ATLAS low pile-up data taking and future prospects

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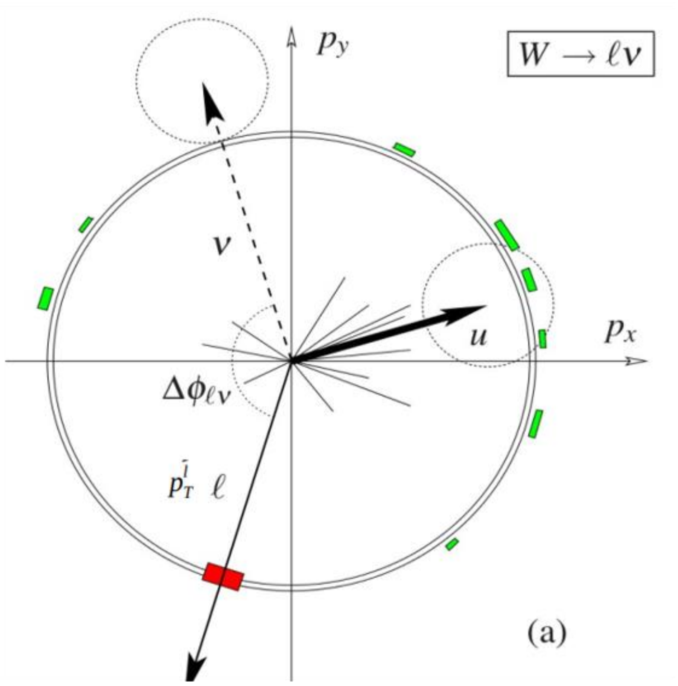
$\mathrm{m_W}$ measurement strategy in ATLAS

$$\mathrm{m_T} = \sqrt{2\mathrm{p_T^l}\mathrm{E_T^{miss}}\left(1 - \cos\left(\phi_\mathrm{l} - \phi_{\mathrm{E_T^{miss}}}\right)\right)}$$

$\vec{\mathrm{p}}_\mathrm{T}^\mathrm{miss} = -(\vec{\mathrm{p}}_\mathrm{T}^\mathrm{l} + \vec{\mathrm{u}}_\mathrm{T})$ for the neutrino

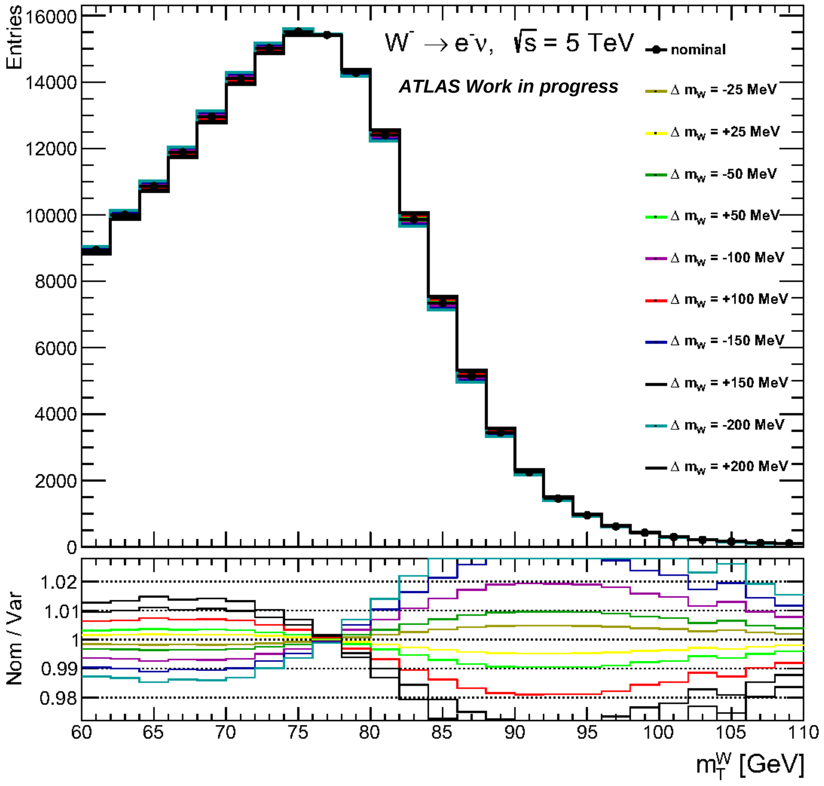


- $\mathrm{m_T}$ is less affected by $\mathrm{p_T^W}$ variations but suffers from pile-up.
- $\mathrm{p_T^l}$ is less sensitive to pile-up but more sensitive to $\mathrm{p_T^W}$ modelling

The leptonic decay of W boson is associated with the hadronic recoil:

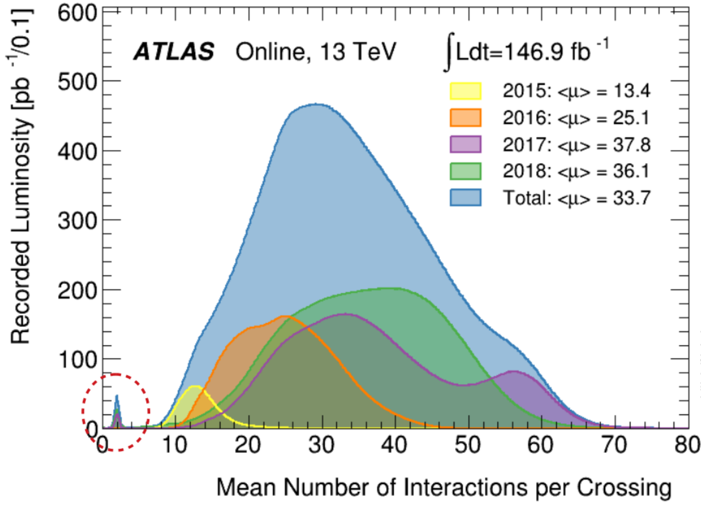
$$\vec{\mathrm{p}}_\mathrm{T}^\mathrm{V} = -\Sigma\vec{\mathrm{p}}_\mathrm{T}^{\mathrm{ISR}\,q,g} = -\vec{\mathrm{u}}_\mathrm{T}$$

$\mathrm{u_T}$ and lepton pseudo-rapidity η_l can be used for categorization to constrain theoretic systematics.

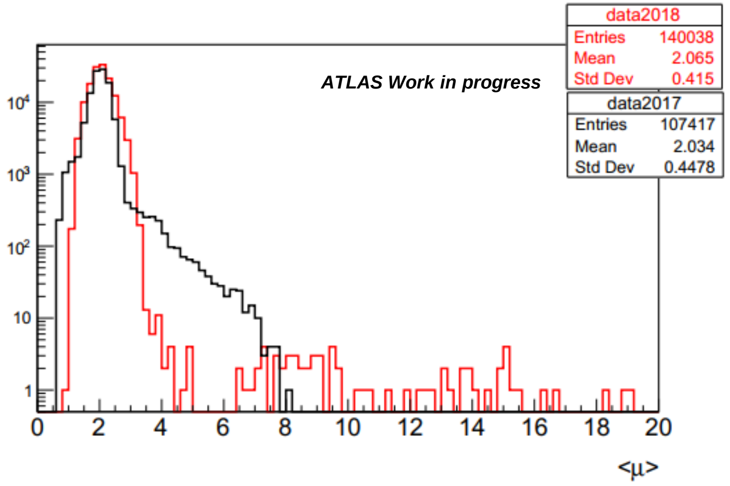


Kinematic distributions with different $\mathrm{m_W}$ predictions are obtained from reweighting the resonance of the baseline simulation.

ATLAS Run2 low-mu data



Luminosity and <mu> of 13 TeV dataset



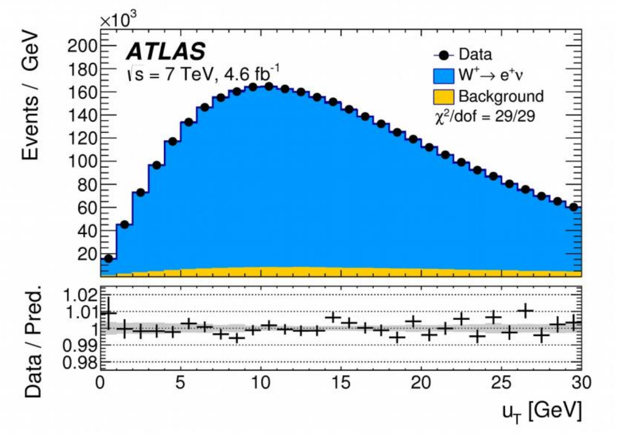
Pile-up condition of 13 TeV low-mu data

	2017, $\sqrt{s}$=5.02 TeV	2017+2018, $\sqrt{s}$=13 TeV
Luminosity (pb^{-1})	258.4	335.180
W^{+} events after selection	811K	2.06M
W^{-} events after selection	509K	1.59M
Total W events after selection	1.32M	3.64M

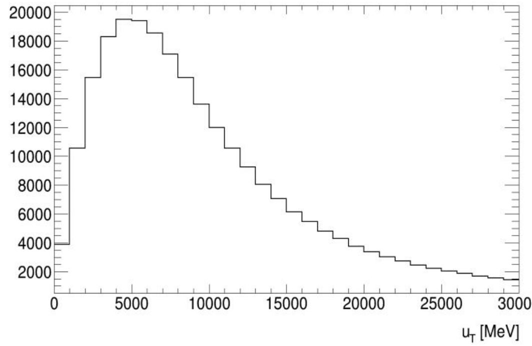
8 decay channels with Run2 low-mu datasets: 5/13 TeV, +/-, e/μ.

Low-mu data for W precision measurement

u_T spectrum

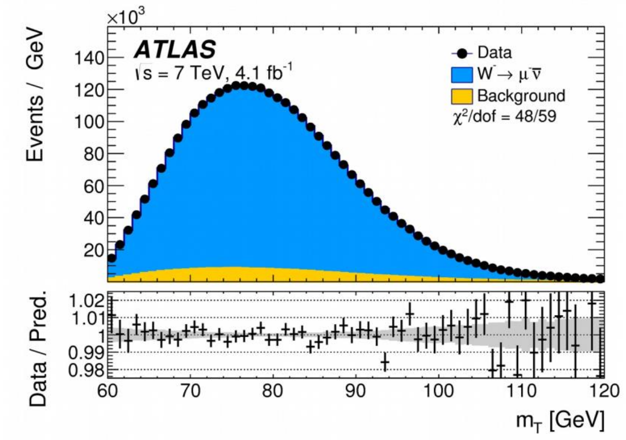


μ~9

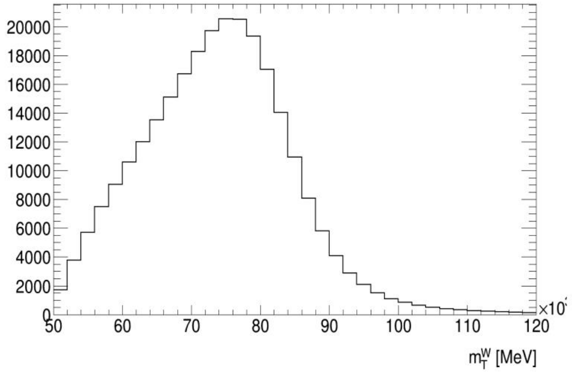


μ~2

m_T spectrum



μ~9



μ~2

- Low pile-up offers better resolution of the recoil $\mathrm{u_T}$
  => better neutrino $\mathrm{E_T^{miss}}$
  => $\mathrm{m_T}$ more sensitive to W mass.

- The direct measurement of $\mathrm{p_T^W}$ is possible thanks to the better $\mathrm{u_T}$ resolution, which constrains the uncertainty of $\mathrm{p_T^W}$ modelling.

- Suppression of multi-jet background.

Overall status of low-mu $\mathrm{m_W}$ analysis

Data and signal MC samples are ready.

Experimental & background uncertainties we work on:

- Recoil calibration, lepton SF, lepton calibration.
- Luminosity, background cross-section uncertainties.
- Data-driven soft-QCD background (a.k.a. multijet).

Theoretical uncertainties we work on:

- PDF, spin-correlation, electroweak correction.
- Propagation of $\mathrm{p_T^W}$ uncertainties from direct measurement.
- QCD scale variation and the uncertainty between PDF sets.

Current MC samples and event selection

A MC 16 campaign was produced to match the low-mu condition in data:

- W & Z production: Powheg+Pythia8 AZNLO, CT10 PDF
- Top-related background: Powheg+Pythia8
- Di-boson background: Sherpa
- Minimum-bias events: Pythia8 A3 tune with NNPDF2.3LO

Cut	Description
One charged lepton	Exactly one electron or muon
Lepton trigger matched	• 1 electron, $E_T > 15$ GeV, loose ID. • Or 1 muon, $E_T > 14$ GeV.
Isolation	Ptcone20 / Min(p_T^l, 50GeV) < 0.1
Kinematics	$p_T^l > 25$ GeV
	$E_T^{miss} > 25$ GeV
	$m_T > 50$ GeV
	$u_T < 25$ GeV

Analysis cuts for signal selection

Electron SF and calibration

- The electron reconstruction SF: extrapolation of the standard high-mu SFs to the low-mu regime applied to both the 5 and 13 TeV datasets.
- The identification SF: measured in-situ separately for the 5 and 13 TeV data.
- Isolation and trigger efficiencies SF: measured in-situ using the 5 and 13 TeV combined datasets.

- The global strategy of electron energy calibration follows the high-mu standard calibration methodology.
- Electron energy scale and resolution corrections are measured in-situ using Z->ee events from the low-mu dataset.

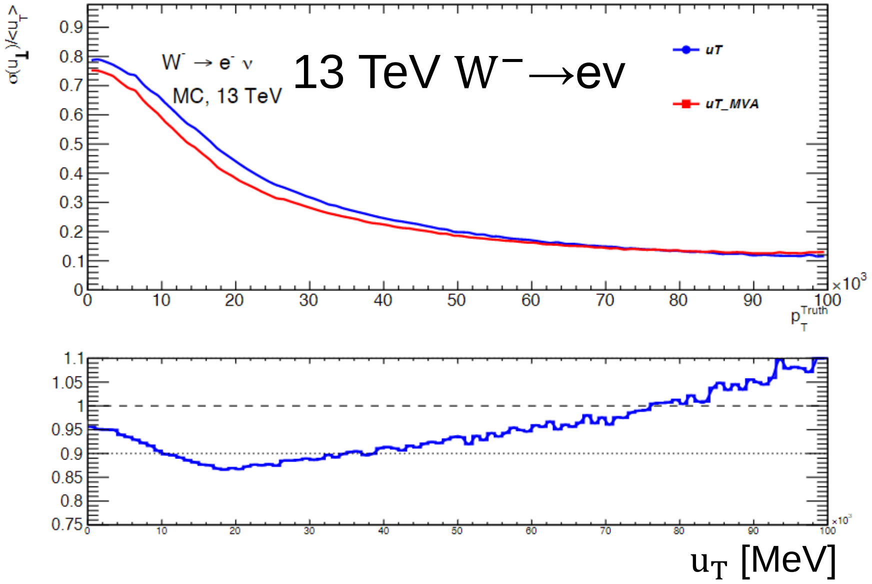
Muon SF and calibration

- Muon reconstruction and TTVA requirements efficiencies: the in-situ measurement with Z->μμ events are compatible with the high-mu measurements.
- The muon trigger and isolation efficiencies: measured in-situ separately for 5 and 13 TeV data.

- Momentum scale and resolution: derived from the high-mu data.
- Sagitta bias correction: derived from 2017 datasets.

Hadronic recoil calibration and correction

- The calibration is performed in-situ with Z events.
- Uncertainties due to Z -> W extrapolation are considered.
- 10% improvement in resolution could be achievable with [ML techniques]().

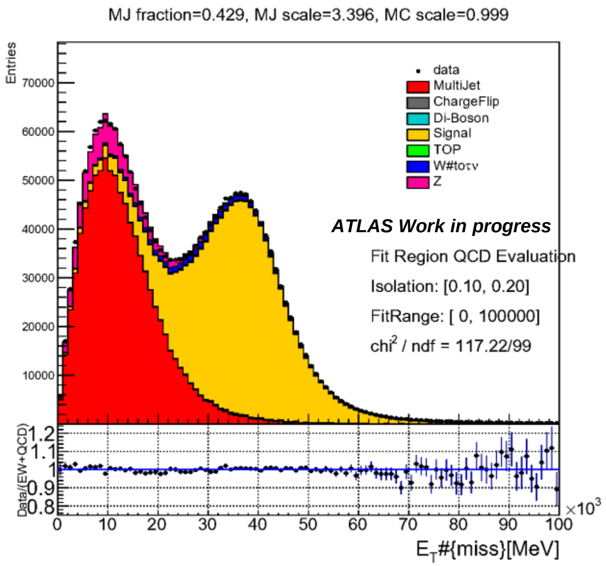


Simulated recoil resolution as a function of u_T. MVA brings a better resolution up to 70 GeV.

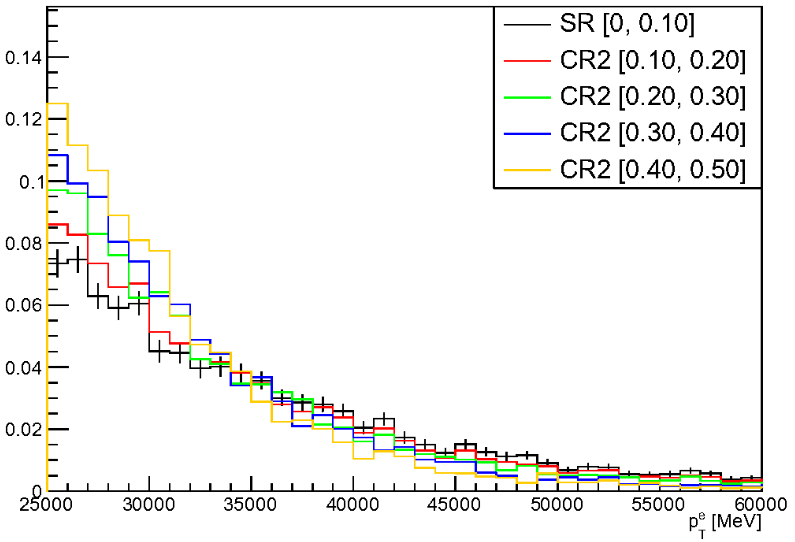
Multijet estimation

- MJ sources: heavy quark decay, in-flight pion decay, photon conversion.
- The data-driven ABCD method consists of two parts:

(a) Determination of the yield. (b) Derivation of the MJ shape.



MJ fraction fit in p_T^W analysis: MET in 13 TeV $W^-\rightarrow e\nu$ channel.



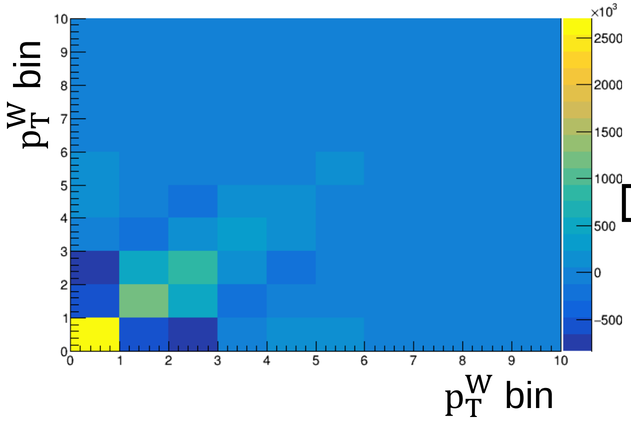
Shape extrapolation in p_T^W analysis: p_T^e in 13 TeV $W^-\rightarrow e\nu$ channel.

The same data-driven method is applied to the low-mu W mass measurement as well.

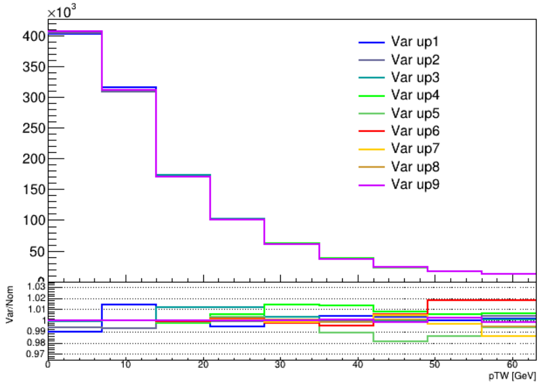
The shape extrapolation is optimized for lower statistics in the control regions after categorization.

Propagation of p_T^W uncertainties (preliminary)

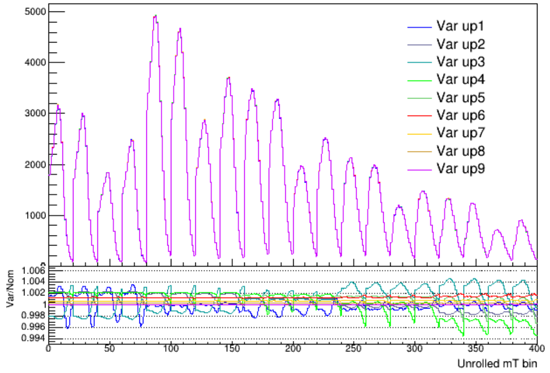
- Low-mu measurement of p_T^W: hopefully the total uncertainty <2%
- The orthogonalized p_T^W uncertainty variations are derived from an eigenvalue decomposition of the covariance matrix at unfolded level.
- The underlying (rapidity inclusive) p_T^W distributions are 1D-reweighted to these unfolded level uncertainty variations, propagating the uncertainty to other kinematic distributions, such as m_T and p_T^l.



Covariance matrix of p_T^W uncertainty at unfolded level



Orthogonal uncertainty variations of p_T^W



Uncertainty variations propagated to m_T (with categorization)

Current status of statistical analysis

- Profile likelihood fit: HistFactory + RooFit

- W mass extraction based on $\mathrm{m_T}$ (most sensitive observable at low-mu)

- 20 categories in each of the 8 channels

  5 $\mathrm{u_T}$ bins: [0, 5, 10, 15, 20, 25] GeV

  4 η_e bins: [0, 0.6, 1.2, 1.8, 2.47], skipping the transitional region of EM.

  4 η_μ bins: [0, 0.8, 1.4, 2.0, 2.4]

PLH-fit for W mass

Profile likelihood fit used in the on-going Run2 low-mu analysis:

Overall signal normalization.

$$P\left(\mathrm{n_i}, \mathrm{a_p} \middle| \alpha_{\mathrm{mW}}, \alpha_{\mathrm{p}}, \Phi, \lambda\right) = \prod_{\mathrm{i\in bins}} \mathrm{Pois}(\mathrm{n_i}|\mathrm{v_i}) \times \mathrm{G}(\mathrm{L_0}|\lambda, \Delta_{\mathrm{L}}) \times \prod_{\mathrm{p\in syst.}} \mathrm{f_p}(\mathrm{a_p}|\alpha_{\mathrm{p}})$$

Modelling in Signal Region: The total prediction $\mathrm{v_i}$ is described by a POI ($\alpha_{\mathrm{mW}} \propto \mathrm{m_W}$), along with NPs for background and systematics.

Luminosity constraint.

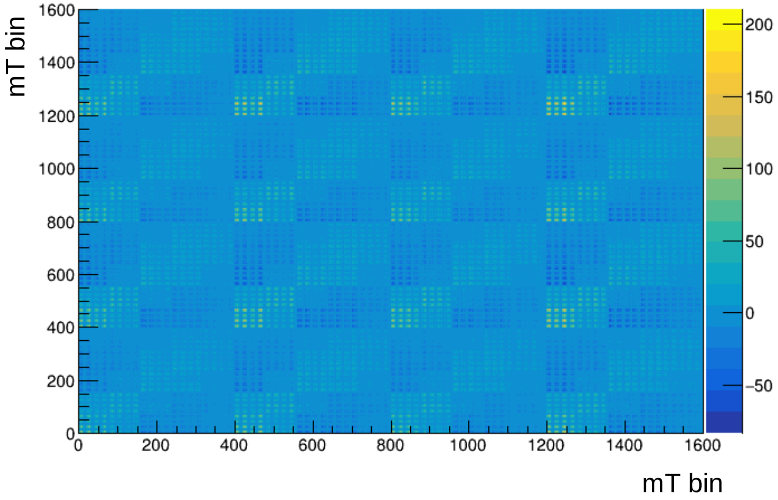
NP constraints according to the auxiliary measurements.

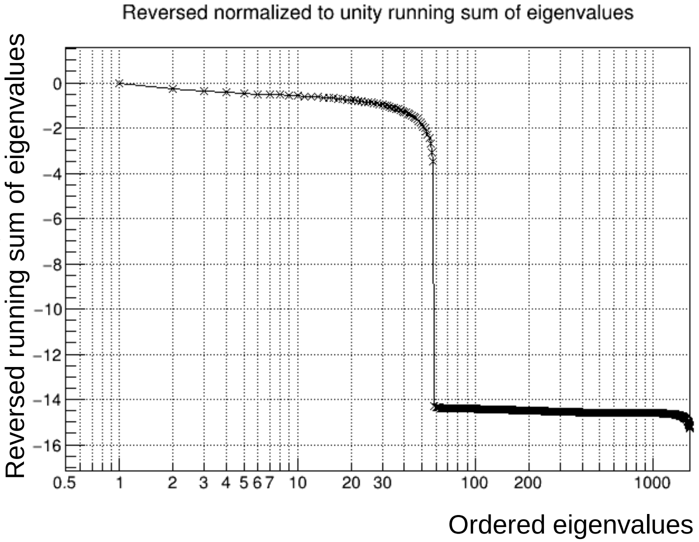
- The joint fit of signal and systematic parameters provides corrections to small biases, plus the power to constrain systematic uncertainties.

Reduction of nuisance parameters

- An eigenvalue decomposition of the covariance matrix is performed for each systematic group: recoil, electron SF, muon SF …
- The number of orthogonal uncertainty variations are pruned according to the significance of the corresponding eigenvalues.

Covariance matrix: Recoil @13 TeV





The cut-off is set to eigenvalue significance <1%.

Total number of NPs can be reduced from a few thousands to ~500 with this method.

The small variations below the cut-off are taken into account later by summing them up in a bin-by-bin uncorrelated manner.

Handling of MC statistics

- Given the large MC samples, it is possible to avoid the additional NPs introduced by Barlow-Beeston Light prescription.
- Approximation: scale down both data and prediction in the fit.

$$\mathrm{P}\left(\mathrm{n_i}, \mathrm{a_p} \middle| \alpha_{\mathrm{mW}}, \alpha_{\mathrm{p}}, \Phi, \lambda\right) = \prod_{\mathrm{i} \in \mathrm{bins}} \mathrm{Pois}(\mathrm{n_i} | \mathrm{v_i}) \mathrm{G}(\mathrm{L} | \lambda, \Delta_{\mathrm{L}}) \prod_{\mathrm{p} \in \mathrm{syst.}} \mathrm{f_p}(\mathrm{a_p} | \alpha_{\mathrm{p}})$$

$$\Downarrow$$

$$\mathrm{P}'\left(\mathrm{n_i}, \mathrm{a_p} \middle| \alpha_{\mathrm{mW}}, \alpha_{\mathrm{p}}, \Phi, \lambda\right) = \prod_{\mathrm{i} \in \mathrm{bins}} \mathrm{Pois}(\mathrm{n}'_{\mathrm{i}} | \mathrm{v}'_{\mathrm{i}}) \mathrm{G}(\mathrm{L} | \lambda, \Delta_{\mathrm{L}}) \prod_{\mathrm{p} \in \mathrm{syst.}} \mathrm{f_p}(\mathrm{a_p} | \alpha_{\mathrm{p}})$$

$\mathrm{n}'_{\mathrm{i}}/\mathrm{n_i} = \mathrm{v}'_{\mathrm{i}}/\mathrm{v_i} = \dfrac{(\text{data stat.})^2}{(\text{data stat.})^2 + (\text{MC stat.})^2 + (\textbf{truncated syst.})^2}$ is calculated independently for each bin.

The small uncertainty variations below the cut-off in the NP reduction can be added back in the denominator.

Uncertainty decomposition for PLH-fit

- For a given probability model, the post-fit value of POI depends on the data and the auxiliary measurements for systematics: $\hat{\alpha}_{mW} = \hat{\alpha}_{mW}(\vec{\mathrm{n}}_{\mathrm{i}}, \vec{\mathrm{a}}_{\mathrm{p}})$
- If $\vec{\mathrm{n}}_{\mathrm{i}}$ and $\vec{\mathrm{a}}_{\mathrm{p}}$ are independent, the total uncertainty of POI at the value inferred by the fit can be decomposed via an uncertainty propagation:

$$\mathrm{Unc.}(\hat{\alpha}_{mW}) = \sqrt{\sum\nolimits_{\mathrm{i}} \left(\frac{\partial \hat{\alpha}_{mW}}{\partial \mathrm{n}_{\mathrm{i}}} \Delta \mathrm{n}_{\mathrm{i}}\right)^2 + \sum\nolimits_{\mathrm{p}} \left(\frac{\partial \hat{\alpha}_{mW}}{\partial \mathrm{a}_{\mathrm{p}}} \Delta \mathrm{a}_{\mathrm{p}}\right)^2}$$

$\Delta \mathrm{n}_{\mathrm{i}}$: STDEV of data.
$\Delta \mathrm{a}_{\mathrm{p}}$: STDEV of global observable.

Data statistics:
Generate bootstrap toys of data n_i, then calculate the standard deviation of these toys in W mass.

Systematics:
Fluctuate the global observable a_p according to the auxiliary measurement, then calculate the standard deviation of these fluctuations in W mass.

When data statistics is under Gaussian approximation, the uncertainty decomposition can be performed analytically. Analytical solution worked out by Andres.

Progress in low-mu m_W fit and prospects

- The statistical power of Run2 low-mu data 7~ 8 MeV.

- Total uncertainty from a very preliminary PLH-fit, including the currently available systematics and applying the data scaling: ~ 20 MeV.

- Expecting to have PDF uncertainty 5~6 MeV and p_T^W uncertainty 2~3 MeV.

If 1 fb^{-1} of low-mu data taking is possible during Run3, we will be hoping for a total uncertainty of ~ 10 MeV.

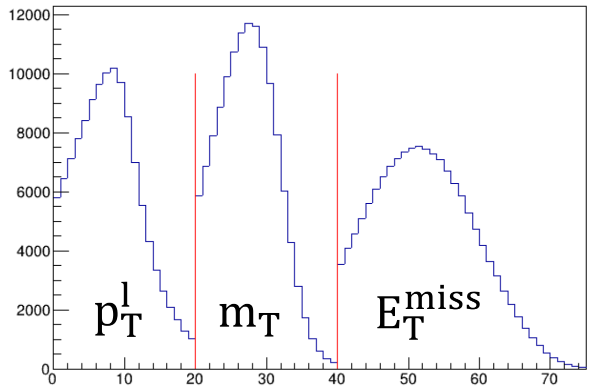
More ideas about PLH-fit

Combination of multiple statistically correlated observables in a PLH-fit:

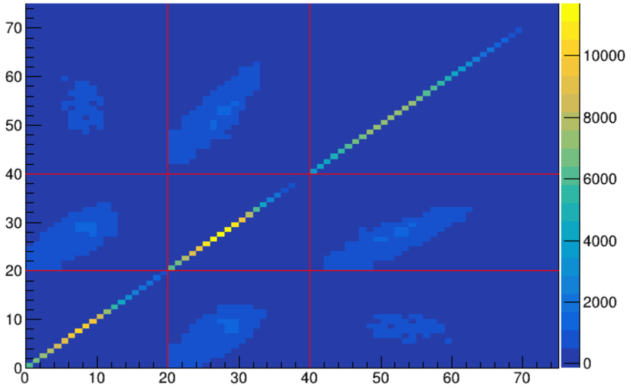
- Run bootstrap toys of data and global observables. This method of combination has been studied in the 7 TeV re-analysis.
- Fit a linear combination of observables.

$$\text{e.g. } SmT = (1 - \alpha - \beta) \times m_T + \alpha \times p_T^l + \beta \times E_T^{miss}$$

- ‘Data rotation’ (being studied by Andres).



Concatenated kinematic distribution



Concatenated statistical covariance matrix

(a) The concatenated statistical covariance matrix is diagonalized via $C_{stat.} = R \cdot D_{diag} \cdot R^T$.
(b) For concatenated kinematic distribution H, $H' = R \cdot H$ becomes bin-by-bin uncorrelated.

Summary

- The W mass measurement using ATLAS Run2 low-mu data is going on. A profile likelihood fit is introduced to infer W mass from data. A few approaches have been considered for helping the PLH-fit benefit from the combination of statistically correlated observables.
- We are working on the systematic uncertainties for low-mu W mass analysis. The statistical and systematical uncertainties in the PLH-fit will be presented by a dedicated uncertainty decomposition.
- For a preliminary study, $\mathrm{p_T^W}$ uncertainties from the measurement will be propagated to the W mass fit. A final strategy for $\mathrm{p_T^W}$ uncertainties has to be decided later (parton shower tuning?).
- Long low-mu data-taking in Run3: aiming at ~10 MeV precision for a single ATLAS measurement.

Backup

The unfolding procedures: $\mathrm{u_T}$ -> $\mathrm{p_T^W}$

- Due to the neutrino in the decay product, $\mathrm{p_T^W}$ can only be inferred from recoil $\mathrm{u_T}$ via $\vec{\mathrm{p}}_\mathrm{T}^\mathrm{W} + \vec{\mathrm{u}}_\mathrm{T} = 0$.

- The reco-level $\mathrm{u_T}$ goes through **Iterative Bayesian Unfolding** to correct for the detector effects, revealing the true underlying $\mathrm{p_T^W}$ distribution.

- The purity and efficiency corrections are accounted for in the unfolding procedure.

Uncertainty propagation for $\mathrm{p_T^W}$ unfolding

- **Data statistics** $\widetilde{U}_j^{\alpha} = \sum_i U_{ij}(D_i^{\alpha} - B_i)$

Fluctuate the data -> calculate the spread at unfolded level.

- **MC statistics** $\widetilde{U}_j^{\alpha} = \sum_i U_{ij}^{\alpha}(D_i - B_i)$

Fluctuate the migration matrix, efficiency and purity corrections
-> calculate the spread at unfolded level.

- **Experimental** systematics $\widetilde{U}_j^{\alpha} = \sum_i U_{ij}^{\alpha}(D_i - B_i)$

Vary the migration matrix, efficiency and purity corrections.

- **Background** systematics $\widetilde{U}_j^{\alpha} = \sum_i U_{ij}(D_i - B_i^{\alpha})$

Vary the estimation of background.

$\mathrm{p}_\mathrm{T}^\mathrm{W}$ reweighting

- To correct for the $\mathrm{p}_\mathrm{T}^\mathrm{W}$ mis-modelling, the data/MC agreement is optimized at reco-level by reweighting the truth-level $\mathrm{p}_\mathrm{T}^\mathrm{W}$ distribution.
- Once the reweighting function is determined, it will be used to correct the $\mathrm{p}_\mathrm{T}^\mathrm{W}$distribution in the MC. The W mass analysis uses the same correction of underlying $\mathrm{p}_\mathrm{T}^\mathrm{W}$distribution.

Optimization of reco-level distribution.

$$\chi^2 = \sum_{ij} \Delta_i^T C_{ij}^{-1} \Delta_j ,$$

$$\Delta_i = (D_i - B_i) - \sum_{j} R_{ij} \times (w_T(p_T^W))_j$$

i: reco-level bin
j: truth level bin

$$(w_T(p_T^W))_j = N_j \left[\left(1 + a\, p_{T,j}^W + b\, {p_{T,j}^W}^2\right) * \left(1 - c + c * r_{\mathrm{NNPDF/CT10}}(p_{T,j}^W)\right)\right]$$

Bias uncertainties are assigned to the $\mathrm{p}_\mathrm{T}^\mathrm{W}$ unfolding to account for:

(a) The uncertainty in the fit of reweighting function.

(b) The arbitrariness of the parameterization form of the reweighting function.

(c) The possible mis-modelling of ($\mathrm{p}_\mathrm{T}^\mathrm{W}$, y) correlation.

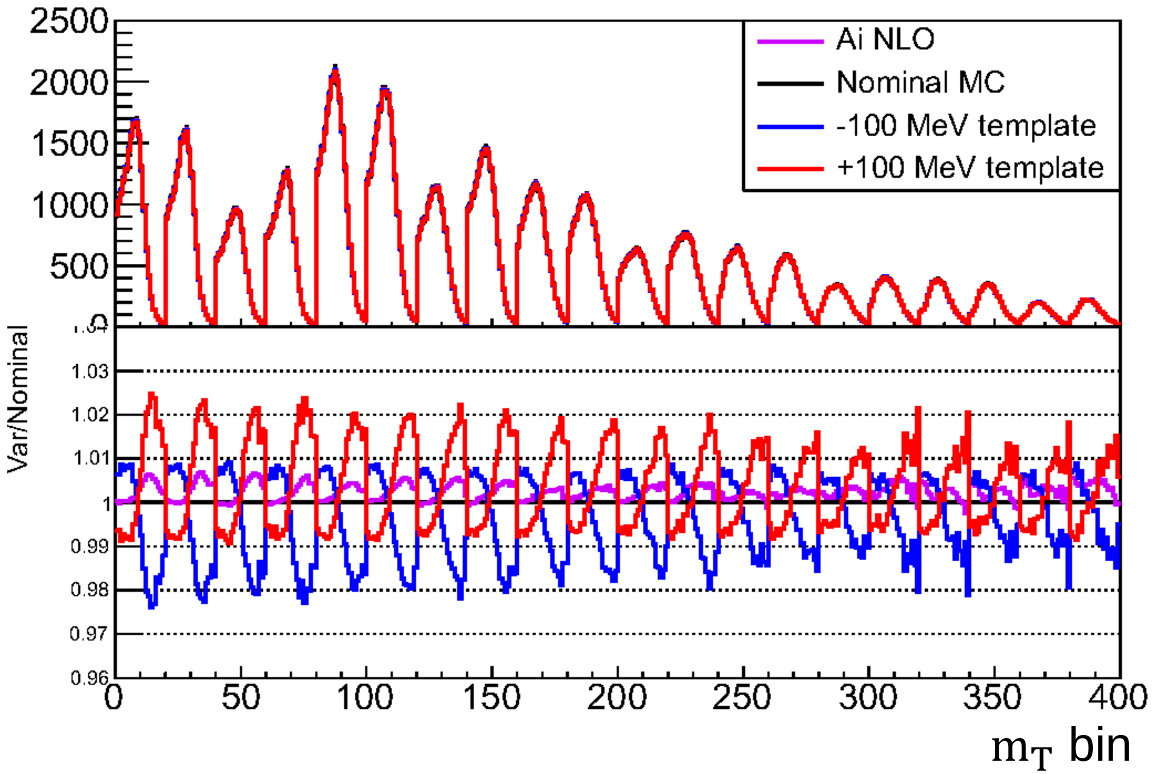
QCD baseline model and uncertainties

- W polarization: Ai’s are calculated by DYTURBO CT10NNLO PDF.
- W rapidity: Taken from Powheg at NLO accuracy.
- $\mathrm{p}_\mathrm{T}^\mathrm{W}$: The underling $\mathrm{p}_\mathrm{T}^\mathrm{W}$ based on Powheg+Pythia8 is reweighted according to the strategy in $\mathrm{p}_\mathrm{T}^\mathrm{W}$ measurement. Before a parton showing tuning is available, only the inclusive rapidity variations of $\mathrm{p}_\mathrm{T}^\mathrm{W}$ can be obtained from the direct measurement.

- To-dos: fixed-order NNLO for rapidity, QCD scale variations, variation of PDF uncertainties between PDF sets, decorrelate PDF uncertainty from Ai’s and so.

Spin-correlation uncertainty

Ai's@NLO will be taken as the uncertainty variation.



60 < m_T < 100 GeV for 5 TeV $W^-\rightarrow e\nu$ channel, categorized in u_T and η_l.

- Needs to further validate if the NNLO vs NLO deviation can be profiled as a systematic variation to represent spin-correlation uncertainty in the statistical analysis.

- Alternative plan:

Use offset method to assess spin-correlation uncertainty (no profiling).

EW correction: baseline and uncertainties

- Baseline QED FSR: Powheg+Pythia8 interfaced to PHOTOS++.
- Systematics:

➢ Uncertainty in QED FSR correction.

➢ Pure weak and IFI corrections.

➢ Final-state lepton pair production.

- **Winhac** will be used to get preliminary numbers for EW uncertainties. The generator-level distributions will be folded to detector-level.
- Powheg EW, an NLO QCD+EW generator, is an available tool for this. Careful validation might be needed for W mass.