Inclusive top pair production at Tevatron and LHC in electron/muon final states

- Introduction
- Inclusive cross sections
- Conclusions & Outlook

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VI. International Workshop on Top Quark Physics
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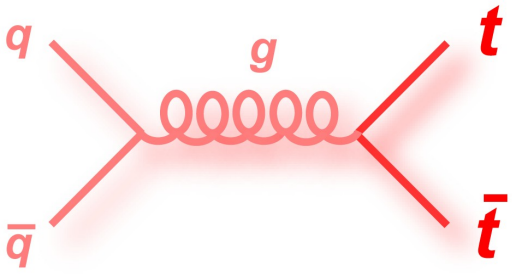
Content

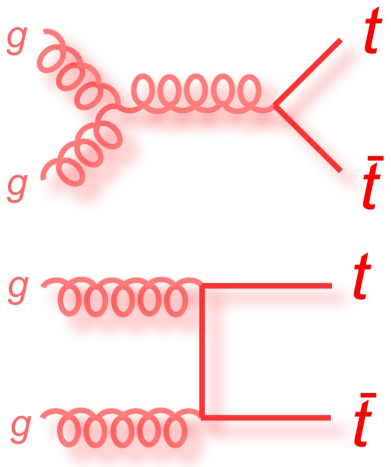
- CDF: dilepton decay channel — CDF-CONF-10878, and [arxiv:1304.7961]
- D0: l+jets, dilepton — PRD 84, 012008 (2011), PLB 704, 403 (2011)
  l+jets (full Run II) NEW — D0-CONF-6379
- ATLAS: lepton+jets at 8 TeV — ATLAS-CONF-2012-149
  Dilepton at 8 TeV NEW — ATLAS-CONF-2013-097
- CMS: lepton+jets at 7 TeV, 8 TeV — Phys. Lett. B 720 (2013) 83, CMS-PAS-TOP-12-006
  Dilepton at 8 TeV — CMS-PAS-TOP-12-007

Top quark – Recap

- Strong interaction: Top pairs



$q\bar{q}$ annihilation



gg fusion

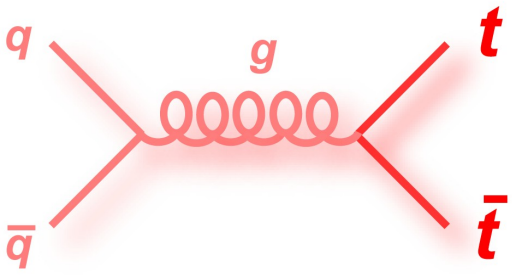
Tevatron vs. LHC:
(1.96 TeV 7/8 TeV)

$q\bar{q}$: ~85% ~15/13% (~10%, 14 TeV)

gg: ~15% ~85/87% (~90%, 14 TeV)

Top quark – Recap

- Strong interaction: Top pairs



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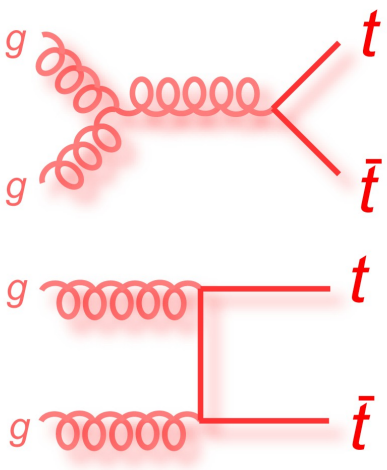
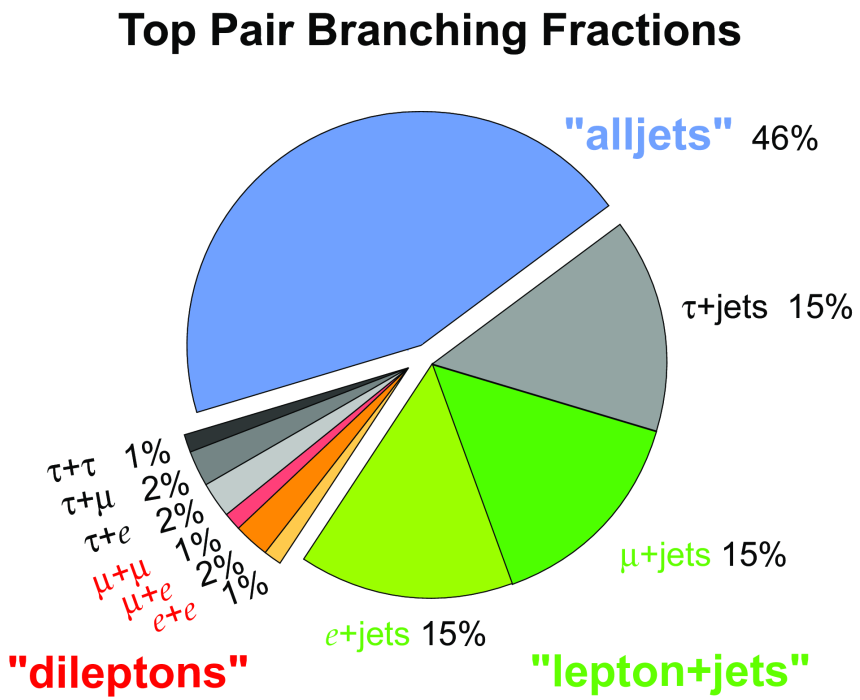


gg fusion

- It is the heaviest fundamental particle discovered so far
- top decay: $t \to Wb$ ~100%



Tevatron vs. LHC:
(1.96 TeV 7/8 TeV)

$q\bar{q}$: ~85% ~15/13% (~10%, 14 TeV)

gg: ~15% ~85/87% (~90%, 14 TeV)

- Samples classified according to W-decay: dilepton ($\ell\ell$), lepton+jets (ℓ+jets), all jets

Top quark – Theory

- Inclusive cross sections **test QCD calculations** and **enhance our understanding** of top quark production:
  - Recently all channels included
  - Real challenge to experiments:
    - ~ 3.5 % for Tevatron
    - ~ 4.4 % (4.2%) for LHC 7 (8) TeV

(Czakon, Fiedler, Mitov); Phys. Rev. Lett. 110, 252004 (2013) [arxiv:1303.6254]

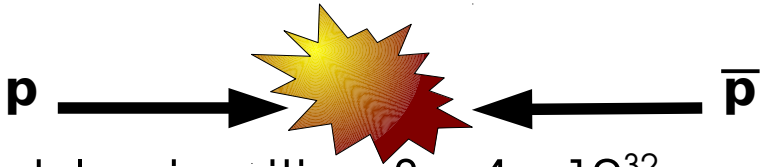
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$^{+0.110(1.5\%)}_{-0.200(2.8\%)}$	$^{+0.169(2.4\%)}_{-0.122(1.7\%)}$
LHC 7 TeV	172.0	$^{+4.4(2.6\%)}_{-5.8(3.4\%)}$	$^{+4.7(2.7\%)}_{-4.8(2.8\%)}$
LHC 8 TeV	245.8	$^{+6.2(2.5\%)}_{-8.4(3.4\%)}$	$^{+6.2(2.5\%)}_{-6.4(2.6\%)}$

- **Search for new physics** contribution

- Remark: Experimental determination of cross sections use theory predictions at tree or NLO for extrapolation

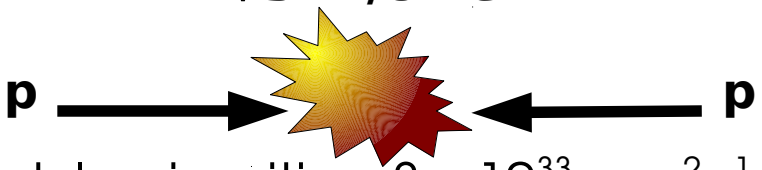
Accelerators

$\sqrt{s}$=1.96 TeV

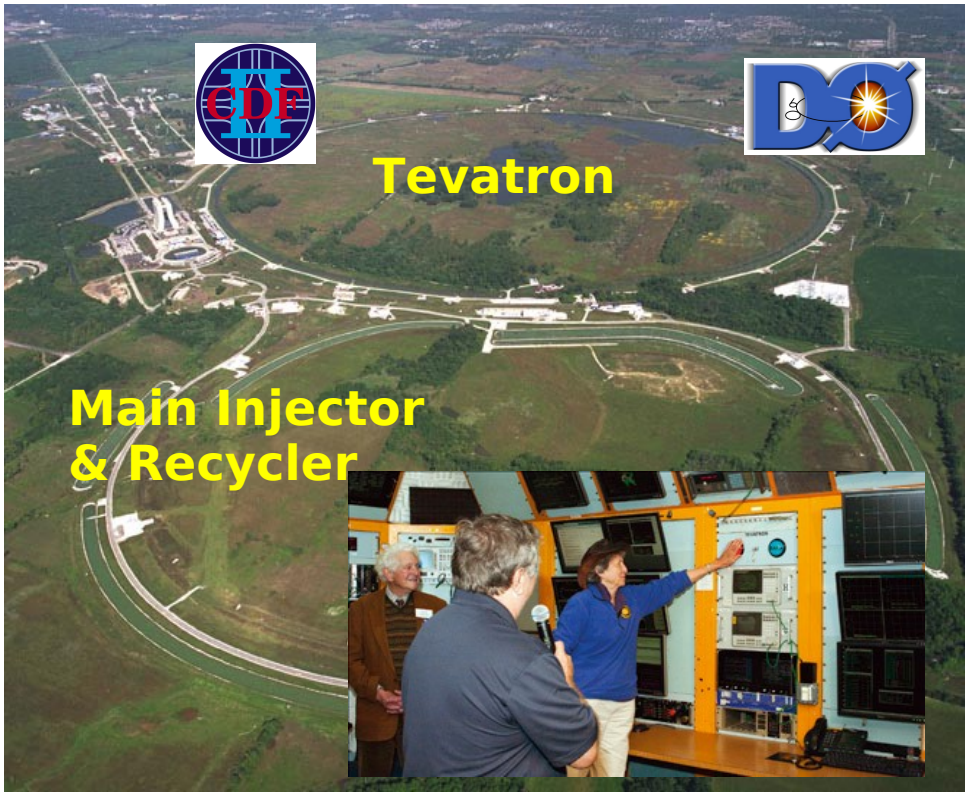


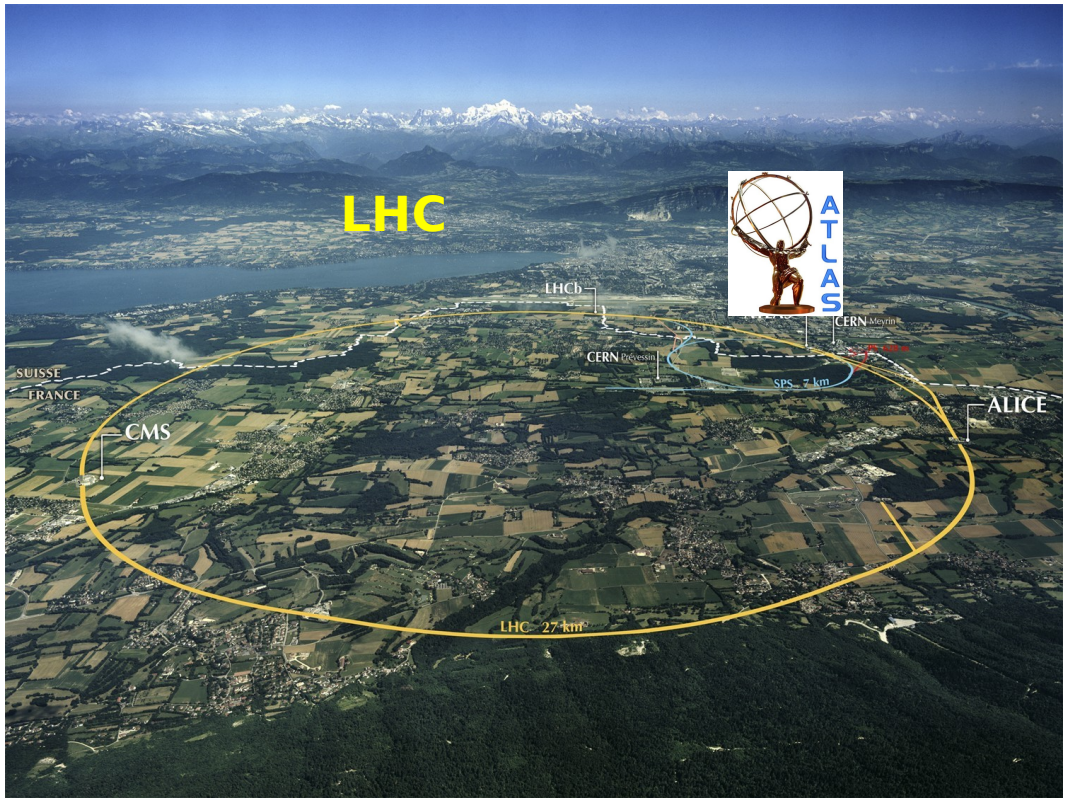
- Peak luminosities: 3 – 4 x 10^{32} $cm^{-2}s^{-1}$
- ~10 fb^{-1}/experiment recorded
- Tevatron shutdown September 2011

$\sqrt{s}$=7/8 TeV



- Peak luminosities: 8 x 10^{33} $cm^{-2}s^{-1}$
- ~5 (25) fb^{-1}/experiment recorded
- LHC consolidation/upgrades till 2015



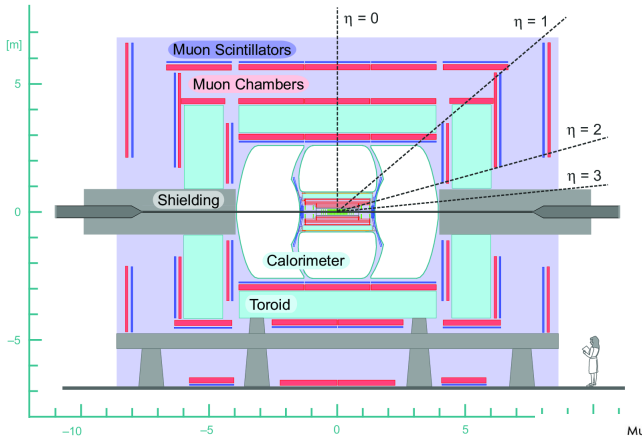


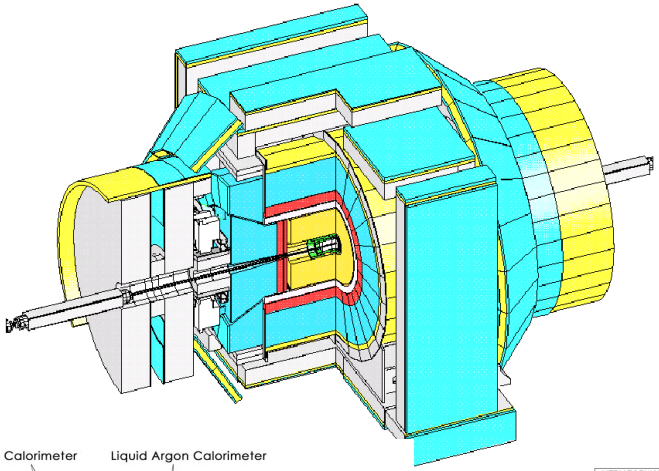
Big thanks to the Accelerator Divisions!

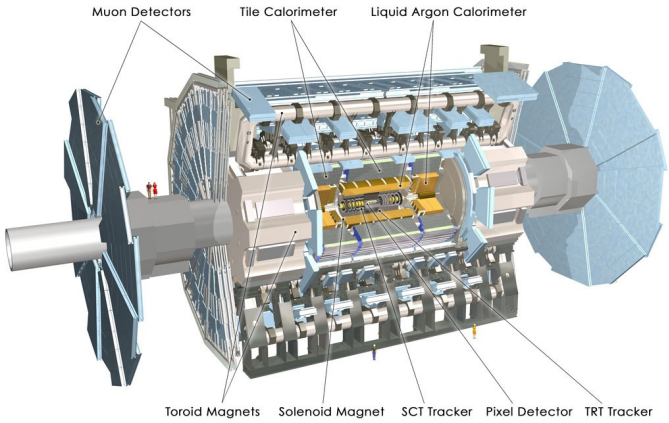
Detectors

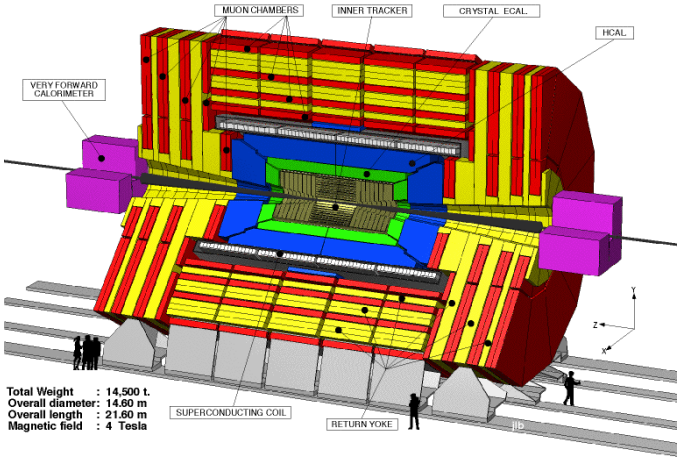
General purpose 4π detectors:

- **Tracker**: Detection and momentum measurement for charged particles
- **Calorimeter**: Identification and energy measurement of jets and electrons
- **Muon system**: Identification and momentum measurement of muons









- Tevatron: Similar calorimeter and tracker coverages
- LHC: Increased coverage compared to Tevatron

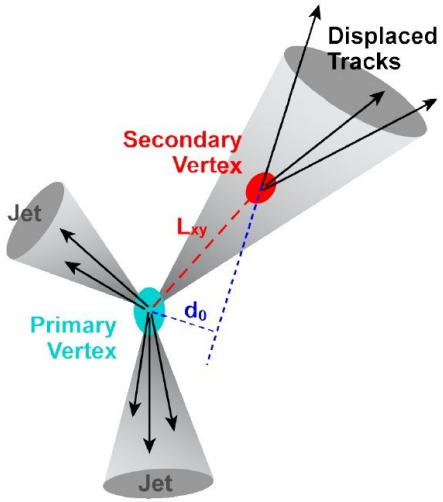
Techniques

- Compare the observed number of events (N^{data}) with prediction
- Cross section is measured by counting events:

  $\sigma = (N^{data} - N^{bg}) / BR \cdot A \cdot \varepsilon \cdot L$
- or by maximizing Poisson likelihood based on N^{data} using N^{pred}:

  $L(\sigma) = P(N^{data}, N^{pred})$

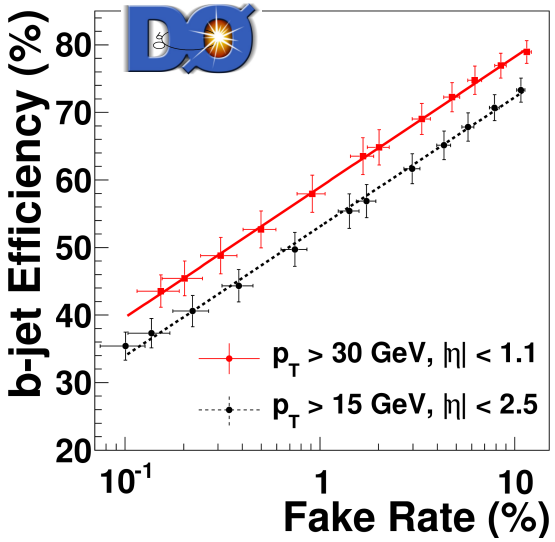
- One of the most important experimental techniques "b-tagging":



- *b*-quarks hadronize before decaying into a *c*-quark:

  → Long-lived *B* hadrons decay some mm away

  → Neural Network and/or Multi-Variate Analysis technique



Dilepton channel

[arxiv:1304.7961]
CDF-CONF-10878

- 579 candidate events in 9.1 fb^{-1} with 155 expected background evts
- 246 candidate events with b-tagged jets in 8.8 fb^{-1} with 22 bg evts

w/o *b*-tag: $\sigma(t\bar{t})$ = (7.66 ± 0.44 (stat) ± 0.52 (syst) ± 0.47 (lumi)) pb ~12.2 %
w *b*-tag: $\sigma(t\bar{t})$ = (7.09 ± 0.49 (stat) ± 0.52 (syst) ± 0.43 (lumi)) pb ~11.8 %

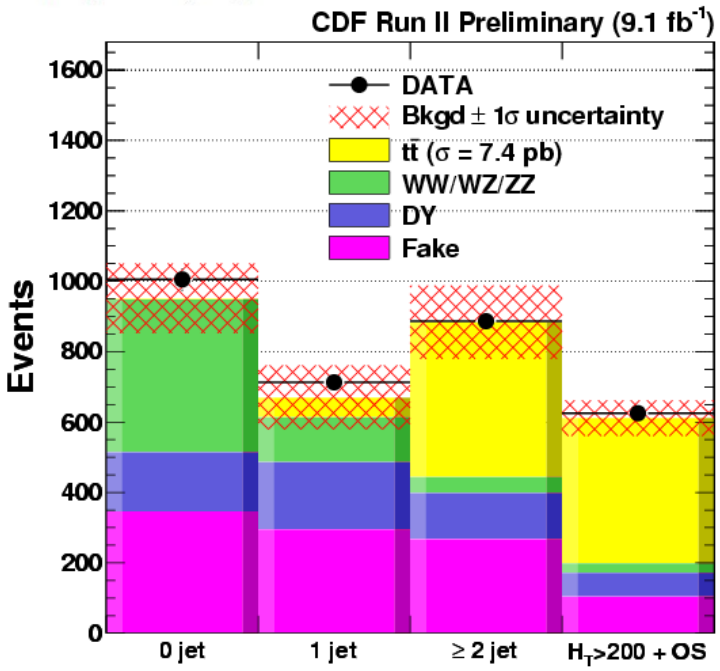
- Most precise prediction at NNLO+NNLL (MSTW2008nnlo):

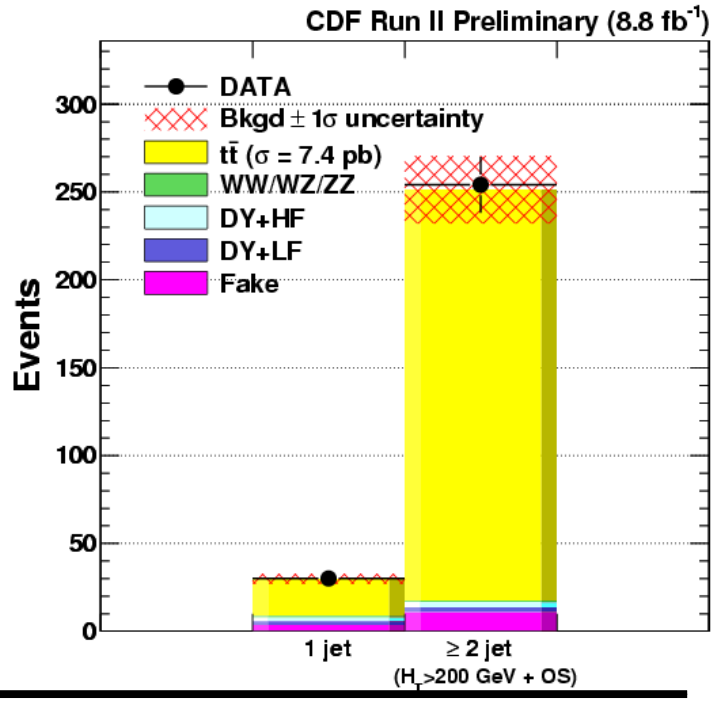
(Czakon, Fiedler, Mitov);
Phys. Rev. Lett. 110, 252004 (2013)
[arxiv:1303.6254]

$$\sigma_{\rm tot}^{\rm res} = 7.24^{+0.23}_{-0.27}({\rm scales} + {\rm pdf})\ {\rm pb}$$

Leading uncertainties:

- background modeling (1st measurement)
- b-tagging (2nd measurement)



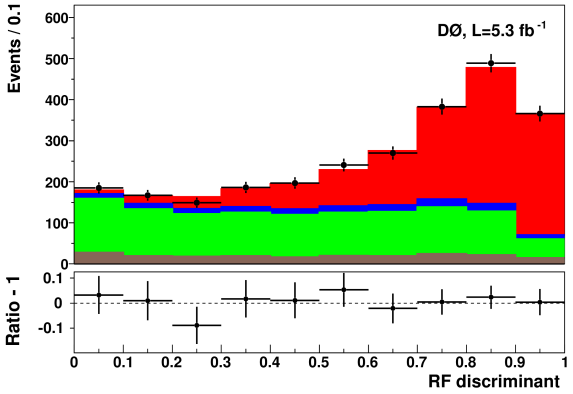


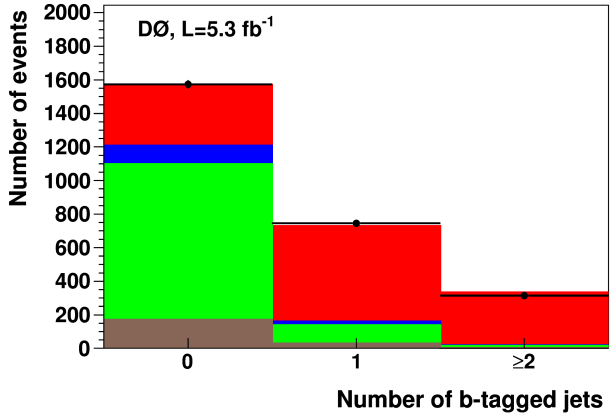
l+jets & dilepton channel

l+jets final state in 5.3 fb^{-1}:

- Discriminant using topological information
- "Counting" by number of b-tags
- Combine both in likelihood fit (→ fit uncertainties)

PRD 84, 012008 (2011)

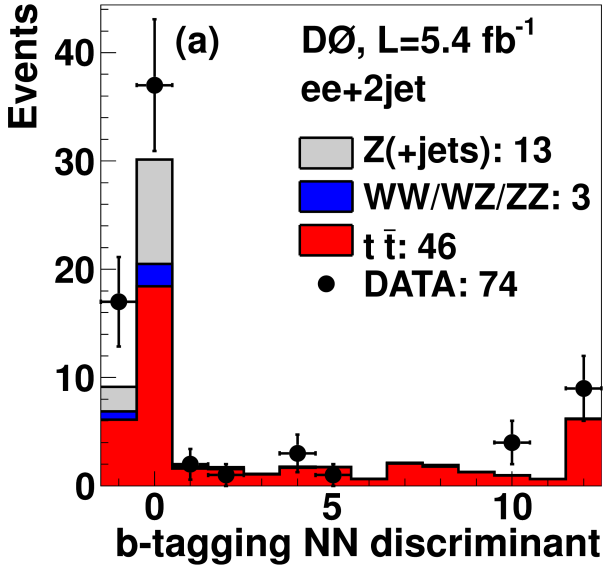




dilepton final state in 5.4 fb^{-1}:

- Likelihood based on b-tagging discriminant distribution (→ fit uncertainties)
- Merges 2-jet events and 1-jet events (eμ only)

PLB 704, 403 (2011)



→ *l+jets:* $\sigma(t\bar{t}) = (7.87\ ^{+0.77}_{-0.64})$ pb ~9.1 %

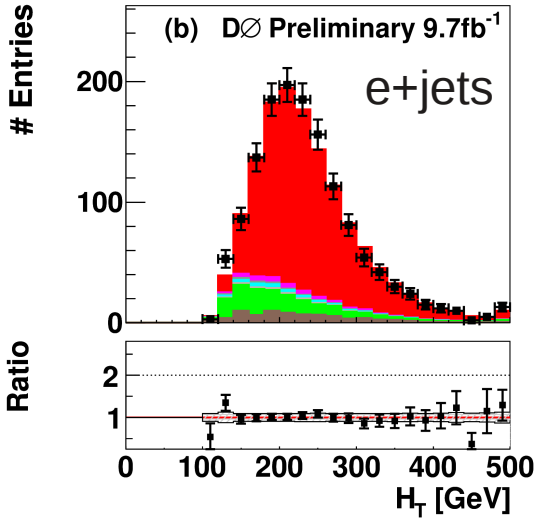
ll: $\sigma(t\bar{t}) = (7.36\ ^{+0.90}_{-0.79})$ pb ~11.5 %

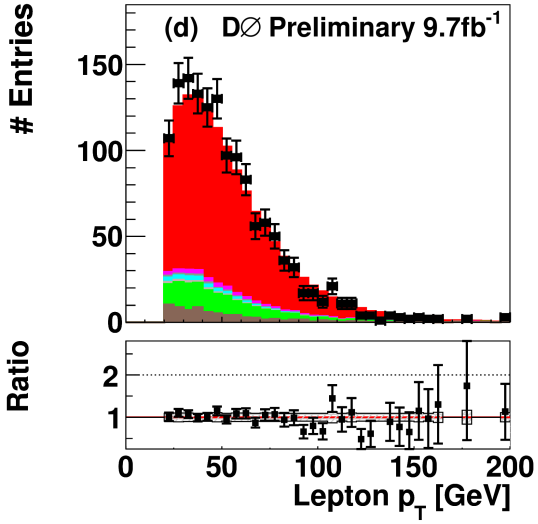
lepton+jets channel

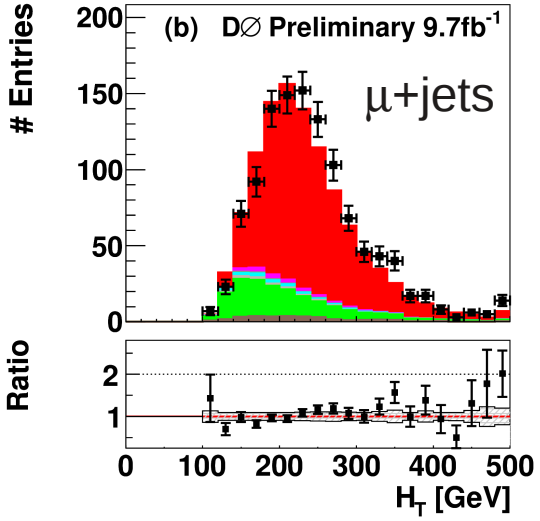
NEW

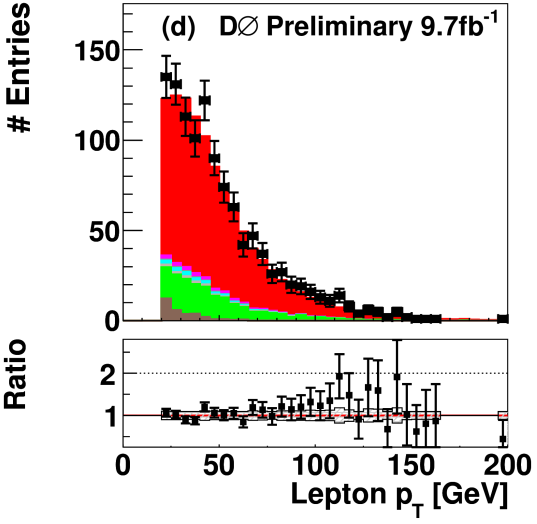
- Method: Kinematic fit of top quarks, derived from differential cross section
  → see talk by Maria Aldaya

- Event selection:
  - e- or μ+jets-trigger
  - ≥ 4 jets: p_T > 20 GeV, $|\eta|$ < 2.5
  - Reconstructed e or μ: p_T > 20 GeV, $|\eta|$ < 2.0 (< 1.1)
  - E_T^{miss} > 20 GeV & additional quality cuts
  - ≥ 1 jet identified as *b*-jet
- Good data-MC agreement









- Dedicated analysis with reduced systematic uncertainties in progress

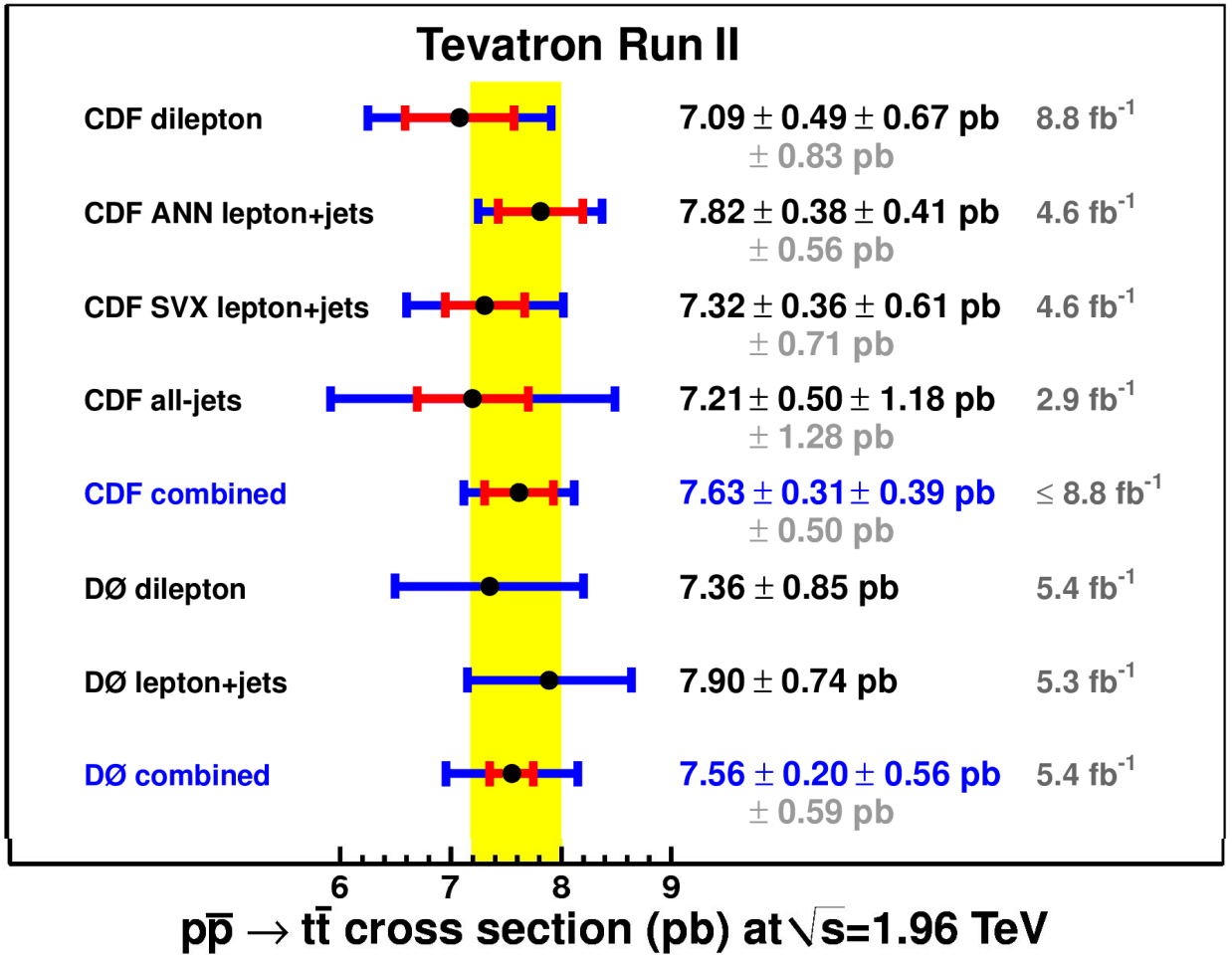
→ *l+jets:* $\sigma(t\bar{t}) = (8.27\ ^{+0.85}_{-0.82})$ pb ~10.2 %

Summary at 1.96 TeV

- Single most precise:
  - ~ 7.1% (CDF)
  - ~ 9.3% (D0)

- Further reduction by combination:

  → see Talk by Serban Protopopescu



- Most precise prediction at NNLO+NNLL (MSTW2008nnlo):

$$\sigma_{\mathrm{tot}}^{\mathrm{res}} = 7.24^{+0.23}_{-0.27}(\mathrm{scales} + \mathrm{pdf})\ \mathrm{pb}$$ ~ 3.5 %

lepton+jets at 7 TeV

- Method: Maximum profile likelihood fit for N_{jet}, N_{tagg} and secondary vertex mass (SVM)
- Sensitive to HF contributions

- Event selection:
  - Single e- or μ-trigger
  - ≥ 1 jets: $p_T > 35$ GeV, $|\eta| < 2.4$
  - Reconstructed e or μ: $p_T > 35$ GeV, $|\eta| < 2.5$ (< 2.1)
  - $E_T^{miss} > 20$ GeV & additional quality cuts
  - ≥ 1 jet identified as *b*-jet

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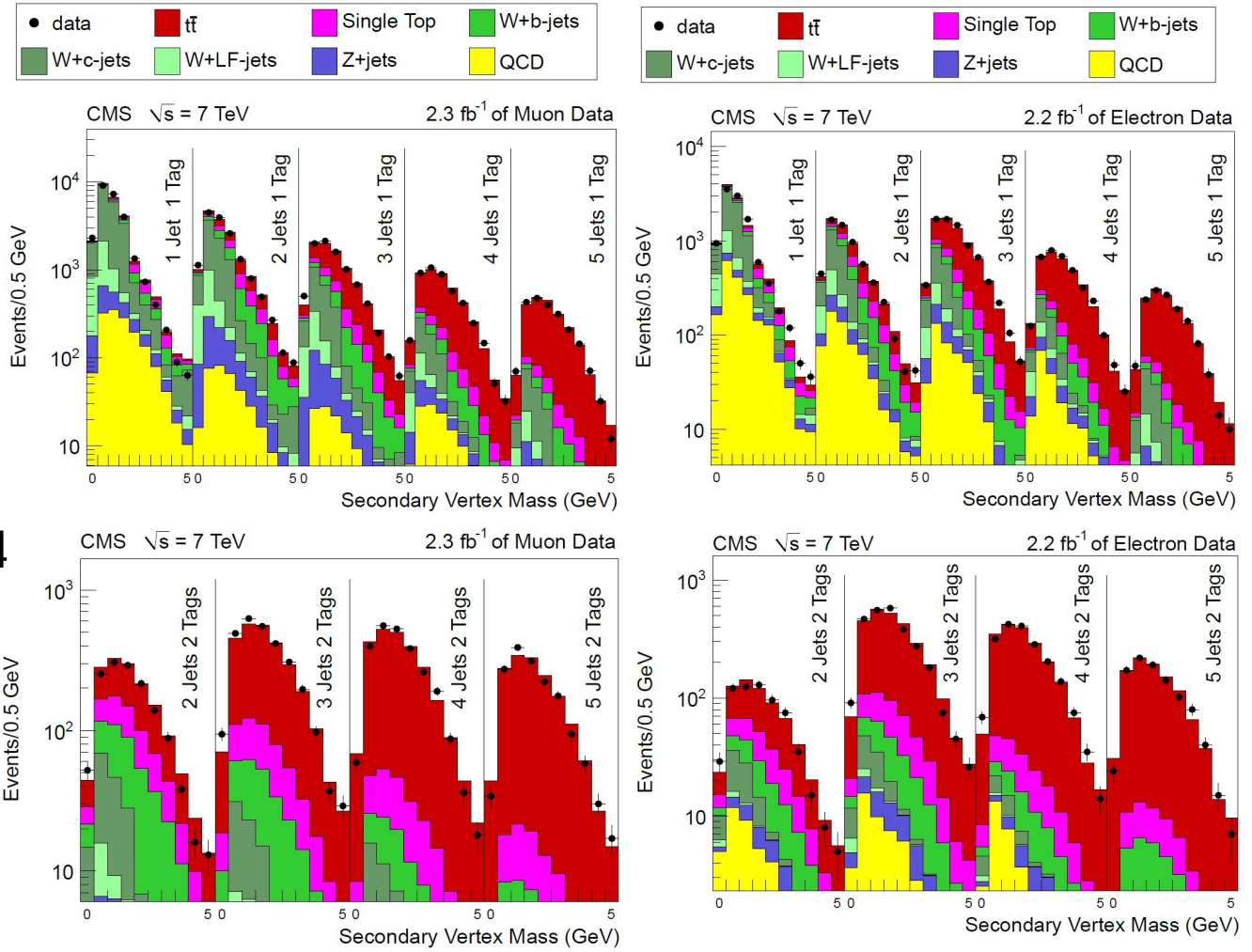

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  - $E_T^{miss} > 20$ GeV
  - ≥ 1 jet identified as *b*-jet

- Theory prediction: [arxiv:1303.6254]

$$\sigma(t\bar{t}) = 172.0^{+4.4}_{-5.8}(\text{scale})\ ^{+4.7}_{-4.8}(\text{pdf})\ \text{pb}$$

Phys. Lett. B 720 (2013) 83

$\sigma(t\bar{t})$ = (158.1 ± 2.1(stat) ± 10.2(syst) ± 3.5(lumi)) pb ~6.9%

lepton+jets at 7 TeV

- Alternative analysis using different selection cuts and amounts of luminosity:
  - A1: No use of *b*-tagging, no E_T^{miss}
    - ≥ 4 jets: p_T > 30 GeV
    - p_T (e,μ) > 35 GeV (26 GeV)
  - A2: Kinematic info of top decays
    - Similar selection as reference

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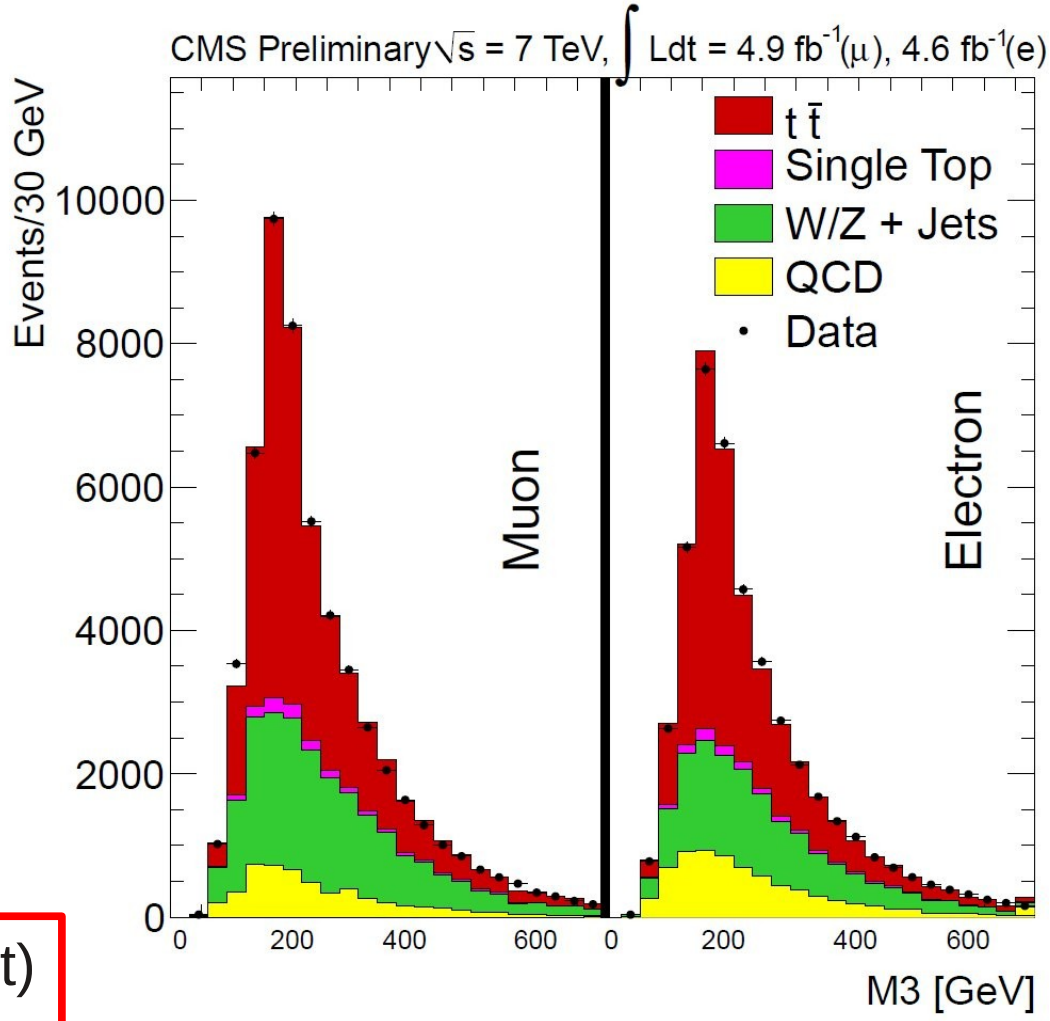


A1: Three Jet combination with highest jet p_T in event

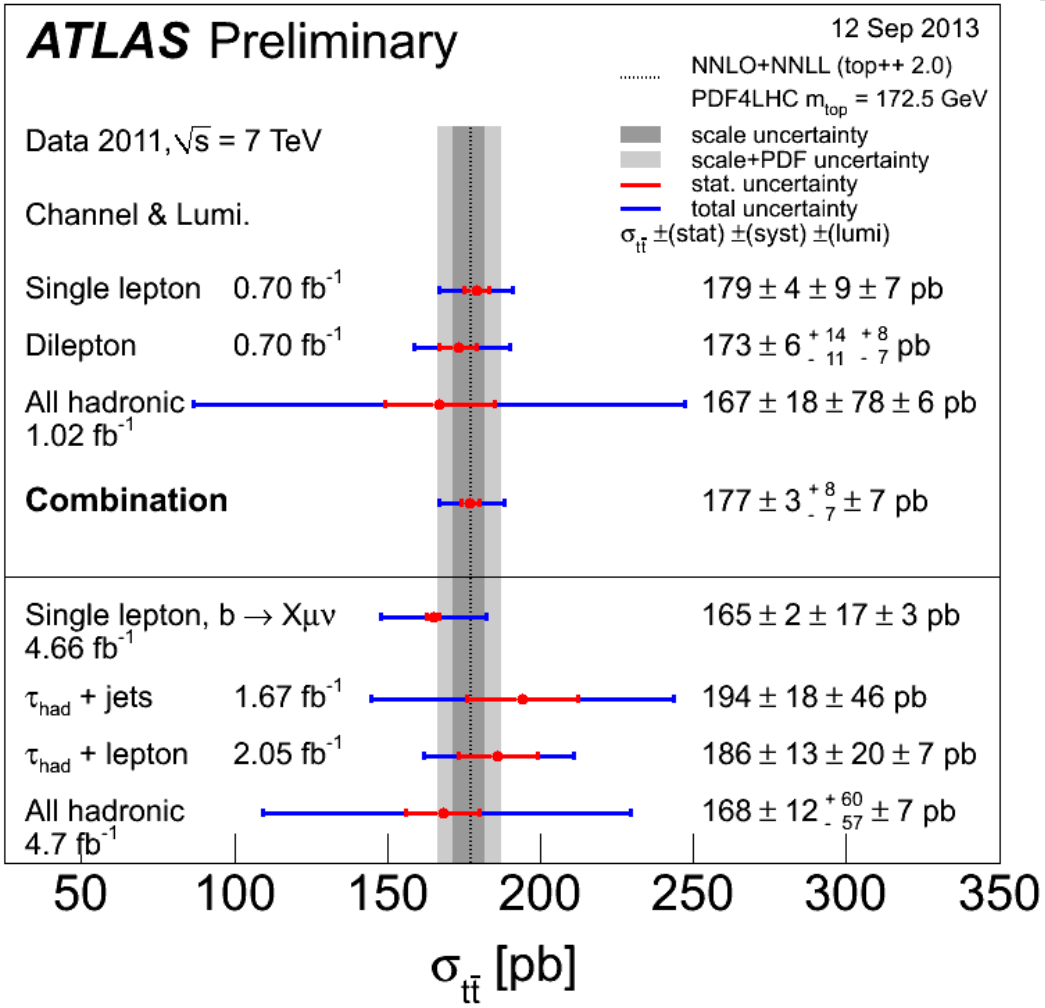
Theory prediction: [arxiv:1303.6254]

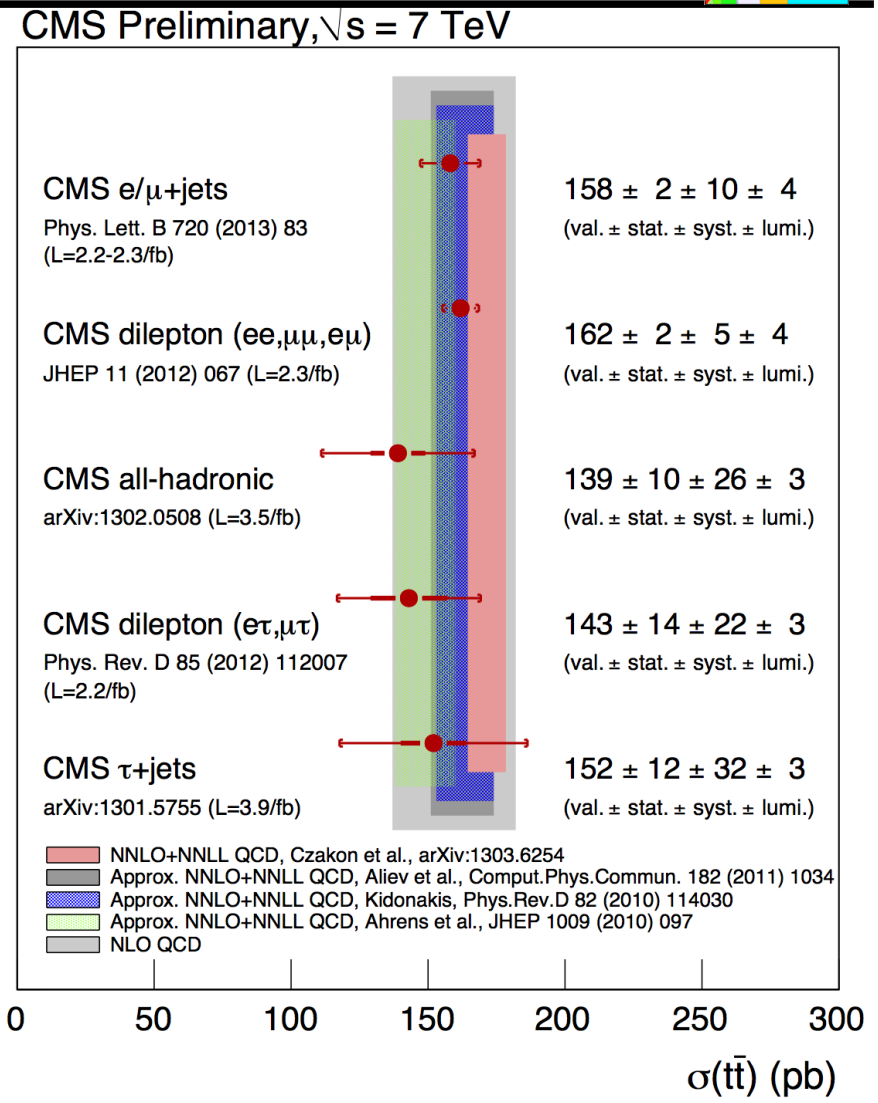
$$\sigma(t\bar{t}) = 172.0^{+4.4}_{-5.8}(\text{scale})\ ^{+4.7}_{-4.8}(\text{pdf})\ \text{pb}$$

$A1: \sigma(t\bar{t})$ = (159.7 ± 2.6 (stat) $^{+13.1}_{-14.7}$ (syst) ± 3.5 (lumi))pb ~9.2 %

$A2: \sigma(t\bar{t})$ = (162.4 ± 5.4 (stat) $^{+7.5}_{-11.0}$ (syst) ± 3.6 (lumi))pb ~7.0 %

Summary at 7 TeV



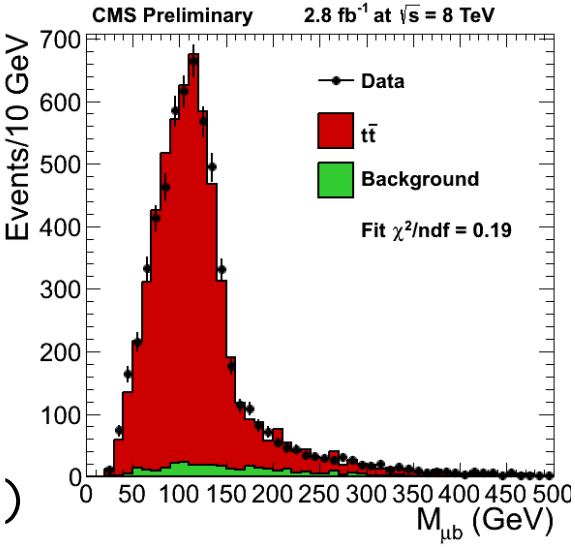


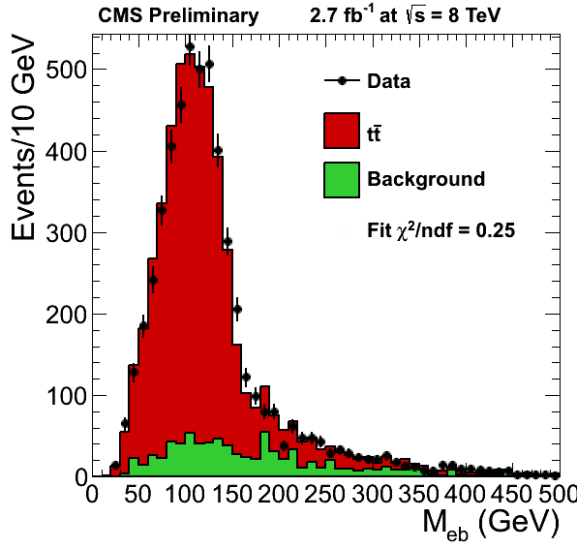
- Further reduction by combination
  - → see Talk by Serban Protopopescu
- Most precise theory prediction by Czakon et al.: ~ 4.4 %

lepton+jets at 8 TeV

CMS-PAS-TOP-12-006

- Method: Template fit to M_{lb} invariant mass distribution
- Event selection:
  - Single e- or μ-trigger
  - ≥ 4 jets: $p_T(1,2) > 45$ GeV, $p_T(3,4) > 35$ GeV, $|\eta| < 2.5$
  - Reconstructed e or μ: $p_T > 30$ (26) GeV, $|\eta| < 2.5$ (< 2.1)
  - ≥ 1 jet identified as *b*-jet





Theory prediction: [arxiv:1303.6254]

$$\sigma(t\bar{t}) = 245.8^{+6.2}_{-8.4}(\text{scale})\ ^{+6.2}_{-6.4}(\text{pdf})\ \text{pb}$$

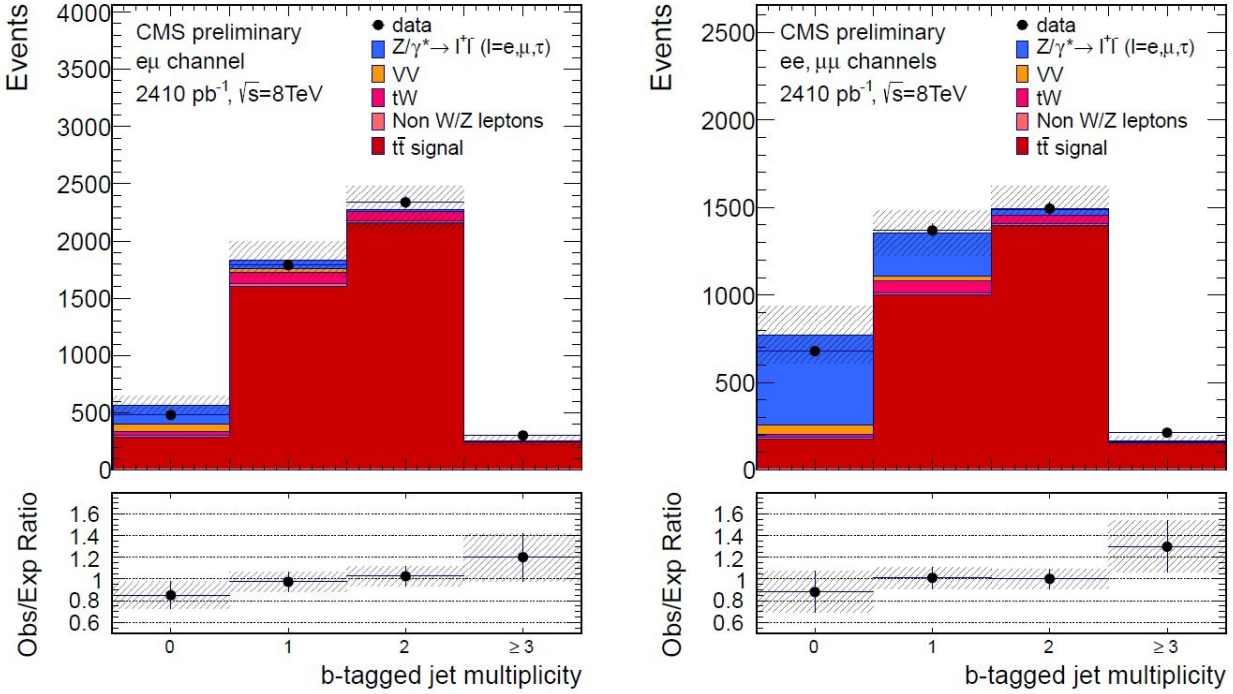
$\sigma(t\bar{t})$ = (228.4 ± 9 (stat) $^{+29.0}_{-26.0}$ (syst) ± 10 (lumi))pb ~13%

Systematic	Combined fit $\delta\sigma_{t\bar{t}}$ (%)	
Jet Energy Scale	+4.3	-5.0
Jet Energy Resolution	+0.5	-1.1
Pileup	+0.7	-0.7
Background Composition	+0.1	-0.1
W + Jets template shape from unweighted 7 TeV	+0.9	-0.9
Normalisation of data-driven multijet shape	+0.9	-0.9
b tagging efficiency measurement	+8.0	-8.0
Trigger Efficiency	+3.2	-2.8
Lepton selection	+2.8	-2.4
Factorization scale (*)	+6.2	-2.1
ME-PS Matching threshold (*)	+4.6	-3.1
PDF uncertainties (*)	+1.6	-2.0
Top Quark Mass (*)	+0.3	-1.4
Total	+12.7	-11.4
Luminosity	+4.4	-4.4

dilepton at 8 TeV

- Extremely clean, very high purity
- Method: Counting
- Event selection:
  - Single e- or μ-trigger
  - ≥ 2 jets: p_T > 30 GeV, $|\eta|$ < 2.5
  - Reconstructed e or μ:
    p_T > 20 GeV, $|\eta|$ < 2.5 (< 2.4)
    for ee, μμ: $|m(ll-Z)|$ > 15 GeV
  - E_T^{miss} > 40 GeV (ee, μμ)
  - ≥ 1 jet identified as *b*-jet

CMS-PAS-TOP-12-007



Theory prediction: [arxiv:1303.6254]

$$\sigma(t\bar{t}) = 245.8^{+6.2}_{-8.4}(\text{scale})\ ^{+6.2}_{-6.4}(\text{pdf})\ \text{pb}$$

$\sigma(t\bar{t})$ = (227 ± 3 (stat) ± 11 (syst) ± 10 (lumi))pb ~7%

Source	μμ	ee	eμ
Trigger & Lepton efficiencies (ID, Iso)	2.2	2.5	1.9
LES	0.3	0.3	0.3
JES	3.5	2.9	2.3
JER	1.7	1.4	1.7
B-tagging	0.9	1.3	0.8
pileup	1.5	1.9	1.4
Branching ratio	1.7	1.7	1.7
Event Q^2 scale	0.7	0.7	0.7
Matching	0.7	0.7	0.7
Total Systematic	5.2	5.1	4.3
Luminosity	4.4	4.4	4.4

lepton+jets at 8 TeV

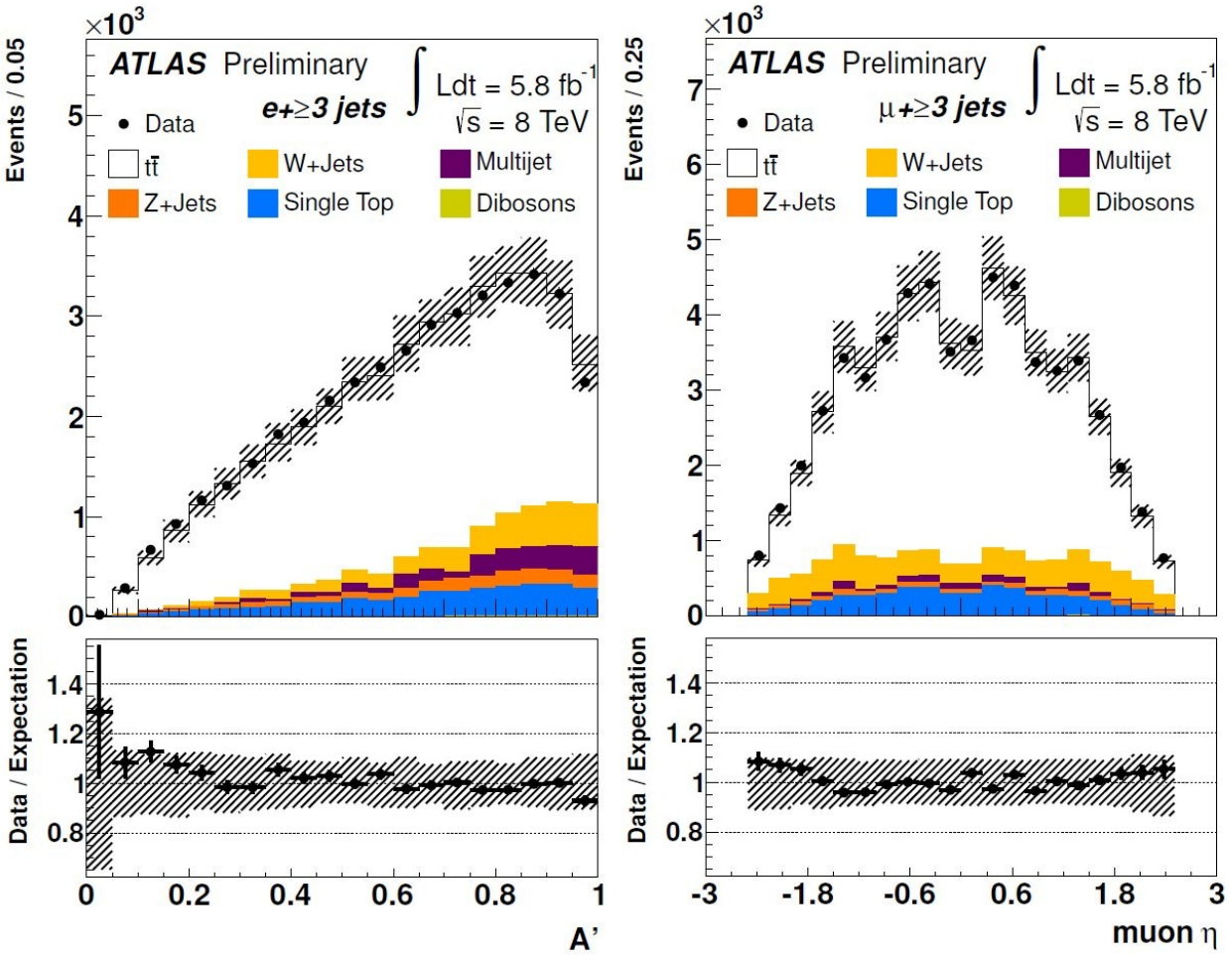
ATLAS-CONF-2012-149

- Method: kinematic fits with *b*-tagging, fit to likelihood discriminant (lepton η, Aplanarity A'):

$$D_i = \frac{L_i^s}{(L_i^s + L_i^b)}$$

- Event selection:
  - Single e- or μ-trigger
  - ≥ 3jets: $p_T > 25$ GeV, $|\eta| < 2.5$
  - Reconstructed e or μ:
    $p_T > 40$ GeV, 2nd e (μ) vetoed
  - $E_T^{miss} > 30$ (20) for e (μ) GeV &
    → e: $M_T(W) > 30$ GeV
    → μ: $(M_T(W) + E_t^{miss}) > 60$ GeV
  - ≥ 1 jet identified as *b*-jet

& additional quality cuts



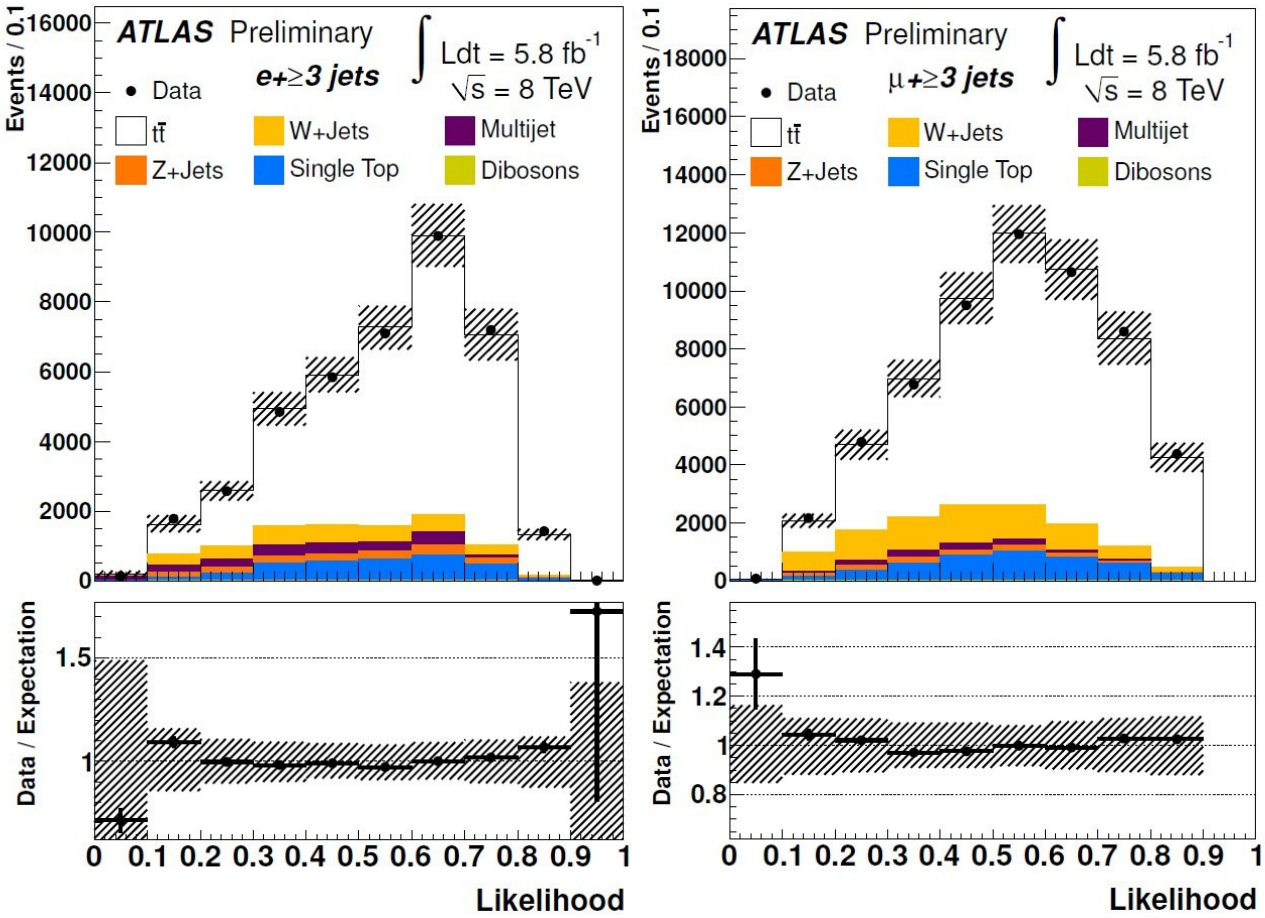
lepton+jets at 8 TeV

ATLAS-CONF-2012-149

- Method: kinematic fits with *b*-tagging, fit to likelihood discriminant (lepton η, Aplanarity A'):

$$D_i = \frac{L_i^s}{(L_i^s + L_i^b)}$$

- Discriminant nicely described
- Systematic uncertainties:
  - Relative 13%, dominant ones:
    - → Signal model
    - → Jet/MET reco. & calib.



QCD at NNLO+NNLL: $252.9^{+13.3}_{-14.5}$ pb

→ $\sigma(t\bar{t})$ = (241 ± 2 (stat) ± 31 (syst) ± 9 (lumi))pb ~13%

Source	*e*+ ≥3 jets	*μ*+ ≥ 3 *jets*	combined
Jet/MET reconstruction, calibration	6.7, -6.3	5.4, -4.6	5.9, -5.2
Lepton trigger, identification and reconstruction	2.4, -2.7	4.7, -4.2	2.7, -2.8
Background normalization and composition	1.9, -2.2	1.6, -1.5	1.8, -1.9
b-tagging efficiency	1.7, -1.3	1.9, -1.1	1.8, -1.2
MC modelling of the signal	±12	±11	±11
Total	±14	±13	±13

dilepton (eμ) at 8 TeV

NEW

ATLAS-CONF-2013-097

- Extremely clean, very high purity
- Method: simultaneously determine $\sigma(t\bar{t})$ and the efficiency to reconstruct & *b*-tag jets

$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} 2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\text{bkg}}$$

$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} C_b\epsilon_b{}^2 + N_2^{\text{bkg}}$$

- $\epsilon_{e\mu}$ Efficiency to pass eμ preselection
- ϵ_b Combined probability for a jet from $t \to Wq$ to be within acceptance, reconstructed as jet and *b*-tagged
- C_b Correlations between two *b*-tagged jets

dilepton (eμ) at 8 TeV

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- Event selection:
  - Single e- or μ-trigger
  - ≥ 1 jets: $p_T > 25$ GeV, $|\eta| < 2.5$
  - Reconstructed e and μ with $p_T > 25$ GeV, $|\eta| < 2.5$
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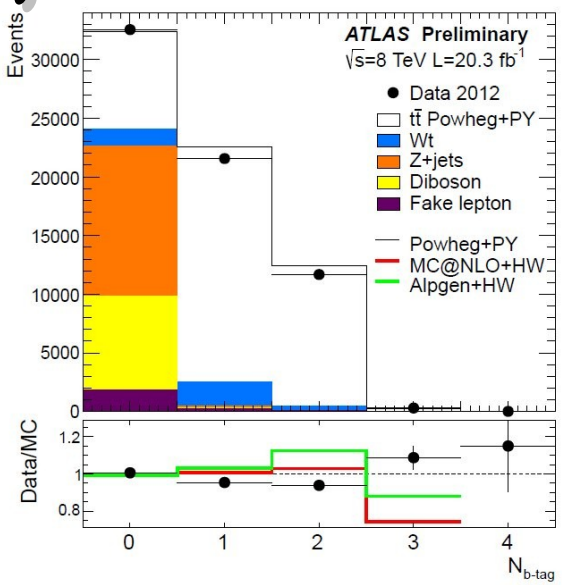

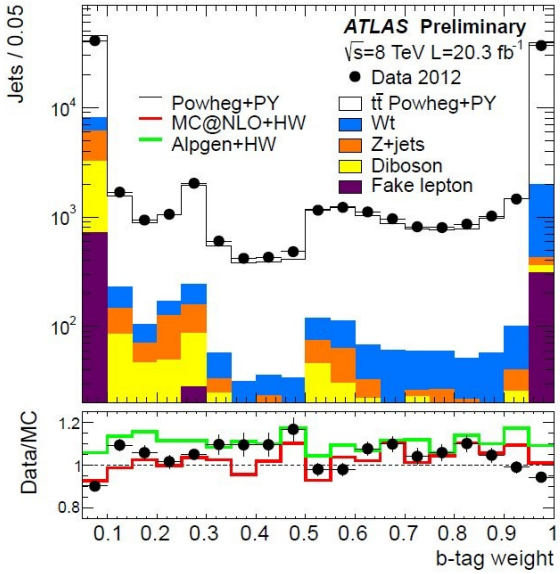

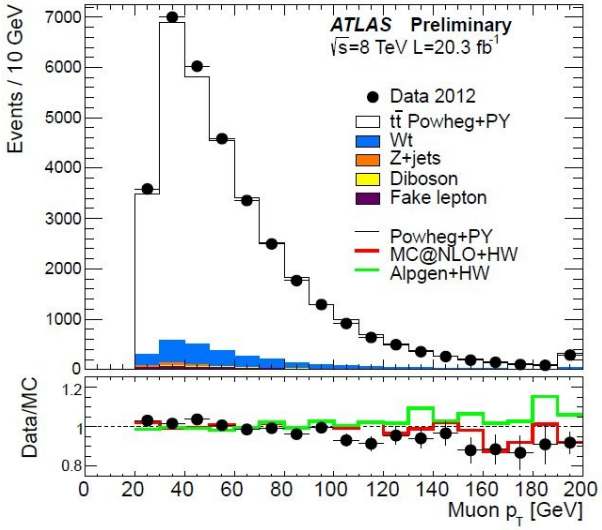

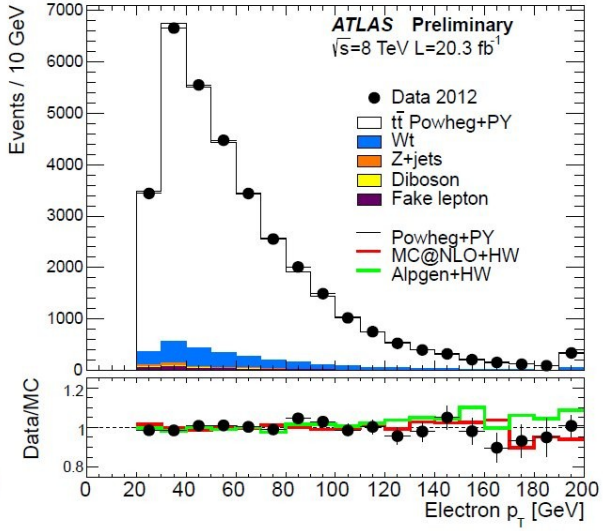

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ATLAS-CONF-2013-097

dilepton (eμ) at 8 TeV

NEW

Uncertainty	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\epsilon_b/\epsilon_b$ (%)
Data statistics	-	-	0.72	1.7	0.57
$t\bar{t}$ modelling	0.91	-0.61	1.52	3.6	0.61
Initial/final state radiation	-0.76	0.26	1.23	2.9	0.37
Parton density functions	1.08	-	1.09	2.6	0.06
QCD scale choices	0.30	-	0.30	0.7	0.00
Single-top modelling	-	-	0.38	0.9	0.56
Single-top/$t\bar{t}$ interference	-	-	0.15	0.4	0.25
Single-top Wt cross-section	-	-	0.70	1.7	0.24
Diboson modelling	-	-	0.42	1.0	0.19
Diboson cross-sections	-	-	0.03	0.1	0.01
Z+jets extrapolation	-	-	0.05	0.1	0.02
Electron energy scale/resolution	0.43	0.01	0.48	1.1	0.03
Electron identification/isolation	1.28	0.00	1.42	3.4	0.05
Muon momentum scale/resolution	0.01	0.01	0.05	0.1	0.02
Muon identification/isolation	0.50	0.00	0.52	1.2	0.01
Lepton trigger	0.15	0.00	0.16	0.4	0.01
Jet energy scale	0.46	0.07	0.49	1.2	0.11
Jet energy resolution	-0.44	0.04	0.59	1.4	0.08
Jet reconstruction/vertex fraction	0.02	0.01	0.04	0.1	0.01
b-tagging	-	0.13	0.42	1.0	0.09
Pileup modelling	-0.30	0.05	0.28	0.7	0.05
Misidentified leptons	-	-	0.38	0.9	0.12
Total systematic	2.29	0.69	3.12	7.4	1.02
Integrated luminosity	-	-	3.11	7.4	0.11
LHC beam energy	-	-	1.70	4.0	0.00
Total uncertainty	2.29	0.69	4.77	11.3	1.17

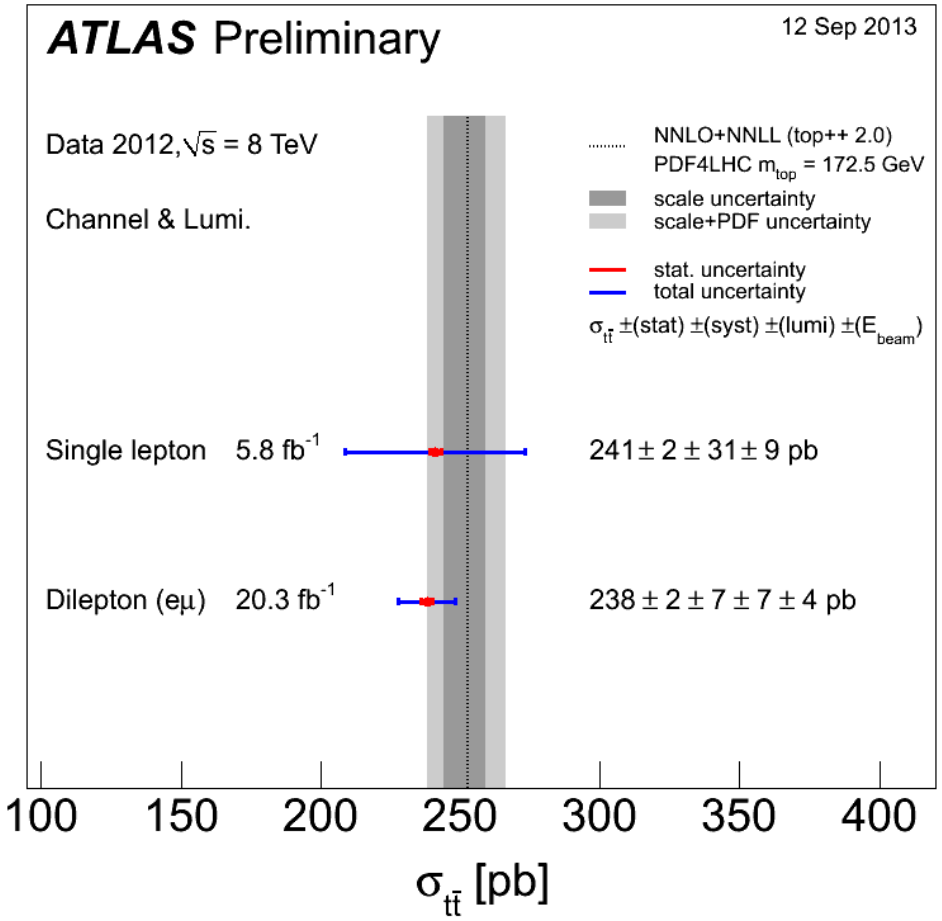
Event counts	N_1	N_2
Data	21559	11682
Wt single top	2070 ± 220	360 ± 120
Dibosons	120 ± 90	3 ± 6
$Z(\rightarrow \tau\tau \rightarrow e\mu)$+jets	210 ± 10	8 ± 1
Misidentified leptons	240 ± 70	110 ± 60
Total background	2640 ± 250	480 ± 140

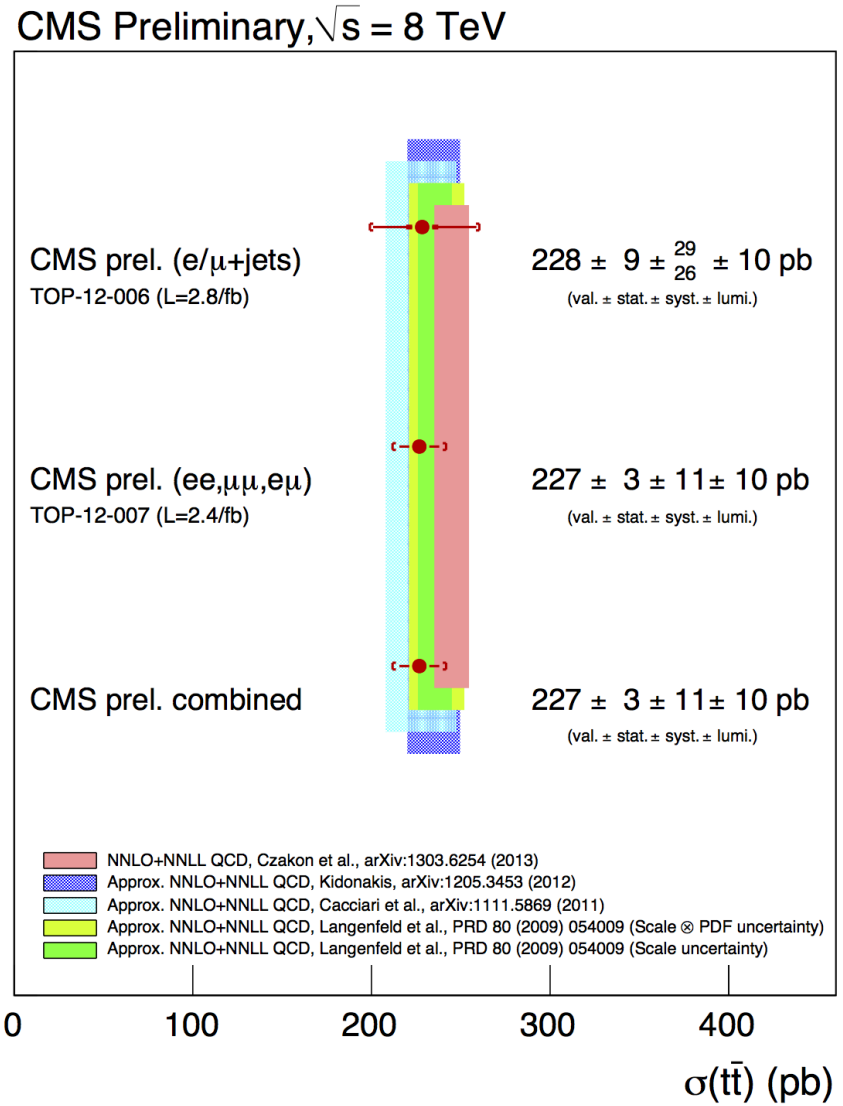
- Most precise measurement:
  - 4.7 % uncertainty
  - Dominant ones are:
    → Signal model, e-ID, PDFs
    → Largest: Luminosity & beam
- Theory prediction: $\sigma(t\bar{t})$ (NNLO+NNLL):
  - $252.9^{+13.3}_{-14.5}$ pb
  - 5.5 % uncertainty
  - Includes scale, α_s and PDF

There is an uncertainty of 0.66% on the beam energy, translating to a 1.7% uncertainty on $\sigma(t\bar{t})$

$$\sigma(t\bar{t}) = (\ 237.7 \pm 1.7\ (\text{stat}) \pm 7.4(\text{syst}) \pm 7.4(\text{lumi}) \pm 4.0(\text{beam energy}))\ \text{pb}$$

Summary at 8 TeV





- Further reduction by combination
  - → see Talk by Serban Protopopescu
- Most precise theory prediction by Czakon et al.: ~ 4.2 %

Conclusions

- Presented recent cross-section measurements at Tevatron & LHC

- Tevatron: → Results are in **good agreement** with theory
- LHC: → All results at 7/8TeV are compatible between exp. and theory
  → High precision measurements @8 TeV despite the higher pile-up environment compared to 7 TeV
  → **Most precise** measurement to date in **dilepton channel** by ATLAS
  → **Challenging theory predictions**

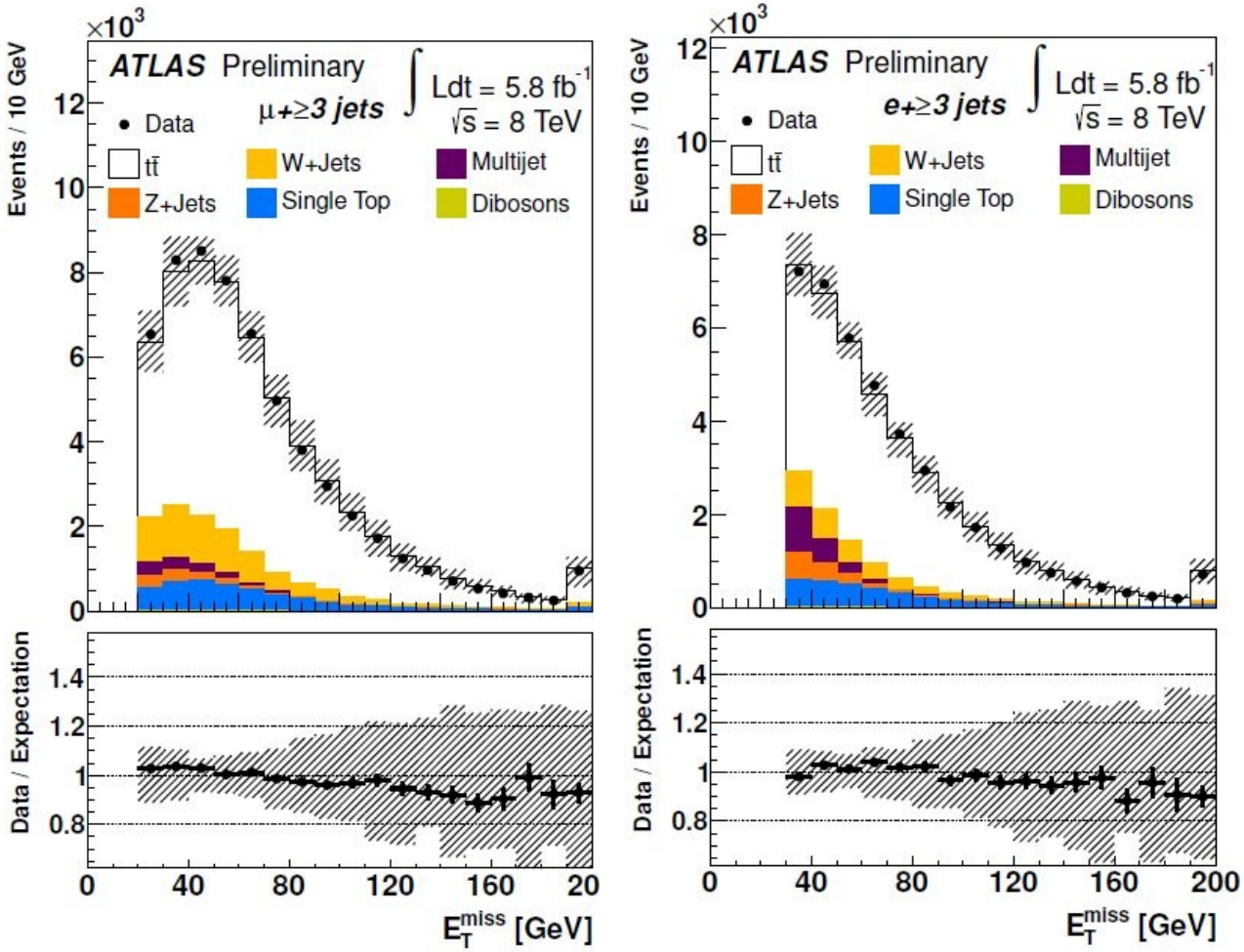
Outlook:

- Final results to come from Tevatron very soon
- More high precision results to come for LHC

Additional material

lepton+jets at 8 TeV

	e+≥3 jets	μ+≥3 jets
$t\bar{t}$	31000^{+2900}_{-3100}	44000±4000
W+jets	5700±2400	9000±4000
Multijet	1900± 900	1100± 500
Z+jets	1400± 600	1200± 500
Single top	3260± 160	4610± 230
Dibosons	115± 6	158± 8
Total Expected	43000±4000	61000±6000
Data	40794	58872



lepton+jets at 7 TeV

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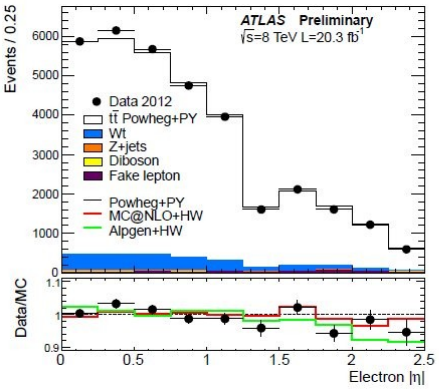
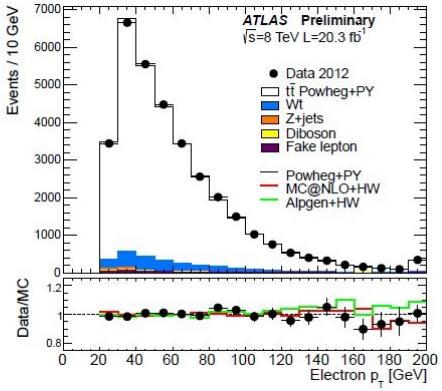
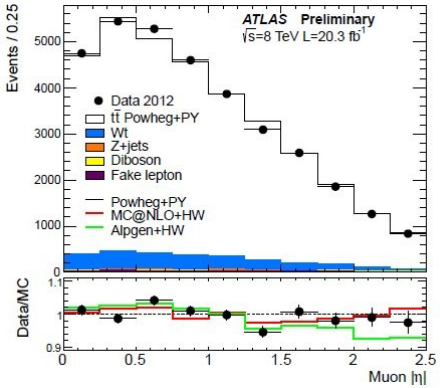
	$t\bar{t}$	Single t	W + b	W + c	W + LF	Z + jets	c_{Q^2}	b-tag	JES	Mistag
$t\bar{t}$	1.00	−0.13	−0.48	0.33	0.03	0.07	−0.07	−0.70	−0.81	0.00
Single t	−0.13	1.00	−0.52	0.04	0.03	−0.03	0.06	−0.08	0.09	−0.00
W + b	−0.48	−0.52	1.00	0.05	0.13	−0.16	0.27	0.26	0.42	−0.02
W + c	0.33	0.04	0.05	1.00	0.01	0.15	0.71	−0.38	−0.26	−0.02
W + LF	0.03	0.03	0.13	0.01	1.00	−0.19	0.21	−0.03	−0.05	−0.83
Z + jets	0.07	−0.03	−0.16	0.15	−0.19	1.00	0.23	−0.01	−0.10	0.01
c_{Q^2}	−0.07	0.06	0.27	0.71	0.21	0.23	1.00	−0.02	0.15	−0.02
b-tag	−0.70	−0.08	0.26	−0.38	−0.03	−0.01	−0.02	1.00	0.43	−0.02
JES	−0.81	0.09	0.42	−0.26	−0.05	−0.10	0.15	0.43	1.00	0.01
Mistag	0.00	−0.00	−0.02	−0.02	−0.83	0.01	−0.02	−0.02	0.01	1.00

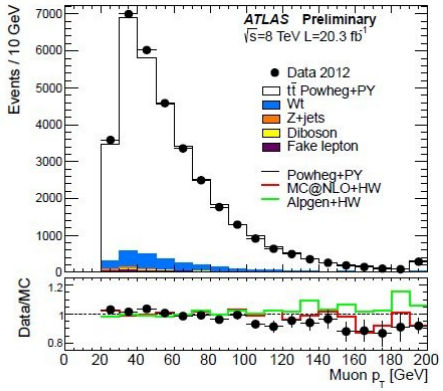
Fit parameters	Electron + jets	Muon + jets	Combined
$\sigma_{t\bar{t}}$ (pb)	160.6 ± 6.6	164.2 ± 5.5	158.1 ± 4.1
Single top	1.05 ± 0.10	1.08 ± 0.10	1.17 ± 0.10
W + b jets	1.19 ± 0.35	0.95 ± 0.18	1.28 ± 0.16
W + c jets	1.54 ± 0.15	1.48 ± 0.05	1.55 ± 0.04
W + LF jets	0.20 ± 0.08	0.57 ± 0.07	0.52 ± 0.06
Z + jets	1.13 ± 0.29	1.08 ± 0.29	1.43 ± 0.29
c_{Q^2}	1.02 ± 0.16	0.94 ± 0.06	1.05 ± 0.05
b-tag	0.95 ± 0.01	0.97 ± 0.01	0.96 ± 0.01
JES	1.00 ± 0.02	0.98 ± 0.01	1.00 ± 0.01
Mistag	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10

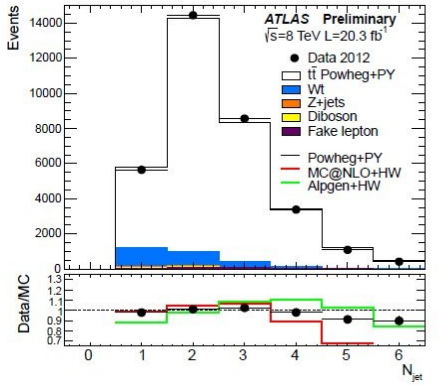
dilepton (eμ) at 8 TeV

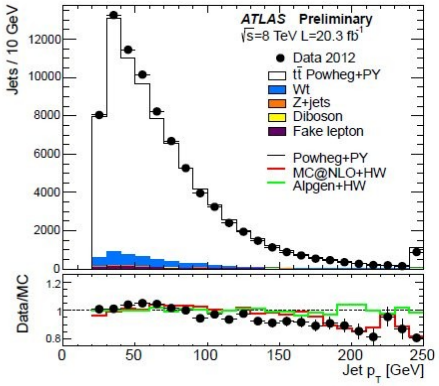


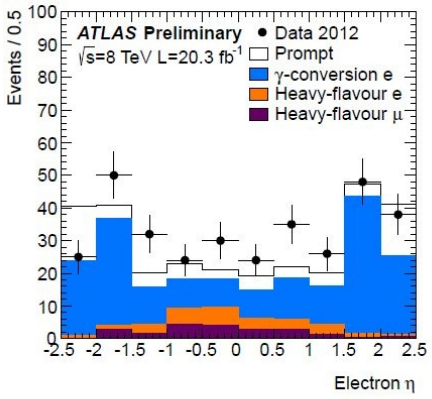




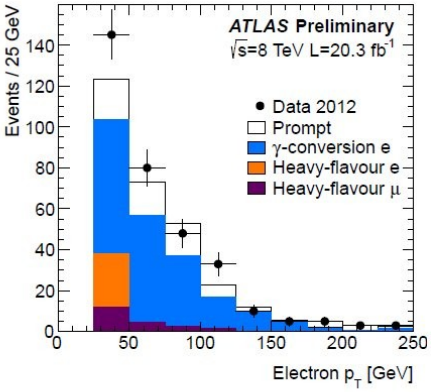








(a)



(b)