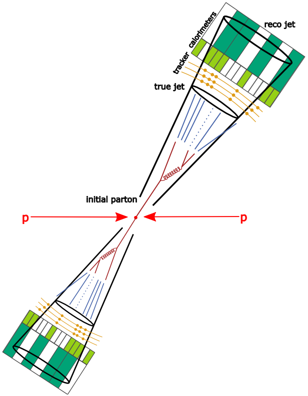
Exploring Surprising Non-Perturbative Effects in Drell-Yan plus Jets

Standard Model at the LHC 2025

Stefan Gieseke, **Maximilian Horzela**, Manjit Kaur, Dari Leonardi, Klaus Rabbertz, Aayushi Singla, Cedric Verstege

unless otherwise indicated the presented contents were originally made public on arXiv:2412.19694

Triple Differential Measurement of Dijet



- Multidifferential cross section measurement with LHC data unfolded for detector effects

  EPJC 77 (2017) 746, EPJC 85 (2025) 72

  $\langle p_T \rangle \leftarrow$ Energy scale of hard collision

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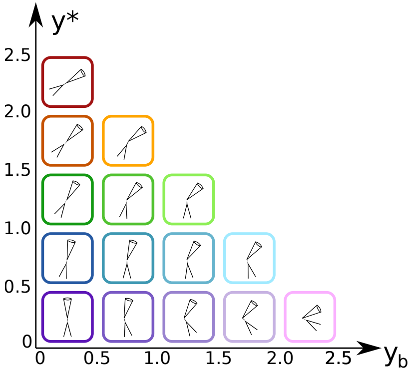

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  $y_b = \frac{1}{2}|y^{\text{jet1}} + y^{\text{jet2}}| \leftarrow x_1, x_2$

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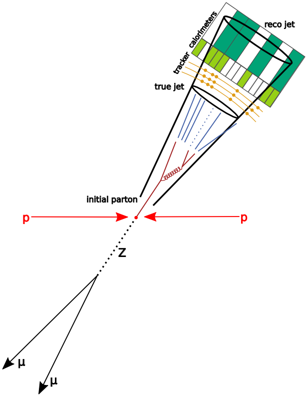
$\rightarrow$ Tuned for tests and interpretations of perturbative modelling, i.e. PDFs

Triple Differential Measurement of Z+Jet



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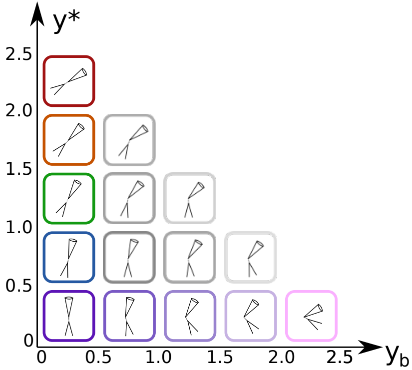
- Add complementary sensitivity with additional final states

Non-perturbative Contributions to Dijet

- Estimation of non-perturbative (NP) effects
  - → Additional precision limitations for perturbative interpretation
- NP correction factor

$$C_{\mathrm{NP}} = \frac{\mathrm{ME} + \mathrm{PS} + \mathrm{Had} + \mathrm{MPI}}{\mathrm{ME} + \mathrm{PS}}$$



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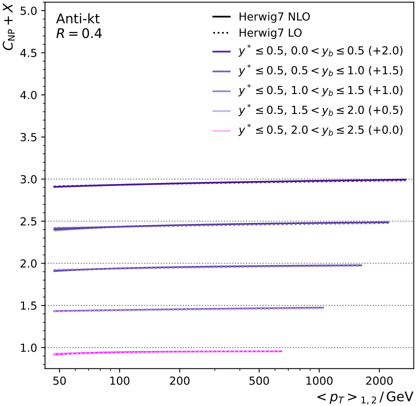
  - No significant y_b dependence



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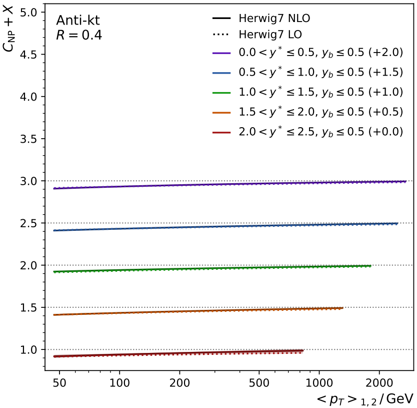

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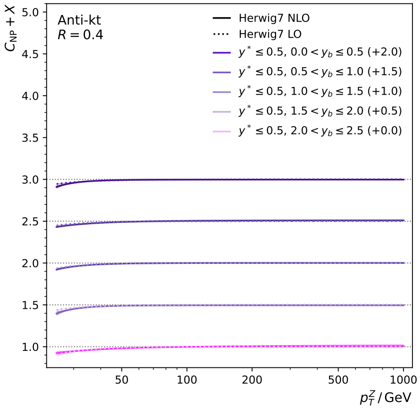

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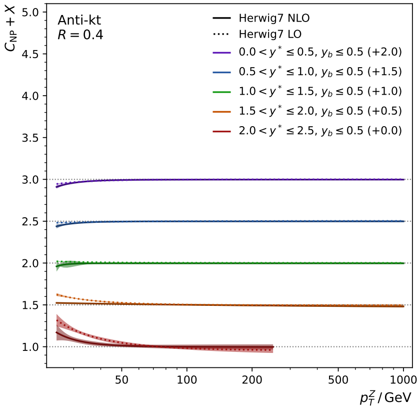

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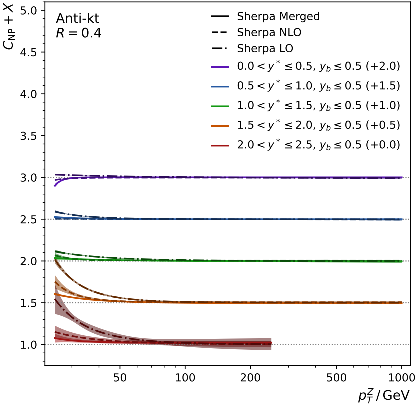

Hadronization Effects in Z+Jet

- Estimate influence by Hadronization with

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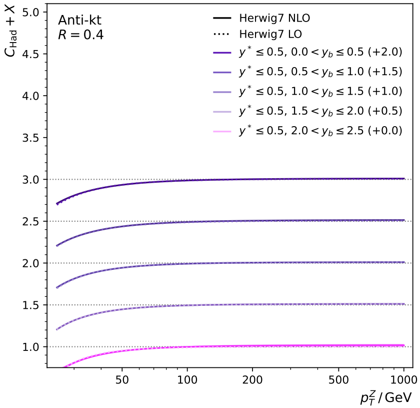

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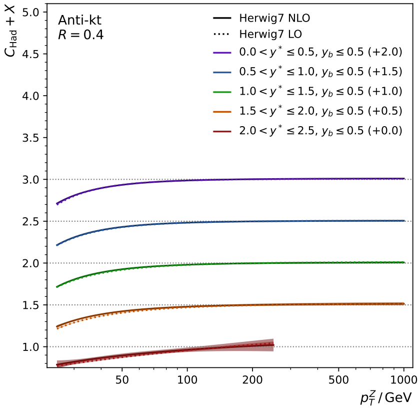

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Underlying Event (UE) Effects in Z+Jet

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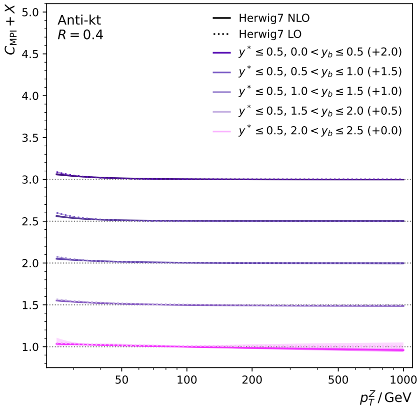

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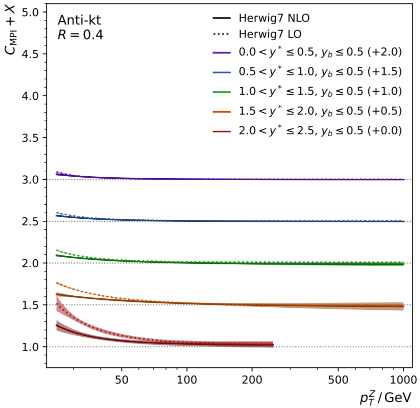
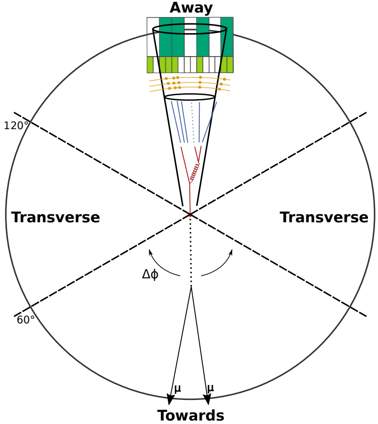
→ Origin of observed trends in UE modelling



A Deeper Look into the UE in Z+Jet

- Measure activity, e.g. N_{ch}, $\sum_{i=1}^{N_{\text{ch}}} p_T^{\text{ch}}$, in "Rick-Field-style" analysis
  - Towards: Leading hard object
  - Away: Hard hadronic recoil
  - Transverse: Soft UE contributions
  - → Important input for tuning of UE models



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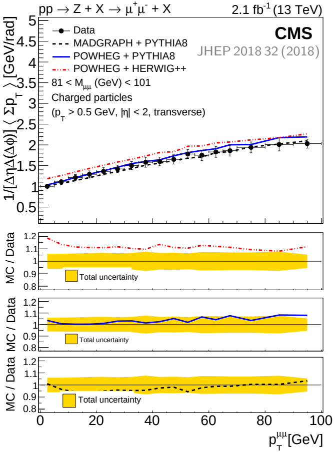
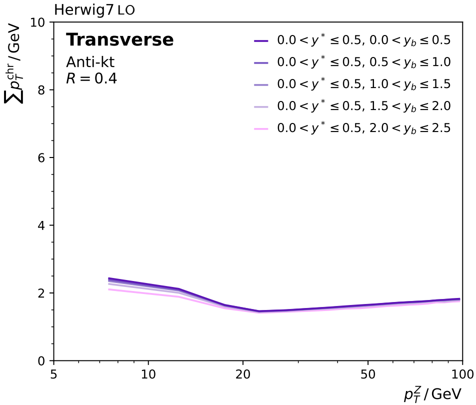
  $\longrightarrow$ Important input for tuning of UE models
- Most recent analyses by ATLAS EPJC 79 666 (2019) and CMS JHEP 2018 32 (2018) with $\sqrt{s} = 13$ TeV low-pileup data
  - Single differential in p_T^Z

  $\longrightarrow$ What to expect differentially in y^* (y_b)?



UE Activity in the Transverse Region



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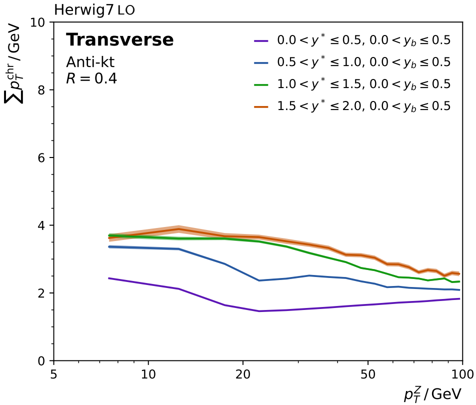

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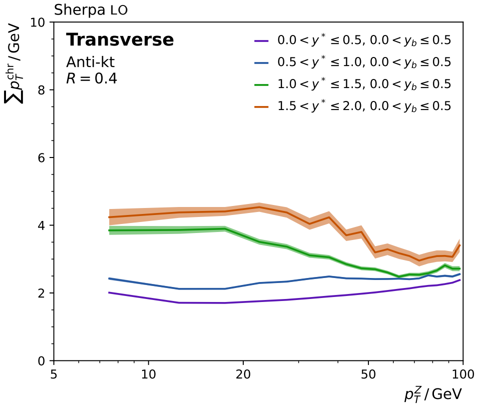

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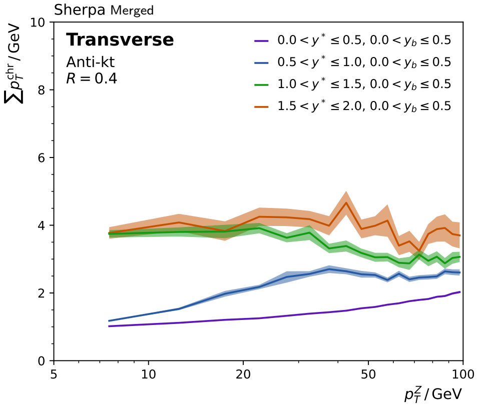

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- Slight dependence on perturbative order

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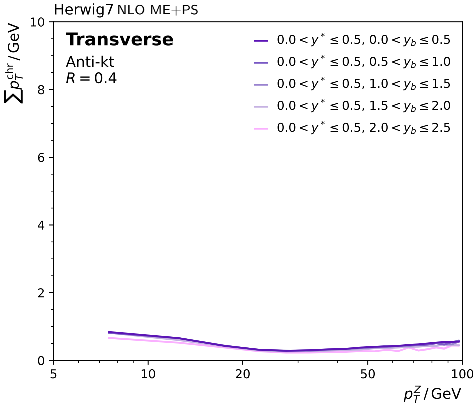

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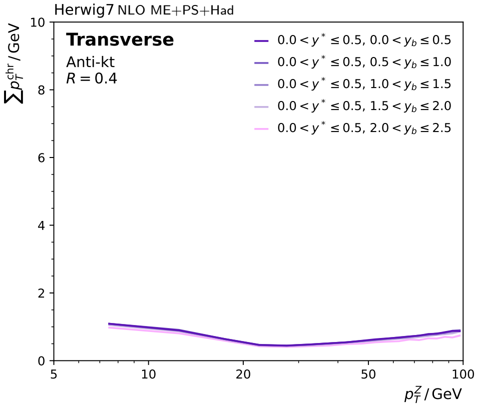

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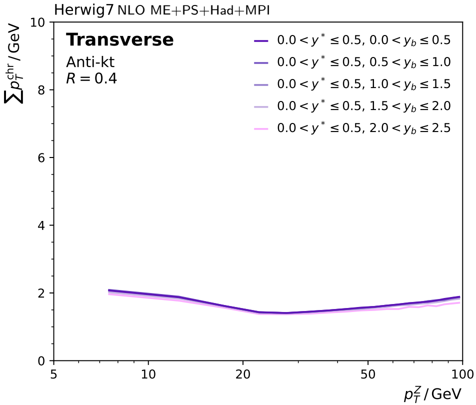

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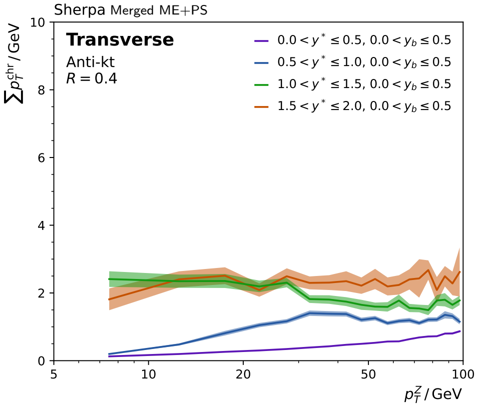

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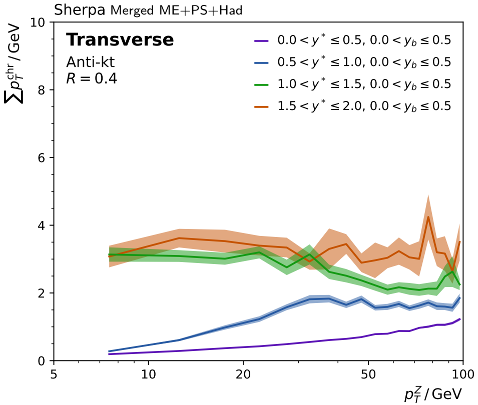

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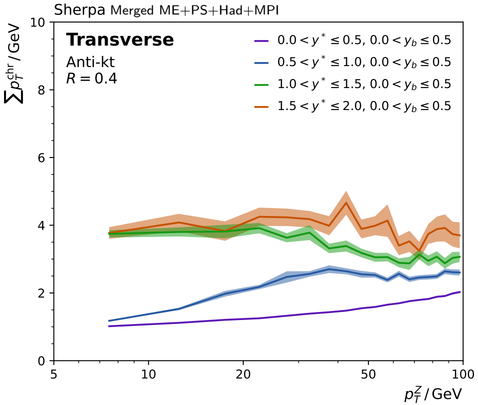

- Showing $\sum_{i=1}^{N_{ch}} p_T^{ch}$, same for N_{ch}
- MPI (and Hadronization) introduce additional activity
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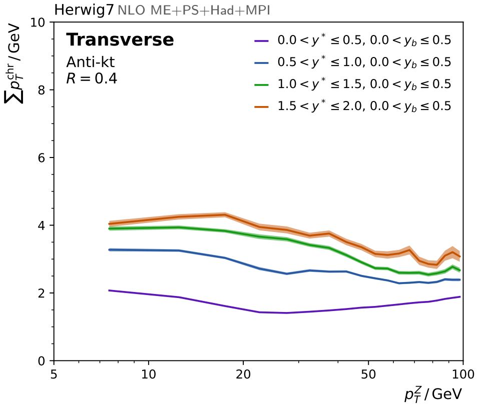
Conclusions

- Something surprising and special is happening in the soft (NP) region in Z+jet production
  - Shows some perturbative dependence
  - Originates in the PS but gets enhanced in MPI modelling

  Consistent trends between different models, but some differences

- There exists no directly sensitive data

→ Measure dependency of Z+jet production on y^* in the soft regime



Backup

Derivation of NP-Correction Factors

- $\frac{d^3\sigma}{dX\,dy_b\,dy^*} = \frac{N_{\text{eff}}(\Delta X, \Delta y_b, \Delta y^*)}{N_{\text{eff,tot}}}\sigma_{\text{incl}}$
  with $N_{\text{eff},\mathcal{S}} = \sum_{i\in\mathcal{S}} w_i$ for all events i in phase space $\mathcal{S}$
- $C_{\text{NP}}^{\text{PO}} = \frac{\sigma^{\text{PO}}_{\text{ME+PS+Had+MPI}}}{\sigma^{\text{PO}}_{\text{ME+PS}}}$ for an MC generation at perturbative order PO
- Fit $f(x) = a \cdot \ln(x/\text{GeV})^b + c$ to smoothen statistical fluctuations

UE Analysis Object Definitions and Selections

- Jet
  - Anti-k_T with R=0.4
  - $|\eta| < 2.4$
  - $p_T^{\text{Jet1}} > 25$ GeV
  - $\Delta R(\mu, \text{jet}) = \sqrt{(\phi_{\text{jet}} - \phi_\mu)^2 + (\eta_{\text{jet}} - \eta_\mu)^2} > 0.3$
- Dimuon (Z)
  - $p_T^\mu > 25$
  - $|\eta_\mu| < 2.4$
  - $m_Z - 20$ GeV $< m_{\mu^+\mu^-} < m_Z + 20$ GeV
  - 5 GeV $< p_T^Z < 100$ GeV
- Charged Final State Particles
  - $|\eta| < 2.4$
  - $p_T > 500$ MeV