

Probing SMEFT Effect in Polarized WZ production at the LHC

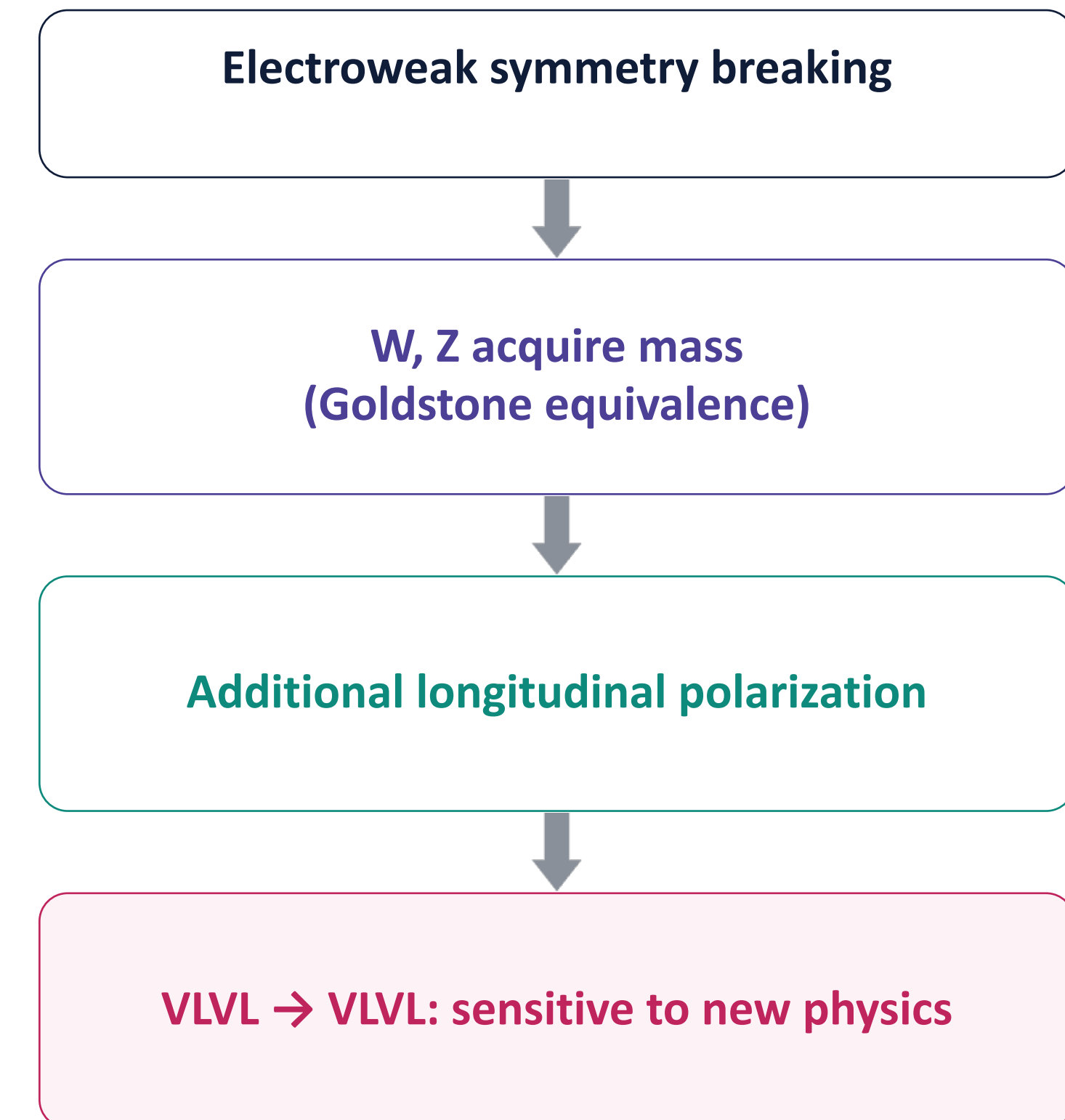
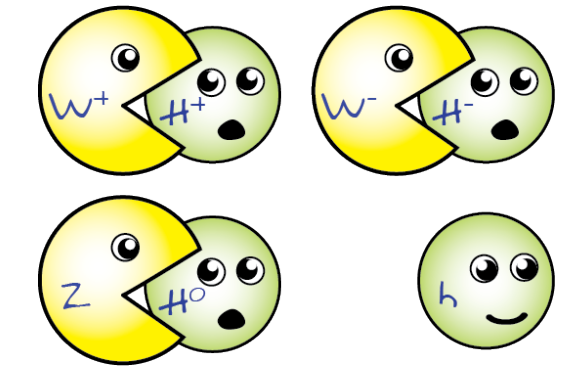
Joint WZ polarization fractions as a probe of dimension-6 SMEFT operators

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Why weak- boson polarization?

- Longitudinal W & Z bosons originate from the Higgs mechanism (Goldstone bosons)
- Polarization fractions give a direct test of electroweak symmetry breaking, beyond the inclusive production rate
- SMEFT operators modify helicity amplitudes- different operators can leave distinct polarization fingerprints
- ATLAS has already observed joint longitudinal WZ polarization [Phys. Lett. B 843 (2023) 137895].



Joint Polarization at the LHC

- W & Z bosons are jointly produced in four polarization configurations:

WTZT

WTZL

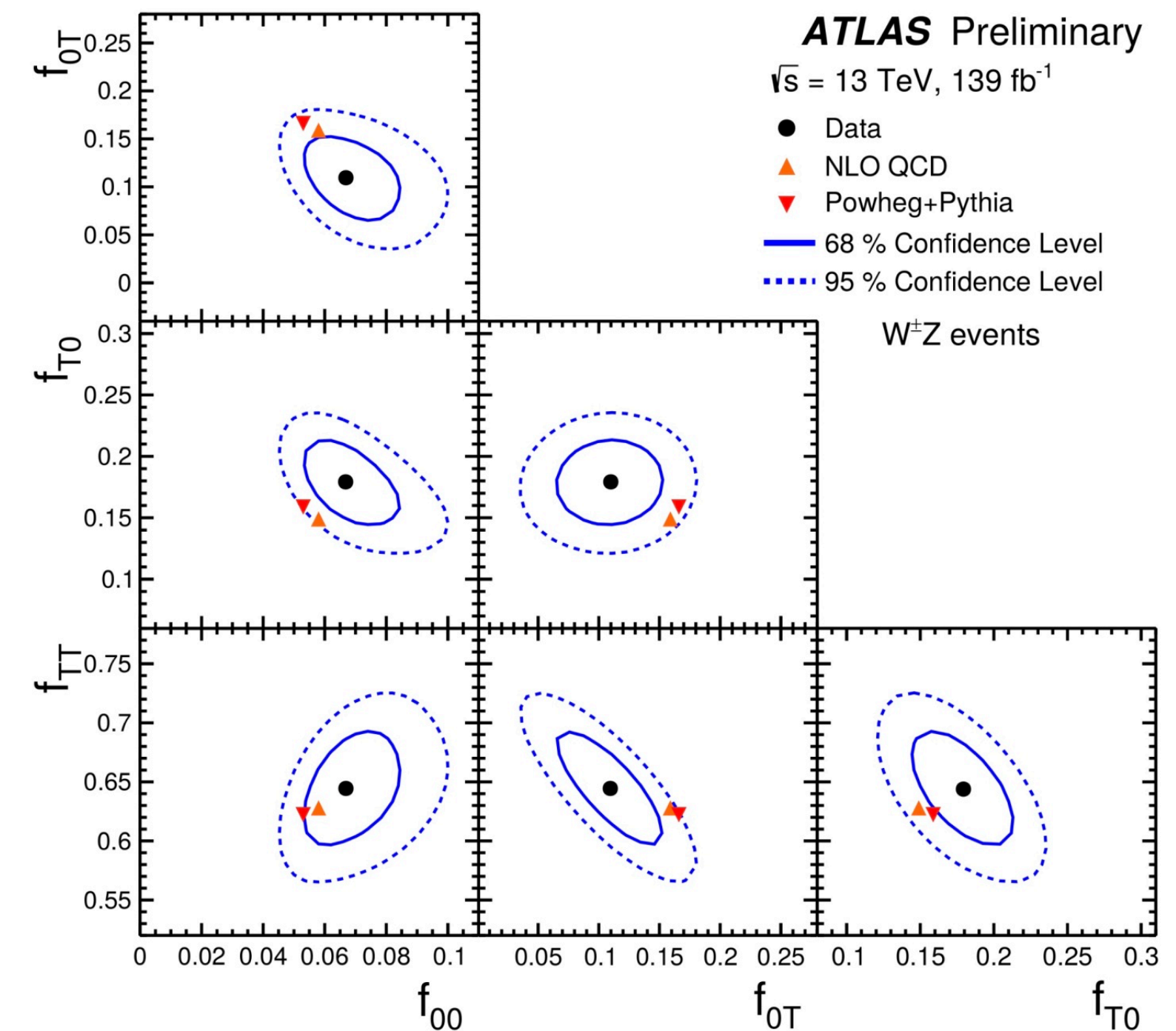
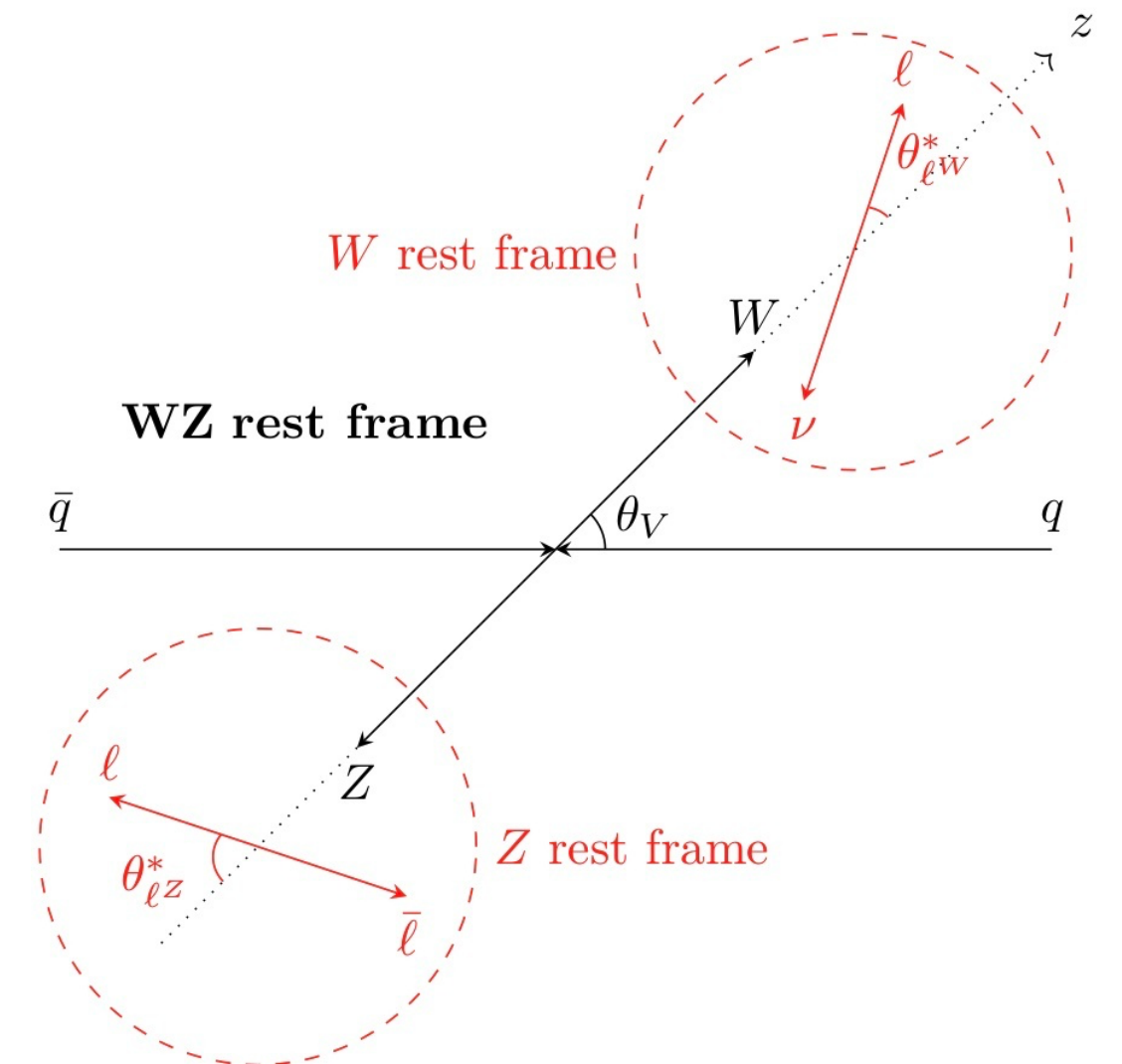
WLZT

WLZL

- WTZT dominates the rate (~74% at SM level, this analysis)
- WLZL is only ~6% of events, small but the channel most directly tied to EWSB
- Polarization measurements are now experimentally accessible and provide a new probe of the electroweak sector
- ATLAS & CMS polarization-fraction measurements are consistent with SM predictions - setting the stage to look for EFT deviations

WZ rest frame

Maximize the decorrelation of LL(00) and TT polarization modes



This analysis

Feasibility study

1

Does SMEFT modify the polarization *composition*, not just the overall rate?

2

Which dimension-6 operators leave the largest polarization fingerprint?

3

Can machine learning sharpen sensitivity to polarization beyond individual observables?

Approach: dedicated WLZL/WLZT/WTZL/WTZT samples (MadGraph5_aMC@NLO) → SM–EFT comparison of cross sections & kinematics → ML-based polarization scores, trained on SM and applied unchanged to EFT.

SMEFT operators & benchmark

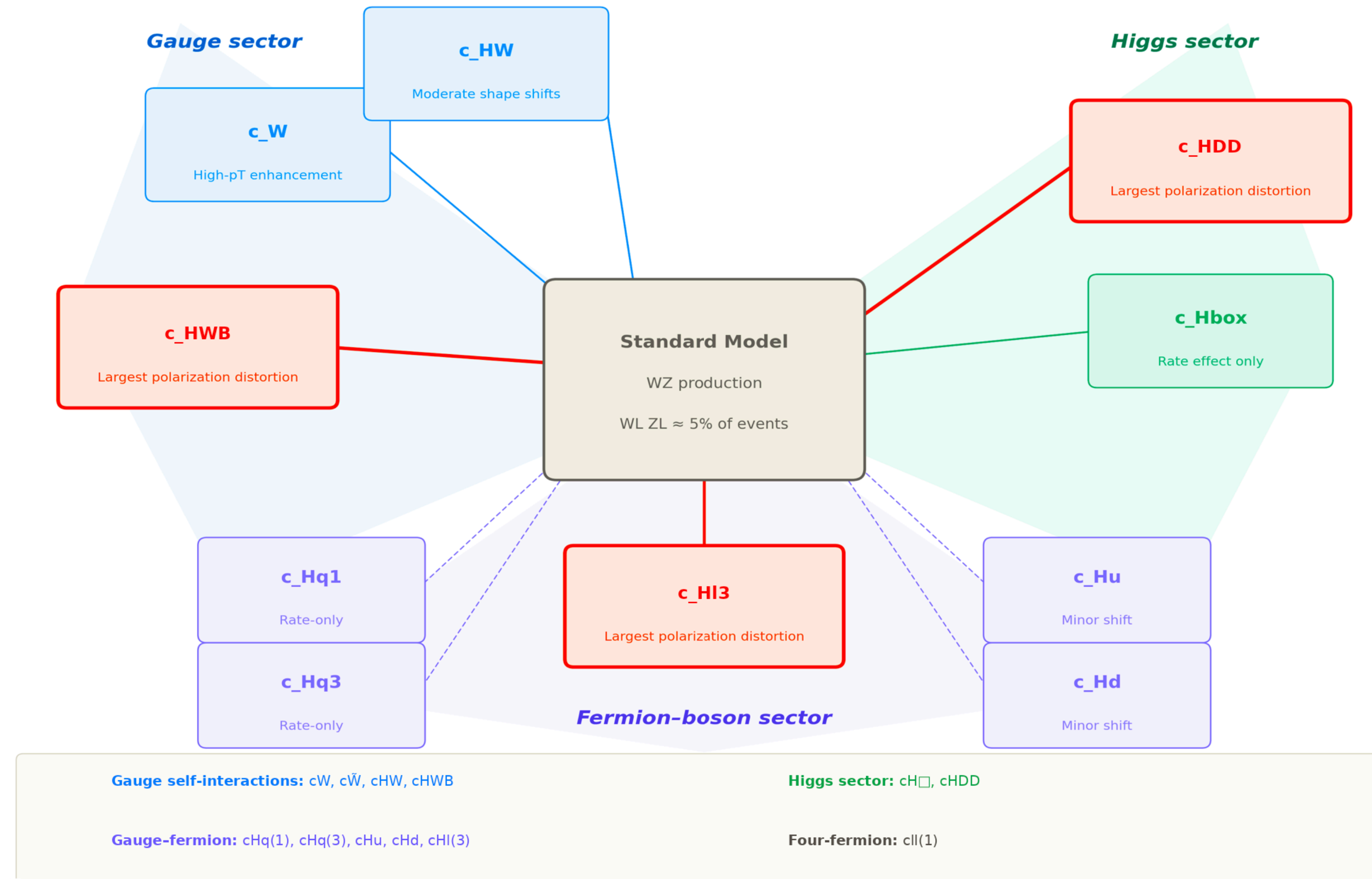
- One operator switched on at a time
- All other Wilson coefficients are set to zero
- Benchmark:

$$C_i/\Lambda^2 = 1\text{TeV}^{-2}$$

- Identify operators with the largest impact on polarization observables

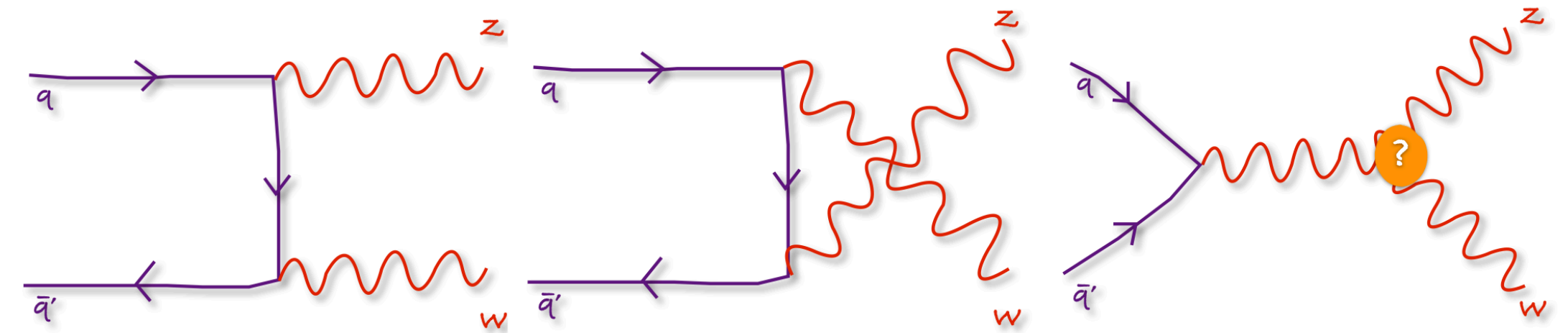
SMEFT dimension-6 operators in polarized WZ production

$C_i/\Lambda^2 = 1\text{TeV}^{-2}$ | one operator at a time | $WZ \rightarrow 3\ell$ fully leptonic



Samples

- Fully leptonic channel $pp \rightarrow W^\pm Z \rightarrow \ell^\pm \nu; \ell^+ \ell^-$ (representative decay: $W \rightarrow e \nu; Z \rightarrow \mu^+ \mu^-$)
- Sample generation:
 - Dedicated LHE-level samples for WLZL, WLZT, WTZL, WTZT: 105 events per channel and benchmark, MadGraph5_aMC@NLO, 5-flavour scheme
 - Parton Showering with PYTHIA and detector simulations with Delphes using default ATLAS parameters (ongoing)



Cross-checked at LO

SM and SMEFT polarized samples validated across four generators: MadGraph5_aMC, Powheg-Box, Sherpa, Whizard.

Agreement is good; residual differences trace to the Breit–Wigner / narrow-width / double-pole approximations each uses — see backup.

Kinematic variables

- Reconstructed observables used to compare EFT and SM predictions in leptonic WZ events

Lepton Kinematics

- $p_T(\ell^+)$, $p_T(\ell^-)$ — transverse momentum of leptons
- $\eta(\ell^+)$, $\eta(\ell^-)$ — pseudorapidity
- $\phi(\ell^+)$, $\phi(\ell^-)$ — azimuthal angle

Missing Energy

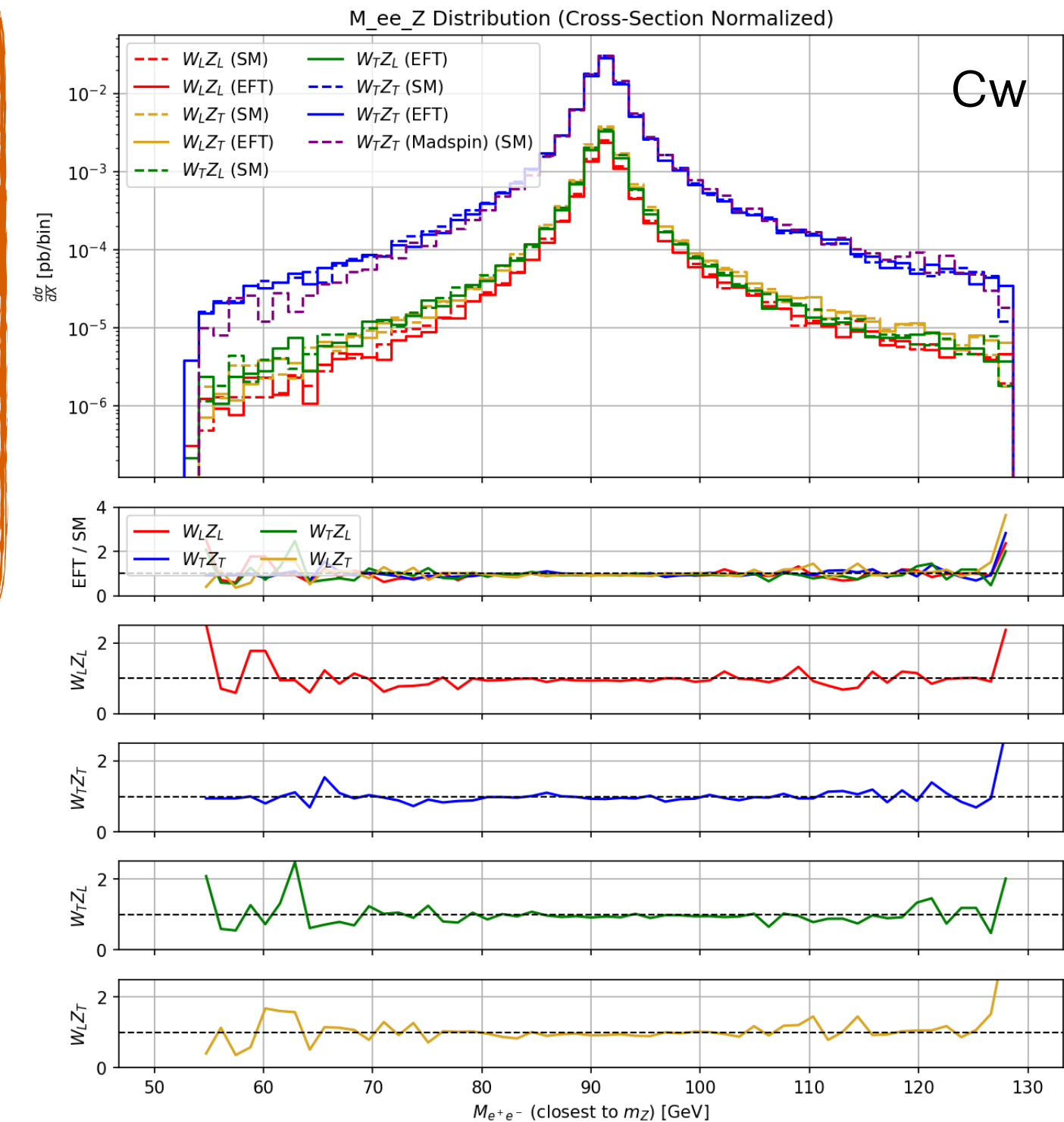
- ETmiss — missing transverse energy
- $\phi(\text{ETmiss})$ — azimuthal angle of missing transverse energy

Lepton Pair Observables

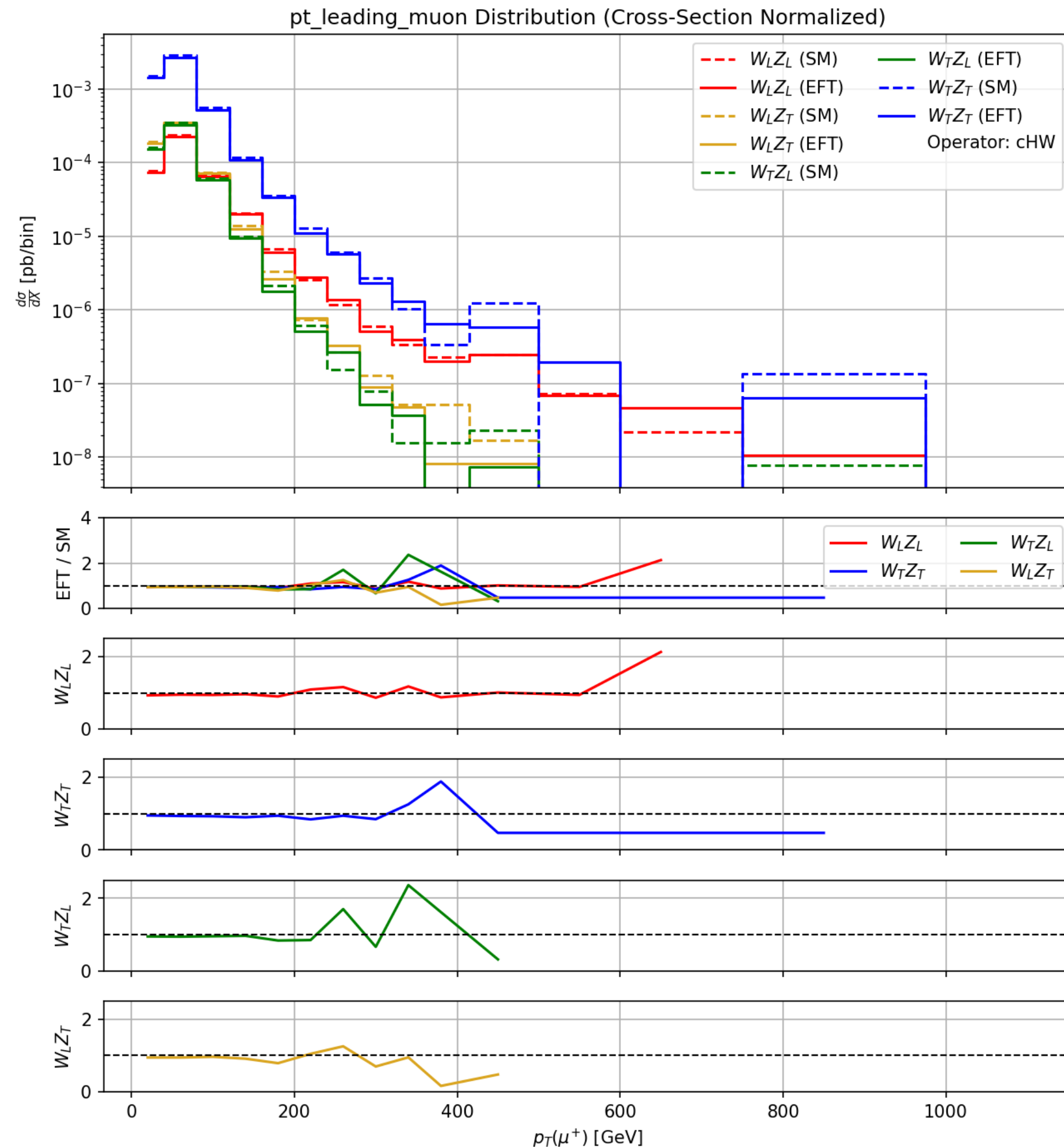
- $M_{\ell^+\ell^-}$, $M_{\ell^+\ell'^+}$ — invariant mass of lepton pairs
- $\Delta R(\ell^+, \ell^-)$, $\Delta R(\ell^+, \ell'^+)$ — angular separation between leptons
- $\Delta\phi(\ell^+, \ell^-)$, $\Delta\phi(\ell^+, \ell'^+)$ — azimuthal angle difference
- $\Delta y(\ell^+, \ell^-)$ — rapidity difference between leptons

Angular observables

- $\cos\theta^*$ — helicity angle
- $\cos\theta^*_{\text{rec}}$ — reconstructed helicity angle
- $\cos\Delta\phi$ — angular correlation observable



EFT Effects in Polarized WZ Production



Largest deviations observed in high-pT tails.

Leading Muon pT distribution — EFT vs SM

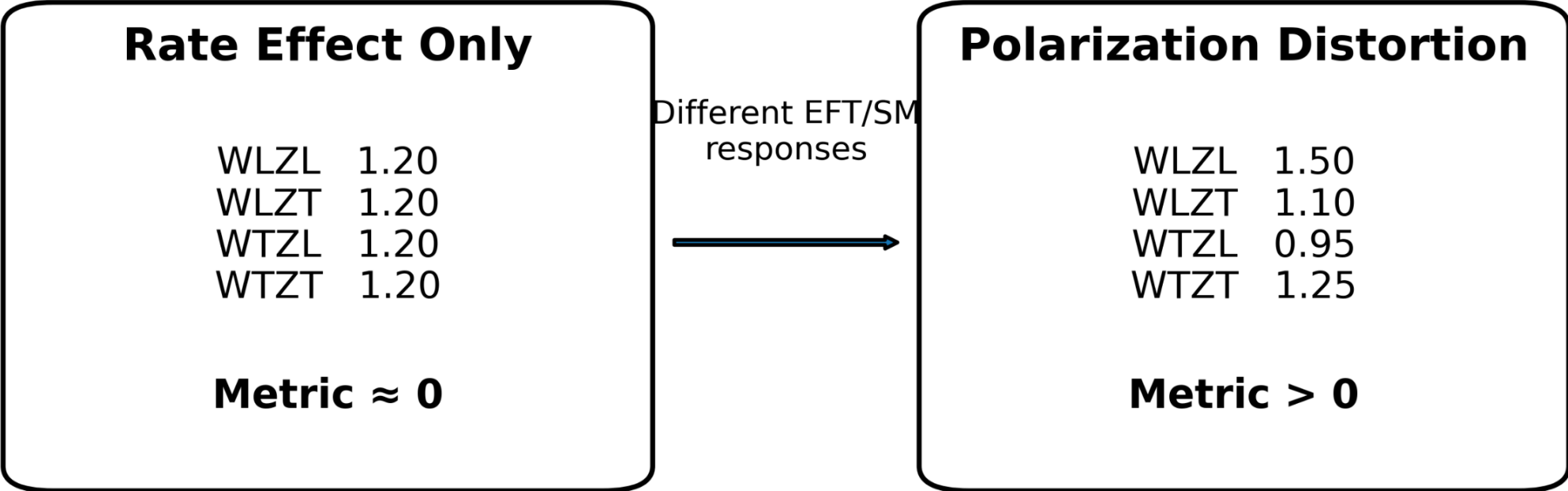
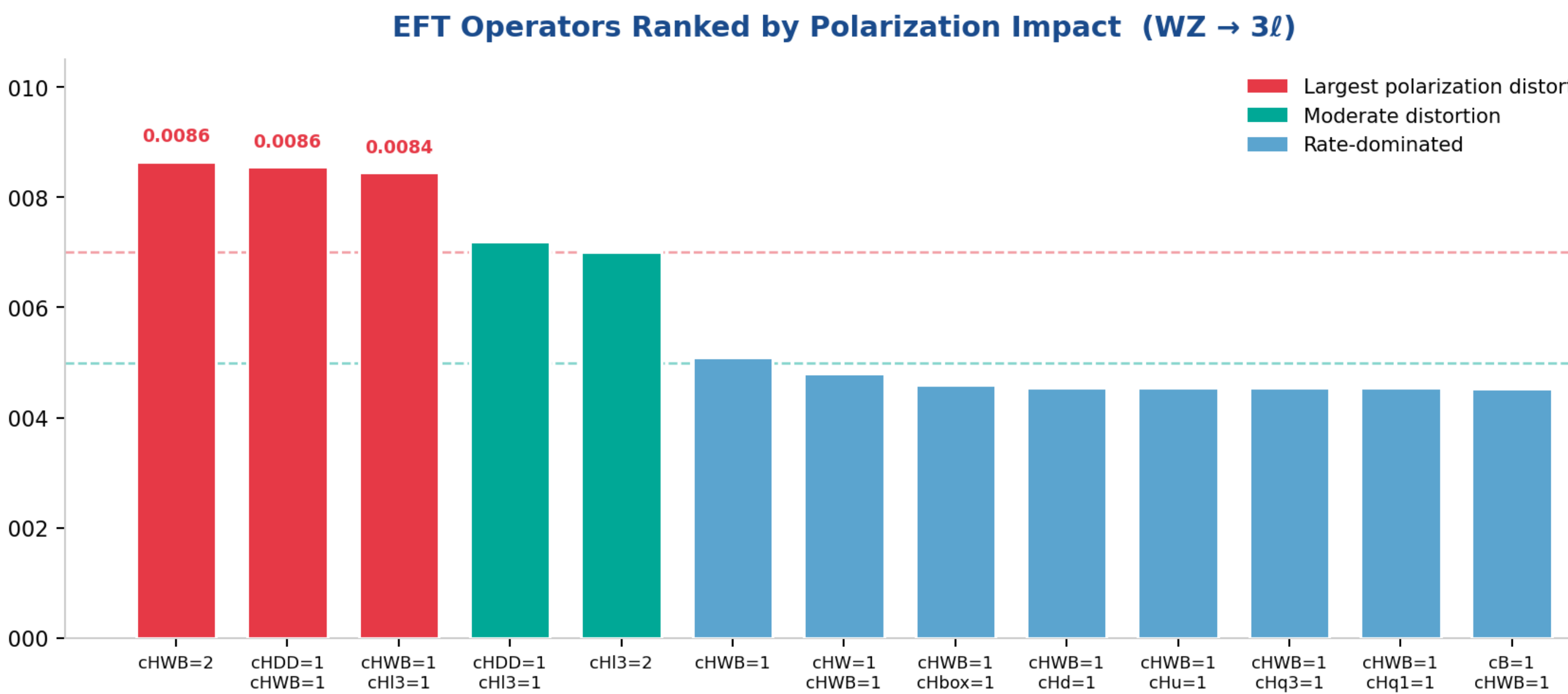
- Clear EFT enhancement visible in the high-pT region (> 200 GeV).
- Transverse modes ($W_T Z_T, W_T Z_L$) show the largest deviation from SM.
- Shape consistent with energy-growing behavior of dimension-6 operator CW.
- Confirms EFT sensitivity in polarization-dependent kinematic observables.

First clear observable EFT effect in the study.

EFT Operators Ranked by Polarization Impact

- EFT points ranked using polarization shape metric
- compute EFT/SM ratios for:
 - WLZL, WLZT, WTZL, WTZT
- Measure the spread of these four ratios
 - Small metric : all channels change equally, simple normalization effect
 - Large metric: channels change differently, polarization composition is modified

- c_{HWB} , c_{HDD} and c_{HI3} operators show the largest polarization distortions



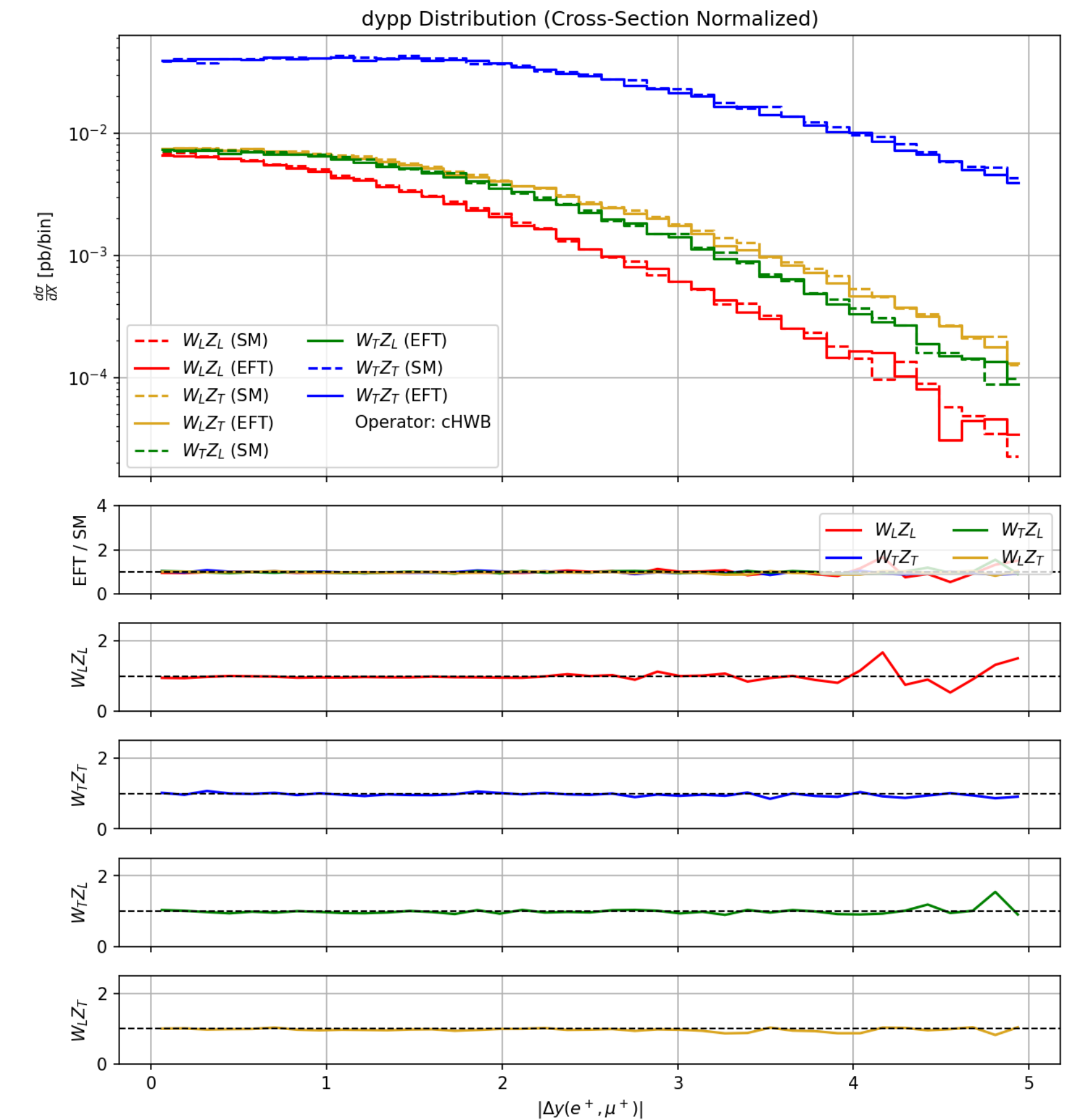
Uniform scaling → overall rate change only

|

Non-uniform scaling → modified LL/LT/TL/TT composition

Machine learning for polarization

- Polarization is not observable event-by-event — it is encoded statistically across many correlated kinematic and angular observables.
- Individual variables give limited separation; a classifier can combine the full event topology.
- Baseline: a Random Forest trained *only on SM* samples to separate fully-longitudinal WLZL from fully-transverse WTZT.
- Top features are angular: $|\Delta y(e^+, \mu^+)|$, $\Delta R(e^+, e^-)$, $\Delta \phi$; consistent with polarization encoded in decay-product correlations.



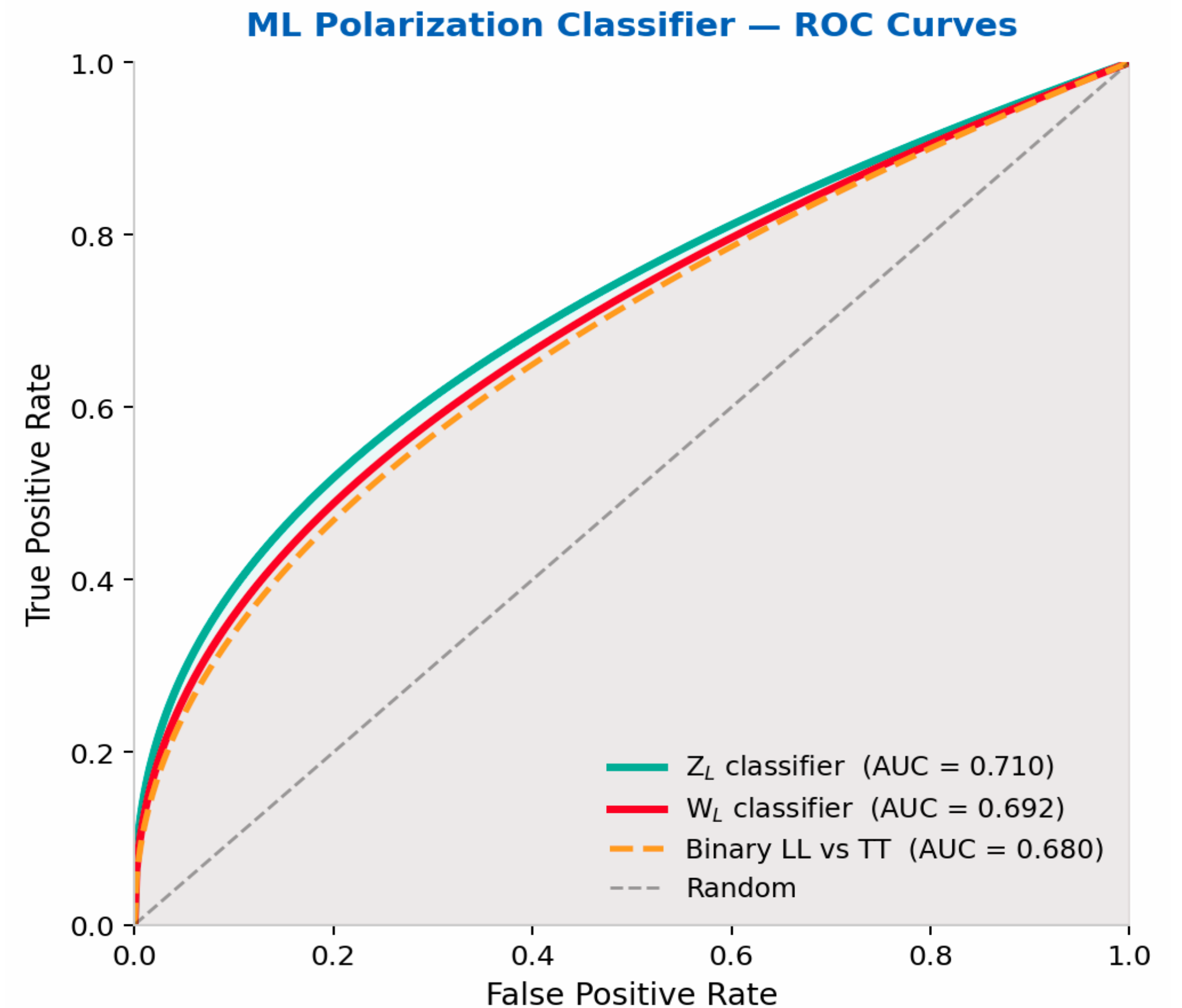
Top Feature: $\Delta y(e^+, \mu^+)$

- Measures **rapidity separation** between leptons from W and Z decays.
- Encodes **boson angular correlations**, sensitive to polarization.
- **Longitudinal states** → more forward-backward → larger $|\Delta y|$
- **Transverse states** → more central → smaller $|\Delta y|$
- Consistent with the model's feature importance ranking.

Beyond binary: boson-level scores

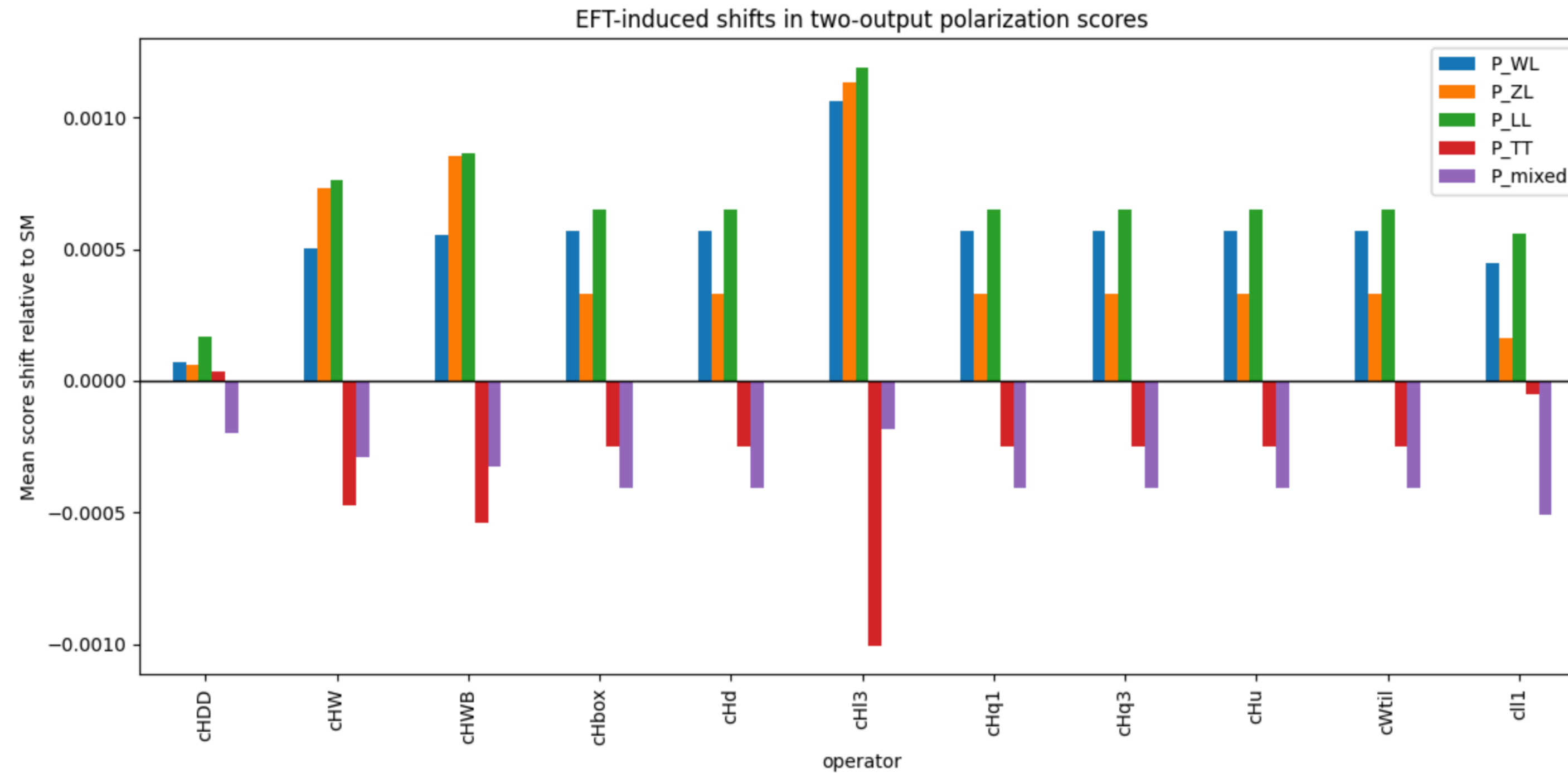
- Binary loses information:
 - Mixed states LT/TL contain longitudinal information.
 - W and Z polarization can be affected differently by EFT.
 - Binary classification compresses polarization information.

Approach:
DNN to predict $P(W_L)$ and $P(Z_L)$ independently
Built PLL, PTT and Mixed
Trained on SM events



EFT induced shifts in polarization Scores

We run EFT events through the network trained only on SM, and compare its average output to the SM baseline. Each bar is how far that average moves, per operator, for one of five scores (PWL, PZL, PLL, PTT, Pmixed), above zero means the EFT sample looks *more* like that state, below zero *less*.



Largest shift: cHl(3) ($\approx 1.7\sigma$), and cHWB ($\approx 1.4\sigma$).

All shifts stay below 2σ at current MC statistics but a network that has never seen an EFT event is still picking up structure it induces.

Significance Zshift checks each shift against the samples' statistical noise — full definition & pipeline in backup.

Summary & Outlook

- Polarized WZ production is a powerful, largely complementary probe of SMEFT, sensitive event when the inclusive rate barely moves
 - cHWP, cHDD, cH(3) drive the largest polarization composition distortions; cH3, cHWP, cH(1) the largest ML-score shifts
 - ML models trained only on SM samples generalize to EFT samples and recover operator-dependent polarization fingerprints
- Carried out within the COMETA group - a publication describing these results is in preparation.



Thank You.

References

Backup

- [1] ATLAS Collaboration, G. Aad et al., *Observation of gauge boson joint-polarisation states in $W\pm Z$ production from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys. Lett. B 843 (2023) 137895, arXiv:2211.09435
- [2] G. Pelliccioli, G. Zanderighi, *Polarised-boson pairs at the LHC with NLOPS accuracy* (2023)
- [3] U. Haisch, J. Linder, G. Pelliccioli, E. Re, G. Zanderighi, *Polarized-boson pairs at NLO in the SMEFT*, JHEP (Nov. 2025)
- [4] G. Pelliccioli, E. Re, *SMEFT effects on spin correlations and entanglement at NLO QCD in di-boson production at hadron colliders* (2026)
- [5] G. Pelliccioli, R. Poncelet, *Precise predictions for joint polarisation fractions in WZ production at the LHC*, arXiv:2510.25898
- [6] ATLAS Collaboration, G. Aad et al., *Studies of the Energy Dependence of Diboson Polarization Fractions and the Radiation-Amplitude-Zero Effect in WZ Production with the ATLAS Detector*, Phys. Rev. Lett. 133 (2024) 101802, arXiv:2402.16365

Backup — generator validation (LO)

Backup

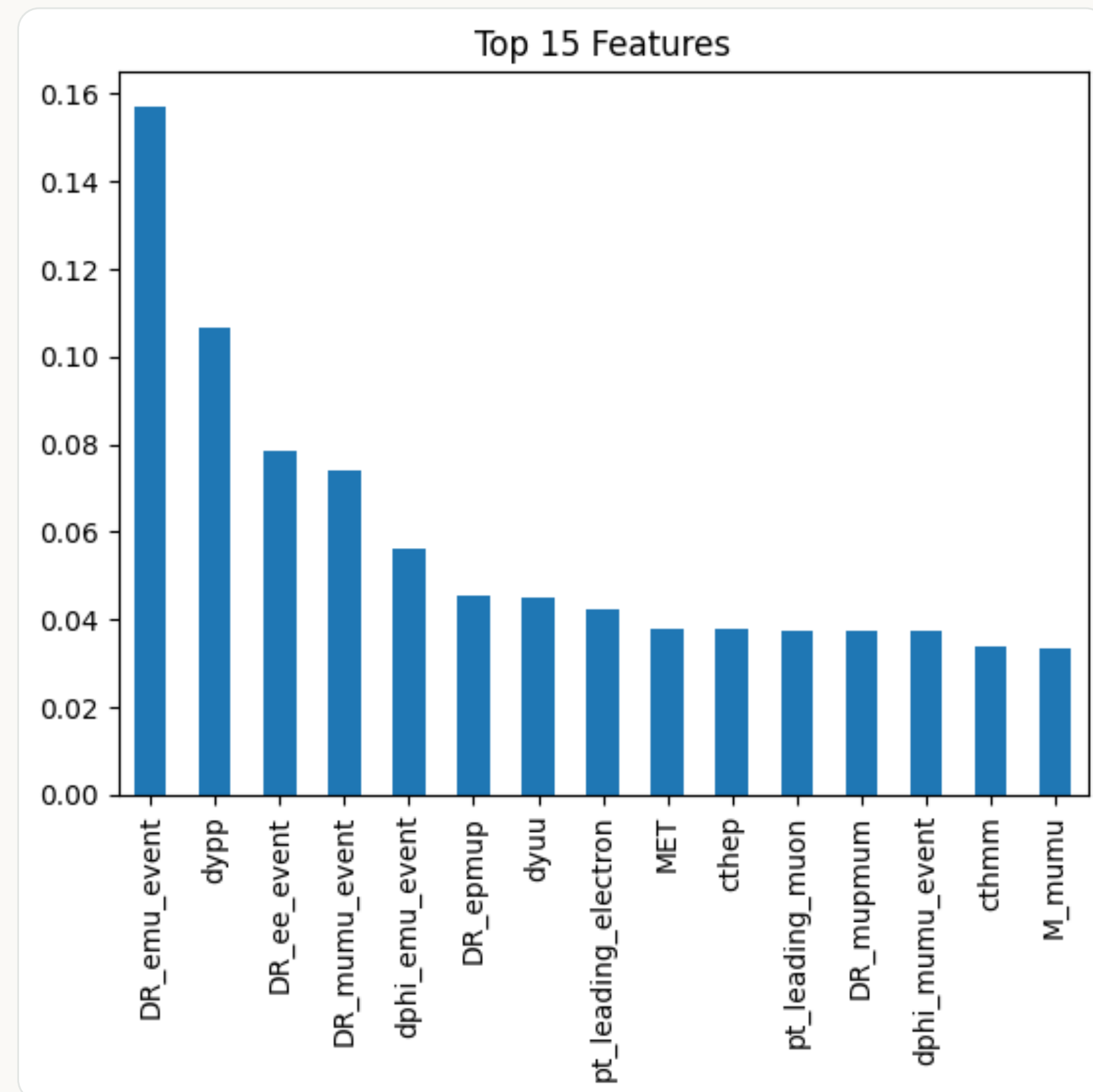
Inclusive SM cross sections [fb] for $W^+(e^+\nu_e)Z(\mu^+\mu^-)$ at LHC@13 TeV, $66 < M_{\mu^+\mu^-} < 116$ GeV, $c_W = 1$ TeV²:

Generator	Unpol.	LL	LT	TL	
MG5_aMC (BW)	64.14	3.887	5.982	5.441	
Sherpa (NWA)	62.36	3.727	5.795	5.254	
Whizard (DPA)	61.27	3.657	5.693	5.147	
Powheg-Box (DPA)	61.20	3.649	5.666	5.143	

Good agreement across all four tools; residual differences trace to the Breit–Wigner (BW), narrow-width (NWA), and double-pole (DPA) approximations each uses. EFT6 linear and quadratic terms validated the same way.

Backup — feature importance

Backup



- Angular observables — rapidity differences, angular separations, azimuthal differences — dominate the ranking.
- Top feature: $|\Delta y(e^+, \mu^+)|$ — the rapidity separation between the positive leptons from the W and Z decays.
- Longitudinal states are more forward–backward (larger $|\Delta y|$); transverse states are more central — consistent with the model's ranking.

Backup — how the score shift is computed

Backup

The network learned what “longitudinal-looking” kinematics are — purely from SM events. We then run EFT events through that *same, unchanged* network and check: does the average score move?



- **Score moves up** — the EFT events look *more* like that polarization state to the network than SM events do.

- **Score moves down** — the EFT events look *less* like that polarization state.

We also check each shift against the sample's statistical noise (a significance Z_{shift}), so a shift only counts if it's bigger than we'd expect from finite Monte Carlo statistics alone.