Universität Siegen

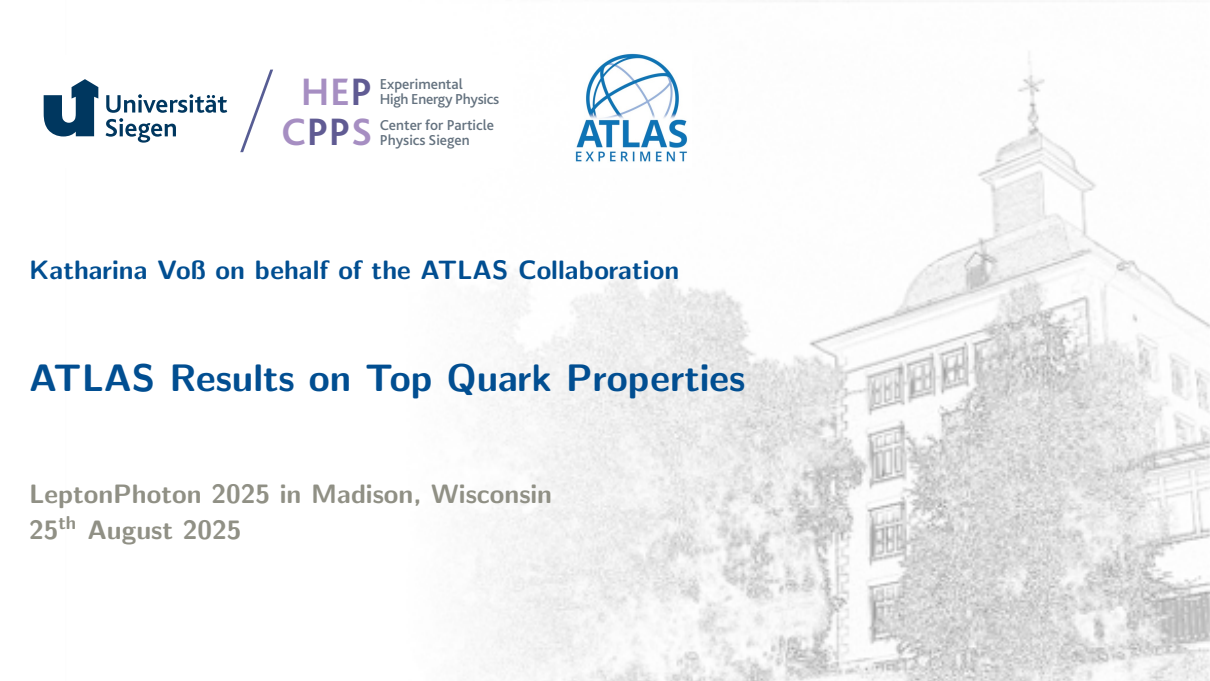
HEP Experimental High Energy Physics
CPPS Center for Particle Physics Siegen

ATLAS EXPERIMENT

Katharina Voß on behalf of the ATLAS Collaboration

ATLAS Results on Top Quark Properties

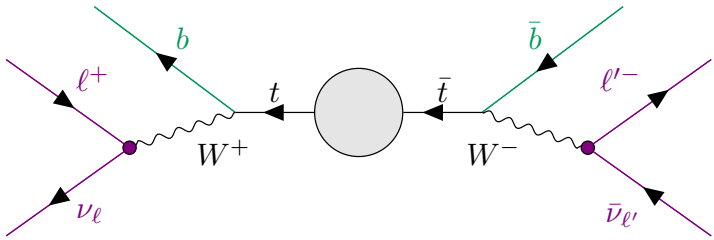
LeptonPhoton 2025 in Madison, Wisconsin
25th August 2025



Studying Top Quark Properties in $t\bar{t}$ Events

Why $t\bar{t}$ in dileptonic decay?

- **large data set**
  Run 2, $\sqrt{s} = 13\,\text{TeV}$, $140\,\text{fb}^{-1}$
  $\rightarrow$ 10 M $t\bar{t}(\rightarrow \ell\ell)$ pairs
- **characteristic topology**
  - 2 opposite charge leptons
  - 2 b-jets
- **small background**



Quantum entanglement

Entanglement in top quarks
[Nature 633, 542–547 (2024)]
Channel: $e\mu$
Background: $< 10\,\%$

Lepton flavour universality

$e - \mu$ **universality**
[Eur. Phys. J. C 84 (2024) 993]
Channel: ee,$e\mu$,$\mu\mu$
Purest SR, background: $\sim 4\,\%$

$e - \tau$ **universality**
[JHEP 05 (2025) 038]
Channel: ee,$e\mu$
Background: 7.9 % (ee) & 0.9 % ($e\mu$)

Entanglement in Top Pairs: Analysis Strategy [Nature 633, 542–547 (2024)]

Entanglement in $t\bar{t}$ production: spin quantum state of the tops cannot be described independently of each other
$\rightarrow$ detectable through $D = \mathrm{tr}[C]/3 < -1/3$ with C spin correlation matrix of $t, \bar{t}$

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How to measure it experimentally?

$$D = -3 \langle \cos \varphi \rangle$$

with φ: angle between the two charged leptons after boosting to $t\bar{t}$ rest frame and then to rest frame of parent top-quark

Why leptons? Spin information of the top-quark can be extracted from angular variables of leptons from decay

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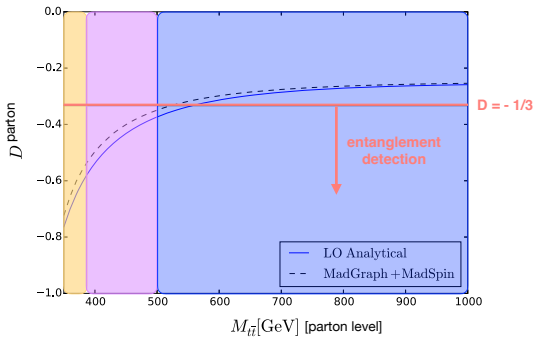
Which phase space to measure entanglement in $t\bar{t}$?

- Signal Region: $340 < m_{t\bar{t}}^{\mathrm{reco}} < 380$ GeV
- Validation Region 1: $380 < m_{t\bar{t}}^{\mathrm{reco}} < 500$ GeV
- Validation Region 2: $m_{t\bar{t}}^{\mathrm{reco}} > 500$ GeV

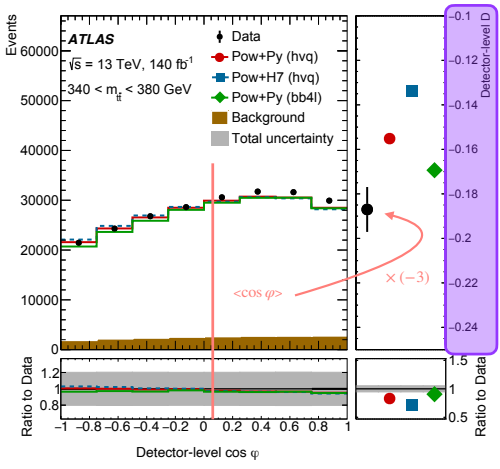


[Eur. Phys. J. C 136 (2021) 907]

Entanglement in Top Pairs: How to measure D? [Nature 633, 542–547 (2024)]

Measure entanglement marker on detector level

$$D^{\text{detector}} = -3 \langle \cos \varphi^{\text{detector}} \rangle$$



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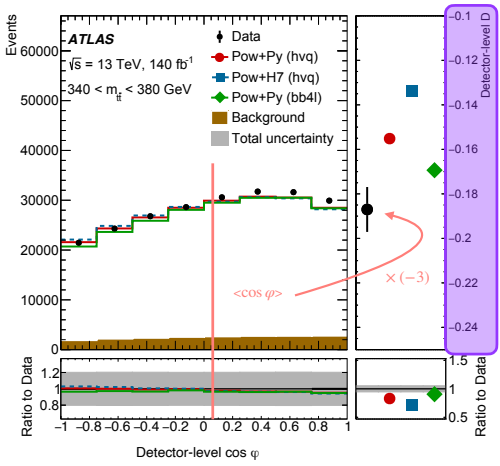
Entanglement marker $D < -1/3$ defined on parton level

Strategy:

$$D^{\text{detector}}(\text{data}) \rightarrow D^{\text{particle}}(\text{data}) < D^{\text{particle}}_{\text{limit}} \leftarrow D^{\text{parton}}_{\text{limit}} = -1/3$$



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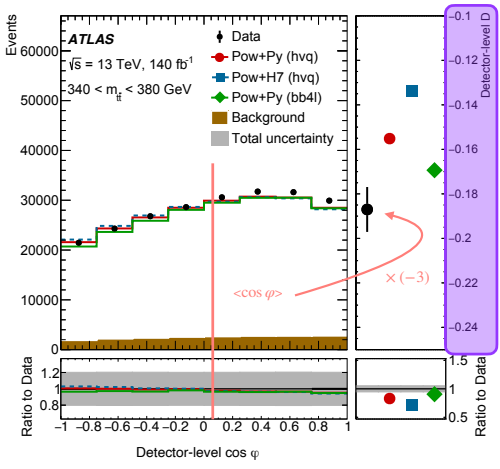
First step:

$$D^{\text{detector}} \xrightarrow{?} D^{\text{particle}}$$

$\rightarrow$ use a calibration curve $D^{\text{particle}}(D^{\text{detector}})$



Entanglement in Top Pairs: Calibration Curve [Nature 633, 542–547 (2024)]

Strategy:

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First step:

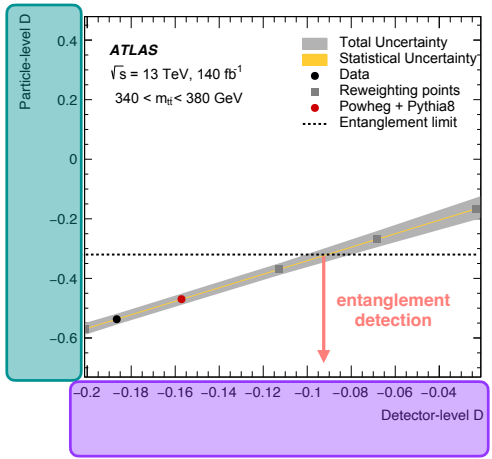
$$D^{\text{detector}} \xrightarrow{?} D^{\text{particle}}$$

Derive calibration curve $D^{\text{particle}}(D^{\text{detector}})$
$\rightarrow$ reweighting to alternative D^{parton} based on truth level quantities

Uncertainties on calibration curve:

- new calibration curve for each syst. uncertainty j
  $C_j = D_j^{\text{particle}}(D_j^{\text{detector}})$

Most dominant uncertainty: $t\bar{t}$ modelling
(top-quark decay)



Entanglement in Top Pairs: Results [Nature 633, 542–547 (2024)]

$D^{\text{detector}}(\text{data}) \rightarrow D^{\text{particle}}(\text{data}) < D^{\text{particle}}_{\text{limit}} \leftarrow D^{\text{parton}}_{\text{limit}} = -1/3$

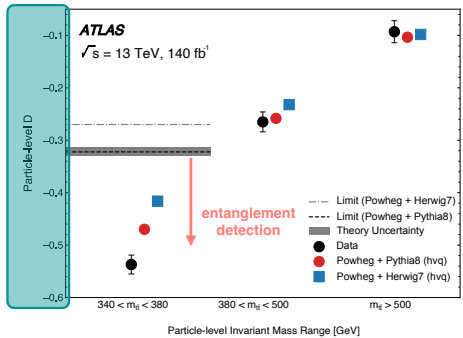
Next step: $D^{\text{particle}}_{\text{limit}} \overset{?}{\leftarrow} D^{\text{parton}}_{\text{limit}}$
$\rightarrow$ use $D^{\text{particle}}(D^{\text{parton}})$ calibration curve

- Powheg+Pythia8: $D^{\text{particle}}_{\text{limit}} = -0.322 \pm 0.009$
  $\rightarrow$ $t\bar{t}$ modelling uncert. except PS

Particle-level fit result:
$D^{\text{particle}}(\textit{data}) = -0.537 \pm 0.002(\text{stat.}) \pm 0.019(\text{syst.})$

$$D^{\text{particle}}(\textit{data}) = -0.537 \pm 0.019$$
$$< -0.322 \pm 0.009 = D^{\text{particle}}_{\text{limit}}$$

First observation of quantum entanglement with top quarks with more than 5σ



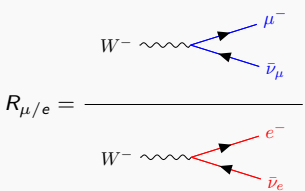
$\rightarrow$ first observation of quantum entanglement in a pair of quarks
$\rightarrow$ highest-energy observation of entanglement
$\rightarrow$ novel approach to study quantum information effects also at colliders
Confirmed also by CMS measurement [Rep. Prog. Phys. 87 (2024) 117801]

Testing lepton universality

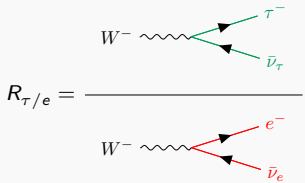
Are the W-boson couplings to all lepton flavours the same as predicted by SM?

Lepton flavour universality tests with on-shell W-bosons in ATLAS

Measuring $R_{\mu/e}$
[Eur. Phys. J. C 84 (2024) 993]



Measuring $R_{\tau/e}$
[JHEP 05 (2025) 038]



(phase space differences due to lepton masses negligible in on-shell W-boson decay)

→ different lepton decay channels lead to quite different analysis strategies

Testing lepton universality

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Lepton flavour universality tests with on-shell W-bosons in ATLAS

Measuring $R_{\mu/e}$
[Eur. Phys. J. C 84 (2024) 993]

$$R_{\mu/e} = \frac{W^- \to \mu^- \bar{\nu}_\mu}{W^- \to e^- \bar{\nu}_e}$$

Measuring $R_{\tau/e}$
[JHEP 05 (2025) 038]

$$R_{(\tau\to e)/e} = \frac{W^- \to \tau^- (\to e^- \bar{\nu}_e \nu_\tau) \bar{\nu}_\tau}{W^- \to e^- \bar{\nu}_e}$$

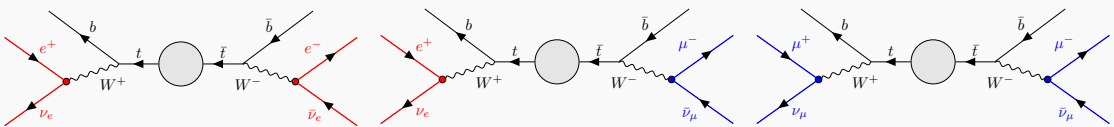
(phase space differences due to lepton masses negligible in on-shell W-boson decay)

→ different lepton decay channels lead to quite different analysis strategies

Measuring $R_{\mu/e}$: Analysis strategy [Eur. Phys. J. C 84 (2024) 993]

General analysis strategy

Fit $R_{e/\mu}$ by comparing the measured $t\bar{t}$ cross section in the ee, $e\mu$ and $\mu\mu$ channel
$\rightarrow$ differences in W branching fractions = differences in $t\bar{t}$ cross sections in different decay channels



$\rightarrow$ also $W \rightarrow \tau \rightarrow e/\mu$ decays are included with SM $\mathcal{B}(W \rightarrow \tau\nu)$

Analysis method already applied for precise $t\bar{t}$ cross-section measurement at $\sqrt{s} = 5, 13$ and 13.6 TeV
[JHEP 06 (2023) 138] [JHEP 07 (2023) 141] [PLB 848 (2024) 138376]

Advantage when measuring the ratio: systematic uncertainties, which are the same in all decay channels cancel
One of the dominant systematics in cross-section measurements: $t\bar{t}$ and Wt modelling!

Measuring $R_{\mu/e}$: Signal region [Eur. Phys. J. C 84 (2024) 993]

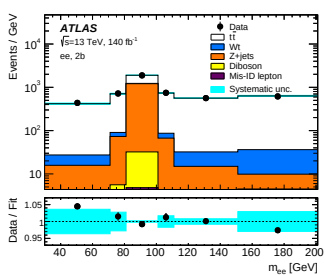
Which signal regions to extract the cross-section ratios?

- $e\mu$ channel: N_{ev} with $N_b = 1$ and $N_b = 2$
- $ee/\mu\mu$ channel: N_{ev} in bins of $m_{\ell\ell}$ ($N_b = 1$ and $N_b = 2$ region)
  $\rightarrow$ handle on Z+jets background

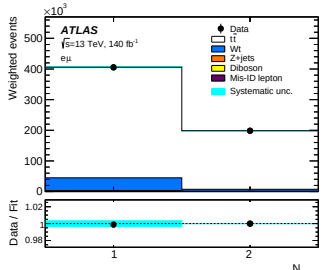
In-situ lepton isolation efficiency measurement

lepton isolation efficiency depends on lepton p_{T}, η + hadronic environment (standard SF: from $Z \rightarrow \ell\ell$)
$\rightarrow$ in-situ SF derivation from $t\bar{t}$ and $Z \rightarrow \ell\ell$

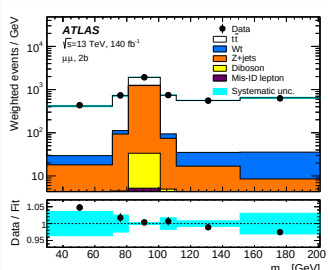
ee channel - m_{ee}



$e\mu$ channel - $N_{b-\text{jets}}$



$\mu\mu$ channel - $m_{\mu\mu}$



Measuring $R_{\mu/e}$: R_Z measurement [Eur. Phys. J. C 84 (2024) 993]

Challenge: systematic uncertainties on e and μ efficiencies do not cancel in $R_W^{\mu/e} = \frac{\mathcal{B}(W\to\mu\nu)}{\mathcal{B}(W\to e\nu)}$

Solution: instead of R_W measure R_{WZ} and R_Z

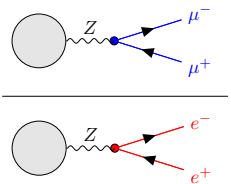
$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}} = \frac{\mathcal{B}(W\to\mu\nu)}{\mathcal{B}(W\to e\nu)} \cdot \sqrt{\frac{\mathcal{B}(Z\to ee)}{\mathcal{B}(Z\to\mu\mu)}}$$

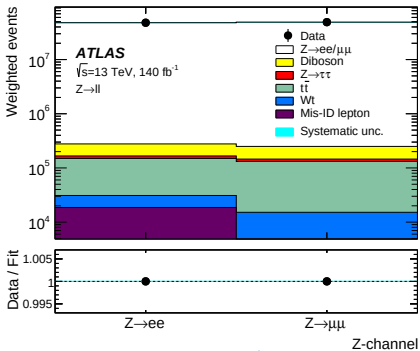
→ later use precisely measured R_Z value at LEP+SLD

$$R_W^{\mu/e} = R_{WZ}^{\mu/e}\sqrt{R_Z^{\mu\mu/ee}}$$

Need a handle on R_Z → use $Z \to ll$ events!

$$R_Z = \frac{\mathcal{B}(Z\to\mu\mu)}{\mathcal{B}(Z\to ee)} =$$



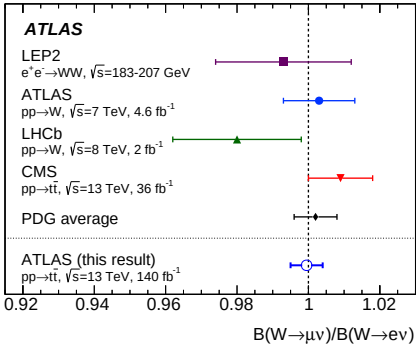


Measuring $R_{\mu/e}$: Results [Eur. Phys. J. C 84 (2024) 993]

Calculation of final $R_W^{\mu/e}$ value

$$R_W^{\mu/e}(\text{ATLAS}) = R_{WZ}^{\mu/e}(\text{ATLAS}) \cdot \sqrt{R_Z^{\mu\mu/ee}}(\text{LEP+SLD})$$

- From likelihood fit in this analysis
  $R_{WZ}^{\mu/e}(\text{ATLAS}) = 0.9990 \pm 0.0022\ (\text{stat.}) \pm 0.0036\ (\text{syst.})$
  Dominant uncertainties: PDF, muon ID, fake leptons
- LEP+SLD result [Phys.Rept.427:257-454,2006]
  $R_Z^{\mu\mu/ee}\ (\text{LEP+SLD}) = 1.0009 \pm 0.0028\ (\text{stat.+syst.})$



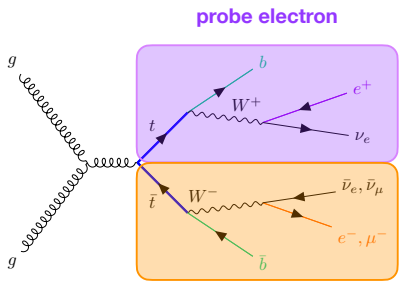
Final result $R_W^{\mu/e} = 0.9995 \pm 0.0022(\text{stat.}) \pm 0.0036(\text{syst.}) \pm 0.0014(\text{LEP+SLD})$
→ most precise single measurement and more precise then previous PDG average
→ relative uncertainty of 0.45 %

Measuring $R_{\tau/e}$: Analysis strategy [JHEP 05 (2025) 038]

General analysis strategy

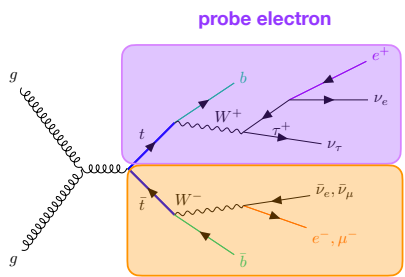
Extract $R_{\tau/e}$ by comparing fraction of probe electrons from $W \to e$ and $W \to \tau \to e$ decays

Why $\tau \to e$? Cancellation of experimental uncertainties in ratio



Probe electron
→ measure $R_{\tau/e}$

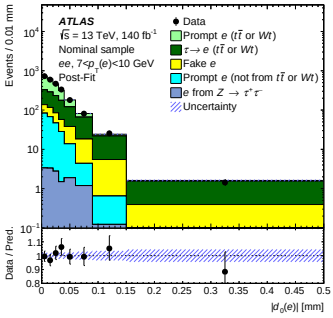
Tag electron or muon
→ select events



Challenge: How to distinguish probe electron originating from $W \to e$ and $W \to \tau \to e$?

Measuring $R_{\tau/e}$: $W \to e$ vs. $W \to \tau \to e$ [JHEP 05 (2025) 038]

$7 < p_{\mathrm{T}}(e) < 10$ GeV



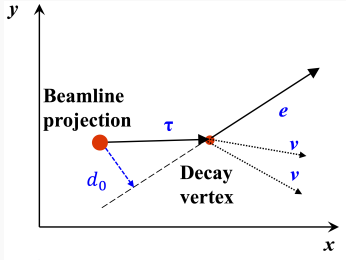
$W \to \tau \to e$ small p_{T}, high $|d_0|$

Two neutrinos in $W \to \tau \to e$ decay

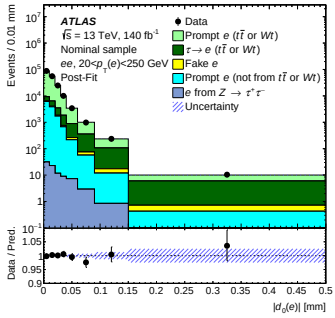
$\to$ softer p_{T} spectrum of probe e

Displaced τ decay vertex

$\to$ larger e-track impact parameter d_0



$20 < p_{\mathrm{T}}(e) < 250$ GeV

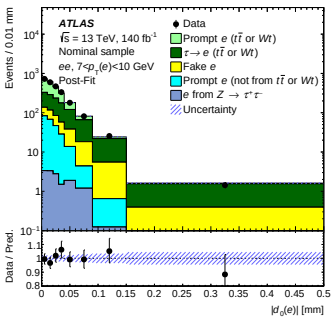


$W \to e$ high p_{T}, small $|d_0|$

Fit strategy to measure $R_{\tau/e}$:
2D profile likelihood fit of $|d_0|$ and p_{T} of the probe electron simultaneous in ee and μe channel

Measuring $R_{\tau/e}$: $W \to e$ vs. $W \to \tau \to e$ [JHEP 05 (2025) 038]

$7 < p_{\mathrm{T}}(e) < 10$ GeV



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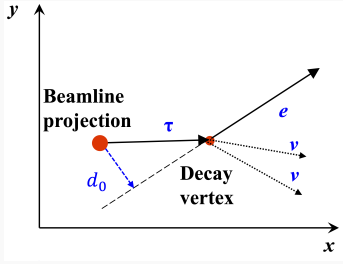

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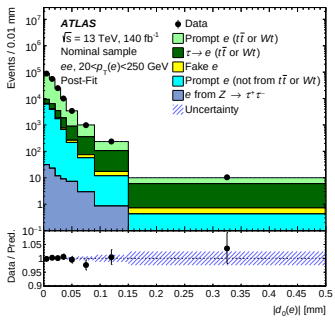


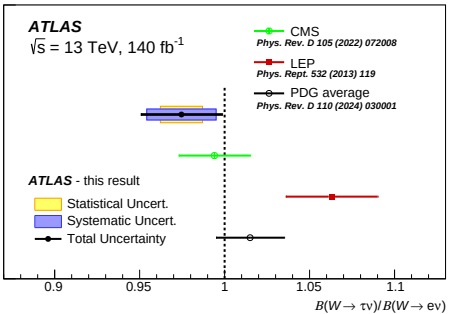
$W \to e$ high p_{T}, small $|d_0|$

Challenge: $|d_0|$ calibration $\to$ calibration done in Z+jet events in 39 p_{T}, η bins

Measuring $R_{\tau/e}$: fit result [JHEP 05 (2025) 038]

Profile likelihood fit to extract $R_{\tau/e}$ & two normalisation factors

$R_{\tau/e} = 0.975 \pm 0.012(\text{stat}) \pm 0.020(\text{syst})$
$\rightarrow$ good agreement with SM and CMS



Most important systematic uncertainties:

Uncertainty group	$\sigma(R_{\tau/e})$
Modelling of $t\bar{t}$ and Wt	0.011
d_0 calibration	0.006
Background estimation	0.005
Electron reconstruction, identification, and isolation	0.005

- **Modelling of $t\bar{t}$ and Wt**
  $\rightarrow$ NNLO differential reweighting, alternative PS

Summary

Latest results on top quark properties by the ATLAS experiment:

Quantum entanglement with top quark pairs

- $D^{\text{particle}} = -0.537 \pm 0.002(\text{stat.}) \pm 0.019(\text{syst.})$

→ first observation of quantum entanglement of a pair of quarks with more than 5σ

→ focus on threshold region which will be discussed in some of the next talks [in this session] and in [ATLAS $t\bar{t}$ threshold measurement talk on Wednesday]

ATLAS achieves highest-energy detection of quantum entanglement

28 September 2023 I By ATLAS Collaboration

Quantum entanglement is one of the most astonishing properties of quantum mechanics. If two particles are entangled, the state of one particle cannot be described independently from the other. This is a unique property of the quantum world and forms a crucial difference between classical and quantum theories of physics. It is so important, the 2022 Nobel Prize in Physics was awarded to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science".

Testing lepton universality

- $e - \mu$ universality in on-shell W-decays: $R_W^{e/\mu} = 0.9995 \pm 0.0022(\text{stat.}) \pm 0.0036(\text{syst.}) \pm 0.0014(\text{ext.})$
- $e - \tau$ universality in on-shell W-decays: $R_{\tau/e} = 0.975 \pm 0.012(\text{stat}) \pm 0.020(\text{syst})$
- $\mu - \tau$ universality [Nature Phys. 17 (2021) 813] $R_{\tau/\mu} = 0.992 \pm 0.007(\text{stat}) \pm 0.011(\text{syst})$

→ good agreement with the SM

Measuring the delicate balance of lepton flavours

25 March 2024 I By ATLAS Collaboration

In a new result presented at the Moriond EW conference, physicists at the ATLAS Collaboration tested lepton flavour universality between muons and electrons. The precision of the result stands as the best yet-achieved in W-boson decays by a single experiment and surpasses the world average.

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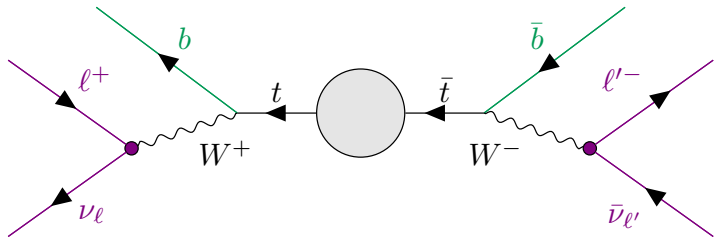
Back Up

Studying Top Quark Properties in $t\bar{t}$ Events

Why $t\bar{t}$ in dileptonic decay?

- large data set
  Run 2, $\sqrt{s} = 13\,\text{TeV}$, $140\,\text{fb}^{-1}$
  $\rightarrow$ 10 M $t\bar{t}(\rightarrow \ell\ell)$ pairs
- characteristic topology
  - 2 opposite charge leptons
  - 2 b-jets
- small background



Quantum entanglement

Entanglement in top quarks
[Nature 633, 542–547 (2024)]
Channel: $e\mu$
OS(e,μ)
$N_b \geq 1$, $N_j \geq 2$
Background: $< 10\,\%$

Lepton flavour universality

$e - \mu$ **universality**
[Eur. Phys. J. C 84 (2024) 993]
Channel: ee,$e\mu$,$\mu\mu$
OS(ℓ,ℓ), $m_{\ell\ell} > 30\,\text{GeV}$
$N_b = 1, N_b = 2$
Purest SR, background: $\sim 4\,\%$

$e - \tau$ **universality**
[JHEP 05 (2025) 038]
Channel: ee,$e\mu$
OS(ℓ,ℓ), $N_b \geq 2$
$m_{\ell\ell} > 15\,\text{GeV}$, $|m_{ee} - m_Z| > 5\text{GeV}$
Background: 7.9 % (ee) & 0.9 % ($e\mu$)

Entanglement in Top Pairs: Entanglement marker D

Spin density matrix $\rho \rightarrow$ describes spin quantum state of the $t\bar{t}$ system

$$\rho = \frac{1}{4}\left[I_4 + \sum_i (B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j\right], \text{tops unpolarised } B_i^{+/-} = 0, \text{ spin correlation matrix } C_{ij}$$

Is $t\bar{t}$ entangled? = Is ρ non-separable, i.e. can not be written as $\rho = \sum_n p_n \rho_n^t \otimes \rho_n^{\bar{t}}, \sum_n p_n = 1, p_n \geq 0$?
= (Peres-Horodecki): is $\rho^{T_2} = \sum_n p_n \rho_n^a \otimes (\rho_n^b)^T$ not a physical state, i.e. is ρ^{T_2} not non-negative?
$\rightarrow$ plug in and find sufficient condition for entanglement: $tr[C] < -1$

How to relate this to experiment? Angular differential cross section in terms of $\vec{q}_\pm$ lepton direction in parent $t/\bar{t}$ rest frame (optimal top spin analysing power)

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\Phi_+ \Phi_-} = \frac{1 + \vec{B}^+ \vec{q}_+ - \vec{B}^- \vec{q}_- - \vec{q}_+ C \vec{q}_-}{(4\pi^2)} \xrightarrow[\text{leaving } \cos\varphi \text{ fixed}]{\int \text{ over common rotation of } \vec{q}_\pm} \frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}\left[1 - \frac{tr[C]}{3}\cos\varphi\right] = \frac{1}{2}\left[1 - D\cos\varphi\right]$$

Such that $D = \frac{tr[C]}{3} < -1/3$ means entanglement!
How to relate this to average $\cos\varphi$**?**

$$\langle\cos\varphi\rangle = \int_{-1}^{1} d(\cos\phi)\cos\phi\left(\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi}\right) = \int_{-1}^{1} d(\cos\phi)\cos\phi\frac{1}{2}\left[1 - D\cos\varphi\right] = -\frac{D}{3} \Leftrightarrow D = -3\langle\cos\phi\rangle$$

Entanglement in Top Pairs: D Reweighting [Nature 633, 542–547 (2024)]

How to derive calibration curve?

Challenge:

Degree of entanglement is inherent in MC generators

$\rightarrow$ cannot be changed

Solution:

For reweighting use D dependence

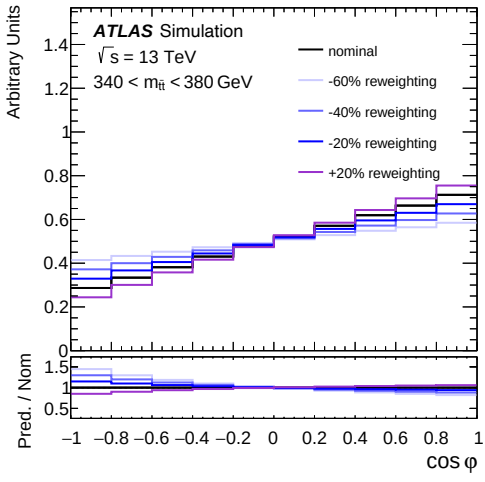
$(1/\sigma)d\sigma/d\cos\phi = (1/2)(1 - D\cos\phi)$

$\rightarrow$ apply event weights depending on parton level quantities

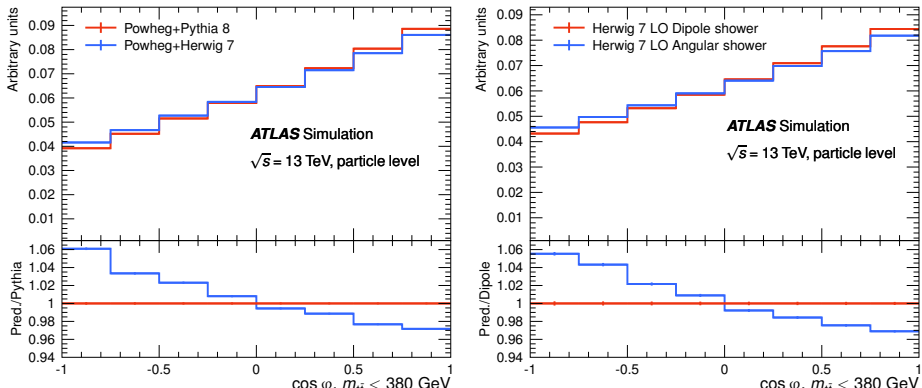
$$w(\cos\phi, m_{t\bar{t}}, k) = \frac{1 - D^{\mathrm{MC}}(m_{t\bar{t}}) \cdot k \cdot \cos\phi}{1 - D^{\mathrm{MC}}(m_{t\bar{t}}) \cdot \cos\phi}$$

with

- $k = 1 - 60\,\%, 1 - 40\,\%, 1 - 20\,\%, 1 + 20\,\%$
- $D^{\mathrm{MC}}(m_{t\bar{t}})$ fitted



Entanglement in Top Pairs: Powheg+Herwig7 [Nature 633, 542–547 (2024)]



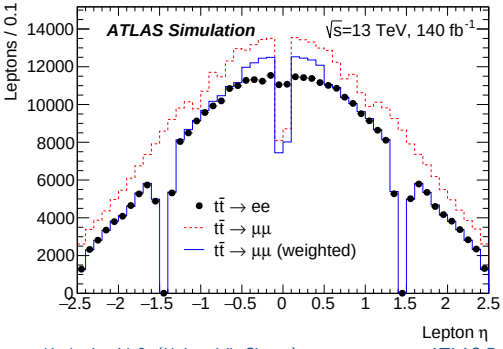
→ difference between alternative Powheg+Pythia8 and Powheg+Herwig7 models seems to be due to different parton shower ordering

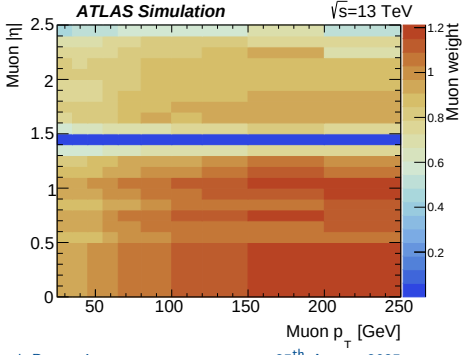
→ special attention needed in parton shower matching for future quantum information studies at LHC

Measuring $R_{\mu/e}$: Muon weighting [Eur. Phys. J. C 84 (2024) 993]

One of the dominant systematics in cross-section measurements: $t\bar{t}$ and Wt modelling!
$\rightarrow$ variations are the same for $ee, e\mu, \mu\mu$ events at particle level!
Challenge: cancellation in ratio only if reconstruction and identification efficiencies are the same for e and μ
Solution: Derive per-muon weights to ensure same p_{T}, η distribution of e and μ

$$w_\mu(p_{\mathrm{T}}, \eta) = w_0 \frac{N^{ee}_{t\bar{t}}(p_{\mathrm{T}}, \eta)}{N^{\mu\mu}_{t\bar{t}}(p_{\mathrm{T}}, \eta)}$$

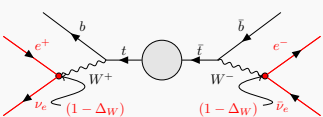




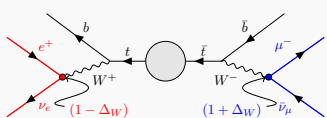
Measuring $R_{\mu/e}$: Parametrisation [Eur. Phys. J. C 84 (2024) 993]

$$R_W^{\mu/e} = \frac{\mathcal{B}(W \to \mu\nu)}{\mathcal{B}(W \to e\nu)} = \frac{\bar{W}(1+\Delta_W)}{\bar{W}(1-\Delta_W)} \Leftrightarrow \Delta_W = \frac{R_W^{e/\mu} - 1}{R_W^{e/\mu} + 1}$$

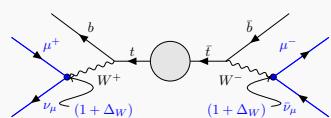
ee channel



eμ channel

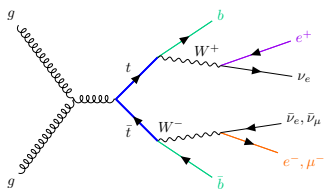


μμ channel



Measuring $R_{\tau/e}$: Event selection [JHEP 05 (2025) 038]

Goal: select dileptonically decaying $t\bar{t}$ events with at least one $W \to e$ or one $W \to \tau \to e$
Why $\tau \to e$? Cancellation of experimental uncertainties in ratio

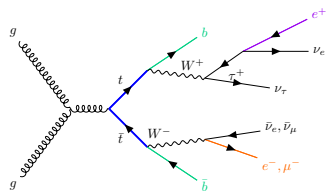


Tag lepton
$N_e^{tag} = 1$ or $N_\mu^{tag} = 1$
$\to$ matched to single lepton trigger
$p_T^e \geq 27$ GeV, $|\eta^e| \leq 2.47$
$p_T^\mu \geq 27.3$ GeV, $|\eta^\mu| \leq 2.5$

Probe electron
$N_e = 1$
$7 < p_T < 250$ GeV, $|\eta| \leq 2.47$

opposite sign leptons
$m_{\ell\ell} > 15$ GeV
$|m_{ee} - m_Z| > 5$ GeV

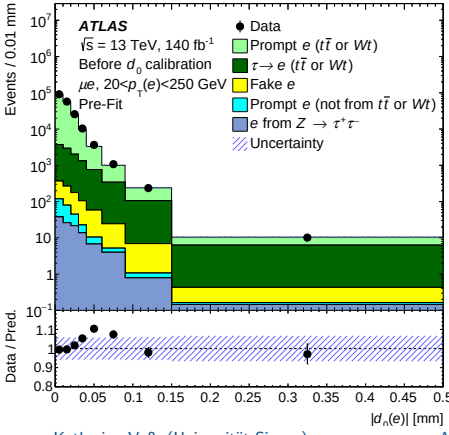
$N_b^{70\%} \geq 2$
DL1r b-tagging,
$p_T \geq 25$ GeV, $|\eta| \leq 2.5$



Measuring $R_{\tau/e}$: d_0 calibration [JHEP 05 (2025) 038]

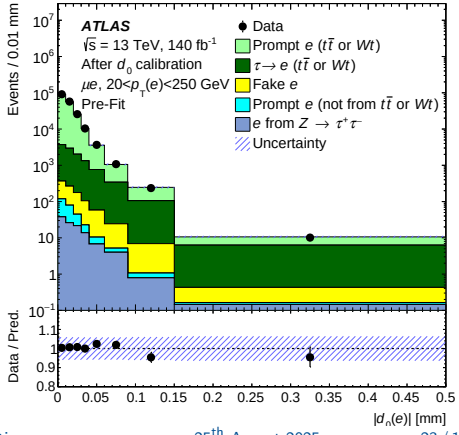
Challenge: calibration of transverse impact parameter $|d_0|$
Advantage of d_0 w.r.t. the beamline: independent of hard process

Before d_0 calibration



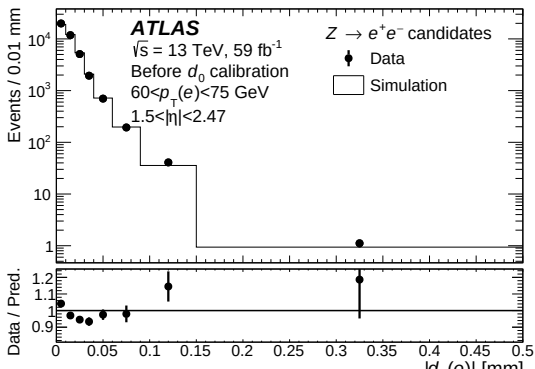
⇒
d_0 calibration
of prompt e
in Z+jet events
⇒

After d_0 calibration



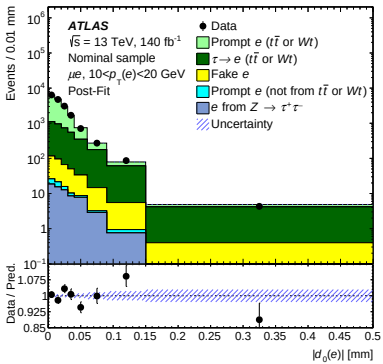
Measuring $R_{\tau/e}$: d_0 calibration

Calibration of $d_0(p_T, |\eta|)$ of prompt e with $Z \to ee$ events
$\to$ 39 bins of $(p_T, |\eta|)$



Measuring $R_{\tau/e}$: profile likelihood fit

μe channel, $10 < p_{\mathrm{T}}(e) < 20$ GeV



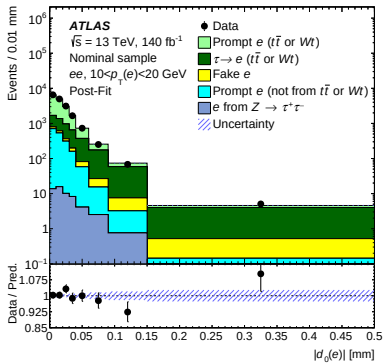
- $N_{\tau\to e} = N^{\text{pre-fit}}_{\tau\to e} \cdot R_{\tau/e} \cdot k_{\text{sig}} \cdot k(\mu/e) \cdot f(\vec{\theta})$
- $N_{\text{prompt e}} = N^{\text{pre-fit}}_{\text{prompt e}} \cdot k_{\text{sig}} \cdot k(\mu/e) \cdot f(\vec{\theta})$
- $N_{\text{bkg}} = N^{\text{pre-fit}}_{\text{bkg}} \cdot k(\mu/e) \cdot f(\vec{\theta})$

Normalisation factors:

- POI $R_{\tau/e}$: $W \to \tau \to e$ events
- k_{sig}: $t\bar{t}$ & tW signal events
- $k(\mu/e)$: all events in μe channel $\to$ differences in selection eff. of tag μ and e

Nuisance parameters $\vec{\theta}$

ee channel, $10 < p_{\mathrm{T}}(e) < 20$ GeV



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Lepton flavour universality measurements

ATLAS (140 fb^{-1}, Run2)

- $e-\mu$ universality [Eur. Phys. J. C 84 (2024) 993]
  $R_W^{e/\mu} = 0.9995 \pm 0.0022(\text{stat.}) \pm 0.0036(\text{syst.}) \pm 0.0014(\text{ext.})$
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- $\mu-\tau$ universality [Nature Phys. 17 (2021) 813]
  $R_{\tau/\mu} = 0.992 \pm 0.007(\text{stat}) \pm 0.011(\text{syst})$
  $\rightarrow$ similar analysis strategy as $R_{\tau/e}$-measurement
  Leading syst: d_0 templates, parton shower variations, muon efficiencies

CMS [Phys. Rev. D 105 (2022) 072008]
35.9 fb^{-1} of 2016 Run2 data
Using $ee, e\mu, \mu\mu$ channel + hadronically decaying τ channels
$\rightarrow$ split in N_j, N_b bins + bins in kinematic variable
(subleading lepton p_{T} for $\ell\ell'$-channels)

- $R_{\mu/e} = 1.009 \pm 0.009$
- $R_{\tau/e} = 0.994 \pm 0.021$
- $R_{\tau/\mu} = 0.985 \pm 0.020$