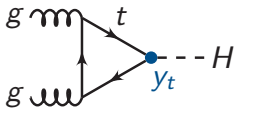
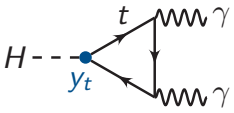
Top Quark Physics

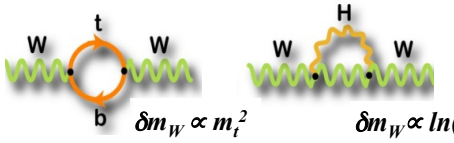
Andreas B. Meyer
on behalf of the ATLAS and CMS Collaborations

XXXVII Physics in Collision, Prague, 5 Sept 2017

Top Quark Physics







- **Heaviest known elementary particle**
  - Strong coupling to Higgs (EWK loops, gg → H)

- **Timescales → unique features, bare quark**

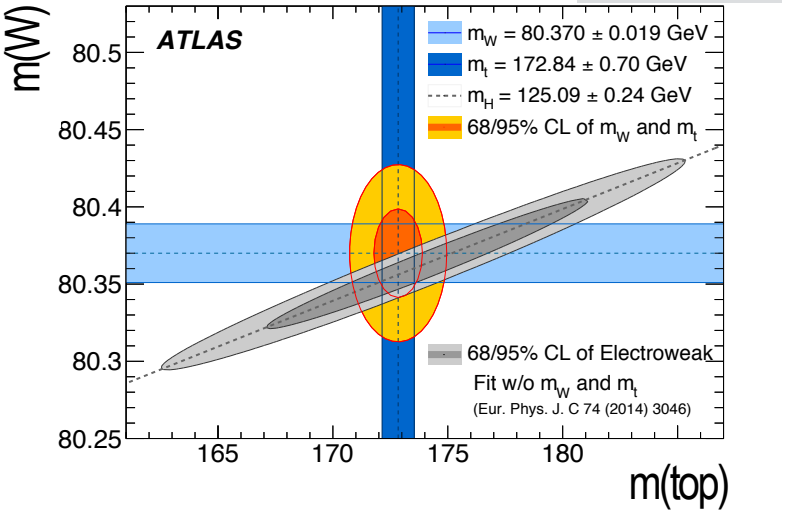
$$\underbrace{\frac{1}{m_t}}_{\text{production}\ 10^{-27}\ \text{s}} < \underbrace{\frac{1}{\Gamma_t}}_{\text{lifetime}\ 10^{-25}\ \text{s}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\text{hadronization}\ 10^{-24}\ \text{s}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\text{spin-flip}\ 10^{-21}\ \text{s}}$$

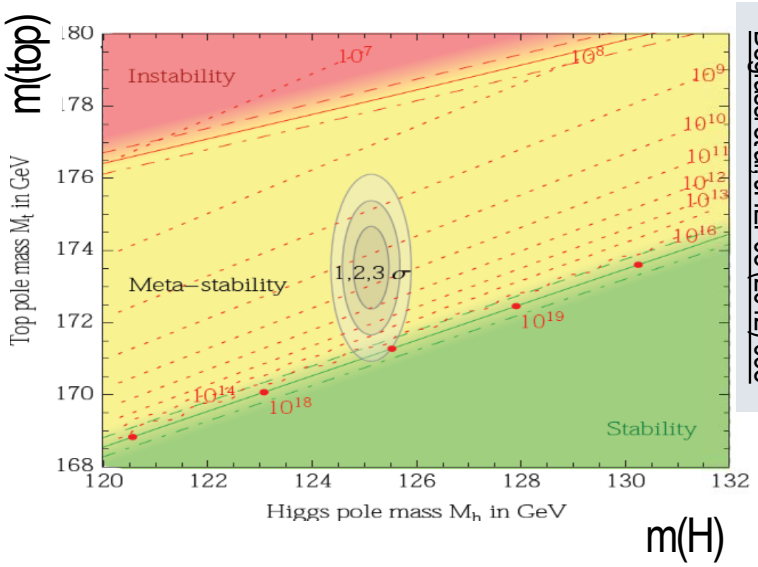
- **Precision measurements of SM parameters**

$$m_t,\ V_{tb},\ Y_t,\ \alpha_S,\ \textit{PDF}$$

- **Search for New Physics**
  - through precision measurements of top quark properties and couplings (esp. in case new physics would couple to mass)
  - top is background to many searches

arXiv:1701.07240





Degrassi et al, JHEP08 (2012) 098

Top Quark Physics in Production and Decay

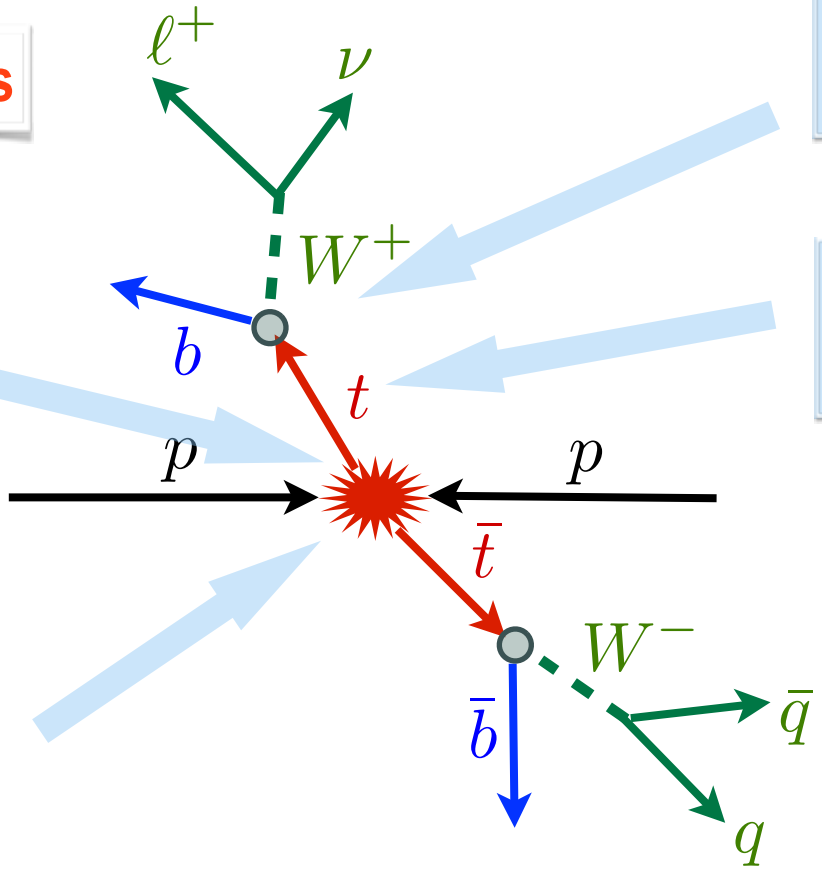
Top Quark Pairs

W-Helicity Fractions
Branching Ratios, V_{tb},
Rare Decays, FCNC

Spin Correlations
Polarisation
Asymmetries

Mass
Mass Difference,
Width, Charge

cross sections,
kinematics, QCD
parameters,
resonances,
new particles

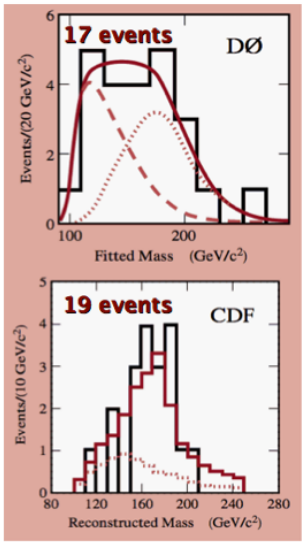


EWK Single-Top Production

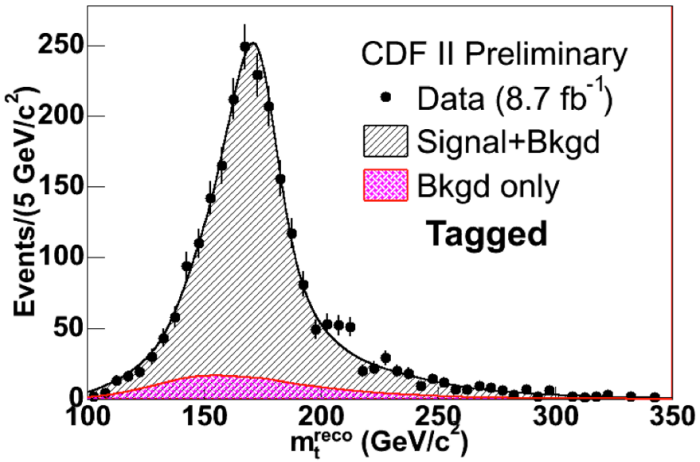
s, t, tW channel production,
Polarisation, V_{tb}, FCNC, W-helicity, mass

Earlier Top-Quark Results

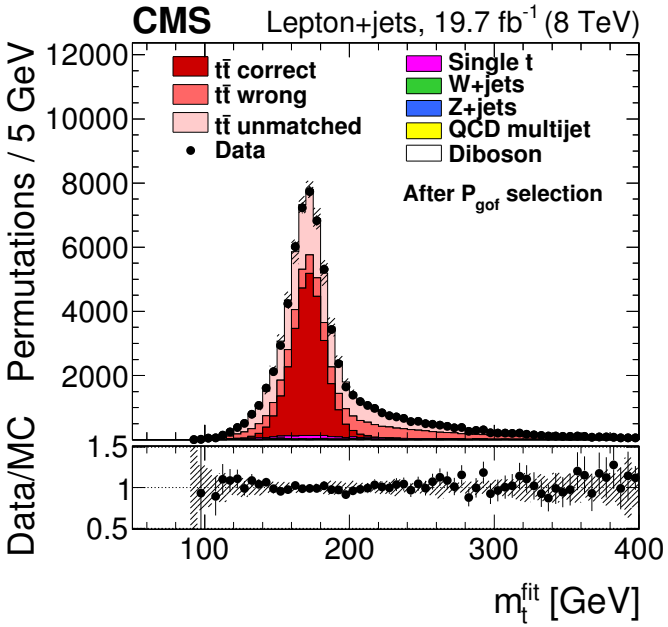
36 events



1000s of events



100000s of events

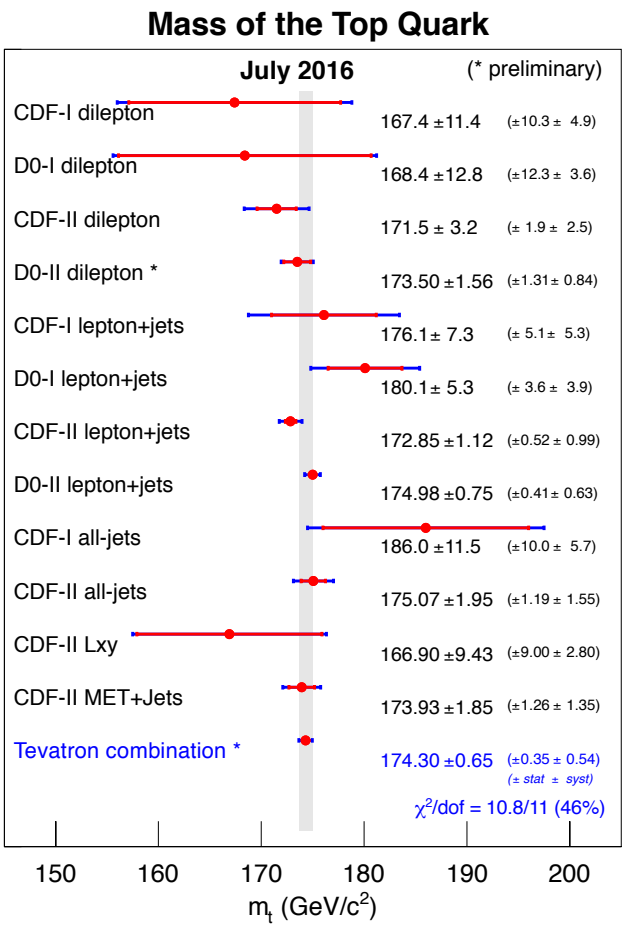


- **Tevatron $p\bar{p}$ 1.96 TeV**
  - discover
  - scrutinise and measure
  - establish top as SM quark
- **LHC Run-I pp (7 and 8 TeV)**
  - pp: complementary initial state
  - superior statistics ⟶ top factory

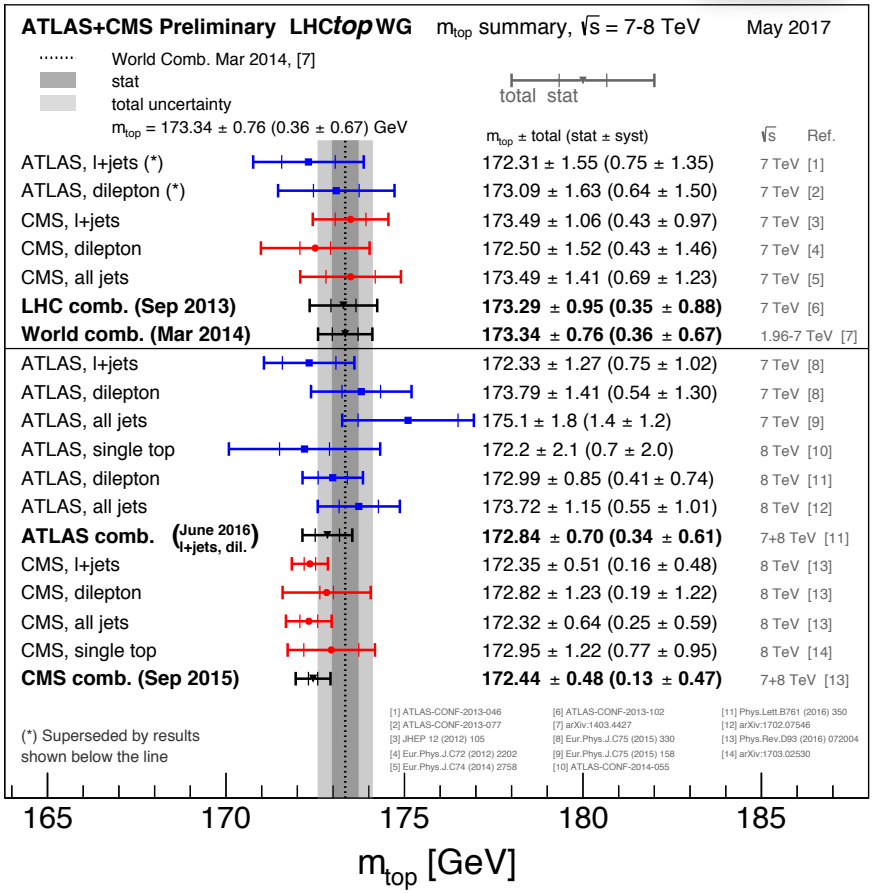
1995 — **2010** — **2012**

Top Quark Mass

Tevatron and LHC Run-I



LHCtopWG



Tevatron Run-I and Run-II Combination

$m_{top} = 174.30 \pm 0.65_{syst}$ GeV

CMS Run-I Combination

$m_{top} = 172.44 \pm 0.48_{syst}$ GeV

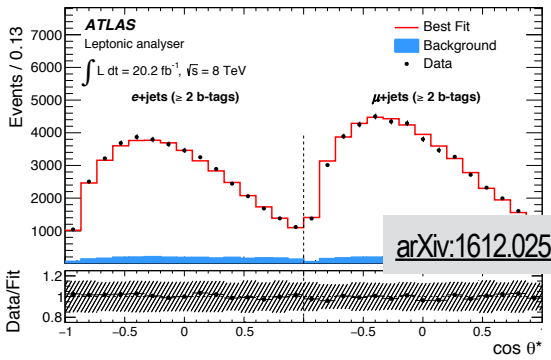
ATLAS Combination (8 TeV to come)

$m_{top} = 172.84 \pm 0.70_{syst}$ GeV

Top Quark Properties

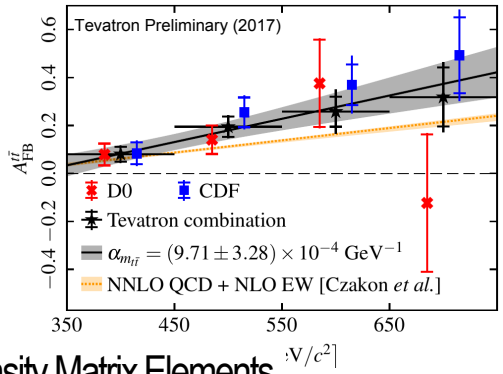
Tevatron and LHC Run-I

W Polarisation

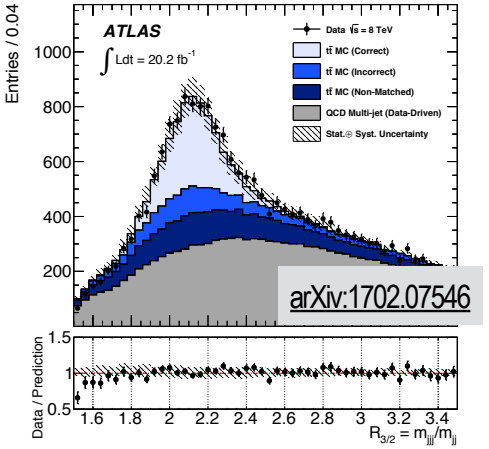


arXiv:1612.02577

Charge and FB Asymmetry

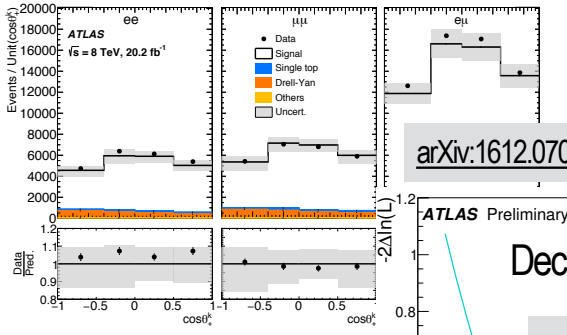


More Mass Measurements (tt)



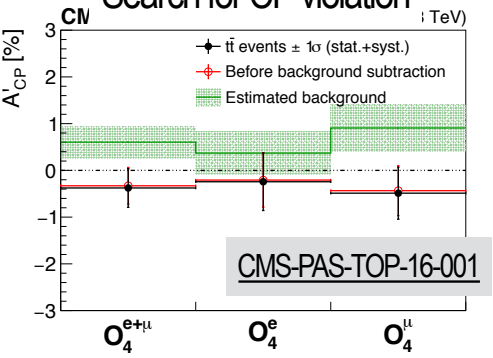
arXiv:1702.07546

Spin Density Matrix Elements



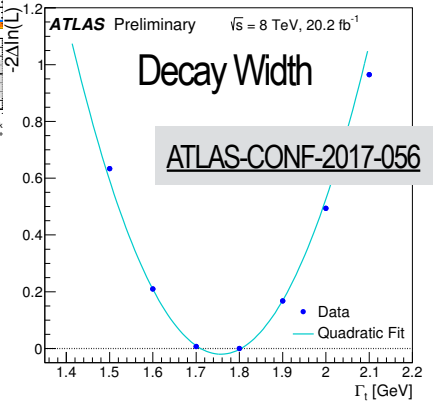
arXiv:1612.07004

Search for CP violation



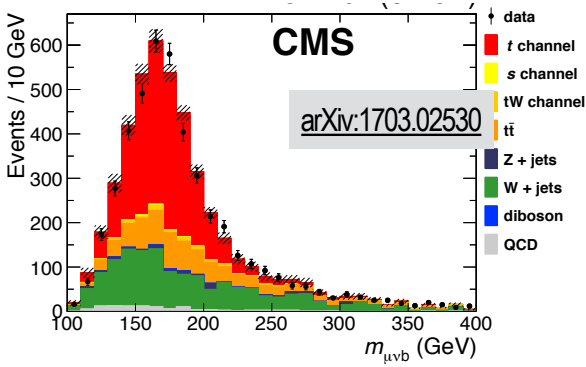
CMS-PAS-TOP-16-001

Decay Width



ATLAS-CONF-2017-056

Alternative Mass Measurements



arXiv:1703.02530

- **Tevatron and LHC Run-I Legacies:**
  Detailed measurements of top quark properties and cross sections

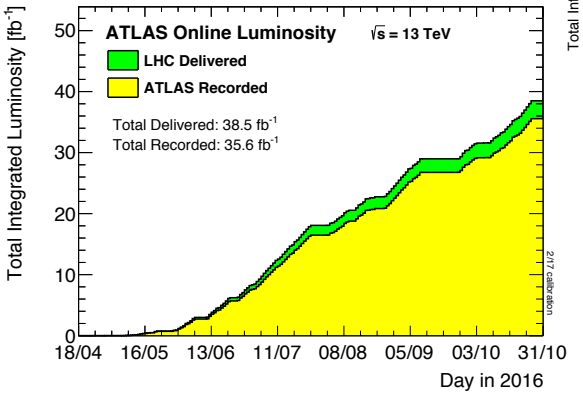
2012 → **2017**

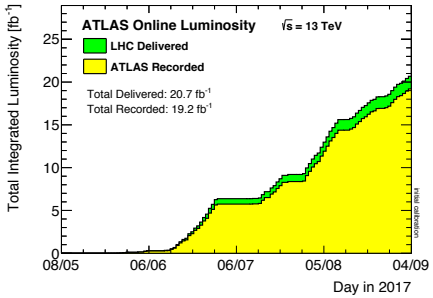
The Present: LHC Run-II

Top-Quark Physics Frontiers:

- Ultimate precision
- Differential distributions
- Production in association

>100 fb^{-1} per Experiment



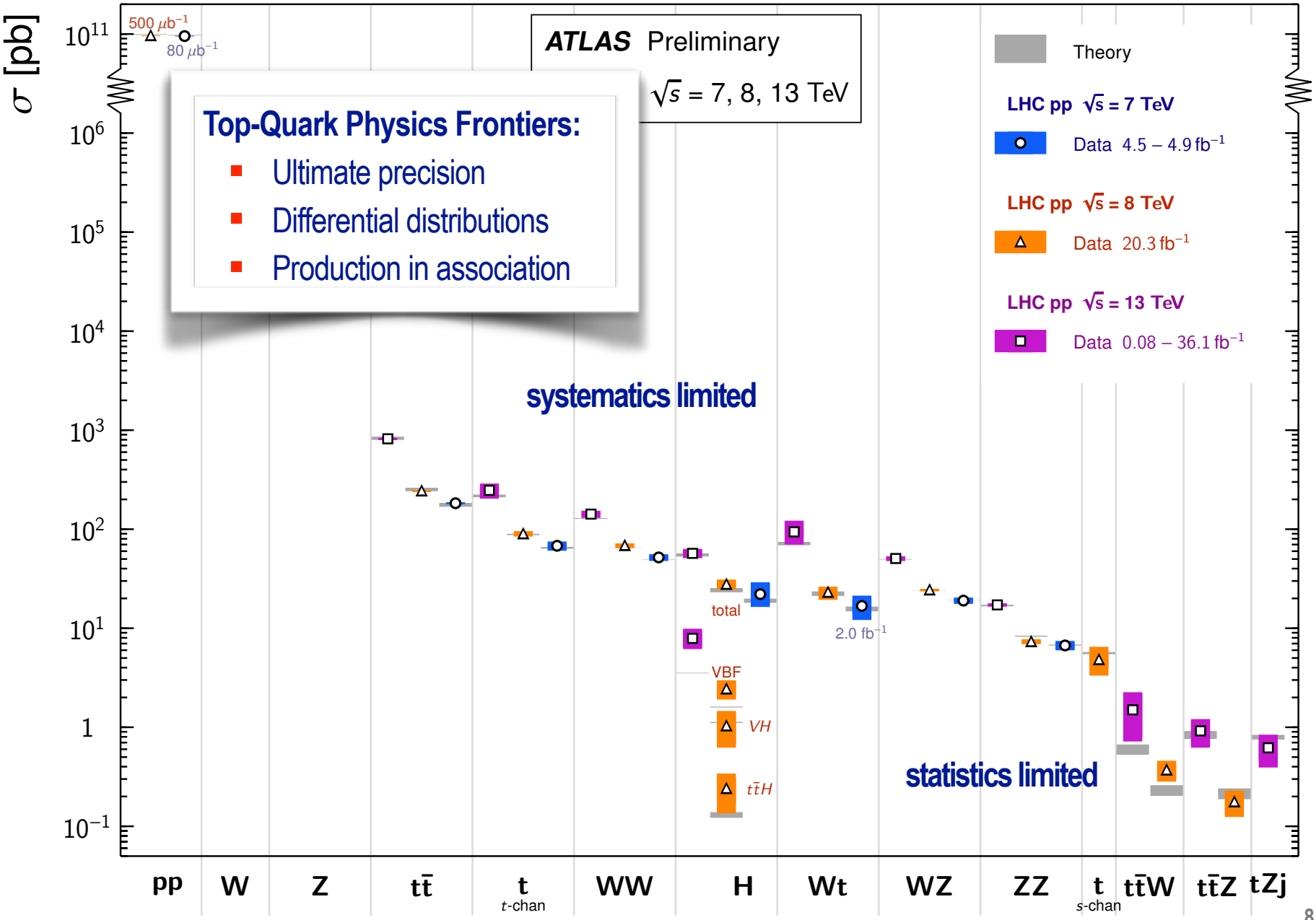


120 100 80 60 40 20

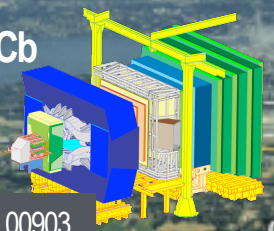
2015 2016 2017 2018

Standard Model Total Production Cross Section Measurements

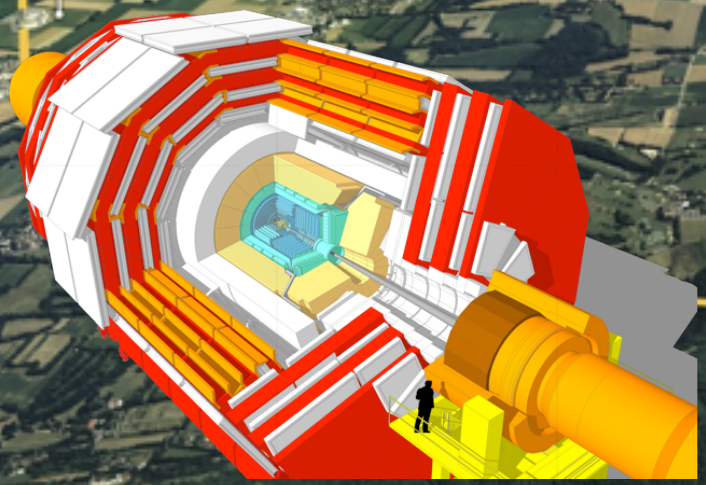
Status: July 2017



The Top-Quark Factory LHC

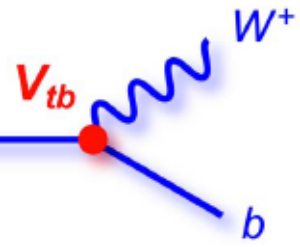


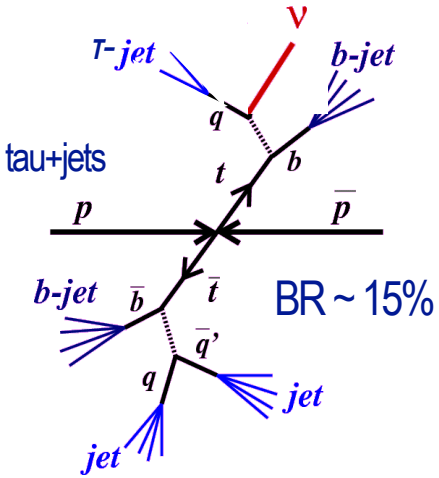
arXiv:1506.00903
arXiv:1610.08142

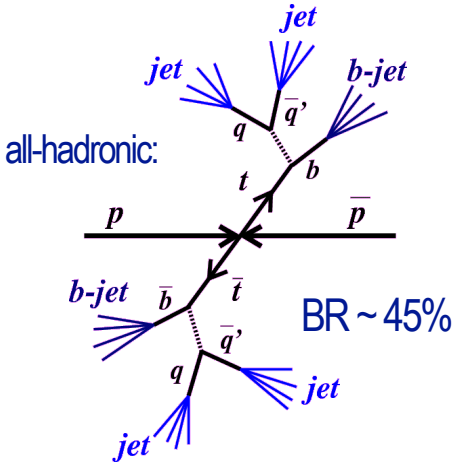


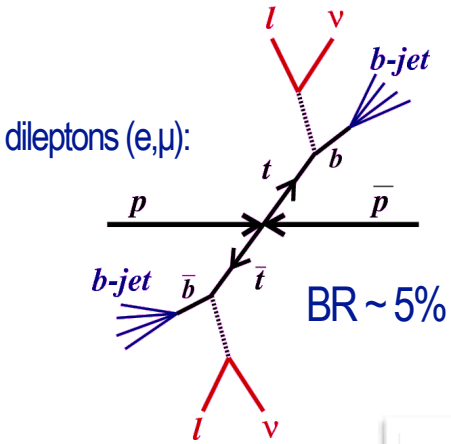
- LHC Run-I ('10-'12): 25 fb^{-1}
  - Peak inst. luminosity: 0.8 x 10^{34} $cm^{-2}s^{-1}$
    ~ 7000 top quark pairs per hour (8 TeV)
  - > 5,000,000 top each CMS and ATLAS
- LHC Run-II ('15-'18): 100 fb^{-1} (13 TeV)
  - Cross section increase by about factor ~3
  - Peak inst. luminosity: 1.7 x 10^{34} $cm^{-2}s^{-1}$
  - Expected: 80,000,000 tt and 80,000 ttZ
  - About 50% of Run-II already on tape

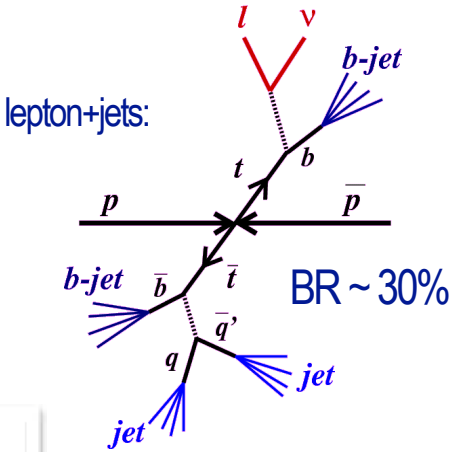
$t\bar{t}$ Event Signatures











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

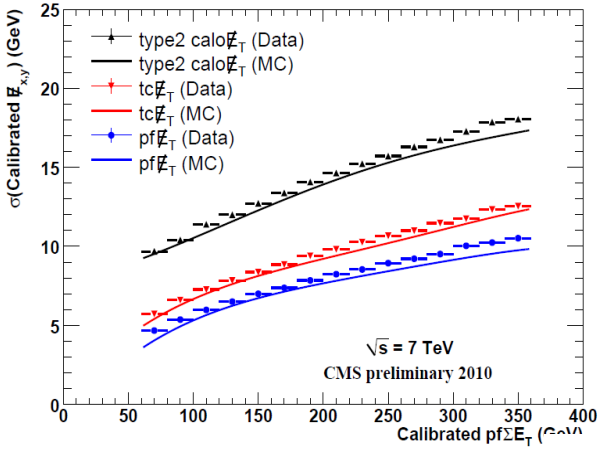
dileptons

Top quark events have all experimental signatures: leptons, jets, b-jets, missing transverse energy

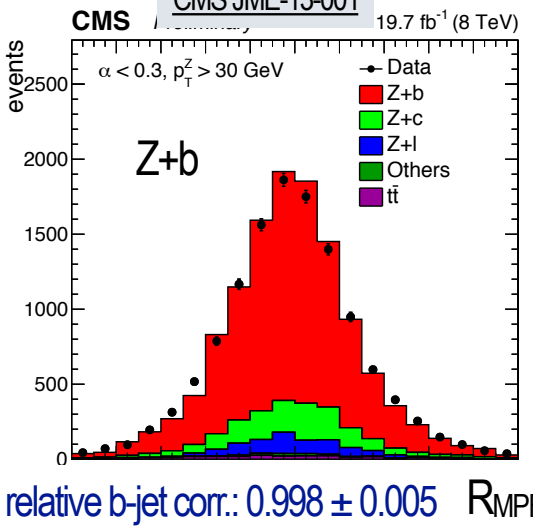
Experimental Ingredients

- **Jet (and E_T^{miss})**
  - Event-by-event pile-up subtraction based on charged component
  - Resolution and scale mostly from γ-jet and Z-jet balance.
  - b-jet energy scale directly accessible through Z+b

CMS DP-2012/012



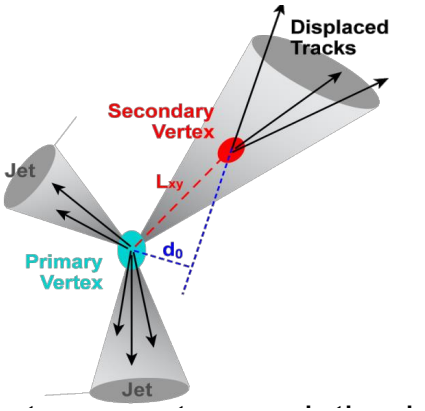
CMS JME-13-001



relative b-jet corr.: 0.998 ± 0.005 R_{MPF}

- **Isolated Leptons (e, μ or τ)**
  - Calibrations and efficiencies from dilepton resonances (Z, ϒ, J/ψ)

- **b-tagging**
  - Combination of several techniques (vertex, impact parameter, tracks/ leptons within jets)



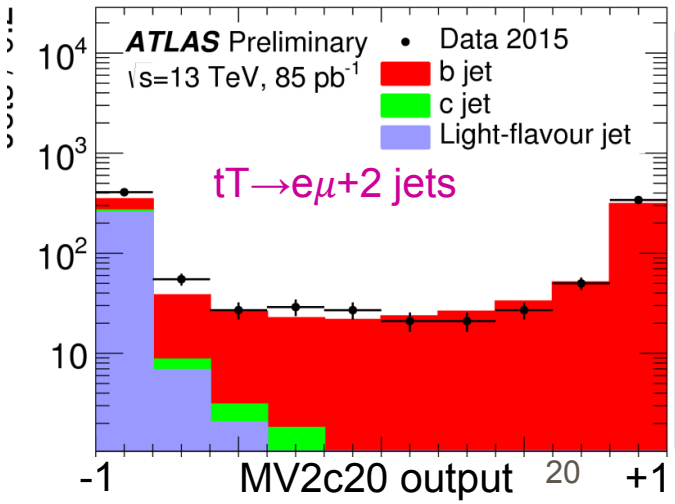
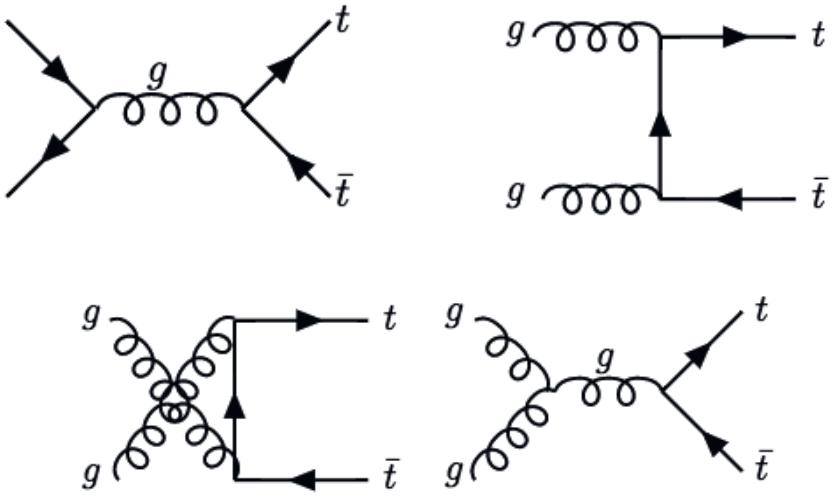


Fig taken from R.Hawkings TOP2016

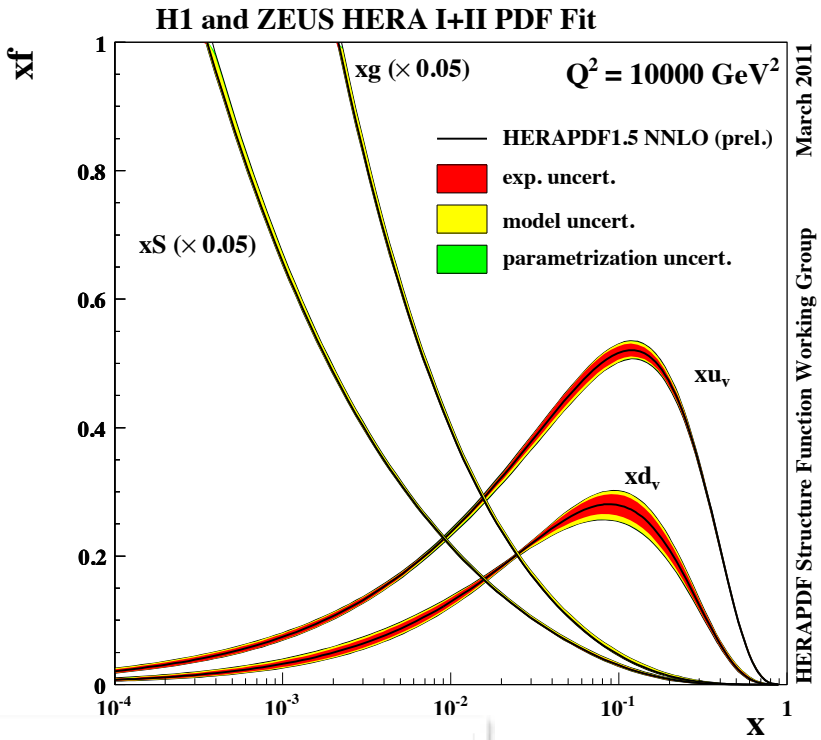
Top quark physics: require high-precision leptons, jets and b-tagging

Top-Quark Pair Production



	LHC (13 TeV)	Tevatron
gg/gq	~90%	~15%
$q\bar{q}$	~10%	~85%

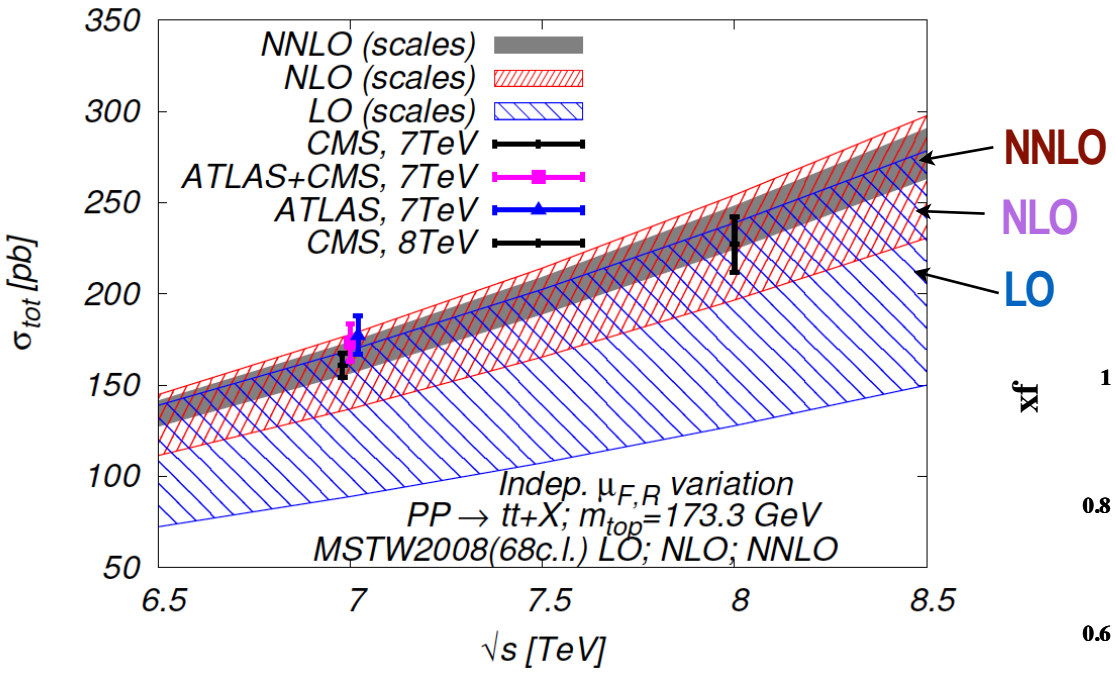
$$\sigma(7\ \text{TeV}) = 177\ \text{pb} \pm 7\%$$
$$\sigma(8\ \text{TeV}) = 253\ \text{pb} \pm 6\%$$
$$\sigma(13\ \text{TeV}) = 832\ \text{pb} \pm 5\%$$
$$R_{13/8} = 3.28$$



Top quark pair production at LHC predominantly from gluons

Top-Quark Pair Production

Czakon, Fiedler, Mitov PRL 110 (2013) 252004



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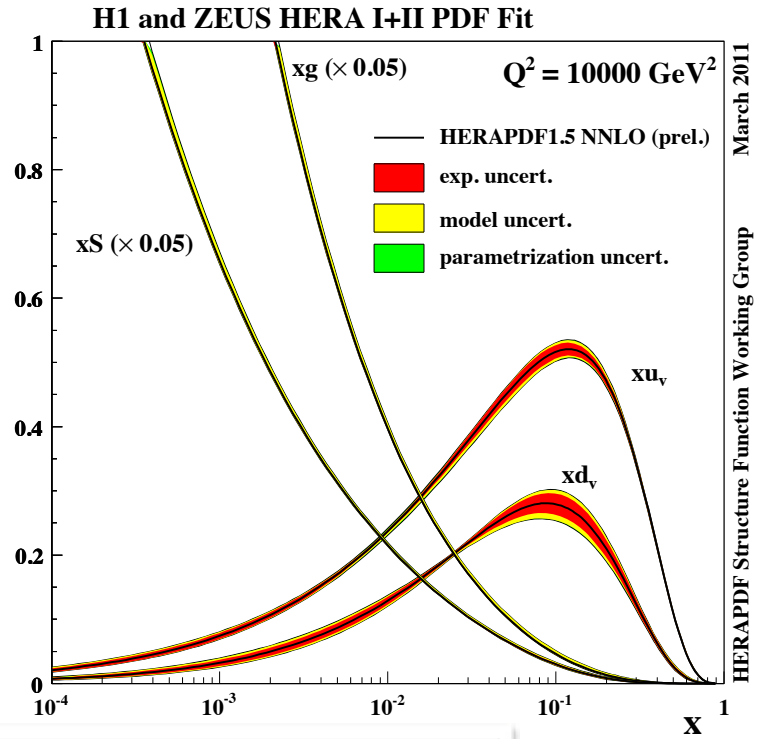
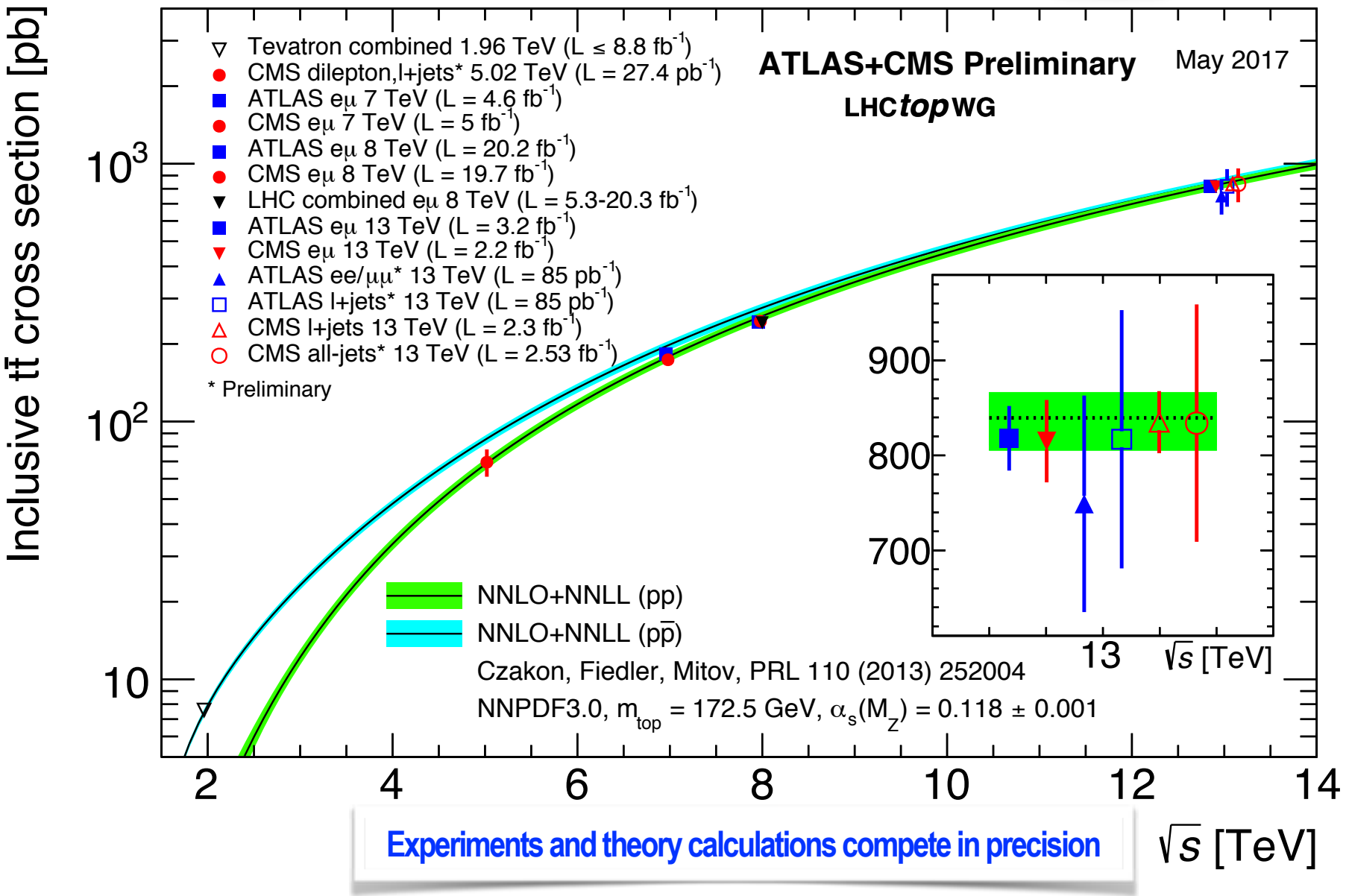


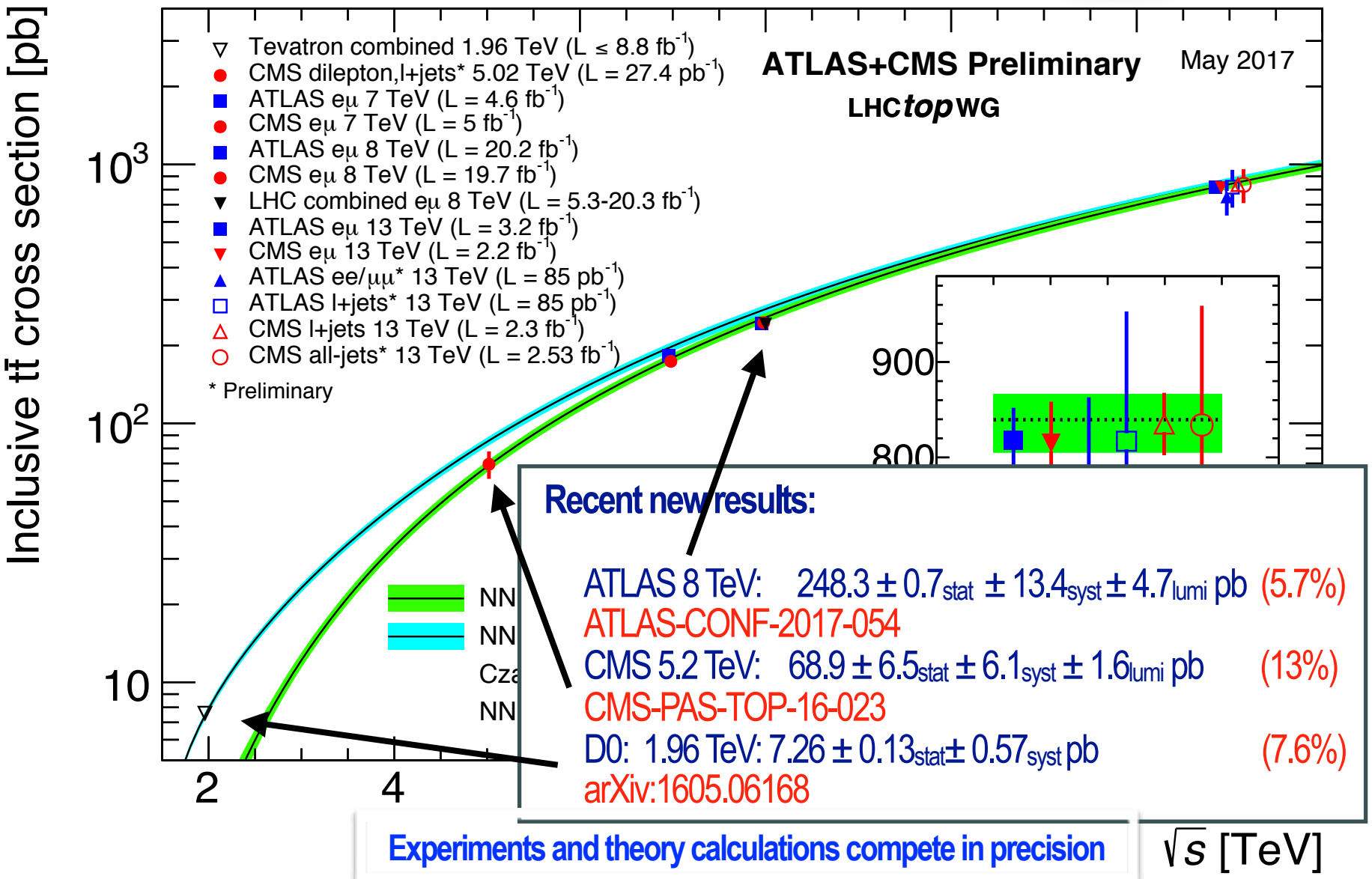
Full NNLO available since early 2013 - scale and pdf uncertainties 2-3%

σ_{tt} (Tevatron, Run-I and Run-II)



σ_{tt} (Tevatron, Run-I and Run-II)

LHCtopWG



Recent new results:

ATLAS 8 TeV: $248.3 \pm 0.7_{stat} \pm 13.4_{syst} \pm 4.7_{lumi}$ pb (5.7%)
ATLAS-CONF-2017-054

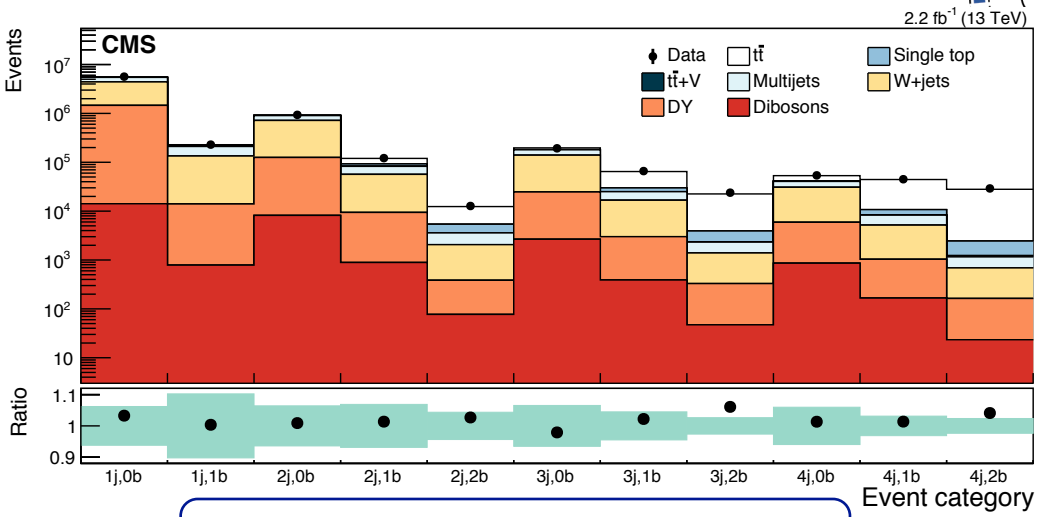
CMS 5.2 TeV: $68.9 \pm 6.5_{stat} \pm 6.1_{syst} \pm 1.6_{lumi}$ pb (13%)
CMS-PAS-TOP-16-023

D0: 1.96 TeV: $7.26 \pm 0.13_{stat} \pm 0.57_{syst}$ pb (7.6%)
arXiv:1605.06168

Experiments and theory calculations compete in precision

Inclusive $t\bar{t}$ Production

- **CMS:**
  - in-situ determination of systematics through nuisance parameter fits
  - Dominant systematics:
  - Background, lepton-ID, b-identification, Luminosity
- **ATLAS**
  - in-situ determination of b-tagging
  - tt/Z cross section ratio: alternative luminosity measure and sensitivity to PDF

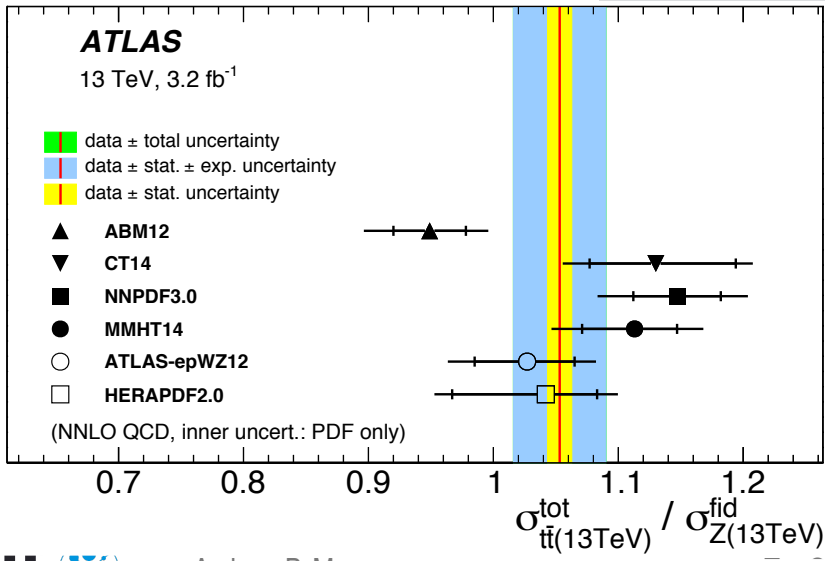


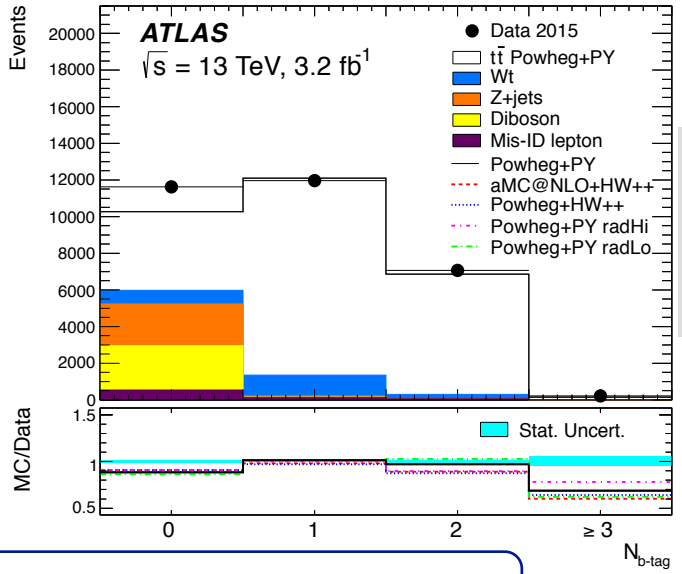
arXiv: 1701.06228

$\sigma_{tt} = 888 \pm 2_{stat} +26\text{-}28_{syst} \pm 20_{lumi}$ pb

3.9 %

arXiv: 1612.03636



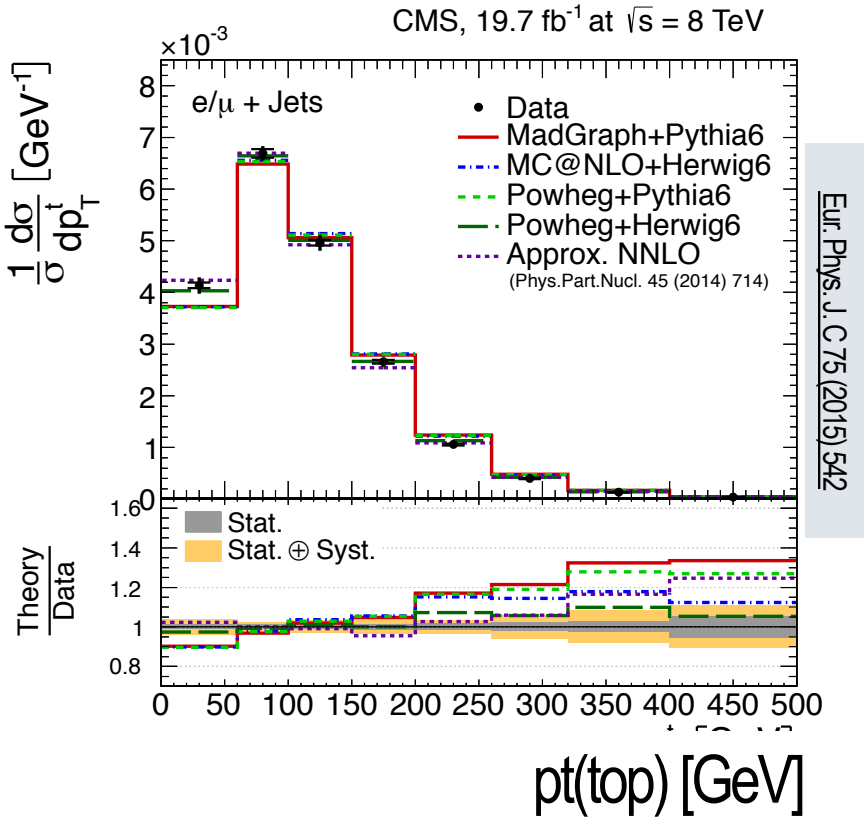


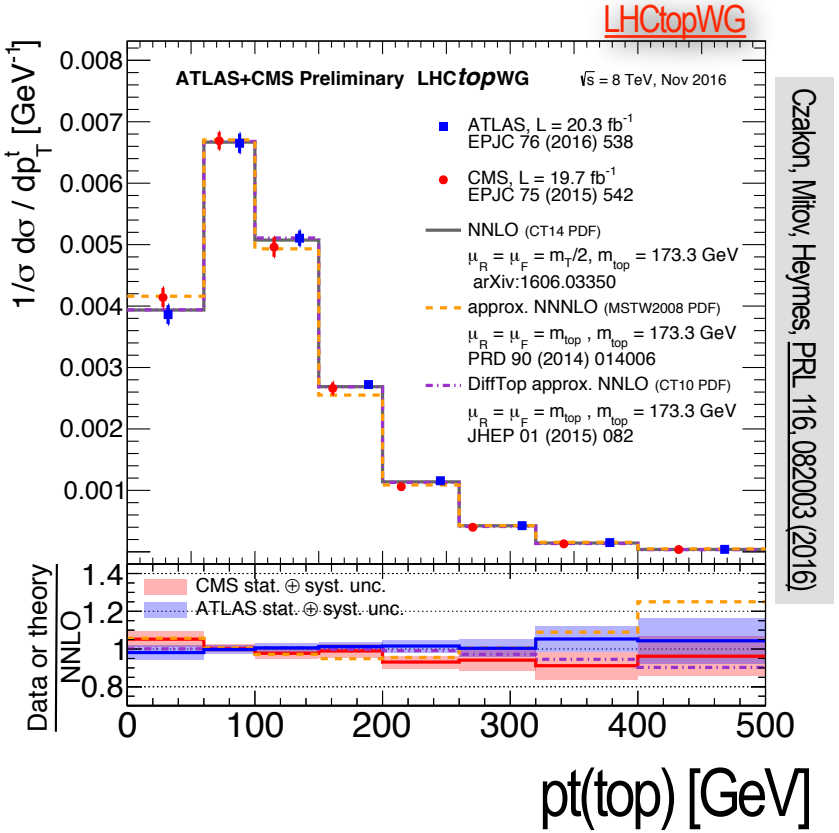
arXiv: 1606.02699

$\sigma_{tt} = 818 \pm 8_{stat} \pm 27_{syst} \pm 19_{lumi}$ pb

4.1 %

$t\bar{t}$ differential distributions: p_T(top)



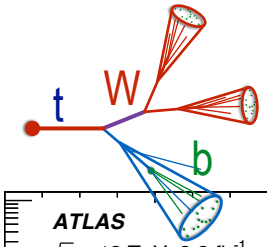


Results in dilepton, l+jets and all-jet final states
NLO calculations do not describe pt(top) -
all other distributions ok

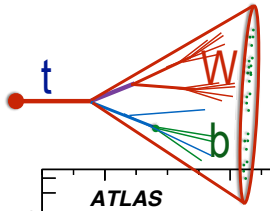
Since 2013: NNLO calculation available:
CMS and ATLAS data well described

$t\bar{t}$ differential distributions: p_T(top)

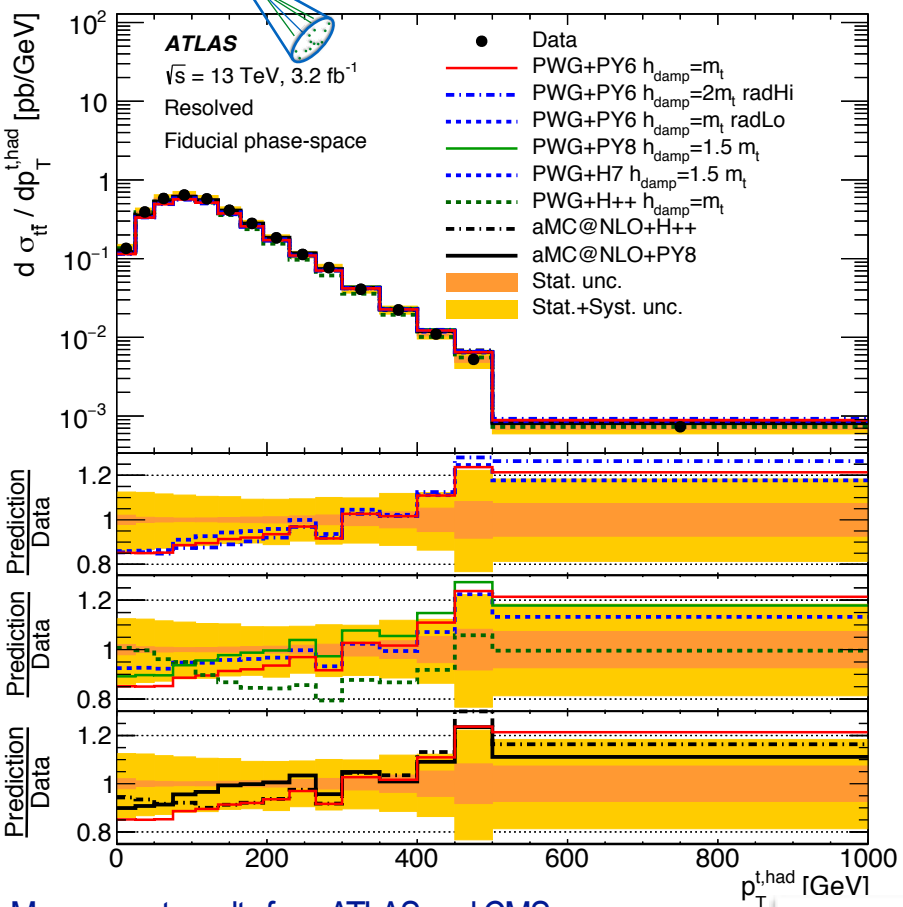
arXiv:1708.00727

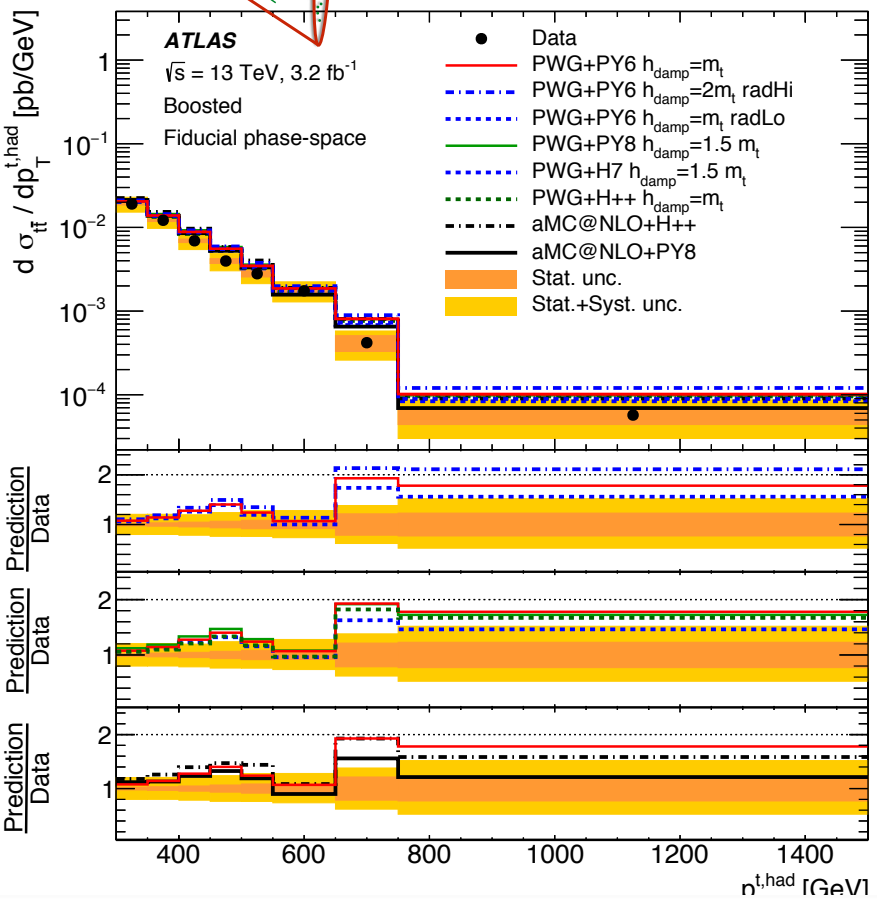


"resolved": 3 jets k_T=0.4



"boosted": 1 (top-tagged) jet k_T=1.0





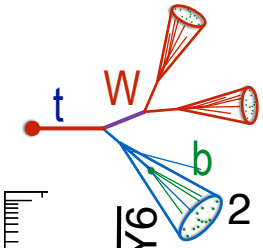
Many recent results from ATLAS and CMS:

arXiv:1610.04191, arXiv:1708.07638, CMS-PAS-TOP-16-013, ATLAS-CONF-2016-100, arXiv:1607.07281, arXiv:1612.05220

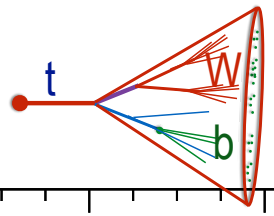
Same findings at 13 TeV as for 8 TeV, also with new MC generators aMC@NLO and POWHEG v2

$t\bar{t}$ differential distributions: p_T(top)

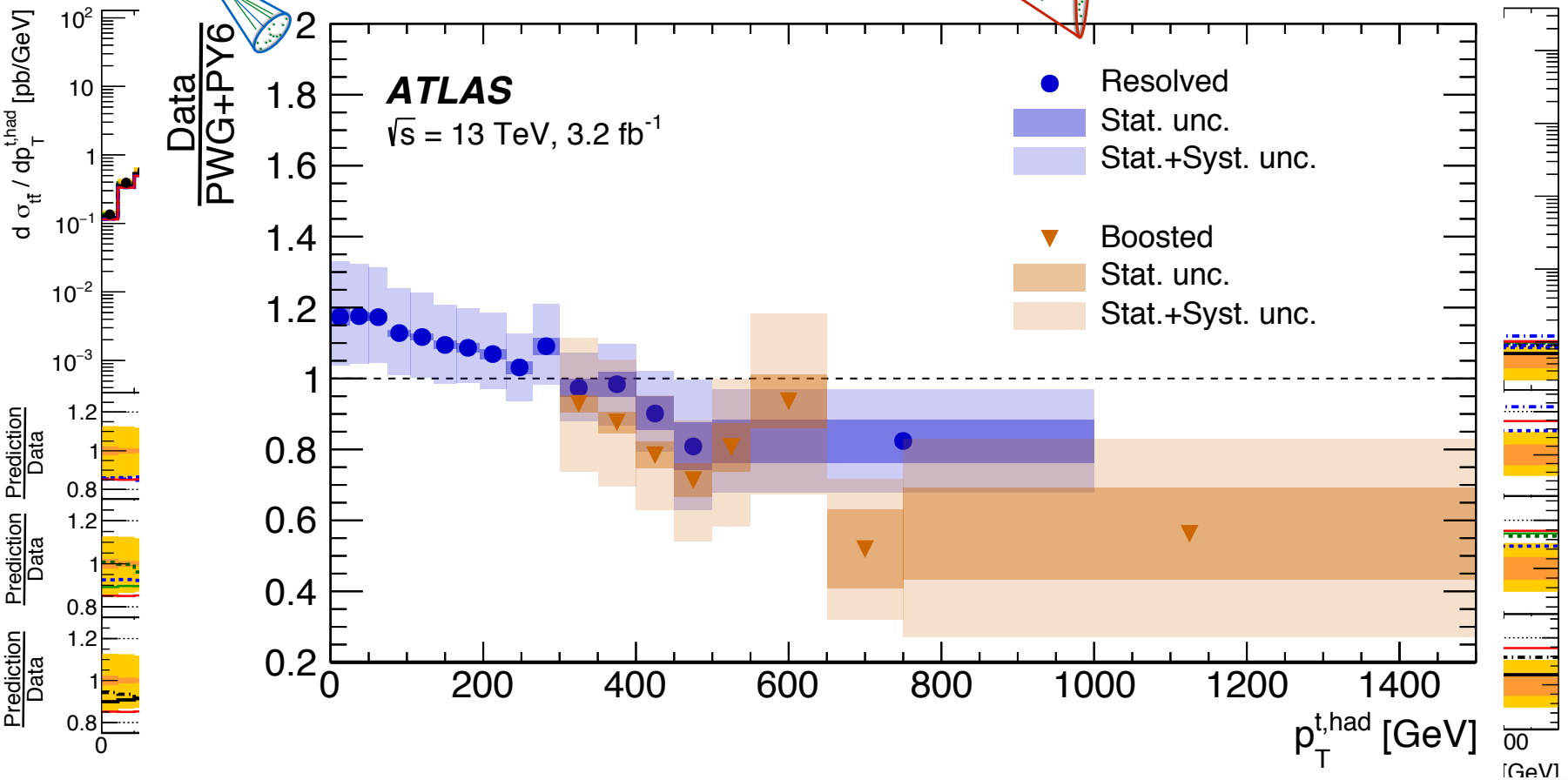
arXiv:1708.00727



"resolved": 3 jets k_T=0.4



"boosted": 1 (top-tagged) jet k_T=1.0



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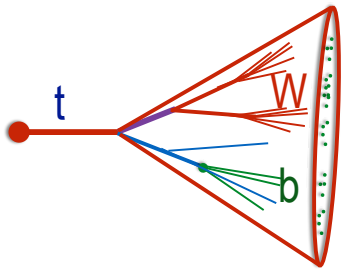
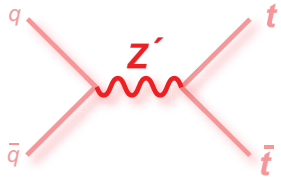
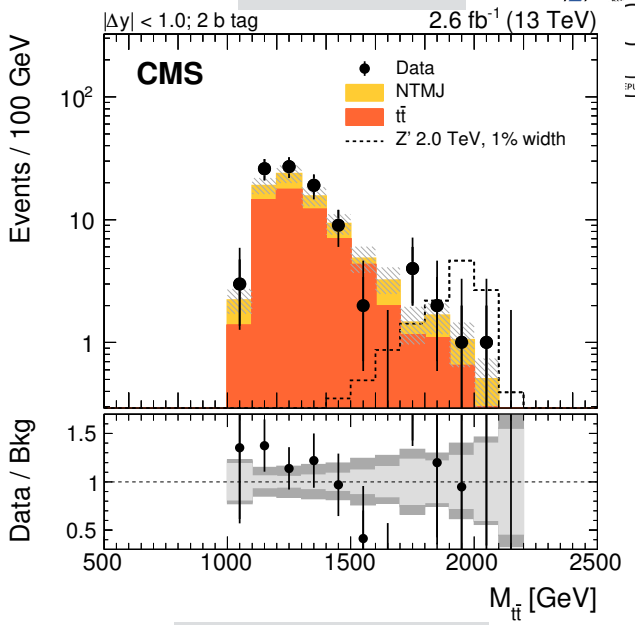
Boosted Top Quarks



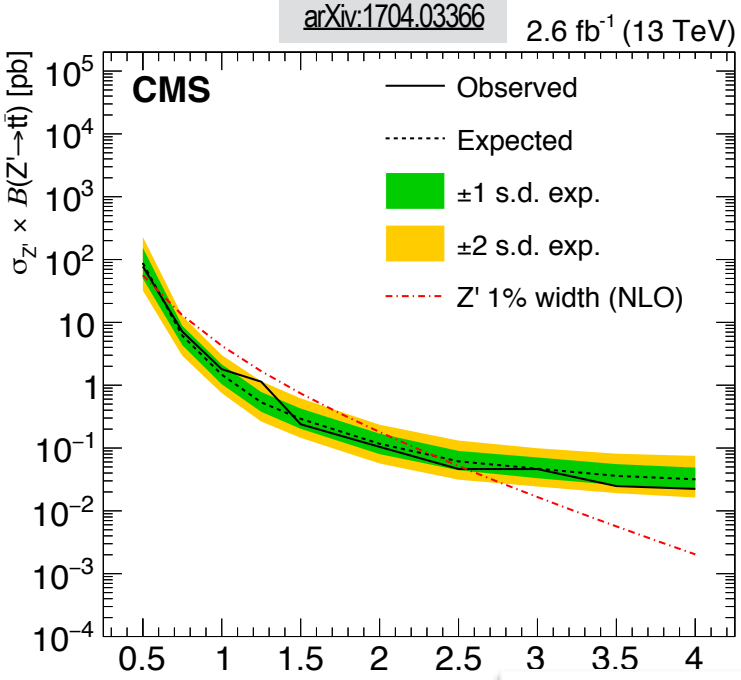
- **Top-quarks as a search tool**
  - High mass particles decaying to high momentum top quarks
- **Example: Z' → tt resonance**
  - Good understanding of m_{tt} required



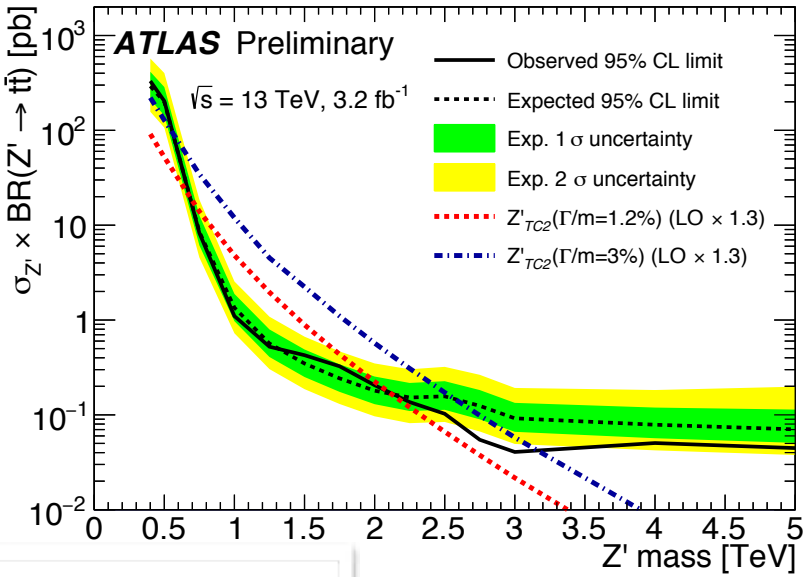
arXiv:1704.03366



arXiv:1704.03366



ATLAS-CONF-2016-014



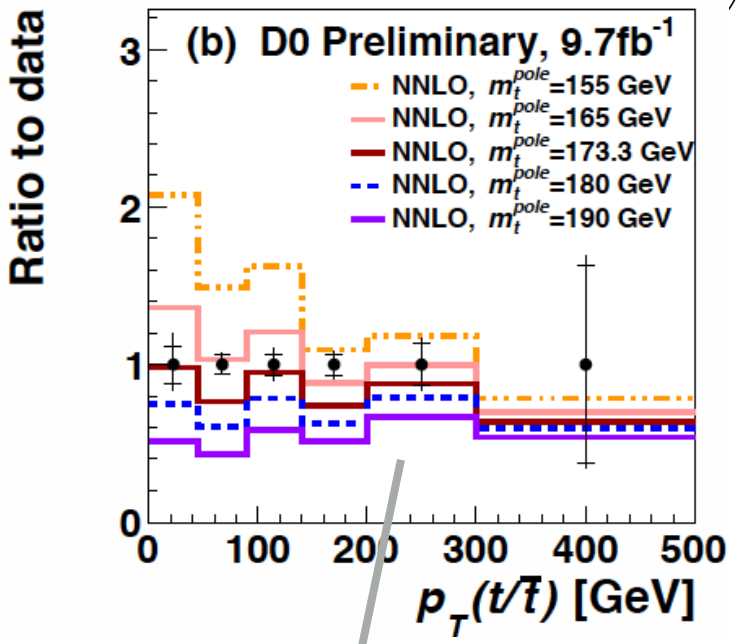
Lower limits: m(Z'(Γ/M = 1%)) > 2.5 TeV

σ_{tt}: Mass from Cross Sections

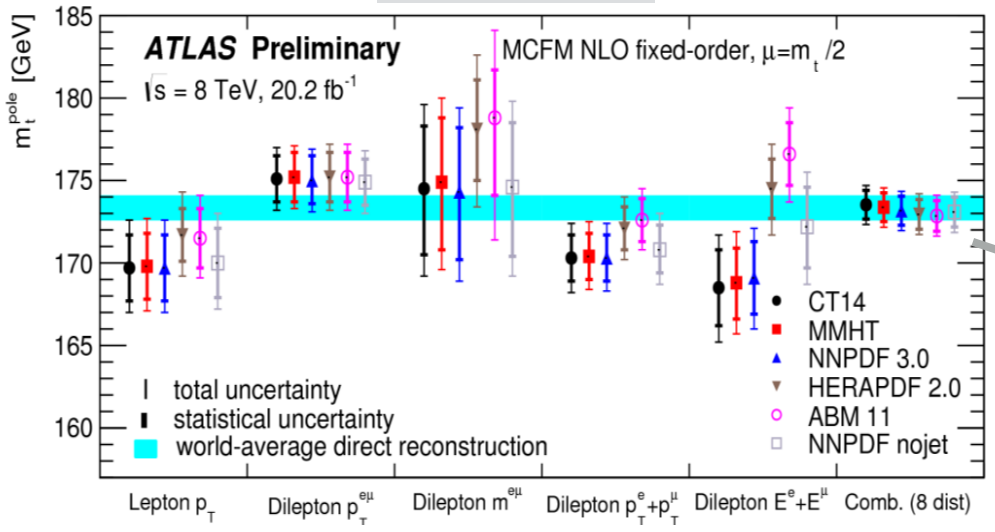
- **Use inclusive and differential cross section measurements to constrain pole mass**
  - theoretically well defined
  - current analyses: fixed α_S and PDF

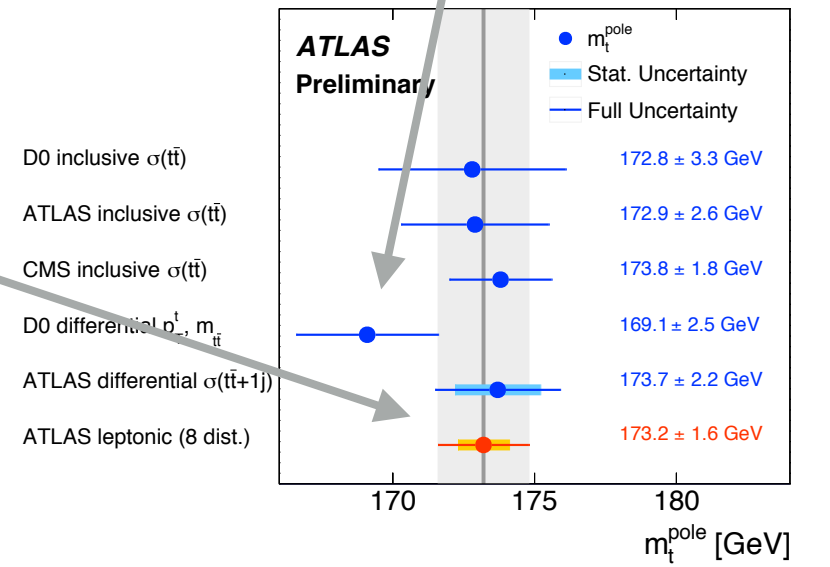
- **Latest results:**
  - D0: Fit to m_{tt} and pt(top) spectra
  - ATLAS: Fit of mass to eight lepton distributions

D0 6473



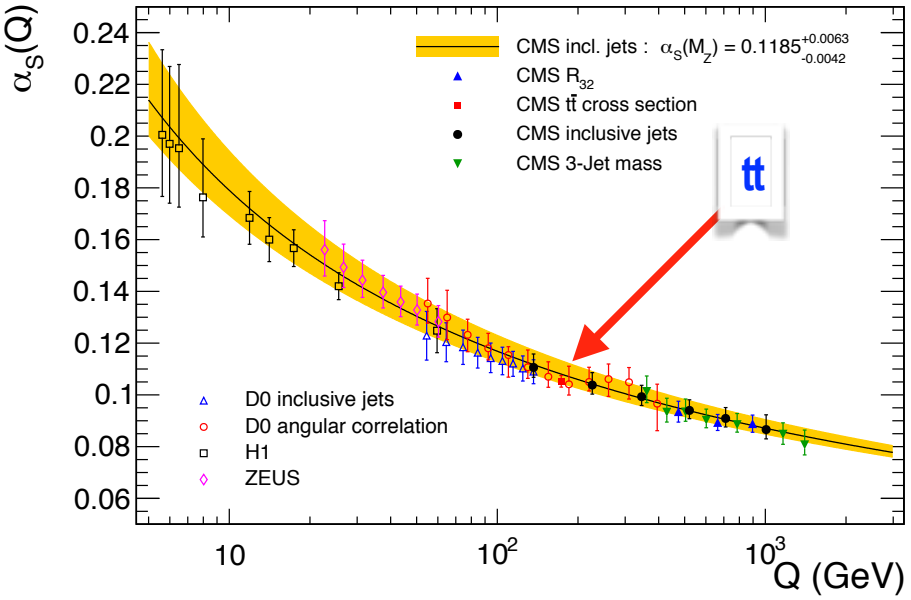
ATLAS-CONF-2017-044



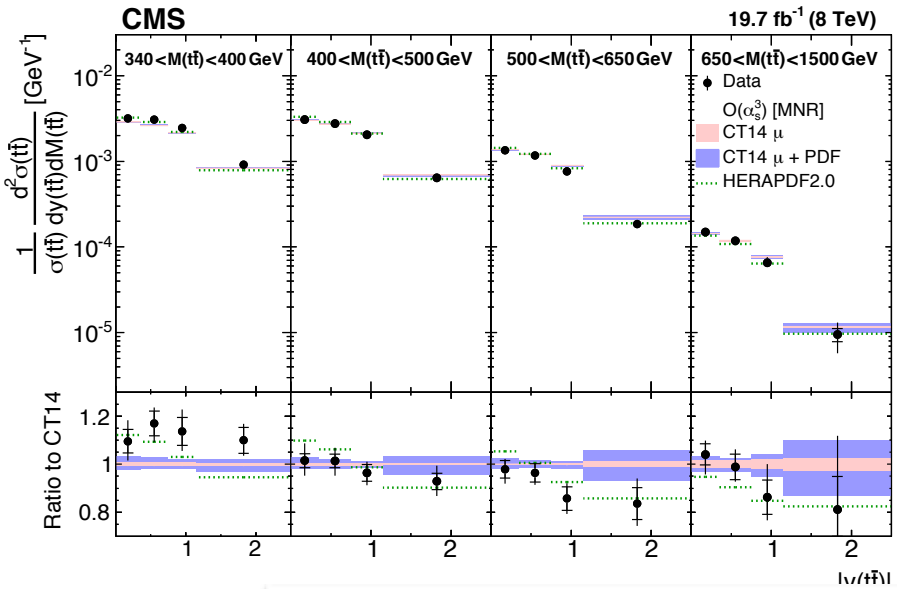


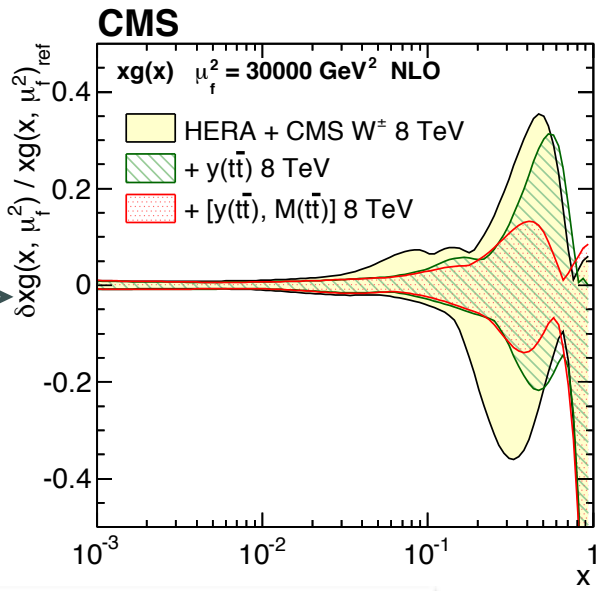
σ_{tt}: α_S or PDF

- Alternatively determine α_S or PDF
- Double-differential tt measurements provide improved sensitivity for PDF



EPJC 75 (2015) 288

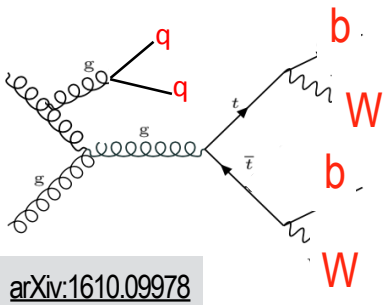




arXiv:1703.01630

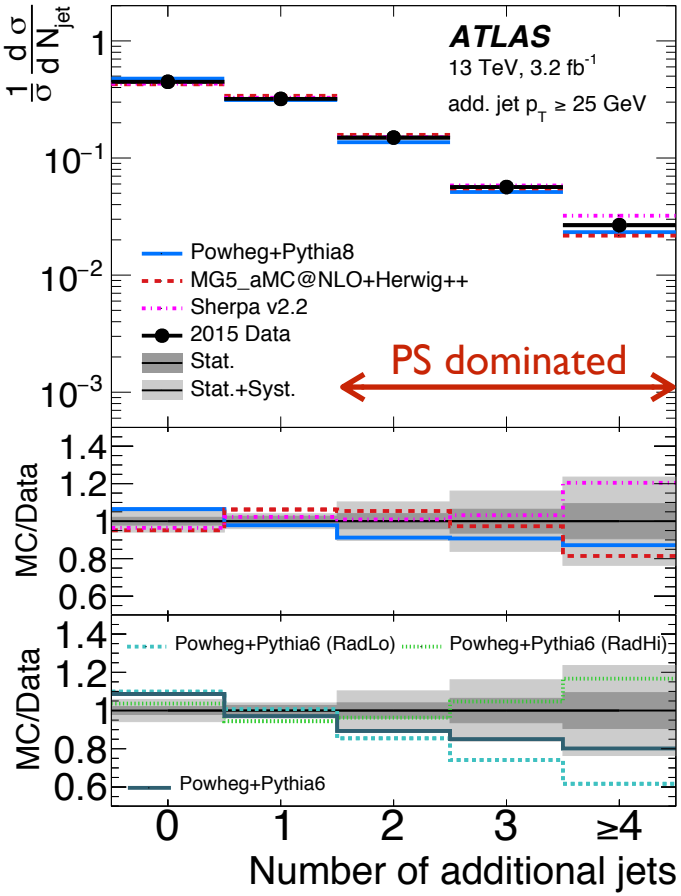
Run-II: Aim to constrain α_S, m(top) and PDF simultaneously

$t\bar{t}$+jets

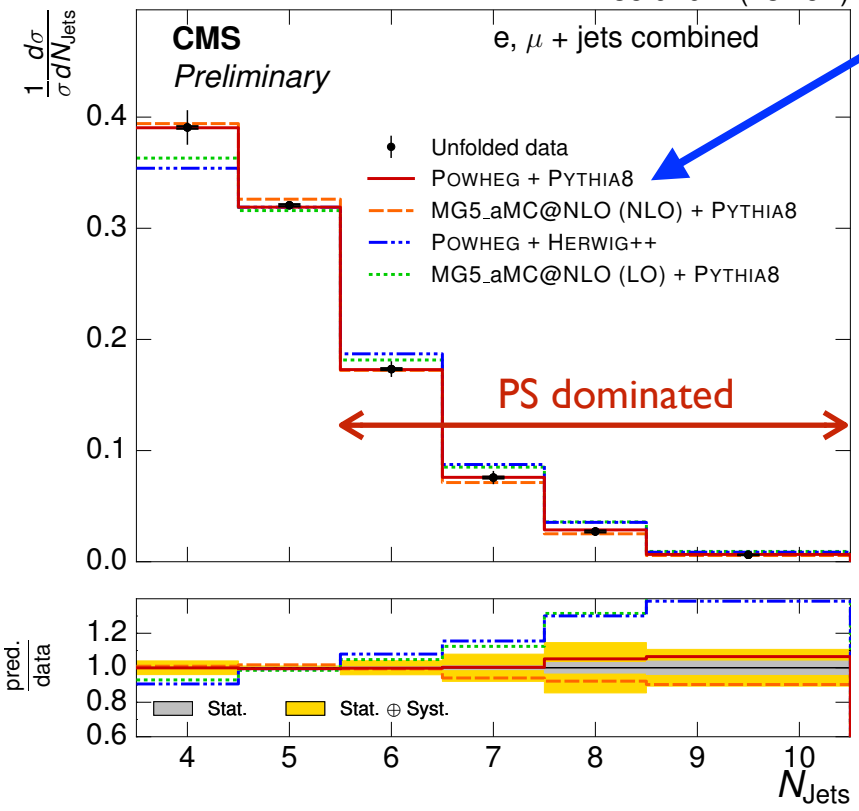


- tt+j is dominant background in many search analyses
- New era of MC generators for Run-II (NLO ME+PS):
  - Powheg v2, aMC@NLO, Sherpa, …
  - PYTHIA8 and HERWIG++/7

arXiv:1610.09978



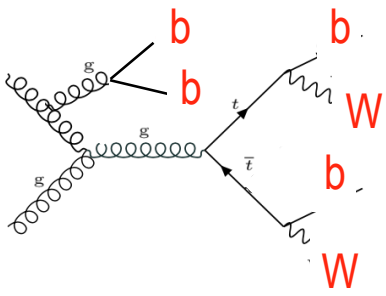
CMS-PAS-TOP-16-014



new tune

Substantial tuning efforts to achieve optimal description of the data by MC

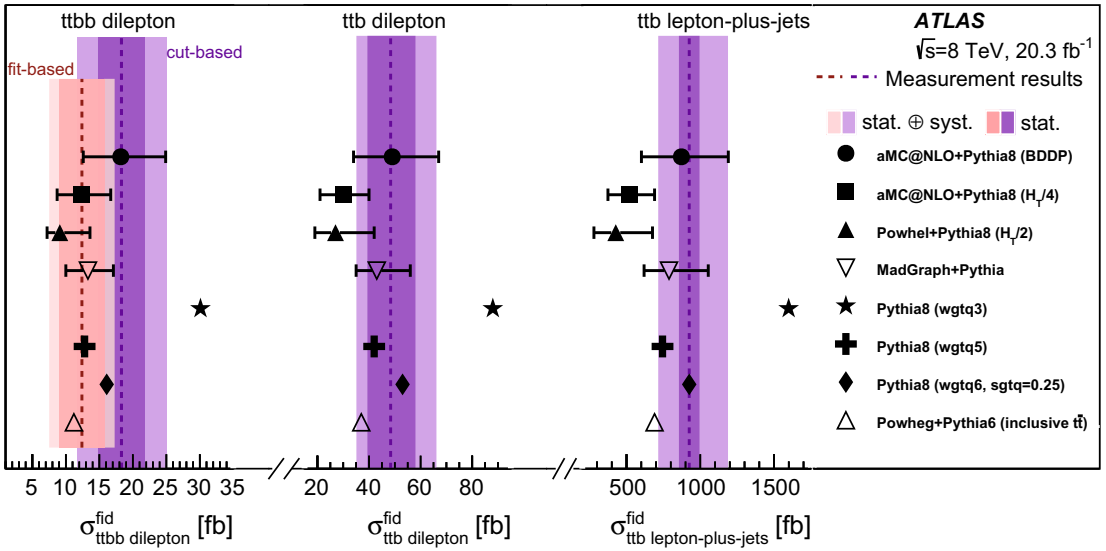
$t\bar{t}+b\bar{b}$



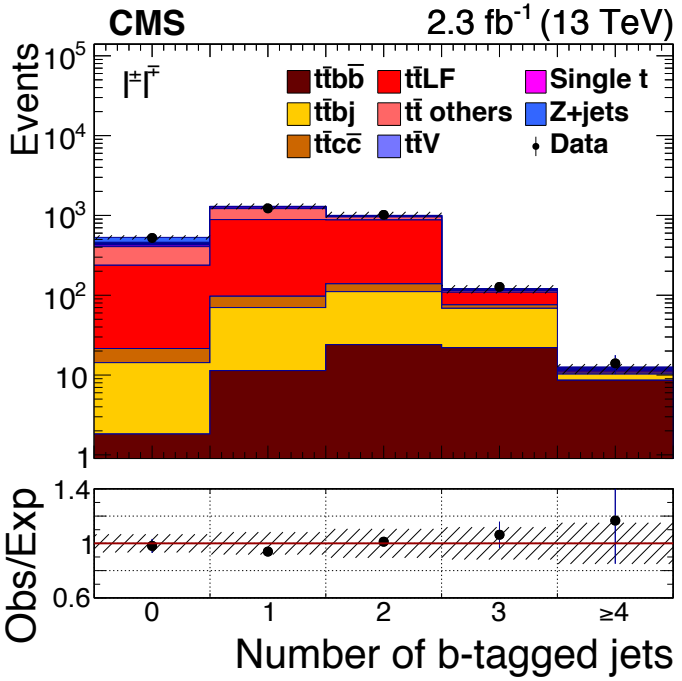
- **tt+b is dominant background esp. to ttH with H → bb**
- **Precise calculations are a challenge for theory**

- **Analysis:**
  - 3 or 4 b-jets, fit to b-tag discriminator in categories of jets and b-jets
- **CMS (13 TeV):**
  - 2ℓ, pt(jet)>20 GeV - low, but currently also used for ttH analysis
- **ATLAS (8 TeV):**
  - 1ℓ and 2ℓ, pt(jet)>25 GeV

arXiv:1508.06868



arXiv:1705.10141

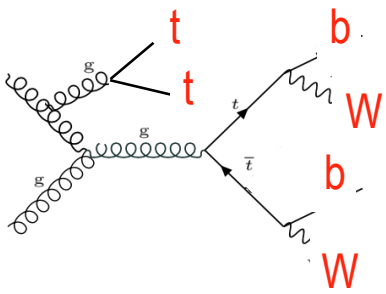


CMS: $\sigma_{ttbb}/\sigma_{ttjj} = 0.022 \pm 0.003_{stat} \pm 0.006_{syst}$

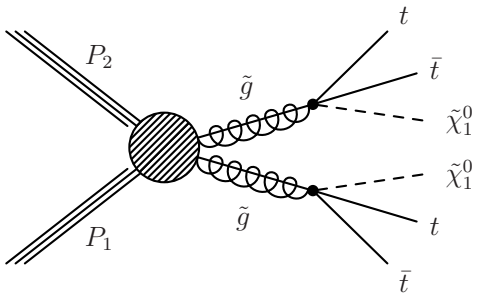
Powheg: $\sigma_{ttbb}/\sigma_{ttjj} = 0.012 \pm 0.001_{stat}$

Data becoming more precise than current predictions

$t\bar{t}+t\bar{t}$

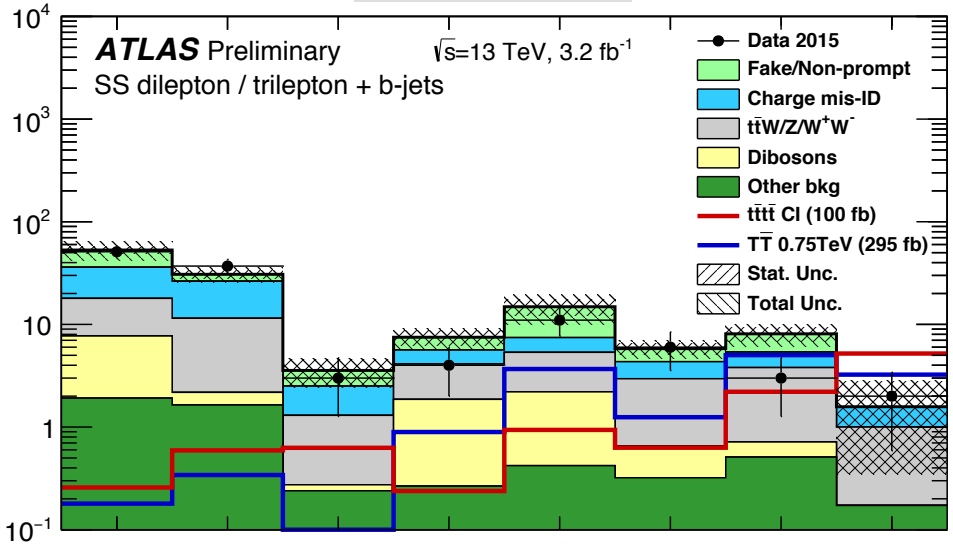


- tttt cross section very small (SM: ~9 fb)
- Expect enhancement from new physics, e.g.:



- Signature: many ℓ, many jets (including 4 b-jets), H_T, missing E_T
- Several analyses: Fit in categories, in-situ constraint of dominant bg (e.g. tt+W or Z)

ATLAS-CONF-2016-032

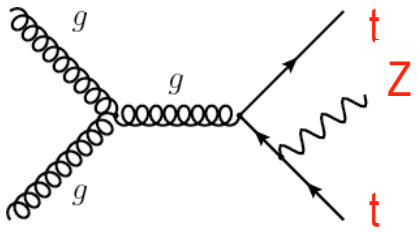


Limits from 4-top searches at 13 TeV:

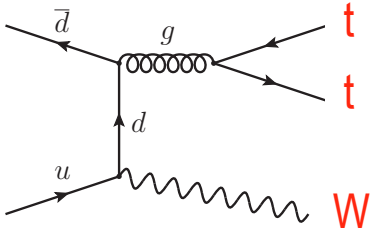
Dataset	Analysis	Limit (95 CL) obs (exp.)	Reference
3.2 fb^{-1}	1ℓ fit in categories	**6.5(9.1) × σ_{SM}**	ATLAS-CONF-2016-020
3.2 fb^{-1}	ℓℓ (same sign) fit in categories	**4.6(3) × σ_{SM}**	ATLAS-CONF-2016-032
2.6 fb^{-1}	1+2ℓ comb. BDT	**8(8) × σ_{SM}**	CMS arXiv: 1702.06164
36 fb^{-1}	2ℓ fit in categories	**4.6(2.9) × σ_{SM}**	CMS arXiv: 1704.07323

Upper limits approaching SM cross section expectation

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

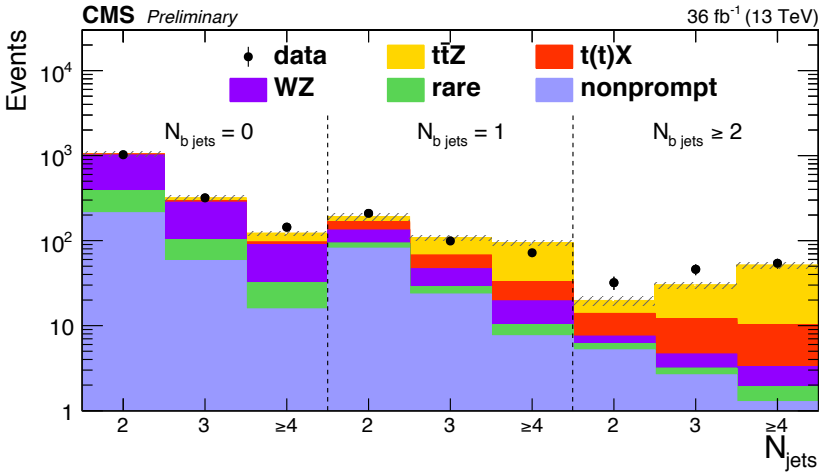


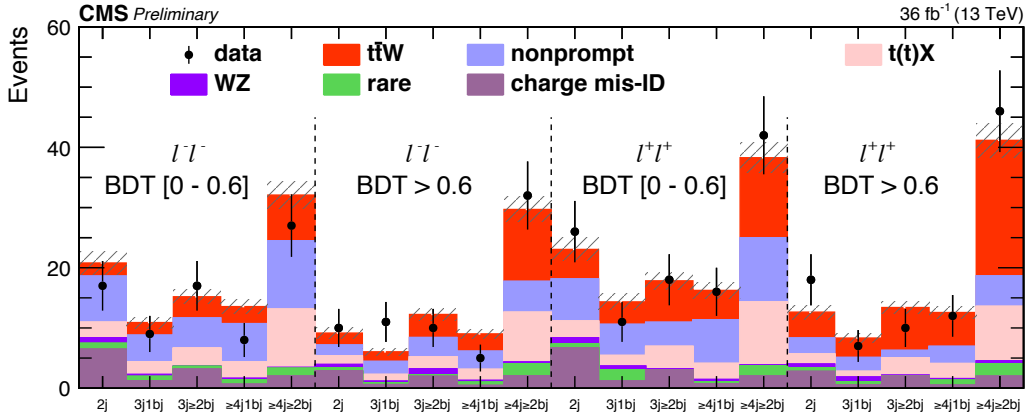
3ℓ or 4ℓ + b-jets



2ℓ (same-sign) + b-jets

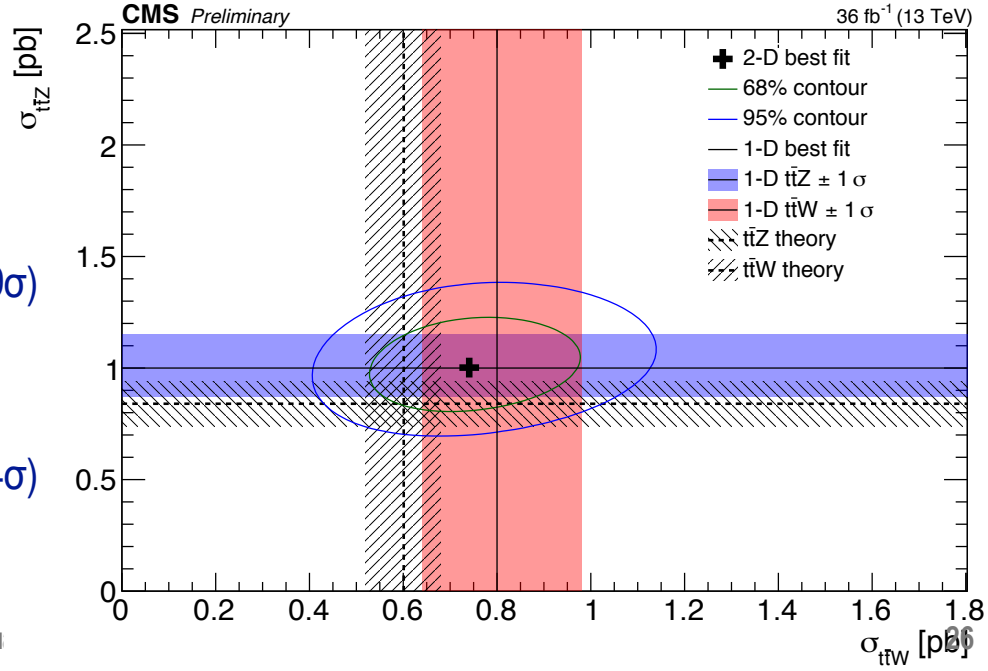
CMS-PAS-TOP-17-005





- **CMS (full 2016, 36 fb^{-1}):**
  - Leptons and b-jets, overlap with ttH (H⟶ multi-ℓ)
  - Fit to jet and b-jet categories (ttZ), BDT (ttW)
  - Significance obs(exp.): ttW: 4.6σ(5.5σ), ttZ: 9.5σ(9.9σ)

- **ATLAS (2015, 3.2 fb^{-1}):** arXiv:1609.01599
  - Significance obs(exp.): ttW: 2.2σ(1.0σ), ttZ: 3.9σ(3.4σ)



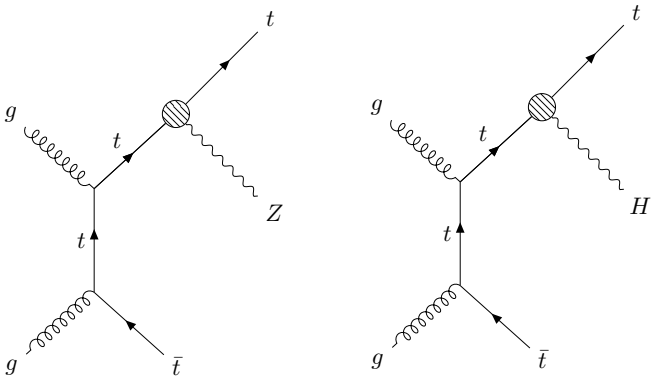
ttZ joining precision regime

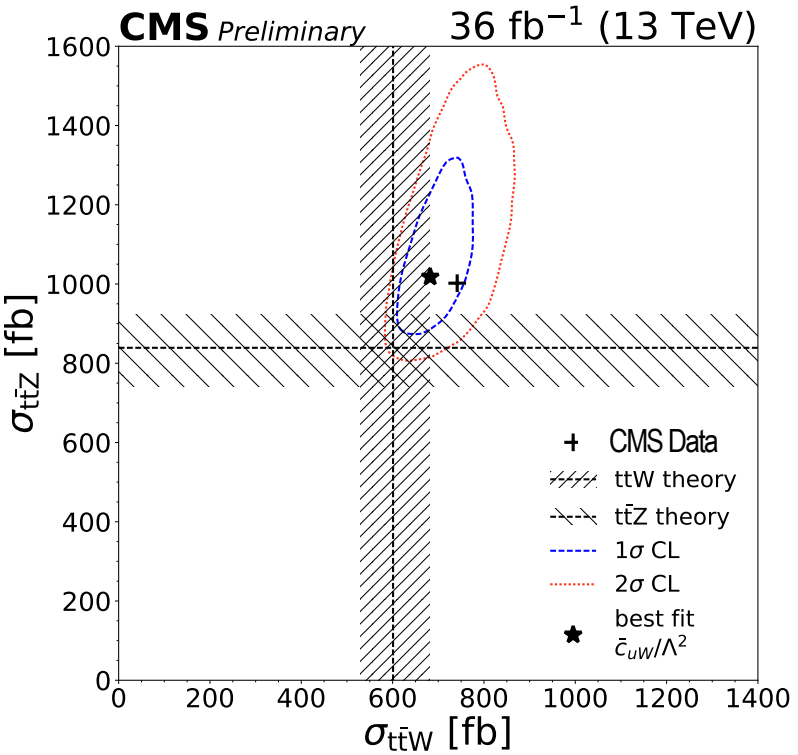
Effective Field Theory Interpretation

CMS-PAS-TOP-17-005

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i c_i \mathcal{O}_i + \frac{1}{\Lambda^2}\sum_j c_j \mathcal{O}_j + \cdots$$

- **EFT Lagrangian:**
  - Expansion by inverse energy scale 1/Λ
  - 59 (B and L-conserving) dim-6 operators
  - Model-independent search for new phenomena
- **First approach:**
  - Only consider those operators with impact on ttW, ttZ and ttH, not those for tt, WW, ZZ, WZ
  - One coefficient c_j at a time
  - Determine best c_j from simultaneous fit to signal strengths for ttZ and ttW, i.e. possible effects on acceptance/kinematics are not corrected for





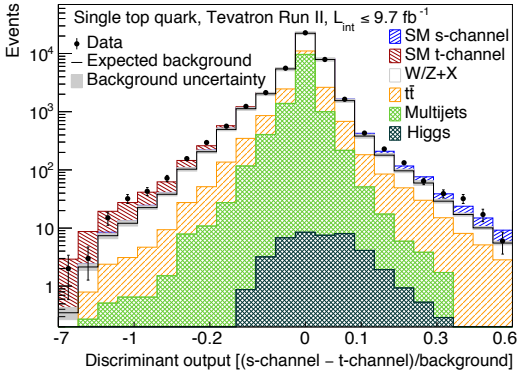
Wilson coefficient	Best fit [TeV^{-2}]	1σ CL [TeV^{-2}]
$\lvert\bar{c}_{uB}/\Lambda^2\rvert$	1.6	[0.0, 2.3]
$\lvert\bar{c}_{u}/\Lambda^2 + 10.9\ \text{TeV}^{-2}\rvert$	11.1	[2.7, 15.6]
$\bar{c}_{uW}/\Lambda^2$	1.8	[-2.4, -0.8] and [0.7, 2.4]
$\bar{c}_{Hu}/\Lambda^2$	-9.4	[-10.3, -8.1] and [0.1, 2.1]

observed values are very similar to SM-expected

Single-Top Production

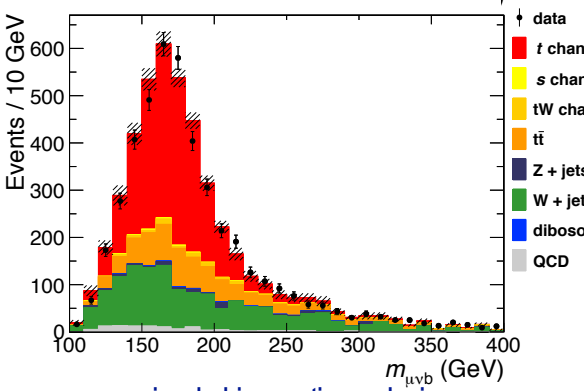
- Test of EW interactions
- Sensitivity to b-PDF and u/d-PDF
- V_{tb} / 4th generation / FCNC

D0 and CDF combined arXiv:1503.05027

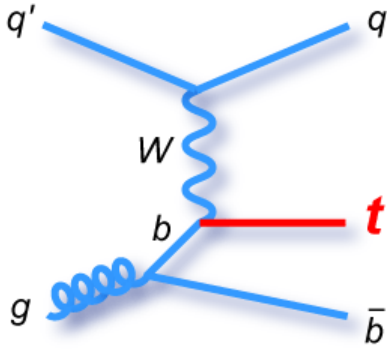


complex multivariate analysis

LHC Run-I



simple kinematic analysis

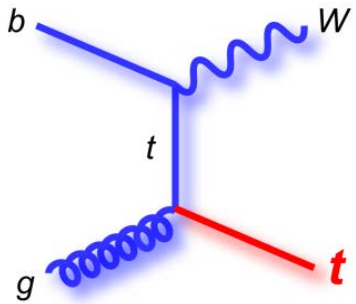


$\sigma(7\ \text{TeV}) = 64\ \text{pb} \pm 4.5\%$

$\sigma(8\ \text{TeV}) = 85\ \text{pb} \pm 4.4\%$

$\sigma(13\ \text{TeV}) = 217\ \text{pb} \pm 4.1\%$

$R_{13/8} = 2.6$

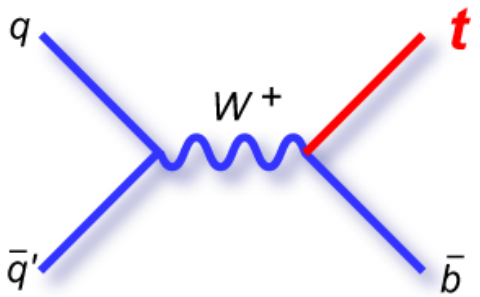


$\sigma(7\ \text{TeV}) = 15.7\ \text{pb} \pm 7.6\%$

$\sigma(8\ \text{TeV}) = 22.4\ \text{pb} \pm 6.8\%$

$\sigma(13\ \text{TeV}) = 71.7\ \text{pb} \pm 5.3\%$

$R_{13/8} = 3.2$



$\sigma(7\ \text{TeV}) = 4.3\ \text{pb} \pm 4.4\%$

$\sigma(8\ \text{TeV}) = 5.2\ \text{pb} \pm 4.2\%$

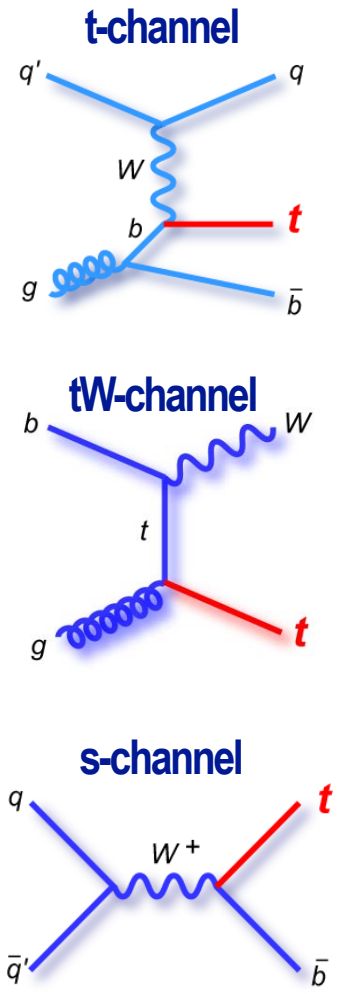
$\sigma(13\ \text{TeV}) = 10.3\ \text{pb} \pm 3.9\%$

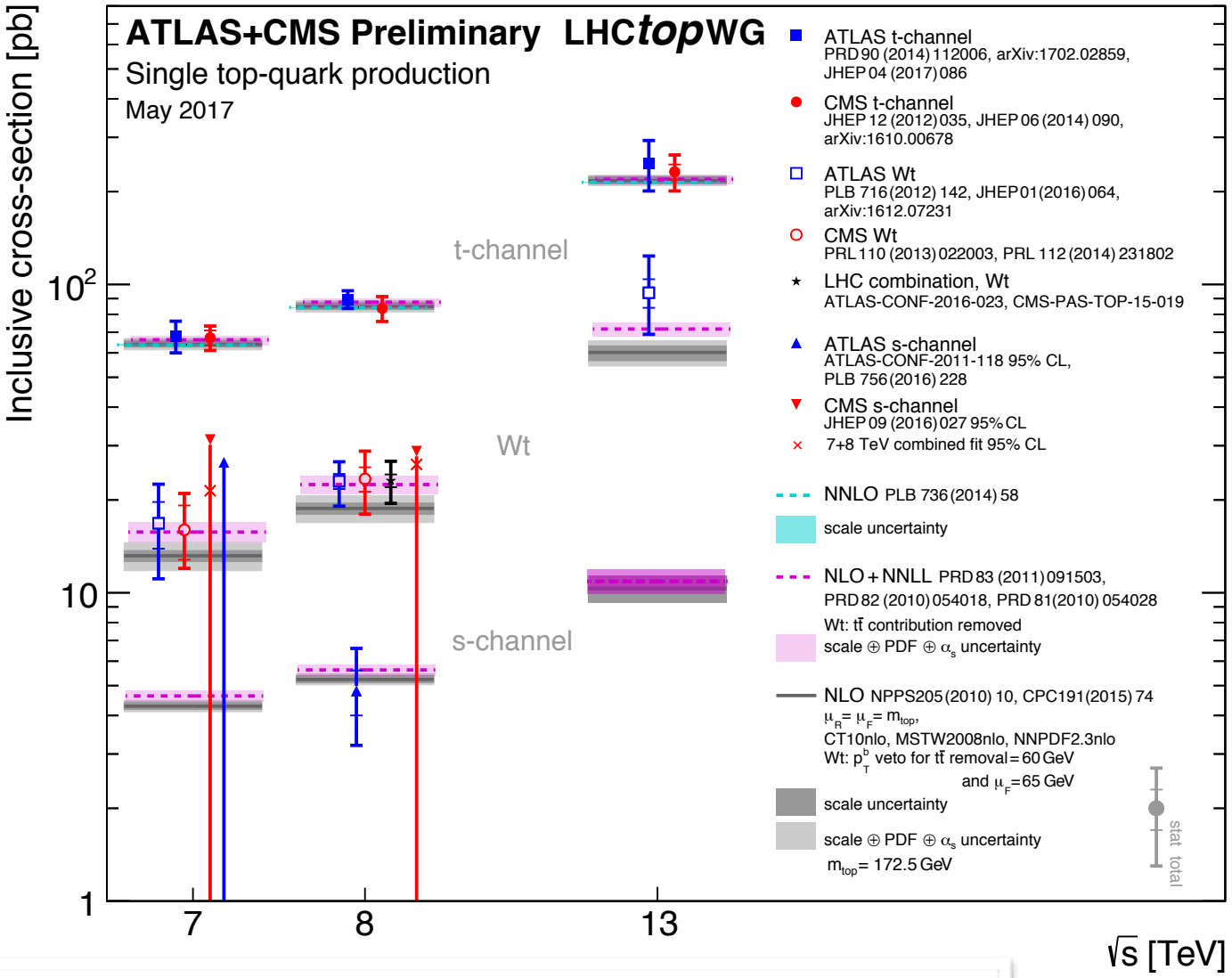
$R_{13/8} = 1.9$

Single-top cross sections at Run-II are as large as the tt cross section at Run-I

Single-Top Quark Cross Sections

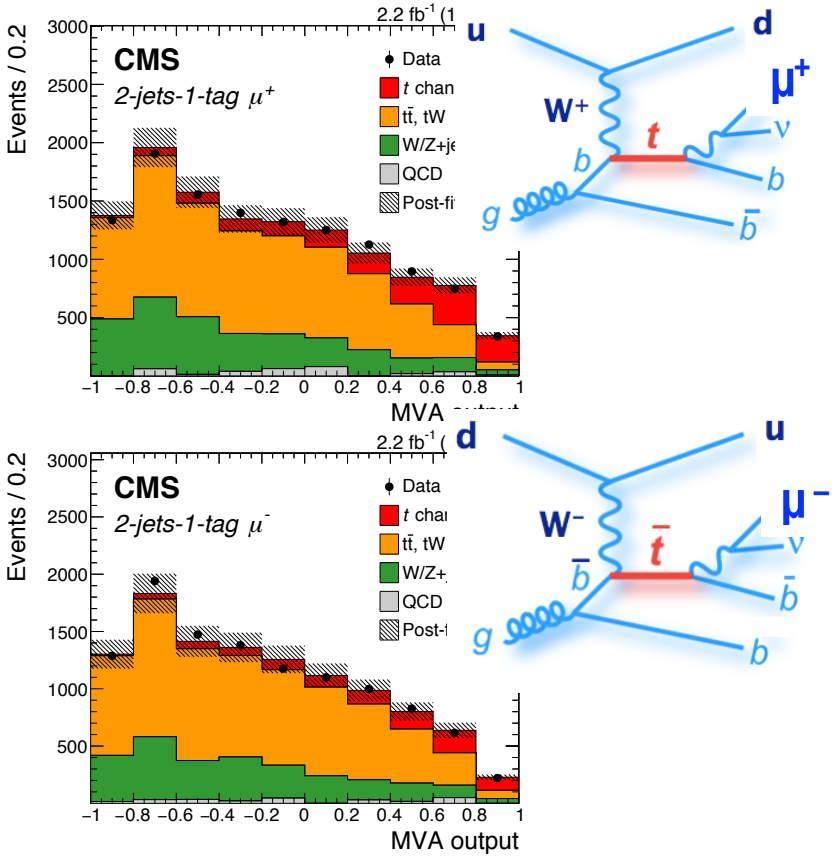
LHCtopWG





Single-top cross sections at Run-II are as large as the tt cross section at Run-I

Single-top quark (t-channel)

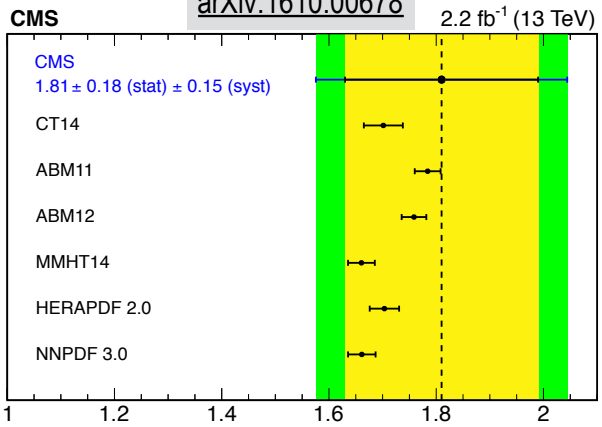


$\sigma_{t(CMS,\ 13\ TeV)} = 238 \pm 13_{stat} \pm 29_{syst} \pm 5_{lumi}$ pb

$\sigma_{t(ATLAS,\ 13\ TeV)} = 247 \pm 6_{stat} \pm 45_{syst} \pm 5_{lumi}$ pb

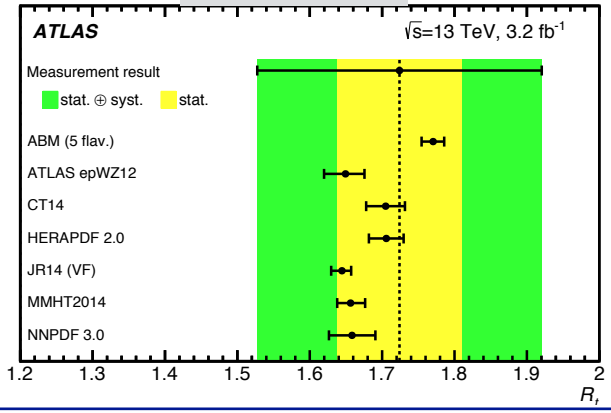
$\sigma_{t(NNLO)} = 217 + 6.6\text{-}4.6_{scale} \pm 6.2_{PDF+\alpha S}$ pb

arXiv:1610.00678



$R_t = 1.81 \pm 0.18_{stat} \pm 0.15_{syst}$

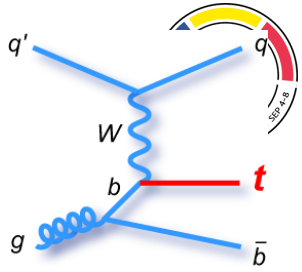
arXiv:1609.03920



$R_t = 1.72 \pm 0.09_{stat} \pm 0.18_{syst}$

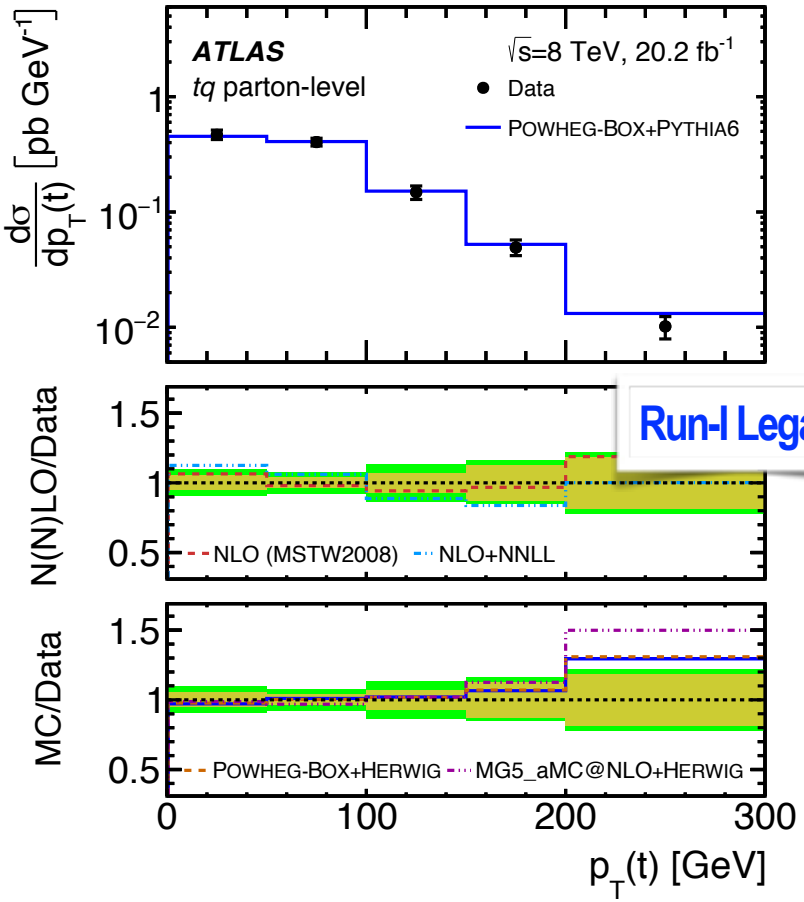
Cross section ratio R_t: sensitivity to u/d

Single-Top Quark Differential Cross Sections



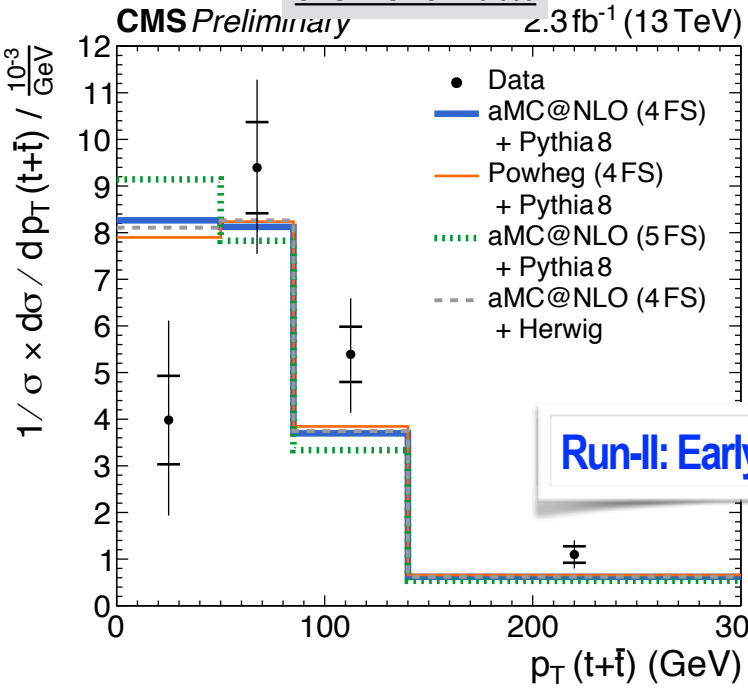
- Full Run-I statistics (20fb^{-1}) were already large enough for precise differential measurements
- Results available at parton-level and particle-level (minimal theoretical assumptions)

arXiv:1702.02859



Run-I Legacy

CMS-PAS-TOP-16-003



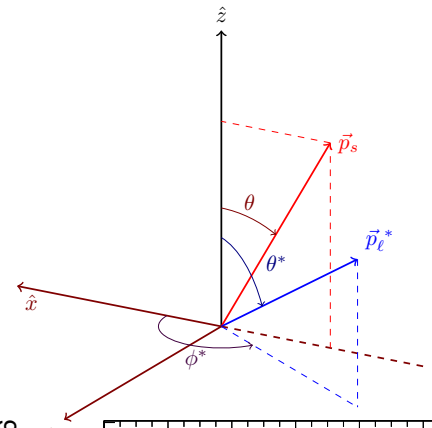
Run-II: Early Analysis

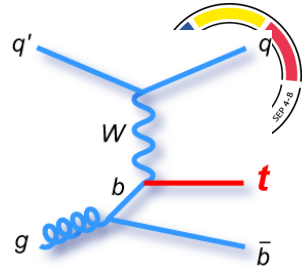
Results with more Run-II data expected soon
TOP2017 in 2 weeks from now

Single-Top Quark Polarization

- V-A: expect top quarks to be highly polarised: $P \approx 1$

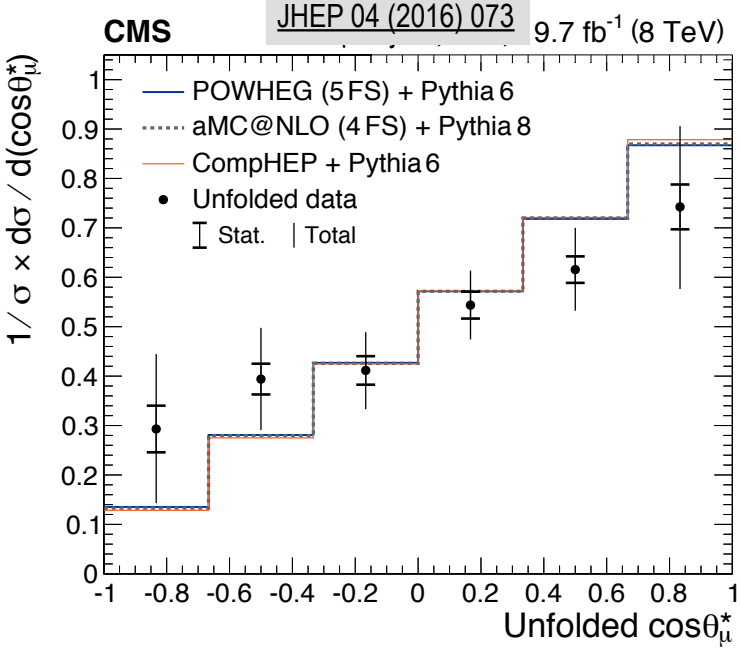
$$\frac{1}{2}\alpha_\ell P = A_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

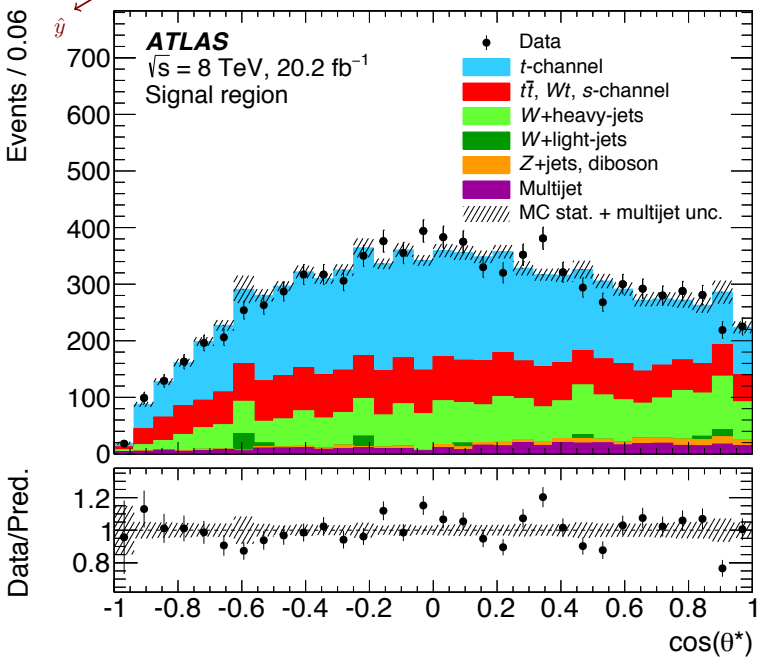




arXiv:1707.05393

JHEP 04 (2016) 073





$A_{FB} = 0.26 \pm 0.03_{stat} \pm 0.10_{syst}$

Simultaneous determination of all anomalous Wtb couplings and top polarisation

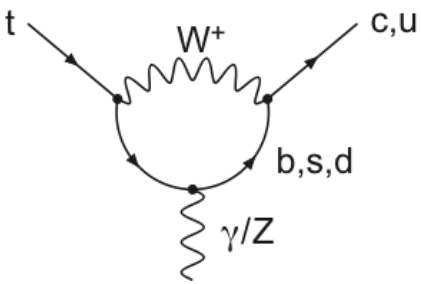
ATLAS: arXiv:1702.08309

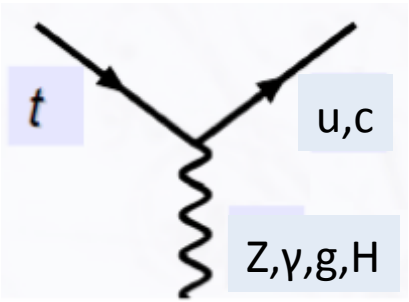
$A_{FB} = 0.49 \pm 0.03_{stat} \pm 0.05_{syst}$

$A_{FB}^{SM} = 0.45$

$P > 0.72$ (95% CL)

Flavour Changing Neutral Currents

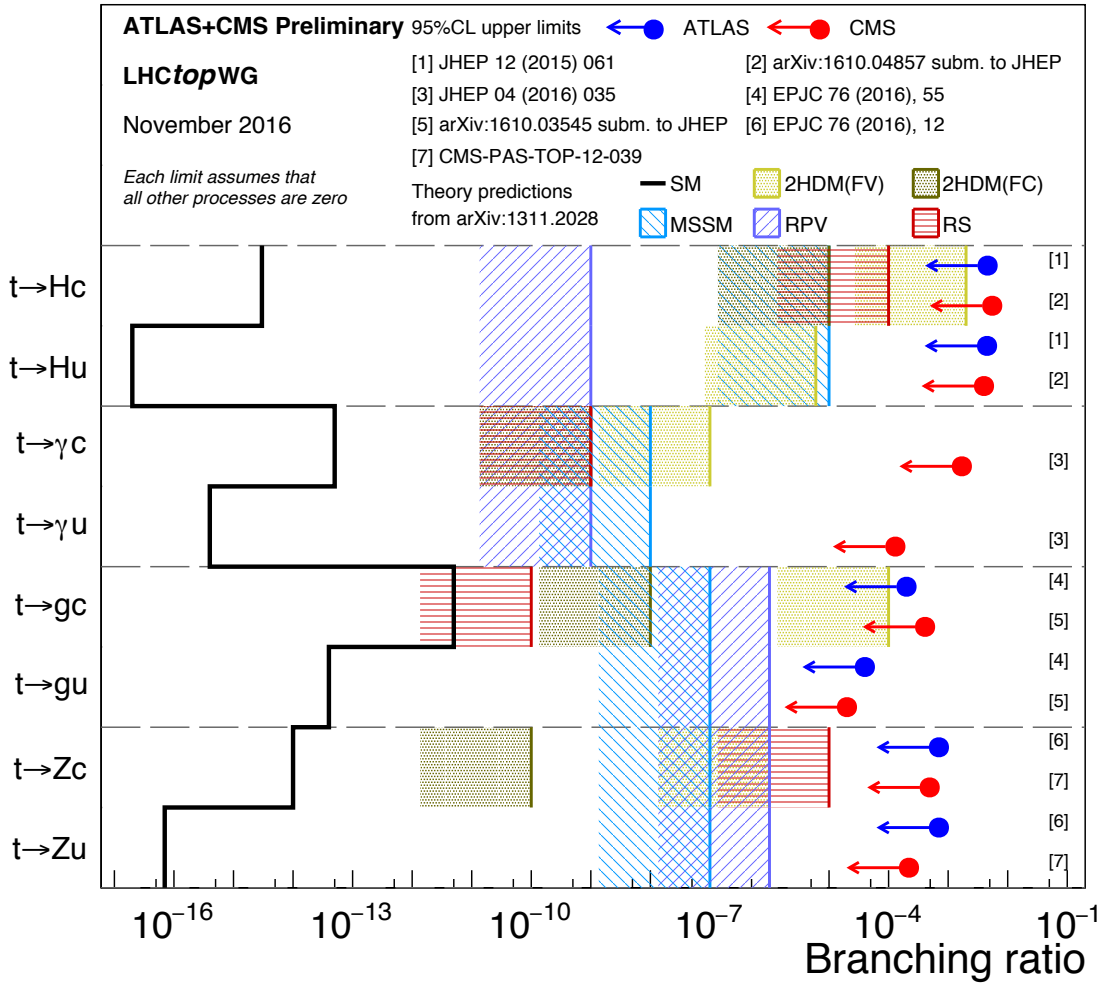




ACTA Phys. Pol. B 35 (2004)

SM: BR ~ 10^{-12} ... 10^{-17}

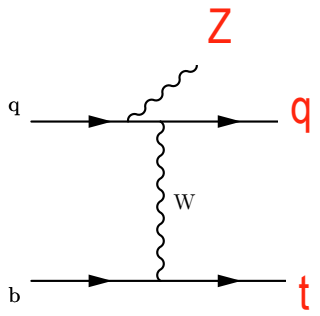
BSM: BR ~ 10^{-5} ... 10^{-9}



LHC data closing in on some BSM scenarios with enhanced FCNC

tZq

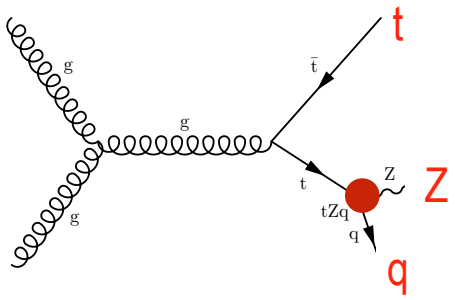
SM



- **ATLAS (Run-II, full 2016 data)**

  First evidence: 4.2σ(5.3σ) obs(exp)

  $\sigma_{tqZ} = 600 \pm 170_{stat} \pm 140_{syst}$ fb



FCNC

- **CMS (Run-I):**

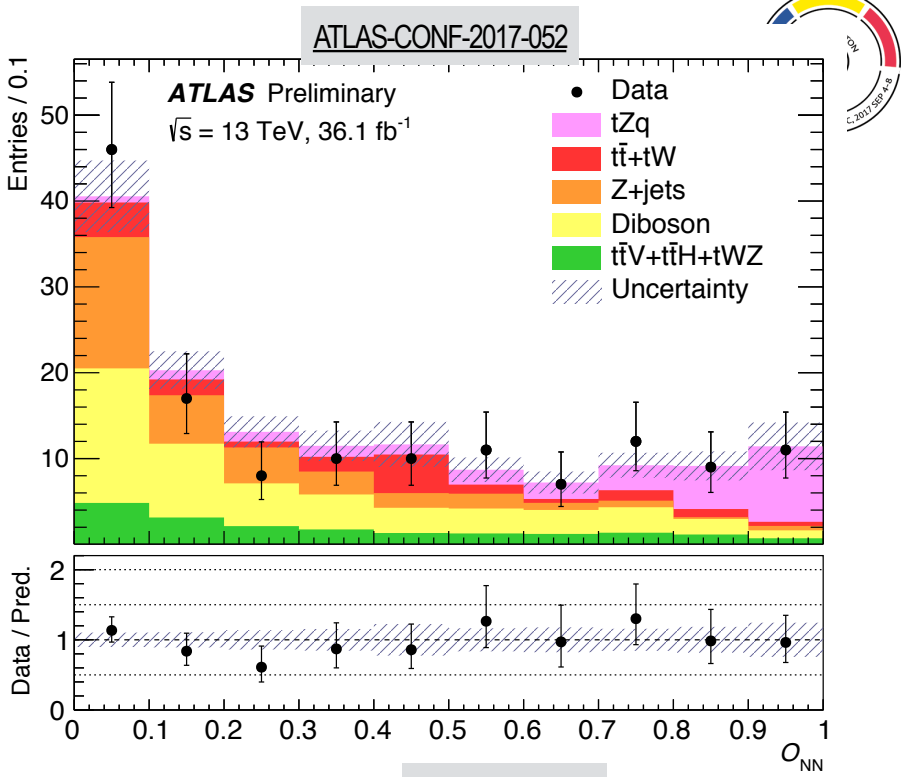
  Significance: 1.8σ(0.8σ) obs(exp)

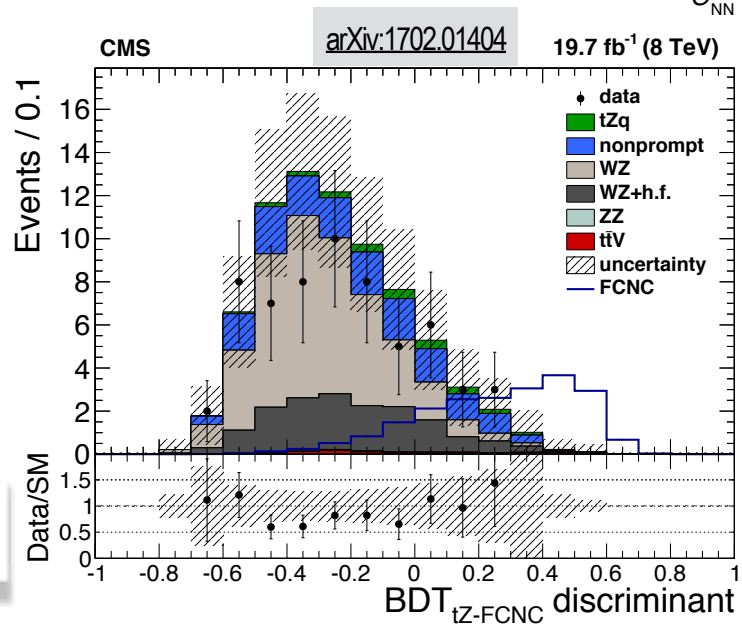
  Limits 95% C.L. on FCNC:

  BR(t→Zu) < 0.022 (0.027) obs(exp)

  BR(t→Zc) < 0.049 (0.118) obs(exp)

Another milestone towards the lowest-cross-sections frontier





Summary

- **LHC is a top quark factory**

- **Ultimate precision SM measurements during Run-II (first glimpse)**
  - Test of calculations ⟶ NNLO has a pt-dependent k-factor
  - Tuning of a new generation of MC generators
  - Determination and consistency checks of SM parameters (PDF, α_S, mtop)

- **Associated top quark production becoming fully accessible**
  - First precise measurement of tt+Z cross section
  - systematic and model-independent searches using EFT approach

- **Differential measurements of single-top quark production**
  - Electroweak production of single tops complements top quark pairs

- **Lots more new results expected at TOP2017 and beyond**
- **A factor two more data until end of 2018**

inclusive tt

differential tt

tt+jets

tt+bb

4 top

tt+W

tt+Z

single top

polarisation

tW

V_{tb}

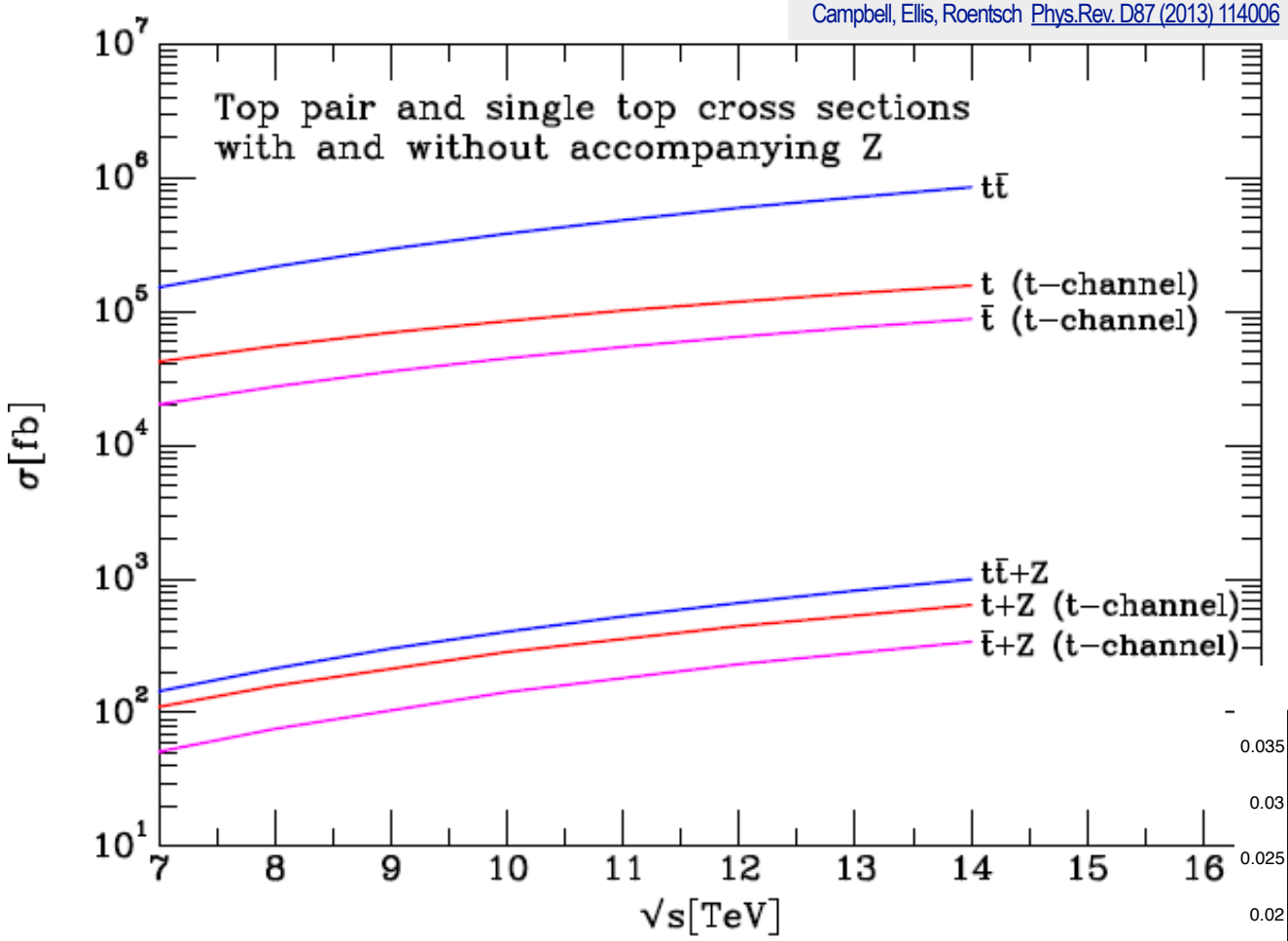
FCNC

Expect top quark physics to play a lead role in direct and indirect searches for new phenomena

Backup

Energy Dependence

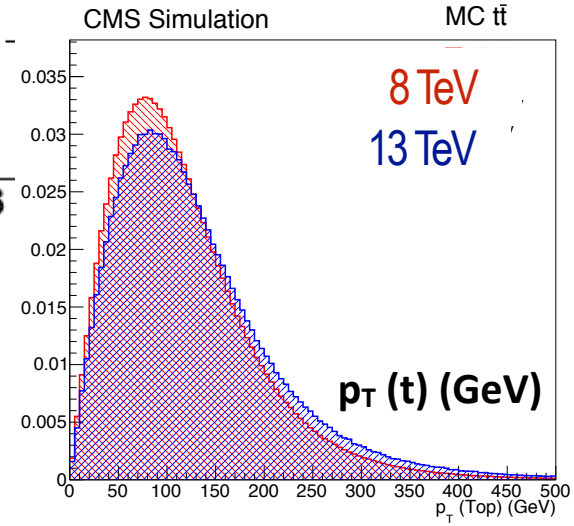
Campbell, Ellis, Roentsch Phys.Rev. D87 (2013) 114006



10 Hz (at 10^{34})

2 Hz (at 10^{34})

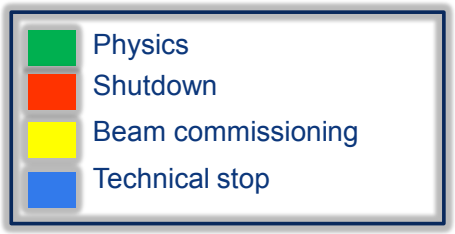
0.01Hz (at 10^{34})

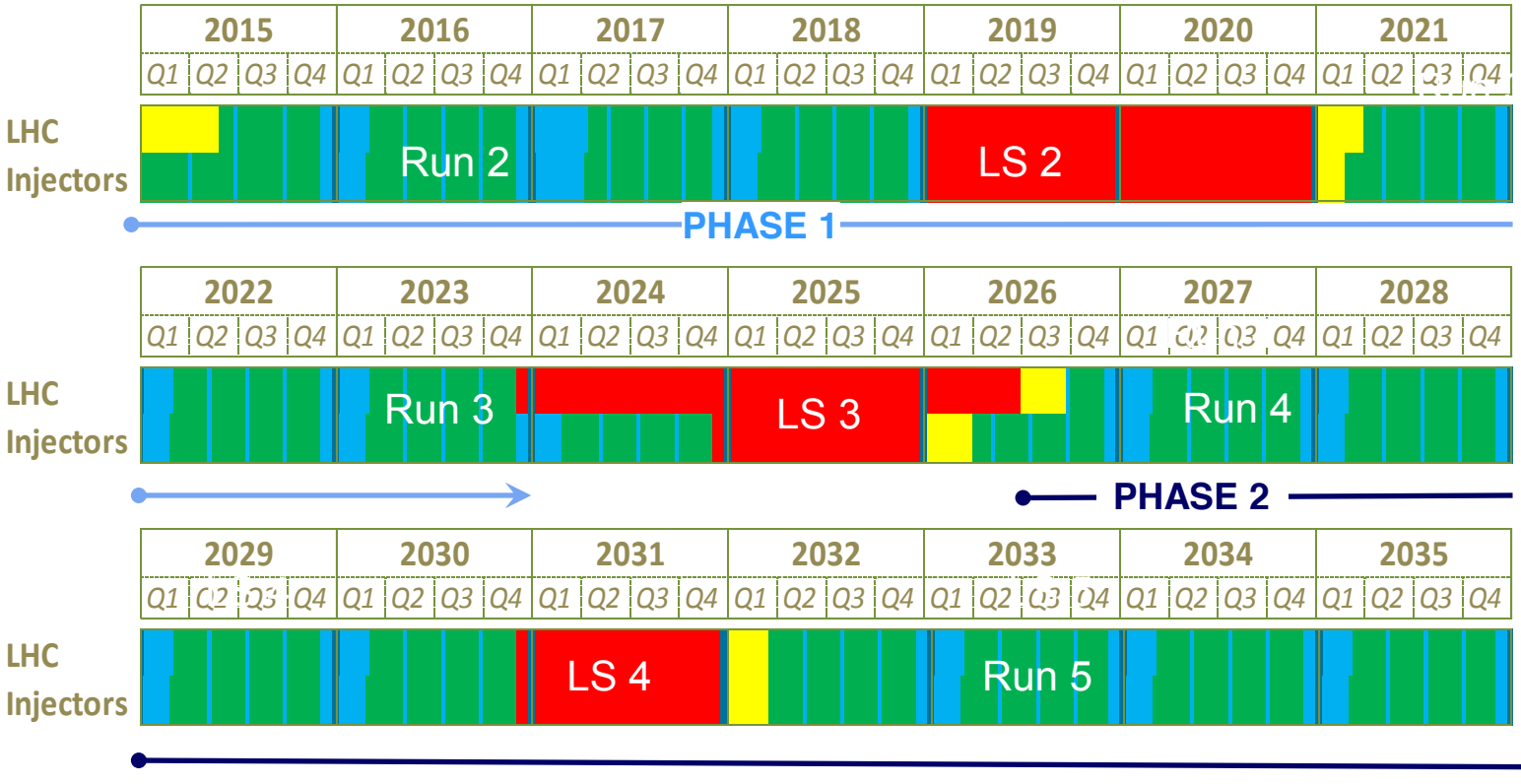


Cross section driven by rise of gluon density to low x:
→ shape of bulk distributions remains similar

LHC roadmap: according to MTP 2016-2020 V2

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC





https://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-long-term.htm