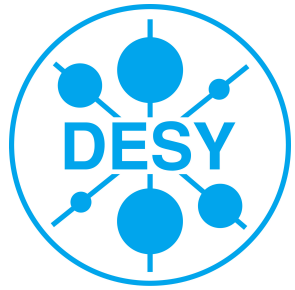


Top Quark Production at CMS

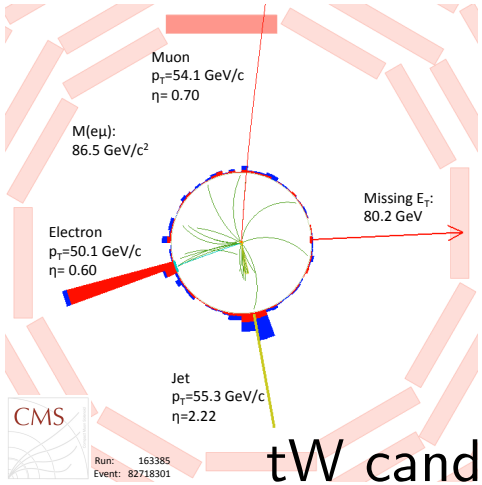
Carmen Diez Pardos
for the CMS collaboration

DESY

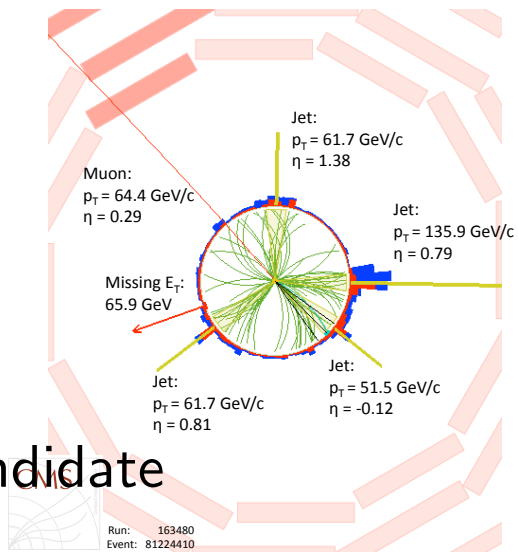
LaThuile 2014: XXVIIIth Rencontres de Physique de la Vallee d'Aoste,
23 Feb-1 Mar 2014
La Thuile (Italy)

Outline

1. Introduction
2. $t\bar{t}$ production
   - $t\bar{t}$+jets
   - $t\bar{t}$+MET
   - $t\bar{t}$+$b\bar{b}$
   - $t\bar{t}$ in association with bosons
3. $t\bar{t}t\bar{t}$ production
4. Single Top
   - t-channel
   - tW-channel
   - s-channel
5. Summary and outlook



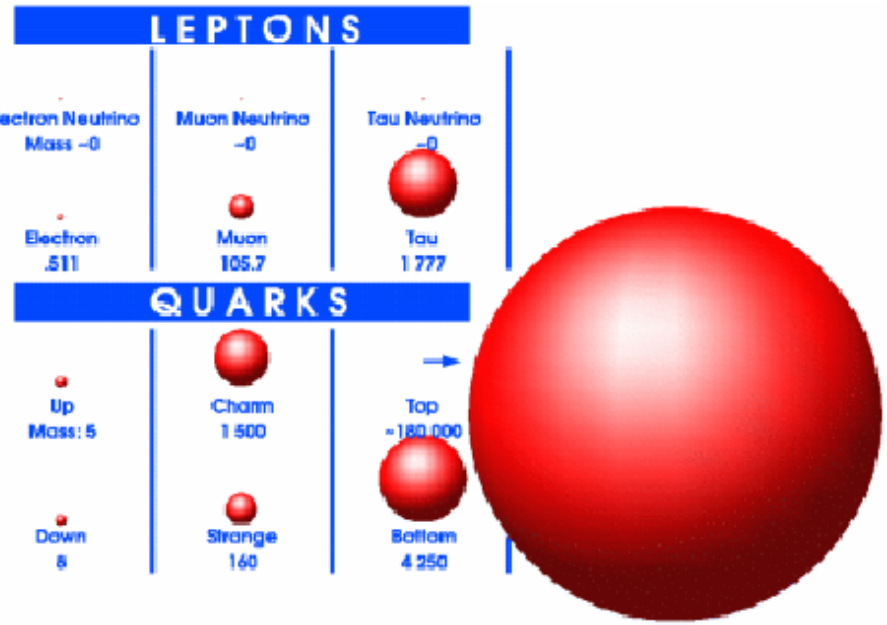
tW candidate

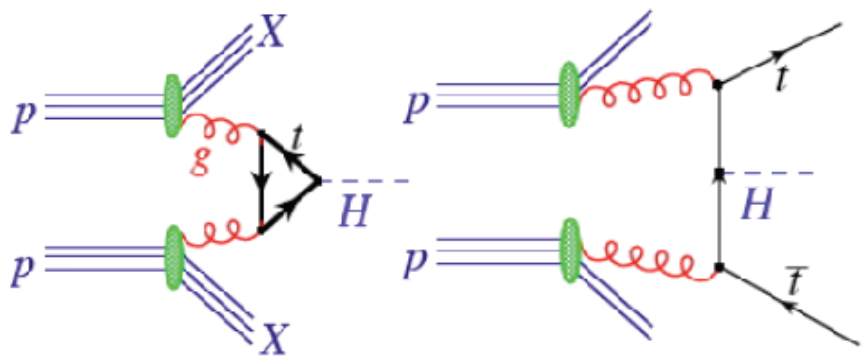


$t\bar{t}$ candidate

The top quark: a unique particle

- Most massive elementary particle known to date. Special role in many theories beyond the Standard Model.
- Short-lived, decays before hadronizing. Possible to study the properties of a bare quark.
- Precision tests of perturbative QCD.
- Main background in many BSM searches.
- Essential to study Higgs properties, measure top Yukawa coupling

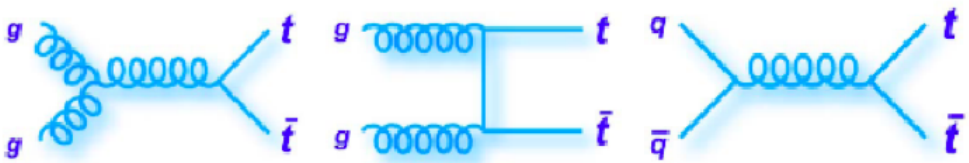




This talk focuses on the latest results available on Top Quark Production (mostly 8 TeV)

Top quark production

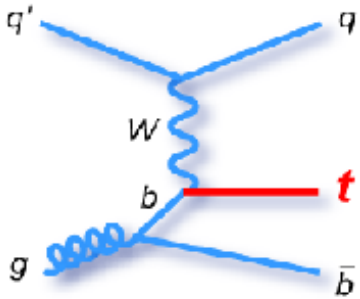
$t\bar{t}$ production mainly by gluon fusion at LHC (∼80% at 7-8 TeV)



- Full NNLO+NNLL calculation available [Czakon, Fiedler, Mitov, arXiv:1303.6254]

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$^{+0.110(1.5\%)}_{-0.200(2.8\%)}$	$^{+0.169(2.4\%)}_{-0.122(1.7\%)}$
LHC 7 TeV	172.0	$^{+4.4(2.6\%)}_{-5.8(3.4\%)}$	$^{+4.7(2.7\%)}_{-4.8(2.8\%)}$
LHC 8 TeV	245.8	$^{+6.2(2.5\%)}_{-8.4(3.4\%)}$	$^{+6.2(2.5\%)}_{-6.4(2.6\%)}$
LHC 14 TeV	953.6	$^{+22.7(2.4\%)}_{-33.9(3.6\%)}$	$^{+16.2(1.7\%)}_{-17.8(1.9\%)}$

t production via EWK interaction

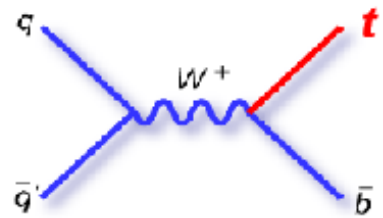


t-channel

$\sigma = 64.57^{+2.63}_{-1.74}$ pb @ 7 TeV

$\sigma = 87.76^{+3.44}_{-1.91}$ pb @ 8 TeV

Phys. Rev. D 83, 091503(R) (2011)

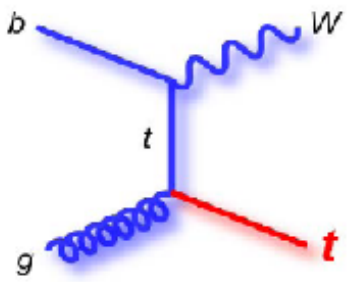


s-channel

$\sigma = 4.63^{+0.20}_{-0.18}$ pb @ 7 TeV

$\sigma = 5.61 \pm 0.22$ pb @ 8 TeV

Phys. Rev. D 81, 054028 (2010)

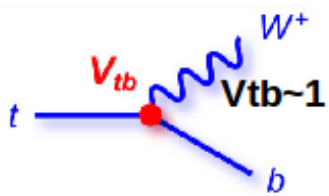


tW-channel

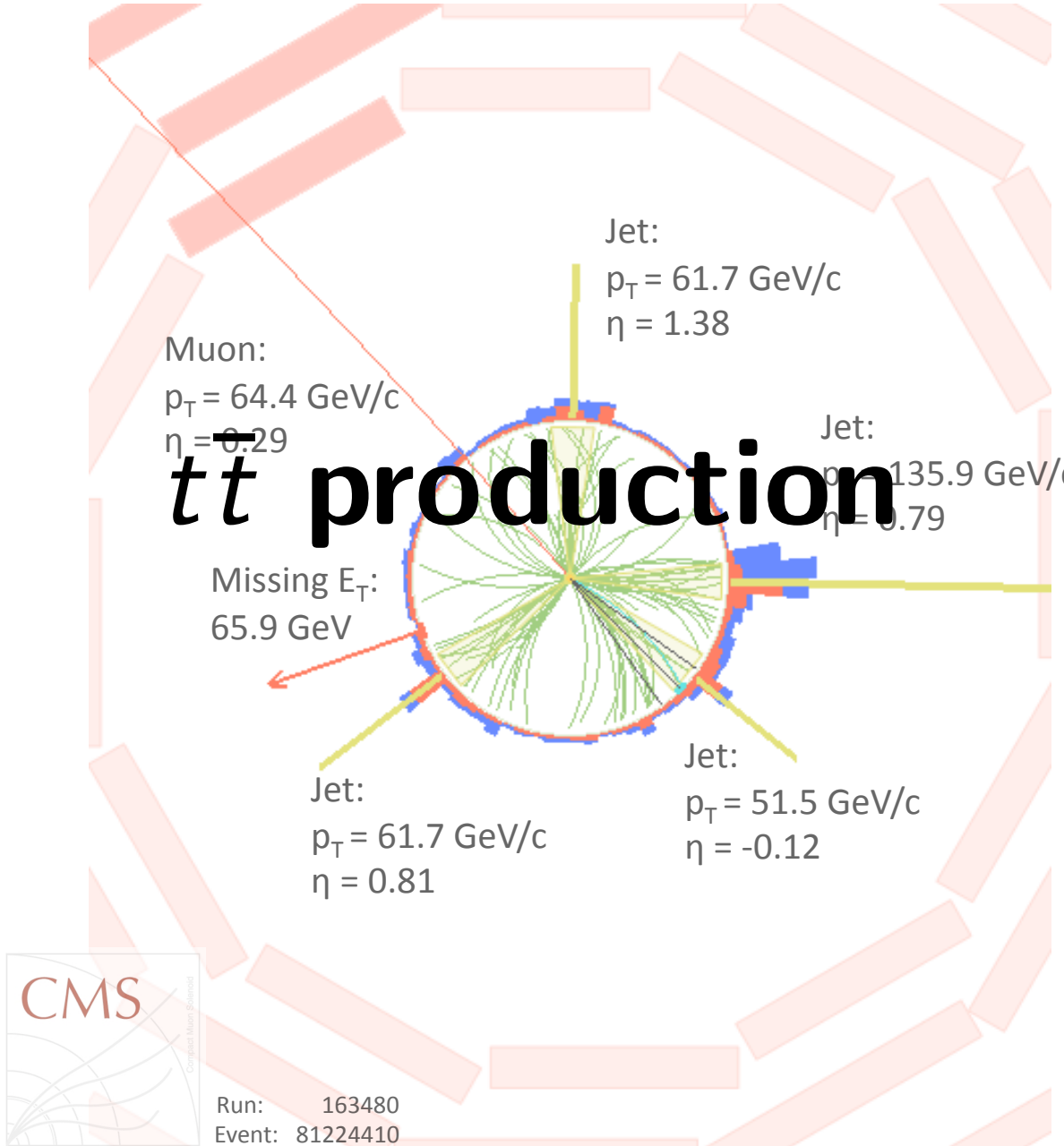
$\sigma = 15.74^{+1.17}_{-1.21}$ pb @ 7 TeV

$\sigma = 22.37 \pm 1.52$ pb @ 8 TeV

Phys. Rev. D 82, 054018 (2010)



Cross section calculated at NLO+NNLL



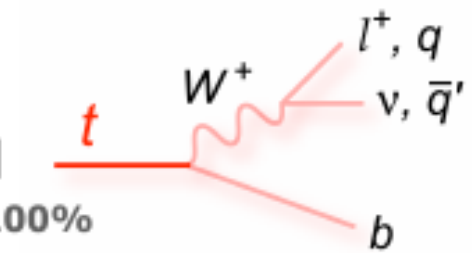
$t\bar{t}$ production

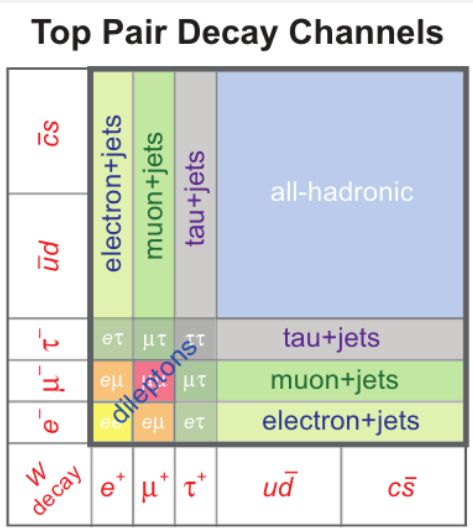
Top quark decay signatures

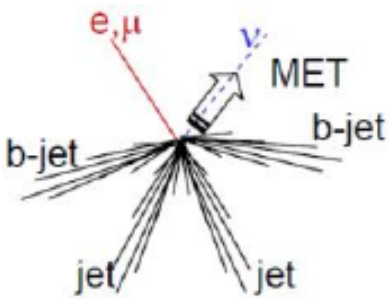
W decay defines final state

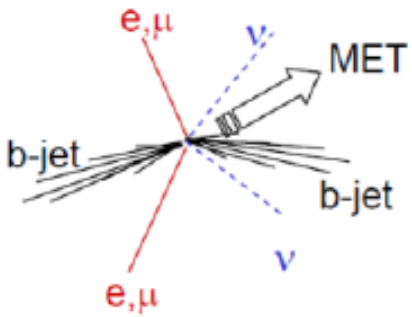
$|Vtb| \gg |Vtd|, |Vts|$

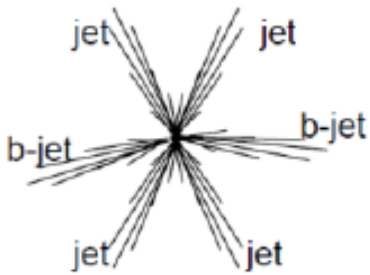
- $t \to Wb$ almost 100%

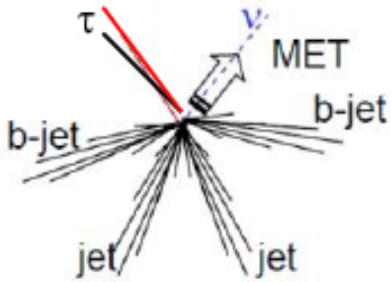












Semileptonic [e/μ]: BR$\sim$30% and manageable BG (ie. W+jets)

Dileptonic [e/μ]: BR$\sim$5% and small BG (ie. DY+jets)

All-jets: BR$\sim$46% but largest BG (ie. QCD multijet)

τ+jets: BR$\sim$15%

single-top is BG for $t\bar{t}$ (and vice-versa)

Top quarks

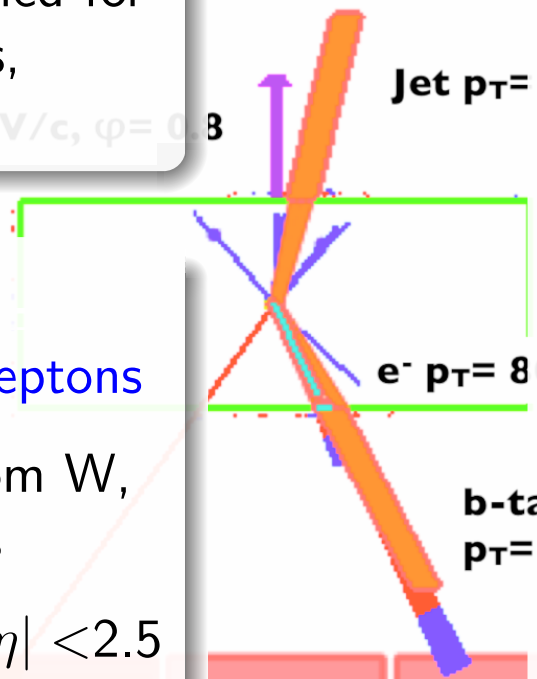
MET

- Typical cut range 20-40 GeV, not applied for all analysis (lep+jets, dilepton)

Leptons

- Up to two high p_T leptons
- Isolated, high p_T from W, soft leptons in b-jets

  With p_T >20 GeV $|\eta|$ <2.5
- Trigger largely based on leptons (Single/double (isolated) lepton)



Jets

- Two to six high p_T jets (up to 2 b-tags, might use τ-tagging)
- Jets defined with anti-kT algorithm with cone ΔR=0.5
- p_T >20-30 GeV $|\eta|$ <2.5
- Trigger on l+jets signatures

b-tagging

- Uses secondary vertices and/or IP information
- Efficiencies and fake rates are calibrated by using data

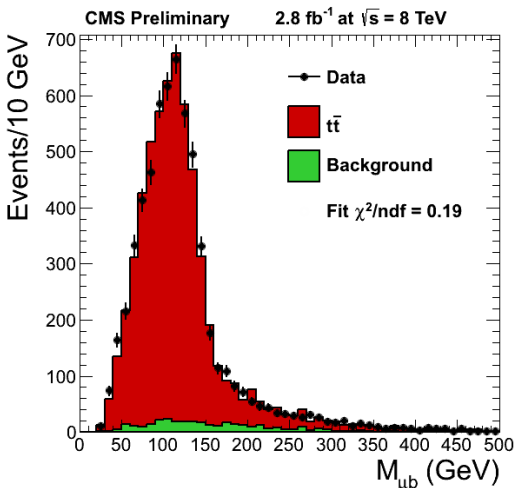
$t\bar{t}$ inclusive cross section (8 TeV)

CMS-PAS-TOP-12-006 (l+jets), JHEP 02 (2014) 024 (dilepton)

l+jets

- 1 isolated high-p_T μ/e, $\geq$4 jets, $\geq$1 b-tagged jet
- Fit to invariant mass of the lepton-bjet system, M_{lb}
- QCD background shape from data
- Main syst.: JES, b-tag, Q^2 & matching scales

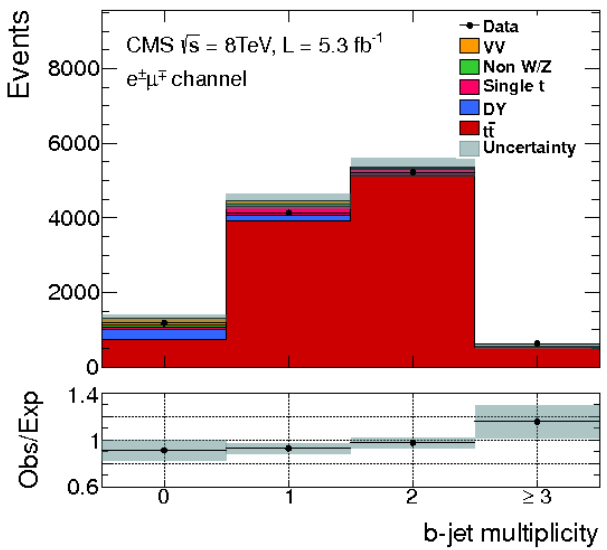
$\sigma_{t\bar{t}} = 228.4 \pm 9.0(stat)^{+29.0}_{-26.0}(syst) \pm 10.0(lum.)$ **pb**



dilepton New!

- 2 OS isolated, high-pT μ/e, $\geq$2 jets, $\geq$1 b-tagged jet
- DY and non-W/Z background estimated from data
- Main syst: JES, model uncertainties

$\sigma_{t\bar{t}} = 239 \pm 2.0(\mathrm{stat}) \pm 11(\mathrm{syst}) \pm 6.0(\mathrm{lum.})$ pb

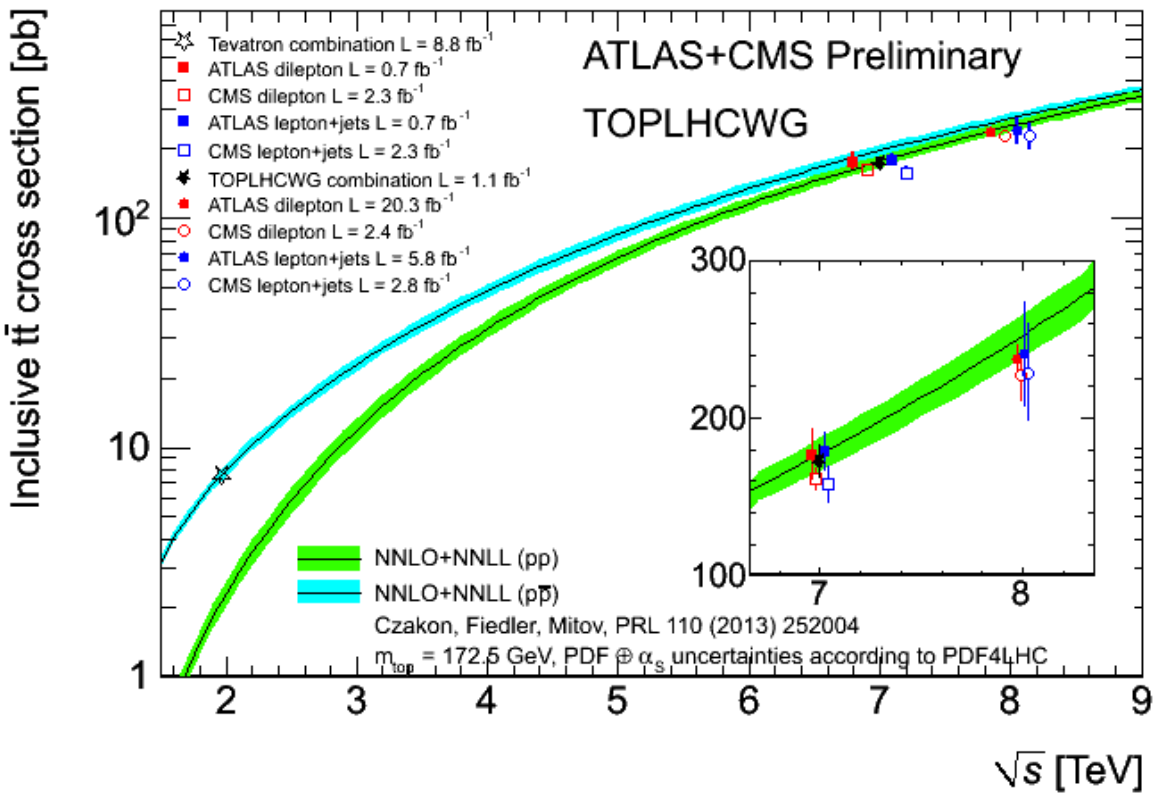


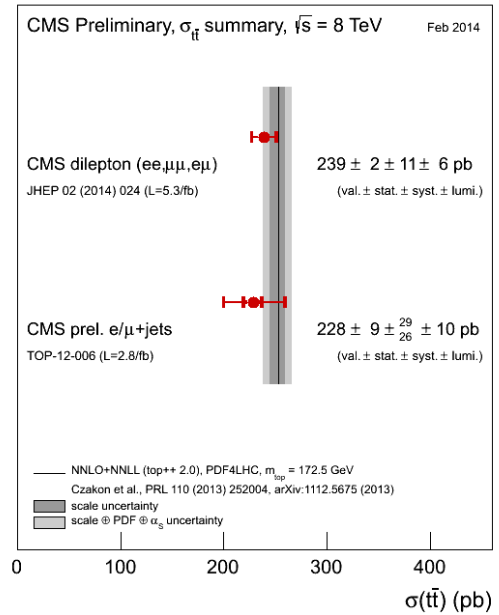
Summary of $t\bar{t}$ inclusive cross section 7 TeV and 8 TeV

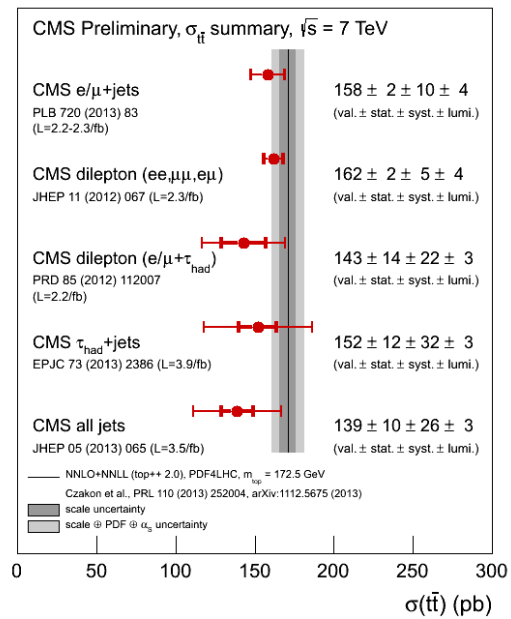
Good agreement between channels and data and predictions NNLO + NNLL.

Systematics limited

Dominated by dilepton results (precision 4-6%)

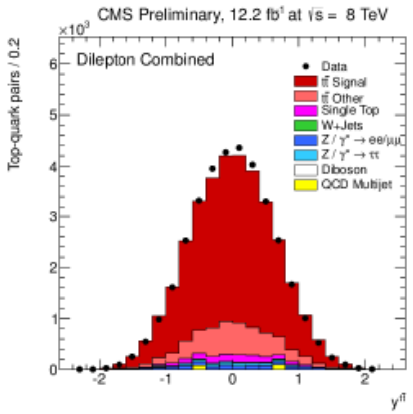




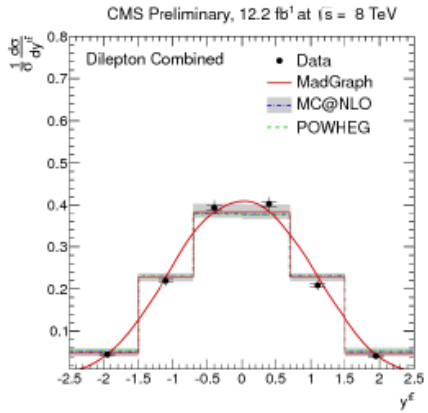


$t\bar{t}$ differential cross section

- Measure top pairs in different regions of the phase space
- $\sigma(t\bar{t})$ vs several kinematic distributions of top, top pairs, (b)-jets, leptons, lepton pairs, MET, etc.
  - Scrutinise theory predictions & models
  - Enhance sensitivity to new physics
  - Extract/use for PDF fits (future)
- Main analysis ingredients:
  - $t\bar{t}$ kinematic reconstruction
  - bin-wise cross section measurement
  - correct for detector effects & acceptance (unfolding)
  - Normalised: many systematics cancel, only shape uncertainties contribute



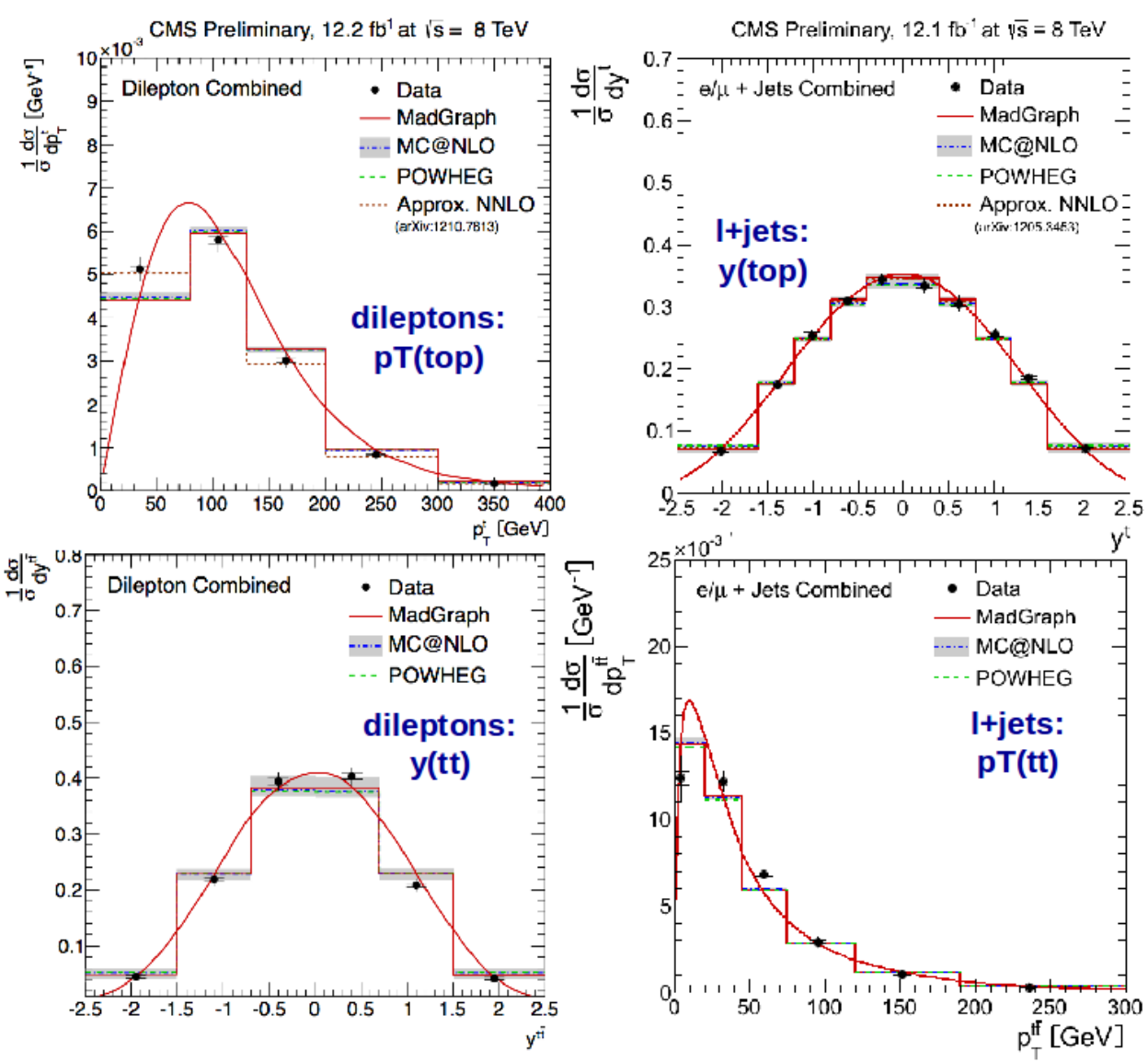
$$\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\sigma}\frac{N^i_{\mathrm{Data}} - N^i_{\mathrm{BG}}}{\Delta^i_X \epsilon^i L}$$



$t\bar{t}$ differential cross section

CMS-PAS-TOP-12-027, CMS-PAS-TOP-12-028

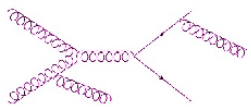
- Comparison to different Monte Carlo (MC) generators & theory calculations
- Typical precision: 5–10% per bin
- Dominant sistematics: signal modelling
- Softer p_T^t spectrum in data, better described by Approx. NNLO
- Results consistent with 7 TeV measurement (EPJ C73 (2013) 2339)



$t\bar{t}$+jets

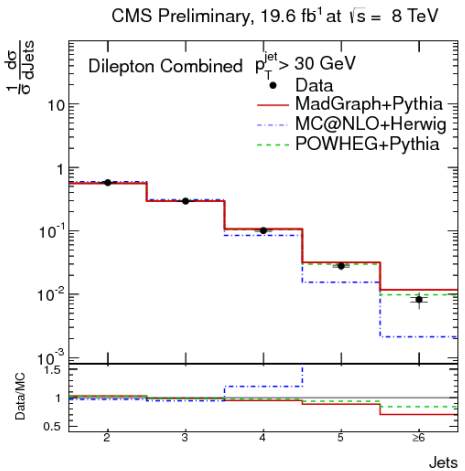
CMS-PAS-TOP-12-041 (dilepton)

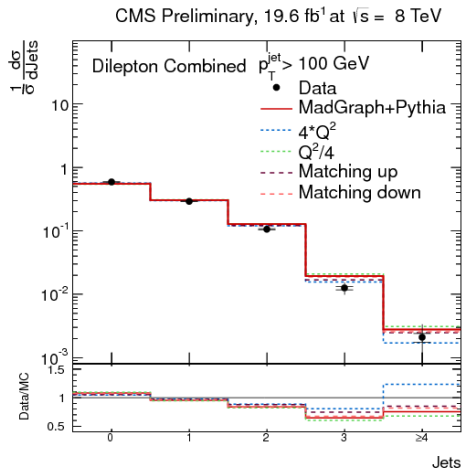
- Large fraction of $t\bar{t}$ events produced with hard jets from ISR/FSR

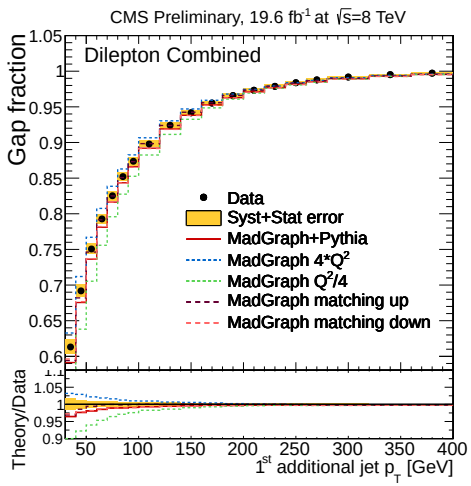


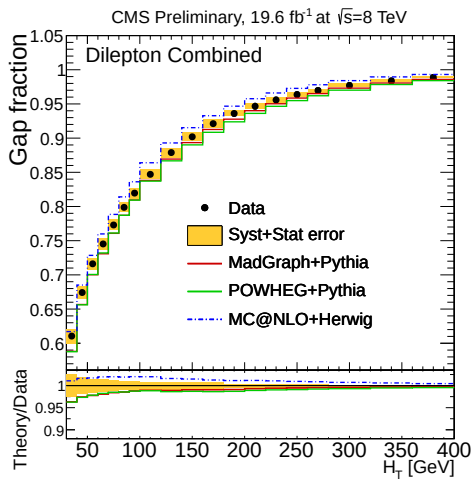
- Large uncertainty due to radiation modelling in MC: Tune MC models with measurements
- Anomalous production of $t\bar{t}$+jets could reveal new physics
- Background for $t\bar{t}$+H and many BSM searches
- Main uncertainties: JES, theory (Q^2 and matching scale, hadronisation)

  Results in agreement with the dilepton, l+jets channels at 7 TeV (TOP-12-023/018).





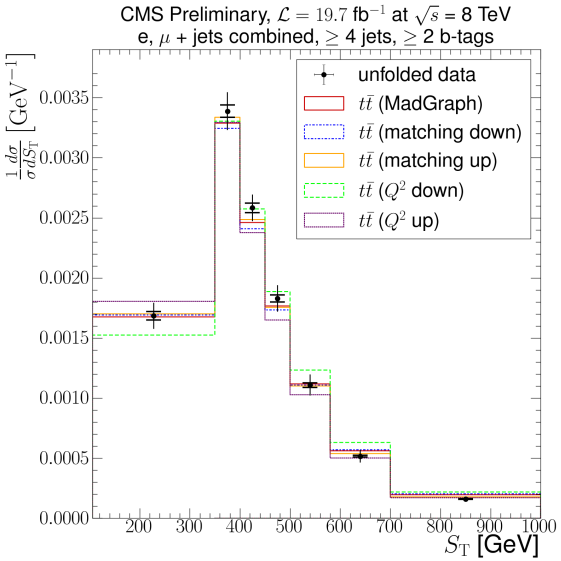


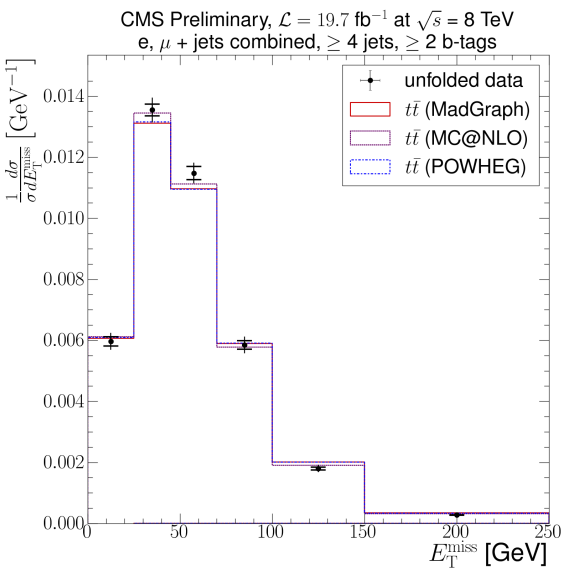


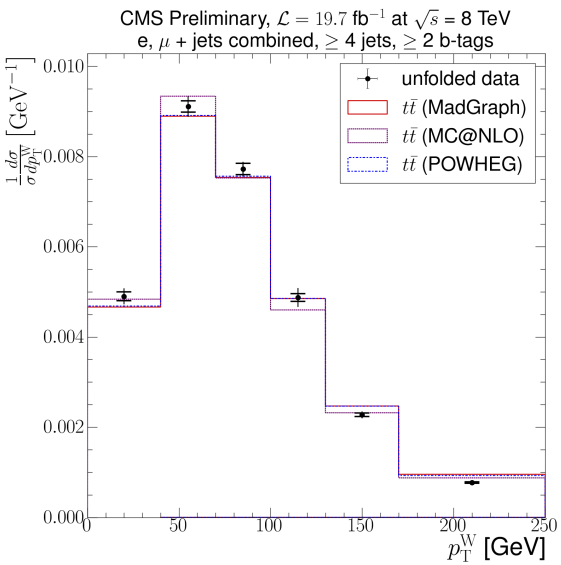
$t\bar{t}$: MET, global event observables

CMS-PAS-TOP-12-042

- l+jets decay channel, no kinematic fit
- Signal extracted from template fit to lepton angular distributions
- Main syst.: JES, modelling of W+jets
- Overall good agreement between data and predictions within uncertainties.
- Similar behaviour observed at 7 TeV (CMS-PAS-TOP-12-019)



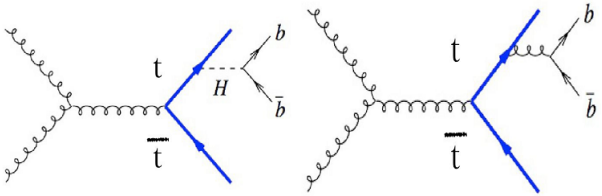




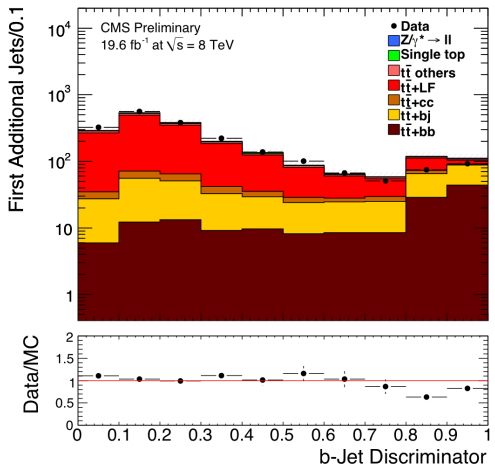
$t\bar{t}+b\bar{b}$: ratio of b- to light-flavour jets

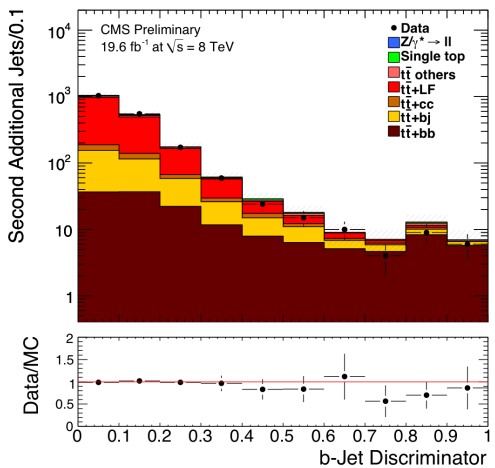
CMS-PAS-TOP-13-010

- Comparison with NLO QCD calculations
- Irreducible BG for $t\bar{t}+\mathrm{H}(b\bar{b})$



- Measure ratio $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$: large cancellation of uncertainties
  - Selection: dilepton events with $\geq$4 jets with $p_T > 20$ (40) GeV, $\geq$2 b–tagged jets
  - Signal extraction by fit to the measured b-tagging algorithm discriminators
  - Corrected to particle level
  - Dominant systematic: mistag efficiency





R=0.023±0.003(stat.)±0.005(sys.) for 20 GeV [MadGraph (Powheg): 0.016 (0.017)]
R=0.022±0.004(stat.)±0.005(sys.) for 40 GeV [MadGraph (Powheg): 0.013 (0.014)]

$t\bar{t}$+W/Z (7 TeV)

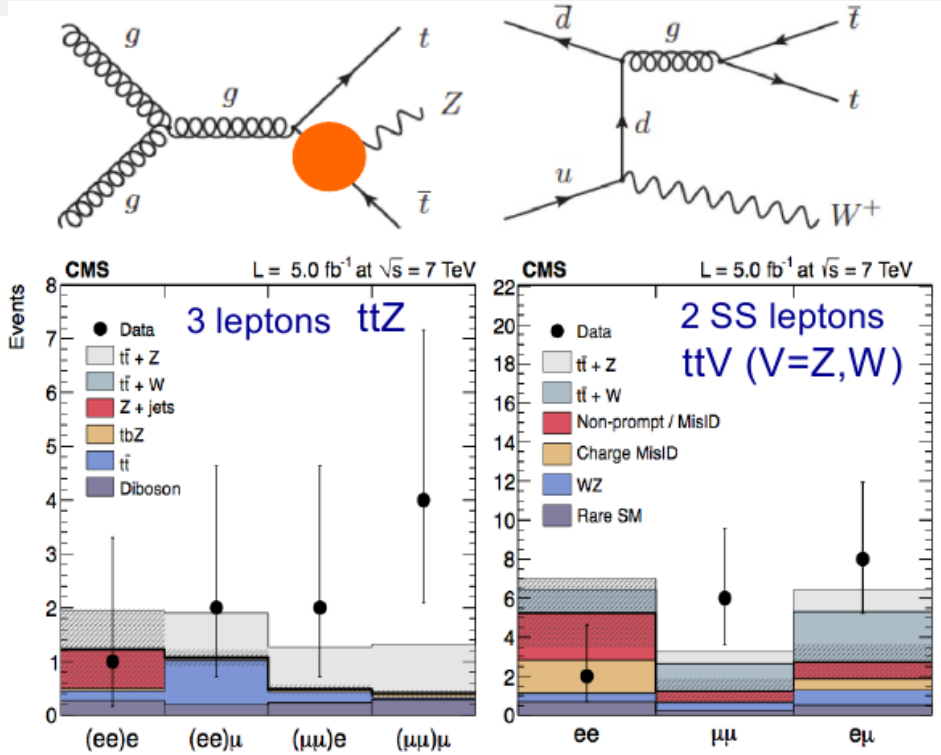
PRL 110 (2013) 172002

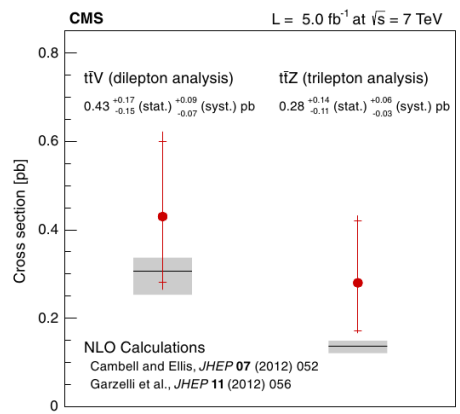
$t\bar{t}$+W/Z are rare processes in the SM

- Measure couplings to bosons
- Important bg for BSM searches
- Investigate top pair in association with extra leptons
- Two independent channels
  - Trilepton channel: exclusive search for ttZ
  - Dilepton channel (SS): inclusive search for ttZ, ttW
- Main syst.: BG estimate

$$\sigma_{t\bar{t}Z} = 0.28^{+0.14}_{-0.11}(\text{stat.})^{+0.06}_{-0.03}(\text{syst.}) \ (3.3\sigma)$$

$$\sigma_{t\bar{t}V} = 0.43^{+0.17}_{-0.15}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.}) \ (3\sigma)$$





$t\bar{t} + \gamma$

CMS PAS TOP-13-011 **New!**

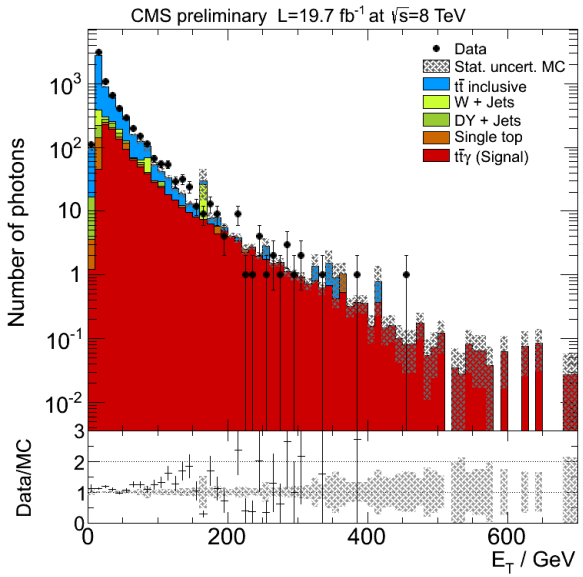
- Measurement performed in the μ+jets channel
- Selection: $E_T(\gamma) > 20$ GeV, $\Delta R(\gamma, b) > 0.1$.
- Prompt photons estimated from binned maximum likelihood fit to charged hadron isolation (E of all charged hadronic PF candidates $\Delta R < 0.4$)
- Largest systematic uncertainty is due to the modeling of the background template.

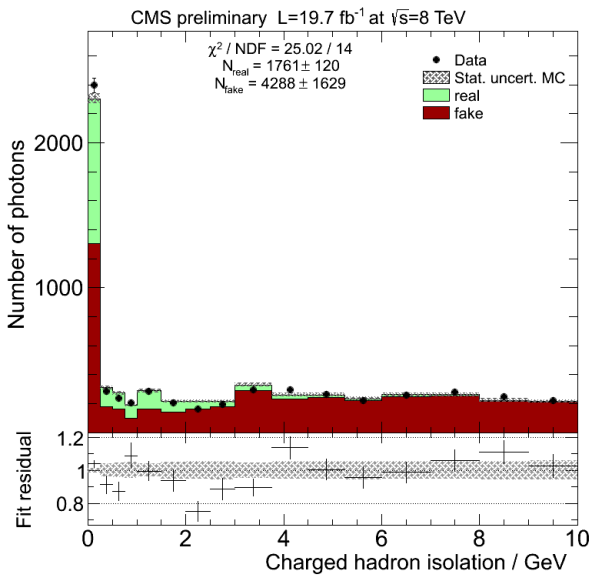
$$\sigma(t\bar{t}+\gamma)/\sigma(t\bar{t}) = (1.07 \pm 0.07(\text{stat}) \pm 0.27(\text{syst})) \cdot 10^{-2}.$$

$$\sigma(t\bar{t}+\gamma) = 2.4 \pm 0.2(\text{stat}) \pm 0.6(\text{syst}) \text{ pb.}$$

(Using $\sigma_{t\bar{t}}^{CMS} = 227 \pm 15$ pb)

- Result in agreement with SM expectation ($\sigma(t\bar{t}+\gamma) = 1.8 \pm 0.5$pb).

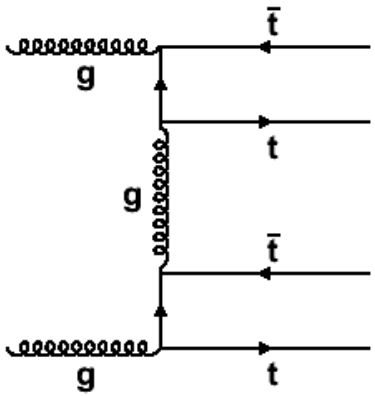




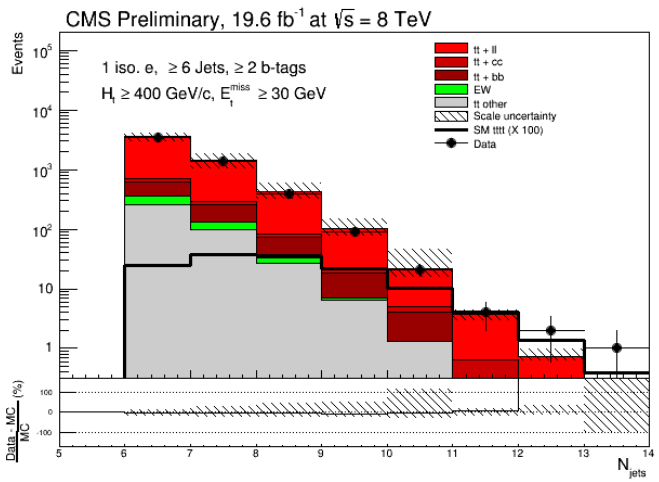
Search for standard model four top quark production

CMS-TOP-13-012 New!

Four top production is mainly produced via gluon fusion in the LHC $\sigma^{SM}_{t\bar{t}t\bar{t}} \sim 1.3$ fb@8 TeV

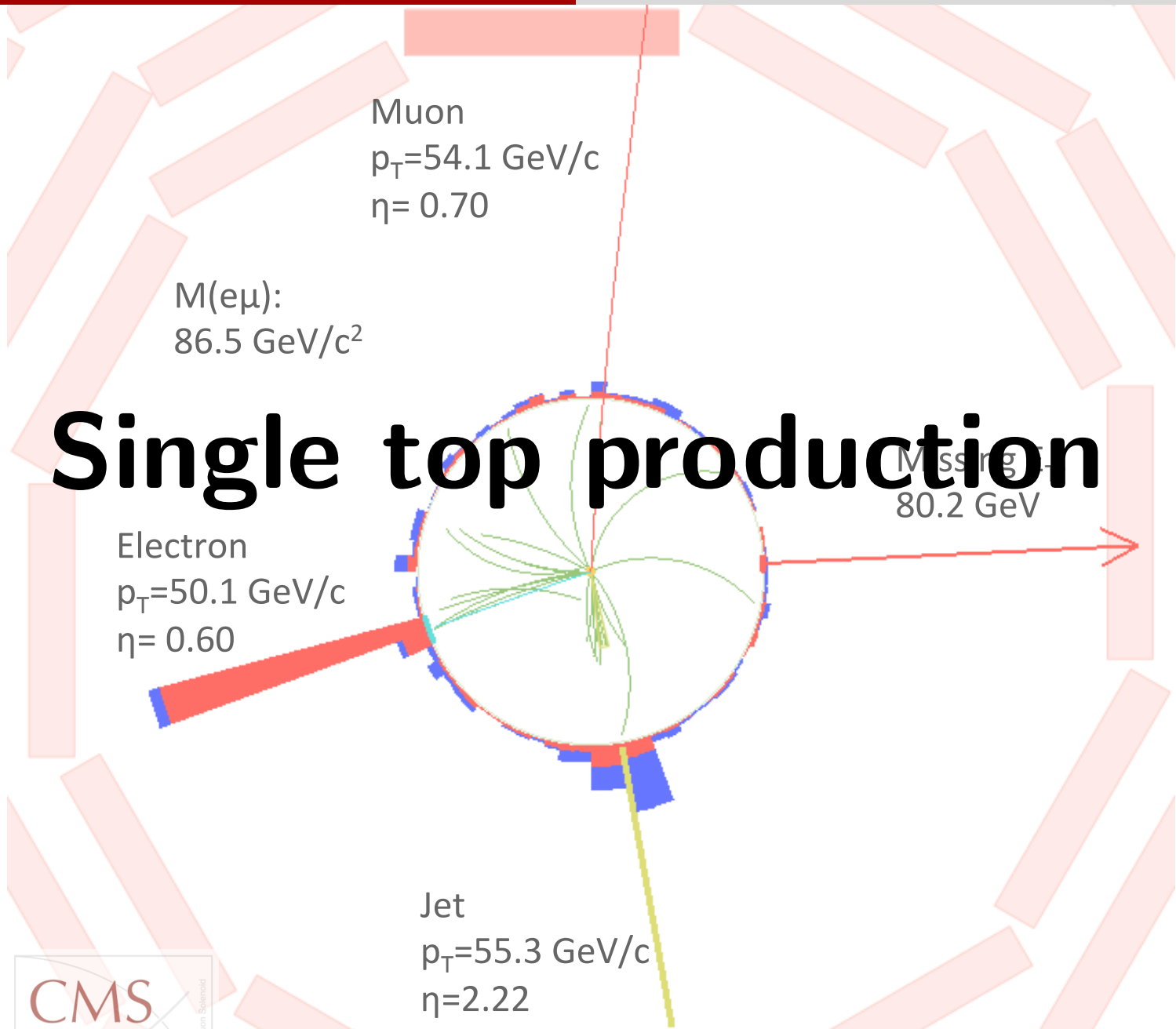


- Studied μ/e+jets final states
- Selection: $\geq$6 jets, $\geq$2 b-tagged jets, H_T, MET cuts
- Main background is $t\bar{t}$+jets 0(5) larger
- Event classification scheme based on a BDT algorithm
- The limit setting: simultaneous maximum likelihood fit to the BDT output distributions



Upper limits on the SM $\sigma_{t\bar{t}t\bar{t}}$ of 42^{+18}_{-13} fb (expected) and 63 fb (observed) at 95%CL

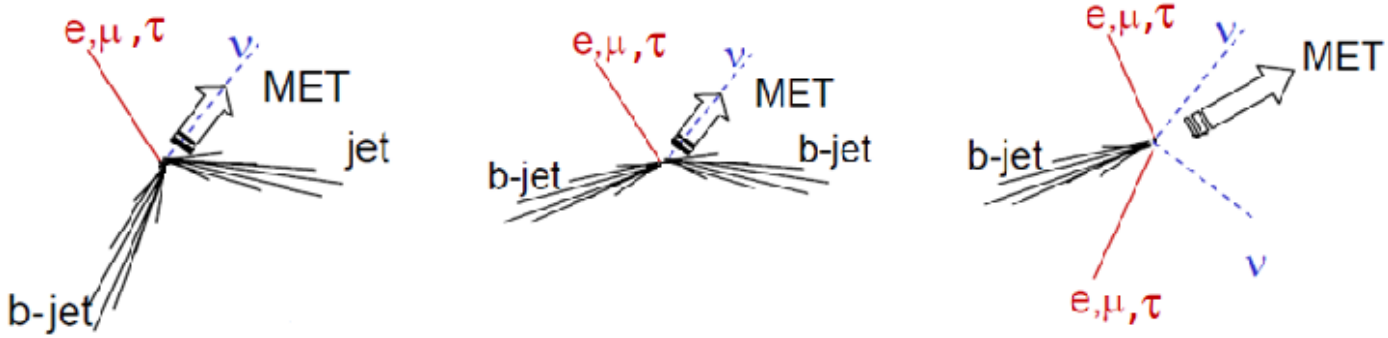
Single top production



Single Top production via EWK interaction

- Direct probe of Wtb coupling and of Vtb in CKM matrix.
- Sensitivity to b-quark PDF
- Constrain u/d PDF models (ratio of top/anti-top cross-sections)
- Important background for Higgs searches in associated production W/ZH→qqbb
- Probe for new physics: 4th gen., FCNC, contributions from additional bosons

Challenging, due to large BGs: top-pair production (both semileptonic and dileptonic), W(lν)+jets, multijet QCD



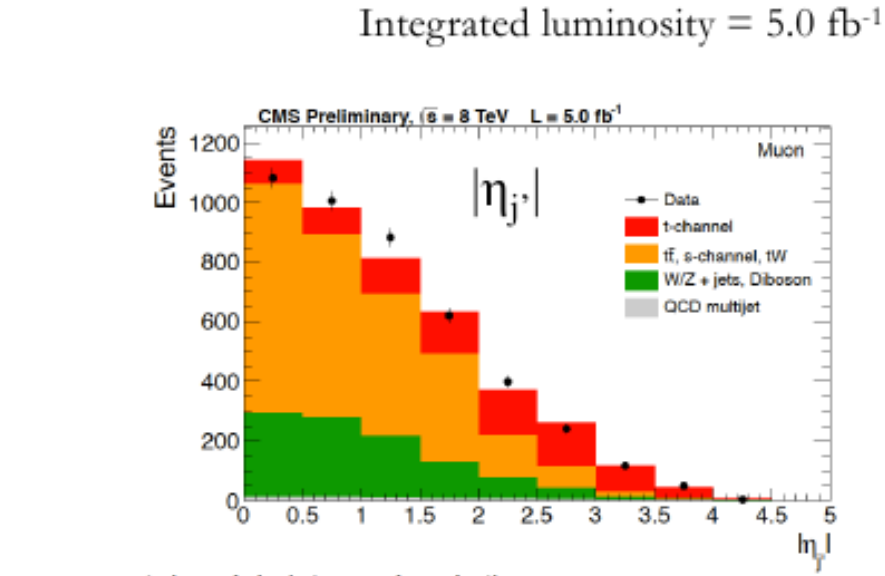
t-channel inclusive cross section

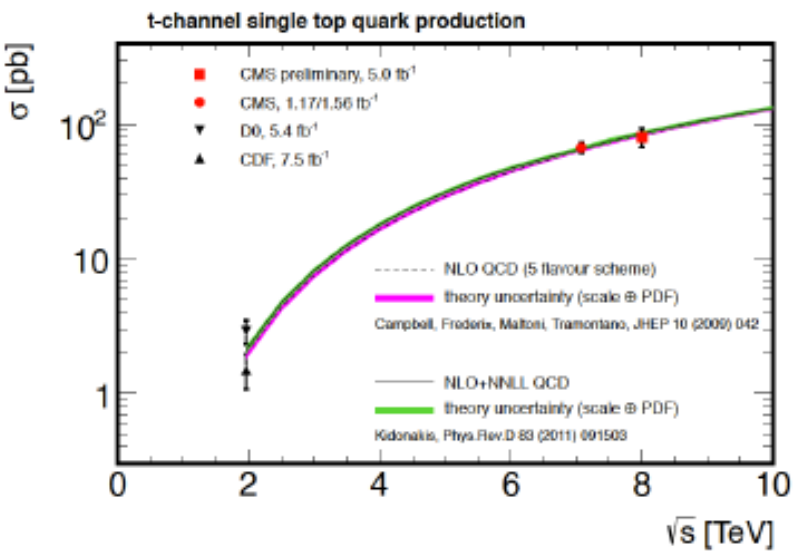
CMS-PAS-TOP-12-011

- Selection: 1 isolated high-p_T muon, 1 central b-tagged jet, 1 forward light jet, M_T(W)
- Template analysis $|\eta_{j'}|$: fit to the pseudorapidity of the recoil jet in the signal region (2jets,1bjet) $130 < m_t < 220$ GeV
- Data-driven QCD, W+jets and $t\bar{t}$
- Main syst. uncertainty: JES

σ=80.1±13.0 pb, $|Vtb| = 0.96 \pm 0.08(\text{exp.}) \pm 0.02(\text{th.})$, constrained $|Vtb| > 0.81$ at 95%CL

7 TeV: σ=67.2±6.1 pb
(JHEP 12 (2012) 035)

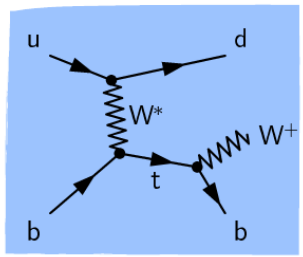


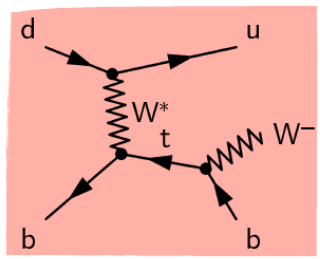


t-channel charge ratio

CMS-PAS-TOP-12-038

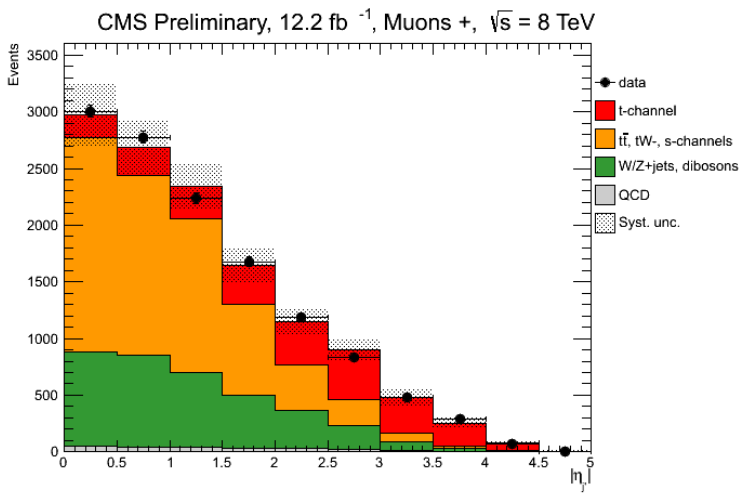
- t ($\bar{t}$) t-channel prod. happens mainly via u(d)-b W exchange
- pp collisions the u density is almost twice the d density: $\sigma_t/\sigma_{\bar{t}}$ is expected to be larger than 1
- μ and electron channels considered
- Analysis performed fitting the $\eta_{j'}$ distribution of the non b-tagged jet and separating l^+ and l^-
- Main systematic uncertainties: PDF, BG estimation

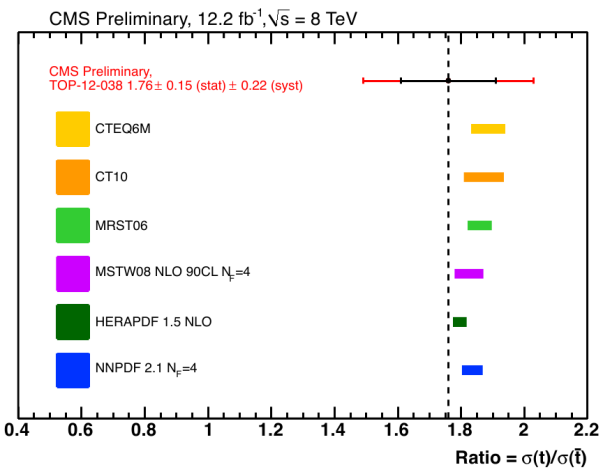




R=1.76±0.14(stat)±0.21(syst)

$\sigma_t = 49.9 \pm 1.9(\text{stat}) \pm 8.9(\text{syst})$ pb, $\sigma_{\bar{t}} = 28.3 \pm 2.4(\text{stat}) \pm 4.9(\text{syst})$ pb





Observation of tW-channel (8TeV)

arXiv:1401.2942

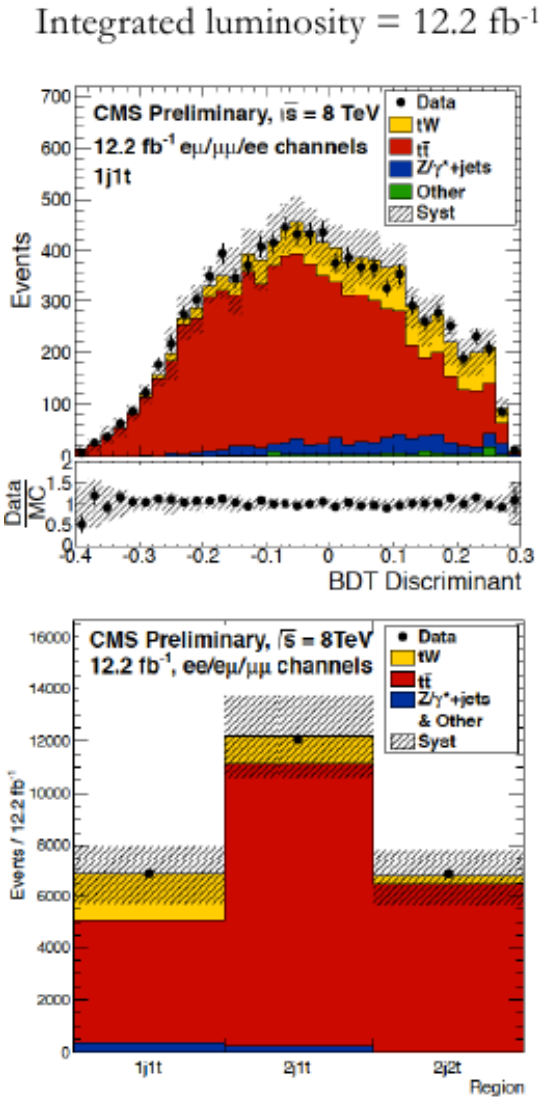
- 2 opposite sign isolated leptons, MET (2 neutrinos), 1 jet (coming from b quark)
- Signal extraction procedure: fit to BDT discriminant in the signal region (1j1t) and in control regions (2j1t, 2j2t), tt background dominated.
- Main BGs: top pair production, DY (Z+jets), W+jets, other single top processes
- Main syst.: matching thresholds, Q^2 scales

σ_{tW}=23.4±5.4 pb (σ_{tW}^{SM}=22.2±0.6±1.4 pb, arxiv:1210.7813v2)

$|V_{tb}|$= 1.03±0.12(exp.)±0.04(th.),

$|V_{tb}| > 0.78$ @ 95% CL

Significance 6 σ (expected: 5.4±1.5σ)



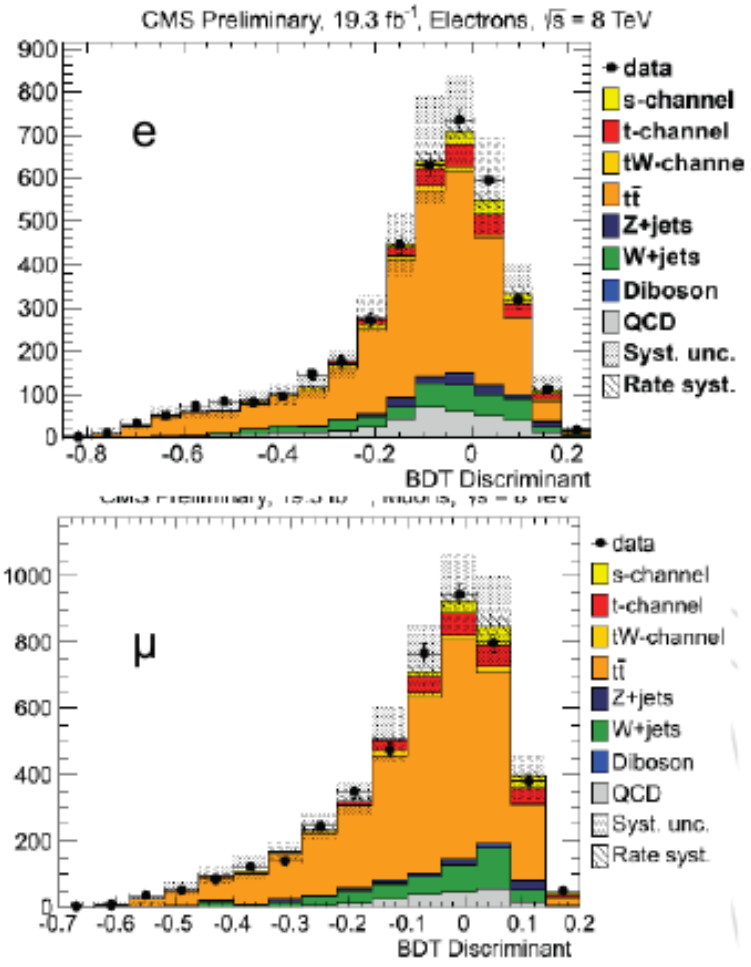
Search for single top production in the s-channel

CMS-PAS-TOP-13-009

Sensitive to new physics, W' bosons, charged Higgs bosons

- Smallest cross section at the LHC
- Signal signature: lepton + jets
  - e/μ and MET from the W decay
  - Two high p_T jets, at least one of which comes from a b-quark
- Main BGs: $t\bar{t}$, W+b jets, t-channel
- Main syst.: JES, matching thresholds, Q^2 scales
- Multivariate analysis based on Boosted Decision Trees

$\sigma_{schannel} < 11.5$ (17.0,9.0) pb @ 95% CL, observed (expected with SM signal, with BG only)



Summary and outlook

- Top quark physics: key to QCD, EWK and new physics
- In the last years, the LHC has become a real 'top factory':
  - Most analyses are systematics limited

◇ Precision regime: $\sigma_{t\bar{t}} < 5\%$ (inclusive cross section available up to full NNLO, same precision as data), differential measurements

◇ Presented measurement of $t\bar{t} + \gamma$, $t\bar{t}$+W/Z (7TeV) cross sections

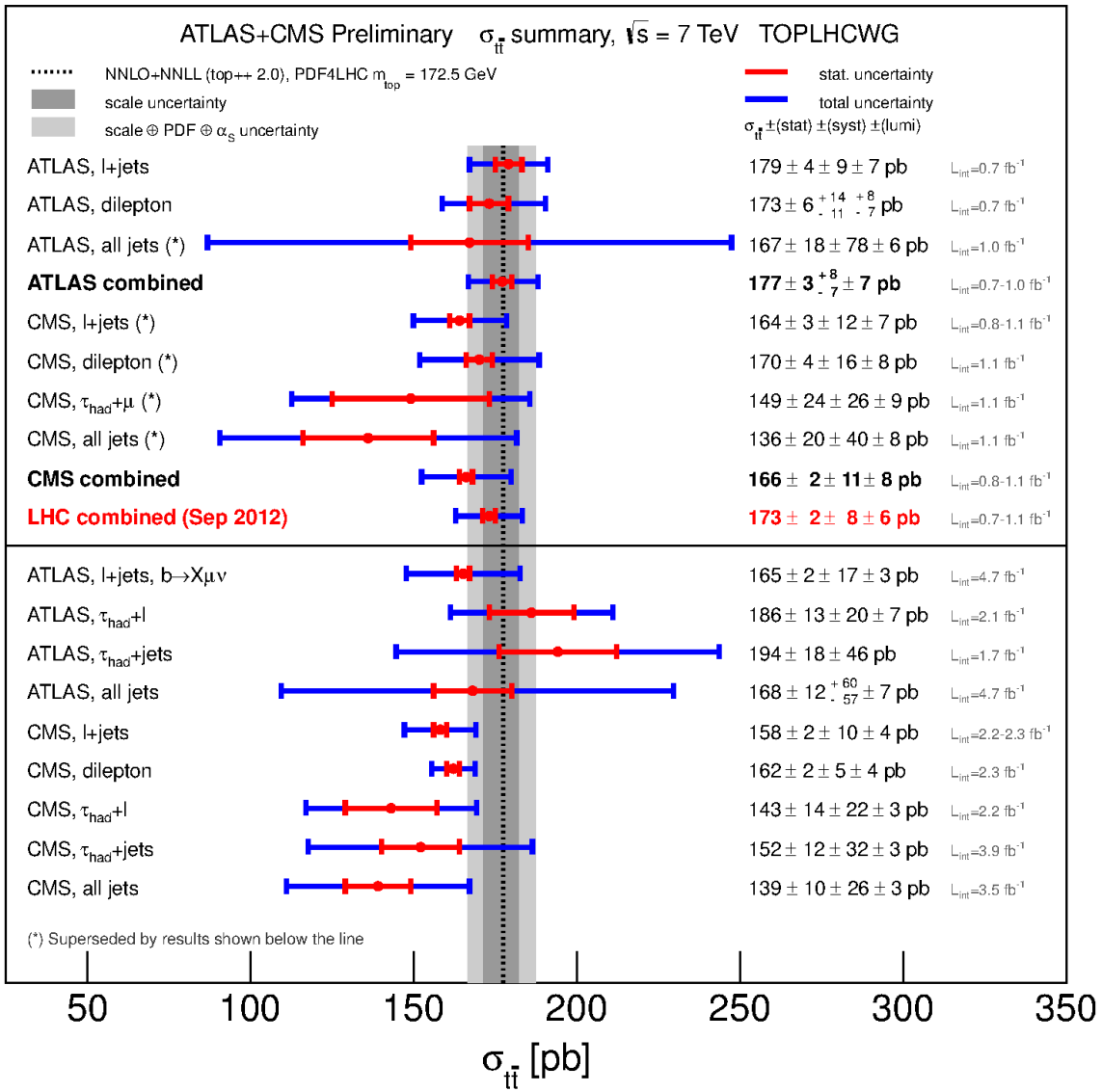
◇ First limits to $t\bar{t}t\bar{t}$ production

◇ Single top production: t-channel cross section measured at all energies, tW observed (8 TeV) and upper limit set on s-channel cross section

- All results so far in agreement with SM predictions
- CMS public Top Physics results available from: https://twiki.cern.ch/twiki/bin/view/CMSPublic/TopPhysicsResults

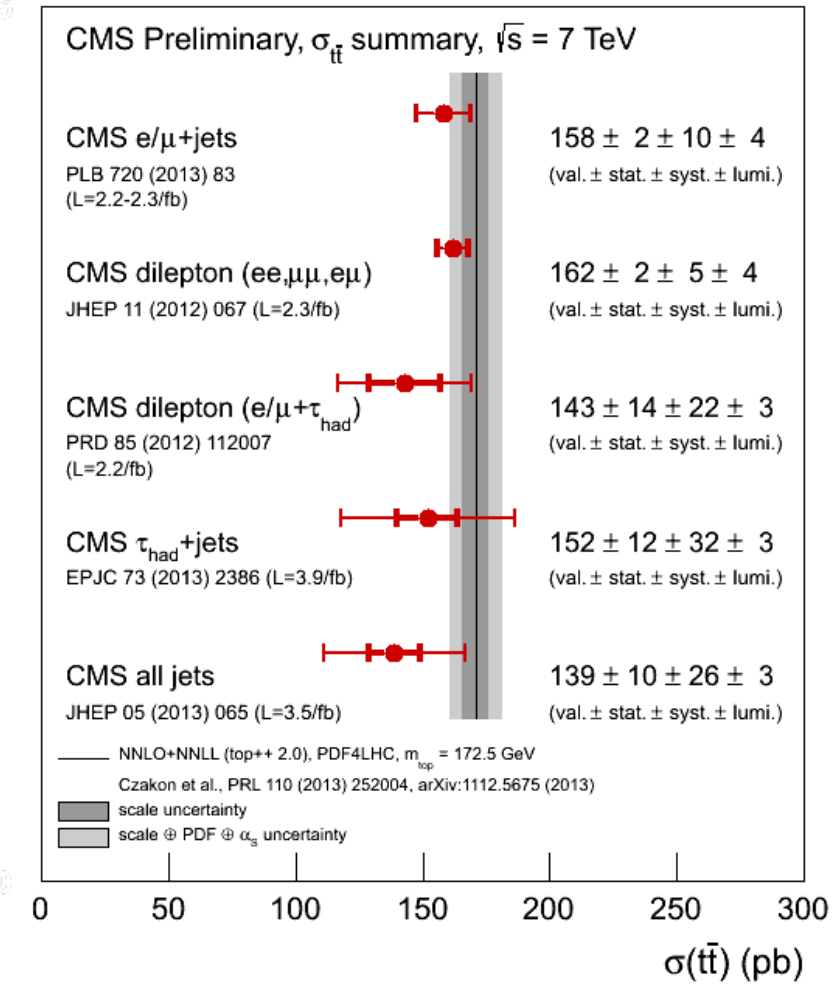
BACK UP

LHC combined result at 7 TeV



$t\bar{t}$ inclusive cross section (7 TeV)

- All final states investigated (except $\tau\tau$)
- Similar event selection in dilepton and lepton+jets modes
  - All hadronic: at least 6 high-pT jets, at least 2 b-tagged
  - τ+jets: at least 3 high-pT jets (>1 b-tagged) + tau jet; fed into ANN: Reconstruct hadronic tau, large multijets background
- Measurements from likelihood fits
- Data-driven estimates for main backgrounds



◇ Good agreement between channels and data and predictions NNLO + NNLL.

◇ Precision dominated by the dilepton result (∼4%)