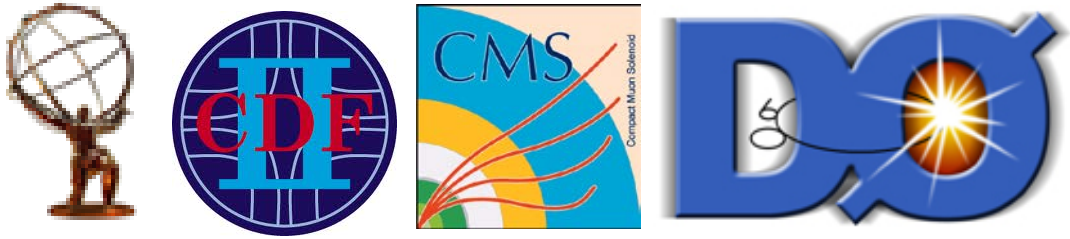


Top Quark Pair Production

Frank-Peter Schilling

Karlsruhe Institute of Technology (KIT)

HCP 2012, Kyoto (Japan)

November 2012

Outline

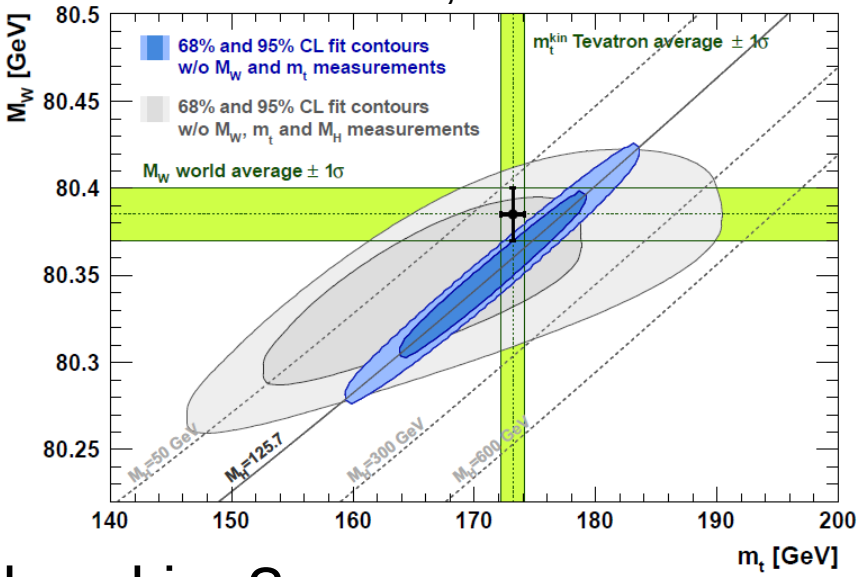
- ttbar total cross section at 2, 7 and 8 TeV
- Differential ttbar cross sections
- Measurements of ttbar+ (b-)jets, γ, W, Z

More details in parallel session this afternoon, and at:
ATLAS results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
CDF results:
http://www-cdf.fnal.gov/physics/new/top/top.html
CMS results:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
D0 results:
http://www-d0.fnal.gov/Run2Physics/top/

Why is Top interesting?

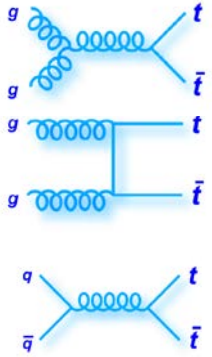
- Heaviest known fundamental particle
  - Yukawa coupling y_t~1
- Decay before hadronization
  - access to spin structure
- Presence in virtual loops
  - Consistency of SM (m_t,m_W,m_H)

Gfitter, arXiv:1209.2716



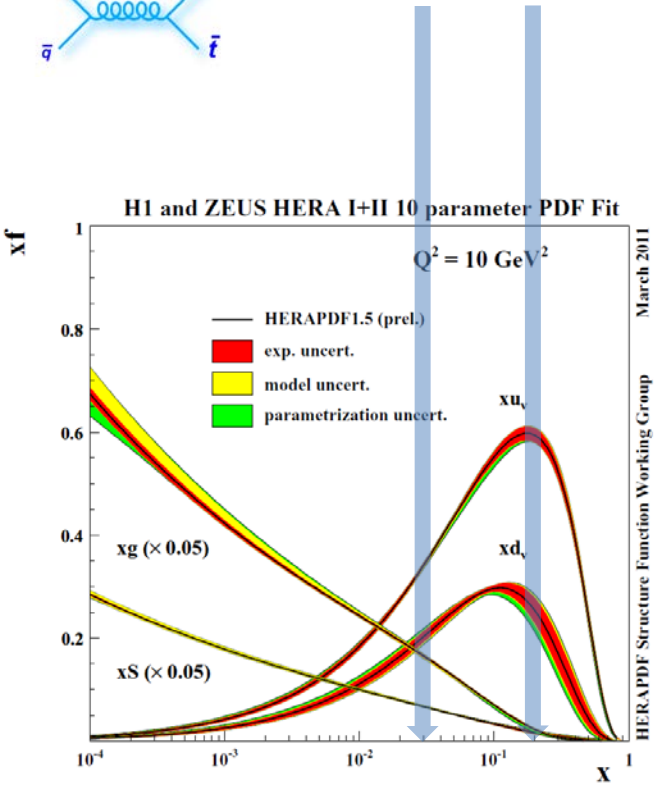
- Special role in EWK symmetry breaking?
- New particles which decay dominantly into top quarks
  - Super-symmetric partners (3rd gen squarks), Z' bosons
- New particles may be produced in top decays, e.g. H^+
- Detailed study of top needed (differential distributions!)
  - may reveal non-SM contributions
  - LHC has already produced several million top quark pairs!

Top quark pair production and decay

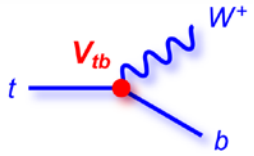


Production:

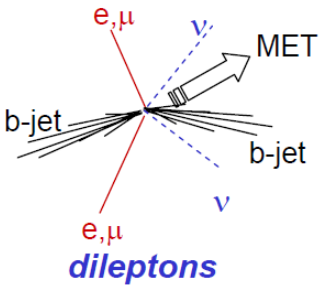
	LHC-7	Tevatron
gg	~80%	~15%
qq	~20%	~85%

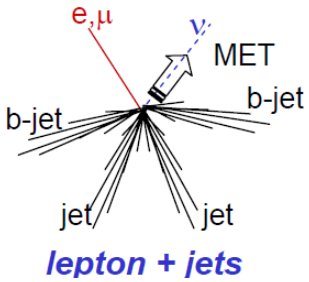


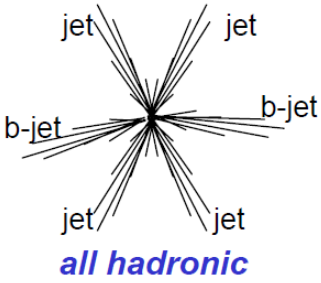
Decay:



(almost 100%)







BR: ~5% ~30% ~46%

Bkgd: few (mainly Z+jets) moderate (mainly W+jets) huge (mainly QCD)

Cross section measurement:

- Traditionally: counting experiment
- More precise: likelihood fit, also incorporating systematics via nuisance parameters

Important systematic uncertainties:

- Jet energy scale, b-tagging
- Signal modeling in MC

(Brief) Theory Status

- Approximate NNLO calculations for σ_{tot} by several groups
  - scale unc. 5…9%
- Since recently: pieces of exact NNLO exist (all except gg->tt)

  [Baernreuther, Czakon, Mitov 2012]
  - See next talk for details!

Approx. NNLO theory calculations, LHC at 7 TeV		
Authors	σ(tt) ±scale ±PDF [pb]	Details
NLO QCD (MCFM)	160 +20-21 +8-9	MSTW 90%CL, m_t=173 GeV
Kidonakis (arXiv:1009.4935)	163 +7-5 +9-9	MSTW 90%CL, m_t=173 GeV
Aliev et al. (HATHOR 1.2) (arXiv:1007.1327)	164 +5-9 +9-9	MSTW 90%CL, m_t=173 GeV
Ahrens et al. (arXiv:1003.5827)	155 +8-9 +8-9	MSTW 90%CL, m_t=173.1 GeV
Beneke et al. (arXiv:1109.1536)	163 +7-8 +15-14	MSTW 90% CL (incl. α_s), m_t=173.3 GeV
Czakon, Mitov (TOP++ 1.4) (arXiv:1210.6832)	154 +9-8 +4-4	MSTW 68%CL, m_t=173.3 GeV
Moch et al. (HATHOR 1.3) (arXiv:1203.6282)	175 +10-13 +5-5	MSTW 68%CL, m_t=173 GeV

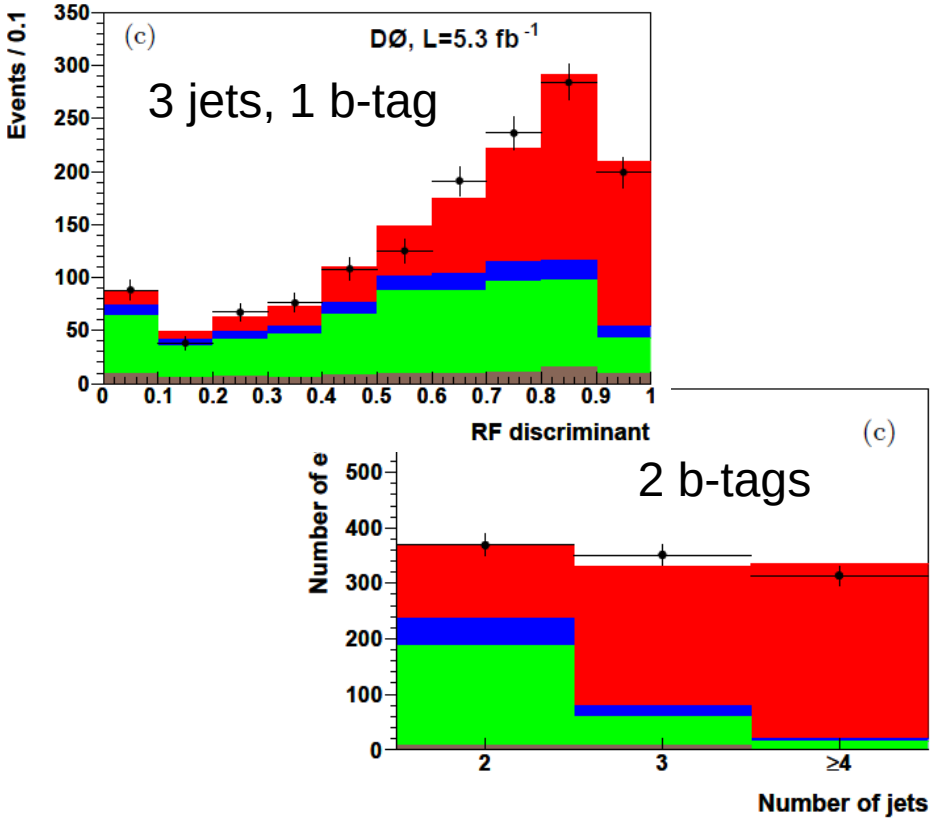
- NLO+PS MC matched implementations (POWHEG, MC@NLO)
- tt+jets (incl. tt+bb)
  - Full NLO calculations for 1 and 2 extra jets (incl. differential distributions)
- tt+V (V=γ,W,Z)
  - NLO exists, also interfaced to PS in aMC@NLO, POWHEG+HELAC

Total Cross Section at the Tevatron

l+jets channel: best single measurements

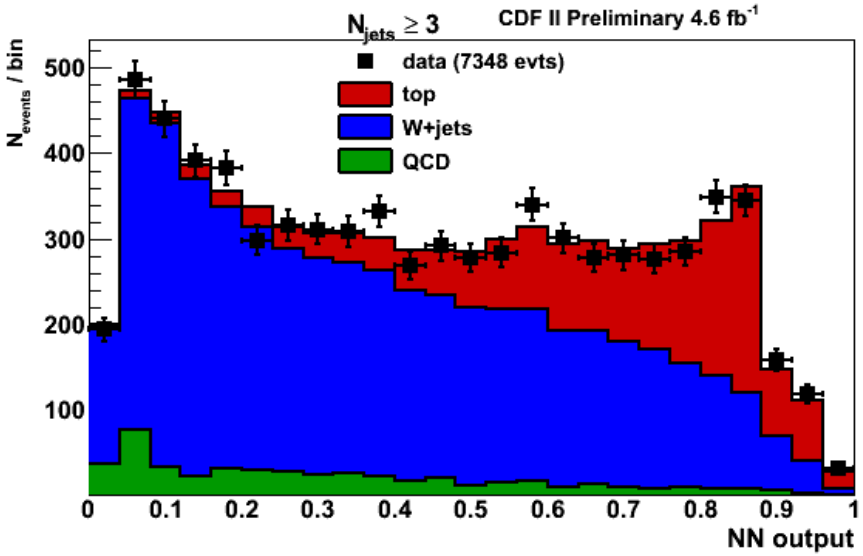
D0, 5.3/fb, arXiv:1101.0124

- profile likelihood over N(jets)xN(b-tags)
- nuisance params. for systematics



$$\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}\,(\text{stat} + \text{syst} + \text{lumi})\ \text{pb} \quad (9.1\%)$$

CDF, 4.6/fb, arXiv:1004.3224

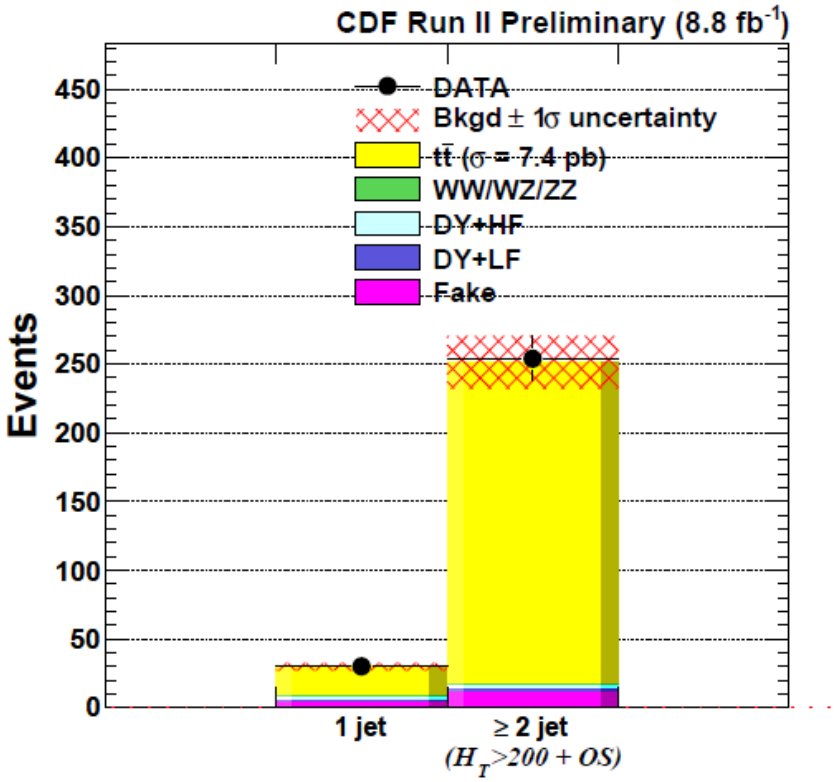


- NN discriminant using kinematic variables (no b-tagging)
- combined with b-tagged analysis
- reduced uncertainty due to measurement of ratio σ(tt)/σ(Z/γ*)

$$\sigma_{t\bar{t}} = 7.70 \pm 0.52\ \text{pb} \quad (6.8\%)$$

New measurements using full dataset

CDF dilepton, 8.8/fb, Note 10878

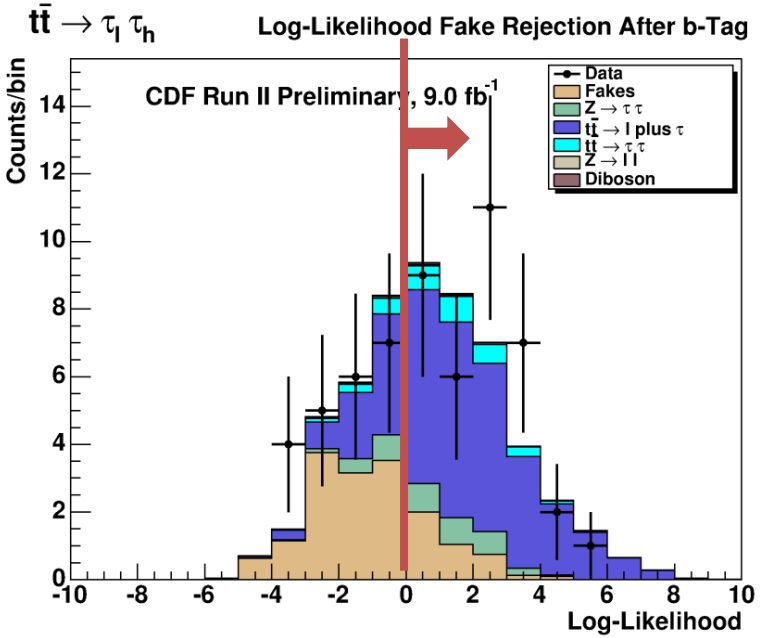


- 254 events with 2 jets, 1 b-tag

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

(11.5%)

CDF tau+lepton+jets, 9.0/fb, Note 10562



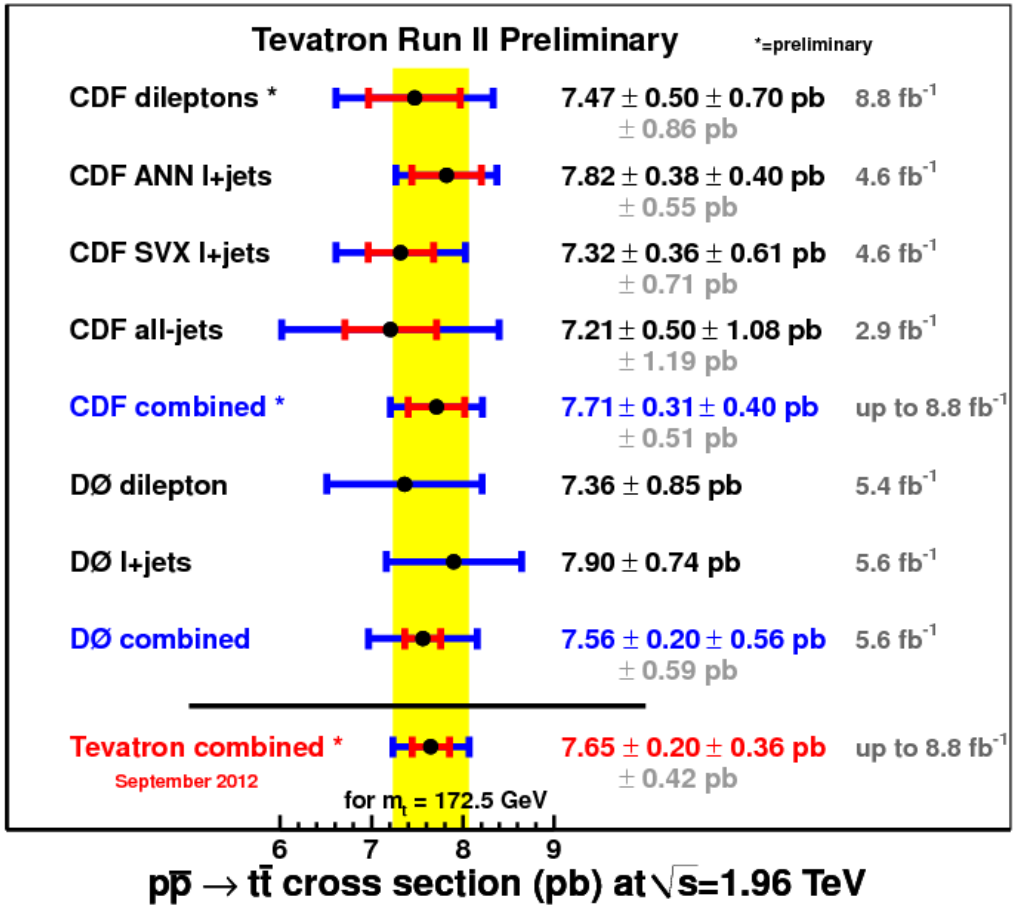
- Selection: 1 tau, 1 e/μ, 2 jets, 1 b-tag
- Reduced tau fakes using kinematic likelihood
- 36 events selected in 9.0/fb

$$\sigma_{t\bar{t}} = 8.2 \pm 2.3(stat.)^{+1.2}_{-1.1}(syst.) \pm 0.5(lum.) \text{ pb}$$

Tevatron Combination

D0 Note 6363, CDF Note 10926

- NEW (September 2012): first combination of CDF and D0 ttbar cross sections
- Careful treatment of (un)correlated systematics
- Combination using BLUE
- Relative weights: 60% CDF, 40% D0
- Precision of combination 5.5%



Good agreement with theory!

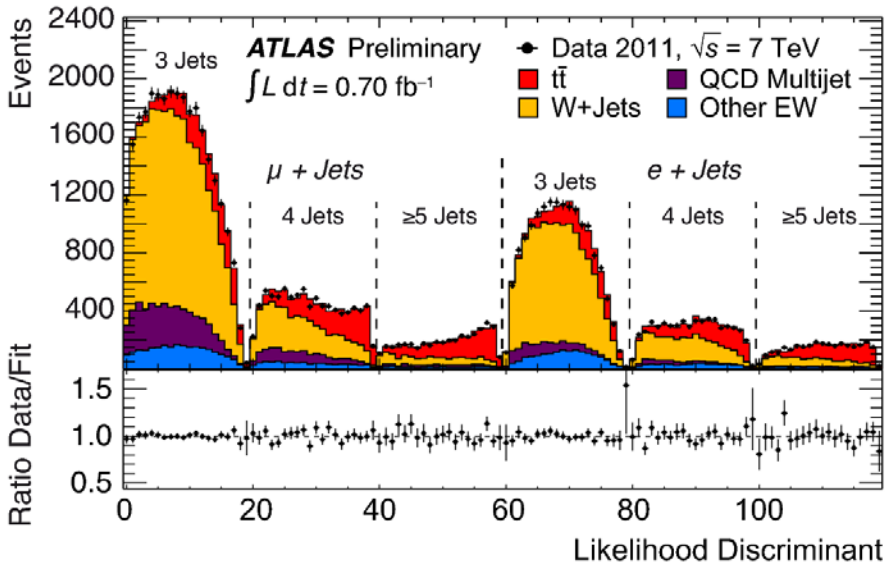
NNLO+NNLL (TOP++ 1.3, mt=172.5, incl. NNLO qq->tt):

$$7.24^{+0.15}_{-0.24}\,(scale)^{+0.18}_{-0.12}\,(PDF)\,\text{pb}$$

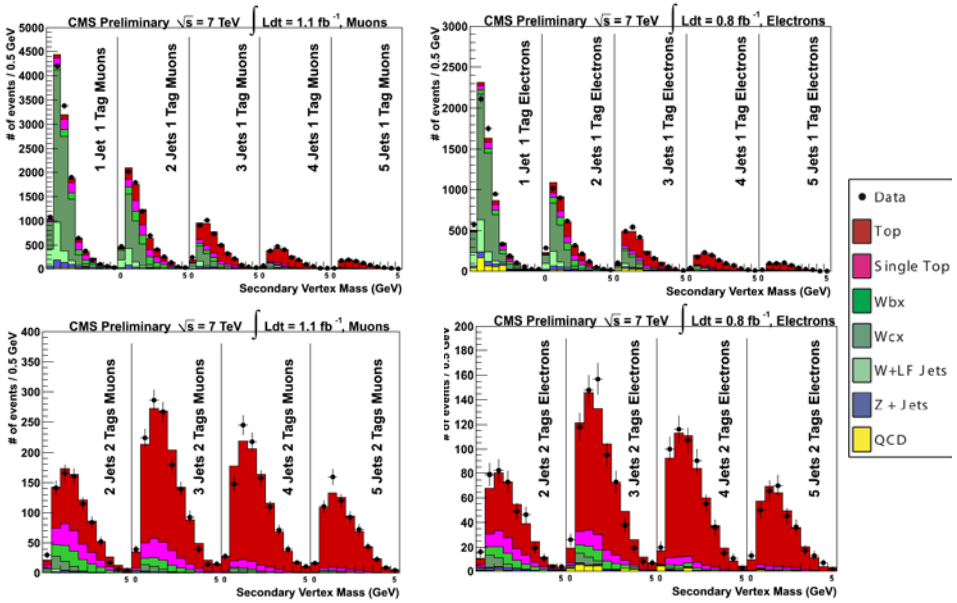
Total Cross Section at the 7 TeV LHC

Lepton+Jets Channel

ATLAS, 0.7/fb, ATLAS-CONF-2011-121



CMS, 0.8-1.1/fb, CMS-PAS-11-003



- Likelihood based on kinematic variables (without b-tagging)
- Profiling of systematic uncertainties

$$\sigma_{t\bar{t}} = 179.0 \pm 9.8\ (\text{stat+syst}) \pm 6.6(\text{lumi})\ \text{pb}$$

(7%)

- With b-tagging: fit svx mass in N(jets, b-tags) plane
- Profiling of major systematics

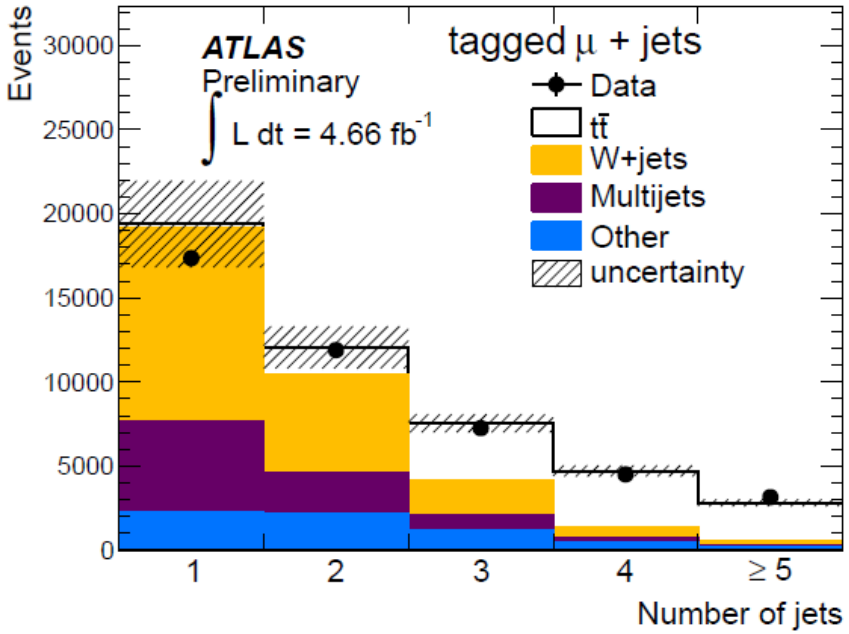
$$\sigma_{t\bar{t}} = 164.4 \pm 2.8(\text{stat.}) \pm 11.9(\text{syst}) \pm 7.4(\text{lum.})\ \text{pb}$$

(9%)

Recent measurements

ATLAS l+jets, 4.7/fb, ATLAS-CONF-2012-131

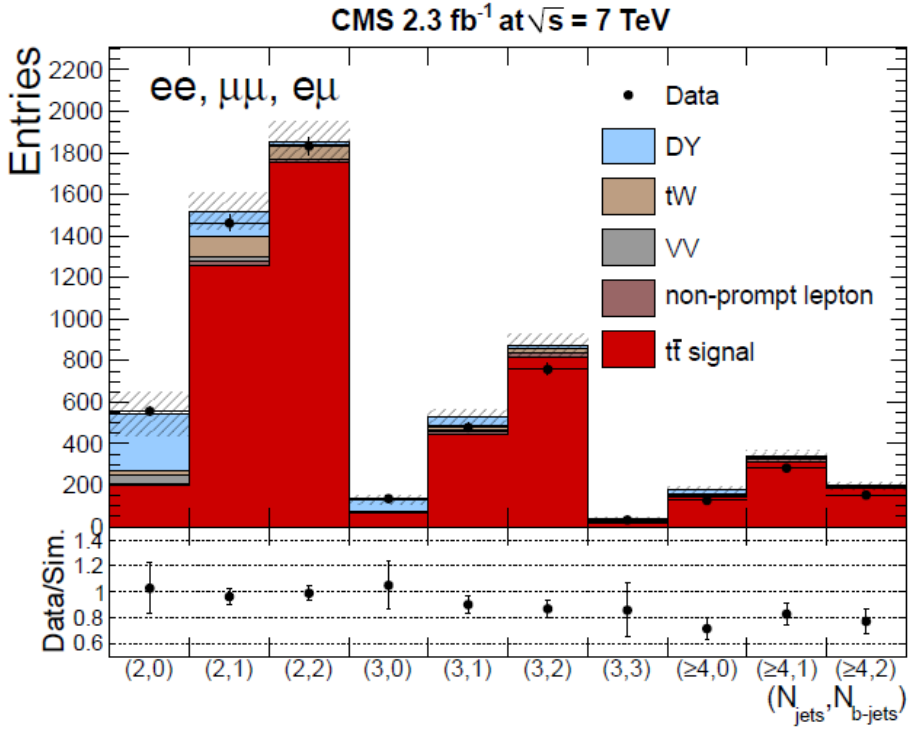
- Use soft muon tagger (>90% eff.) inside jet to identify b-jets since BR(b->μX)~20%
- orthogonal b-tagging systematics



$$\sigma_{t\bar{t}} = 165 \pm 2(\text{stat.}) \pm 17(\text{syst.}) \pm 3(\text{lumi.})\ \text{pb}$$

(11%)

CMS dilepton, 2.3/fb, arXiv:1208.2671



- Profile likelihood method in N(jets,b-tags) that incorporates systematics via nuisance parameters

$$\sigma_{t\bar{t}} = 161.9 \pm 2.5\,(\text{stat.})\,^{+5.1}_{-5.0}\,(\text{syst.}) \pm 3.6\,(\text{lumi.})\ \text{pb}$$

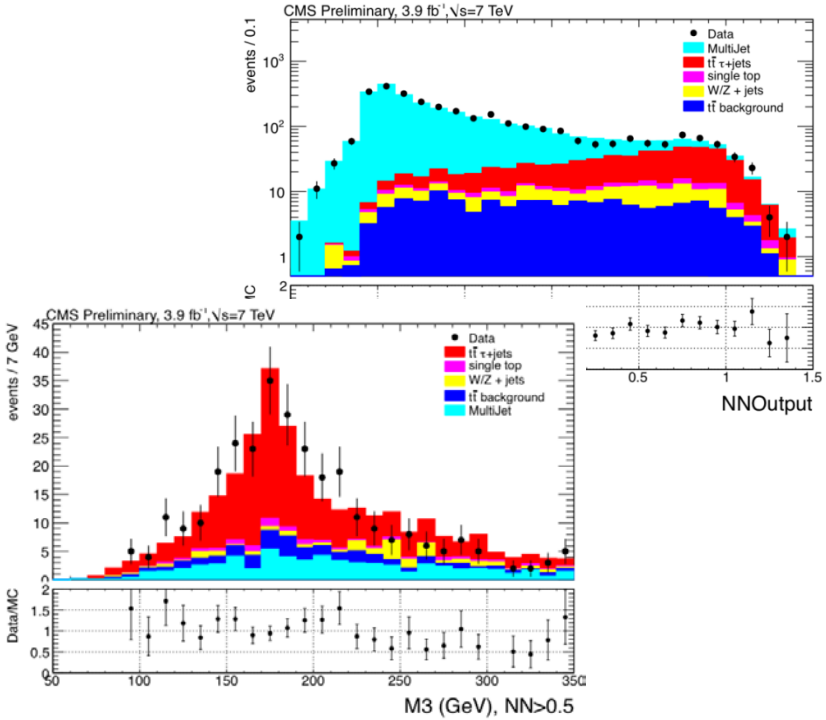
(5%)

Single most presicse σ(tt) measurement!

τ+jets and hadronic channels

τ+jets channel:

CMS, 3.9/fb, CMS-PAS-TOP-11-004



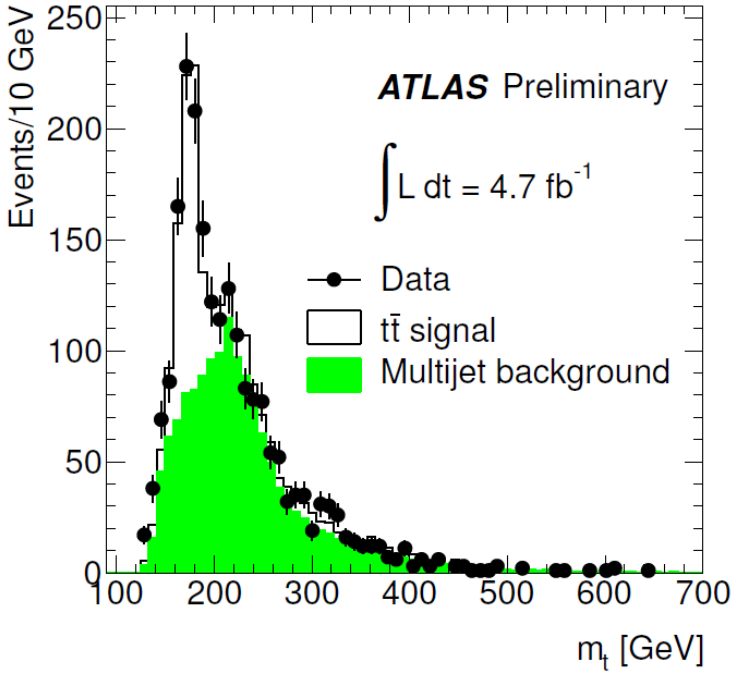
$$\sigma_{t\bar{t}} = 156 \pm 12\,(\text{stat.}) \pm 33\,(\text{sys.}) \pm 3\,(\text{lumi})\,\text{pb}$$

ATLAS,1.7/fb, ATLAS-CONF-2012-032

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

Hadronic channel:

ATLAS, 4.7/fb, ATLAS-CONF-2012-031



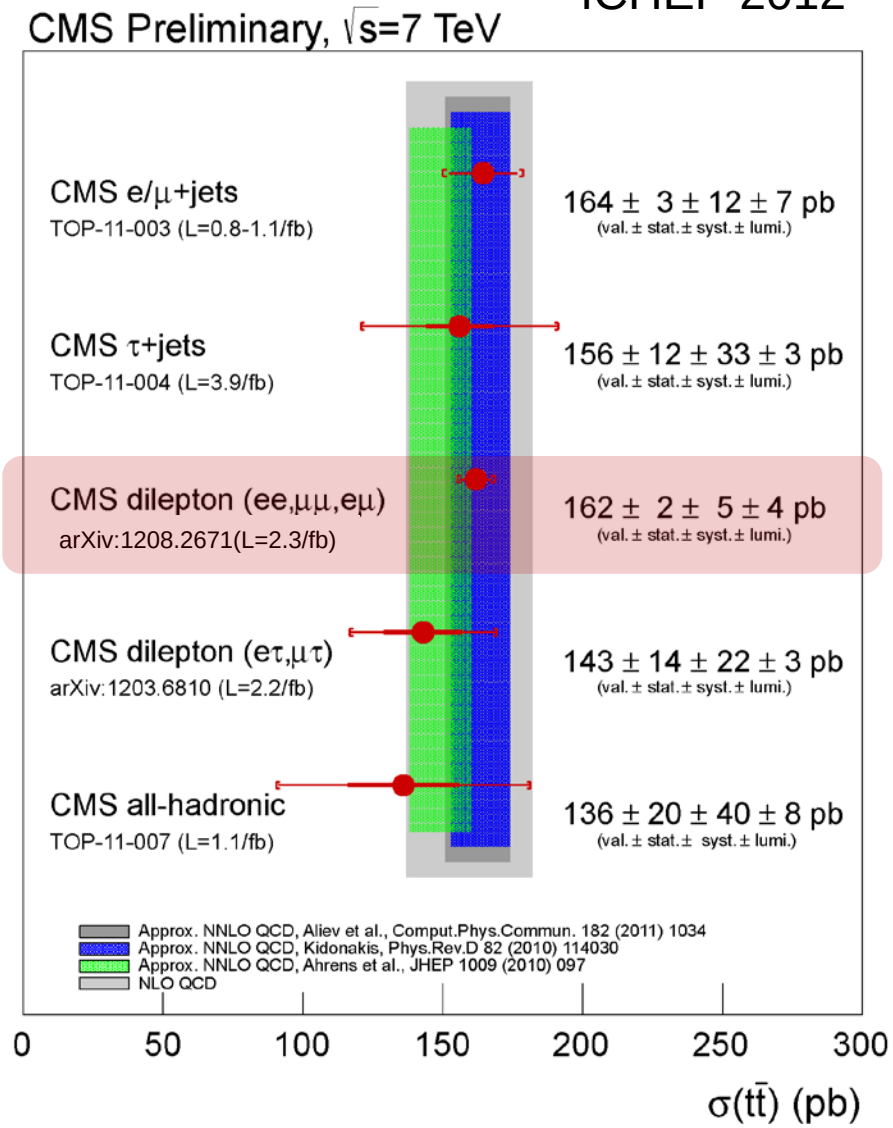
$$\sigma_{t\bar{t}} = 168 \pm 12(\text{stat.})^{+60}_{-57}(\text{syst.}) \pm 6(\text{lum.})\,\text{pb}$$

CMS, 1.1/fb, CMS-PAS-TOP-11-007

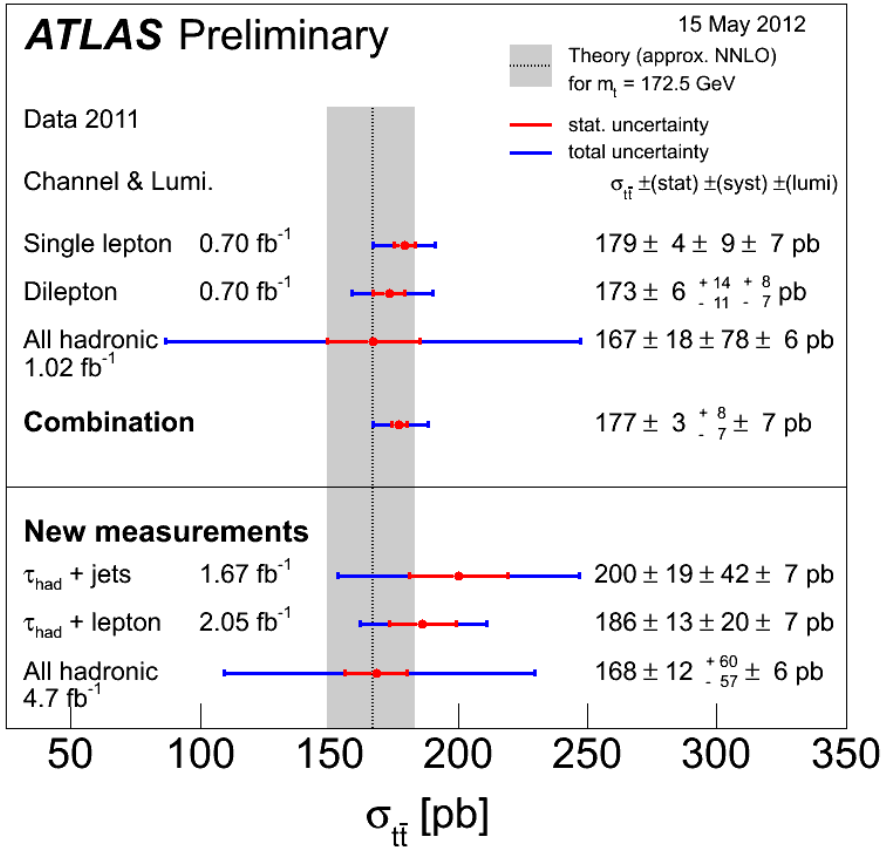
$$\sigma_{t\bar{t}} = 136 \pm 20\,(\text{stat.}) \pm 40\,(\text{sys.}) \pm 8\,(\text{lumi.})\,\text{pb}$$

Overview of 7 TeV measurements

ICHEP 2012



May 2012

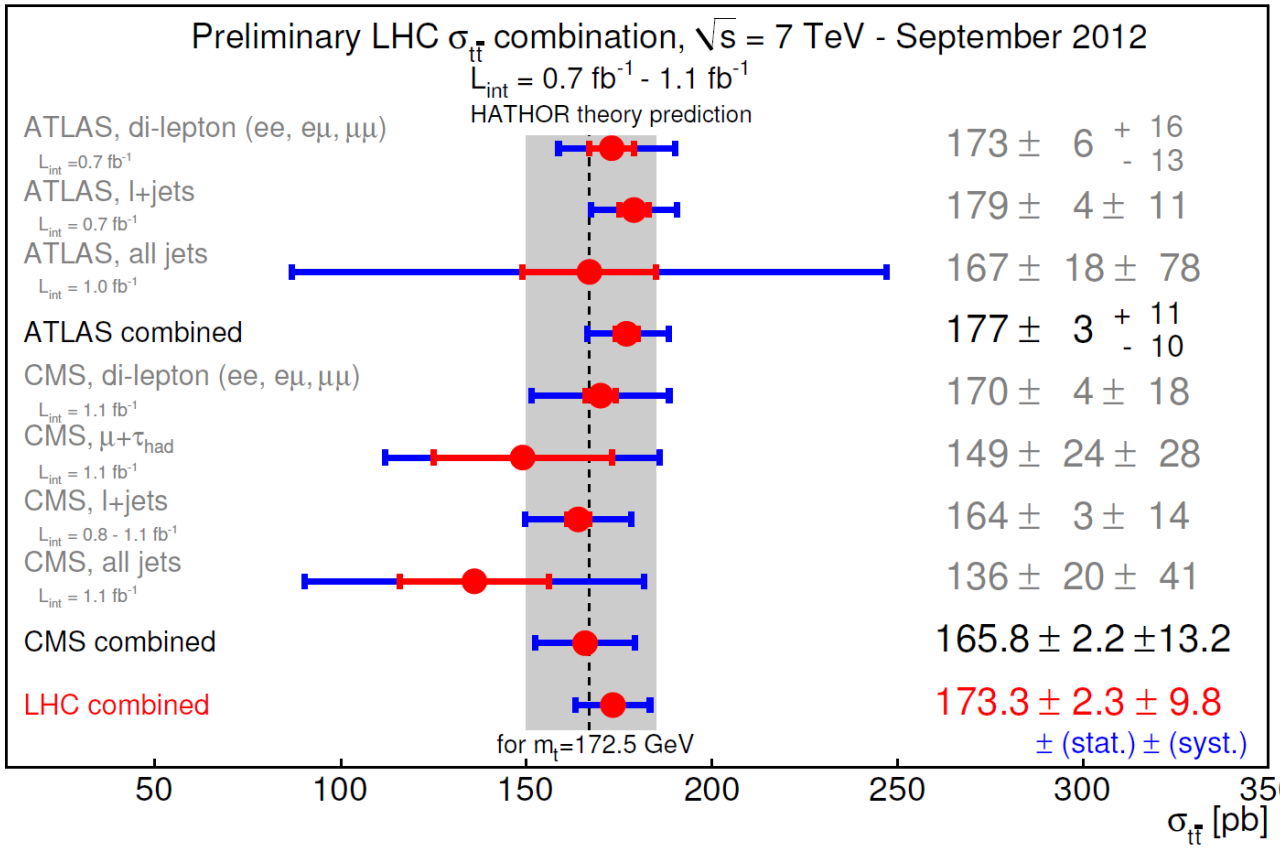


[does not include new l+jets measurement with soft muon b-tag]

LHC Combination

ATLAS-CONF-2012-134
CMS-PAS-TOP-12-003

- NEW September 2012
- Use individual ATLAS, CMS combinations as input
- Use BLUE method
- Weights: ATLAS 67%, CMS 33%
- Uncertainty 5.8%

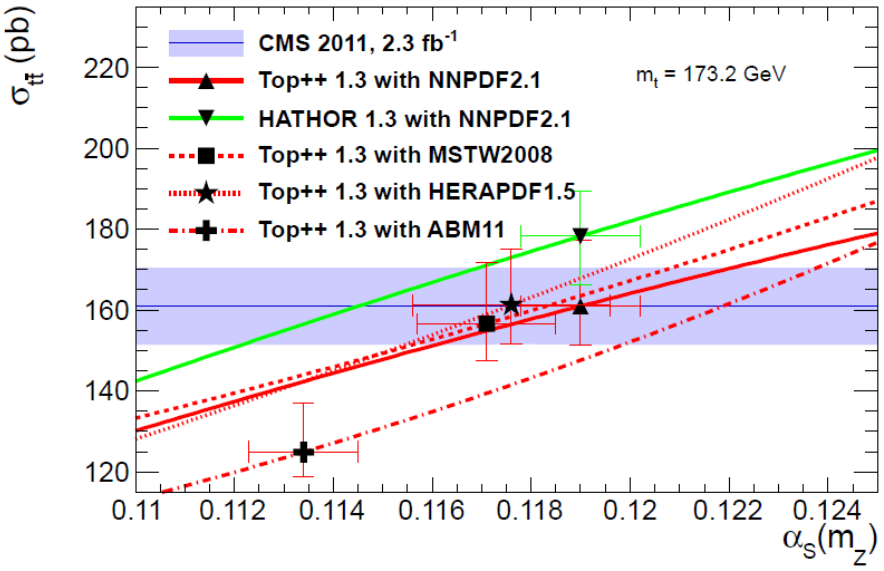


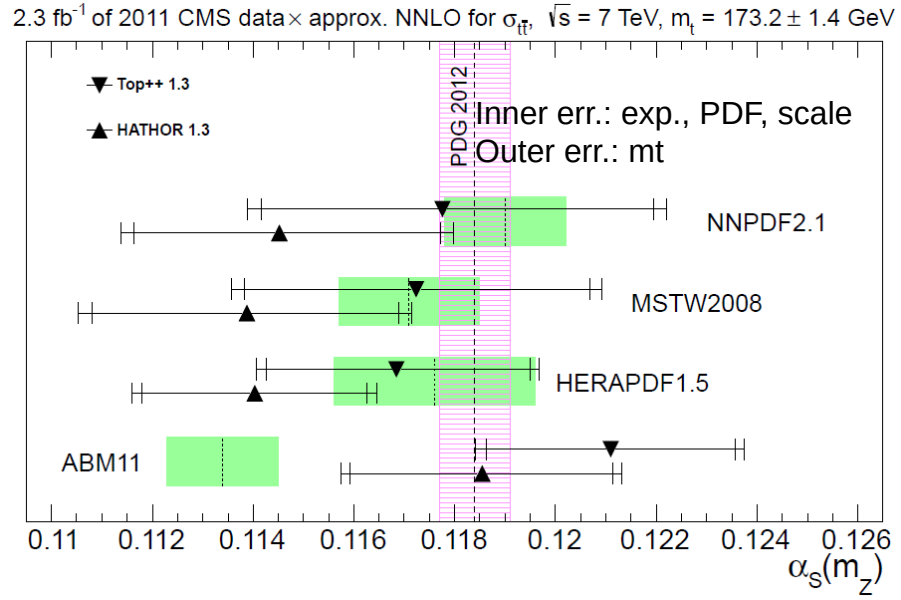
Not using latest measurements based on full dataset, e.g. CMS dilepton …

First determination of α_s from tt cross section

CMS PAS TOP-12-022

- Exploit theory relation $\sigma_{tt}(m_t,\alpha_s)$ - as in approximate NNLO (HATHOR, TOP++) for given set of PDF
- Experimental input: CMS dilepton cross section, world average m_t





- Most likely α_s per PDF set obtained by likelihood maximization
- HATHOR yielding systematically lower results due to theory approximations (larger σ_{tt})

First determination from ttbar / precision comparable with jet-based extractions

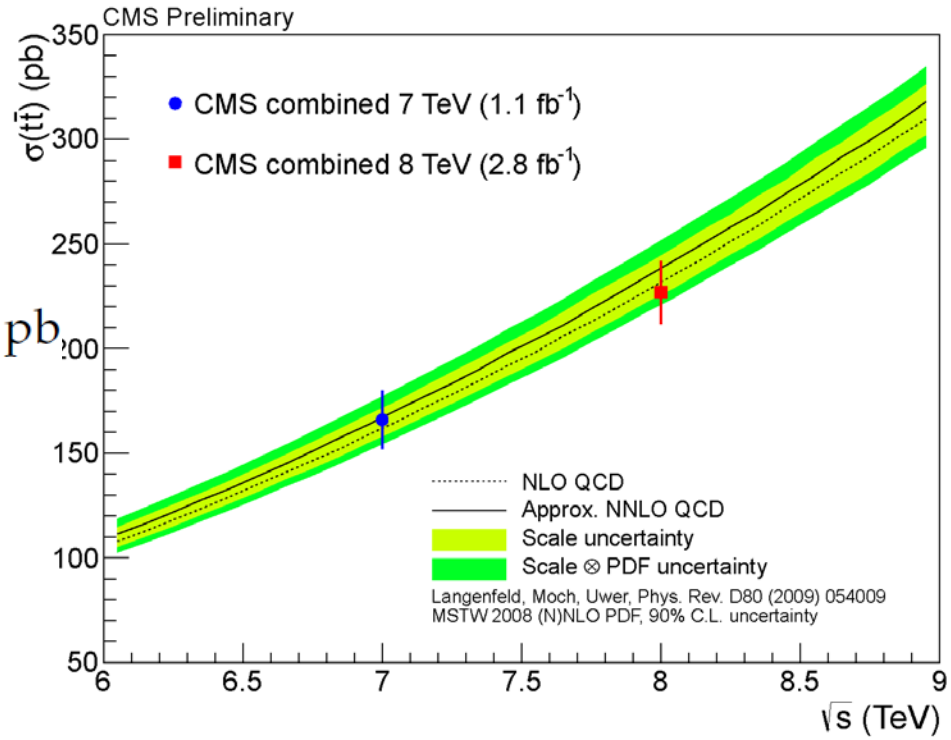
Total Cross Section at the 8 TeV LHC

Cross section at the 8 TeV LHC

CMS, 2.8/fb,
TOP-12-006 and TOP-12-007

- Combination of measurements in lepton+jets and dilepton channels

$$\sigma_{t\bar{t}} = 227 \pm 3\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 10\,(\text{lumi})\ \text{pb}$$



NEW: ATLAS l+jets, 5.8/fb,
ATLAS-CONF-2012-149

- lepton + 3 jets (one b-tagged)
- kinematical likelihood discriminant fit

$$\sigma_{t\bar{t}} = 241 \pm 2\,(\text{stat.}) \pm 31\,(\text{syst.}) \pm 9\,(\text{lumi.})\ \text{pb}$$

Theory: σ_{tt}=220 +13-11 (scale) +5-6 (PDF) pb
[TOP++1.4, Czakon & Mitov, arXiv:1210.6832]

Plan: (double) ratios e.g.
tt/Z(8) / tt/Z(7)
sensitive to new physics

Differential Cross Sections

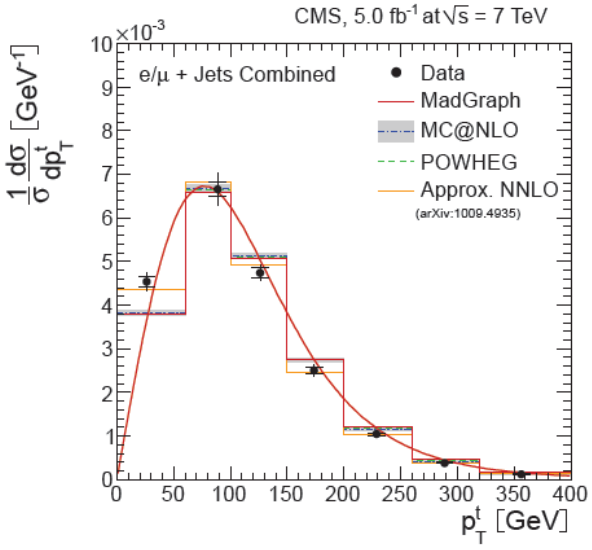
Motivation:

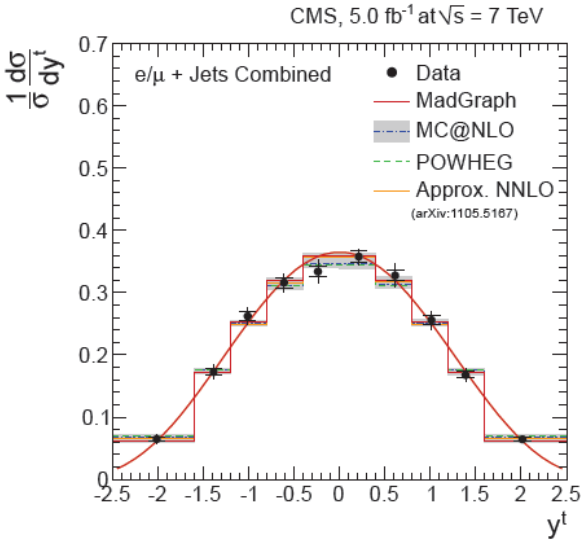
- Profit from huge sample of tt events at LHC
- Validation of MC models
- Reduction of systematic uncertainties due to tt modeling
- Important for searches/measurements where top is large background (e.g. Higgs, SUSY)

Techniques:

- Unfolded cross sections for comparisons with theory and across experiments
- Quote results at hadron or parton level, within visible phase space or extrapolated to full phase space

Top quark p_T,y and MET

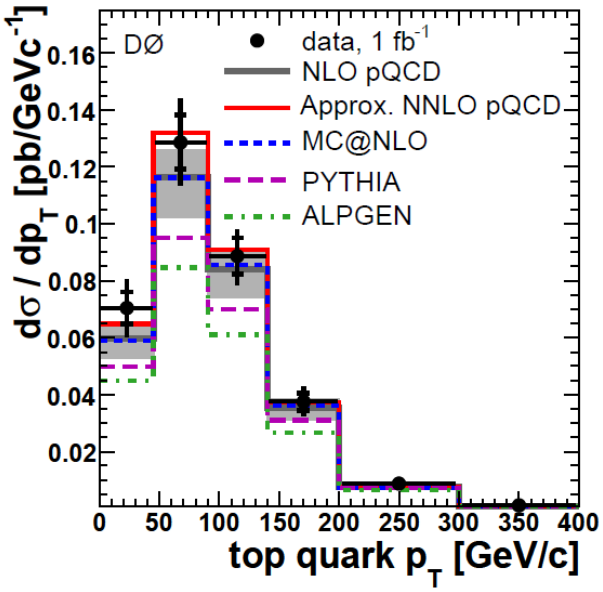




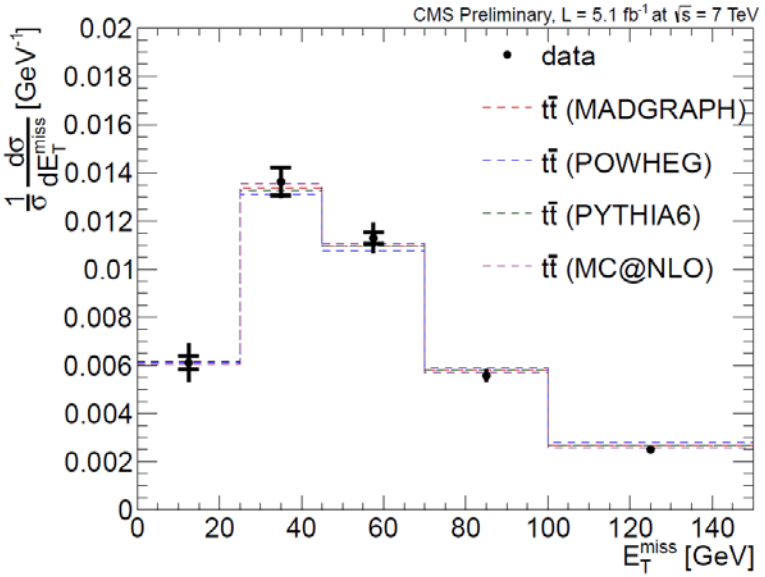
NEW: CMS l+jets, 5.0/fb
arXiv1211.2220

CMS l+jets, 5.1/fb,
PAS-TOP-12-019

Approx. NNLO:
Improved descr.
at low Pt



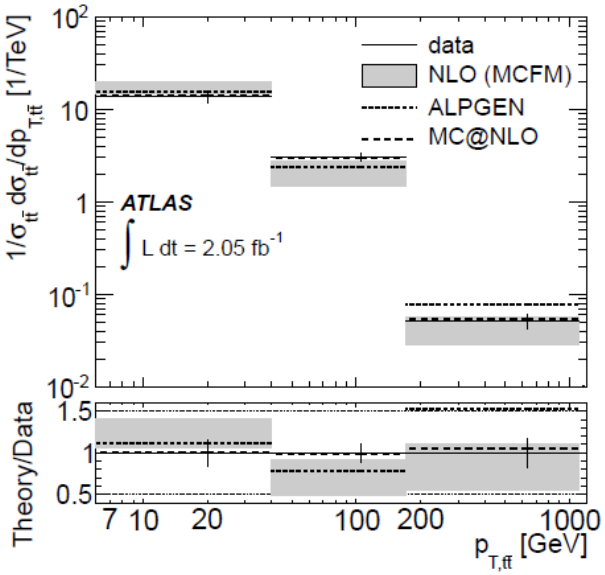
D0 l+jets, 1/fb
arXiv:1001.1900

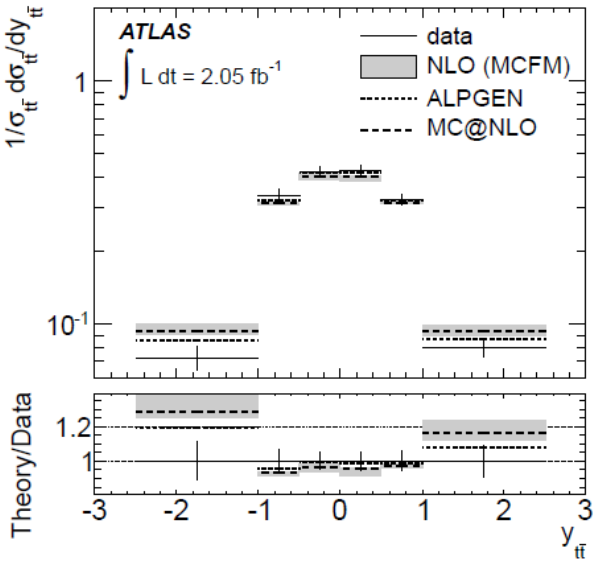


Good agreement of shapes with MC models

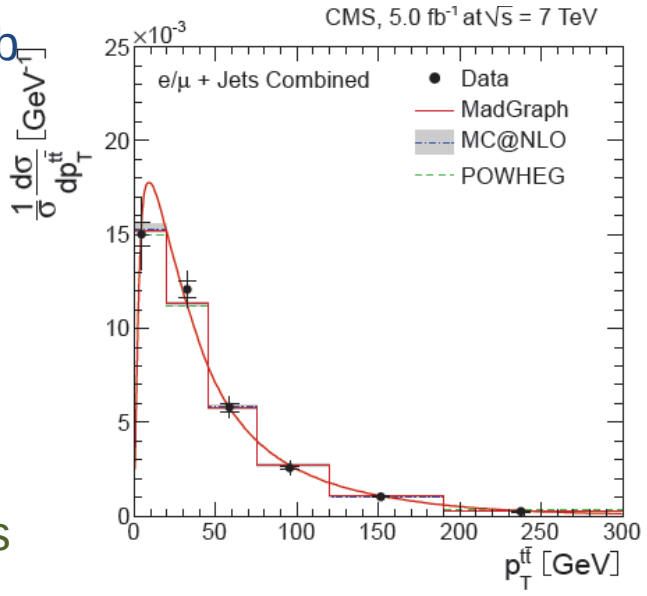
p_T,y of tt system

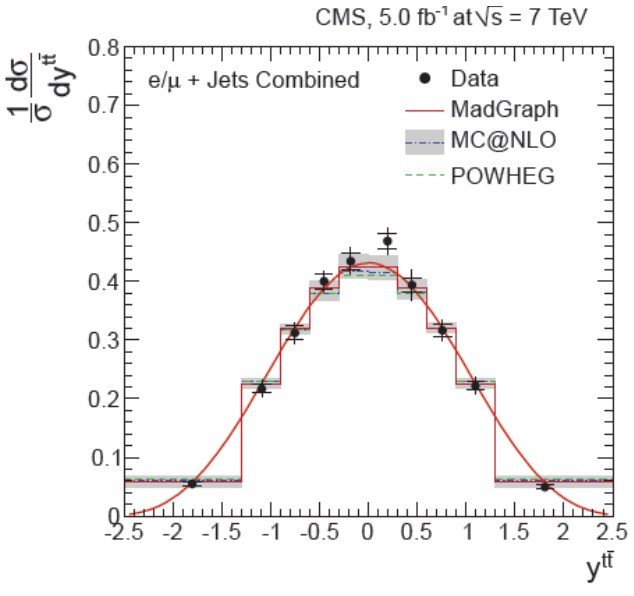
ATLAS l+jets, 2.1/fb,
arXiv:1207.5644





NEW: CMS l+jets, 5.0/fb
arXiv1211.2220

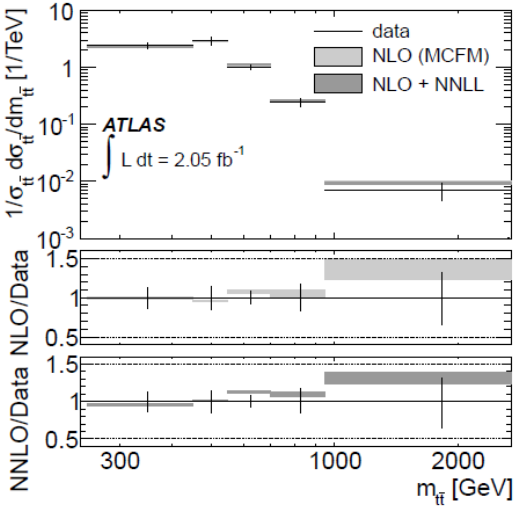


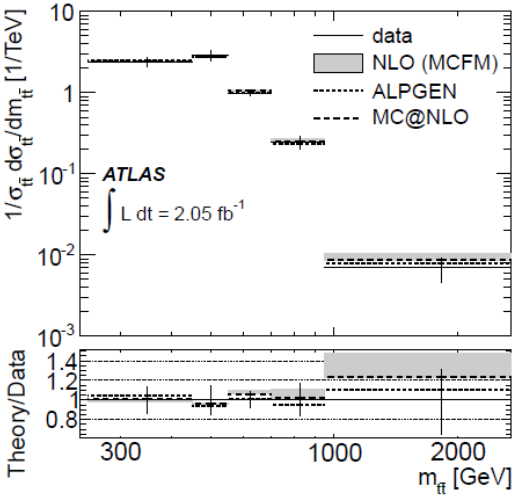


Good agreement of
shapes with MC models

tt invariant mass distribution

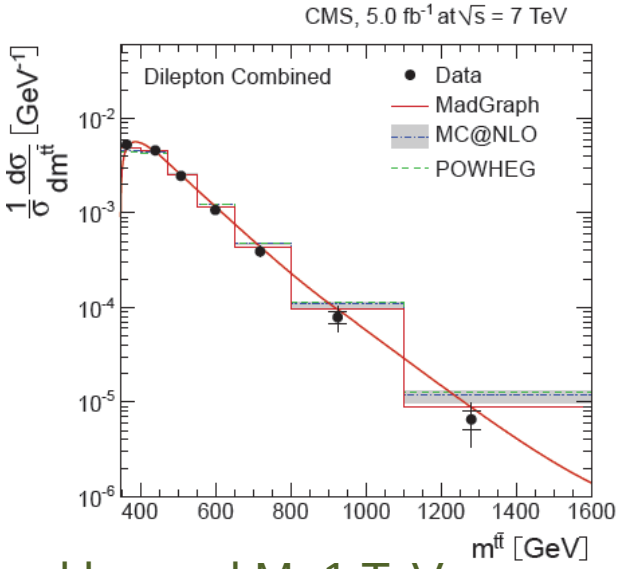
Sensitive to new physics coupling to tt, e.g. Z'->tt …



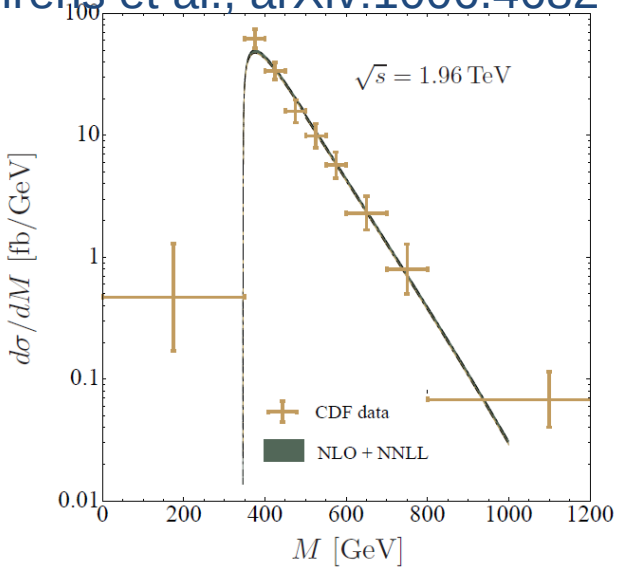


ATLAS l+jets, 2.1/fb, arXiv:1207.5644

CMS dilepton, 5.0/fb arXiv1211.2220 (NEW)



CDF, 2.7/fb, arXiv:0903.2850
Ahrens et al., arXiv:1006.4682

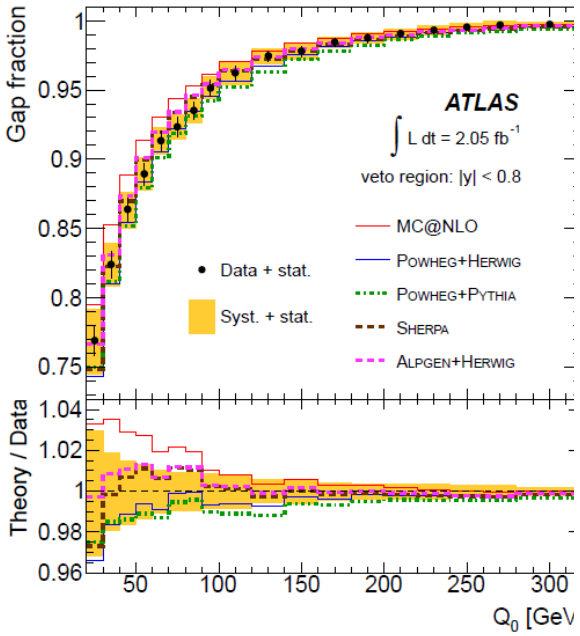


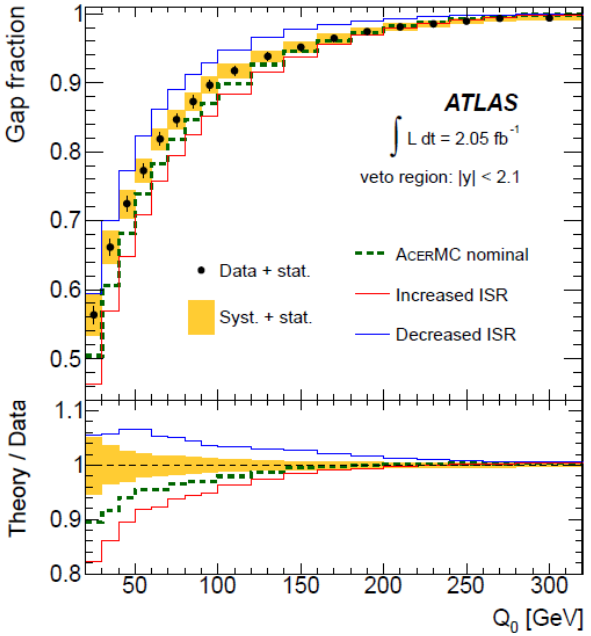
Good agreement observed beyond M=1 TeV
See talk by Bernd Stelzer for dedicated M(tt) searches

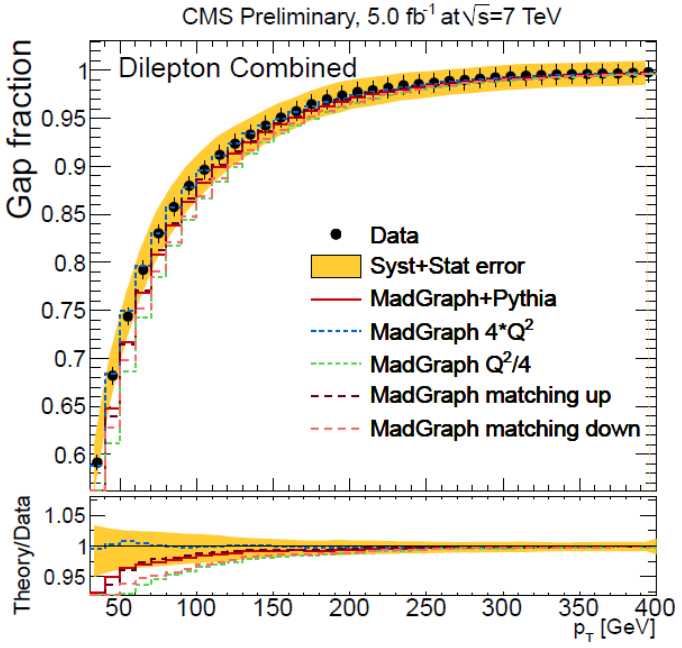
ttbar with veto on extra jets

ATLAS, 2.1/fb, arXiv:1203.5015 - CMS, 5.0/fb, CMS PAS TOP-12-023

- Corrected fraction of ttbar events with no extra jet above a given Pt cut
- Compared with ME+PS and NLO generators
- Exp. uncertainties often smaller than spread between models







Central region:
Too few jets from MC@NLO

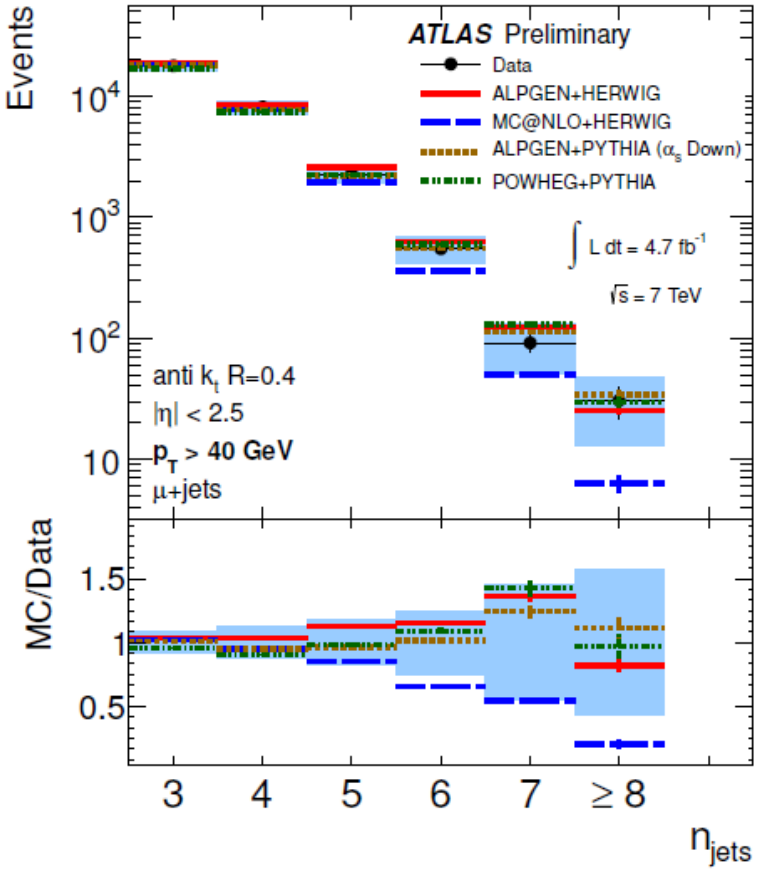
- Constrain parameters of QCD radiation model (ISR/FSR, Q2, matching threshold)
- Reduction of systematic uncertainties

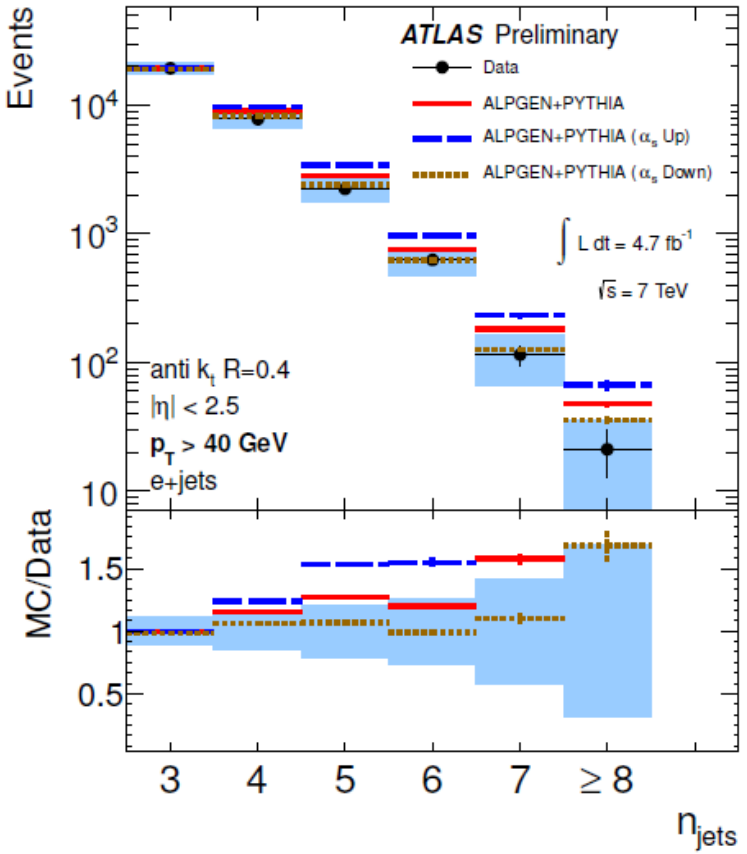
ttbar in association with (b-)jets

tt+jets

NEW: ATLAS l+jets, 4.7/fb, ATLAS-CONF-2012-155

Contributions from tt+1,2,… additional jets enhanced for N(jets)>4 (l+jets)



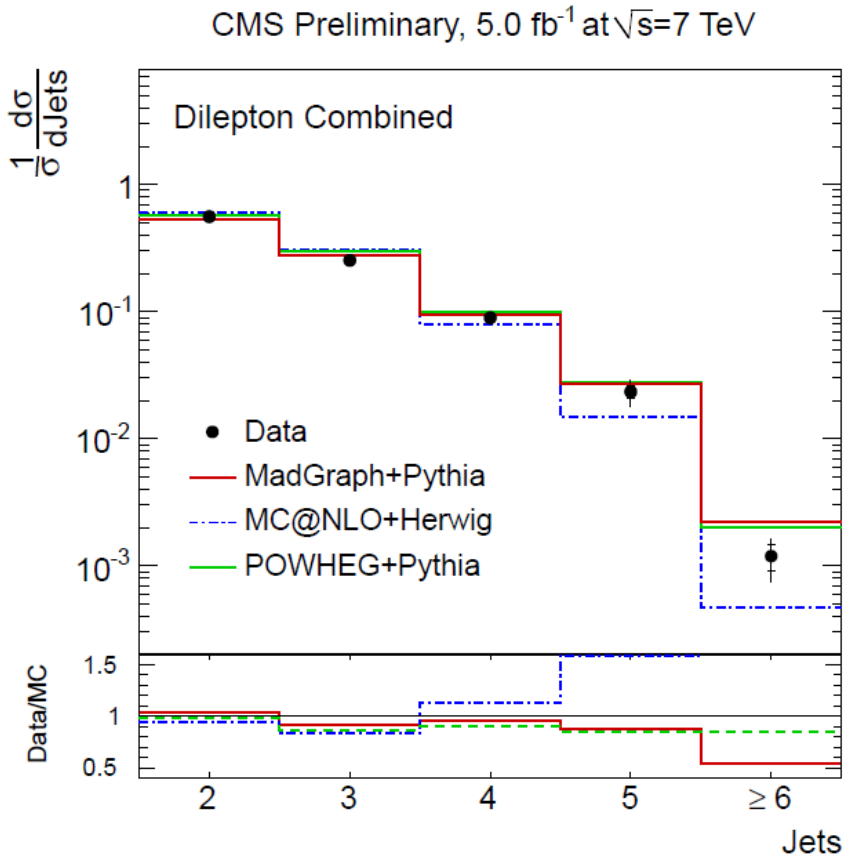


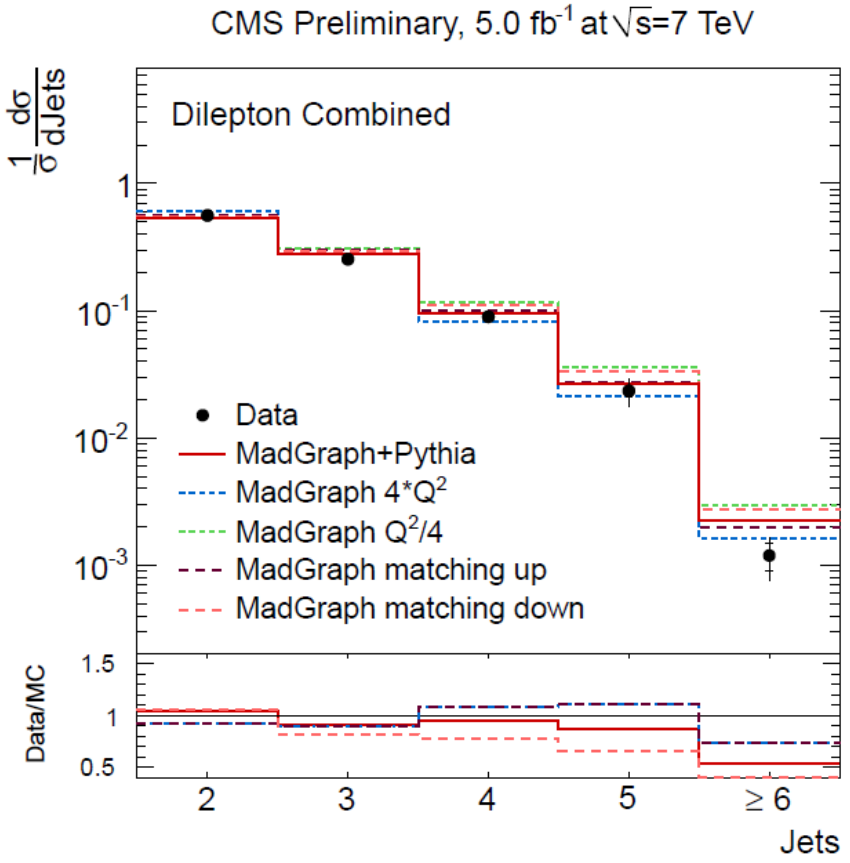
MC@NLO underestimates large N(jets)
[known: PS over-emphasized w.r.t. ME for tt+j]
POWHEG in better agreement with data

Lower alpha-s value in ME favored for ALPGEN +PYTHIA

tt+jets (cont.)

CMS dileptons, 5/fb, CMS-PAS-TOP-12-023



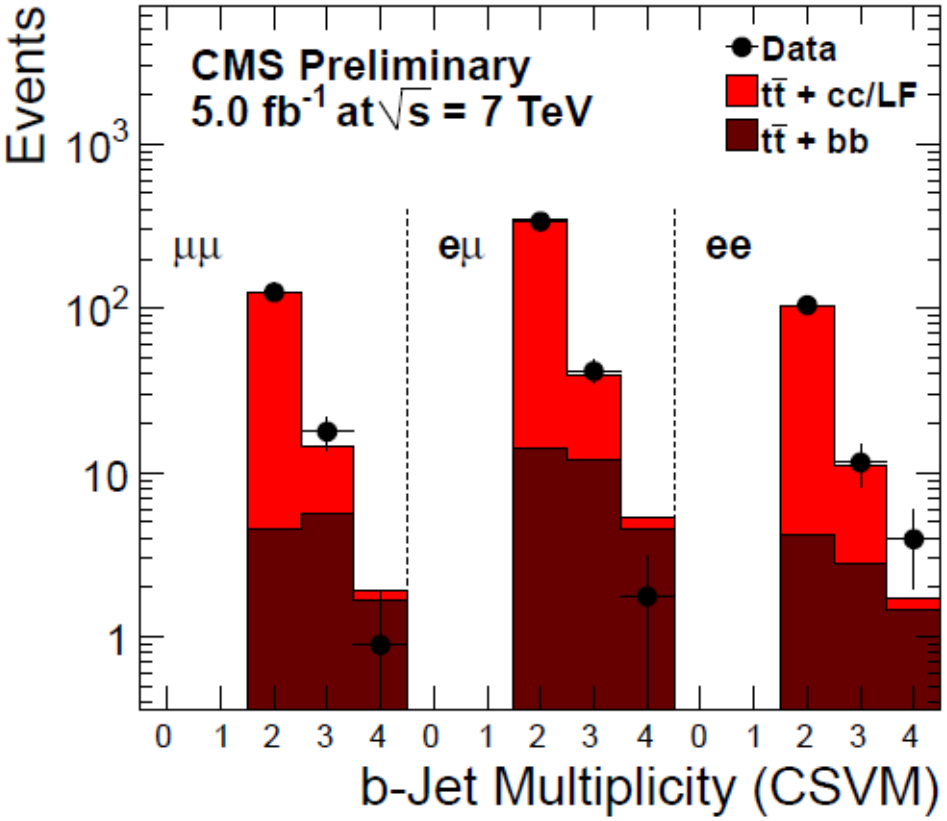


- Observe differences in models with respect to add'l. parton radiation
- Constrain parameter ranges (Q2, ISR/FSR)
- Aim at comparison with NLO calculations

First measurement of σ(ttbb)/σ(ttjj)

ttjj and ttbb are important backgrounds for ttH(bb) …

CMS dileptons, 5/fb, CMS-PAS-TOP-12-024



- b-jet multiplicity in dilepton events with >=4 jets
- Cross section ratio at particle level in visible phase space

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 3.6 \pm 1.1(\text{stat.}) \pm 0.9(\text{syst.})\%$$

- Madgraph 1.2%
- Powheg 1.3%

Aim at comparisons
with NLO QCD calculations

tt+V

tt+ γ/W/Z

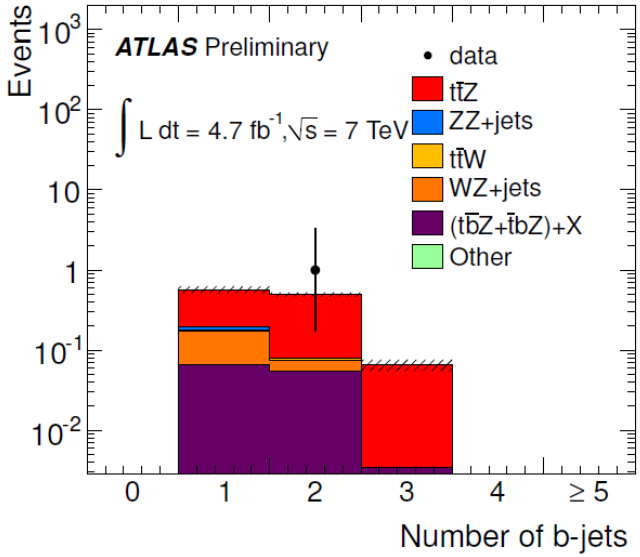
Goal: measure couplings to bosons

[tt+gamma (ATLAS-CONF-2011-153)]

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

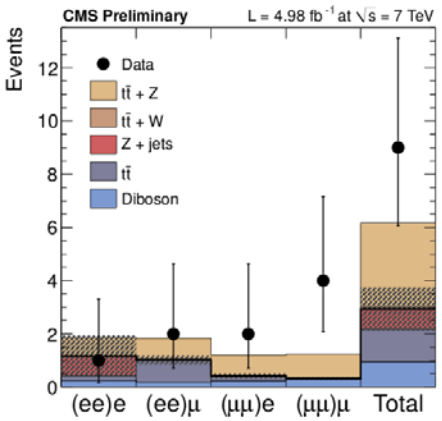
($p_{T,\gamma}$>8 GeV) consistent with NLO

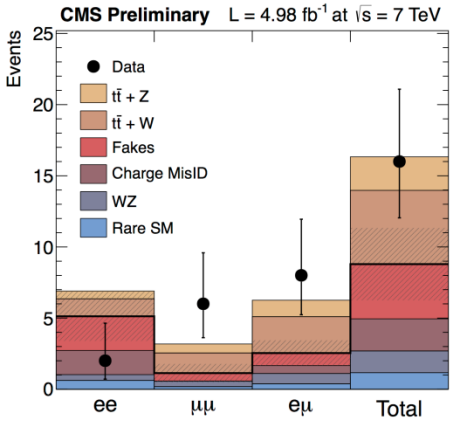
[ATLAS ttZ search, 4.7/fb, ATLAS-CONF-2012-126]



Upper limit σ(ttZ)<0.71 pb @95%CL
Consistent with SM σ=0.14 pb

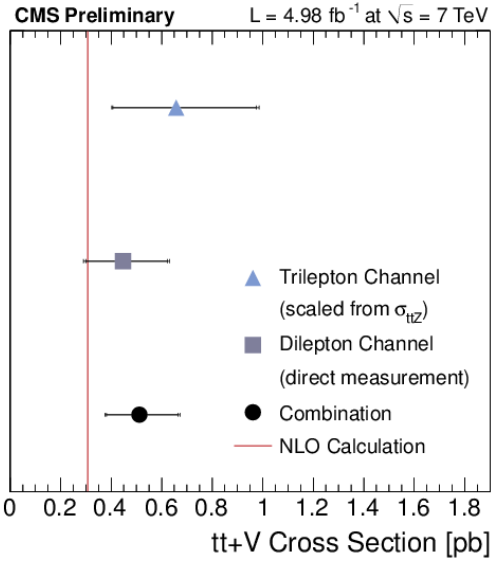
[CMS tt+W/Z, 5.0/fb, CMS PAS-TOP-12-014]





Trileptons

Dileptons



4.7σ evidence for ttV

consistent with NLO QCD

Conclusions

- The era of precision top quark physics, started at the TEVATRON, is continuing at LHC
  - 5% precision on total cross section (CMS dilepton), competing with theory uncertainty
  - First round of differential cross section measurements
  - Measurements of tt+X, where X=(b-)jets, γ, W, Z
- Next: Even more precise total and differential cross sections
  - Validate MC models (and variations), compare with (N)NLO
  - Constraints on m_t, xg(x,Q2) and α_s
- Beyond precision QCD:
  - Understanding ISR in gg->ttbar important also for gg->H
  - tt+jj, tt+bb major backgrounds for ttH
  - Constrain backgrounds in Higgs/SUSY searches/measurements