Top Quark Physics at ATLAS and CMS

Carmen Diez Pardos
for the ATLAS and CMS collaborations

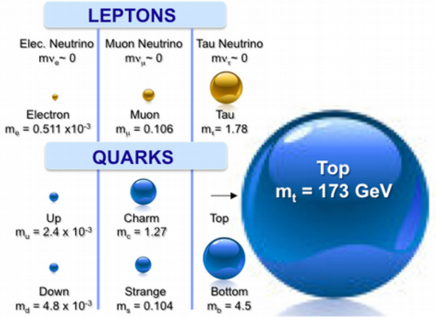
DESY

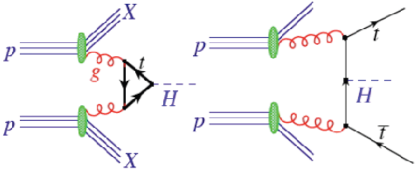
Corfu2017: Workshop on the Standard Model and Beyond,

2-10 Sept 2017, Corfu (Greece)

The top quark: a unique particle

- Most massive elementary particle known to date. Special role in many theories beyond the Standard Model
- Short-lived, decays before hadronizing. Possible to study the properties of a bare quark
- Precision tests of perturbative QCD
- Main background in many BSM searches
- Essential to study Higgs properties, measure top Yukawa coupling

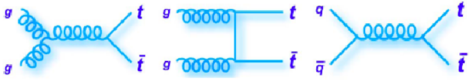




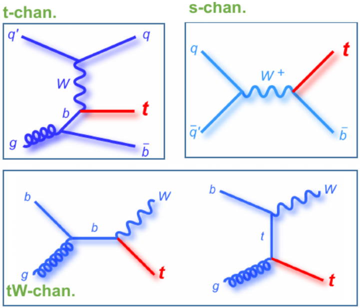
This talk will focus on a small set of recent results (mostly) from Run-2 13 TeV

Top quark production

$t\bar{t}$ production mainly by gluon fusion at LHC (~85% at 13 TeV)



t production via EWK interaction



- Full NNLO+NNLL calculation available [Czakon, Fiedler, Mitov, arXiv:1303.6254]

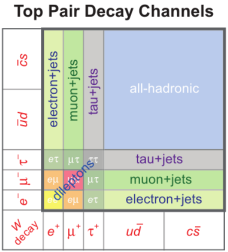
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$	$+16.2(1.7\%)$ $-17.8(1.9\%)$

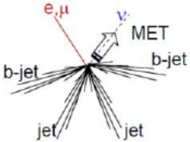
LHCTopWG

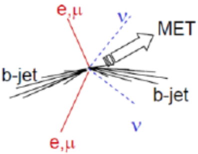
	8TeV	13 TeV	order
t-chan.	84^{+3}_{-3} pb	217^{+9}_{-8} pb ($213.7^{1.6}_{0.8}$pb)	NLO (NNLO)
tW-chan.	22^{+4}_{-4} pb	71^{+4}_{-4} pb	aNNLO
s-chan.	$5.2^{+0.22}_{-0.20}$ pb	10^{+4}_{-4} pb	NLO

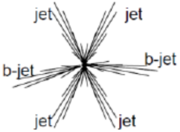
Top quark decay signatures

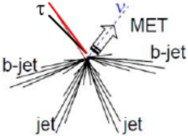
W decay defines final state











Semileptonic [e/μ]: BR$\sim$30% and manageable BG (ie. W+jets)

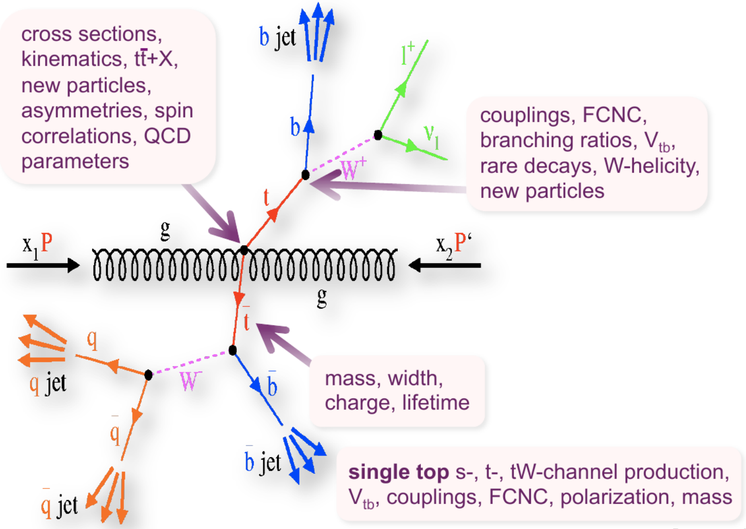
Dileptonic [e/μ]: BR$\sim$5% and small BG (ie. DY+jets)

All-jets: BR$\sim$46% but largest BG (ie. QCD multijet)

τ+jets: BR$\sim$15%

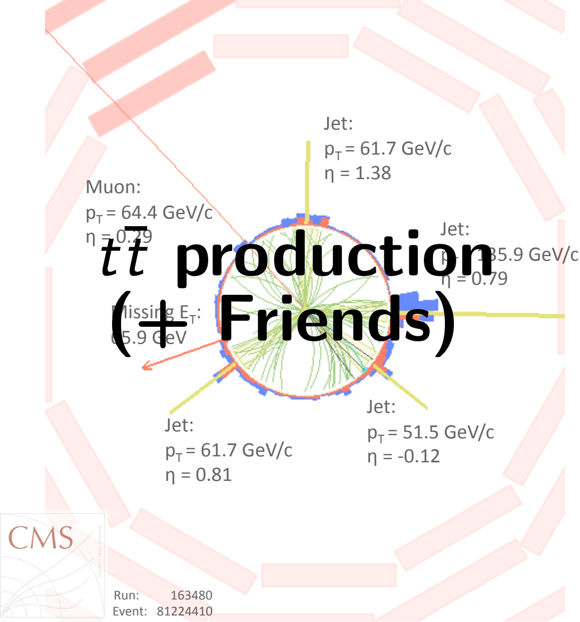
single-top is BG for $t\bar{t}$ (and vice-versa)

The top quark: areas of study



Drawing: M. Aldaya

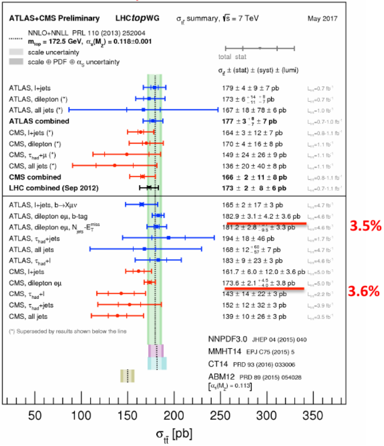
$t\bar{t}$ production (+ Friends)



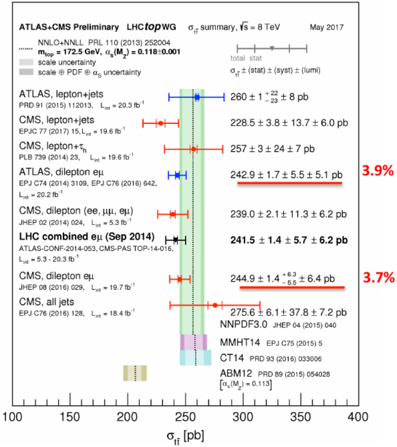
Overview of cross section measurements: 7 and 8 TeV

A fine crop of measurements

$\sqrt{s} = 7\,\text{TeV}$



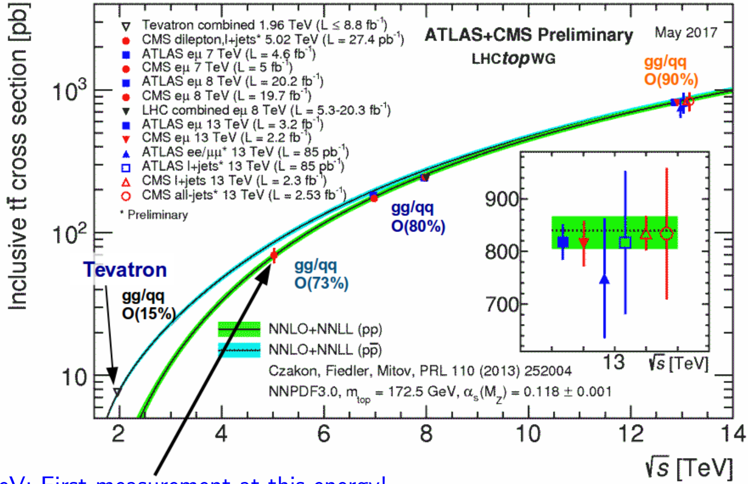
$\sqrt{s} = 8\,\text{TeV}$



- Ultimate precision reached: $e\mu$ channel best sensitivity
- Main systematics are difficult to overcome (eg. luminosity)

$t\bar{t}$ cross section measured at all energies

Dependence as a function of $\sqrt{s}$ well understood!



5.02 TeV: First measurement at this energy!

$\sigma(t\bar{t}) = 69.5 \pm 8.4$ pb (limited by statistical uncertainty) [CMS-TOP-16-023]

Differential regime

Scrutinize $t\bar{t}$ production as a function of many kinematic observables: further understanding of QCD, enhance sensitivity to new physics

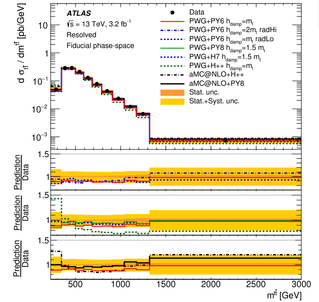
- Comparisons with state-of-the-art predictions (MC generators; high order predictions; different matching schemes, scales and tunes)
- Extraction of mass, α_S, contrain PDF

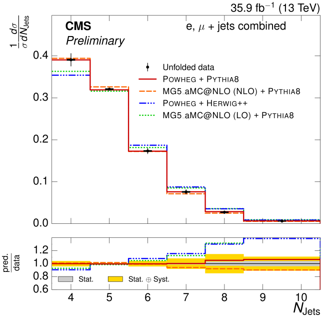
Strategy:

- Use final-state products to reconstruct top quark candidates
- Correct for detector, parton shower, acceptance effects (unfolding)

Plethora of results: Absolute or normalised cross sections, full or fiducial phase space, parton or particle level, resolved and boosted regime

arXiv:1708.00727, CMS-PAS-TOP-16-014

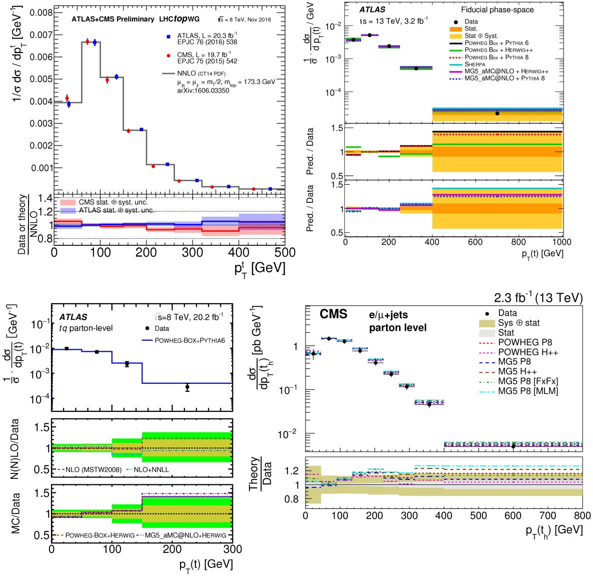




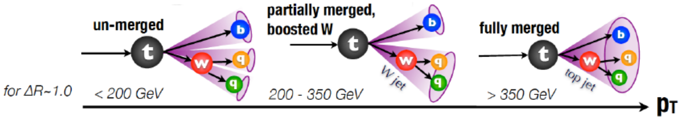
Top quark p_T distribution

- p_T^t spectrum is softer in data than in (most) MC simulations: visible everywhere!
- Better described by beyond NLO QCD: NNLO QCD + NLO EWK (arXiv:1705.04105)

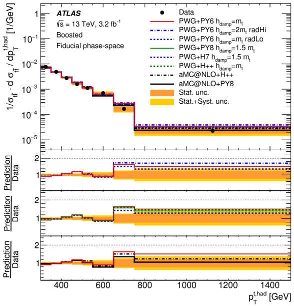
Eur. Phys. J. C 77 (2017) 531, Eur. Phys. J. C77 (2017) 299, PRD 95 (2017) 092001

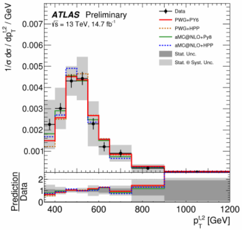


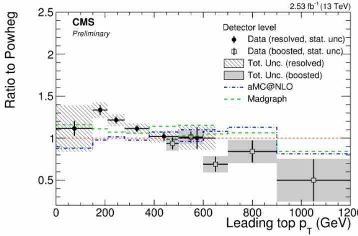
Boosted regime (13 TeV)



- 10× boosted signatures at 13 than at 8 TeV ($m_{t\bar{t}} > 1$ TeV)
- High p_T top quarks appear in many new physics scenarios





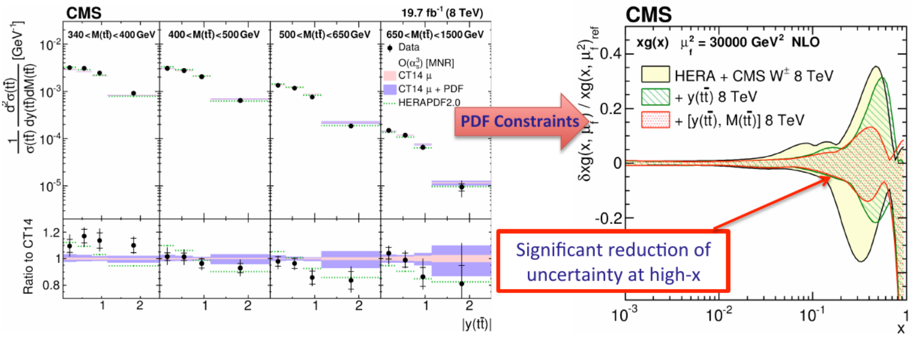


l+jets: arXiv:1708.00727, all jets: ATLAS-CONF-2016-100, CMS-TOP-16-013

p_T^t spectrum is measured beyond the TeV scale

Zooming in: double differential $t\bar{t}$ cross sections EPJC 77 (2017) 459

- First measurement of its kind at the LHC!
- Bin $t\bar{t}$ events in two variables of p_T^t, y^t, $m_{t\bar{t}}$, $y_{t\bar{t}}$
- Explore sensitivity to fundamental parameters using correlations of $m_{t\bar{t}}$, $y_{t\bar{t}}$



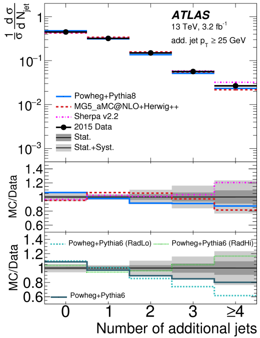
- Main uncertainties: modelling
- Run-II: improve precision, extend phase space, go 3D differential, constrain m_t, α_S, PDF

$t\bar{t}$+jets

- Measurement of additional jet activity important for tuning MC generator parameters:

  Parton shower and hadronization

- Discriminating power between models and tuning parameters already at hand



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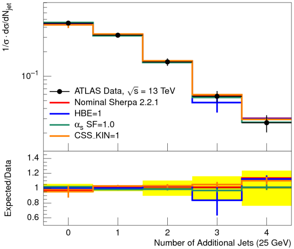
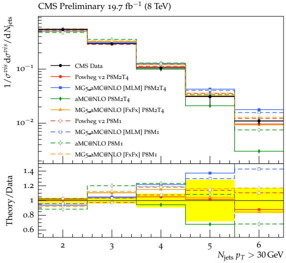


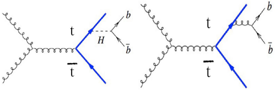


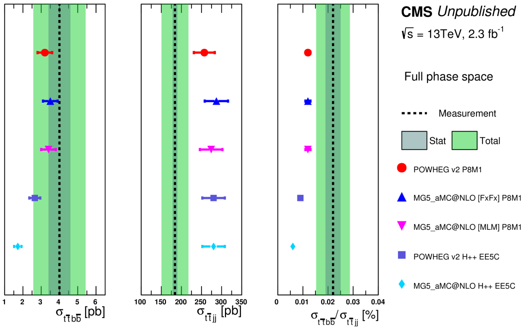
ATL-PHYS-PUB-2017-007

CMS-PAS-TOP-16-021

$t\bar{t}b\bar{b}$: Studying heavy flavour content in $t\bar{t}$ events arXiv:1705.10141

- Test NLO QCD calculations
- Irreducible BG for $t\bar{t}$+H($b\bar{b}$)
- Measure ratio $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$: large cancellation of uncertainties
  - Selection: dilepton events with ≥4 jets, ≥2 b–tagged jets
  - Signal extraction by fit to the measured b-tagging algorithm discriminators
  - Main uncertainties: JES & JER, mistag efficiency, modelling

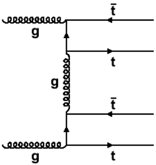




R=0.022±0.003(stat.)±0.006(sys.)

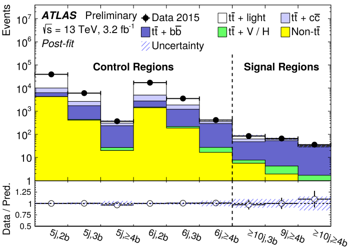
Search for SM four top quark production at 13 TeV

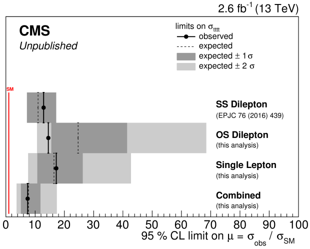
Phys. Lett. B 772 (2017) 336, ATLAS: CONF-2016-020, CONF-2016-032



- Tiny cross section in SM: $\sigma^{SM}_{t\bar{t}t\bar{t}} \sim 9$ fb@13 TeV
- Many BSM models predict an increase: Particles decaying to top quarks or modified couplings, massive coloured bosons, composite Higgs/top, extra dimensions, SUSY...
- Event categorization in Njets, Nbjets and/or template fits to BDT classifier

  Getting close! CMS: SS with 35.9 fb^{-1} obs. (exp.) limit 4.6 ($2.9^{+1.4}_{-0.9}$) $\times\sigma^{SM}_{t\bar{t}t\bar{t}}$ (acc. EPJC, arXiv:1704.07323)



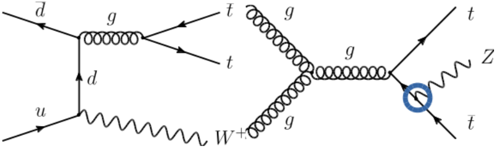


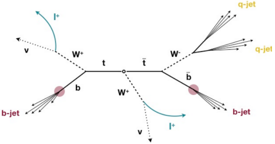
~100 fb^{-1} should suffice to reach the SM cross section!

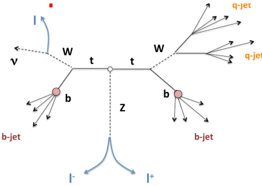
$t\bar{t}$+W/Z

- Measure couplings to bosons
- Important background for BSM searches

- Analyses are performed in bins of the number of selected leptons (2,3,4)
- Different number of leptons → different admixture of $t\bar{t}W$ and $t\bar{t}Z$ processes
  - Same-sign dilepton analysis: $t\bar{t}W$
  - Trilepton and four-lepton analysis: $t\bar{t}Z$ process

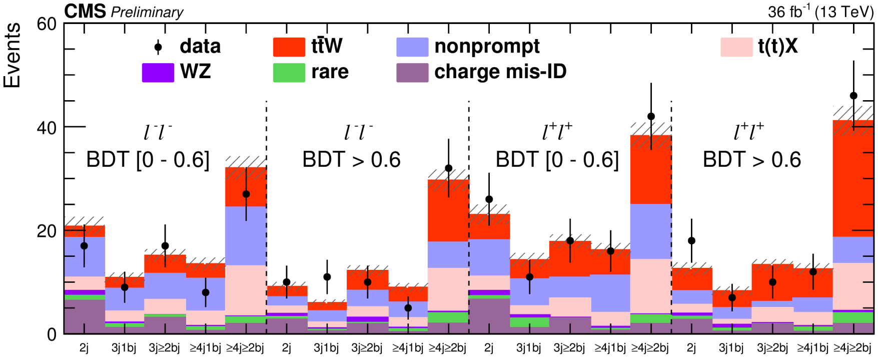




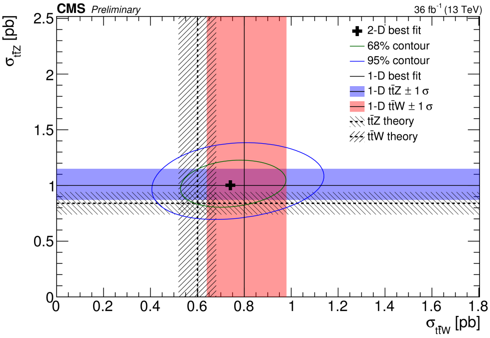


$t\bar{t}$+W/Z at 13 TeV [CMS PAS-TOP-17-005, EPJC 77 (2017) 40]

- Fit for $t\bar{t}Z$ and $t\bar{t}W$ simultaneously in a binned likelihood fit
- Further split into categories depending on jet multiplicity, number of b-tagged jets, optimised individually to increase sensitivity



$t\bar{t}$+W/Z Results

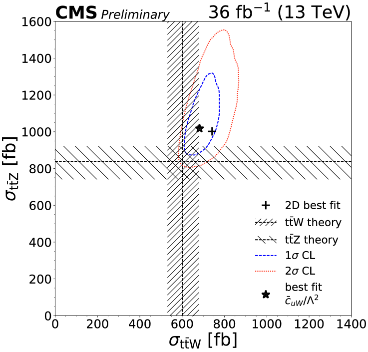


- $\sigma(t\bar{t}W) = 0.80^{+0.12}_{-0.11}(\text{stat})^{+0.13}_{-0.12}(\text{syst})$ pb (ATLAS: $\sigma(t\bar{t}W) = 0.90 \pm 0.3$ pb with 3.2 fb^{-1} at 13 TeV)
- $\sigma(t\bar{t}Z) = 1.00^{+0.09}_{-0.08}(\text{stat})^{+0.12}_{-0.10}(\text{syst})$ pb (ATLAS: $\sigma(t\bar{t}Z) = 1.5 \pm 0.8$ pb)

$>$ 5σ for both processes simultaneously at 13 TeV

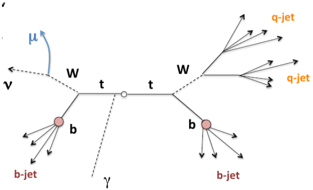
- Interpreted in the framework of Effective field theories (EFT):

  Constraints on dimension-6 operators



$t\bar{t} + \gamma$: l+jets, 8 TeV [arXiv:1706.03046]

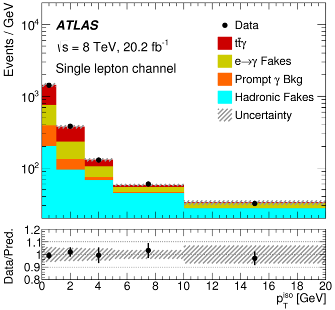
Sensitive to $t\gamma$ coupling and models with composite top quarks and excited top quark production ($t^{\star} \to t\gamma$)



- Selection: l+jets + high E_T photon
- Prompt photons estimated from template fit to photon isolation variable
- Largest systematic uncertainty: hadron, electron fakes, jet energy scale
- Fiducial cross section: $\sigma_{t\bar{t}+\gamma} \cdot BR = 139 \pm 7(\text{stat}) \pm 17(\text{syst}) \pm 1(\text{lumi})$ fb

  Consistent with SM expectation at NLO ($\sigma_{t\bar{t}+\gamma} = 151 \pm 24$fb).

→ Also measured differential cross sections!

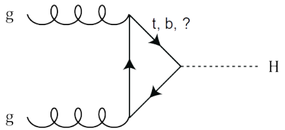


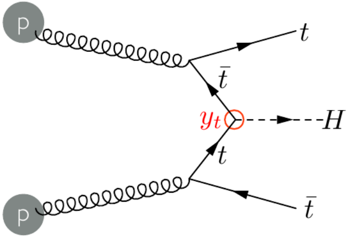
★ CMS measurement [arXiv:1706.08128]
$\sigma_{t\bar{t}+\gamma} \cdot BR = 127 \pm 27$ (stat+syst) fb

Top-Higgs coupling: the hunt for $\mathrm{t\bar{t}H}$

Best direct probe of the top-Higgs Yukawa coupling, vital step towards verifying the SM nature of the Higgs boson

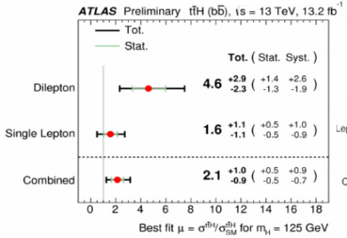
- Top quark is the most strongly-coupled SM particle ($y_t \sim 1$)
- Direct measurement of y_t in $\mathrm{t\bar{t}H}$ production:
  - Allows probing new physics in gg→H and H→ $\gamma\gamma$ effective vertices

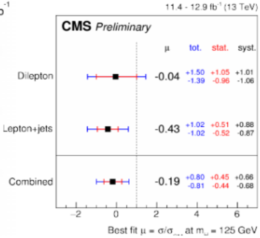


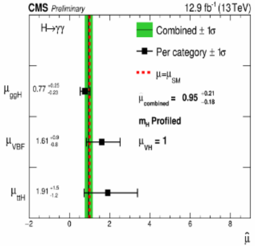


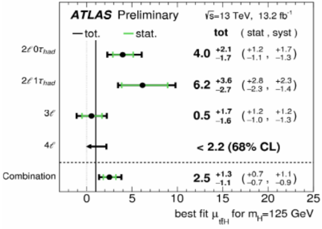
- Limited by statistics in Run-1
- One of the physics targets for Run-2: $\sim 4\times$ cross section, understanding of $\mathrm{t\bar{t}}$+X is crucial

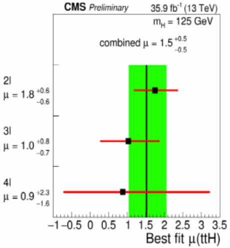
$t\bar{t}H$: The hunt is on!

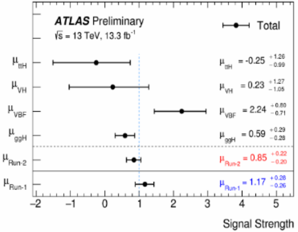






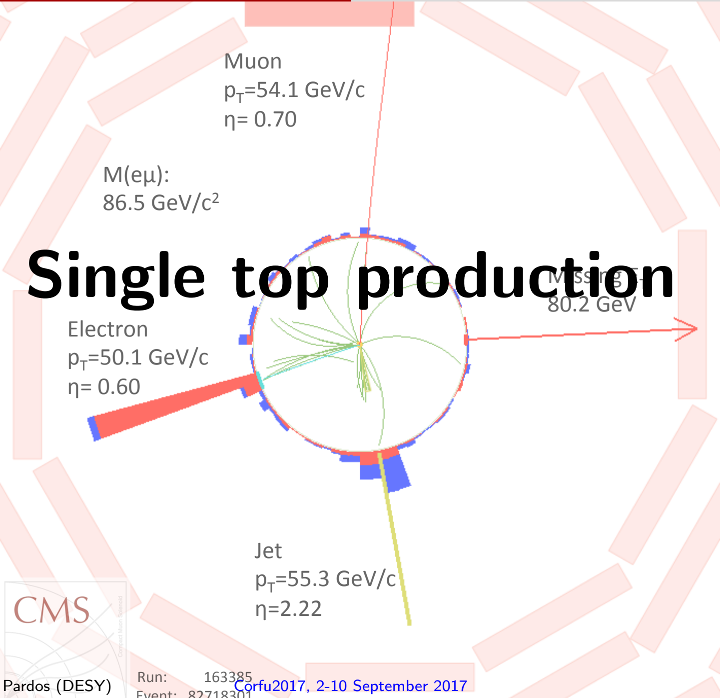






$t\bar{t}H$ multilepton: at the moment most sensitive decay channel, with 35.9 fb^{-1} CMS has evidence of $t\bar{t}H$ production with a significance of 3.3 σ (2.5 exp.)

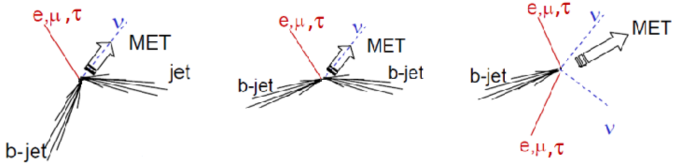
Single top production



Single Top production via EWK interaction

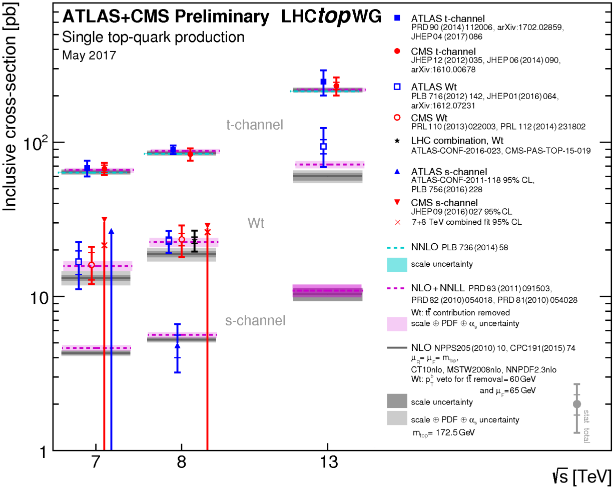
- Direct probe of Wtb coupling and of Vtb in CKM matrix.
- Sensitivity to b-quark PDF
- Constrain u/d PDF models (ratio of top/anti-top cross-sections)
- Important background for Higgs searches in associated production W/ZH$\rightarrow$qqbb
- Probe for new physics: 4th gen., FCNC, contributions from additional bosons

Challenging, due to large BGs: top-pair production (both semileptonic and dileptonic), W(lν)+jets, multijet QCD



Single Top production via EWK interaction

- Main production mode: t-channel, measured to high precision: Properties, differential distributions
- First observation of tW process
- Study of s-channel
- Rare single top modes explored (tZq, tγ)

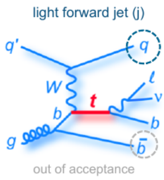


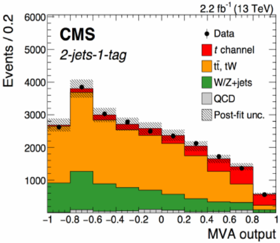
Run-II: ramping up towards new era of high-precision in single top

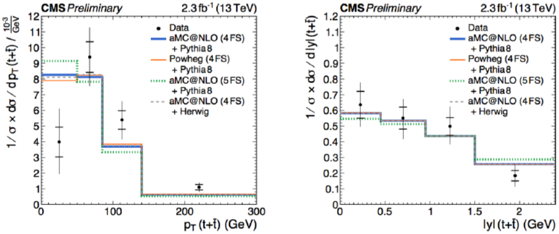
t-channel inclusive and differential (13 TeV)

- Selection: 1 isolated high-p_T muon, 1 central b-tagged jet, 1 forward light jet
- Neural network to enhance S/B

  $\sigma^{ATLAS} = 247 \pm 46$ pb
  (arXiv:1609.03920)
  $\sigma^{CMS} = 232 \pm 31$ pb
  (arXiv:1610.00678, acc. PLB)

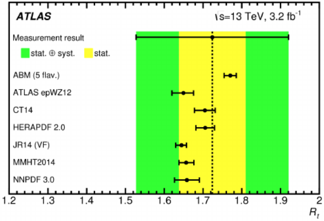






CMS-TOP-16-004

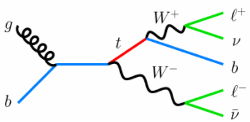
Normalised cross section well described by MC, dominated by total syst. uncertainty

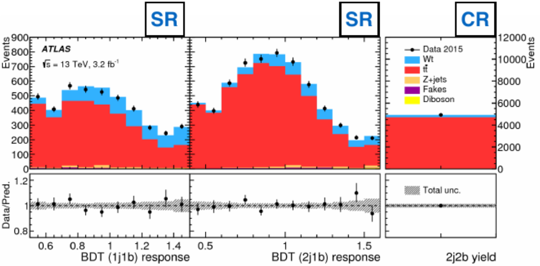


tW-channel (13 TeV)

[arXiv:1612.07231]

- 2 opposite sign isolated leptons, MET (2 neutrinos), 1 jet (coming from b quark)
- Signal extraction procedure: fit to BDT discriminant in the 2 signal regions (1j1t,2j2t) and to the yields in the control region, $t\bar{t}$ background dominated
- Main syst.: jet energy scale, NLO matrix element, jet energy resolution





σ_{tW}=94±10(stat)$^{+28}_{-22}$(syst)±2(lumi) pb

Significance 4.5 σ (expected: 3.9 σ)

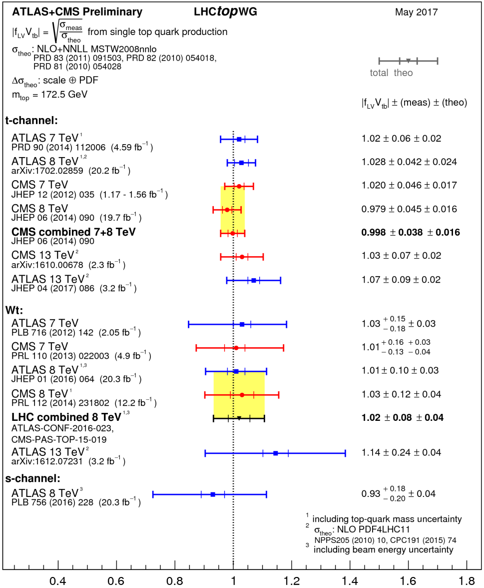
Single top and $|Vtb|$

- $\sigma_{meas.}/\sigma_{theo.} = |f_{LV} Vtb|^2$

  Assumptions:

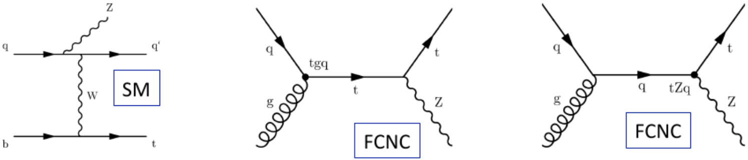
- Wtb SM-like, left-handed, weak coupling
- $|Vtb| >> |Vts| >> |Vtd|$

Agreement in all 3 processes with SM



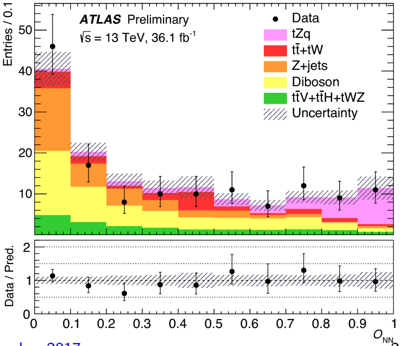
Evidence for tZq

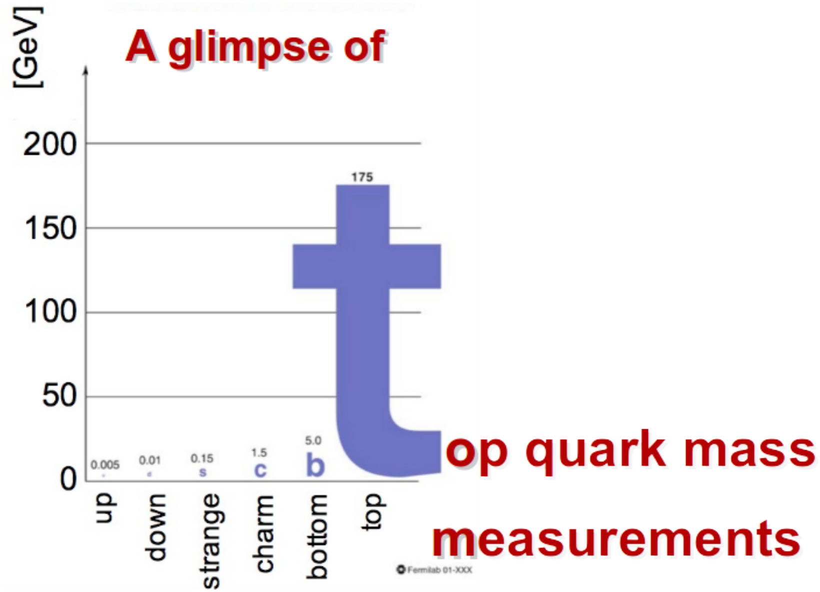
[13 TeV: ATLAS-CONF-2017-052]



- Sensitive to tZ-coupling, triple-boson coupling, backgrounds for searches.
- Trilepton channel is most promising for first observation

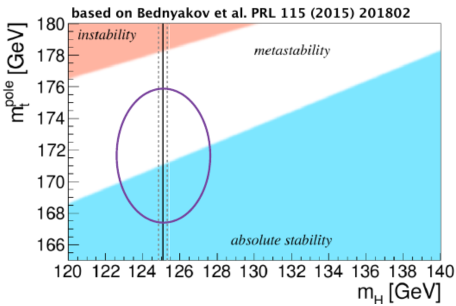
- Neural network is used to enhance S/B
- Binned maximum likelihood fit used to extract the cross section
- $\sigma_{tZq} = 600 \pm 170(\text{stat}) \pm 140(\text{syst})$ fb
  4.2 σ obs. (5.4 σ exp.)

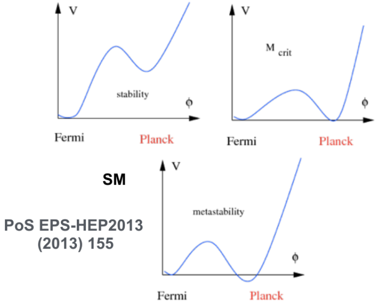



[GeV]
A glimpse of
200
150
100
50
0
175
0.005
0.01
0.15
1.5
5.0
s
c
b
t
op quark mass
measurements
up
down
strange
charm
bottom
top
Fermilab 01-XXX

Why measure the *top quark mass*

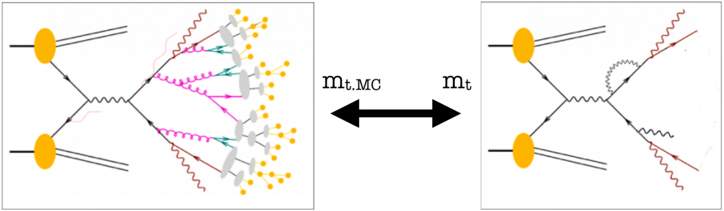
- EWK vacuum stability critically depends on Higgs-boson mass and top-quark (pole) mass
- Role in EW symmetry breaking? m_t is close to scale of EWSB, so t might play a special role
- Role in non SM-physics? (like topcolor models for EW dynamical breaking)





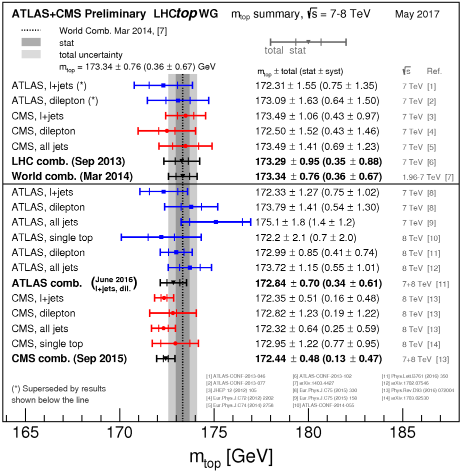
Study the top quark mass in detail and from many perspectives

- Highly precise direct/*standard* measurements → Already at 0.3% precision level!
  - Using final states from MC simulation (models)
  - Measure MC parameter m_{t},(MC) (in principle depends on generator)



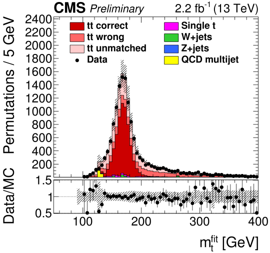
- Use extraction methods complementary to standard measurements
- Directly extract mass in well-defined scheme by confronting measured and predicted observables → Precision from inclusive cross section ∼1%

Standard measurements



ATLAS and CMS in good agreement, some tension with Tevatron average (174.30±0.65 GeV)

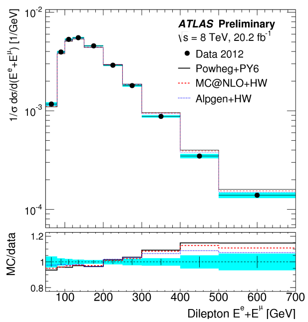
- First measurement at 13 TeV in l+jets (prec.: 0.46%) [CMS-TOP-16-022]



- Most precise measurements from CMS l+jets (0.51 GeV) and from ATLAS dilepton (0.84 GeV)
- Precision limited by understanding hadronization modeling
- Different ways to improve: cleaner observables, avoid jets, theoretically calculable observables

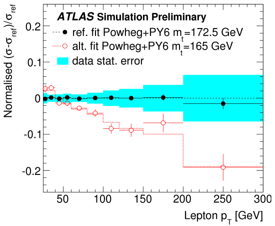
Mass measurements from cross sections

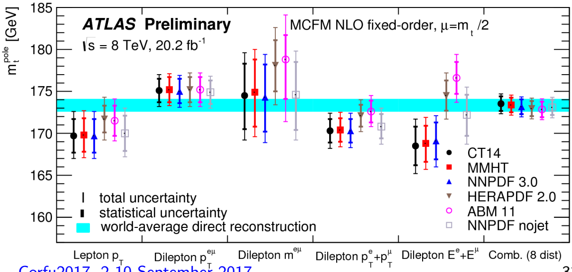
Exploring differential distributions



- Measure a number of lepton differential cross sections in $t\bar{t}$ $e\mu$ events
- Define likelihood for prediction
- m_t^{pole} obtained fitting the individual distributions and the combination, constraining the syst. uncertainties with nuisance parameters

[ATLAS-CONF-2017-044]





Summary and outlook

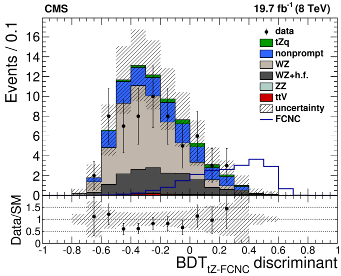
- In Run-I, the LHC became a real *top quark factory*
  - Top quark measurements entered precision regime
  - Started to challenge theory predictions in many respects
- Run-2 data is taking a central stage in SM top studies
  - Single top quark and $\mathrm{t\bar{t}}$ inclusive cross sections
  - Plethora of differential measurements
  - Rare processes (ttV, 4top, tZq)
- ... and BSM searches with top quarks ongoing in a multitude of channels
- Coming up Next: Precision measurements of properties and top mass, FCNC, anomalous couplings, EFT with 13 TeV data

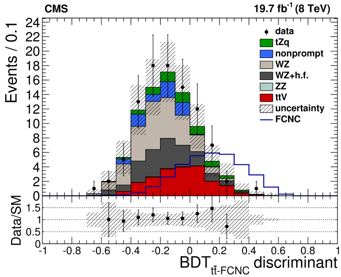
The ultimate potential for top physics at the LHC is ahead of us!

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html

BACK UP

Search for tZq: FCNC rare decays [8 TeV: JHEP 07 (2017) 003]





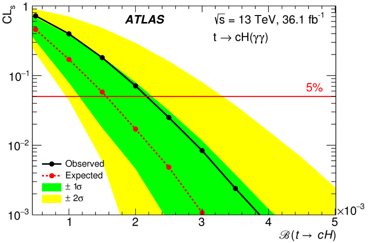
$\mathcal{B}(t \to Zu) = 0.1\%$ (FCNC)

- Sought for t→Zq: BR SM = O(10^{-15})
- In models beyond SM: BR BSM ∼ O(10^{-4})
- Decay can be found in the FCNC production mode gg→ $t\bar{t}$ →tZq: needs to be distinguished from SM and the suppressed FCNC production of tZq

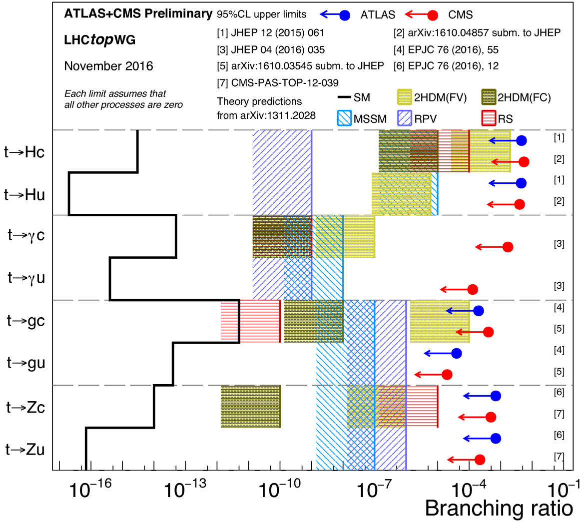
Branching fraction	Expected	68% CL range	95% CL range	Observed
$\mathcal{B}(t \to Zu)$ (%)	0.027	0.018 – 0.042	0.014 – 0.065	0.022
$\mathcal{B}(t \to Zc)$ (%)	0.118	0.071 – 0.222	0.049 – 0.484	0.049

Status of search for FCNC rare decays

- No signs of flavour physics associate with top quarks
- First results at 13 TeV $t \to qH$, $H \to \gamma\gamma$



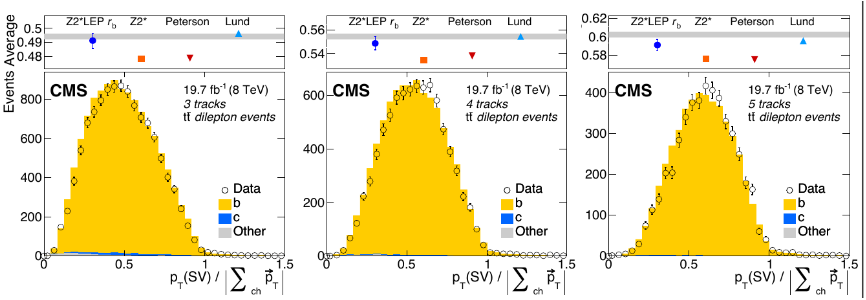
arXiv:1707.01404



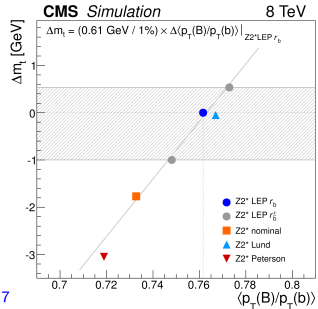
- b fragmentation modelling ~1 GeV
- Significant dependence on b-fragmentation modelling: Possible to constrain from data?
- Top quark p_T ~800 MeV
- Experimental < 500 MeV
  - Lepton energy scales
  - Secondary vertex modeling
- Fully complementary to standard methods

Source	Δm_t [GeV]	
Theoretical uncertainties		
μ_R/μ_F scales $t\bar{t}$	+0.22	−0.20
μ_R/μ_F scales t (t-channel)	−0.04	−0.02
μ_R/μ_F scales tW	+0.21	+0.17
Parton shower matching scale	−0.04	+0.06
Single top quark fraction	−0.07	+0.07
Single top quark diagram interference (*)	+0.24	
Parton distribution functions	+0.06	−0.04
Top quark p_T	+0.82	
Top quark decay width (*)	−0.05	
b quark fragmentation	+1.00	−0.54
Semileptonic B decays	−0.16	+0.06
b hadron composition (*)	−0.09	
Underlying event	+0.07	+0.19
Color reconnection (*)	+0.08	
Matrix element generator (*)	−0.42	
$\sigma(t\bar{t}$ + heavy flavor)	+0.46	−0.36
Total theoretical uncertainty	+1.52	−0.86
Experimental uncertainties		
Jet energy scale	+0.19	−0.17
Jet energy resolution	−0.05	+0.05
Unclustered energy	+0.07	−0.00
Lepton energy scale	−0.26	+0.22
Lepton selection efficiency	+0.01	+0.01
b tagging	−0.02	−0.00
Pileup	−0.05	+0.07
Sec.-vertex track multiplicity (*)	−0.06	
Sec.-vertex mass modeling (*)	−0.29	
Background normalization	< 0.03	
Total experimental uncertainty	+0.43	−0.44
Total systematic uncertainty	**+1.58**	**−0.97**
Statistical uncertainty	**±0.20**	

b-fragmentation modelling in data



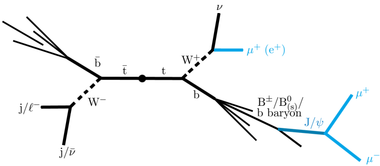
- Compare fraction of jet-momentum carried by secondary vertex for different fragmentation function shapes (Proxy for parton-to-hadron momentum transfer)
- CMS standard Z2* tune reweighed to describe LEP b-fragmentation function measurements
- Z2* LEP rb tune gives best description

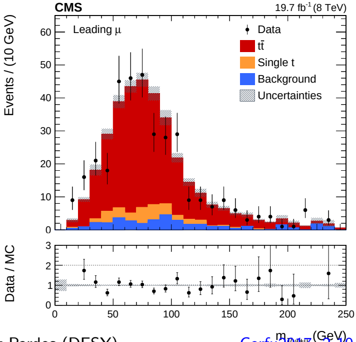


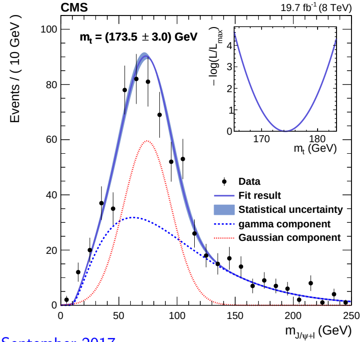
Using charmed mesons might provide an even cleaner observable [JHEP12(2016)123]

J/ψ: reduce sensitivity to jet reconstruction jet modelling and pQCD effects

- Use dileptonic and l+jets channels
- Reconstruct $J/\Psi \to \mu\mu$
- Fit peak and background of lepton + J/Ψ invariant mass
- Calibrate m_t using MC







J/ψ

$m_t = 173.5 \pm 3.0$ (stat) ± 0.9 (syst) GeV

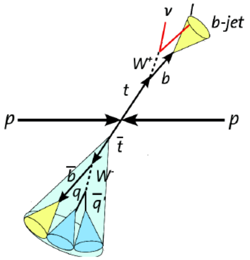
- From 3 GeV to around 0.7 GeV with 100 fb^{-1} at 13 TeV
- <1 GeV syst. uncertainty
  - b-fragmentation ~0.3 GeV
  - Limited by p_T^t, QCD scales
- Relevant experimental uncertainties $\leq$ 100MeV!

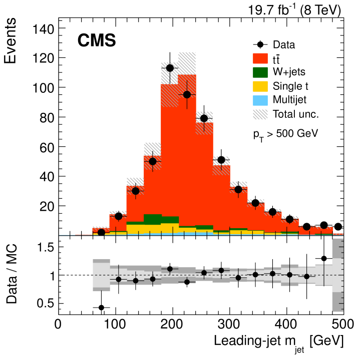
Source	Value (GeV)
Experimental uncertainties	
Limited size of the simulation samples	±0.22
Muon momentum scale	±0.09
Electron momentum scale	±0.11
Modeling of the J/ψ meson candidate mass distribution	+0.09
Jet energy scale	<0.01
Jet energy resolution	<0.01
Trigger efficiencies	±0.02
Pileup	±0.07
Theoretical uncertainties	
Background normalization	±0.01
Matrix-element generator	−0.37
Factorization and renormalization scales	+0.12, −0.46
Matching of matrix element and parton shower	+0.12, −0.58
Top quark transverse momentum	+0.64
b quark fragmentation	±0.30
Underlying event	±0.13
Modeling of color reconnection	+0.12
Parton distribution functions	+0.39, −0.11
Total (in quadrature)	+0.89, −0.94

m_t from boosted top jets 8 TeV [arXiv:1703.06330]

Top mass extraction from normalised cross section as a function of merged jet mass

- Jet mass: invariant mass of all stable particles in a jet
- Boosted top quarks: decay products merge, reconstruction of the full top quark in one jet $\rightarrow m_{jet} \sim m_t$
- Select 1 jet clustered by Cambridge-Aachen algorithm with R = 1.2 (to increase statistics) and pT > 400 GeV and 1 lepton with pT > 45 GeV





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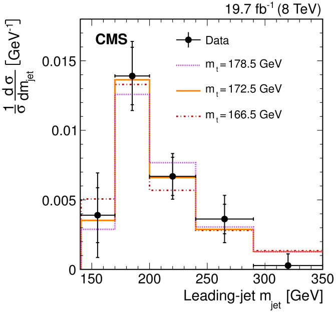
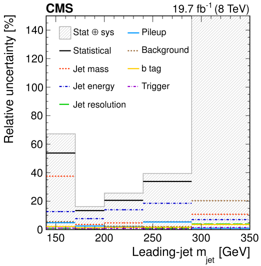
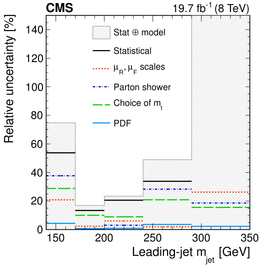






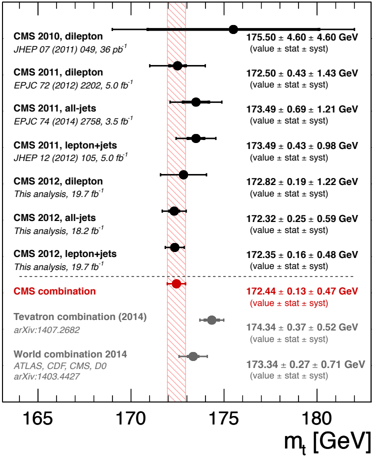
- Extraction from the differential σ at particle level
- Fiducial region with merged top quark decays in hadronic final states
- Limitations: statistics, jet mass resolution (large R, pileup)

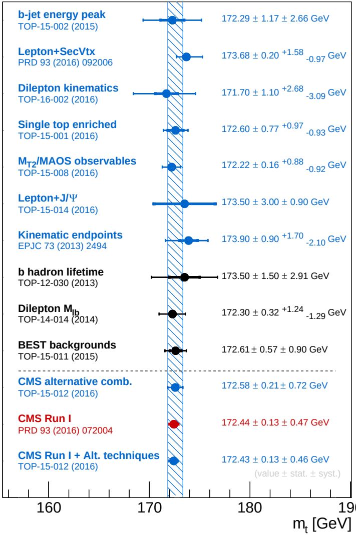
$$m_t = 170.8 \pm 6.0\ (\text{stat}) \pm 2.8\ (\text{syst}) \pm 4.6\ (\text{mod}) \pm 4.0\ (\text{theo})\ \text{GeV}$$

$\rightarrow$ Proof of principle for a new determination method of the mass

Goal is an extraction from EFT calculations (JHEP 12 (2015) 059, PRL 117 (2016) 232001)

A fine crop of measurements





- Most precise: l+jets 500 MeV uncertainty
- Run I *standard* combination: 490 MeV precision (0.3%)
- Run I *alternative* combination: 750 MeV precision (0.43%) [CMS-PAS-TOP-15-012]