Measurements of asymmetries in top-quark production and tests of lepton universality in ATLAS

Nello Bruscino - Sapienza Università di Roma & INFN Roma1
on behalf of the ATLAS Collaboration

TOP2020 - 13th International Workshop on Top-Quark Physics
14-18.09.2020

The top quark

Production time		Decay time		Hadronisation time		Spin-Decorr. time
$\frac{1}{m_t}$	$<$	$\frac{1}{\Gamma_t}$	$<$	$\frac{1}{\Lambda_{QCD}}$	$<$	$\frac{m_t}{\Lambda}$
~10^{-27} s		**~10^{-25} s**		**~10^{-23} s**		**~10^{-22} s**

Why top quarks?

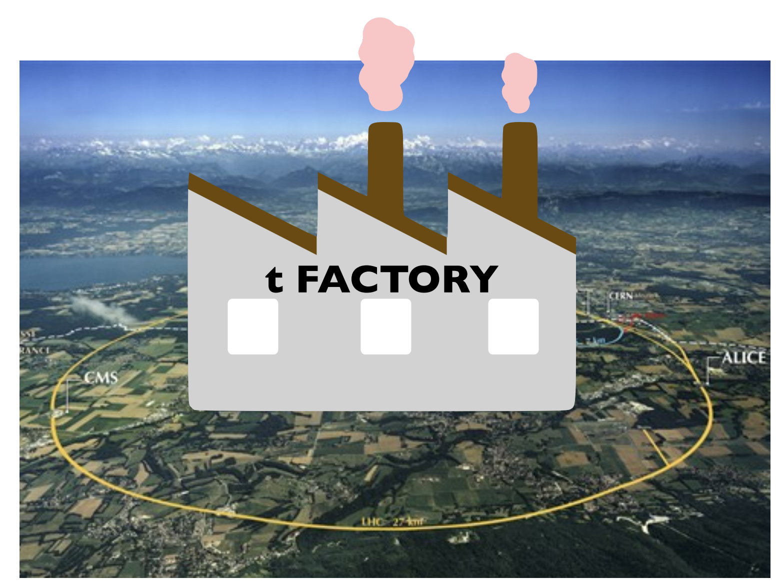
- heaviest known particle, only "bare" quark
- high statistics allows **precision measurements** and search for **new physics**

Copious production at the LHC (top-factory):

- ~150/fb @13TeV collected in Run 2 by ATLAS…

$$N = \mathscr{L} \cdot \sigma_{t\bar{t}},$$
$$\sigma_{t\bar{t}} \sim 830\,\text{pb}, \quad \Longrightarrow$$
$$\mathscr{L} \sim 15 \cdot 10^{33}\,\text{cm}^2\,\text{s}^{-1}$$

~750 $t\bar{t}$ pairs produced/minute
(125M @150/fb)



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Production properties

- Cross-section and Kinematics of $t\bar{t}$
- Charge asymmetry
- Top quark polarization
- FCNCs
- Many more . . .

Decay properties

- W-helicity
- CLFV: $t \rightarrow ll'q$
- FCNC: eg. $t \rightarrow hu$, $t \rightarrow hc$, $t \rightarrow Zu$, $t \rightarrow Zc$, $t \rightarrow \gamma u$, $t \rightarrow \gamma c$
- Jet shapes and colour flow
- Anomalous couplings
- Many more . . .

Properties of W-boson from $t\bar{t}$ events

- Measurement of universality of leptons to W boson through:

$$R(\tau/\mu) = \frac{BR(W \rightarrow \tau\nu)}{BR(W \rightarrow \mu\nu)}$$

NEW!

Fundamental properties of the top quark

- Mass
- Width
- Spin (indirectly)
- Charge

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Talk: [$t\bar{t}$ x-sec allhad]
Riccardo Poggi, Wed 16/09 h15:20

Talk: [$t\bar{t}$/singletop x-sec & syst reduction]
Olga Bylund, Mon 14/09 h15:00

Decay properties

- W-helicity
- CLFV: $t \to ll'q$
- FCNC: $t \to qg$, $t \to hu$, $t \to hc$, $t \to Zu$, $t \to Zc$, $t \to \gamma u$, $t \to \gamma c$
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Fundamental properties of the top quark

Talk: BSM top quark interactions
Mohammad Kareem, Wed 16/09 h17:30

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Fundamental properties of the top quark

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- Charge

Talk: $t\bar{t}$+γ/Z/W
Rustem Ospanov, Tue 15/09 h15:30

Talk: 4 tops
Erich Varnes, Fri 18/09 h14:30

Top properties

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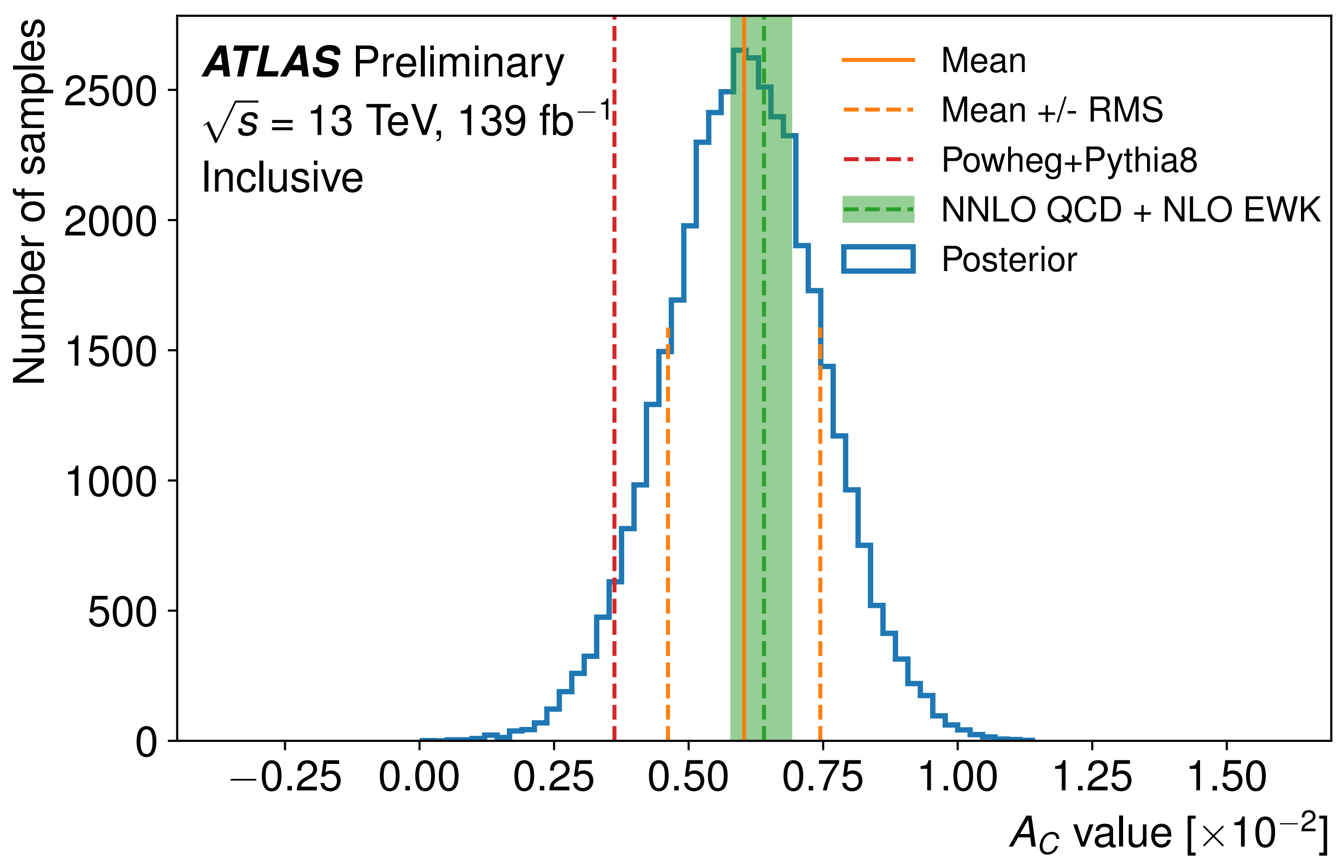
Charge asymmetry



Charge asymmetry

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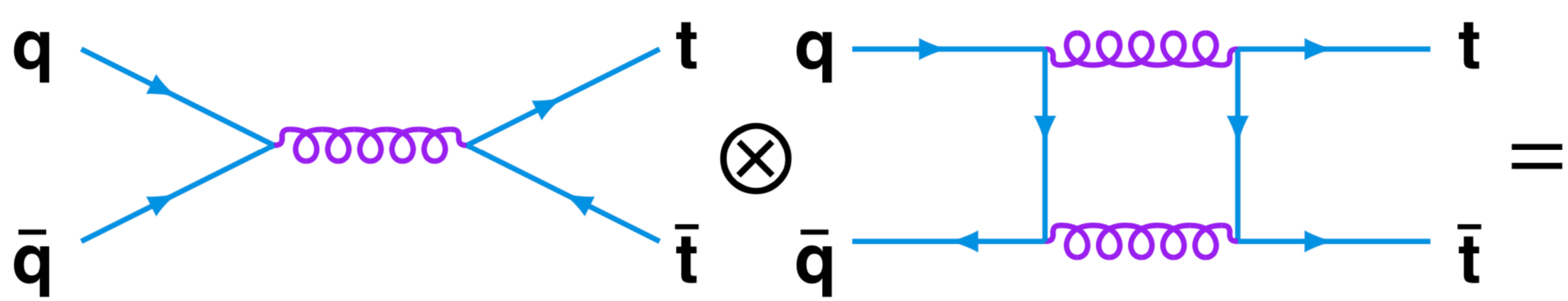

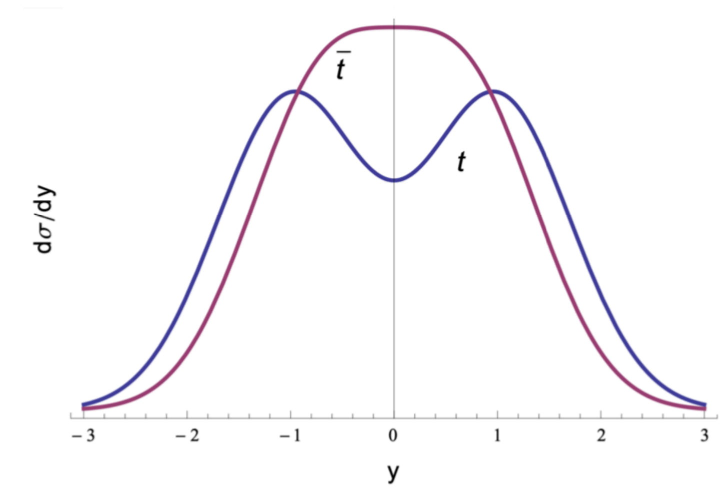

At leading order $t\bar{t}$ production is charge symmetric

- higher orders interference in qg and $q\bar{q}$, and EW contributions lead to asymmetries
- also BSM physics can lead to enhancements!

The gg initiated process remains charge symmetric to all orders

- this dilutes the asymmetry significantly
- challenging to measure at the LHC ($q\bar{q}$ ~ 10% of production fraction @13 TeV)

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \qquad \Delta|y| = |y(t)| - |y(\bar{t})|$$

Charge asymmetry

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Extracted from 139/fb @13TeV data using single lepton (e/μ) selections

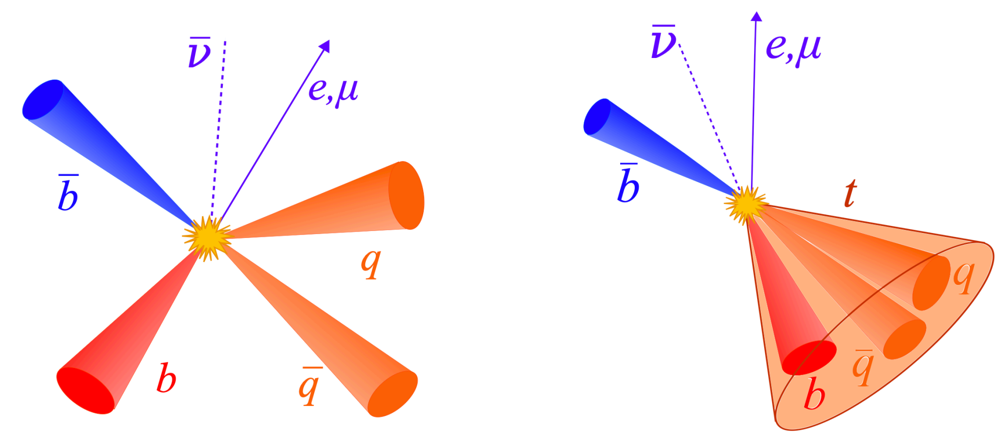
- resolved+boosted ($p_T(t) \gtrsim 400$ GeV)

Resolved: BDT to assign the different jets to the top systems

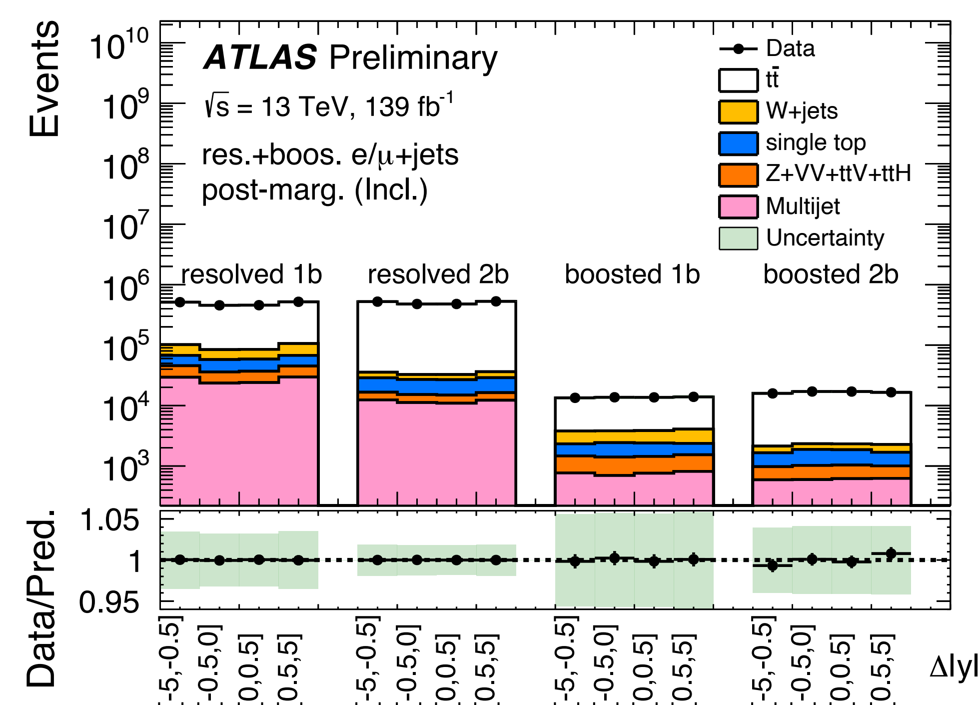
- using KLFitter, masses of hadronic top and W, various angular variables
- best combination considered and only events with good reconstruction retained

Boosted: hadronic top reconstructed as a single large-R jet

- mass and τ_{32} used to "tag" hadronic tops
- leptonic side reconstructed from the E_T^{miss}, lepton and a R=0.4 jet



Resolved **Boosted**



Charge asymmetry

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ATLAS EXPERIMENT

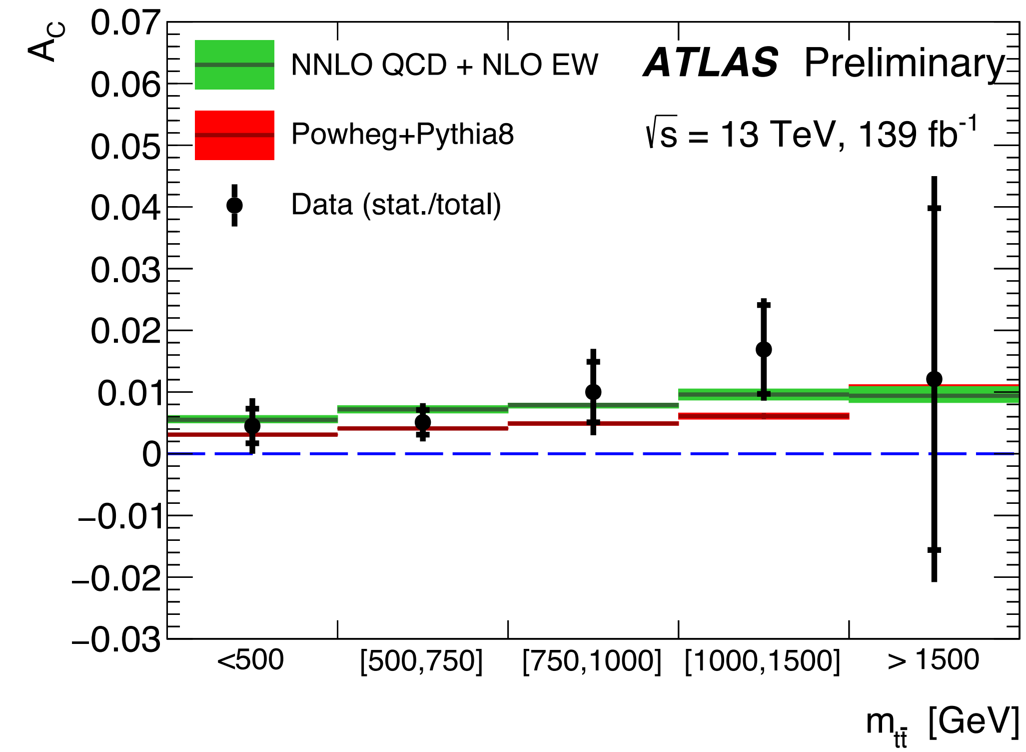
|Δy| unfolded using a likelihood-based technique called "fully bayesian unfolding"

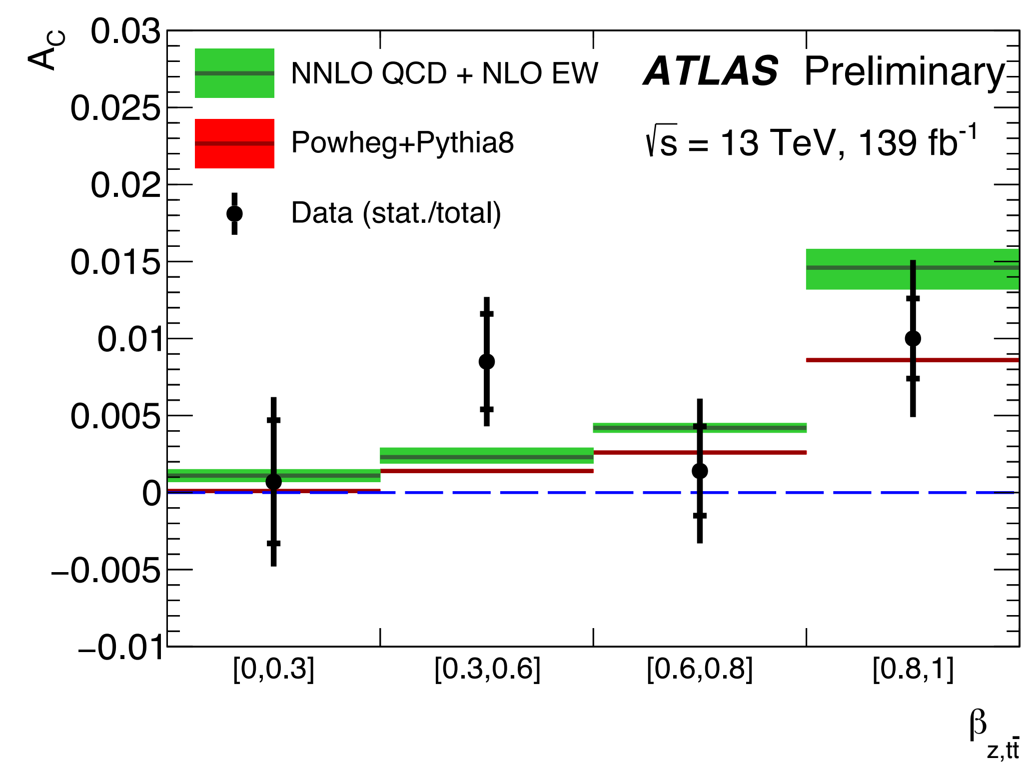
- inclusive and differential in bins of the $m_{t\bar{t}}$ and $\beta_{z,t\bar{t}}$ (absolute longitudinal boost of $t\bar{t}$ system in the z-direction)

Inclusive charge asymmetry $A_C = (0.6 \pm 0.15)\%$

- in agreement with NNLO QCD + NLO EW predictions
- **4σ from 0-asymmetry hypothesis**
- EFT limits based on the inclusive and $m_{t\bar{t}}$ results

First evidence for charge asymmetry in pp collisions!





Charge asymmetry

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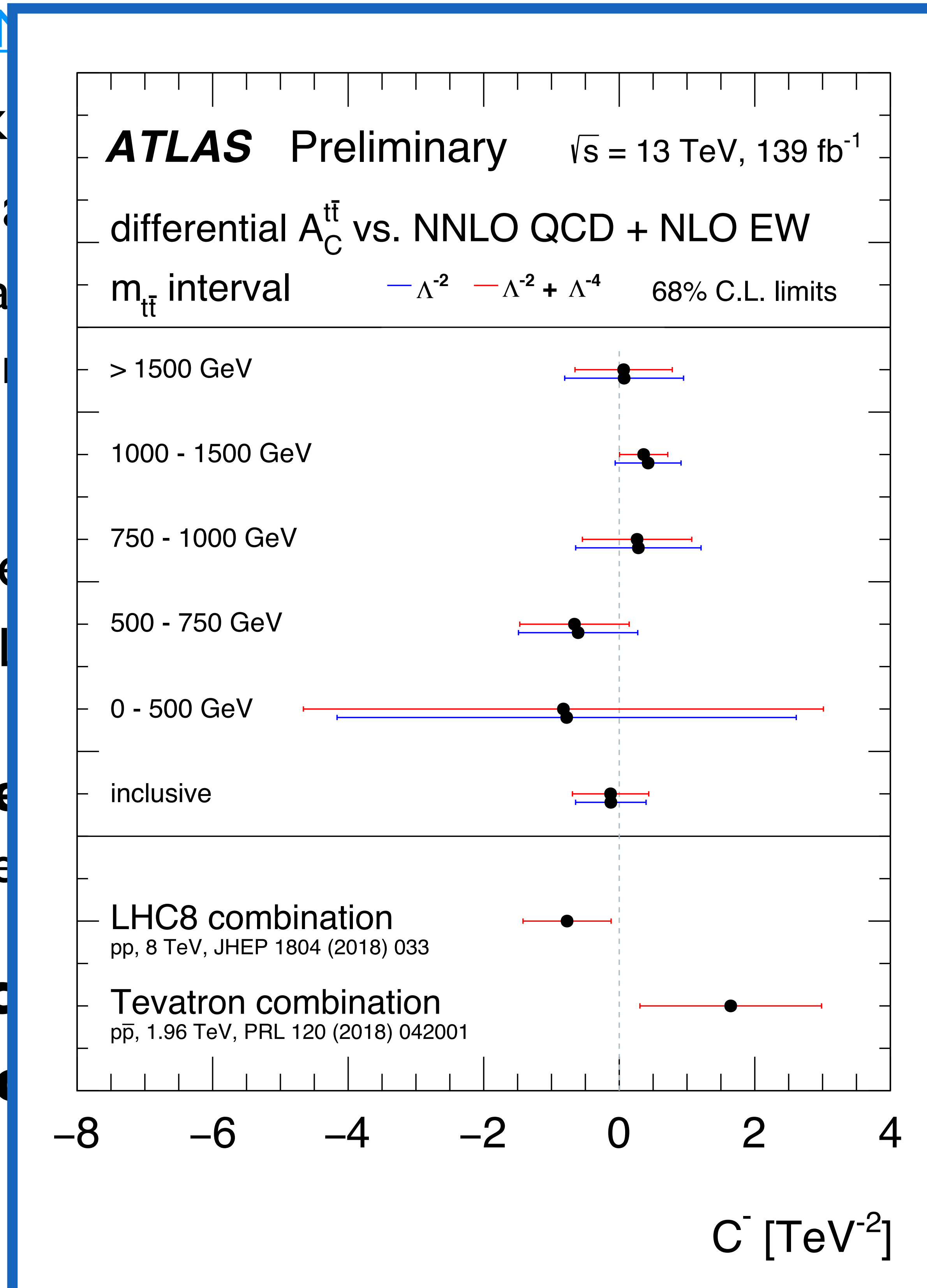
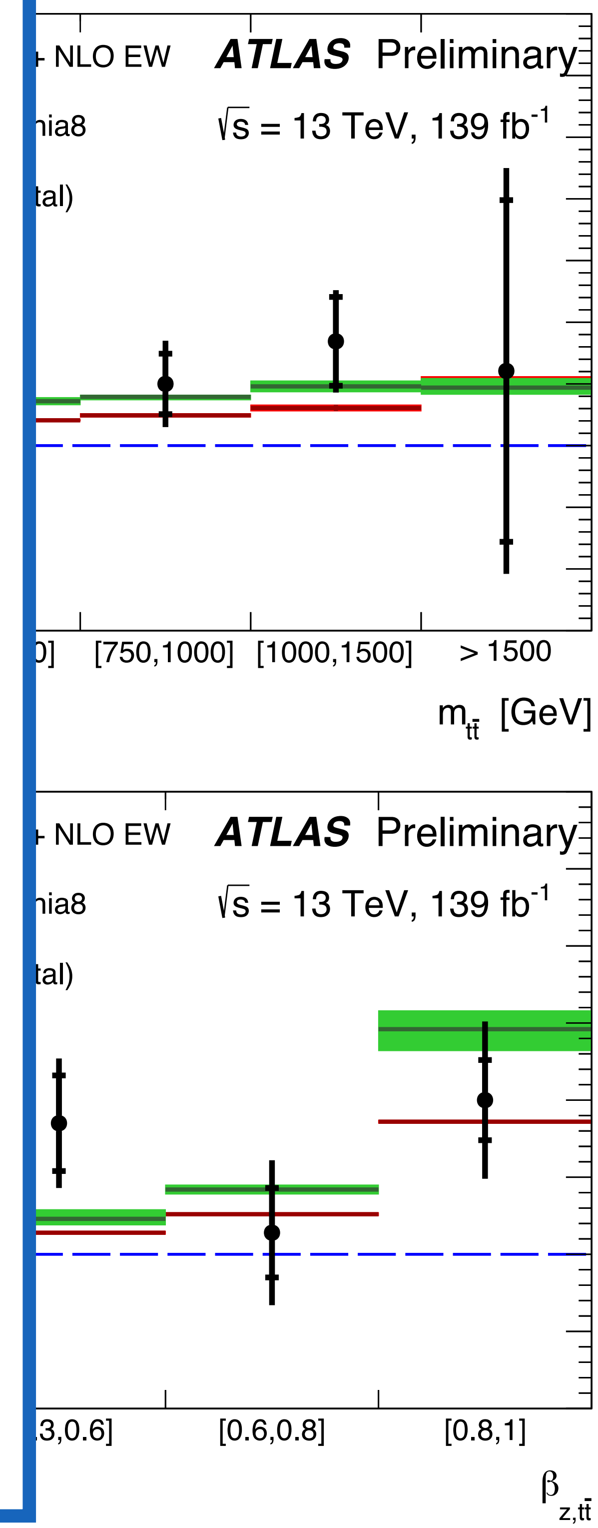
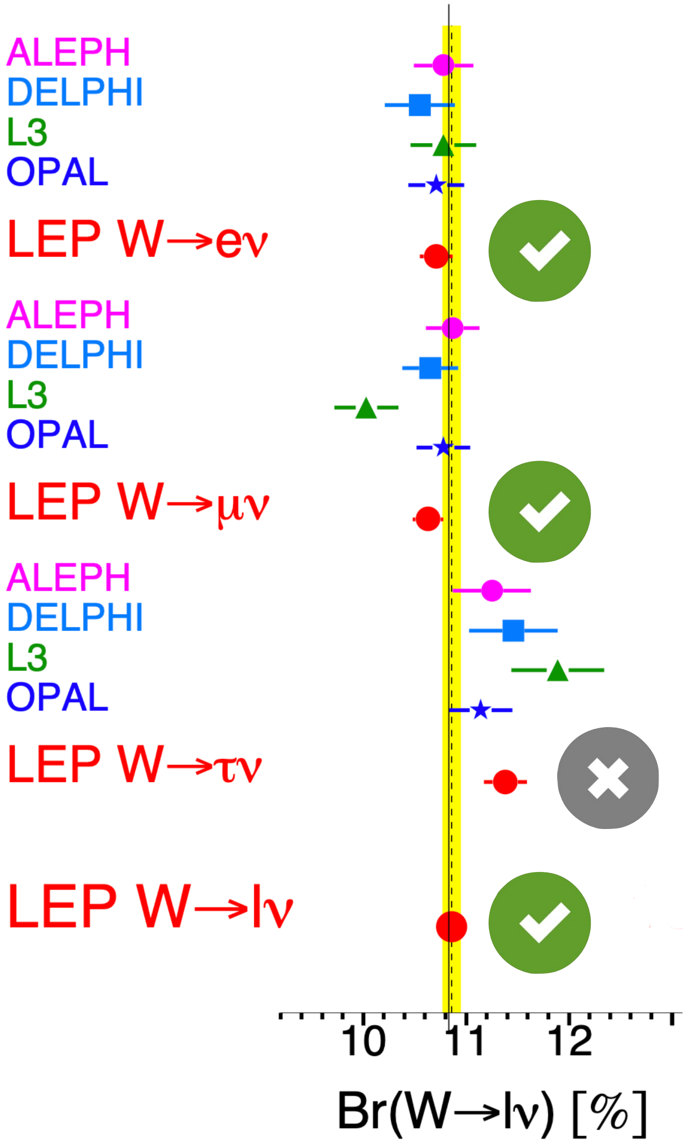




Lepton flavour universality



Lepton flavour universality

arXiv:2007.14040 - **Submitted to Nature Physics**

ATLAS EXPERIMENT

Fundamental assumption of Standard Model (SM)

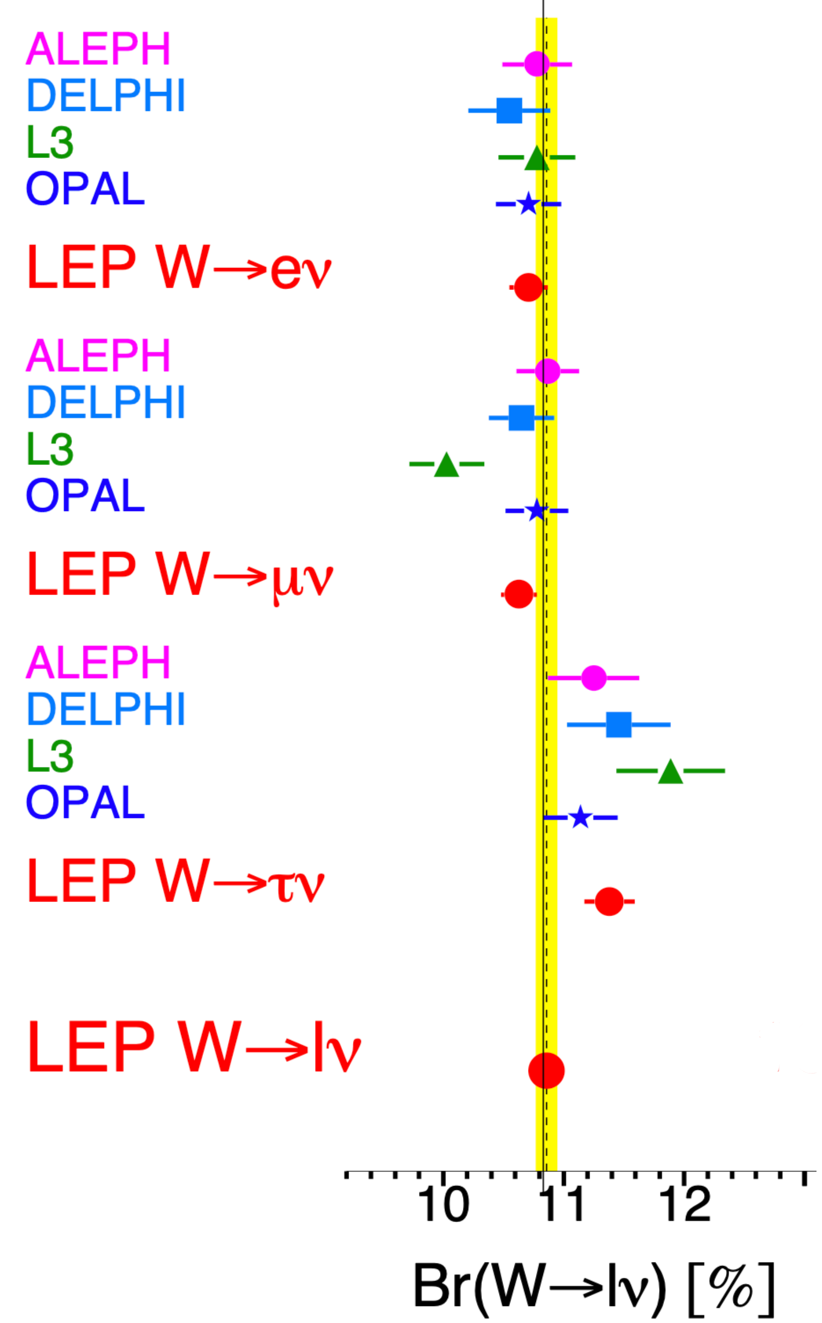
- universal coupling of the different generations of leptons to the gauge bosons
- → all charged leptons (e, μ, τ) have same coupling strength to W boson

W boson decays precisely measured at LEP

- however, observed 2.7σ deviation from SM prediction for BR(W → τν)

Measuring R(τ/μ) = BR(W → τν)/BR(W → μν) with a precision of 1-2% would either prove LEP discrepancy or rule it out

Phys.Rept. 532 (2013) 119-244

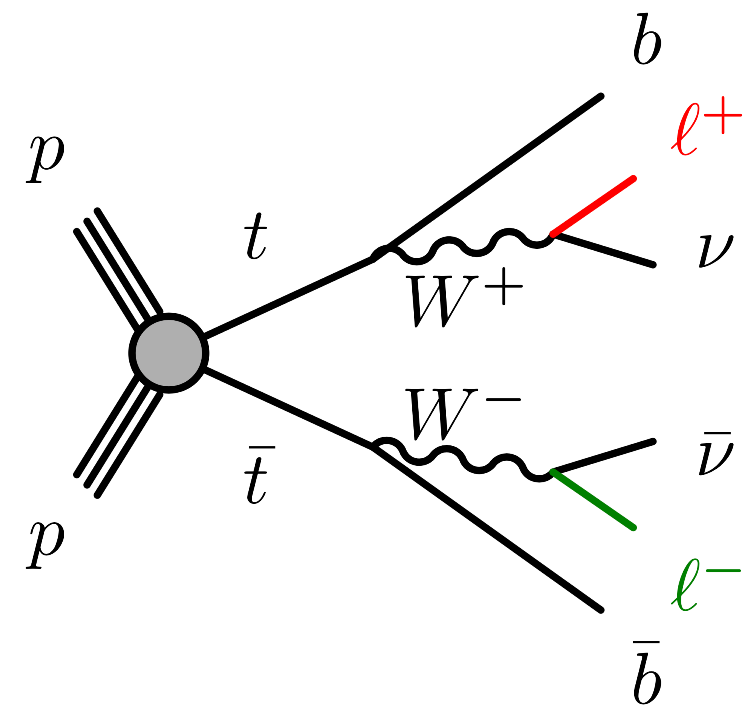


LFU - Analysis strategy

arXiv:2007.14040 - **Submitted to Nature Physics**

In dilepton $t\bar{t}$ events, a large, unbiased sample of W-bosons can be obtained

- one decaying top used to trigger the event (tag lepton)
- the other top used to provide an (unbiased) set of W bosons for the measurement (probe lepton)
- as low in p_{T}(probe μ) as reconstruction allows
- only look at leptonic tau decays to profit from smaller reconstruction uncertainties



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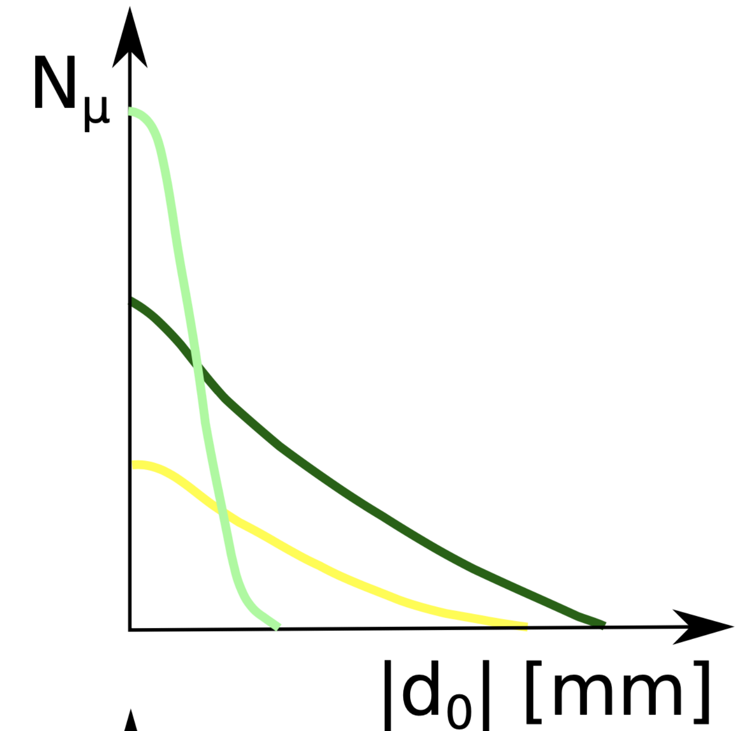
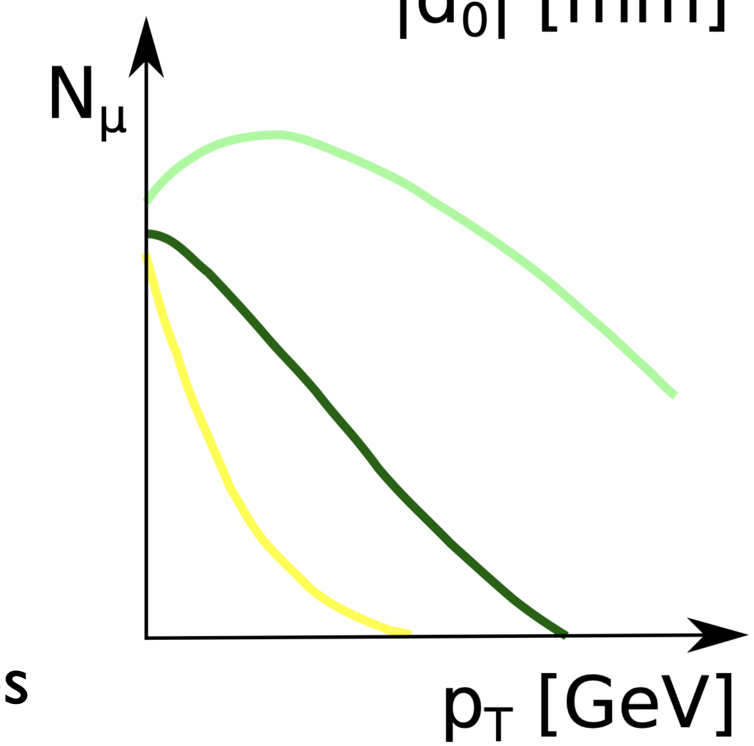


Main goal: distinguish **prompt muons** vs. **taus decaying into muons** and **muons from hadron decays**

- p_T(probe μ) and unsigned transverse impact parameter with respect to beamline ($|d_0^\mu|$) as discriminating variables



LFU - Analysis strategy

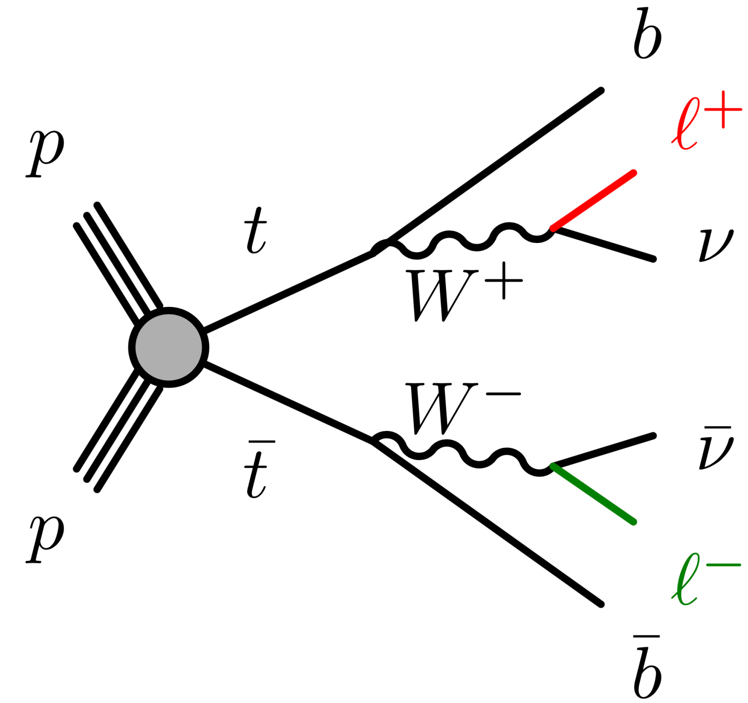
arXiv:2007.14040 - **Submitted to Nature Physics**

Applying standard $t\bar{t}$ (di-lepton, eμ/μμ) selection:

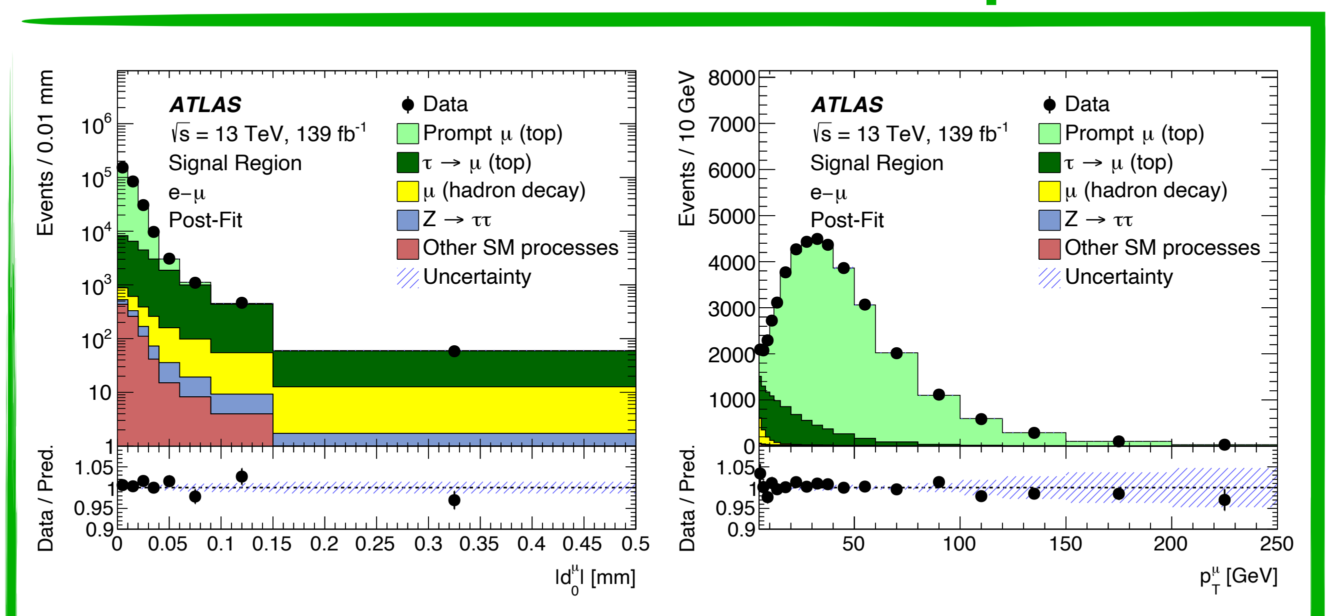
- 2 b-tagged jets, 2 oppositely charged leptons
- Z boson veto for di-muon channel
- **tag lepton** must pass trigger requirement
- **probe muon** must have $p_T > 5$GeV
  - allows to probe a large p_T range

Remaining backgrounds for the measurement:

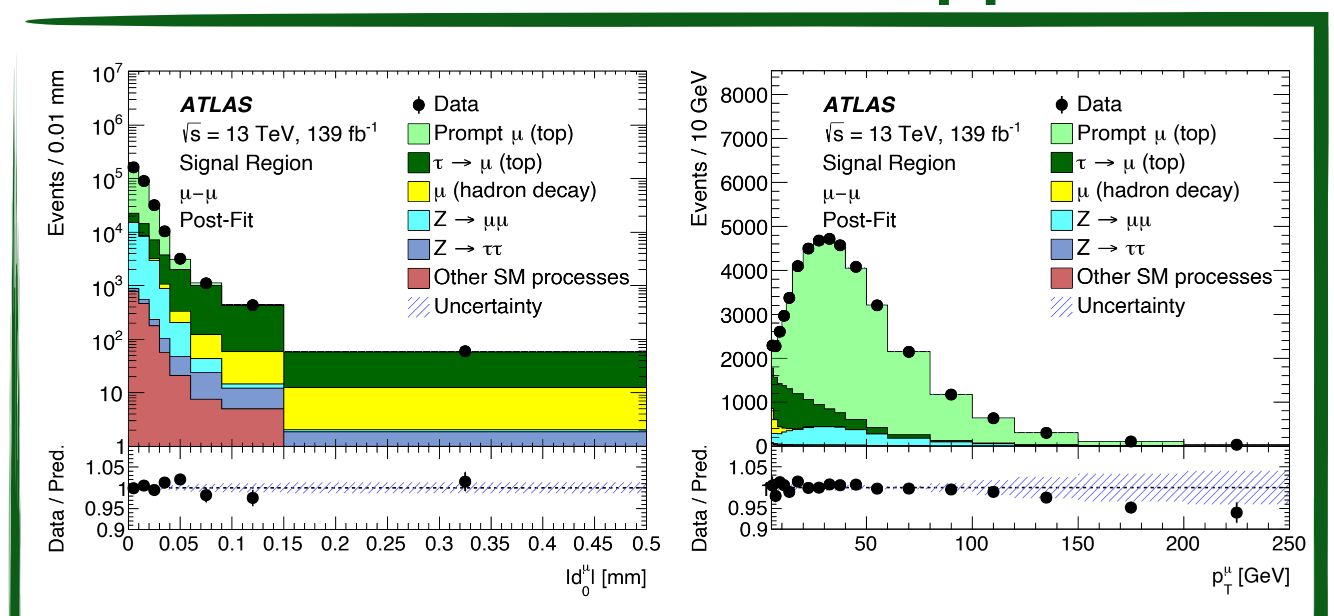
- hadrons decaying into muons
- Z+2b-tagged jets in di-muon channel



eμ channel



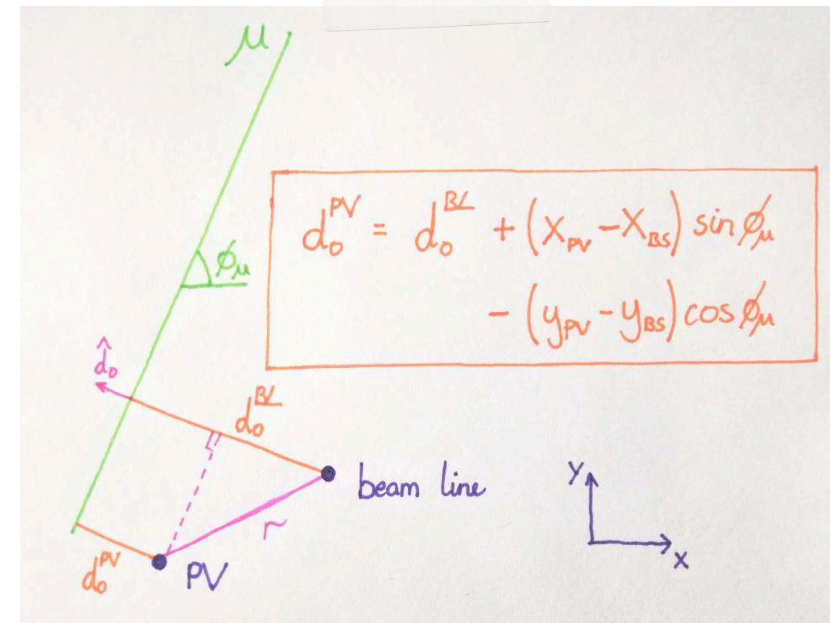
μμ channel



d_0^{μ} parameter

arXiv:2007.14040 - **Submitted to Nature Physics**

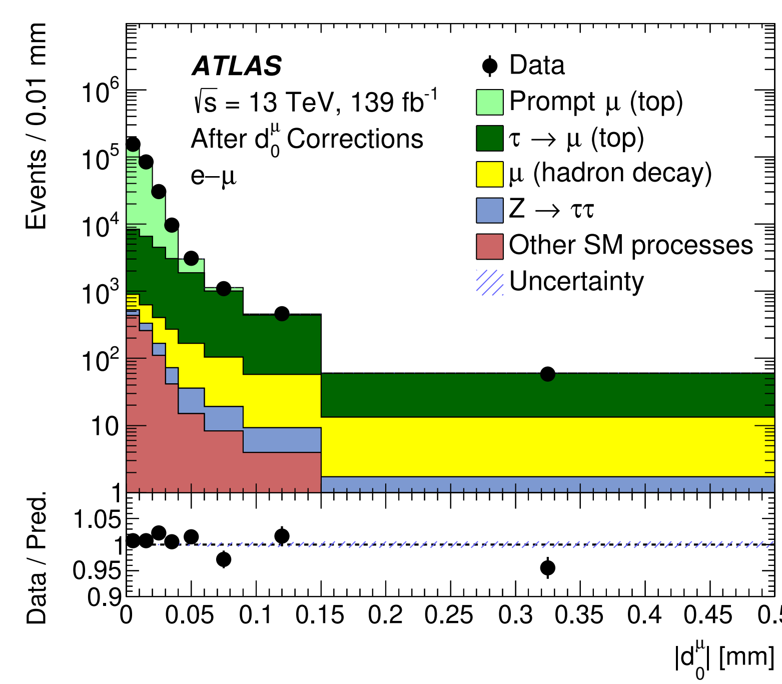
Distance of closest approach of muon tracks in transverse plane with respect to beamline (process independent)



Determine shape of $|d_0^{\mu}|$ in 33 kinematic bins (p_T^{μ}, $|\eta^{\mu}|$) from data using $Z \to \mu\mu$ selection

- subtract remaining backgrounds estimated in MC
- shapes as prompt muon templates in signal region
- residual resolution correction from data

After d_0^{μ} correction



Systematic uncertainty due to application of $|d_0^{\mu}|$ shape from Z boson decays to $t\bar{t}$ signal region:

- estimated by ratio of $|d_0^{\mu}|$ between $t\bar{t}$ and $Z \to \mu\mu$
- done separately for core and tail of $|d_0^{\mu}|$ distribution

Muons from b/c-hadrons

arXiv:2007.14040 - **Submitted to Nature Physics**

Largest background at large $|d_0^\mu|$ from b/c-hadrons decaying into muons

Estimated in same sign (SS) control region:

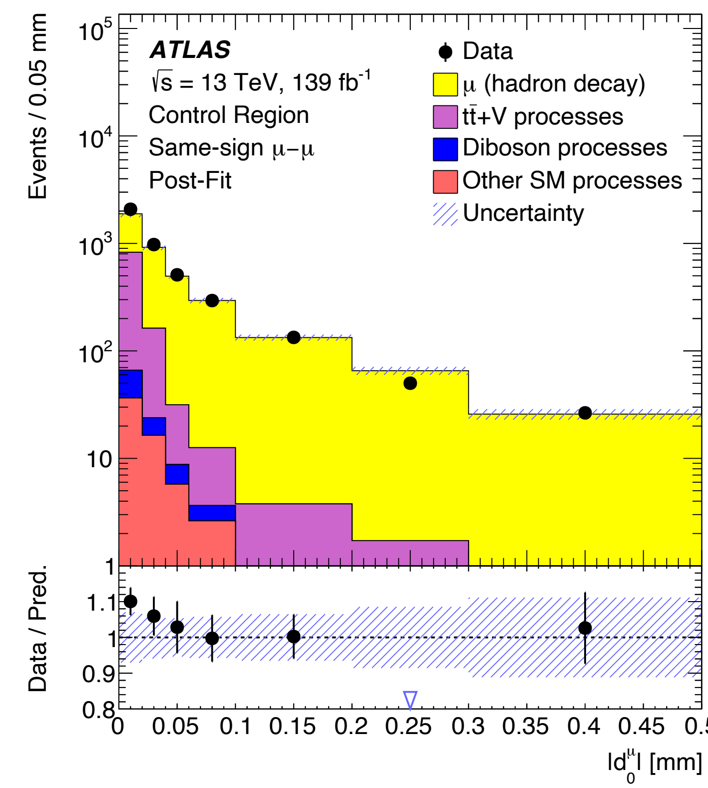
- shape of $|d_0^\mu|$ in SS region taken from MC
- prompt contribution ($t\bar{t}$+V) from p_T>30 GeV region subtracted
- data/MC ratio in SS region to signal region

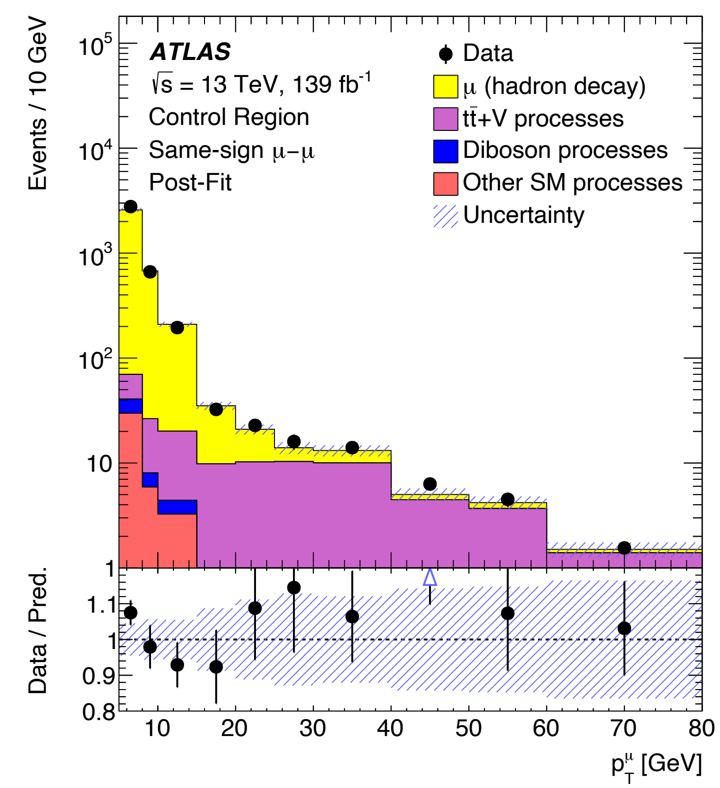
Reasonably good Data/MC agreement

- distributions are well modelled in signal region

Modelling differences between SS and OS from MC

Other uncertainties arising from limited statistics of SS region, MC modelling and p_T threshold for prompt contribution





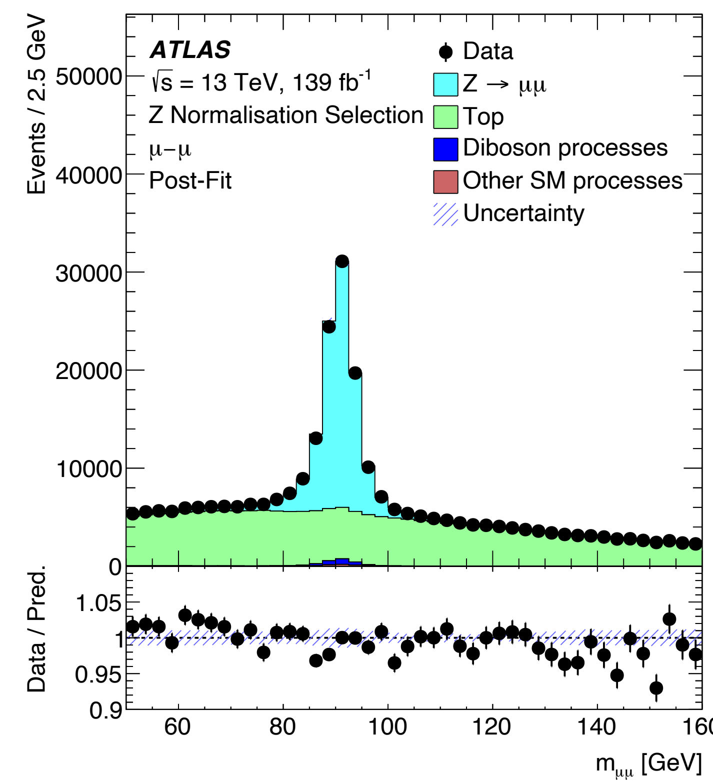
Z background in μμ region

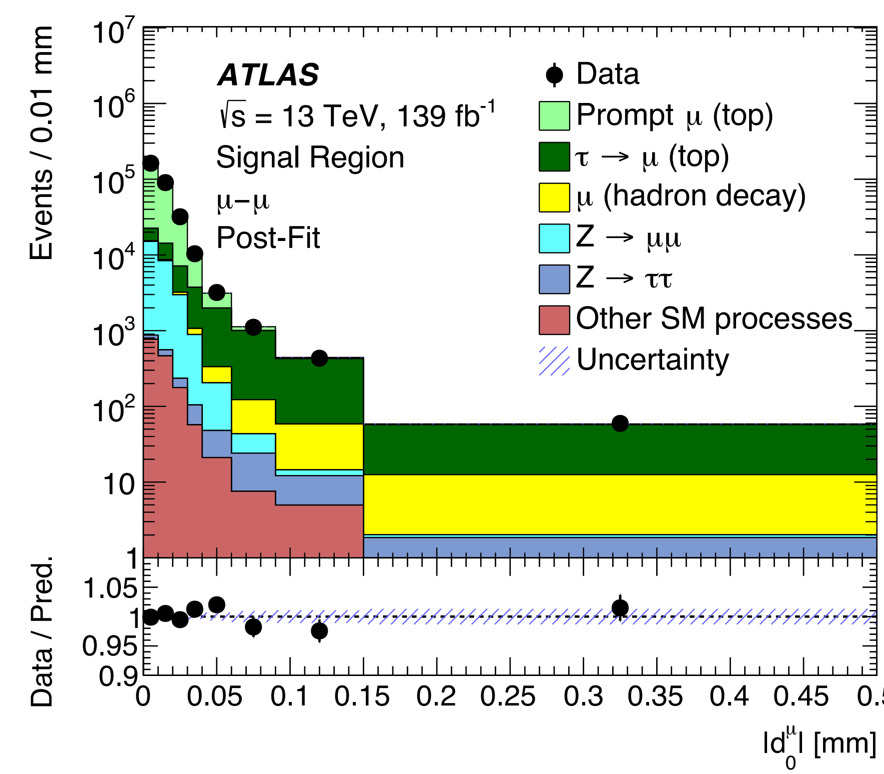
[arXiv:2007.14040](https://arxiv.org/abs/2007.14040) - **Submitted to Nature Physics**

Although Z-veto is applied in μμ channel, residual contribution from Z+2b-tagged jets left

- estimated from data by removing Z veto
- $m_{\mu\mu}$ distribution fit between 50 GeV and 140 GeV
  - convolution of Breit-Wigner and Gaussian for $Z \rightarrow \mu\mu$
  - 3rd order Chebychev polynomial for background
- Normalisation factor: 1.36 ± 0.01

Use other fit functions to estimate systematic uncertainty





[arXiv:2007.14040](https://arxiv.org/abs/2007.14040) - **Submitted to Nature Physics**

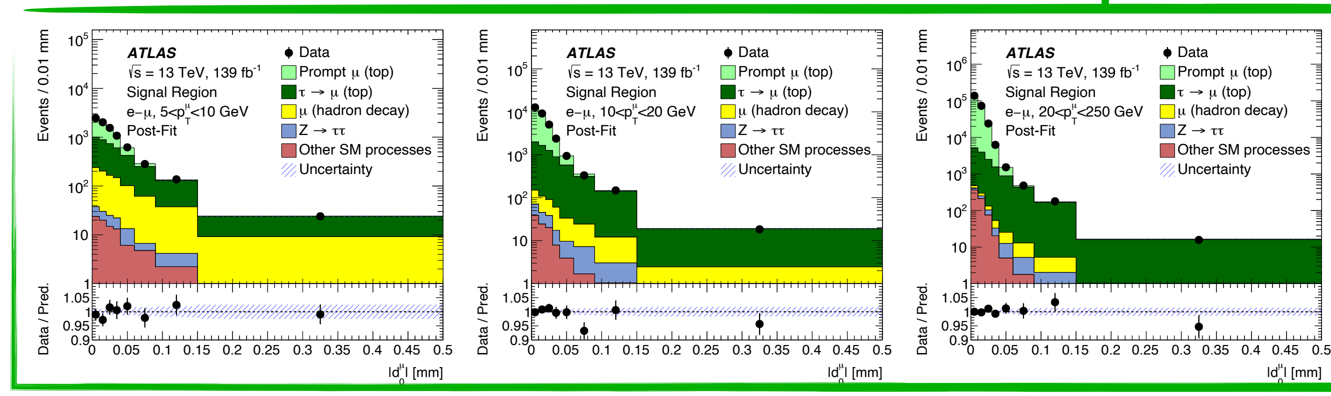
For both channels (eμ/μμ), perform 2D profile likelihood fit in muon

- $|d_0^\mu|$: [0, 0.01, 0.02, 0.03, 0.04, 0.06, 0.09, 0.15, 0.5] mm
- p_T : [5,10,20,250] GeV

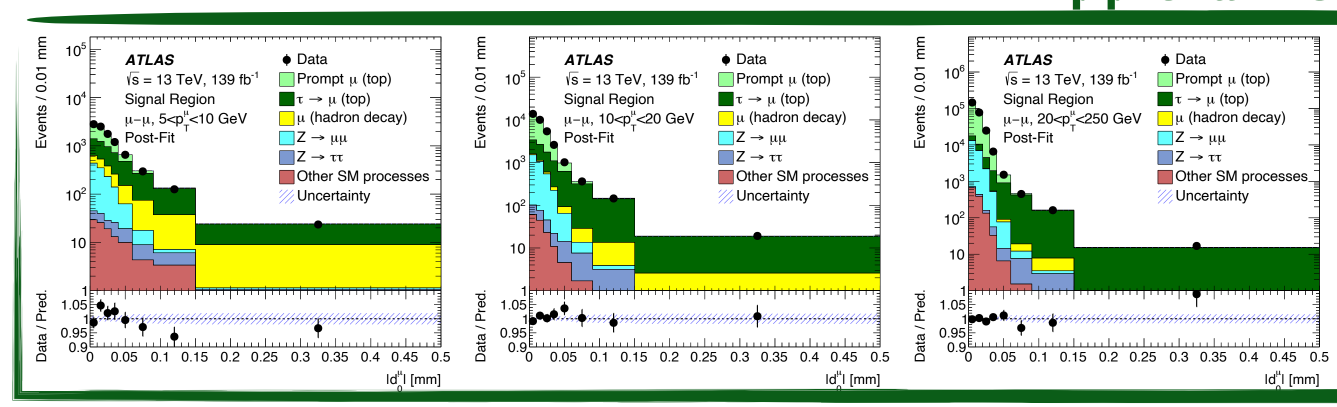
Freely floating parameters:

- $R(\tau/\mu) = BR(W \to \tau\nu)/BR(W \to \mu\nu)$
- scaling factor for top processes applied to both prompt muons and leptonic tau decays

eμ channel



μμ channel



Many uncertainties correlated between prompt muons and leptonic τ decays

- → mostly cancel out for probe muons

Good Data/MC agreement observed in each signal region bin

Systematic uncertainties

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Uncertainty of measurement dominated by systematic uncertainty

- leading one is the extrapolation uncertainty on prompt $|d_0^\mu|$ templates
- theoretical modelling uncertainties (such as parton shower or scale variations)
- hadron to muon decay background normalisation in SS region, i.e. due to MC generator used in estimate
- muon isolation requirements efficiency and low-p_T muon reconstruction efficiency

Source	**Impact on $R(\tau/\mu)$**
Prompt d_0^μ templates	0.0038
$\mu_{(prompt)}$ and $\mu_{(\tau\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
$\mu_{(had.)}$ normalisation	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_T spectum variation	0.0026
$\mu_{(had.)}$ parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{(\tau\to\mu)}$ and $\mu_{(had.)}$ d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \to \mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**

LFU results

arXiv:2007.14040 - **Submitted to Nature Physics**

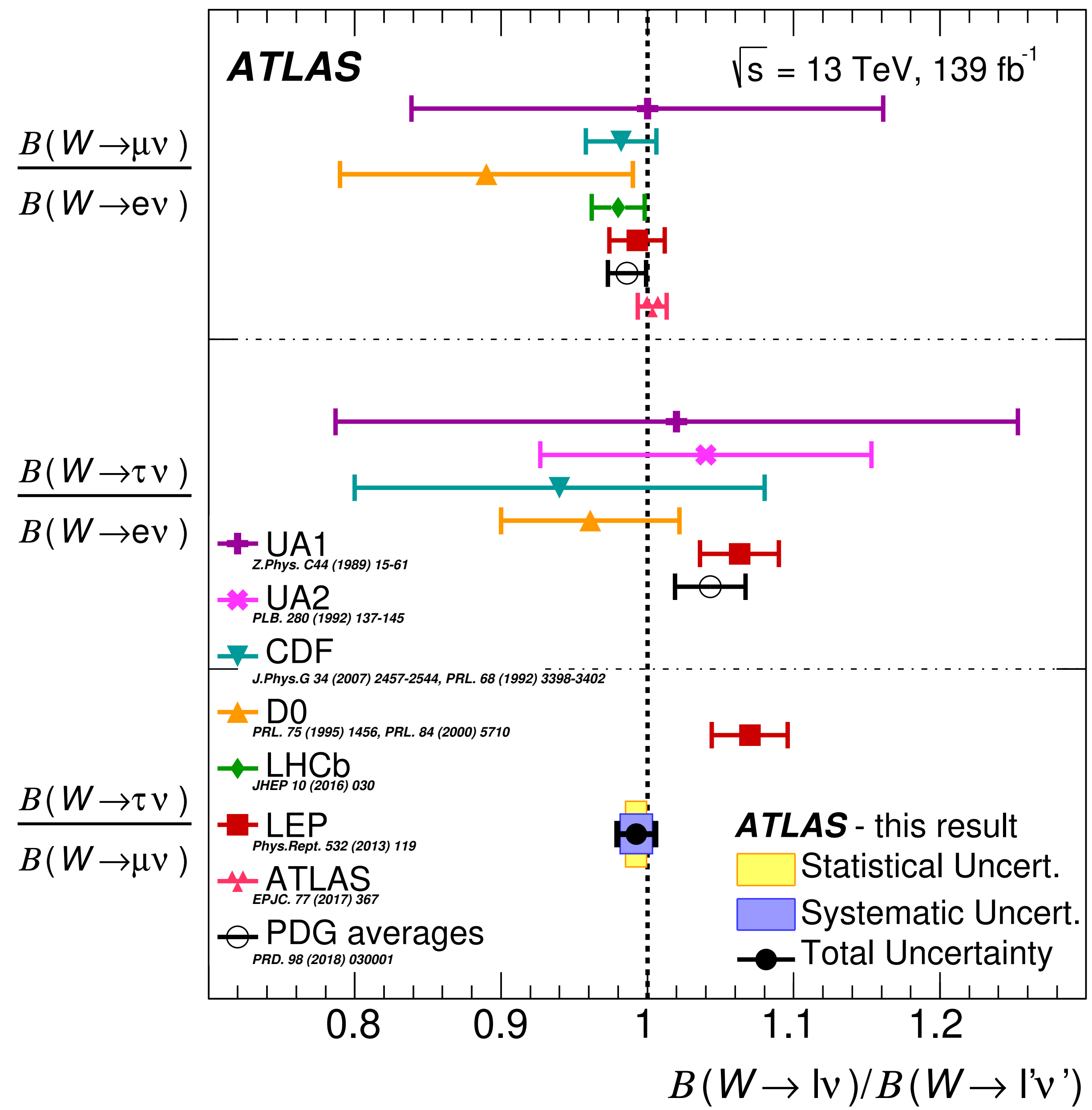
ATLAS EXPERIMENT

$R(\tau/\mu) = 0.992 \pm 0.013\ [\pm 0.007(\text{stat}) \pm 0.011(\text{syst})]$

Observation in very good agreement with SM expectation

Most precise measurement to date

- improves over LEP combination by a factor two



Conclusions

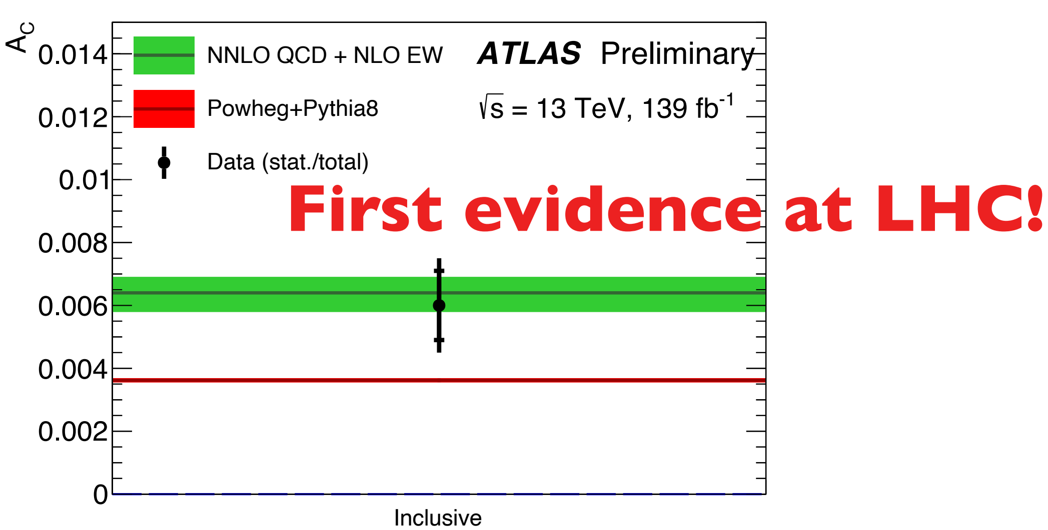
The top quark has come a long way since 1995 (discovery)

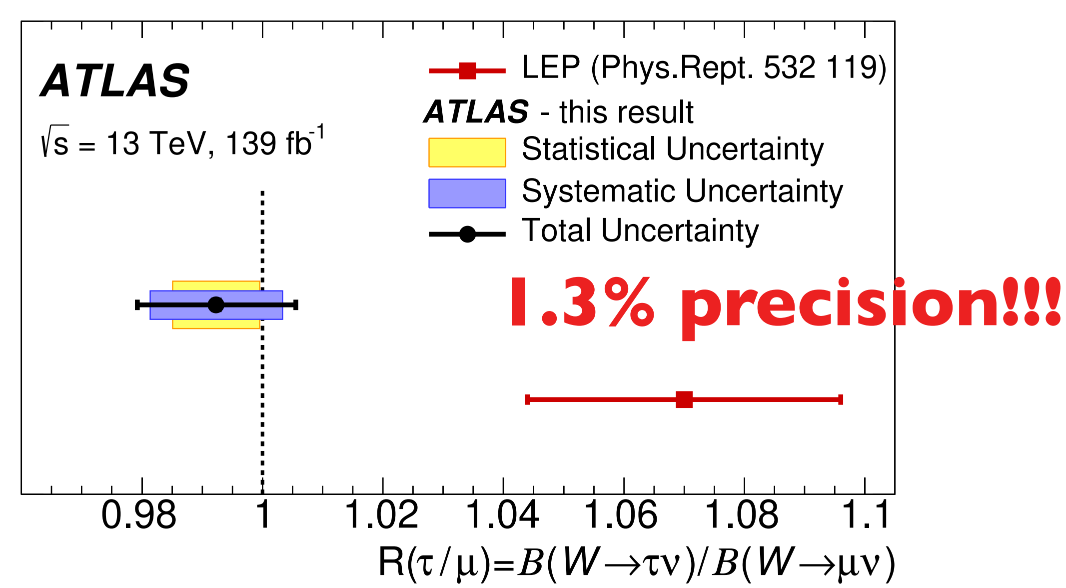
- back then: missing quark, similar to other quarks
- today: know that top quark is special

In precision era, top quark is key to an abundance of different research areas

- many different properties of top quarks (and W boson) measured by ATLAS
- so far, Standard Model describes data extremely well
- more results with the Run 2 dataset in the pipeline
- Run 3 (and beyond) promise even larger datasets

Many more exciting top physics results still to come!





Backup

Charge asymmetry

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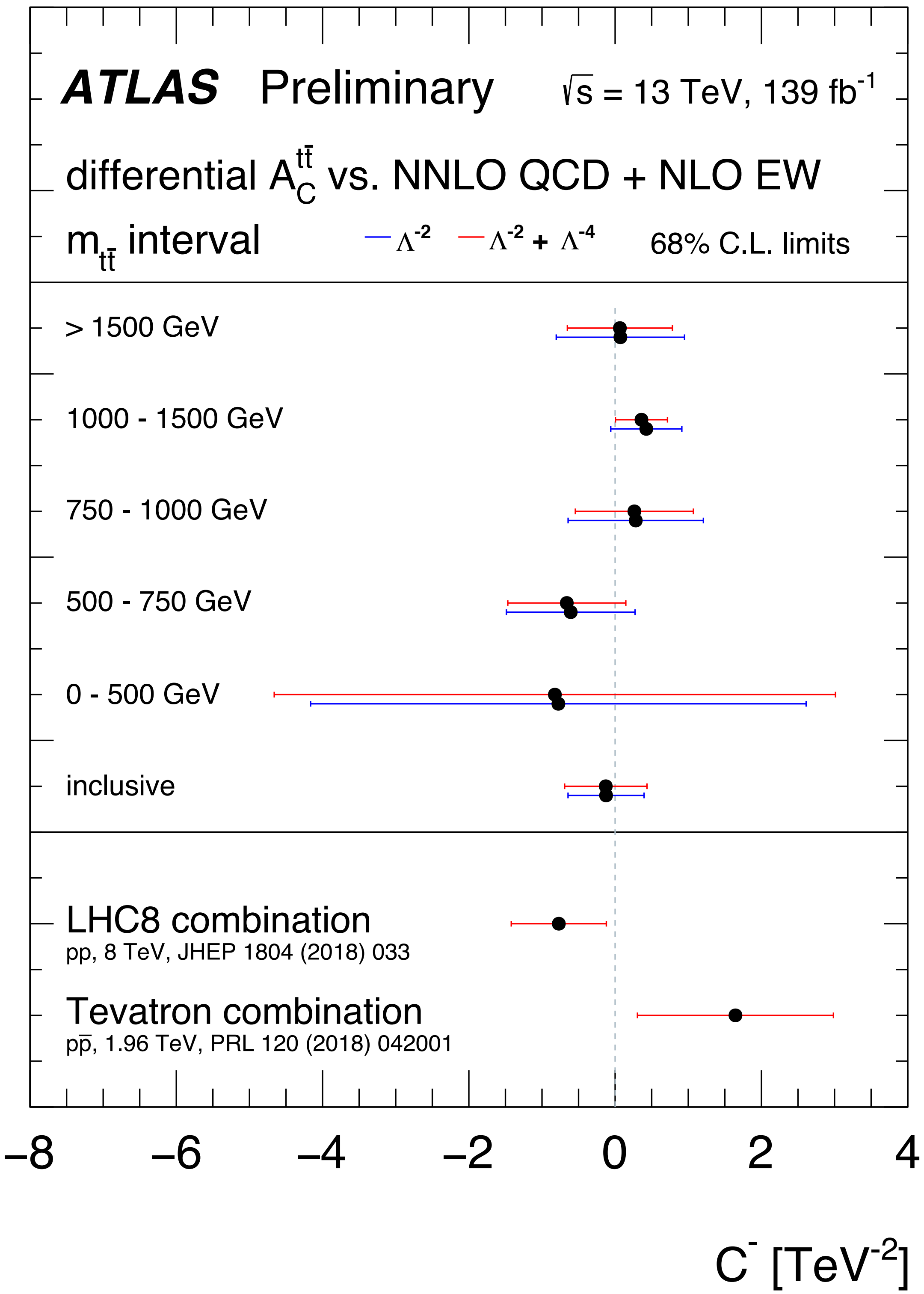


Measurements reinterpreted in EFT

- C^- = 4-fermion operator assuming flavour conservation and equal *u-d* type couplings (maps onto axi-gluon)
- theory paper: **JHEP03(2011)125**

Inclusive and differential results surpass ATLAS+CMS Run I combination

- no large dependence on quadratic terms
- dimension 6 approach is stable and appropriate

d_0^μ correction

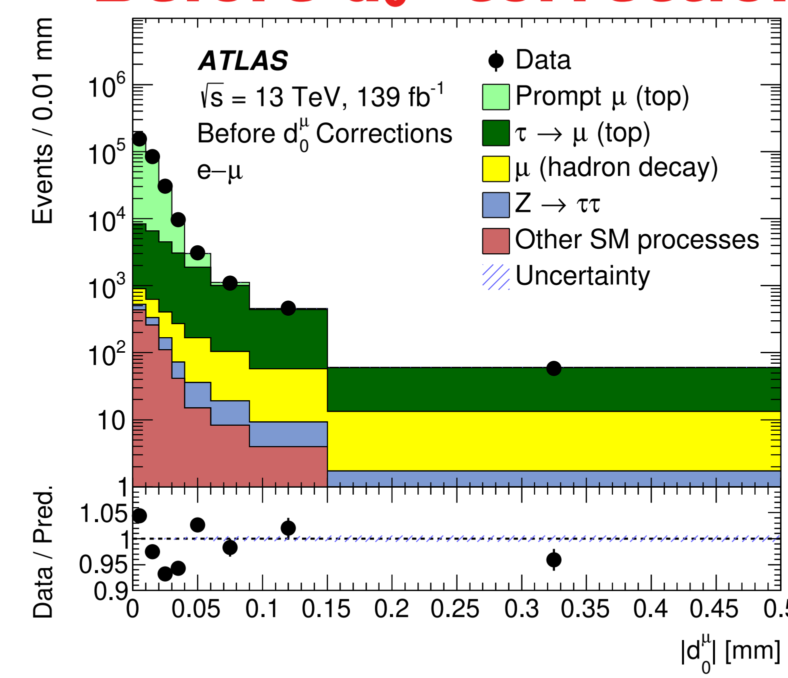
arXiv:2007.14040 - **Submitted to Nature Physics**

Corrections to account for differences in the resolution of the detector between the data and simulation

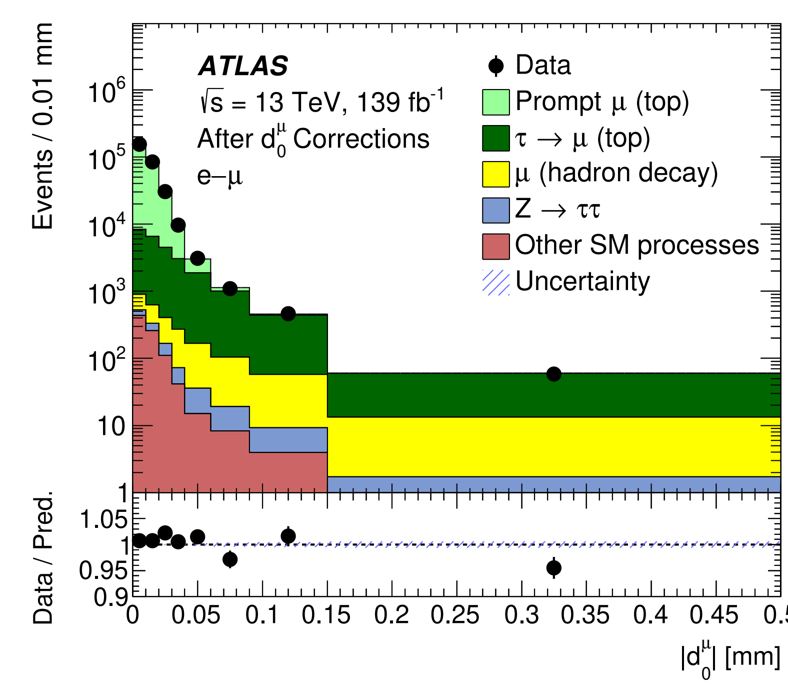
- applied to processes with significant decay-vertex displacement, i.e. muons from τ decays and hadron decays
- for the considered d_0^μ range, the resolution measured from prompt muons is applicable to those with significant displacement

- $p_T^\mu = 20$ GeV → resolution ~14 μm
- $|d_0^\mu|$ core < 0.02 mm

Before d_0^μ correction



After d_0^μ correction



LFU - Miscellaneous

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