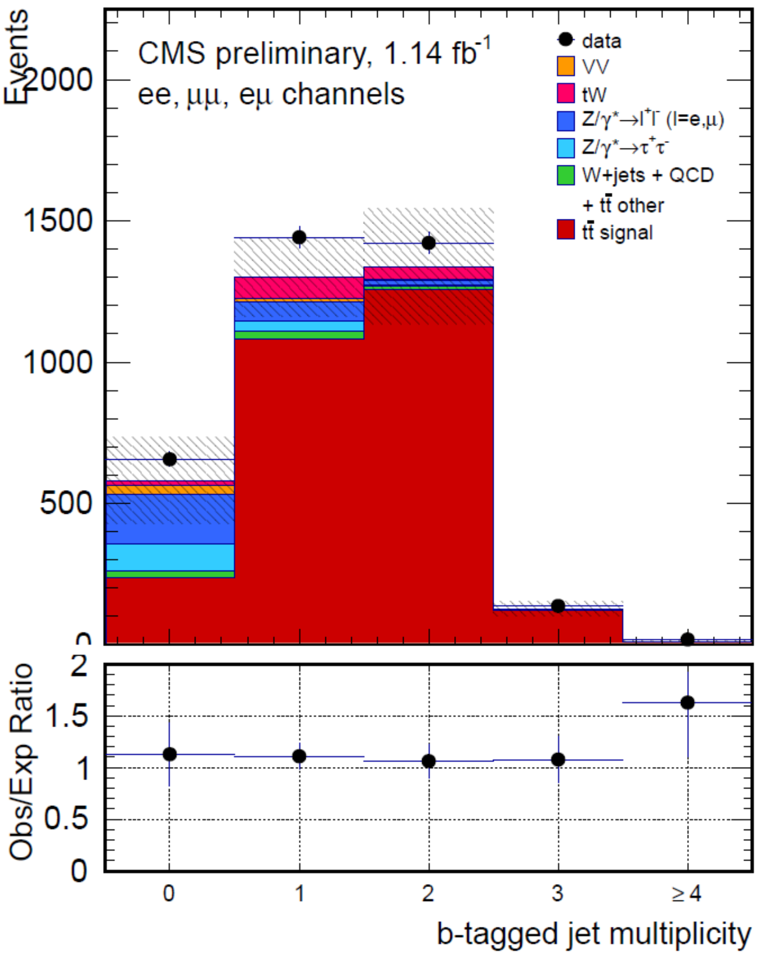
- Jets
  - Pt>30 GeV, |eta|<2.5
- b-jet identification
  - Track-counting algorithm
  - Here: eff ~80%, mistag rate 10%

Top pair cross section in dileptons (PAS TOP-11-005, L=1.1/fb)

Counting experiment in dilepton final state:
ll + 2jets + MET + 1btag
Measure separately and combine ee,mumu,emu
DY, QCD, W+jets BG estimated from data

Source	ee	$\mu\mu$	$e\mu$
Dilepton $t\bar{t}$	$427.5 \pm 19.7 \pm 44.5$	$559.3 \pm 22.9 \pm 56.3$	$1487.2 \pm 37.3 \pm 139.2$
VV	$2.6 \pm 1.6 \pm 0.8$	$3.4 \pm 1.9 \pm 1.1$	$6.9 \pm 2.6 \pm 2.2$
Single top - tW	$22.9 \pm 4.8 \pm 7.3$	$28.9 \pm 5.4 \pm 9.2$	$73.4 \pm 8.6 \pm 23.3$
Drell-Yan $\tau\tau$	$6.9 \pm 2.6 \pm 2.2$	$8.8 \pm 3.0 \pm 2.9$	$27.3 \pm 5.2 \pm 8.8$
Drell-Yan ee, $\mu\mu$	$38.2 \pm 4.3 \pm 19.1$	$50.5 \pm 5.1 \pm 25.2$	-
QCD/W+jets	2.9 ± 4.3(tot.)	7.6 ± 4.7(tot.)	30.0 ± 12.0(tot.)
Total background	73.6 ± 22.2(tot.)	99.1 ± 28.6(tot.)	137.6 ± 29.6(tot.)
Data	589	688	1742
Cross section, pb	$189.9 \pm 8.9 \pm 21.4 \pm 8.5$	$165.8 \pm 7.4 \pm 18.5 \pm 7.5$	$169.9 \pm 4.4 \pm 16.2 \pm 7.6$

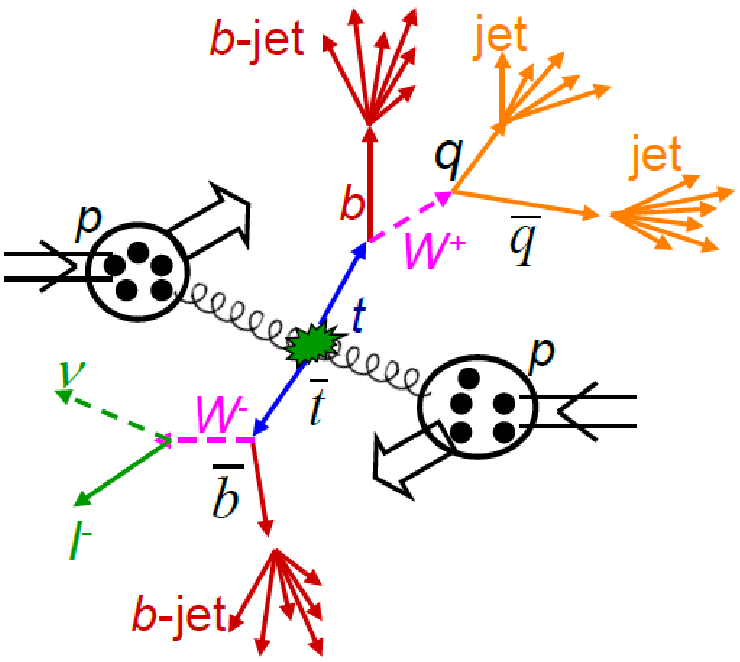
Source	ee	$\mu\mu$	$e\mu$
Lepton efficiencies	3.0	1.6	2.3
Lepton selection model	4.0	4.0	4.0
Jet and $\not{E}_T$ energy scale	1.9	1.7	1.9
B-tagging	5.0	5.0	5.0
Pileup	4.0	4.0	4.0
Branching ratio	1.7	1.7	1.7
Decay model (from [9])	2.0	2.0	2.0
Event Q^2 scale (from [9])	2.3	2.3	1.7
Top quark mass (from [9])	2.6	2.6	1.5
Jet and $\not{E}_T$ model (from [9])	3.2	3.2	0.4
Shower model (from [9])	0.7	0.7	0.7
Total Systematic	10.0	9.6	8.8
Luminosity	4.5	4.5	4.5



$$\sigma_{t\bar{t}} = 169.9 \pm 3.9\ (\text{stat.}) \pm 16.3\ (\text{syst.}) \pm 7.6\ (\text{lumi.})\text{pb}$$

Lepton+jets: Event selection

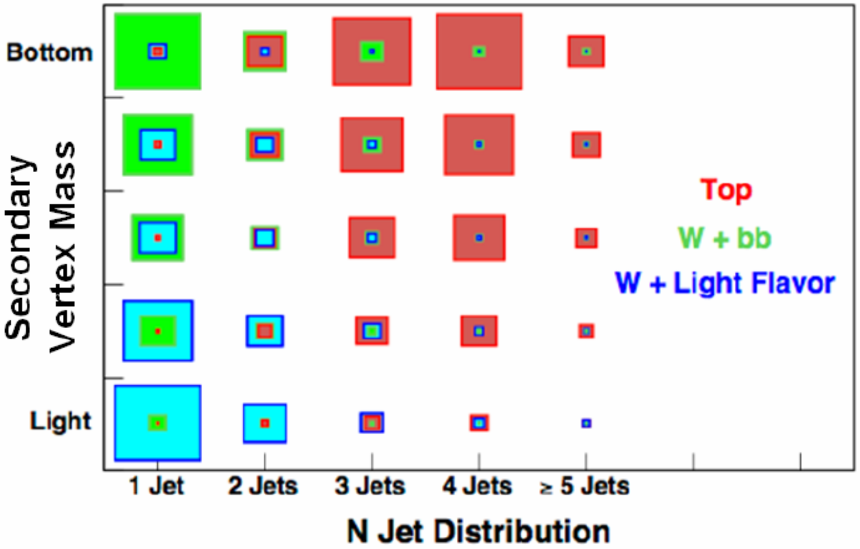
- Considered modes:
  - o e+jets, mu+jets
- Single lepton triggers used
  - o Muons (Pt>30 GeV)
  - o Electrons (Pt>27…42 GeV)
- Exactly one isolated lepton
  - o Muons: Pt>35 GeV,|eta|<2.1
    - Rel. Isolation < 0.125
  - o Electrons: Pt>45 GeV, |eta|<2.5
    - Rel. Isolation, conversion veto
- Jets
  - o Pt>30 GeV, |eta|<2.4



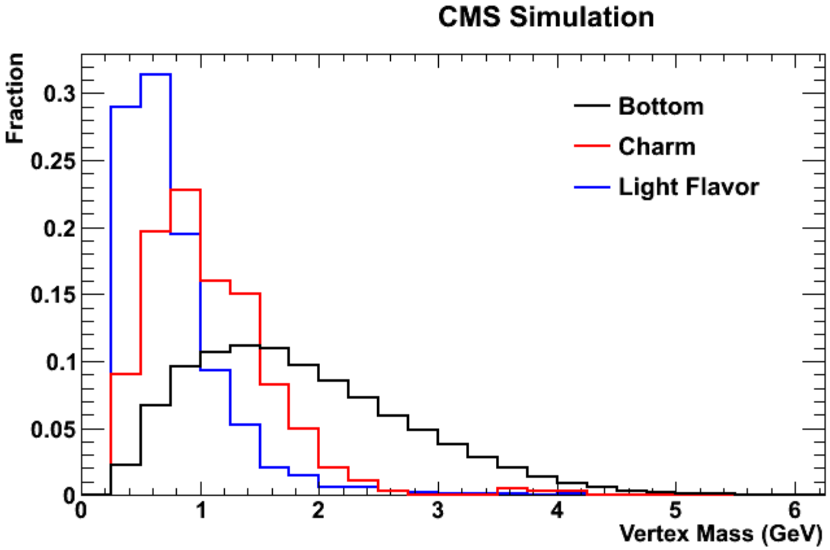
- Missing transverse energy
  - o MET>20 (30) GeV for mu(e)
- b-tagging:
  - o SV tagging algorithm used

Top pair cross section in l+jets with b-tagging (TOP-11-003, L=0.8-1.1/fb)

- Use events with >=1 b-tag
  - o Secondary vertex (SV) algorithm
- Template fit of SV mass in 2D N(jets), N(tags) plane
  - o Separation of signal and various backgrounds

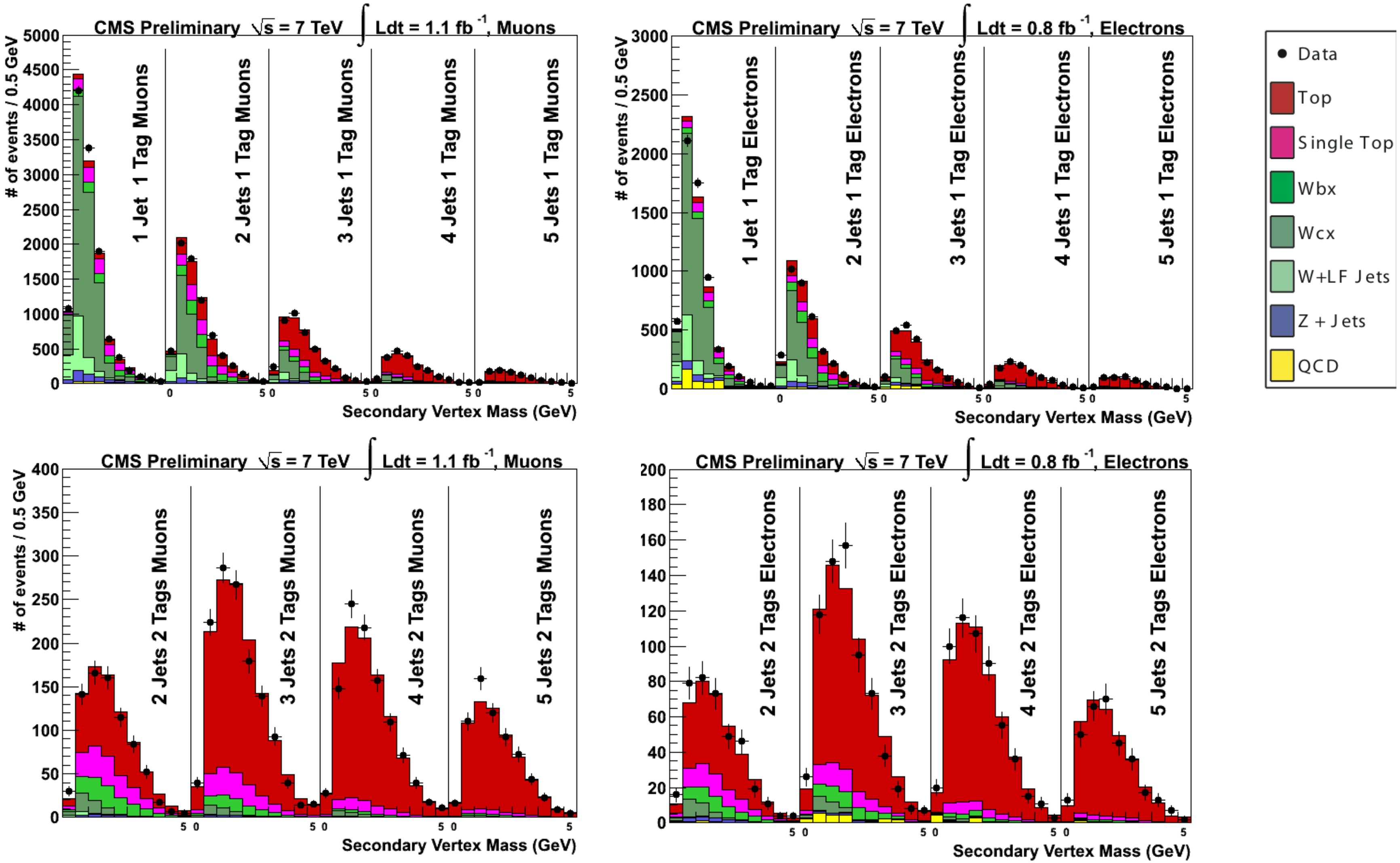


- Most important systematics fitted in situ (nuisance parameters in profile likelihood)
  - o Jet energy scale
  - o B-tag efficiency
  - o W+jets ren./fac. scale



Top pair cross section in e/mu+jets+btag (PAS TOP-11-003, L=0.8-1.1/fb)

- Fit result for e+jets, mu+jets, 1 tag, 2 tag samples



Top pair cross section in l+jets with b-tagging (TOP-11-003 , L=0.8-1.1/fb)

Obtained result for BG normalizations :

BG scale factor	Fit result
W+b scale factor (w.r.t. MC sc. to incl. NNLO)	1.2 +/- 0.3
W+c-jets scale factor (w.r.t. MC sc. to incl. NNLO)	1.7 +/- 0.1

JES/ b-tag SF consistent with input, but uncertainty reduced!

Source	Muon Analysis	Electron Analysis	Combined Analysis
Quantity	Uncertainty (%)		
Lepton ID/reco/trigger	3.4	3	3.4
$\not{E}_T$ resolution due to unclustered energy	< 1	< 1	< 1
$t\bar{t}$ +jets Q^2 scale	2	2	2
ISR/FSR	2	2	2
ME to PS matching	2	2	2
Pile-up	2.5	2.6	2.6
PDF	3.4	3.4	3.4
Profile Likelihood Parameter	Uncertainty (%)		
Jet energy scale and resolution	4.2	4.2	3.1
b-tag efficiency	3.3	3.4	2.4
W+jets Q^2 scale	0.9	0.8	0.7
Combined	7.8	7.8	7.3

Systematic uncertainties extracted in the fit

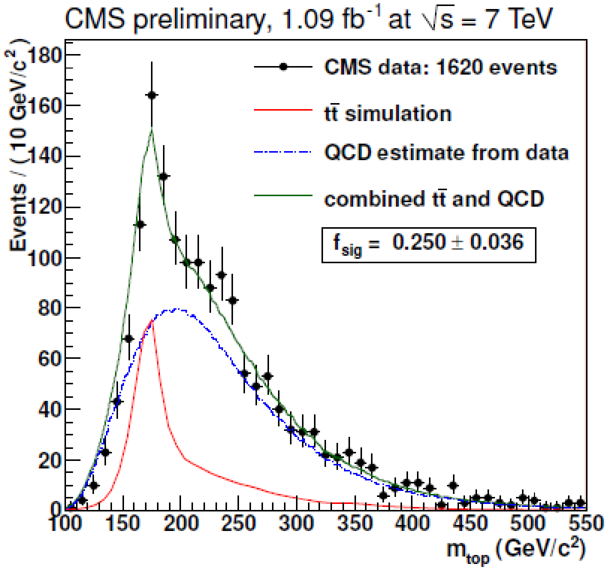
Result:

$$\sigma_{t\bar{t}} = 164.4 \pm 2.8(\text{stat.}) \pm 11.9(\text{syst.}) \pm 7.4(\text{lum.})\ \text{pb}$$

Total uncertainty 8.7% (most precise CMS indiv. Measurement)

tau-mu and hadronic channels

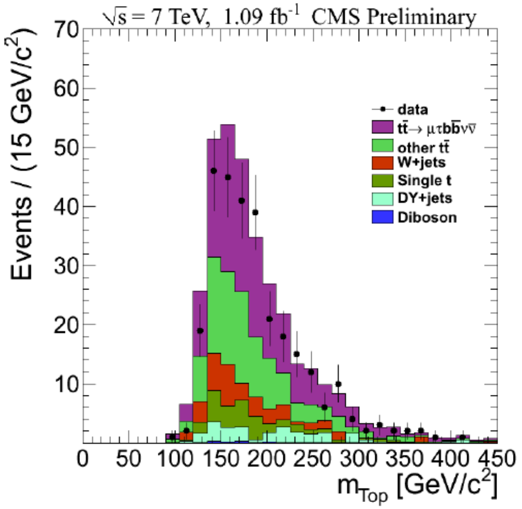
- Hadronic channel (TOP-11-007, L=1.1/fb)
  - o 6 jets, 2 tight b-tags
  - o QCD shape from data
  - o Fit m(top) distribution



Dominant systematics:
JES, b-tagging, background model

$$\sigma_{t\bar{t}} = 136 \pm 20\,(\text{stat.}) \pm 40\,(\text{sys.}) \pm 8\,(\text{lumi.})\ \text{pb}$$

- tau-mu dilepton channel (TOP-11-006, L=1.1/fb)
  - o Tau reconstruction using 'hadron plus strips' algorithm
  - o 1mu+1tau+2jets+1btag+MET
  - o Counting experiment



Dominant systematics:
tau fake BG (from data), tau ID

$$\sigma_{t\bar{t}} = 148.7 \pm 23.6(\text{stat.}) \pm 26.0(\text{syst.}) \pm 8.9(\text{lumi.})\ \text{pb}$$

Top pair cross section combination (PAS TOP-11-024)

<u>NEW (November 2011)</u>

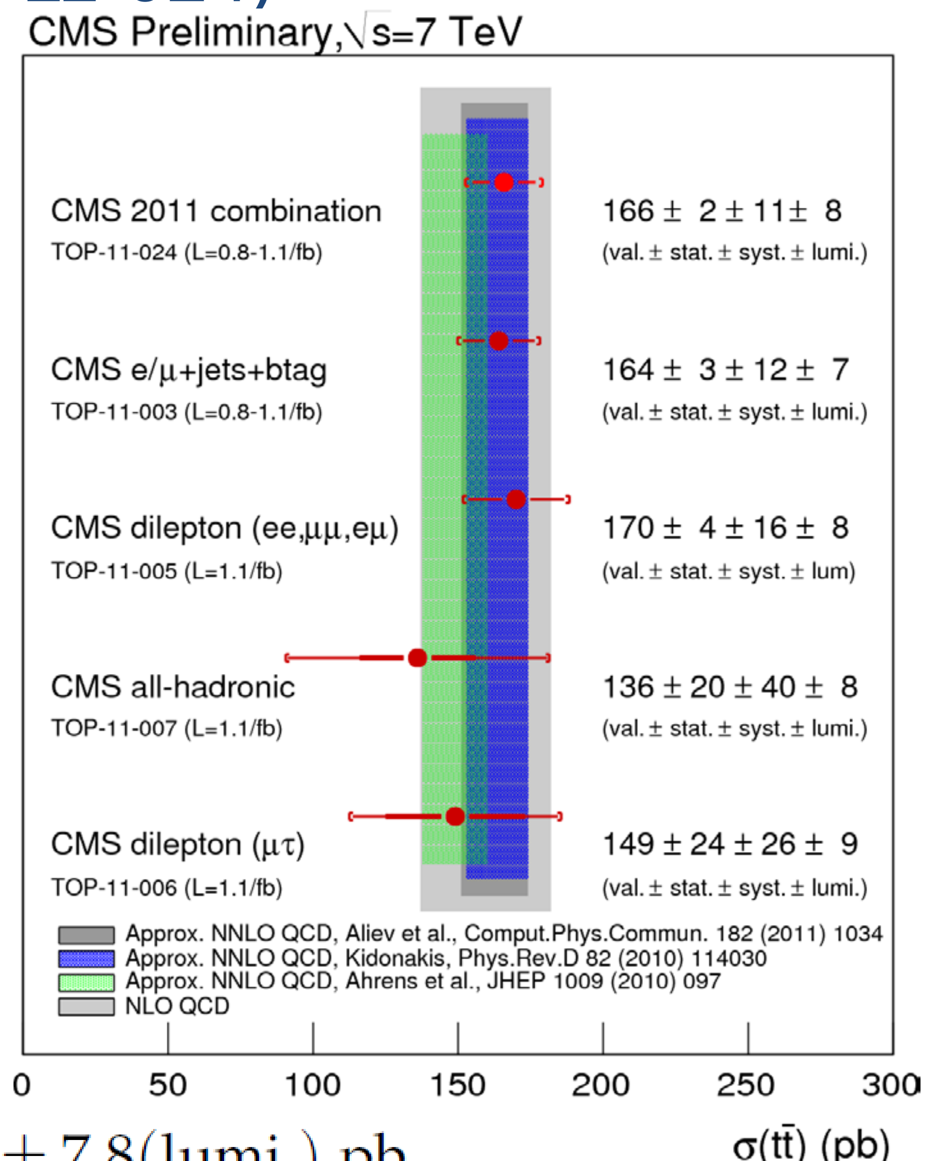
Method:

start from l+jets profile likelihood and include other channels

cross check with BLUE

Precision: 8%

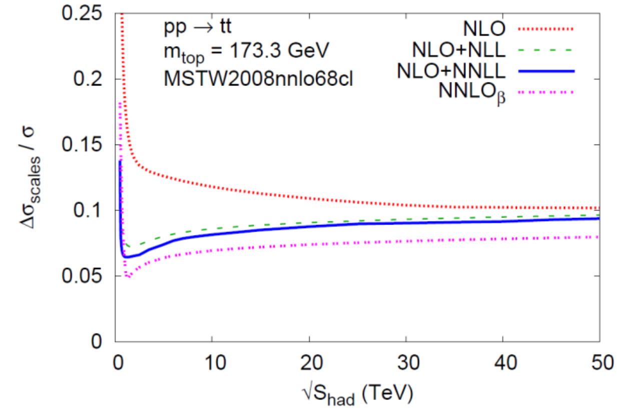
Start to become sensitive to differences between various approximations to NNLO theory!

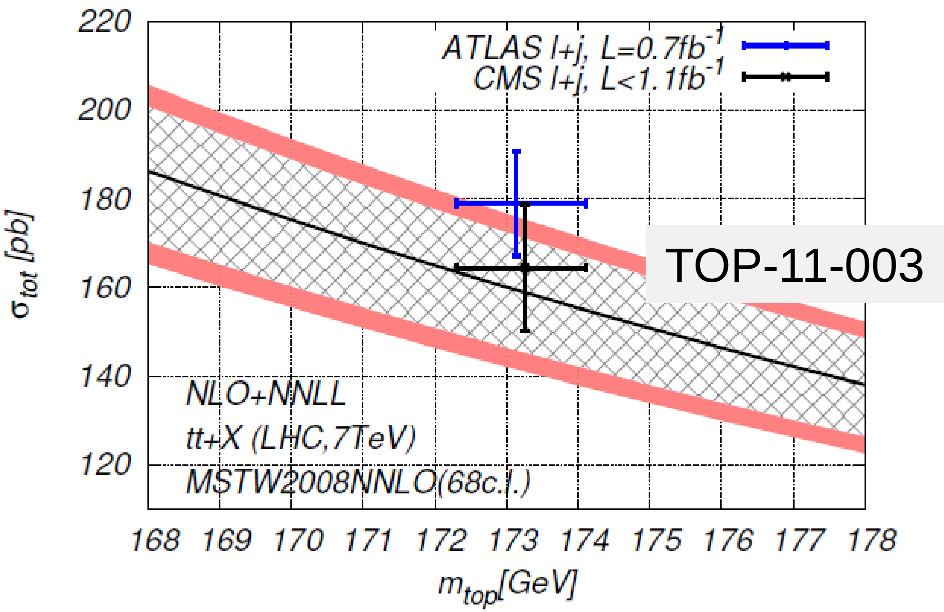


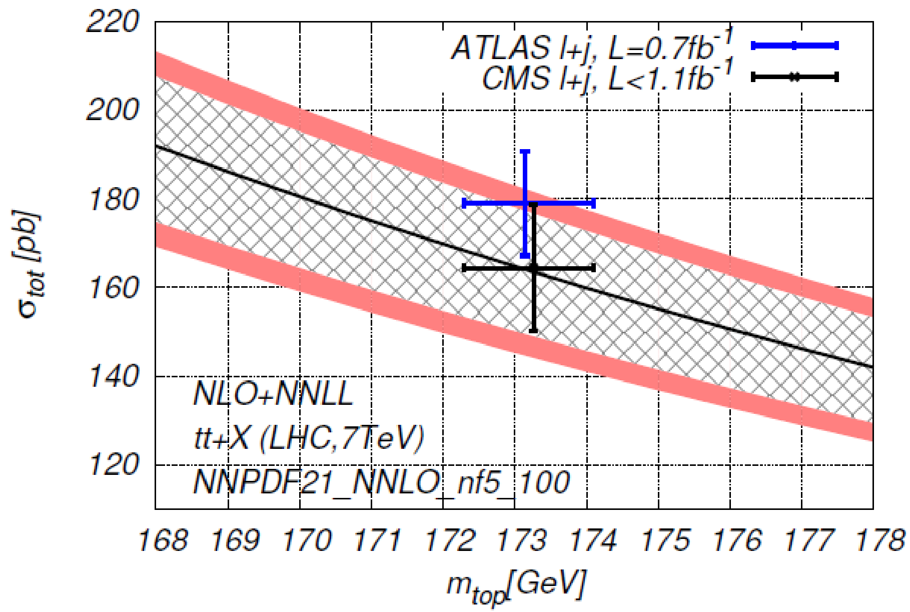
$$\sigma_{t\bar{t}} = 165.8 \pm 2.2(\text{stat.}) \pm 10.6(\text{syst.}) \pm 7.8(\text{lumi.})\ \text{pb}$$

Top pair cross section

- New paper by Cacciari, Czakon, Mangano, Mitov, Nason: http://arxiv.org/abs/1111.5869
  - New: NNLL soft gluon resummation
  - Central value similar to other approx. NNLO calculations
  - Somewhat increased scale unceratiny

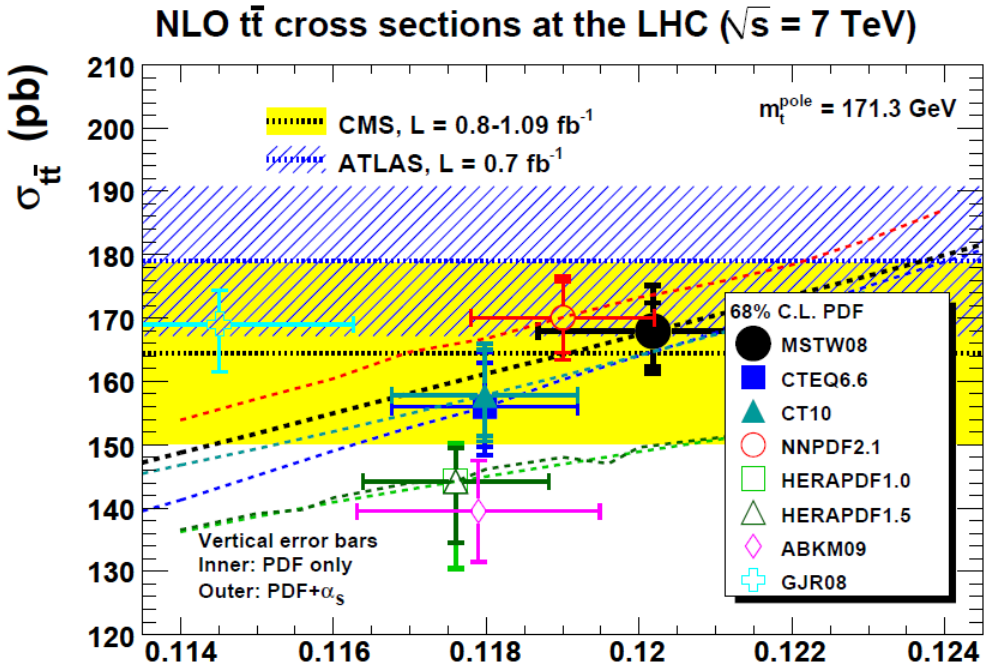




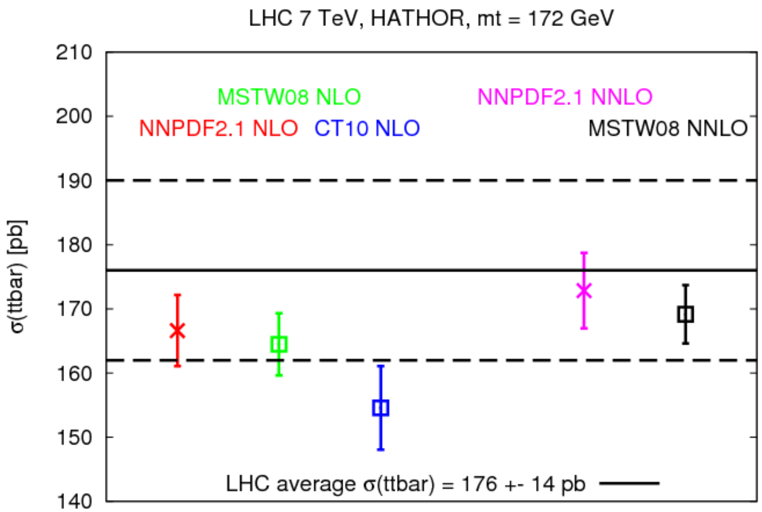


Excellent agreement!
Exp. ~ Theor. Uncertainty!

PDF sensitivity



NLO (Graeme Watt)



NNLO (Juan Rojo)

- Starting to become sensitive to PDF differences
- Similarly interesting for ttbar/Z ratio
  - o PDF uncertainties anti-correlated

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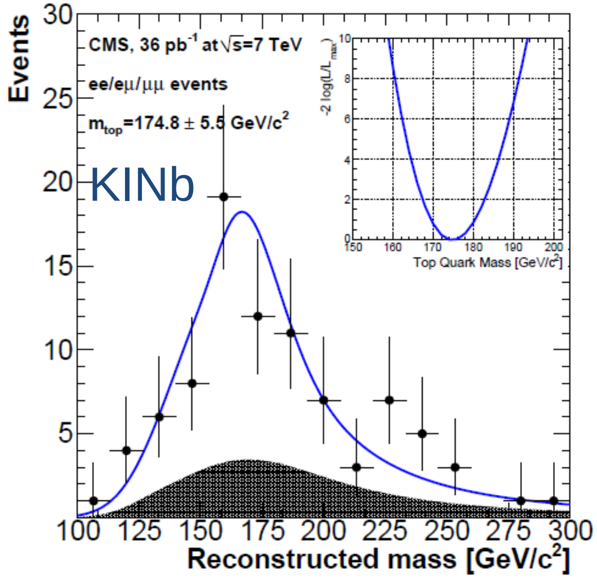
- Single top cross section
- Top pair invariant mass distribution
- Charge asymmetry & same-sign tops

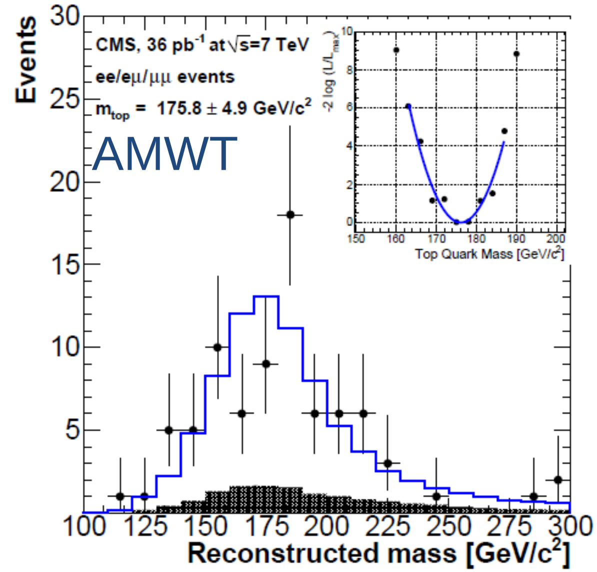
Top mass in Dileptons
[JHEP 07 (2011) 049, L=36/pb]

- Event selection similar to cross section measurement
  - No b-tagging requirement, but b-likeness used in jet assignment
- 2 methods to deal with underconstrained system
  - Analytical Matrix Weighting Technique (AMWT)
    - Assign weight for each solution based on PDF, kinematics
    - For each event, take m(top) with highest sum of weights
    - Based on MWT method from D0: PRL 80 (1998) 2063
  - KINb Method
    - Pz(tt) drawn from MC distribution
    - Accept solution with lowest m(ttbar)
    - Chose combination with largest number of solutions
    - m(top) from Gaussian fit around peak of solutions
    - Based on KIN method from CDF: PRD 73 (2006) 112006

Top mass in Dileptons

[JHEP 07 (2011) 049, L=36/pb]





Max. likelihood fit to mass distributions

- Systematics dominated by JES, PU UE
- Two results are combined

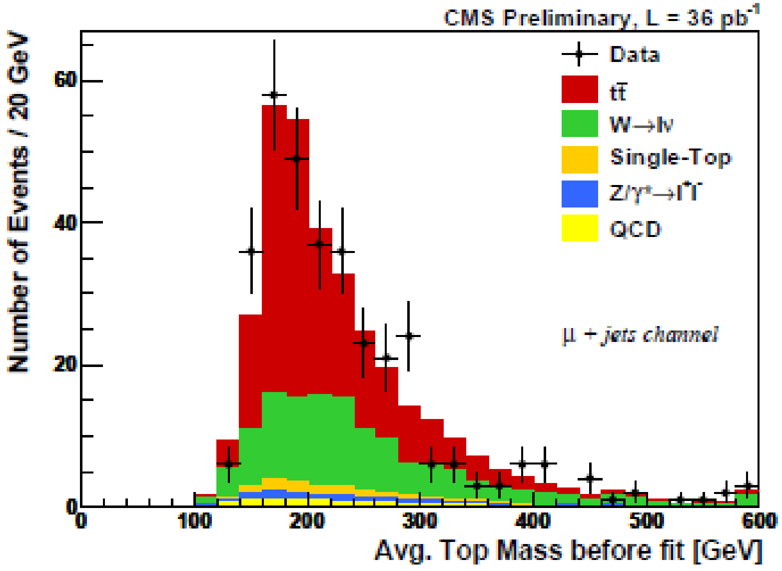
Method	Measured m_{top} (in GeV/c^2)
AMWT	$175.8 \pm 4.9\,(\text{stat.}) \pm 4.5\,(\text{syst.})$
KINb	$174.8 \pm 5.5\,(\text{stat.})^{+4.5}_{-5.0}\,(\text{syst.})$
Combined	$175.5 \pm 4.6\,(\text{stat.}) \pm 4.6\,(\text{syst.})$

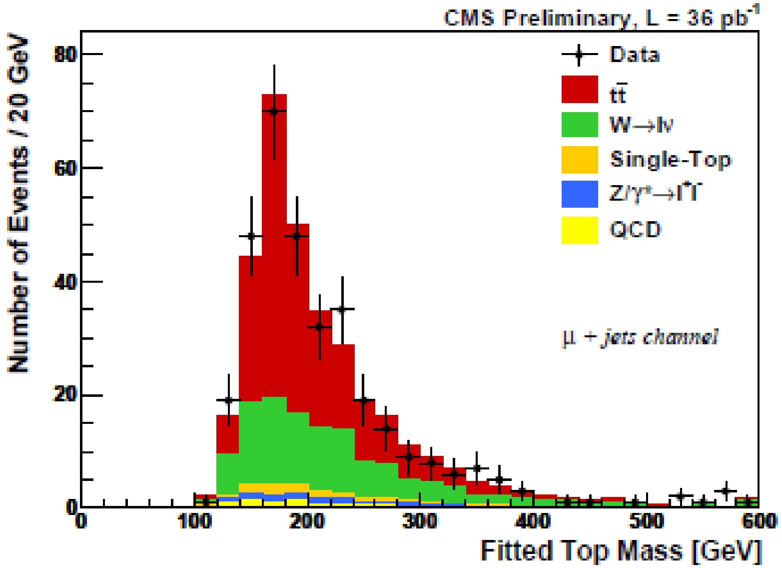
Source	KINb	AMWT
Overall jet energy scale	+3.1/−3.7	3.0
b-jet energy scale	+2.2/−2.5	2.5
Lepton energy scale	0.3	0.3
Underlying event	1.2	1.5
Pileup	0.9	1.1
Jet-parton matching	0.7	0.7
Factorisation scale	0.7	0.6
Fit calibration	0.5	0.1
MC generator	0.9	0.2
Parton density functions	0.4	0.6
b-tagging	0.3	0.5

First m(top) measurement at LHC
Good agreement with world average

Top mass in lepton+jets (PAS TOP-10-009)

- Using the "Ideogram method" (DELPHI,D0,CDF)
- Event selection as for cross section analysis
  - o signal fraction ~55% for >=4 jets
- Kinematic fit
  - o Constrained fit requiring m(t)=m(tbar) applied to up to 24 jet combinations per event



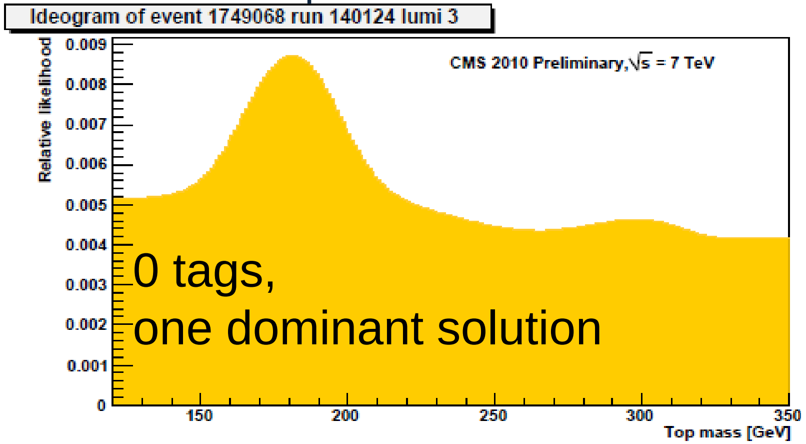


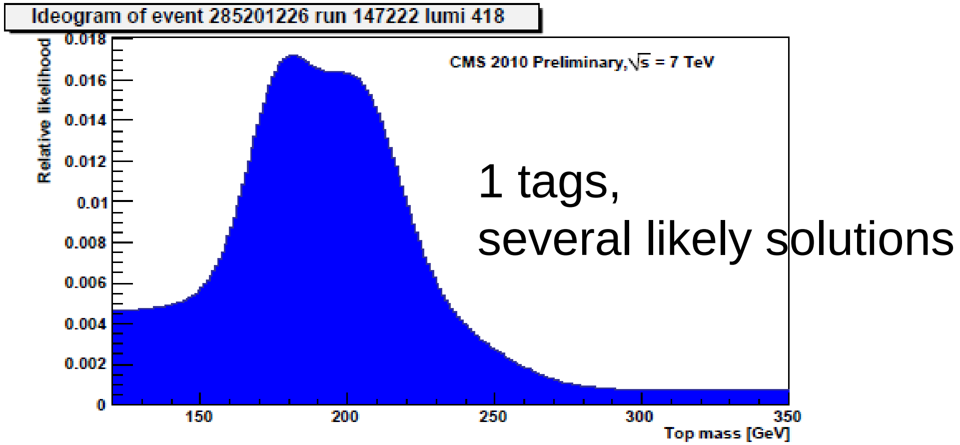
Top mass in lepton+jets (PAS TOP-10-009)

- Event likelihood (== Ideogram)

$$\mathcal{L}_{event}\left(x|m_t, f_{t\bar{t}}\right) = f_{t\bar{t}} P_{t\bar{t}}\left(x|m_t\right) + \left(1 - f_{t\bar{t}}\right) P_{bkg}\left(x\right)$$

  - o x: observables (fitted mass & uncertainty, chi^2, N-btags)
  - o Signal probability density $P_{t\bar{t}}\left(x|m_t\right) = P_{t\bar{t}}\left(n_{btag}\right) \cdot P_{t\bar{t}}\left(x_{mass}|m_t\right)$
    - Sum over permutations and indiv. Weights (correct perm.: analytical function; wrong perm: shape from MC)
    - Consistency of b-tags folded in
  - o Background probability density $P_{bkg}\left(x\right)$
    - Shape from MC simulation

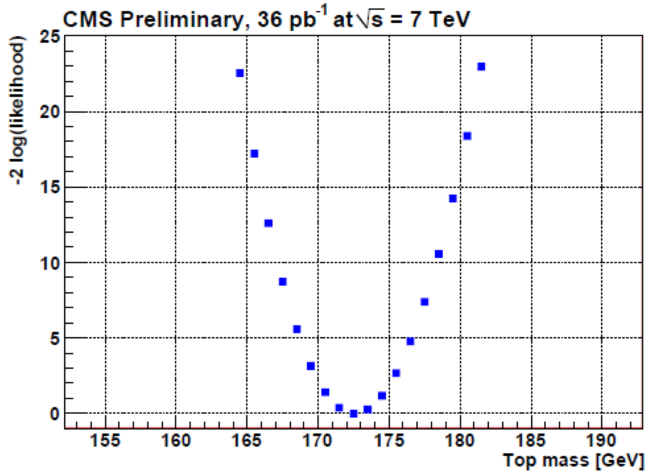




Top mass in lepton+jets (PAS TOP-10-009)

- Construct sample likelihood and minimize

$$\mathcal{L}_{\text{sample}}\left(m_t, f_{t\bar{t}}\right) = \Pi_j \mathcal{L}_{\text{event},j}\left(m_t, f_{t\bar{t}}\right)$$



Central Result:

$$m_t = 173.1 \pm 2.1(\text{stat})^{+2.4}_{-2.1}(\text{JES}) \pm 1.4(\text{other syst})\ \ \text{GeV}$$

Combination with dilepton channel measurement:

$$m_t = 173.4 \pm 1.9(\text{stat}) \pm 2.7(\text{syst})\ \ \text{GeV}$$

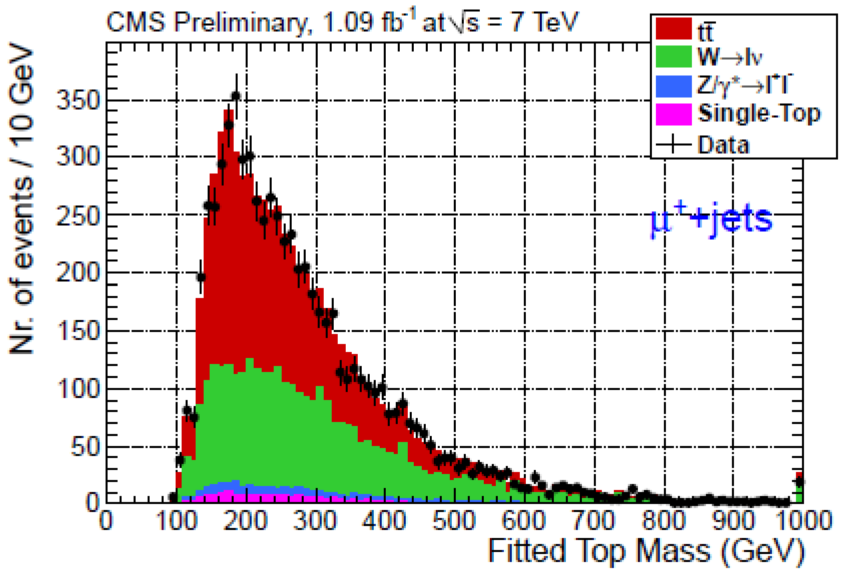
- Systematics
  - o Dominated by jet energy scale

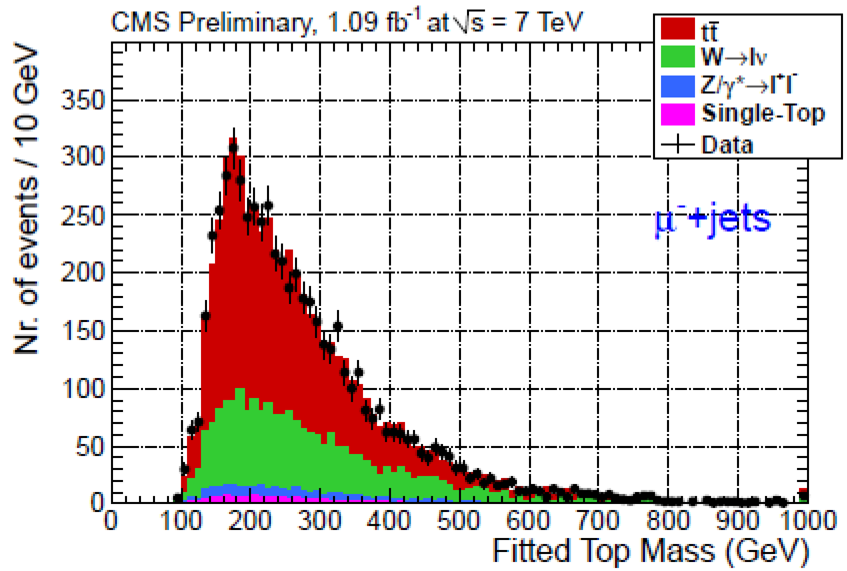
Source	Ideogram analysis δm_t (GeV)
JES (overall data/MC)	+2.4-2.1
JES p_T and η dependence	-
light vs b-jet scale	-
JER (10% effect)	0.07
MET (10% effect)	0.4
Factorization scale	1.1
ME-PS matching threshold	0.4
ISR/FSR	0.2
Underlying event	0.2
Pile-up effect	0.1
PDF	0.1
Background	0.5
B-tagging	0.05
Fit calibration statistics	0.1
Total systematic uncertainty	+2.8- 2.5

Top-antitop Mass Difference (PAS TOP-11-019, L=1.1/fb)

- Direct measurement of quark-antiquark mass difference
  - o Test of CPT invariance
  - o 2 sigma deviation reported by CDF
- Uses ideogram method

Source of systematic effect	Uncertainty on Δm_t (GeV)
Jet Energy Scale	0.16
Jet Energy Resolution	0.18
b vs $\bar{b}$ Jet Response	0.10
Signal fraction	0.03
Background composition	0.13
Pileup	0.1
b-tagging efficiency	0.08
b vs $\bar{b}$ tagging efficiency	0.17
Fit calibration statistics	0.3
Parton distribution functions	0.05
Total	0.47



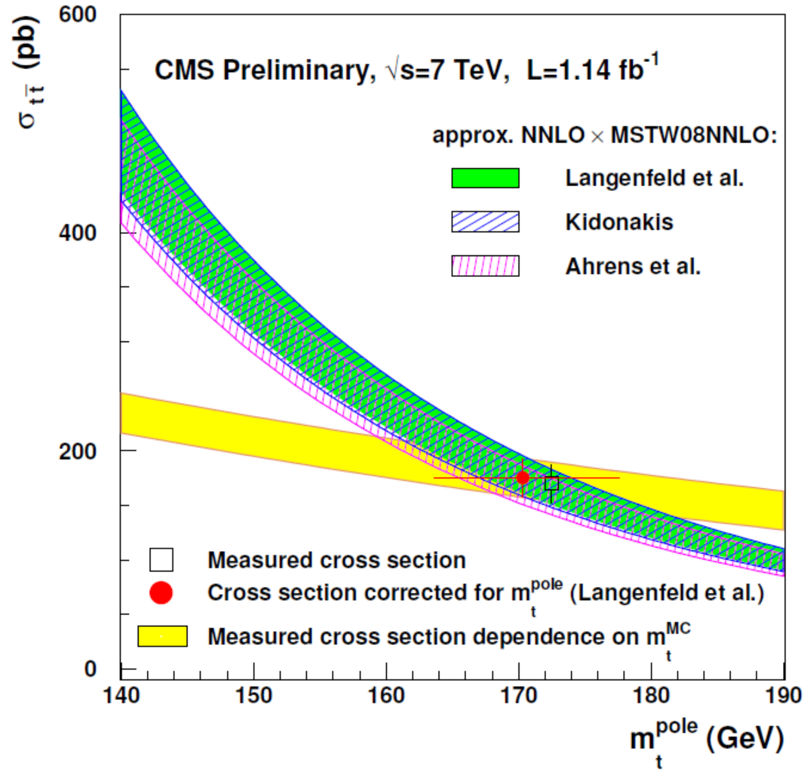


$$\Delta m_t^{\text{measured}} = -1.20 \pm 1.21\ (\text{stat}) \pm 0.47\ (\text{syst})\ \text{GeV}$$

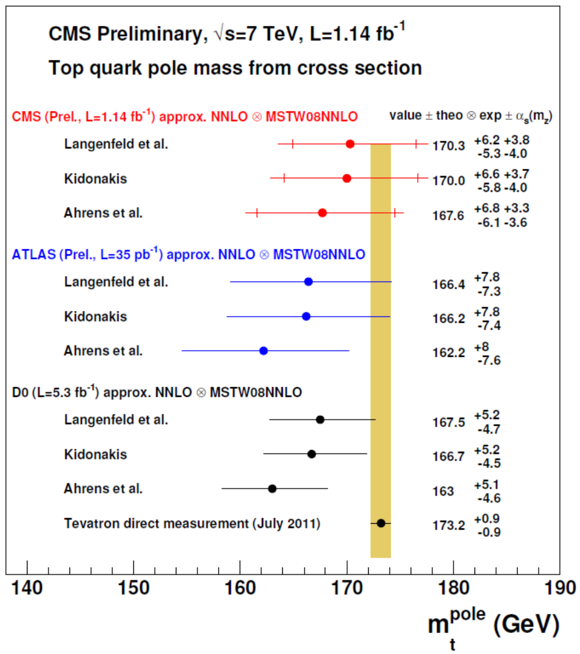
World's best measurement!

Determination of Top Mass from cross section (PAS TOP-11-008)

Using dilepton cross section (TOP-11-005)
Exploit strong dependence of theory cross section on mtop



Important cross check to direct measurements



Can also determine MSbar mass:

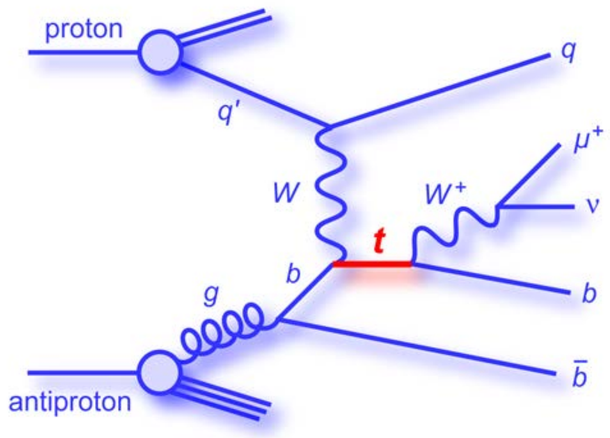
Approx. NNLO × MSTW08NNLO	m_t^{pole} / GeV	$m_t^{\overline{MS}}$ / GeV
Langenfeld et al. [7]	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis [8]	$170.0^{+7.6}_{-7.1}$	–
Ahrens et al. [9]	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$

Outline

- Top pair cross section
- Top mass (difference)
- Single top cross section
- Top pair invariant mass distribution
- Charge asymmetry & same-sign tops

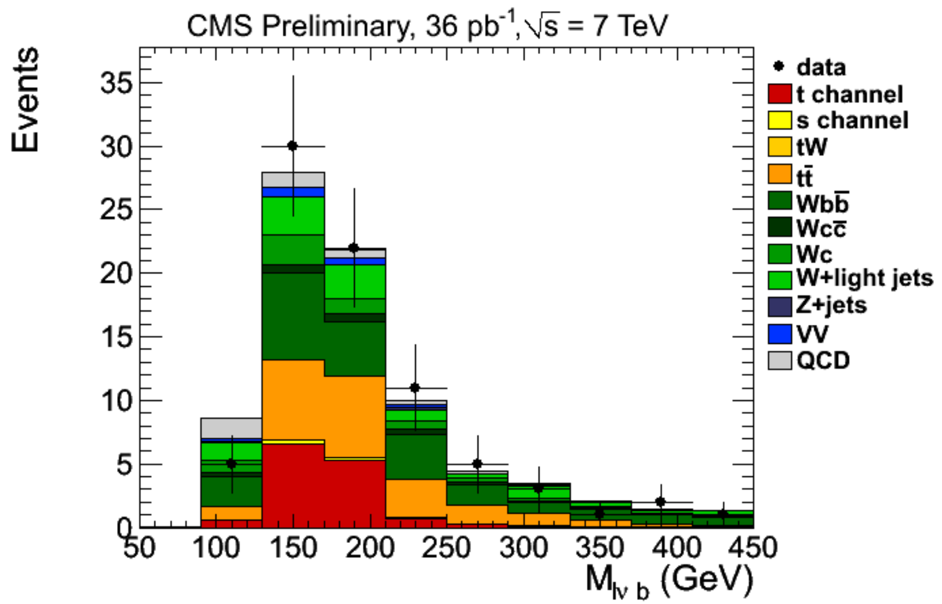
t-channel single top cross section
[PRL 107 (2011) 091802, L=36/pb]

- Selection of single top events
  - o 1 isolated electron (Pt>30 GeV) or muon (Pt>20 GeV)
  - o 2 jets, Et>30 GeV, |eta|<5.0
    - One "tight" b-tag
    - One "loose" b-veto (2D ana)
  - o transv. W mass > 40(50) GeV



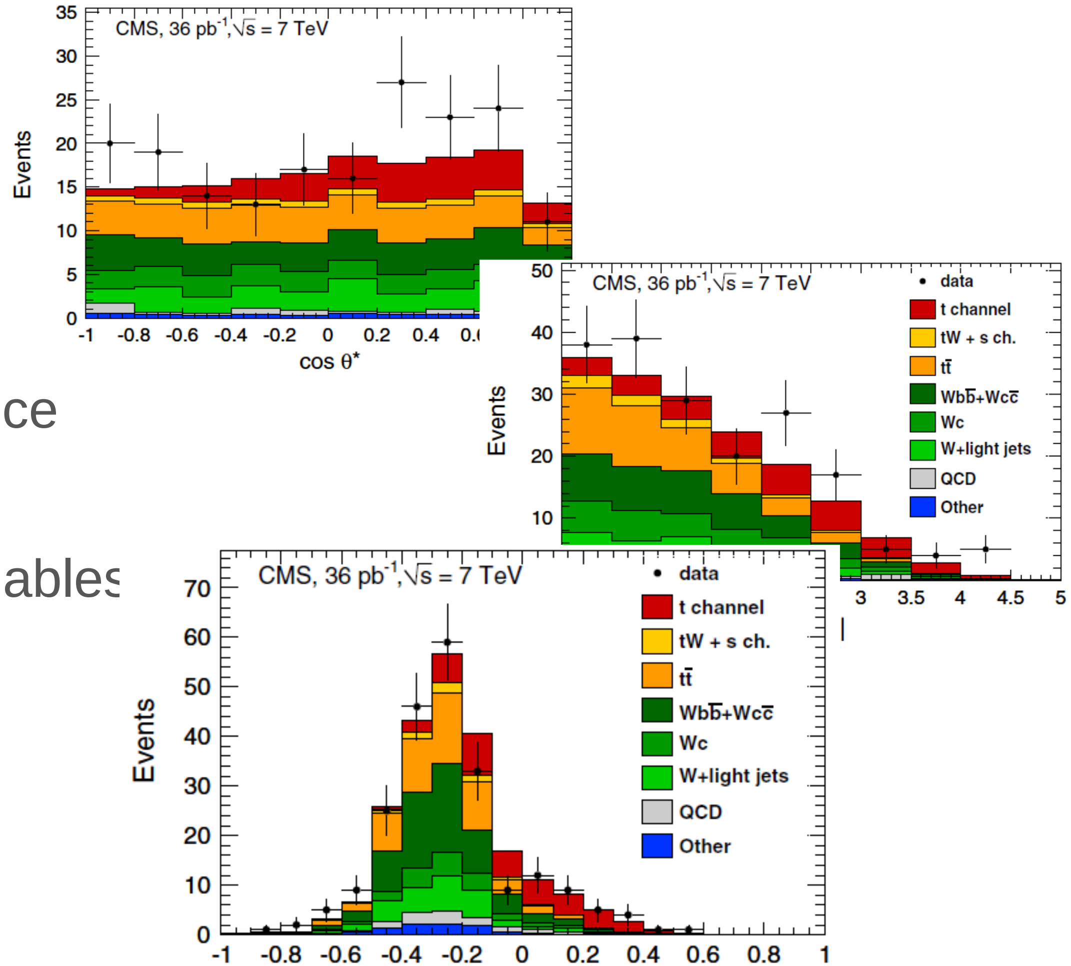
- Reconstruct m(top) using W mass constraint

- Small S/B: 2 complementary methods:
  - o 2D analysis
  - o Boosted Decision Tree analysis



t-channel single top cross section
[PRL 107 (2011) 091802, L=36/pb]

- 2D simultaneous fit
  - o Variables used :
    - angle between l and light jet
    - rapidity of light jet:
  - o W+light shape from data
  - o Minimum model dependence
- Boosted Decision Tree
  - o 37 well modelled input variables
  - o Fit to BDT output
  - o Systematics included via nuisance parameters
  - o Maximum performance



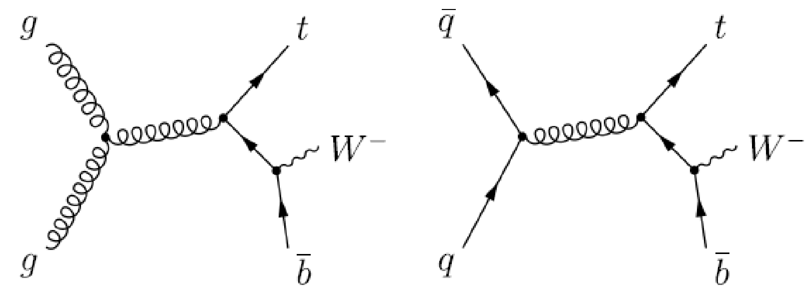
$$\sigma = 83.6 \pm 29.8(stat. + syst.) \pm 3.3(lumi.)\ \text{pb}$$

$$|V_{tb}| = \sqrt{\frac{\sigma^{exp}}{\sigma^{th}}} = 1.16 \pm 0.22(exp) \pm 0.02(th)$$

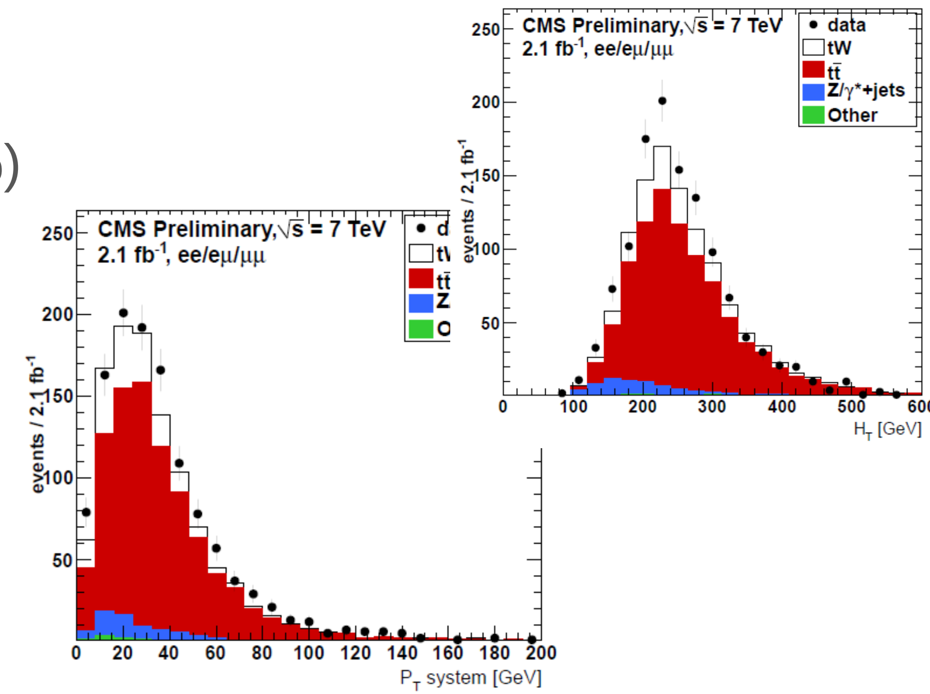
Single top tW Channel

[PAS TOP-11-022, L=2.1/fb]

- Problem of signal definition:
  - o NLO diagrams mix with top pair production
  - o Two approaches considered
    - Diagram removal (DR): remove doubly resonant contributions
    - Diagram subtraction (DS): subtract gauge invariant term which locally cancels tt contribution
  - o Difference as systematic (few %)



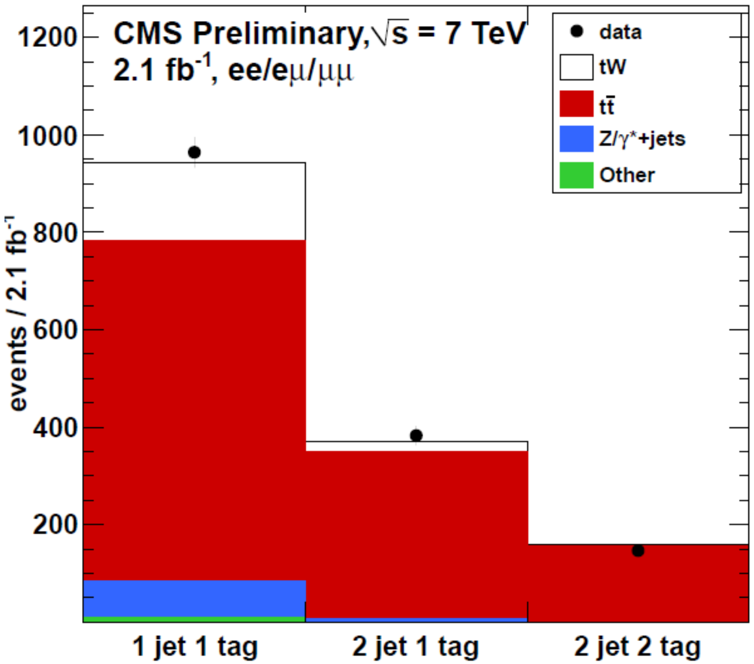
- Event selection
  - o 2 leptons (e or mu), ==1 b-jet
  - o Pt(l+l+jet,MET)<60 GeV
  - o HT>160 GeV (emu only)



Single top tW Channel

[PAS TOP-11-022, L=2.1/fb]

- Cross section from simultaneous fit in signal (1 jet, 1 tag) and two sideband (2 jet 1 tag, 2 jet 2 tag) regions



Systematic uncertainty ($ee/e\mu/\mu\mu$) [%]	signal tW	$t\bar{t}$	$Z/\gamma^\star$	other
Luminosity	4.5	4.5	-	4.5
Pile-up multiplicity	0.48/0.55/0.73	⋆	-	⋆
Trigger Efficiency	1.5	1.5	-	1.5
Muon reconstruction and identification	- /1/1	- /1/1	-	- /1/1
Electron reconstruction and identification	2/2/ -	2/2/ -	-	2/2/ -
JES	$^{-2.5}_{+1.6}/^{-2.4}_{+0.1}/^{-0.6}_{+1.0}$	$^{-5.6}_{+4.4}/^{-6.0}_{+4.7}/^{-5.9}_{+2.3}$	-	⋆
JER	1.1/0.5/0.4	3.1/3.9/4.4	-	⋆
B-tagging	$^{-9.5}_{+10}/^{-9.8}_{+9.8}/^{-9.5}_{+10}$	$^{-8.5}_{+10}/^{-11}_{+10}/^{-9.1}_{+11}$	-	⋆
Factorization/Normalization Scale (Q^2)	7.7/6/10	7.7/11/12	-	⋆
ME/PS matching thresholds	-	5.7/0.7/2.3	-	⋆
ISR/FSR	-	8.9/7.3/7.3	-	⋆
DR/DS scheme	8.2/9.1/6.6	-	-	⋆
E_T^{miss} modeling	2.3/0.9/0.9	⋆	-	⋆
PDF uncertainties	4.5/4.5/4.5	⋆	-	⋆
Background Normalization	-	15/15/15	50/ 50/ 50	⋆
Simulation statistics	3.5/1.9/2.7	-	-	17/21/11

Systematics on top pair production reduced to ones affecting relative population of regions

Cross section measurement:

$$22^{+9}_{-7}\ (\mathrm{stat} \oplus \mathrm{syst})\ \mathrm{pb}$$

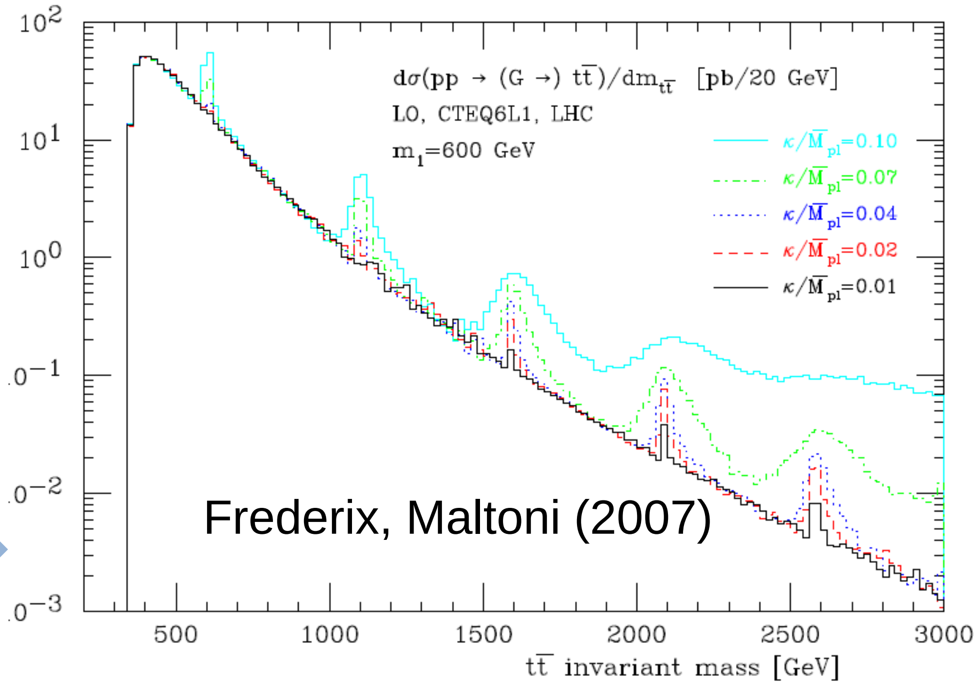
Obs. Significance 2.7sigma

Outline

- Top pair cross section
- Top mass (difference)
- Single top cross section
- Top pair invariant mass distribution
- Charge asymmetry & same-sign tops

Top pair invariant mass

- Search for new particles decaying into top pairs
  - o Spin 0 (e.g. MSSM Higgs)
  - o Spin 1 (e.g. Technicolor, Topcolor Z' bosons)
  - o Spin 2 (KK graviton excitations)

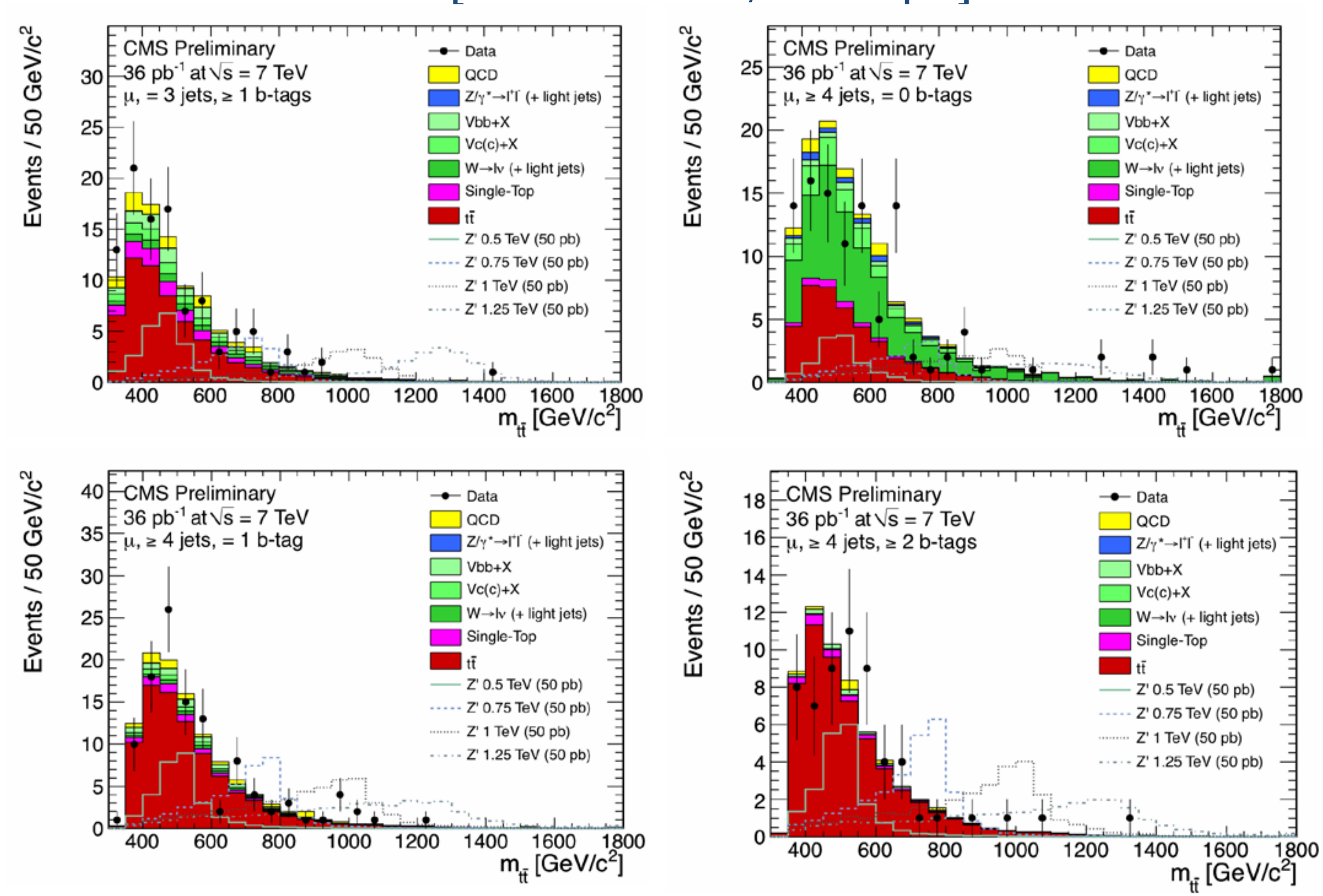


- Distortions in m(ttbar) shape also predicted in other models

- Reconstruction:
  - o Standard reconstruction at low mass
  - o At high mass jets, leptons close by (due to top quark boost) ➔ "top tagging"

Top pair invariant mass: low mass analysis

[TOP-10-007, L=36/pb]



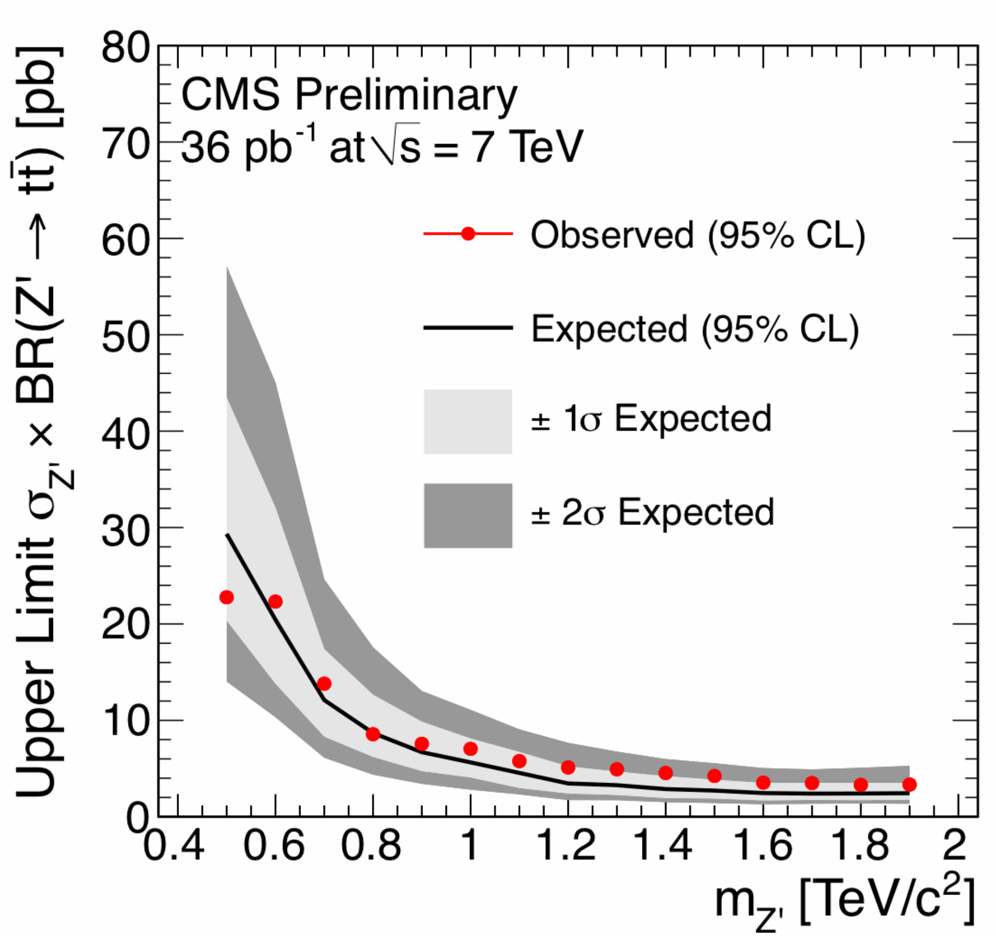
Here:
mu+jets only

- Categorize events in N(jets), N(tags), e/mu
- Fit templates of SM backgrounds and narrow Z' signal
  - o Systematics included as nuisance parameters modifying template shapes & normalizations

Top pair invariant mass: low mass analysis

[TOP-10-007, L=36/pb]

- Derive 95% CL upper limit
- Limit presented in (cross section x BR) of a narrow Z'
  - Not tied to a specific Z' model
- Exclusion possible for models predicting ~10pb for M(Z')~1 TeV

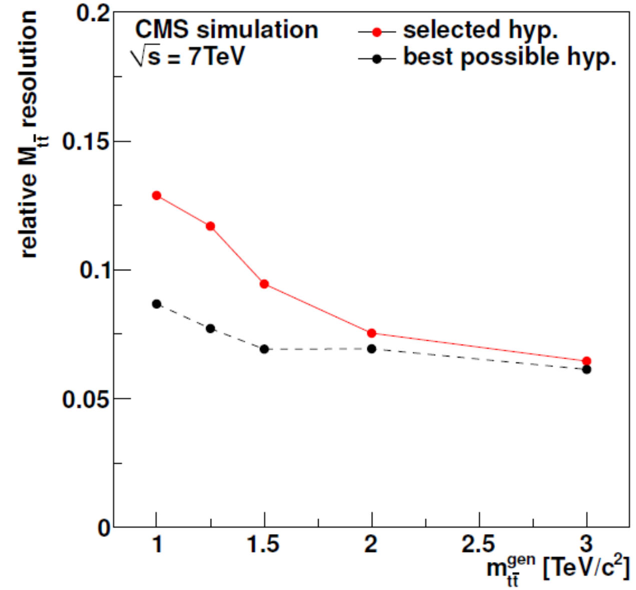


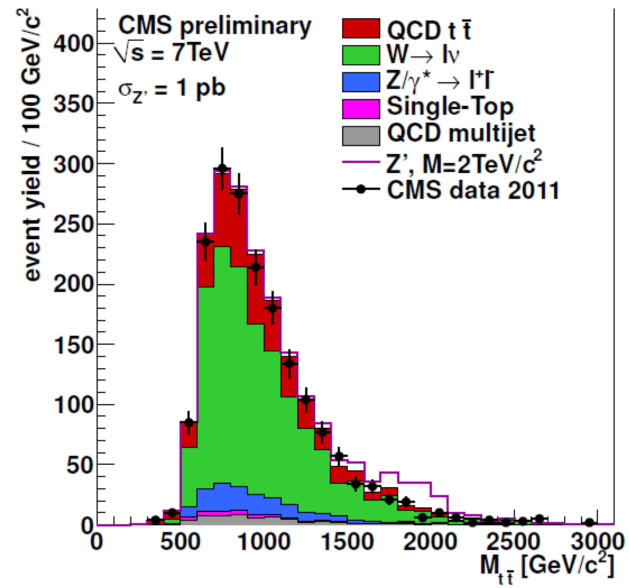
Even more interesting with 2011 data (in progress …)

M(ttbar): High mass analysis in mu+jets

[EXO-11-055, L=1.1/fb]

- High mass: top decay products collimated
  - o No lepton isolation, instead dR(mu,jet)>0.5 or Pt(rel)>25 GeV
  - o Only >= 2 jets, Pt>250,50 GeV
  - o HT(lep)>150 GeV
- M(ttbar) reconstruction using topological criteria
  - o dR(top decay products) small
  - o dR(top, antitop) large
- QCD from data sideband

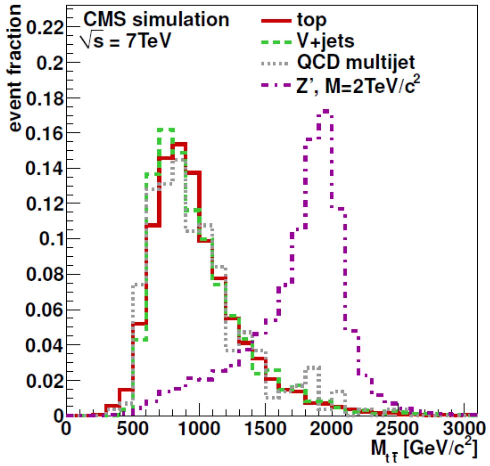




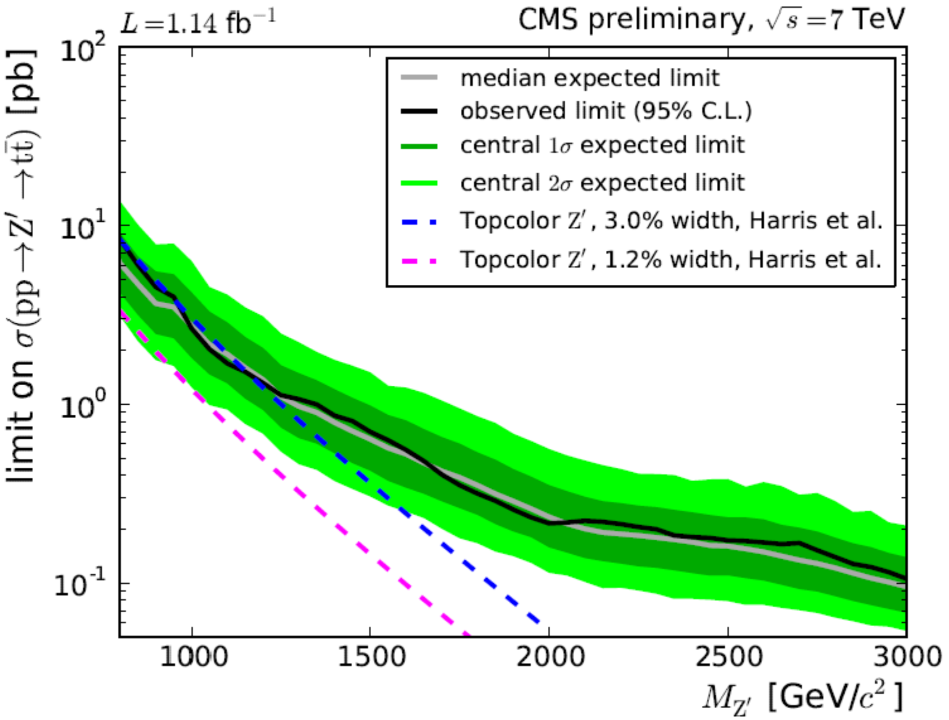
M(ttbar): High mass analysis in mu+jets

[EXO-11-055, L=1.1/fb]

- Statistical analysis
  - o template shapes in HT(lep) and M(ttbar) for signal and backgrounds
  - o Systematics considered via nuisance parameters and shifted templates



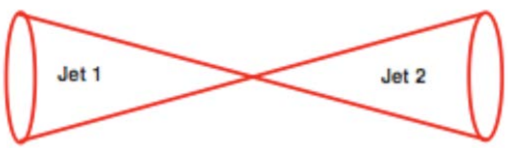
- Obtain limit for narrow Z' (1% width)
- Exclude Topcolor Z' (Harris et al.) with 3% width
  - o 805<M<935 and 960<M<1060 GeV



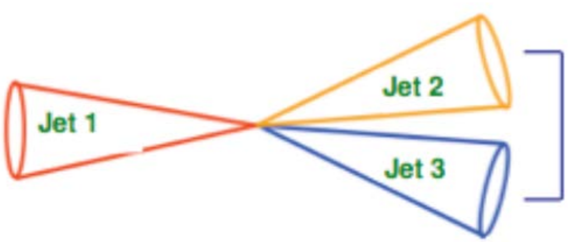
M(ttbar): High mass analysis in hadronic

[EXO-11-006, L=0.9/fb]

- Two hemishpere types
  - o Type-1: high boost, one "top jet"
  - o Type-2: moderate boost, two jets (often one "W-jet" with 2 subjets, one extra jets)
- Analysis channels
  - o Type 1+1



  - o Type 1+2

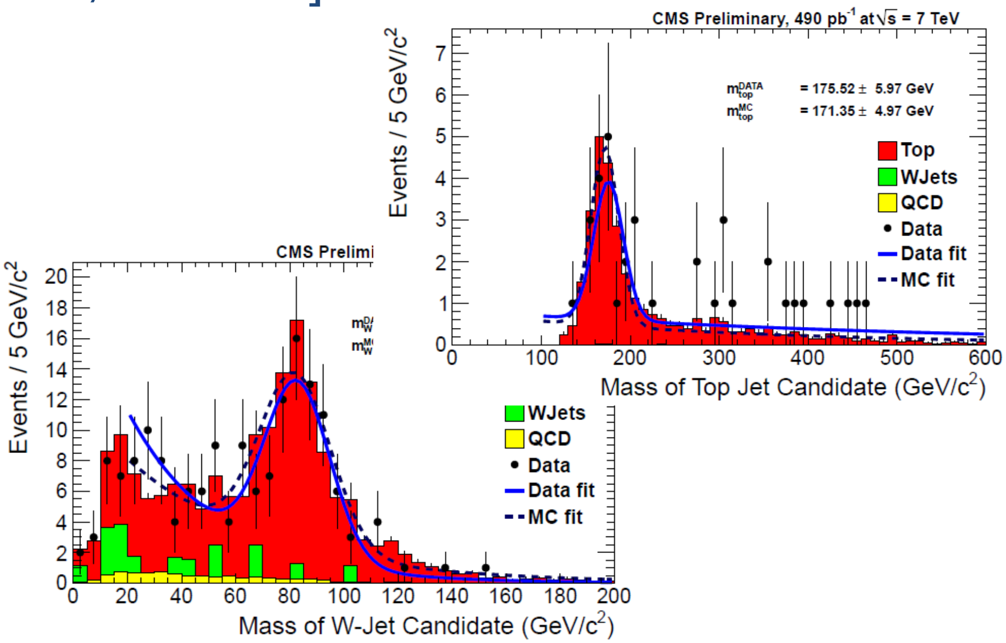


- Top tagging algorithm:
  - o Cambridge-Aachen jets (R=0.8)
  - o Find subjets using top tagging algoríthm (Kaplan et al.; CMS JME-09-001)
    - N(subjets)>=3
    - 140<M(jet)<250 GeV
    - M(min)>50 GeV
- W tagging algorithm
  - o CA jets with R=0.8
  - o Jet pruning algorithm (S. Ellis et al.)
    - N(subjets)>=2
    - 60<m(jet)<100 GeV

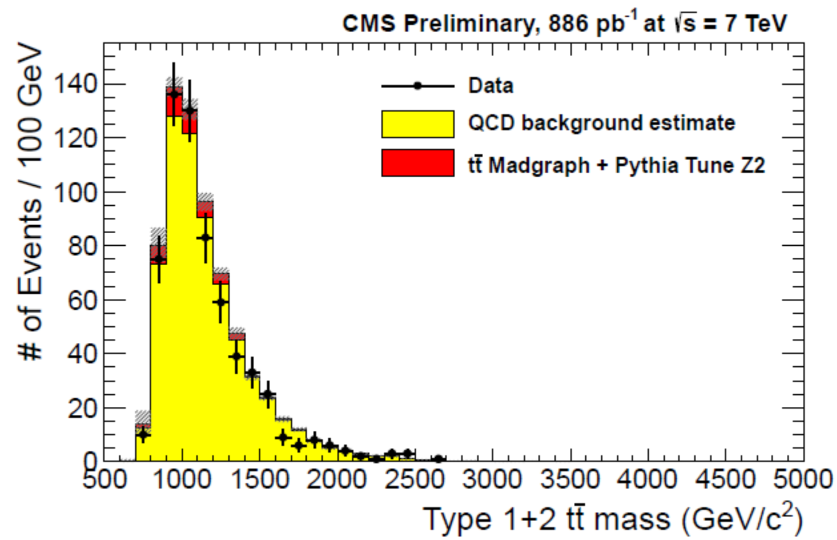
M(ttbar): High mass analysis in hadronic

[EXO-11-006, L=0.9/fb]

- Check of energy scale using semileptonic ttbar sample with boosted W jet



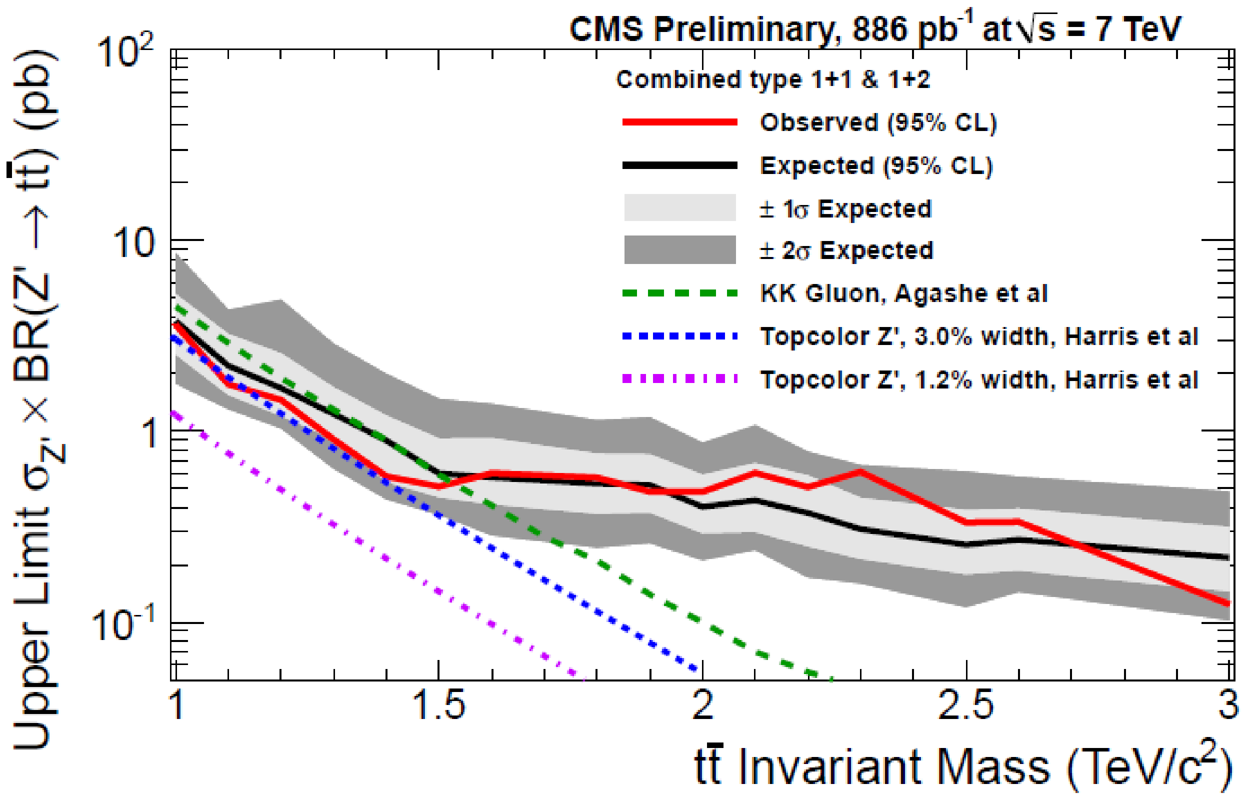
- intermediate mass search in type 1+2 (3 jets)
  - o 1 top jet with Pt>350 GeV
  - o 2 jets from jet pruning algo Pt>200/30 GeV
- high mass search in type 1+1 (2 jets)
  - o 2 top jets, Pt>350 GeV

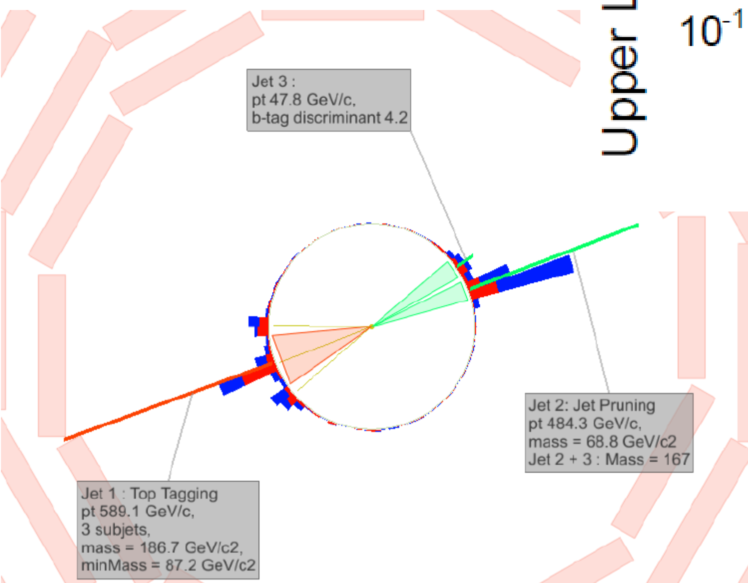


M(ttbar): High mass analysis in hadronic
[EXO-11-006, L=0.9/fb]

Sub-pb limit for M>1.1TeV

KK-Gluon model excluded for 1.0<M<1.5 TeV





Golden 1+2 candidate, M=1.35 TeV

Outline

- Top pair cross section
- Top mass (difference)
- Single top cross section
- Top pair invariant mass distribution
- Charge asymmetry & same-sign tops

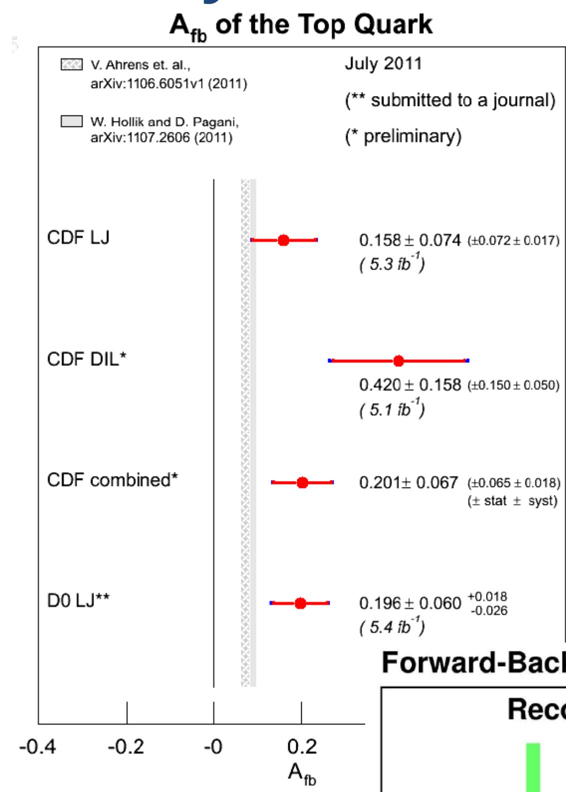
Forward-backward asymmetry at the Tevatron

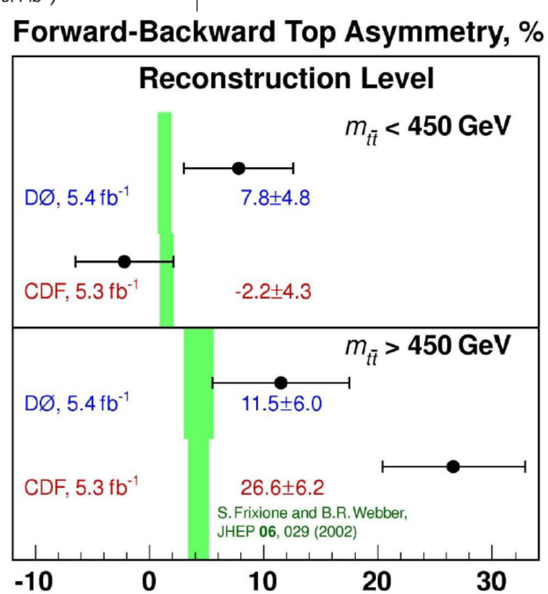
- ttbar forward-backward asymmetry in ppbar collisions

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

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

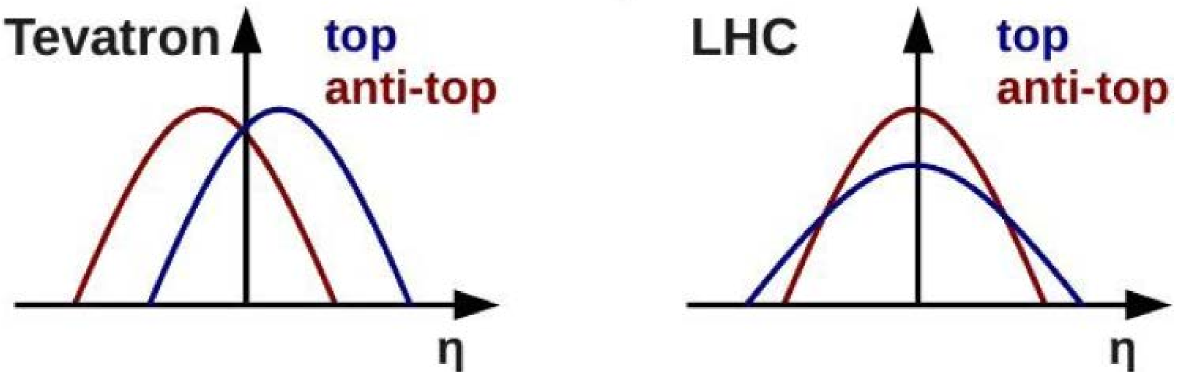
  - o LO: no asymmetry in SM
  - o NLO, small asymmetry
    - interference of diagrams that differ under charge conjugation (ISR-FSR, Born-Box)
- Measured asymmetry larger than predicted
  - o esp. at high M(ttbar) mass
  - o e.g. CDF, PRD 83 (2011) 112003 3 sigma effect for M>450 GeV!





Forward-backward asymmetry

- New particles produced via pp->X->ttbar could increase the measured asymmetry
  - o Axigluons, new weak bosons, extra dimensions
- Models must accommodate measured cross section and M(ttbar) spectrum
- From Tevatron to LHC



  - o No forward-backward asymmetry due to symmetric initial state
  - o But: quarks have on average more momentum than anti-quarks
  - o Boost difference, resulting in small central-decentral asymmetry
    - Diluted due to ~85% gg initial states

Charge Asymmetry

[arXiv:1112.5100, L=1.1/fb]

- Variables used:

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

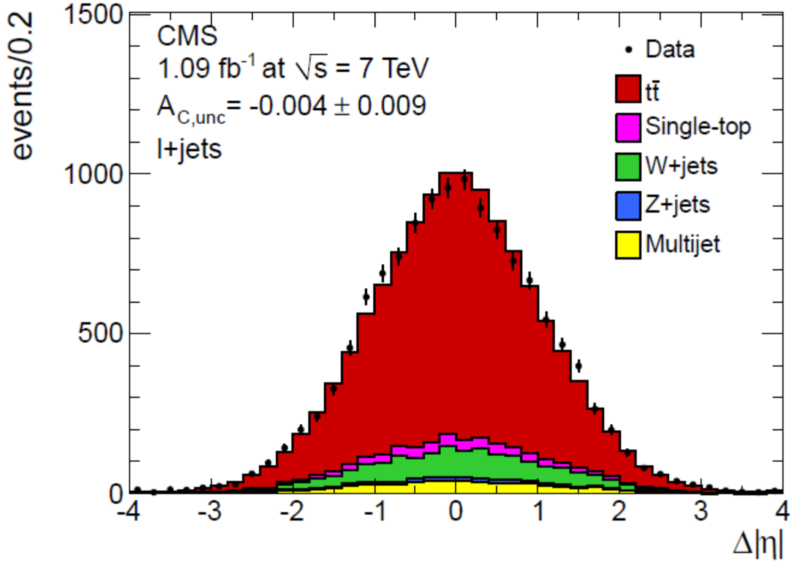
- SM Prediction (G. Rodrigo)

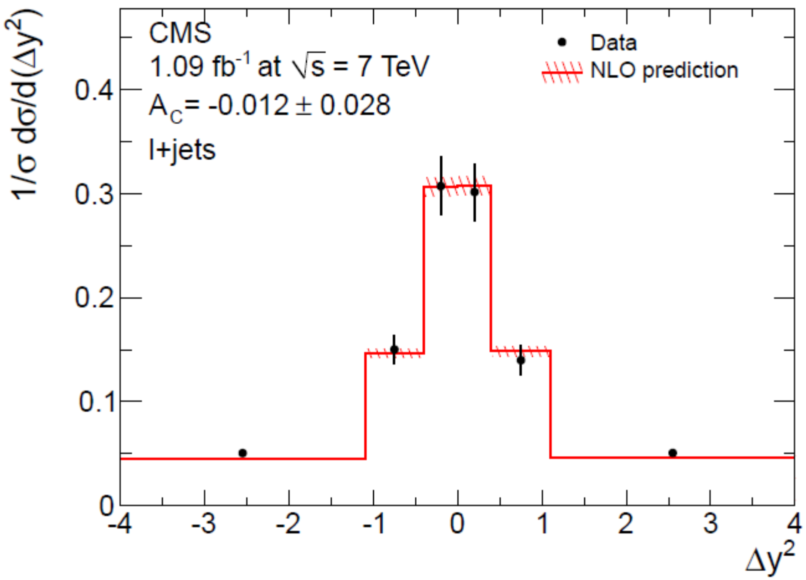
$$A_C^{\eta} = 0.013 \pm 0.001$$
$$A_C^{y} = 0.011 \pm 0.001$$

- Z' with mass ~1TeV:

A_C-A_C^{SM}~-0.02, -0.03

- Regularized unfolding to extract true asymmetry





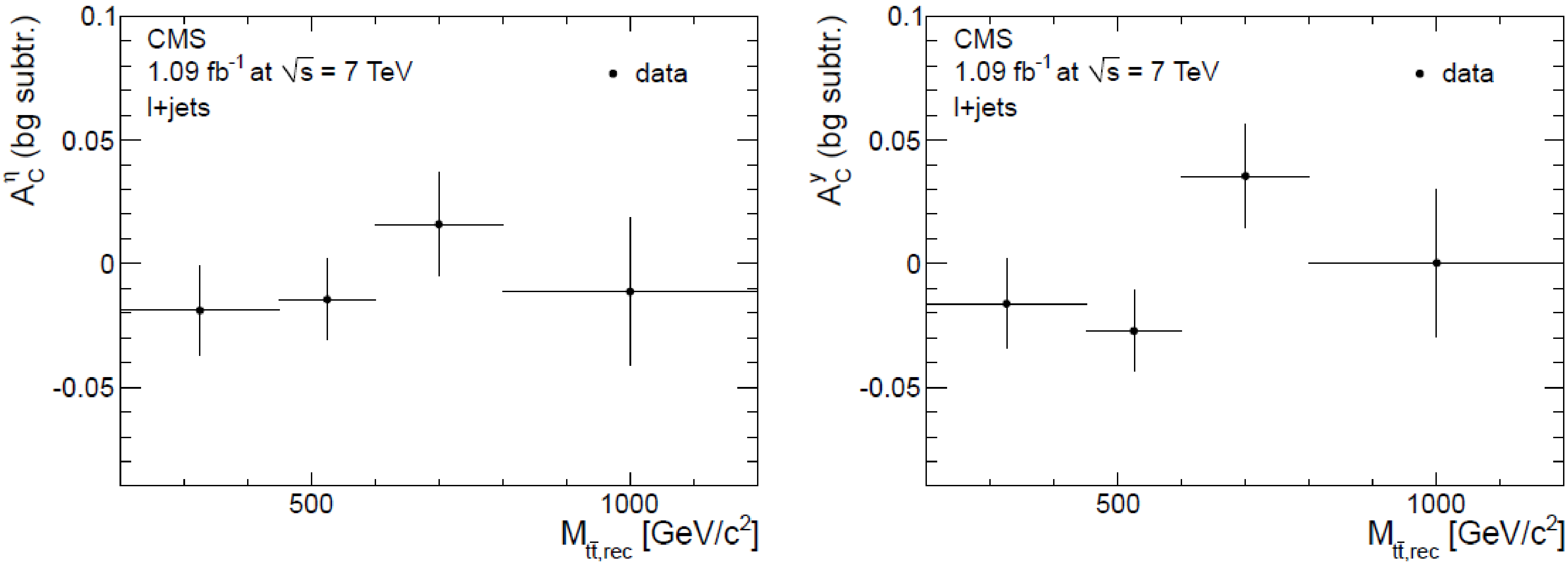
Charge Asymmetry

[arXiv:1112.5100, L=1.1/fb]

Asymmetry	A_C^η	A_C^y
Uncorrected	-0.004 ± 0.009 (stat.)	-0.004 ± 0.009 (stat.)
BG-subtracted	-0.009 ± 0.010 (stat.)	-0.007 ± 0.010 (stat.)
Final corrected	-0.017 ± 0.032 (stat.) $^{+0.025}_{-0.036}$ (syst.)	-0.013 ± 0.028 (stat.) $^{+0.029}_{-0.031}$ (syst.)
Theory predictions	0.0136 ± 0.0008	0.0115 ± 0.0006

Stat ~ syst uncertainties

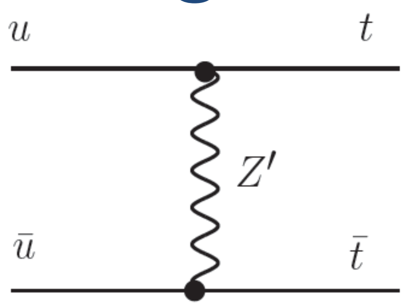
Need to reduce dominating theory systematics

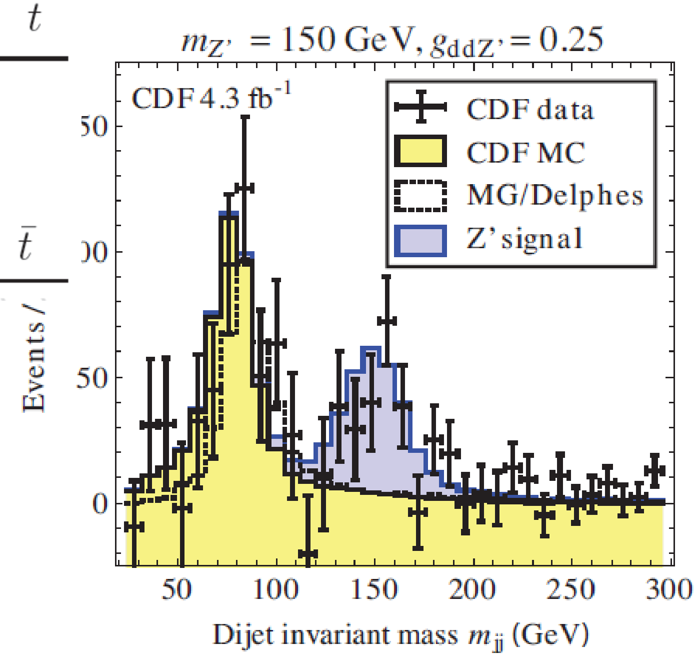


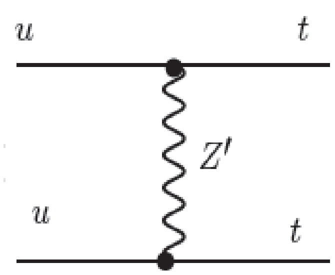
Raw asymmetry vs mass

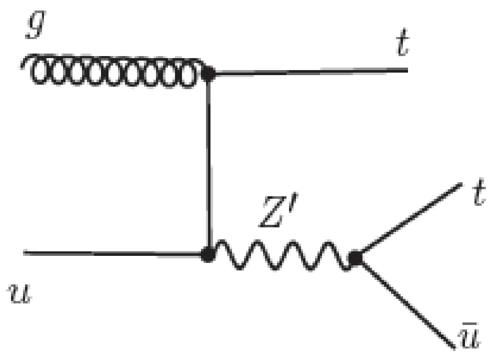
Afb and same-sign Top Pairs

- FCNC in top sector could explain Afb at Tevatron
  - o t-channel exchange of Z' coupling to u and t [S. Jung et al., …]
- Could also explain CDF Wjj bump (which D0 does not see…)
  - o [Buckley et al.; Jung et al.; Fox et al., Cheung et al., …]
- Should manifest as same-sign top pair production
  - o esp. viable at pp machine
- ➔Search for same sign tops in CMS data
  - o Consider model of Berger et al. (arXiv:1101.5625)







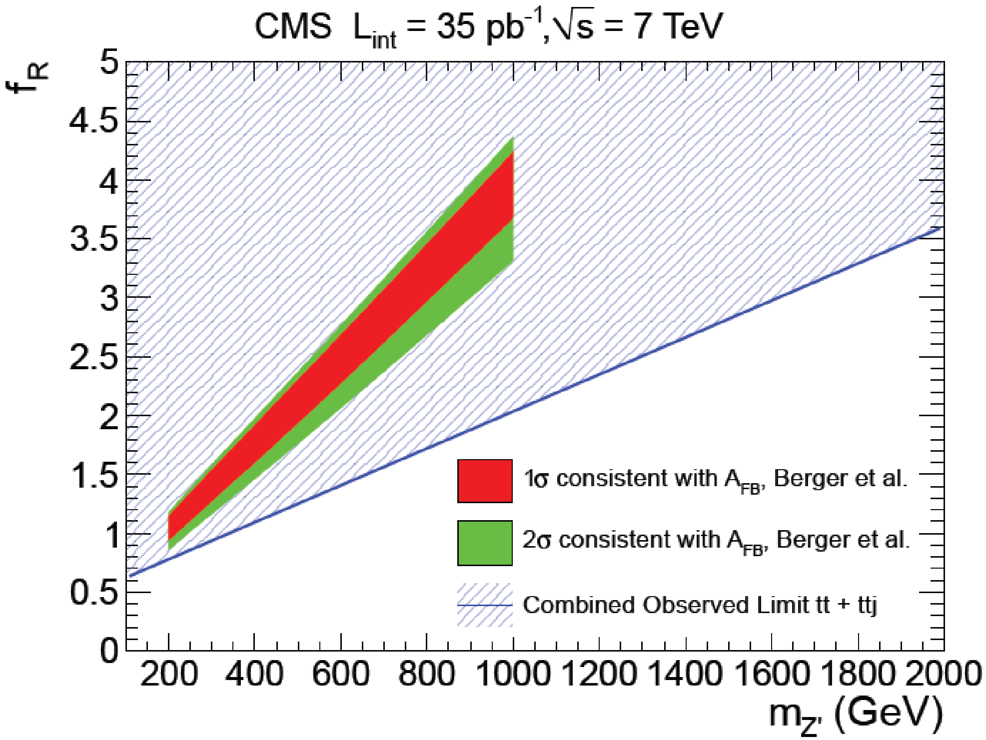


Same-sign Top search

[*JHEP 08 (2011)* 005, L=36/pb]

- Event selection similar to std. dilepton top pair selection,but:
  - o 2 positively charged leptons (search for pp->tt)
- Result with 35/pb of 2010 data:
  - o 2 events (SM: 0.9+/-0.6)
- Considered Model (Berger et al.):

$$\mathcal{L} = g_W \bar{u} \gamma^\mu (f_L P_L + f_R P_R) t Z'_\mu + h.c.$$



- Turn into limit on pp->tt(j) vs f_r and M(Z')
- Exclude parameter space favoured by Tevatron Afb, xsection measurements!

Conclusions

- Top physics program at LHC / CMS is in full swing
- Many interesting results obtained already
  - cross section, mass (difference), M(ttbar) resonances, charge asymmetry, single top production …
- Many new results in the pipeline for Moriond
- With 4.7/fb on tape, most analyses are already limited by systematics
  - Main goal to improve understanding on experimental (e.g. JES, b-tag) and theoretical side (c.f. TOPLHCWG)
- Entering regime of precision / differential measurements
  - Surpassed Tevatron in N(tops) produced
  - starting to compete with CDF/D0 on m(top)
- So far no discrepancies from SM observed
  - But stay tuned (SUSY with light 3rd gen in the spotlight)