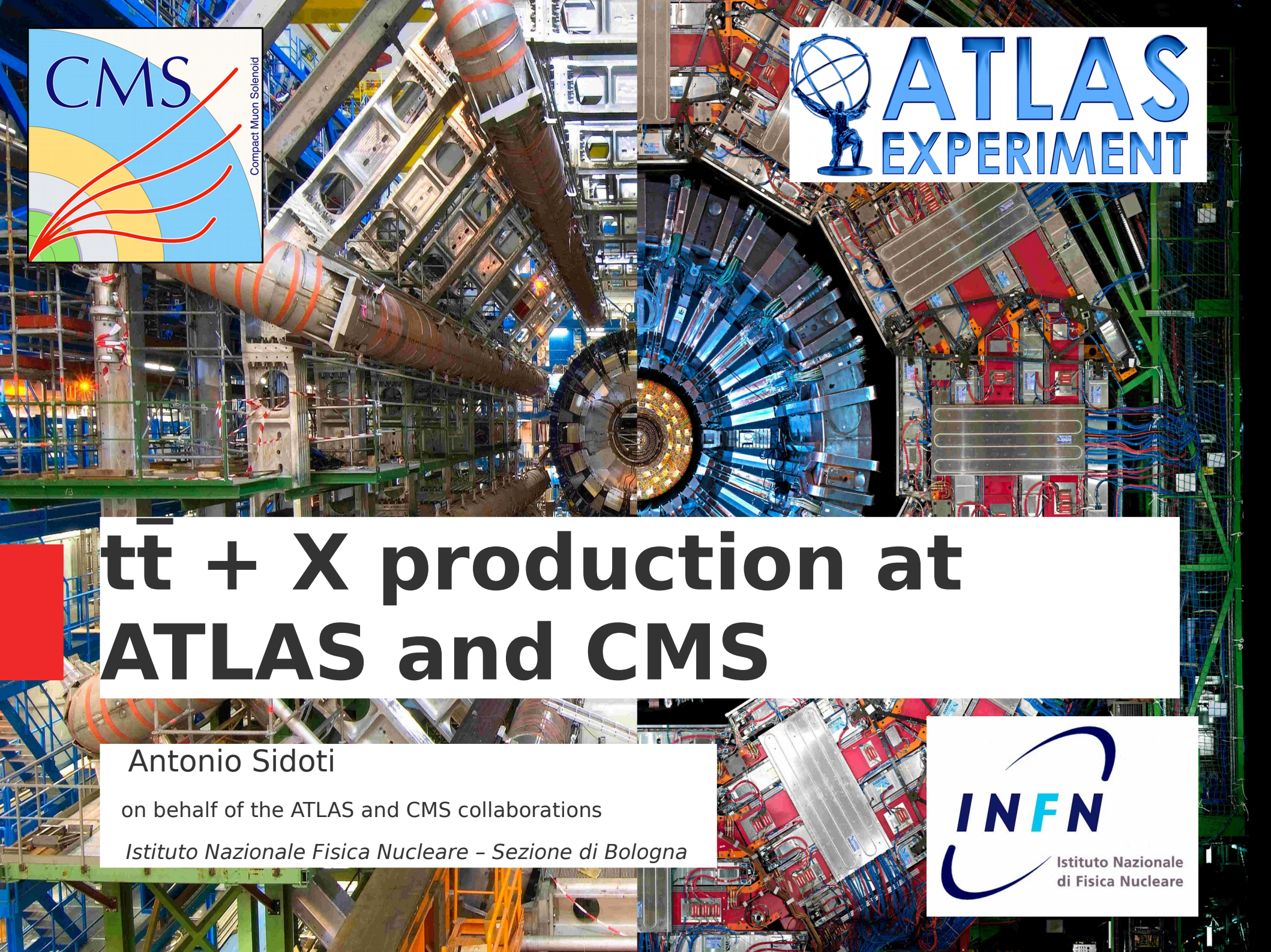


$t\bar{t}$ + X production at ATLAS and CMS

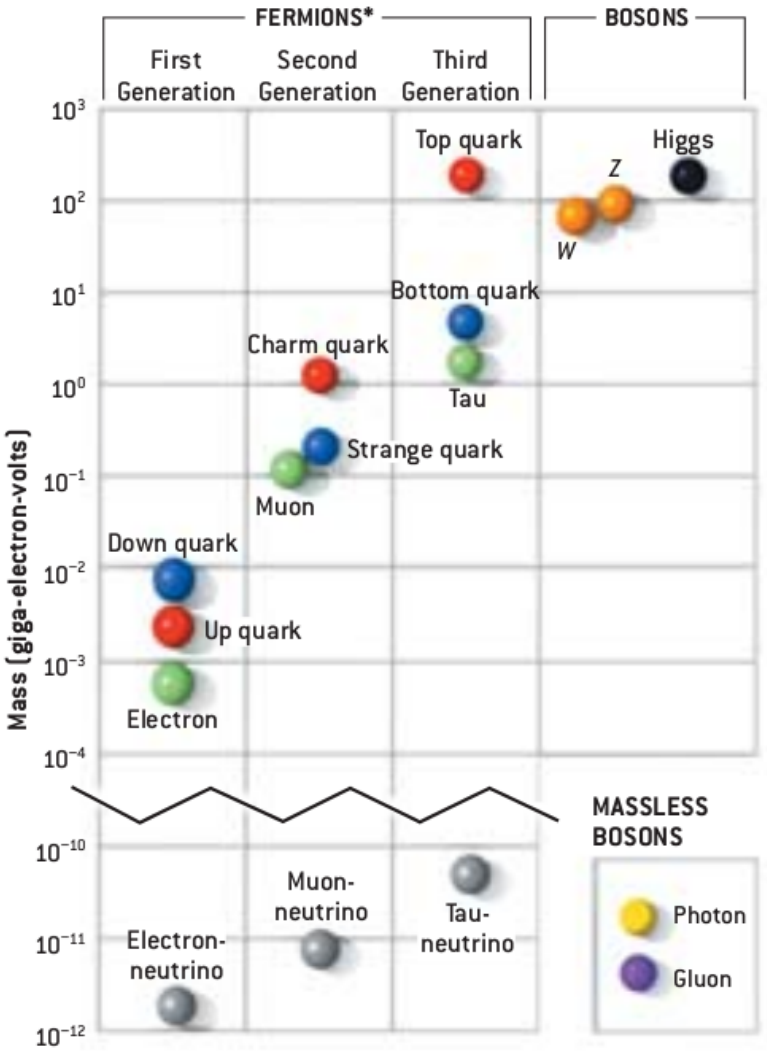
Antonio Sidoti

on behalf of the ATLAS and CMS collaborations

Istituto Nazionale Fisica Nucleare – Sezione di Bologna

INFN
Istituto Nazionale
di Fisica Nucleare

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)

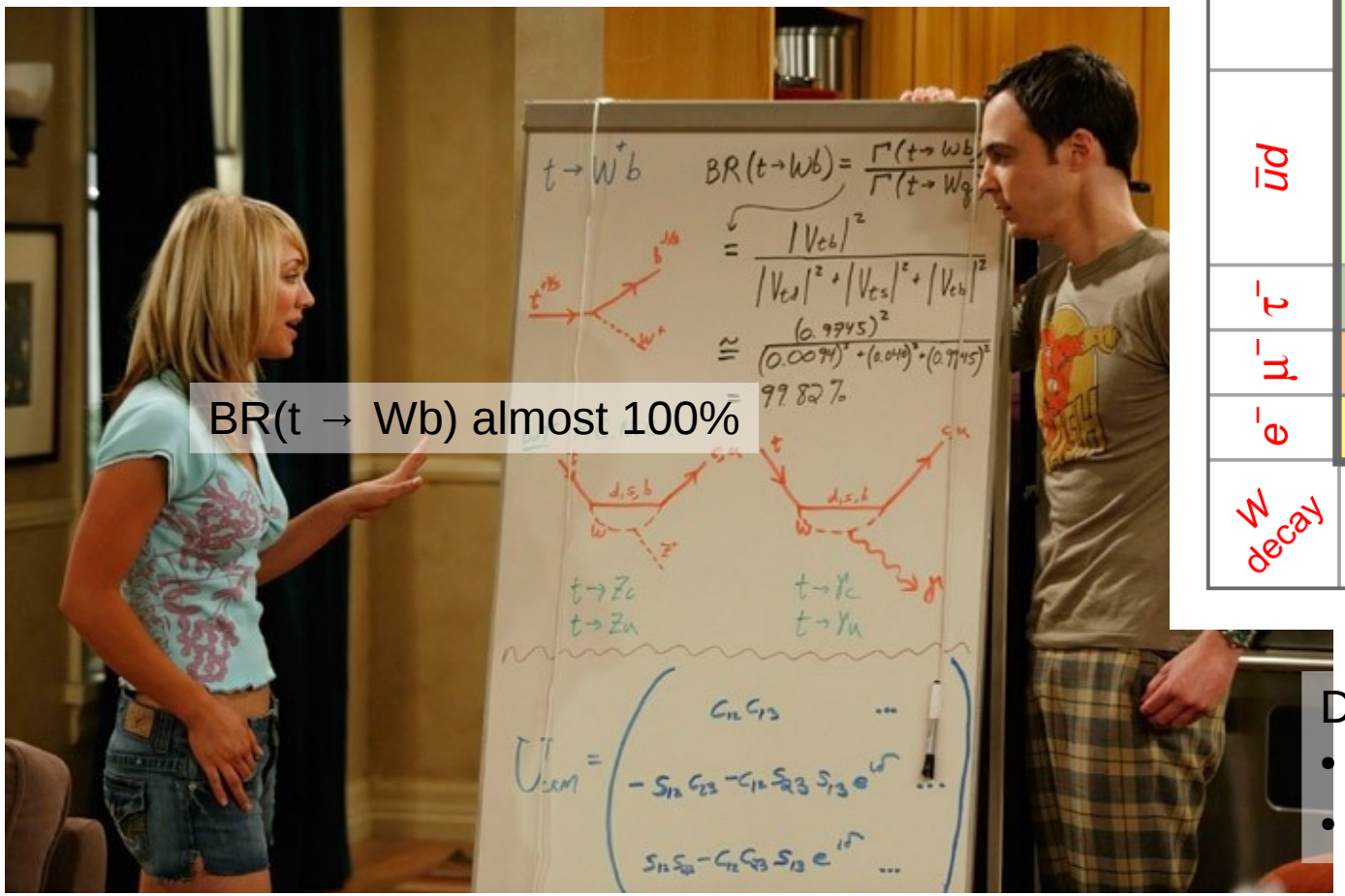
$\sqrt{s}$	7 TeV	8 TeV	13 TeV
$\sigma(t\bar{t})$ (pb)	177	253	830

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

Different final state according to W boson decay modes.



W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
e^-	ee	eμ	eτ	electron+jets	
μ^-	eμ	μμ	μτ	muon+jets	
τ^-	eτ	μτ	ττ	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)

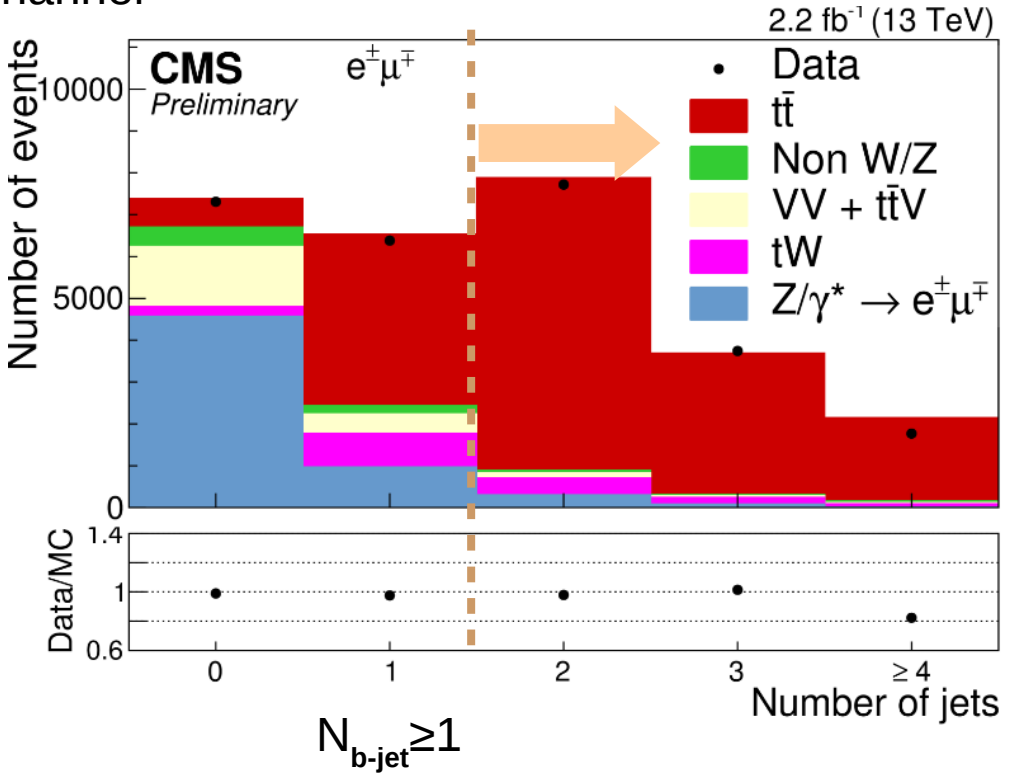
Measurements at √s=7, 8 and 13 TeV

$t\bar{t}$ 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%

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

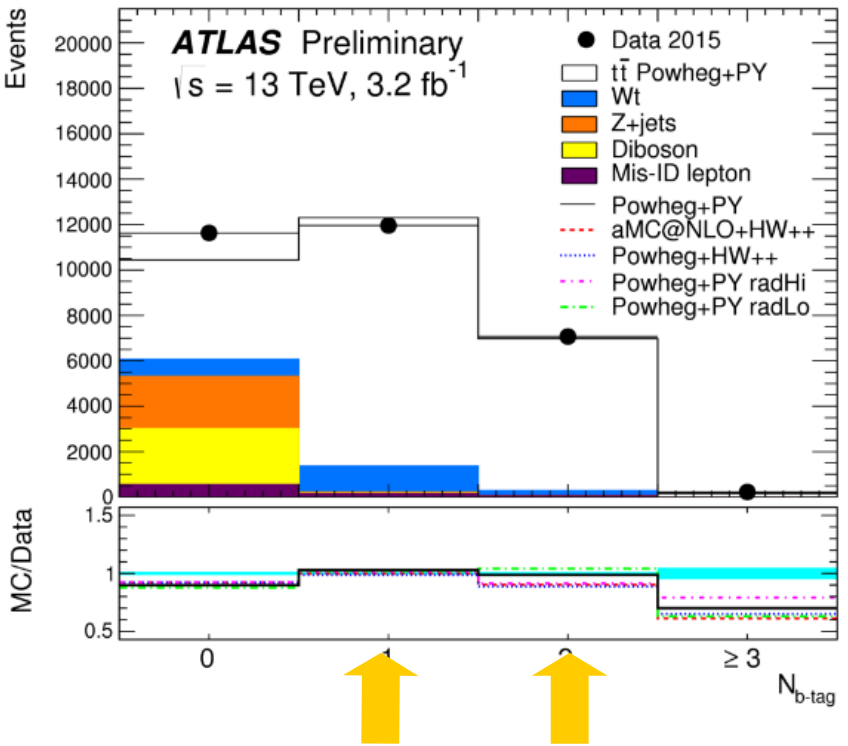
$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\text{bkg}}$$

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

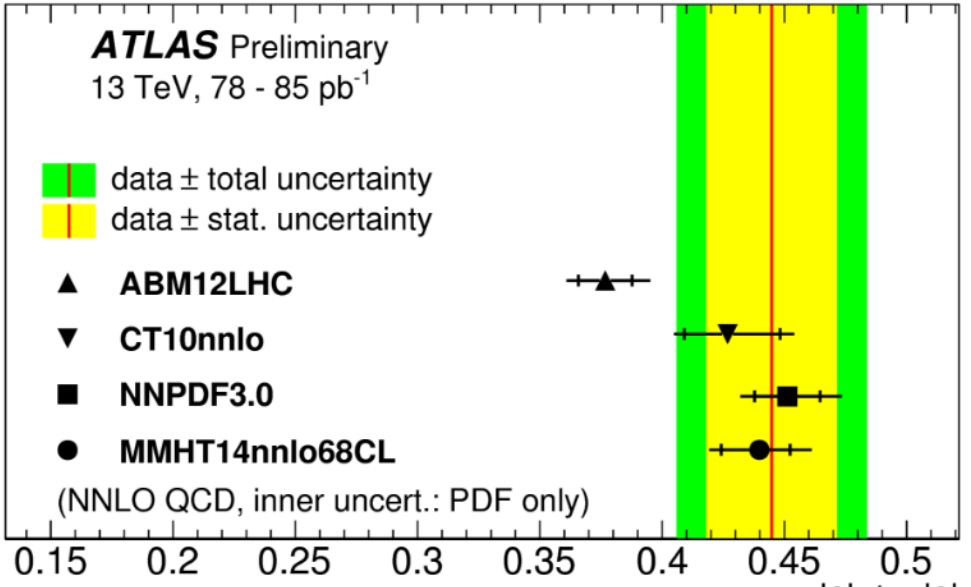
Ratio $t\bar{t}$ to Z production at 13 TeV: ATLAS

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

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

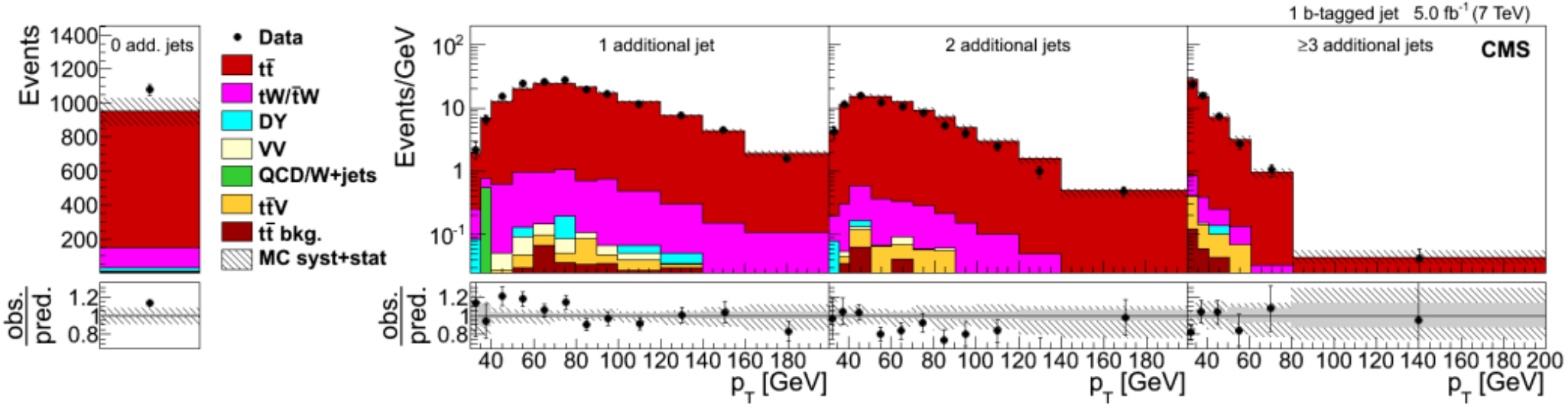


Powerful test of Parton Distribution Functions

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

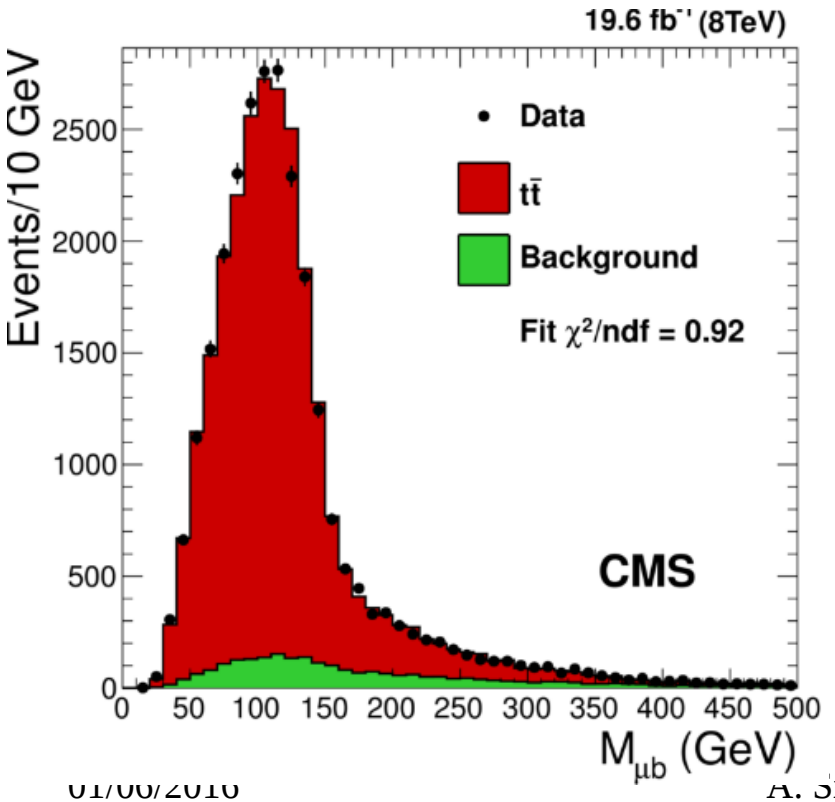
$t\bar{t}$ inclusive cross section legacy measurement at 7 and 8 TeV: CMS lep+jet

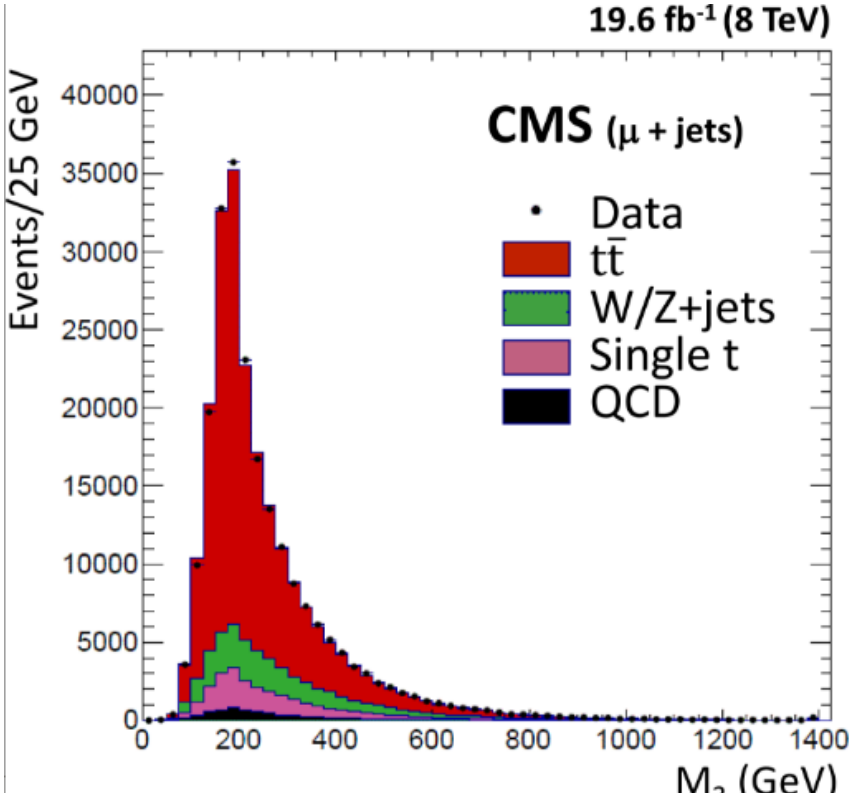
Complementary measurement in lep+jet fitting M_{lb} (Invariant mass)

$\sigma_{t\bar{t}}$(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





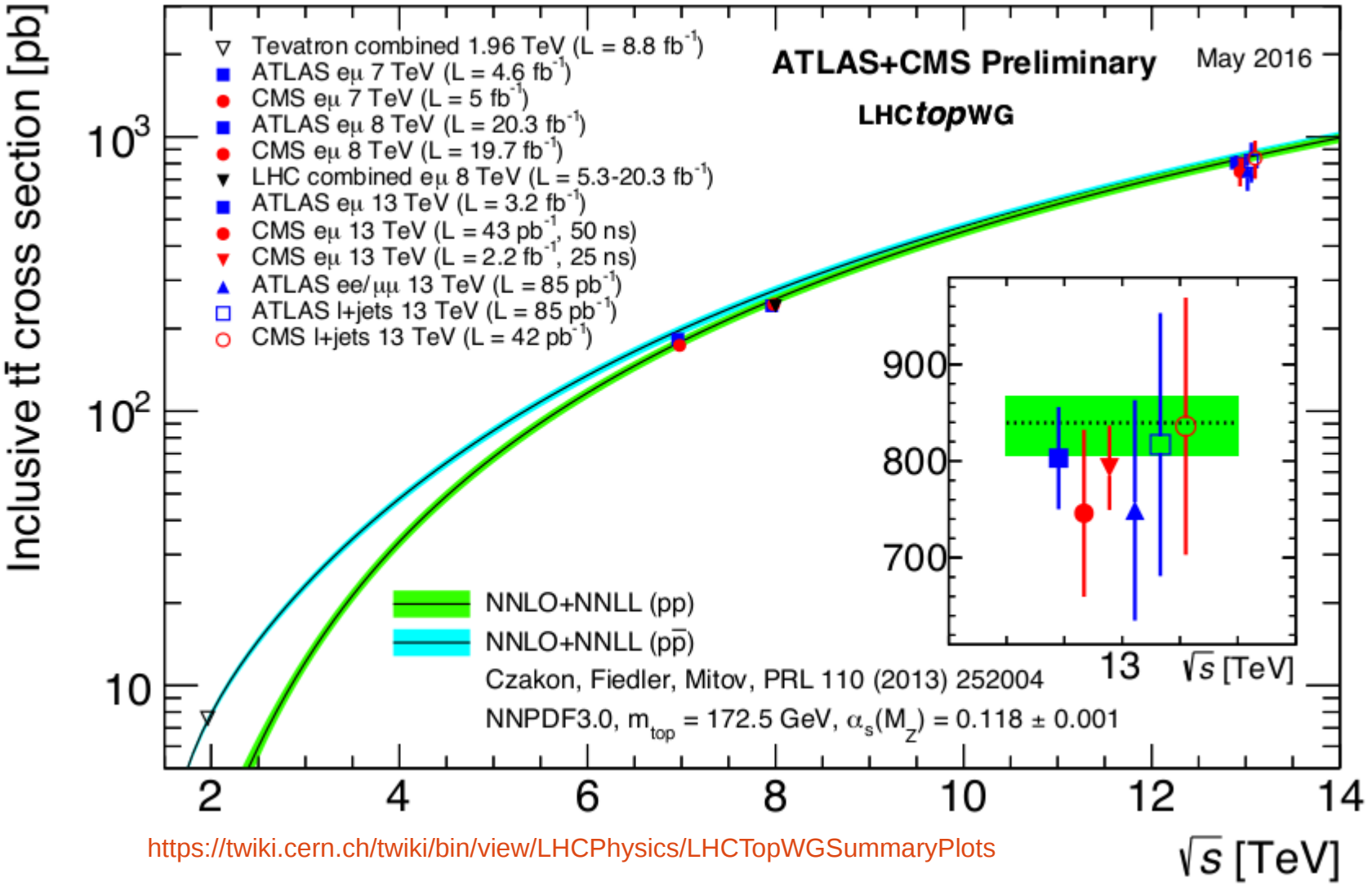
CMS (8 TeV lep+jet):
arXiv: 1602.09024(Subm. EPJC)

$t\bar{t}$ 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)

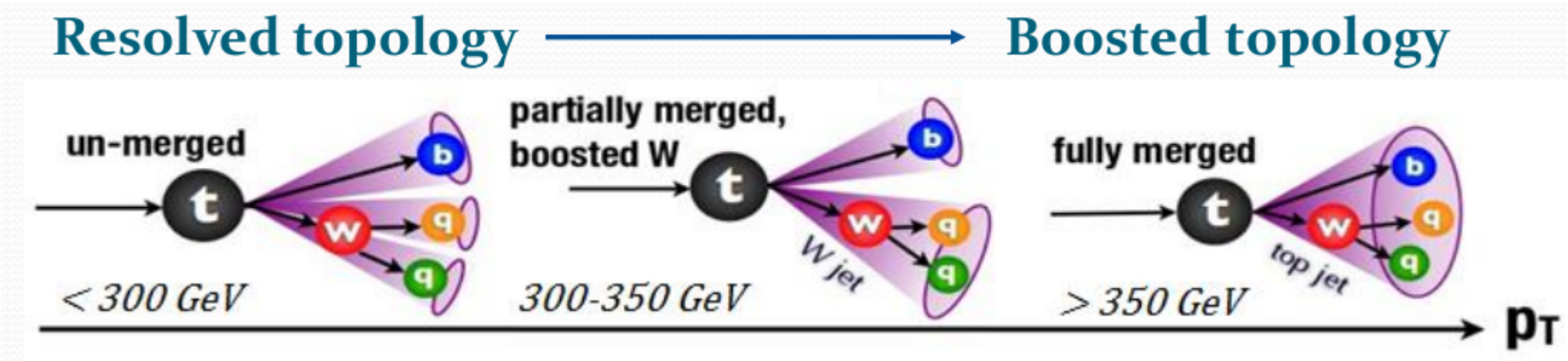
- Detector: $\not{E}_T$, N_{jet}, N_{bjet}
- Radiation sensitive: $\Delta\phi$,...

CMS and ATLAS are providing RIVET routines easing comparison with theory

Two kinematical regimes:

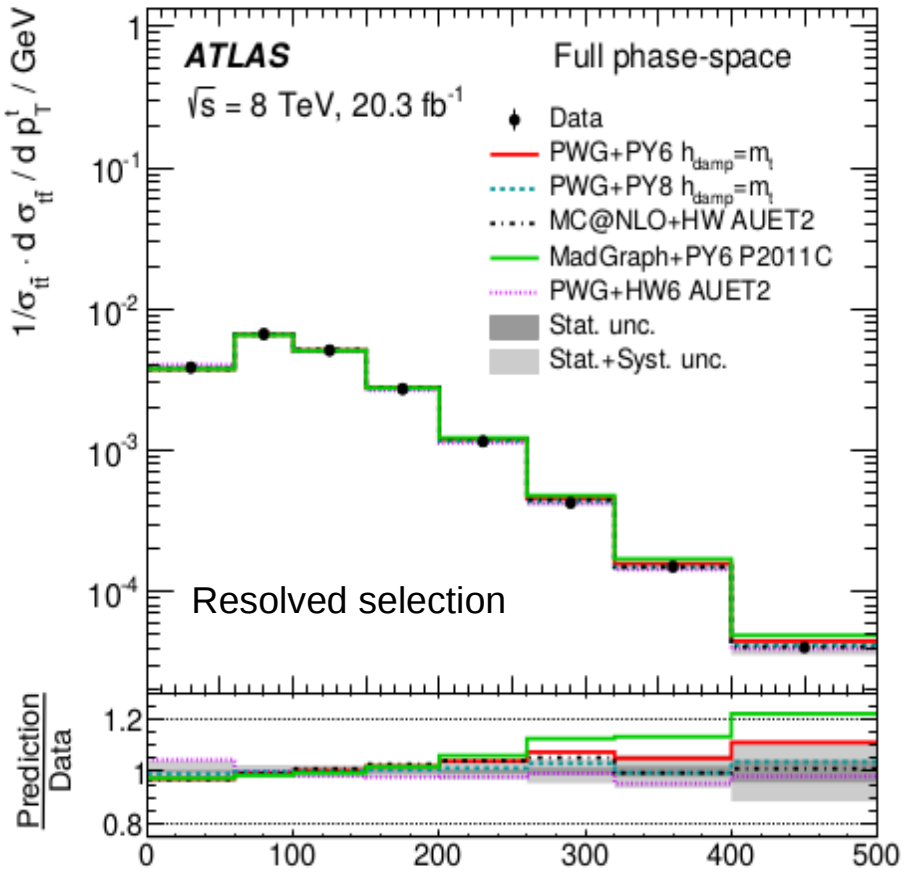
- Resolved (top quark with low P_T)
- Boosted (enhanced at 13 TeV, BSM may increase this region)

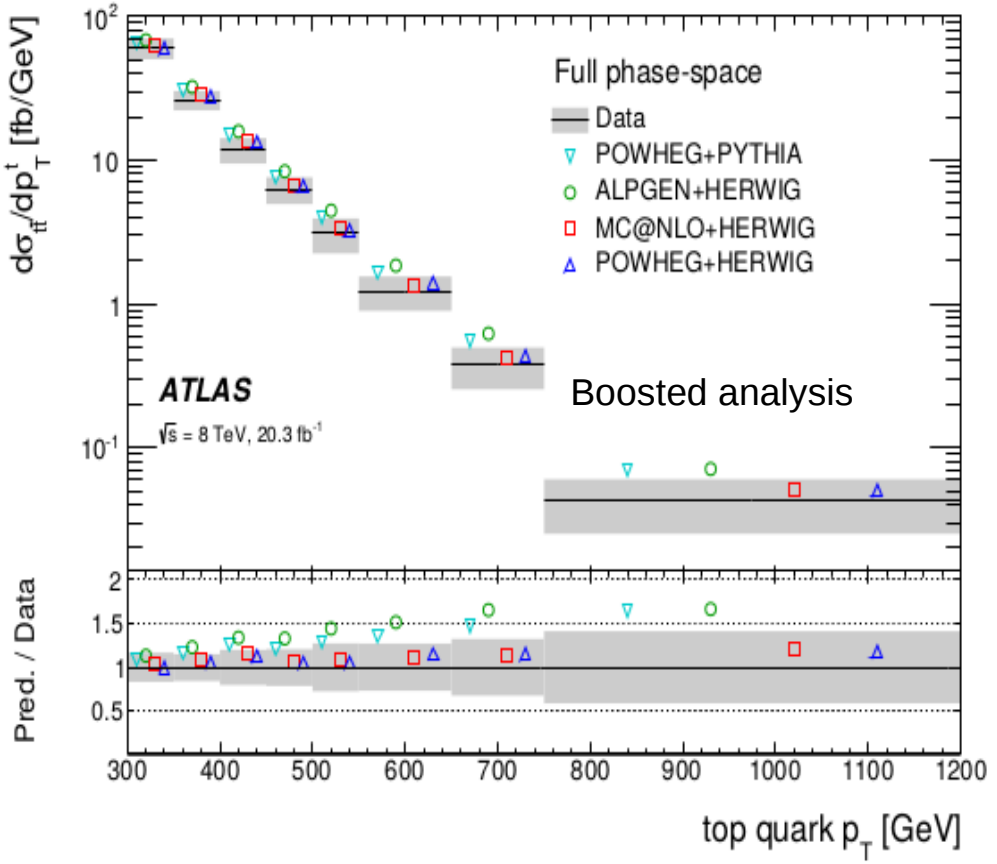
→ use jet substructure to reduce QCD background



Differential xsection Measurement: 8 TeV

8 TeV measurements: Parton level





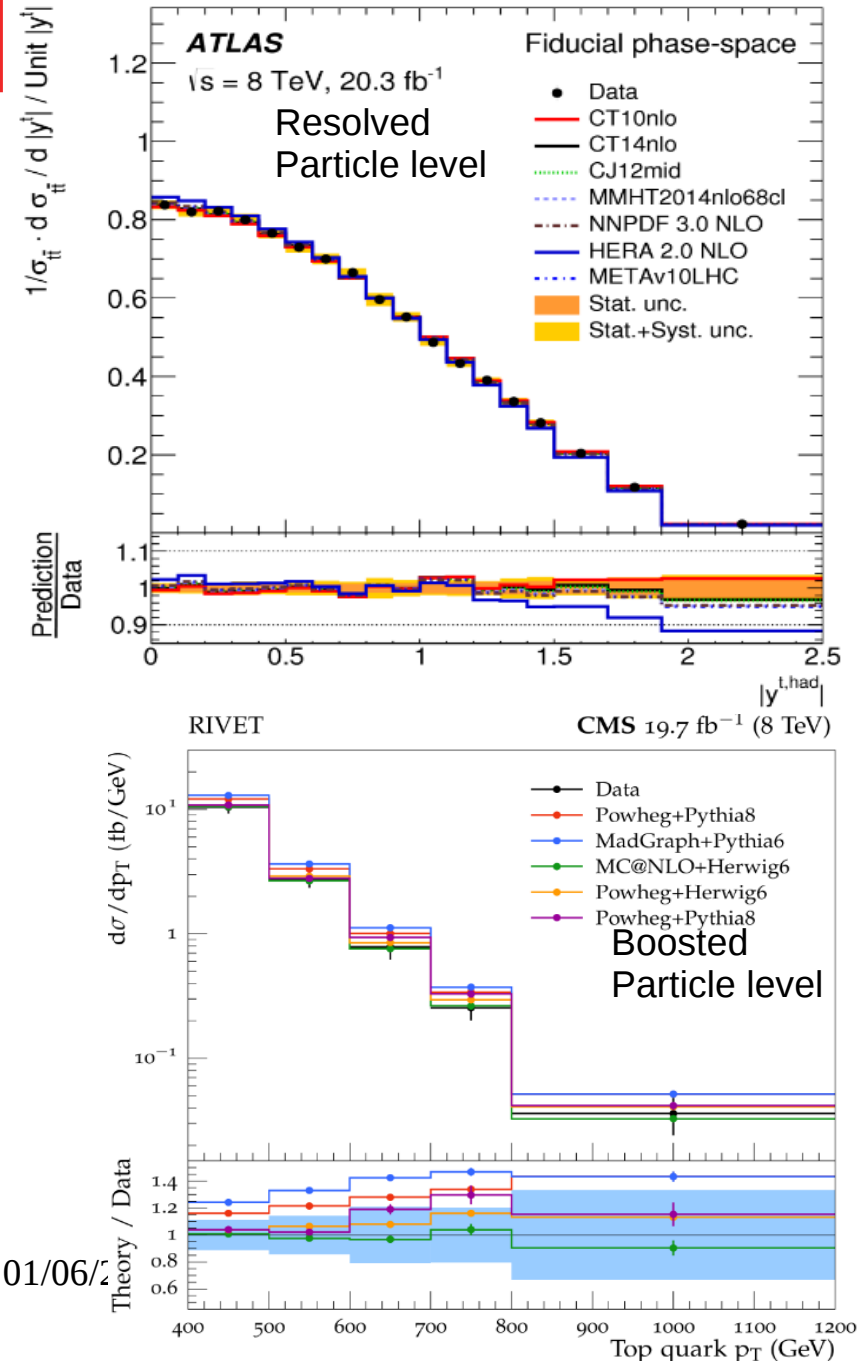
Differential cross section as a function of P_T of reconstructed top (hadronic)

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)

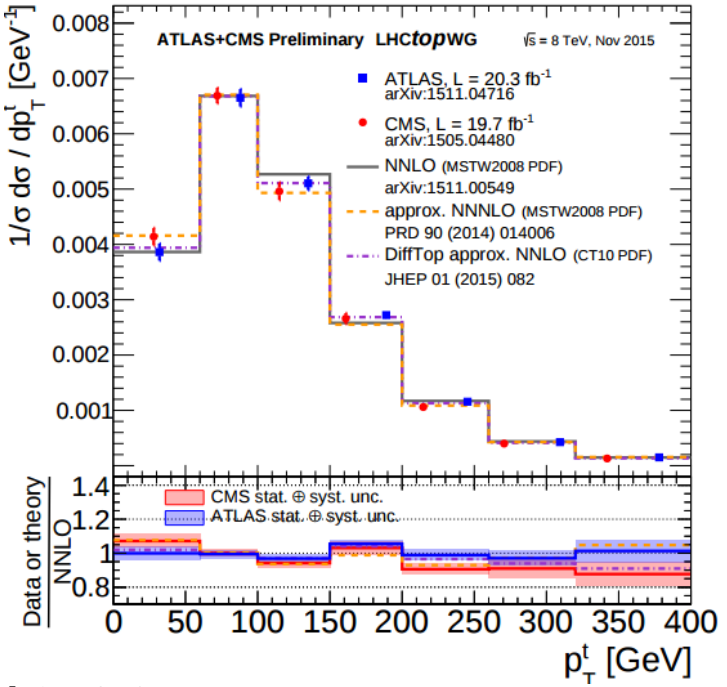
Differential xsection Measurement: 8 TeV



PDF variations enhanced in large Pt bin

Comparison with differente NLO generators

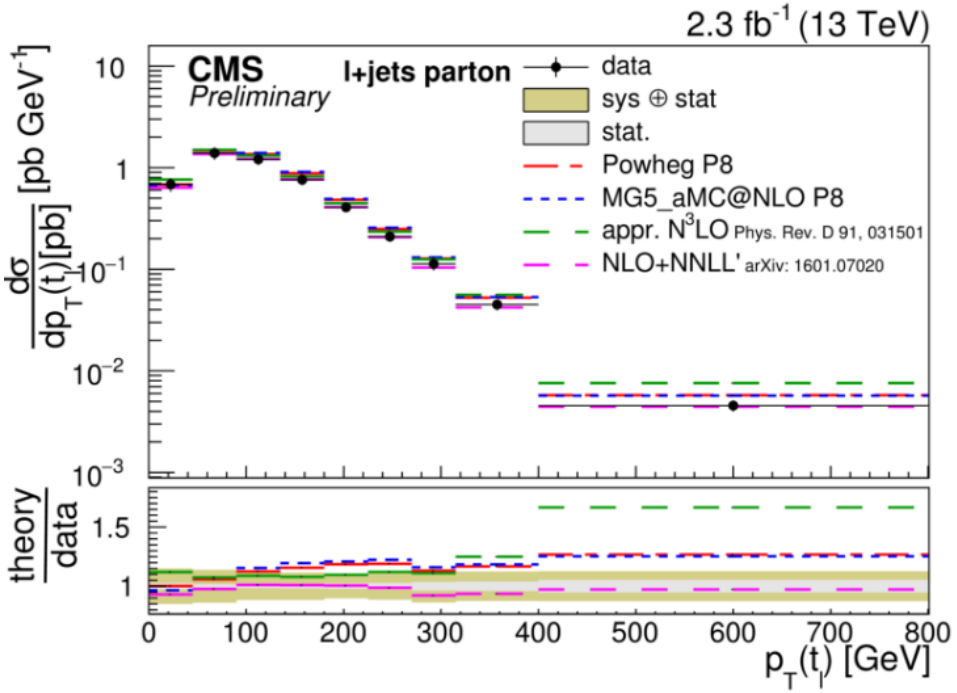
Discrepancy seems to be reduced with NNLO predictions

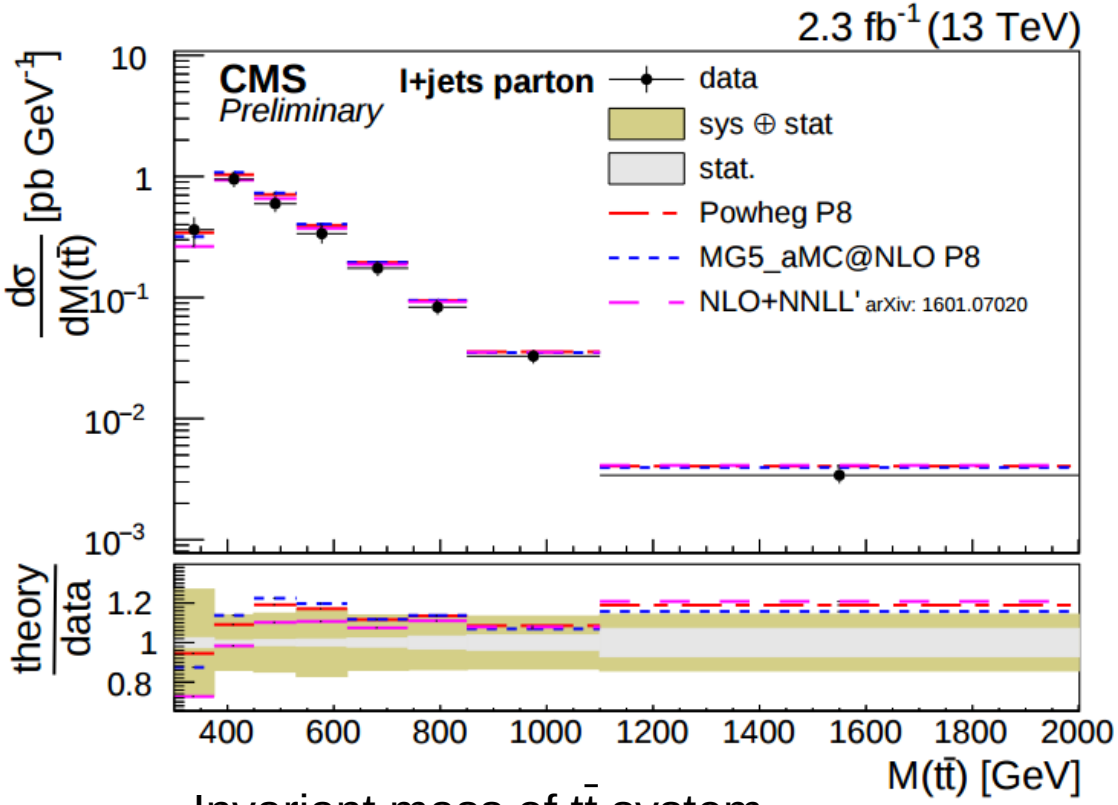


https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCTopWGSummaryPlots/tt_xsec_diff_8TeV_toppt.pdf

Differential xsection Measurement: 13 TeV

First 13 TeV differential measurement





Momentum of hadronic top

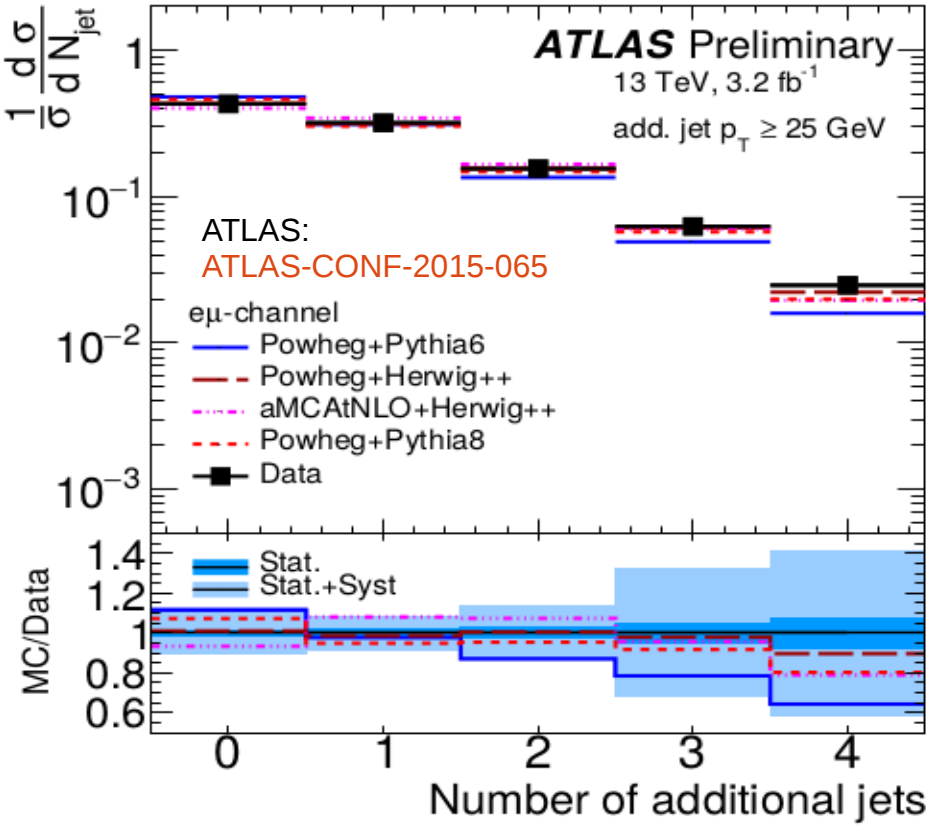
Lepton + jet selection
Particle level measurement

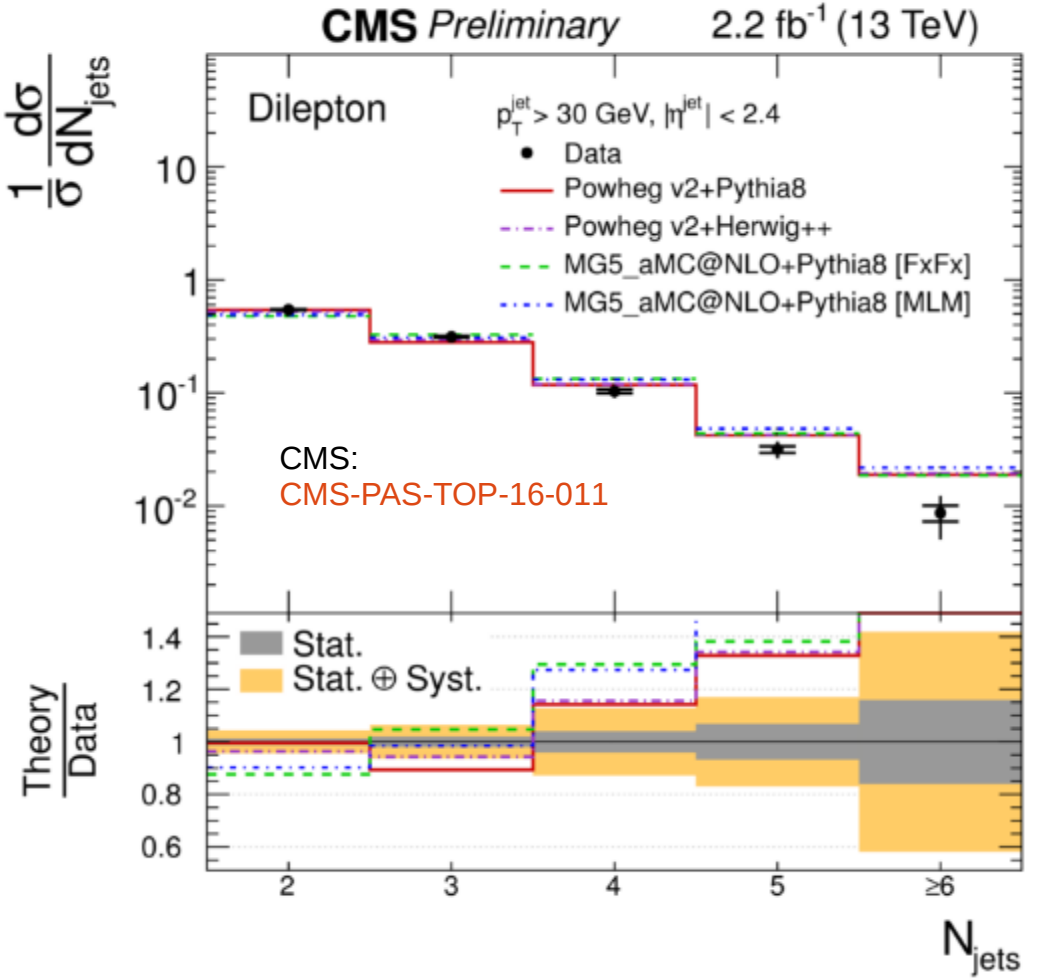
CMS:
(lep + jet) CMS-PAS-TOP-16-008
(dilepton) CMS-PAS-TOP-16-011

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





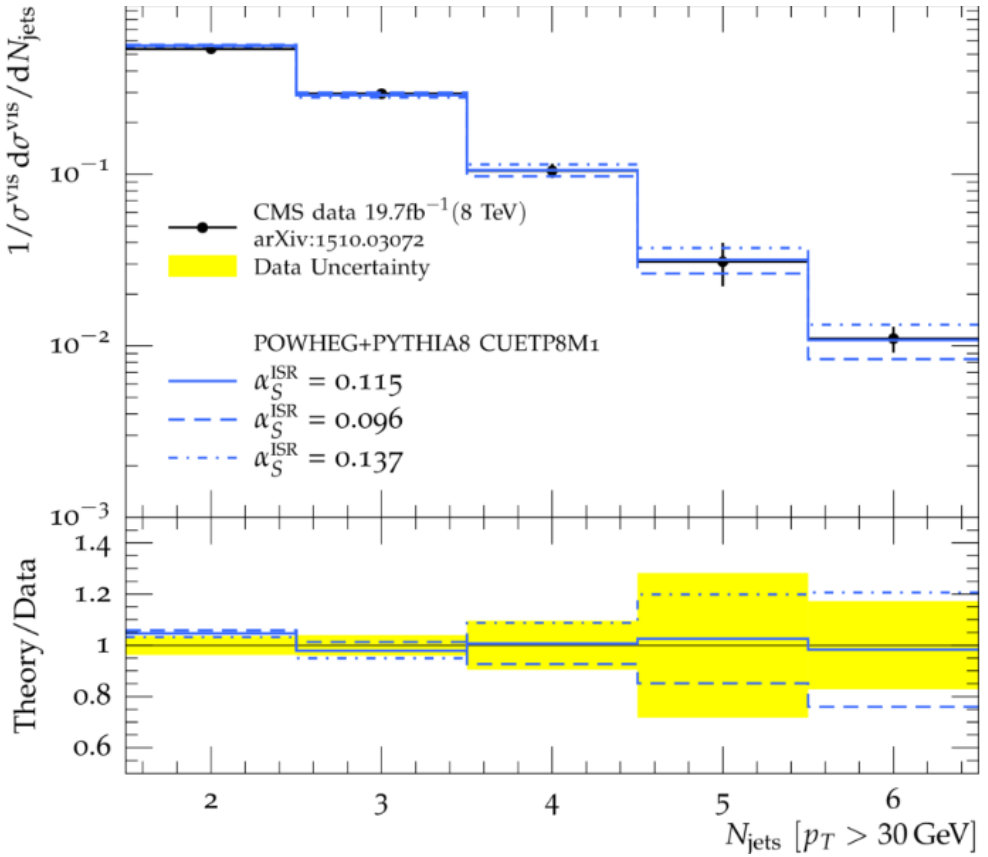
Sensitive to higher order QCD effects

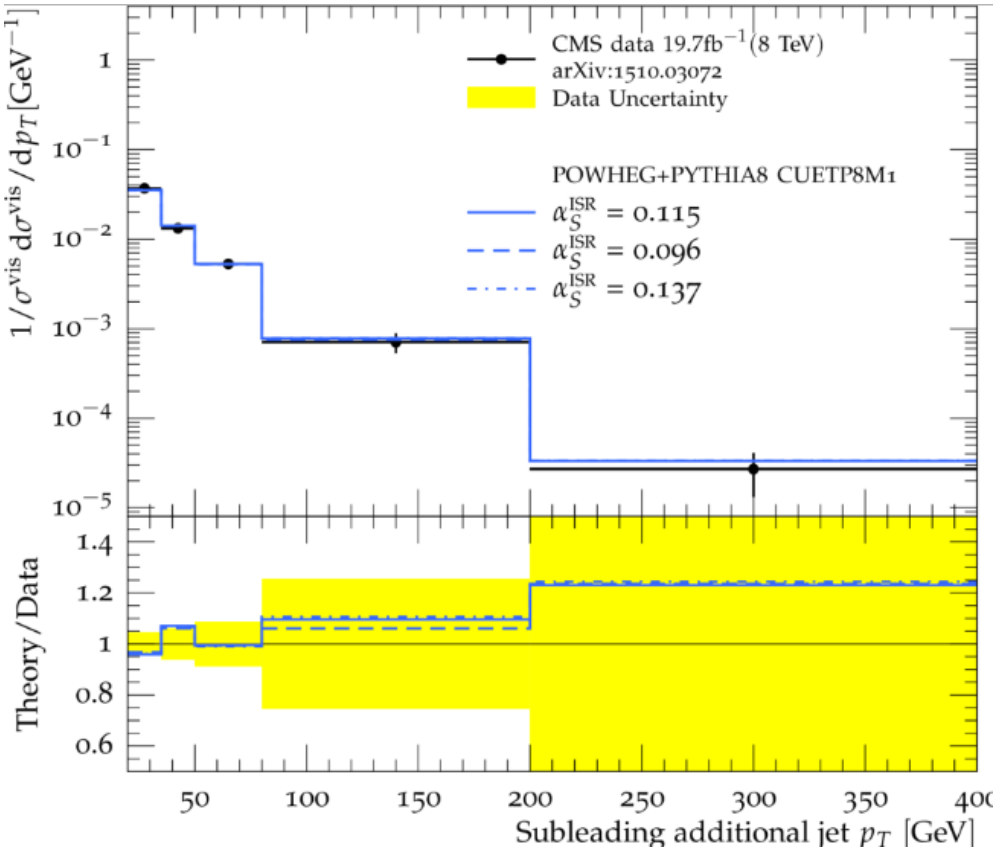
Mismodeling of $t\bar{t}$+jets → uncertainties in measurements where $t\bar{t}$+jets are background

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%

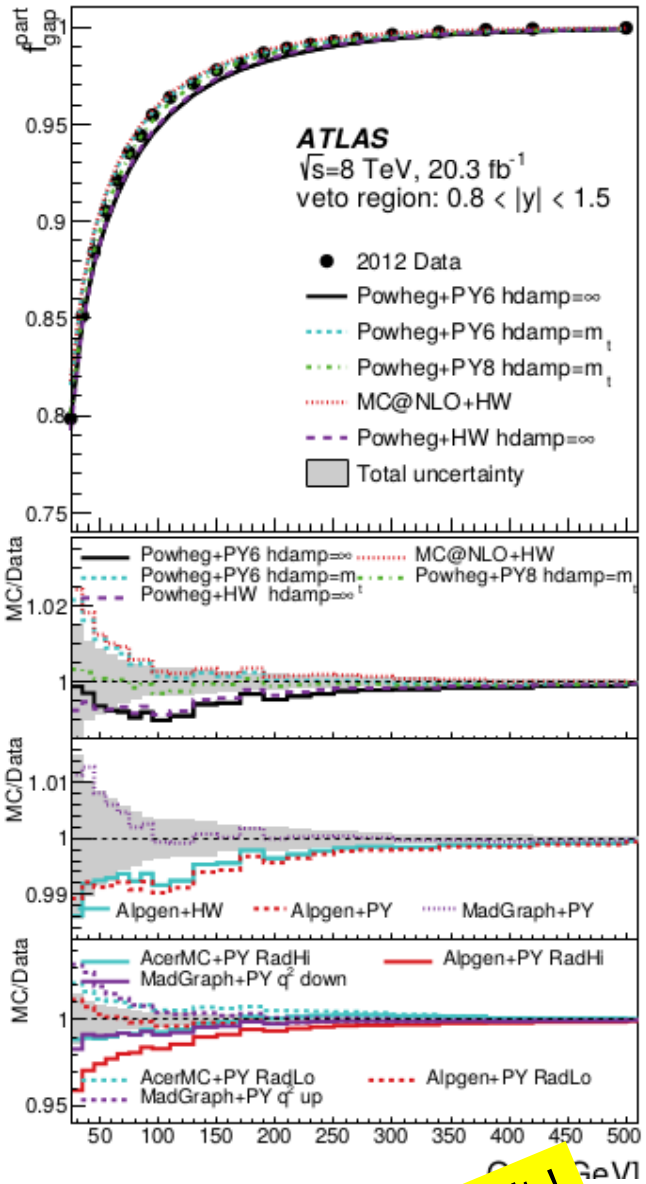
$t\bar{t}$+jets: 13 TeV

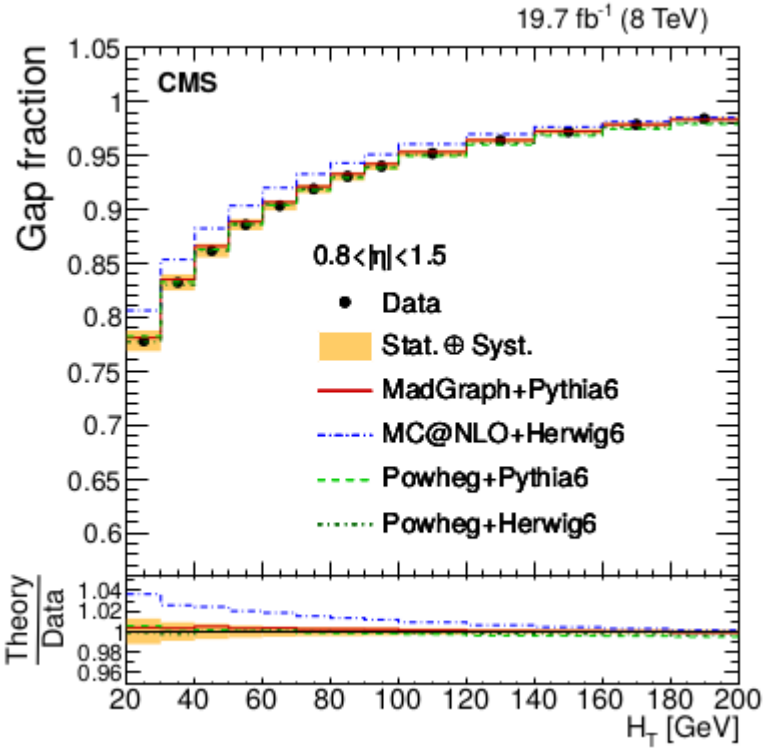




Large dependence on α_s in ISR

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





Jet gap fraction sensible to extra jet activity

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

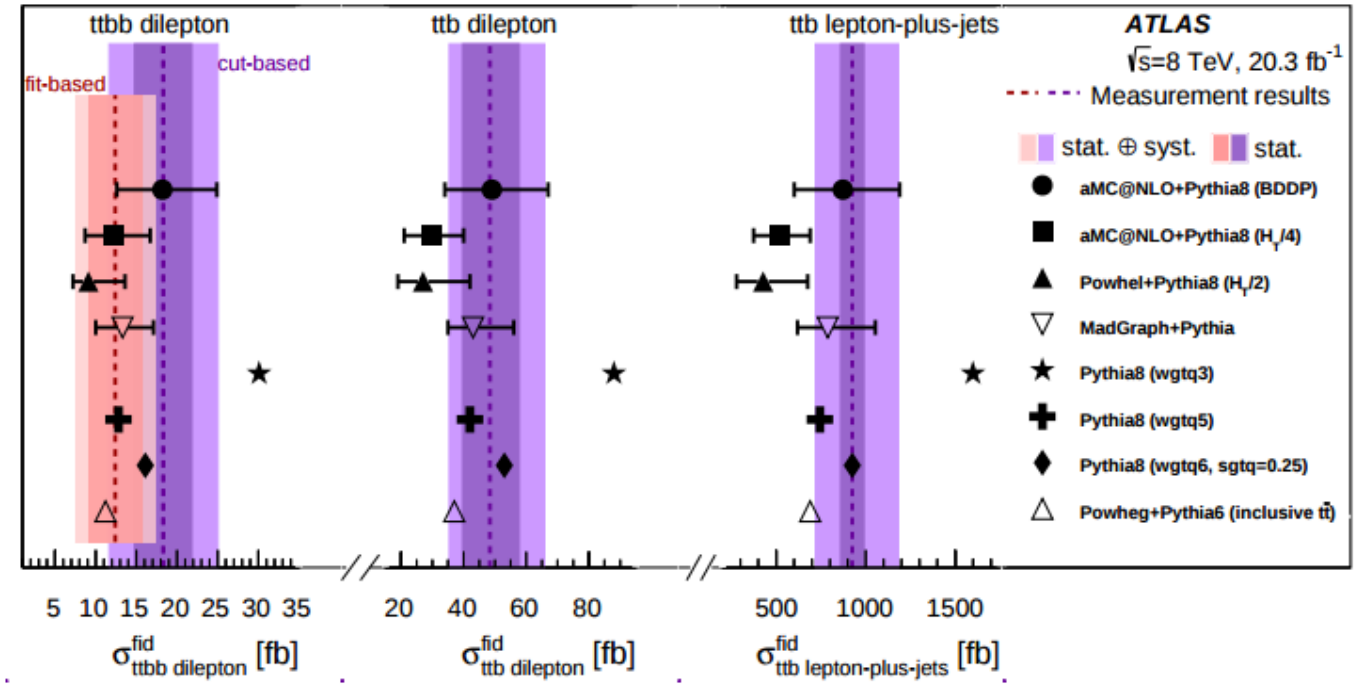
ATLAS:
In preparation
CMS:
CMS-TOP-12-041 (accepted by EPJC)

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)

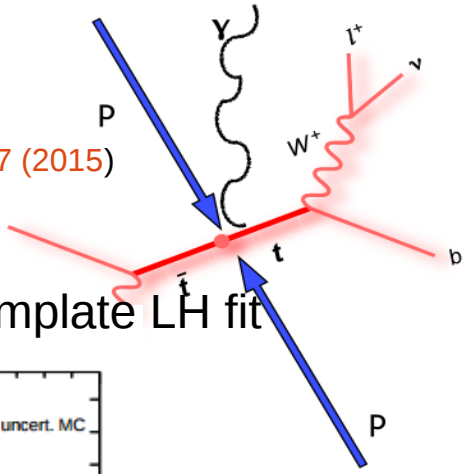
$t\gamma$ vertex accessible only measuring $t\bar{t}+\gamma$ production

Distinguish γ radiation::

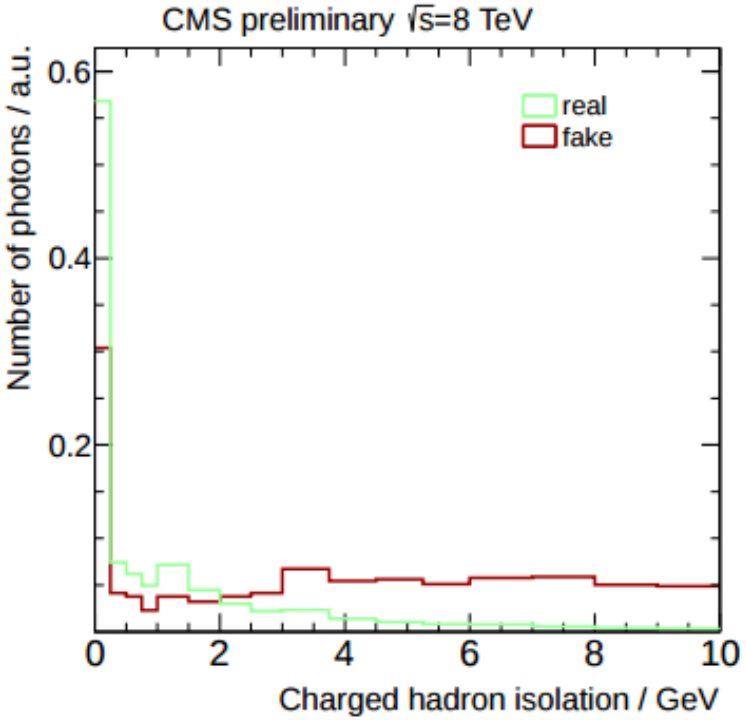
in top production or decay processes

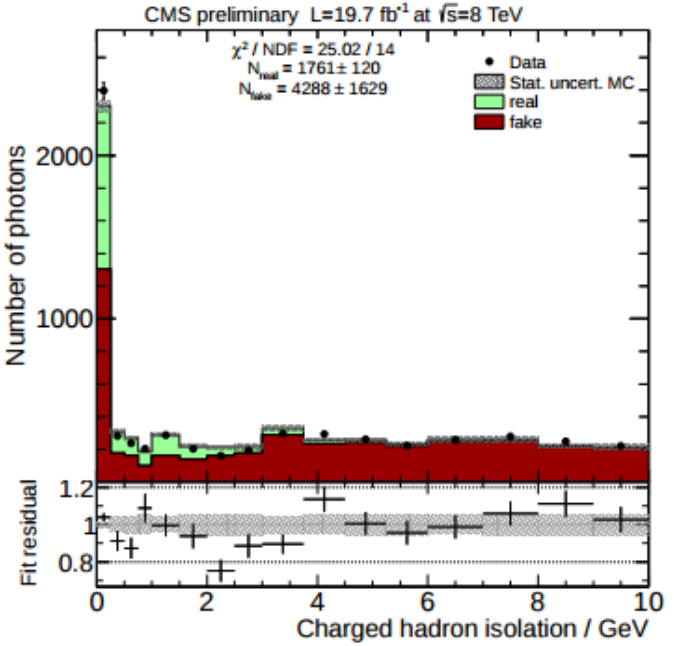
→ interference with NLO

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

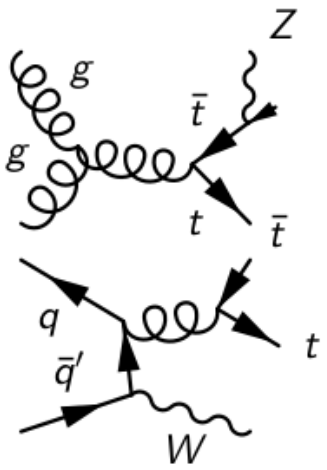
$\sigma_{theo}(t\bar{t}\gamma)xBR = 48\pm10$ fb (LO + k factors) fb

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

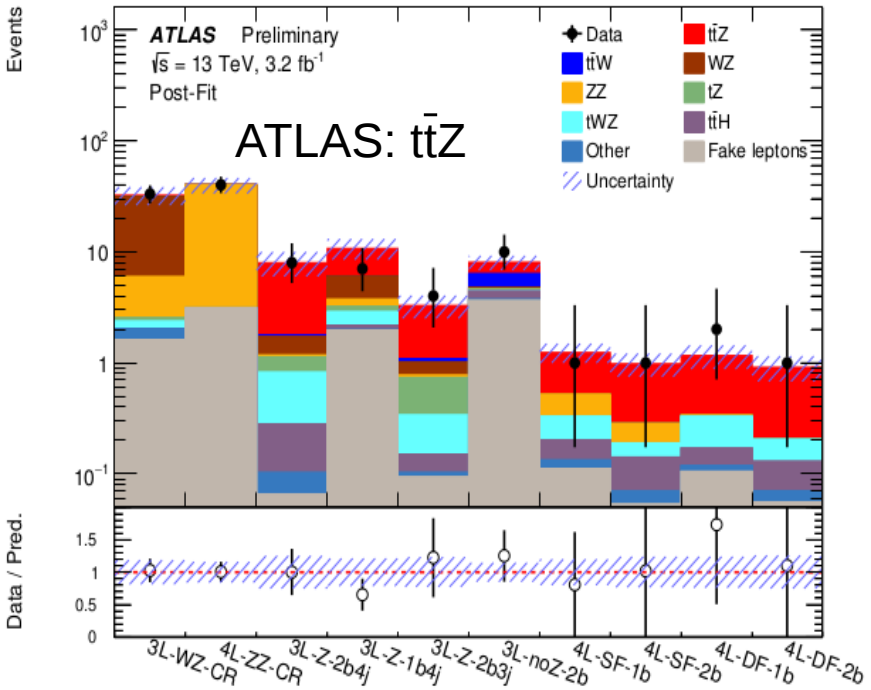
Method: cut&count analysis using different signal regions (different jet multiplicities and b-tag multiplicities)
Evaluate reducible background using data-driven methods

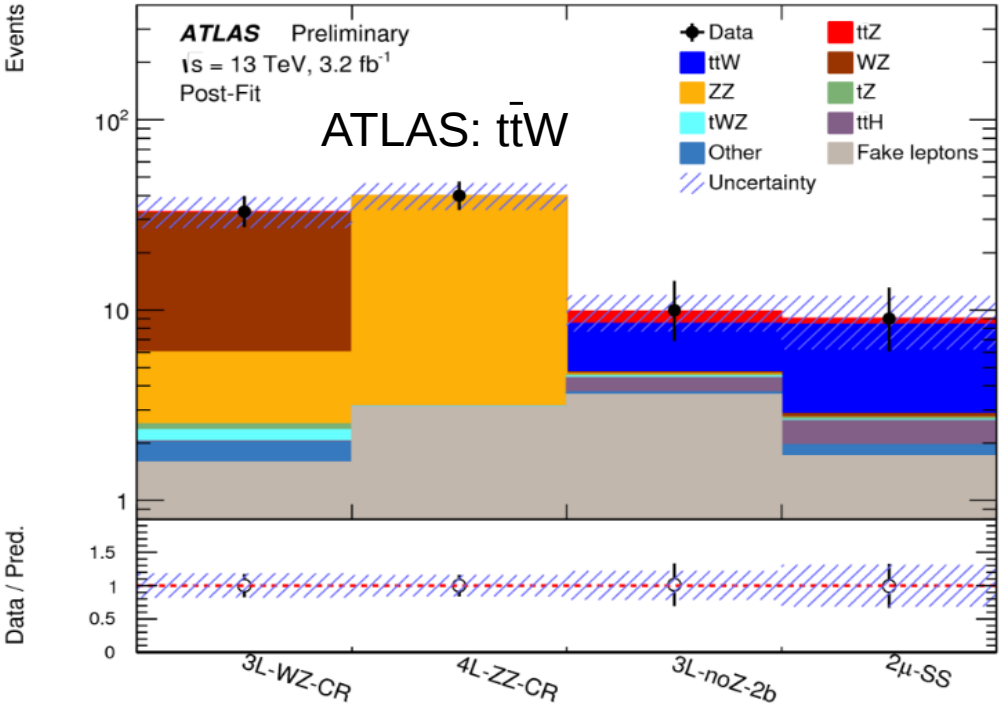
With more statistics → go differential!
Handle for anomalous gauge couplings or EFT studies

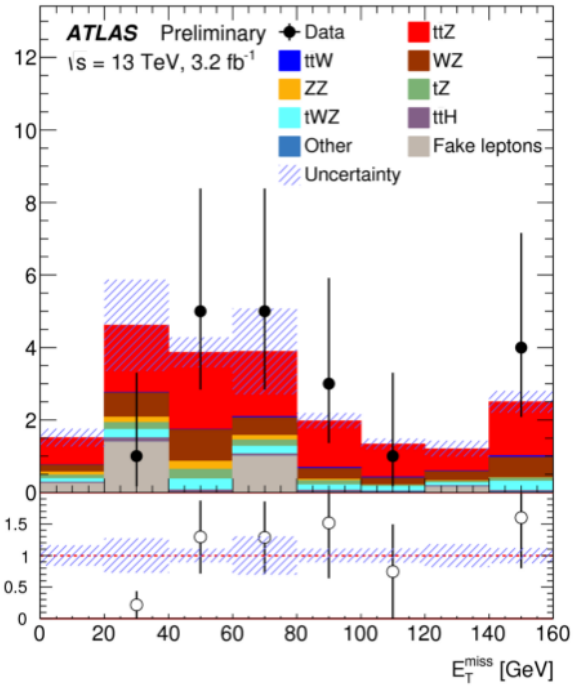
ATLAS: (ttW and ttZ @ 13 TeV)
ATLAS-CONF-2016-003

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

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

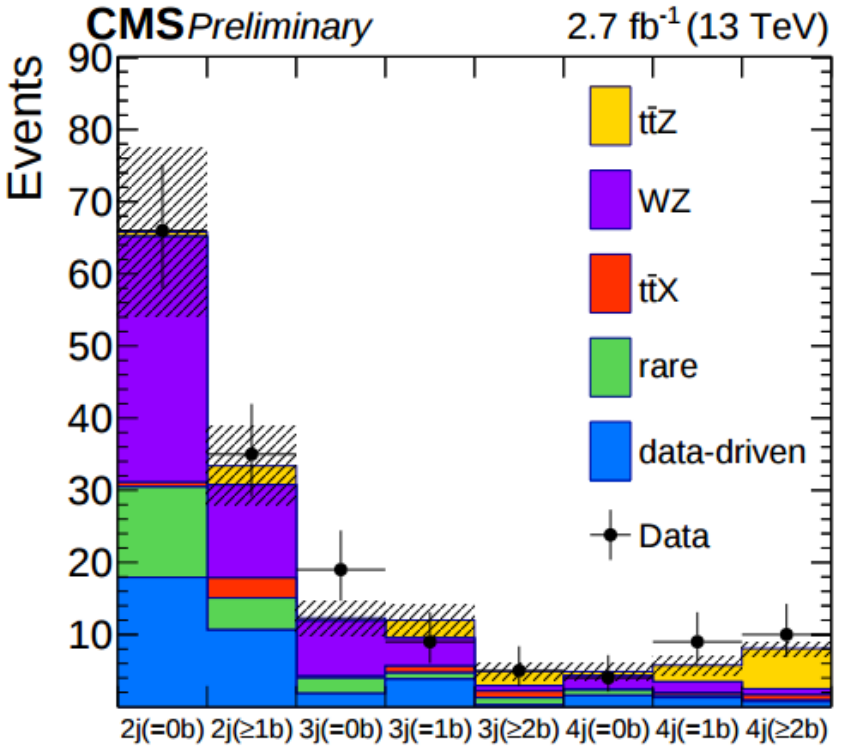




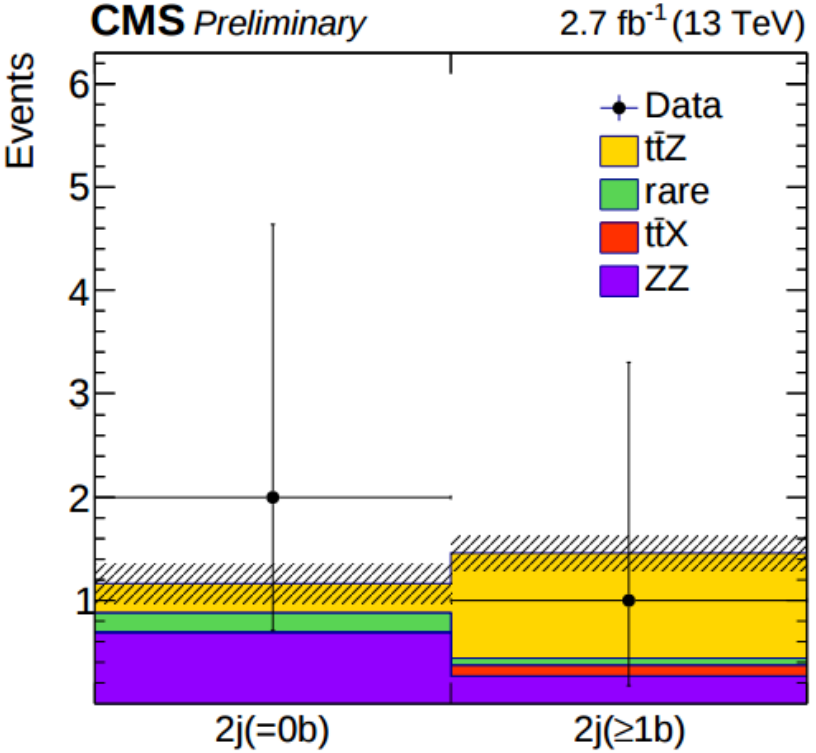


Pre-fit 3-lep ttZ Signal region

$t\bar{t}W$ 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

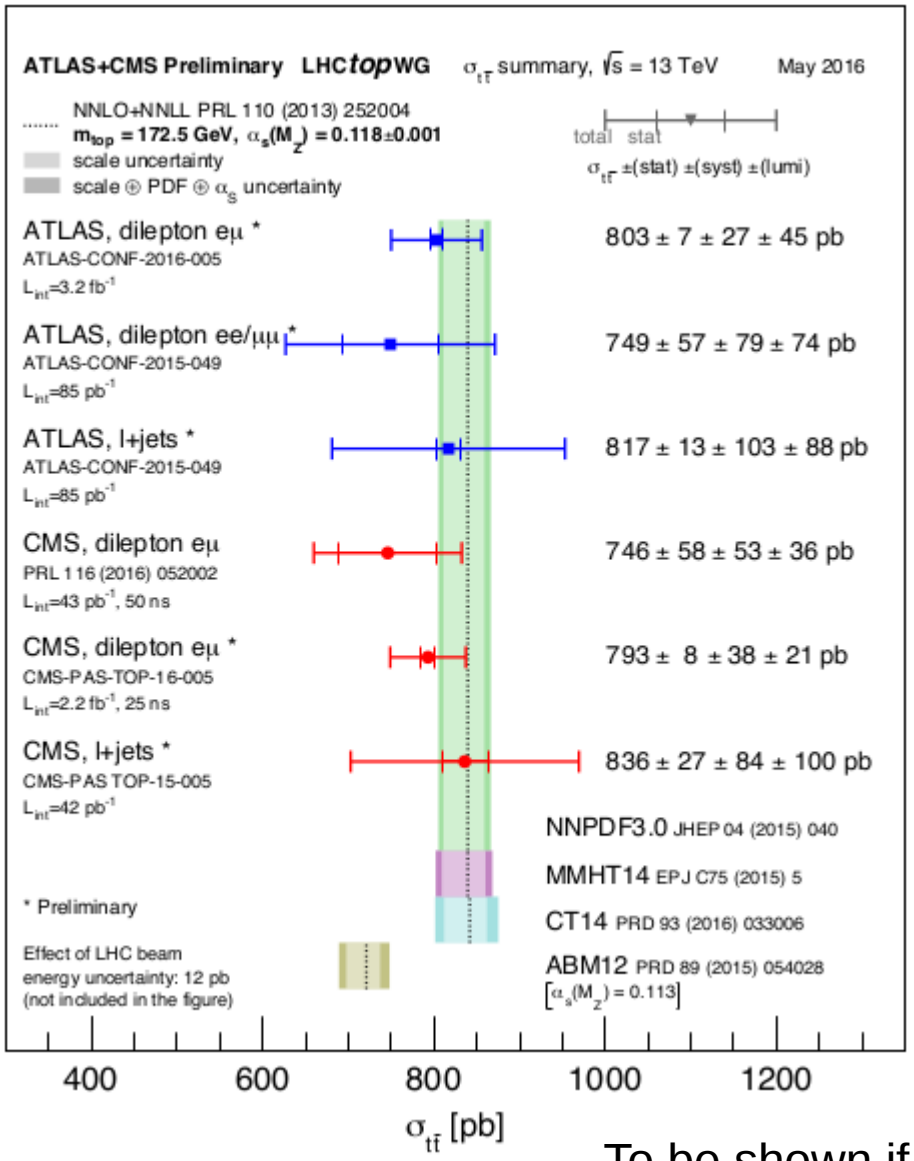
→ Search for physics BSM (enhanced in boosted region?)

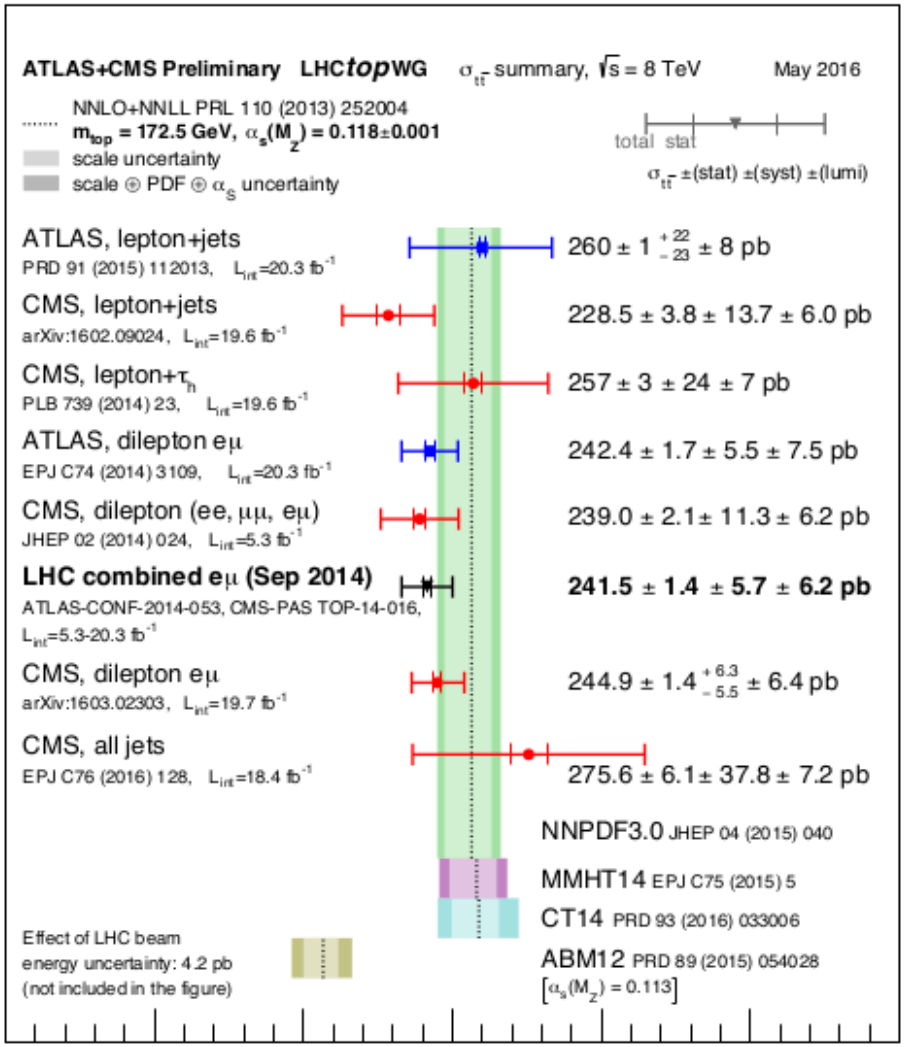
Improve precision and MC tuning of $t\bar{t}$+γ/jet(HF) /W/Z for better background determination

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

Backup

Ttbar xsection Measurements

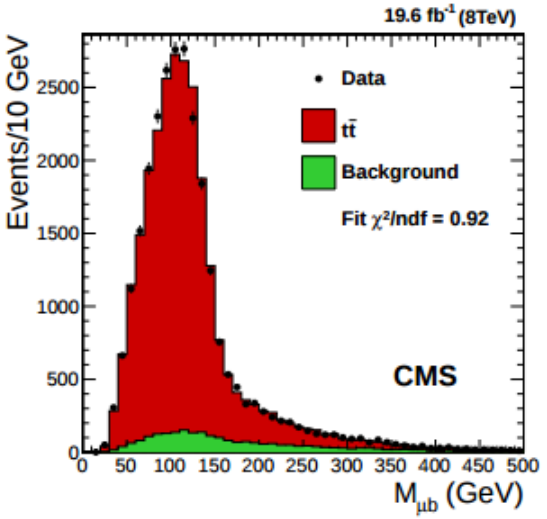


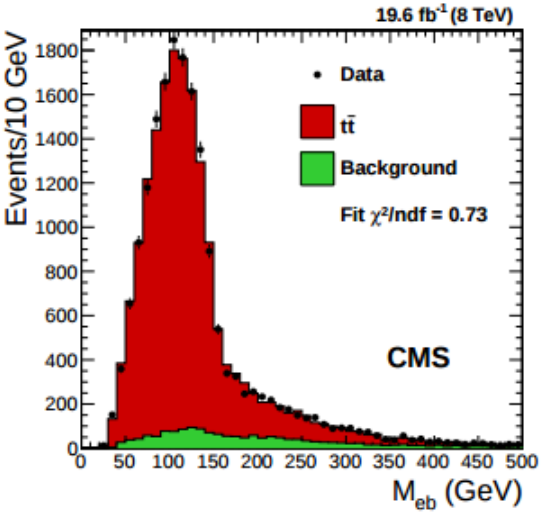


To be shown if approved

Ttbar inclusive cross section measurement at 7 and 8 TeV: CMS (Legacy)

Source	Uncertainty [%] 7 TeV	8 TeV
Trigger	1.3	1.2
Lepton ID/isolation	1.5	1.5
Lepton energy scale	0.2	0.1
Jet energy scale	0.8	0.9
Jet energy resolution	0.1	0.1
tW/$\bar{t}$W	1.0	0.6
DY	1.4	1.3
$t\bar{t}$ bkg.	0.1	0.1
$t\bar{t}V$	0.1	0.1
Diboson	0.2	0.6
W+jets/QCD	0.1	0.2
b-tag	0.5	0.5
Mistag	0.2	0.1
Pileup	0.3	0.3
μ_R, μ_F scales	0.3	0.6
ME/PS matching	0.1	0.1
MADGRAPH vs POWHEG	0.4	0.5
Hadronisation (JES)	0.7	0.7
Top quark p_T modelling	0.3	0.4
Colour reconnection	0.1	0.2
Underlying event	0.1	0.1
PDF	0.2	0.3
Integrated luminosity	2.2	2.6
Statistical	1.2	0.6





Ttbar differential xsection

- ATLAS: resolved

==1 E/mu PT>25 GeV
Resolved:
>=4 jets PT> 25 GeV
(>=2 btag jets)
Boosted:
>=1 bjet (70% eff)
>=1 1jet R=0.4 (PT>25 GeV)
DeltaR(lep)<1.5
1 Large R jet PT>300 GeV
sqrt{d12}>40 m>100
DeltaR(lep)>1.5
MET>20 && MET+MTW> 60 GeV

CMS:
Resolved
Both lep+jet and dilep
Ptlep(e/mu)> 33/33 GeV
Ptlet (e/muj)>20/20
Boosted
PTJet>35 GeV
Ptjet(R=0.7)>400 GeV
Ptlep(e/mu)> 35/20 GeV

Differential xsection Measurement

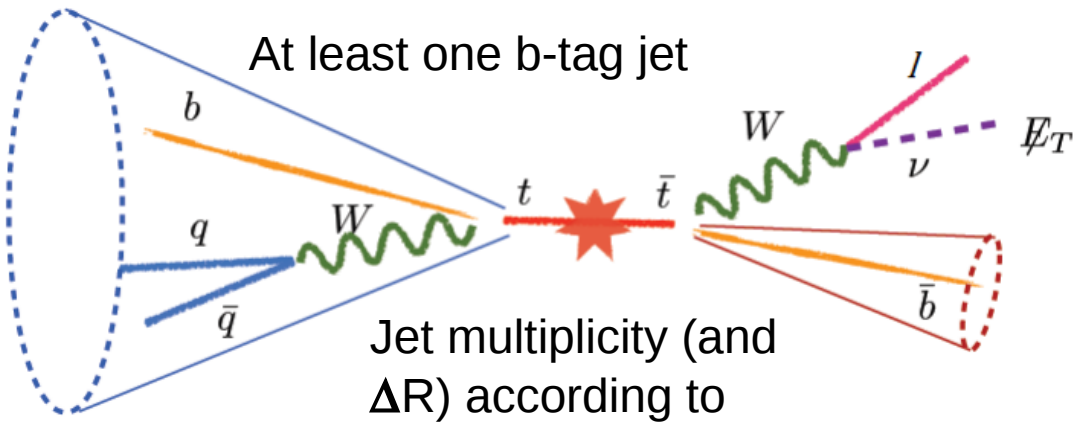
Lepton + jet channel reconstructed: e/μ (CMS also dilepton)
Reconstructed variables:
Hadronic top: P_T, y; $t\bar{t}$ system P_T, y,...
→ Particle level (Fiducial phase space)
→ Parton Level (Full phase space)

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

$\not{E}_T$>25 GeV

One isolated letpon P_T>25 GeV (e/μ)

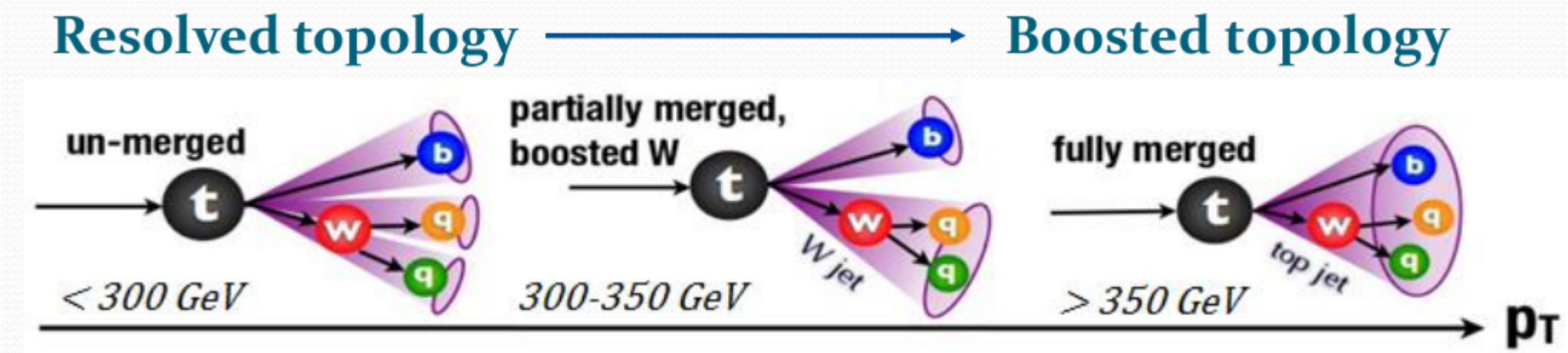
At least one b-tag jet



Jet multiplicity (and ΔR) according to topologies

Two kinematical regimes:
Resolved (small boost of top quark)
Boosted (requirement Large-R jets)
→ use jet substructure to reduce QCD background

Both CMS and ATLAS are providing RIVET routines easing comparison with theory



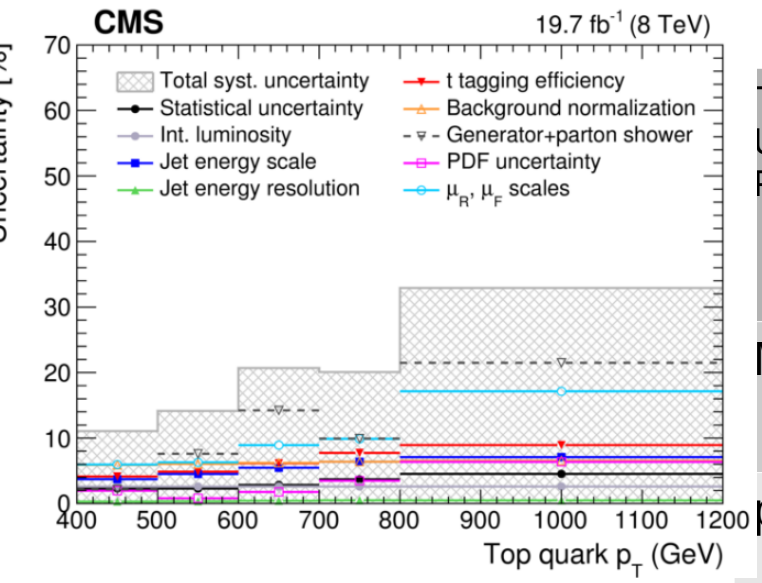
Differential xsection

source	particle [%]	parton [%]
statistical uncertainty	1–5	1–5
b tagging	2–3	2–3
jet energy scale	5–7	6–8
jet energy resolution	< 1	< 1
lepton selection	3	3
$E_{\mathrm{T}}^{\mathrm{miss}}$ (non jet)	< 1	< 1
pileup	< 1	< 1
background	1–3	1–3
PDF	< 1	< 1
fact./ren. scale	< 1	< 1
NLO generator	1–6	1–10
parton shower scale	1–5	2–9
POWHEG + PYTHIA8 vs. HERWIG++	< 3	1–12

CMS

Typical uncertainties

Differential xsection Measurement: 8 TeV



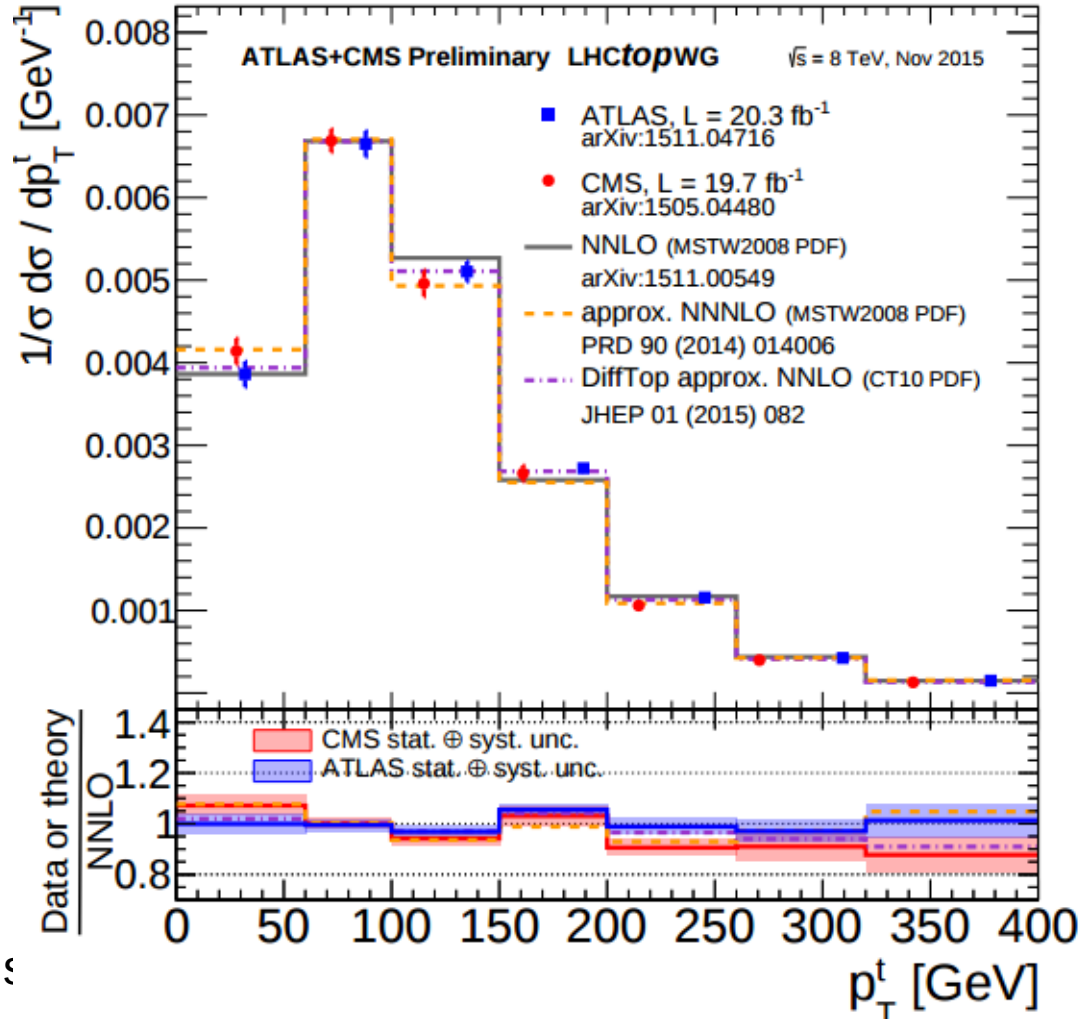
Typical Uncertainties Particle-Level (%)	ATLAS Resolved arXiv: 1511.04716	ATLAS Boosted Phys. Rev. D93 (2016) 032009	CMS Resolved EPJC 75 (2015) 542	CMS Boosted arXiv:1605.00116
Modelling	3.2~8	7~27	3	4~30
pdf	<1	0.3~1.2	0.1	1~8
Jet Energy Scale	1-4.4	13-22	1.6	4~8
b-tagging	0-2	0,3~4.4	0.6	~

Range of uncertainties for various P_T bins

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

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

Differential xsection Measurement: 8 TeV

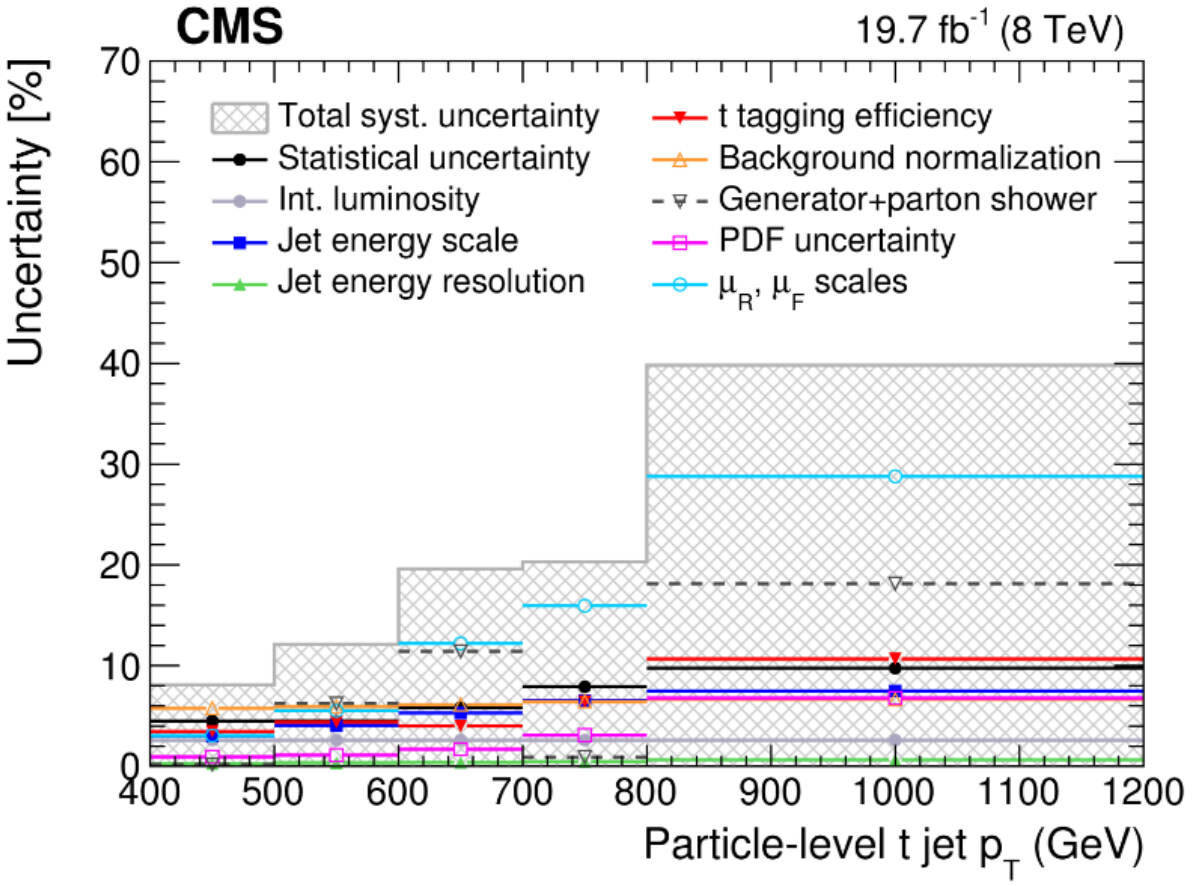


Resolved s

Comparison with NNLO predictions

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

Ttbar differential xsection: Boosted

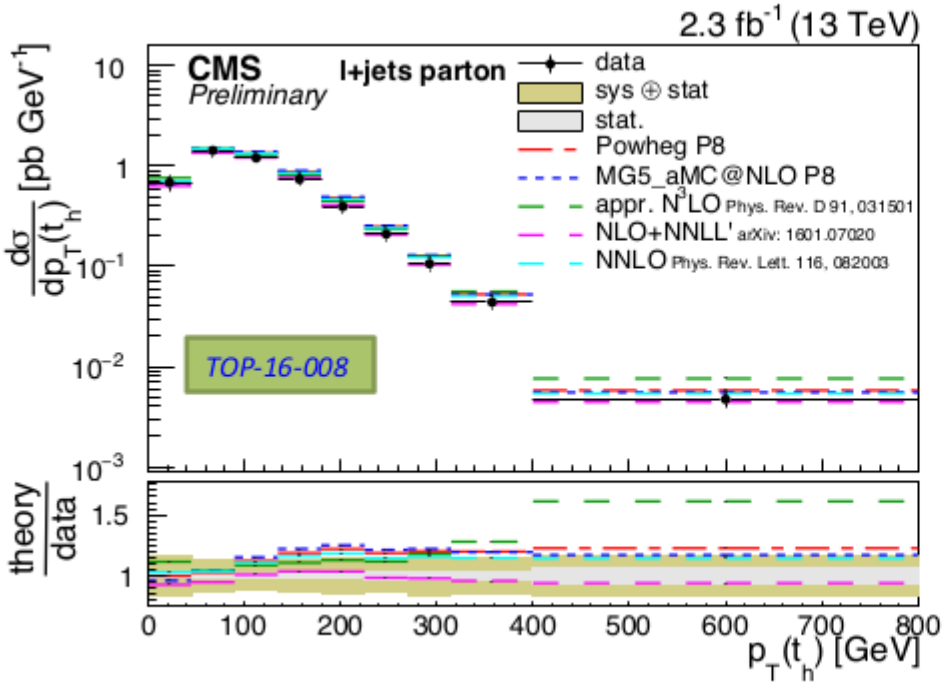


http://arxiv.org/abs/1605.00116

Systematic uncertainties

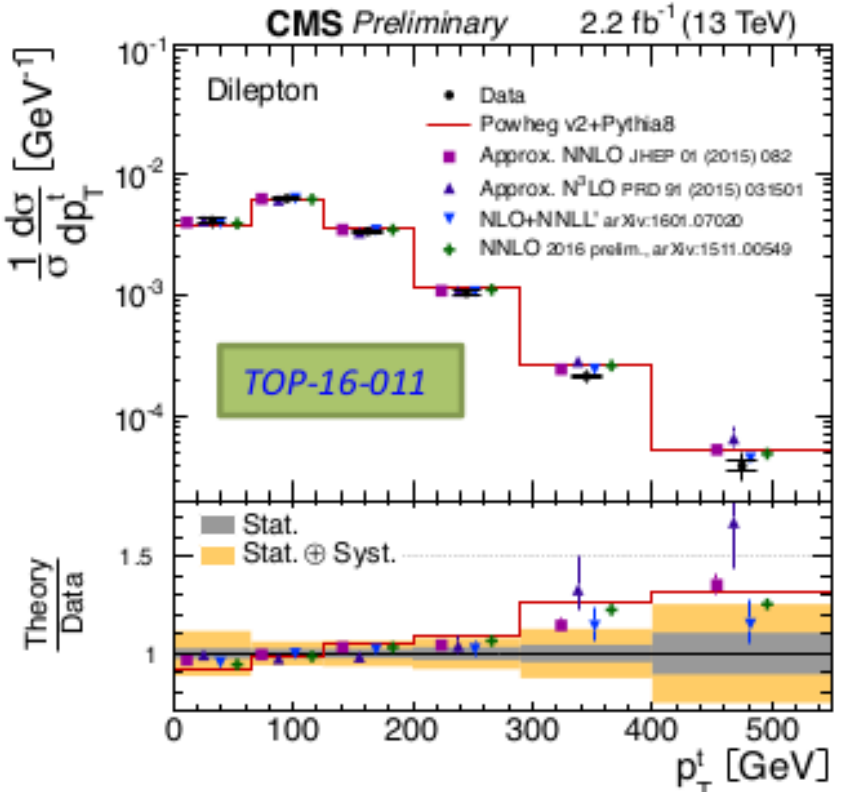
Differential xsection Measurement: 13 TeV

First 13 TeV Measurement differential measurement



Momentum of hadronic top

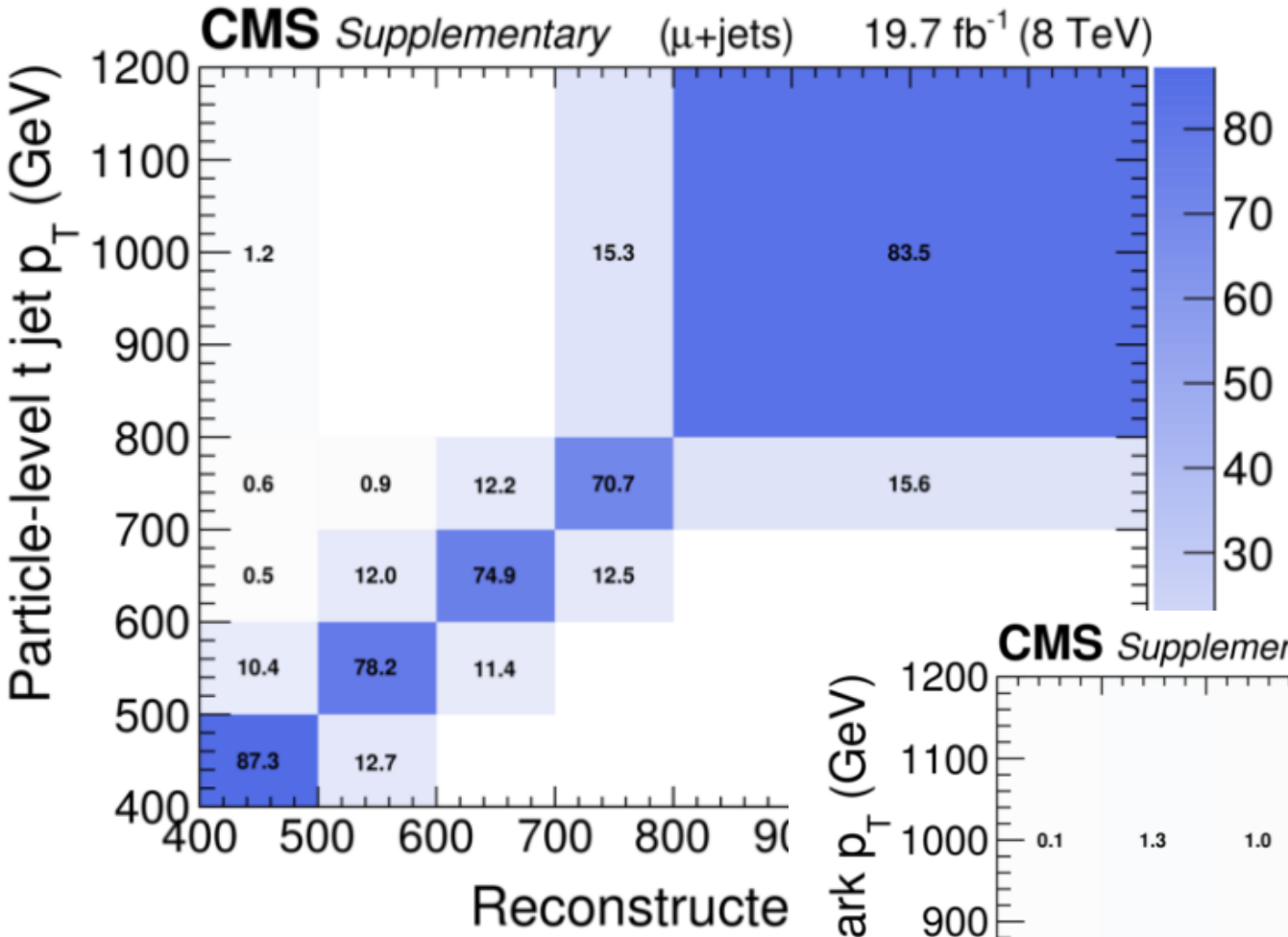
Lepton + jet selection
Parton level measurement

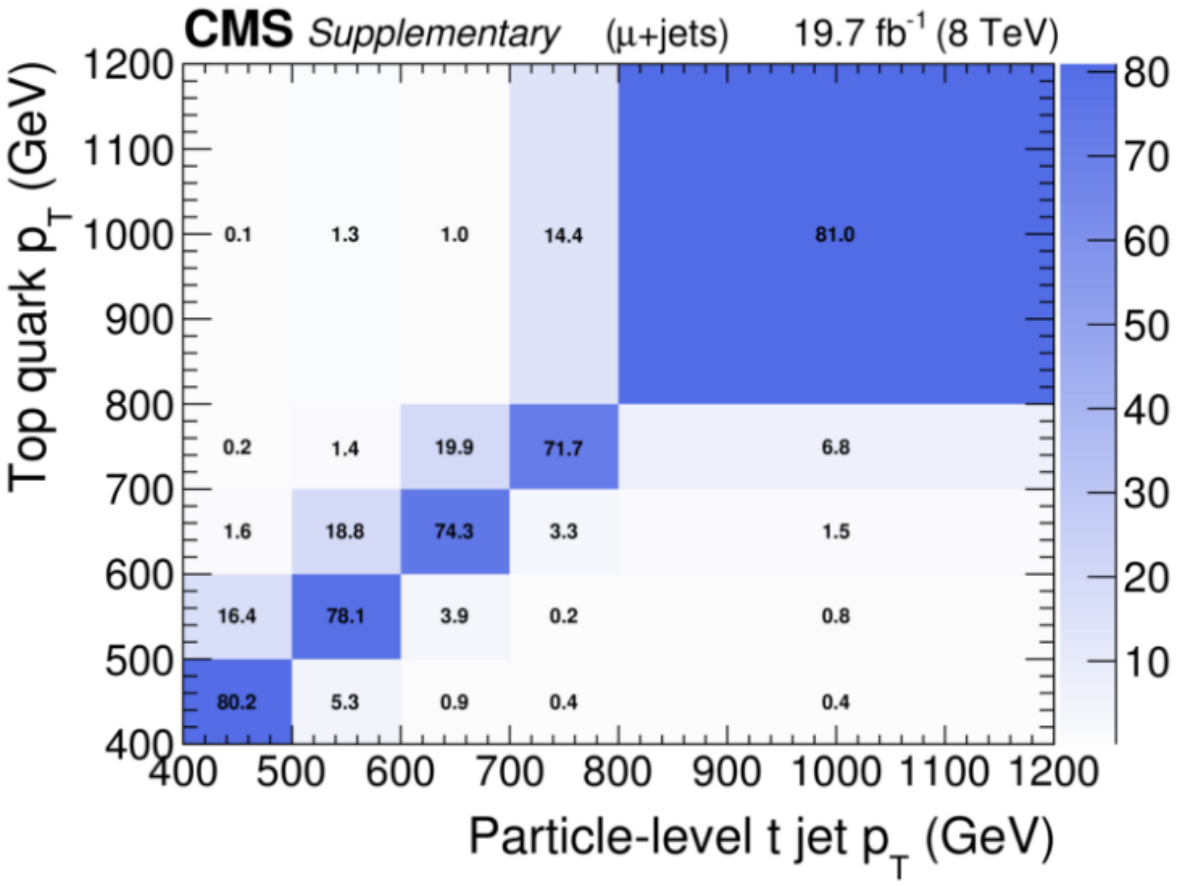


Invariant mass of tt system
→ test production modes at threshold
BSM searches:

- Bumps for X →tt
- Interference SM ←→ BSM
- Test EW corrections

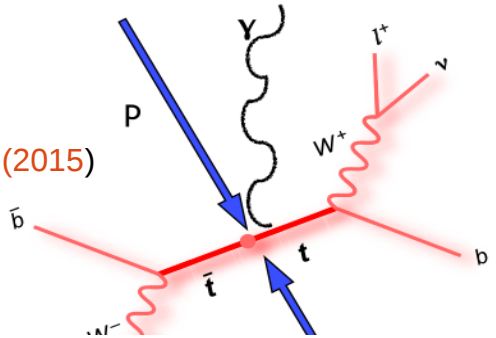
CMS:
(lep + jet) CMS-PAS-TOP-16-008
(dilepton) CMS-PAS-TOP-16-011


CMS Supplementary (μ+jets) 19.7 fb-1 (8 TeV)
Particle-level t jet pT (GeV)
Reconstructe
1200
1100
1000
900
800
700
600
500
400
1.2
15.3
83.5
0.6
0.9
12.2
70.7
15.6
0.5
12.0
74.9
12.5
10.4
78.2
11.4
87.3
12.7
80
70
60
50
40
30


CMS Supplementary (μ+jets) 19.7 fb-1 (8 TeV)
Top quark pT (GeV)
Particle-level t jet pT (GeV)
1200
1100
1000
900
800
700
600
500
400
0.1
1.3
1.0
14.4
81.0
0.2
1.4
19.9
71.7
6.8
1.6
18.8
74.3
3.3
1.5
16.4
78.1
3.9
0.2
0.8
80.2
5.3
0.9
0.4
0.4
80
70
60
50
40
30
20
10

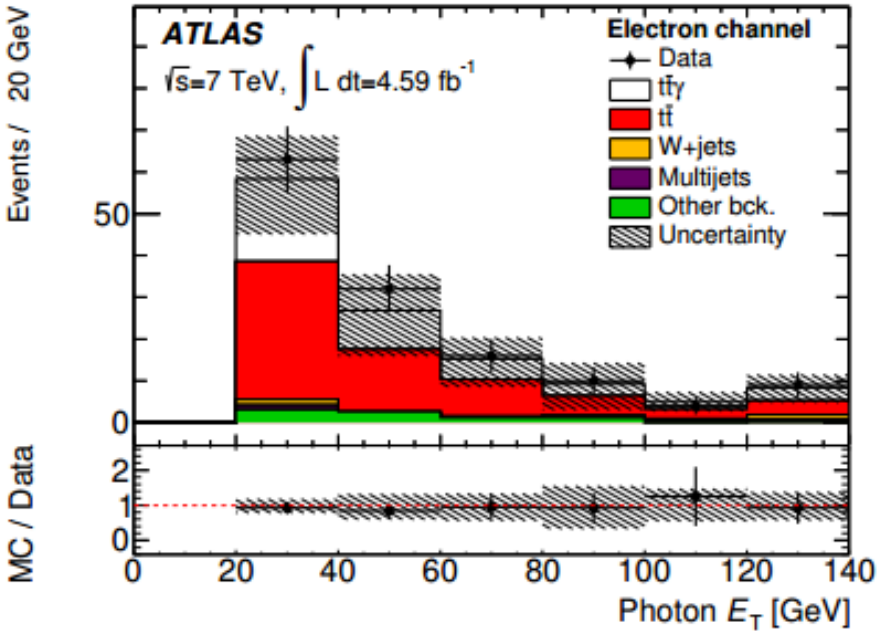
$t\bar{t}\gamma$ (7 TeV ATLAS - 8 TeV CMS)

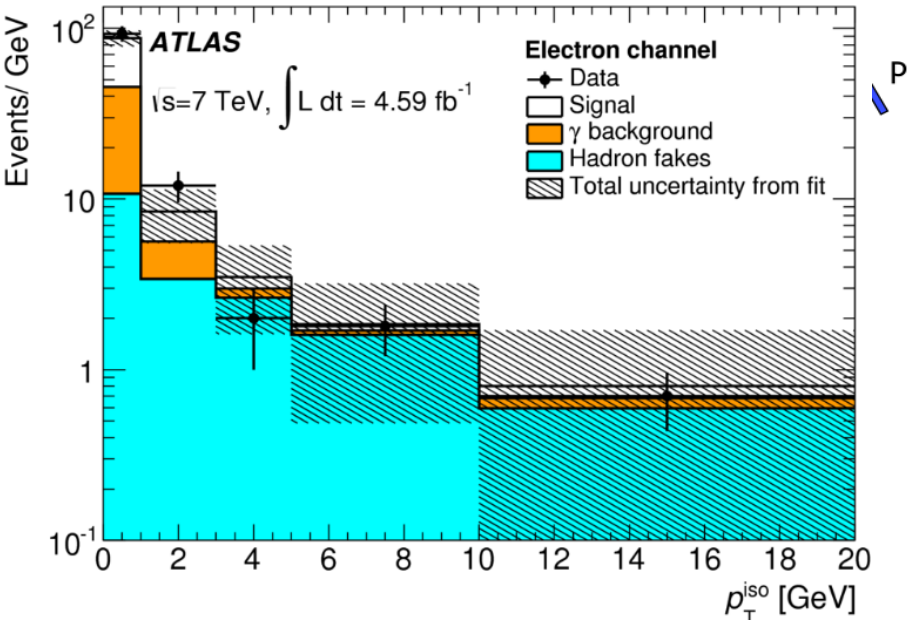
ATLAS:
Phys. Rev. D 91, 072007 (2015)
CMS:
CMS PAS TOP-13-011



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

Distinguish γ radiation::
in top production or decay processes
→ interference with NLO



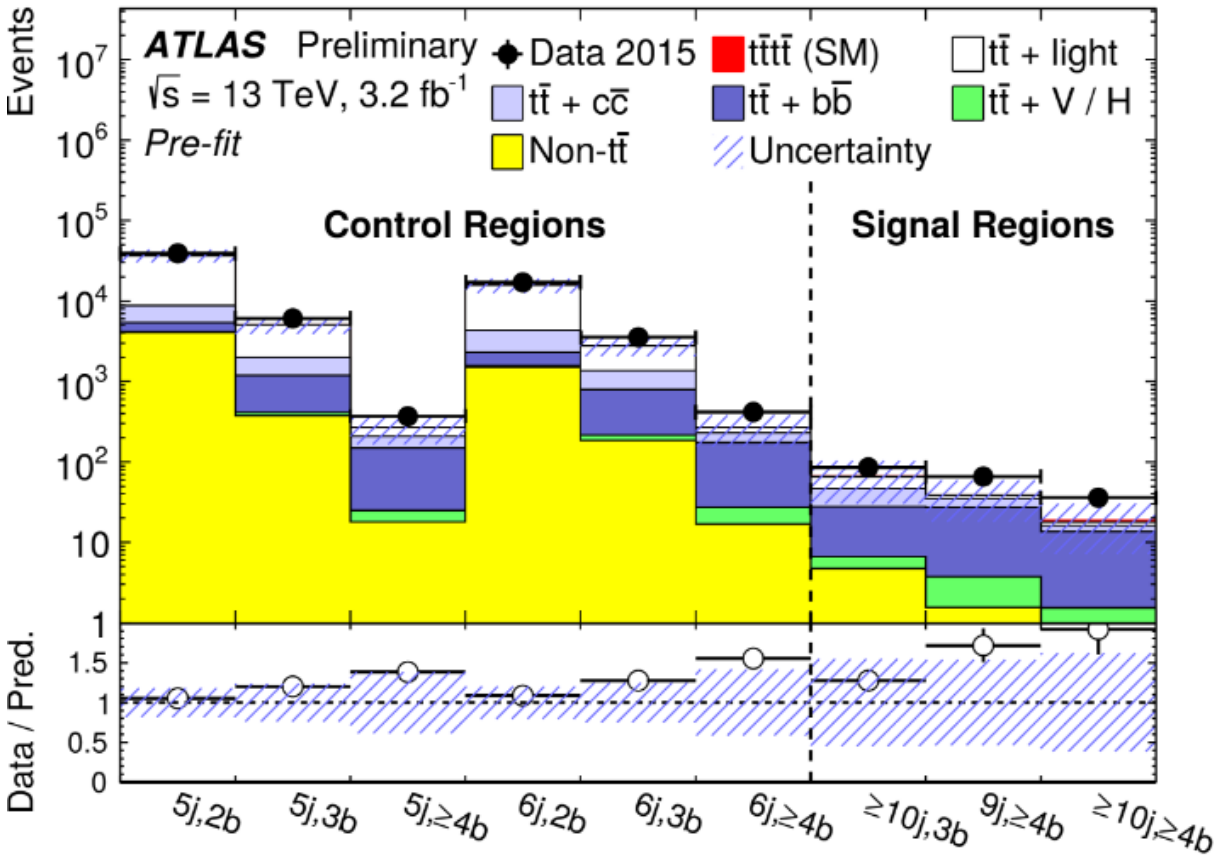


Fiducial cross section:
ATLAS: $P_T\gamma > 20$ GeV) $\Delta R(\gamma,l)>0.7$
CMS: $\Delta R(\gamma,b\text{-jet})>0.1$
(measurement of $pp \rightarrow WWbb\gamma$)

ATLAS:
$\sigma_{fid}(t\bar{t}\gamma) \times BR = 63 \pm 8(stat)^{+17}_{-13}(syst) \pm 1(lumi)$ fb
$\sigma_{theo}(t\bar{t}\gamma) \times BR = 48 \pm 10$ fb (LO + k factors) fb

CMS
$\sigma_{fid}(t\bar{t}\gamma) = 2.4 \pm 0.2(stat) \pm 0.6(syst)$ pb
$\sigma_{theo}(t\bar{t}\gamma) = 1.8 \pm 0.5$ pb (LO k factors) pb

$t\bar{t}+t\bar{t}$ (4 tops)

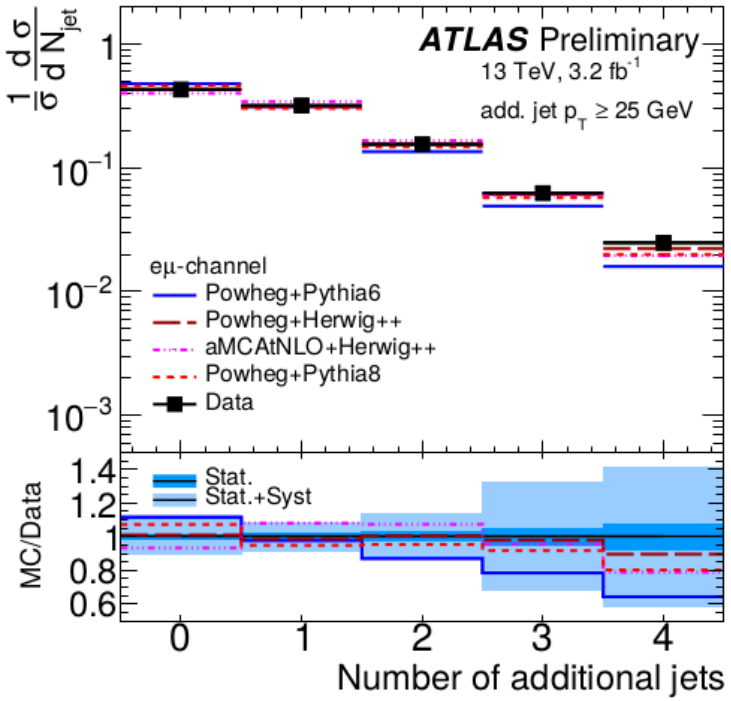


Pre-fit

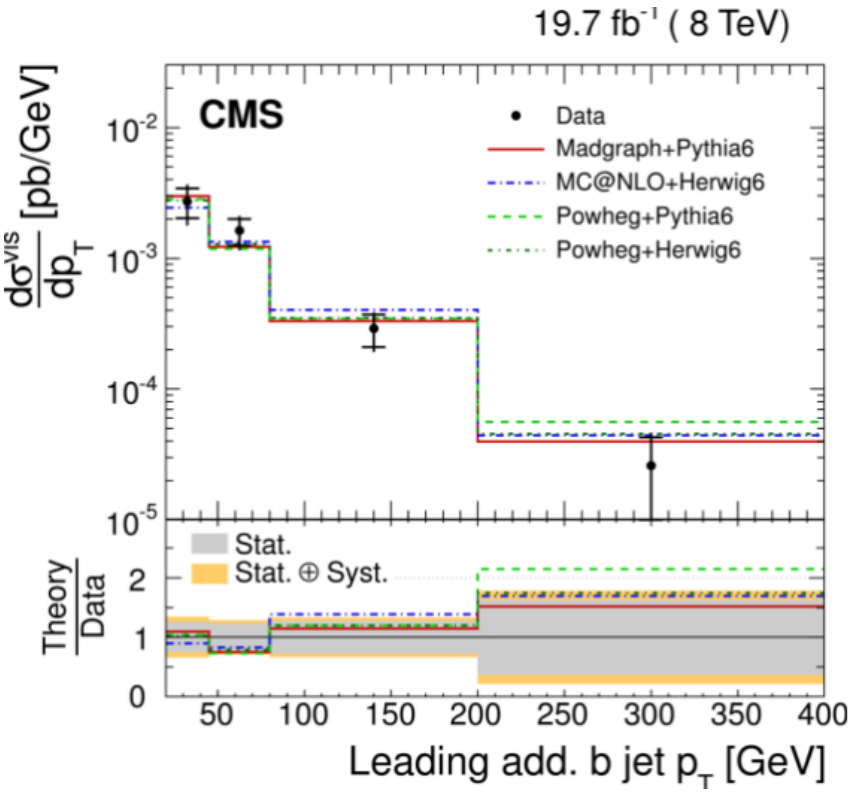
ATLAS:
ATLAS-CONF-2016-020

$t\bar{t}$+jets

Sensitive to higher order QCD effects
→ mismodeling of tt+jets → unertainties in measurementes where tt+jets are background



Jet multiplicity (different PTJet threshold)
Comparison with aMCAtNLO and POWEG+Pythia



CMS: differential cross section
as a function of pt of b-jet

ATLAS:
ATLAS-CONF-2015-065
CMS:
arXiv:1510.03072 accepted Eur. Phys. J. C