# A (personal) overview of recent top-quark measurements at the LHC

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TECHNION
Israel Institute of Technology

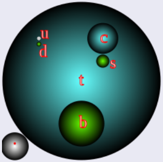
# Introduction

The top-quark was

- introduced in 1973 to explain weak CP violation
- discovered in 1995 (CDF and D0 at Tevatron)

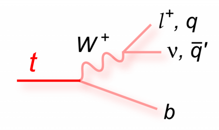
The LHC is a top-quark factory $\longrightarrow$ $\sim 10^9$ top-quarks produced since 2012 ($\sim$ 95% of them in Run 2)

Heaviest particle discovered




$\longrightarrow$ Strongly impact electroweak vacuum stability / BSM scenarios

Decay before hadronizing




$\longrightarrow$ Only chance to study a (almost) free quark
Possible to talk of parton level

# Top-quark properties

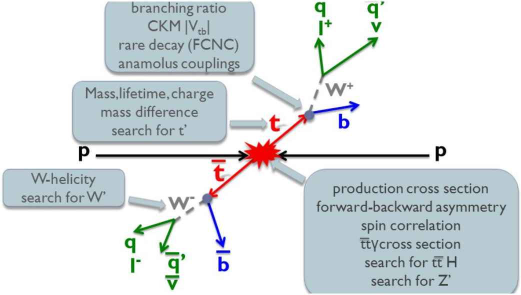
Properties:

- charge
- mass
- width
- spin
- couplings
- ... and more

$\longrightarrow$

Top-quark related free parameters:

- in the SM:
  - top-quark mass, $m_t$
  - three CKM matrix elements: $V_{tu}$, $V_{tc}$, $V_{tb}$
- in BSM scenarios:
  - couplings to new particles
  - new couplings to SM particles

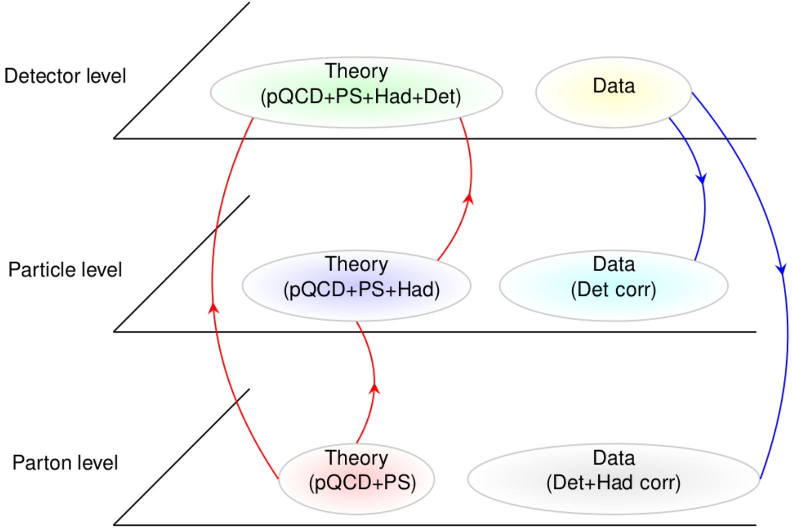



Lots of different topics and analyses !

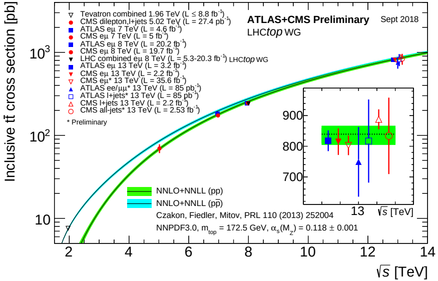
A personal selection of the most recent results reported here

# Data-to-theory comparsions

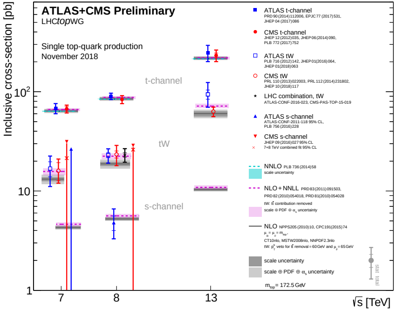
Top-quark cannot be measured directly
Its properties are inferred from a data-to-theory comparison



Top-quark mostly produced in pairs.




Single-top production is the second most-abundant topology




Measurements agree well with theoretical predictions

Single-top production is the second

T

Inclusive $t\bar{t}$ cross section [pb]

## New CMS result - August '19 - CMS-PAS-TOP-18-005

measurement $\sigma_{t\bar{t}}$ in dileptonic final state with one $\tau$ lepton

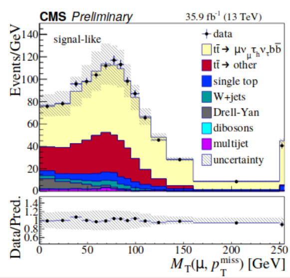
$$\sigma_{t\bar{t}}(\ell\tau_h) = 781 \pm 7(\text{stat}) \pm 62(\text{syst}) \pm 20(\text{lumi})\ \text{pb}$$

- hadronic $\tau \rightarrow$ decay only
- increased precision thanks to shape fit to $M_T(\ell, p_T^{\text{miss}})$ in signal-like and bkg-like regions.
- Lepton flavour universality preserved

$$\frac{\sigma_{\ell\tau_h}}{\sigma_{\ell\ell}} = 0.973 \pm 0.009(\text{stat}) \pm 0.066(\text{syst})$$

- ratio of partial widths agree wih expectations

$$\frac{\Gamma_{t\rightarrow\tau_h\nu b}}{\Gamma_{t\rightarrow\text{all}}} = 0.1050 \pm 0.0009(\text{stat}) \pm 0.0071(\text{syst})$$




main systematics uncertainty from $\tau$ identification

# More cross sections...

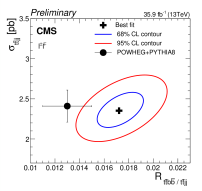
Large data sample allows to measure processes with small cross section.
More recent updates are from CMS

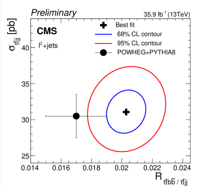
## $t\bar{t}b\bar{b}$ and $t\bar{t}jj$

Irridducible bkgs to $t\bar{t}H(b\bar{b})$ signal.
Available at NLO (+PS), but large unc.

CMS - August results (CMS-PAS-TOP-18-002)

- semileptonic and dileptonic channels
- smaller unc. thanks to more stat and improved fit (syst as nuisance par)




- slightly higher $\sigma^{meas}_{t\bar{t}b\bar{b}}$ than NLO+PS

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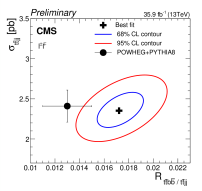
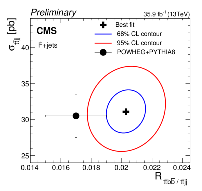


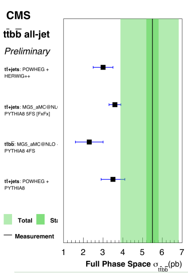




- slightly higher $\sigma^{\text{meas}}_{t\bar{t}b\bar{b}}$ than NLO+PS

## $t\bar{t}b\bar{b}$ fully hadronic

CMS - May results (CMS-PAS-TOP-18-011)

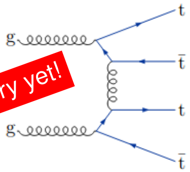
- challenging fully hadronic final state!
- $\geq$ 8 jets, $\geq$ 4 $b$-jets
- many systematics contribute equally ($t\bar{t}$ modelling, $b$-tag, MC stat)




measured $\sigma_{t\bar{t}b\bar{b}}$ (green) slightly higher than NLO+PS (markers)

# ...and more cross sections!

Searches for $t\bar{t}t\bar{t}$ production $\longrightarrow$ very very challenging experimentally!
NLO QCD prediction is $\sigma^{\rm SM}_{t\bar{t}t\bar{t}} \sim$ 12fb




No discovery yet!

ATLAS Phys. Rev. D 99 (2019) 052009

- $\ell$+jets and $\ell^+\ell^-$+jets channels
- combination with J. High EnergyPhys. 12 (2018) 039
  multi-$\ell$ and $\ell^\pm\ell^\pm$+jets meas.
- $\sigma^{\rm meas}_{t\bar{t}t\bar{t}} < 5\sigma^{\rm SM}_{t\bar{t}t\bar{t}}$
- set limit on anomalous four-top-quark coupling in EFT

CMS CMS-PAS-TOP-17-019

- $\ell$+jets and $\ell^+\ell^-$+jets channels
- MVA analysis on jet properties
- no observation $\rightarrow$ 1.4 $\sigma$ evidence
- $\sigma_{t\bar{t}t\bar{t}} <$ 48fb @ 95% CL
- EFT interpretation

CMS CMS-PAS-TOP-18-003

- multi-$\ell$ and $\ell^\pm\ell^\pm$+jets
- Classification + BDT
- uses 137 fb$^{-1}$ int. lumi
- significance of 2.4$\sigma$
- constraints top-Yukawa and set limits on heavy (pseudo-)scalar

# Differential lepton cross sections in $t\bar{t}$

Increased statistics makes possible to measure $t\bar{t}$ differential cross sections with high precision. Recent results from ATLAS at 13 TeV.

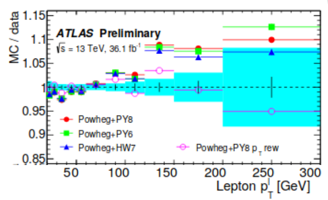
ATLAS $e^{\pm}\mu^{\mp}$+jets ATLAS-CONF-2019-041

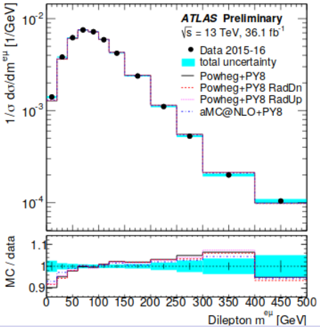
- clean channel → precision
- measure $\sigma_{t\bar{t}}^{\text{incl}}$ and extract $m_{\text{pole}}$
- $\frac{\sigma_{t\bar{t}}(13\text{TeV})}{\sigma_{t\bar{t}}(7-8\text{TeV})}$ and $\frac{\sigma_{t\bar{t}}/\sigma_Z(13\text{TeV})}{\sigma_{t\bar{t}}/\sigma_Z(7-8\text{TeV})}$
- 1-D and 2-D leptonic differential distributions at particle level

Cross sections ratios and double ratios compatible with NNLO+NNLL

Lepton $p_T$ harder than data, in POWHEG.

No MC describe low $m_{e\mu}$



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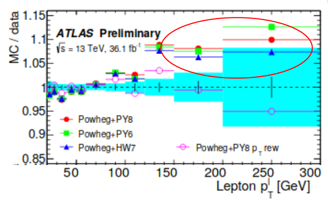
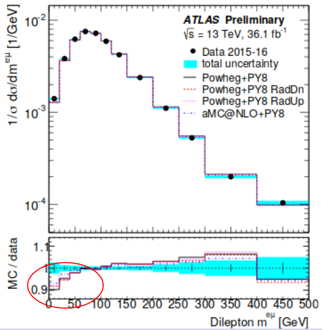


# Differential $t\bar{t}$ cross sections

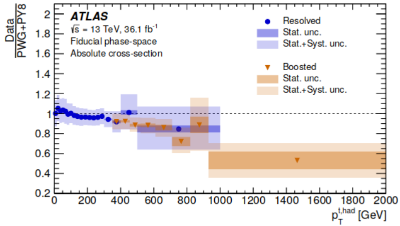
Increased statistics makes possible to measure $t\bar{t}$ differential cross sections with high precision. Recent results from ATLAS at 13 TeV.

ATLAS semileptonic: arXiv:1908.07305

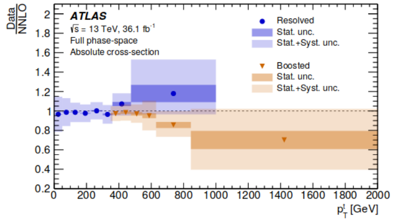
- resolved and boosted topologies
- particle and parton level
- 1-D and 2-D differential
- Data compared to MCs at particle level and also to NNLO pQCD at parton level
- not enough $p_T$ reach to evaluate the impact of NLO EW

MCs overestimate data in the tails of $p_T^{had}$, $m_{t\bar{t}}$, $H_{t\bar{t}}$ at particle level

NNLO describes data better than NLO+PS, at parton level



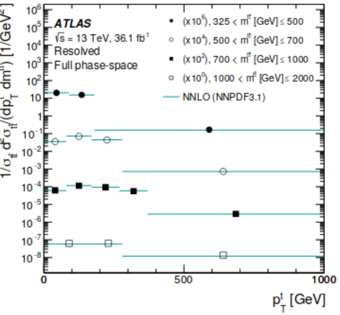

Particle Level

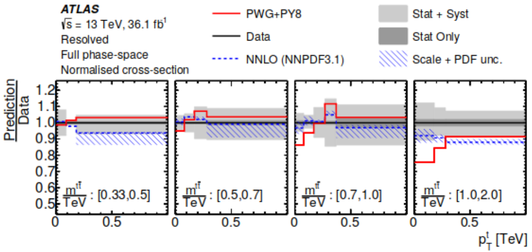



Parton Level

# ATLAS $t\bar{t}$ differential cross section

$\frac{d^2\sigma}{dp_T \ dm_{t\bar{t}}}$ 2-D differential cross section at parton level




Overall good argreement

$\frac{d^2\sigma}{dp_T \ dm_{t\bar{t}}}$ is interesting

unfolded data better described

at low $p_T$ by NLO+PS

at hight $p_T$ by NNLO pQCD

# $V_{tb}$ coupling

**JHEP 05 (2019) 088**

ATLAS + CMS combination of 7 and 8 TeV single-$t$ cross-sections allows to measure the largest CKM matrix element ($V_{tb}$)

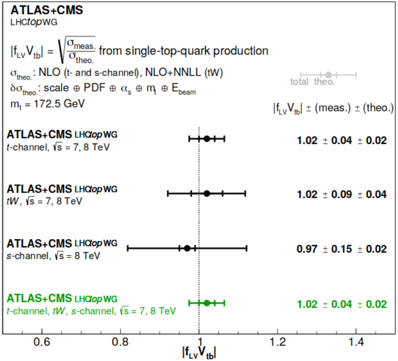
- assuming $|V_{td}|, |V_{ts}| \ll |V_{tb}|$
- left handed *Wtb* weak coupling

$$|f_{LV} V_{tb}| = \sqrt{\frac{\sigma^{\text{meas}}}{\sigma^{\text{SM}}}}$$

$f_{LV}$ form factor for left-handed coupling (==1 in the SM)

$$|f_{LV} V_{tb}| = 1.02 \pm 0.04$$

largest unc. from single-$t$ modelling and theo. cross section



# Charge asymmetry

**ATLAS-CONF-2019-026 - July ’19**

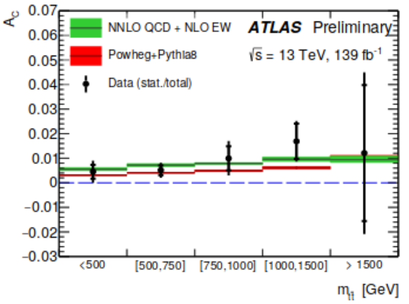
Inclusive and differential charge asymmetry $A_C$ measurements in $t\bar{t}$ with $L = 139\ \text{fb}^{-1}$ at 13 TeV

- asymmetry originates from beyond-LO corrections to $t\bar{t}$ producion
- more forward $t$ and more central $\bar{t}$ are expected in $pp$ collisions

$$A_C = \frac{N(|y_t| - |y_{\bar{t}}| > 0) - N(|y_t| - |y_{\bar{t}}| < 0)}{N(|y_t| - |y_{\bar{t}}| > 0) + N(|y_t| - |y_{\bar{t}}| < 0)}$$

$4\sigma$ evidence for charge asymmetry
$A_C = 0.0060 \pm 0.0015$ (from SM $A_C \sim 0.0064$)
compatible with SM

- $\ell$+jets final states
- resolved and boosted topologies
- unfolding to parton level
- EFT interpretation



# Top width

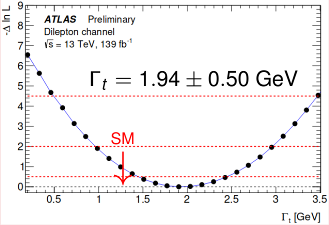
## ATLAS-CONF-2019-038 - August '19

Measurement of top-quark decay width $\Gamma_t$ with $L = 139\ \text{fb}^{-1}$ at 13 TeV

- short lifetime $\rightarrow$ large decay width
- at NNLO $\Gamma_t = 1.322$ GeV

  for $m_t = 172.5$ GeV

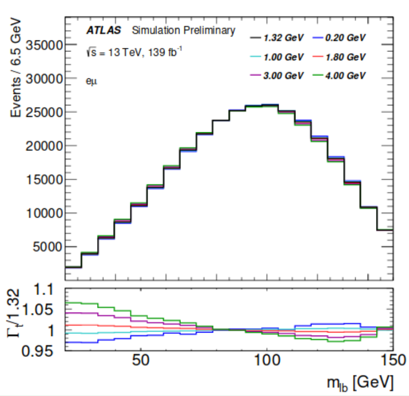
  with only 6% theo unc.
- sensitive to BSM physics




systematics incorporated in the fit and constrained by simultaneous fit to $m_{b\bar{b}}$

leading syst are jet related and $t\bar{t}$ modelling

- dilept. final states
- $\Gamma_t$ extracted **directly** from data/MC comparison of $m_{\ell b}$ at detector level



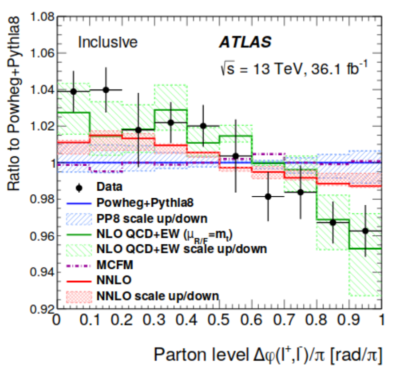

$m_{\ell b} < 150$GeV avoid NLO effects in $t$ decay

# Polarisation and spin correlations at 13 TeV

In SM $t\bar{t}$ production the spins of $t$ and $\bar{t}$ are predicted to be correlated.
Top lifetime is shorter than hadronisation and spin decorrelation time scales
Top-quark spin information is passed to top decay products

**ATLAS-CONF-2016-10**

- $e^{\pm}\mu^{\mp}$ only
- unfold to parton and particle levels
- measures $\Delta\eta(\ell_1, \ell_2)$ inclusively and $\Delta\phi(\ell_1, \ell_2)$ also in $m_{t\bar{t}}$ bins



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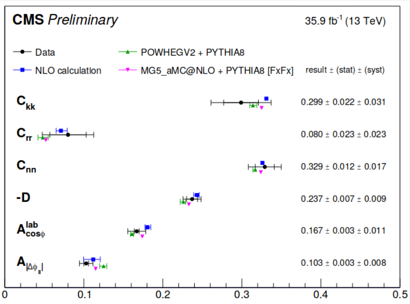
## CMS-PAS-TOP-18-006

- $e^{\pm}\mu^{\mp}$, $e^{+}e^{-}$, $\mu^{+}\mu^{-}$ channels
- extracts the (15) coefficients of top spin dependent parts of $t\bar{t}$ production
- measures 15 (indip) observables, unfolded to parton level




## ATLAS-CONF-2016-10

- $e^{\pm}\mu^{\mp}$ only
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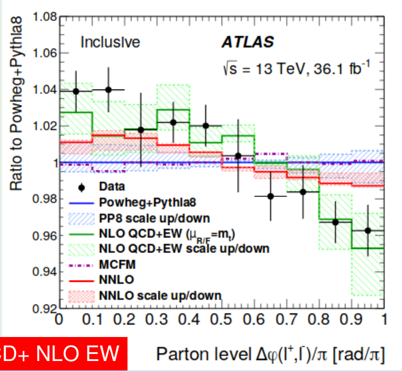



**CMS agrees with NLO QCD, ATLAS prefers NLO QCD+ NLO EW**

**Top-quark mass relevance**

- self-consistency checks of SM ( $m_t$, $m_W$, $m_H$ are related)
- electro-weak vacuum stability (running of Higgs quartic coupling)
- affects BSM scenarios (large mass value)

Top-quark mass ($m_t$) is a free parameter of the SM can be determined via:

- Global fits (PRD 96 (2017) 014011, JHEP 2016 (2016) 135, EPJC 78 (2018) 675)
- Dedicated experimental measurements

**Top-quark mass experimental measurements need special attention!**

Extraction can be done from data-to-MC or data-to-pQCD comparisons.
No analytical relation exist between the top-quark mass as implemented in MCs ($m_t^{\mathrm{MC}}$) and the parameter of the Lagrangian ($m_t^{\mathrm{pole}}$, $m_t^{\overline{\mathrm{MS}}}$, . . . )

Various solutions under study / used

- theo. work for $m_t^{\mathrm{MC}} \leftrightarrow m_t^{\mathrm{pole}}$ relation ongoing
- Use $m_t^{\mathrm{MC}}$ and add 0.5 GeV unc. (∼leading one!).
- measurements of $m_t^{\mathrm{pole}}$ and $m_t^{\overline{\mathrm{MS}}}$ with more precise evaluation of theo unc.

New results published by CMS and ATLAS in the past months

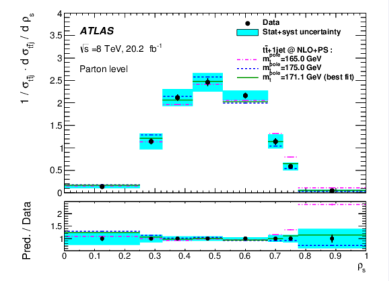
# Pole mass

Needs for a $m_t^{\text{pole}}$ or $m_t^{\overline{\text{MS}}}$ measurement:

- Observable(s) sensitive to $m_t$
- Calculations of the observables at least at NLO QCD
- Theo corr. under control (small unc.)

## TOPQ-2017-09 $m_t^{\text{pole}} = 171.1 \pm 1.1$ GeV

- $t\bar{t} + 1$jet topology, still 8 TeV!
- unfold to parton and particle levels
  $m_t$ from parton level only
- one very sensitive observable

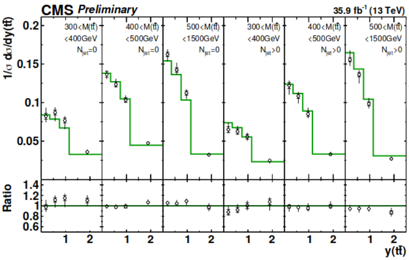



largest unc: modelling and scale variations

## CMS-TOP-18-004 $m_t^{\text{pole}} = 170.5 \pm 0.8$ GeV

Top-quark mass extracted from 3-D $t\bar{t}$ differential cross section $\frac{d^3\sigma_{t\bar{t}}}{dm_{t\bar{t}}\ dy_{t\bar{t}}\ dN_j}$

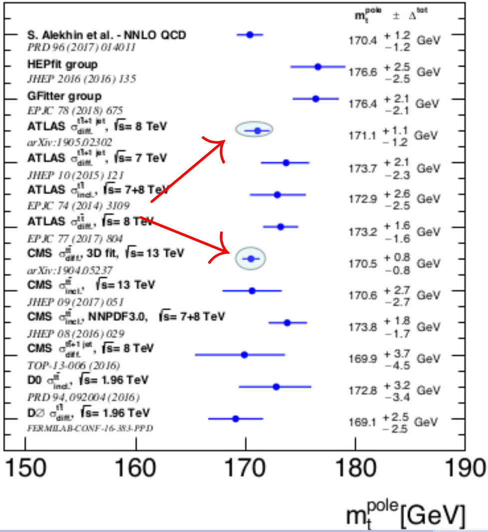
- parton level comparsion to NLO QCD
- simultaneous fit of $m_t^{\text{pole}}$, $\alpha_s$, PDFs
- theo. unc. from scale varaitions




main unc. from fit and scale var.

theoretical uncertainties evaluated with 100 MeV precision and total $\Delta m_t^{\text{pole}} \lesssim 1$ GeV !

summary of all $m_t^{pole}$ measurements




## Global fits

EW fits prefer high mass
$m_t^{pole} \sim 176.5 \pm 2$ GeV

NNLO QCD global fit gives
$m_t^{pole} = 170.4 \pm 1.2$ GeV

Recent $m_t^{MC}$ combinations of ATLAS and CMS
$m_t^{MC}(\text{ATLAS}) = 172.7 \pm 0.5$ GeV
$m_t^{MC}(\text{CMS}) = 172.4 \pm 0.5$ GeV

world avg. (from PDG 2018)
$m_t^{MC}(\text{World}) = 173.1 \pm 0.9$ GeV
(no additional 0.5 GeV theo. unc. considered)

**My naive combination** of recent $m_t^{pole}$ measurements
$m_t^{pole} = 170.7 \pm 0.7$ GeV

# Top mass running and Yukawa coupling

Top-quark mass is a parameter of the Lagrangian:

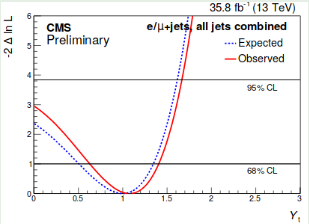
- proportional to top-Yukawa coupling $Y_t$ in the SM
- in $\overline{\text{MS}}$-like schemes it has scale-dependent running

## CMS-PAS-TOP-17-004

constrain $Y_t$ from semilep. $d\sigma_{t\bar{t}}/dX$

- EW corrections to $t\bar{t}$ depend on $Y_t$
- Add LO EW to parton level NLO QCD (through reweighting)
- fold to detecor level and compare with data (prof likleilhood fit)

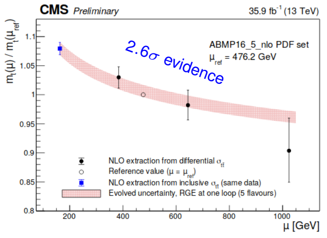
3D distribution of $m_{t\bar{t}}$, $\Delta y_{t\bar{t}}$, $N_j$ is used




## CMS-PAS-TOP-19-007 August '19

first measurement of running $m_t(\mu)$

- $e^{\pm}\mu^{\mp}$+jets unfolded to parton level
- comparison to NLO QCD in $\overline{\text{MS}}$ renorm. scheme
- measure $\sigma_{t\bar{t}}$ in four $m_{t\bar{t}}$ bins and extract $m_t^{\overline{\text{MS}}}(\mu = m_{t\bar{t}})$ in each bin




consider ratios to get shape and simplify systematics

# Summary and conclusions

Many top-quark related results from the LHC experiments in the last months. A personal selection of recent analyses was shown.

Onorable mentions:

- LHCb measured $t\bar{t}$ production too (JHEP 08 (2018) 174 )
- CMS jet-mass of boosted hadronic tops (CMS-PAS-TOP-19-005 , August '19 )

Interesting since probes different fiducial volume (forward/high $p_T$ top)

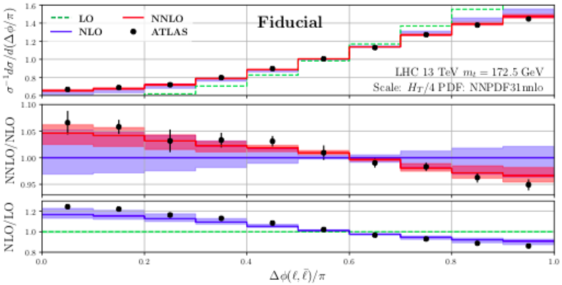
Recent results take advantage of successfull operation of the LHC and its experiments

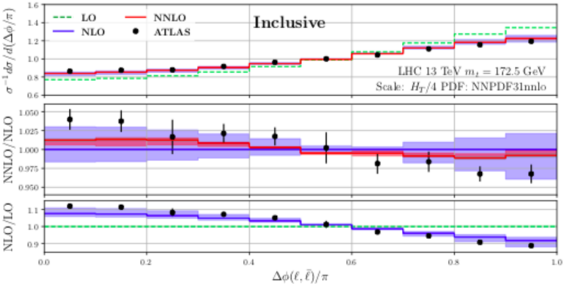
- large dataset (up to $L = 139\text{fb}^{-1}$ , 4x increase in $t\bar{t}$ xsec from 8 to 13 TeV)
- improved knowledge of detectors behaviour (reduced syst)

- parton and particle levels give complementary information
- overall good data-theory agreement
- first time results with new approaches and methods
- there is still room for improvements!

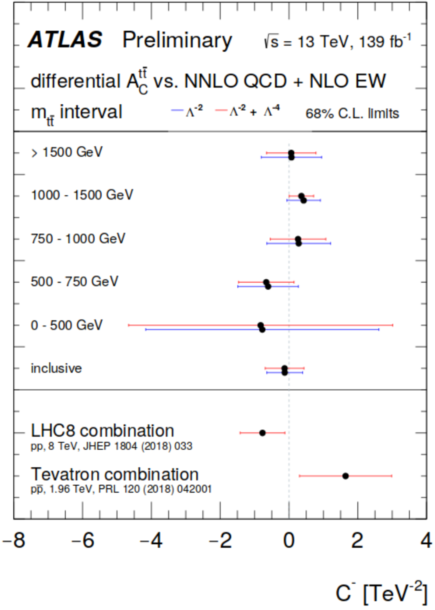
# Back-up

# ATLAS spin correlations




particle level better described by NNLO than parton level




EFT expansion

$$\mathcal{L} = \mathcal{L}^{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i + \dots$$

can be rearranged so that only one operator, with Wilson coefficient $C^-$ contributes to charge asymmetry.

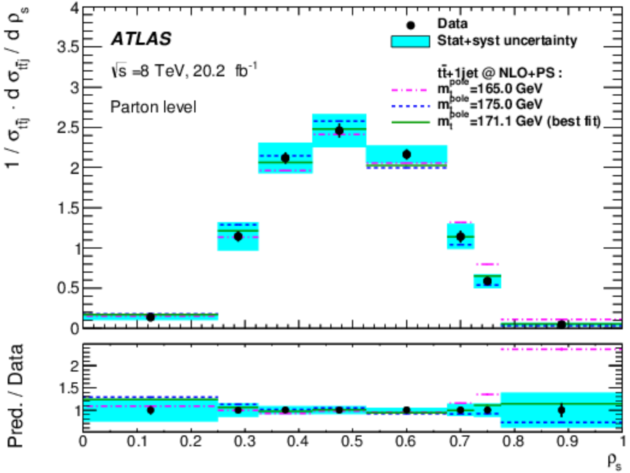
Impact of considering first $\Lambda^{-4}$ evaluated (ensures $\Lambda$ expansion is under control)

# Top-quark mass

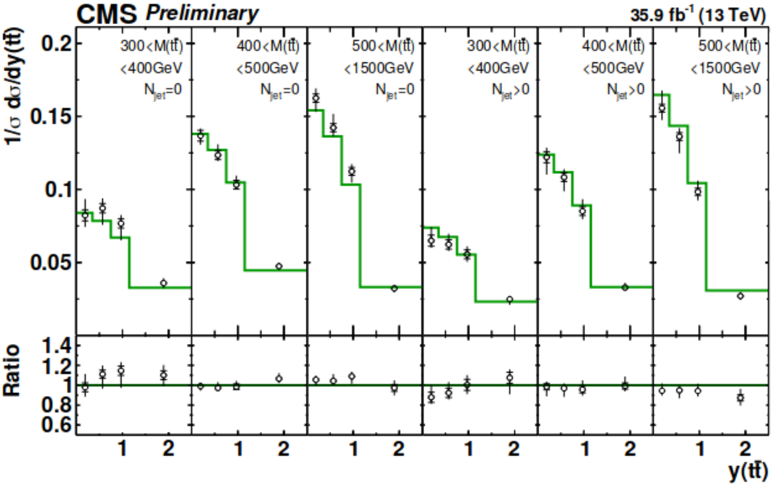
## Additional uncertainty on $m_t^{MC}$, from arXiv:1803.08153

additional 0.5 GeV unc. on $m_t$ to cover the ambiguity in the kinematic top quark mass definition, the colour structure of the fragmentation process, and the perturbativerelation between pole and MS mass

# ATLAS pole mass



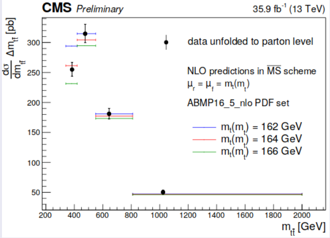
# CMS pole mass



## CMS running mass

$m_t^{\overline{MS}}(\mu = m_t^{\overline{MS}})$ extracted in $m_{t\bar{t}}$ bins comparing unfolded data to MCFM (NLO accuracy)

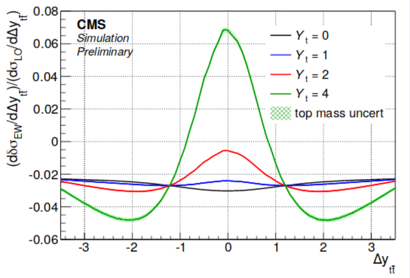
Values are evolved to $m_t^{\overline{MS}}(\mu = m_{t\bar{t}})$ with *RunDec*

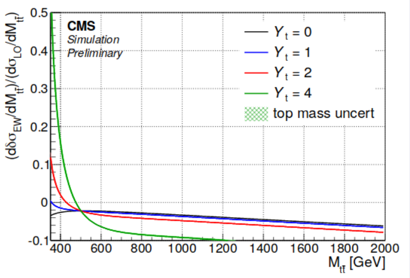



PDFs + $\alpha_s$ uncertainties considered
no scale uncertainty needed (since it is what is measured)

## CMS Yukawa constraint

LO EW corrections from *Hathor*



# CMS Jet mass from boosted hadronic top