Top Cross Sections and Asymmetries

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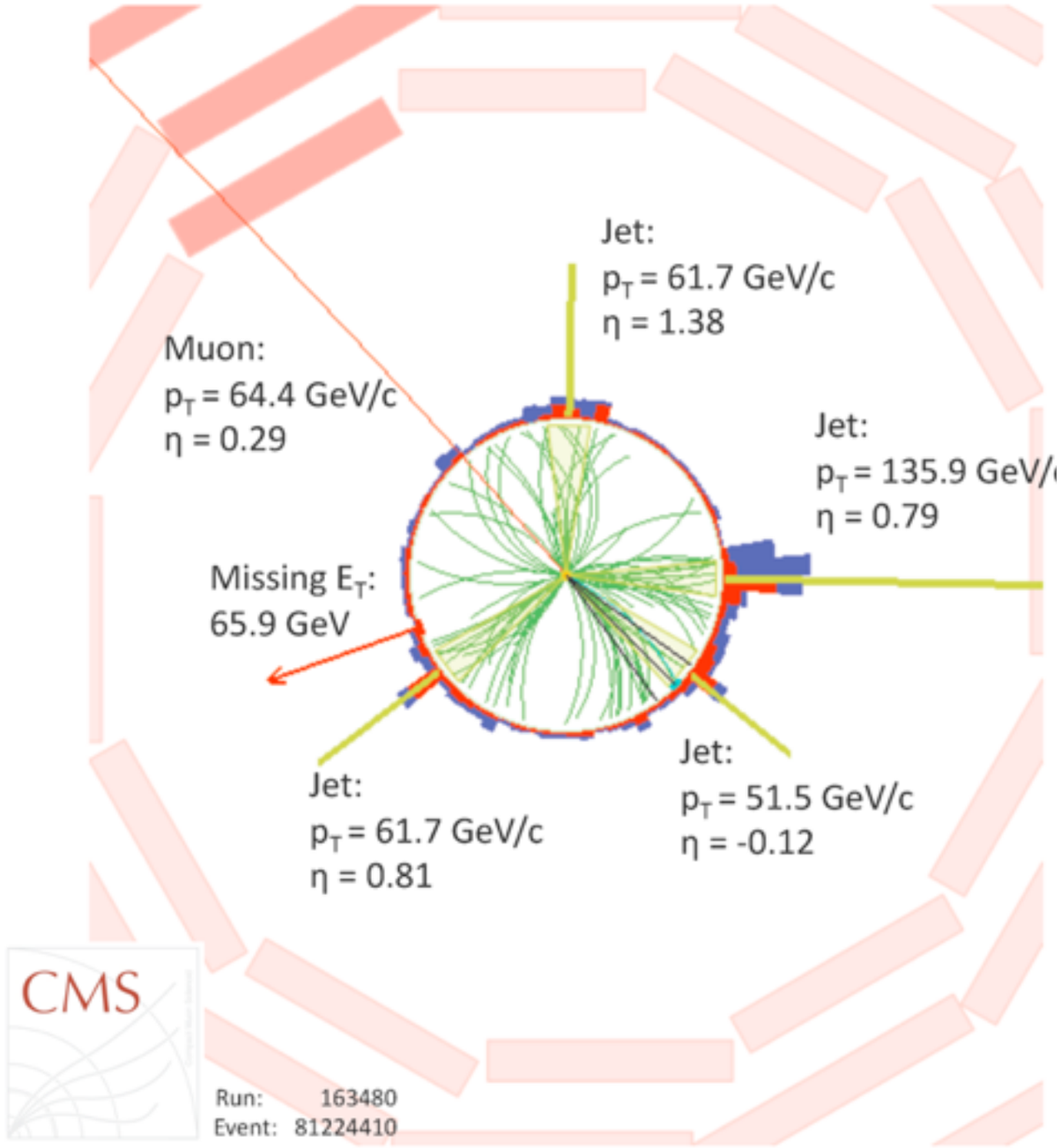
on behalf of the
ATLAS, CDF, CMS, DØ
Collaborations

19 January 2014

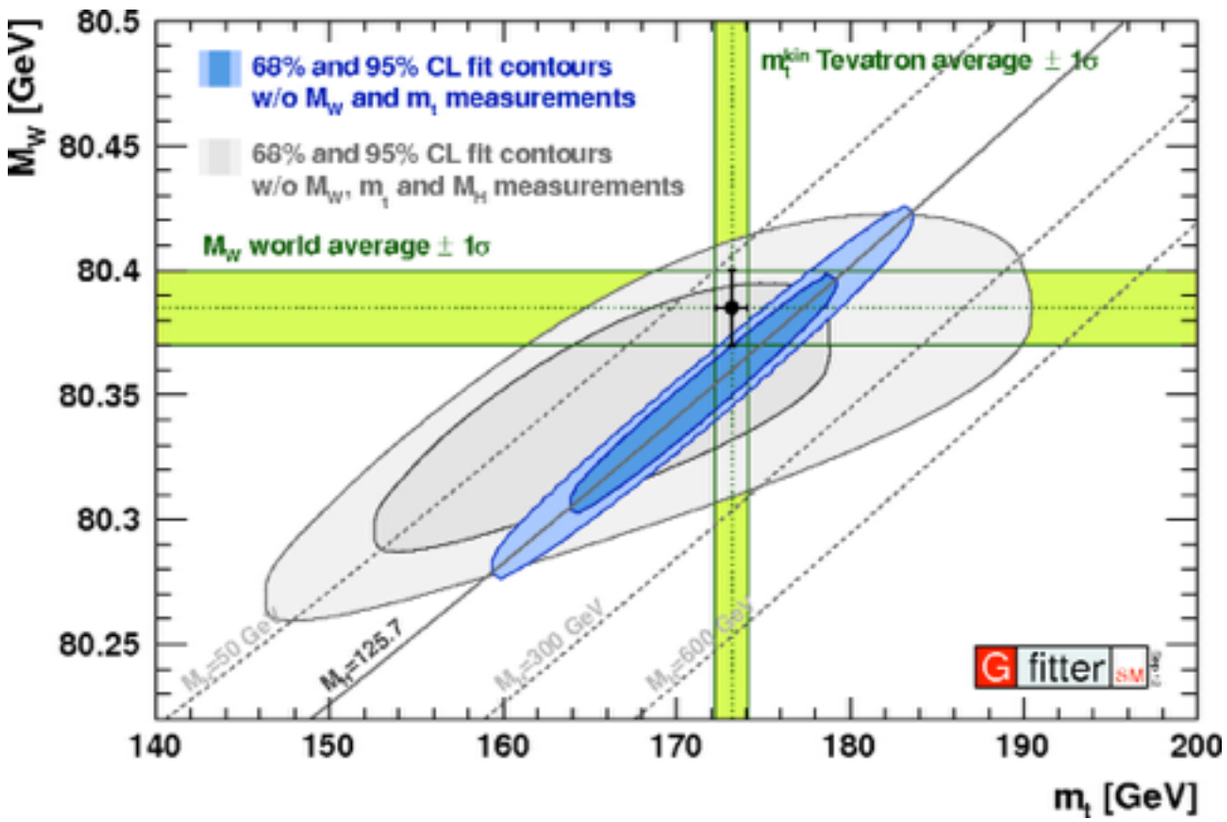
Aspen Winter Conference 2014



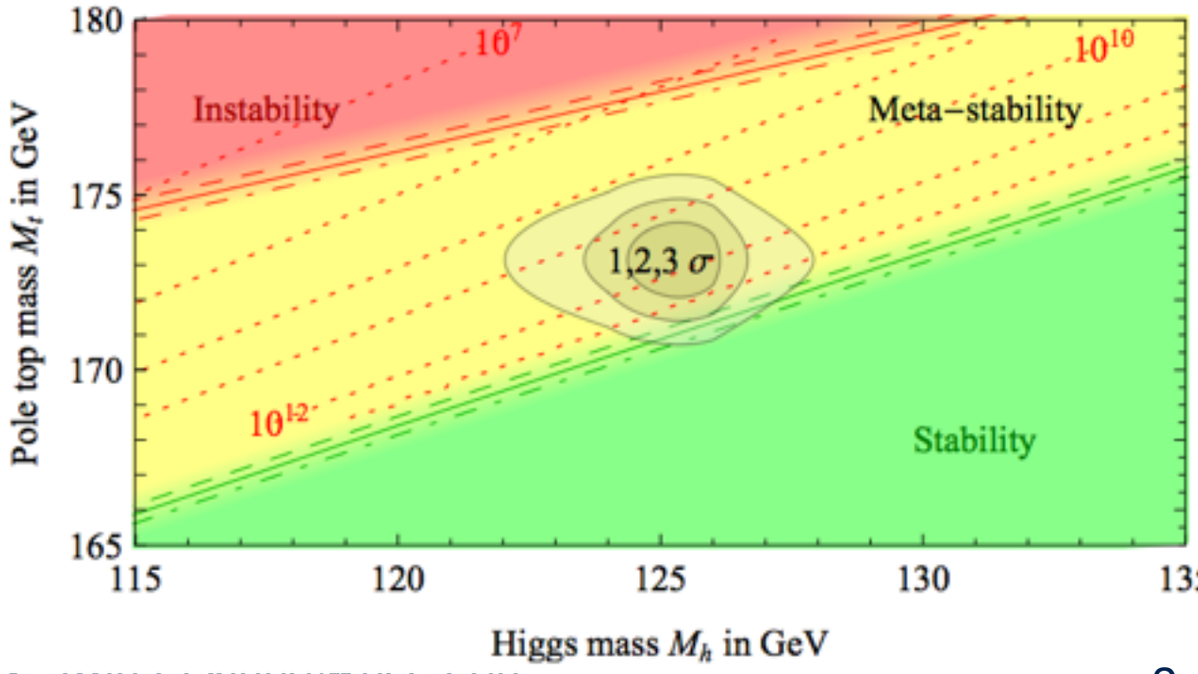
Motivation for Top Physics

- Top is the heaviest SM fermion
  - may play an unusual role in EWSB or a special role in new physics
- Production is a precision test of QCD and EW theories
  - discrepancy may point to NP especially if it couples to mass
- Is top a SM quark?
  - pair production QCD
  - single top EW
  - measurement of properties, mass, and couplings testable in production and decay
- Top mass (cf talk by K-J Grahn)
  - prime interest for testing SM

arXiv:1209.2716



arXiv:1205.6497

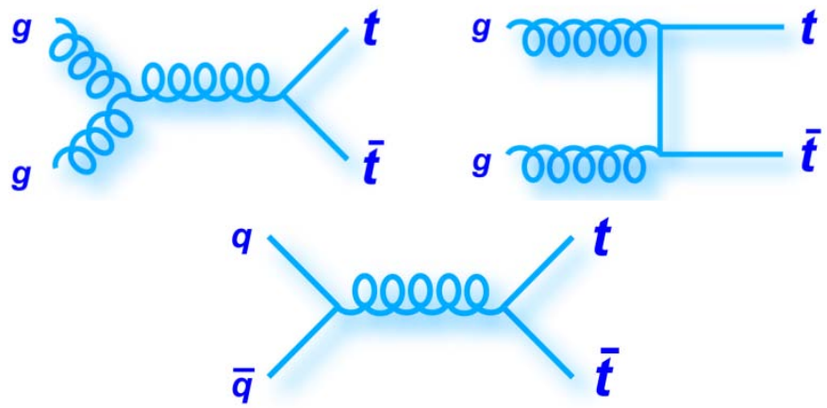


Outline

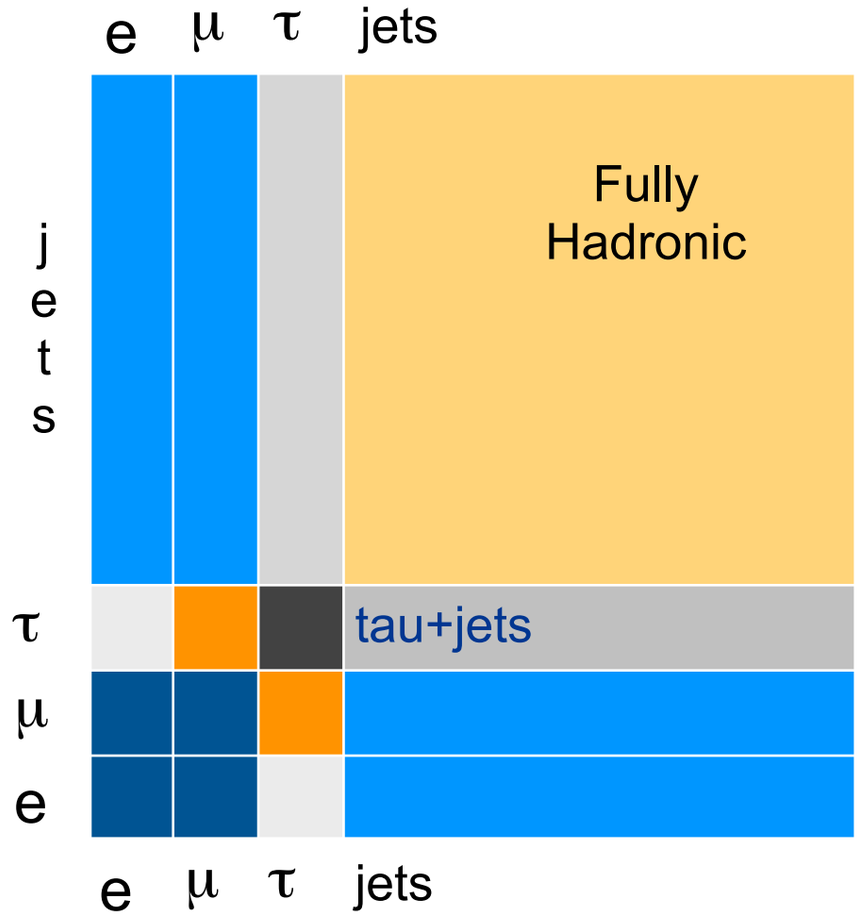
- Top pair cross sections
  - hadronic, semi-leptonic, dileptonic channels
  - comparison to standard model (QCD) calculations
- Top pair production Charge Asymmetry
  - Tevatron and LHC
- Single Top production
  - t-channel review
  - s-channel evidence from the Tevatron
  - tW production observation at the LHC

Top Pair Cross Section

- SM Production
  - gluon fusion ~15% Tevatron, 85% LHC,
  - qq̄ annihilation ~85% Tevatron, 15% LHC
- SM cross sections (NNLO+NNLL)
  - Tevatron pp-bar 1.96 TeV
    - 1.96 TeV $\sigma = 7.16^{+0.11}_{-0.20}{}^{+0.17}_{-0.12}$ pb
  - LHC pp (scale, pdf)
    - 7 TeV $\sigma = 172^{+4.4}_{-5.8}{}^{+4.7}_{-4.8}$ pb
    - 8 TeV $\sigma = 246^{+6.2}_{-8.4}{}^{+6.2}_{-6.4}$ pb
    - 14 TeV $\sigma = 954^{+23}_{-34}{}^{+16}_{-18}$ pb
- SM Decay
  - Expect ~100% t→Wb ($|V_{tb}|\sim 1$)
  - tt̄ channels characterized by W decays
    - dilepton: $t\bar{t} \to W^+bW^-\bar{b} \to \ell^+\nu b \ell^-\bar{\nu}\bar{b}$
    - lepton+jets: $t\bar{t} \to \ell\nu b q_i q_j \bar{b}$



M.Czakon et al. PRL 110 (2013) 252004
(m_t=173.3 GeV, MSTW2008nnlo68cl)



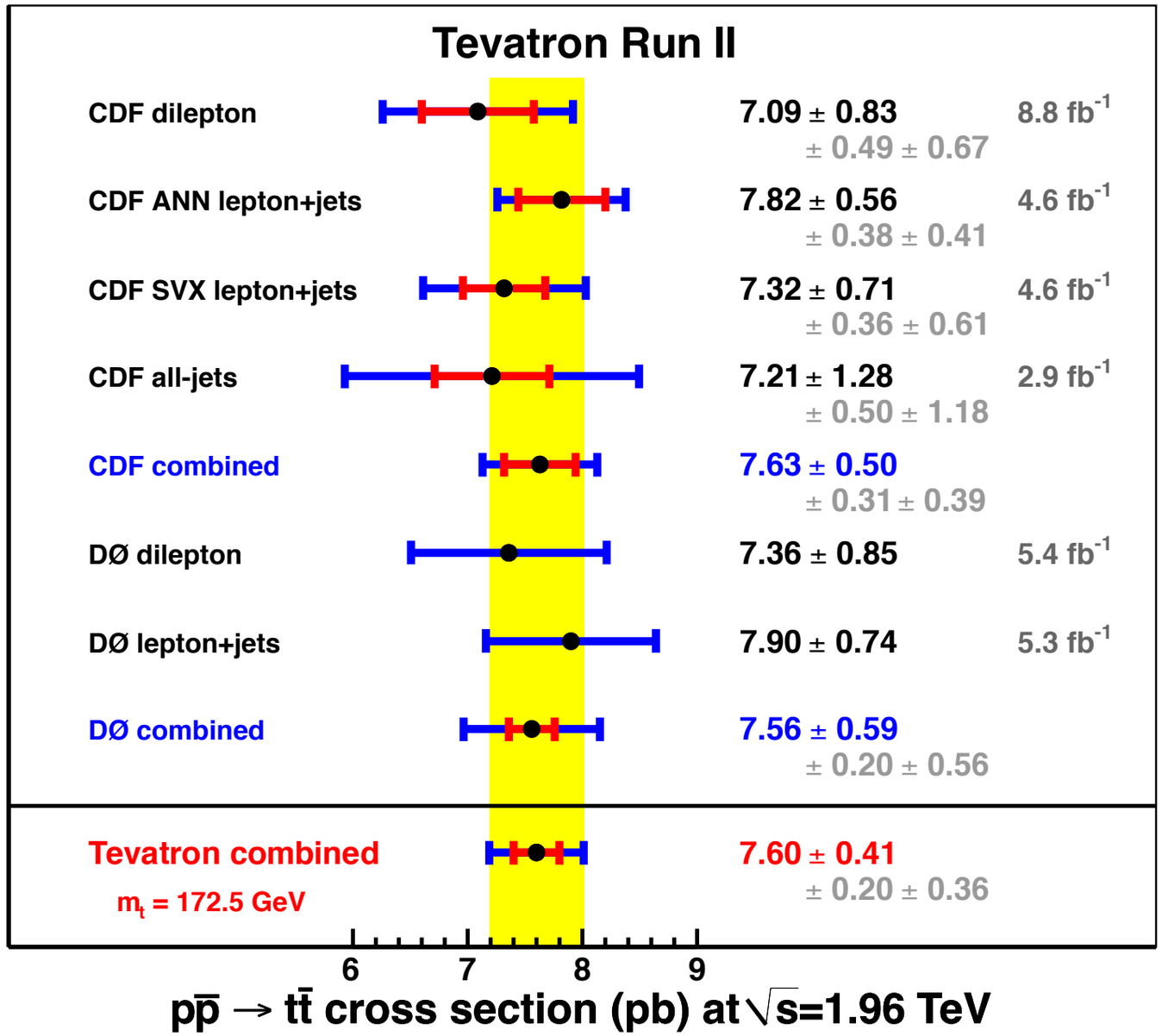
New

Tevatron Combination

CDF dilepton PRD **88**, 091103(2013)
CDF lepton+jets PRL **105**, 012011(2010)
CDF all jets PRD **81**, 052011 (2010)
DØ dilepton/lepton+jets PLB **74**, 403 (2011)

- Six analyses in three channels
  - Dilepton, Lepton+jets, All-jets
  - kinematic selection + b-tagging
- **B**est **L**inear **U**nbiased **E**stimate
  - correlations included
  - experiments are first combined individually then jointly
  - BLUE gives weight ratio of 60:40
- m_t dependence given
- 25% improvement possible
  - Additional data to be analyzed
  - luminosity uncertainty via Z/γ*

arXiv:1309.7570 CDF+D0 combination

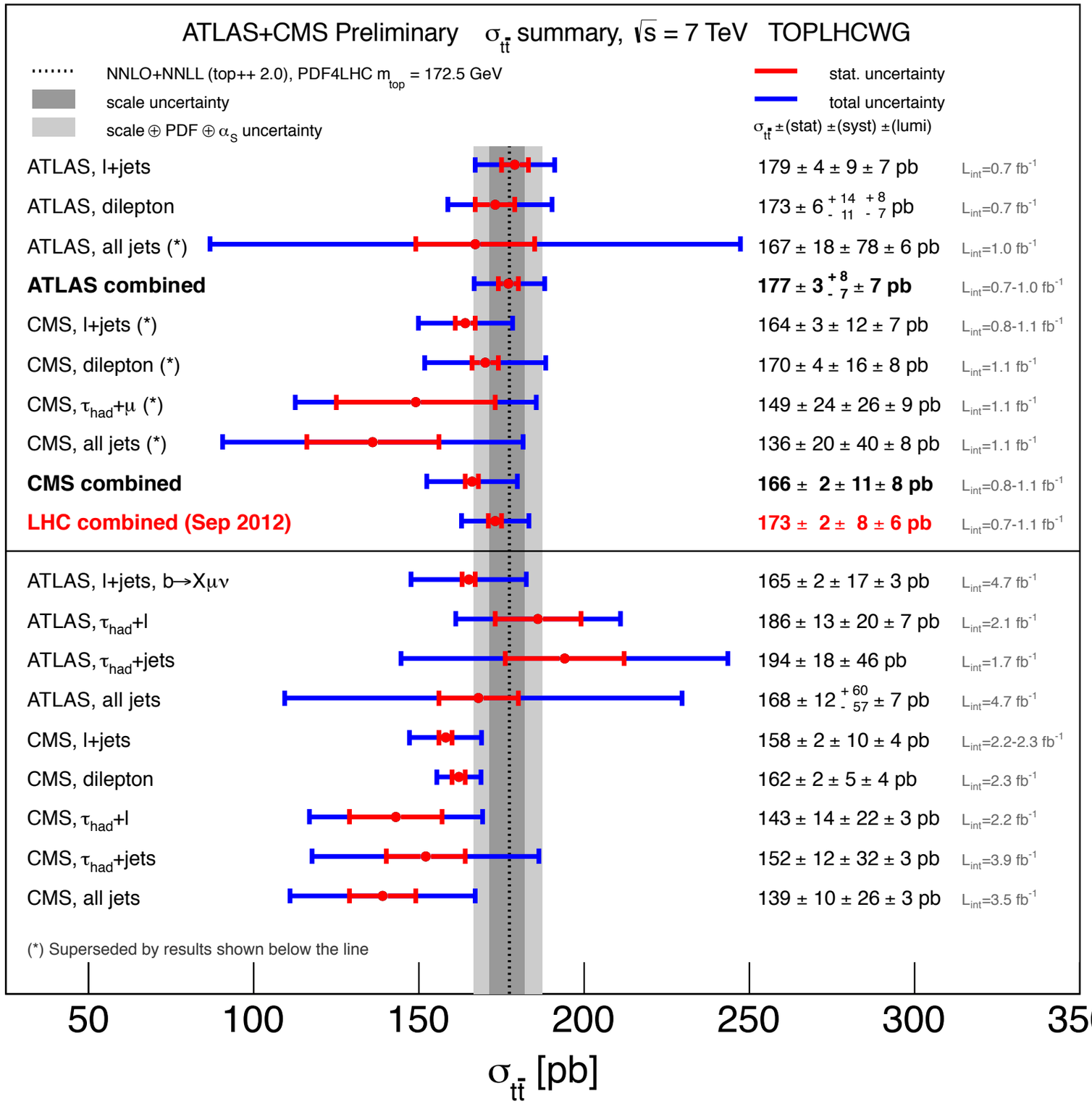


5.4% measurement in agreement with

$\sigma_{NNLO}=7.35^{+0.28}_{-0.33}$ pb (m_t=172.5 GeV)

LHC 7 TeV Compilation

- pair production seen in many channels
- σ_{tt} in good agreement with NNLO QCD
- no surprise in tau channels
- Analyses have evolved with added luminosity & techniques



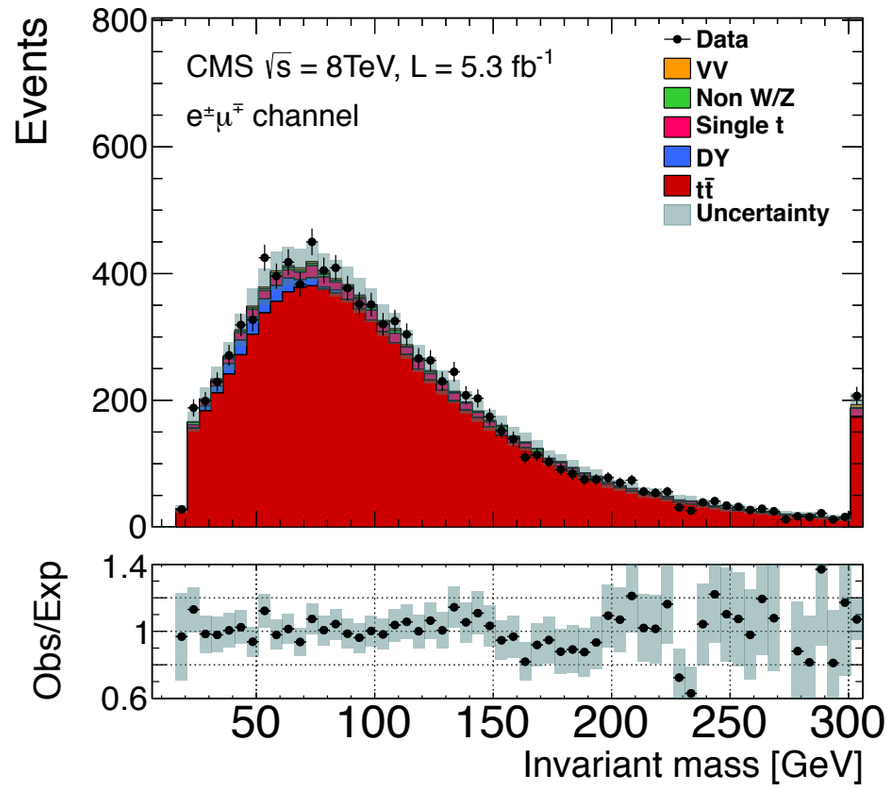
New

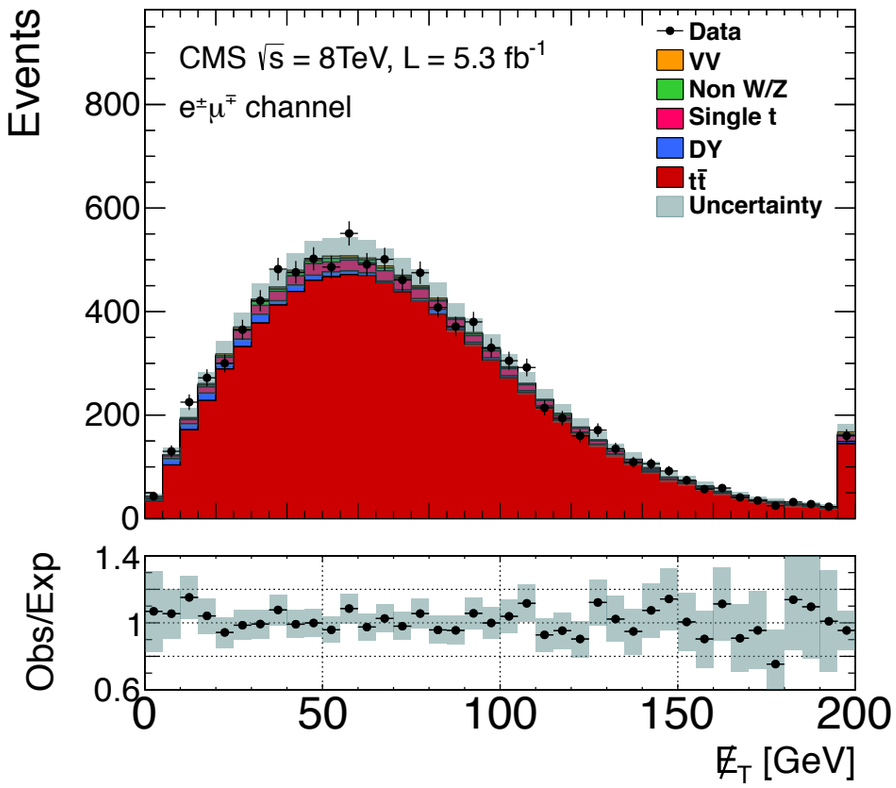
CMS 8 TeV σ_{tt} dilepton channel

arXiv:1312.7582 to appear in JHEP

- counting experiment
- eμ,ee,μμ channels
- high purity selection
  - isolated leptons p_T>20 GeV
  - ≥ 1 b-tagged jet
  - missing E_T>40 for ee & μμ
- Backgrounds from data (except: VV)

	Number of events		
Source	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Drell–Yan	386±116	492±148	194±58
Non-W/Z leptons	25±10	114±46	185±72
Single top quark	127±28	157±34	413±88
VV	30±8	39±10	94±21
Total background	569±120	802±159	886±130
$t\bar{t}$ dilepton signal	2728±182	3630±250	9624±504
Data	3204	4180	9982





σ_{tt}=239 ± 2 (stat) ±11 (syst) ± 6 (lumi) pb

NNLO+NNLL: $\sigma_{tt}=253^{+6.4}_{-8.6}$(Q² scale)±11.7 (pdf+$\alpha_S$) pb

New

CMS 8 TeV σ_{tt} dilepton channel

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Uncertainties

Source	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Trigger efficiencies	4.1	3.0	3.6
Lepton efficiencies	5.8	5.6	4.0
Lepton energy scale	0.6	0.3	0.2
Jet energy scale	10.3	10.8	5.2
Jet energy resolution	3.2	4.0	3.0
b-jet tagging	1.9	1.9	1.7
Pileup	1.7	1.5	2.0
Scale (μ_F and μ_R)	5.7	5.5	5.6
Matching partons to showers	3.9	3.8	3.8
Single top quark	2.6	2.4	2.3
VV	0.7	0.7	0.5
Drell–Yan	10.8	10.3	1.5
Non-W/Z leptons	0.9	3.2	1.9
Total systematic	18.6	18.6	11.4
Integrated luminosity	6.4	6.1	6.2
Statistical	5.2	4.5	2.6

Leading sources: JES, simulation q^2 scale

σ_{tt}=239 ± 2 (stat) ±11 (syst) ± 6 (lumi) pb

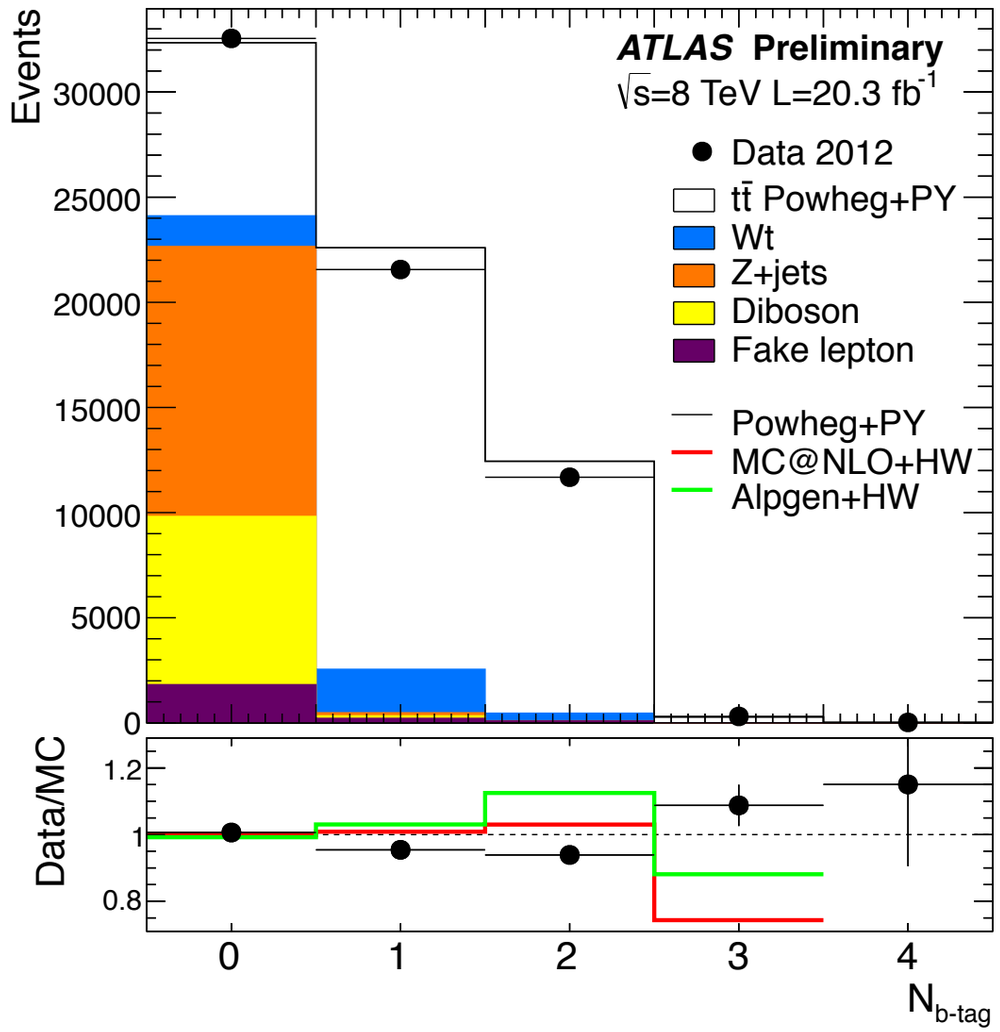
NNLO+NNLL: $\sigma_{tt}=253^{+6.4}_{-8.6}$($Q^2$ scale)±11.7 (pdf+α_S) pb

New

ATLAS 8 TeV eμ 20 fb^{-1}

ATLAS-CONF-2013-097

- Candidate selection
  - eμ only (lowest DY bkgd)
  - isolated leptons p_T>25 GeV
  - 1 or 2 b-tagged jets
  - *in situ* b-tag efficiency extraction
- backgrounds from simulation & data

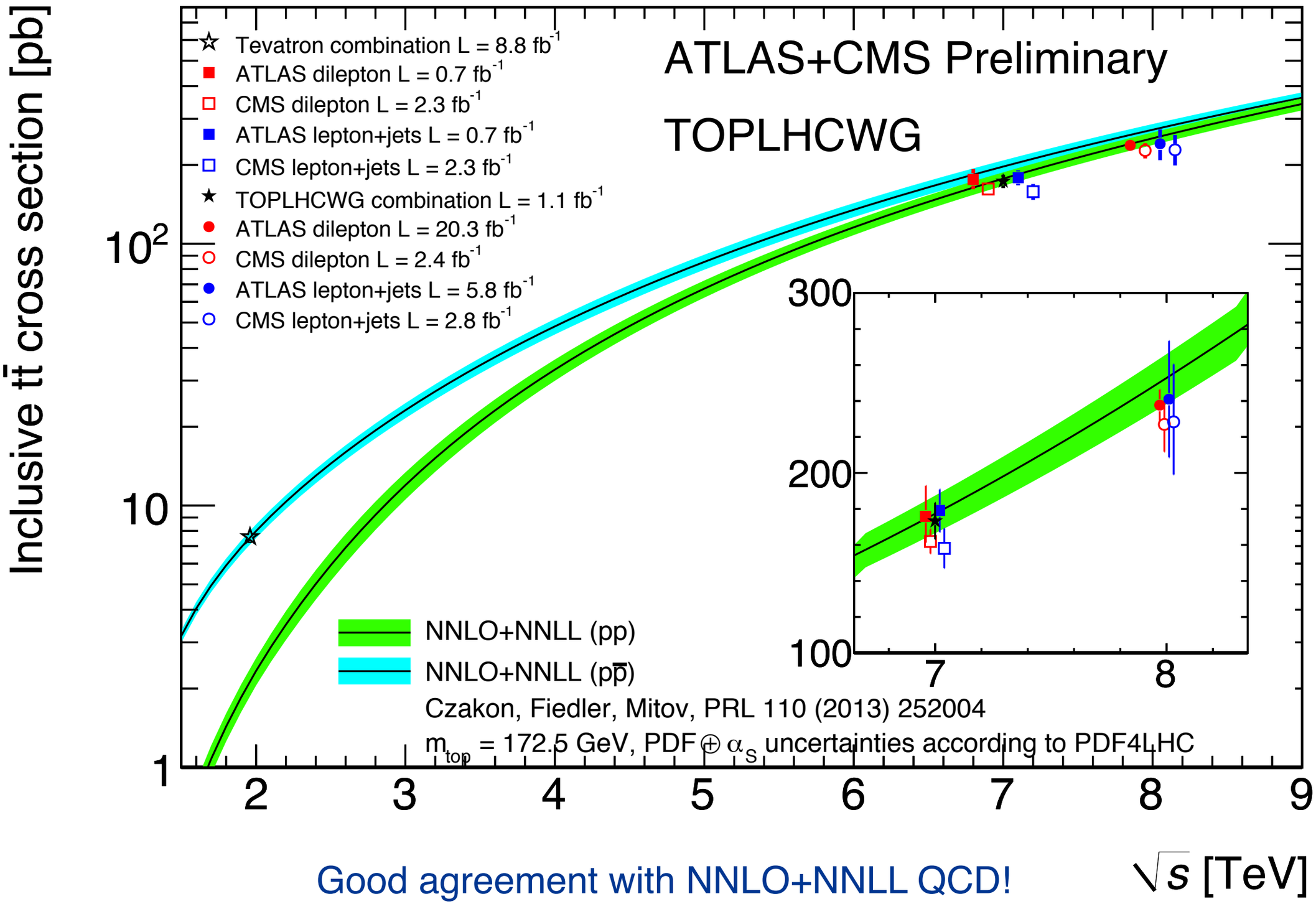


Event counts	N_1	N_2
Data	21559	11682
Wt single top	2070 ± 220	360 ± 120
Dibosons	120 ± 90	3^{+6}_{-3}
$Z(\rightarrow \tau\tau \rightarrow e\mu)$+jets	210 ± 10	8 ± 1
Misidentified leptons	240 ± 70	110 ± 60
Total background	2640 ± 250	480 ± 140

σ_{tt}=237.7 ± 1.7 (stat) ± 7.4 (syst) ± 7.4 (lumi) ± 7.4 (E_{beam}) pb [4.8%]

NNLO+NNLL: $\sigma_{tt}=253^{+6.4}_{-8.6}$ (Q^2 scale)±11.7 (pdf+α_S) pb

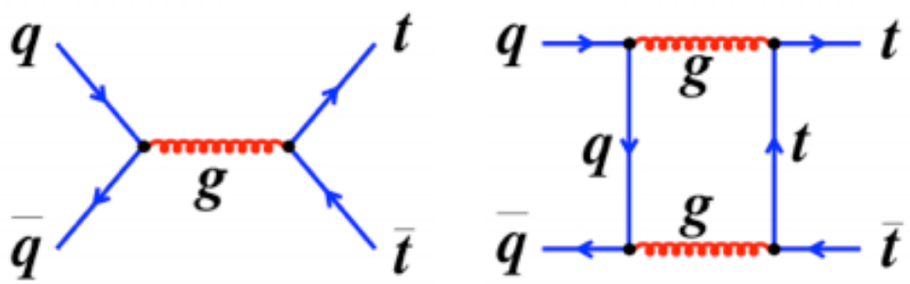
Top-pair production summary

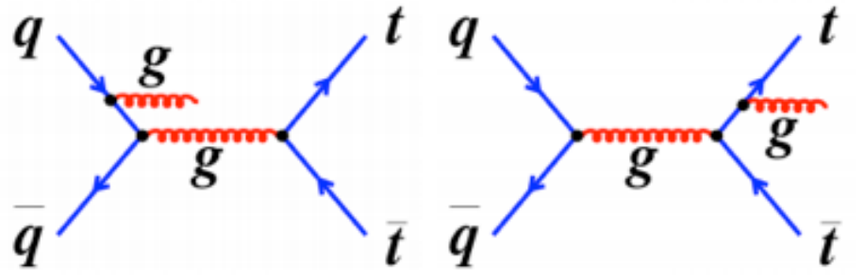


Good agreement with NNLO+NNLL QCD!

Charge Asymmetry in t tbar production

Top - Anti Top asymmetries
from interference of
LO, box, radiative diagrams

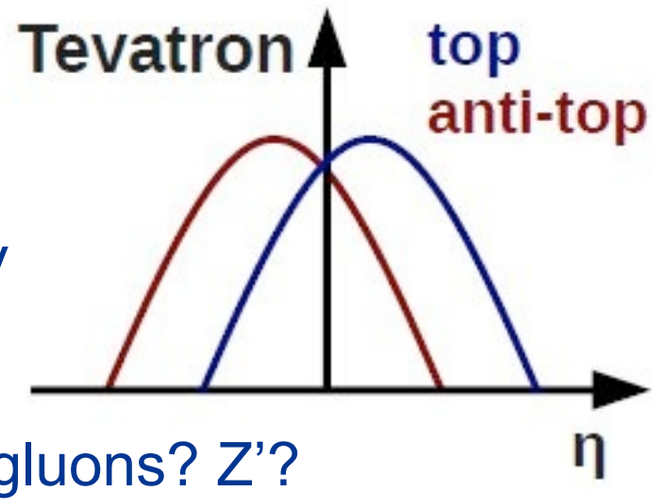




$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \qquad \Delta y = y_t - y_{\bar{t}}$$

Look at (pseudo)rapidity or rapidity difference

<u>Forward-backward</u>
Observed by D0 & CDF
~2σ larger A_C than QCD
CDF more so M_{tt}>450 GeV



Perhaps new physics? Axigluons? Z'?
Spurred detailed studies of full data samples
additional asymmetries using leptons from top decay

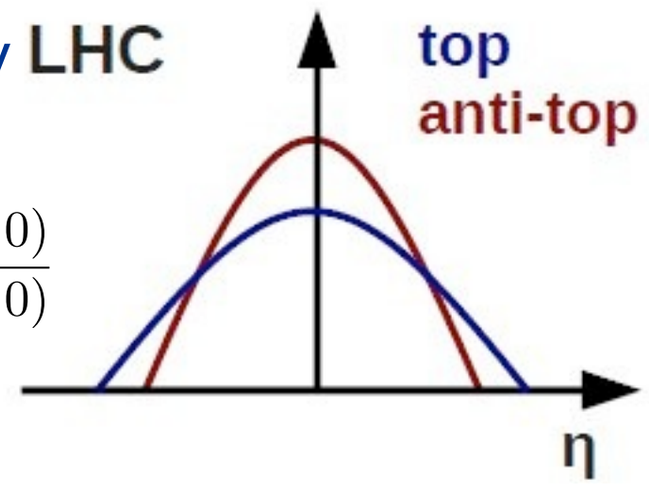
QCD calculations:
Tevatron A_C~5%
LHC A_C~1% (dilution from gg production)

Kuhn & Rodrigo PRL 81, 49 (1998)
Bernreuther & Si PRD 86, 034026 (2012)

<u>Central-beamward</u>
Measurements at 7, 8 TeV
from ATLAS & CMS

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

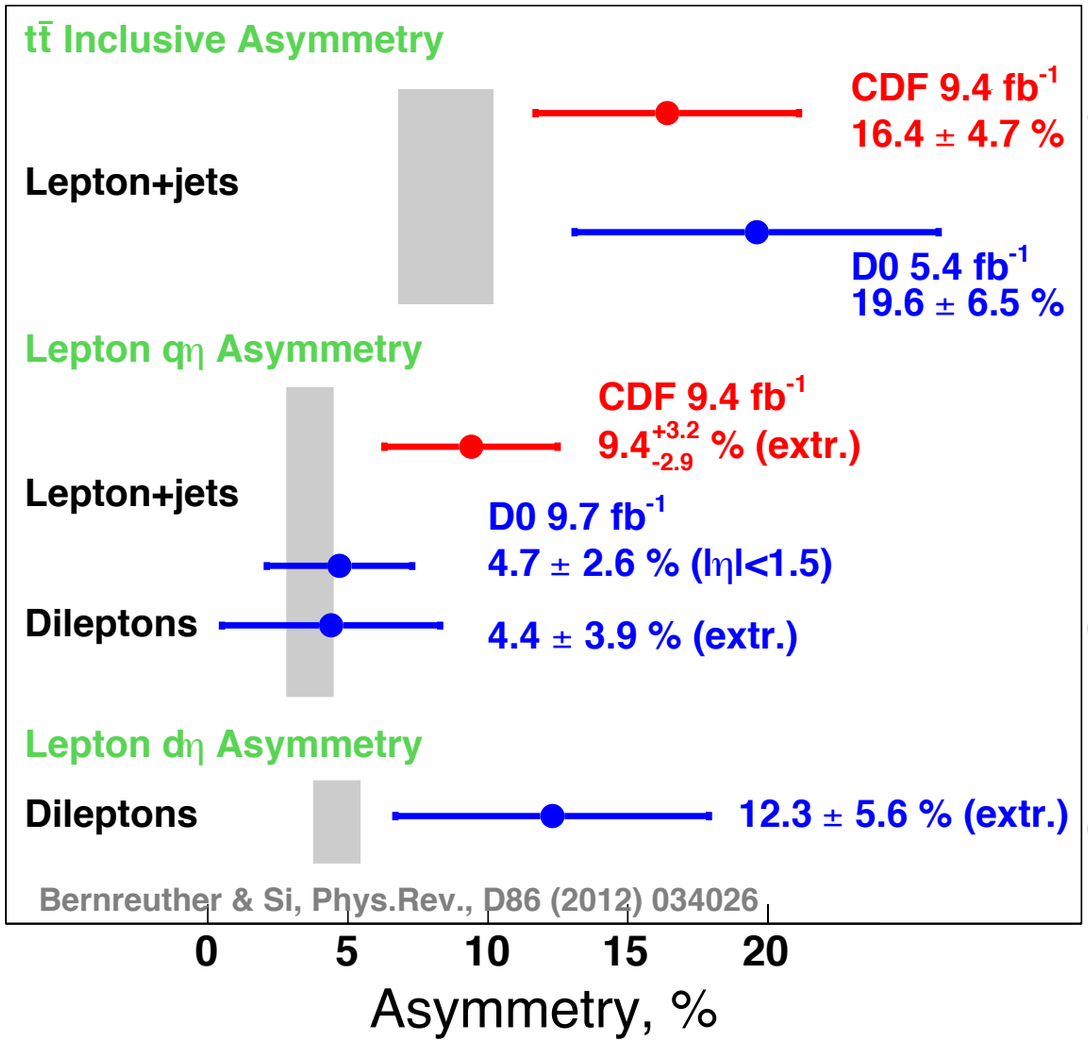
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



Also sensitive to New Physics
e.g. t-channel exchange of Z' with flavor changing couplings

Tevatron t tbar Charge Asymmetry

Tevatron Summary from TOP 2013 V.Sharyy



a. PRD 87 092002 (2013)
b. PRD 84 112005 (2011)
c. PRD 88 072003 (2013)
d. PRD 88 112002 (2013)

Significant recent work

- inclusion of full Run 2 data samples
- new observables
  - lepton charge asymmetry
  - differential distributions

Tension between QCD and experiment has eased but not fully resolved.

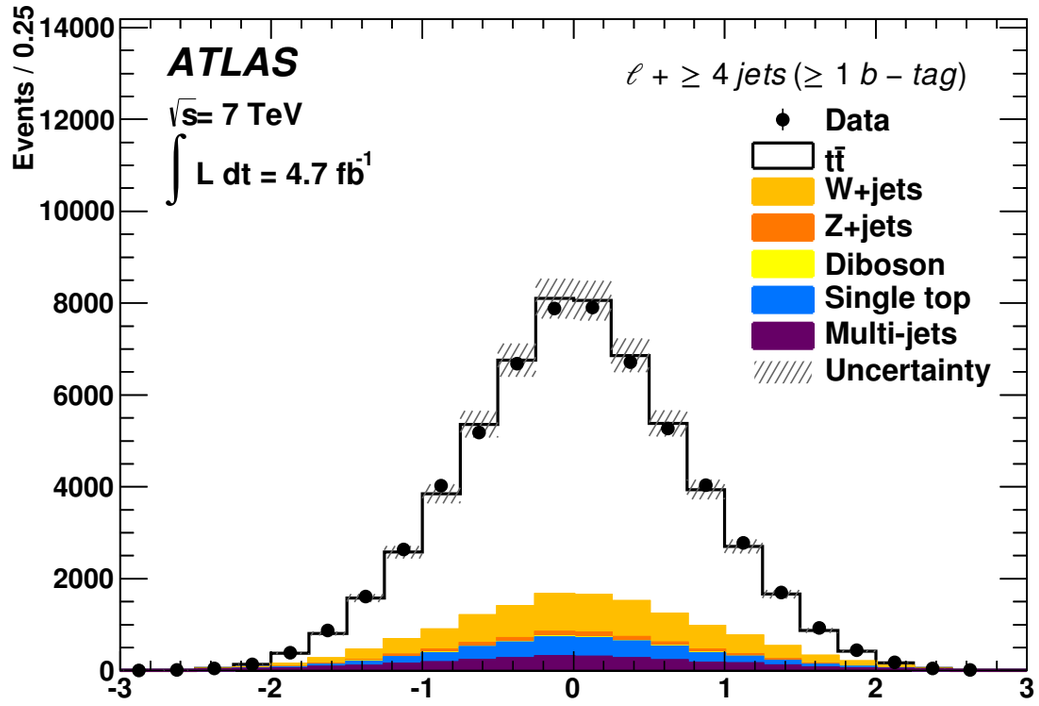
New

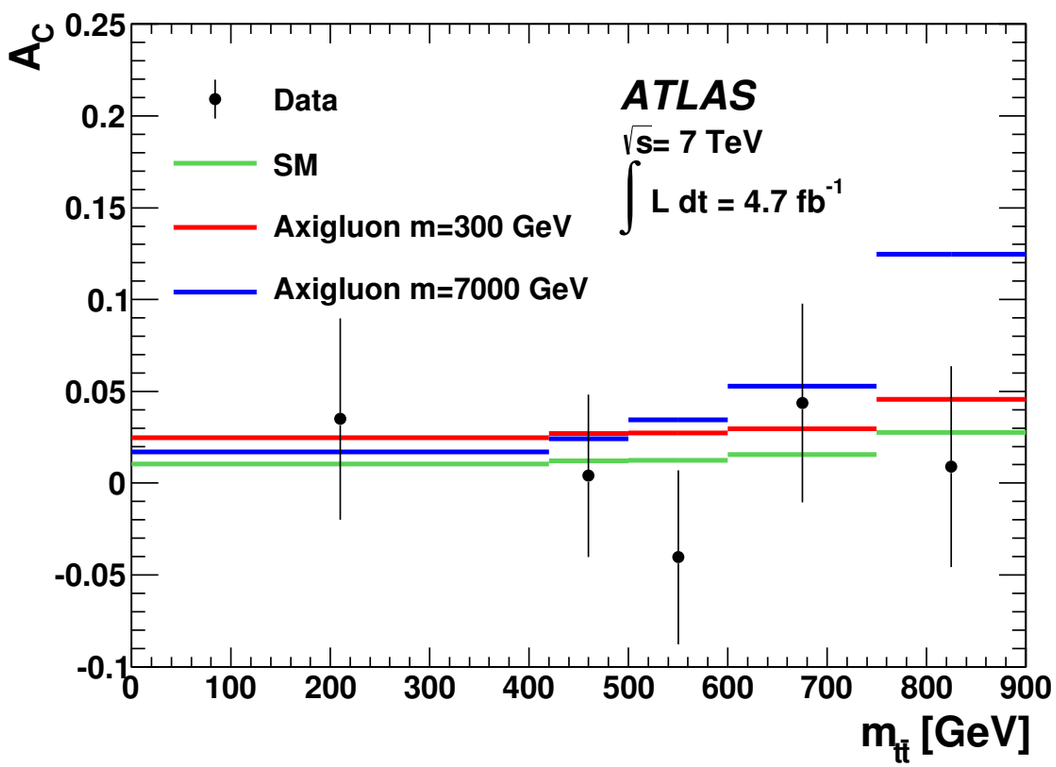
arXiv:1311.6724 sub to JHEP

ATLAS A_C in l+jet

- 7 TeV (4.7 fb^{-1})
- select t tbar events in e/μ+jets channel
  - isolated high p_T lepton
  - b-tagged jet(s)
  - MET & $M_T(W)$ used to suppress multi jets
- kinematic fit for top solution
  - t tbar likelihood
  - solution for t tbar system
- unfold to parton level
- Asymmetries compatible with QCD (and zero)

A_C	Data	Theory
Unfolded	0.006 ± 0.010	0.0123 ± 0.0005
Unfolded with $m_{t\bar{t}} > 600$ GeV	0.018 ± 0.022	$0.0175^{+0.0005}_{-0.0004}$
Unfolded with $\beta_{z,t\bar{t}} > 0.6$	0.011 ± 0.018	$0.020^{+0.006}_{-0.007}$



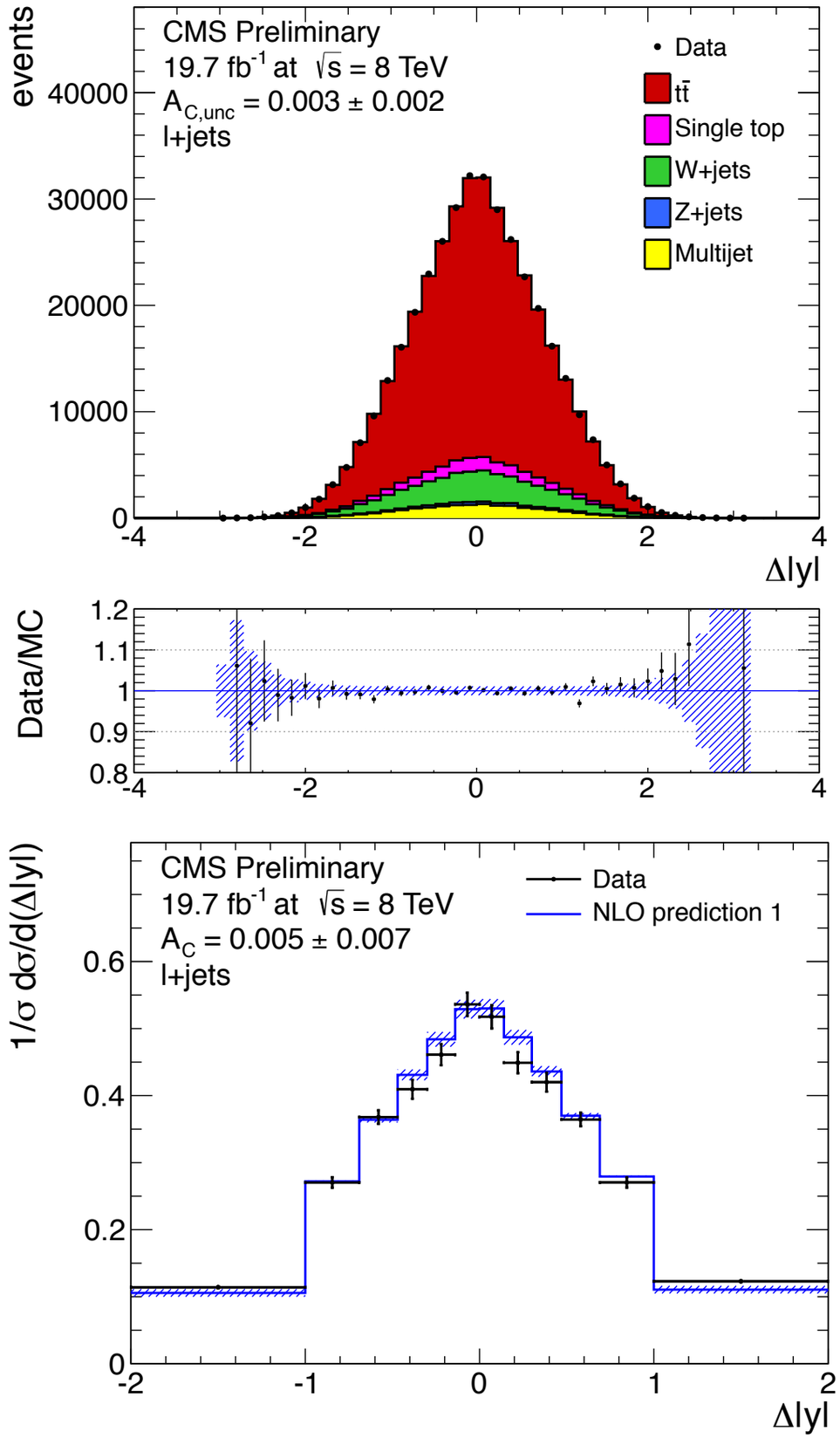


New

CMS-TOP-PAS-12-033

CMS A_C in l+jet

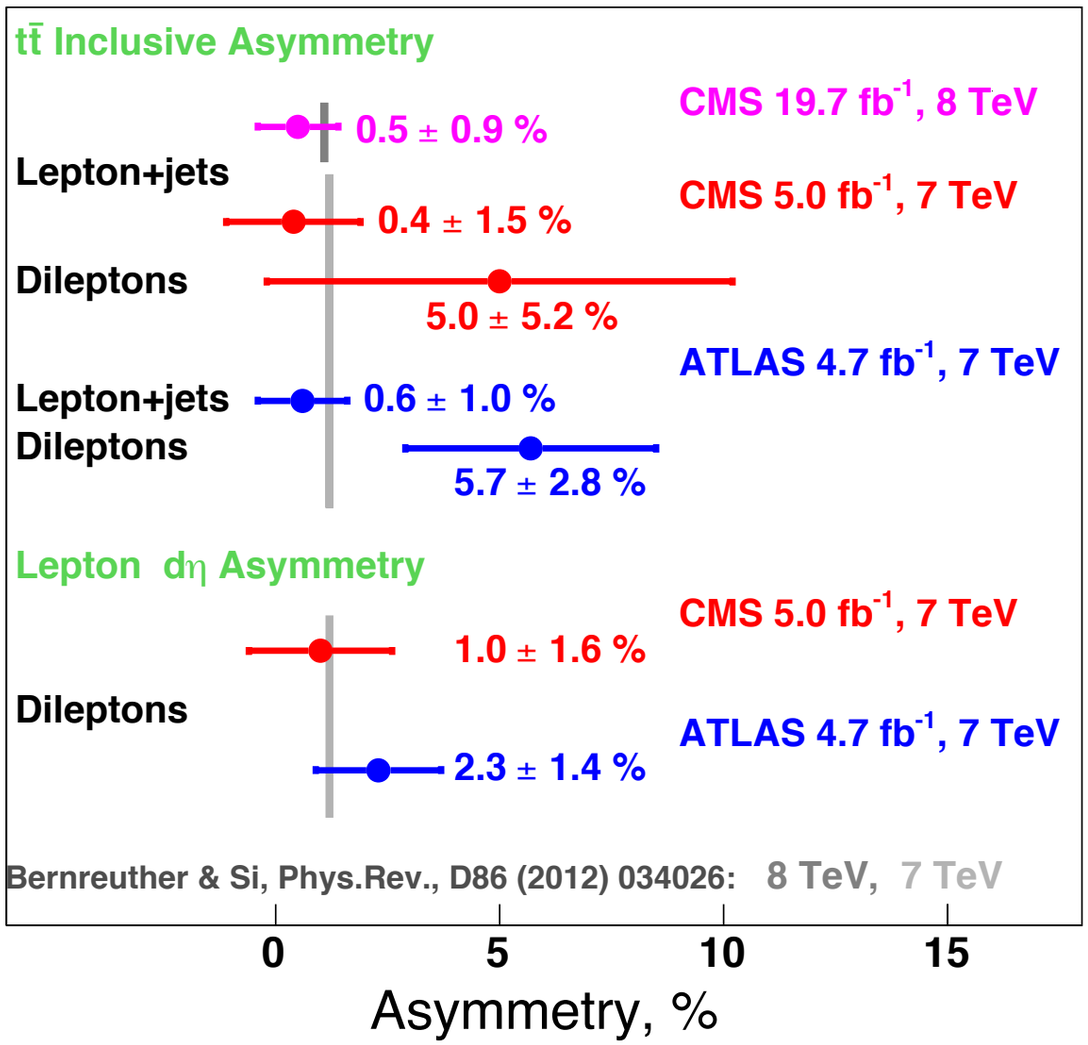
- 8 TeV (19.7 fb^{-1})
- e/μ + jets channel
  - isolated lepton
  - b-tagged jets
- control backgrounds with fit to kinematic distributions: M3, $M_T(W)$
- top reconstruction & unfolding to parton level
- Results consistent with theory
  - vs m(tt), y(tt), p_T(tt)



Asymmetry	A_C
Reconstructed	0.003 ± 0.002 (stat.)
BG-subtracted	0.002 ± 0.002 (stat.)
Unfolded	0.005 ± 0.007 (stat.) ± 0.006 (syst.)
Theory prediction [Kühn, Rodrigo] [9, 33]	0.0102 ± 0.0005
Theory prediction [Bernreuther, Zi] [34, 35]	0.0111 ± 0.0004

LHC t tbar Charge Asymmetry

LHC Summary from TOP 2013 V.Sharyy

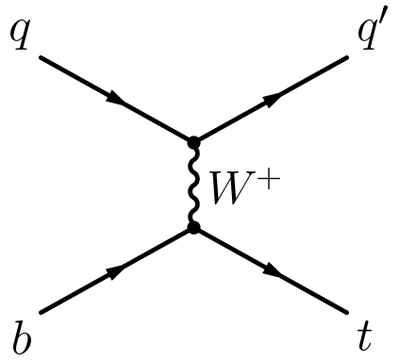


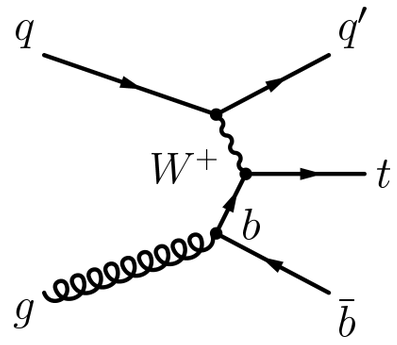
- Nice suite of measurements
  - 8 TeV still in progress for full data sample & channels
- A_C still compatible with zero
- Also compatible with SM
  - no hints of anomalous AC
- Some exotic models are ruled out via other channels
  - e.g. axigluon in m(t tbar) tail

Single Top Production

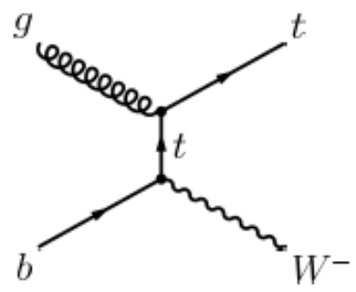
- Standard Model Electroweak Production

t channel

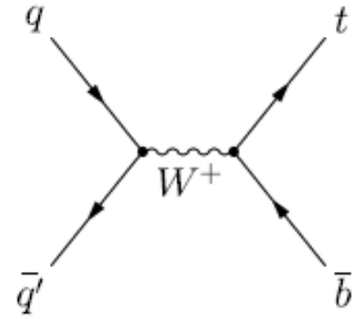




tW channel



s channel



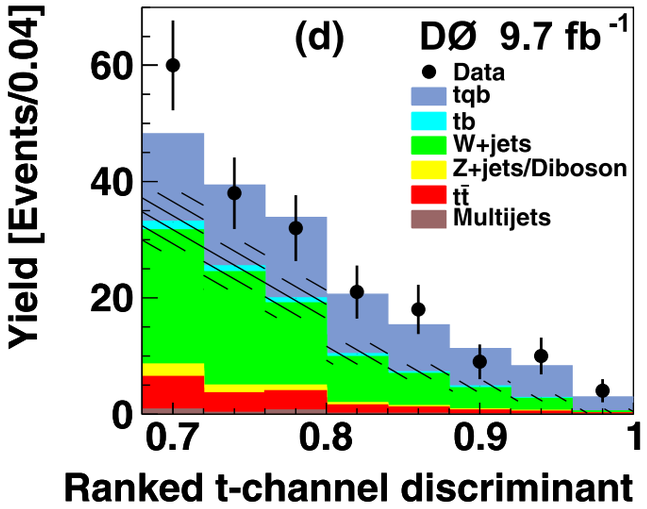
- Probes New Physics through top couplings
  - non-SM production or decay
- Single top discovered at the Tevatron
  - s+t-channel combined; now evidence for s-channel
- LHC t-channel measurements at 7 TeV and 8 TeV
  - tW channel now the focus of attention

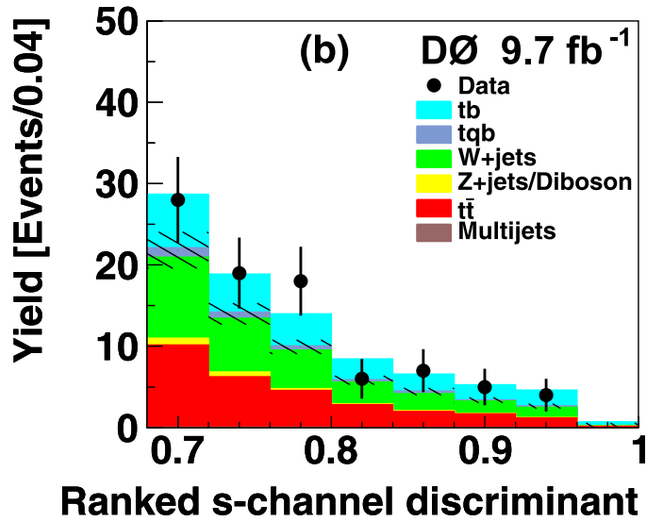
PLB 726, 656 (2013)
New

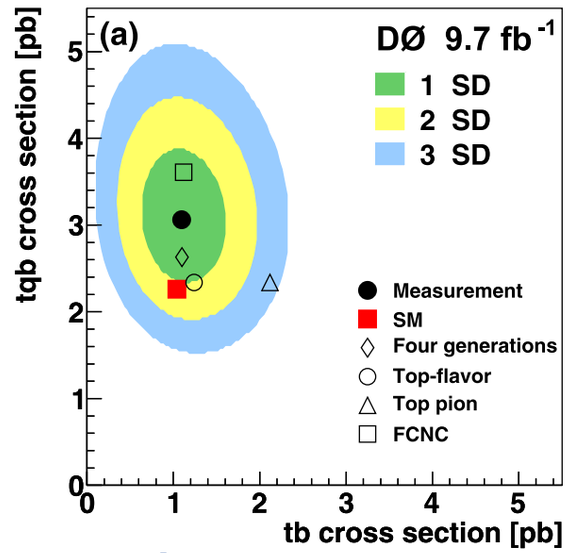
Latest Single Top at Tevatron

- DØ joint analysis of s- and t-channel using multiple MVAs
- Selection for t→Wb→$\ell\nu$b
  - one isolated e/μ
  - 2 or 3 jets, p_T>20 GeV, leading p_T>25
  - MET>20 (25) GeV for 2 (3) jets
- Bin in N_{jet} [2,3] $N_{b\text{-tag}}$ [1,2]
- Design MVAs for each channel (s/t) & bin to maximize sensitivity and suppress t tbar & W+jets
  - Matrix element, BDT, BNN
- Combined MVAs for s,t, s+t channel with Bayesian Neural Net
- Binned likelihood fit to extract σ's independently and jointly
  - s-channel p-value 10^{-4} (3.7σ)

Evidence for s channel







t-chan: σ_{tbq}=3.07 $^{+0.54}_{-0.49}$ pb

s-chan: σ_{tb}=1.10 $^{+0.33}_{-0.31}$ pb

s+t-chan: σ_{tb+tbq}=4.11 $^{+0.60}_{-0.55}$ pb

Compatible with SM prediction: σ_{tb}=1.04±0.08 pb

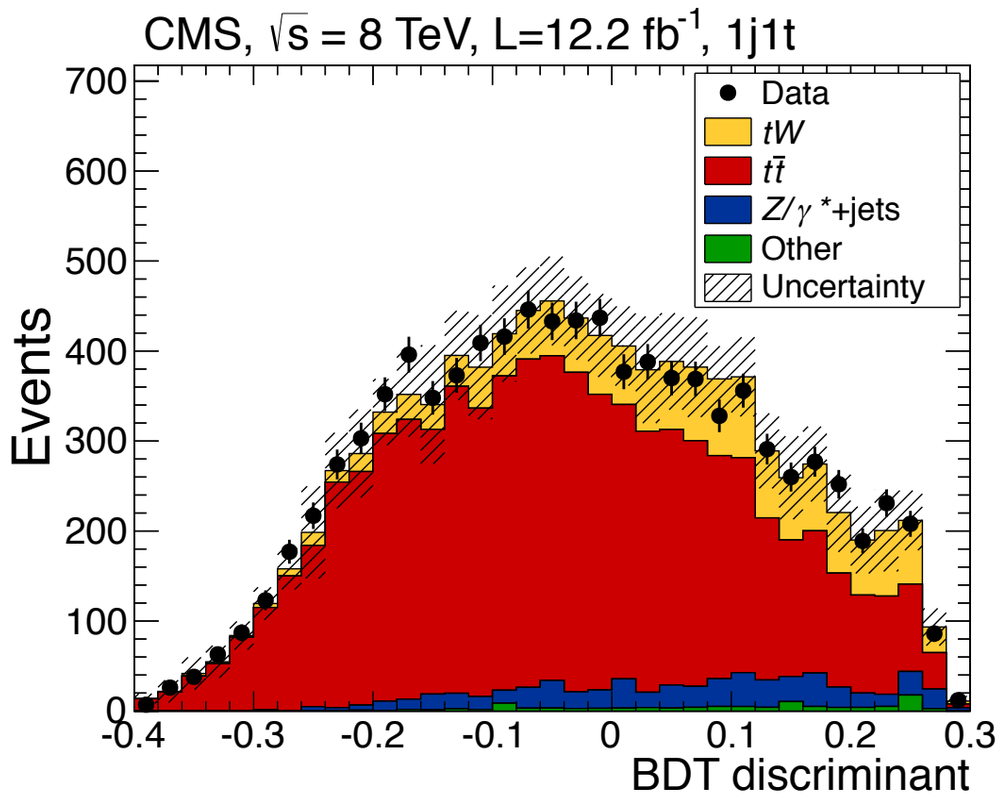
Kidonakis PRD 74 114012 (2006) σ_{tqb}=2.26±0.12 pb

C.f. CDF NOTE 11045 s-chan: 1.38±0.38 pb (4.2σ)

New
arXiv:1401.2942 sub to PRL

tW production at CMS

- 8 TeV (12.2 fb^{-1})
- tW in two lepton channel
  - isolated lepton e/μ
  - jets p_T>30 (loose jets p_T>20)
  - ee, μμ: veto [81,101] GeV and require MET>50 GeV (Z/γ*)
- #jets, #b-tags: 1j1t,2j1t,2j2t
  - 1j1t - tW signal region
  - 2j1t,2j2t - t tbar control region
- Main Backgrounds from t tbar, Z +jets
- BDT of 13 variables
- simultaneous fit to signal & control regions



σ_{tW}=23.4±5.4 pb
p-value 5×10^{-10} (6.1σ)
expected sig. 5.4±1.4σ
SM: 22.2±0.6(scale)±1.4(pdf) pb

Two cross checks confirm the first observation (>5σ) of tW in agreement with SM cross section

c.f. ATLAS-CONF-2013-100 4.2σ evidence

Summary & Outlook

- Top quark has been studied at Tevatron & LHC
  - Pair production: precise measurement matches NNLO calculations in QCD
    - at Tevatron @ 1.96 TeV and LHC @ 7 TeV & 8 TeV
  - Charge asymmetry: next step test of QCD with sensitivity to new physics from new objects/amplitudes
    - Anomalous A_{FB} at Tevatron has less tension but still interesting
    - LHC experiments have measurements ruling out many exotic explanations for A_{FB}, but not yet sensitive to SM A_C
  - Single top: in agreement with SM expectations
    - t-channel well established at Tevatron & LHC
    - s-channel evidence from Tevatron experiments
    - tW-channel observation at LHC
- So far, top looks very much like a SM quark in production & decay
- More to come
  - Finalizing legacy Tevatron analyses full data sample
  - LHC 7/8 TeV legacy analyses & LHC 13 TeV in 2015

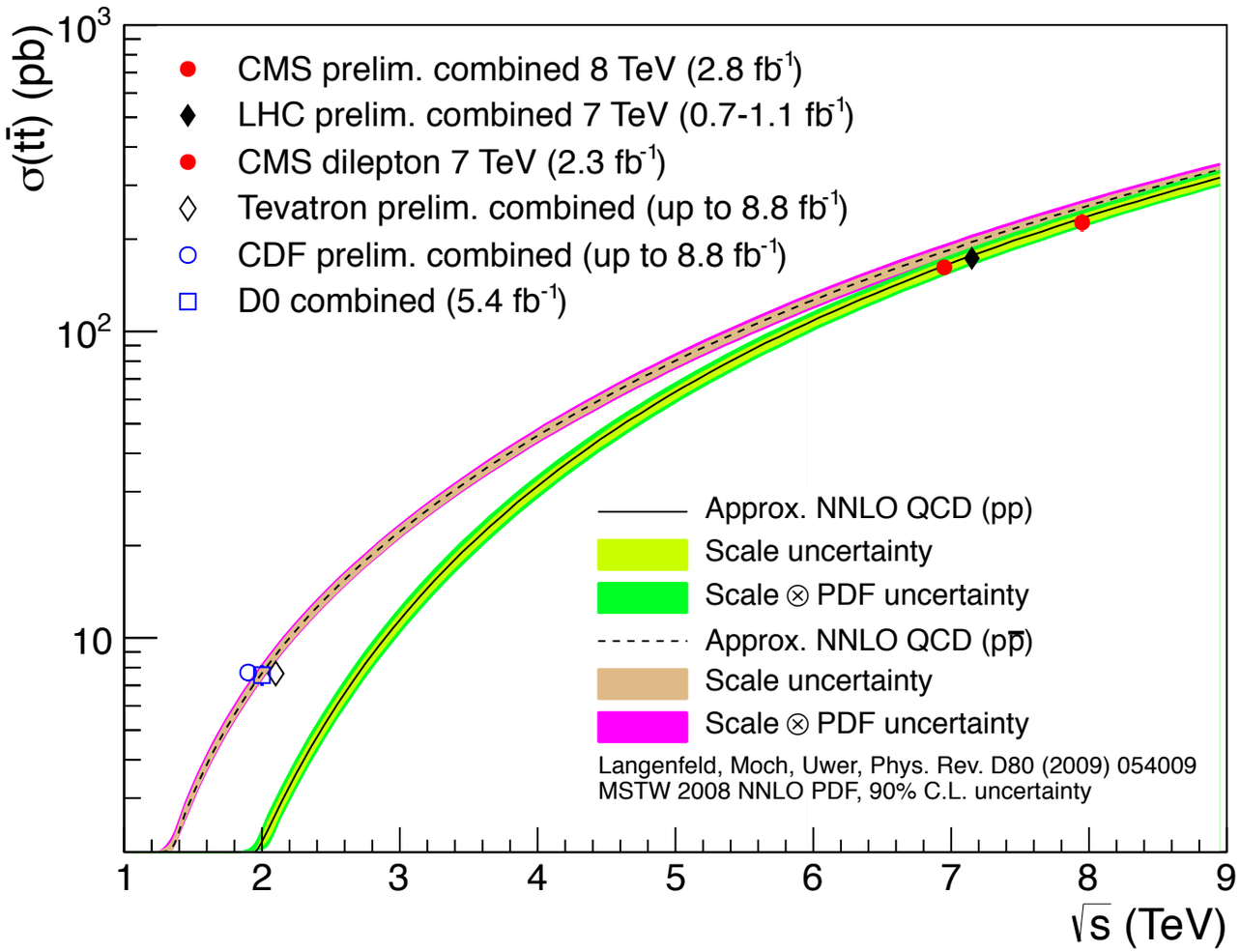
Other results of interest

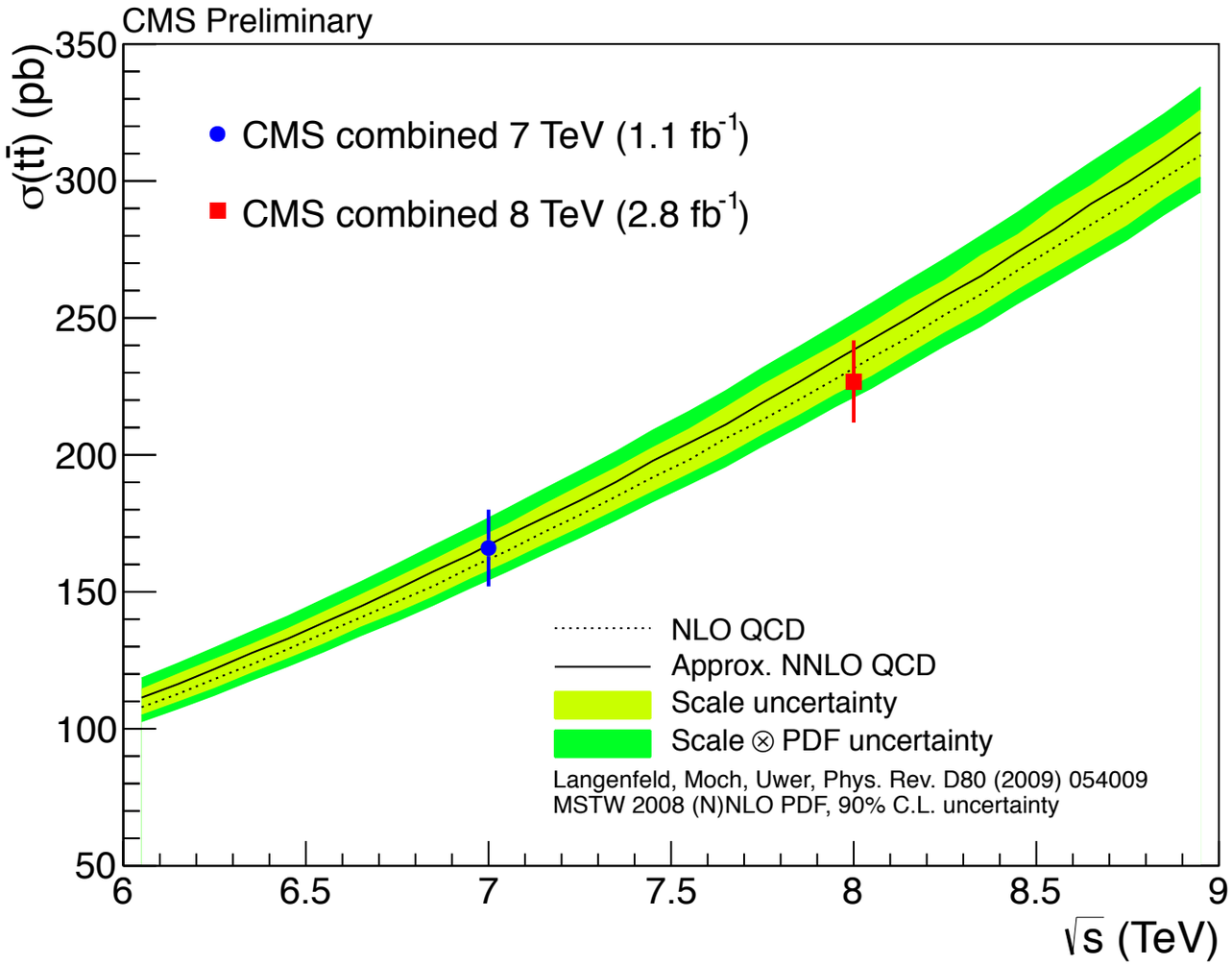
No time to cover these interesting results

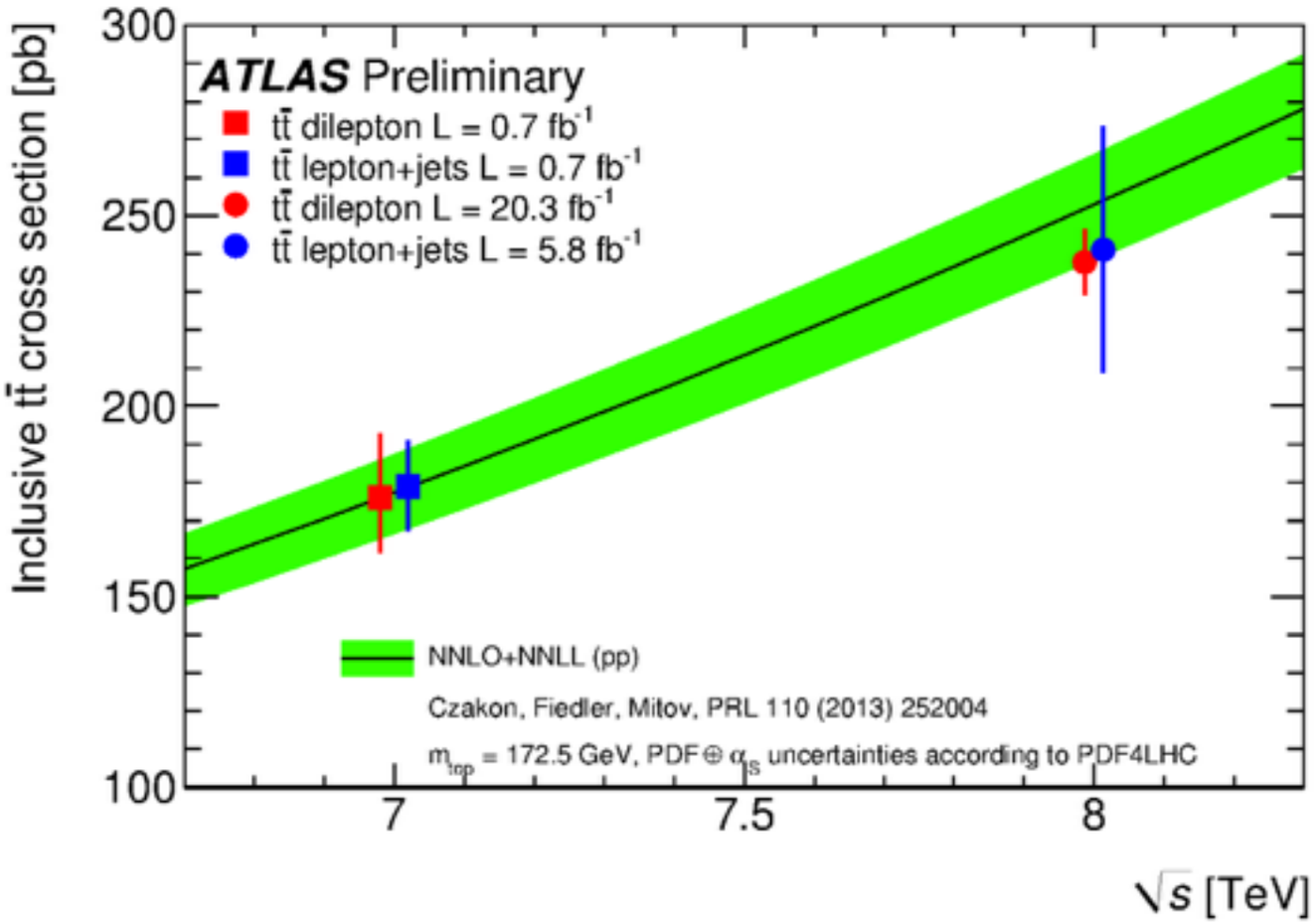
- Differential cross sections
- Associated production of top quark-antiquark pairs
  - with vector bosons
  - with photons
  - with additional jets
  - with heavy flavor jets
  - with H boson
- Properties in top decay
  - W polarization in top decays
  - Top polarization in t tbar production
  - Spin correlations in t tbar production
  - Searches for FCNC t→Zq

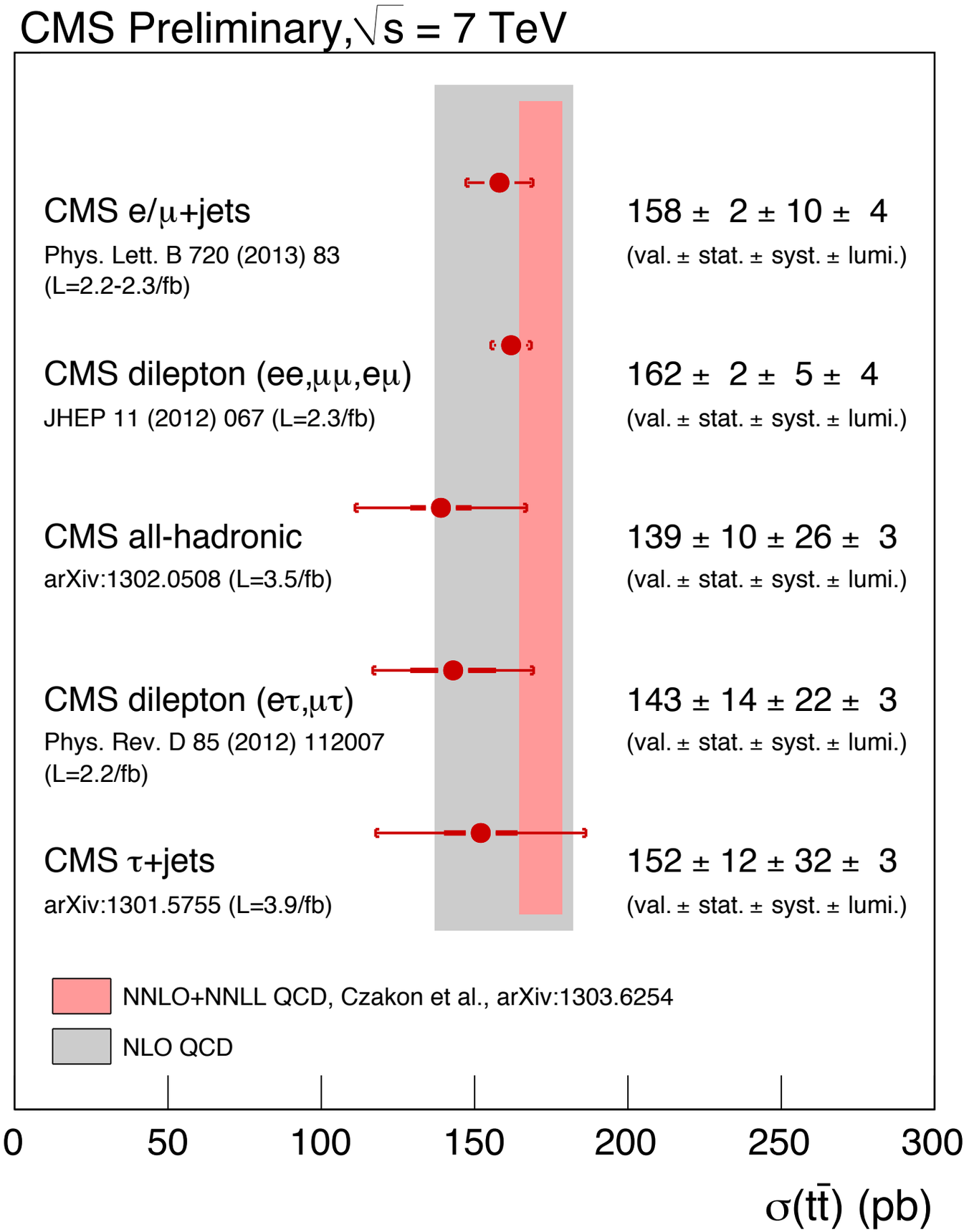
No surprises but lots of potential!
Adding to our understanding of top

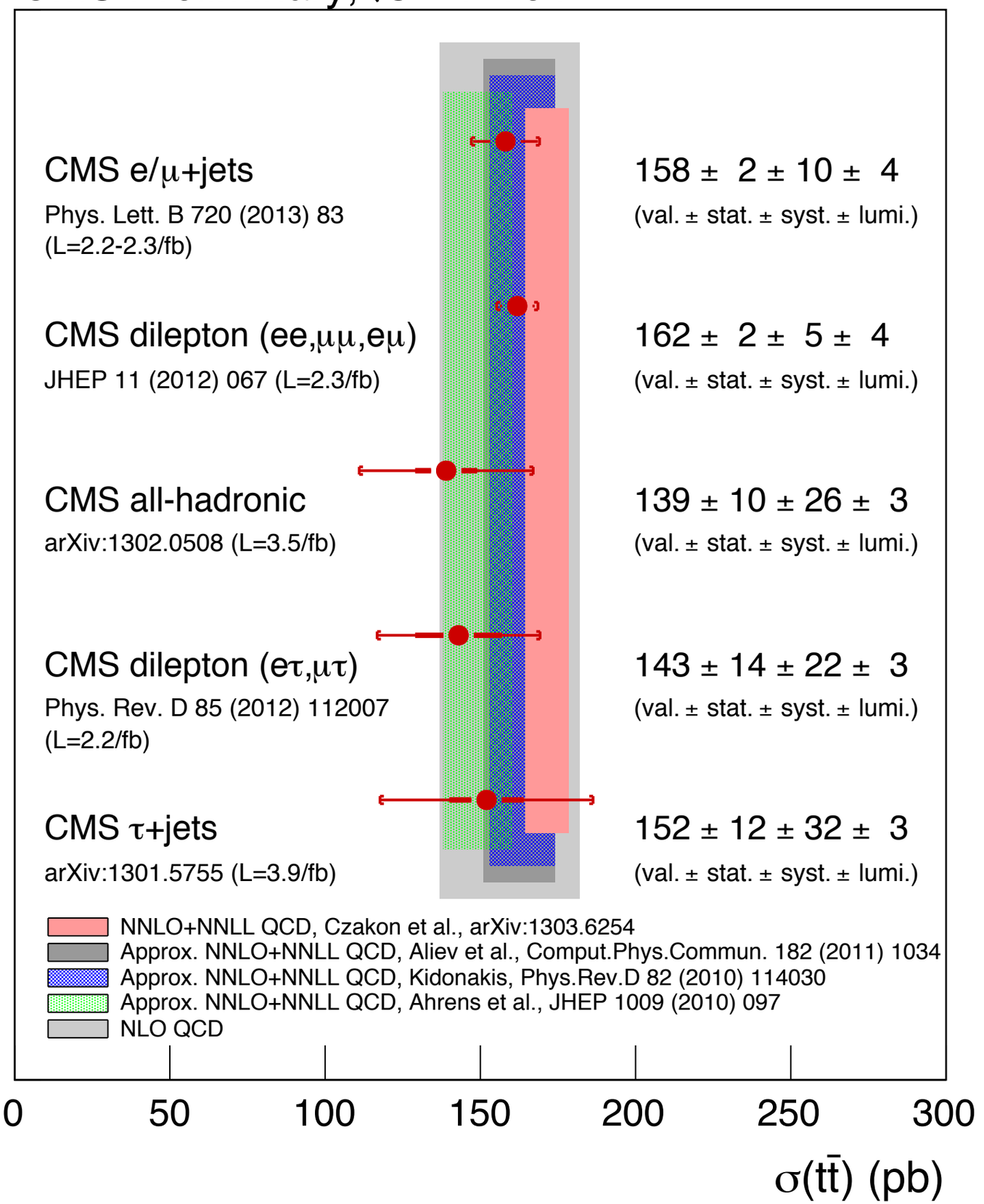
Backup Slides


$\sigma(t\bar{t})$ (pb)
10^3
10^2
10
CMS prelim. combined 8 TeV (2.8 fb^{-1})
LHC prelim. combined 7 TeV (0.7-1.1 fb^{-1})
CMS dilepton 7 TeV (2.3 fb^{-1})
Tevatron prelim. combined (up to 8.8 fb^{-1})
CDF prelim. combined (up to 8.8 fb^{-1})
D0 combined (5.4 fb^{-1})
Approx. NNLO QCD (pp)
Scale uncertainty
Scale ⊗ PDF uncertainty
Approx. NNLO QCD ($p\bar{p}$)
Scale uncertainty
Scale ⊗ PDF uncertainty
Langenfeld, Moch, Uwer, Phys. Rev. D80 (2009) 054009
MSTW 2008 NNLO PDF, 90% C.L. uncertainty
1
2
3
4
5
6
7
8
9
$\sqrt{s}$ (TeV)


CMS Preliminary
σ(tt̄) (pb)
350
300
250
200
150
100
50
CMS combined 7 TeV (1.1 fb-1)
CMS combined 8 TeV (2.8 fb-1)
NLO QCD
Approx. NNLO QCD
Scale uncertainty
Scale ⊗ PDF uncertainty
Langenfeld, Moch, Uwer, Phys. Rev. D80 (2009) 054009
MSTW 2008 (N)NLO PDF, 90% C.L. uncertainty
6
6.5
7
7.5
8
8.5
9
√s (TeV)


ATLAS Preliminary
tt̄ dilepton L = 0.7 fb-1
tt̄ lepton+jets L = 0.7 fb-1
tt̄ dilepton L = 20.3 fb-1
tt̄ lepton+jets L = 5.8 fb-1
NNLO+NNLL (pp)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
mtop = 172.5 GeV, PDF ⊕ αs uncertainties according to PDF4LHC
Inclusive tt̄ cross section [pb]
300
250
200
150
100
7
7.5
8
√s [TeV]


CMS Preliminary, √s = 7 TeV
CMS e/μ+jets
Phys. Lett. B 720 (2013) 83
(L=2.2-2.3/fb)
158 ± 2 ± 10 ± 4
(val. ± stat. ± syst. ± lumi.)
CMS dilepton (ee,μμ,eμ)
JHEP 11 (2012) 067 (L=2.3/fb)
162 ± 2 ± 5 ± 4
(val. ± stat. ± syst. ± lumi.)
CMS all-hadronic
arXiv:1302.0508 (L=3.5/fb)
139 ± 10 ± 26 ± 3
(val. ± stat. ± syst. ± lumi.)
CMS dilepton (eτ,μτ)
Phys. Rev. D 85 (2012) 112007
(L=2.2/fb)
143 ± 14 ± 22 ± 3
(val. ± stat. ± syst. ± lumi.)
CMS τ+jets
arXiv:1301.5755 (L=3.9/fb)
152 ± 12 ± 32 ± 3
(val. ± stat. ± syst. ± lumi.)
NNLO+NNLL QCD, Czakon et al., arXiv:1303.6254
NLO QCD
0
50
100
150
200
250
300
σ(tt̄) (pb)


CMS Preliminary, $\sqrt{s}$ = 7 TeV
CMS e/μ+jets
Phys. Lett. B 720 (2013) 83
(L=2.2-2.3/fb)
158 ± 2 ± 10 ± 4
(val. ± stat. ± syst. ± lumi.)
CMS dilepton (ee,μμ,eμ)
JHEP 11 (2012) 067 (L=2.3/fb)
162 ± 2 ± 5 ± 4
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CMS all-hadronic
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139 ± 10 ± 26 ± 3
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CMS dilepton (eτ,μτ)
Phys. Rev. D 85 (2012) 112007
(L=2.2/fb)
143 ± 14 ± 22 ± 3
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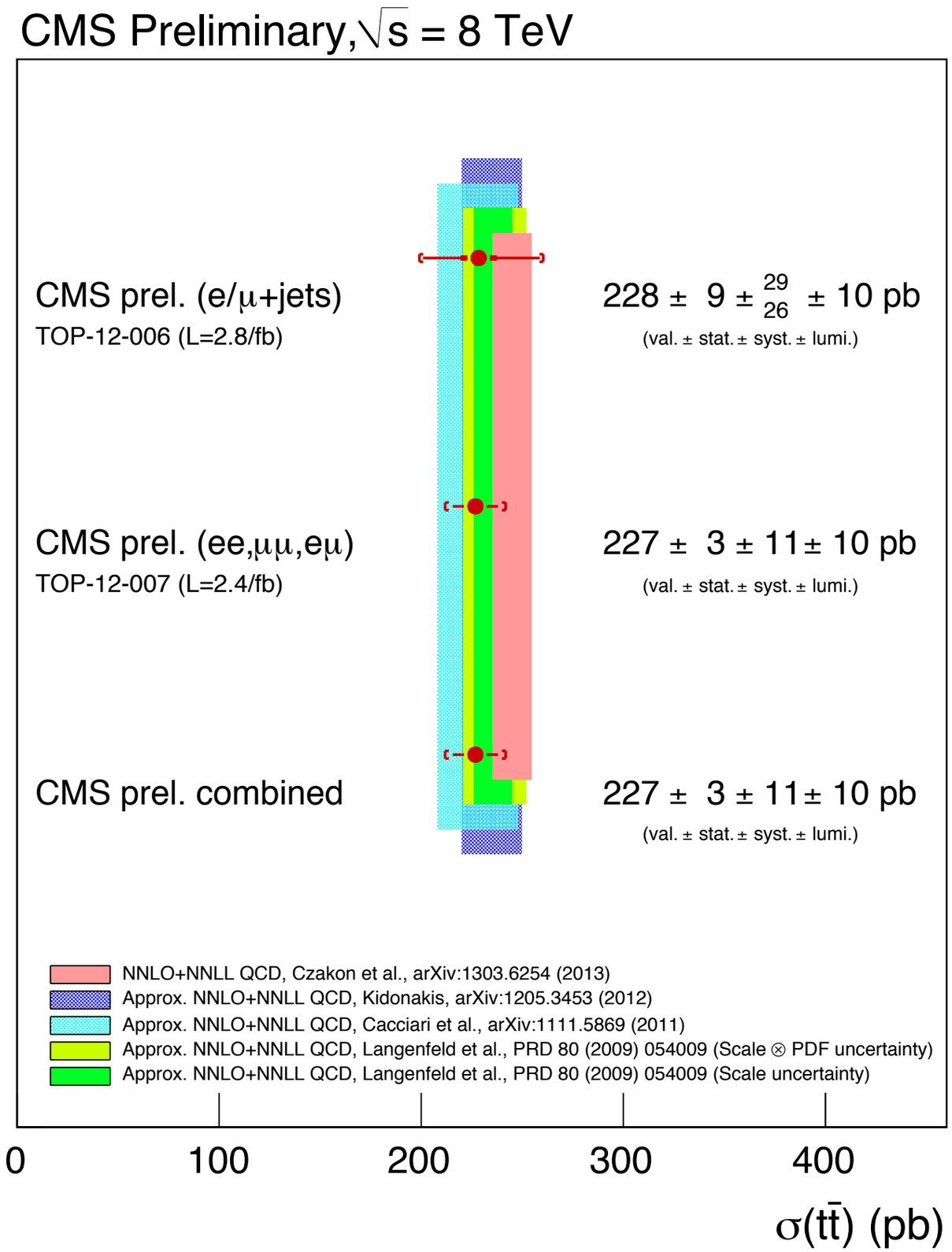
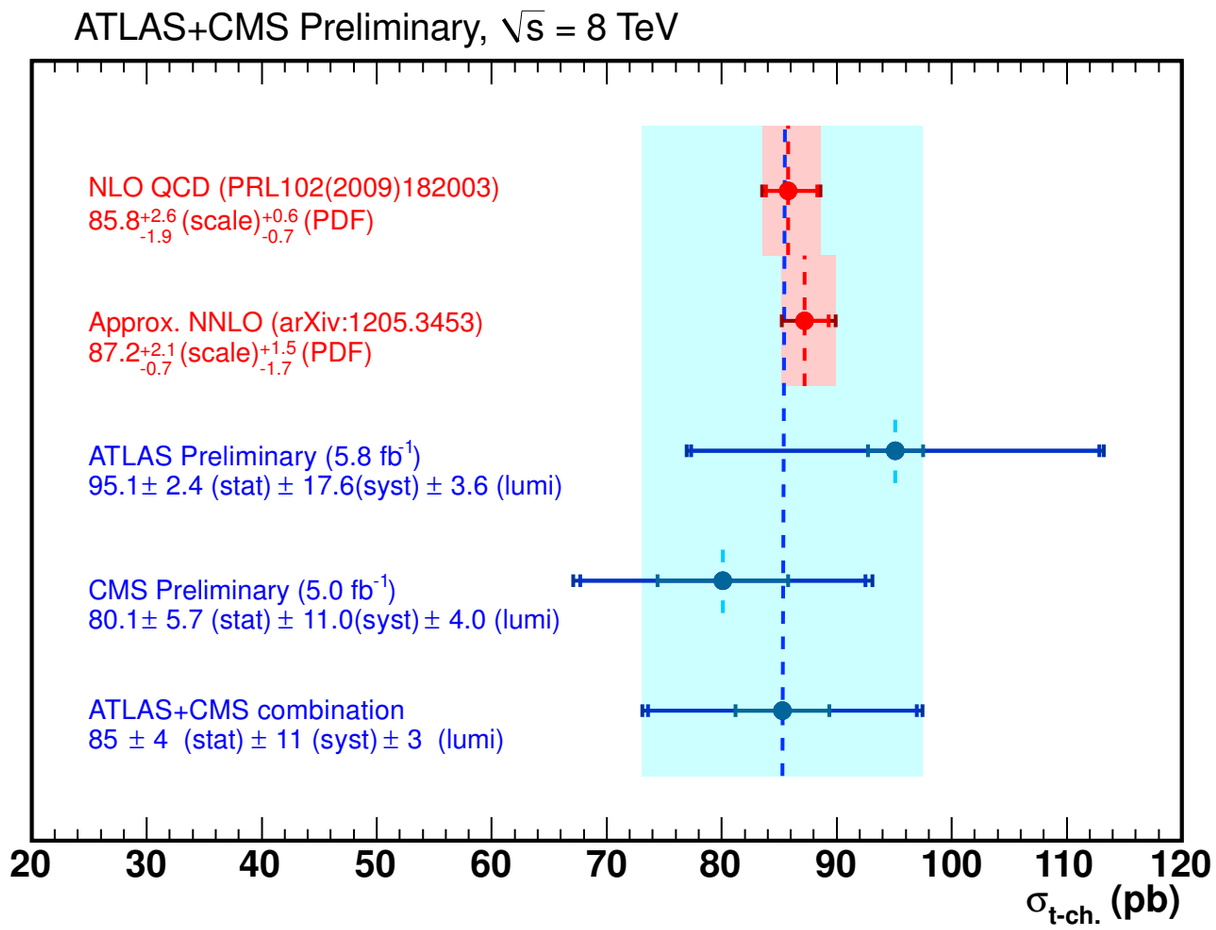
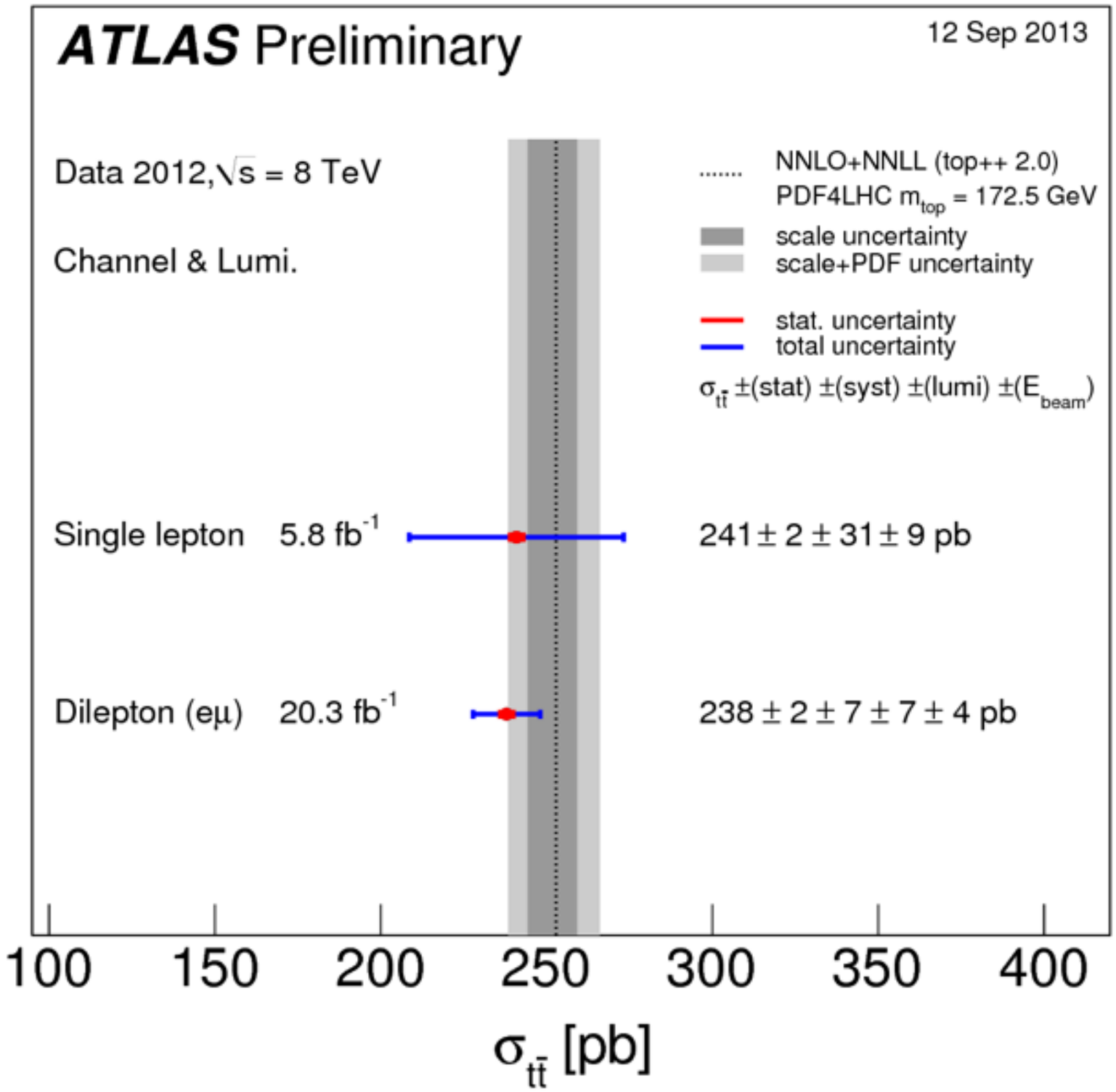
CMS τ+jets
arXiv:1301.5755 (L=3.9/fb)
152 ± 12 ± 32 ± 3
(val. ± stat. ± syst. ± lumi.)
NNLO+NNLL QCD, Czakon et al., arXiv:1303.6254
Approx. NNLO+NNLL QCD, Aliev et al., Comput.Phys.Commun. 182 (2011) 1034
Approx. NNLO+NNLL QCD, Kidonakis, Phys.Rev.D 82 (2010) 114030
Approx. NNLO+NNLL QCD, Ahrens et al., JHEP 1009 (2010) 097
NLO QCD
0
50
100
150
200
250
300
σ(tt̄) (pb)


CMS Preliminary, $\sqrt{s}$ = 8 TeV
CMS prel. (e/μ+jets)
TOP-12-006 (L=2.8/fb)
228 ± 9 ± 29/26 ± 10 pb
(val. ± stat. ± syst. ± lumi.)
CMS prel. (ee,μμ,eμ)
TOP-12-007 (L=2.4/fb)
227 ± 3 ± 11 ± 10 pb
(val. ± stat. ± syst. ± lumi.)
CMS prel. combined
227 ± 3 ± 11 ± 10 pb
(val. ± stat. ± syst. ± lumi.)
NNLO+NNLL QCD, Czakon et al., arXiv:1303.6254 (2013)
Approx. NNLO+NNLL QCD, Kidonakis, arXiv:1205.3453 (2012)
Approx. NNLO+NNLL QCD, Cacciari et al., arXiv:1111.5869 (2011)
Approx. NNLO+NNLL QCD, Langenfeld et al., PRD 80 (2009) 054009 (Scale ⊗ PDF uncertainty)
Approx. NNLO+NNLL QCD, Langenfeld et al., PRD 80 (2009) 054009 (Scale uncertainty)
0
100
200
300
400
σ(tt̄) (pb)

ATLAS+CMS Single Top 8 TeV

t-channel results @ 8 TeV




ATLAS Preliminary
12 Sep 2013
Data 2012, √s = 8 TeV
Channel & Lumi.
NNLO+NNLL (top++ 2.0)
PDF4LHC m_top = 172.5 GeV
scale uncertainty
scale+PDF uncertainty
stat. uncertainty
total uncertainty
σ_tt̄ ±(stat) ±(syst) ±(lumi) ±(E_beam)
Single lepton 5.8 fb^-1 241 ± 2 ± 31 ± 9 pb
Dilepton (eμ) 20.3 fb^-1 238 ± 2 ± 7 ± 7 ± 4 pb
100 150 200 250 300 350 400
σ_tt̄ [pb]