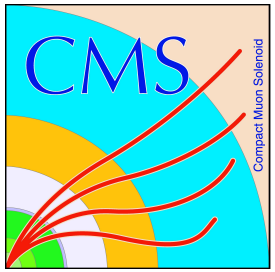


Measurements of the top quark pair production cross section in pp collisions

EPS-HEP 2015

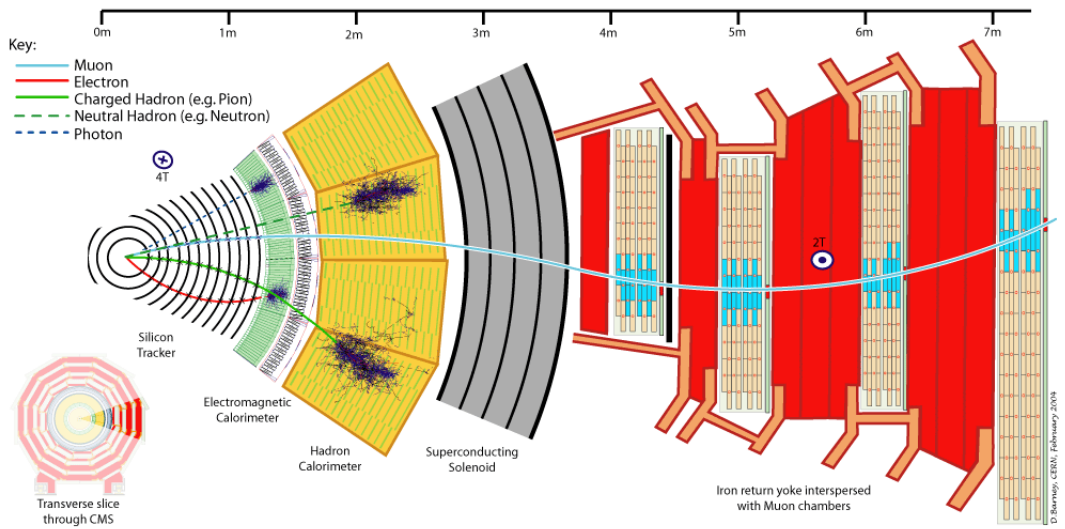
European Physical Society Conference on High Energy Physics

Eleni Ntomari for the CMS collaboration

July 23, 2015

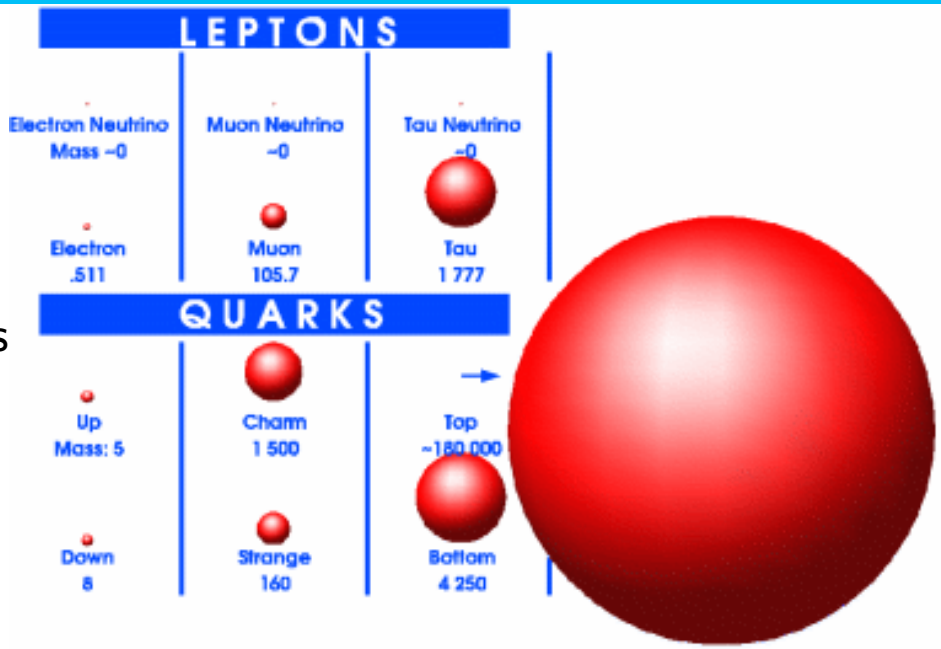
Outline

- Top quark pair production and decay
- Inclusive cross sections
  - 7 TeV (dilepton, lepton+jets, fully hadronic)
  - 8 TeV (dilepton, lepton+jets, τ+jets)
  - 8 TeV Combination of ATLAS and CMS
  - α_s extraction from $\sigma(t\bar{t})$
- Top quark pair + jets ($b\bar{b}$, $t\bar{t}$)



Top quarks: key to QCD, electroweak (EWK) and new physics

- The most massive known particle
- Decays before hadronisation:
  study properties of bare quark
- Essential to study Higgs properties
  – Sensitivity to Higgs through loop corrections
  – Measure top Yukawa coupling;
  Yukawa coupling to Higgs $\sim$1

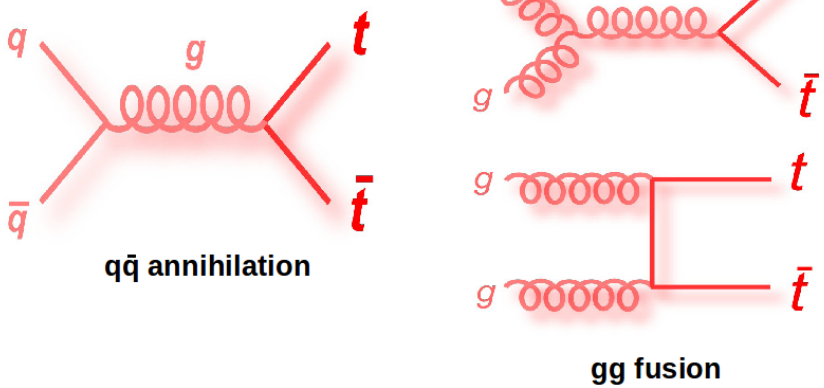


Measuring $\sigma_{t\bar{t}}$ is the first fundamental step for understanding top physics

- Huge relevance for SM and BSM:
  - In the frame of Standard Model, test QCD predictions at NNLO
  - Sensitive to New Physics Beyond the Standard Model
  - Test the presence of new production mechanisms
  - Help constraining modeling PDFs (essential ingredient in QCD calculation)
  - Determination of m_t^{pole} or α_s
- Important background for many Higgs and BSM searches at LHC

Top quark production in pp collisions at the LHC

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



LHC Run I: Top Quark Factory

- peak inst. luminosity: $8 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
- 7000 top quark pairs per hour (8 TeV)
- 20 fb^{-1} (8 TeV) + 5 fb^{-1} (7 TeV) recorded: $\sim$ 6M top quark pairs produced at CMS

Full NNLO+NNLL calculation[1]

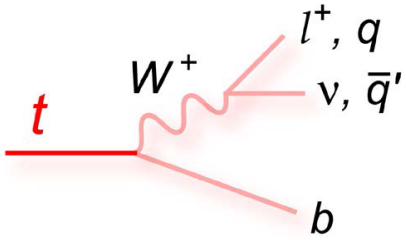
$\sqrt{s}$ [TeV]	$\sigma_{t\bar{t}}$(NNLO+NNLL)[2] [pb] (172.5 GeV)	Scale uncert. [pb]	PDF+α_s[3] uncert. [pb]	Mass uncert. [pb]
7	177.3	+4.6 -6.0	+9.0 -9.0	+5.4 -5.3
8	252.9	+6.4 -8.6	+11.7 -11.7	+7.6 -7.3
13	831.8	+19.8 -29.2	+35.1 -35.1	+23.2 -22.5

[1] https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO

[2] calculated using Top^{++}(v2.0)

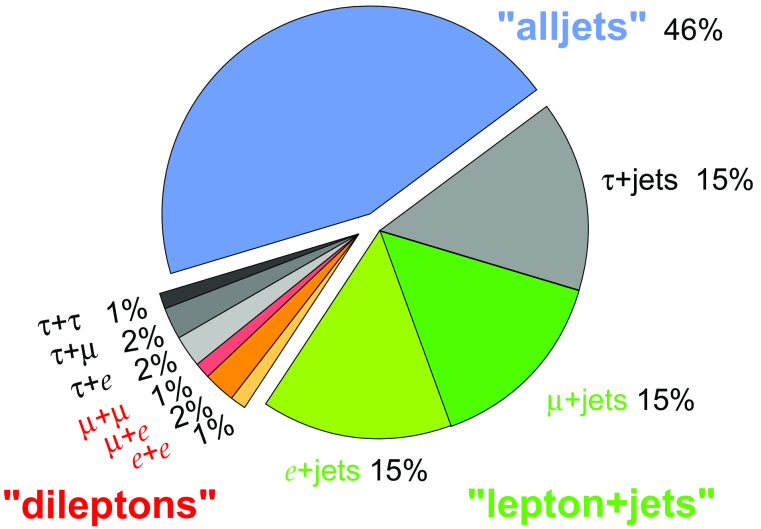
[3] calculated following PDF4LHC prescription

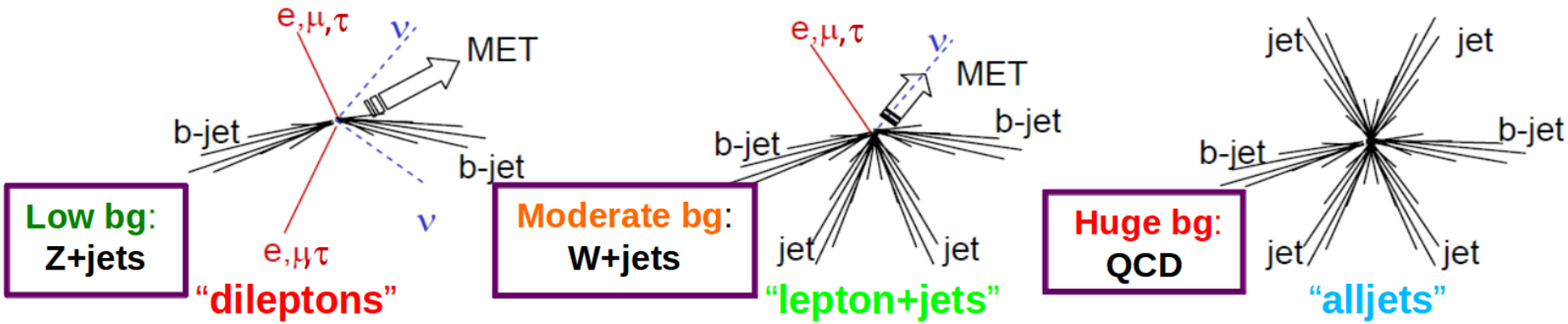
Top quark decay



- Decays into W-boson and b-quark ∼100%
- Final state topology depends on W decay: **"dileptons"**, **"lepton+jets"**, **"alljets"**

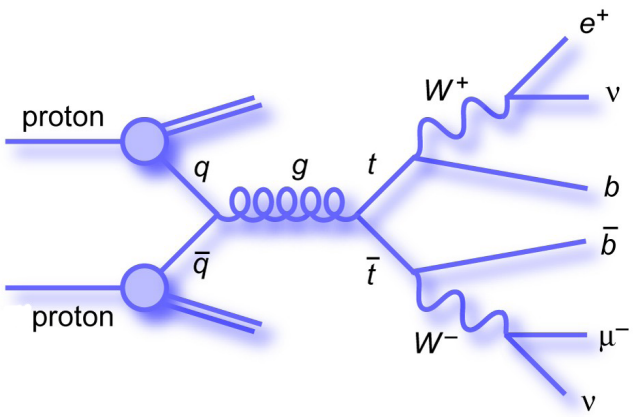
Top Pair Branching Fractions





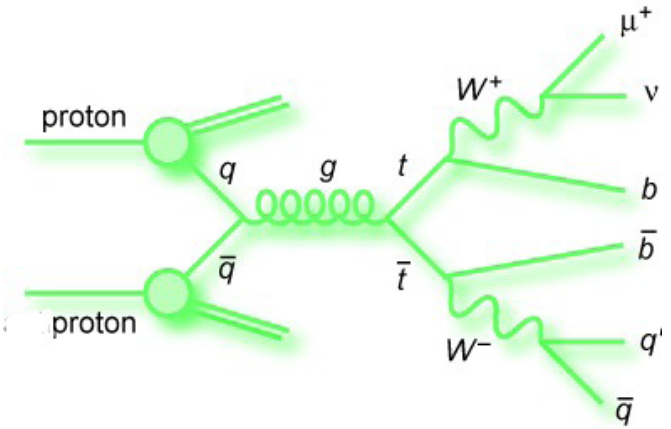
Typical event selection for $t\bar{t}$ analyses

Dilepton decay mode



- $\geq$ 2 opposite sign isolated leptons (p_T >20 GeV, $|\eta|$ <2.4)
- $\geq$ 2 jets (anti-k_T, R<0.5, p_T > 30 GeV, $|\eta|$ <2.4)
- $\geq$ 1 b-tagged jet
- For same flavour channels QCD & Z veto (MET>40 GeV, exclude $m_Z \pm 15$ GeV)

Lepton+jets decay mode



- $\geq$ 1 isolated lepton (electron or muon) (p_T >26, 30 GeV, $|\eta|$ <2.1, 2.5)
- $\geq$ 4 jets (anti-k_T, R<0.5, p_T >45, 45, 35 and 35 GeV, $|\eta|$ <2.5)
- $\geq$ 1 b-tagged jets

$t\bar{t}$ Inclusive Cross Section at 8 TeV: Dilepton

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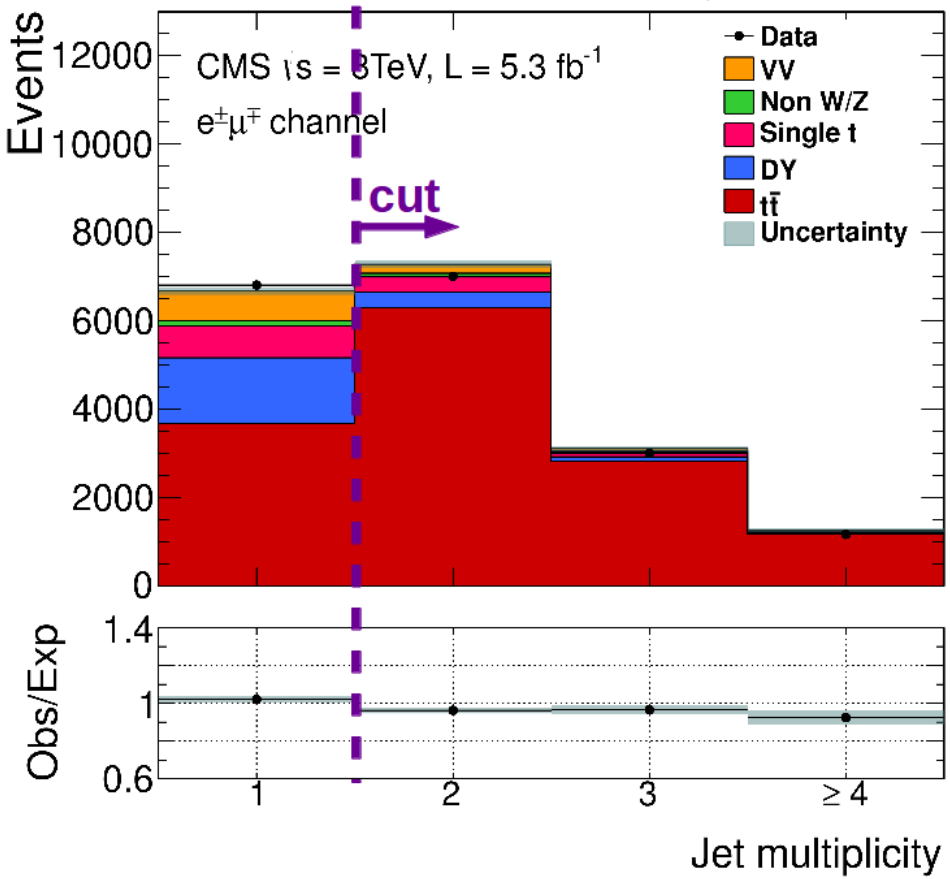
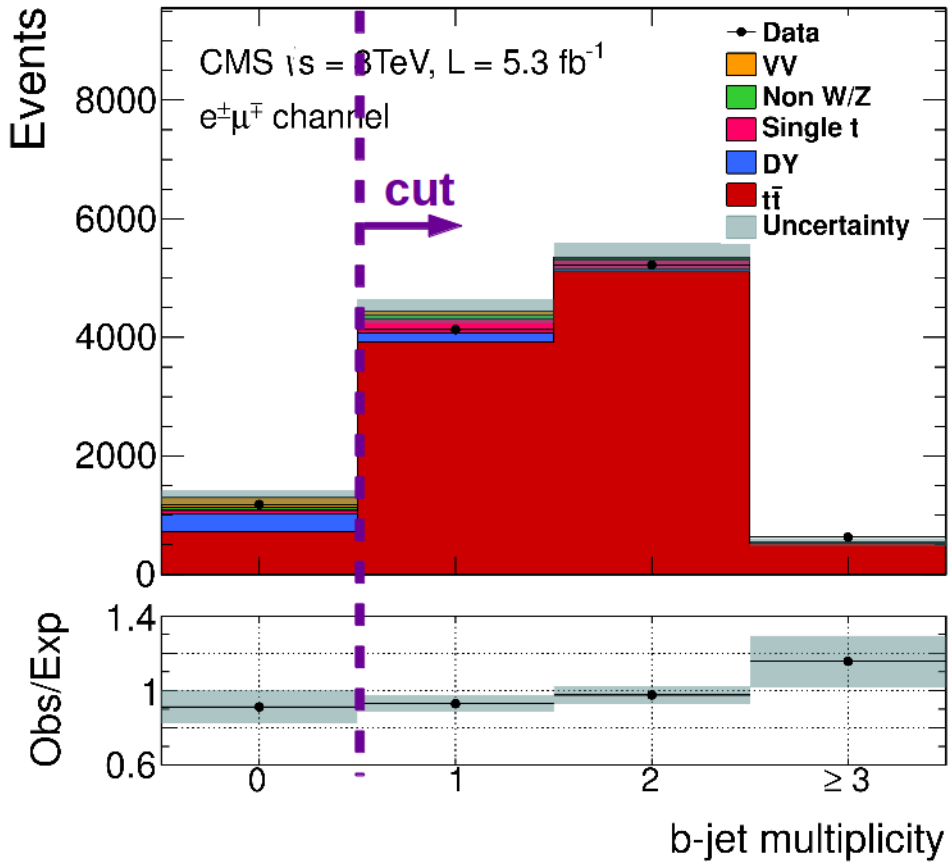
- Small background and clean final state
- Cut and count analysis
- Baseline MC: MadGraph+Pythia



- Drell-Yan and non-W/Z background estimated from data
- Dominant syst.: JES and background



$\sigma_{t\bar{t}} = 239 \pm 2\ (\text{stat.}) \pm 11\ (\text{syst.}) \pm 6\ (\text{lum.})\ \text{pb} \rightarrow 5\%$ total uncertainty

$t\bar{t}$ Inclusive Cross Section at 8 TeV: τ + leptons

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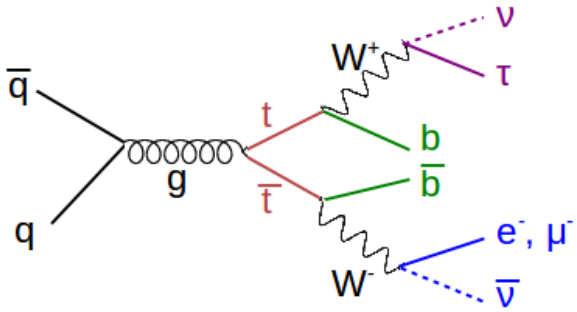
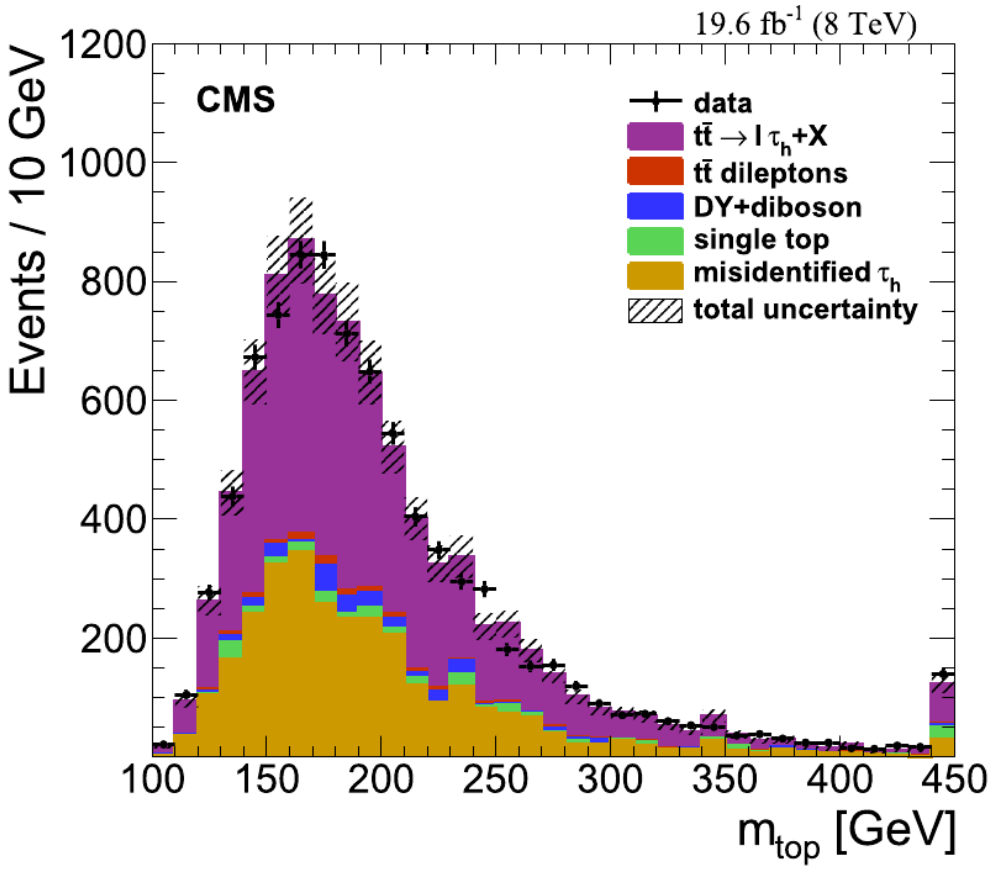


- Important channel for charged Higgs boson searches
- Selection:
  - One isolated lepton (e, μ)
  - $\geq$ 3 jets (one b-tagged)
  - τ decaying into hadrons
  - MET
- Cut and Count method
  - Determine τ fakes from multijet
  - W+jets from data



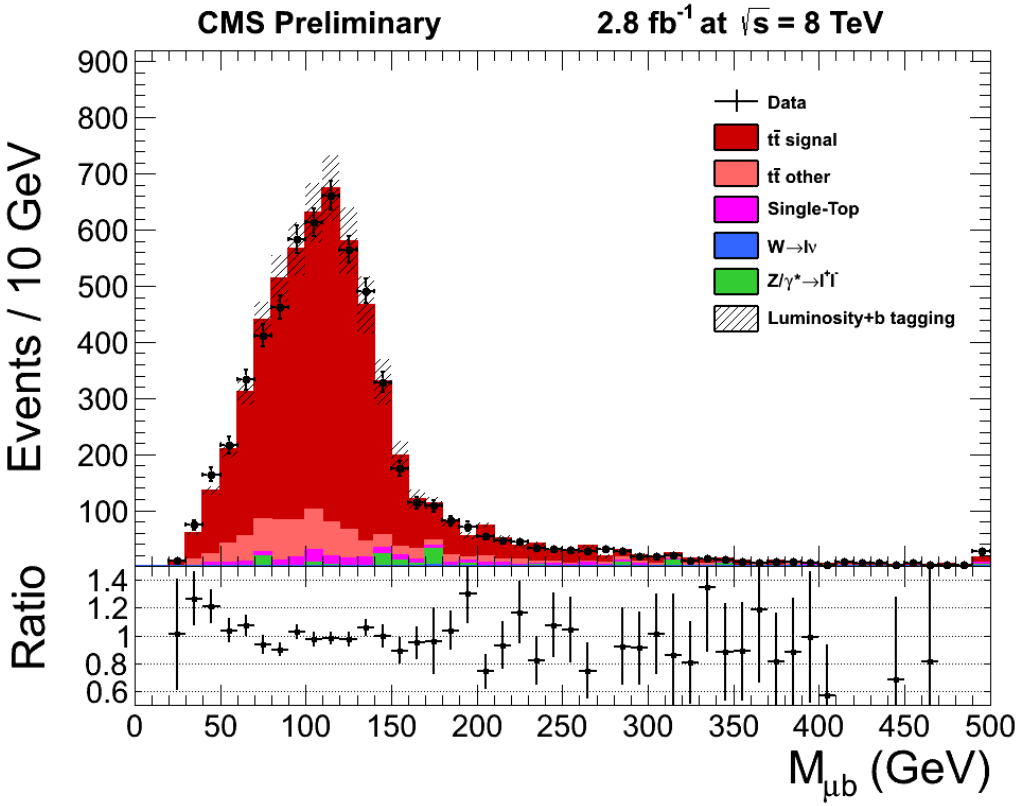
- Systematics dominated by fake τ and b-tag uncertainties

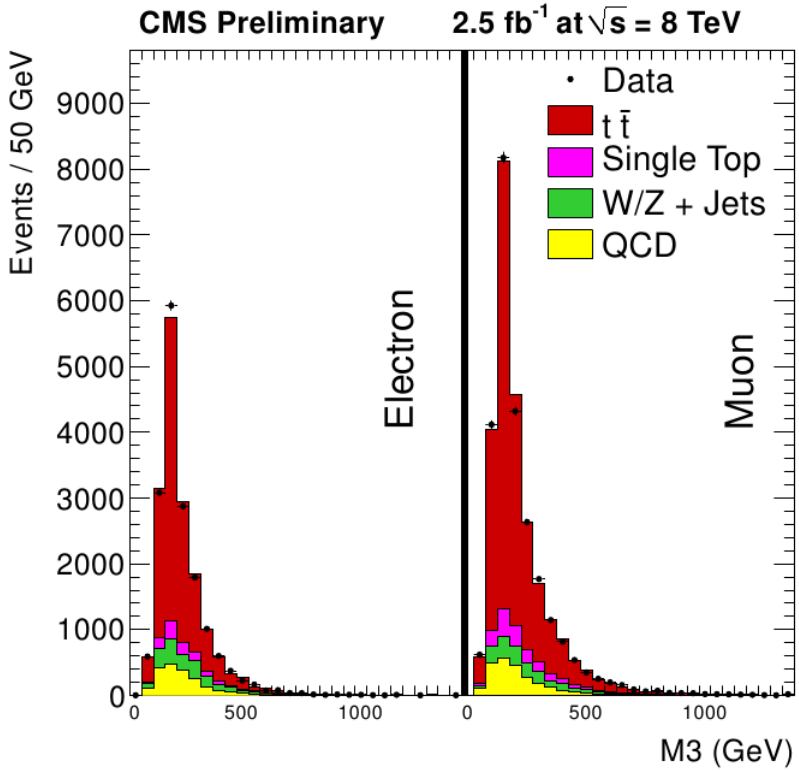
$\sigma_{t\bar{t}} = 257 \pm 3$ (stat.) ± 24 (syst.) ± 7 (lum.) pb $\rightarrow$ 9.8% total uncertainty

$t\bar{t}$ Inclusive Cross Section at 8 TeV: e/μ + jets

CMS-PAS-TOP-12-006

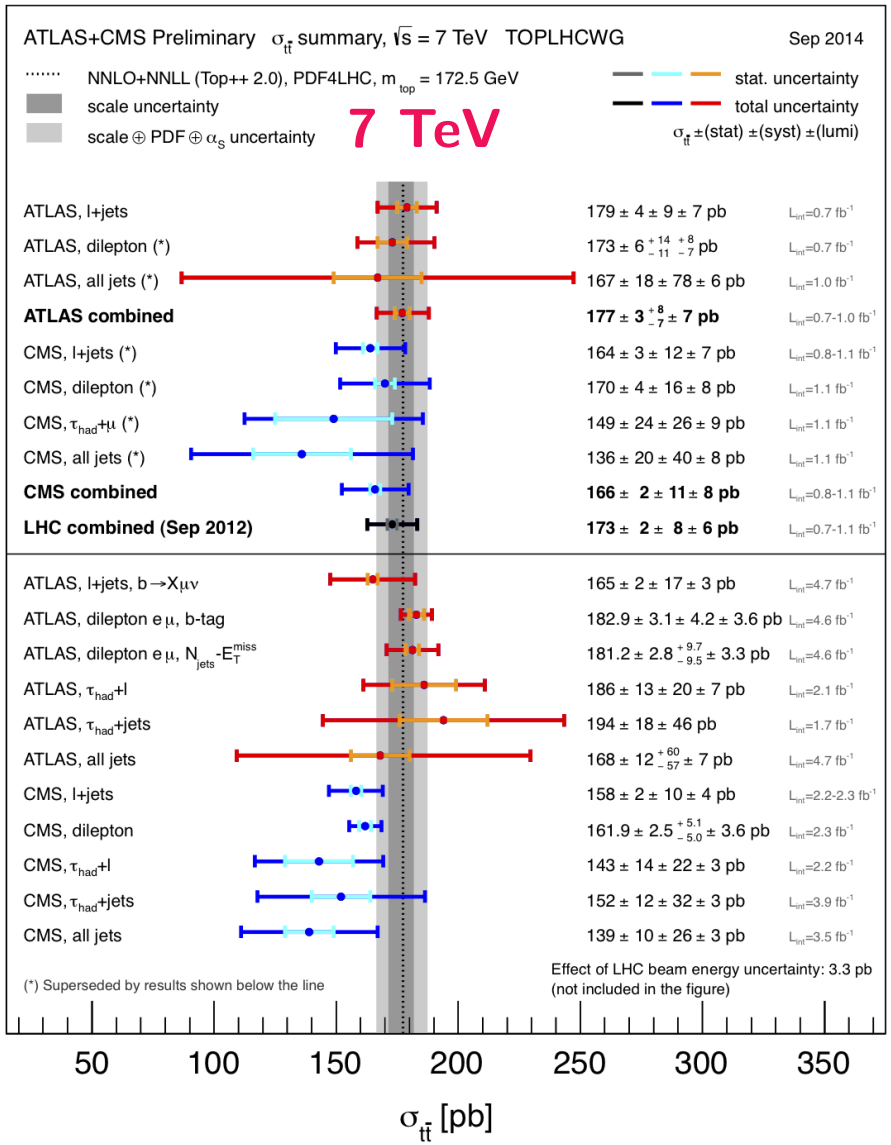
- Two approaches: Binned likelihood fit of signal and background to:
  - Lepton and b-tagged jet invariant mass (M_{lb}) in data
  - Mass of the 3-jet combination with the event's highest transverse momentum (M3)
- QCD background shape from data

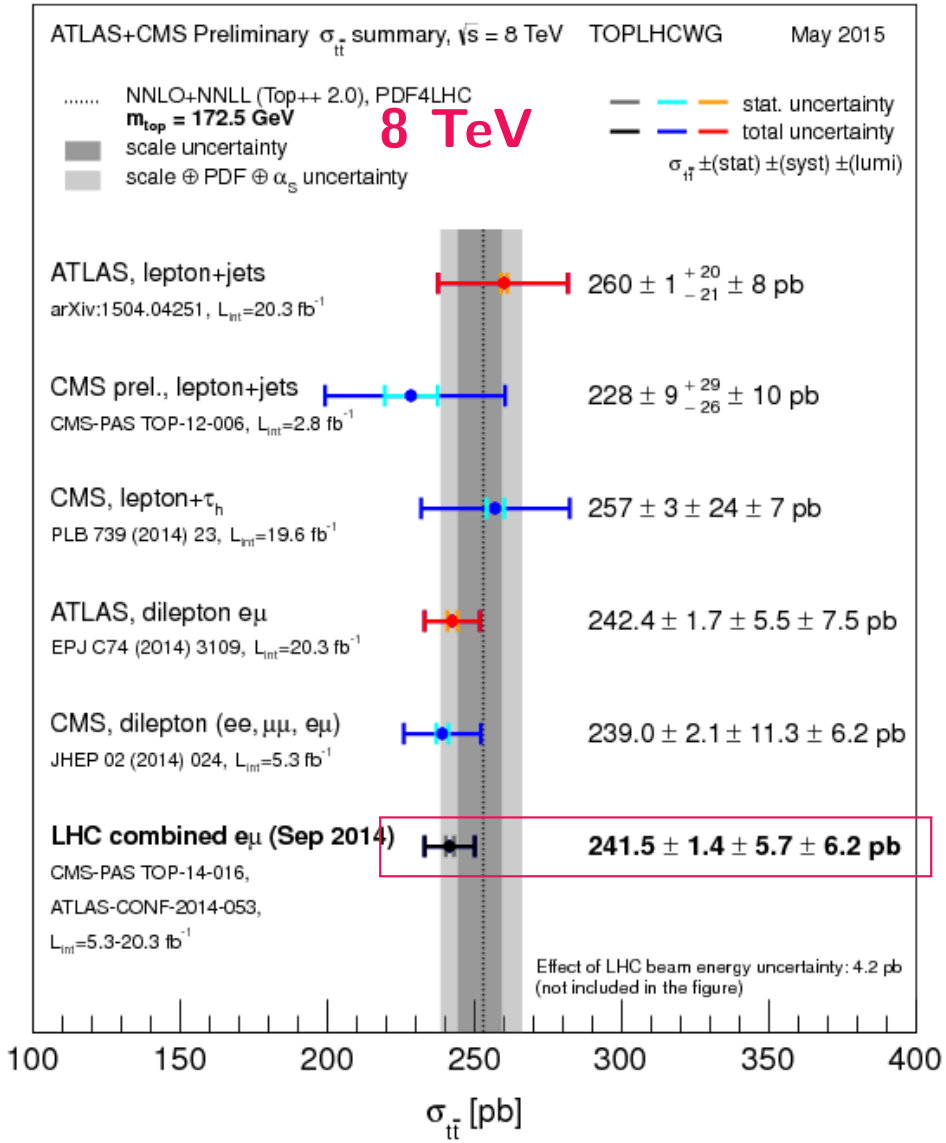




$$\sigma_{t\bar{t}} = 228.4 \pm 9.0\ (\text{stat.})\ ^{+29.0}_{-26.0}\ (\text{syst.}) \pm 10.0\ (\text{lum.})\ \text{pb} \rightarrow\ ^{+14.0}_{-12.8}\%\ \text{total uncertainty}$$

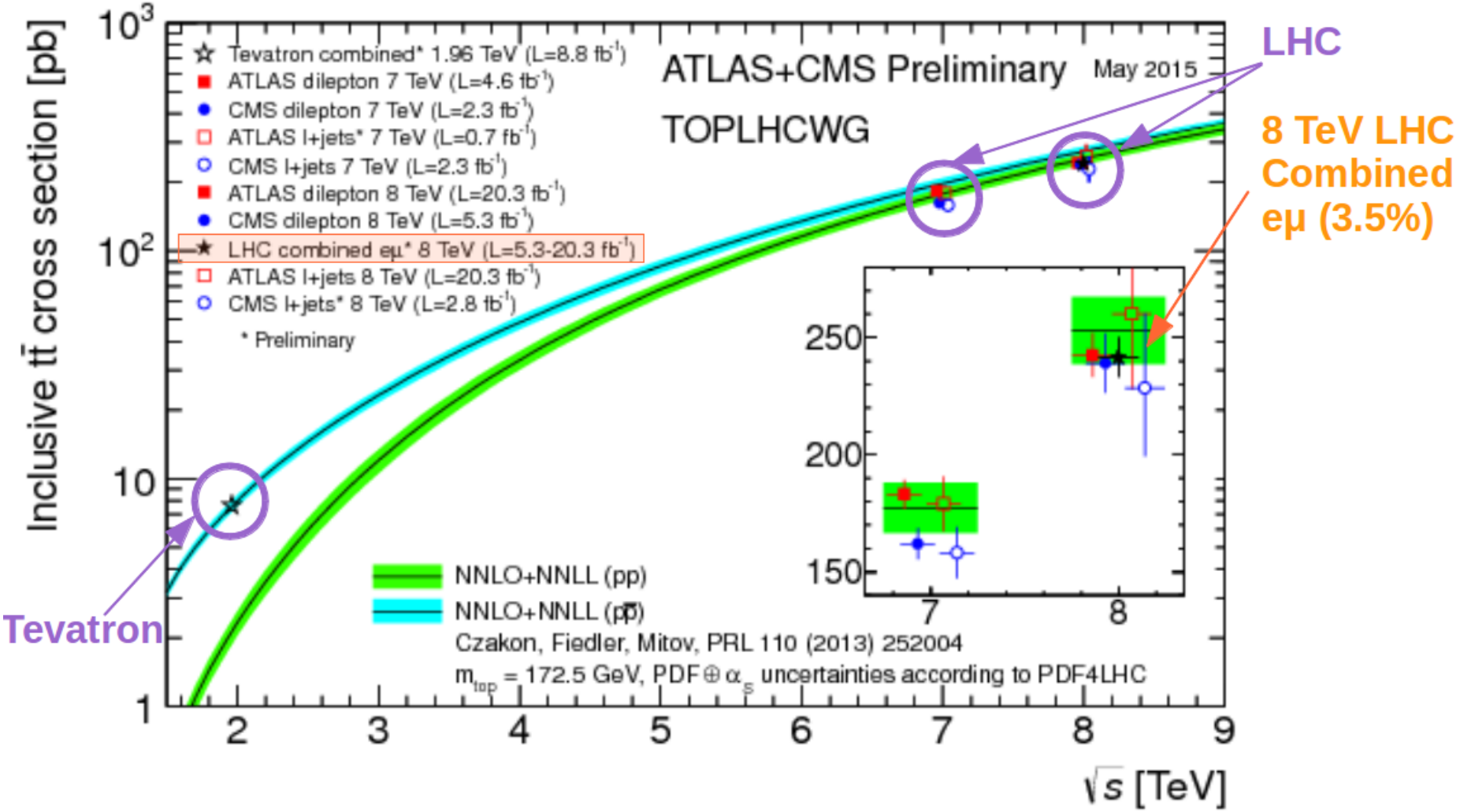
Summary of $t\bar{t}$ Inclusive Cross Sections (7 & 8 TeV)





- Good agreement between channels, experiments and theory (systematics-limited precision)

Summary of $t\bar{t}$ Inclusive Cross Sections



- Good agreement between data and prediction, as well as between experiments
  - LHC combination at 8TeV for $e\mu$ channel: 3.5% (most precise result) (CMS-PAS TOP-14-016 / ATLAS-CONF-2014-054)

$\alpha_s(M_Z)$ from Top Pair Cross Section

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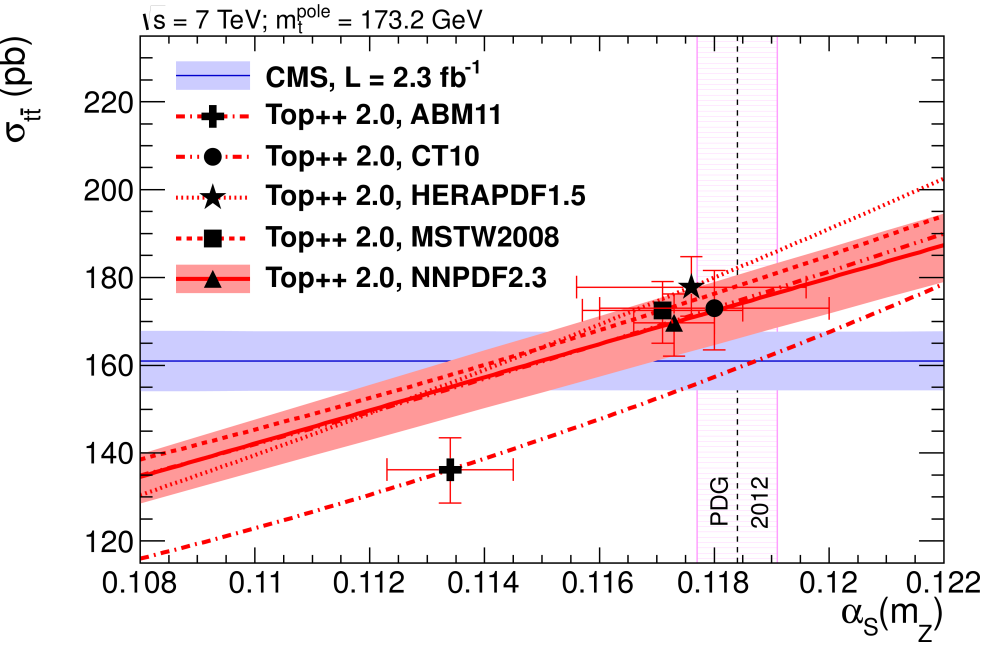
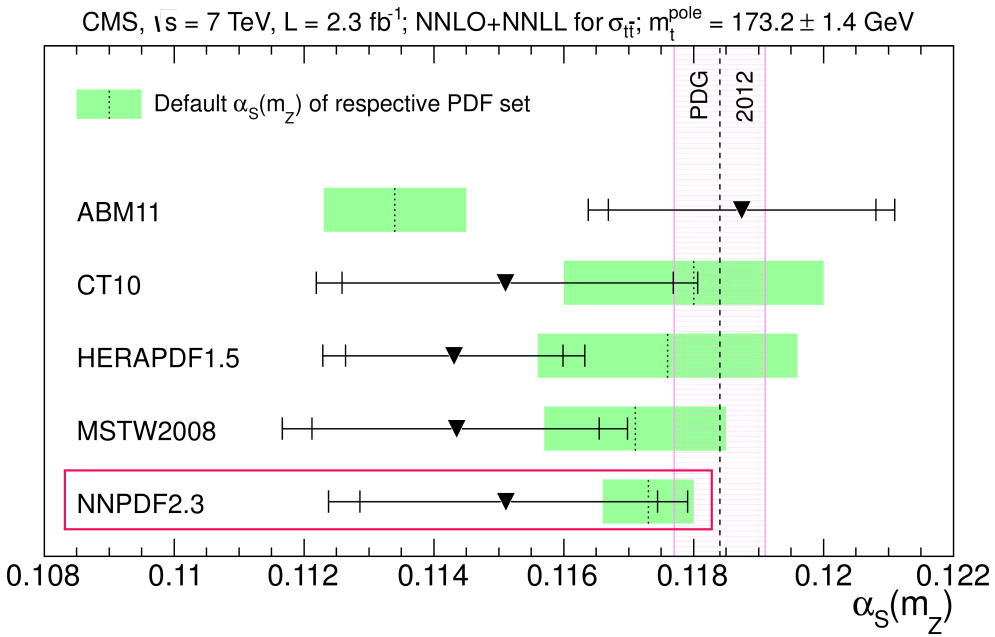
- Use high precision measurements of $\sigma(t\bar{t})$ to:
  - determine α_s for a fixed m_t^{pole} for different PDF sets
  - or determine m_t^{pole} for a fixed α_s → See talk from J. Kieseler
- Most probable result from joint likelihood between theory and experiment





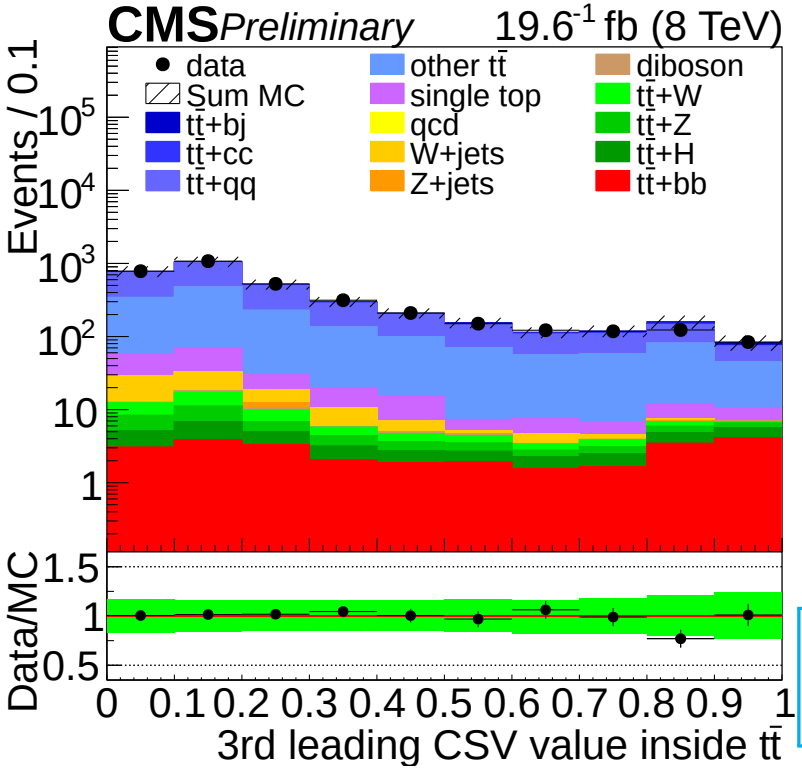
- First α_s determination from $\sigma(t\bar{t})$ and first result at full NNLO QCD obtained at a hadron collider → NNPDF2.3: $\alpha_s(m_Z) = 0.1151^{+0.0028}_{-0.0027}$ (NNPDF2.3)

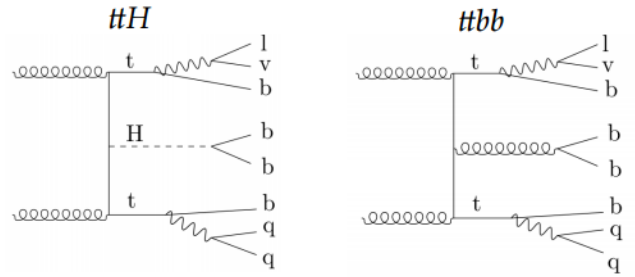
Cross section ratio $\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}$: e/μ + jets

CMS TOP-13-016

- Irreducible non resonant background in the search for $t\bar{t}H(b\bar{b})$
- Test validity of NLO QCD calculations
- Measurement of ratio $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$: large uncertainties cancellation
  - Selection: one isolated lepton, $\geq$4 jets, $\geq$2 b-tagged jets
  - Signal extraction by fit to the measured b-tagging discriminator
  - Dominant systematic: mistag efficiency

NEW





Jet p_T >40 GeV

$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}^{NLO}(m_t = 173.5\ GeV, CT10) = 0.0109\ ^{+0.0043}_{-0.0026}$
[arXiv:1403.2046]

$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}^{hardB} = 0.0117 \pm 0.0040(\text{stat.}) \pm 0.0003(\text{syst.})$

$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}^{hadronB} = 0.0151 \pm 0.0049(\text{stat.}) \pm 0.0004(\text{syst.})$

* Jet flavour at gen. level defined by the flavor of the leading quark (hardB) or by the presence of a B hadron in the list of jet constituents (hadronB)

Cross section ratio $\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}$: Dilepton

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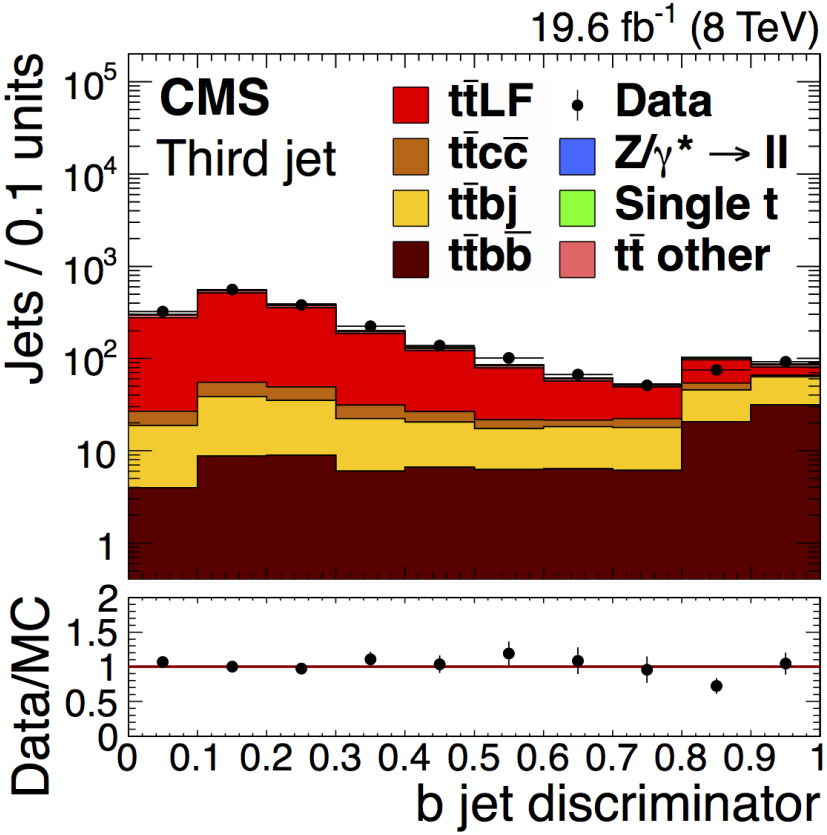
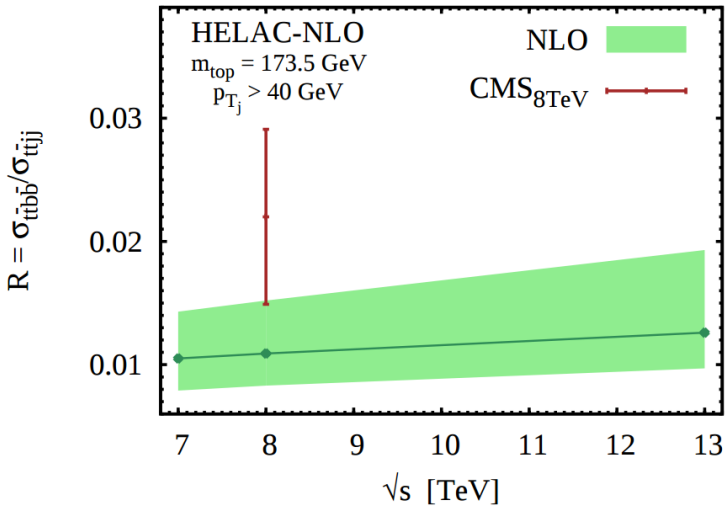
- Similar analysis strategy with CMS TOP-13-016
  - Selection: dilepton events with $\geq$4 jets, $\geq$2 b-tagged jets





- Combination of three dilepton categories (ee, $e\mu$, $\mu\mu$)

Jet p_T >40 GeV

$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}^{NLO}(m_t = 173.5\ GeV, CT10) = 0.0109\ ^{+0.0043}_{-0.0026}$ [arXiv:1403.2046]

$$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)} = 0.022 \pm 0.004\ (\text{stat.}) \pm 0.005\ (\text{syst.})$$

$t\bar{t}t\bar{t}$

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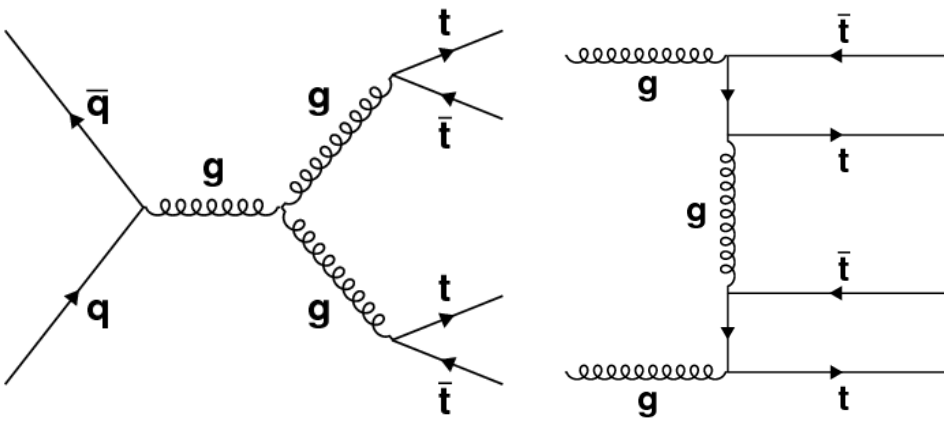
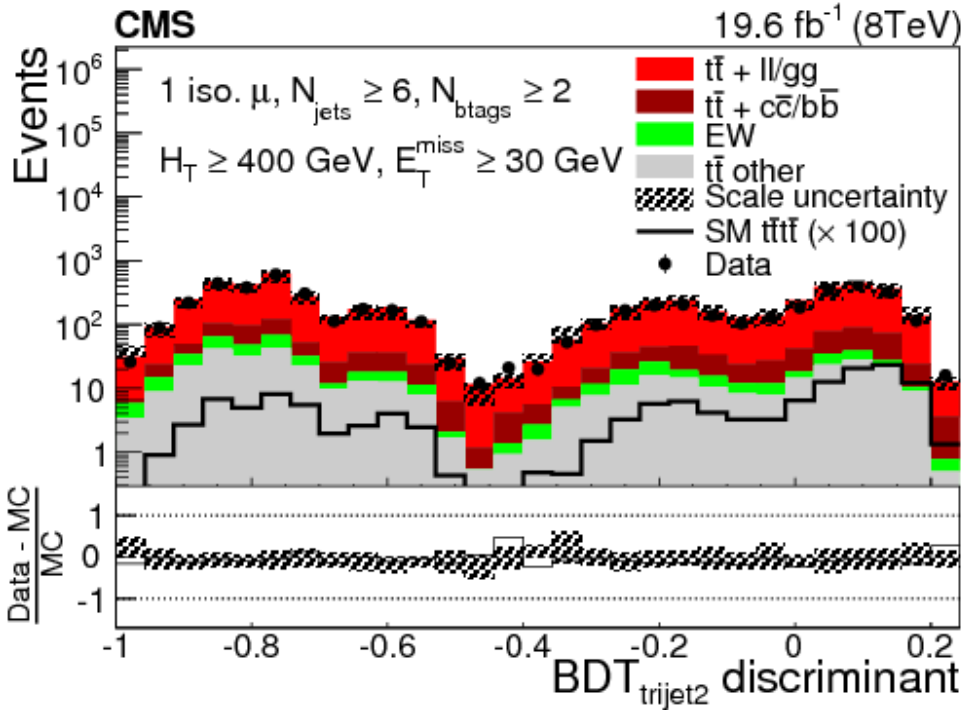
- $\sigma_{t\bar{t}t\bar{t}^{SM}} \approx 1$ fb at 8 TeV (LO)$\rightarrow$ very low cross section!
  - $\sim$9-15 times larger cross section in Run II
- Selection: 1 lepton (e, μ), $\geq$6 jets, $\geq$2 b-tagged jets, H_T >400 GeV, E_T^{miss} $\geq$30 GeV
- Main background: $t\bar{t}$+jets (5 orders of magnitude larger cross section)
- Event classification scheme based on a BDT algorithm
  - Top content, event activity and b-jet content
- Limit setting: simultaneous fit to BDT output distributions

Limits on $\sigma^{SM}_{(t\bar{t}t\bar{t})}$ at 95% C.L. :
expected: 32 $\pm$ 17 fb
observed: 32 fb



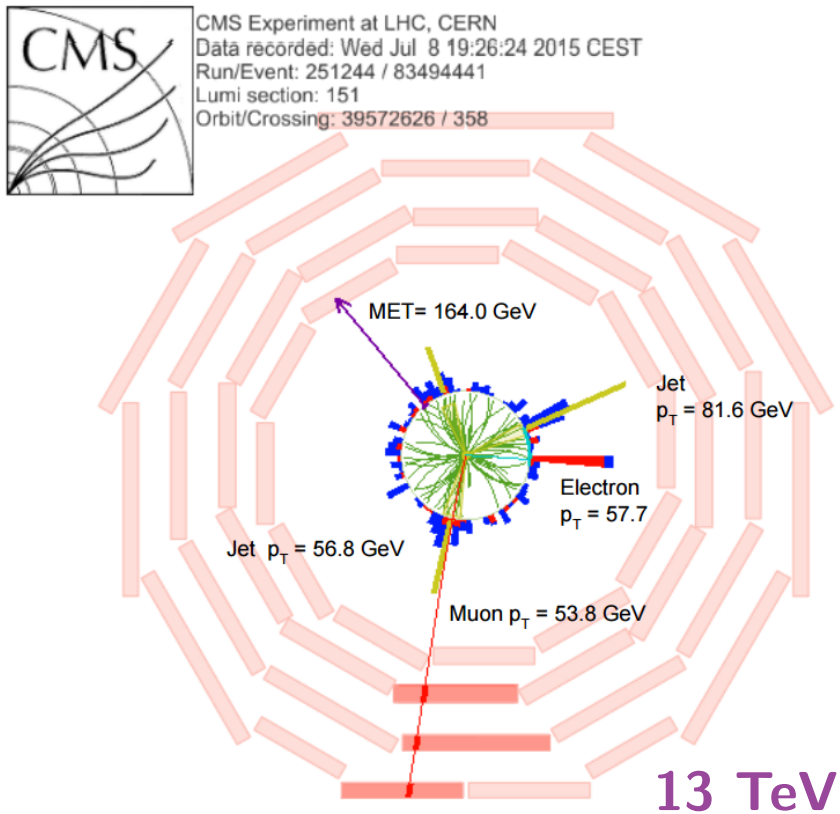


Summary and Outlook

- **LHC: Run I $\sim$ 6M top quark pairs in CMS**
- Many measurements available for $\sigma_{t\bar{t}}$ in different channels with increasing precision, competing with NNLO theory
- Precise measurements of the $\sigma_{t\bar{t}}$ allows to perform measurements of other interesting parameters such as α_s
- All results so far in agreement with SM predictions
- Measurements of $t\bar{t}b\bar{b}$ and $t\bar{t}t\bar{t}$ (dominated by statistics)
- More 8 TeV results close to be public

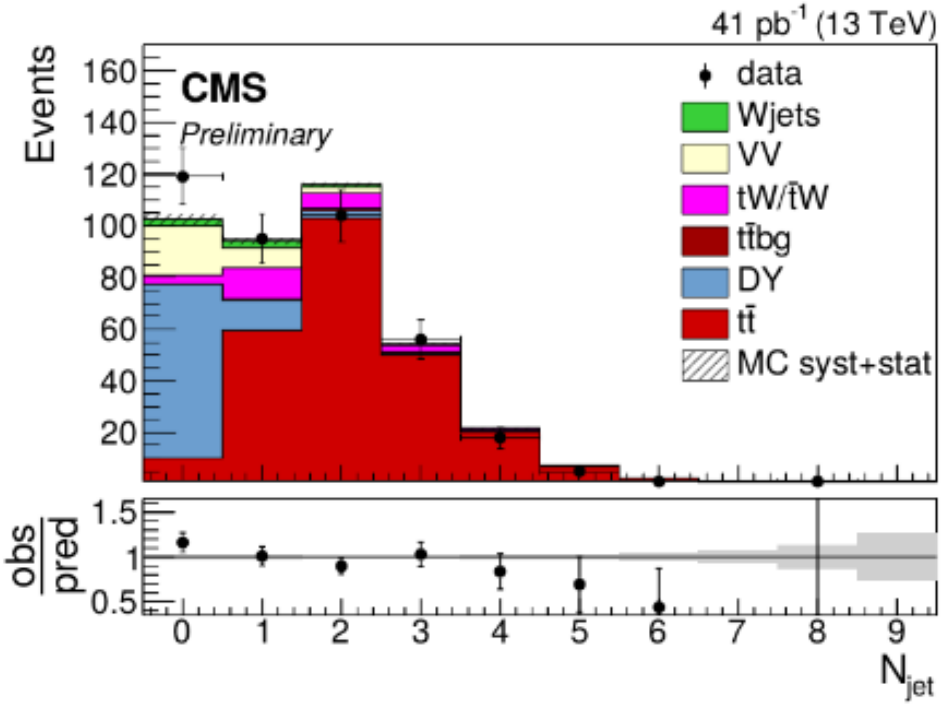
- **Top community has already started looking at LHC Run II data**
  - More top quarks: $\sigma_{t\bar{t}}$ increases by a factor $\sim$3 !
  - Reach higher $m_{t\bar{t}}$, p_T^t ranges
  - Measurement of the ratio of $\sigma_{t\bar{t}}$ at different $\sqrt{s}$: expected to contribute to a better knowledge of NNLO PDFs

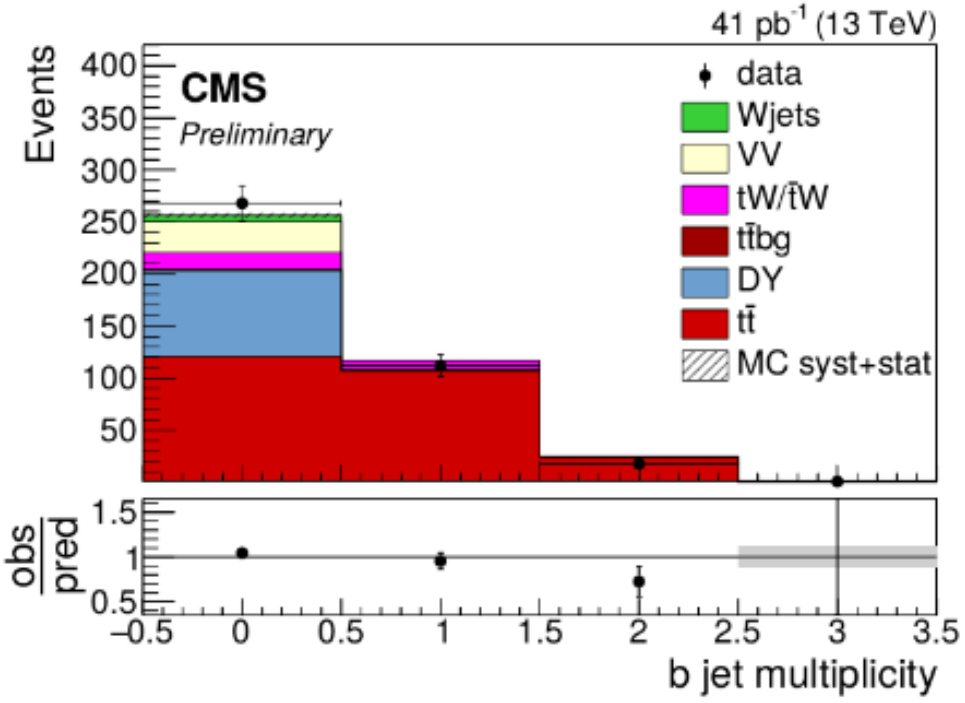
- All CMS top public results can be found in: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP



Hot off the Press!

First Jet and b-jet multiplicities in the $e\mu$ channel at 13 TeV





[CMS DP-2015/019]

Stay tuned !