Inclusive $t\bar{t}$ Cross Section at CMS

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Top Quark Physics at the Precision Frontier

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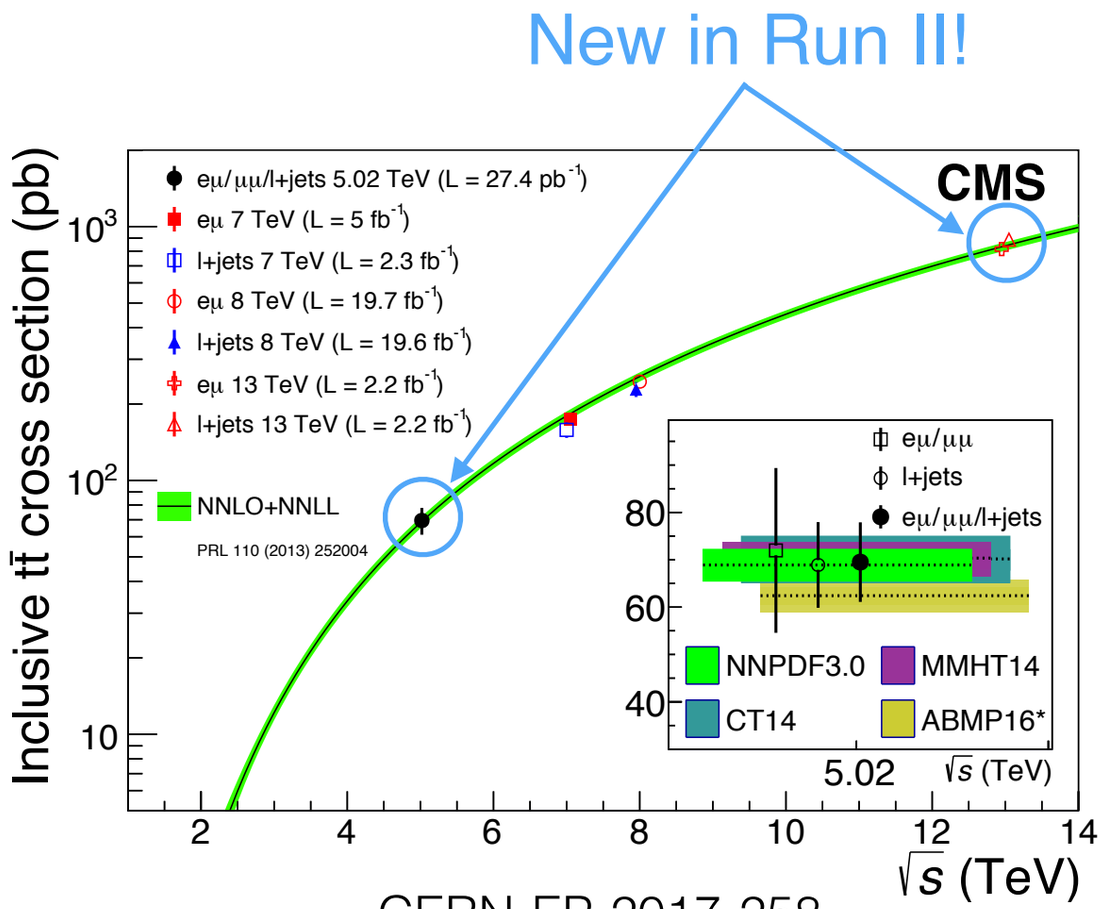
Overview

- Introduction
- Run II standard measurements of inclusive $t\bar{t}$ cross section
  - Dileptonic, semileptonic, all-hadronic
  - How to improve sensitivity?
- Run II new measurements of inclusive $t\bar{t}$ cross section
  - 5 TeV, pPb
- Parameter extraction
  - Top pole mass, α_S, PDF, EFT, etc.

Introduction

- Ongoing series of inclusive $\mathrm{t\bar{t}}$ cross section measurements since start of LHC data taking
  - 5, 7, 8, and 13 TeV
  - Dileptonic, semileptonic, and hadronic final states
- Can reinterpret measurements to place limits on SM parameters
- Entering era of systematically limited measurements
  - How to continue improving measurement precision?



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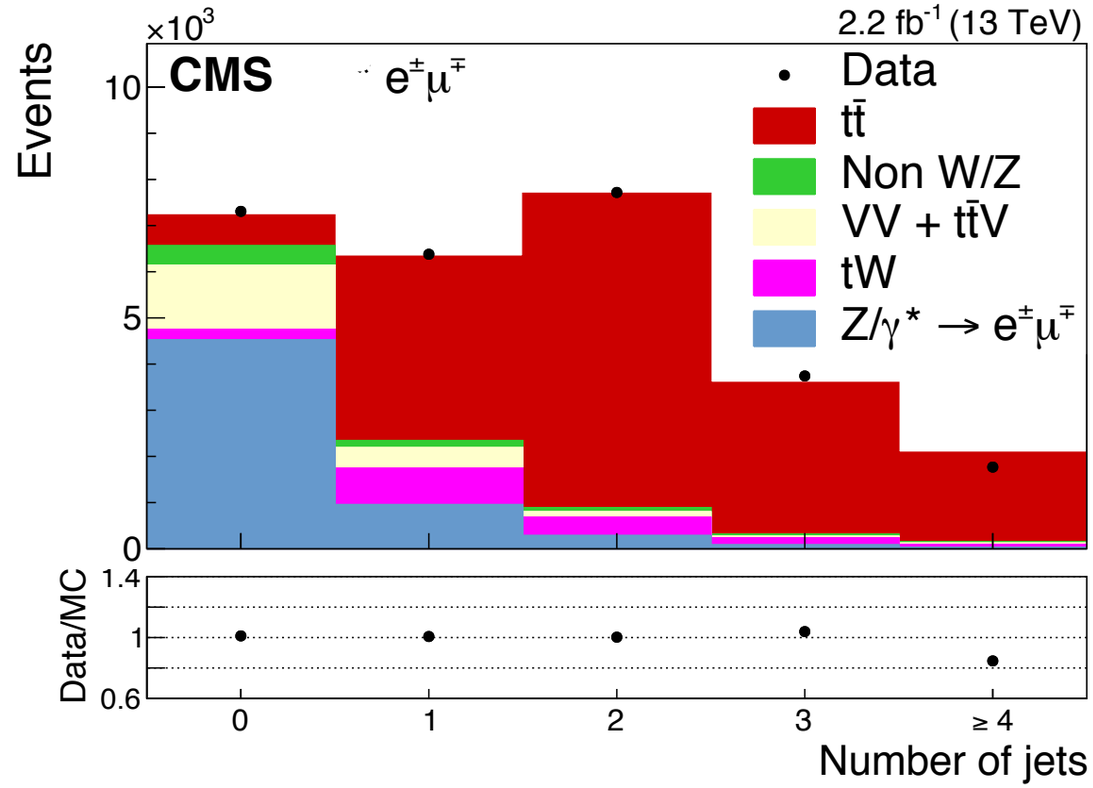
Eur. Phys. J. C 77 (2017) 172

Dileptonic Inclusive $t\bar{t}$ Cross Section

- $t\bar{t} \to e^{\pm}\mu^{\mp}bb$
  - OS eμ pair, p_T > 20 GeV
  - ≥2 jets, p_T > 30 GeV
  - ≥1 b tagged jet



- 2015 13 TeV dataset, 2.2 fb^{-1}
- Analysis: counting experiment
- Result: $\sigma_{t\bar{t}} = 815 \pm 9\,(\mathrm{stat}) \pm 38\,(\mathrm{sys}) \pm 19\,(\mathrm{lumi})\,\mathrm{pb}$

  (Reference: $\sigma^{\mathrm{NNLO}} = 832^{+20}_{-29}\,(\mathrm{scale}) \pm 35\,(\mathrm{PDF} + \alpha_{\mathrm{S}})\,\mathrm{pb}$)

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Dileptonic Inclusive $t\bar{t}$ Cross Section

- Systematically limited
- Experimental uncertainties dominate
  - Lepton efficiencies
  - Jet energy scale
- Generator uncertainty also significant
  - Difference between Powheg v2 and MG5_aMC@NLO

Source	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Experimental		
Trigger efficiencies	9.9	1.2
Lepton efficiencies	18.9	2.3
Lepton energy scale	<1	≤0.1
Jet energy scale	17.4	2.1
Jet energy resolution	0.8	0.1
b tagging	11.0	1.3
Mistagging	<1	≤0.1
Pileup	1.5	0.2
Modeling		
μ_F and μ_R scales	<1	≤0.1
$t\bar{t}$ NLO generator	17.3	2.1
$t\bar{t}$ hadronization	6.0	0.7
Parton shower scale	6.5	0.8
PDF	4.9	0.6
Background		
Single top quark	11.8	1.5
VV	<1	≤0.1
Drell–Yan	<1	≤0.1
Non-W/Z leptons	2.6	0.3
$t\bar{t}V$	<1	≤0.1
Total systematic (no integrated luminosity)	37.8	4.6
Integrated luminosity	18.8	2.3
Statistical	8.5	1.0
Total	43.0	5.3

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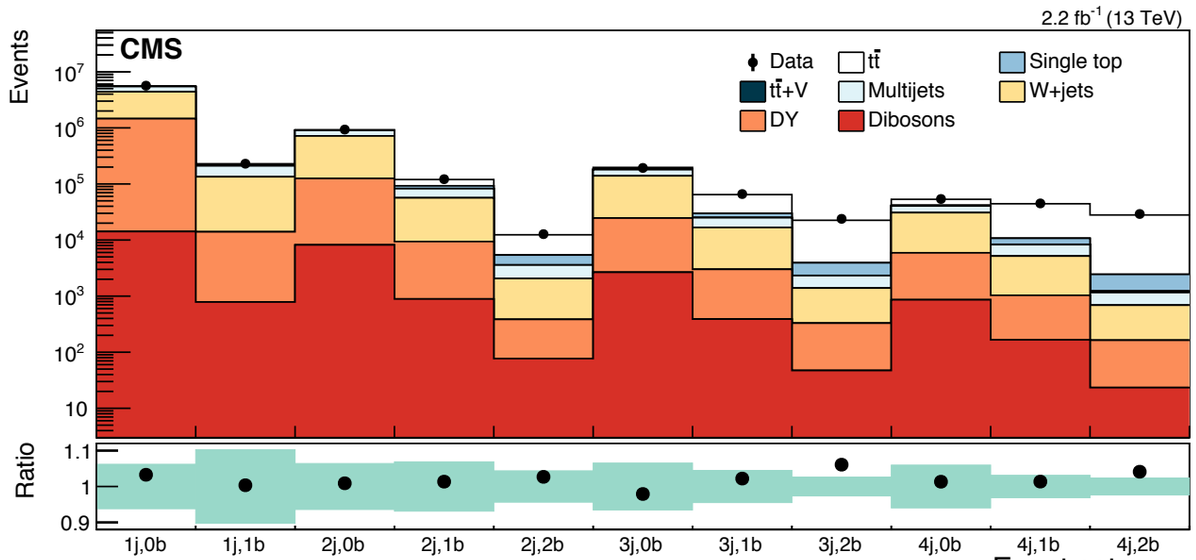
Semileptonic Inclusive $t\bar{t}$ Cross Section

- $t\bar{t} \to \ell bbjj \quad \ell = (e, \mu)$
  - ==1 lepton, $p_T > 30$ GeV
  - ≥1 jet, $p_T > 30$ GeV



- 2015 13 TeV dataset, 2.2 fb^{-1}
- Analysis: fit in bins of N_{jets}, $N_{b\ tag}$, lepton flavor, lepton charge
- Result: $\sigma_{t\bar{t}} = 888 \pm 2\,(\mathrm{stat})\ ^{+28}_{-26}\,(\mathrm{sys}) \pm 20\,(\mathrm{lumi})\,\mathrm{pb}$

  (Reference: $\sigma^{\mathrm{NNLO}} = 832^{+20}_{-29}\,(\mathrm{scale}) \pm 35\,(\mathrm{PDF} + \alpha_{\mathrm{S}})\,\mathrm{pb}$)

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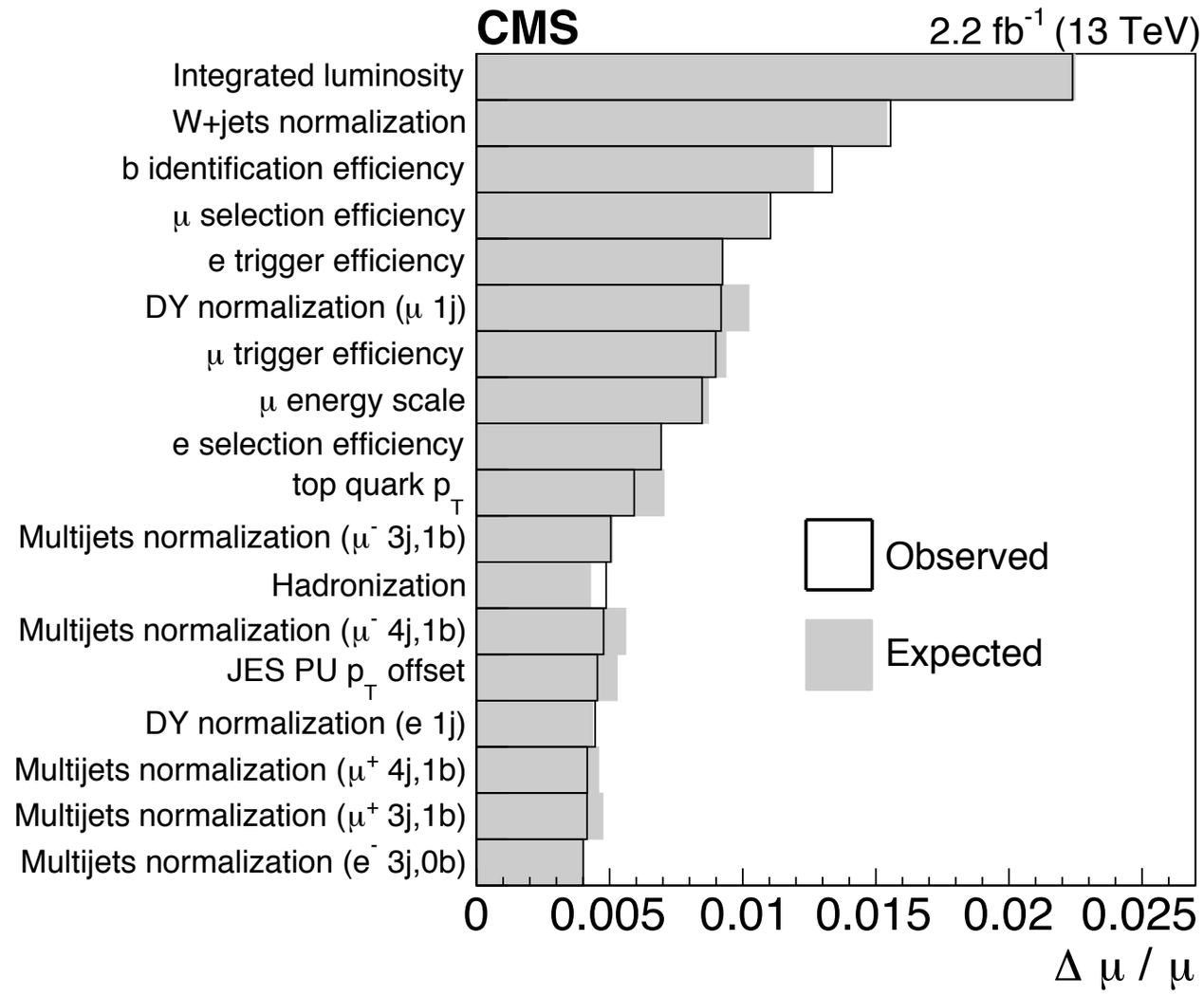
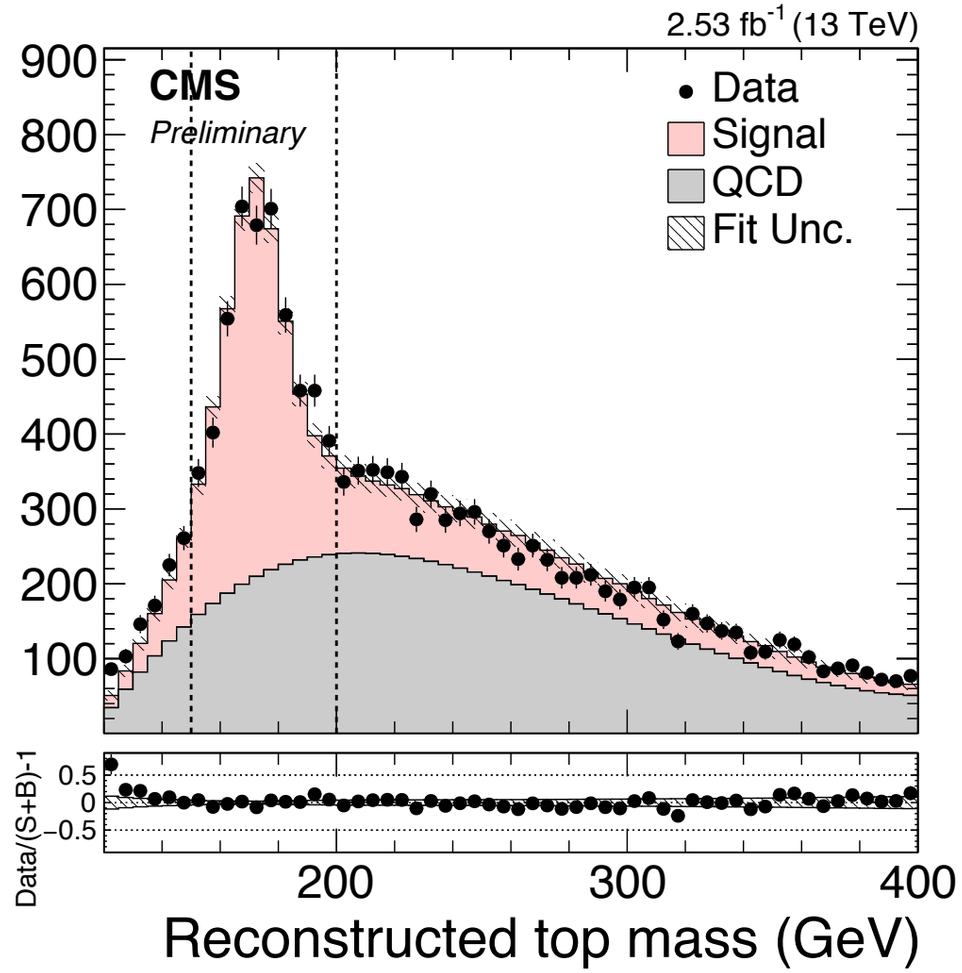
Semileptonic Inclusive $t\bar{t}$ Cross Section

- Systematically limited
- Experimental uncertainties dominate
  - W+jets rate
  - b tag efficiency
  - Lepton efficiencies



All-hadronic Inclusive $t\bar{t}$ Cross Section

- $t\bar{t} \rightarrow bbjjjj$
  - ≥6 jets, p_T > 45 GeV
  - H_T > 500 GeV
    - ≥2 b tagged jets
- 2015 13 TeV dataset, 2.53 fb^{-1}
- Analysis: fit to reconstructed top mass



- Result: $\sigma_{t\bar{t}} = 834 \pm 25\,(\text{stat})\ ^{+118}_{-104}\,(\text{sys}) \pm 23\,(\text{lumi})\,\text{pb}$

  (Reference: $\sigma^{\text{NNLO}} = 832^{+20}_{-29}\,(\text{scale}) \pm 35\,(\text{PDF} + \alpha_S)\,\text{pb}$)

All-hadronic Inclusive $t\bar{t}$ Cross Section

- Systematically limited
- Experimental uncertainties dominate
  - Jet energy scale, QCD rate, b tag efficiency
  - Parton shower also contributes
    - Difference between Pythia8, Herwig++
  - Less sensitive than dileptonic, semileptonic measurements

Source	(%)
QCD background modeling	$-1.0, +6.6$
Subdominant backgrounds	± 4.0
Jet energy scale	$-8.2, +9.0$
Jet energy resolution	$-0.7, +0.8$
b tagging	$-5.5, +6.2$
Trigger efficiency	$-2.9, +3.2$
Scale (μ_F and μ_R)	$-1.5, +0.0$
PDF	± 1.0
Parton shower	$-5.0, +2.5$
NLO generator	± 2.0
Total systematic	$-12.4, +14.1$
Statistical	± 3.0
Integrated luminosity	± 2.7

Improving Systematic Limitations

- 13 TeV measurements all systematically limited
- Many common sources of systematic uncertainty
  - Mainly experimental: lepton efficiencies, JES, b tag efficiency, etc.
- Ways to improve
  - Cross section from fit instead of counting experiment
  - Improved a priori measurement of efficiencies
  - Combination of measurements

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Inclusive $t\bar{t}$ cross section at 5 TeV

2015 5 TeV dataset, 27.4 pb^{-1}

Dileptonic

- $t\bar{t} \to e^{\pm}\mu^{\mp}bb,\ \mu^{\pm}\mu^{\mp}bb$
  - OS leptons, μ(e) p_T > 18(20) GeV
  - ≥2 jets, p_T > 25 GeV
  - Z veto, MET cut
- Analysis: counting experiment

Semileptonic

- $t\bar{t} \to ebbjj,\ \mu bbjj$
  - ==1 lepton, μ(e) p_T > 25(40) GeV
  - ≥2 non-b-tagged jets, p_T > 30 GeV
- Analysis: fit in bins of e/μ, 0/1/≥2 additional b tagged jets
  - Fit min dR of non-b-tagged jets

Statistically limited, semileptonic channel most sensitive

Combined result: $\sigma_{t\bar{t}} = 69.5 \pm 6.1\,(\mathrm{stat}) \pm 5.6\,(\mathrm{sys}) \pm 1.6\,(\mathrm{lumi})\,\mathrm{pb}$

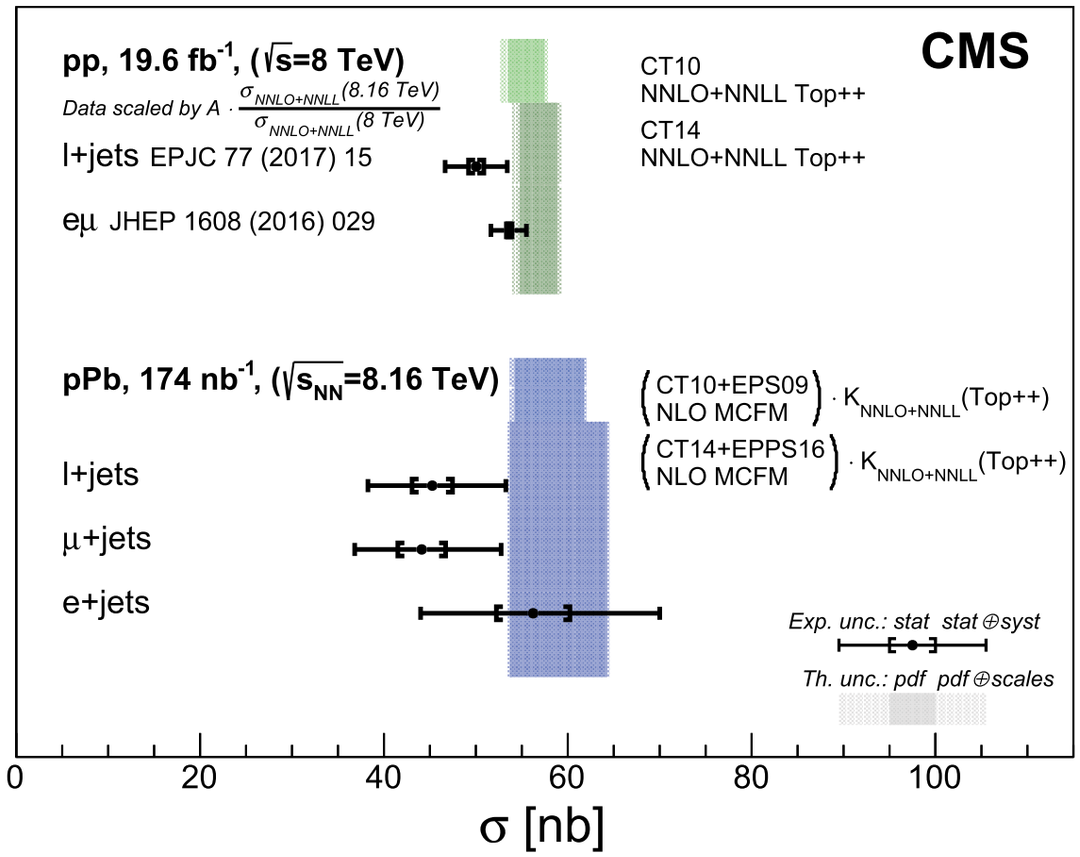
(Reference: $\sigma^{\mathrm{NNLO}} = 68.9^{+1.9}_{-2.3}\,(\mathrm{scale}) \pm 2.3\,(\mathrm{PDF})\ ^{+1.4}_{-1.0}\,(\alpha_S)\,\mathrm{pb}$)

Phys. Rev. Lett. 119 (2017) 242001

Inclusive $t\bar{t}$ Cross Section in pPb Collisions

- $t\bar{t} \to \ell bbjj \quad \ell = (e, \mu)$
  - ==1 μ(e), p_T > 30 GeV
  - ≥4 jets, p_T > 25 GeV
- 2016 8.16 TeV pPb dataset, 174 nb^{-1}
- Analysis: fit reconstructed W mass in bins of 0/1/≥2 b tags
- Result: $\sigma_{t\bar{t}} = 45 \pm 8$ nb

(Reference: $\sigma^{\mathrm{NNLO}} = 59.0 \pm 5.3\,(\mathrm{PDF})^{+1.6}_{-2.1}\,(\mathrm{scale})\,\mathrm{nb}$)



Systematically limited
Dominant uncertainties: b tagging efficiency, background modeling

Extracting Parameter Limits

- Inclusive $\mathrm{t\bar{t}}$ cross section depends on top quark pole mass, strong coupling constant α_S, gluon PDF

- Measured inclusive cross sections reinterpreted to provide bounds on these parameters

- Limit precision relies on:

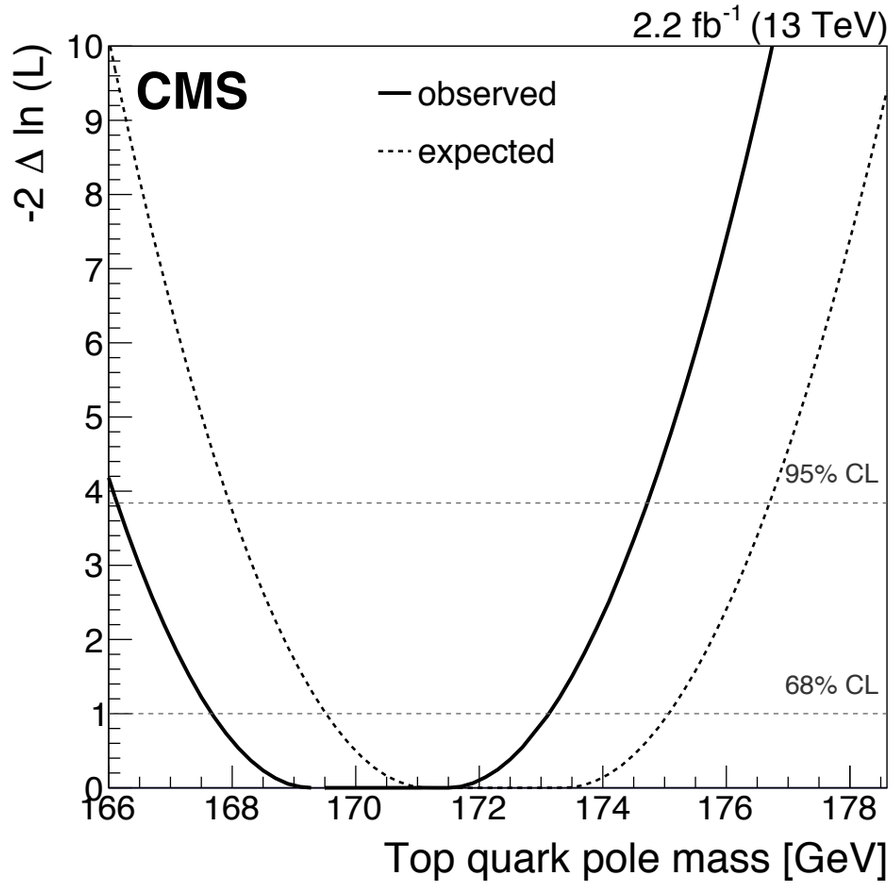
  - Precision of inclusive $\mathrm{t\bar{t}}$ cross section measurement

  - Uncertainty in dependence of measurement on parameter

  - Uncertainty in theoretical dependence of inclusive cross section on parameter

Limits on Top Pole Mass

- Run II: **170.6 ± 2.7 GeV**
  - From 13 TeV semileptonic measurement of inclusive cross section
  - Cross section measurement uncertainty dominates
- Run I: **173.8 +1.7/-1.8 GeV**
  - From combination of 7 and 8 TeV dileptonic measurements of inclusive cross section (JHEP 08 (2016) 029)
- Can we benefit from further combination?



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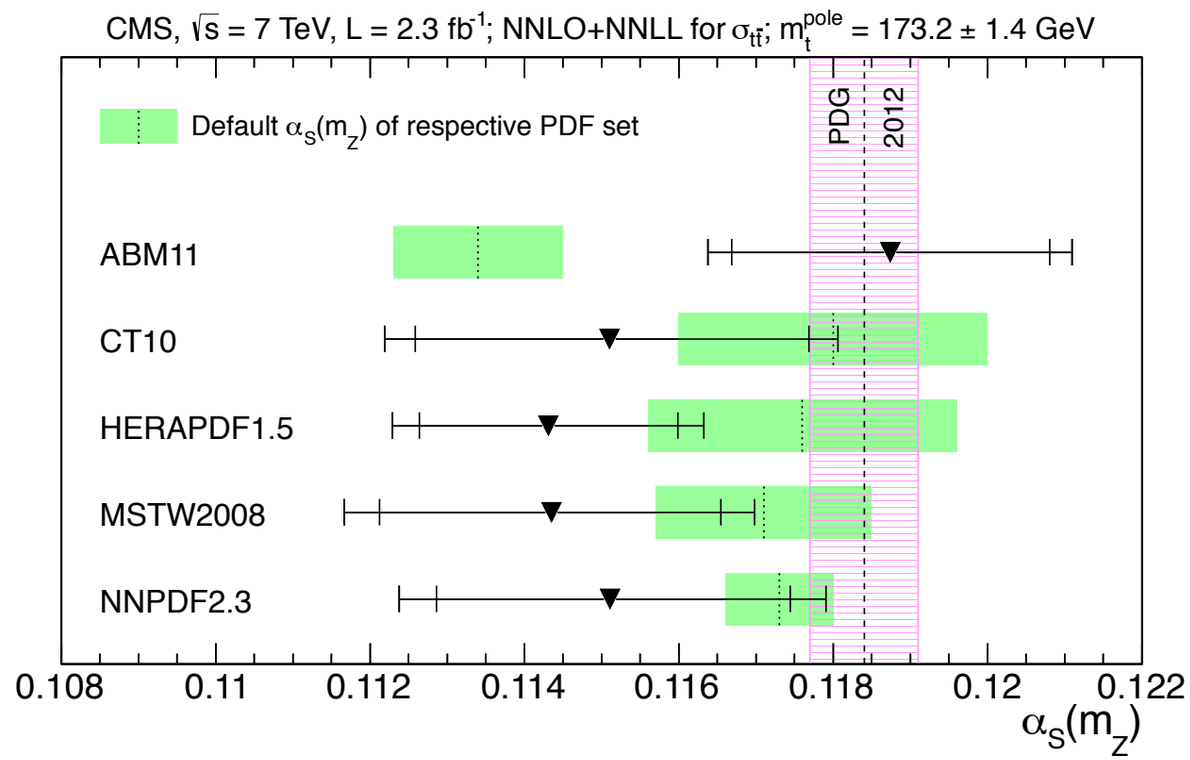
Limits on α_S

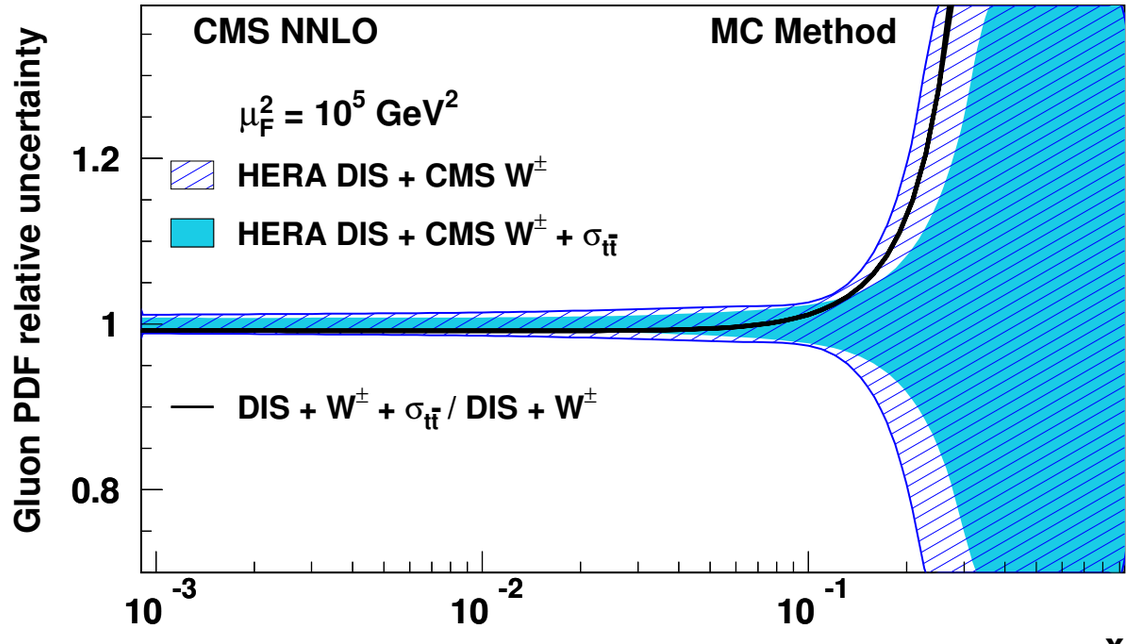
- No limit yet on α_S from Run II data
- Run I α_S limit from 7 TeV dileptonic measurement of inclusive cross section
  - Dominant uncertainties:
    - Uncertainty on inclusive cross section measurement
    - PDF



Phys. Lett. B, 728 (2014) 496

Limits on Gluon PDF

- PDFs measured through fit to many CMS measurements
  - Including inclusive $t\bar{t}$ cross section
  - 13 TeV inclusive cross section measurements not yet applied to PDFs
  - 5 TeV inclusive cross section measurement moderately improves PDF precision at high x



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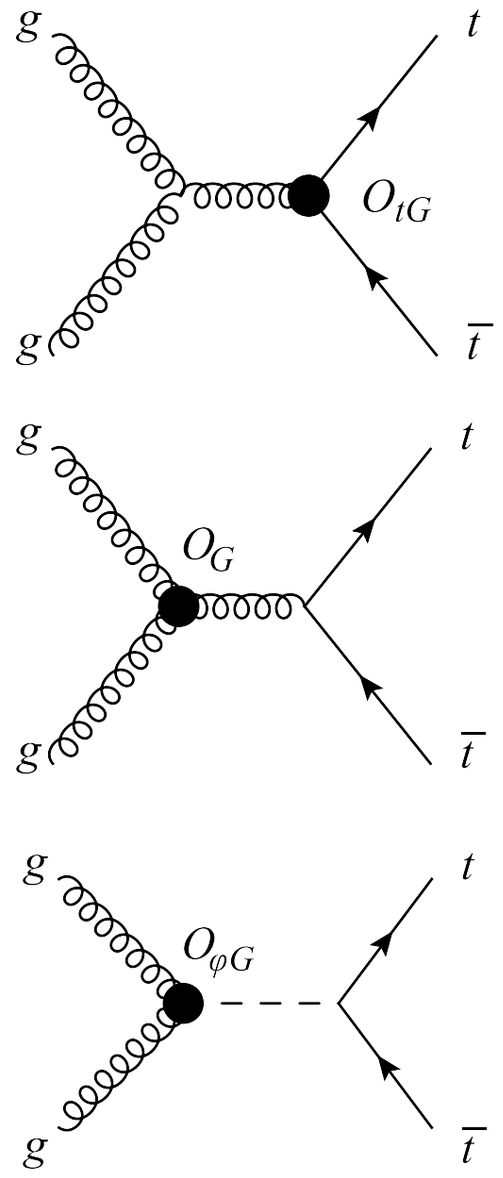
EFT Interpretation

- Impact of generic new physics beyond LHC energy reach modeled by adding higher-order EFT terms to SM Lagrangian

  - 6th-dimensional operator O_{tG} has dominant effect on inclusive $t\bar{t}$ cross section, followed by O_G and $O_{\phi G}$

- Ongoing work to reinterpret $t\bar{t}$ cross sections as EFT limits

  - Dedicated CMS subgroup



Sample diagrams for O_{tG}, O_G, $O_{\phi G}$

Phys. Rev. D, 83 (2011) 034006