Differential cross sections
measurements oriented to final state objects

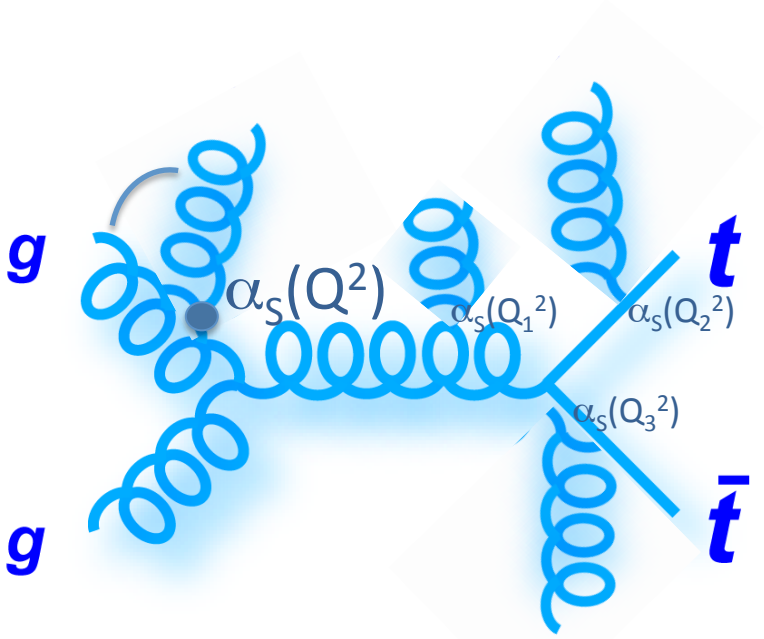
Judith Katzy (DESY)
with help of Maria Aldaya (DESY)
on behalf of ATLAS & CMS

Motivation for $t\bar{t}$+jets

- Study QCD radiation at high scales
  - Tevatron: ~ every 3rd top event contains an additional jet; first pioneering study on tt+1jet from CDF (2009);
  - LHC large phase space for QCD radiation due to higher sqrt(s); ~ 2 third of top events used in measurements have an additional jet
- Large systematic uncertainties related to QCD radiation
  - Changes in acceptance
  - Jet combinations in top quark reconstruction
- Radiation described by QCD MC models with free model parameters
  - Define and measure appropriate observables to provide input for MC tuning
- Background processes for searches (BSM, rare SM, Higgs)

QCD radiation in top pair production

- Scale and coupling strength of the emission
  - factorisation and renormalisation scale
  - Functional form
  - Multiple scales within one event
- Approximations in calculations
  - ME vs PS
  - NLO vs multileg (new: NLO plus multileg)
  - ME+PS matching algorithm + scale
- Predictions
  - jet multiplicity, E, angle, shape
  - parton p_t, p_t of ttbar system



QCD (MC) predictions of radiation

Measurements $|\eta|<2.5$, $p_t>20$ GeV

Single jet based observables

N_{jet}, jet p_t, η, jet shapes

Integrated observables

jet veto, H_T, S_T

Indirect observables (recoil)

Lepton p_t, E_{tmiss}, p_t^W

Derived quantities

top p_t, ttbar p_t

The Measurements

- Measurements performed in fiducial volume ("visible phase space") to minimise model dependencies
  - Recent development: expand "fiducial region" also to object definition and parton proxy
- Correction of detector level effects through "unfolding" to particle level
- Measurements in single-lepton and di-lepton channel at 7 TeV and 8 TeV

Fiducial object definition*

based on stable particles (τ>0.3*10^{-10} sec) within observable η range

ATLAS	CMS
Leptons (e, μ, ν) not from hadron decay e, μ 4-momentum incl. clustering with γ in cone with R=0.1	Leptons after radiation (status code 3) from Pythia with W mother
Jets: clusters all but the prompt particles (i.e. ν, μ from hadron decays are inside jets)	
Anti-kt R=0.4	Anti-kt R=0.5
B-jets: If a stable B-hadron with intial p_t>5 GeV Ghost matched to the jet -> corresponding to non-prompt Bs from electro-weak decays	B-jets: If one of the decay products of a B-hadron are clustered within a jet

*for tt+jets; other analysis may use different definitions

See also Top LCPP WG: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ParticleLevelTopDefinitions

Fiducial kinematic phase space for tt+jets

ATLAS single-lepton channel

- Exactly one e or μ with $|\eta|<2.5$, $p_t>25$ GeV
- No additional e or μ with $p_t>15$ GeV & $|\eta|<2.5$
- $E_{tmiss} > 30$GeV & $m_T(W)>35$ GeV
- >= 3 Jets with $p_t>25$ GeV & $|\eta|<2.5$ incl. >=1 b-tagged jet
- No jet-jet pair with dR<0.5
- No jet-e or jet-μ pair with dR<0.4

CMS single-lepton channel

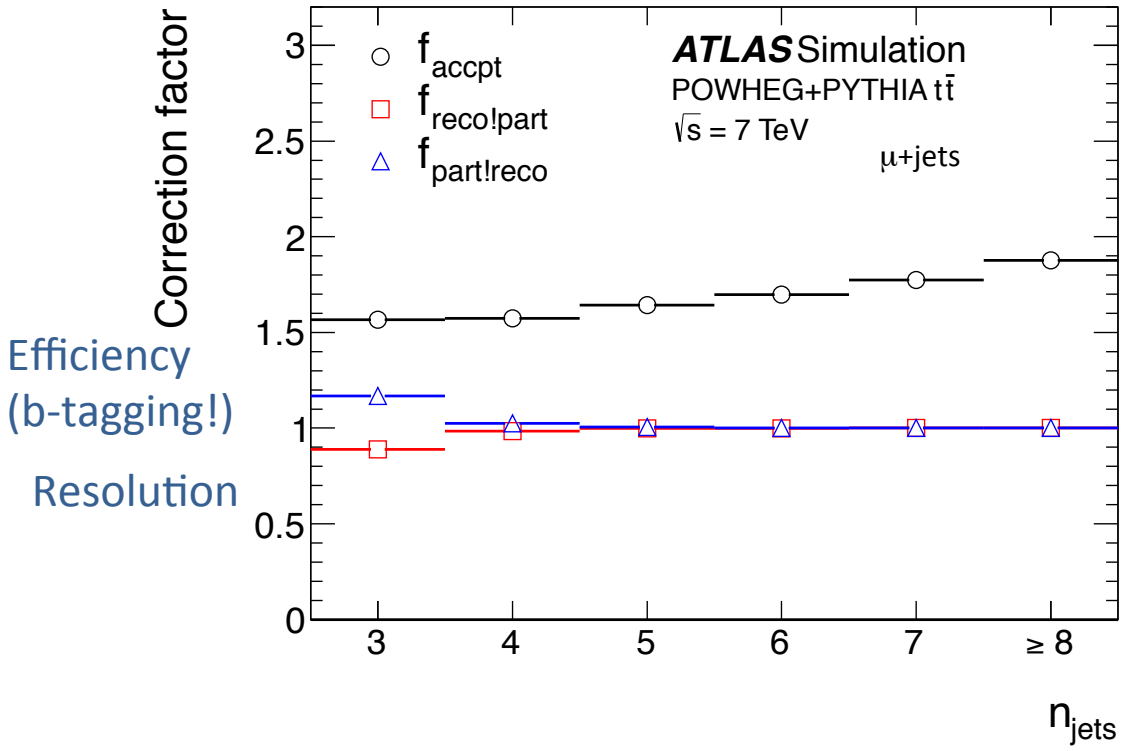
- Lepton with $|\eta|<2.5$(e) , $|\eta|<2.1(\mu)$, $p_t>30$ GeV
- 2 b-jets+1 jet with $|\eta|<2.4$, pt>35 GeV
- Jet removal if dR (jet,lepton)<0.4

CMS di-lepton channel: lower pt cuts to 20 GeV (leptons) and 30 GeV (jets)

arXiv:1407.0891

Correction to particle level

Global efficiency correction factors + iterative Bayesian unfolding



f_{accept} = #evets @ particle level in fiducial volume / # events @ reco level in fiducial volume

$f_{reco!part}$:# events reco jets no particle jets

$f_{part!reco}$: # events particle jets no reco jets

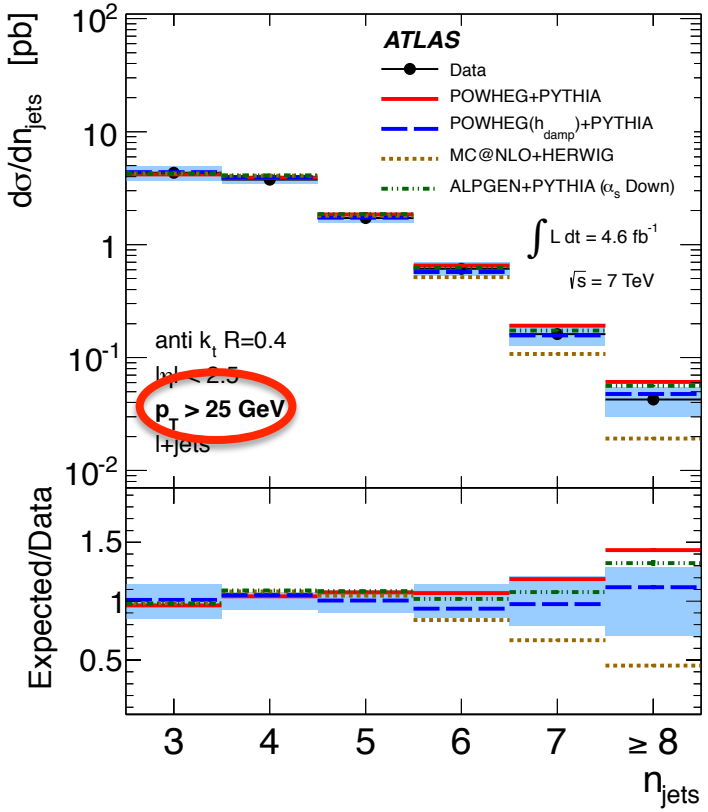
Still large corrections needed for detector level effects but reduced dependence on MC model

arXiv:1407.0891

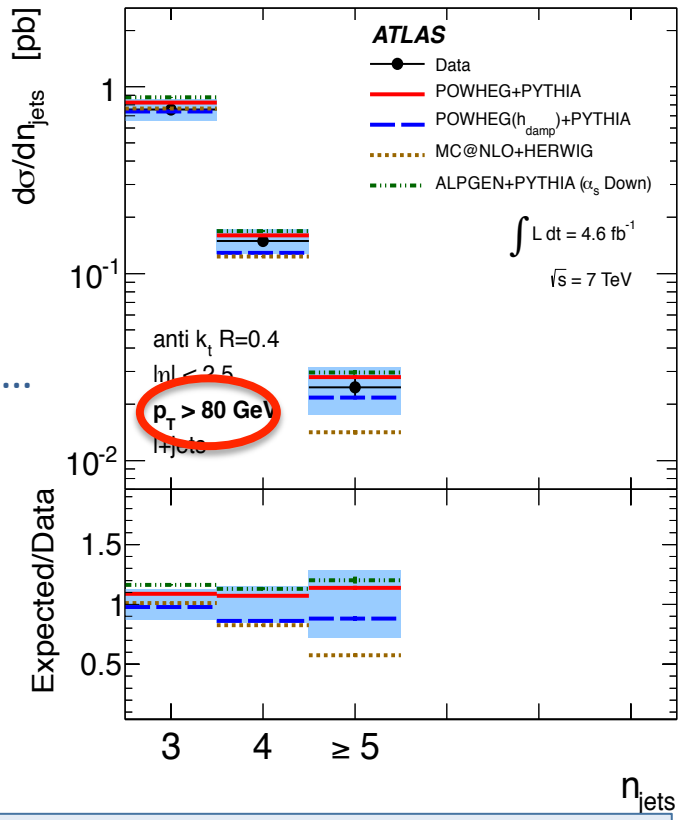
ATLAS Jet Multiplicities for single-lepton channel

NEW

Differential cross section at 7 TeV as a function of jet multiplicity with several p_t threshold



p_t>40 GeV...p_t>60GeV...

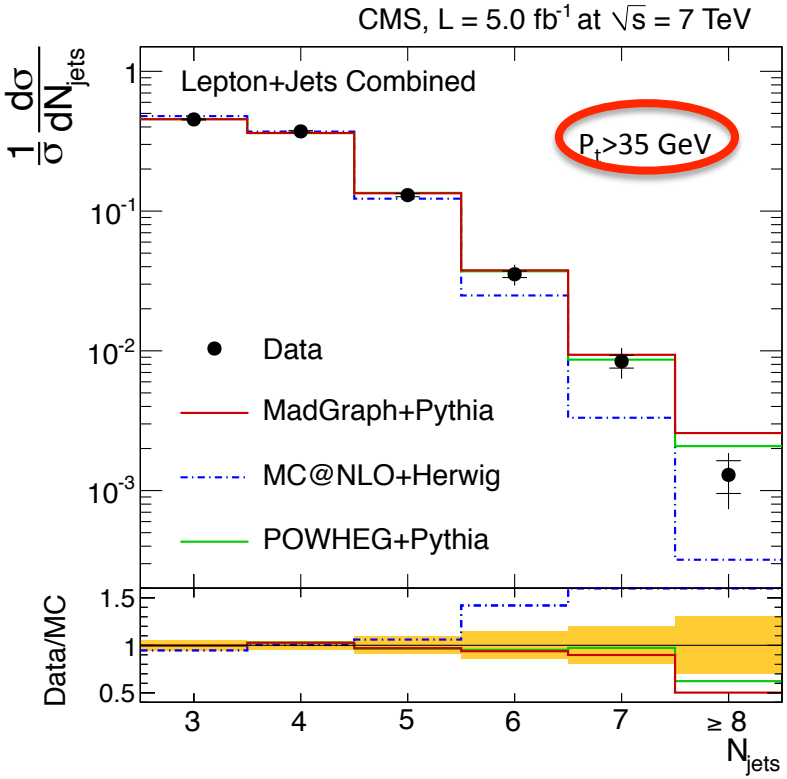


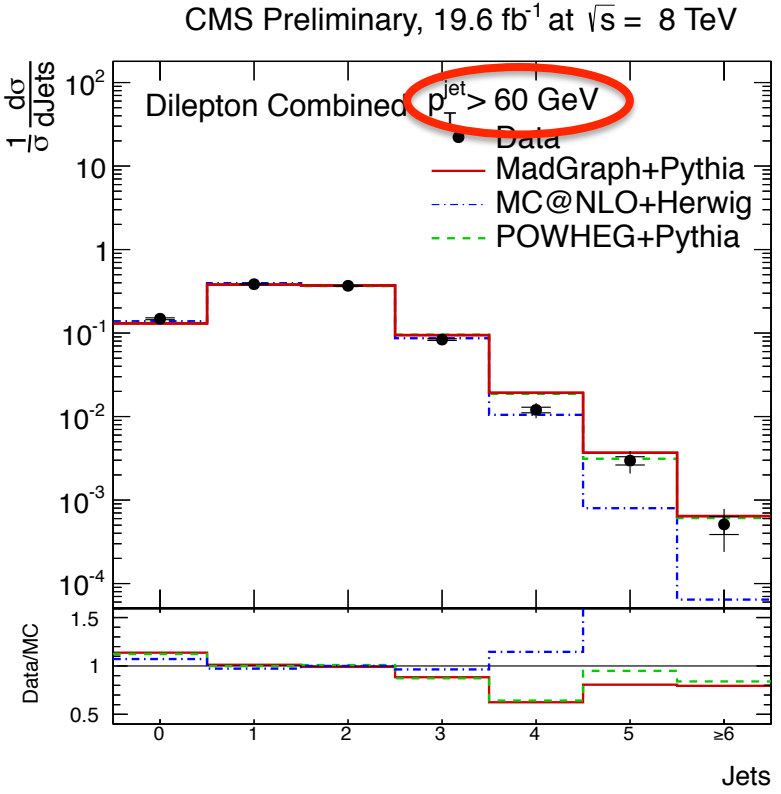
- Uncertainties dominated by JES and MC modeling of QCD radiation
- High multiplicity measurements limited by statistics
- Model differences increase with jet multiplicities and jet p_t threshold
- Data have discriminating power between different MC models
  - -MC@NLO too few jets
  - -POWHEG & ALPGEN with appropriate settings describe data

arXiv:1404.3171 CMS-PAS TOP-12-041

NEW CMS jet multiplicity in single- and di-lepton channel

Normalised cross section at 7 TeV and 8 TeV for p_t thresholds up to 100 GeV



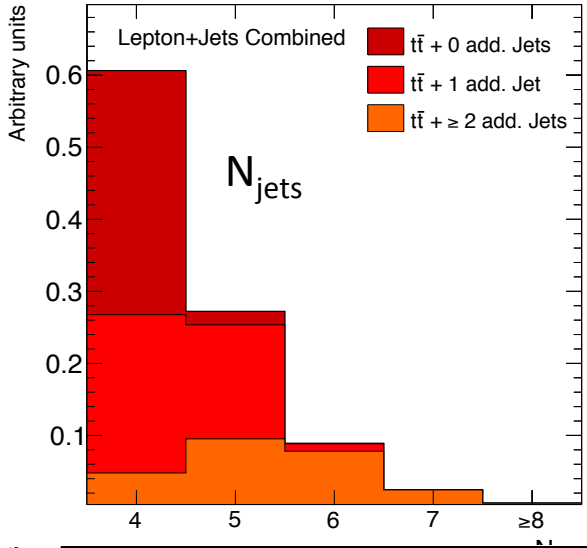


- Consistent results across different top-decay channels, at different energies and between both experiments
- Large uncertainties at high jet multiplicities dominated by JES and MC modeling
- Uncertainties at high jet multiplicities @ 7 TeV of similar size as ATLAS measurement

arXiv:1404.3171

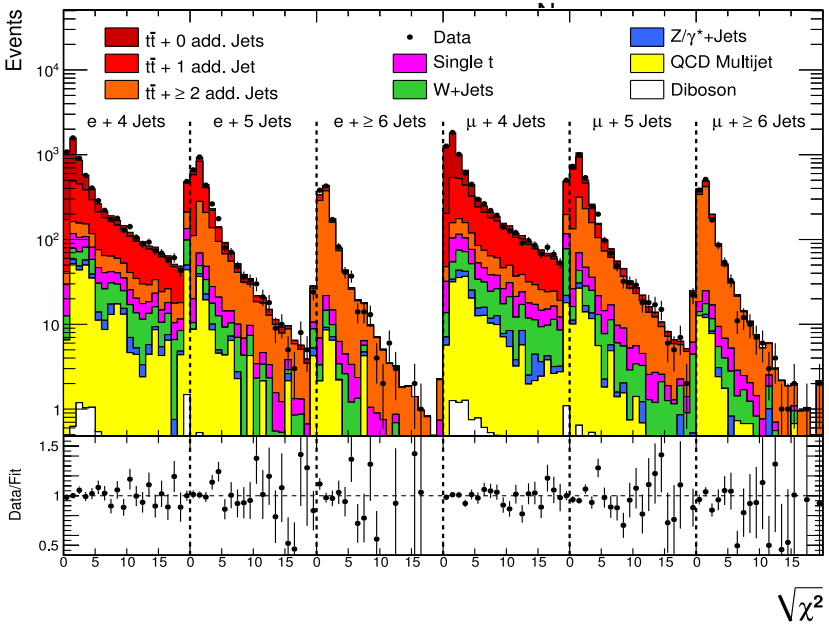
Additional jet multiplicities

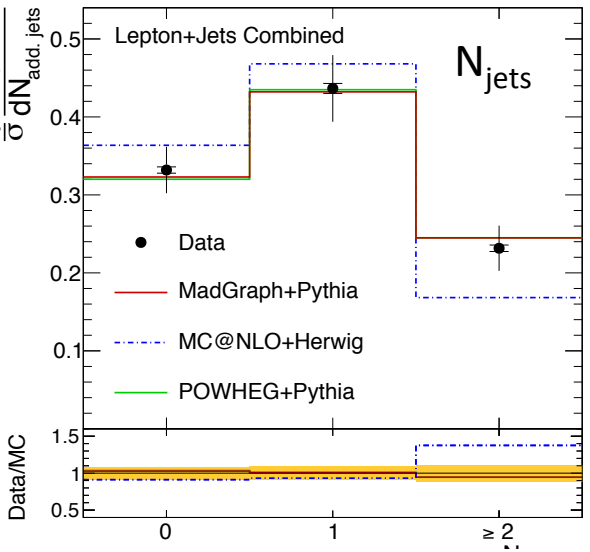
NEW



- Determine jets not from top/anti-top decay through template fit
- Event classification at truth level:
  - dR(jet, top decay product)<0.5
  - Top decay products: 2 b quarks, jets and lepton from W decay
- Additional jet definition in data:
  - Reconstruct tt system by minimising

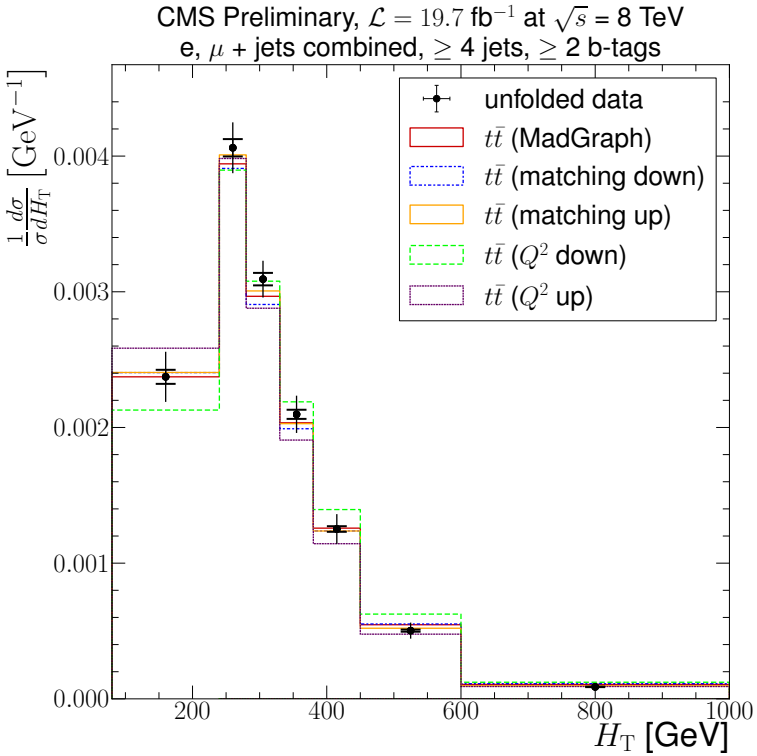
$$\chi^2 = \left(\frac{m_{W^{had}}^{rec} - m_{W^{had}}^{true}}{\sigma_{W^{had}}}\right)^2 + \left(\frac{m_{t^{had}}^{rec} - m_{t^{had}}^{true}}{\sigma_{t^{had}}}\right)^2 + \left(\frac{m_{t^{lep}}^{rec} - m_{t^{lep}}^{true}}{\sigma_{t^{lep}}}\right)^2$$

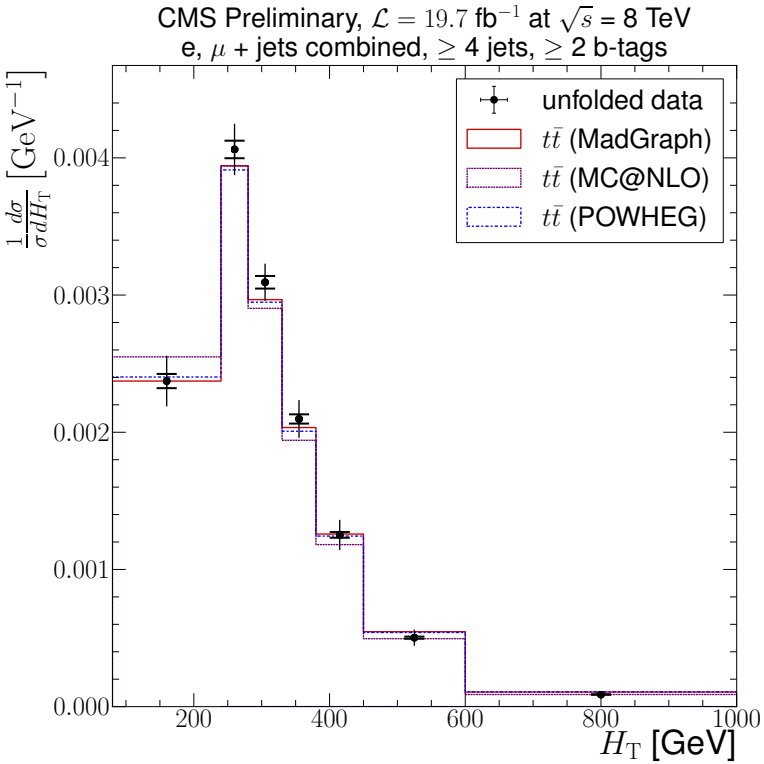




CMS-PAS-TOP-12-042

H_T in ttbar events



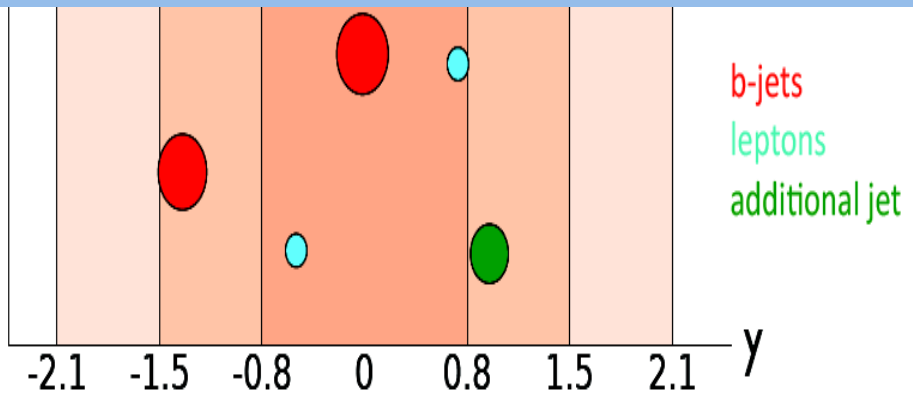


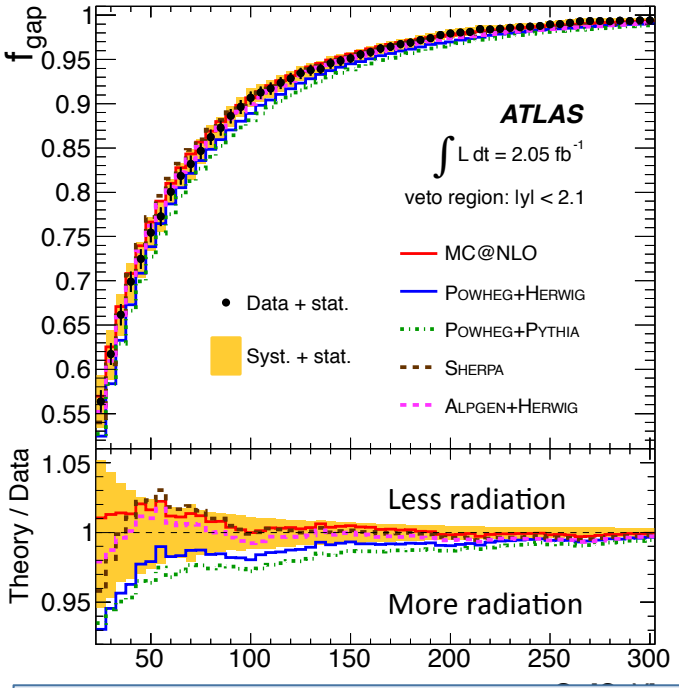
Measurement of normalised cross section as a function of H_T, S_T, Etmiss
Interesting observables particularly for SUSY searches
Preliminary data have too large uncertainties to constrain QCD MC models

Eur.Phys.J. C72 (2012) 2043

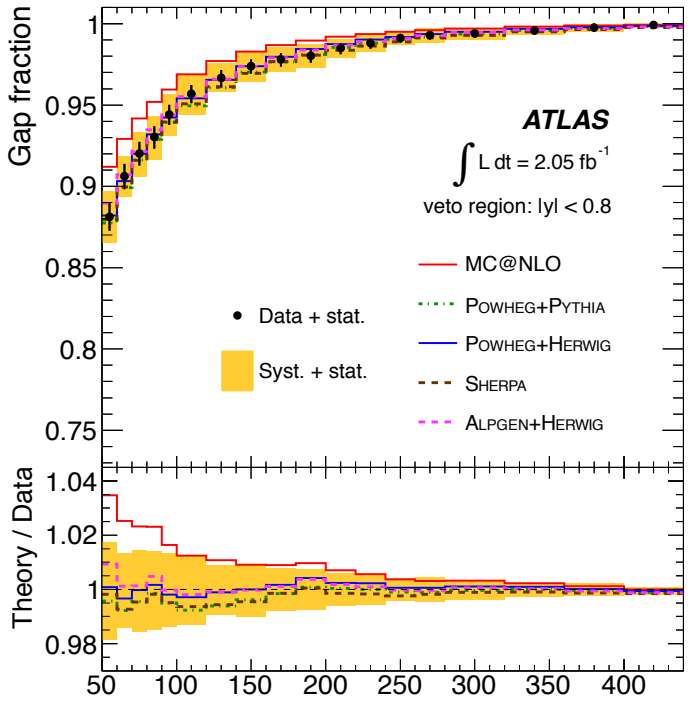
Jet Veto ("gap fraction") analysis

Di-lepton channel





p_t threshold for first additional jet

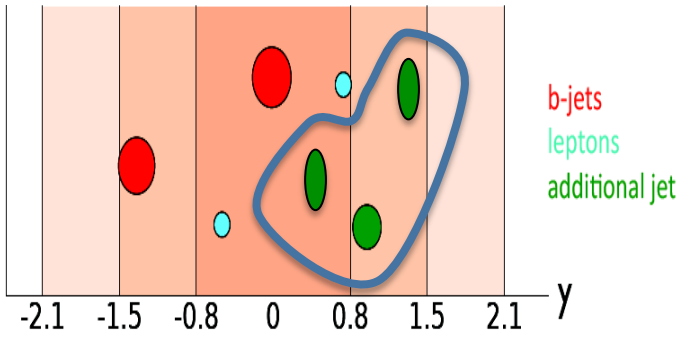


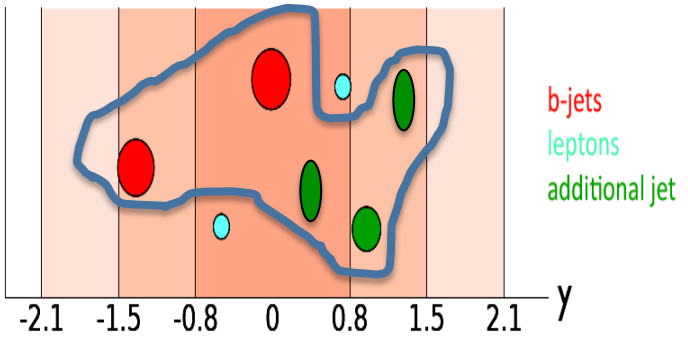
p_t threshold of p_t sum of additional jet

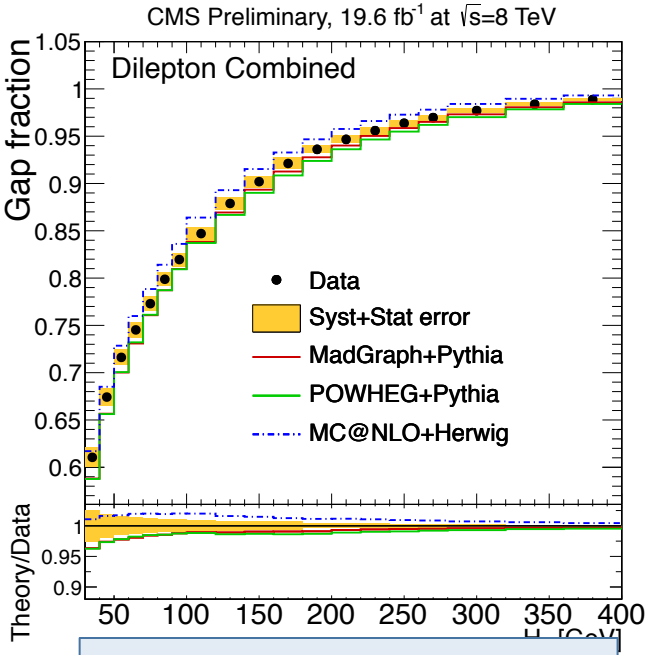
CMS-PAS-TOP-12-041

CMS-PAS-TOP-12-042

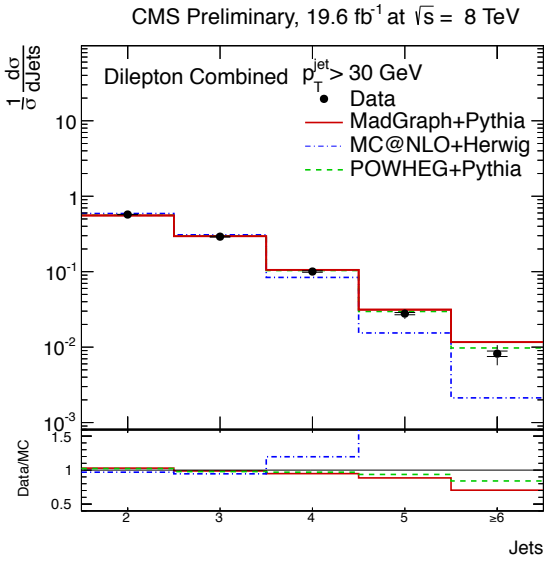
Comparison of $t\bar{t}$+jets observables

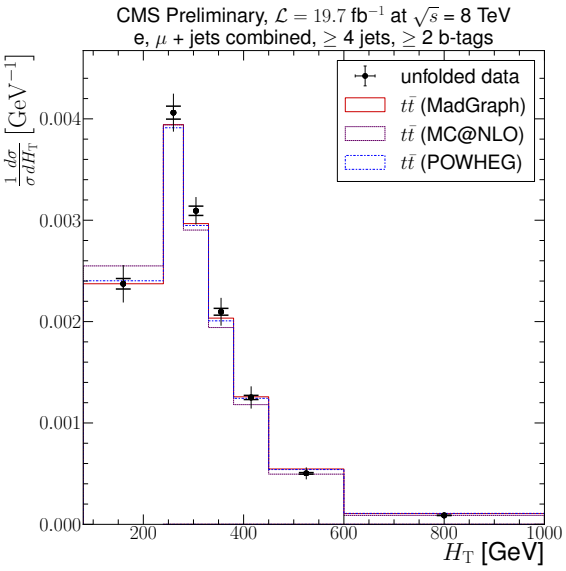






Sum p_t of additional jets





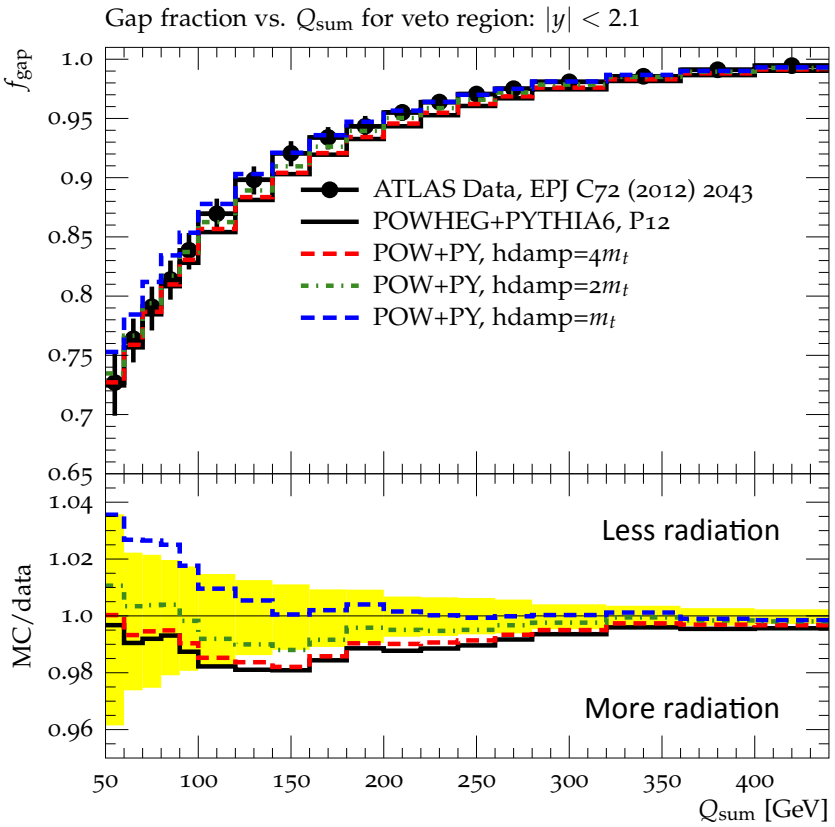
Lots of different observables

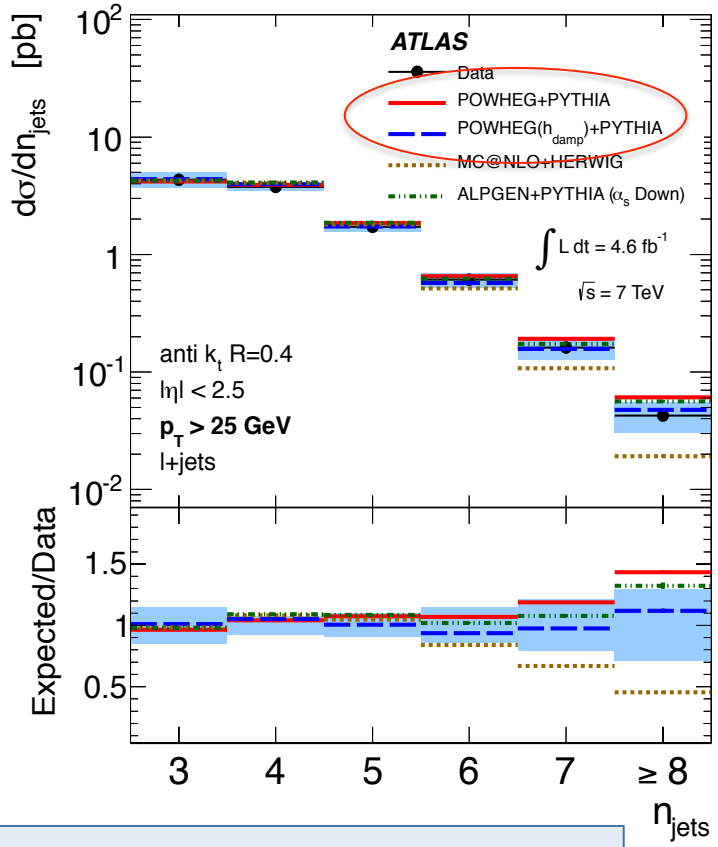
- Different sensitivities?
- Consistent picture of QCD radiation?

ATL-PHYS-PUB-2013-005

Constraint predictions of PowHe

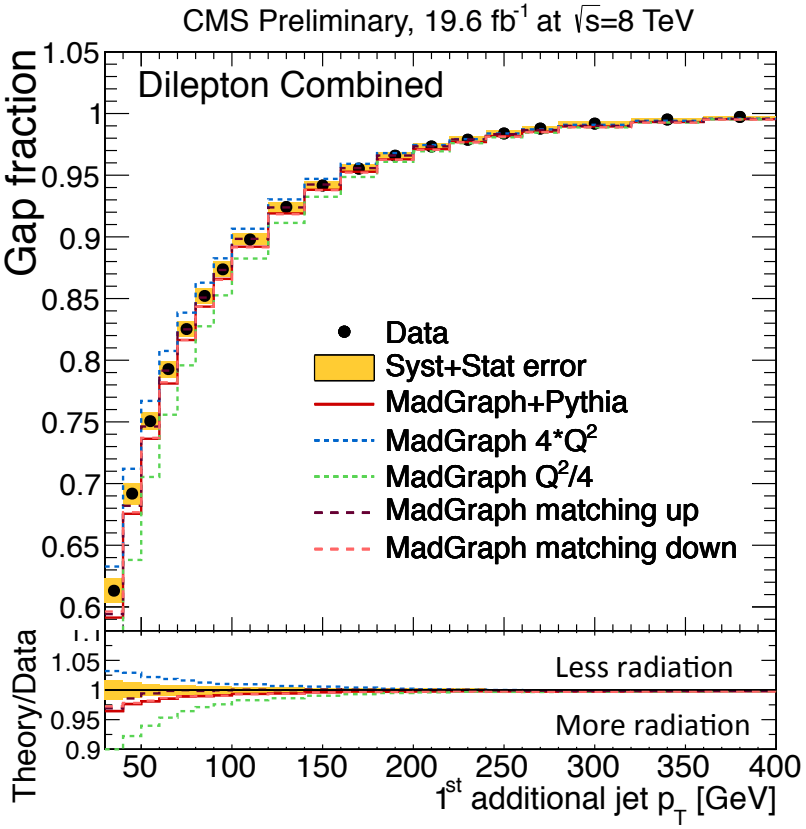
NEW

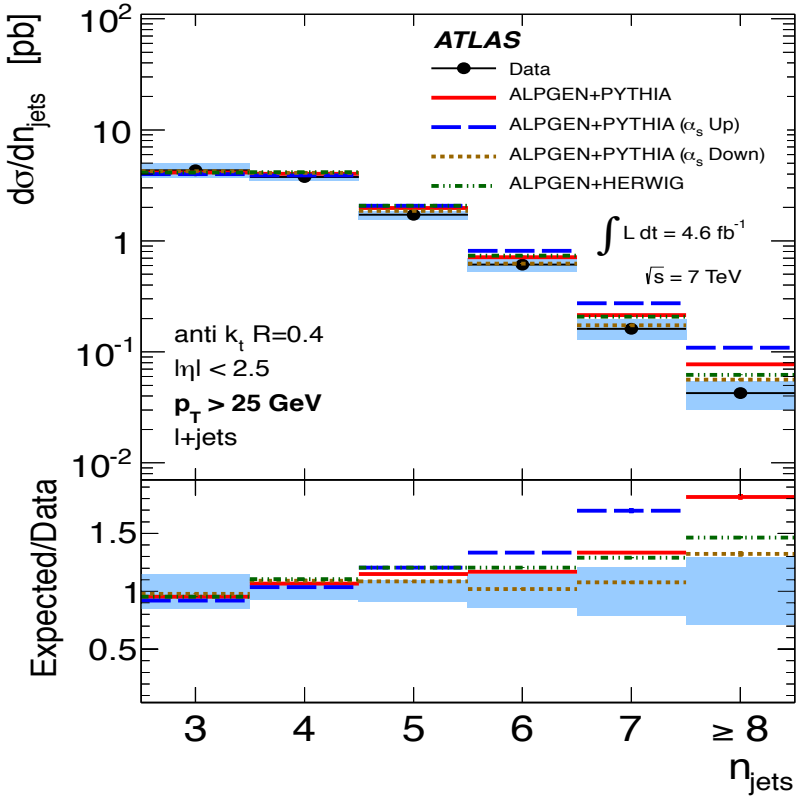




POWHEG: NLO ME for top pair, LO ME for first emission, matched to PS
Free model parameter to regulate hardness of first radiation (hdamp)
Measurements are sensitive to the setting of this free model parameter
Best description of tt data with hdamp ~ m_{top}

Constrain predictions of scale variations





- Vary α_S in ME+PS (ATLAS), only in ME (CMS) by a factor 2 up and down
- Higher α_S and more PS excluded by all data
- Data better described by $4*Q^2$ / α_S Down
- Potential to further reduce scale variations with data @ 8 TeV

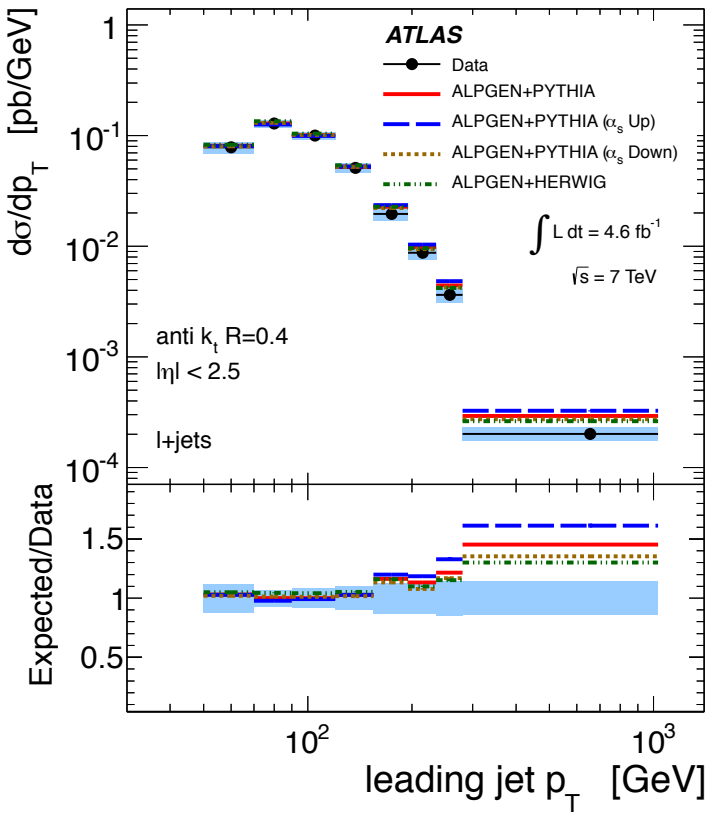
Reminder:
CMS $4*Q^2$ = ATLAS α_S Down; CMS $Q^2/4$ = ATLAS α_S up

arXiv:1407.0891

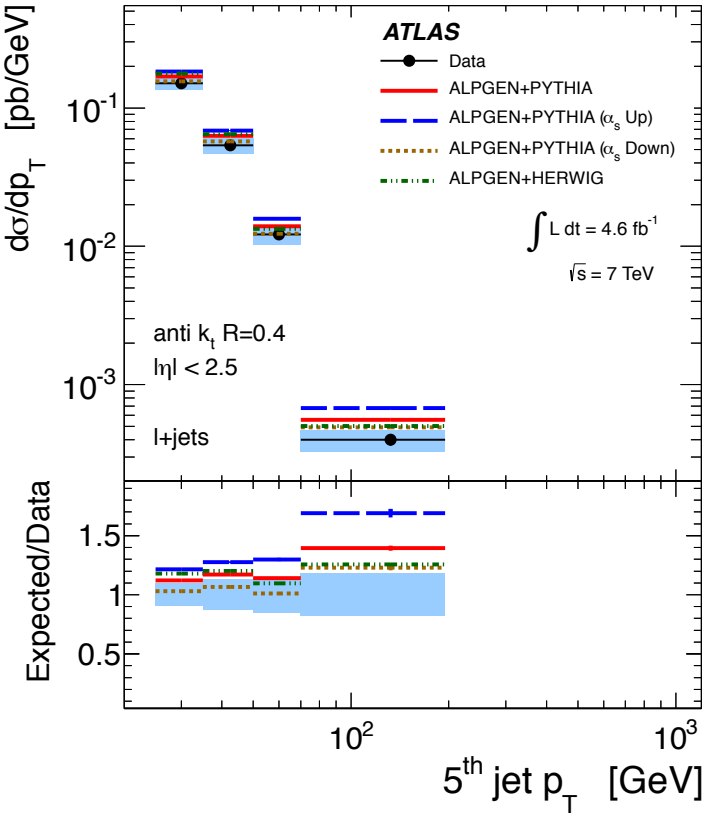
jet p_T in $t\bar{t}$ events

NEW

Ordered jets in p_t and unfold single p_t spectrum
Additional requirement: leading jet p_t > 50 GeV, sub-leading jet p_t>35 GeV



High probability: jet from top decay

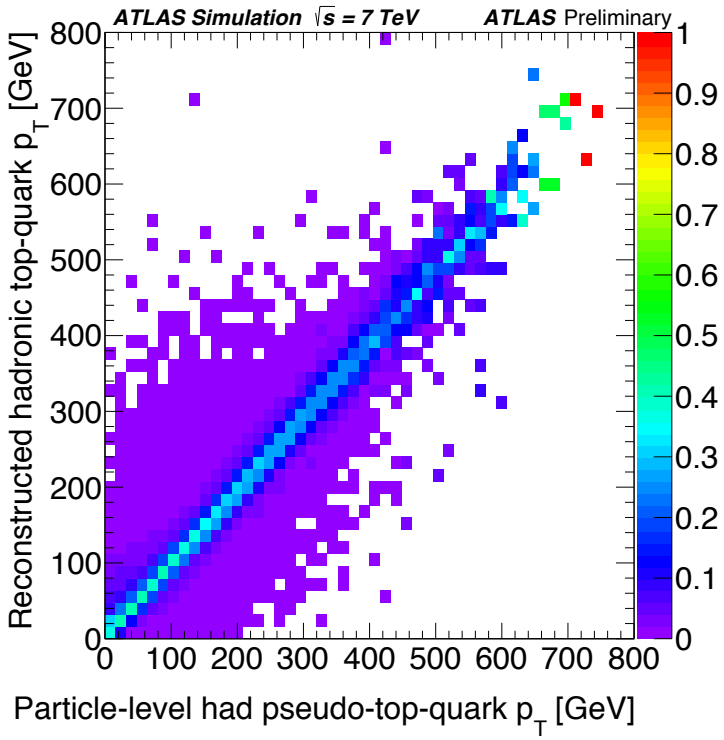


High probability: additional jet

Soft scale preferred by data @ high p_t of leading jet and p_t of 5th jet

Pseudo-top method

NEW



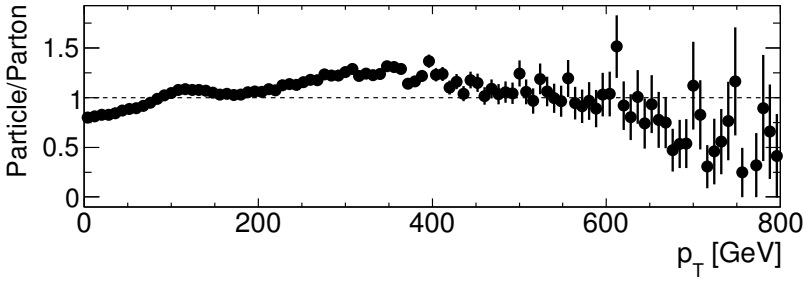
Very good correlation between reco- and particle level

Assumed top decay products:
2 highest p_t b-jets, lepton, 2 highest p_t jets

Leptonic top:
b-jets with lowest $d\phi$(jet,lepton),
lepton, E_{tmiss}

Hadronic top:
b-jet,

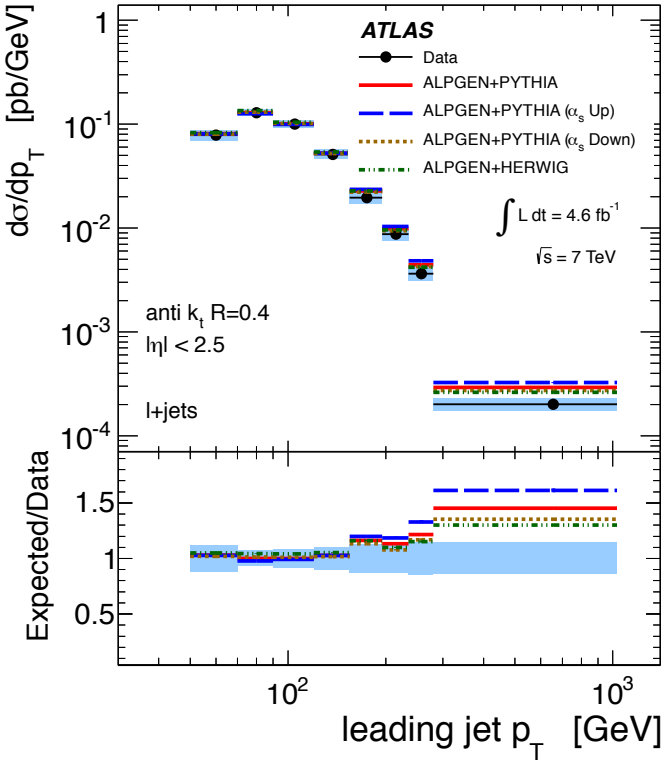
2 highest p_t jets



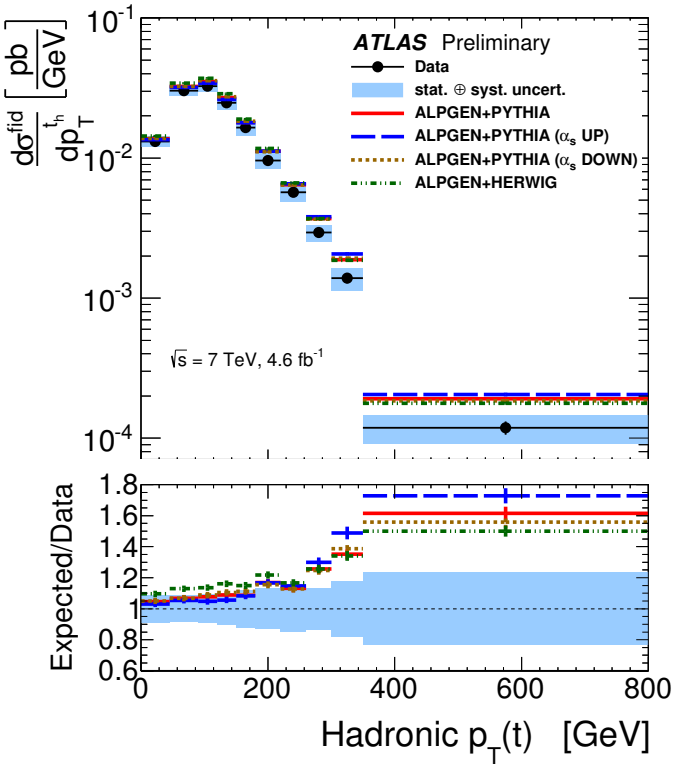
Some shape differences between particle and parton level

Top decay products vs pseudo top

Fiducial phase space:
>=1 b-jet, 1 lepton, >=3 jets,
1st jet p_t>50 GeV, 2nd jet p_t>35 GeV



Fiducial phase space:
2 b-jets, 1 lepton, >=4 jets



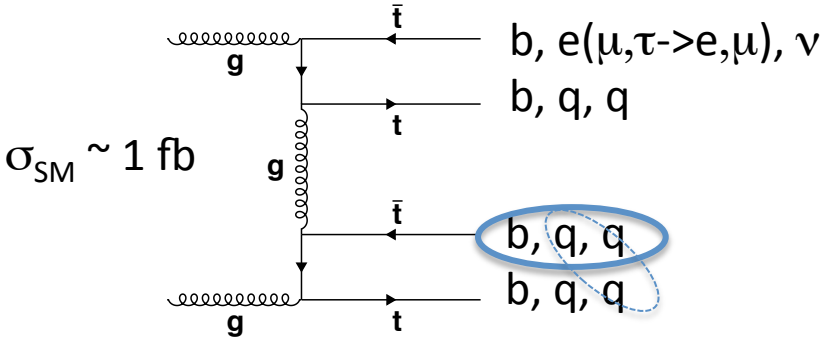
Consistent data – mc description between the observables

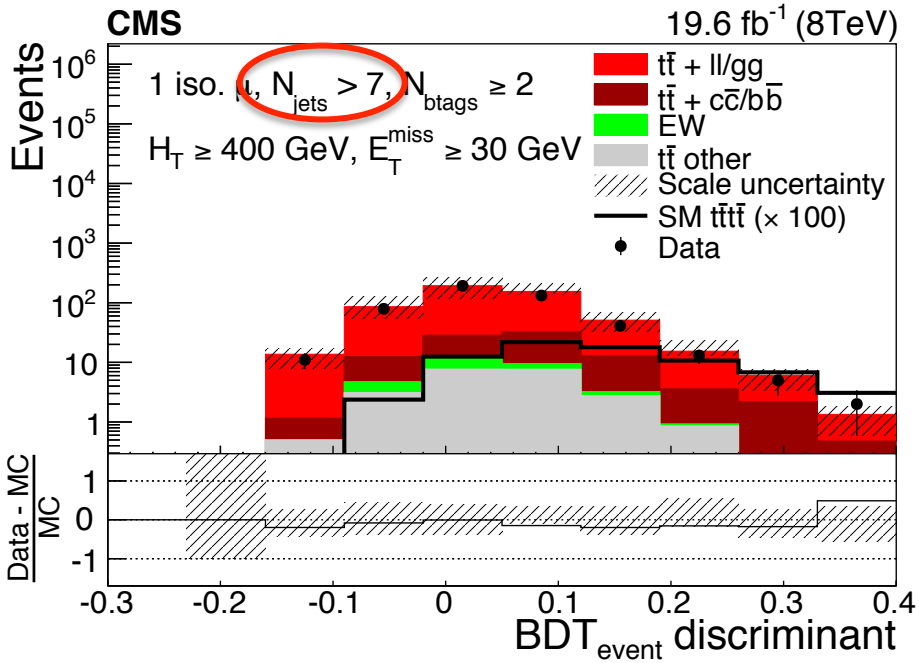
NEW

Search for SM production of $t\bar{t}t\bar{t}$

arXiv:1409.7339

8 TeV data, 19 fb^{-1}
Single-lepton channel, N_{bjets}>=2, $N_{jet(30GeV)}$>=6, E_{tmiss}>30GeV, H_T>400GeV





BDT_{event} with 10 variables:
Top quark multiplicity
Jet activity: Njet, Nbjet, H_T, p_{T5}, p_{T6}

Simultaneous fit to signal + background of BDT_{event} in 6 regions (e,μ, Njet=6, 7, >7)

Limit @ 95%CL : σ_{tttt} < 32 fb
Expected: σ_{tttt} < 32 +/- 17 fb

Summary

- Pioneering work to define observables in a model independent way at all levels of physics analysis (object level, parton proxie)
- Many different observables related to QCD radiation have been measured
  - Published results on 7 TeV show discriminating power for some MC models; first MC optimisations to these observables performed
  - However large uncertainties in the most sensitve regions therefore limited improvements with respect to scale uncertainties
- Preliminary 8 TeV data have significant smaller errors and are very promising to reduce uncertainties on QCD radiation
- Cross section limits for rare SM final state of 32 fb

References

- CDF ttbar+1 jet:

  http://www-cdf.fnal.gov/physics/new/top/2009/xsection/ttj_4.1invfb/

Backup

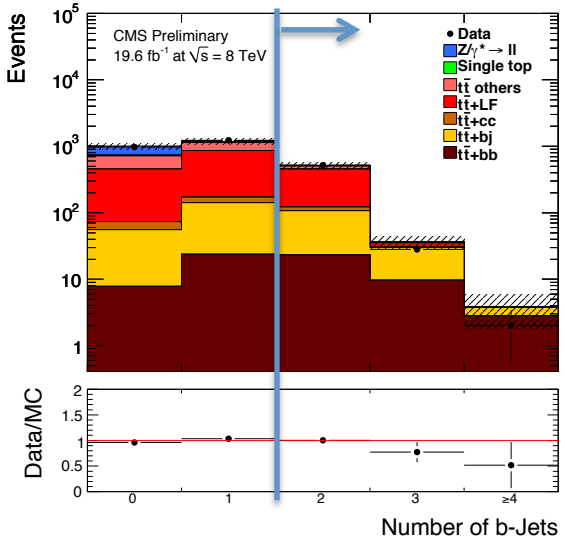
$t\bar{t}$+Heavy Flavour

- Largest and irreducible background to ttH(H->bb)
- Test of QCD predictions with heavy quarks

- Production:
  - Gluon splitting of ISR and FSR into bb, cc pair
  - b(c)-quark in proton PDF could lead to tt+b, tt+c

- Measurement:
  - Challenge: separation of different flavour of additional jets in top pair production
  - Current available publication: ratio of tt+HF/tt+LF to reduce experimental uncertainties

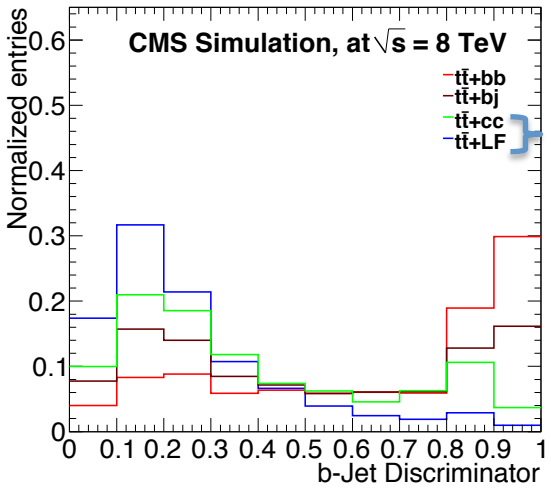
Ratio of tt+HF/tt+LF

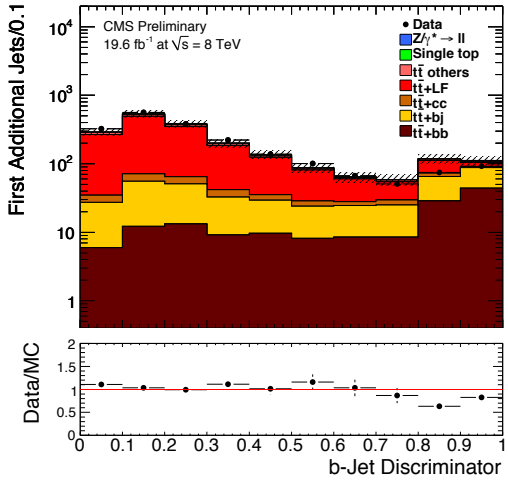


- Analyse di-lepton ttbar events with 2 b-tagged jets, >=2 additional jets
- Event classification at particle level:
  - Tt+bb: 2 tagged b-jets
  - tt+bj: 1 tagged b-jets, 1 jet
  - tt+cc: 2 tagged c-jets
  - tt+LF: 2 untagged jets
- Fit b-jet Discriminator of 1st and 2nd additional jet

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.023 \pm 0.003(\text{stat.}) \pm 0.005(\text{syst.}) \text{ at } p_{\text{T}} > 20\ \text{GeV}/c$$

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.022 \pm 0.004(\text{stat.}) \pm 0.005(\text{syst.}) \text{ at } p_{\text{T}} > 40\ \text{GeV}/c$$

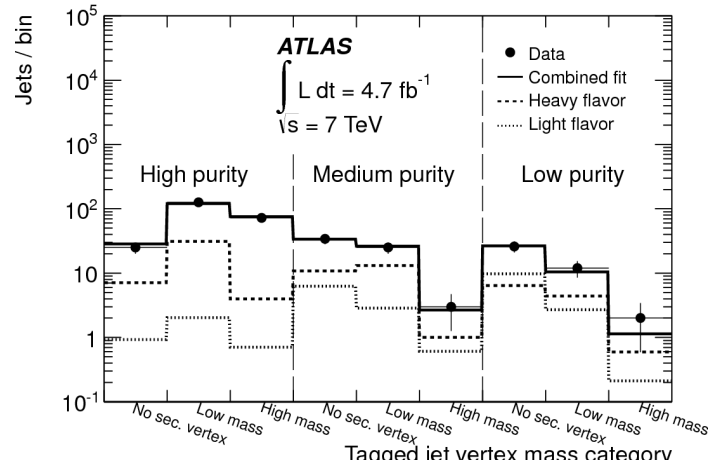


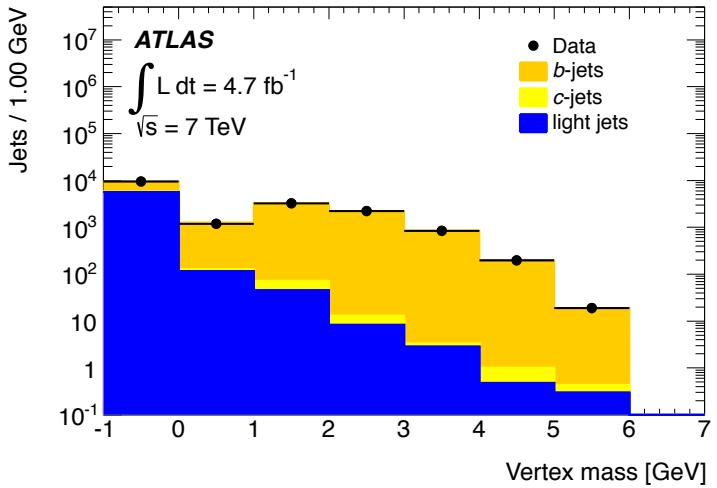


σ_{ttHF} = 58.9 +/- 12.3(stat)+/-15.3(sys)

arXiv:1304.6386

Ttbar+HF/tt+LF





Analyse di-lepton ttbar events with
2 b-tagged jets, >=1 additional jets

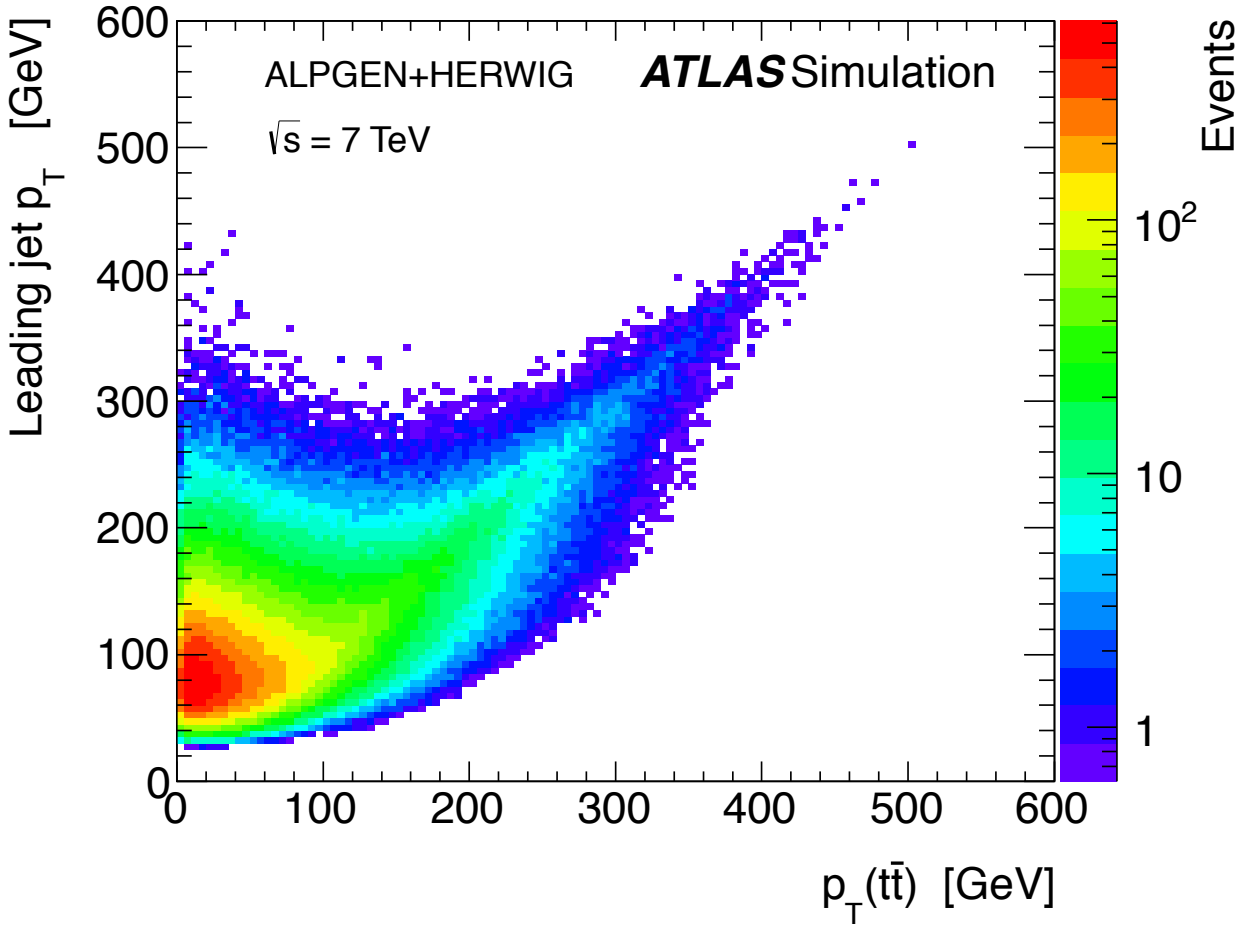
Measurement definition:
Tt+HF = Tt+b, tt+c

$$R_{\mathrm{HF}} = \frac{\sigma_{\mathrm{fid}}(tt + \mathrm{HF})}{\sigma_{\mathrm{fid}}(tt + j)}$$

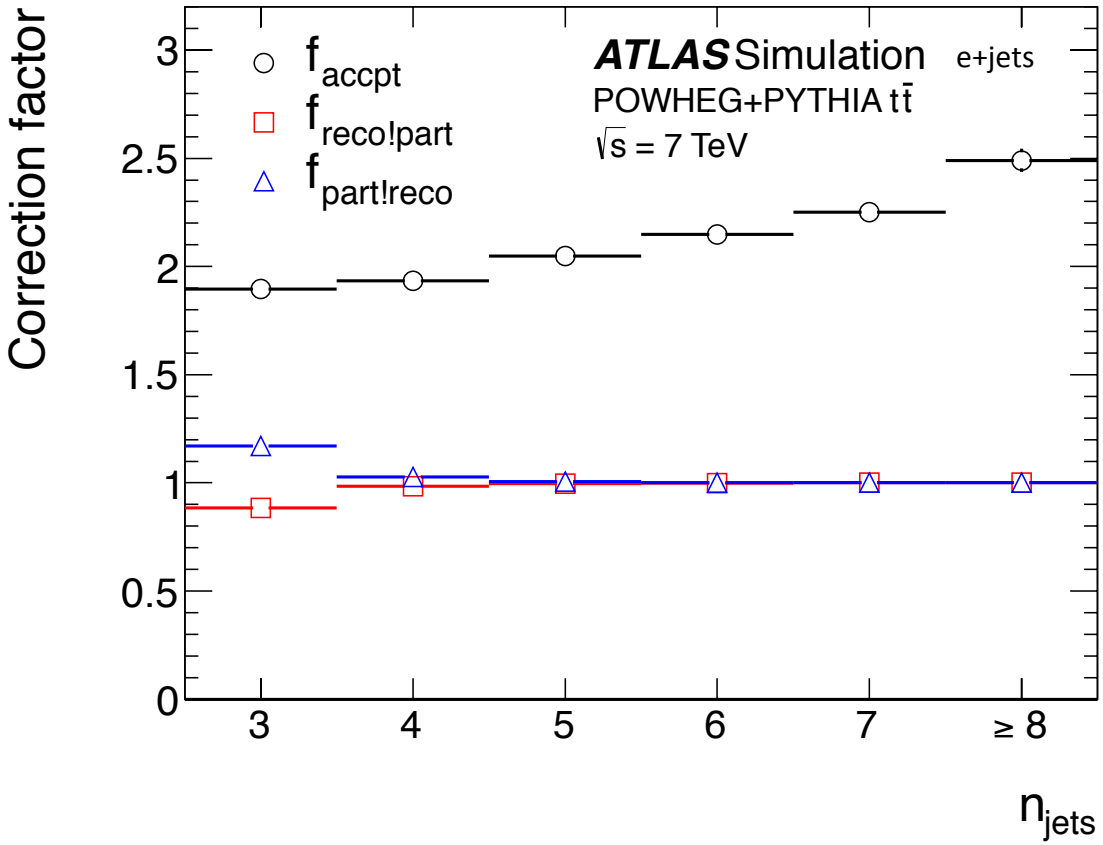
R_{HF} determined from likelihood fit to vertex mass distribution

R_{HF} = [7.1 +/- 1.3 (stat) $^{+5.3}_{-2.0}$ (syst)] %
Alpgen: R_{HF} = 3.4 +/- 1.1(syst)
POWHEG:R_{HF} = 5.2 +/- 1.7(syst)

From particle level to parton level



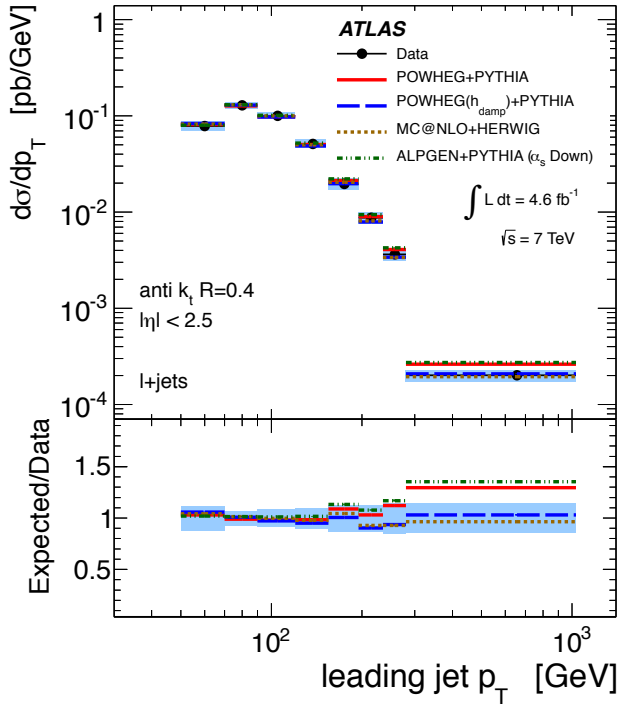
Correction to particle level

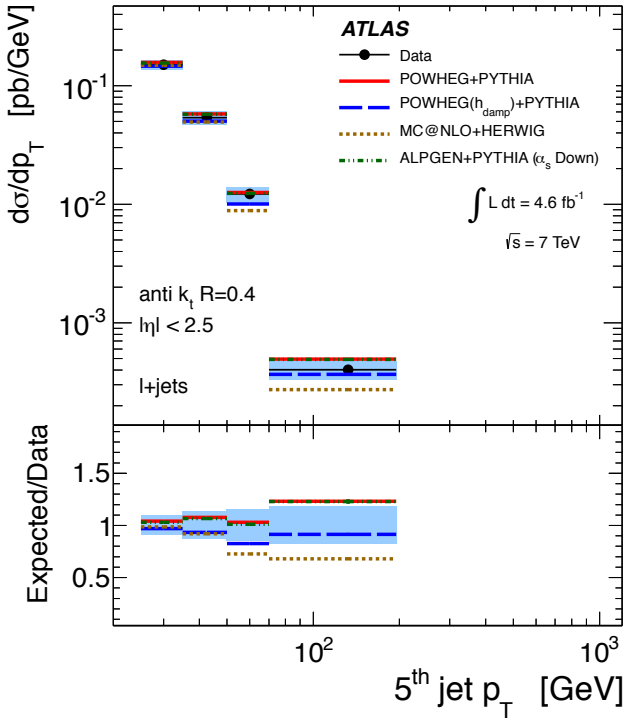


Acceptance (b-tagging!, lepton efl

Resolution effects of particle vs
Reco level jets

jet p_T in ttbar events
MC model comparisons





Ttbar+jets at the Tevatron

CDF conference study 2009, 4.1 fb^{-1} data, data driven background
2 dimensional likelihood fit to jet multiplicity distribution to extract $\sigma(tt+0)$, $\sigma(tt+1jet)$ in full phase space

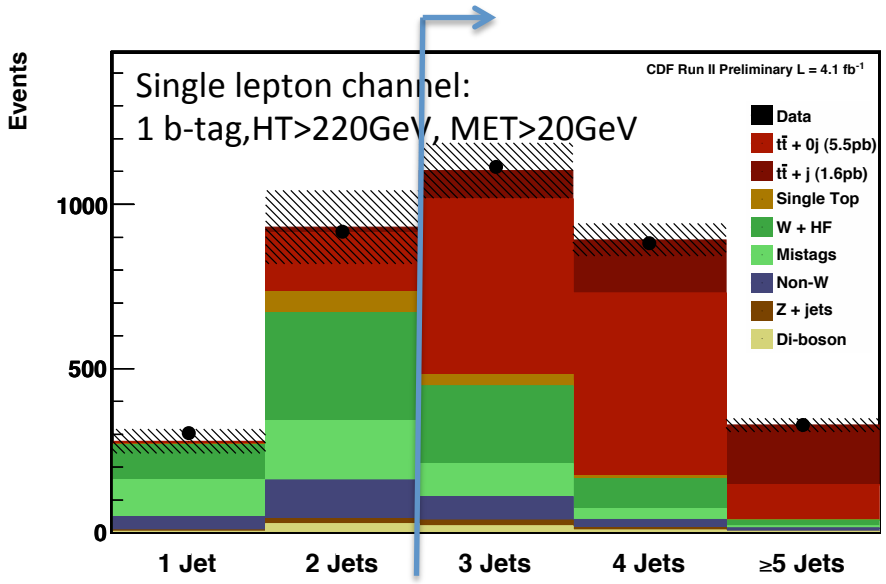
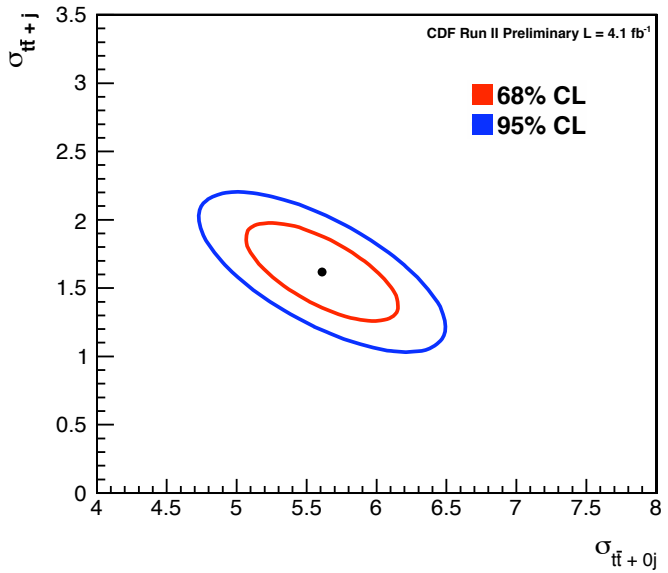


FIG. 1: Predicted vs Observed as a function of jet multiplicity



Signal MC: Pythia, Q2 ordered shower

Ttbar+1 jet =1.6 +/- 0.2 (stat) +/- 0.5 (sys) pb
Ttbar+0 jet = 5.5 +/-0.4 (stat) pb
SM prediction (NLO): 1.79 + 0.16 -0.31 pb

http://www-cdf.fnal.gov/physics/new/top/2009/xsection/ttj_4.1invfb/