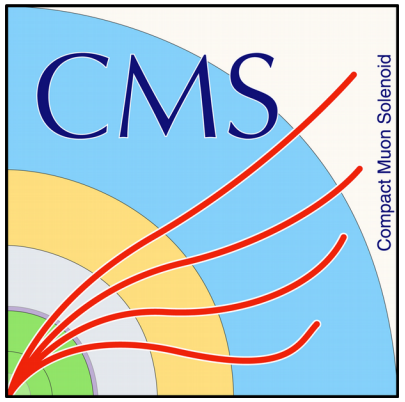


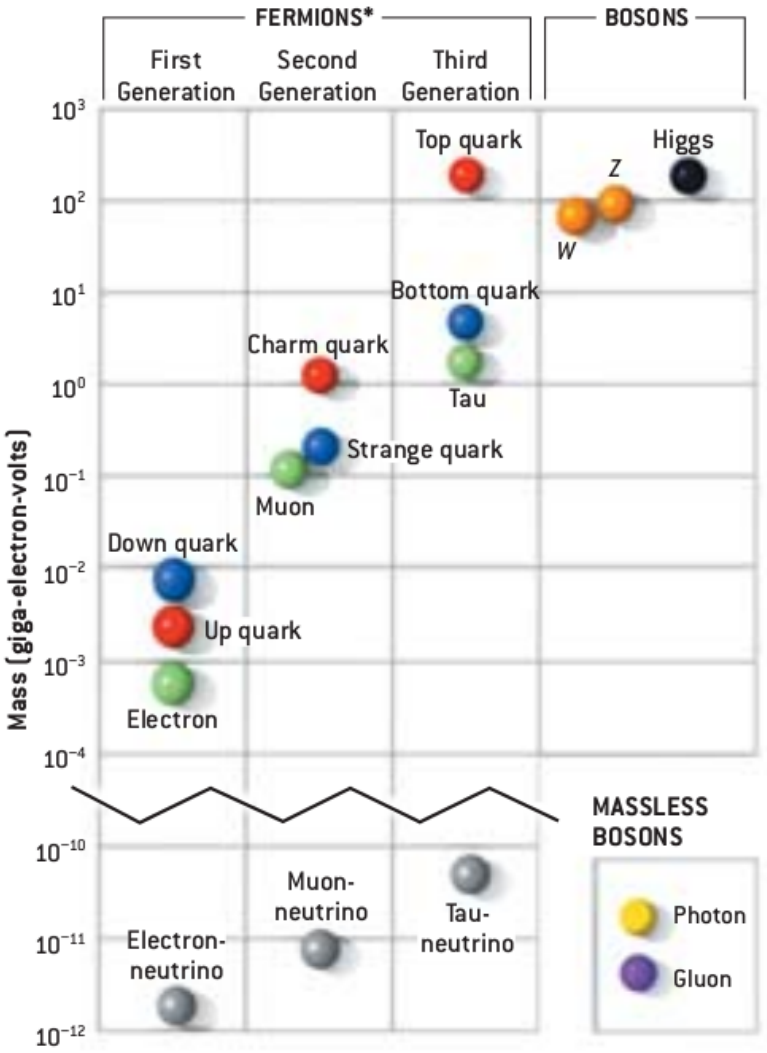
$t\bar{t}$ + X production at ATLAS and CMS

Antonio Sidoti

on behalf of the ATLAS and CMS collaborations

Istituto Nazionale Fisica Nucleare – Sezione di Bologna

Top quark



Try to avoid repetitions with M. Aldaya Martin on Tuesday plenary session

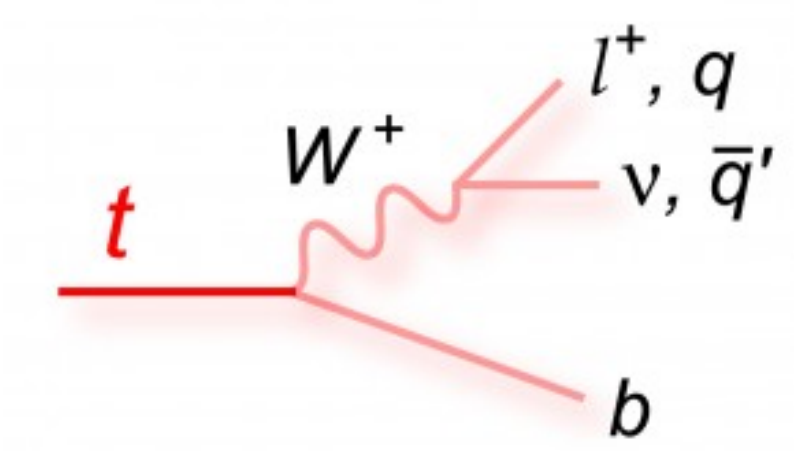
- Top quark elementary particle with the largest mass
→ Largest Yukawa coupling
Deviation from SM predictions → Hints of BSM
- Top quark decays before hadronization
→ ~ free quark
→ Test of perturbative QCD
- $t\bar{t}$ pairs produced with large statistics at LHC
→ Main background to many BSM searches (cf .C. Lee presentation on plenary)

$\sqrt{s}$	7 TeV	8 TeV	13 TeV
$\sigma(t\bar{t})$ (pb)	177	253	830

Uncertainties: PDF → ~5 %, Scale and α_s → :~3%

NNLO+NNLL Predictions
(Czakon and Mitov Comput.Phys.Commun. 185 (2014) 2930)
$t\bar{t}$ pairs predominantly produced from $gg \rightarrow t\bar{t}$ at LHC (~90% at $\sqrt{s}$=13 TeV)

Top quark pair decay



BR(t → Wb) almost 100%

Different final state according to W boson decay modes.

W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
e^-	e^-e^+	$e^-\mu^+$	$e^-\tau^+$	electron+jets	
μ^-	μ^-e^+	$\mu^-\mu^+$	$\mu^-\tau^+$	muon+jets	
τ^-	τ^-e^+	$\tau^-\mu^+$	$\tau^-\tau^+$	tau+jets	
$\bar{u}d$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{c}s$					

dileptons

Decay modes considered:

- Lepton +jet (e/μ + jet)
- Dilepton (ee,eμ,μμ)

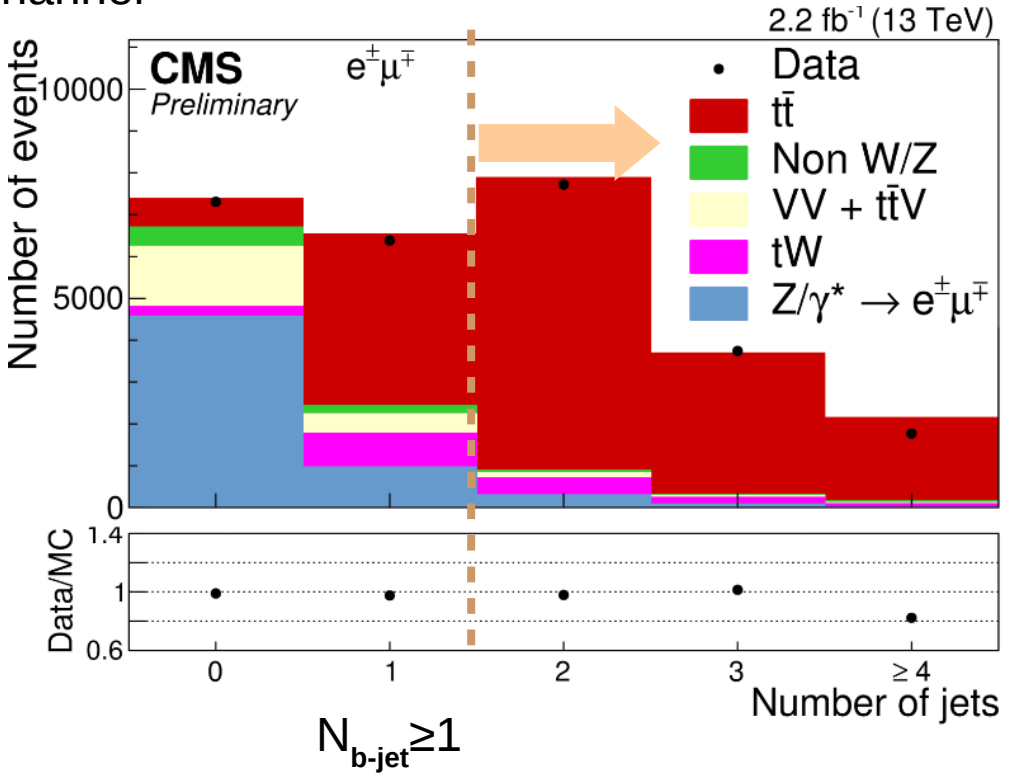
Measurements at √s=7, 8 and 13 TeV

$t\bar{t}$ inclusive cross section measurement at 13 TeV: CMS

Measurement of ttbar cross section in diletpon channel
→ only e μ
Full 2015 statistics: 2.2 fb^{-1}

For M_{top}=172.5 GeV
Theory predictions from:
Czakon and Mitov
Comput.Phys.Commun. 185 (2014) 2930

$\sigma_{t\bar{t}}=832^{+20}_{-29}\pm35$ (pdf) pb at √s=13 TeV



$N_{b\text{-}jet}\geq1$

Cross section measurement cut & count method:

$$\sigma_{t\bar{t}} = \frac{N - N_B}{\mathcal{A}\cdot\mathcal{L}},$$

$\sigma_{t\bar{t}} = 793 \pm 8\,(\text{stat}) \pm 38\,(\text{syst}) \pm 21\,(\text{lumi})\,\text{pb}$

Largest experimental systematics:
Lepton eff (2.3%), Jet Energy scale (2.2%),
btagging (1.4%)
From theory: POWHEG vs MG5_aMC@NLO
NLO Generator (2.1%), Single top quark (1.5 %),

CMS: CMS-PAS-TOP-16-005

$t\bar{t}$ inclusive cross section measurement at 13 TeV: ATLAS

Different method
→ reduce the systematics
Measuring 1 and 2 btag events
Fit simultaneously $\sigma_{t\bar{t}}$ and $\varepsilon_{\text{b-tag}}$ efficiency

1 b-tag Data events

1 b-tag background events

ttbar preselection efficiency =0.83%

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

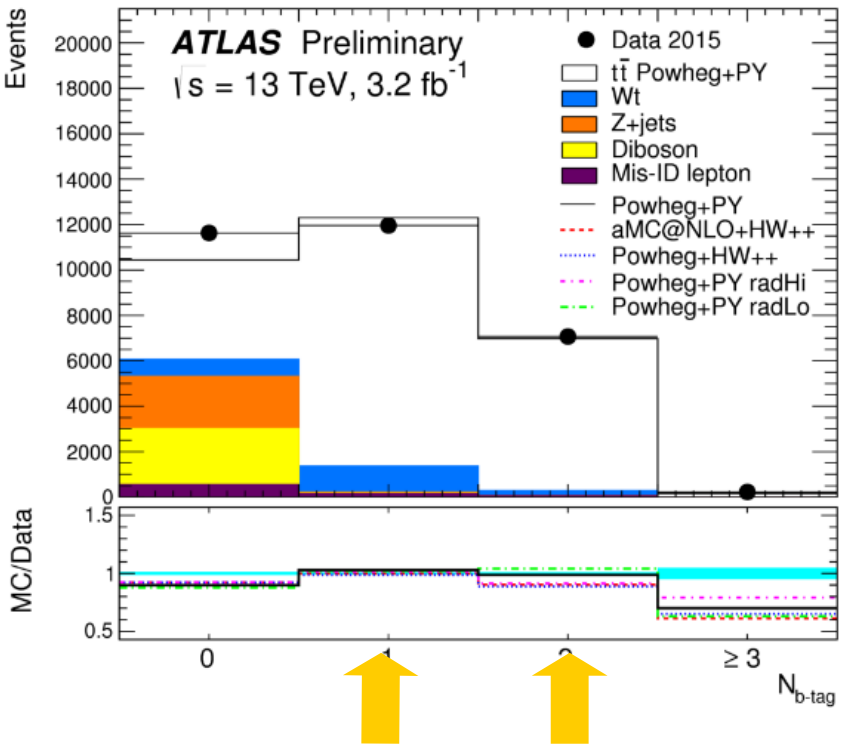
$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\text{bkg}}$$

tagging correlation coefficient

$$C_b = \frac{\varepsilon_{bb}}{\varepsilon^2_b} = 1.002$$

2 b-tag Data events

2 b-tag background events



Largest systematics:
Ttbar hadronization (2.8 %), NLO (0.8%), misidentified leptons (0.6 %)

Event counts	N_1	N_2
Data	11958	7069
Single top	1160 ± 120	224 ± 70
Dibosons	34 ± 12	1 ± 0
$Z(\to \tau\tau \to e\mu)$+jets	37 ± 16	2 ± 1
Misidentified leptons	165 ± 65	116 ± 55
Total background	1390 ± 140	343 ± 89

$$\sigma_{t\bar{t}} = 803 \pm 7\,(\text{stat}) \pm 27\,(\text{syst}) \pm 45\,(\text{lumi}) \pm 12\,(\text{beam})\ \text{pb},$$

$$\sigma^{\text{fid}}_{t\bar{t}} = 11.12 \pm 0.10\,(\text{stat}) \pm 0.28\,(\text{syst}) \pm 0.62\,(\text{lumi}) \pm 0.17\,(\text{beam})\ \text{pb},$$

ATLAS: ATLAS-CONF-2016-005

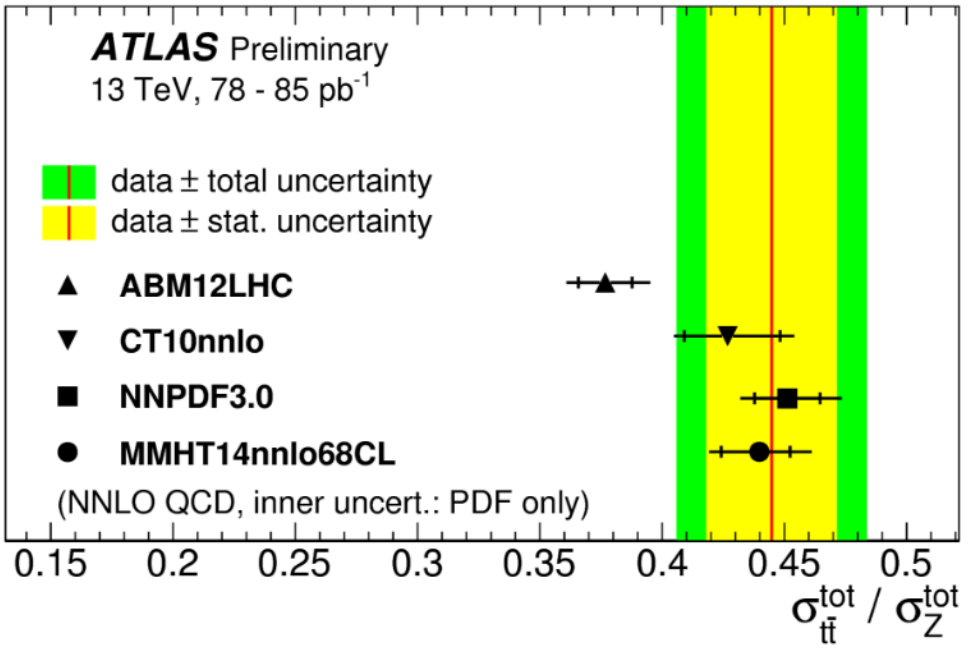
Ratio $t\bar{t}$ to Z production at 13 TeV: ATLAS

To reduce luminosity uncertainties measure ratio wrt well known processes

$$R_{t\bar{t}/Z} = \frac{\sigma_{t\bar{t}}}{0.5\left(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu}\right)},$$

Measure $\sigma(pp \to tt)$ in dilepton (ee,$\mu\mu$) (same method as eμ) or lep (e/μ)+jet

$$R_{t\bar{t}/Z} = 0.445 \pm 0.027\,(\text{stat}) \pm 0.028\,(\text{syst}) = 0.445 \pm 0.039\,,$$

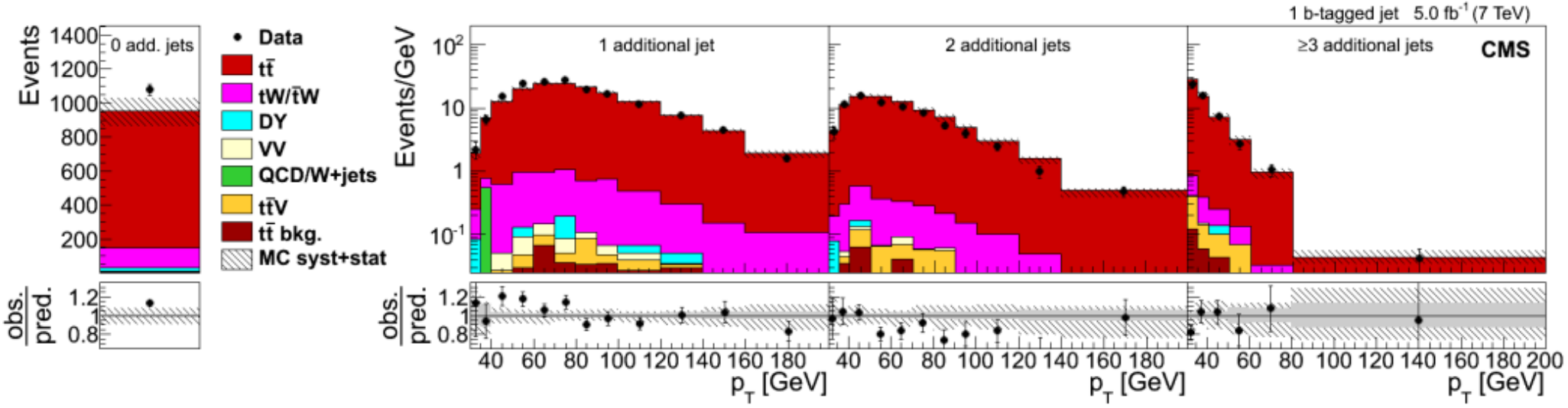


Powerful test of Parton Distribution Functions

Largest systematics:
Ttbar hadronization (4.5 %), NLO (2.2%), Lepton Id & Trigger (2.2%) Z acceptance (1.5%) PDF (1.4%), misidentified leptons (1.4 %). ISR/FSR (1.2%)

ATLAS: ATLAS-CONF-2015-049

$t\bar{t}$ inclusive cross section legacy measurement at 7 and 8 TeV: CMS eμ



Profile LH fit of P_T of additional jets in 0,1 and 2 b-tag regions

P_T of additional jets sensible to modeling uncertainties

Measure visible inclusive cross section → extrapolate to full phase space

$$\sigma_{t\bar{t}} = 173.6 \pm 2.1\,(\text{stat})^{+4.5}_{-4.0}\,(\text{syst}) \pm 3.8\,(\text{lumi})\,\text{pb} \quad \textbf{7 TeV}$$

$$\sigma_{t\bar{t}} = 244.9 \pm 1.4\,(\text{stat})^{+6.3}_{-5.5}\,(\text{syst}) \pm 6.4\,(\text{lumi})\,\text{pb} \quad \textbf{8 TeV}$$

CMS (7 and 8 TeV eμ):
arXiv: 1603.02303

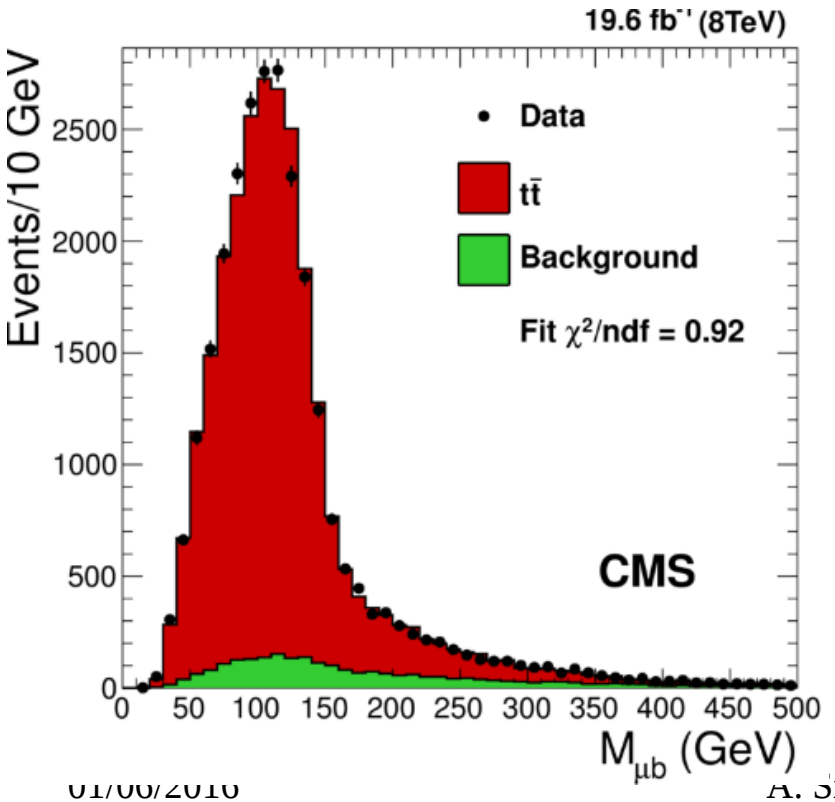
$t\bar{t}$ inclusive cross section legacy measurement at 7 and 8 TeV: CMS lep+jet

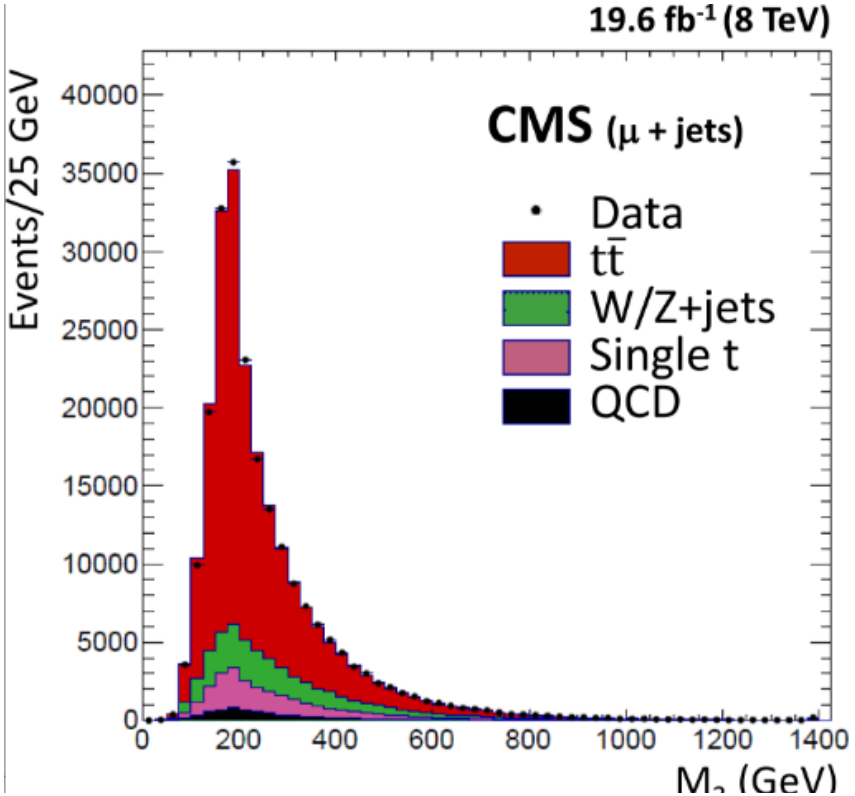
Complementary measurement in lep+jet fitting M_{lb} (Invariant mass)

$\sigma_{t\bar{t}}$(8 TeV) = 228.5±3.8 (stat) ±13.7 (syst) ±6.0(lumi) pb

and M_3 (Invariant mass of 3-jet Had top)

$\sigma_{t\bar{t}}$(8 TeV) = 227.1±2.5 (stat) ±19.1 (syst) ±6.0(lumi) pb





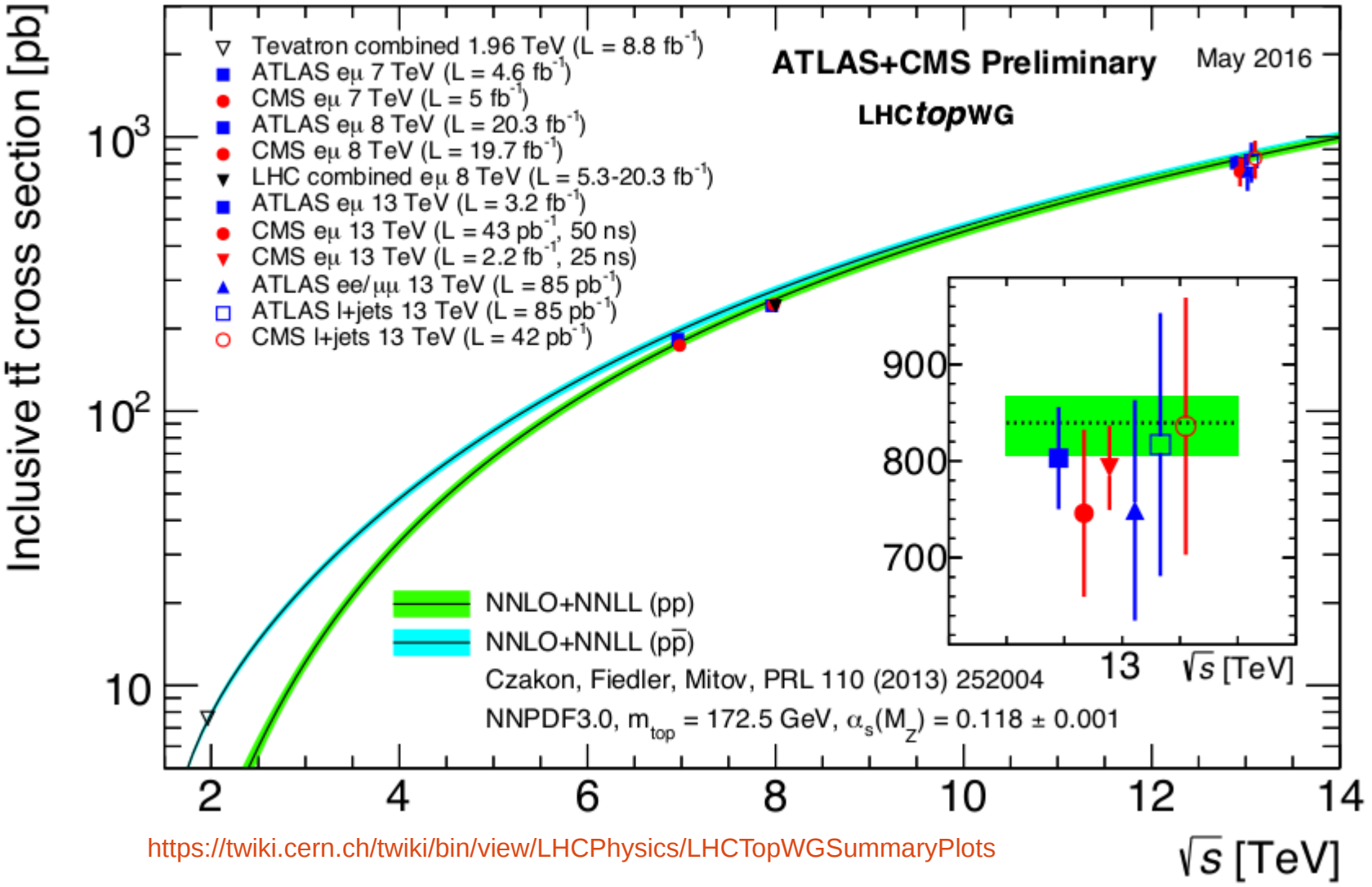
CMS (8 TeV lep+jet):
arXiv: 1602.09024(Subm. EPJC)

$t\bar{t}$ inclusive cross section measurement at 13 TeV vs 8 TeV (eμ and lep+jet): ATLAS and CMS

Comparison of systematic uncertainties

	Run 1 Legacy papers			First Run2 measurement
Systematics (%)	ATLAS Run1 (8 TeV) Eur.Phys.J. C74 (2014) 3109	CMS Run1 (7 and 8 TeV) 1603.02303	CMS Run1 (8 TeV) lep+jet 1602.09024	ATLAS Run2 (13 TeV) ATLAS-CONF -2016-005
PDF	1.1	0.3	2.1	0.5
Modelling	1.2	1.1	4.4	2.8
MC generator	0.9	1.1	3.7	
Lepton Reconstruction & Trigger	0.9	1.9	0.5	0.8
Jet Reconstruction & E_T scale	0.7	0.9	2.2	0.4
b-tagging	0.4	0.5	0.7	0.3
Backgrounds	0.3	1.6	0.3	1.1

15 years of $t\bar{t}$ xsection Measurements



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

Differential xsection Measurement

Lepton + jet channel e/μ (CMS also dilepton)

- Reconstructed variables:

Hadronic top and $t\bar{t}$ system P_T, y,...

→ Particle level (Fiducial phase space)

→ Parton Level (Full phase space)

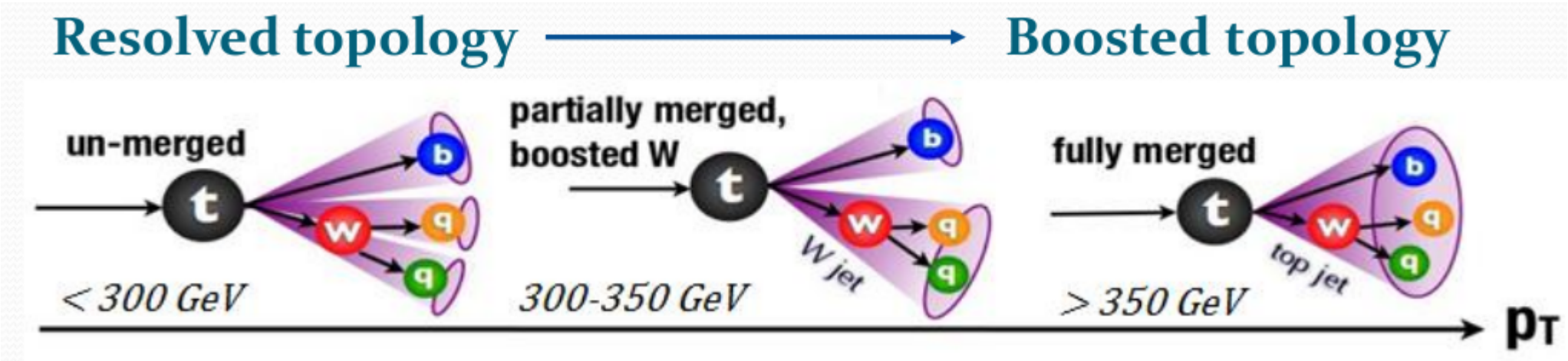
- Detector: $\not{E}_T$, N_{jet}, N_{bjet}
- Radiation sensitive: $\Delta\phi$,...

CMS and ATLAS are providing RIVET routines easing comparison with theory

Two kinematical regimes:

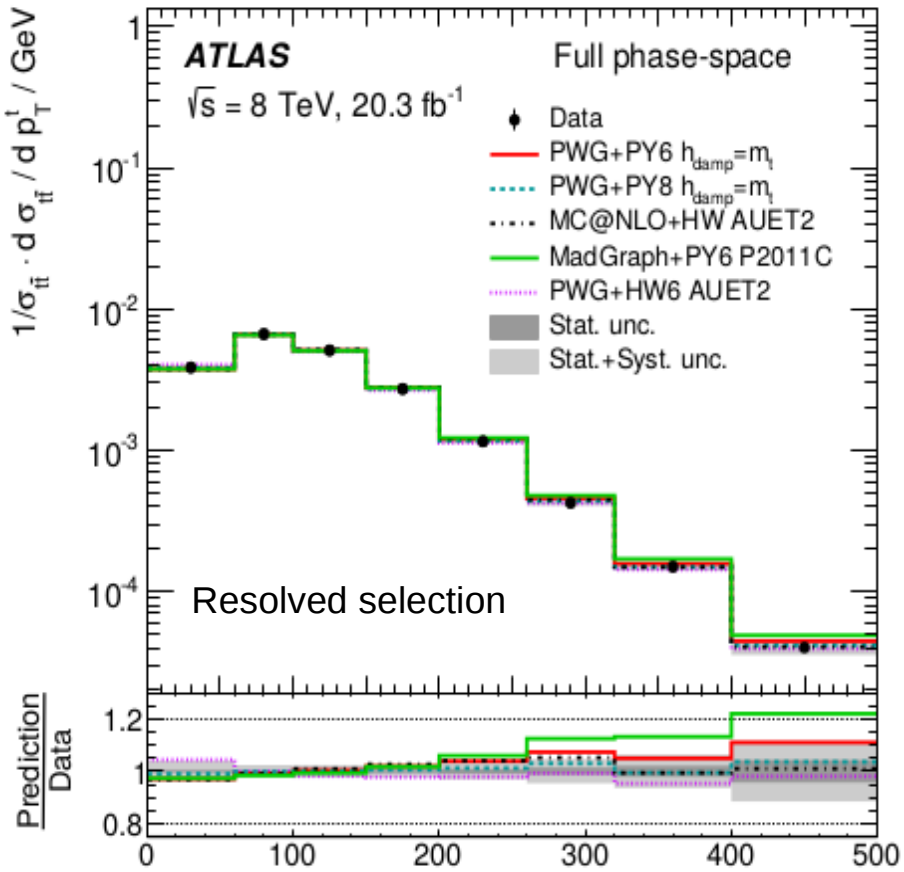
- Resolved (top quark with low P_T)
- Boosted (enhanced at 13 TeV, BSM may increase this region)

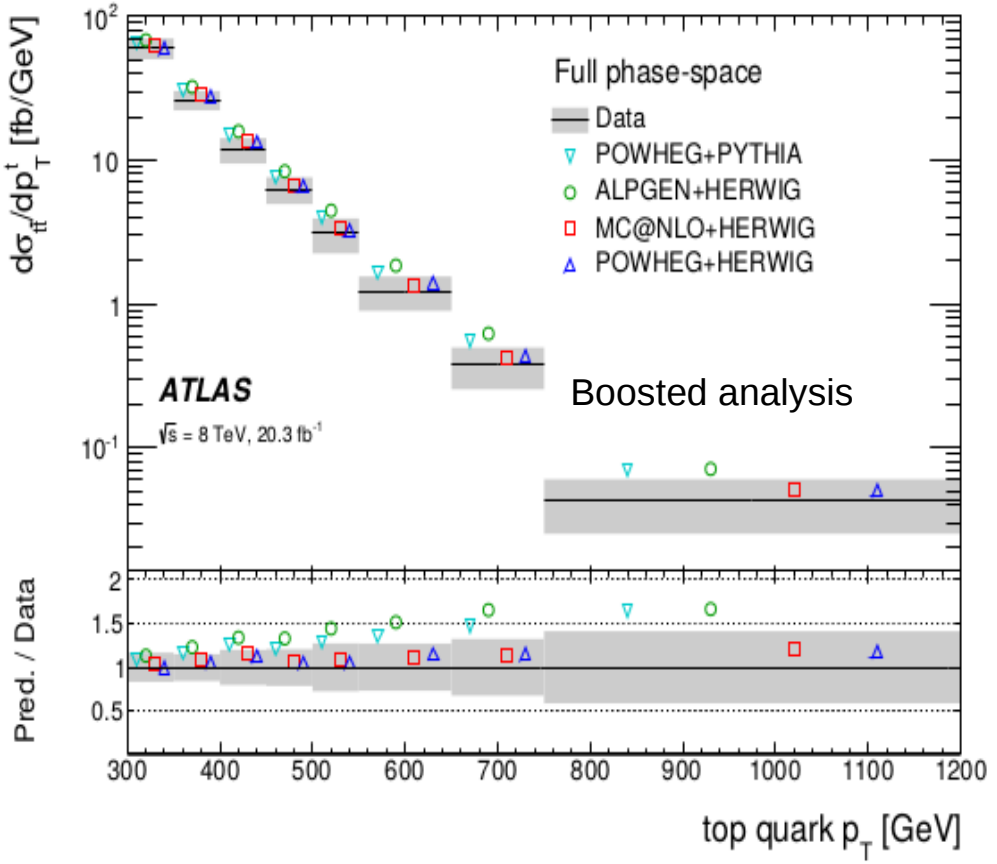
→ use jet substructure to reduce QCD background



Differential xsection Measurement: 8 TeV

8 TeV measurements: Parton level





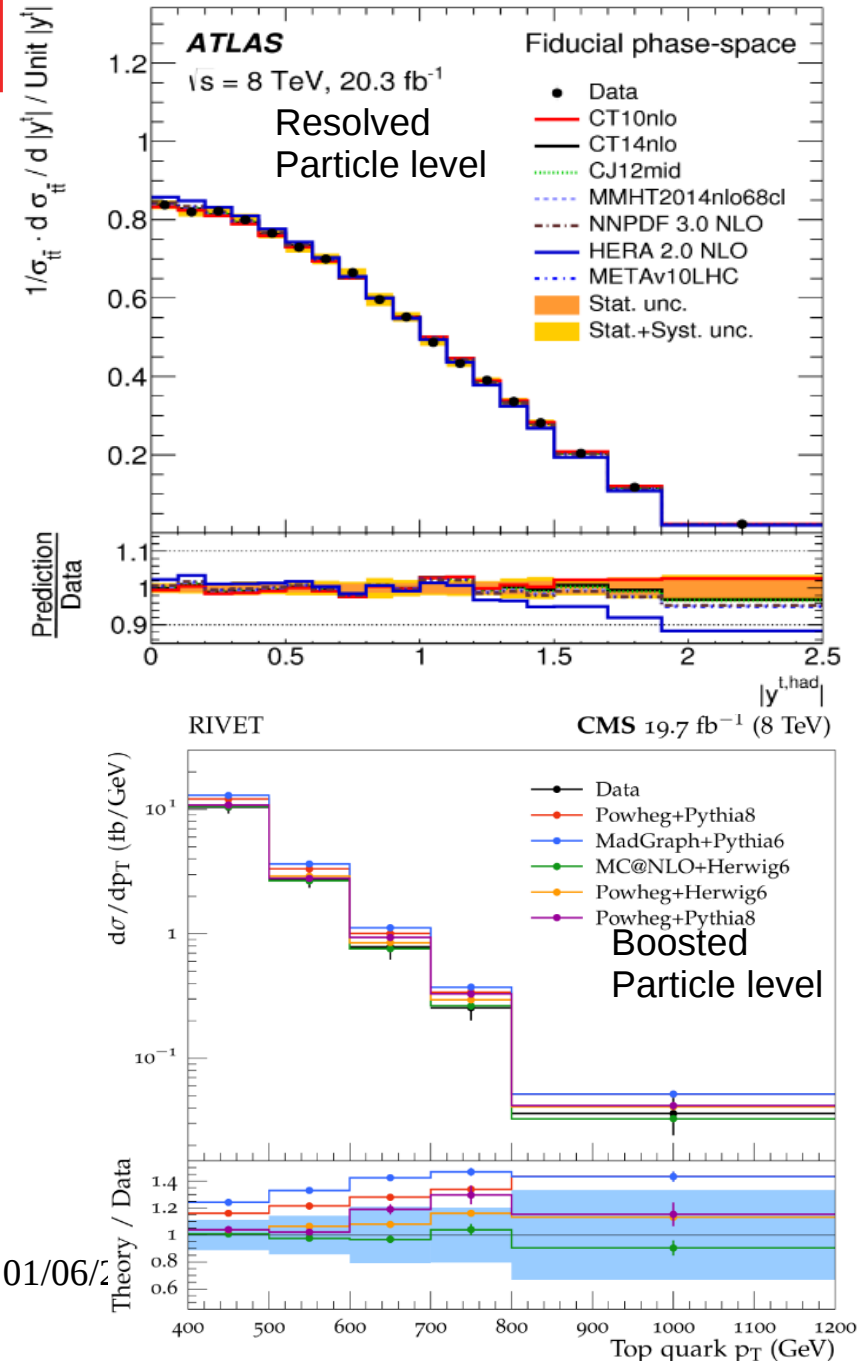
Differential cross section as a function of P_T of reconstructed top (hadronic)

Theoretical predictions overshoot measured data (discrepancy increases with momentum)

ATLAS:
Resolved: arXiv: 1511.04716 (Accepted EPJC)
Boosted Phys. Rev. D93 (2016) 032009 Rivet routine

CMS:
Resolved EPJC 75 (2015) 542 (dilepton)
Boosted arXiv:1605.00116 (Subm Phys Rev D)

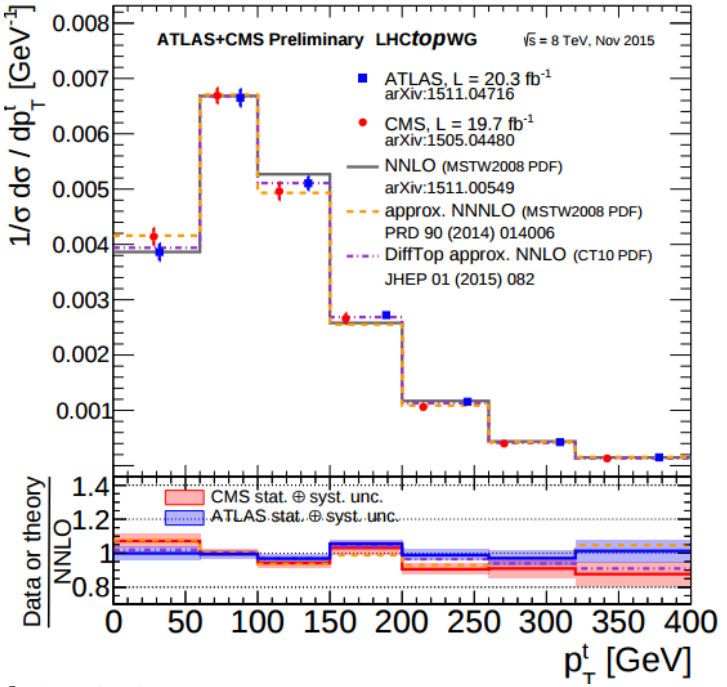
Differential xsection Measurement: 8 TeV



PDF variations enhanced in large Pt bin

Comparison with differente NLO generators

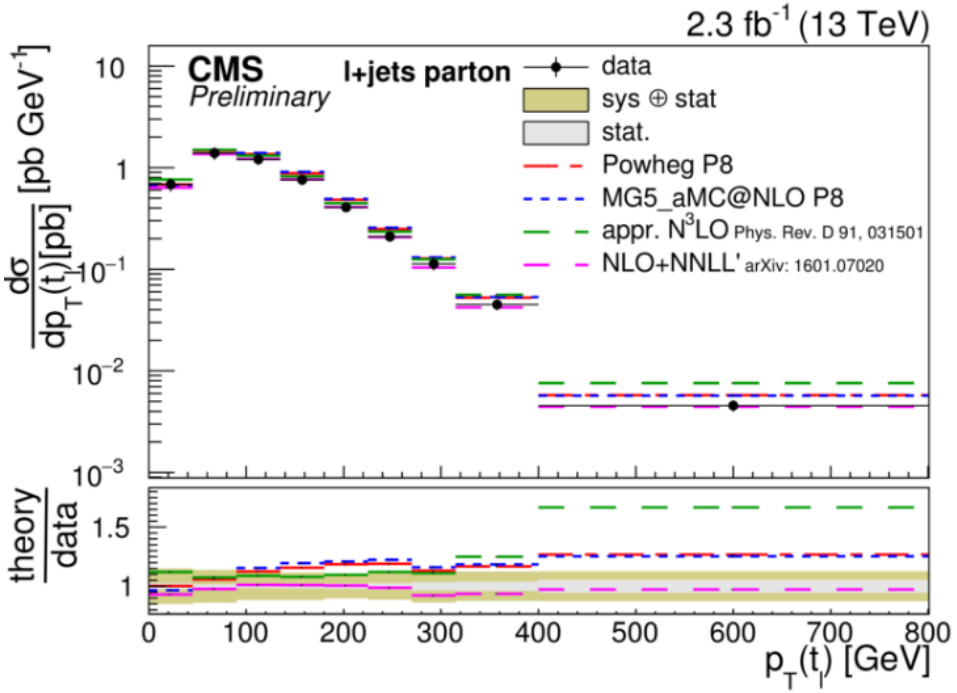
Discrepancy seems to be reduced with NNLO predictions

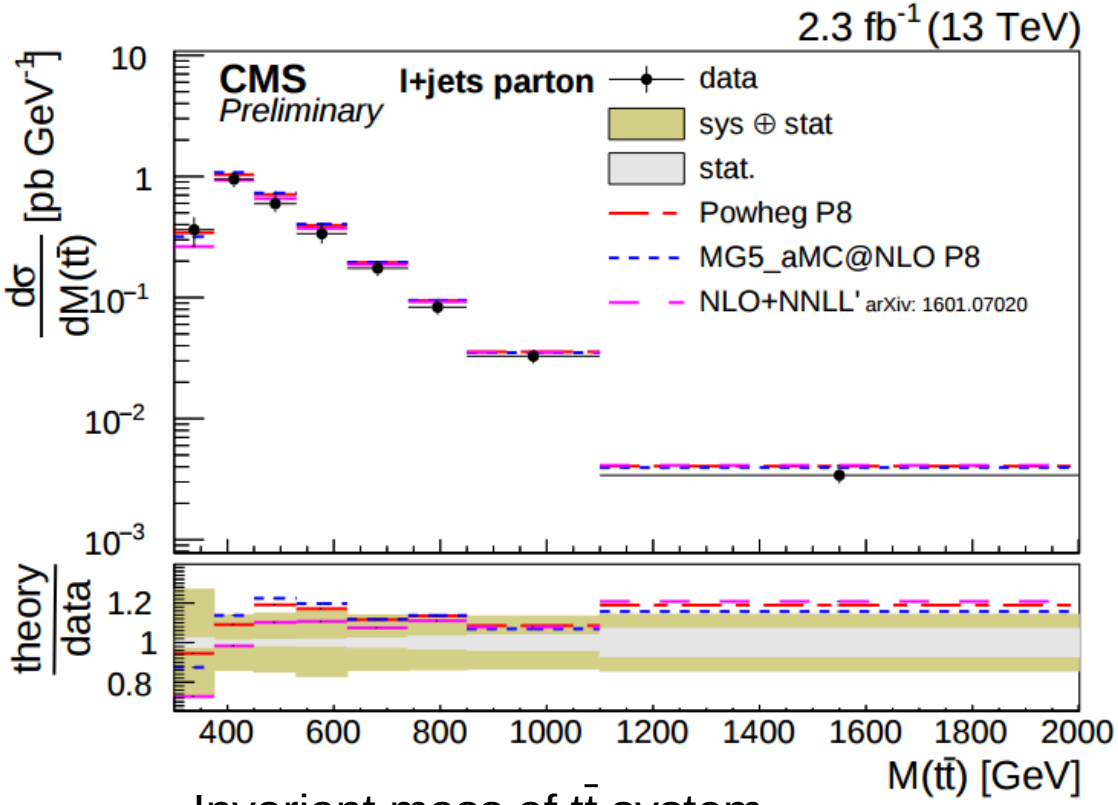


https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCTopWGSummaryPlots/tt_xsec_diff_8TeV_toppt.pdf

Differential xsection Measurement: 13 TeV

First 13 TeV differential measurement





Momentum of hadronic top

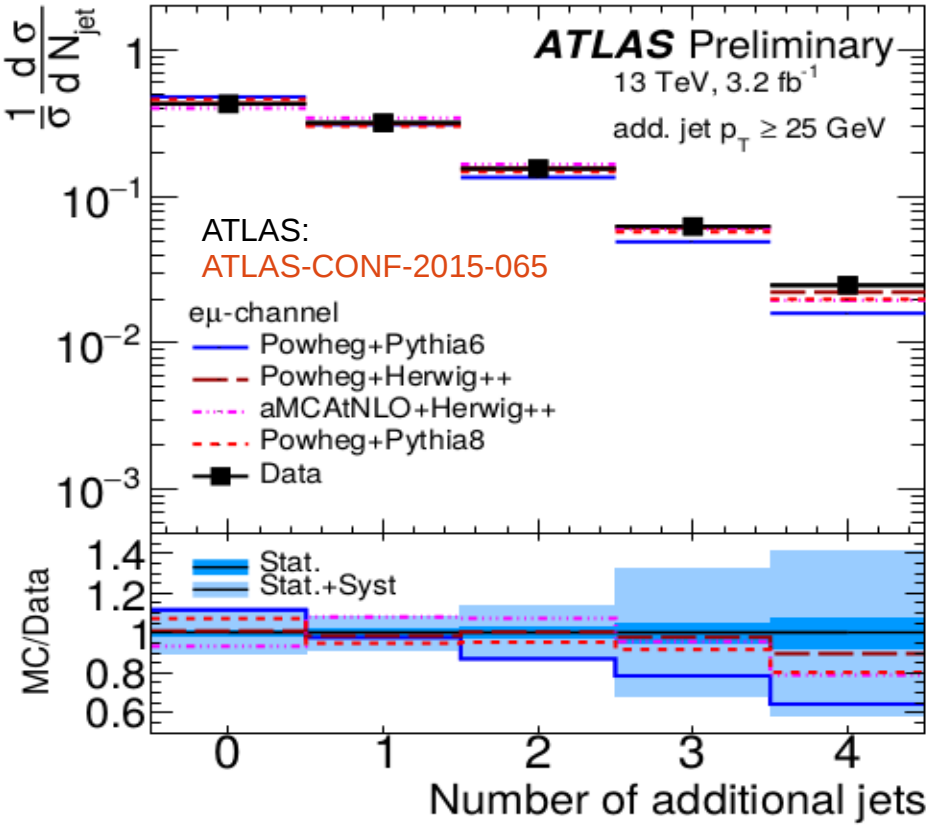
Lepton + jet selection
Particle level measurement

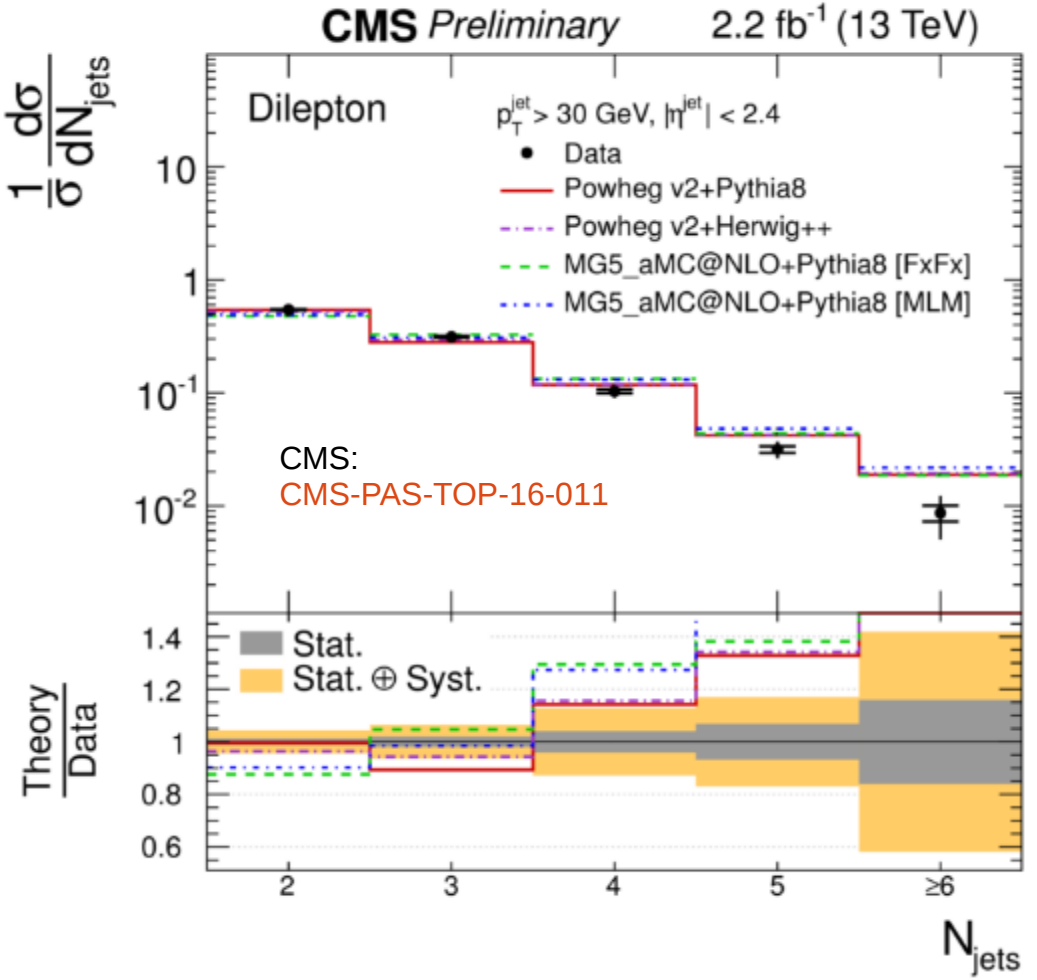
CMS:
(lep + jet) CMS-PAS-TOP-16-008
(dilepton) CMS-PAS-TOP-16-011

Invariant mass of $t\bar{t}$ system

- test production modes at threshold
- BSM searches:
  - Bumps for X → tt
  - Interference SM ↔ BSM
- Test EW corrections

$t\bar{t}$+jets: 13 TeV





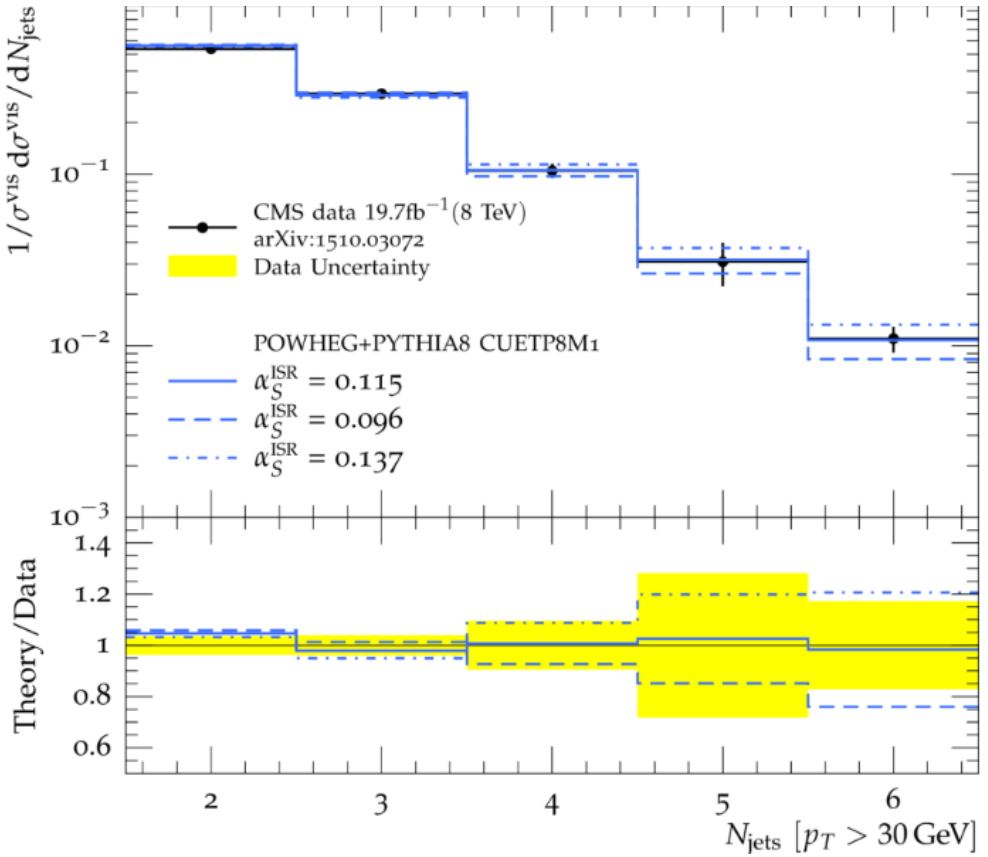
Sensitive to higher order QCD effects

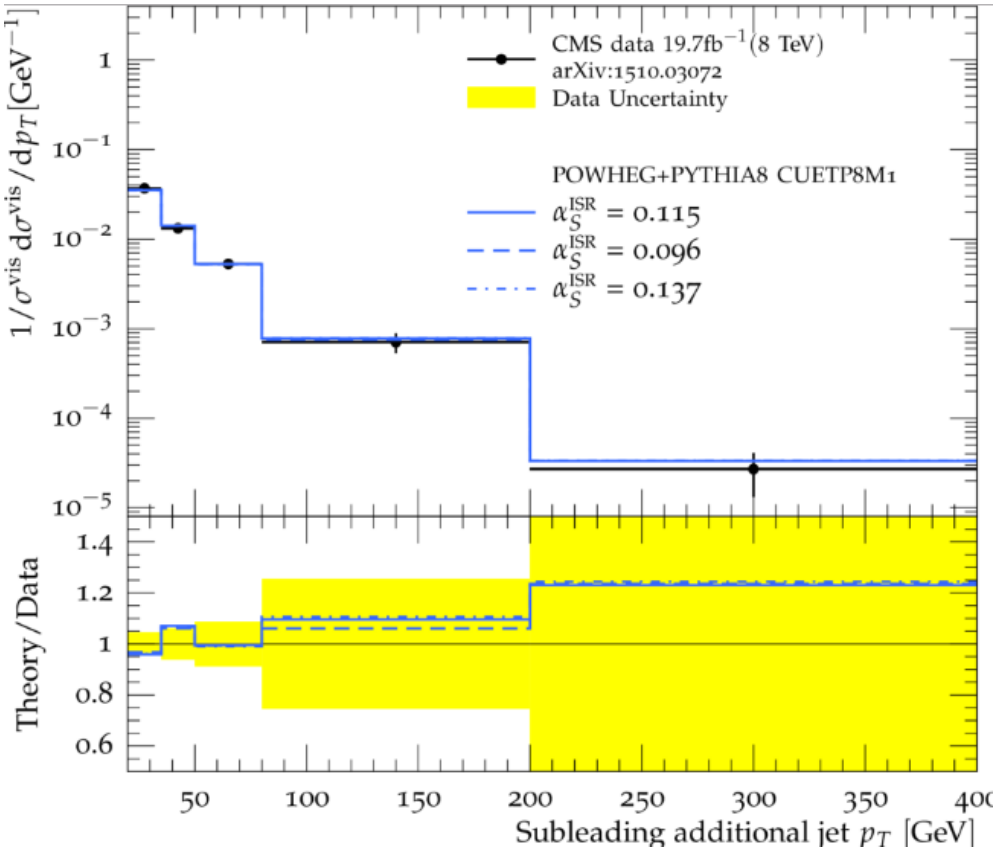
Mismodeling of $t\bar{t}$+jets → uncertainties in measurements where $t\bar{t}$+jets are background

ATLAS main uncertainties:
Jet Energy scales ~5% to 22% Signal modeling 6% to 18%

CMS main uncertainties:
Jet Energy scales ~0.5% to 8% μ_F/μ_R and PS 6% to 10%

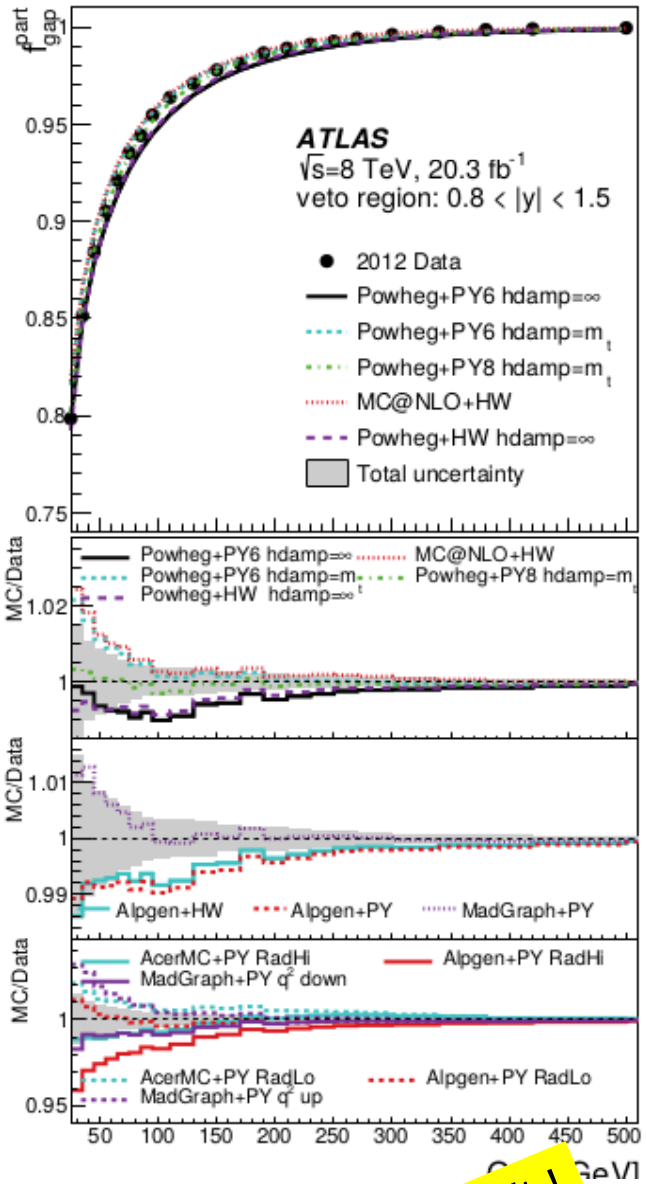
$t\bar{t}$+jets: 13 TeV

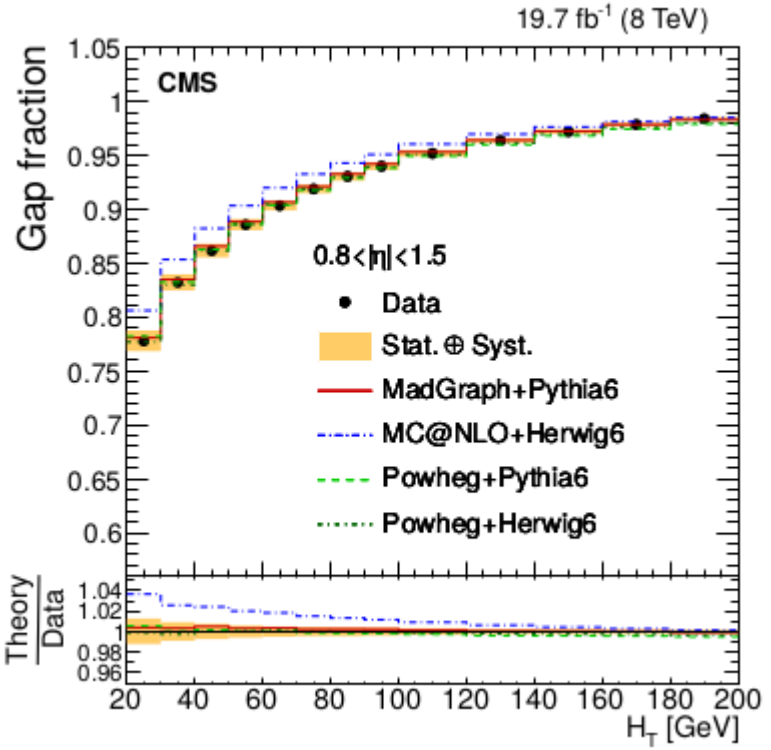




Large dependence on α_s in ISR (cf CMS)

$t\bar{t}$+jet: Jet Rapidity Gap 8 TeV





Jet gap fraction sensible to extra jet activity

$$\text{Gap fraction} = \frac{\#\text{ events with no additional jets in rapidity interval with } \sum E_{T,Jet} > H_T}{\#\text{ Total events}}$$

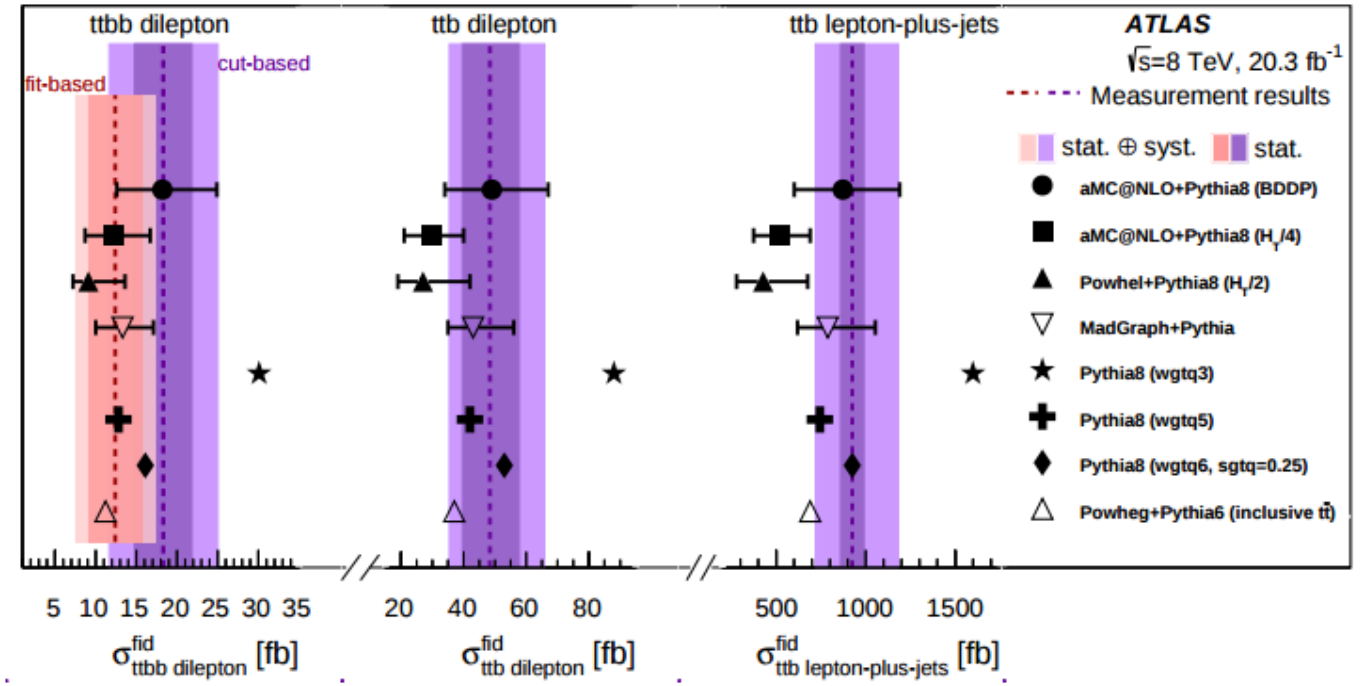
ATLAS:
In preparation
CMS:
CMS-TOP-12-041 (accepted by EPJC)

NEW Result !

$t\bar{t}$+b-jets (8 TeV)

Crucial to understand tt+HF production to reduce uncertainties

Fiducial region:
$P_{T,Jet}$>20 GeV
$|\eta|$<2.5
ΔR_{lj}>0.4



$\sigma(\bar{t}tbb)$(pb)	lep+jet (PAS-TOP-13-016)	Dilepton (Phys Lett B **746**:132)
CMS Parton Level	0.27±0.10(stat) ±0.03(syst)	0.36±0.08(stat) ±0.10(syst)
NLO	0.23±0.05	

Lepton+jet:
Phase space: $P_{TJet,a}$>50 GeV, $|\eta_{Jet,a}|$<2.5, $|\Delta R_{ajj}|$>0.5 (b-parton)
Dilepton:
Phase space: P_{TJet}>40 GeV

ATLAS:
EPJC 2016 76:011
CMS:
CMS-PAS-TOP-13-016 (lep+jet)
arXiv:1510.03072
Phys Lett B 2015 746 132 (dilepton)

$t\bar{t}\gamma$ (7 TeV ATLAS - 8 TeV CMS)

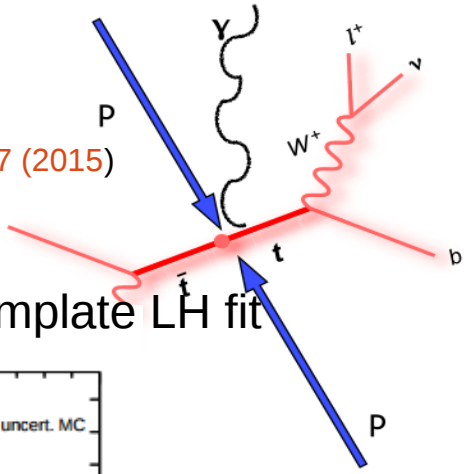
$t\gamma$ vertex accessible only measuring $t\bar{t}+\gamma$ production

Distinguish γ radiation::

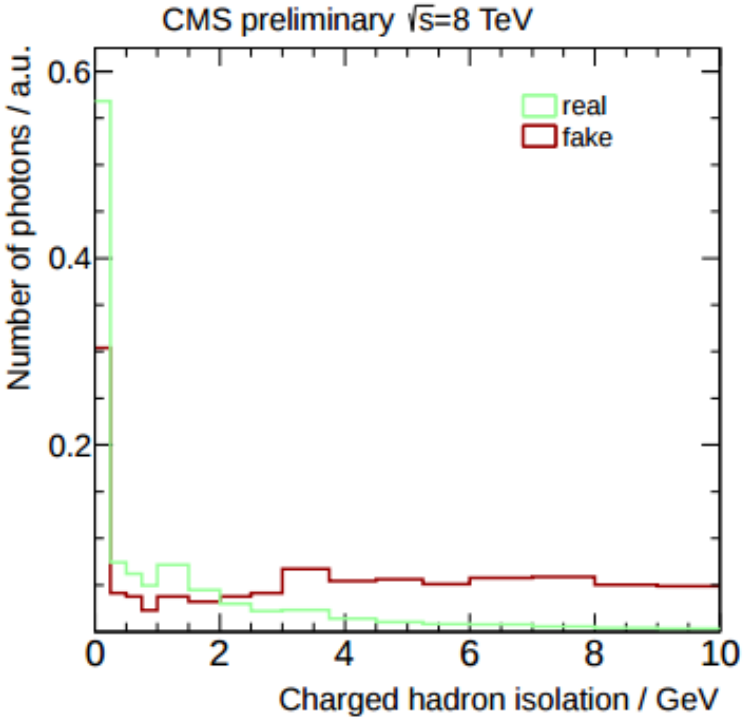
in top production or decay processes

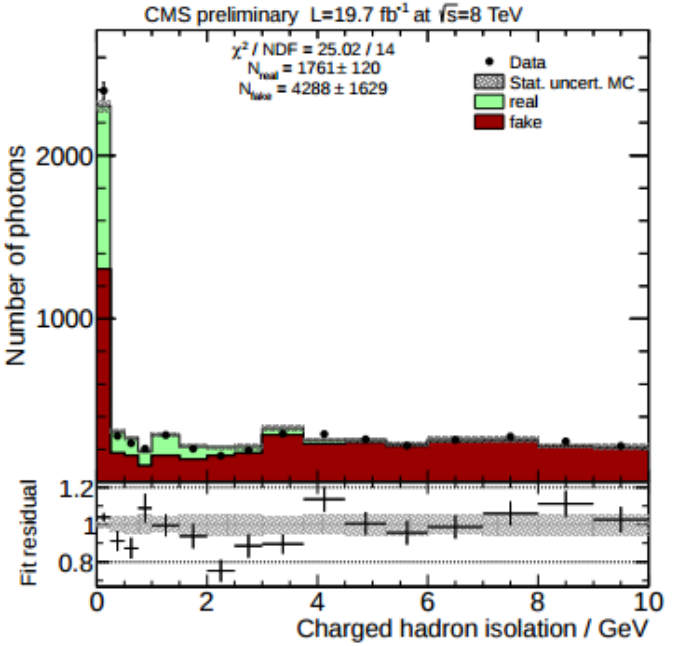
→ interference with NLO

ATLAS:
Phys. Rev. D 91, 072007 (2015)
CMS:
CMS PAS TOP-13-011



Signal estimation with template LH fit





Fiducial cross section:

ATLAS: $P_T\gamma > 20$ GeV) $\Delta R(\gamma,l)>0.7$

CMS: $\Delta R(\gamma,b\text{-jet})>0.1$

(measurement of $pp \rightarrow WWbb\gamma$)

ATLAS:

$\sigma_{fid}(t\bar{t}\gamma)xBR = 63\pm8(stat)^{+17}_{-13}(syst)\pm1(lumi)$ fb

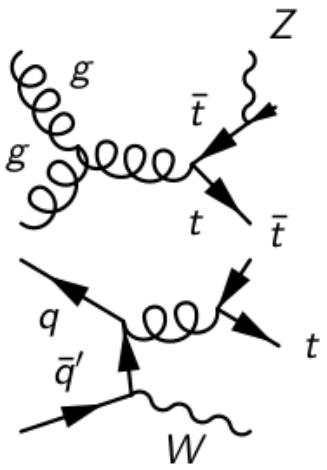
$\sigma_{theo}(t\bar{t}\gamma)xBR = 48\pm10$ fb (LO + k factors) fb

CMS

$\sigma_{fid}(t\bar{t}\gamma)=2.4\pm0.2(stat)\pm0.6(syst)$ pb

$\sigma_{theo}(t\bar{t}\gamma) = 1.8\pm0.5$ pb (LO k factors) pb

$t\bar{t}W$ and $t\bar{t}Z$ (13 TeV)



Theory prediction at 13 TeV ($t\bar{t}Z$ x 3.5 wrt 8 TeV, $t\bar{t}W$ x 2.4)

$$\sigma(t\bar{t}Z) = 839.3^{+80}_{-92}(\text{scale})\ ^{+25}_{-25}(\text{pdf})\ ^{+25}_{-25}(\alpha_s)\ \text{fb}$$

$\sigma(t\bar{t}W)$=570 fb (~10% uncertainty)

Irreducible background for Higgs (ttH) and BSM searches with multileptons signatures

$$\sigma(pp \to t\bar{t}Z) = 1065\ ^{+352}_{-313}(\text{stat.})\ ^{+168}_{-142}(\text{sys.})\ \text{fb}$$

CMS@13 TeV

$\sigma(t\bar{t}Z)$= 0.92±0.30(stat) ±0.11 (syst) pb
$\sigma(t\bar{t}W)$= 1.38±0.70(stat) ±0.33(syst)pb

ATLAS@13 TeV

Multilepton channels:
ATLAS:
$t\bar{t}W$ Same Sign dimuon and trilepton
ATLAS and CMS:
Trilepton and 4-lepton channels

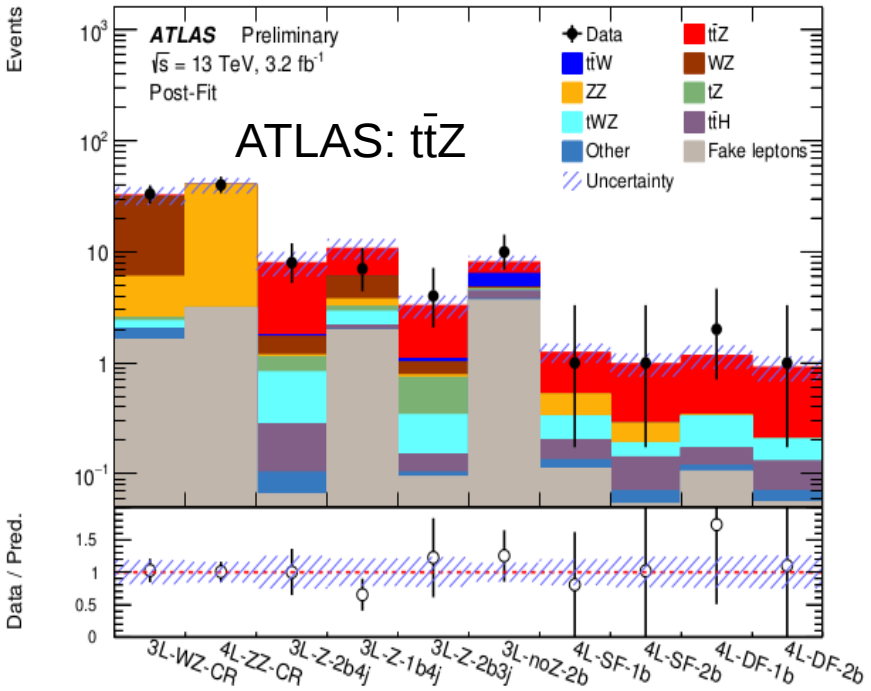
Method: cut&count analysis using different signal regions (different jet multiplicities and b-tag multiplicities)
Evaluate reducible background using data-driven methods

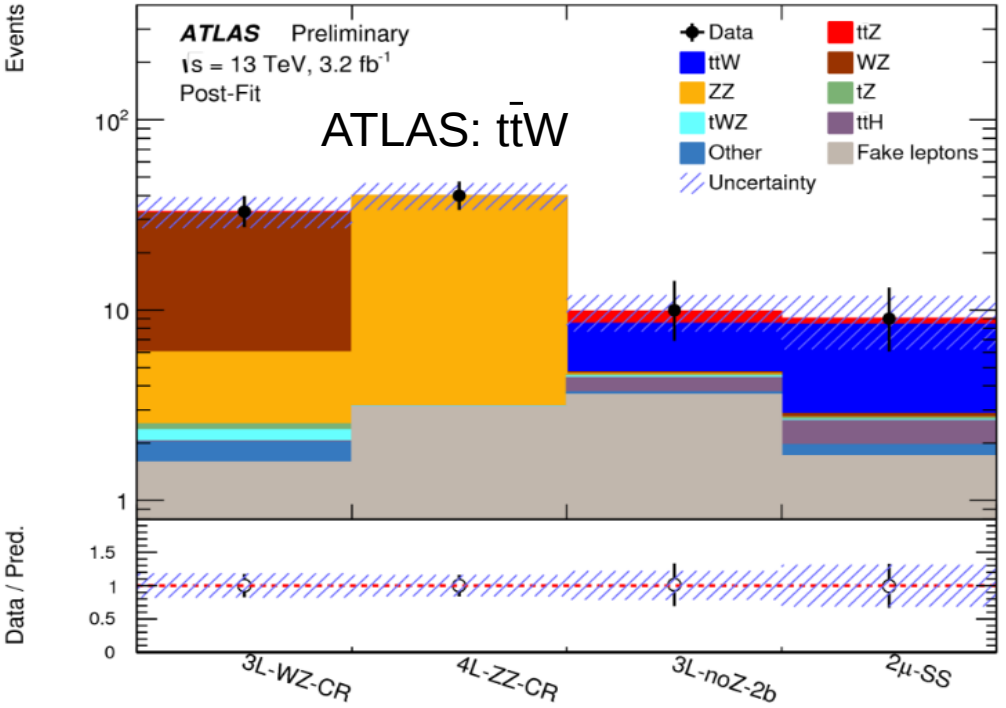
With more statistics → go differential!
Handle for anomalous gauge couplings or EFT studies

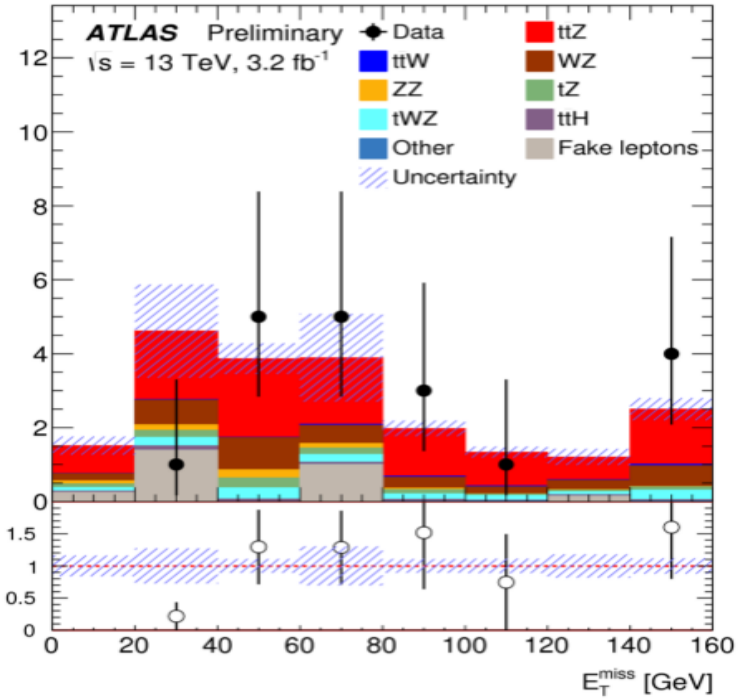
ATLAS: (ttW and ttZ @ 13 TeV)
ATLAS-CONF-2016-003

CMS (ttZ @ 13 TeV):
CMS-PAS-TOP-16-008

$t\bar{t}W$ and $t\bar{t}Z$ (13 TeV)

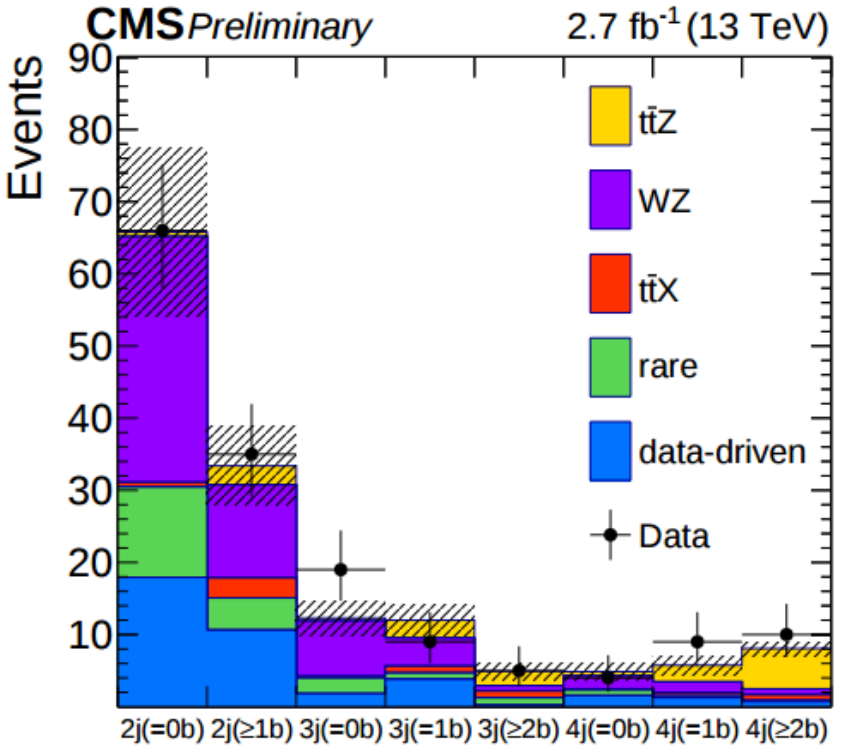




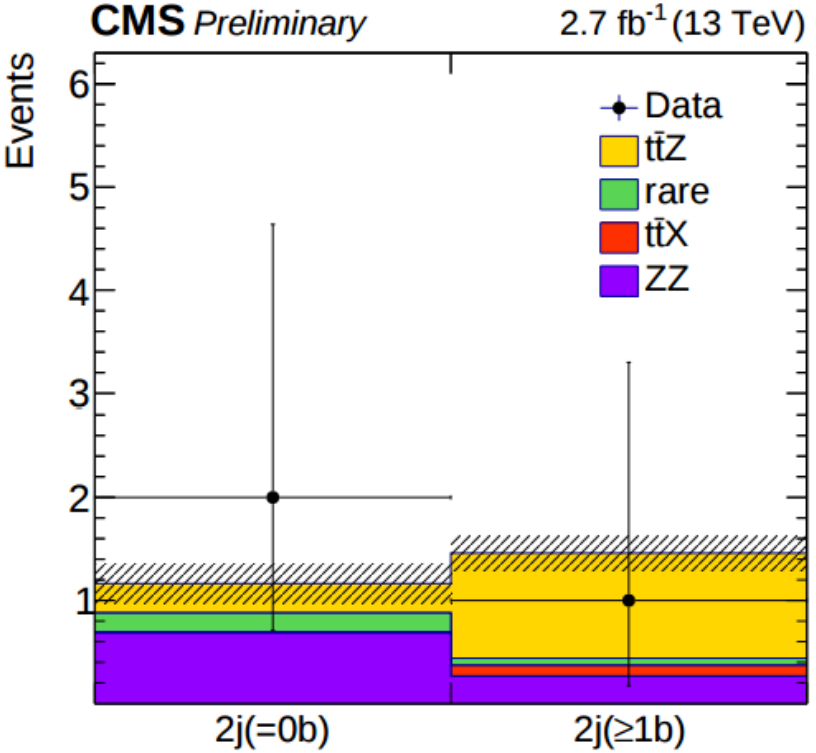


Pre-fit 3-lep ttZ Signal region

$t\bar{t}W$ and $t\bar{t}Z$ (13 TeV)



CMS: three lepton



CMS: four lepton

ATLAS: (ttW and ttZ @ 13 TeV)
ATLAS-CONF-2016-003

CMS (ttZ @ 13 TeV):
CMS-PAS-TOP-16-008

Measurement Summary

Measurements	7 TeV	8 TeV	13 TeV
Inclusive Cross Section	✓	✓	✓
Differential Cross section (Resolved)	✓	✓	✓ (CMS)
Differential Cross section (Boosted)	✓	✓	
tt + jets	✓	✓	✓ (CMS b-jet) (ATLAS jets)
tt + photon	✓	✓	
tt+W/Z		✓	✓ (ATLAS W and Z) ✓ (CMS Z)

Conclusions

Toward precision measurement in $t\bar{t}$ cross section

Exploit increase of $\sqrt{s}$ for differential measurement

→ Search for physics BSM (enhanced in boosted region?)

Improve precision and MC tuning of $t\bar{t}$+γ/jet(HF) /W/Z for better background determination

tt+Z for top-Z boson couplings (BSM searches, EFT parametrization ….)