Measurements of charge and CP asymmetries in *b*-hadron decays using top-quark events collected by the ATLAS detector in *pp* collisions at $\sqrt{s} = 13 TeV$

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IOP HEPP parallel talk 7/4/2025

Introduction: Theory and background

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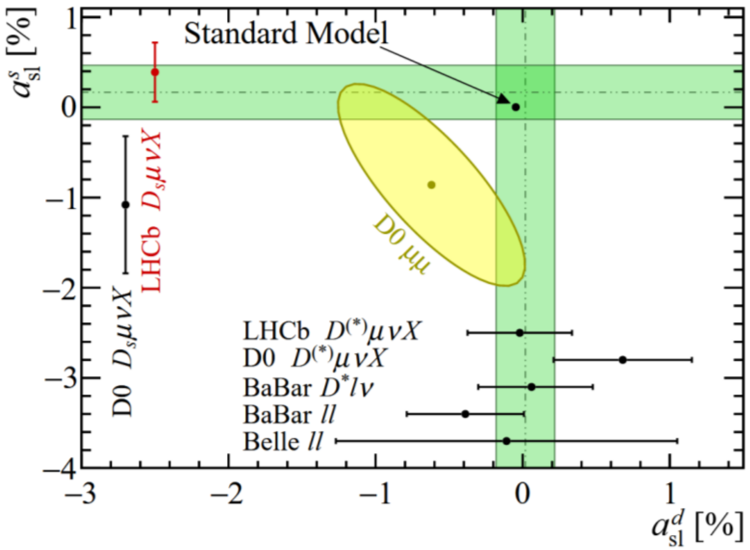
- CPV (Charge-Parity Violation) generates **matter-antimatter asymmetry**
- CPV in the **Standard Model (SM) is insufficient** to explain matter dominated universe
- In 2010, DØ reported an **anomalous asymmetry** from semi leptonic b-hadron decays, **3.6σ from SM** [1]
- Can use **top quark decays as a source of b-hadrons** to measure this at ATLAS
- Following from **statistically-limited** analysis using 20.3 fb-1 Run 1 dataset [2]
- 140 fb-1 Run 2 dataset will **improve statistical uncertainties** and updates to analysis techniques will **improve systematics**
- LHCb has **excluded the DØ measurement as result of indirect (from mixing) CPV** [3] but we are **able to probe the direct case**

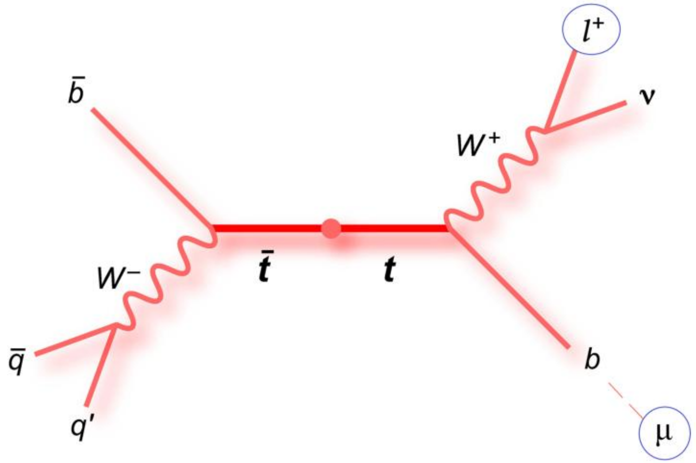


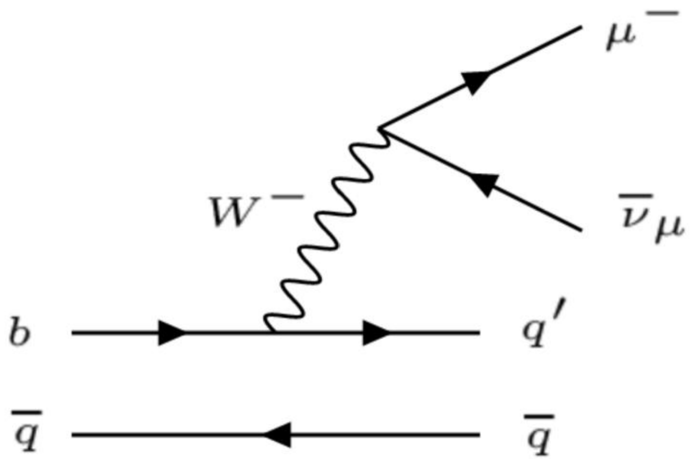
[3]

[1] arXiv:1310.0447v1 [hep-ex] [2] arXiv:1610.07869v2 [hep-ex] [3] PRL 117 (2016) 061803

Charge tagging and soft muons

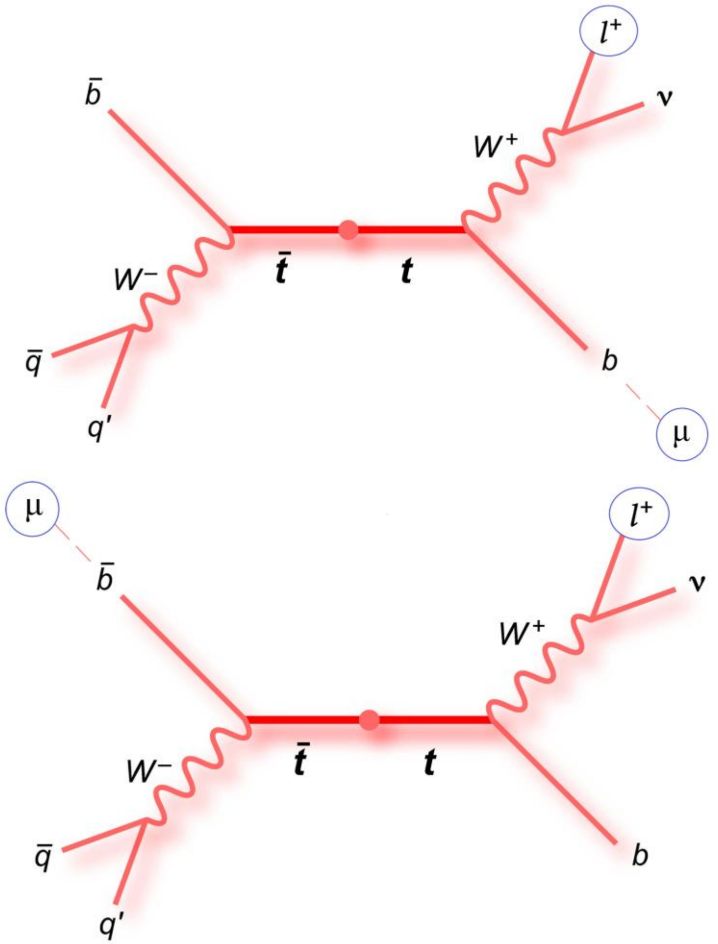
- Use **$t\bar{t}$ lepton + jets channel** with exactly **one prompt lepton**. Also require events to have a **soft muon**.
- Prompt lepton from W-boson decay **tags the b-quark charge at production**
- Soft muons are produced by **semi-leptonic decay of hadrons within b-jets** (Lower p_T hence “soft”). **Tags the b-quark charge at decay**
- Measure these values and **unfold** to build **charge and CPV asymmetries**
- For events where the prompt lepton and soft muon come from opposite sides of the $t\bar{t}$ system, identify and flip the prompt lepton charge. This is known as **same-top/different-top assignment**





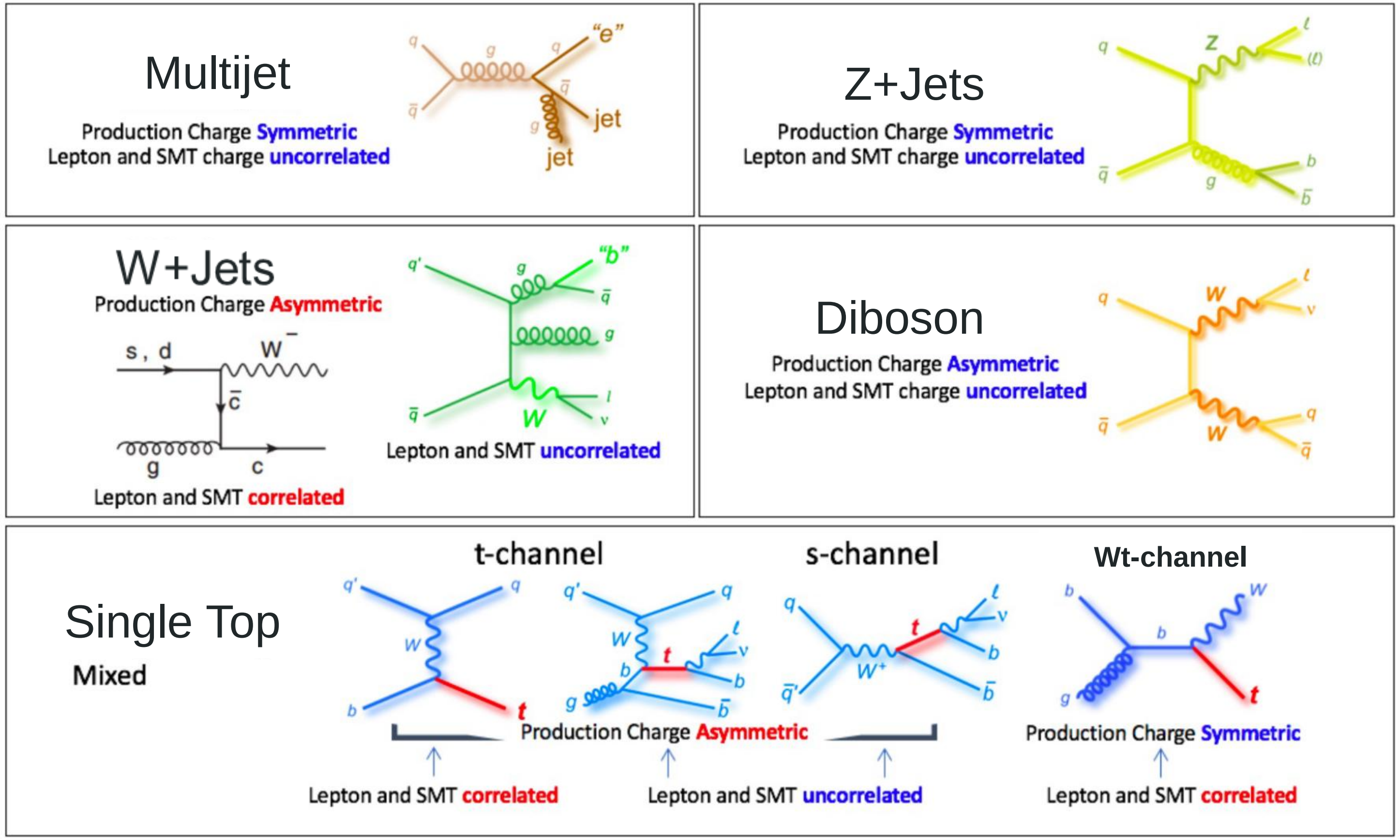
Event selection

- Use **$t\bar{t}$ lepton + jets channel** with **exactly one prompt lepton**
- Also require events to have a **soft muon (pT > 4 GeV)** coming from the semileptonic decay of a *b*-hadron or *c*-hadron originating from the *b*-quark or $\bar{b}$-quark
- The jet producing the soft muon is considered **Soft Muon Tagged (SMT)**
- We require **≥ 4 jets with pT > 25 GeV**, and **≥1 b-jet** (at 77% efficiency working point)
- Most often the **SMT jet and b-tagged jet are the same**

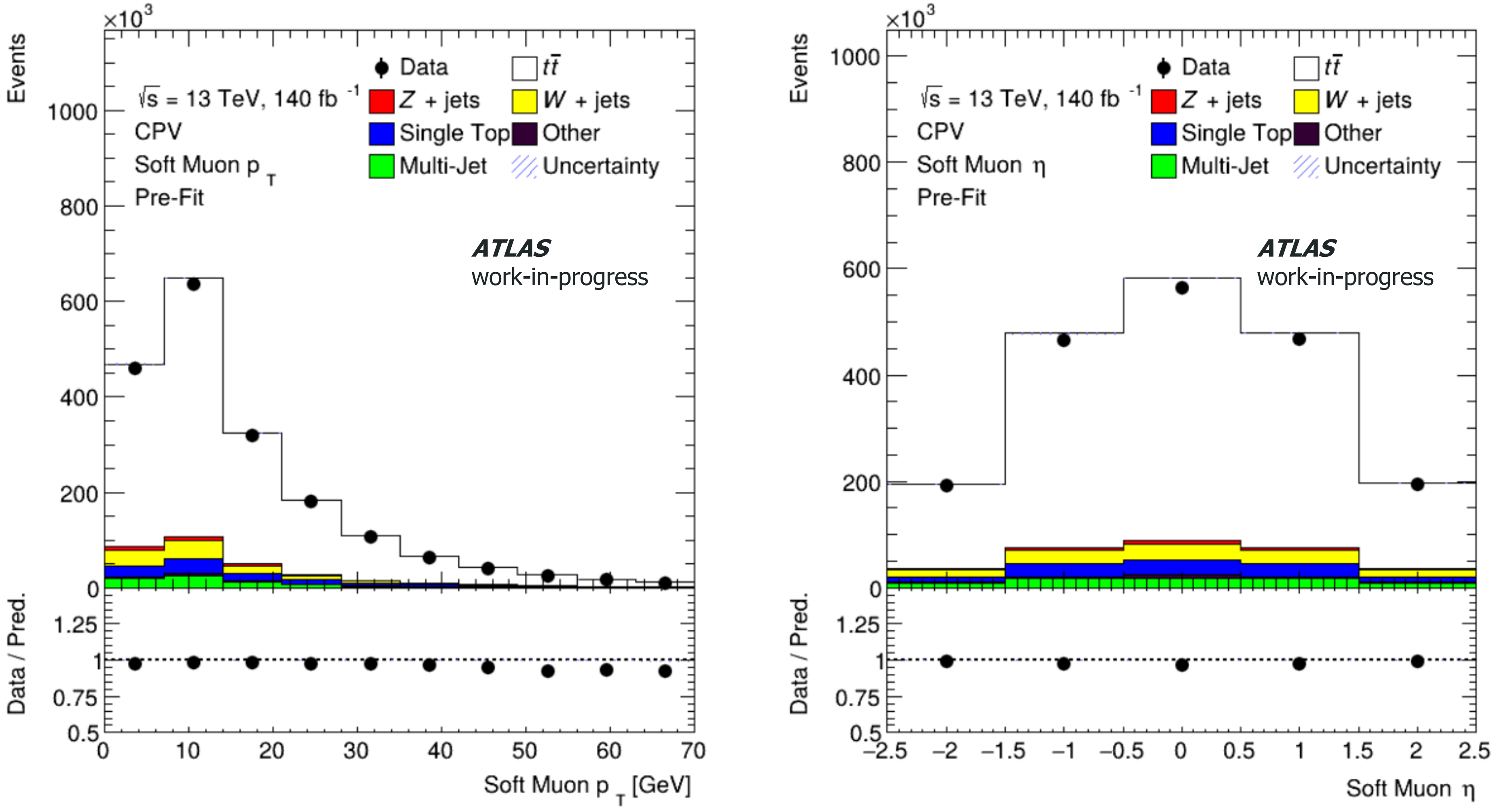


Backgrounds

- Lepton + jets $t\bar{t}$ events with soft muons can be imitated by:
  - **Single top**
  - **W+jets**
  - **Z+jets**
  - **Multijet**
  - **Diboson**
  - **ttV/ttH**
- Multijet yield estimated using **Asymptotic Matrix method**
- Also have **background from within $t\bar{t}$ due to misidentification between prompt and soft muons** – e.g. prompt muons produced close to jets and passing soft muon selection

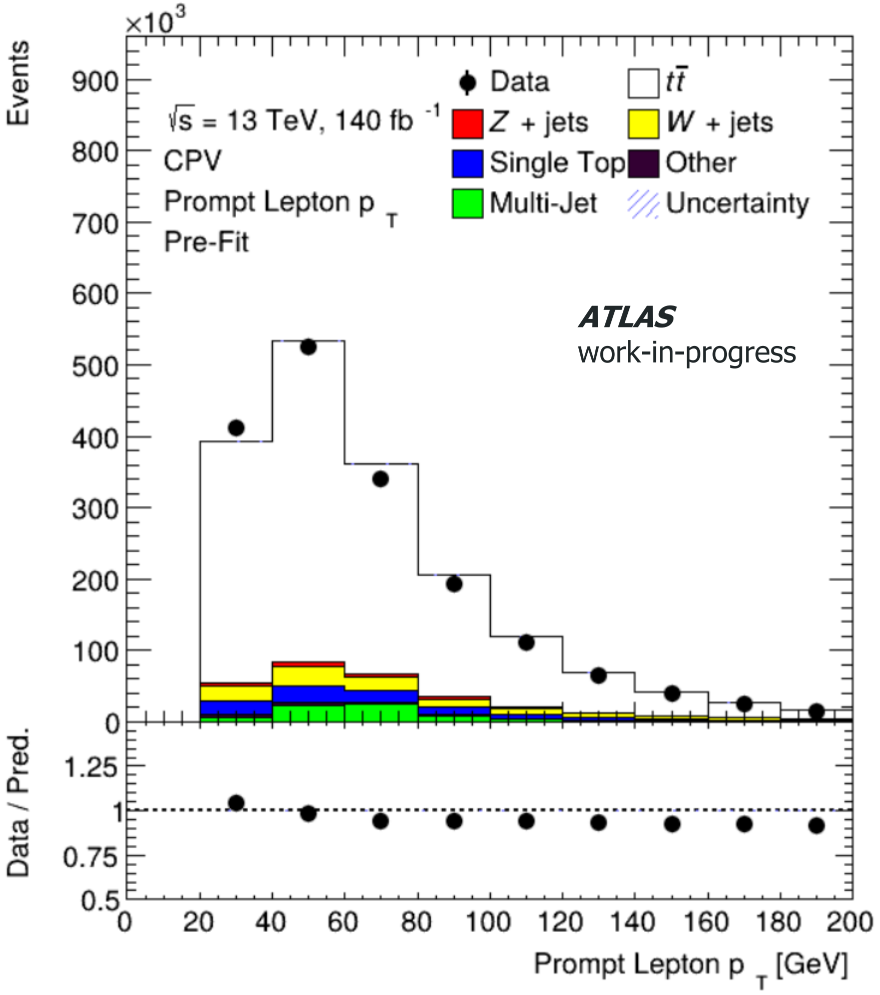


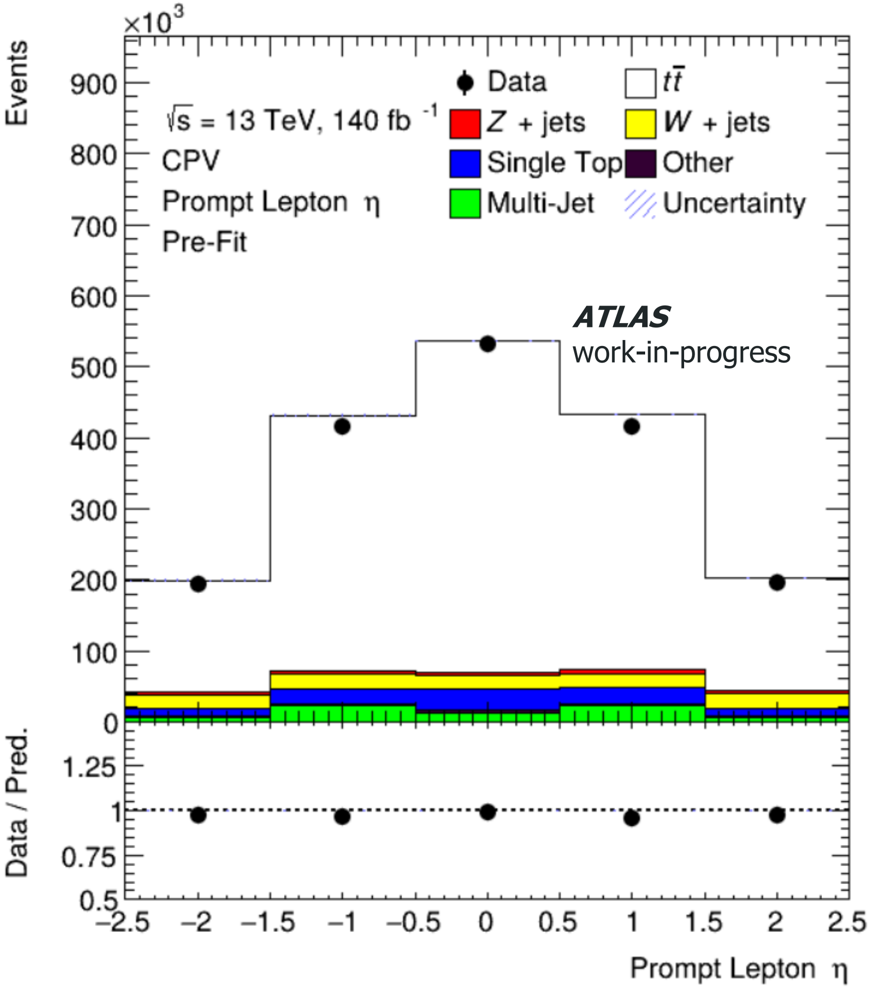
Control Plots: Soft muons



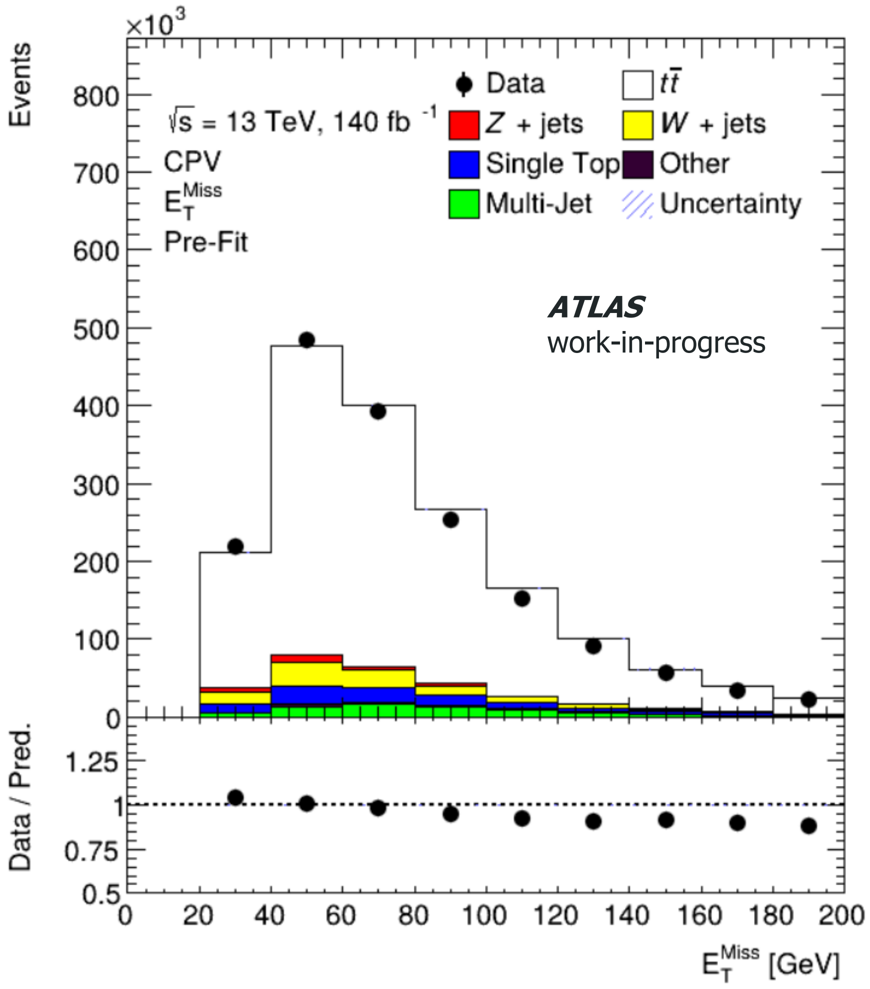
- Good Data-MC agreement
- Distributions follow expected trends

Control Plots: Prompt Leptons





Control Plots: E_T^{Miss} and yields

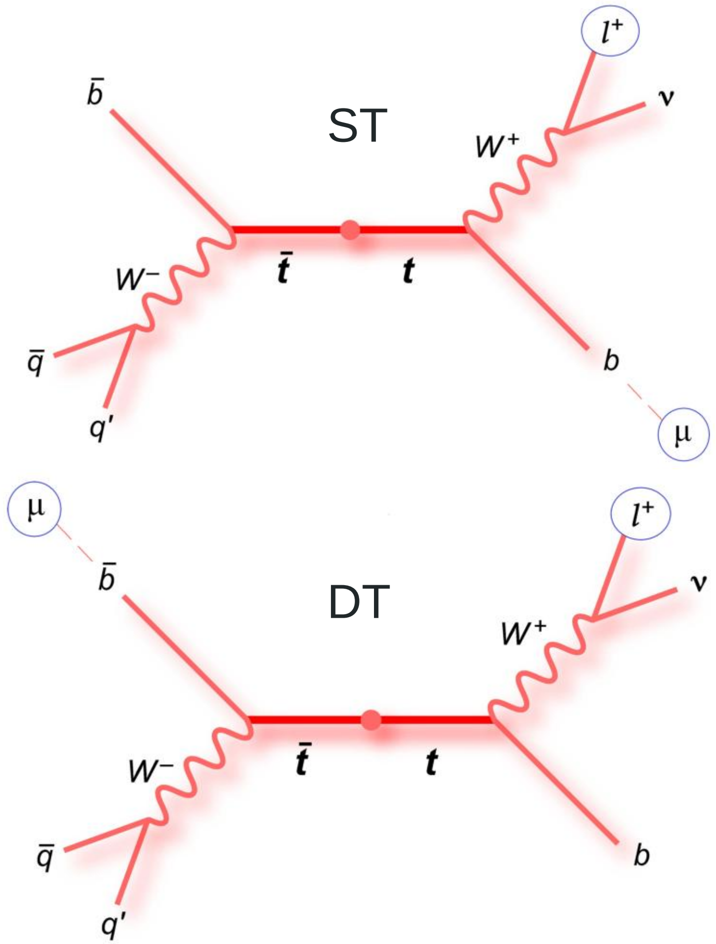


- Event selection **dominated by signal**
- W+Jets and combined single top channels are largest background contributions

Sample	Contribution	Percentage Contribution
$t\bar{t}$	$(1.6168 \pm 0.0005) \times 10^6$	83.7%
W+jets	$(1.0581 \pm 0.0003) \times 10^5$	5.5%
Multijet	$(7.0584 \pm 0.0023) \times 10^4$	3.7%
Single Top (tW-channel)	$(6.6541 \pm 0.0021) \times 10^4$	3.4%
Single Top (t-channel)	$(2.7150 \pm 0.0008) \times 10^4$	1.4%
Z+jets	$(2.6143 \pm 0.0008) \times 10^4$	1.4%
ttV	$(7.4444 \pm 0.0024) \times 10^3$	0.4%
Diboson	$(5.0524 \pm 0.0016) \times 10^3$	0.3%
ttH	$(3.8227 \pm 0.0012) \times 10^3$	0.2%
Single Top (s-channel)	$(1.9449 \pm 0.0006) \times 10^3$	0.1%
Total MC	$(1.9313 \pm 0.0006) \times 10^6$	100%
Experimental Data	$(1.8846 \pm 0.0013) \times 10^6$	–

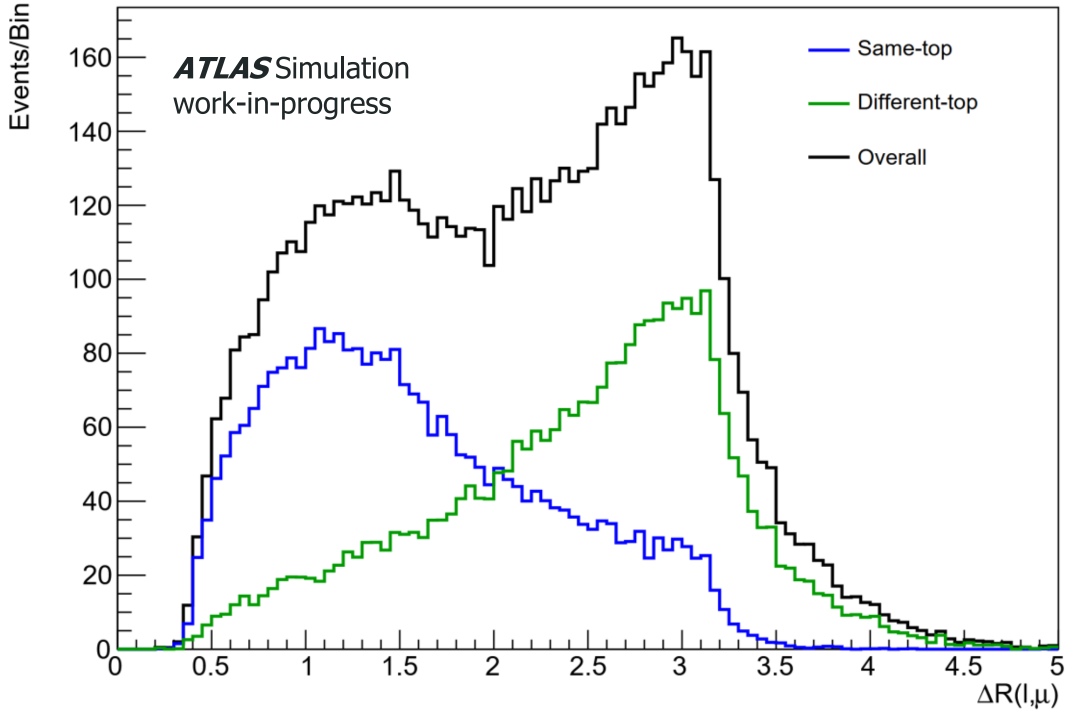
Same Top/Different Top (ST/DT) assignment

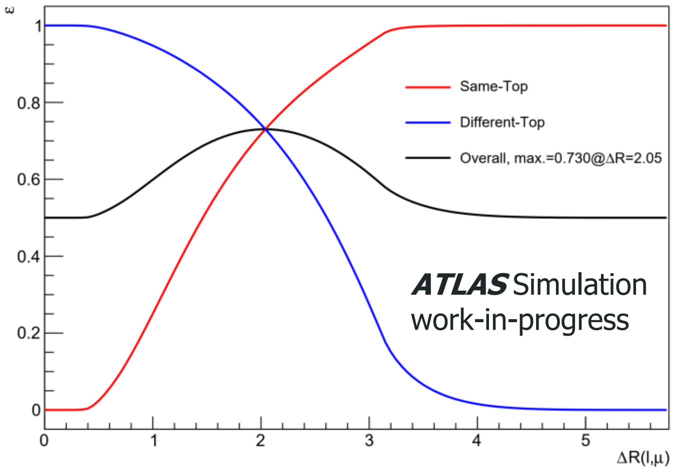
- Essential to determine if prompt lepton and soft muon come from the **same-top (ST)** or **different-top (DT)**
- At 8 TeV, assignment was **sensitive to changes in initial and final state radiation** resulting in **large systematic uncertainty** so **3 new methods are being tested**:
  - **Cut on ΔR** between the prompt lepton and soft muon
  - **SKM (Simple Kinematic Method)**, a simple “top mass” reconstruction
  - **BDT (Boosted Decision Tree)** trained on 4 different feature sets
- Performance evaluated considering efficiency, ε, and purity, ρ. Ultimately, **how systematics are affected will be the most important**

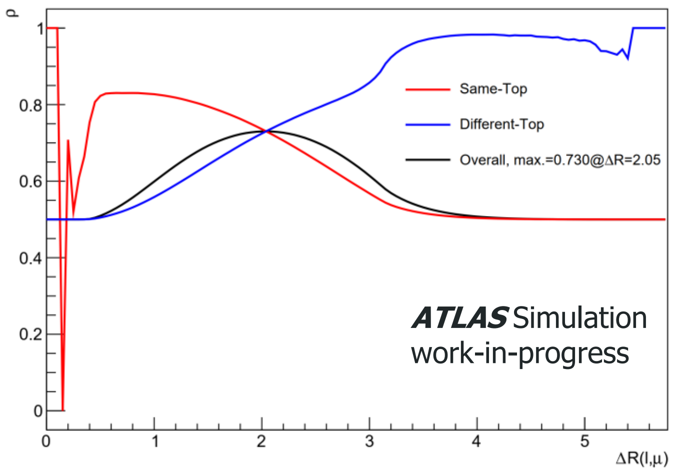


ST/DT: Angular separation (ΔR)

- Place a cut on the **ΔR between the prompt lepton and soft muon**
- $\Delta R(l,\mu) = \sqrt{\Delta\phi(l,\mu)^2 + \Delta\eta(l,\mu)^2}$
- Optimised cut at **ΔR = 2.05**
- Yields: ε = **ρ = 0.730**

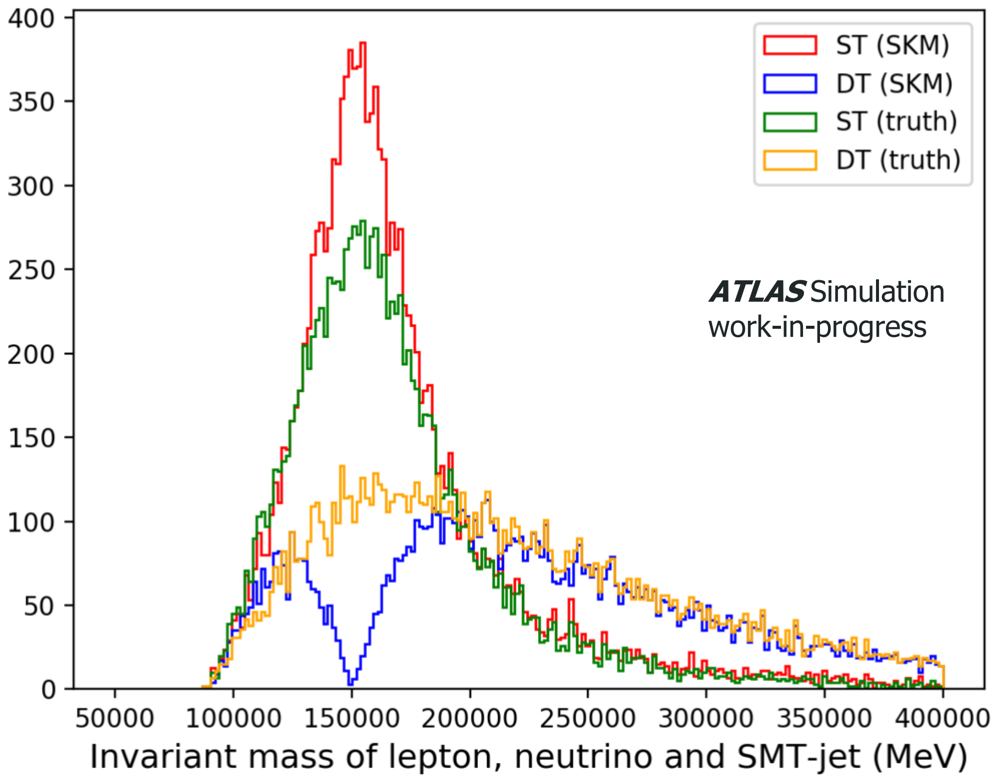






ST/DT: Simple Kinematic Method (SKM)

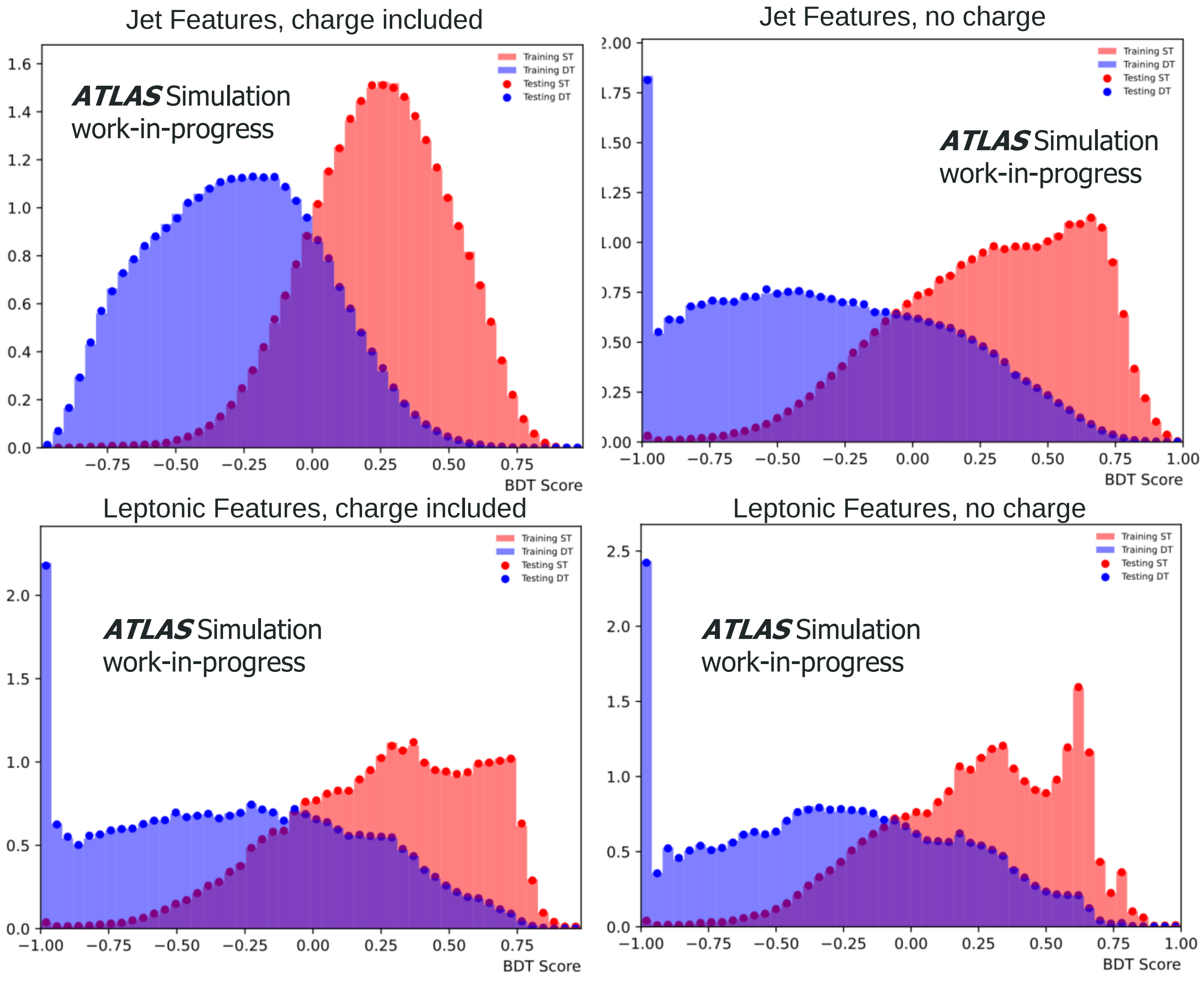
- Method:
    1. Take **SMT jet** and **jet with the highest *b*-tagging score** as the b-jets
    2. Using the constraint $m_W = m_{l\nu}$, the **z-component** of the **neutrino's four momentum is calculated**
    3. Use the *b*-jets to **reconstruct the leptonic top**
    4. Choose *b*-jet that more closely constructs the "top mass". **If the chosen b-jet is an SMT-jet, then this event is assigned ST (if not, then DT).**
- Top mass used is **150 GeV** due to m_W constraint. Tests show **improved efficiency and purity** if this value is used
- Yields: **ρ = 0.678**



ST/DT assignment: BDT

- BDT is trained on **4 feature sets**: **With/without jet variables** and **with/without prompt lepton and soft muon charges**
- Aim is to **reduce initial and final state radiation systematic** and **investigate off diagonal elements in migration matrix**

STDT method	Overall purity
BDT (Leptonic Features, charge included)	0.764
BDT (Leptonic Features, no charge)	0.741
BDT (Jet Features, charge included)	0.823
BDT (Jet Features, no charge)	0.767



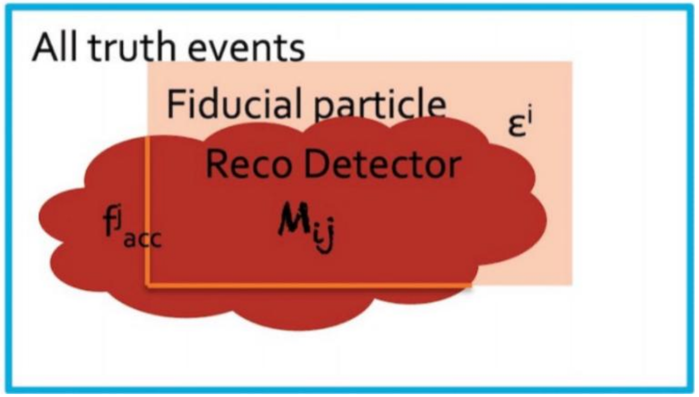
Unfolding

- We **measure the prompt lepton and soft muon charge combination**, and count $N^{l\mu}$ **for** $l\mu \in \{++,--,+-,-+\}$ to build charge and CP asymmetries

- $A^{SS} \equiv \frac{P(b\to l^+)-P(\bar{b}\to l^-)}{P(b\to l^+)+P(\bar{b}\to l^-)} = \frac{\frac{N^{++}}{N^+}-\frac{N^{--}}{N^-}}{\frac{N^{++}}{N^+}+\frac{N^{--}}{N^-}},$

- $A^{OS} \equiv \frac{P(b\to l^-)-P(\bar{b}\to l^+)}{P(b\to l^-)+P(\bar{b}\to l^+)} = \frac{\frac{N^{+-}}{N^+}-\frac{N^{-+}}{N^-}}{\frac{N^{+-}}{N^+}+\frac{N^{-+}}{N^-}}$

- Use unfolding technique to **recover the true distribution** from a reconstructed one



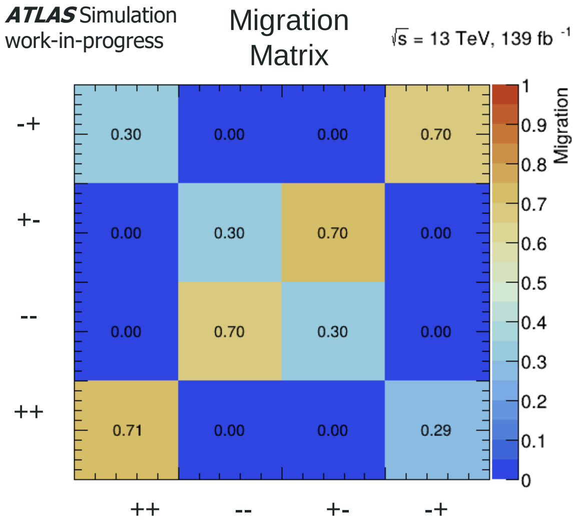
$$N^j_{\text{unfolded}} = \frac{1}{\varepsilon^j} \cdot \sum_i \mathcal{M}^{-1}_{ij} \cdot f^i_{\text{acc}} \cdot (N^i_{\text{data}} - N^i_{\text{bkg}});$$

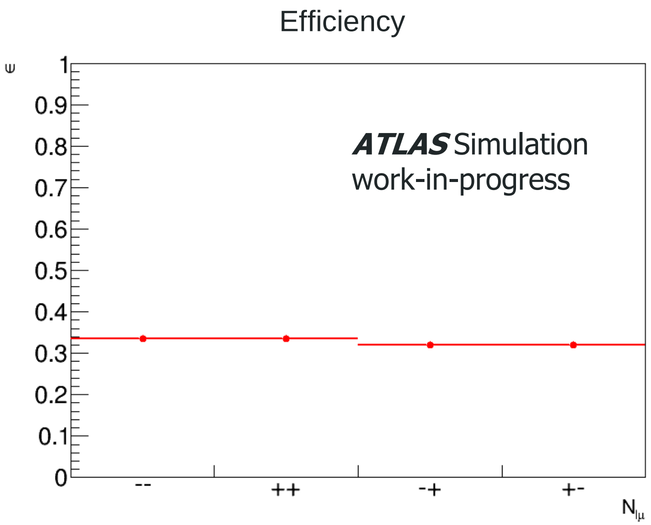
$$\varepsilon^j = \left(\frac{n(\text{reco-level} \cap \text{particle-level})}{n(\text{particle-level})}\right)^j,$$

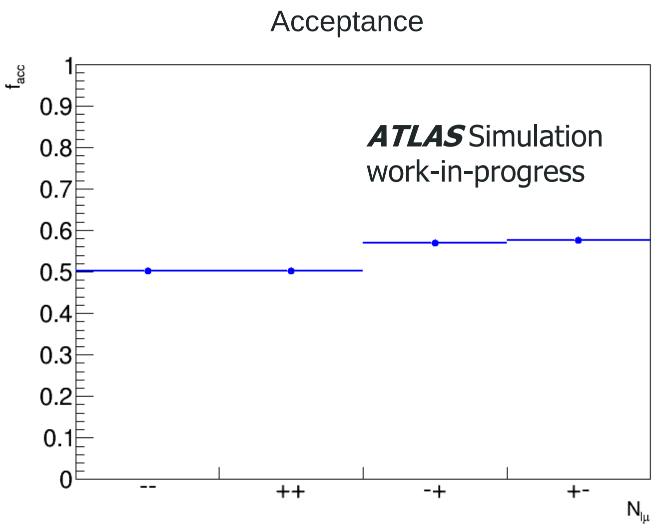
$$f^i_{\text{acc}} = \left(\frac{n(\text{reco-level} \cap \text{particle-level})}{n(\text{reco-level})}\right)^i.$$

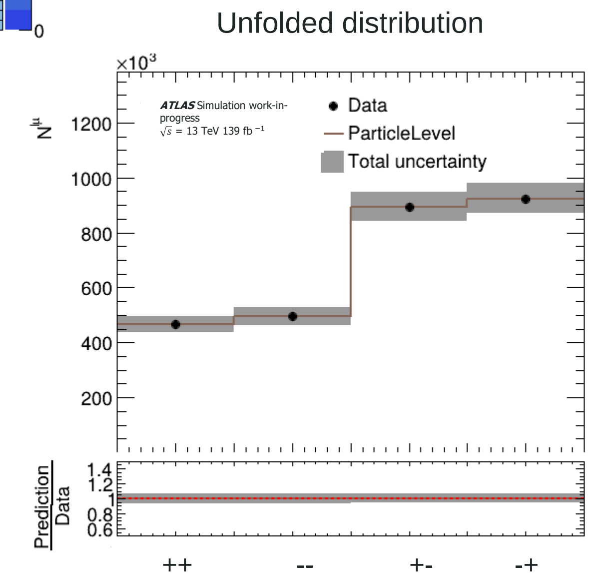
Unfolding (2)

- Previously used **unregularized matrix inversion** [4]
- Testing **Profile Likelihood** method to better handle systematics [5]









[4] https://gitlab.cern.ch/RooUnfold/RooUnfold [5] https://gitlab.cern.ch/TRExStats/TRExFitter

Unfolding: Unregularized matrix inversion

- Comparison between all ST/DT methods. Despite **large performance differences**, **uncertainties are within a few percent**
- Still **missing largest systematics (signal modelling and extra radiation)**

A^{SS}	ΔR	SKM	BDT (jet)	BDT (jet, no charge)	BDT (lep)	BDT (lep, no charge)
Purity	73.0%	67.8%	82.3%	76.7%	76.4%	74.1%
Stat. Uncertainty	16%	17%	14%	15%	15%	15%
Syst. Uncertainty	7.4%	7.8%	5.6%	6.2%	6.7%	7.2%
Total Uncertainty	18%	19%	15%	16%	17%	17%

A^{OS}	ΔR	SKM	BDT (jet)	BDT (jet, no charge)	BDT (lep)	BDT (lep, no charge)
Purity	73.0%	67.8%	82.3%	76.7%	76.4%	74.1%
Stat. Uncertainty	16%	17%	14%	15%	15%	15%
Syst. Uncertainty	6.8%	7.5%	5.1%	5.8%	6.3%	6.8%
Total Uncertainty	17%	18%	15%	16%	16%	17%

Unfolding: Profile Likelihood

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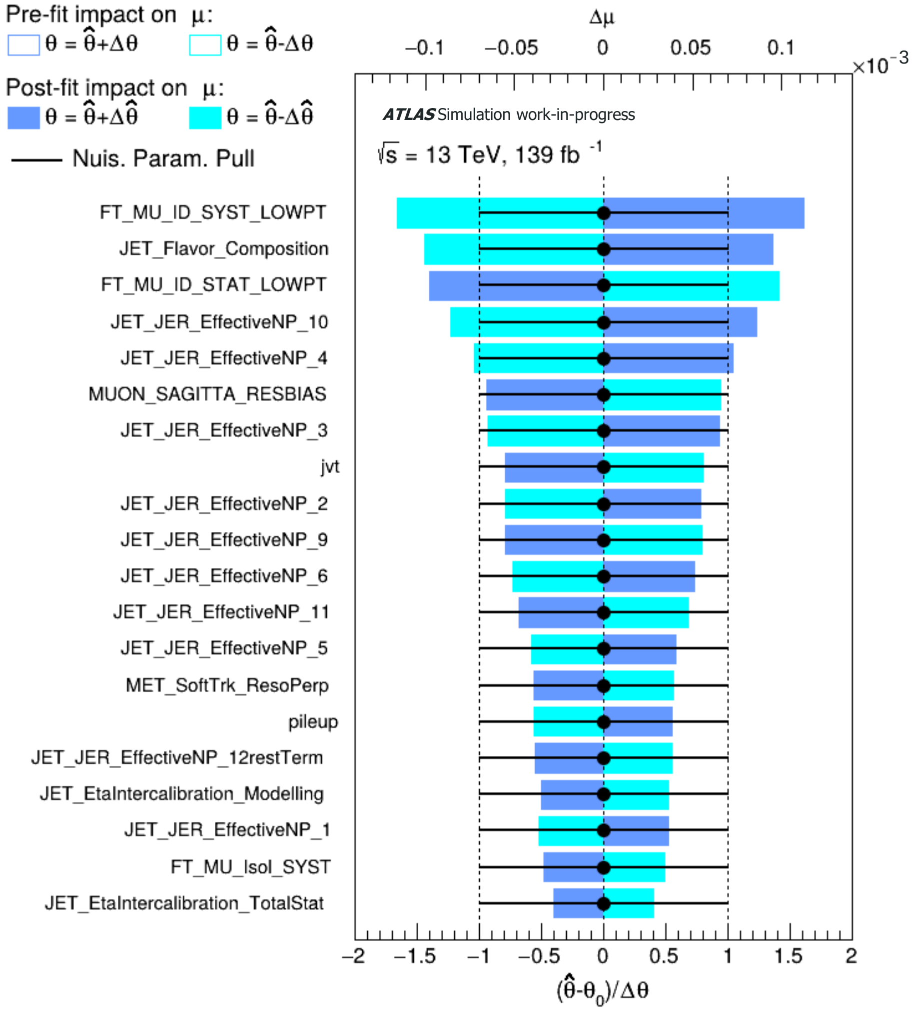
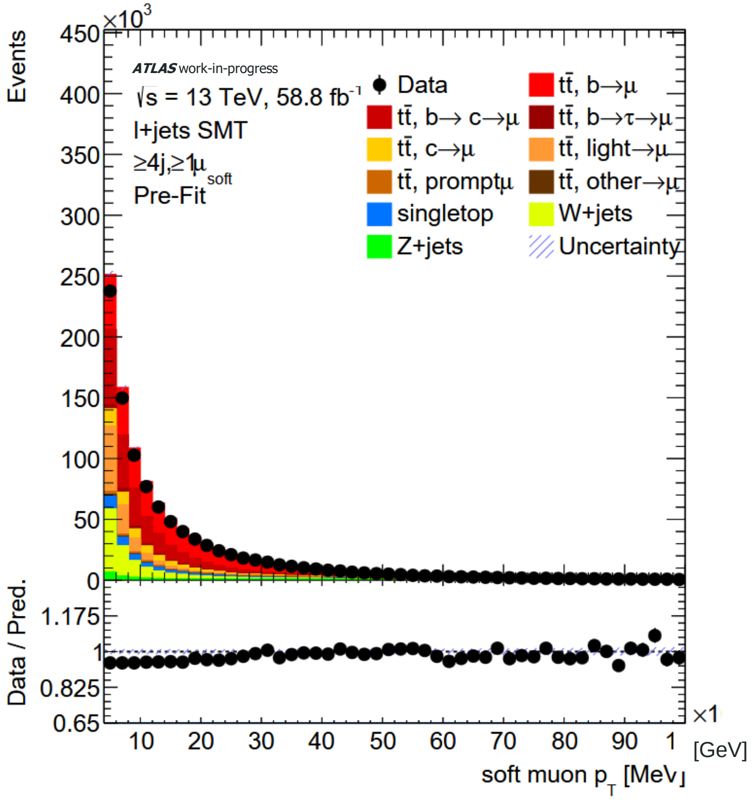
- Mostly **compatible with unregularized matrix inversion**

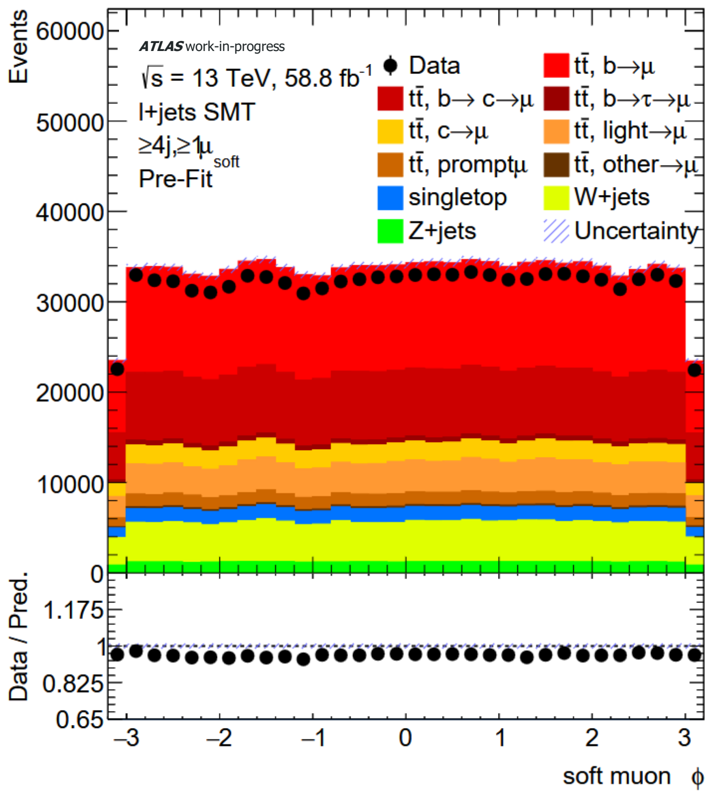
A^{SS}	ΔR	SKM	BDT (jet)	BDT (jet, no charge)	BDT (lep)	BDT (lep, no charge)
Purity	73.0%	67.8%	82.3%	76.7%	76.4%	74.1%
Total Uncertainty (Unregularized matrix inversion)	18%	19%	15%	16%	17%	17%
Total Uncertainty (Profile Likelihood)	18%	22%	15%	16%	17%	17%



Current work and future

- Working on **adding remaining systematics**
- Working on **migration to new software release**
  - Optimising event selection
  - Improved soft muon selections





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Thank you for listening

Backup

Full Event selection

Prompt electron:
- Tight likelihood
- Gradient isolation
- pT > 15 GeV
- d0sig < 5
- |z0sin θ | < 0.5mm
- $|\eta|$ < 2.47
- 1.37 < $|\eta|$ < 1.52 excluded

Prompt muon:
- pT > 25 GeV
- $|\eta|$ < 2.5
- |d0sig| < 3
- |z0sin θ | < 0.5mm
- ΔR > 0.4 from nearest jet
- Gradient isolation
- Medium quality

Soft muon:
- pT > 4 GeV
- $|\eta|$ < 2.5
- |d0| < 3mm
- |z0sin θ | < 3mm
- ΔR < 0.4 from nearest jet
- Only keep highest pT muon for each jet
- Not prompt
- Tight quality

Jets:
- Particle flow algorithm
- pT > 25 GeV
- $|\eta|$ < 2.5
- JVT > 0.59 if pT < 60 GeV, $|\eta|$ < 2.4
- ≥ 4 jets with pT > 25 GeV (excl.SMT-tagged jet)
- ≥1 b-jet (DL1r at 77% efficiency working point)

MET:
- MET > 30 GeV
- MET + MT(W) > 60 GeV

Multijet background estimation

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- Hard to model in MC so a **data-driven technique** is used: The **asymptotic matrix method**

$$\begin{pmatrix} N^t \\ N^l \end{pmatrix} = \begin{pmatrix} \varepsilon_r & \varepsilon_f \\ 1-\varepsilon_r & 1-\varepsilon_f \end{pmatrix} \begin{pmatrix} N_r^l \\ N_f^l \end{pmatrix}$$

$t = tight\ lepton\ selection, \quad l = loose\ lepton\ selection$

- Real efficiency, ε_r, calculated from $Z \rightarrow ee$ **tag and probe** (centrally provided). Fake efficiency, ε_f, **depends on event selection**
- Invert to get the fake background:

$$N_f^t = \varepsilon_f N_f^l = \frac{\varepsilon_f}{\varepsilon_r - \varepsilon_f}\left[(\varepsilon_r - 1)N^t + \varepsilon_r N^l\right]$$

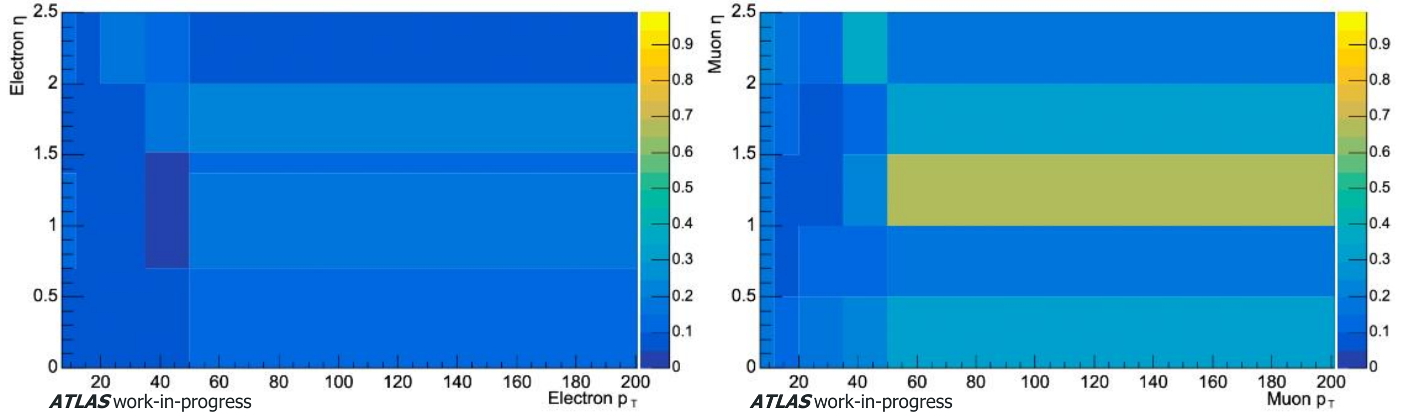
- Apply 'fake' weight to each event:

$$w_i = \begin{cases} \frac{\varepsilon_{f,i}}{\varepsilon_{r,i}-\varepsilon_{f,i}}(\varepsilon_{r,i}-1)\ if\ N^t = 1, N^l = 0 \\ \frac{\varepsilon_{f,i}}{\varepsilon_{r,i}-\varepsilon_{f,i}}\varepsilon_{r,i} \qquad\quad if\ N^t = 0, N^l = 1 \end{cases}, \qquad N_f^t = \sum_i w_i$$

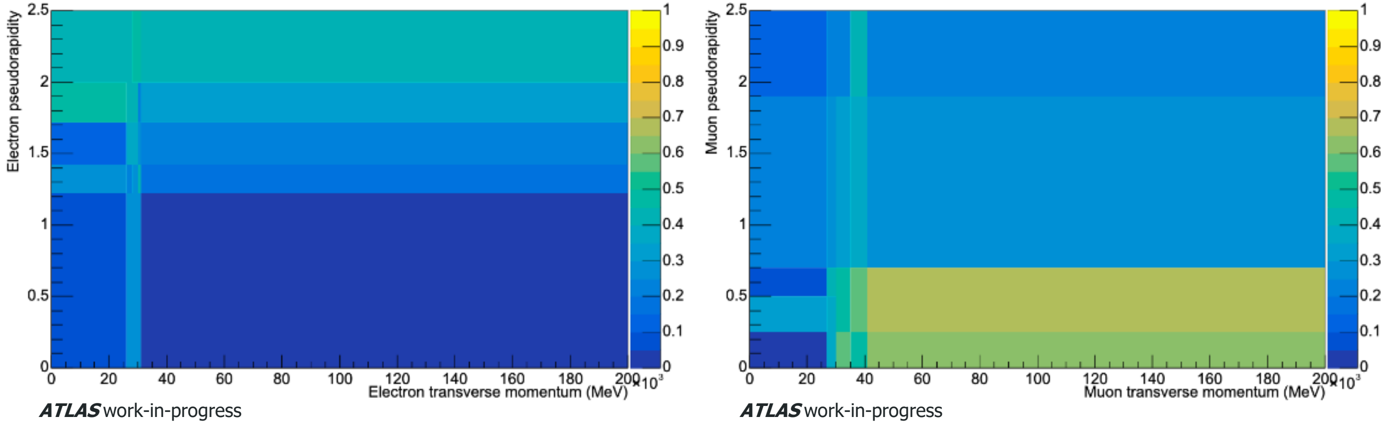
Multijet background estimation (cont.)

- Asymptotic since statistical uncertainty of N_f^t is **only valid for a large number of events**
- To obtain Fake efficiency:
  1. **Apply the event selection to data** but with an **inverted E_t^{miss} cut** and the **$\left(E_t^{miss} + m_T(W)\right) > 60\ GeV$ cut removed**
  2. Take the **ratio of events passing the tight selection vs loose selection** after subtracting the MC signal and other backgrounds
- Minimal difference, **will use central values for R25**

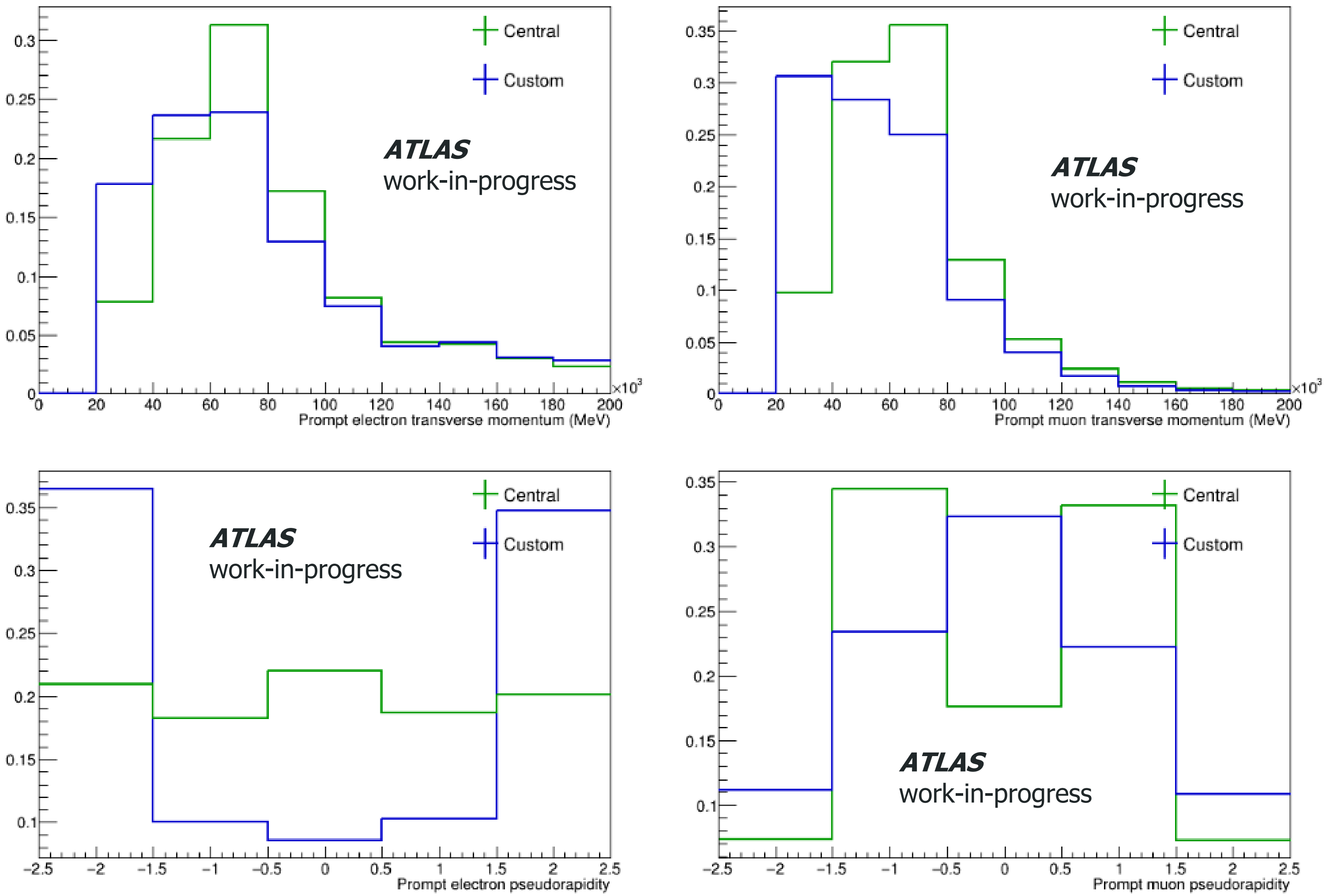
Obtained from central efficiencies



Obtained from custom efficiencies



Multijet background: Central vs Custom



SKM Parameterisation

- Neutrino P_z^{ν} component is calculated as follows:

$$P_z^{\nu} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$where\ a = E_l^2 - \left(P_z^l\right)^2, b = -2P_z^l\left(m_{diff} + P_T^{\nu l}\right), c = \left(E_T^{miss}\right)^2 E_l - m_{diff}^2 - \left(P_T^{\nu l}\right)^2 - 2m_{diff}P_T^{\nu l}$$

$$and\ m_{diff} = \frac{1}{2}\left(\left(m_W^{PDG}\right)^2 - \left(m_l^{PDG}\right)^2\right), P_T^{\nu l} = P_x^{\nu}P_x^l + P_y^{\nu}P_y^l$$

- Top quark mass is reconstructed by:

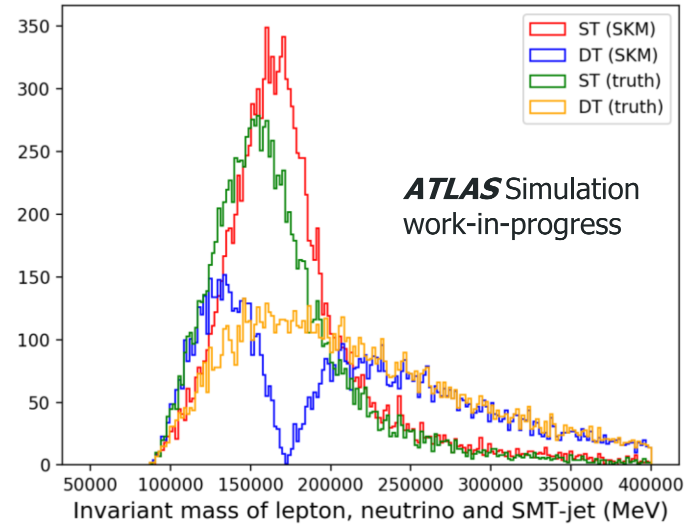
$$M_t^2 = E_t^2 - P_t^2 = \left(E_l + E_\nu + E_{jet}\right)^2 - \left(P_l + P_\nu + P_{jet}\right)^2$$

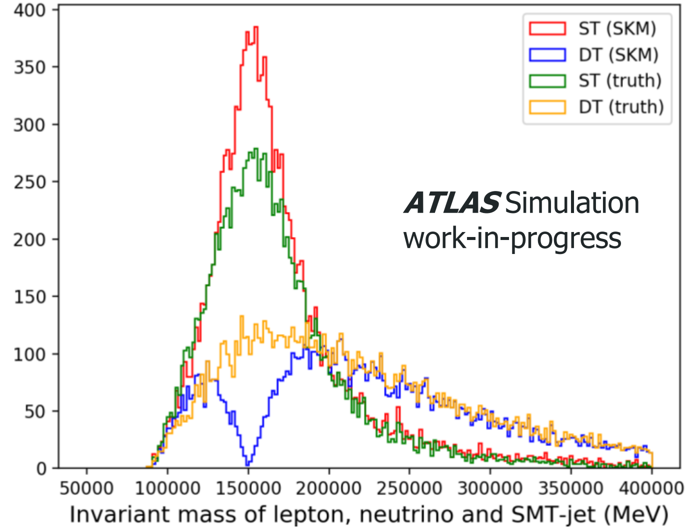
SKM tests

- Compared purity with 150 GeV and 172.57 GeV top masses with 4 methods of choosing additional jets
- Plots show 172.57 GeV (top) and 150 GeV (bottom) comparison

SKM method (m_t =172.57 GeV)	ST purity	DT purity	Overall purity (accuracy)	ST accuracy	DT accuracy
SMT & highest-pt b-jet	0.631 ± 0.004	0.694 ± 0.005	0.657 ± 0.005	0.755 ± 0.004	0.558 ± 0.004
SMT & 1 DL1r jet	0.652 ± 0.004	0.684 ± 0.004	0.666 ± 0.005	0.716 ± 0.004	0.616 ± 0.004
SMT & 2 DL1r jets	0.673 ± 0.005	0.616 ± 0.004	0.639 ± 0.005	0.544 ± 0.004	0.735 ± 0.004
SMT & 3 DL1r jets	0.683 ± 0.005	0.587 ± 0.004	0.618 ± 0.005	0.445 ± 0.004	0.792 ± 0.004

SKM method (m_t =150 GeV)	ST purity	DT purity	Overall purity (accuracy)	ST accuracy	DT accuracy
SMT & highest-pt b-jet	0.630 ± 0.004	0.729 ± 0.005	0.666 ± 0.005	0.805 ± 0.004	0.526 ± 0.004
SMT & 1 DL1r jet	0.653 ± 0.004	0.713 ± 0.004	0.678 ± 0.005	0.762 ± 0.004	0.594 ± 0.004
SMT & 2 DL1r jets	0.688 ± 0.004	0.652 ± 0.004	0.668 ± 0.005	0.617 ± 0.004	0.719 ± 0.004
SMT & 3 DL1r jets	0.712 ± 0.005	0.624 ± 0.004	0.656 ± 0.005	0.527 ± 0.005	0.786 ± 0.004

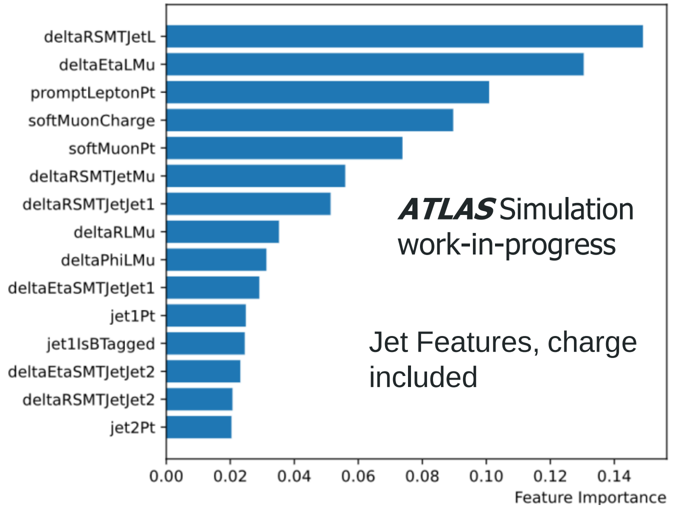


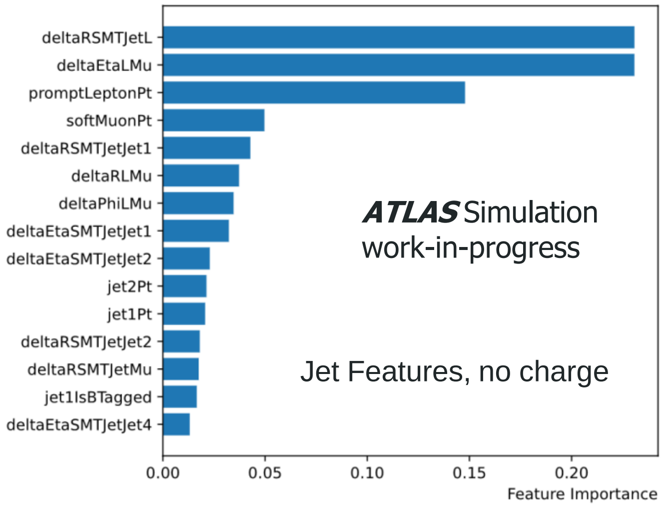


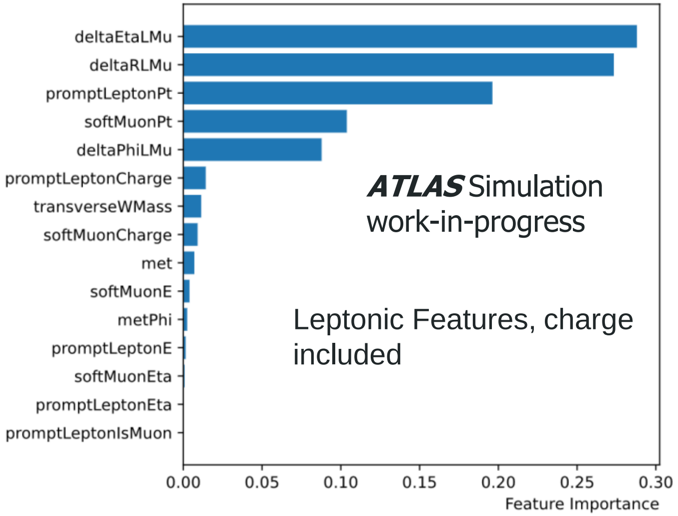
BDT hyperparameter optimisation

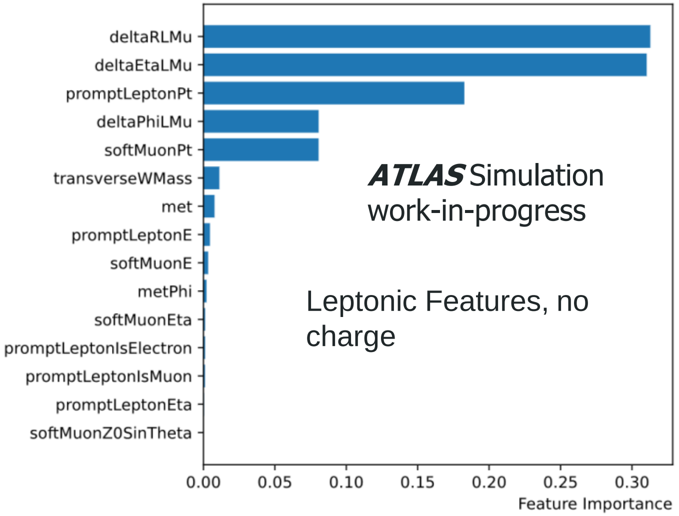
BDT type	Number of estimators	criterion	Maximum depth	Learning rate
Leptonic features, charge included	50	entropy	5	0.3
Leptonic features, no charge	100	gini	5	0.2
Jet features, charge included	100	gini	5	0.3
Jet features, no charge included	50	entropy	5	0.2

BDT feature importance









ST/DT: comparing purities

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ST/DT method	Overall purity (± MC stat)
ΔR Cut	0.730 ± 0.005
SKM	0.678 ± 0.005
BDT (Leptonic Features, charge included)	0.764 ± 0.001
BDT (Leptonic Features, no charge)	0.741 ± 0.001
BDT (Jet Features, charge included)	0.823 ± 0.001
BDT (Jet Features, no charge)	0.767 ± 0.001

Unfolding: Migration matrices

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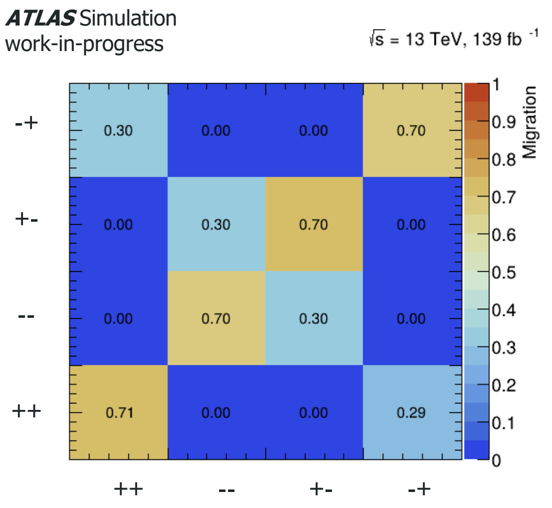
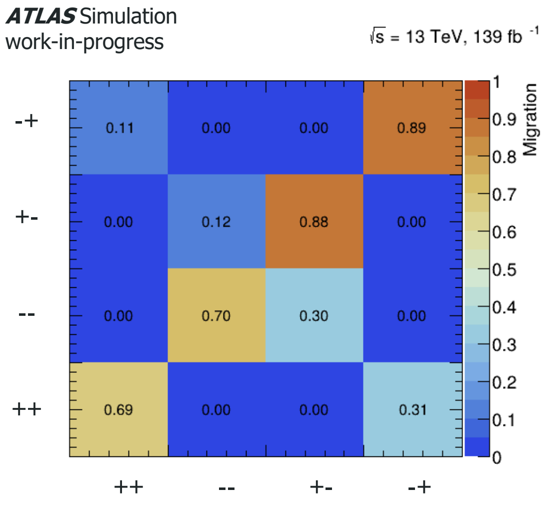
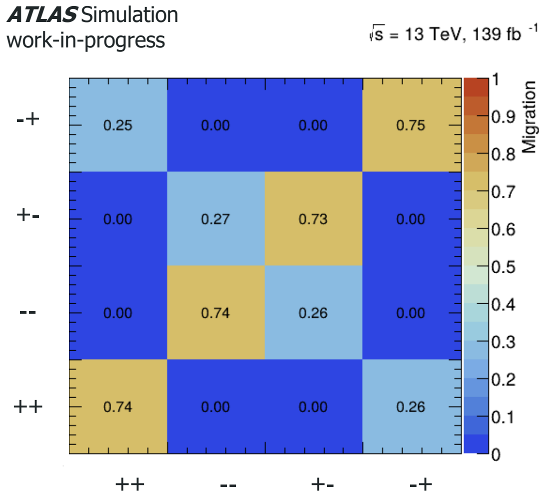
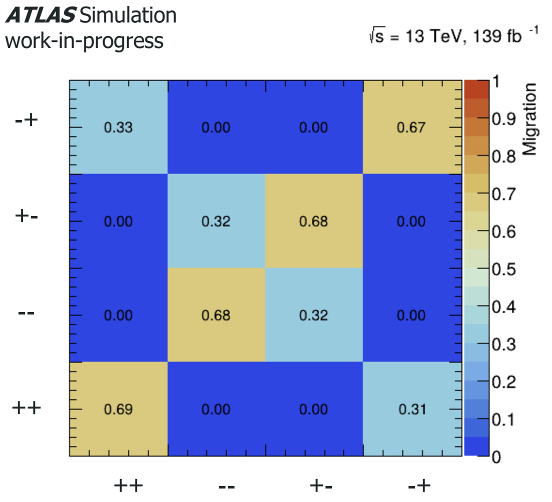
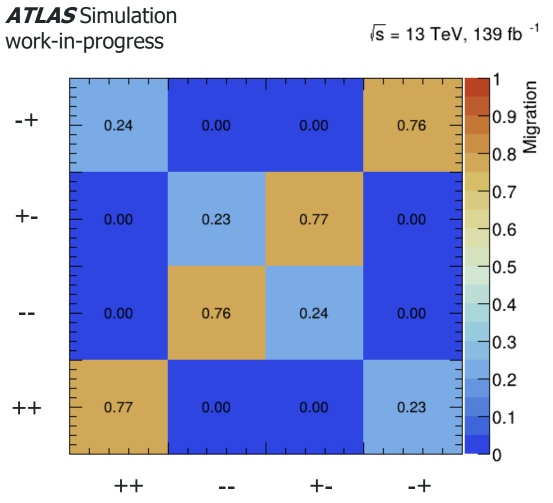
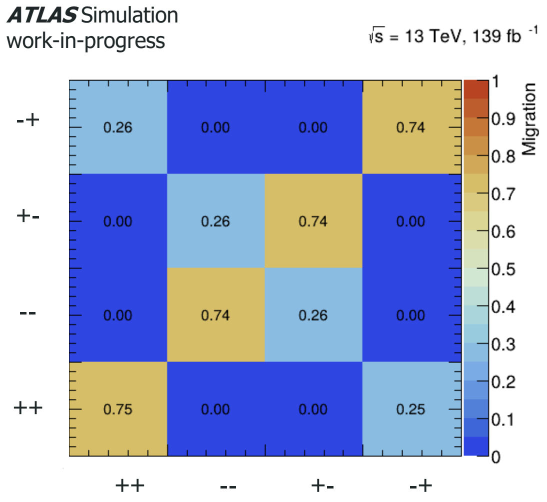




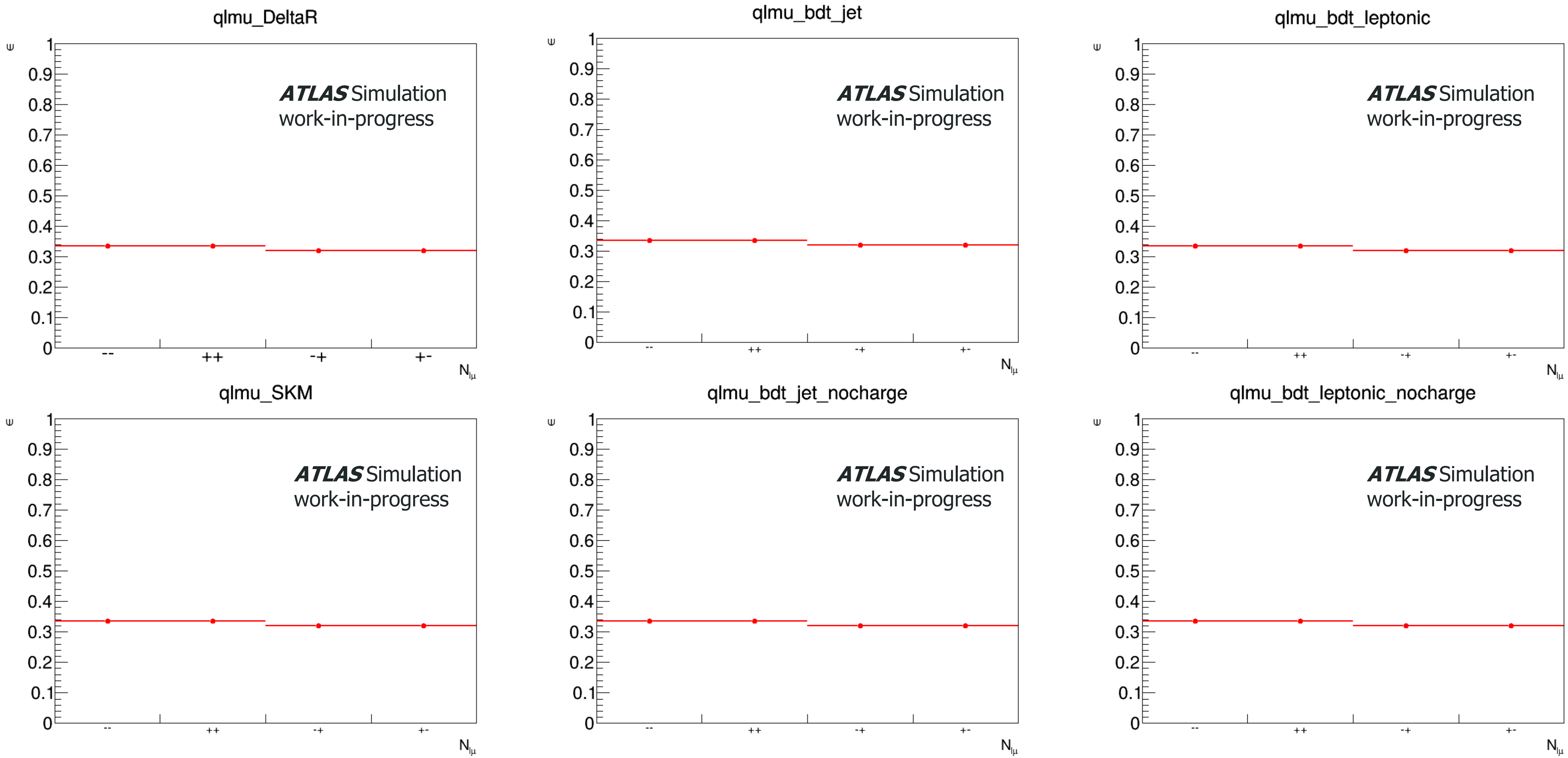




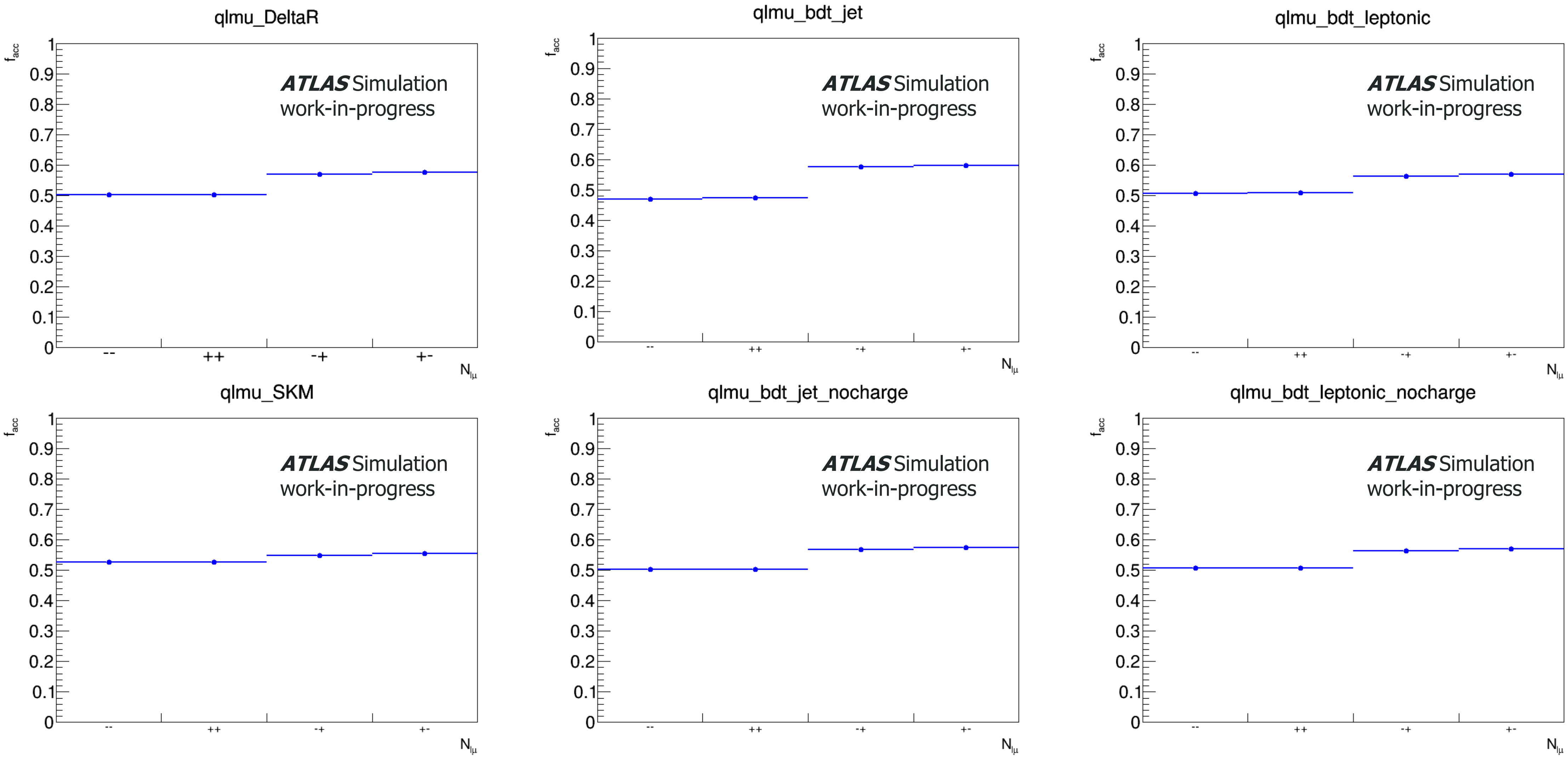




Unfolding: Efficiencies



Unfolding: Acceptances



Charge and CP asymmetries

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- The number of events in each of the decay chains are N_{r_b} , N_{r_c} , $N_{r_{c\bar{c}}}$, $N_{\tilde{r}_b}$, $N_{\tilde{r}_c}$, $N_{\tilde{r}_{c\bar{c}}}$ respectively, which are measured in MC simulations.
- These are used to derive the decay chain fractions:

$$r_b = \frac{N_{r_b}}{N_{r_b}+N_{r_c}+N_{r_{c\bar{c}}}}, \ldots$$

- From a small MC sample (dependent on the fiducial particle level volume):

	r_b	r_c	$r_{c\bar{c}}$	$\tilde{r}_b$	$\tilde{r}_c$	$\tilde{r}_{c\bar{c}}$
Results	0.230	0.743	0.026	0.830	0.071	0.099

- These values are similar to r values obtained in 8 TeV analysis. They will eventually have full systematics applied.

Decay chains contributing to A^{SS}:

N_{r_b}: $t \to \ell^+\nu(b \to \bar{b}) \to \ell^+\mu^+X,$

N_{r_c}: $t \to \ell^+\nu(b \to c) \to \ell^+\mu^+X,$

$N_{r_{c\bar{c}}}$: $t \to \ell^+\nu(b \to \bar{b} \to c\bar{c}) \to \ell^+\mu^+X,$

Decay chains contributing to A^{OS}:

$N_{\tilde{r}_b}$: $t \to \ell^+\nu b \to \ell^+\mu^-X,$

$N_{\tilde{r}_c}$: $t \to \ell^+\nu(b \to \bar{b} \to \bar{c}) \to \ell^+\mu^-X,$

$N_{\tilde{r}_{c\bar{c}}}$: $t \to \ell^+\nu(b \to c\bar{c}) \to l^+\mu^-X,$

Charge and CP asymmetries (cont)

- A relationship between observable charge asymmetries, A^{SS}, A^{OS}, and underlying CPV asymmetries is defined using the decay chain fractions, r_b, etc. :

$$A^{b\ell}_{\mathrm{mix}} = \frac{\Gamma\left(b \to \bar{b} \to \ell^+ X\right) - \Gamma\left(\bar{b} \to b \to \ell^- X\right)}{\Gamma\left(b \to \bar{b} \to \ell^+ X\right) + \Gamma\left(\bar{b} \to b \to \ell^- X\right)},$$

$$A^{bc}_{\mathrm{mix}} = \frac{\Gamma\left(b \to \bar{b} \to \bar{c} X\right) - \Gamma\left(\bar{b} \to b \to c X\right)}{\Gamma\left(b \to \bar{b} \to \bar{c} X\right) + \Gamma\left(\bar{b} \to b \to c X\right)},$$

$$A^{b\ell}_{\mathrm{dir}} = \frac{\Gamma\left(b \to \ell^- X\right) - \Gamma\left(\bar{b} \to \ell^+ X\right)}{\Gamma\left(b \to \ell^- X\right) + \Gamma\left(\bar{b} \to \ell^+ X\right)},$$

$$A^{c\ell}_{\mathrm{dir}} = \frac{\Gamma\left(\bar{c} \to \ell^- X_L\right) - \Gamma\left(c \to \ell^+ X_L\right)}{\Gamma\left(\bar{c} \to \ell^- X_L\right) + \Gamma\left(c \to \ell^+ X_L\right)},$$

$$A^{bc}_{\mathrm{dir}} = \frac{\Gamma\left(b \to c X_L\right) - \Gamma\left(\bar{b} \to \bar{c} X_L\right)}{\Gamma\left(b \to c X_L\right) + \Gamma\left(\bar{b} \to \bar{c} X_L\right)},$$

$$A^{SS} = r_b A^{b\ell}_{mix} + r_c (A^{bc}_{dir} - A^{c\ell}_{dir}) + r_{c\bar{c}} (A^{bc}_{mix} - A^{c\ell}_{dir})$$

$$A^{OS} = \tilde{r}_b A^{b\ell}_{dir} + \tilde{r}_c (A^{bc}_{mix} + A^{c\ell}_{dir}) + \tilde{r}_{c\bar{c}} (A^{c\ell}_{dir})$$