Top Quark Physics

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on behalf of the ATLAS and CMS Collaborations

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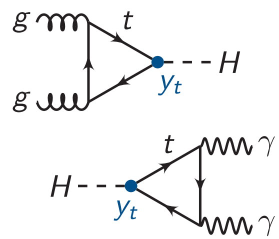
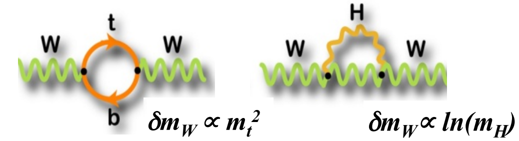
DESY

XXXVII Physics in Collision, Prague, 5 Sept 2017

QUARK - LEPTON
PRAGUE, CZECH REPUBLIC, 2017 SEP 4-8

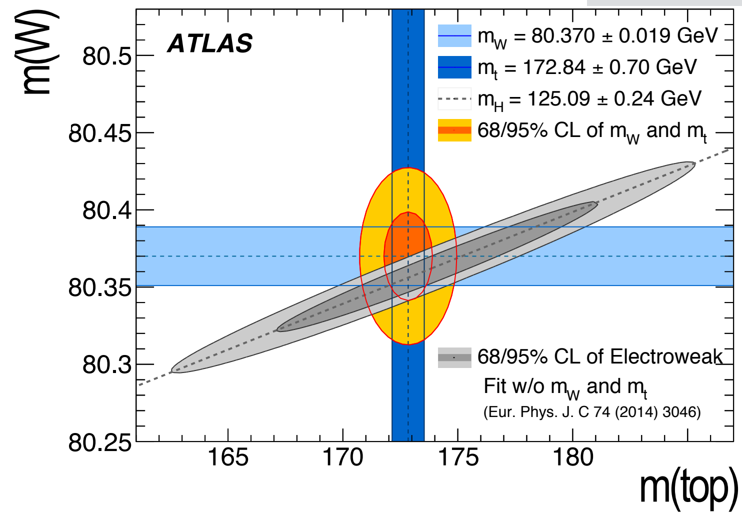
Top Quark Physics





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

arXiv:1701.07240



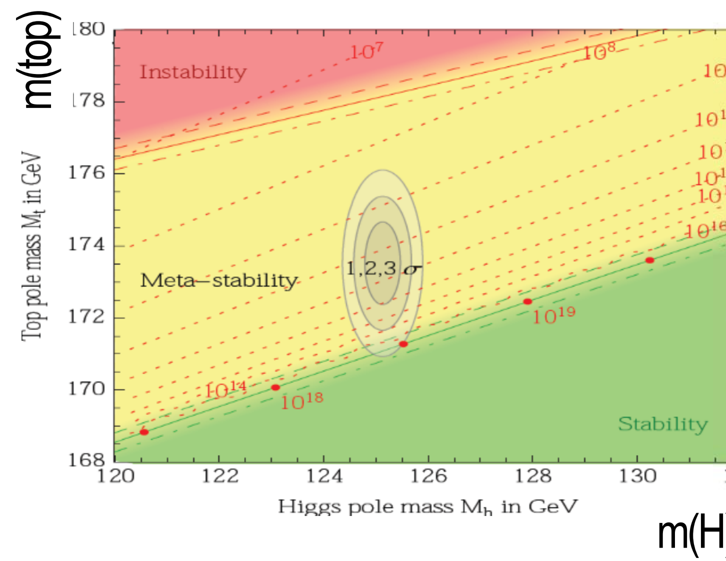
- **Timescales → unique features, bare quark**

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

- **Precision measurements of SM parameters**

$m_t,\ V_{tb},\ Y_t,\ \alpha_S,$ *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



Degrassi et al, JHEP08 (2012) 098

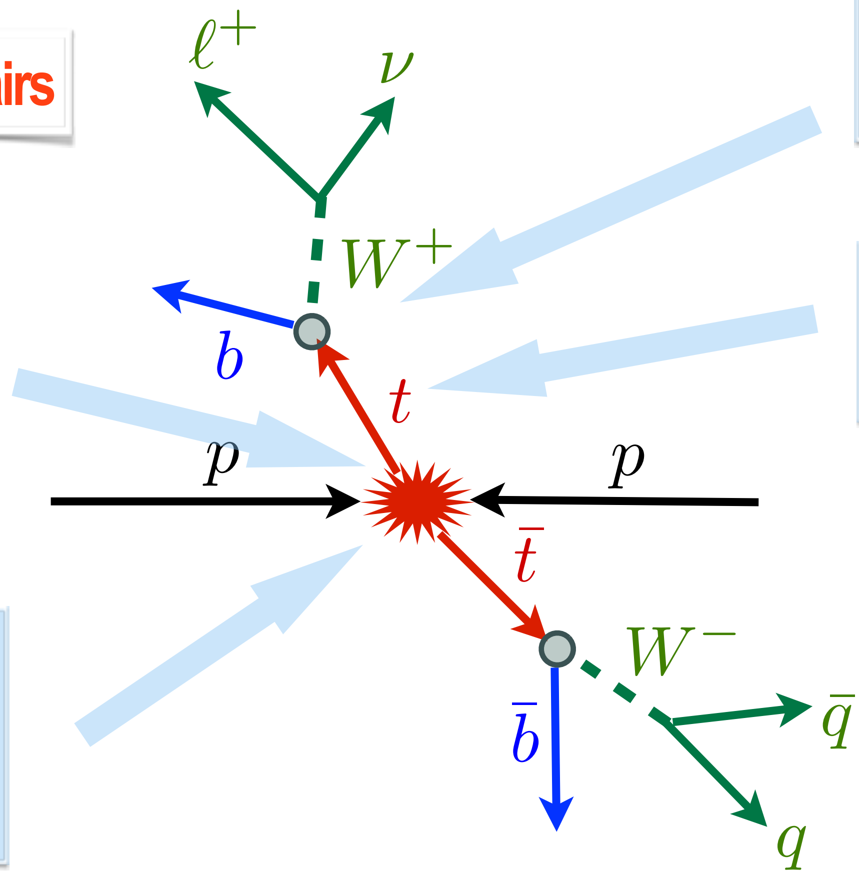
Top Quark Physics in Production and Decay

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

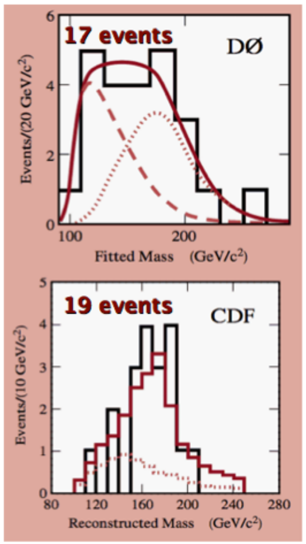
EWK Single-Top Production

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

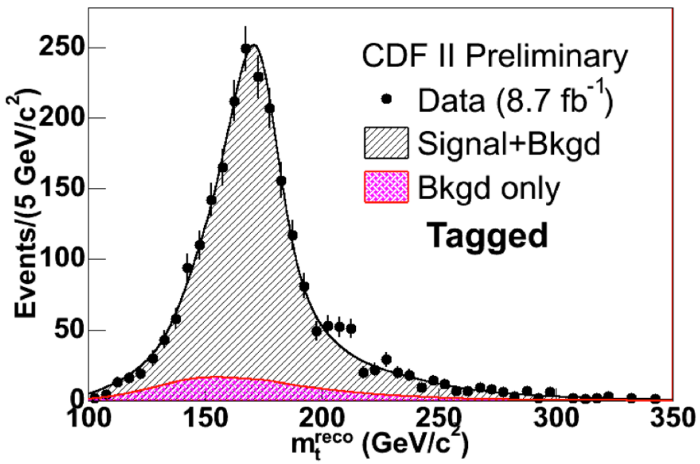
Earlier Top-Quark Results

Tevatron and LHC Run-I

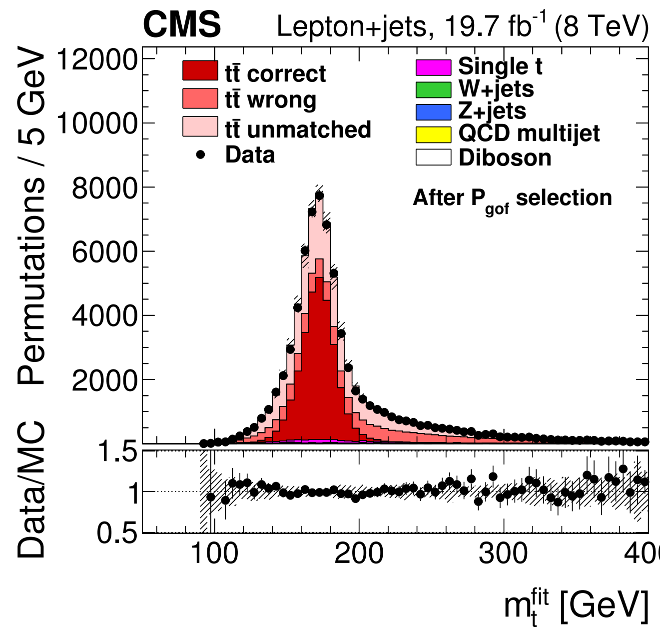
36 events



1000s of events



100000s of events



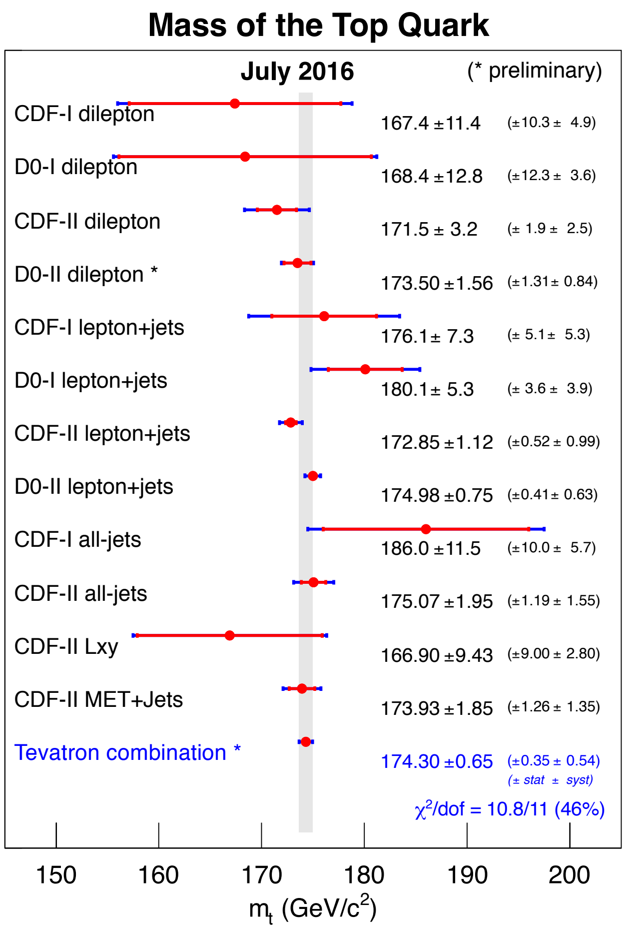
- **Tevatron $p\bar{p}$ 1.96 TeV**
  - discover
  - scrutinise and measure
  - establish top as SM quark
- **LHC Run-I pp (7 and 8 TeV)**
  - pp: complementary initial state
  - superior statistics → top factory

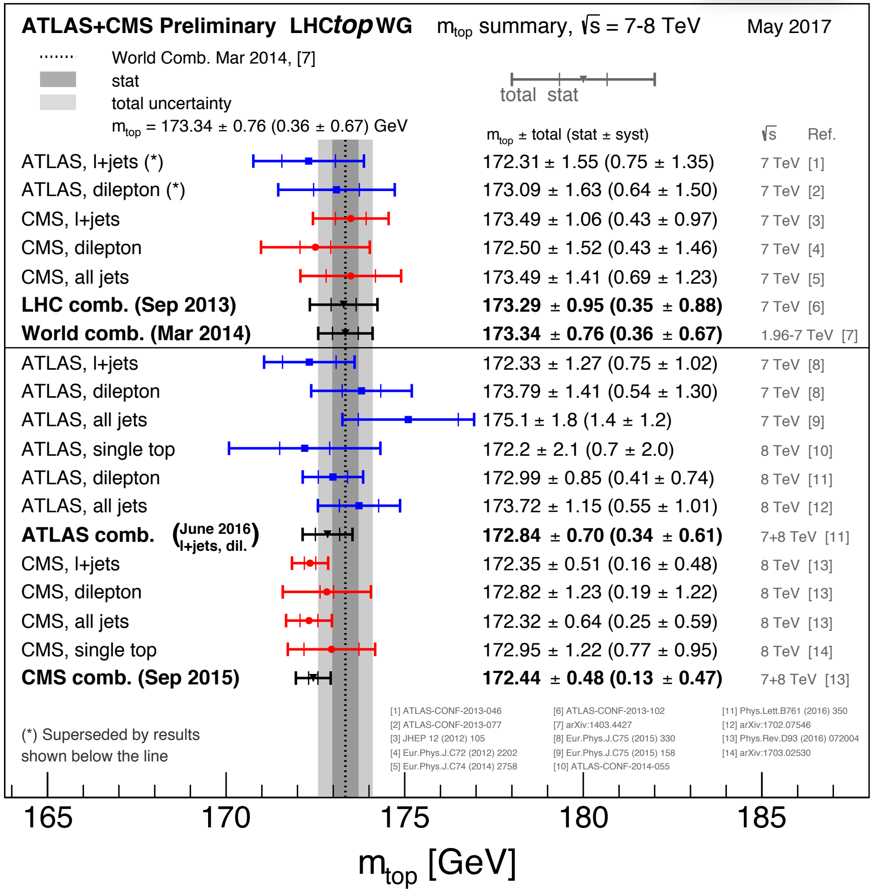
1995 — 2010 — 2012

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

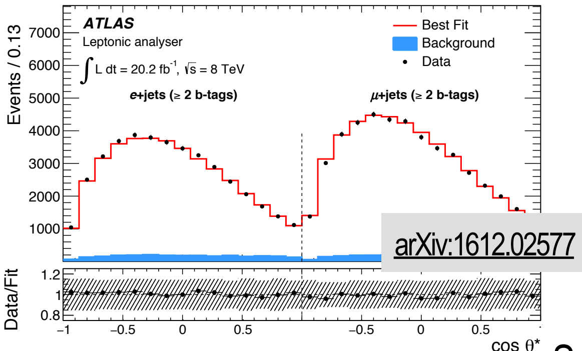
ATLAS Combination (8 TeV to come)

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

Top Quark Properties

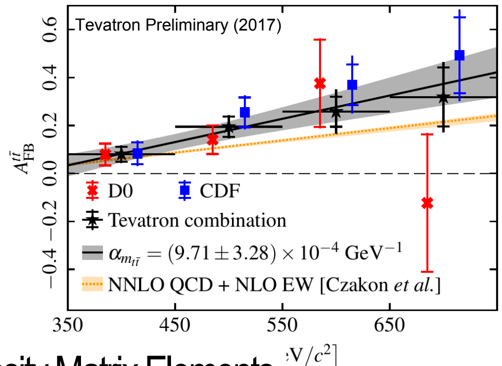
Tevatron and LHC Run-I

W Polarisation

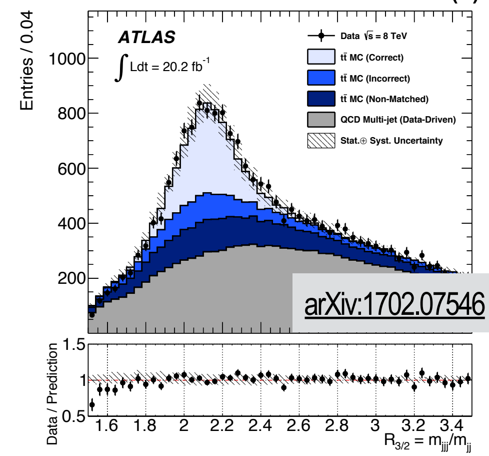


arXiv:1612.02577

Charge and FB Asymmetry

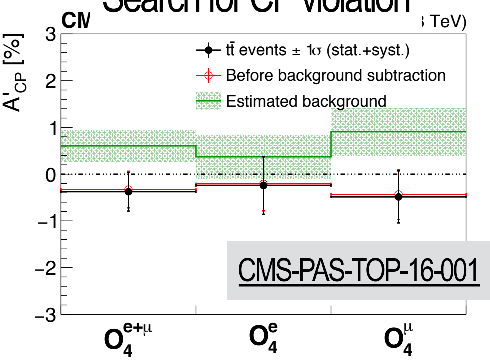


More Mass Measurements (tt)



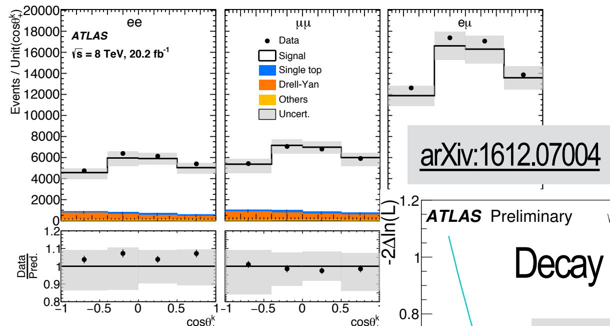
arXiv:1702.07546

Search for CP violation



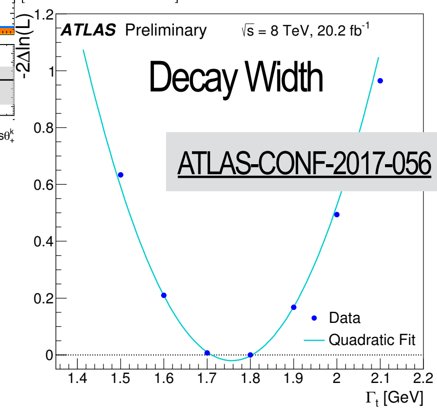
CMS-PAS-TOP-16-001

Spin Density Matrix Elements



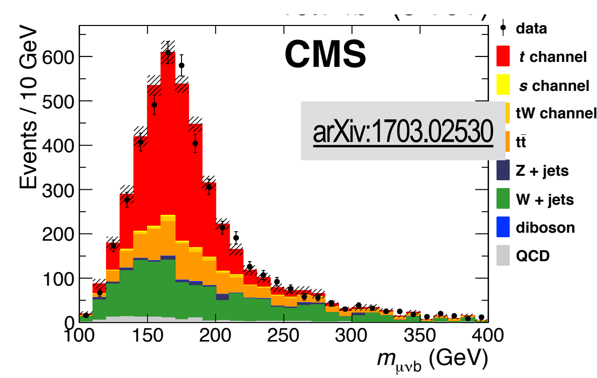
arXiv:1612.07004

Decay Width



ATLAS-CONF-2017-056

Alternative Mass Measurements



arXiv:1703.02530

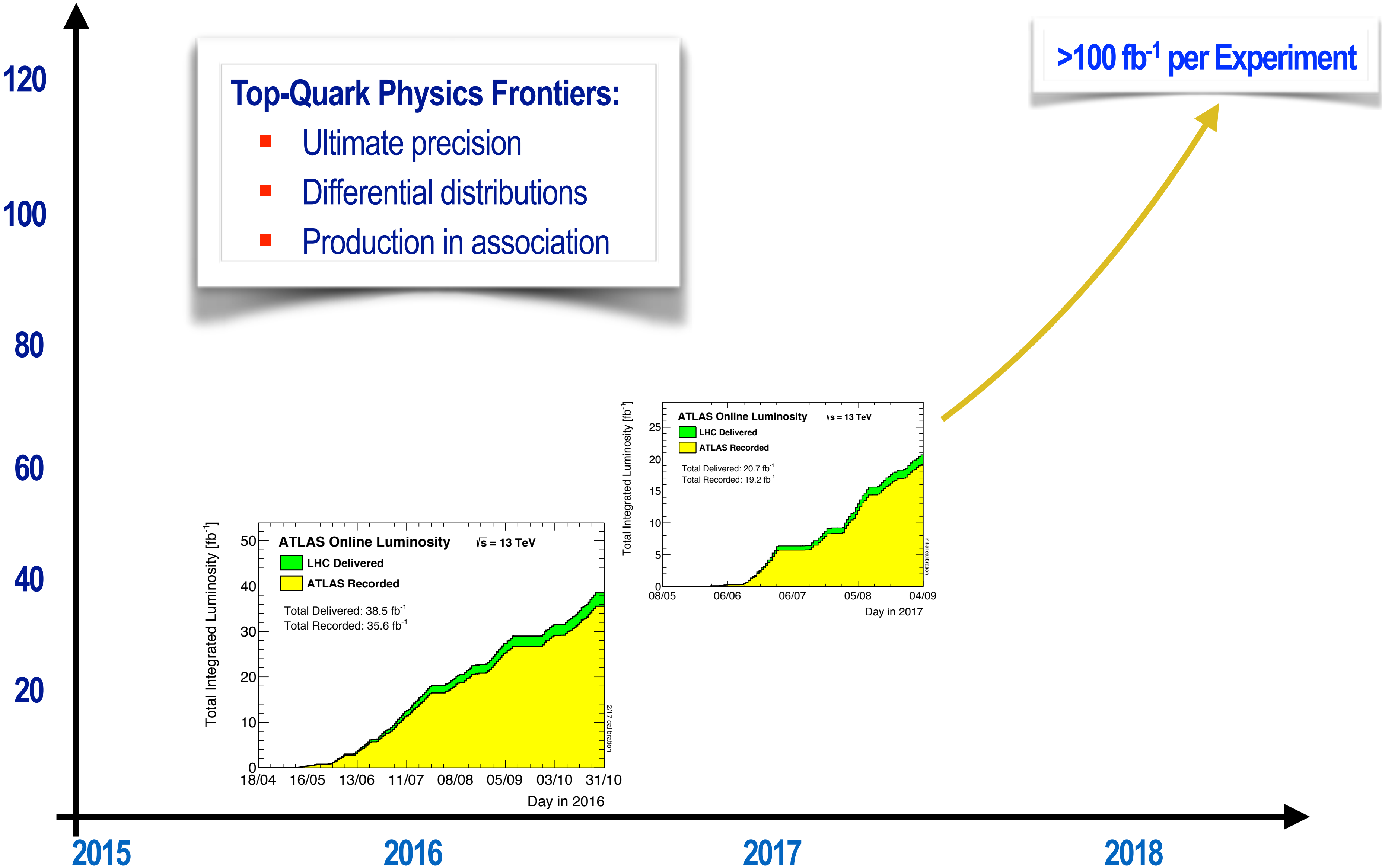
- **Tevatron and LHC Run-I Legacies:**
  Detailed measurements of top quark properties and cross sections

2012 → 2017

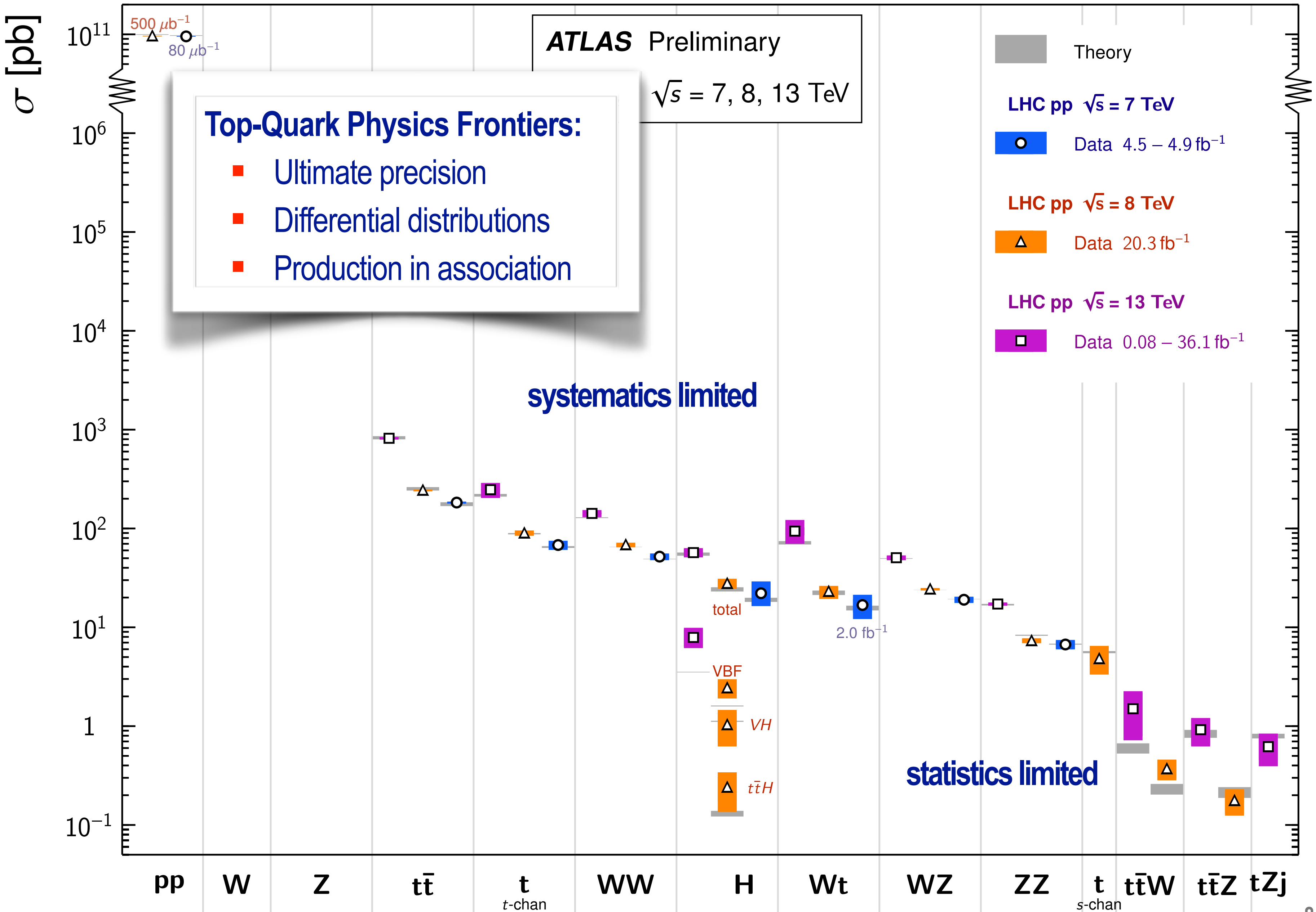
The Present: LHC Run-II

Top-Quark Physics Frontiers:

- Ultimate precision
- Differential distributions
- Production in association



Standard Model Total Production Cross Section Measurements



Top-Quark Physics Frontiers:

- Ultimate precision
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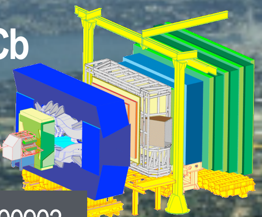
- Production in association

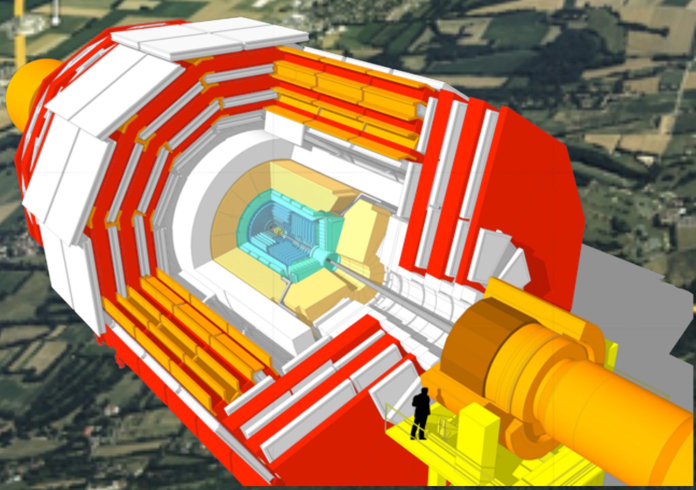
The Top-Quark Factory LHC

LHCb



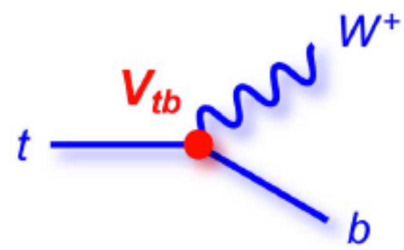
arXiv:1506.00903
arXiv:1610.08142

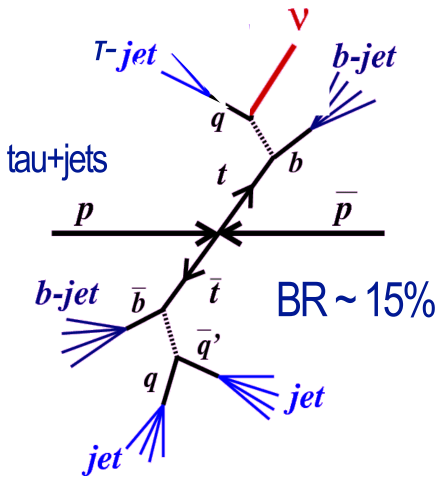
CMS

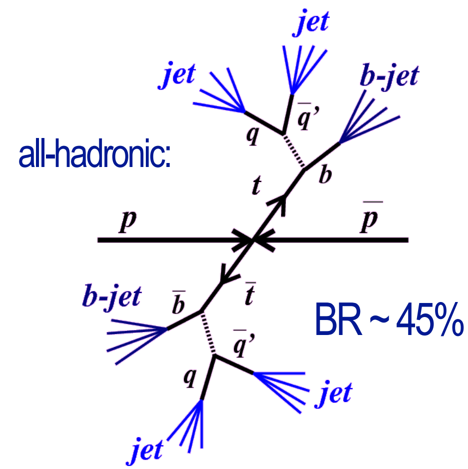


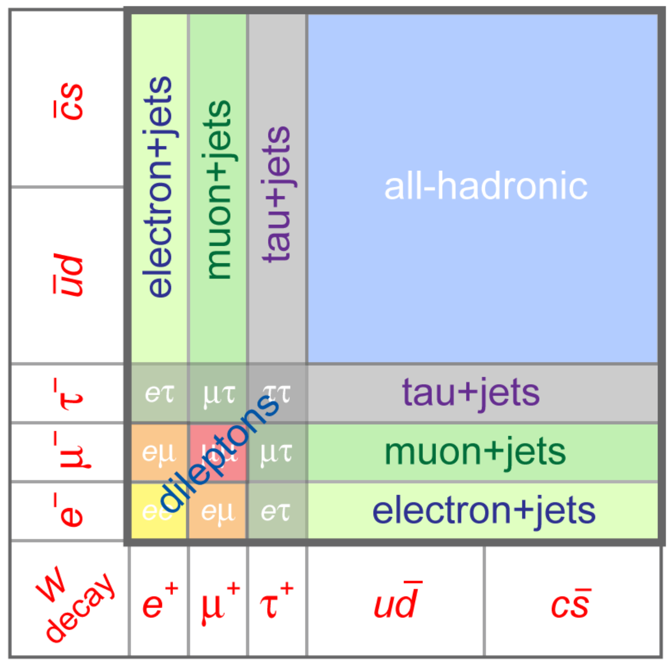
- LHC Run-I ('10-'12): 25 fb^{-1}
  - Peak inst. luminosity: 0.8 x 10^{34} $cm^{-2}s^{-1}$
    ~ 7000 top quark pairs per hour (8 TeV)
  - > 5,000,000 top each CMS and ATLAS
- LHC Run-II ('15-'18): 100 fb^{-1} (13 TeV)
  - Cross section increase by about factor ~3
  - Peak inst. luminosity: 1.7 x 10^{34}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

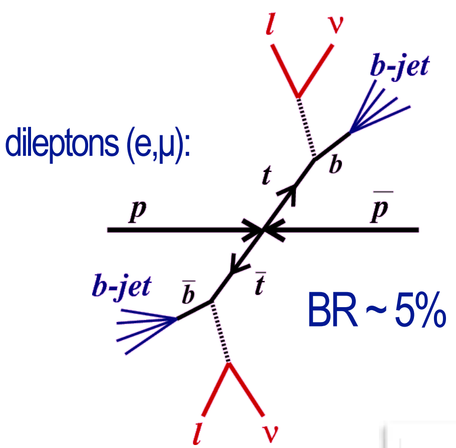
$t\bar{t}$ Event Signatures

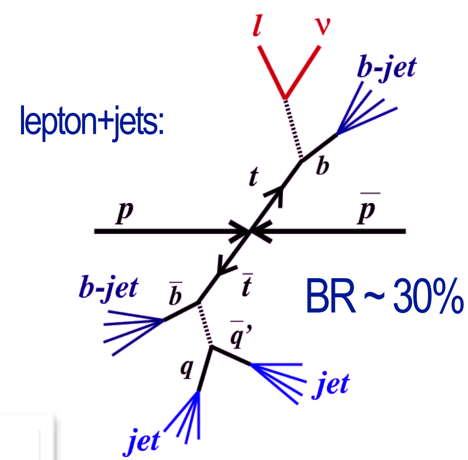












Top quark events have all experimental signatures: leptons, jets, b-jets, missing transverse energy

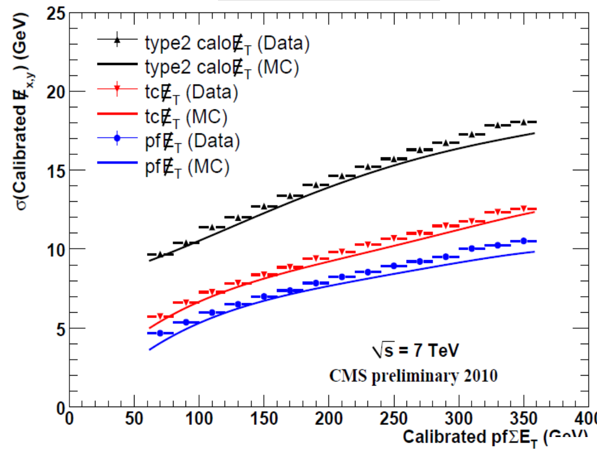
Experimental Ingredients

- **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

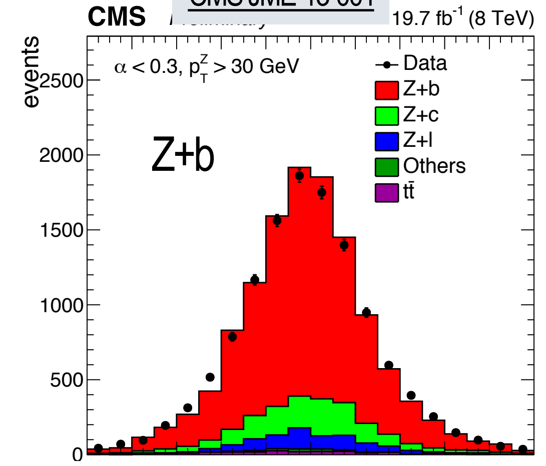
- **Isolated Leptons (e, μ or τ)**
  - Calibrations and efficiencies from dilepton resonances (Z, ϒ, J/ψ)

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

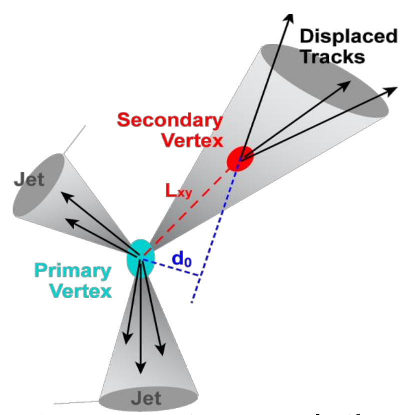
CMS DP-2012/012



CMS JME-13-001



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



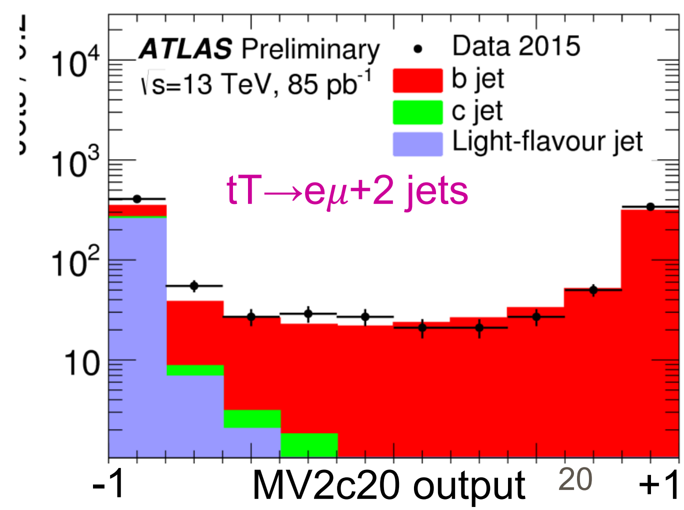
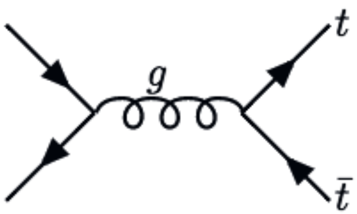
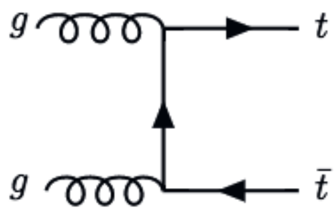


Fig taken from R.Hawkings TOP2016

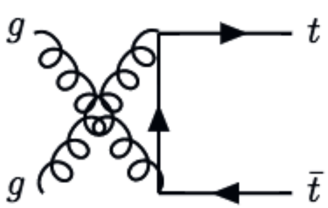
Top quark physics: require high-precision leptons, jets and b-tagging

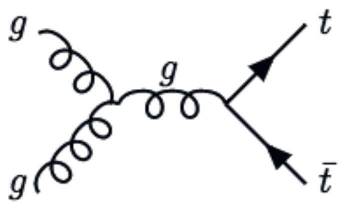
Top-Quark Pair Production

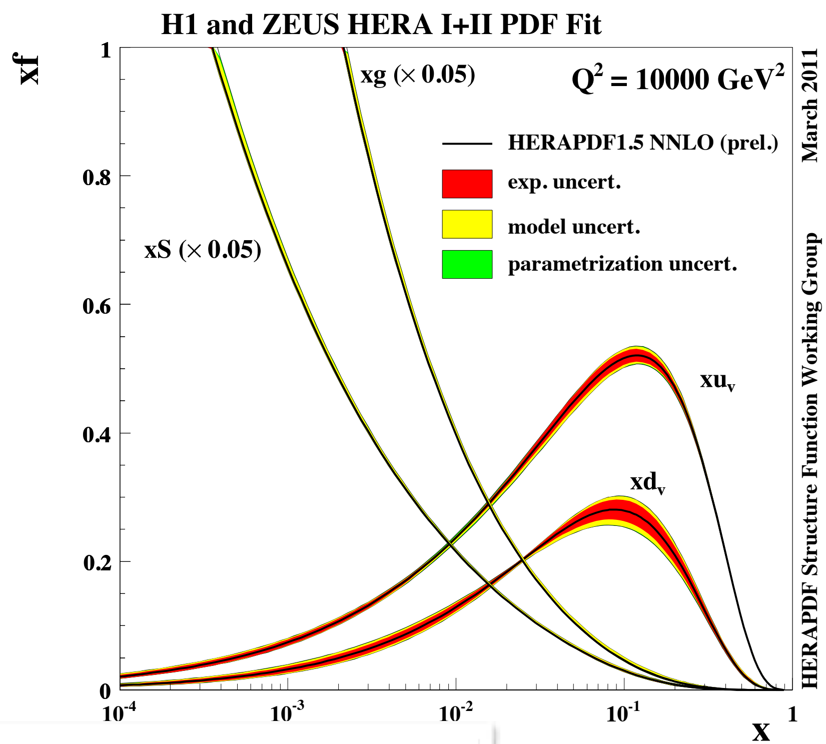




	LHC (13 TeV)	Tevatron
gg/gq	~90%	~15%
$q\bar{q}$	~10%	~85%





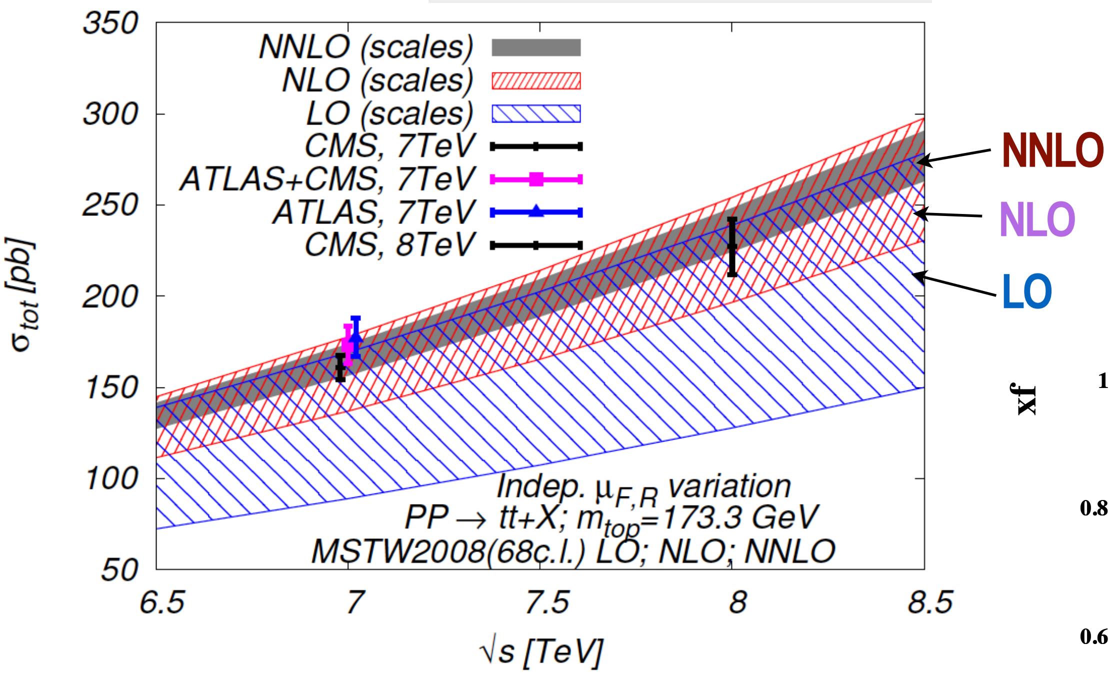


$$\sigma(7\ \text{TeV}) = 177\ \text{pb} \pm 7\%$$
$$\sigma(8\ \text{TeV}) = 253\ \text{pb} \pm 6\%$$
$$\sigma(13\ \text{TeV}) = 832\ \text{pb} \pm 5\%$$
$$R_{13/8} = 3.28$$

Top quark pair production at LHC predominantly from gluons

Top-Quark Pair Production

Czakon, Fiedler, Mitov PRL 110 (2013) 252004



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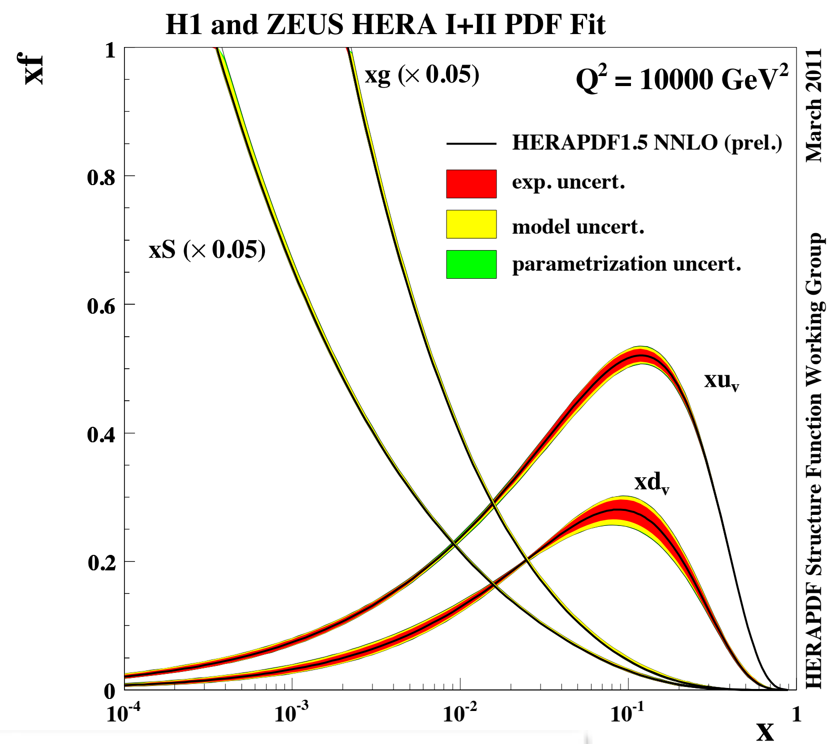
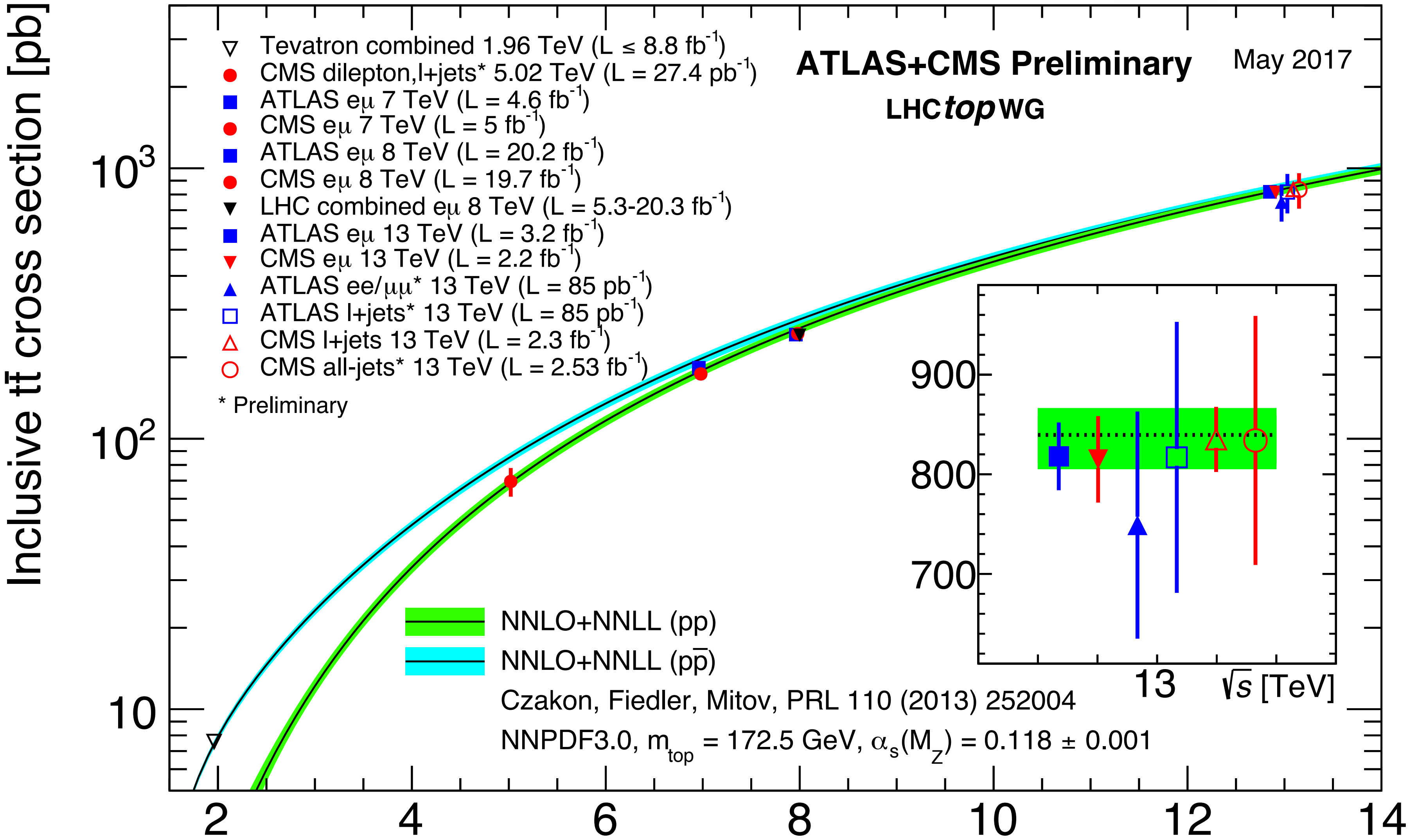


Full NNLO available since early 2013 - scale and pdf uncertainties 2-3%

σ_{tt} (Tevatron, Run-I and Run-II)

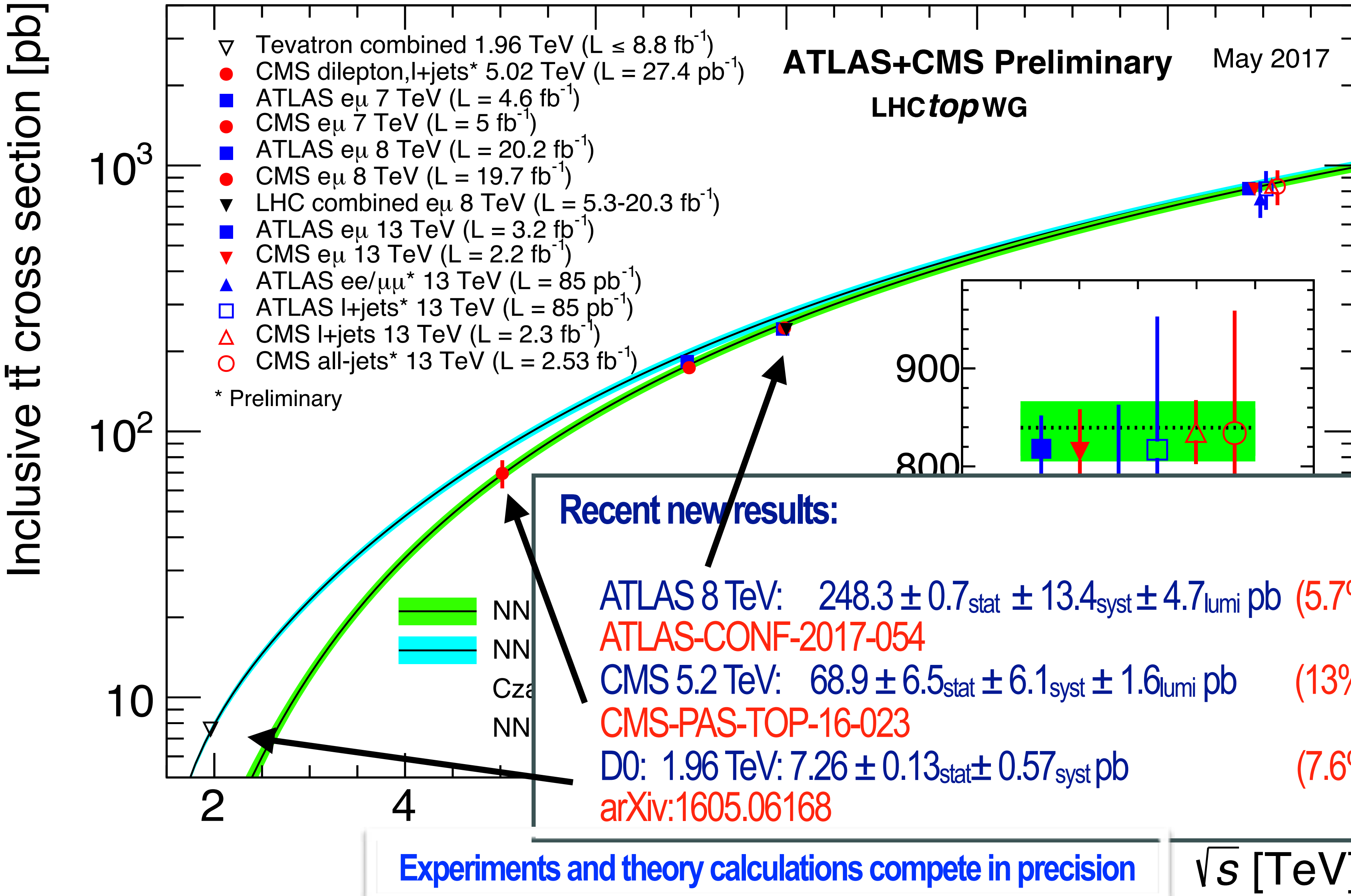
LHCtopWG



Experiments and theory calculations compete in precision

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

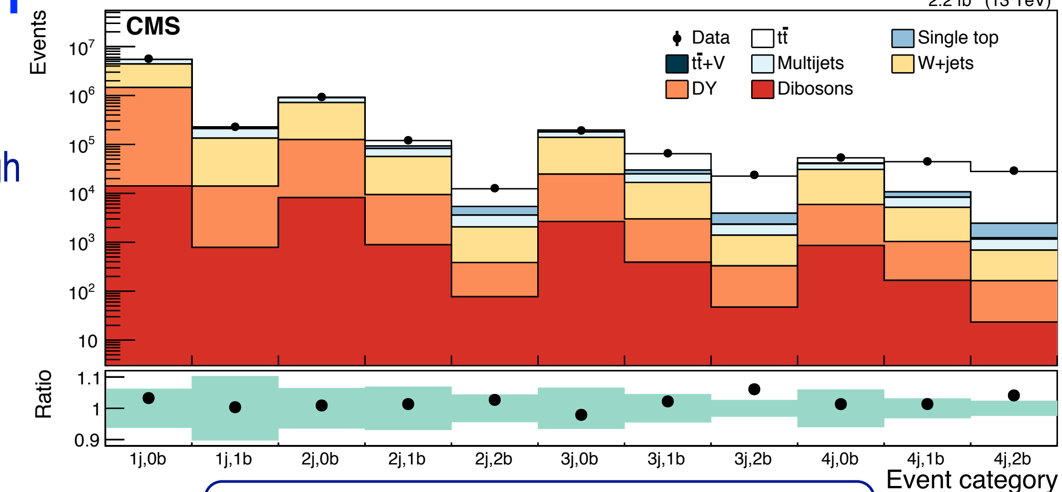
CMS 5.2 TeV: $68.9 \pm 6.5_{stat} \pm 6.1_{syst} \pm 1.6_{lumi}$ pb (13%)
CMS-PAS-TOP-16-023

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

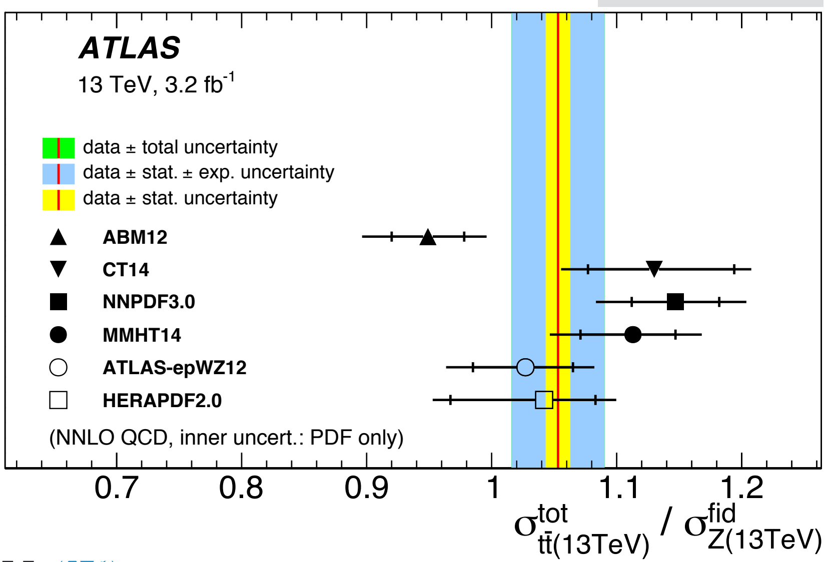


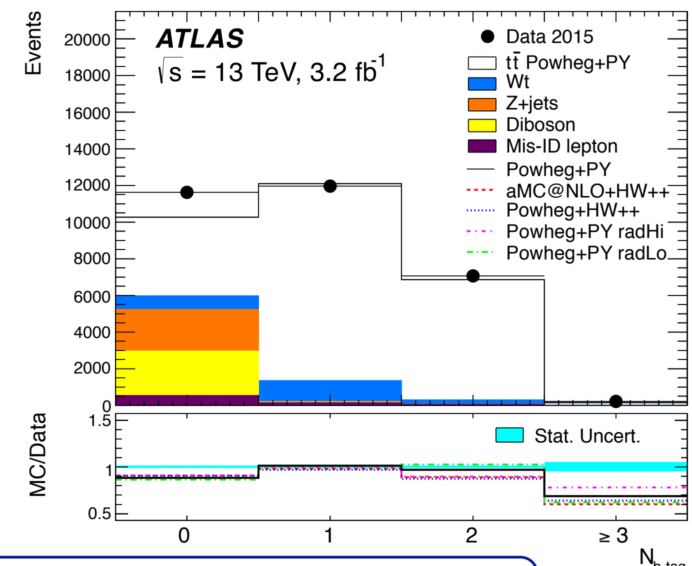
arXiv: 1701.06228

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

3.9 %

arXiv: 1612.03636



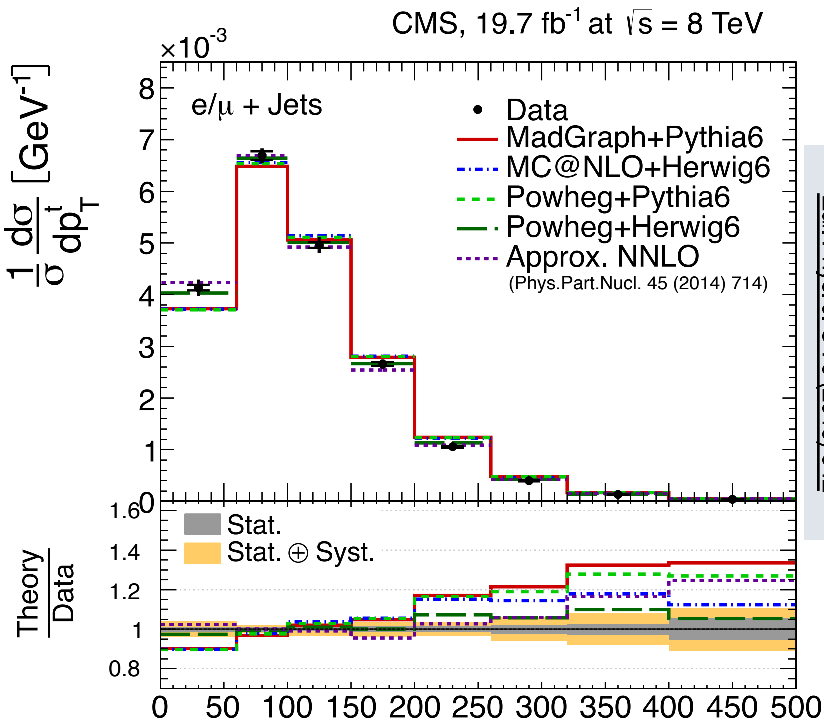


arXiv: 1606.02699

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

4.1 %

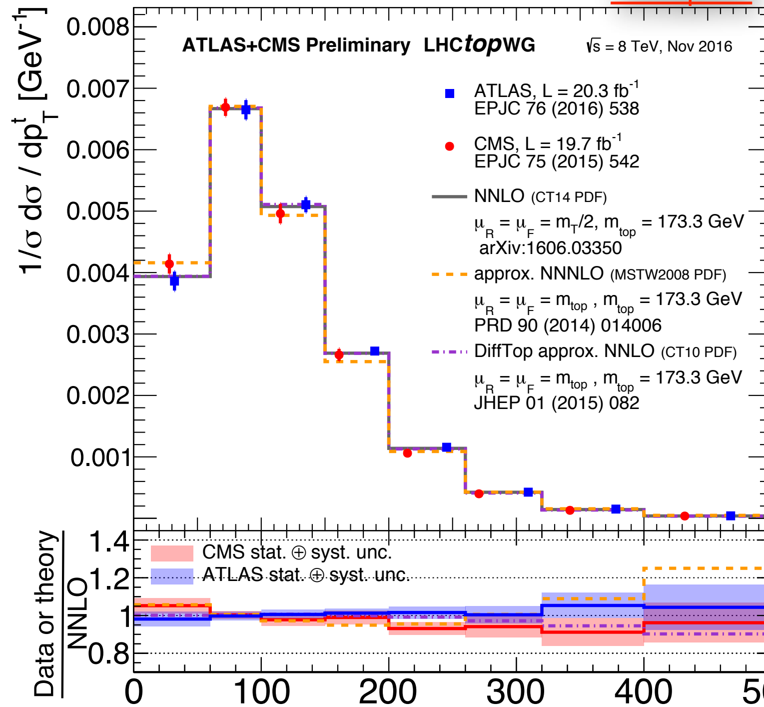
$t\bar{t}$ differential distributions: p_T(top)



Eur. Phys. J. C 75 (2015) 542

pt(top) [GeV]

LHCtopWG



Czakon, Mitov, Heymes, PRL 116, 082003 (2016)

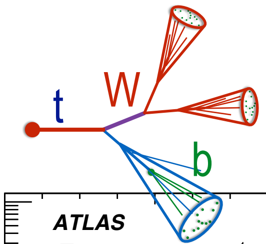
pt(top) [GeV]

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

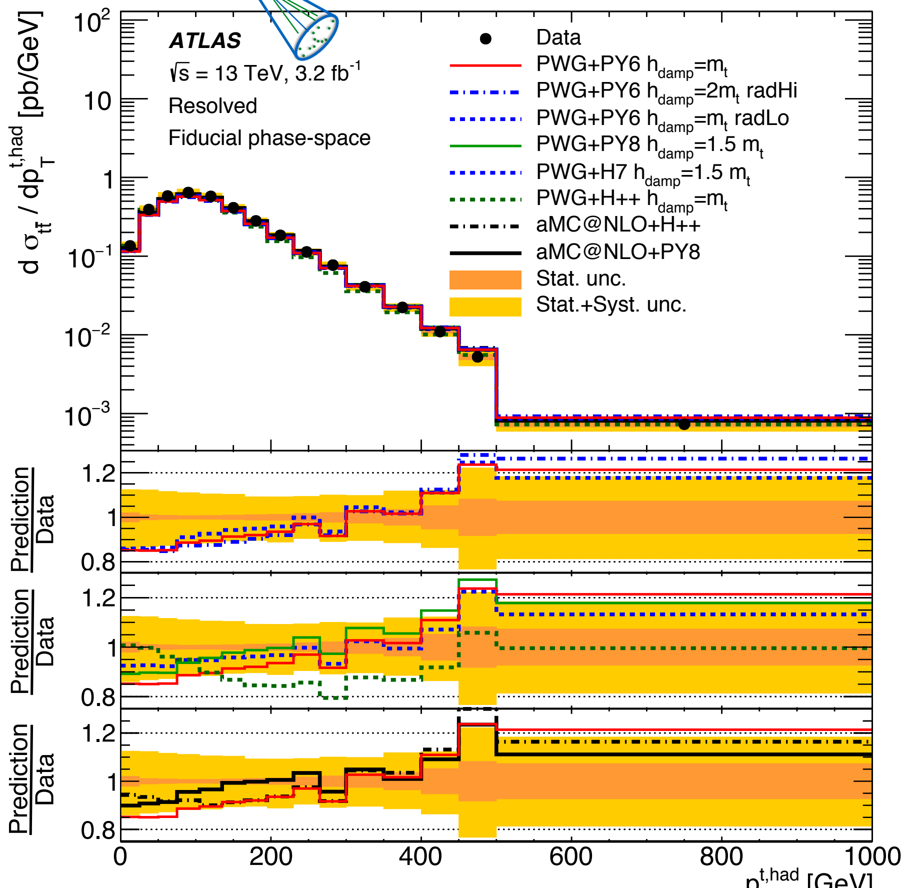
Since 2013: NNLO calculation available:
CMS and ATLAS data well described

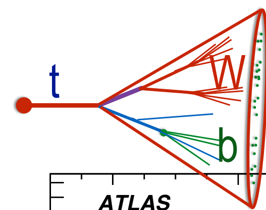
$t\bar{t}$ differential distributions: p_T(top)

arXiv:1708.00727

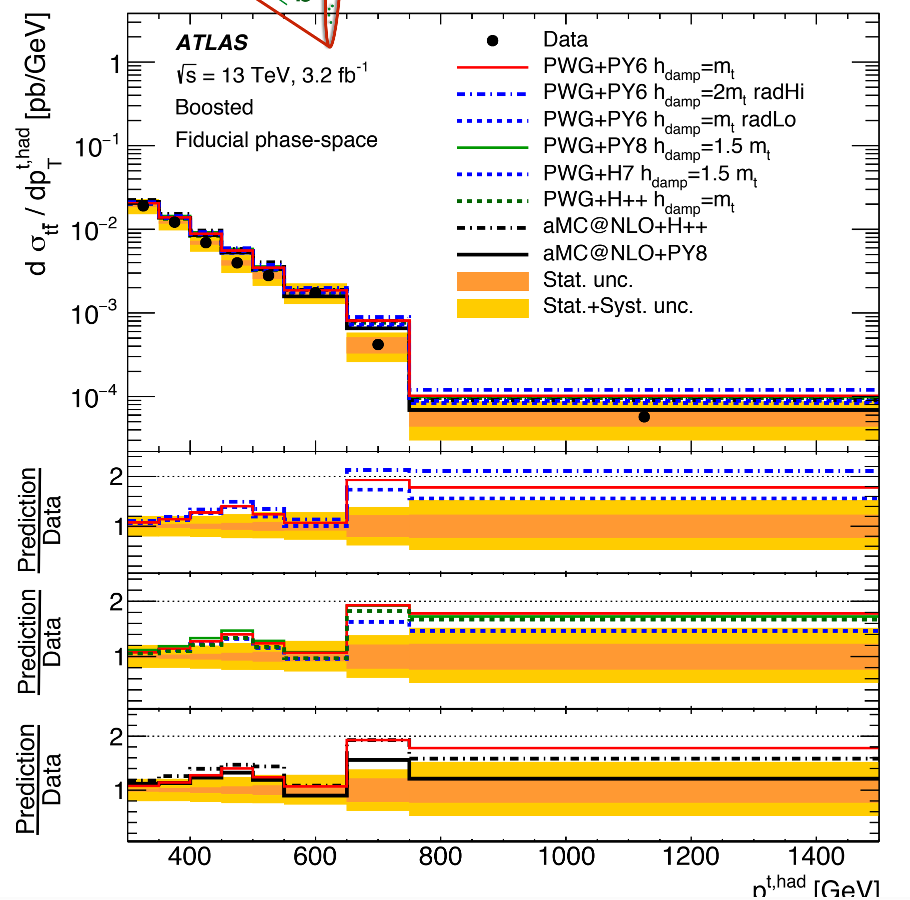


"resolved": 3 jets k_T=0.4





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



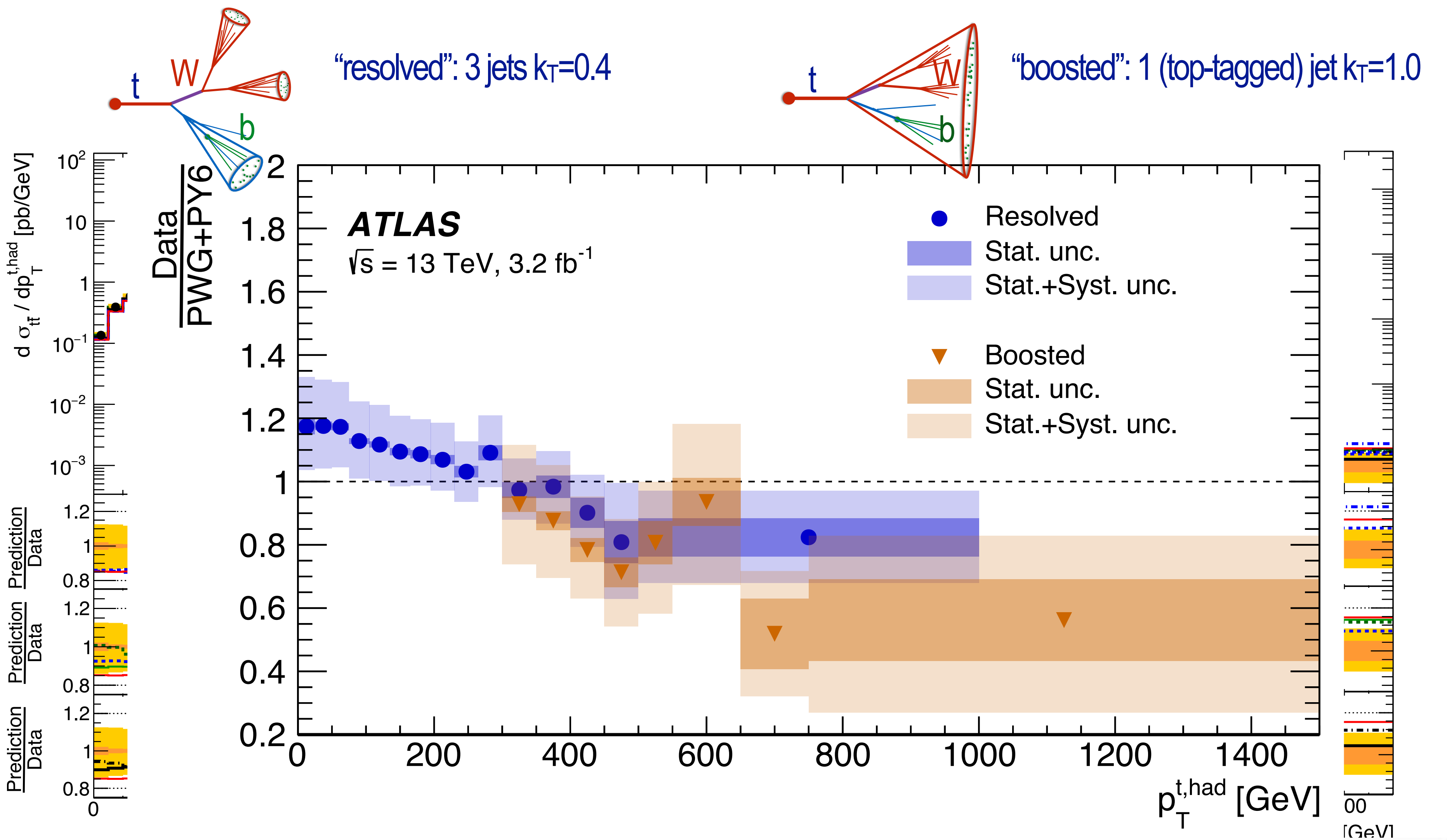
Many recent results from ATLAS and CMS:

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



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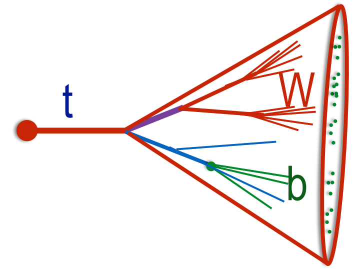
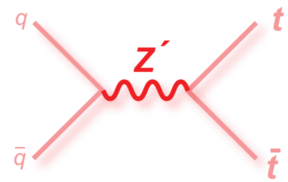
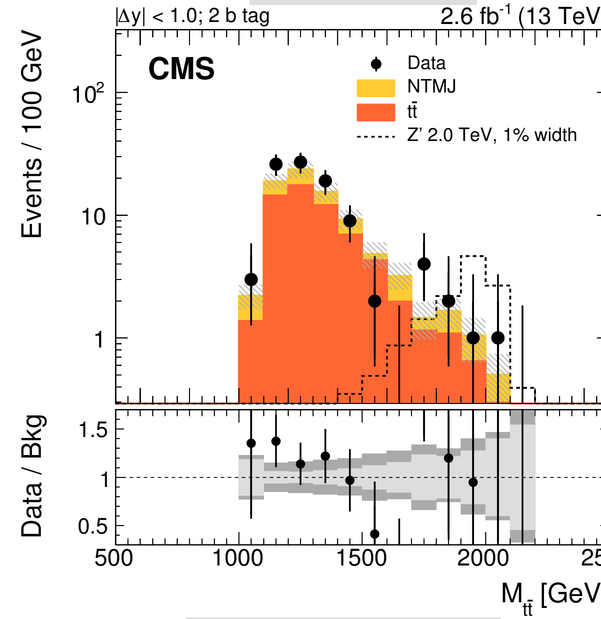
Boosted Top Quarks



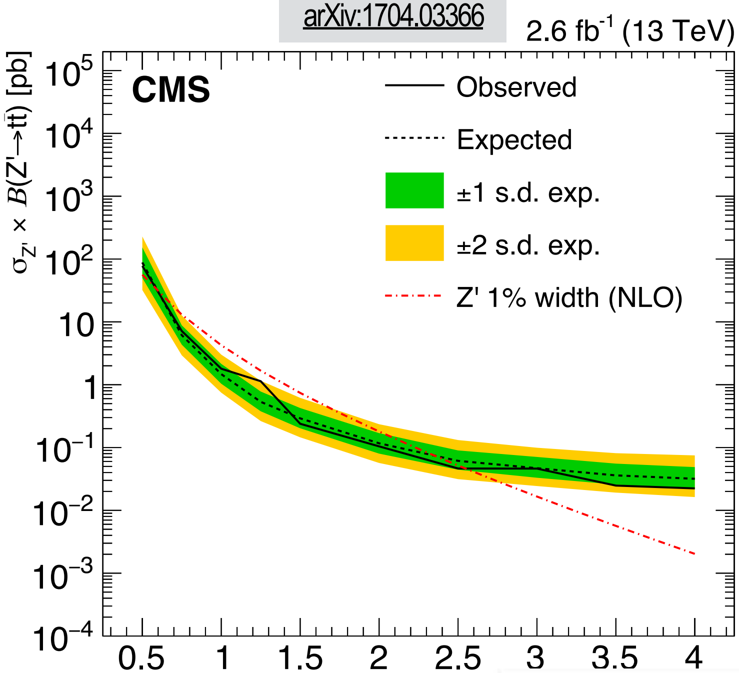
- **Top-quarks as a search tool**
  - High mass particles decaying to high momentum top quarks
- **Example: Z’ → tt resonance**
  - Good understanding of m_{tt} required



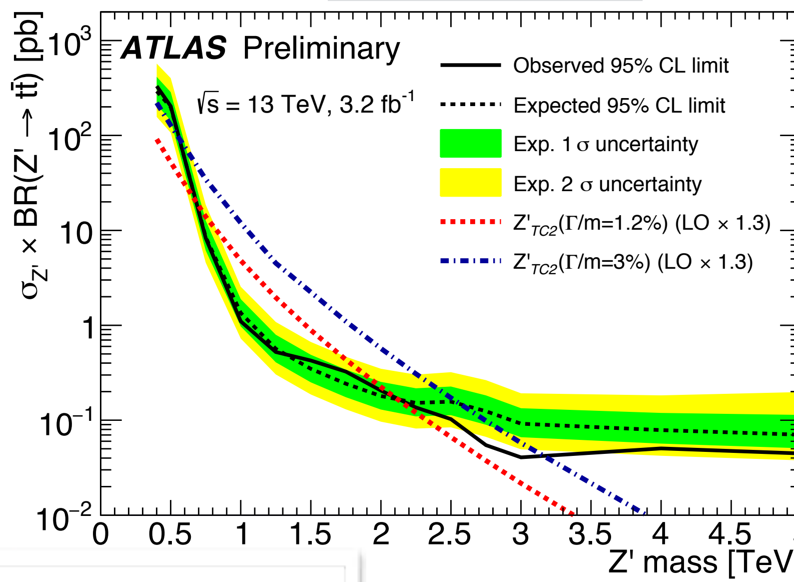
arXiv:1704.03366



arXiv:1704.03366



ATLAS-CONF-2016-014



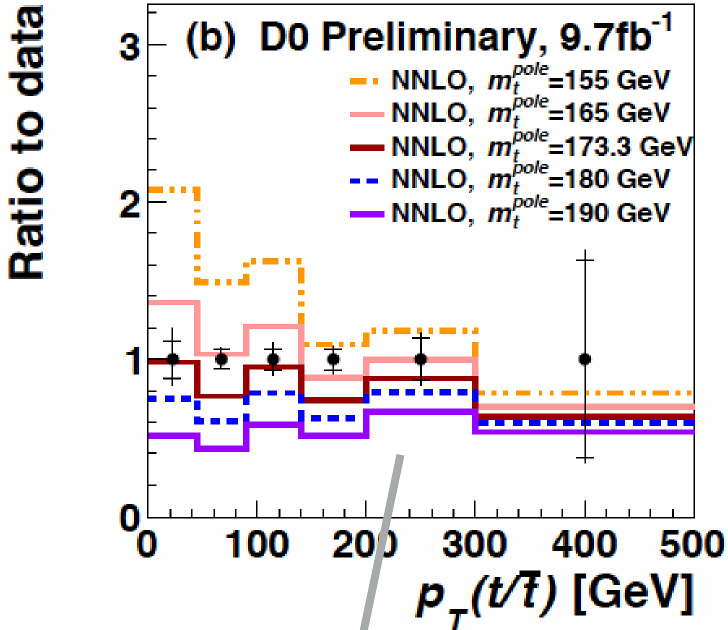
Lower limits: m(Z’(Γ/M = 1%)) > 2.5 TeV

σ_{tt}: Mass from Cross Sections

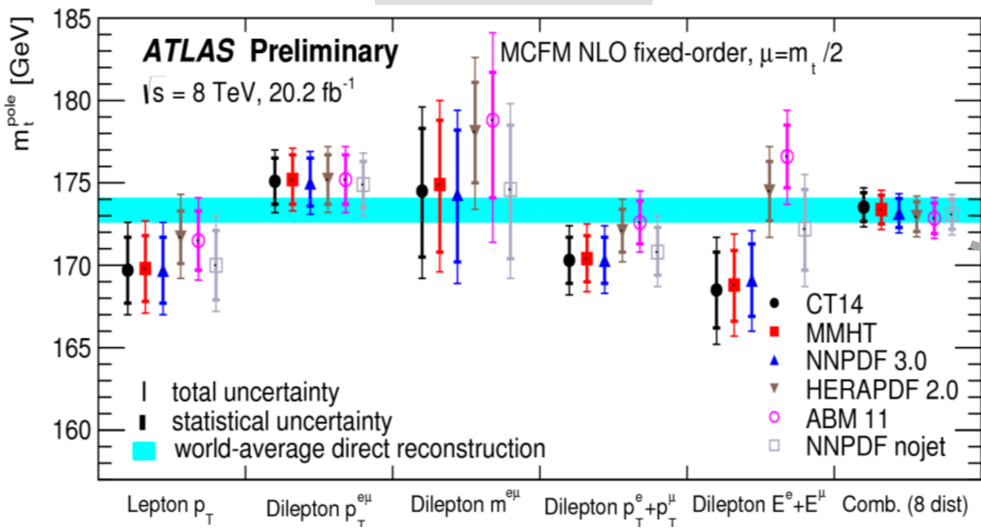
- **Use inclusive and differential cross section measurements to constrain pole mass**
  - theoretically well defined
  - current analyses: fixed α_S and PDF

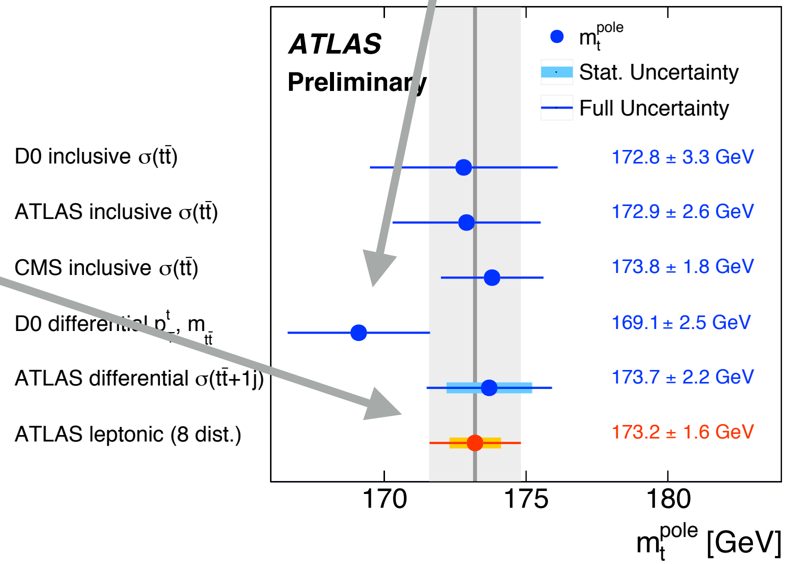
- **Latest results:**
  - D0: Fit to m_{tt} and pt(top) spectra
  - ATLAS: Fit of mass to eight lepton distributions

D0 6473



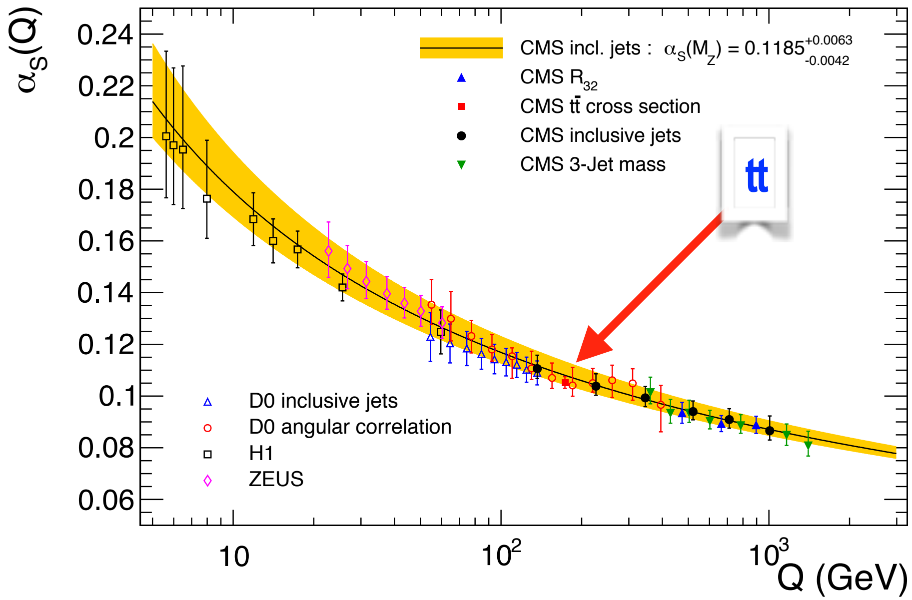
ATLAS-CONF-2017-044



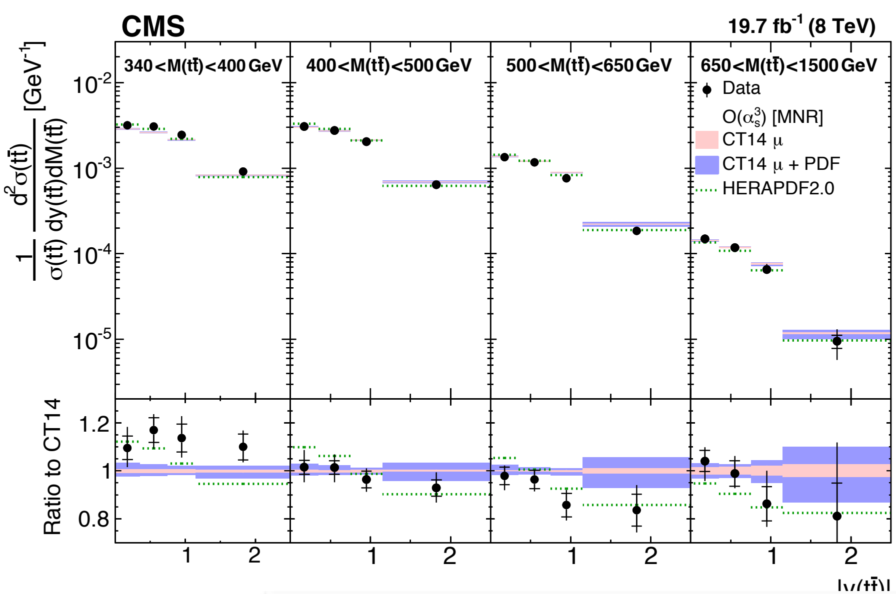


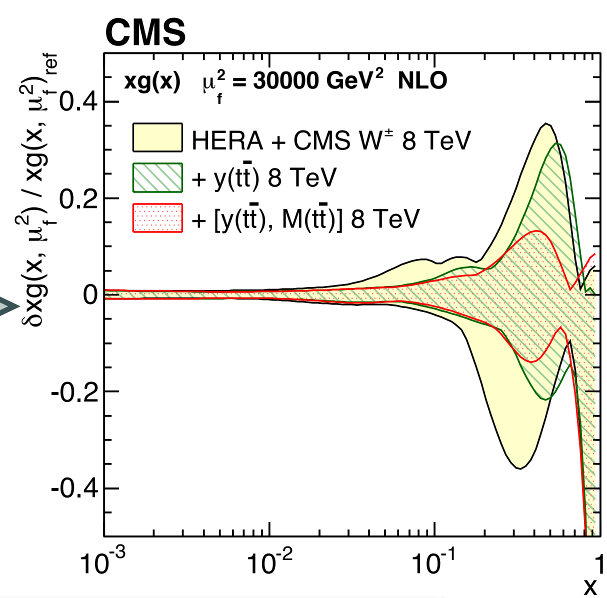
σ_{tt}: α_S or PDF

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



EPJC 75 (2015) 288

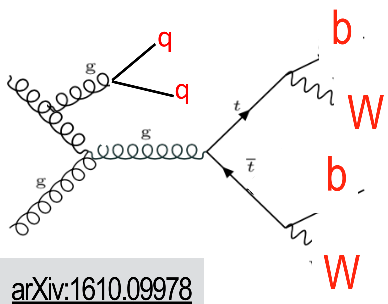




arXiv:1703.01630

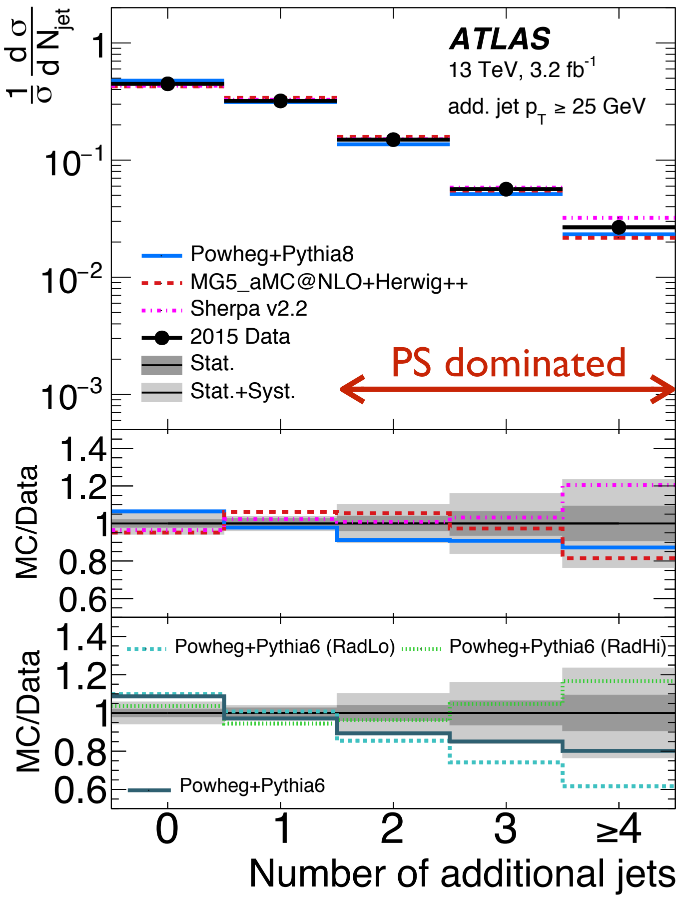
Run-II: Aim to constrain α_S, m(top) and PDF simultaneously

$t\bar{t}$+jets

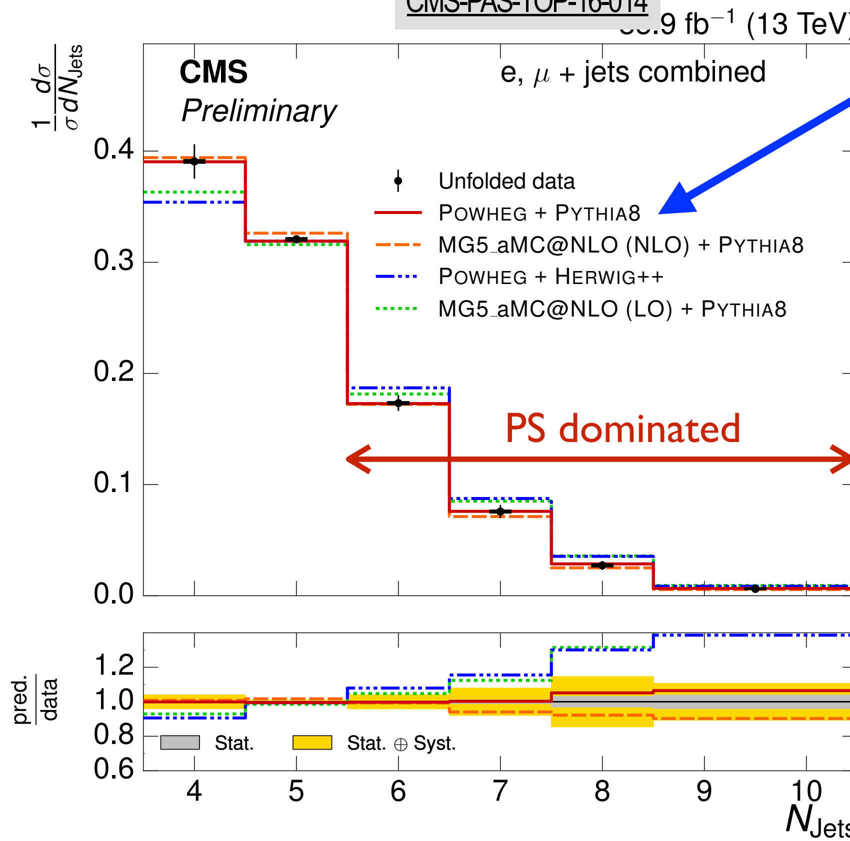


arXiv:1610.09978

- **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



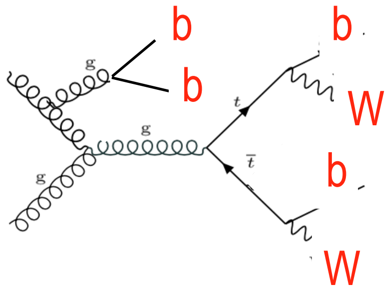
CMS-PAS-TOP-16-014



new tune

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

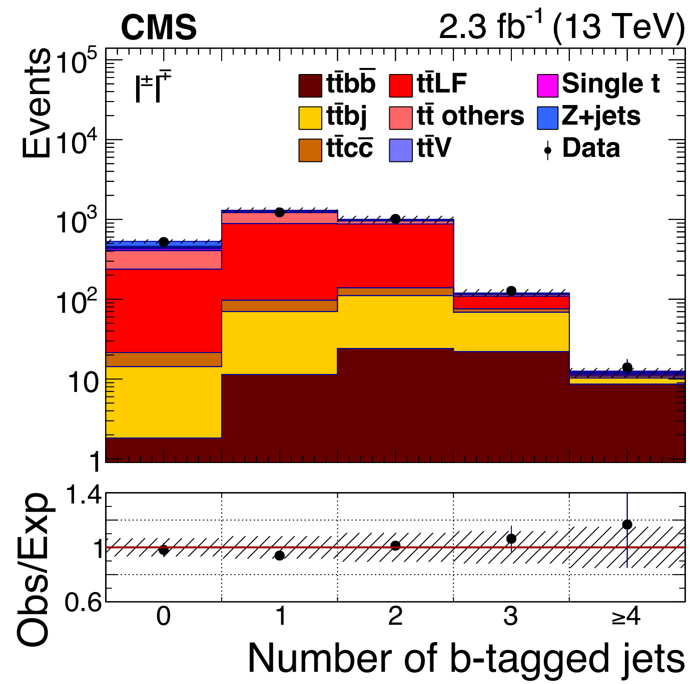
$t\bar{t}+b\bar{b}$



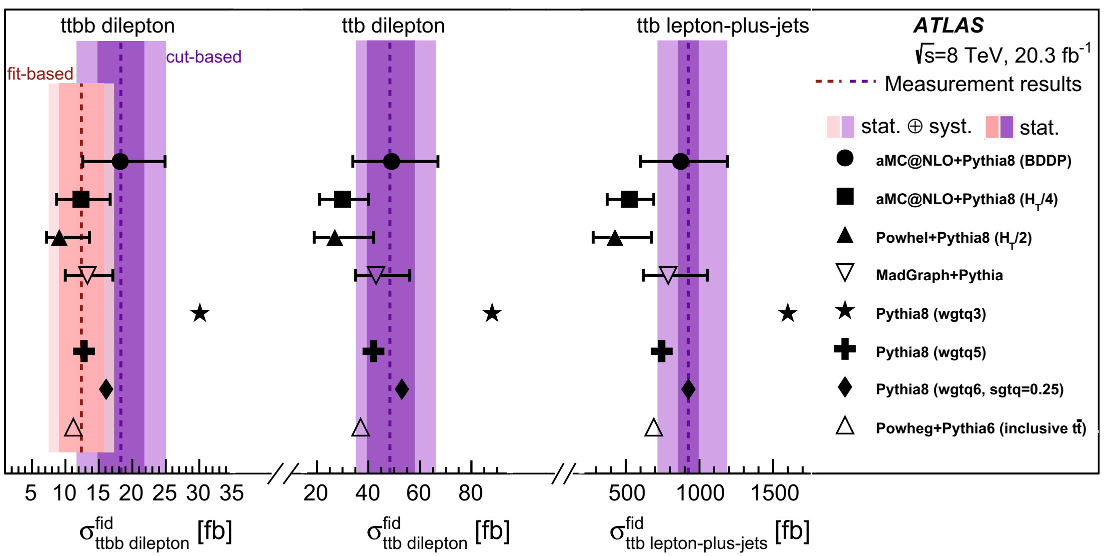
- **tt+b is dominant background esp. to ttH with H → bb**
- **Precise calculations are a challenge for theory**

- **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:1705.10141



arXiv:1508.06868

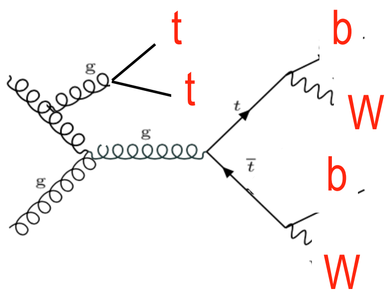


CMS: $\sigma_{ttbb}/\sigma_{ttjj} = 0.022 \pm 0.003_{stat} \pm 0.006_{syst}$

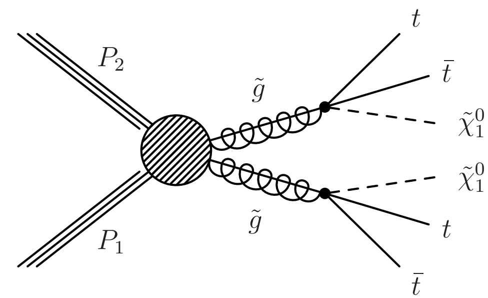
Powheg: $\sigma_{ttbb}/\sigma_{ttjj} = 0.012 \pm 0.001_{stat}$

Data becoming more precise than current predictions

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

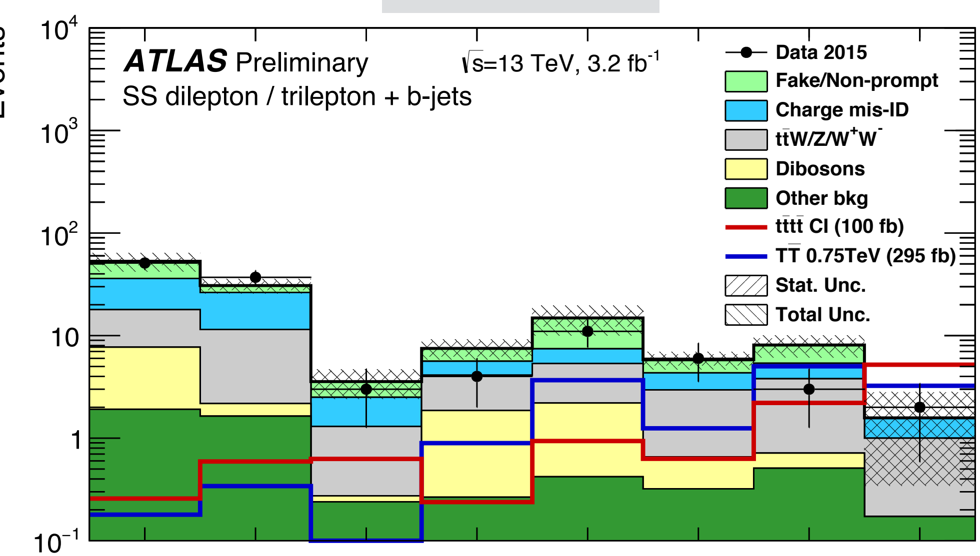


- tttt cross section very small (SM: ~9 fb)
- Expect enhancement from new physics, e.g.:



- 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

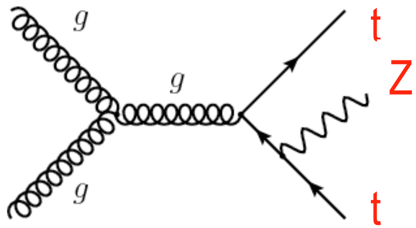


Limits from 4-top searches at 13 TeV:

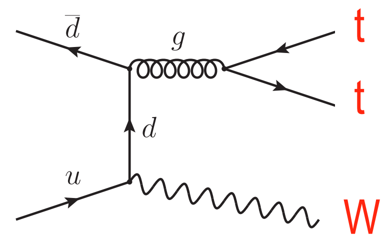
Dataset	Analysis	Limit (95 CL) obs (exp.)	Reference
3.2 fb^{-1}	1ℓ fit in categories	6.5(9.1) × σ_{SM}	ATLAS-CONF-2016-020
3.2 fb^{-1}	ℓℓ (same sign) fit in categories	4.6(3) × σ_{SM}	ATLAS-CONF-2016-032
2.6 fb^{-1}	1+2ℓ comb. BDT	8(8) × σ_{SM}	CMS arXiv: 1702.06164
36 fb^{-1}	2ℓ fit in categories	4.6(2.9)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

Upper limits approaching SM cross section expectation

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

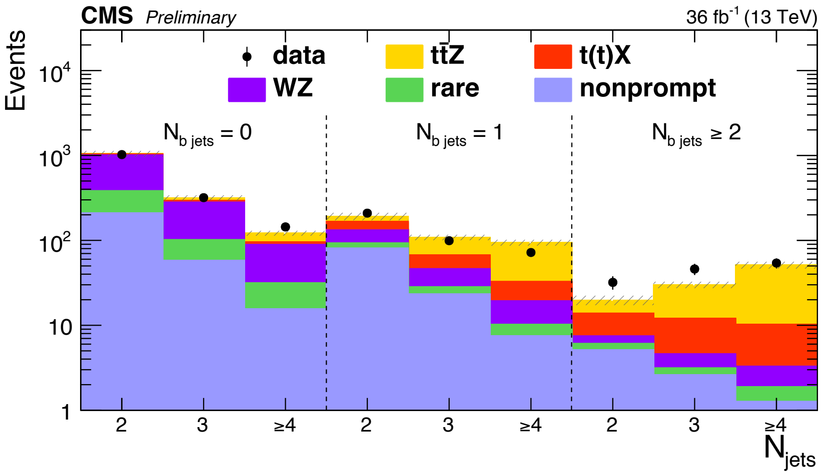


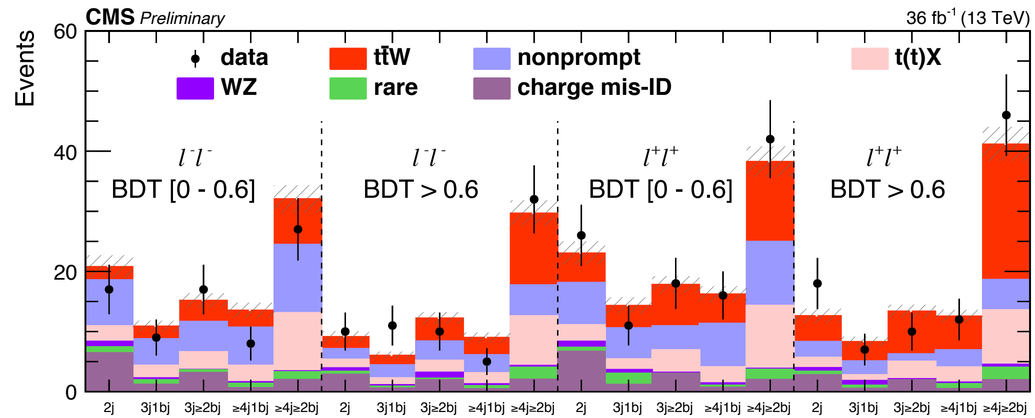
3ℓ or 4ℓ + b-jets



2ℓ (same-sign) + b-jets

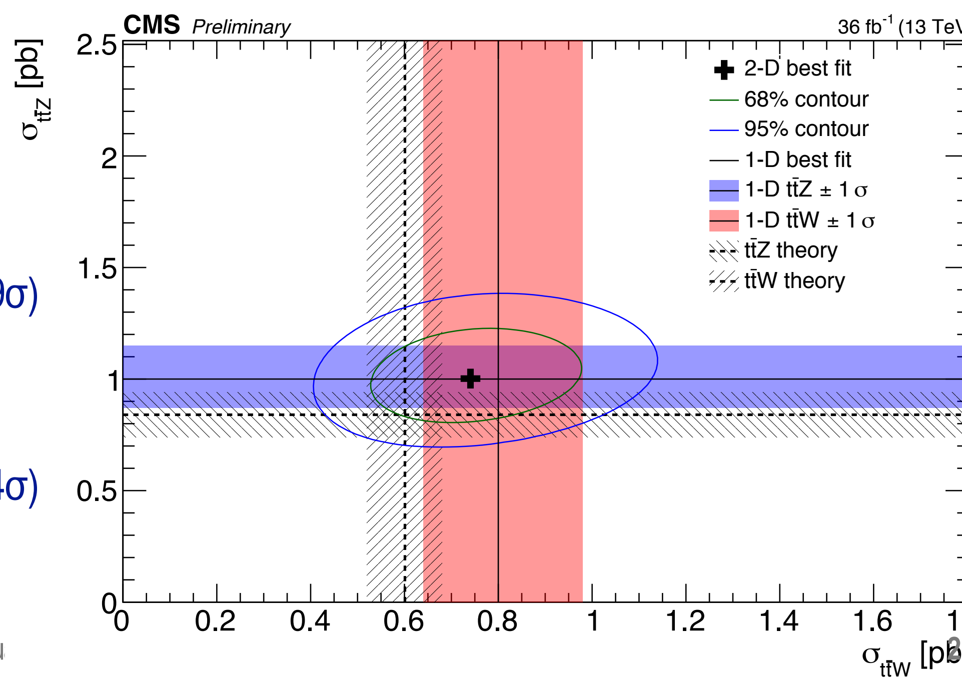
CMS-PAS-TOP-17-005





- **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

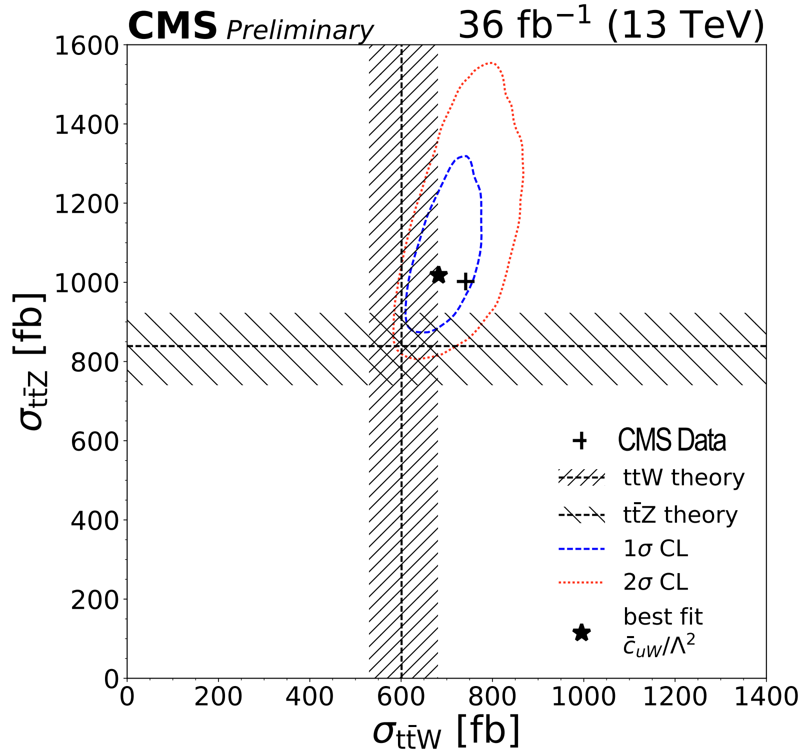


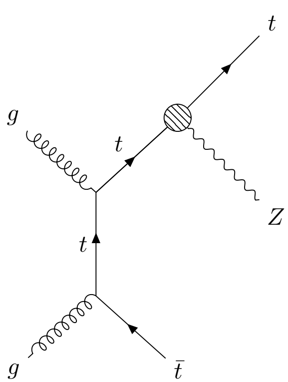
Effective Field Theory Interpretation

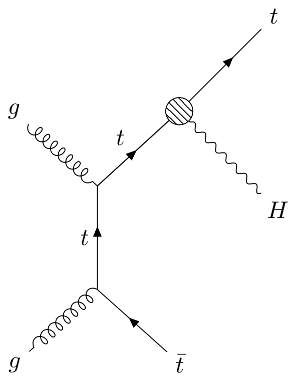
CMS-PAS-TOP-17-005

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

- **EFT Lagrangian:**
  - Expansion by inverse energy scale $1/\Lambda$
  - 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]

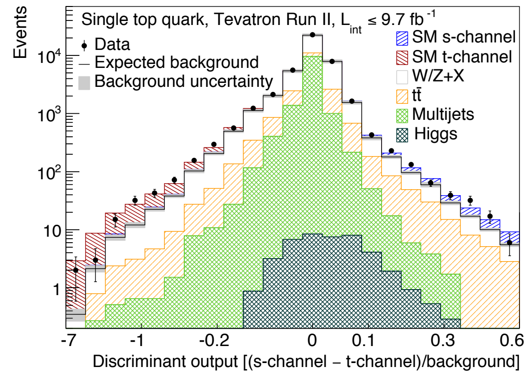
observed values are very similar to SM-expected

Single-Top Production

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

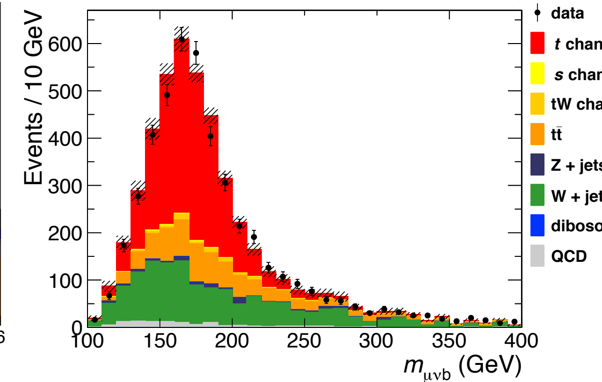
D0 and CDF combined

arXiv:1503.05027

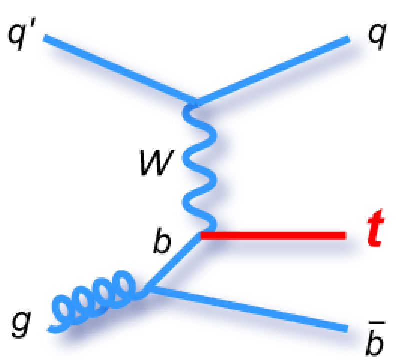


complex multivariate analysis

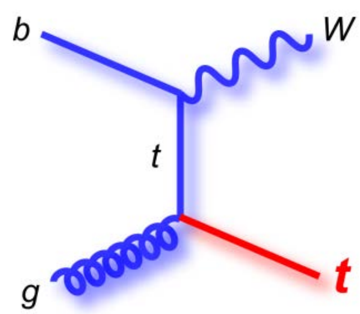
LHC Run-I



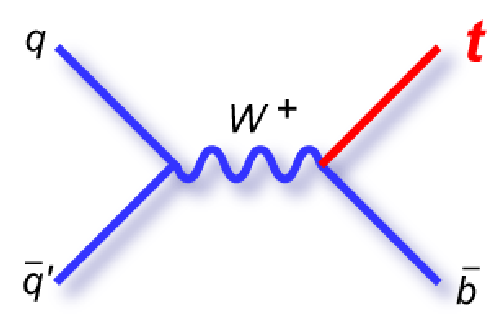
simple kinematic analysis



$$\sigma(7\ \text{TeV}) = 64\ \text{pb} \pm 4.5\%$$
$$\sigma(8\ \text{TeV}) = 85\ \text{pb} \pm 4.4\%$$
$$\sigma(13\ \text{TeV}) = 217\ \text{pb} \pm 4.1\%$$
$$R_{13/8} = 2.6$$



$$\sigma(7\ \text{TeV}) = 15.7\ \text{pb} \pm 7.6\%$$
$$\sigma(8\ \text{TeV}) = 22.4\ \text{pb} \pm 6.8\%$$
$$\sigma(13\ \text{TeV}) = 71.7\ \text{pb} \pm 5.3\%$$
$$R_{13/8} = 3.2$$



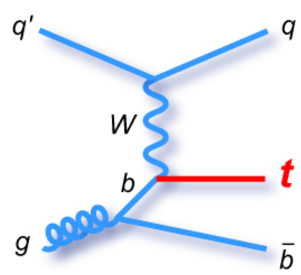
$$\sigma(7\ \text{TeV}) = 4.3\ \text{pb} \pm 4.4\%$$
$$\sigma(8\ \text{TeV}) = 5.2\ \text{pb} \pm 4.2\%$$
$$\sigma(13\ \text{TeV}) = 10.3\ \text{pb} \pm 3.9\%$$
$$R_{13/8} = 1.9$$

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

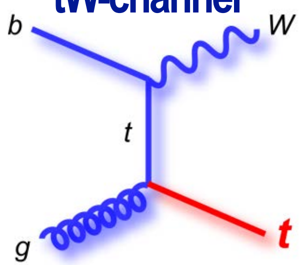
Single-Top Quark Cross Sections

LHCtopWG

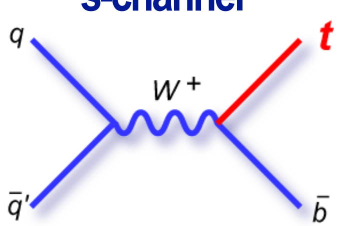
t-channel

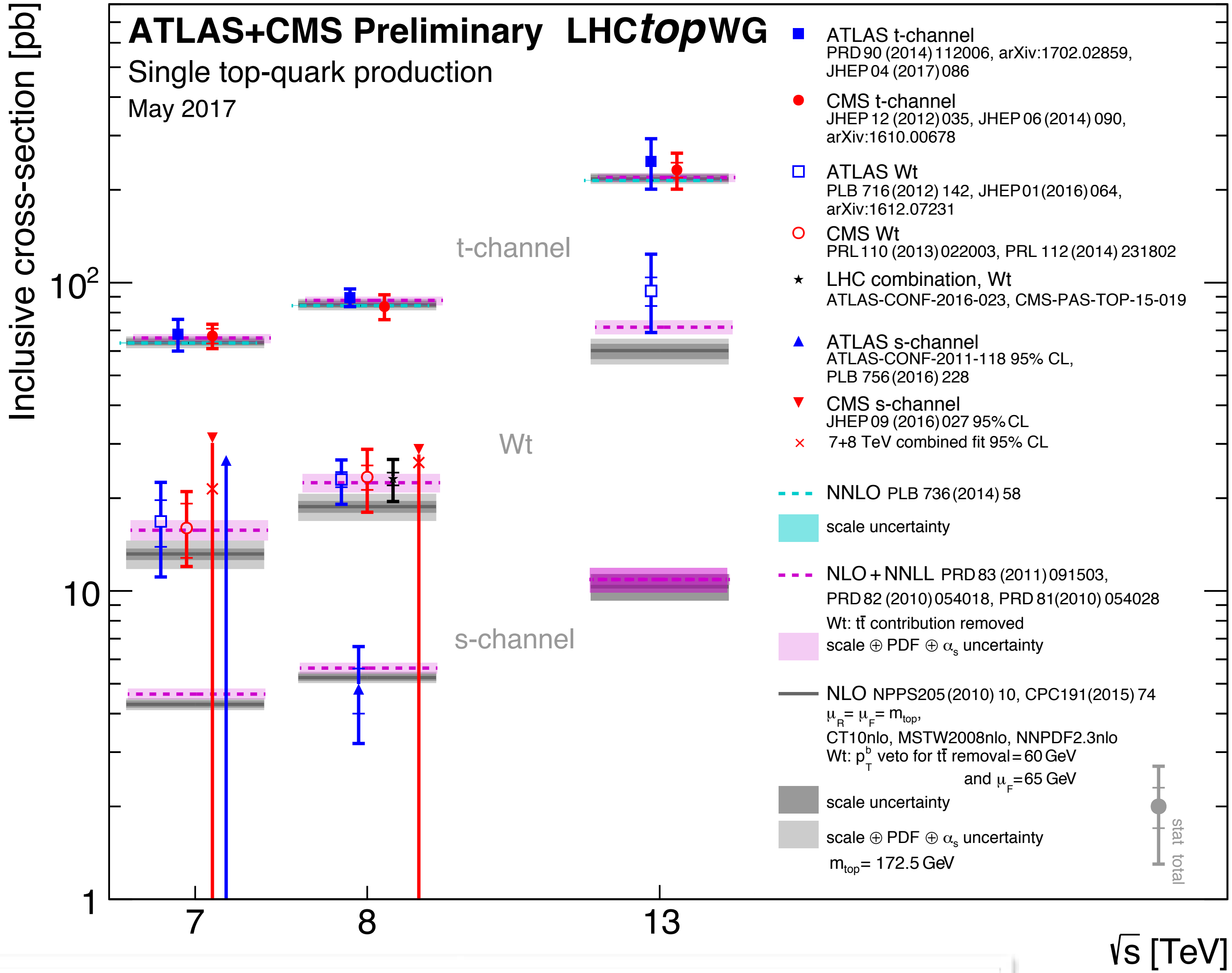


tW-channel



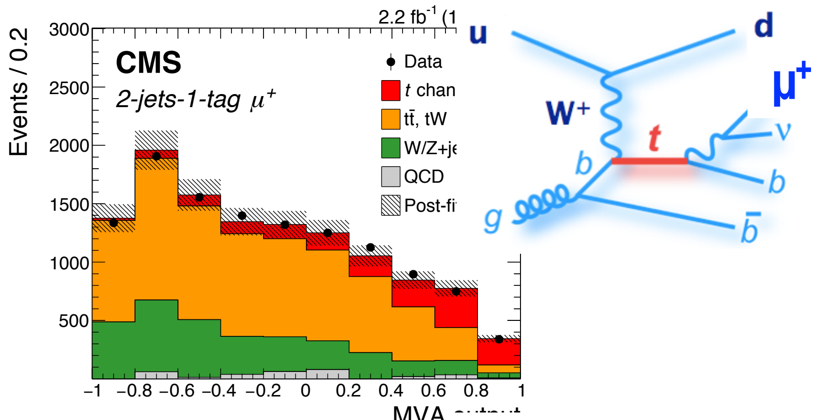
s-channel

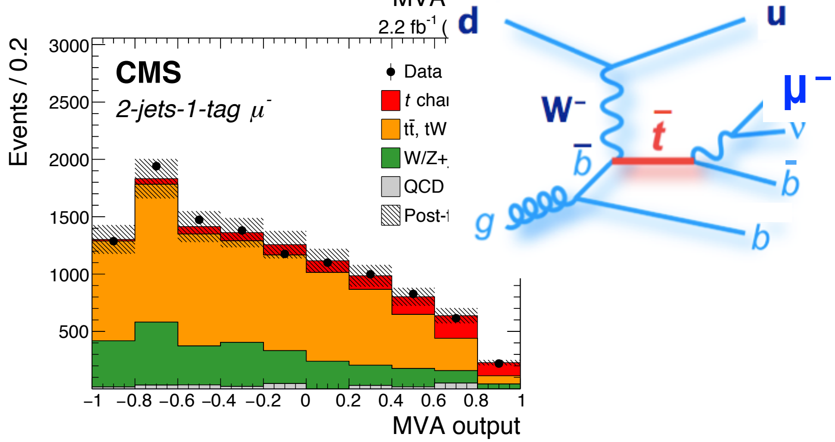




Single-top cross sections at Run-II are as large as the tt cross section at Run-I

Single-top quark (t-channel)



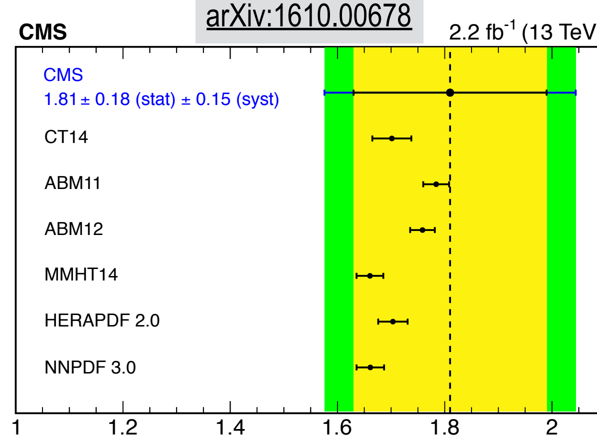


$\sigma_{t(\text{CMS, 13 TeV})} = 238 \pm 13_{stat} \pm 29_{syst} \pm 5_{lumi}$ pb

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

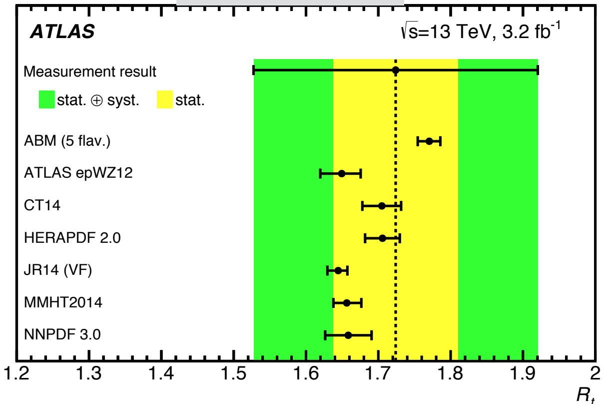
$\sigma_{t(\text{NNLO})} = 217 + 6.6 - 4.6_{scale} \pm 6.2_{PDF+\alpha S}$ pb

arXiv:1610.00678



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

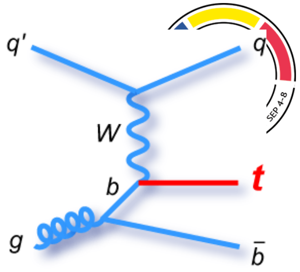
arXiv:1609.03920



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

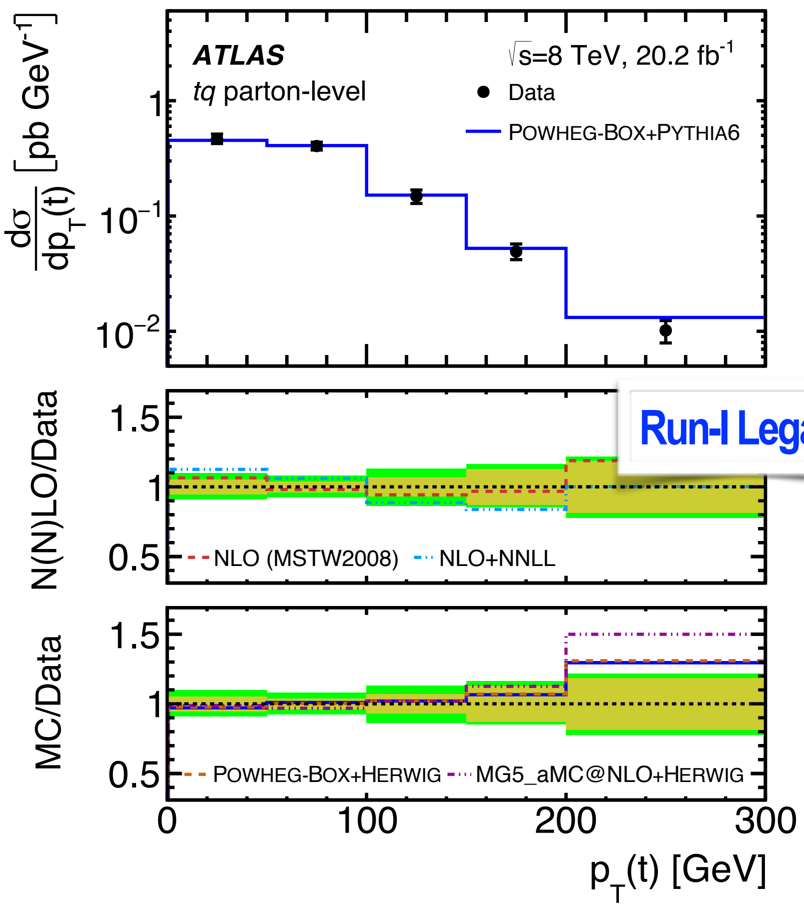
Cross section ratio R_t: sensitivity to u/d

Single-Top Quark Differential Cross Sections



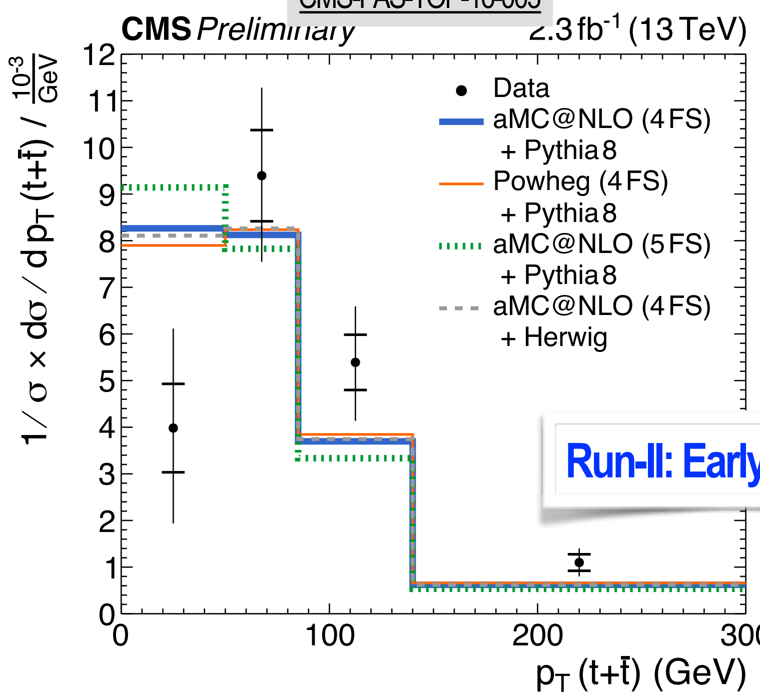
- Full Run-I statistics (20fb^{-1}) were already large enough for precise differential measurements
- Results available at parton-level and particle-level (minimal theoretical assumptions)

arXiv:1702.02859



Run-I Legacy

CMS-PAS-TOP-16-003



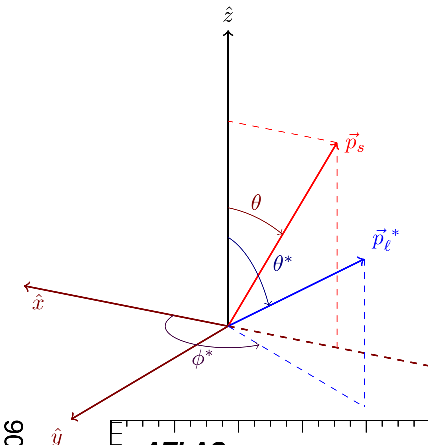
Run-II: Early Analysis

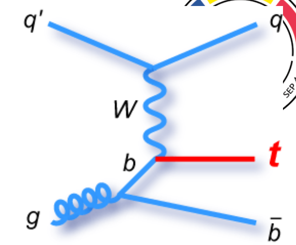
Results with more Run-II data expected soon
TOP2017 in 2 weeks from now

Single-Top Quark Polarization

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

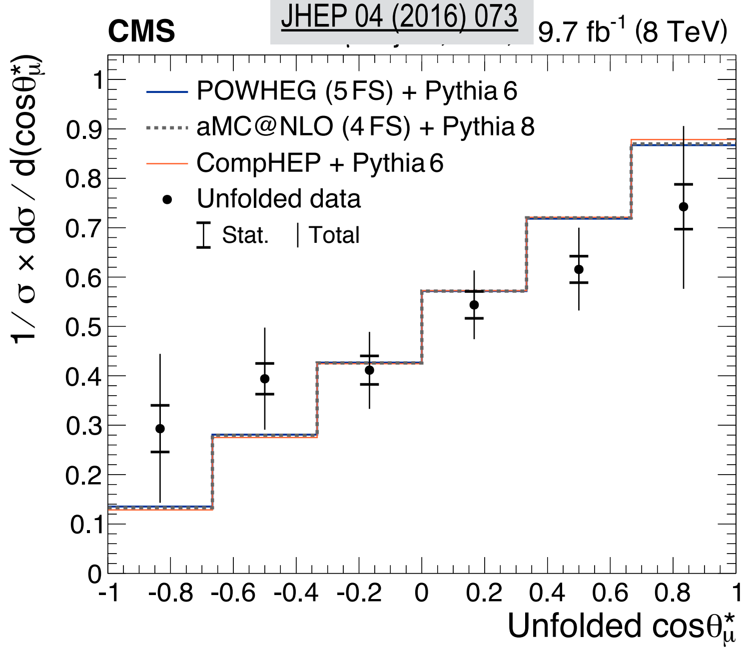
$$\frac{1}{2}\alpha_\ell P = A_{\mathrm{FB}} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

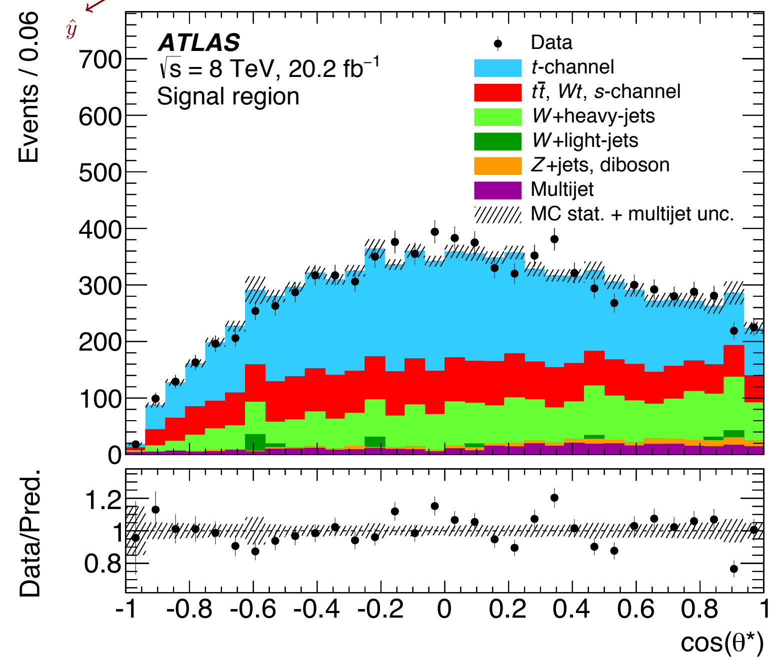




arXiv:1707.05393

JHEP 04 (2016) 073





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

Simultaneous determination of all anomalous W_{tb} couplings and top polarisation

ATLAS: arXiv:1702.08309

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

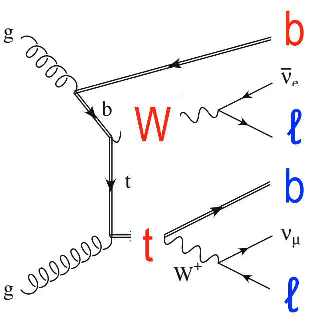
$A_{FB}^{SM} = 0.45$

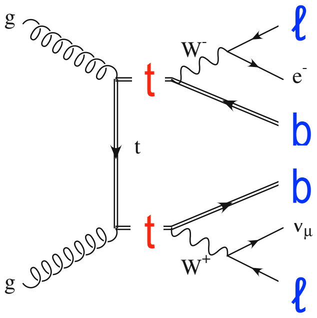
$P > 0.72$ (95% CL)

Single-top tW-channel

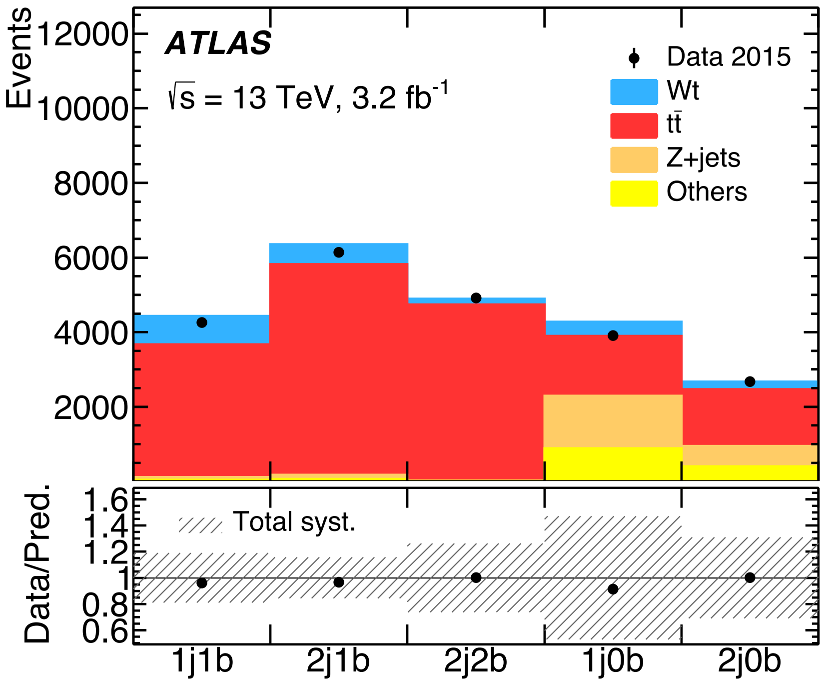
- Same final state as $t\bar{t}$: Interference
- Experimentally: 2nd b is soft → only 1b in detector
- Cross section from fit to BDT discriminants in 1j1b, 2j1b and 2j2b categories

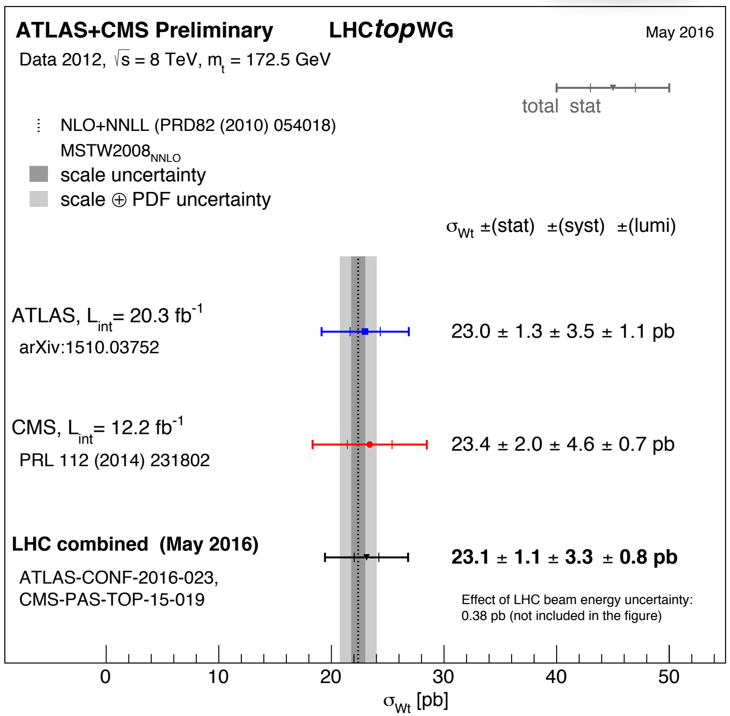
arXiv:1612.07231





LHCtopWG





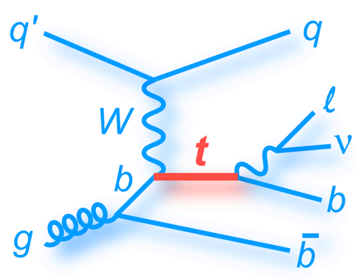
$\sigma_{tW} = 94 \pm 10_{stat} {}^{+28}_{-22}{}_{syst} \pm 2_{lumi}$ pb

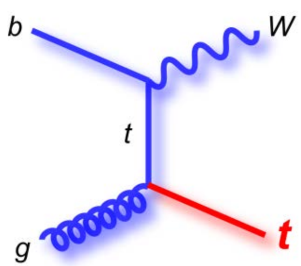
$\sigma_{theory} = 71.7 \pm 1.8_{scale} + 3.4_{PDF}$ pb

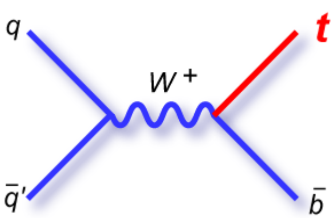
MC to simulate bℓνbℓν final state consistently for tt and tW production now available

V_{tb}

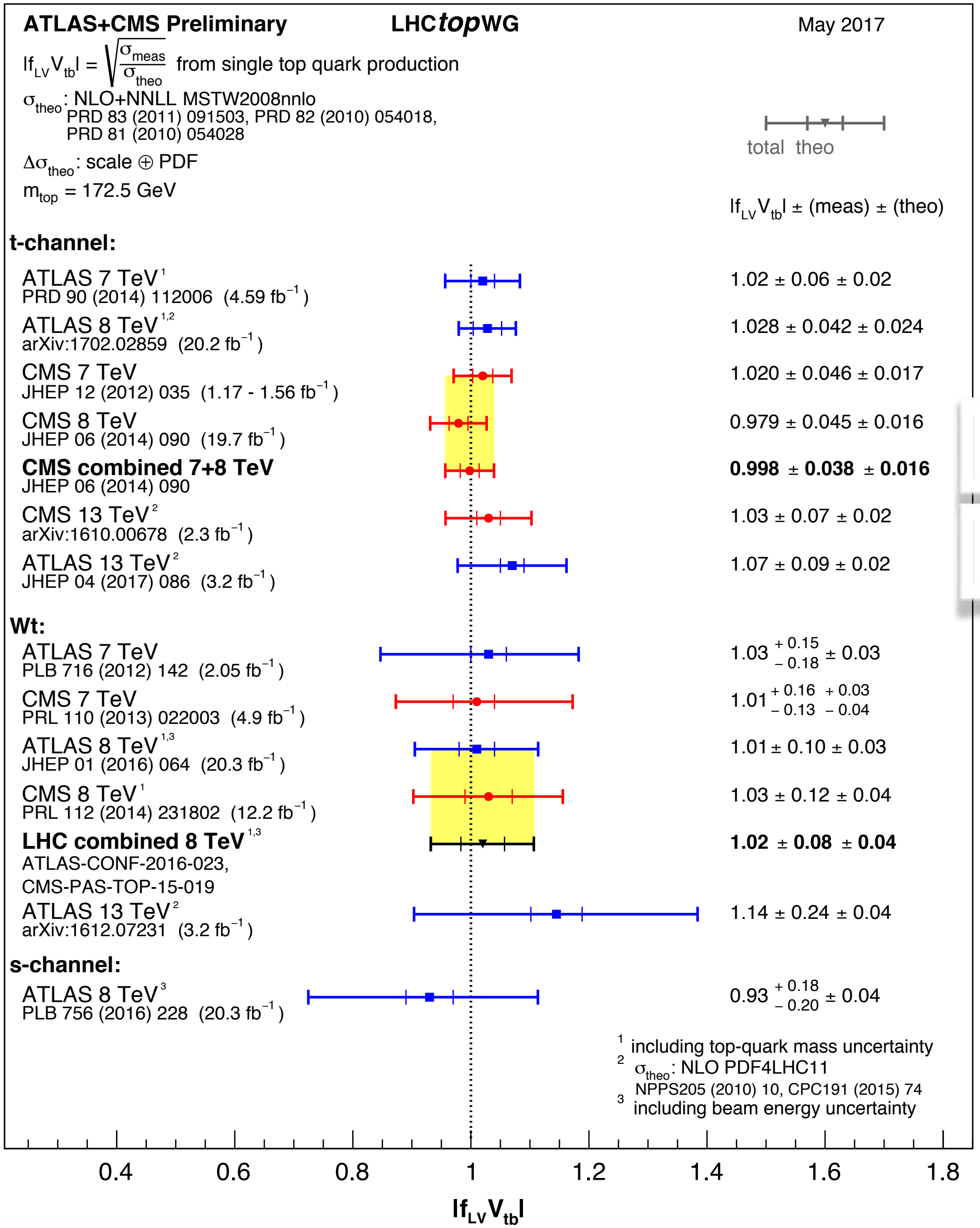
- V_{tb} enters in production and decay $\rightarrow \sigma \propto |f_{LV} V_{tb}|^2$







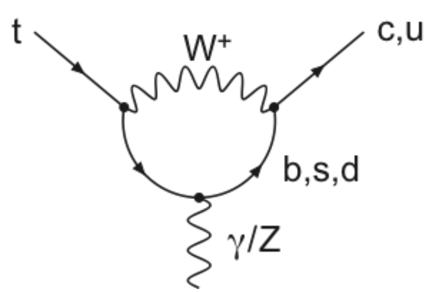
LHCtopWG

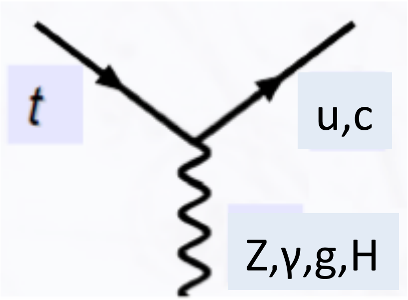


Run-I: $\delta V_{tb} \approx 4\%$

Run-II: $\delta V_{tb} \approx 7\%$

Flavour Changing Neutral Currents

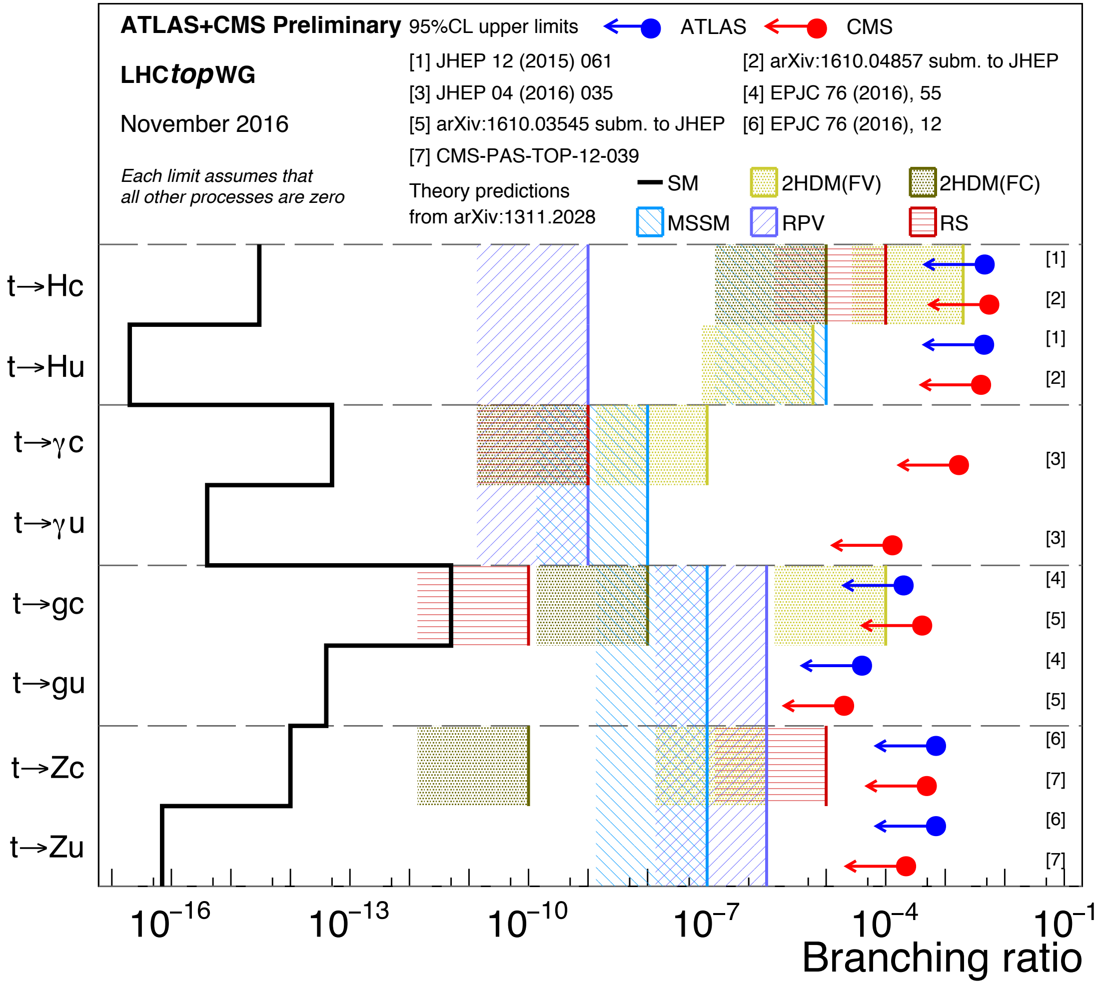




ACTA Phys. Pol. B 35 (2004)

SM: BR ~ 10^{-12} … 10^{-17}

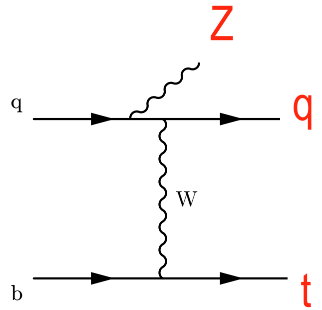
BSM: BR ~ 10^{-5} … 10^{-9}



LHC data closing in on some BSM scenarios with enhanced FCNC

tZq

SM

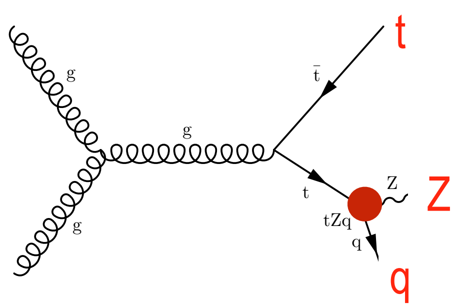


- **ATLAS (Run-II, full 2016 data)**

  First evidence: 4.2σ(5.3σ) obs(exp)

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

FCNC



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

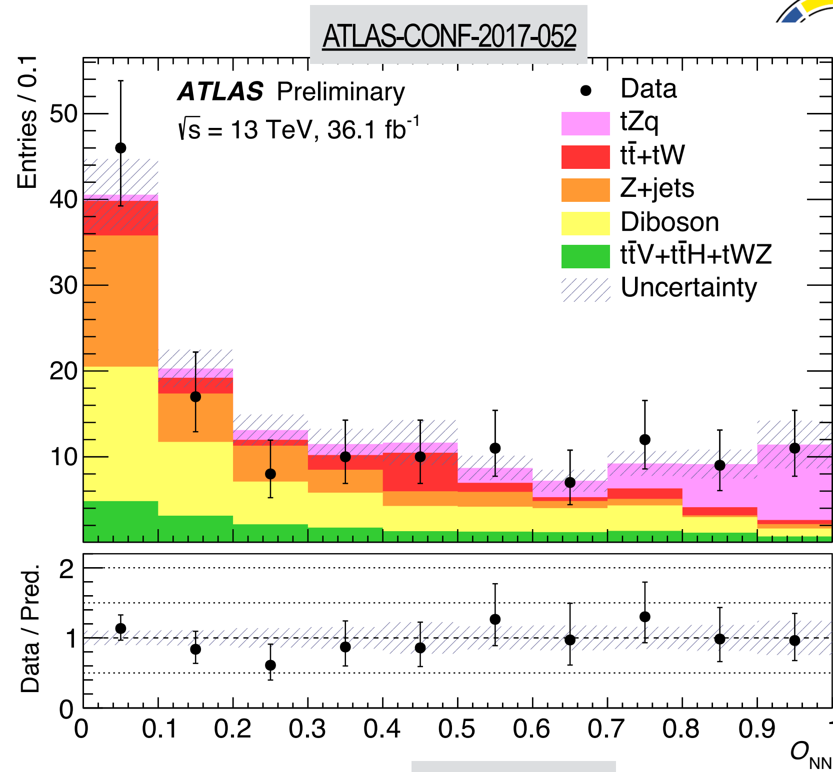
  Significance: 1.8σ(0.8σ) obs(exp)

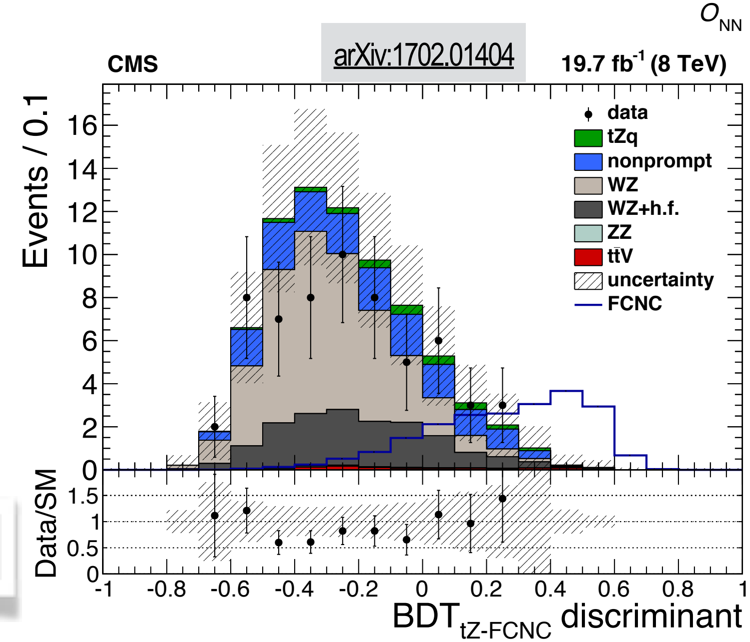
  Limits 95% C.L. on FCNC:

  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}

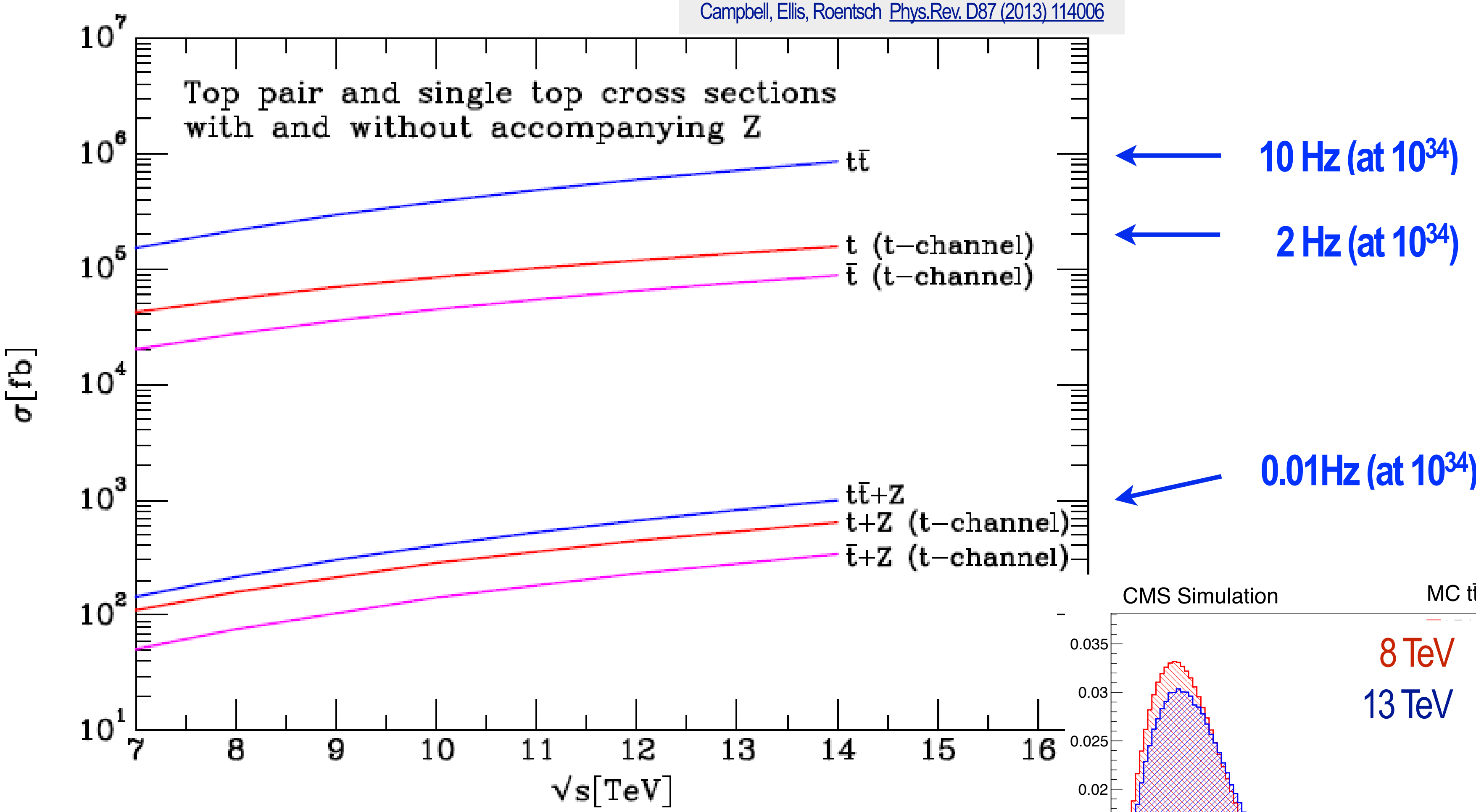
FCNC

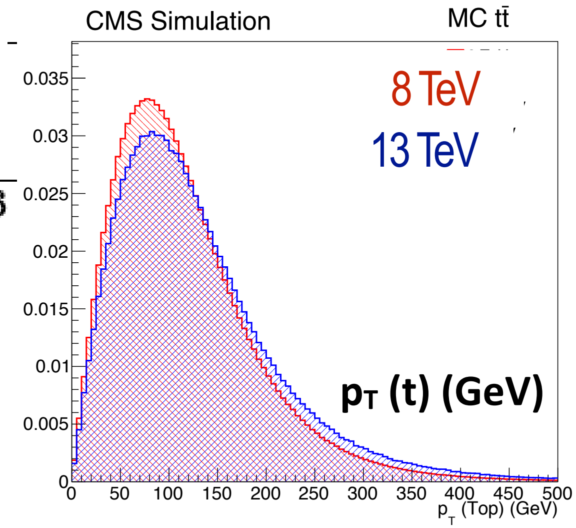
Expect top quark physics to play a lead role in direct and indirect searches for new phenomena

Backup

Energy Dependence

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



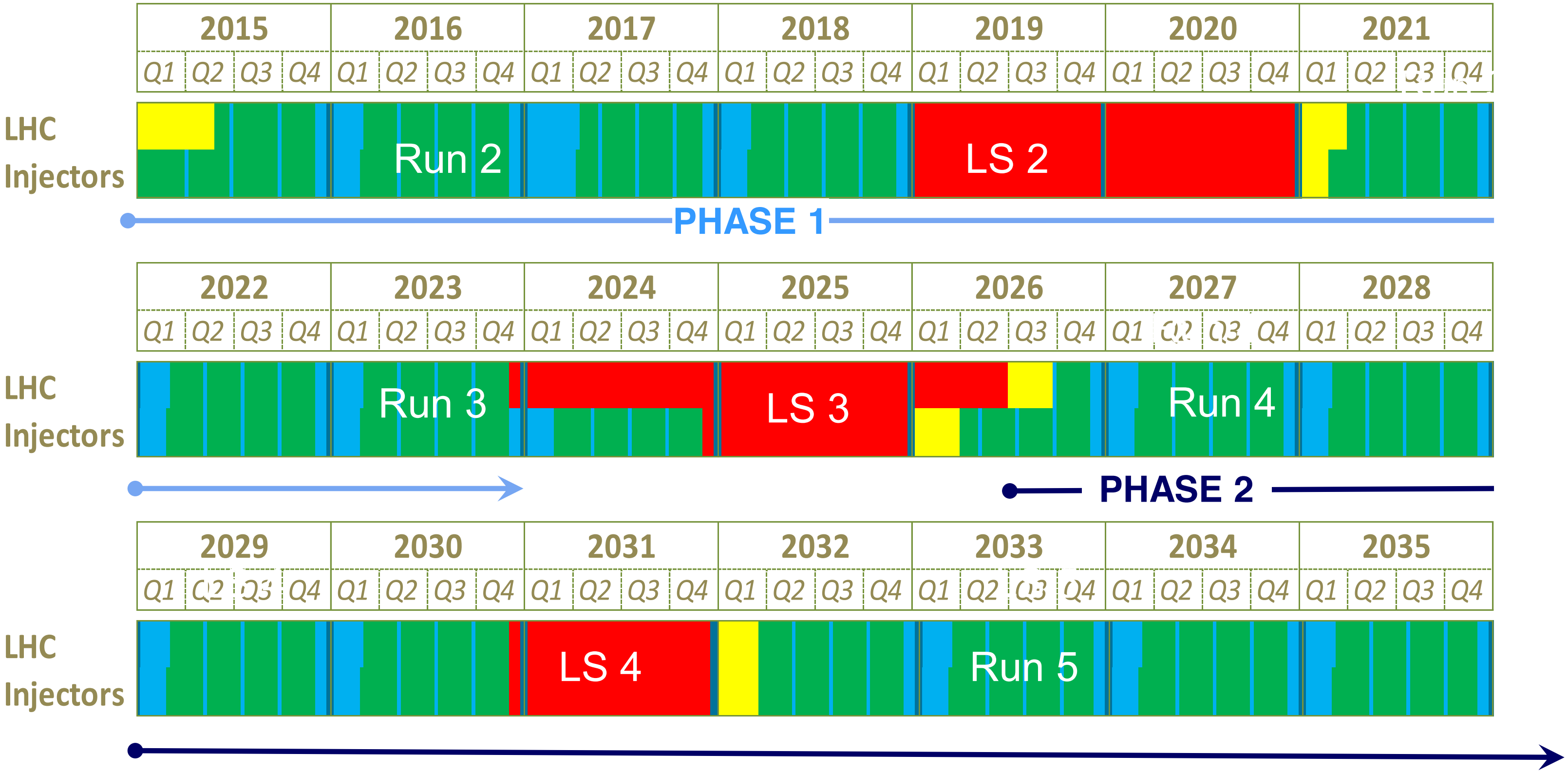


Cross section driven by rise of gluon density to low x:
→ shape of bulk distributions remains similar

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

- Physics
- Shutdown
- Beam commissioning
- Technical stop



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