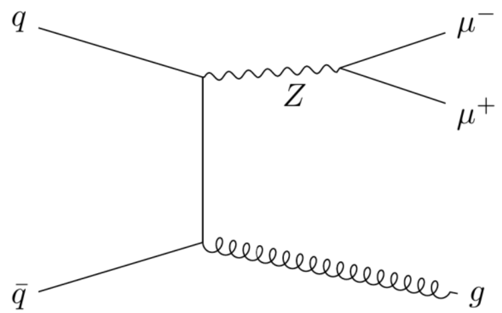
Technische Universität Dresden

Lena Alshut, Erik Bachmann, Mareen Hoppe, Frank Siegert // 17.03.2026

Machine Learning Based Tagging of Vector Boson Polarization

Polarization of massive vector bosons

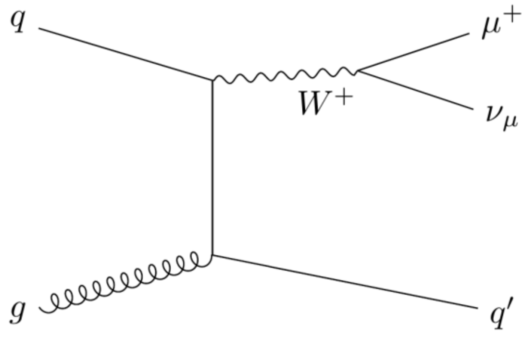


Polarization = alignment of particle's spin along its momentum

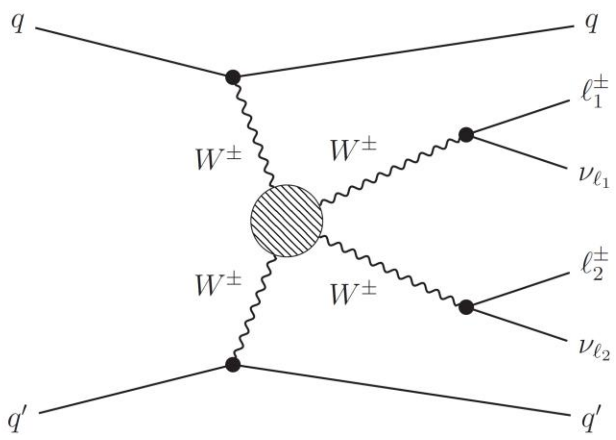
Helicity $h = \vec{S} \cdot \frac{\vec{p}}{|\vec{p}|}$ with eigenvalues

$h = \pm 1$ → **transverse** polarization states

$h = 0$ → **longitudinal** polarization state



- → Longitudinal state only for massive particles
- → $h = 0$ for MVB as direct consequence of EWSB
- → sensitive to SM gauge symmetry structure, EWSB mechanism and BSM physics



Polarization fractions of massive vector bosons

Matrix element:

$$\mathcal{M} = \mathcal{M}_\mu^{\mathcal{P}} \frac{i}{k^2 - M_V^2 + i\Gamma_V M_V} \left(-g^{\mu\nu} + \frac{k^\mu k^\nu}{M_V^2} \right) \mathcal{M}_\nu^{\mathcal{D}}$$ with

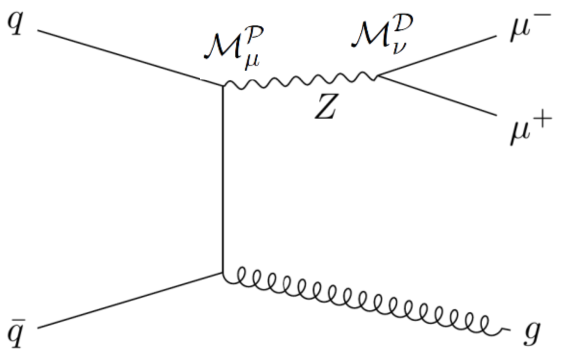
Completeness relation

$$-g^{\mu\nu} + \frac{k^\mu k^\nu}{M^2} = \sum_{\lambda=1}^{4} \varepsilon_\lambda^\mu(k) \varepsilon_\lambda^{\nu^*}(k)$$

$$\mathcal{M} = \sum_\lambda \mathcal{M}_\lambda \quad \text{and} \quad |\mathcal{M}|^2 = \sum_\lambda |\mathcal{M}_\lambda|^2 + \sum_{\lambda \neq \lambda'} \mathcal{M}_\lambda^* \mathcal{M}_{\lambda'} , \qquad \lambda, \lambda' = \mathrm{L}, +, -$$

$$|\mathcal{M}|^2 = |\mathcal{M}_\mathrm{L}|^2 + |\mathcal{M}_\mathrm{T}|^2 + 2\,\mathrm{Re}\,(\mathcal{M}_\mathrm{L}^* \mathcal{M}_+) + 2\,\mathrm{Re}\,(\mathcal{M}_\mathrm{L}^* \mathcal{M}_-)$$

where $|\mathcal{M}_\mathrm{T}|^2 = |\mathcal{M}_+|^2 + |\mathcal{M}_-|^2 + 2\,\mathrm{Re}\,(\mathcal{M}_+^* \mathcal{M}_-)$



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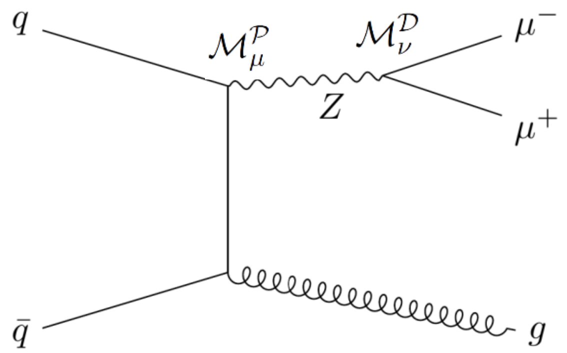
where $$|\mathcal{M}_\mathrm{T}|^2 = |\mathcal{M}_+|^2 + |\mathcal{M}_-|^2 + 2\,\mathrm{Re}\,(\mathcal{M}_+^* \mathcal{M}_-)$$

Polarization fractions: $$r_\mathrm{L} = \frac{|\mathcal{M}_\mathrm{L}|^2}{|\mathcal{M}|^2} \qquad r_\mathrm{T} = \frac{|\mathcal{M}_\mathrm{T}|^2}{|\mathcal{M}|^2}$$

$$r_\mathrm{int} = \frac{2\,\mathrm{Re}\,(\mathcal{M}_\mathrm{L}^* \mathcal{M}_\mathrm{T})}{|\mathcal{M}|^2} = 1 - r_\mathrm{L} - r_\mathrm{T}$$



New approach on VB polarization tagging

Previous studies:
Classification-based formulation

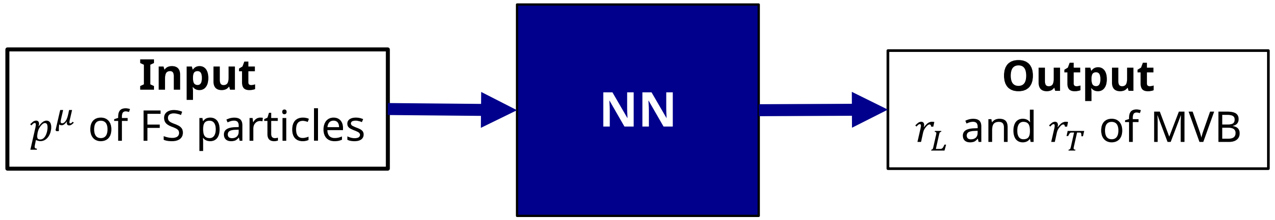
- NN classifiers trained to distinguish between longitudinal and transverse polarization states
- target variable: assignment to **polarization classes** → definition of purely longitudinal and transverse polarized events
- depends on abstract, nonphysical targets with unknown distributions

New approach:
Regression-based formulation

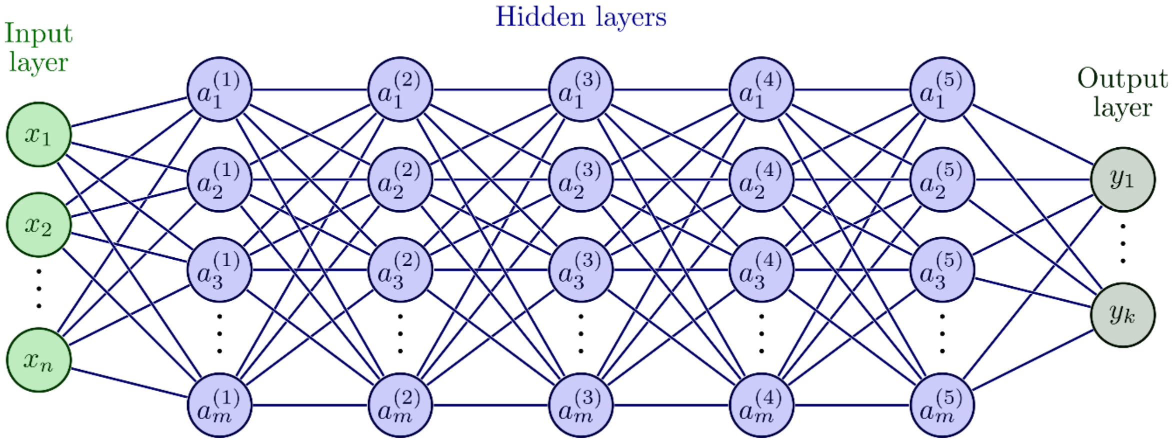
- First proposed by Grossi et al. (2023) [1]
- target variables: **event-level polarization fractions** as physical observables with well-defined distributions
- allows quantitative comparisons between predictions and MC truth
- systematic improvement and more detailed understanding possible

[1] M. Grossi, M. Incudini, M. Pellen, and G. Pelliccioli, *Amplitude-assisted tagging of longitudinally polarised bosons using wide neural networks.* Eur. Phys. J. C 83 (2023) no. 8, 759, arXiv:2306.07726 [hep-ph]. 26

NNs architectures

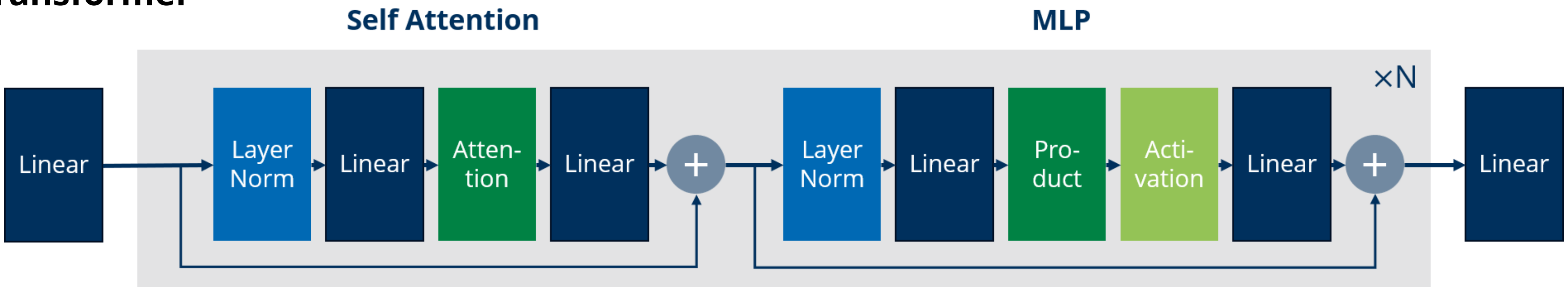


1) **Multilayer perceptron**



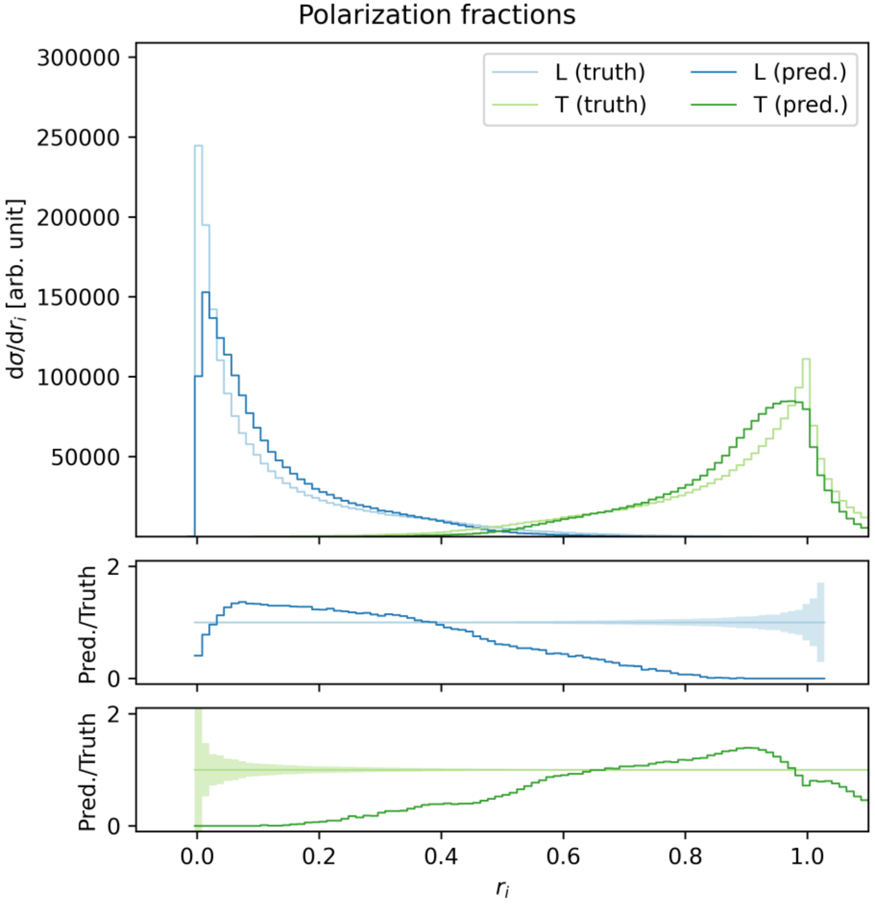
- Optimization of the NN hyperparameters with the framework **OPTIMA**[2]

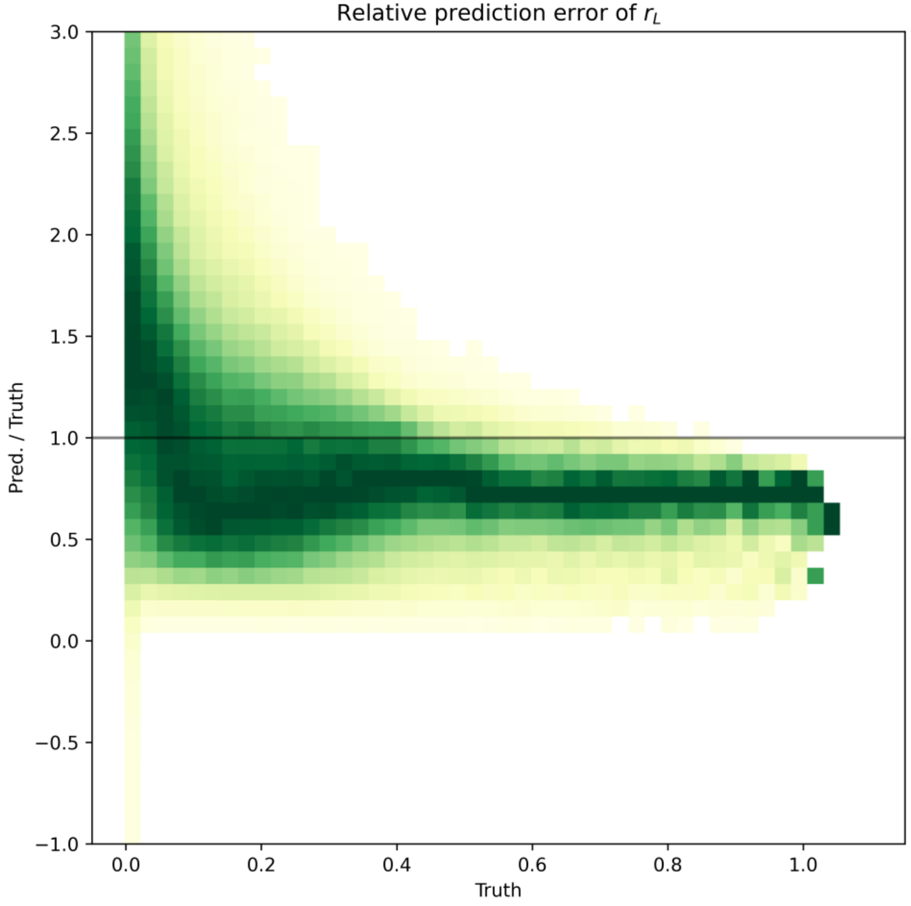
2) **Transformer**



[2] https://pypi.org/project/optima-ml/

First results for $pp \to Zj$ @LO+PS with MLP



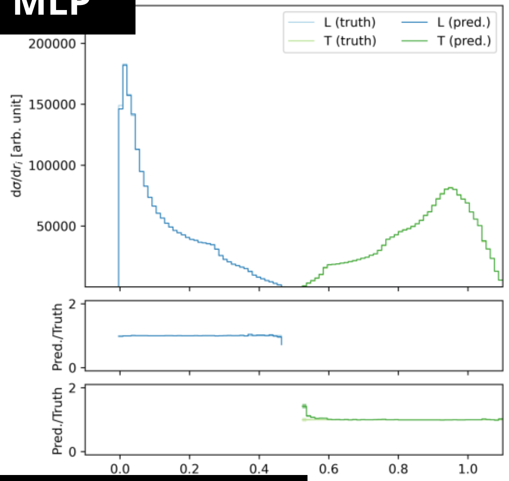


Results for *Z+jets* @ LO

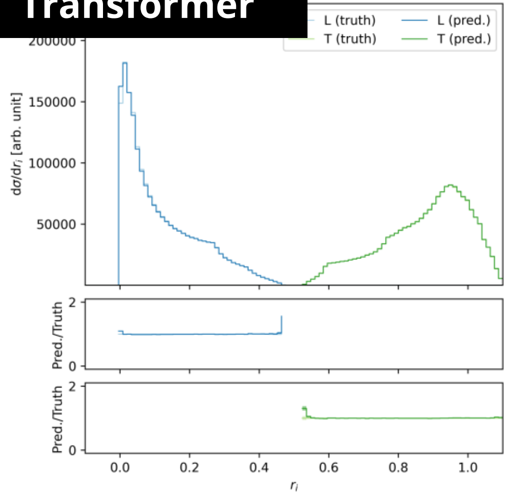
***Z+jets* @ LO** Distribution of r_L and r_T

$qg \to Zq$
PDF excluded

MLP



Transformer

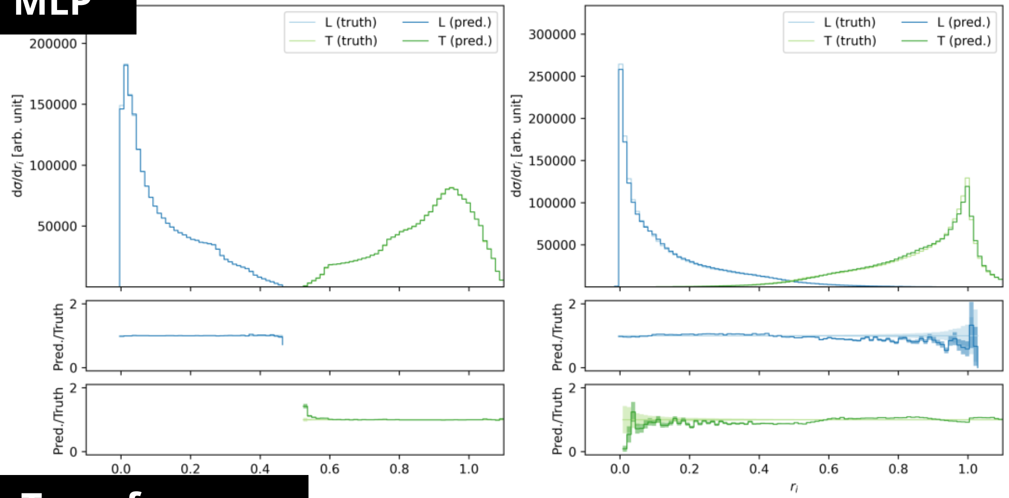


Z+jets @ LO Distribution of r_L and r_T

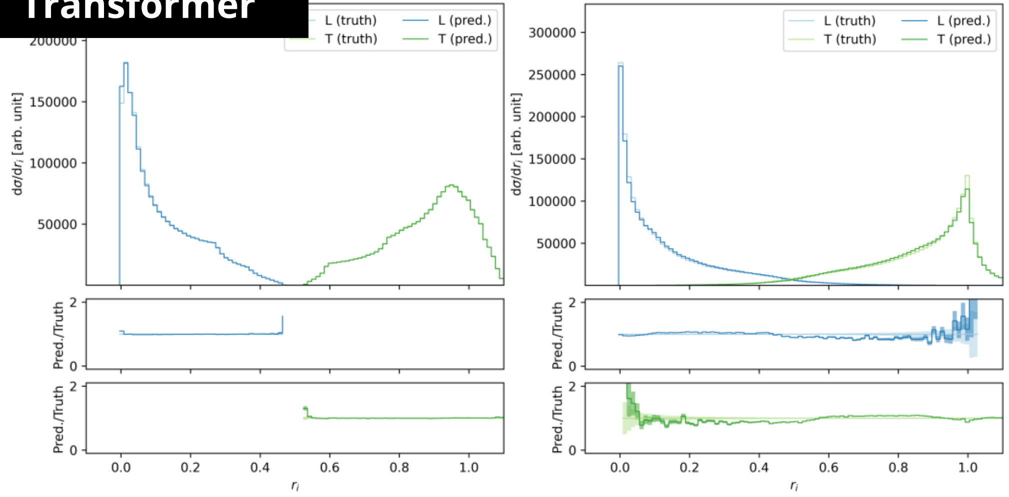
$qg \rightarrow Zq$
PDF excluded

$qg \rightarrow Zq$

MLP



Transformer

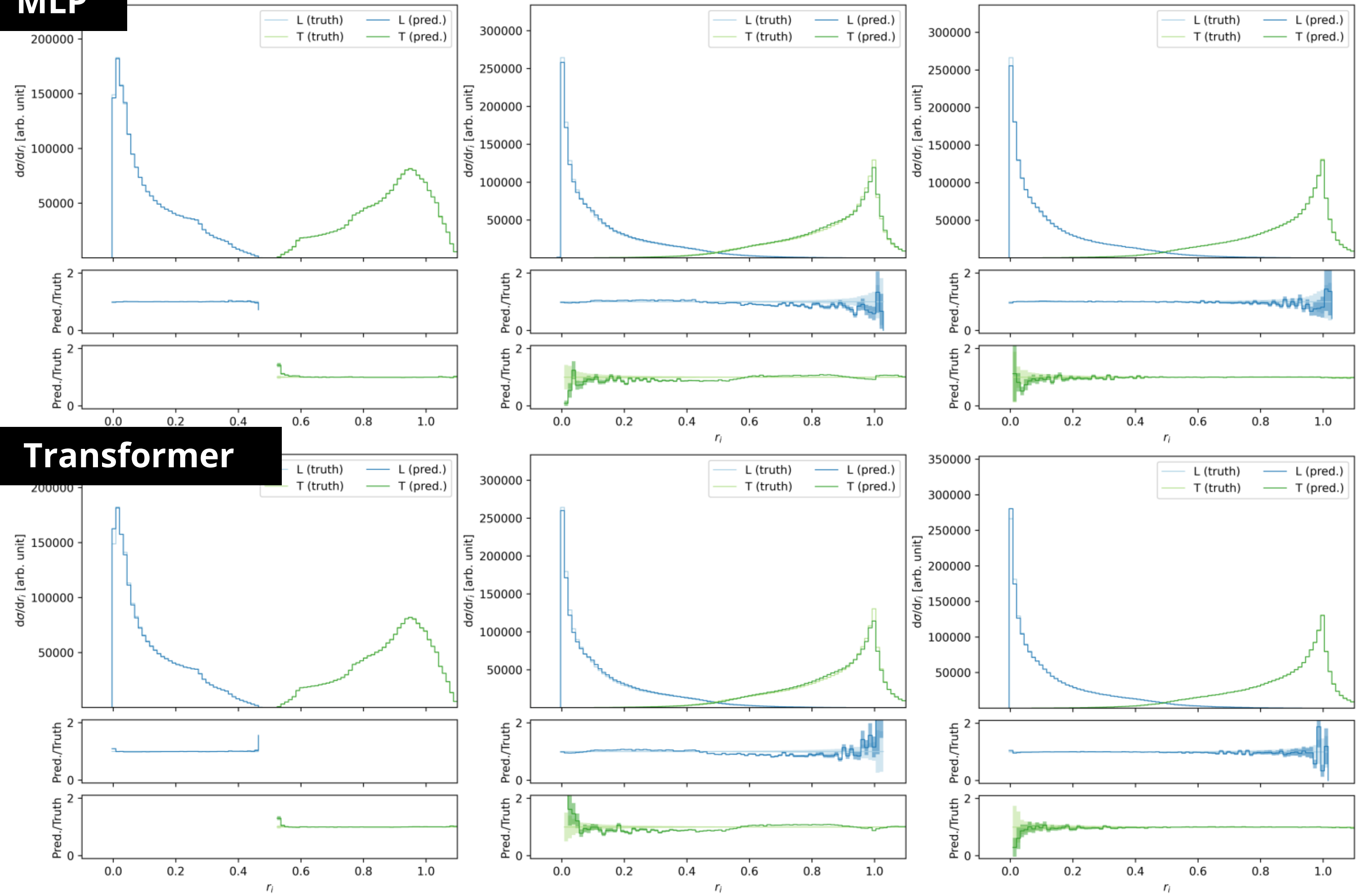


***Z+jets* @ LO** Distribution of r_L and r_T

$qg \to Zq$ PDF excluded	$qg \to Zq$	$qg \to Zq$ $p_{z,q} > 0$

MLP

Transformer

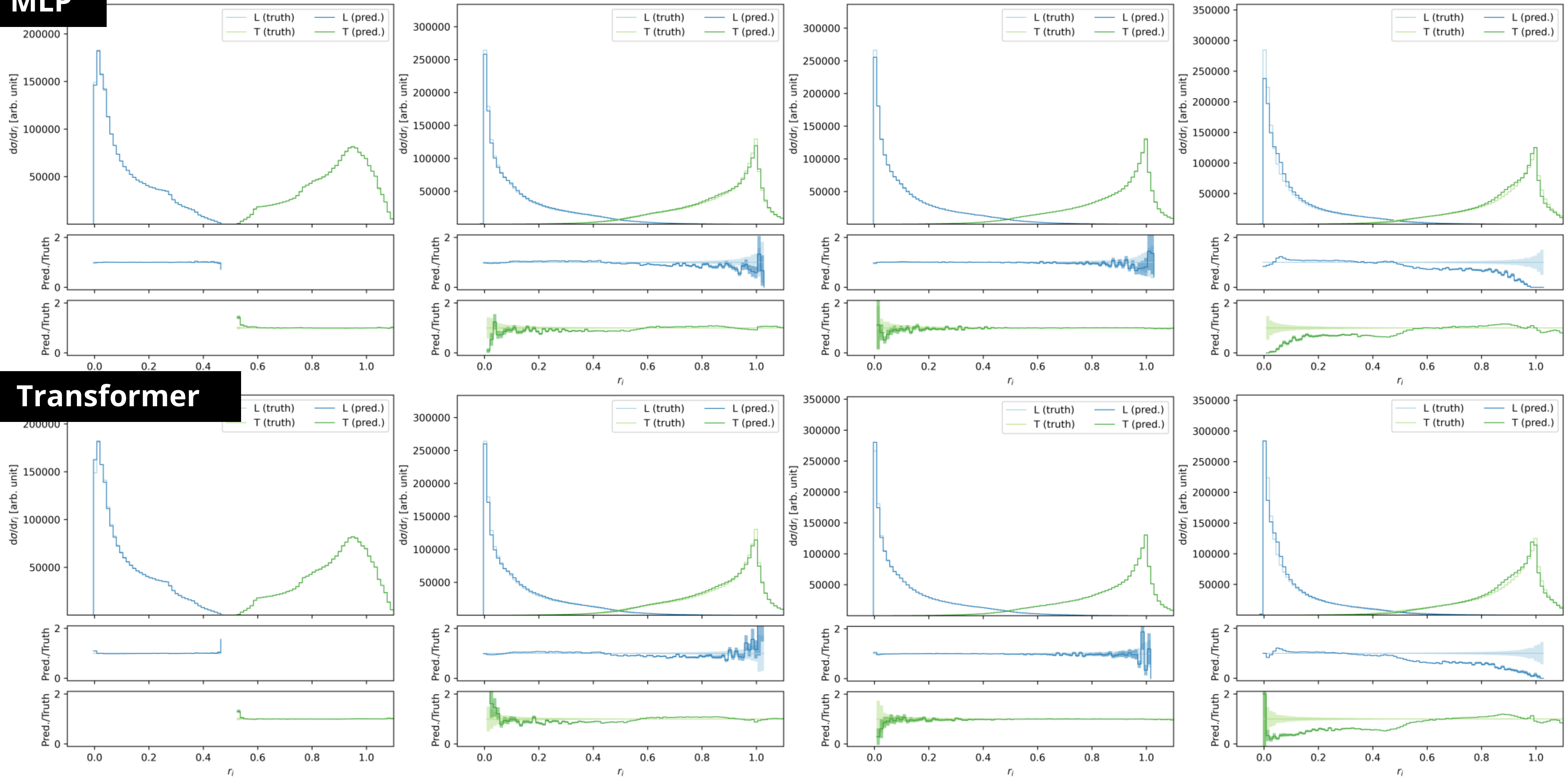


***Z+jets* @ LO** Distribution of r_L and r_T

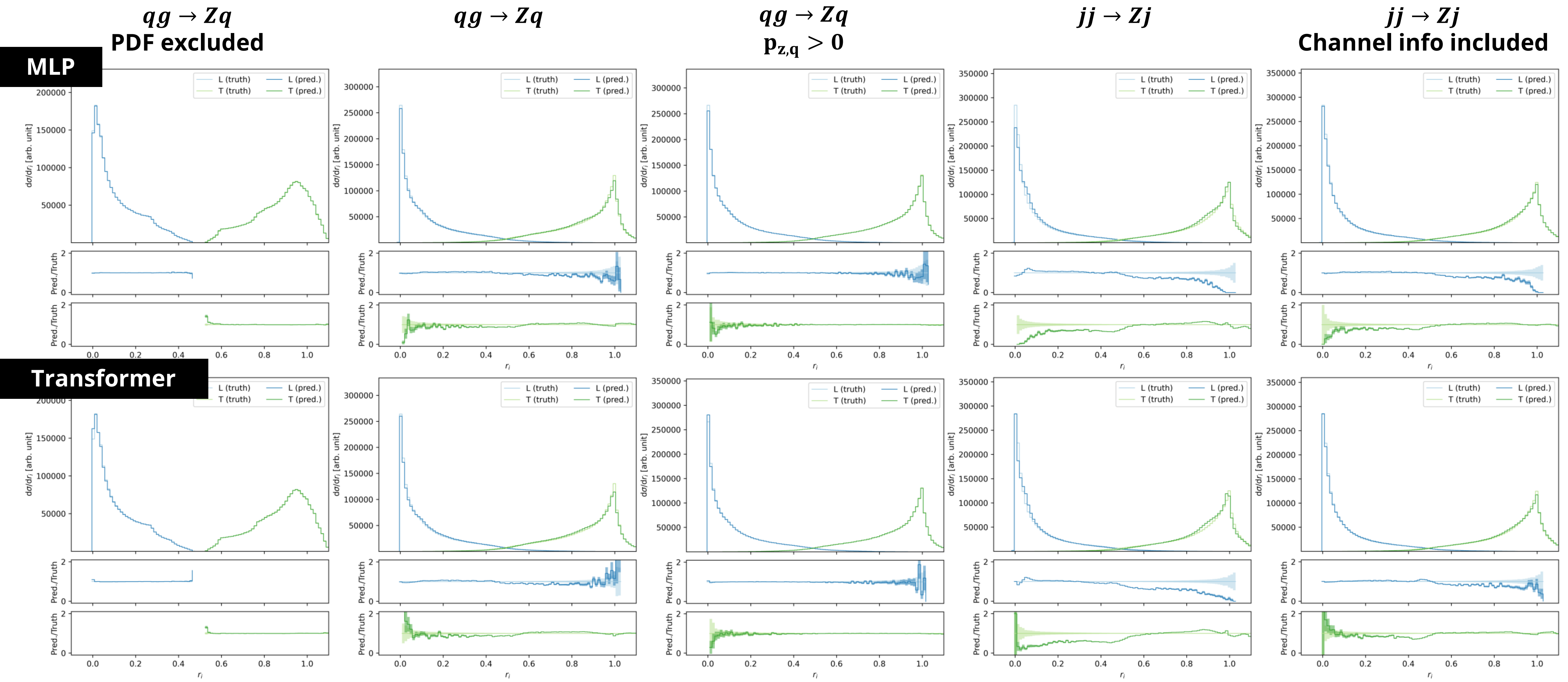
$qg \to Zq$ PDF excluded | **$qg \to Zq$** | **$qg \to Zq$ $\mathbf{p_{z,q}} > 0$** | **$jj \to Zj$**

MLP

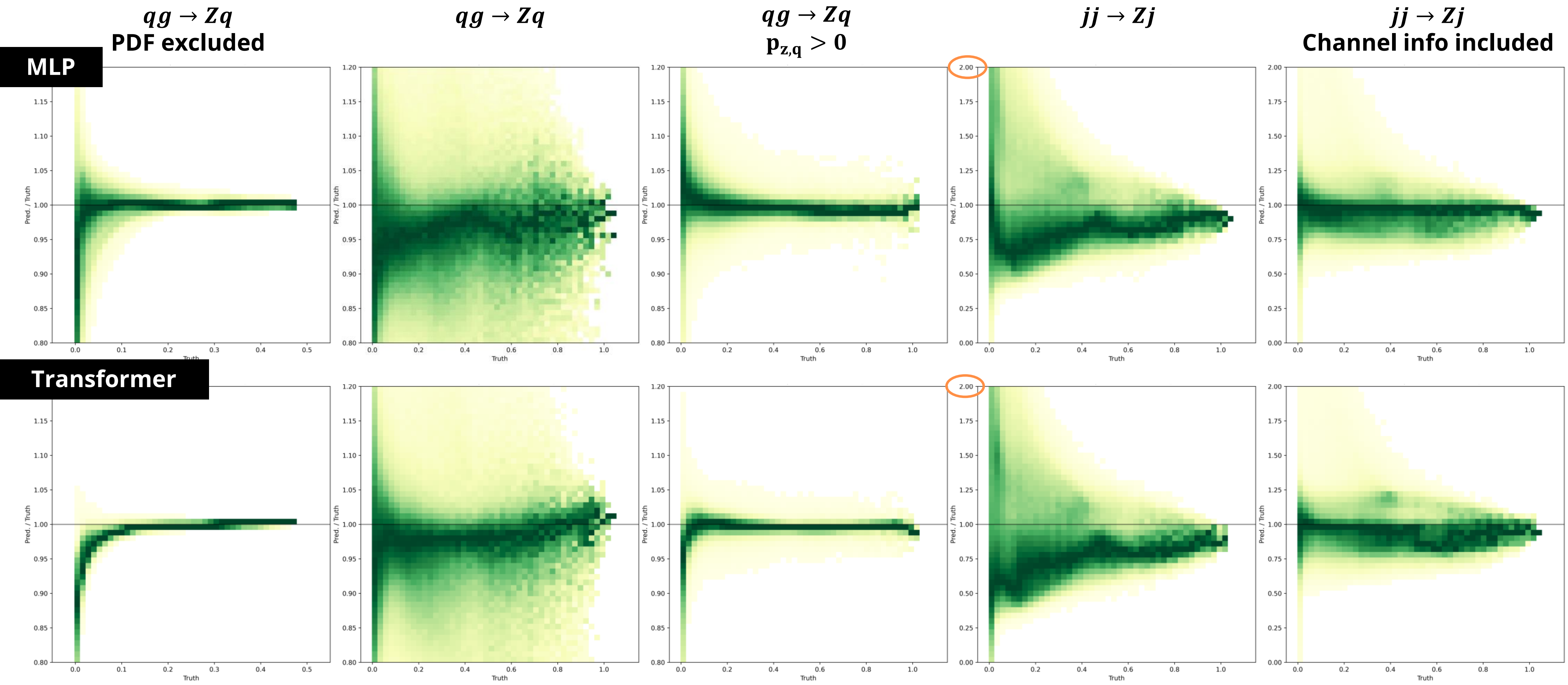
Transformer



Z+jets @ LO Distribution of r_L and r_T



Z+jets @ LO Relative Prediction Error of r_L

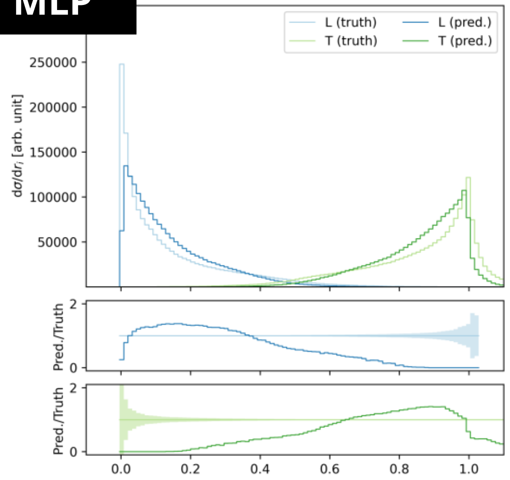


Results for *Z+jets* @ LO+PS

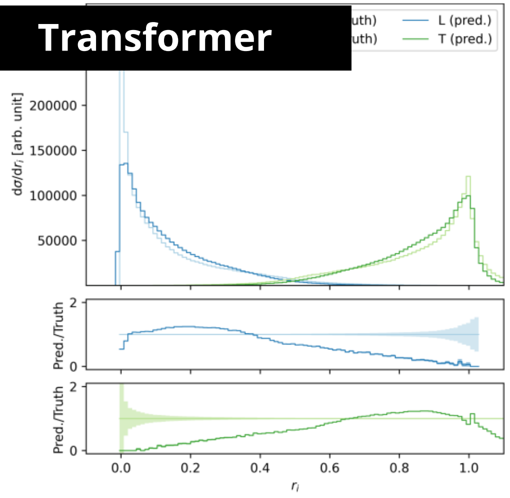
***Z+jets* @ LO+PS** Distribution of r_L and r_T

$qg \to Zq$

MLP



Transformer

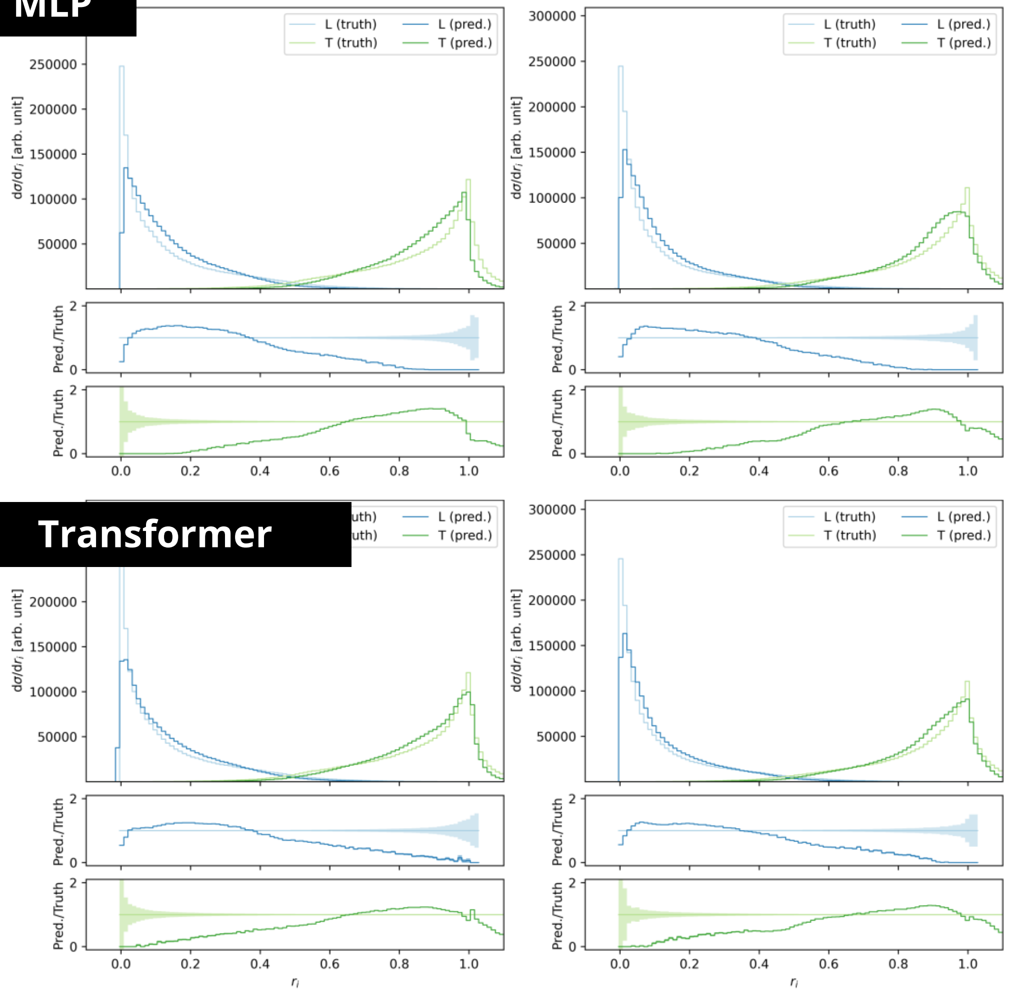


***Z+jets* @ LO+PS** Distribution of r_L and r_T

$qg \to Zq$ $jj \to Zj$

MLP

Transformer

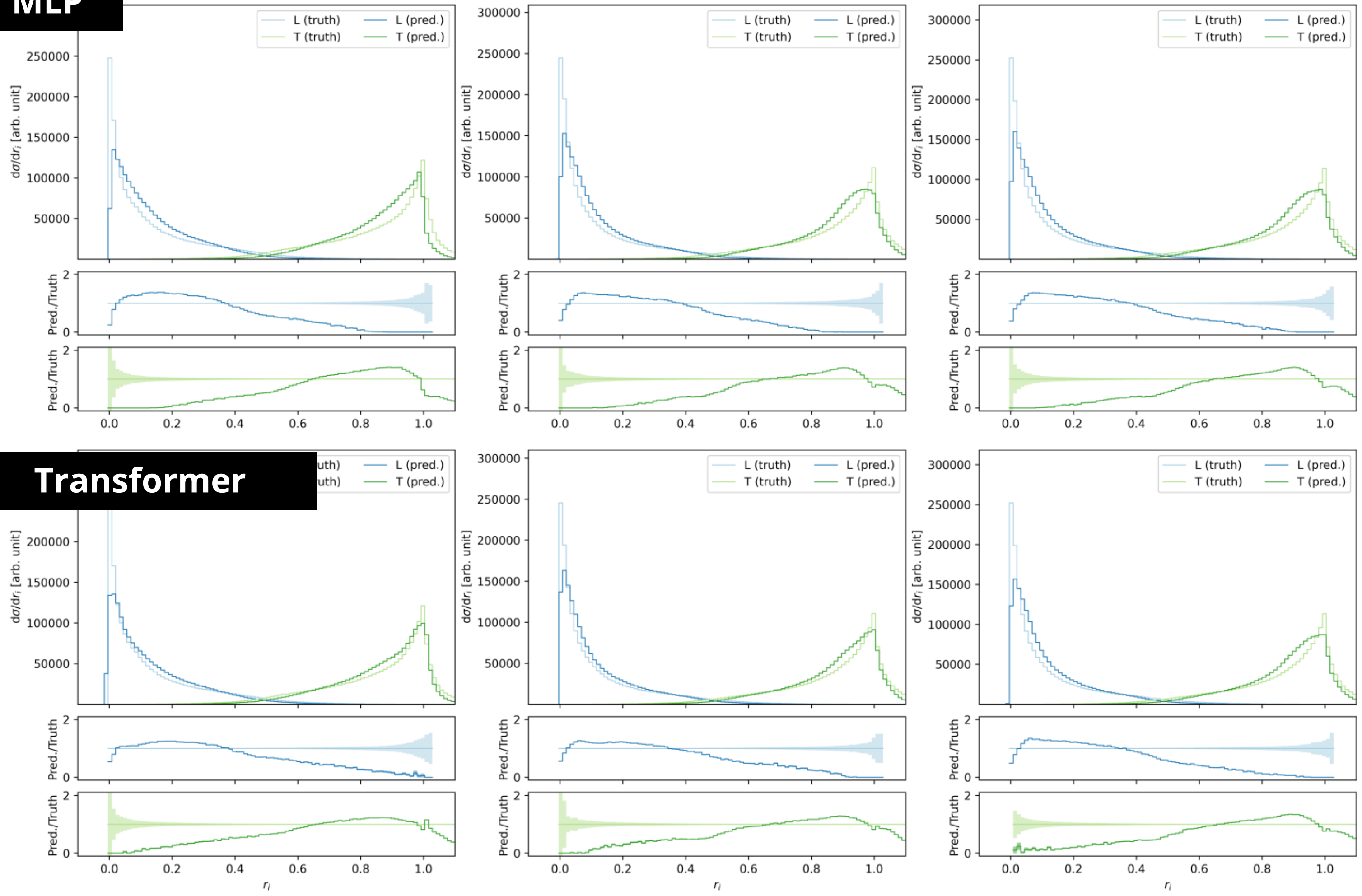


***Z+jets* @ LO+PS** Distribution of r_L and r_T

$qg \to Zq$	$jj \to Zj$	$jj \to Zj$ **QCD shower only**

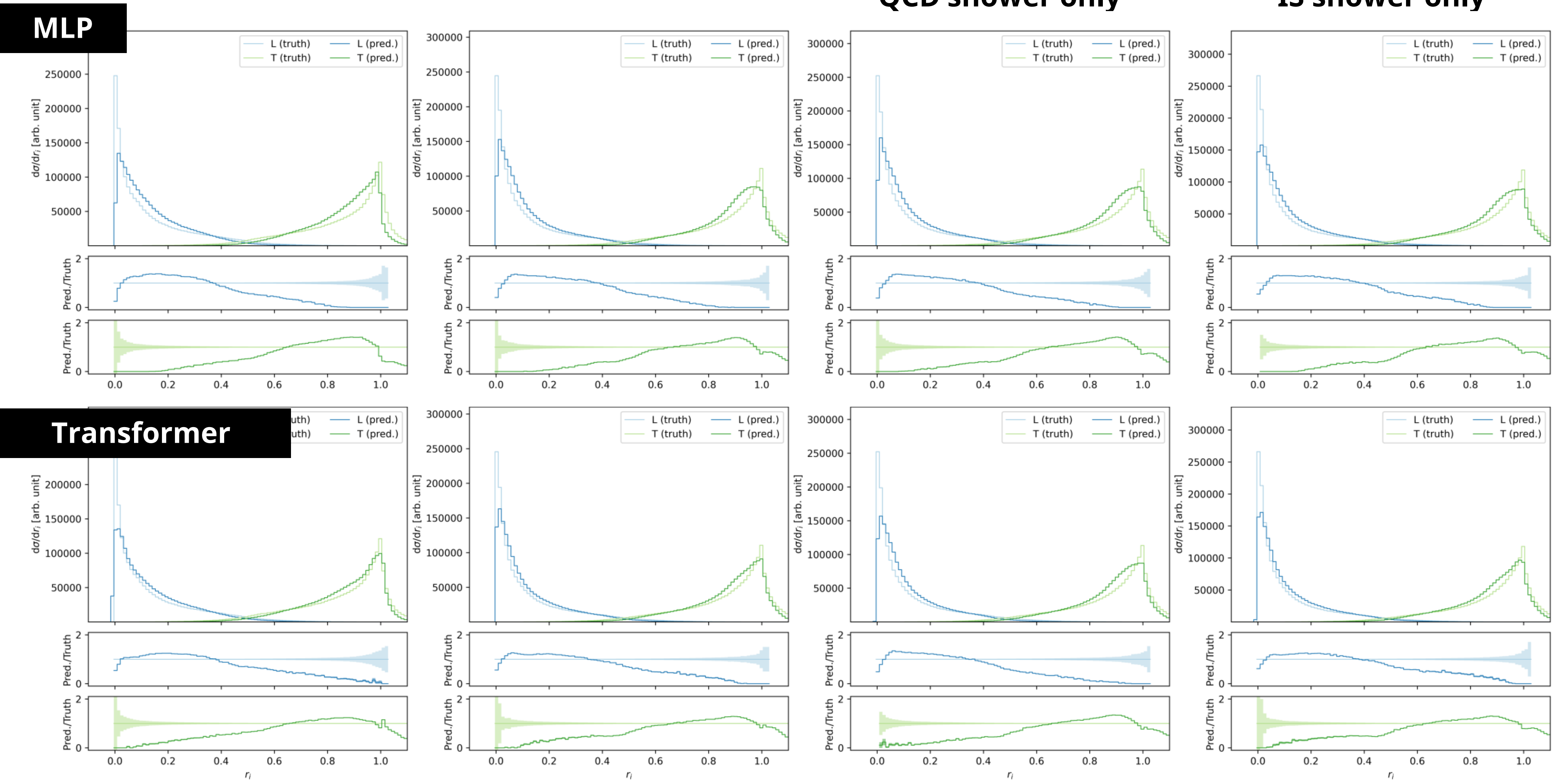
MLP

Transformer



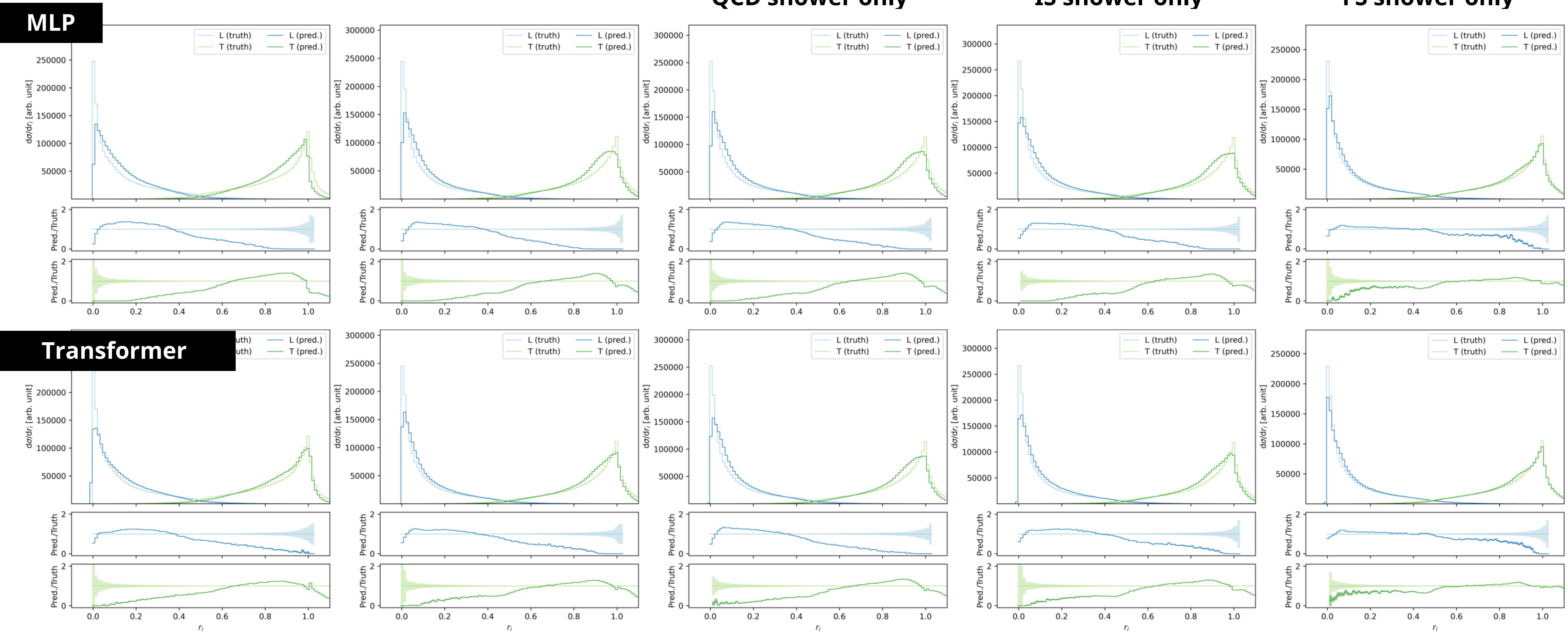
***Z+jets* @ LO+PS** Distribution of r_L and r_T

$qg \to Zq$	$jj \to Zj$	$jj \to Zj$ **QCD shower only**	$jj \to Zj$ **IS shower only**



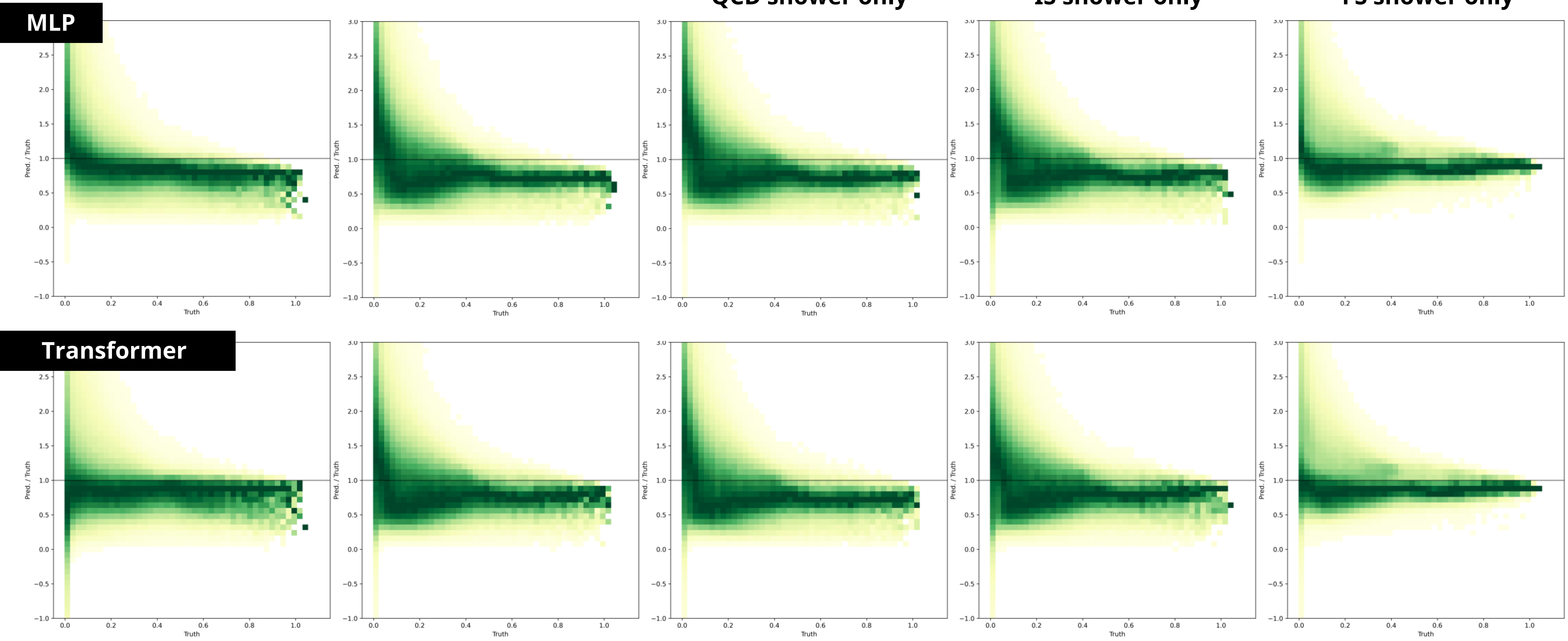
***Z+jets* @ LO+PS** Distribution of r_L and r_T

$qg \to Zq$ | $jj \to Zj$ | $jj \to Zj$ **QCD shower only** | $jj \to Zj$ **IS shower only** | $jj \to Zj$ **FS shower only**



***Z+jets* @ LO+PS** Relative Prediction Error of r_L

$qg \to Zq$	$jj \to Zj$	$jj \to Zj$ **QCD shower only**	$jj \to Zj$ **IS shower only**	$jj \to Zj$ **FS shower only**



Summary and outlook

Starting point: Longitudinal polarization of MVBs is a direct consequence of EWSB

→ serves as a sensitive probe of the Higgs mechanism and potential new physics

So far: classification-based formulation of polarization tagging with NNs

→ depends on abstract, nonphysical target variable with unknown distributions

Now: reformulation of polarization tagging as a regression task on **event-level polarization fractions**

Target variable: physical observables with well-defined distributions

→ quantitative comparisons between predictions and MC truth for systematic improvement

Examplary test case: *Z+jets* production at LO and LO+PS

What has to be taken into account when including **higher orders**?

Future studies: ***W+jets*** production and **diboson studies** like *WZjj-VBS*

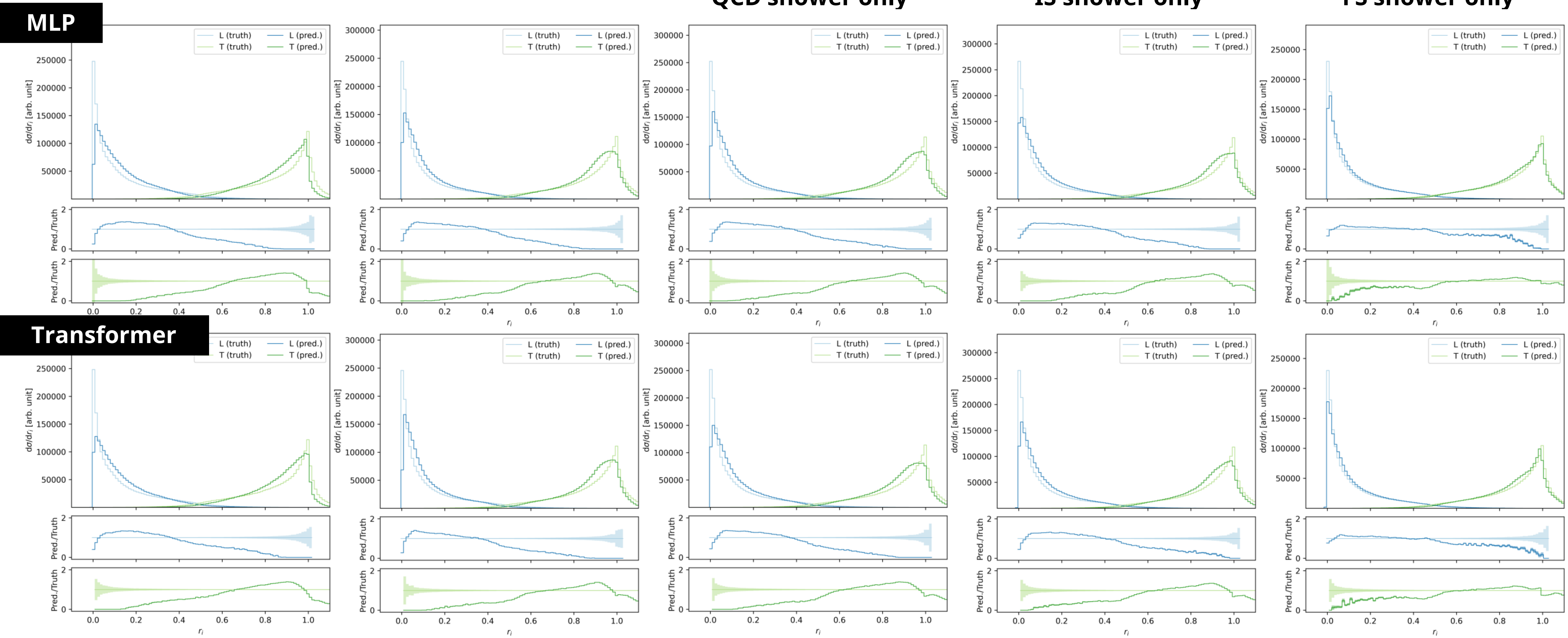
Thank you for your attention!

Appendix

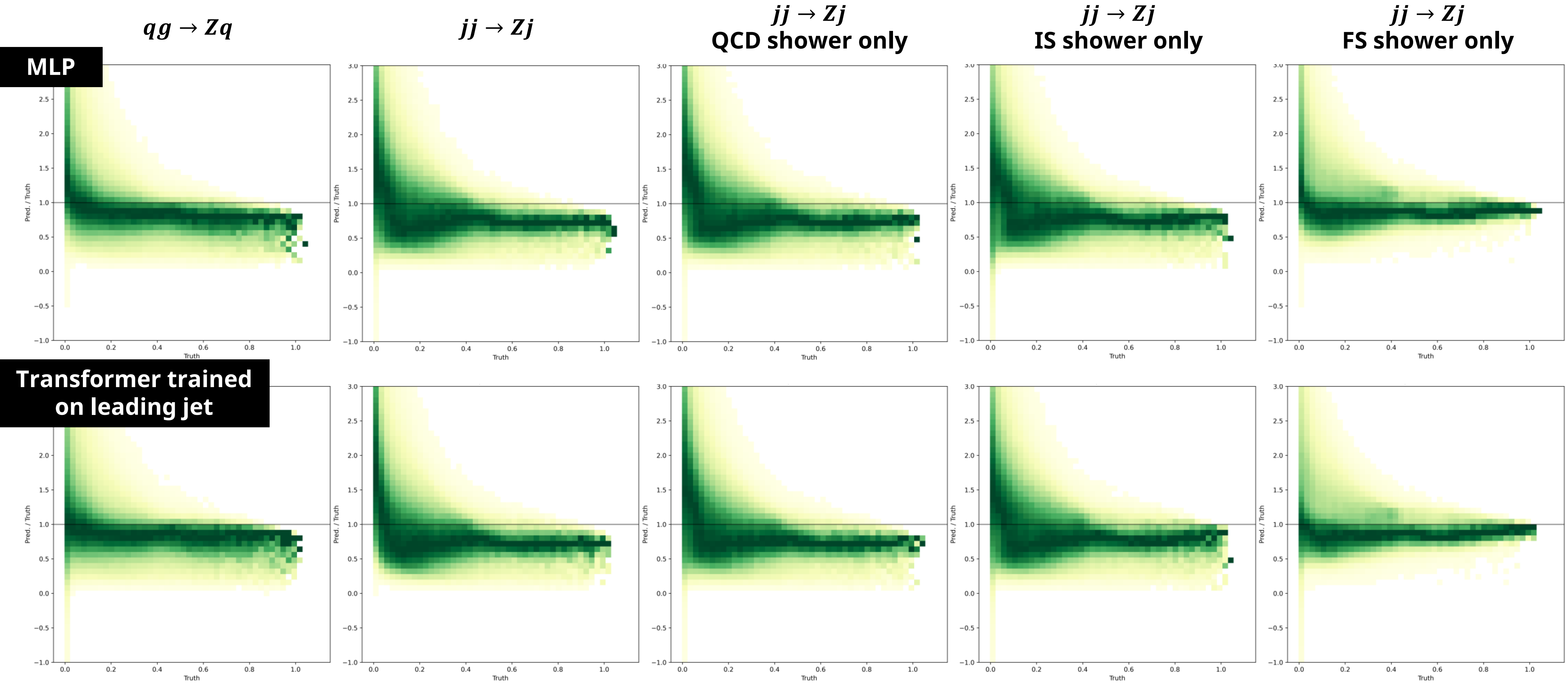
Results for *Z+jets* @ LO+PS

***Z+jets* @ LO+PS** Distribution of r_L and r_T

$qg \to Zq$	$jj \to Zj$	$jj \to Zj$ **QCD shower only**	$jj \to Zj$ **IS shower only**	$jj \to Zj$ **FS shower only**



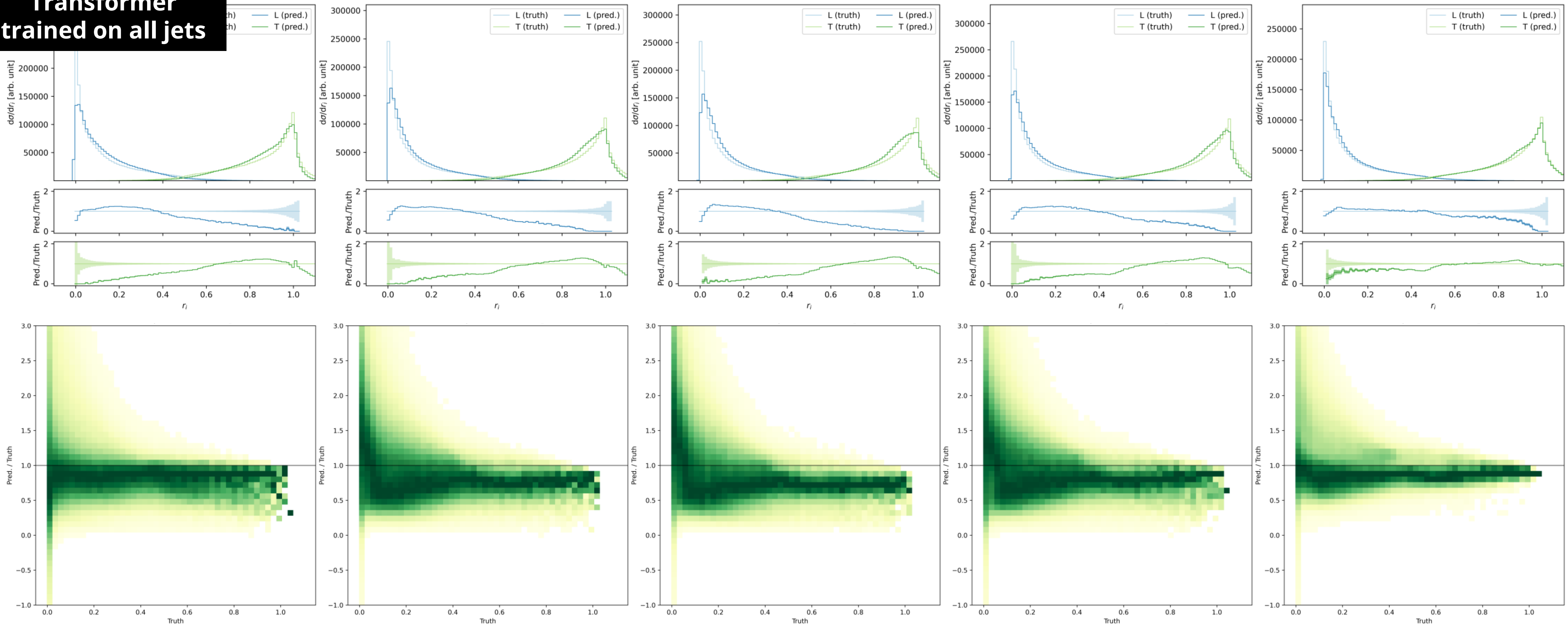
***Z+jets* @ LO+PS** Relative Prediction Error of r_L



Z+jets @ LO+PS

$qg \to Zq$ | $jj \to Zj$ | $jj \to Zj$ QCD shower only | $jj \to Zj$ IS shower only | $jj \to Zj$ FS shower only

Transformer trained on all jets

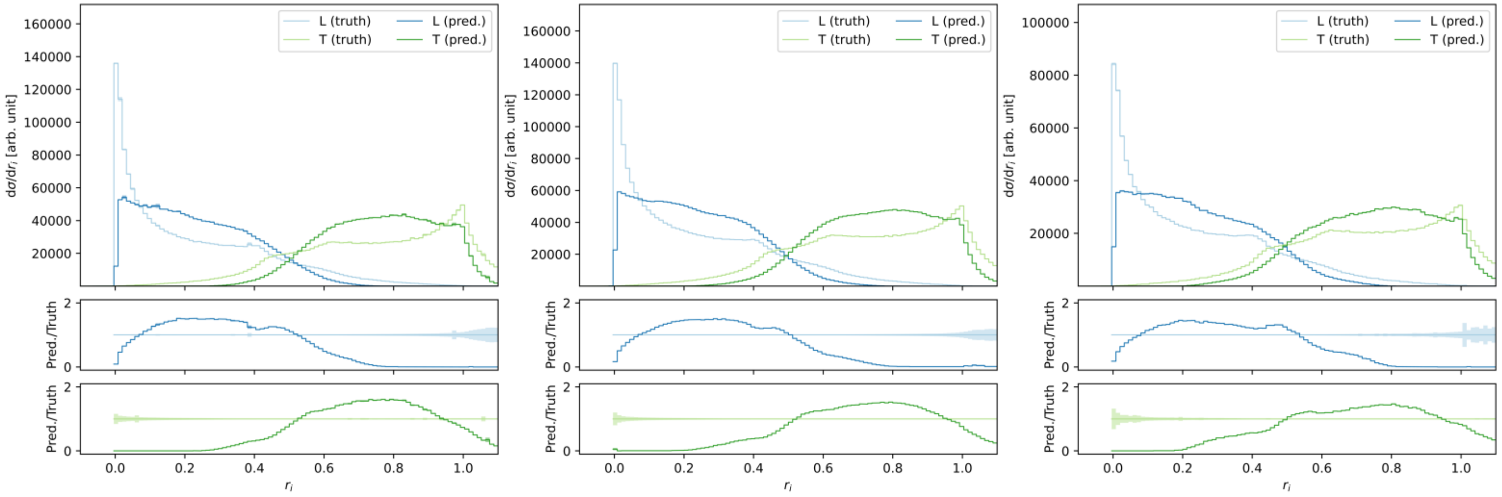


Results for *Z+jets* @ HO+PS

Z+jets @ HO+PS Distribution of r_L and r_T

MLP

$jj \to Zj$	$jj \to Zj$	$jj \to Zj$
1j@NLO + PS	**1j@NLO + 2,3j@LO + PS**	**1,2j@NLO + 3,4j@LO + PS**

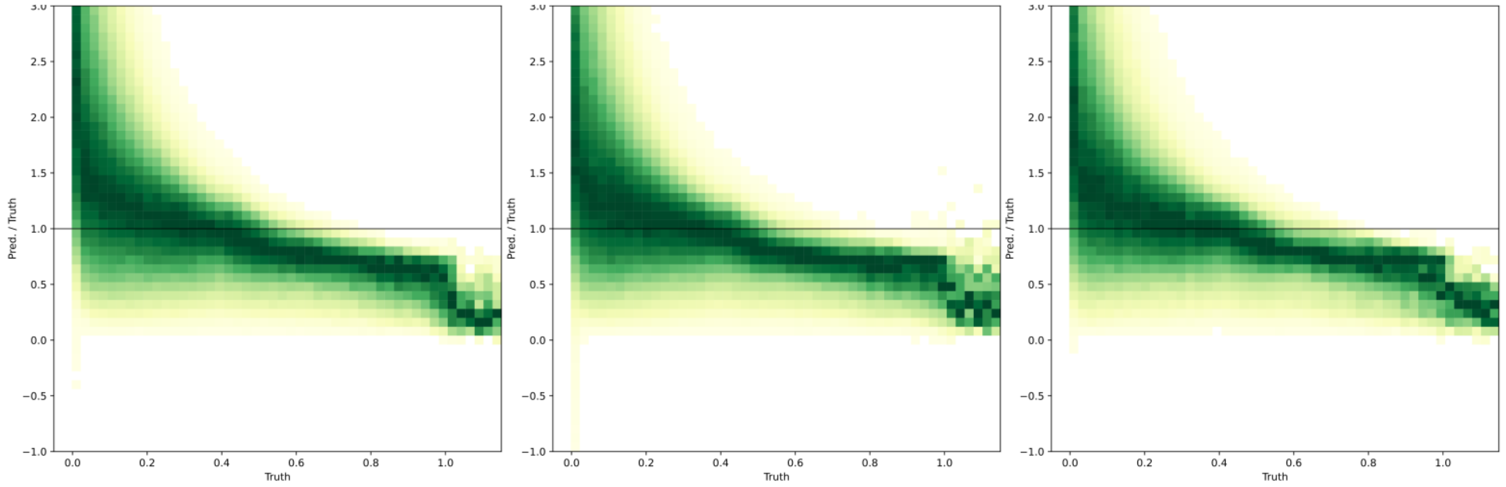


Transformer

***Z+jets* @ HO+PS** Relative Prediction Error of r_L

$jj \to Zj$ **1j@NLO + PS**	$jj \to Zj$ **1j@NLO + 2,3j@LO + PS**	$jj \to Zj$ **1,2j@NLO + 3,4j@LO + PS**

MLP

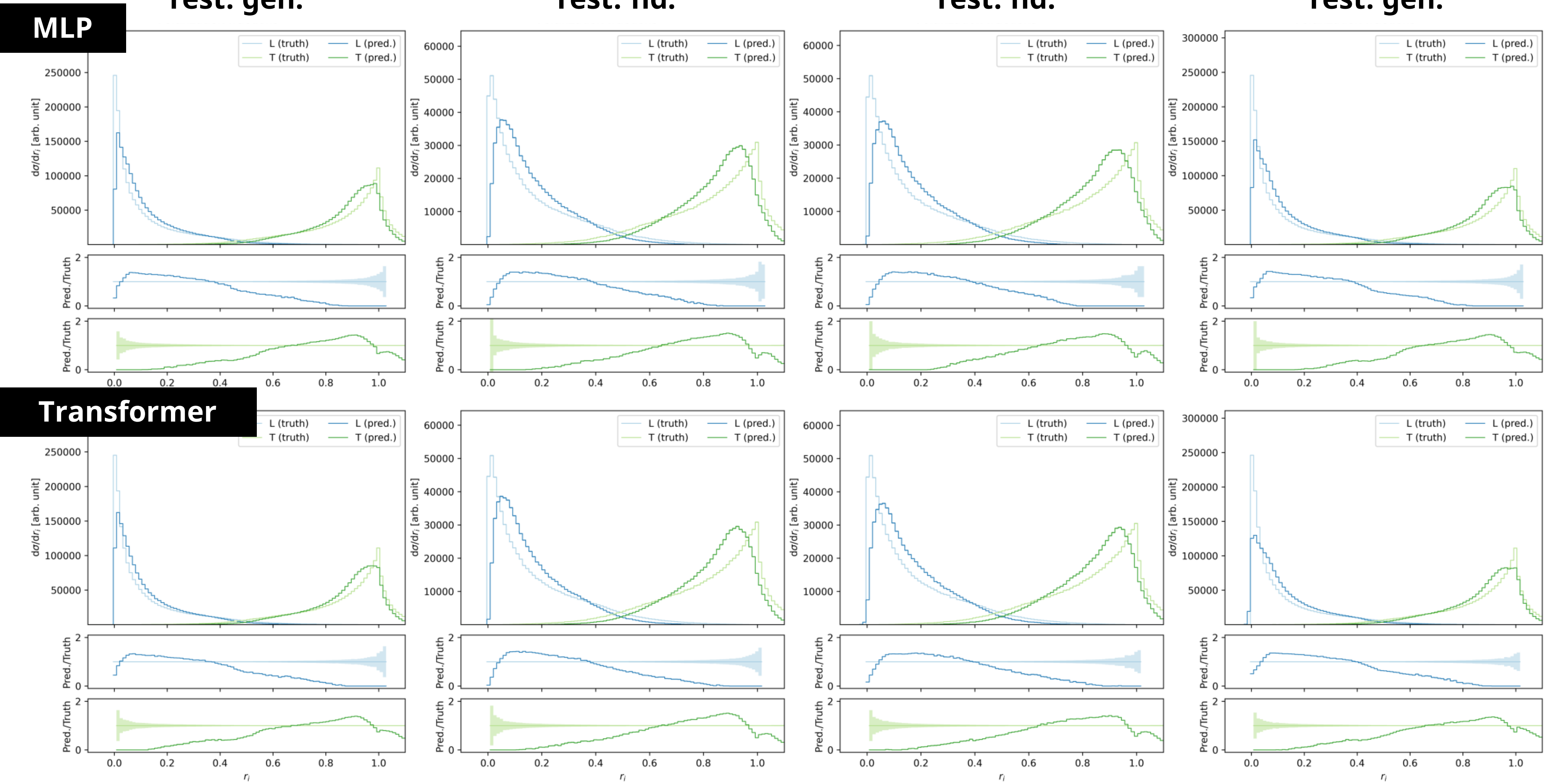


Transformer

Phasespace effects for *Z+jets* @ LO+PS

***Z+jets* @ LO+PS** Distribution of r_L and r_T

Train: gen. Test: gen.	**Train: gen. Test: fid.**	**Train: fid. Test: fid.**	**Train: fid. Test: gen.**



Generator

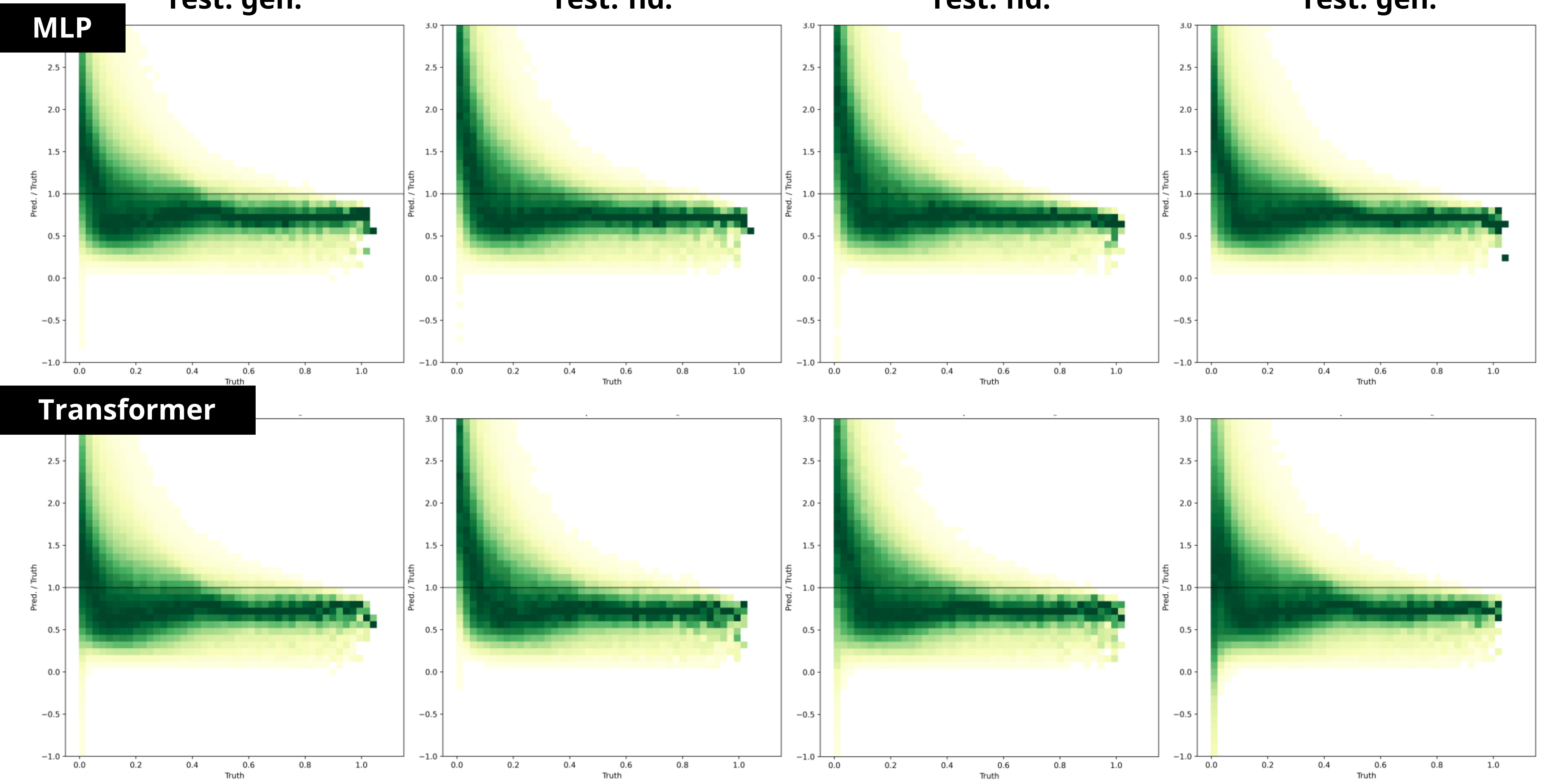
$p_{T,j} > 10$ GeV
$|\eta_j| < 5$
81 GeV $< m_Z <$ 101 GeV
$\Delta R_{jl} > 0.2$

Fiducial

$p_{T,j} > 20$ GeV
$|\eta_j| < 4$
81 GeV $< m_Z <$ 101 GeV
$p_{T,l1} > 20$ GeV
$p_{T,l2} > 20$ GeV
$|\eta_{l1}| < 2.7$
$|\eta_{l2}| < 2.7$
$\Delta R_{jl} > 0.2$

***Z+jets* @ LO+PS** Relative Prediction Error of r_L

Train: gen. Test: gen.	Train: gen. Test: fid.	Train: fid. Test: fid.	Train: fid. Test: gen.



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$p_{T,l2} > 20$ GeV

$|\eta_{l1}| < 2.7$

$|\eta_{l2}| < 2.7$

$\Delta R_{jl} > 0.2$

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→ serves as a sensitive probe of the Higgs mechanism and potential new physics

So far: classification-based formulation of polarization tagging with NNs

→ depends on abstract, nonphysical targets with unknown distributions

Now: reformulation of polarization tagging as a **regression task** on event-level polarization fractions

Input: experimentally accessible final-state quantities

Target: physical observables with well-defined distributions

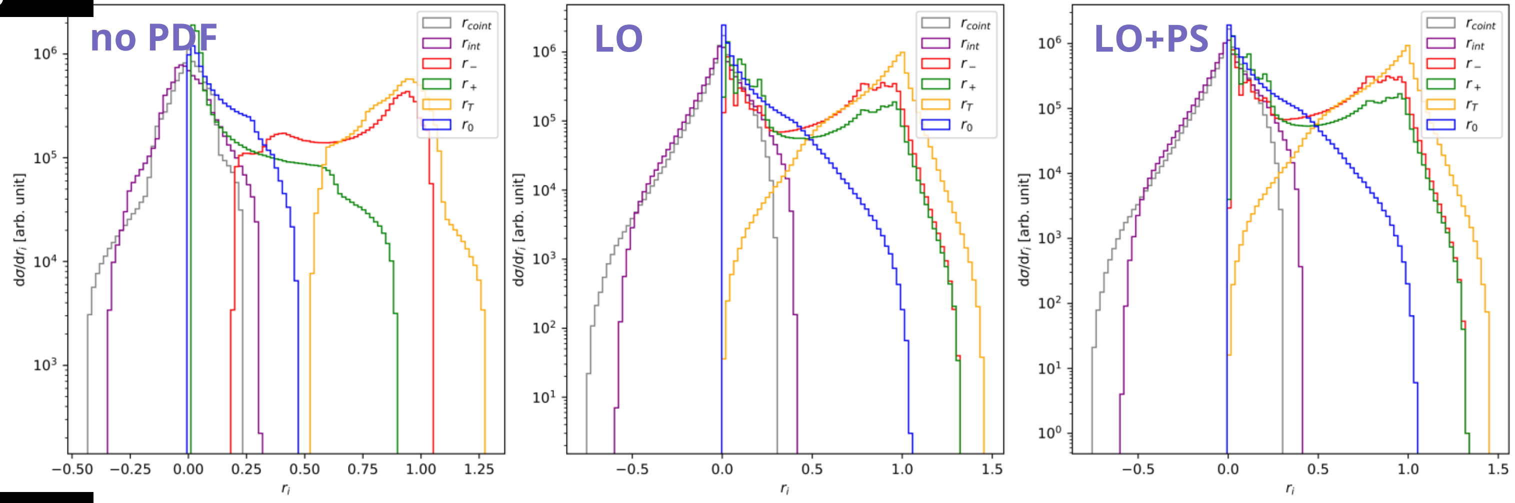
→ quantitative comparisons between predictions and MC truth for systematic improvement

Future studies: *W+jets* as well as diboson studies such as WZjj-VBS

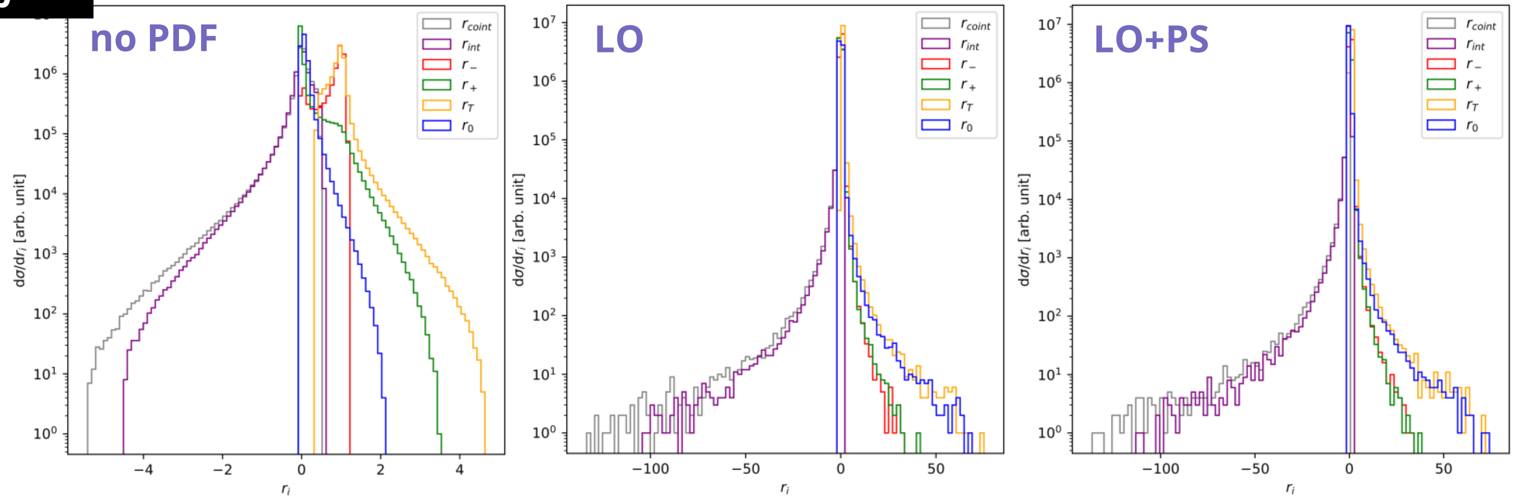
Results for *W+jets* and *WZjj-VBS*

Distribution of the Polarization Fractions

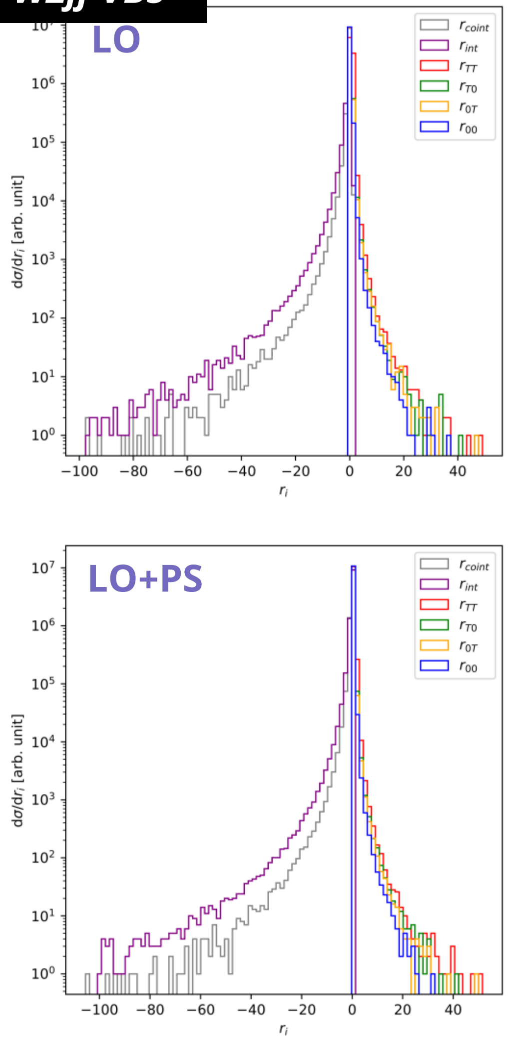
Z+jets



W+jets

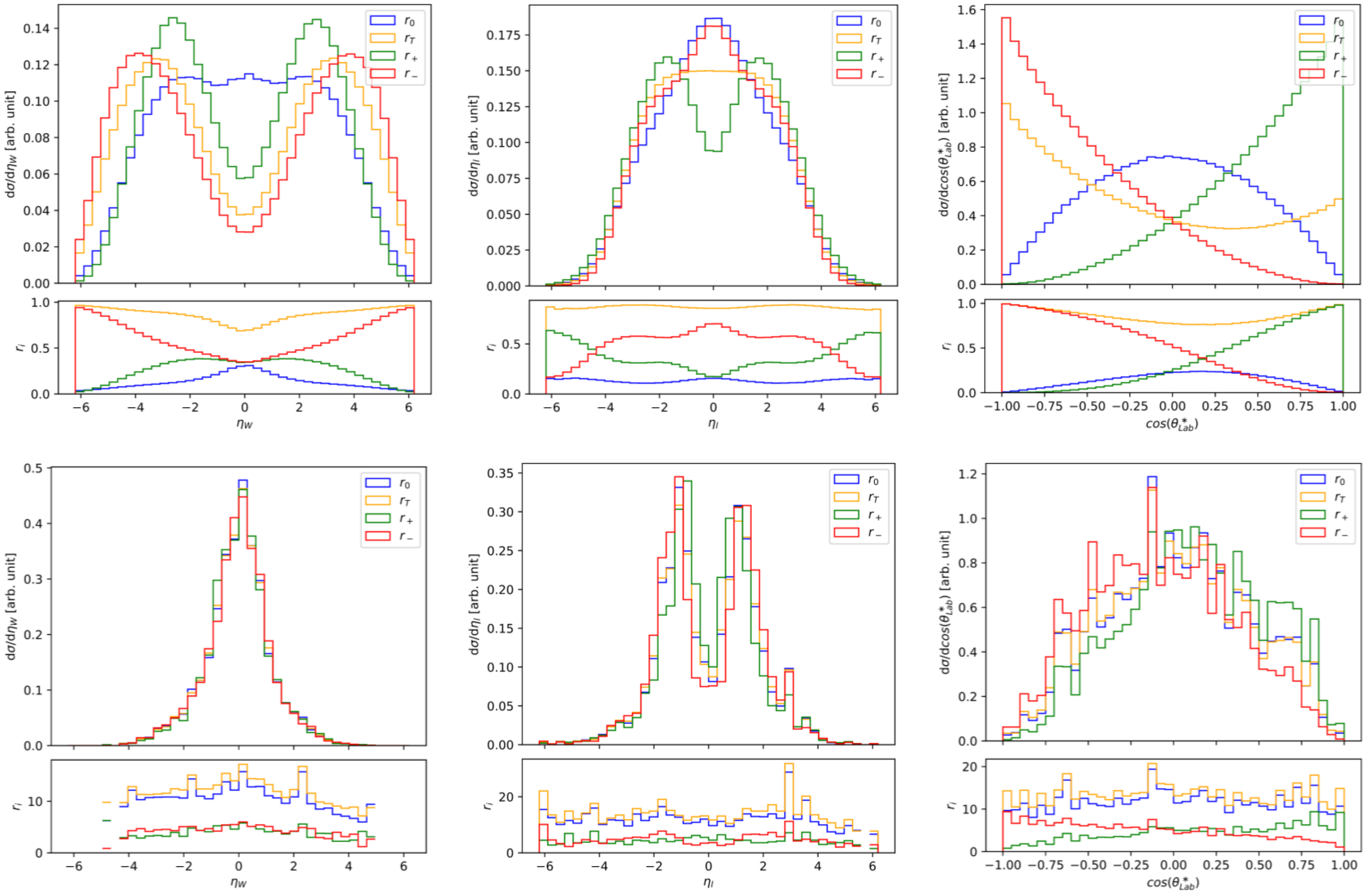


WZjj-VBS



Kinematic Distributions for the Polarized Samples

W+jets

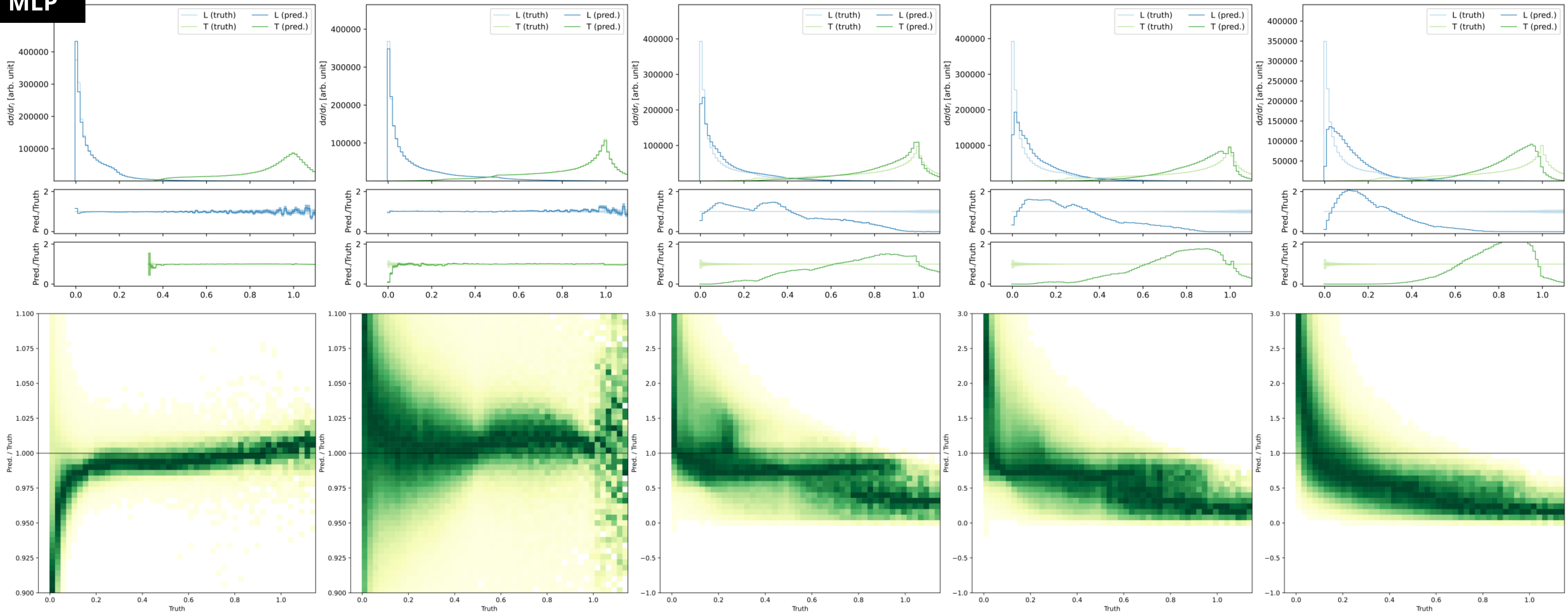


Systematic differences between kinematic distributions for all events vs. only events with extreme fractions!

Results for *W+jets*

MLP

$qg \to W^+q'$ @ LO without PDF	$qg \to W^+q'$ @ LO $p_{z,q} > 0$	$jj \to W^+j$ @ LO	$jj \to W^+j$ @ LO with E_T^{miss}	$jj \to W^+j$ @ LO+PS with E_T^{miss}



Results for *WZjj-VBS*

MLP

$jj \to W^+Zjj$ @ LO with ν_{prompt}	$jj \to W^+Zjj$ @ LO with E_T^{miss}	$jj \to W^+Zjj$ @ LO with auxiliary task	$jj \to W^+Zjj$ @ LO+PS with ν_{prompt}	$jj \to W^+Zjj$ @ LO+PS with E_T^{miss}