Measurement of top-quark mass using top-quark events with J/ψ meson and study of b-quark fragmentation in ATLAS at LHC

Top LHC France

1st year PhD: William Roth[1]

PhD Supervisor: Frédéric Derue[1]

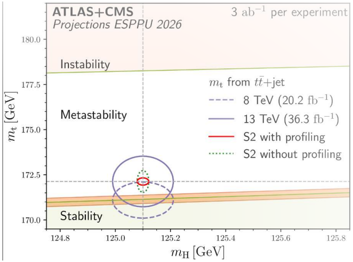
[1]LPNHE Paris – Sorbonne Université – Université Paris Cité – CNRS/IN2P3

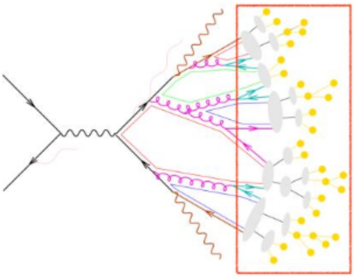
May 26, 2026

ATLAS qualification project: An XML based detector description of the High Granularity Timing Detector (HGTD)
OTP: The Phase-II HGTD task ID 533820 / subtask ID 557746

Motivations for measuring m_{top}

- Electroweak fit
  - Relations in SM between $m_{\text{top}}, m_{\text{W}}$ and m_{H}
  - Internal consistency of the SM
  - Test of high energy scales via radiative corrections
- (Meta)Stability of the Universe
  - Relation between $m_{\text{top}}, m_{\text{H}}$
  - Predict the evolution of the Higgs quartic coupling at high scales, which affects the shape of the Higgs potential
- Direct measurements of m_{top}
  - Using reconstructed decay products
    - In inclusive or exclusive final states $(t\bar{t}, b \to \mu X)$
    - Measurement of Monte-Carlo mass $m(\text{top})^{\text{MC}}$
    - Data compared to MC templates with varying $m(\text{top})^{\text{MC}}$
  - Sensibility to MC modelling of non-perturbative effects
  - High precision: 500 MeV



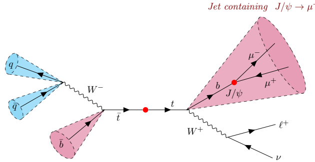


m_{top} measurement using top-quark decays with a $J/\psi \to \mu^+\mu^-$

The use of top-quark events with in final state a B-hadron decaying into $b \to J/\psi \to \mu^+\mu^-$ offers alternative method to measure m_{top} using the sensitivity of $m(\ell J/\psi)$ to m_{top}

- Motivations
  - Using purely leptonic observables
    - ★ Reduced sensitivity to jet-related systematics
  - Long(er) term interest for HL-LHC
  - Help to reduce the uncertainties in combination of all measurements
- CMS J/ψ Run 1 result
  - Measurement of the mass of the top quark in decays with a J/ψ meson in pp collisions at 8 TeV JHEP12(2016)123

$$m_{\text{top}} = 173.5 \pm 3.0\,(\text{stat}) \pm 0.9\,(\text{syst})\ \text{GeV}$$

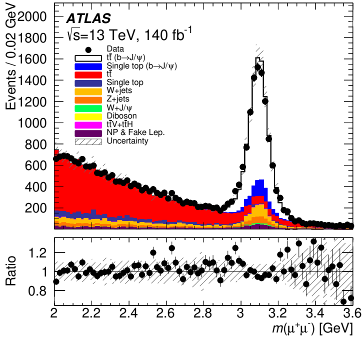


- Challenges
  - Small branching fraction of signal process $\mathcal{B} \approx 10^{-4}$
  - Sensitivity to $b \to B$ fragmentation modelling
- ATLAS related Run 2 result
  - Measurement of the top-quark mass using a leptonic invariant mass in pp collisions at 13 TeV with the ATLAS detector JHEP06(2023)019

$$m_{\text{top}} = 174.41 \pm 0.39\,(\text{stat}) \pm 0.66\,(\text{syst}) \pm 0.25\,(\text{recoil})\ \text{GeV}$$

$J/\psi \to \mu^+\mu^-$ selection

- Full selection (1/2)
  - lepton+jets ≥ 2 jets, ≥ 1 b-tag, 1 isolated ℓ, 2 oppositely signed charged soft-μ
  - Geometric cuts for common origin of J/ψ and b-jet
    - ★ $\Delta R(\mu, \text{jet}) < 0.4$ and $\Delta R(\mu, \mu) < 0.6$



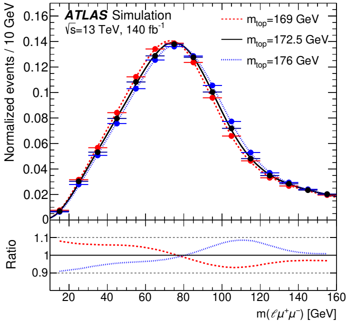
JHEP04(2026)099

- Full selection (2/2)
  - Non-prompt J/ψ reconstruction
    Mass-window and quality cuts
    - ★ $2.9 < m(\mu\mu) < 3.3$ GeV, $\chi^2 < 10$
      $p_\mathrm{T}(\mu\mu) > 8$ GeV, $|y(\mu\mu)| < 2.1$, $\tau(\mu\mu) > 0.1$ ps
  - Reconstruction of $\ell J/\psi$ system
    - ★ $p_\mathrm{T}(\ell\mu\mu) > 25$ GeV & $10 < m(\ell\mu\mu) < 160$ GeV

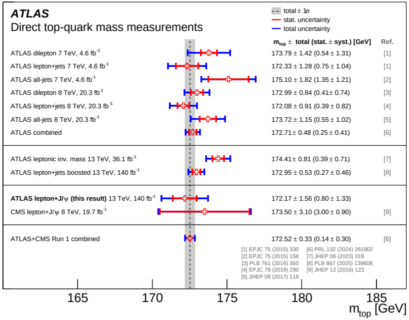
Data	12 165
$t\bar{t}$ ($b \to J/\psi \to \mu^+\mu^-$)	7941 ± 737
Single-top-quark ($b \to J/\psi \to \mu^+\mu^-$)	964 ± 109
$t\bar{t}$	1411 ± 145
Single-top-quark	164 ± 43
$t\bar{t}V + t\bar{t}H$	38 ± 8
W+jets	777 ± 258
Z+jets	468 ± 138
$W + J/\psi$	78 ± 41
diboson	16 ± 9
Non-prompt and fake lepton	322 ± 99
Signal+background	$12\,180 \pm 821$
Expected background fraction	0.27 ± 0.01
Data/(Signal+background)	1.00 ± 0.07

$m(\text{top})$ measurement in top-quark decays with a $J/\psi \to \mu^+\mu^-$

- Invariant mass of isolated lepton and J/ψ system $m(\ell\mu^+\mu^-)$ sensitive to $m(\text{top})$.
- Measure $m(\text{top})$ using templates method.



JHEP04(2026)099

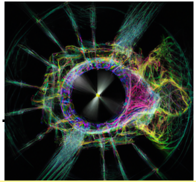


- $m(\text{top}) = 172.17 \pm 0.80\ (\text{stat}) \pm 0.81\ (\text{syst}) \pm 1.07\ (\text{recoil})\ \text{GeV}$.
  - Dominant uncertainties: $\sigma(\text{PS-had}) = 0.40$ GeV, $\sigma(\text{b-frag}) = 0.15$ GeV, $\sigma(\text{recoil}) = 1.07$ GeV.
    - ★ Reduced $\sigma(\text{JES}) = 0.07$ GeV, $\sigma(\text{b-JES}) = 0.04$ GeV !
    - ★ And last uncertainty arises from changing the dipole parton shower gluon-recoil scheme used in top-quark decays : $\sigma(\text{recoil}) = 1.07$ GeV

b-quark fragmentation

State of the art measurement m_{top} with J/ψ using Release 21 software

- Transition AnalysisTop $\rightarrow$ TopCPToolkit
  - Entirely new framework Release 25: start from scratch !
  - Reduced data format DAOD vs DAOD_PHYS
- Soft Muon Tagging Group (SMT).
  - Italian group who measured $m(\text{top})$ and studied b-fragmentation. JHEP 06 (2023) 019. Ref-code: ANA-TOPQ-2024-10.
  - New group for Run2, Run3 analyses.
  - Already have knowledge on new software
  - Aims to study b-quark fragmentation using ATLAS data.



10.5281/zenodo.19683083

FAST FRAMES

10.5281/zenodo.14773274

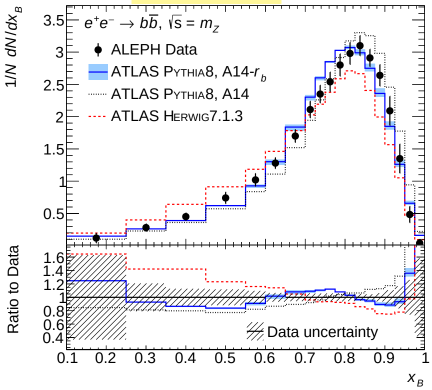
Good opportunity for our purpose to insert into SMT group !

Study on fake lepton background as entry-ticket

b-quark fragmentation

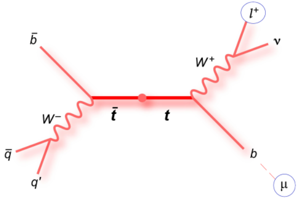
- Fragmentation function.
  - Fragmentation function gives distribution of longitudinal component of B-hadron energy taken to b-quark.
  - Lund-Bowler formula:
    $f(z) = \frac{1}{z^{1+br_b m_b^2}} (1-z)^a \exp\left(-bm_\mathsf{T}^2/z\right)$
    z: longitudinal energy fraction of B-hadron,
    $m_\mathsf{T}^2 = m_B^2 + p_\mathsf{T}^2, a, b, r_b$ free parameters.
  - Tunes in MC samples:
    - ★ A14 based on Monash: uses $r_b = 0.855$ by default.
    - ★ A14-rb fitted by SMT group (2019-2023): uses $r_b = 1.05$ by default in top analysis with B-hadrons.

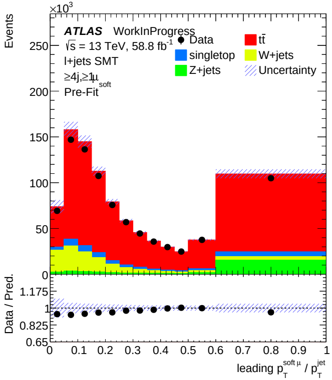
JHEP06(2023)019



b-quark fragmentation using soft-muons

- Result from SMT group Run2
  - Measurement of the top-quark mass using a leptonic invariant mass in pp collisions at 13 TeV with the ATLAS detector
    $m_{\text{top}} = 174.41 \pm 0.39\,(\text{stat}) \pm 0.66\,(\text{syst}) \pm 0.25\,(\text{recoil})$ GeV
    Tuned b-fragmentation parameter: $r_b = 1.05 \pm 0.02$
  - Aims to study b-quark fragmentation using ATLAS data.
  - Event selection
    - ★ Top-quark events lepton+jets channel with low-energy muons inside b-jets $b \to \mu X$ (soft-muons).
    - ★ Tune fragmentation parameters with LHC data.
- Study observable sensitive to b-quark fragmentation.
  - Fraction of b-jet energy taken by soft muon inside b-jet $p_T^{\text{soft-mu}}/p_T^{\text{b-jet}}$ as a proxy sensitive to fraction of b-quark energy taken by B-hadron.
  - Produce plots using new software for the first time

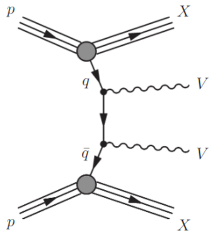


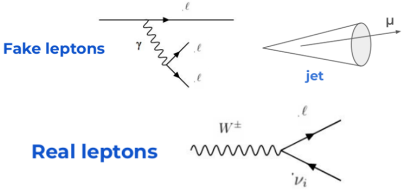


Contribution from fake leptons need to be estimated !

Fake leptons background

- Background processes
  - Processes of same final state as signal process
  - Irreducible background
    - ★ W+jets, Z+jets, diboson
      Estimated using MC simulation
  - Reducible background
    - ★ Hadrons, light jets reconstructed as leptons
    - ★ Non-prompt leptons (semileptonic decay of b-hadron, photon conversion)
      $\rightarrow$ referred to as 'fake leptons'

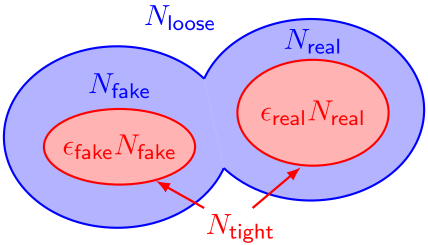




Fake leptons matrix method

Measurement of fake lepton background is based on data events passing the full selection with a looser identification and isolation lepton requirements used along with the measured probability of loose leptons to satisfy the nominal selection requirements (=tight leptons).

- Define loose leptons:
  allow non-isolated/low quality lepton.
- Measure number of event with
  loose N^{loose} and tight leptons N^{tight}.
- Measure real and fake lepton efficiences
  $\epsilon_{\text{real}} = N^{\text{tight}}_{\text{real}} / N^{\text{loose}}_{\text{real}}$, $\epsilon_{\text{fake}} = N^{\text{tight}}_{\text{fake}} / N^{\text{loose}}_{\text{fake}}$.
- Solve the system for $N^{\text{tight}}_{\text{fake}}$:



$$N^{\text{loose}} = N^{\text{loose}}_{\text{real}} + N^{\text{loose}}_{\text{fake}}$$
$$N^{\text{tight}} = N^{\text{tight}}_{\text{real}} + N^{\text{tight}}_{\text{fake}}$$

$$\Longrightarrow \boxed{N^{\text{tight}}_{\text{fake}} = \epsilon_{\text{fake}} N^{\text{loose}}_{\text{fake}} = \frac{\epsilon_{\text{fake}}}{\epsilon_{\text{real}} - \epsilon_{\text{fake}}} \left(\epsilon_{\text{real}} N^{\text{loose}} - N^{\text{tight}} \right)}$$

$\boxed{\text{Need } \epsilon_{\text{real}} \neq \epsilon_{\text{fake}} \ \& \ \epsilon_{\text{fake}} \neq 0}$

Measurement of real and fake efficiencies

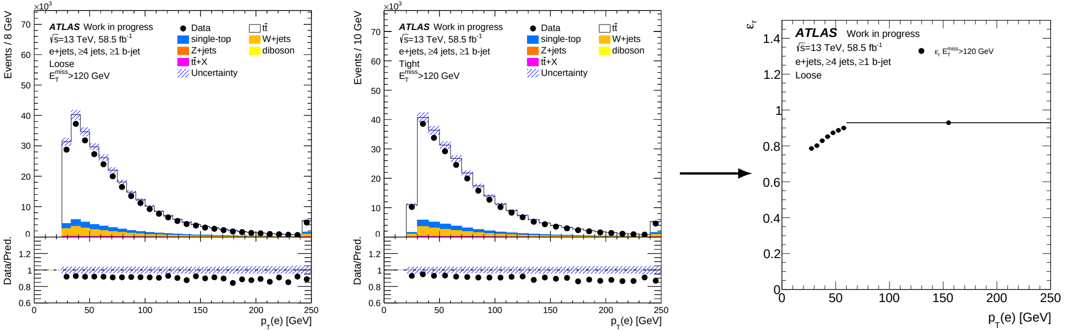
Fake efficiencies are measured in regions enriched in fake leptons, real efficiencies measured in regions enriched in real leptons or using Tag & Probe method in $Z \to \ell^+\ell^-$ events.

- Definition of Tight leptons
  - e-pid: TightLH, e-iso: Tight_VarRad
  - μ-pid: Medium, μ-iso: Tight_VarRad
- Definition of Loose QCD leptons
  - e-pid: LooseBLayerLH, e-iso: Loose_VarRad
  - μ-pid: Loose, μ-iso: Loose_VarRad
- Definition of VeryLoose QCD leptons
  - e-pid: LooseBLayerLH, e-iso: NonIso
  - μ-pid: Loose, μ-iso: NonIso

- ≥ 2 jets pretag – '2j'.
  ≥ 2 jets, ≥ 1 b-jet – '2j1b'.
  ≥ 4 jets pretag – '4j'.
  ≥ 4 jets, ≥ 1b-jet – '4j1b'.
- Enriched in fakes (real):
  $E_T^{miss} < 30$ GeV
  ($E_T^{miss} > 120$ GeV).
- Alternative region for fakes (real):
  $E_T^{miss} < 30$ GeV & $E_T^{miss} + m_T^W < 60$ GeV
  ($E_T^{miss} > 30$ GeV).

How to measure real efficiencies

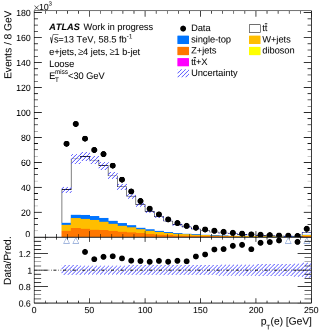
- Data/MC distribution for e+jets events (4j1b), Loose QCD definition, $E_{\mathsf{T}}^{\text{miss}} > 120$ GeV.

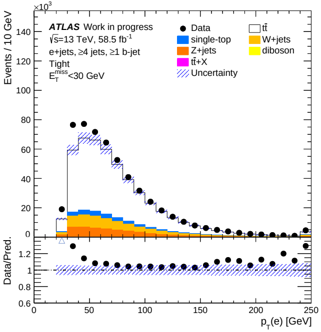


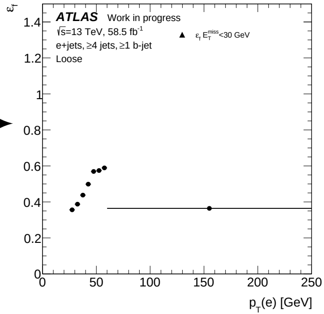
- Assuming small fake fraction in MC $\epsilon_{\text{real}} = N_{\text{MC}}^{\text{tight}} / N_{\text{MC}}^{\text{loose}}$.
  - Fake fraction in MC (4j1b, $E_{\mathsf{T}}^{\text{miss}} > 120$ GeV): $\approx 1\%$ for electrons, muons.
- Ideally should correct efficiency by ratio of loose/tight lepton scale factors.

How to measure fake efficiencies

- Data/MC distribution for e+jets events (4j1b), Loose QCD definition, $E_T^{\text{miss}} < 30$ GeV.

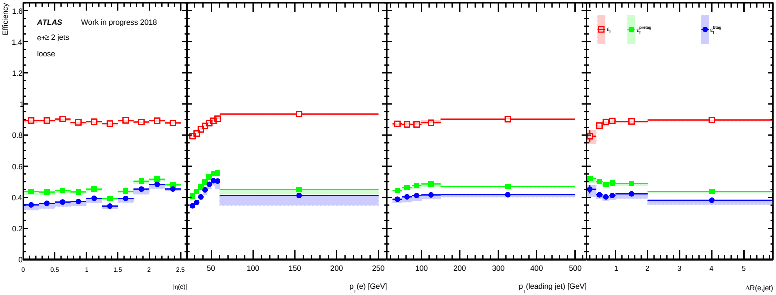






- Remove contamination from real leptons $\epsilon_{\text{fake}} = (N_{\text{data}}^{\text{tight}} - N_{\text{MC}}^{\text{tight}})/(N_{\text{data}}^{\text{loose}} - N_{\text{MC}}^{\text{loose}})$.
  - Fake fraction in MC (4j1b, $E_T^{\text{miss}} < 30$ GeV): $\approx 1\%$ for electrons, muons.

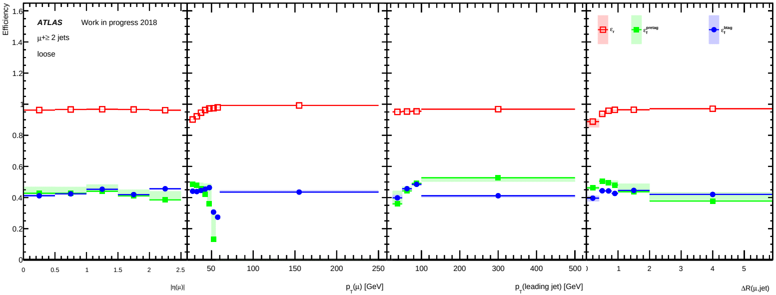
Real and fake efficiencies – 2j – electron – Loose QCD



- ϵ_{real}: $E_T^{\text{miss}} > 120$ GeV
  ϵ_{fake}: $E_T^{\text{miss}} < 30$ GeV
- Alt ϵ_{real}: $E_T^{\text{miss}} > 30$ GeV
  Alt ϵ_{fake}: $E_T^{\text{miss}} < 30$ GeV & $E_T^{\text{miss}} + m_T^W < 60$ GeV
  - Used for systematic uncertainty band.
- $\epsilon_{\text{real}} \approx 90\%, \epsilon_{\text{fake}} \approx 40\%.$

Measure efficiencies for different event variables and choose which ones are more suited...

Real and fake efficiencies – 2j – muon – Loose QCD



- ϵ_{real}: $E_{\text{T}}^{\text{miss}} > 120$ GeV
  ϵ_{fake}: $E_{\text{T}}^{\text{miss}} < 30$ GeV
- Alt ϵ_{real}: $E_{\text{T}}^{\text{miss}} > 30$ GeV
  Alt ϵ_{fake}: $E_{\text{T}}^{\text{miss}} < 30$ GeV & $E_{\text{T}}^{\text{miss}} + m_{\text{T}}^{\text{W}} < 60$ GeV
  - Used for systematic uncertainty band.
- $\epsilon_{\text{real}} \approx 90\%, \epsilon_{\text{fake}} \approx 40\%.$

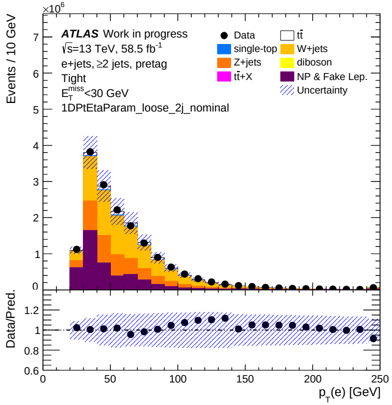
Measure efficiencies for different event variables and choose which ones are more suited...

Results fake lepton estimate

- Produce fake estimate with efficiency maps and parametrization choice using existing algorithm
  - Parametrization of efficiency with lepton variables: $\epsilon = \epsilon(p_{\mathrm{T}}) \times \epsilon(|\eta|) / < \epsilon >$
    - ★ Capture dependance of lepton kinematics
    - ★ Technically only parametrization we could do so far...
  - Produce event weights (fake weights) to apply on loose data:

$$w_i = \frac{\epsilon_{\text{real}}}{\epsilon_{\text{real}} - \epsilon_{\text{fake}}} (\epsilon_{\text{real}} - \delta)$$

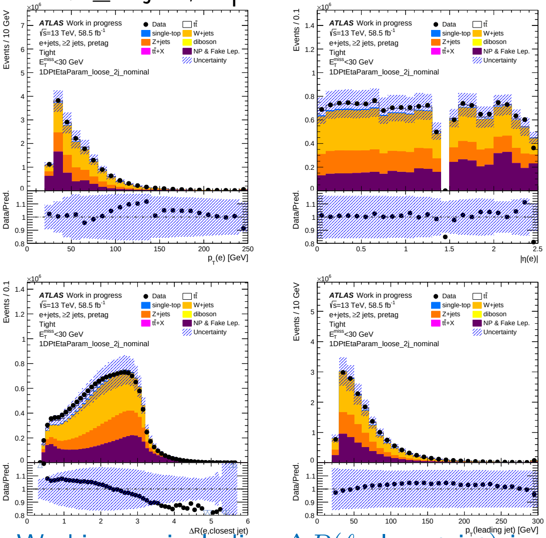
with $\delta = 1$ if lepton is tight, else $\delta = 0$



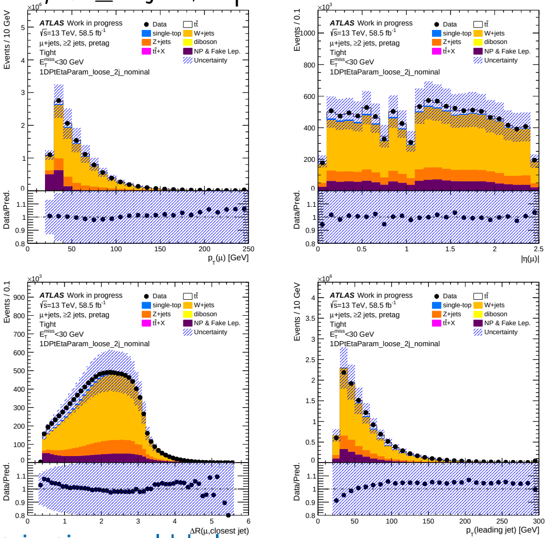
- Obtain estimate in region where real and fake efficiencies are measured and in $t\bar{t}$ signal region
- In general better Data/MC agreement after including the fakes contribution

Results fake lepton estimate – region enriched with fakes – 2j

$e+\geq 2$ jets, $E_T^{\text{miss}} < 30$ GeV



$\mu+\geq 2$ jets, $E_T^{\text{miss}} < 30$ GeV

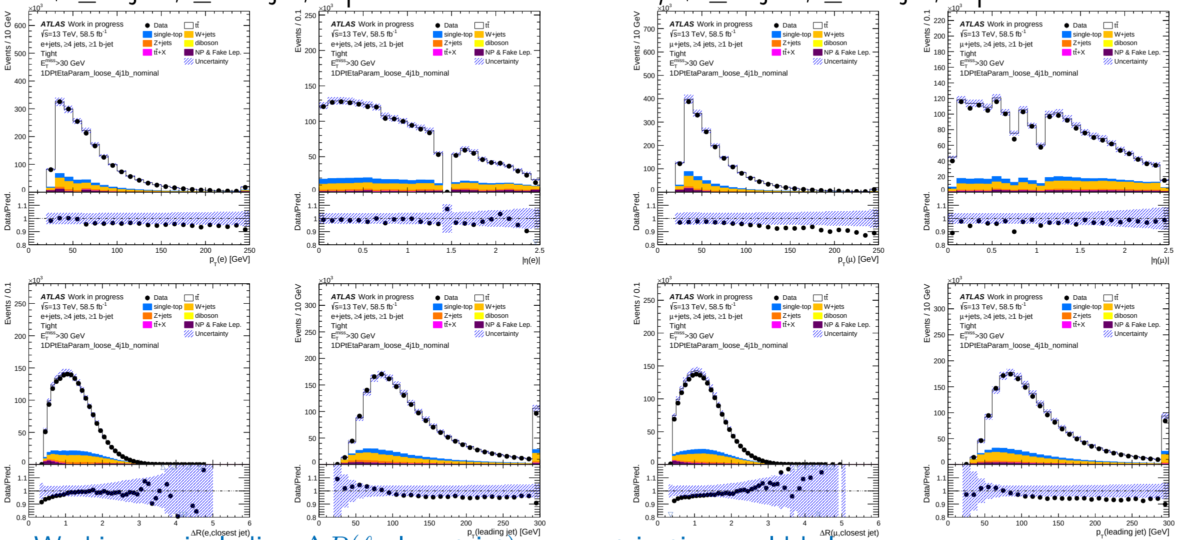


Working on including $\Delta R(\ell, \text{closest jet})$ in parametrization could help

Results fake lepton estimate – $t\bar{t}$ signal region – 4j1b

$e+ \geq 4$ jets, ≥ 1 b-jet, $E_T^{\text{miss}} > 30$ GeV

$\mu+ \geq 4$ jets, ≥ 1 b-jet, $E_T^{\text{miss}} > 30$ GeV



Working on including $\Delta R(\ell, \text{closest jet})$ parametrization could help

Conclusion

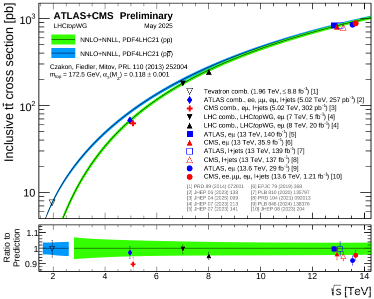
- First result on fake leptons estimate using matrix method in 2018 data, will be used for $J/\psi \rightarrow \mu^+\mu^-$ measurement and shared with SMT group
  - Fake estimate with full Run2 (2015-2018) and Run3 (2022-2024) data ongoing
- Continue learn new analysis software Release 25
- Part of study on b-quark fragmentation using soft-muons in the SMT group
- m_{top} measurement with J/ψ
  - Post-mortem analysis Run2 on b-fragmentation theoretical uncertainties
  - Link between recoil and b-fragmentation uncertainties

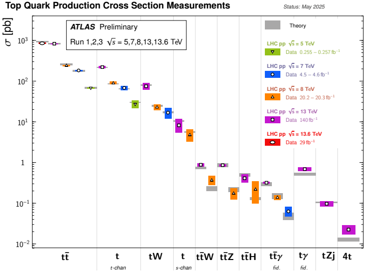
Back-up

Top-quark as a probe for the SM

- Unique properties.
  - Heaviest fundamental particle known: $m(\text{top}) \approx 173$ GeV.
    - ★ Strong coupling to Higgs field.
  - Short lifetime: $\tau(\text{top}) \approx 10^{-25}$ s.
    - ★ Decays before hadronizing.
    - ★ $\mathcal{B}(t \to Wb) \approx 100\%$.
- Top-quark at LHC.
  - Precise measurement of cross-section.
    - ★ 13 TeV ATLAS, $e\mu$, JHEP 07 140 fb^{-1}
      $\sigma(t\bar{t}) = 829 \pm 1$ (stat) ± 13 (syst) ± 8 (lumi) pb (1.8% precision).
    - ★ Predicted at NNLO+NNLL:
      $\sigma(t\bar{t}) = 832 \pm 51$ pb (6.1% precision).
  - Probed cross-sections 800 pb to 20 fb.
    - ★ Allow deep understanding of production mechanisms.

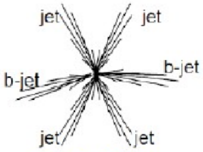
ATL-PHYS-PUB-2025-024



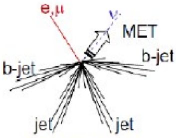


$t\bar{t}$ decay channels

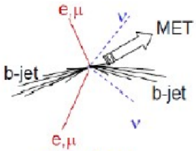
- Fully hadronic ($t\bar{t} \to WbWb \to qq'bqq'b$).
  - Both W bosons decay into quarks, giving jets.
  - Final state: 4 jets, 2 b-jets.
  - $\mathcal{B} \approx 46\%$, large background due to high jet production at LHC.
- Semi-leptonic ($t\bar{t} \to WbWb \to \ell\nu bqq'b$).
  - One W boson decay into lepton and neutrino, other decays into quarks giving jets.
  - Final state: 1 isolated lepton, 2 jets, 2 b-jets, missing transverse energy (MET).
  - $\mathcal{B} \approx 44\%$, reduced background, mainly from W+jets.
  - Used in practice in our analysis.
- Dileptonic ($t\bar{t} \to WbWb \to \ell\nu b\ell\nu b$).
  - Both W bosons decay into leptons and neutrinos.
  - Final state: 2 isolated leptons, 2 b-jets, MET.
  - $\mathcal{B} \approx 10\%$, lowest background, mainly from Z+jets.



all hadronic



lepton + jets

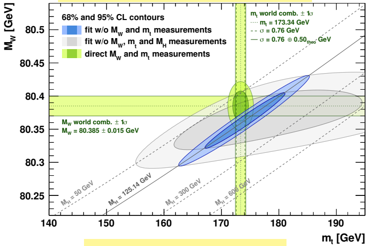


dileptons

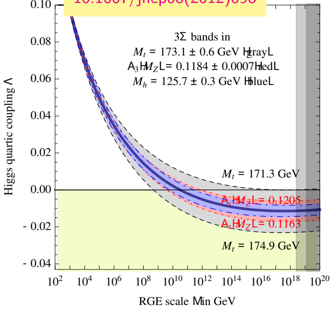
Motivations for measuring $m(\text{top})$

- Check SM consistency.
  - $m(\text{top})$ is a free parameter of SM, needs to be measured precisely.
  - Relationship between $m(\text{top}), m(W), m(Z), m(H)$.
  - At lowest order:
    $m(W) = gv/2, \sin^2\theta_W = \frac{g^2}{g^2+g'^2}, G_F = \frac{\sqrt{2}g^2}{8m(W)^2}$.
  - At higher orders:
    $m(W) = \left(\frac{\pi\alpha}{\sqrt{2}G_F}\right)^{1/2} \sqrt{1+\Delta r}/\sin\theta_W$.
    - ★ Radiative corrections Δr: largest contributions $m(\text{top})^2, \log m(H)$.
- Higgs vacuum stability.
  - Corrections to Higgs potential from quantization.
  - Sensitivity to $m(\text{top})$ at high energies:
    - ★ Measurement compatible with stable, meta-stable vacuum.

10.1140/epjc/s10052-014-3046-5

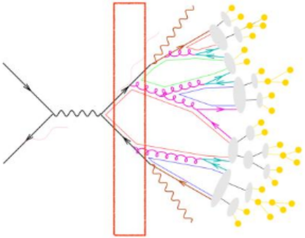


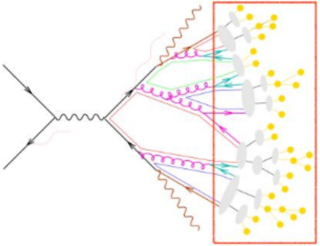
10.1007/jhep08(2012)098



Methods to measure $m(\text{top})$

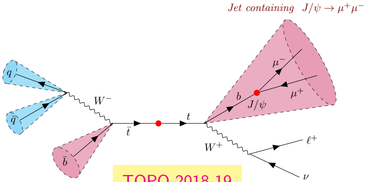
- Indirect measurements of $m(\text{top})$.
  - Based on cross-section measurement.
  - Measurement of pole mass $m(\text{top})^{\text{pole}}$.
  - Precision: 1-2 GeV.
- Direct measurements of $m(\text{top})$.
  - Using reconstructed decay products.
    - ★ In inclusive or exclusive final states $(t\bar{t}, b \to \mu X)$.
    - ★ Measurement of Monte-Carlo mass $m(\text{top})^{\text{MC}}$.
    - ★ Data compared to MC templates with varying values of $m(\text{top})^{\text{MC}}$.
  - Sensibility to MC modelling of non-perturbative effects.
  - High precision: 500 MeV.



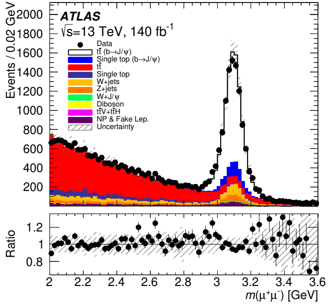


$m(\text{top})$ measurement in top-quark decays with a $J/\psi \to \mu^+\mu^-$

- Direct measurement in top-quark decays with $J/\psi \to \mu^+\mu^-$.
  - Motivations
    - Identify J/ψ resonance in $m(\mu^+\mu^-)$ spectrum.
    - Using purely leptonic variable to reduce effect of Jet Energy Scale (JES).
    - Gain precision on $m(\text{top})$ with future combinaisons.
  - Event selection
    - Events in lepton+jets channel with $b \to J/\psi \to \mu^+\mu^-$.
  - Challenges
    - Small branching fraction: $\mathcal{B}(t\bar{t} \to (W^+b)(W^-b) \to (\ell\nu J/\psi(\to \mu^+\mu^-)X)(qq'b)) \approx 10^{-4}$.
    - Using Run3 data: stat$\times 3$.
    - Sensitivity to signal-process modelling: b-quark fragmentation, hadronization, recoil.

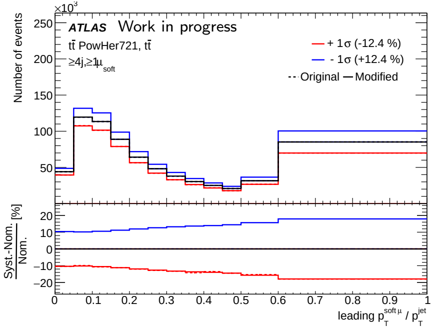


TOPQ-2018-19

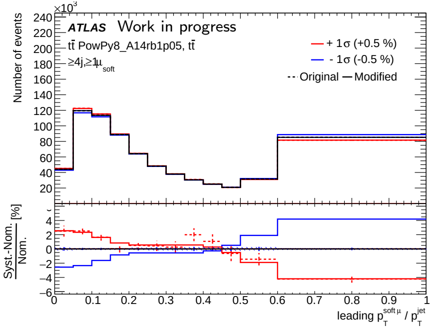


b-quark fragmentation

- Compare predictions of signal-process between Pythia and Herwig.
  - $\approx 10\%$ difference in number of events and small difference in shape.



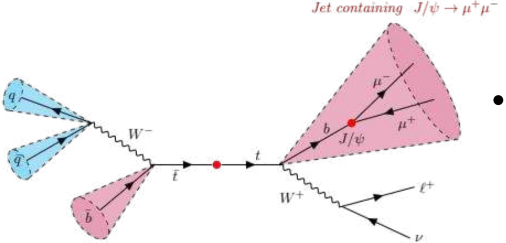
- Compare predictions of signal-process for different r_b values.
  - $\approx 4\%$ difference in number of events and small difference in shape.



- Additional background to estimate.
  - Fake leptons: non-prompt leptons or objects falsely reconstructed as leptons (hadrons, light jets, semileptonic b-decays, photon conversion...).

Data samples, signal and background

- **Data sample**
  - full Run 2 dataset
  - pp collisions at $\sqrt{s}$ = 13 TeV, L=140 fb^{-1}



- **Background composition**
  - $t\bar{t}$ and single top without $b \to J/\psi$ meson
  - $t\bar{t}$ associated vector boson
  - vector boson associated jets
  - vector boson pairs
  - $W+J/\psi$
  - non-prompt and fake leptons
    - data driven matrix method

- **Signal composition**
  - $t\bar{t}$ and single-top quark events with $b \to J/\psi \to \mu^+\mu^-$
  - Both same-top and different-top contributions considered

- **MC setup for $t\bar{t}$ and single-top quark events**
  - Powheg+Pythia8 sample
    - standard A14 tune
  - crucial to control fragmentation, i.e. b-quark → B-hadron momentum transfer JHEP06 (2023) 019
    - use Lund-Bowler model in Pythia8
      $f(z) = (1/z)(1-z)^a e^{(-b m_T^2/z)} (1/z^{r_Q b m_Q^2})$
    - used LEP+SLD $e^+e^- \to Z \to bb$ data to tune r_b
    - A14-r_b tune:
      r_b=0.855 (Monash) → r_b=1.05±0.02

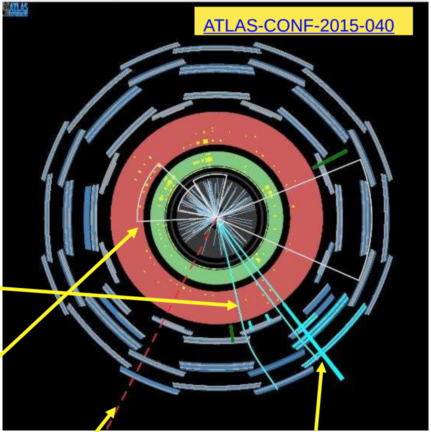
Event reconstruction / preselection

Select events where one top quark decays leptonically (e or μ)
and a b-quark decays into a $J/\psi \rightarrow \mu^+\mu^-$

Trigger
- standard isolated leptons
  - 2015: HLT_e24_lhmedium_L1EM20VH
    e60_lhmedium, e120_lhloose,
    mu20_iloose_L1MU15, mu50
  - 2016-18: HLT_e26_lhtight_nod0_ivarloose
    e60_lhmedium_nod0, e140_lhloose_nod0,
    mu26_ivarmedium, mu50

Isolated lepton
- pid: LHTight for electrons, Medium for muons
- e-isolation: PLVTight
- μ-isolation: PflowTight_FixedRad
- exactly one lepton with p_T>25 GeV for 2015
  with p_T>27 GeV for 2016-2018

Jets
- anti-kt R=0.4
- ≥2 jets with p_T>25 GeV, $|\eta|$<2 .5
- ≥1 b-jet (DL1r)



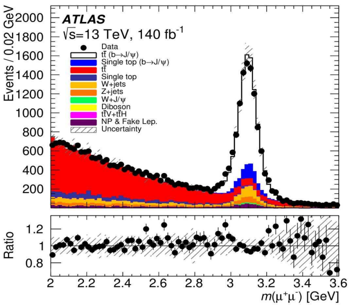
E_T^{miss}
- no cut

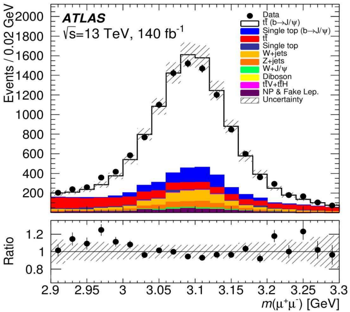
soft-μ
- pid : LowPt
- p_T>3 GeV
- $\Delta R(\mu,jet)$<0.4
- $|\Delta z_0|$<10 mm

$J/\psi \to \mu^+\mu^-$ selection

- **Full selection**
  - ○ ≥ 2 jet, ≥ 1 b-tag, 1 isolated ℓ,
    2 oppositely signed charge soft-μ
  - ○ geometric cuts for common origin of J/ψ and jet
    - $\Delta R(\mu,\text{jet})<0.4$, and $\Delta R(\mu,\mu)<0.6$
  - ○ non-prompt J/ψ reconstruction
    → mass window and quality cuts
    - $2.9<m(\mu\mu)<3.3$ GeV, $\chi2<10$,
      $p_T(\mu\mu)>8$ GeV, $|y(\mu\mu)|<2.1$, $\tau(\mu\mu)>0.1$ ps
  - ○ reconstruction of ℓ J/ψ system
    - $p_T(\ell\,\mu\mu)>25$ GeV & $10<m(\ell\,\mu\mu)<160$ GeV

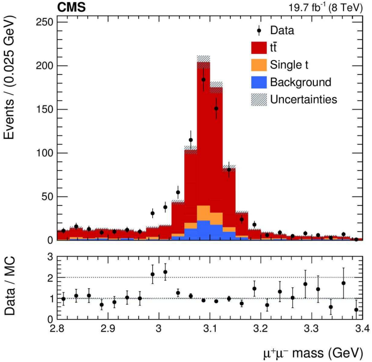
Data	12 165
$t\bar{t}$ ($b \to J/\psi \to \mu^+\mu^-$)	7941 ± 737
Single-top-quark ($b \to J/\psi \to \mu^+\mu^-$)	964 ± 109
$t\bar{t}$	1411 ± 145
Single-top-quark	164 ± 43
$t\bar{t}V + t\bar{t}H$	38 ± 8
W+jets	777 ± 258
Z+jets	468 ± 138
$W + J/\psi$	78 ± 41
diboson	16 ± 9
Non-prompt and fake lepton	322 ± 99
Signal+background	12 180 ± 821
Expected background fraction	0.27 ± 0.01
Data/(Signal+background)	1.00 ± 0.07





CMS $J/\psi \rightarrow \mu^+\mu^-$ selection

- **Full selection** — *JHEP 12 (2016) 123*
  - ≥ 2 jet, p_T(jet)>40 GeV, 1 isolated ℓ with $p_T(\mu)$>26 GeV or p_T(e)30 GeV
    two leptons OS with additional cuts
    2 oppositely signed charged soft-μ, with p_T>4 GeV
  - geometric cuts for common origin of J/ψ and b-jet
  - non-prompt J/ψ reconstruction
    → mass window and quality cuts
    - $3<m(\mu\mu)<3.2$ GeV, $\chi^2<5$, $\tau(\mu\mu)/\sigma(\tau(\mu\mu))>20$



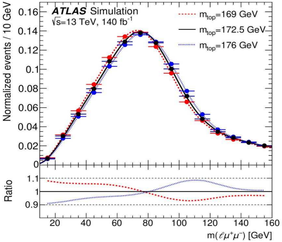
Process	Number of events Leading μ	Leading e
$t\bar{t} \rightarrow b\ell^-\bar{\nu}\bar{b}q\bar{q}'$	228.1 ± 4.0	195.6 ± 3.7
$t\bar{t} \rightarrow b\ell^-\bar{\nu}\bar{b}\ell^+\nu$	66.3 ± 1.7	56.9 ± 1.6
$t\bar{t} \rightarrow b\bar{q}q'\bar{b}q\bar{q}'$	negligible	negligible
Single top quark	39.4 ± 3.8	30.6 ± 3.3
$W \rightarrow \ell\nu$ + jets	18.3 ± 3.2	12.1 ± 2.7
$Z/\gamma^* \rightarrow \ell^+\ell^-$ + jets	4.5 ± 0.9	6.3 ± 1.0
WW, WZ, ZZ	1.1 ± 0.3	1.2 ± 0.3
Predicted yield	357.7 ± 6.6	302.7 ± 5.9
Data	355	311

Unbinned maximum likelihood template fit

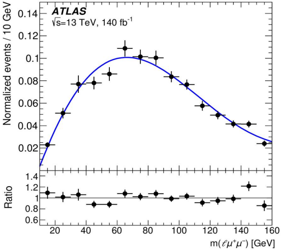
$$\mathcal{L}(m_{\text{top}}) = \prod_{i=1}^{N} f_{m_{\text{top}}\text{-dep.}} P^{m_{\text{top}}\text{-dep.}}(m^i(\ell\mu^+\mu^-)|m_{\text{top}}) + (1 - f_{m_{\text{top}}\text{-dep.}}) P^{m_{\text{top}}\text{-indep.}}(m^i(\ell\mu^+\mu^-))$$

- m_{top} extracted from the m(ℓ μμ) distribution
- templates building
  - templates for m_{top}-dep. from $t\bar{t}$ and single-top-quark with/without $b \rightarrow J/\psi \rightarrow \mu\mu$
    use of 7 $t\bar{t}$ and single-top MC samples with m_{top} : 169, 172, 172.25, 172.5 172.75, 173, 176 GeV
    fitted using the sum of two functions : Gaussian+LogNormal
  - templates for m_{top}-indep. Build from other contributions and fitted using Chebyshev polynomial
  - normalized to unity
- m_{top}-dependent and m_{top}-independent probability density functions : $P^{m_{\text{top}}\text{-dep.}}$ & $P^{m_{\text{top}}\text{-indep.}}$
- $f_{m_{\text{top}}\text{-dep.}}$ fraction of events of the m_{top}-dep. component
- find the value of m_{top} that maximizes the likelihood

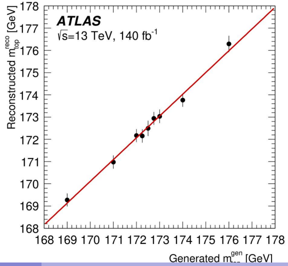
Templates for m_{top}-dep.



Template for m_{top}-indep.



Calibration



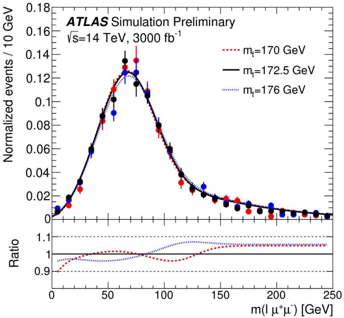
Systematic uncertainties

Source of uncertainty	Unc. in m_{top} [GeV]	Stat. precision [GeV]
Data and Monte Carlo samples		
Statistical error in data	0.80	
Statistical error in signal and background model	0.27	±0.06
Method	0.06	±0.10
Luminosity	0.01	< ±0.005
Pile-up	0.11	±0.02
Modelling of $t\bar{t}$ process		
Matrix element matching	0.14	±0.20
NNLO reweighting	0.01	±0.02
Top-quark decay lineshape	0.07	±0.02
Parton shower and hadronisation	0.40	±0.19
b-hadron production fractions	0.04	±0.02
b-hadron decay BR	0.08	±0.02
Initial-state QCD radiation	0.10	±0.07
Final-state QCD radiation	0.21	±0.05
Underlying event	0.20	±0.12
Colour reconnection	0.04	±0.28
Parton distribution function	0.03	< ±0.005
b-quark fragmentation r_b	0.15	±0.04
Modelling of single-top-quark process		
Matrix element matching	0.02	±0.11
$t\bar{t}$–tW interference	0.15	±0.07
Parton shower and hadronisation	0.09	±0.11
b-hadron production fractions	0.09	±0.07
b-hadron decay BR	0.02	< ±0.005
Initial-state QCD radiation	0.05	±0.04
Final-state QCD radiation	0.06	±0.04
Parton distribution function	0.01	< ±0.005
b-quark fragmentation r_b	0.05	±0.07
Modelling of background processes		
$t\bar{t}V + t\bar{t}H$, diboson	0.02	±0.01
W/Z+jets	0.40	±0.12
$W + J/\psi$	0.04	< ±0.005
Non-prompt and fake lepton	0.15	±0.01
Fake soft-μ	0.01	< ±0.005
Detector response		
Isolated leptons	0.08	±0.01
Soft-μ	0.12	±0.01
Light jet energy scale	0.07	±0.01
b-jet energy scale	0.04	±0.01
Jet energy resolution	0.02	±0.01
Flavour tagging	0.02	< ±0.005
Total systematic uncertainty (excluding recoil)	0.81	±0.15
Total stat. and syst. uncertainty (excluding recoil)	1.14	±0.15
Recoil uncertainty	1.07	±0.22
Total uncertainty	1.56	±0.18

Leading systematic uncertainties : σ(PS-had)=0.40 GeV, σ(stat error in MC)=0.27 GeV, σ(FSR)=0.21 GeV, σ(UE)=0.15 GeV, σ(b-frag)=0.15 GeV, σ(W/Z+j)=0.40 GeV
but reduced σ(JES)=0.07 GeV and σ(b-JES)=0.04 GeV
And last uncertainty arises from changing the dipole parton shower gluon-recoil scheme used in top-quark decays : σ(recoil)=1.07 GeV

Prospects for HL-LHC

- **Motivations**
  - ”Standard Model Physics at the HL-LHC and HE-LHC”, CERN Yellow Report, arXiv:1902.04070 - *ATL-PHYS-PUB-2018-042*
  - projections for m_t accuracy at $\sqrt{s}$=14 TeV at the HL-LHC with 3000 fb^{-1}
- **Results**
  - expected number of events: 2×10^5 candidates
  - 18% increase due to higher cross section
  - 10% increase due to larger coverage $|\eta|<4$



Source of uncertainty	$\sigma(m_{top})$ [GeV]
Statistical uncertainty	0.14
Method uncertainty	0.11
Signal modelling uncertainties	
$t\bar{t}$ NLO modelling	0.06
$t\bar{t}$ PS and hadronisation	0.05
$t\bar{t}$ b-production	0.24
$t\bar{t}$ b-fragmentation	0.11
Initial- and final-state radiation	0.04
Underlying event	0.02
Colour reconnection	0.02
Background modelling uncertainties	0.10
Experimental uncertainties	
Jet energy scale (JES)	0.31
b-jet energy scale (b-JES)	0.06
Jet energy resolution (JER)	0.13
Jet vertex fraction	0.02
Electrons	0.03
Muons	0.09
Pile-up	0.04
Total Systematic uncertainty	0.48
Total	0.50

$$\sigma(m_{top}) = 0.14\ (\text{stat}) \pm 0.48\ (\text{syst})\ \text{GeV}$$

Comparison of b → J/ψ → μ⁺μ⁻ and b → μ results

$b \to J/\psi \to \mu^+\mu^-$

Source of uncertainty	Unc. in m_{top} [GeV]	Stat. precision [GeV]
Data and Monte Carlo samples		
Statistical error in data	0.80	
Statistical error in signal and background model	0.27	±0.06
Method	0.06	±0.10
Luminosity	0.01	< ±0.005
Pile-up	0.11	±0.02
Modelling of $t\bar{t}$ process		
Matrix element matching	0.14	±0.20
NNLO reweighting	0.01	±0.02
Top-quark decay lineshape	0.07	±0.02
Parton shower and hadronisation	0.40	±0.19
b-hadron production fractions	0.04	±0.02
b-hadron decay BR	0.08	±0.02
Initial-state QCD radiation	0.10	±0.07
Final-state QCD radiation	0.21	±0.05
Underlying event	0.20	±0.12
Colour reconnection	0.04	±0.28
Parton distribution function	0.03	< ±0.005
b-quark fragmentation r_b	0.15	±0.04
Modelling of single-top-quark process		
Matrix element matching	0.02	±0.11
$t\bar{t}$–tW interference	0.15	±0.07
Parton shower and hadronisation	0.09	±0.11
b-hadron production fractions	0.09	±0.07
b-hadron decay BR	0.02	< ±0.005
Initial-state QCD radiation	0.05	±0.04
Final-state QCD radiation	0.06	±0.04
Parton distribution function	0.01	< ±0.005
b-quark fragmentation r_b	0.05	±0.07
Modelling of background processes		
$t\bar{t}V + t\bar{t}H$, diboson	0.02	±0.01
W/Z+ jets	0.40	±0.12
$W + J/\psi$	0.04	< ±0.005
Non-prompt and fake lepton	0.15	±0.01
Fake soft-μ	0.01	< ±0.005
Detector response		
Isolated leptons	0.08	±0.01
Soft-μ	0.12	±0.01
Light jet energy scale	0.07	±0.01
b-jet energy scale	0.04	±0.01
Jet energy resolution	0.02	±0.01
Flavour tagging	0.02	< ±0.005
Total systematic uncertainty (excluding recoil)	0.81	±0.15
Total stat. and syst. uncertainty (excluding recoil)	1.14	±0.15
Recoil uncertainty	1.07	±0.22
Total uncertainty	1.56	±0.18

$M_{top} = 172.17 \pm 0.80 \text{ (stat)} \pm 0.81 \text{(syst)} \pm 1.07 \text{(recoil) GeV}$

$b \to \mu$

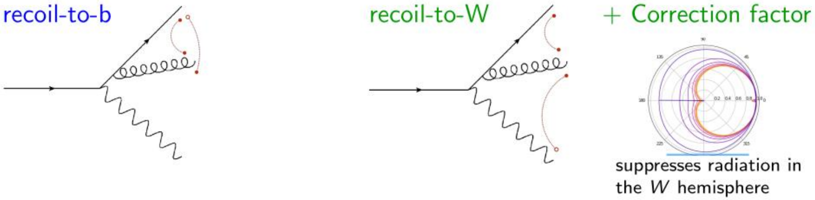
Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Statistical and datasets		
Data statistics	0.39	
Signal and background model statistics	0.17	
Luminosity	< 0.01	±0.01
Pile-up	0.07	±0.03
Modelling of signal processes		
Monte Carlo event generator	0.04	±0.06
b, c-hadron production fractions	0.11	±0.01
b, c-hadron decay BRs	0.40	±0.01
b-quark fragmentation r_b	0.19	±0.06
Parton shower α_S^{FSR}	0.07	±0.04
Parton shower and hadronisation model	0.06	±0.07
Initial-state QCD radiation	0.23	±0.08
Colour reconnection	< 0.01	±0.02
Choice of PDFs	0.07	±0.01
Modelling of background processes		
Soft muon fake	0.16	±0.03
Multijet	0.07	±0.02
Single top	0.01	±0.01
W/Z+jets	0.17	±0.01
Detector response		
Leptons	0.12	±0.01
Jet energy scale	0.13	±0.02
Soft muon jet p_T calibration	< 0.01	±0.01
Jet energy resolution	0.08	±0.07
b-tagging	0.10	±0.01
Missing transverse momentum	0.15	±0.01
Total stat. and syst. uncertainties (excluding recoil)	0.77	±0.03
Recoil uncertainty	0.25	
Total uncertainty	0.81	

$m_{top} = 174.41 \pm 0.39 \text{ (stat)} \pm 0.66 \text{ (syst)} \pm 0.25 \text{ (recoil) GeV}$

Recoil modelling in t → Wb decay

Treatment of recoil in second gluon emission (dipole showers):
- ○ Recoil-to-b (default)
- ○ Recoil-to-W + correction ⇒ recoil-to-top

Talk by P. Skands



- ○ First emission: controlled by Matrix Element Calculation
- ○ Second emission: in dipole showers different possible strategies for the recoil result in different momentum reassignment between t, W, b and different coverage of the phase space