

High Precision for Hard Processes 2026, Karlsruhe

NNLO QCD Predictions for Photon-Associated Hadron Production at the LHC

Gabriele Fiore

Based on arXiv:2610.02327

In collaboration with: *Aude Gehrmann-De Ridder,
Alexander Huss, Francesco Merlotti and Giovanni Stagnitto*

ETH zürich Institute for Theoretical Physics

NNLO
JET

High Precision for Hard Processes 2026, Karlsruhe

Introduction

Fragmentation functions and factorization

Schematic factorization formula:

$$d\sigma^h = \sum_{i,j,p} \int dx_1 dx_2 dz \underbrace{f_{i/h1}(x_1, \mu_F) f_{j/h2}(x_2, \mu_F)}_{\text{Initial state}} \underbrace{d\hat{\sigma}_{ij \rightarrow p+X}(z; \mu_R, \mu_F, \mu_A)}_{\text{Hard scattering}} \underbrace{D_p^h(z, \mu_A)}_{\text{Final State}} \rightarrow \text{FFs describe parton-to-hadron fragmentation.}$$

Initial state
PDFs describe partons
in the incoming protons.

Hard scattering
Calculable perturbatively
in the coupling α_s .

Final State
FFs describe parton-to-hadron fragmentation.

- In the collinear picture, the hadron carries a fraction z of the parent parton momentum: $p(k) \rightarrow h(zk) + X$.
- The non-perturbative fragmentation information is encoded in $D_p^h(z, \mu_A)$.
- The fragmentation scale μ_A separates short- and long-distance contributions. Time-like DGLAP evolution.

To learn about FFs, we need both informative data and reliable hard-scattering coefficients.

Complementary constraints on fragmentation functions

Complementary datasets are needed for global FF fits

SIA

Clean inclusive constraint on flavour-weighted FF combinations.
No incoming hadronic PDFs.

SIDIS

Additional flavour separation through the initial-state PDFs and hadron charge/species.

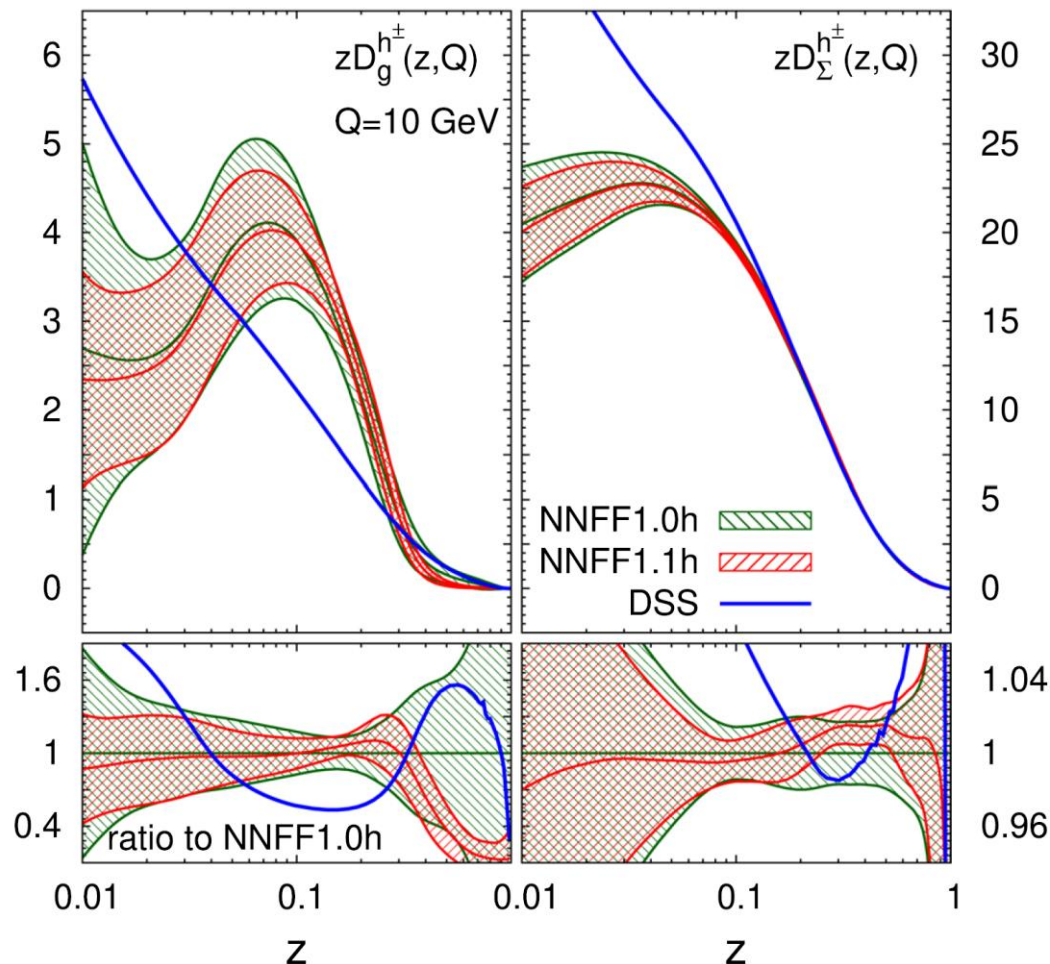
Hadron-collider data

Quark and gluon FFs already at Born level. Complementary partonic mixtures and hard scales.

Global fit of FFs

One common set of FFs, constrained by complementary data using the corresponding factorized predictions.

Hadron-collider data constrain the gluon FF



Bertone et al., 2018

A demonstrated fit constraint

- NNFF1.0h: charged-hadron FFs from SIA-only data.
- NNFF1.1h: hadron-collider spectra added through reweighting.
- The added data reduce the gluon-FF uncertainty; the quark-singlet change is smaller.

Complementary pp data can materially improve FF constraints.

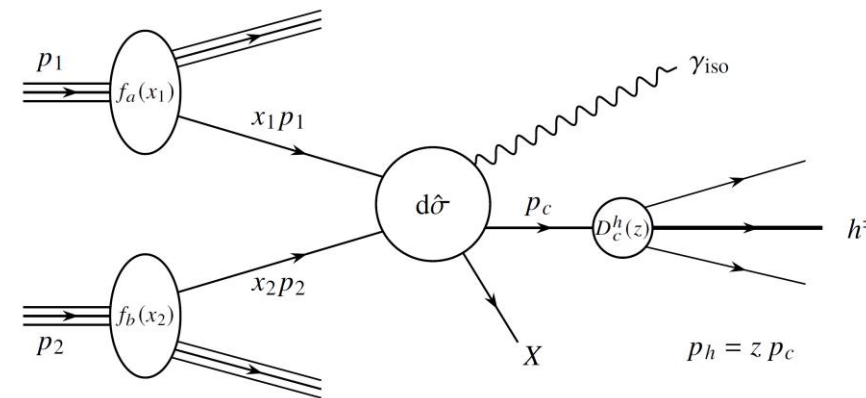
Two ways to measure photon-tagged fragmentation

Focus of our work: $pp \rightarrow \gamma + h + X$ and $pp \rightarrow \gamma + j(h) + X$

Semi-inclusive photon-hadron production

$$pp \rightarrow \gamma + h^\pm + X$$

Select an away-side charged hadron, no reconstructed jet is required. Measure its momentum relative to the photon.

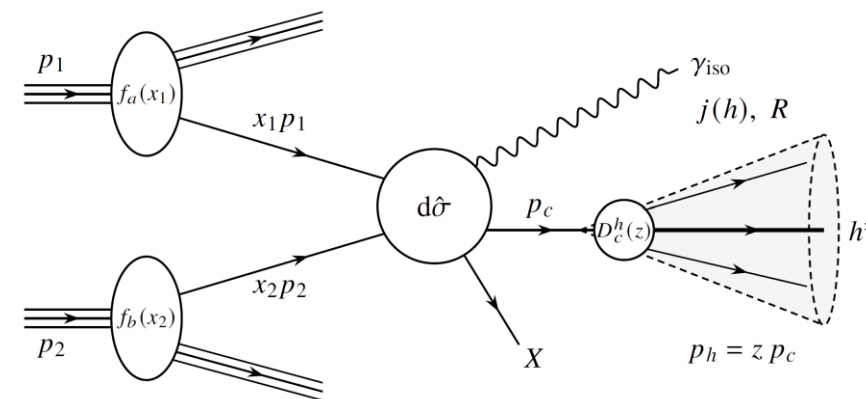


Photon-associated hadron-in-jet production

$$pp \rightarrow \gamma + j(h^\pm) + X$$

Select a charged hadron inside the recoiling jet.

Measure its momentum relative to the jet.



High Precision for Hard Processes 2026, Karlsruhe

Calculation and Inputs

Comparison with ALICE and ATLAS experiments

pp collisions at $\sqrt{s} = 5.02$ TeV

➤ ALICE experiment: isolated photon + charged hadron

Observable: $z_T = \frac{p_T^h}{p_T^\gamma}$

Yield per photon: $\frac{1}{\sigma^\gamma} \frac{d\sigma^{\gamma+h}}{dz_T}$

Away side selection: $|\Delta\phi_{\gamma h}| > 7\pi/8$

No reconstructed jet required.

➤ ATLAS experiment: isolated photon + hadron inside a jet

Observable: $z^h = \frac{p_T^h}{p_T^{j(h)}} \cos \Delta R_{hj}$

Yield per photon-jet pair : $\frac{1}{\sigma^{\gamma+j}} \frac{d\sigma^{\gamma+j(h)}}{dz^h}$

Away side selection $|\Delta\phi_{\gamma j}| > 7\pi/8$

Reconstructed anti- k_t jet, $R = 0.4$.

At Born level, $z_T = z^h = z$. Extra radiation makes the two observables differ.

Hard-scattering order and FF dependence

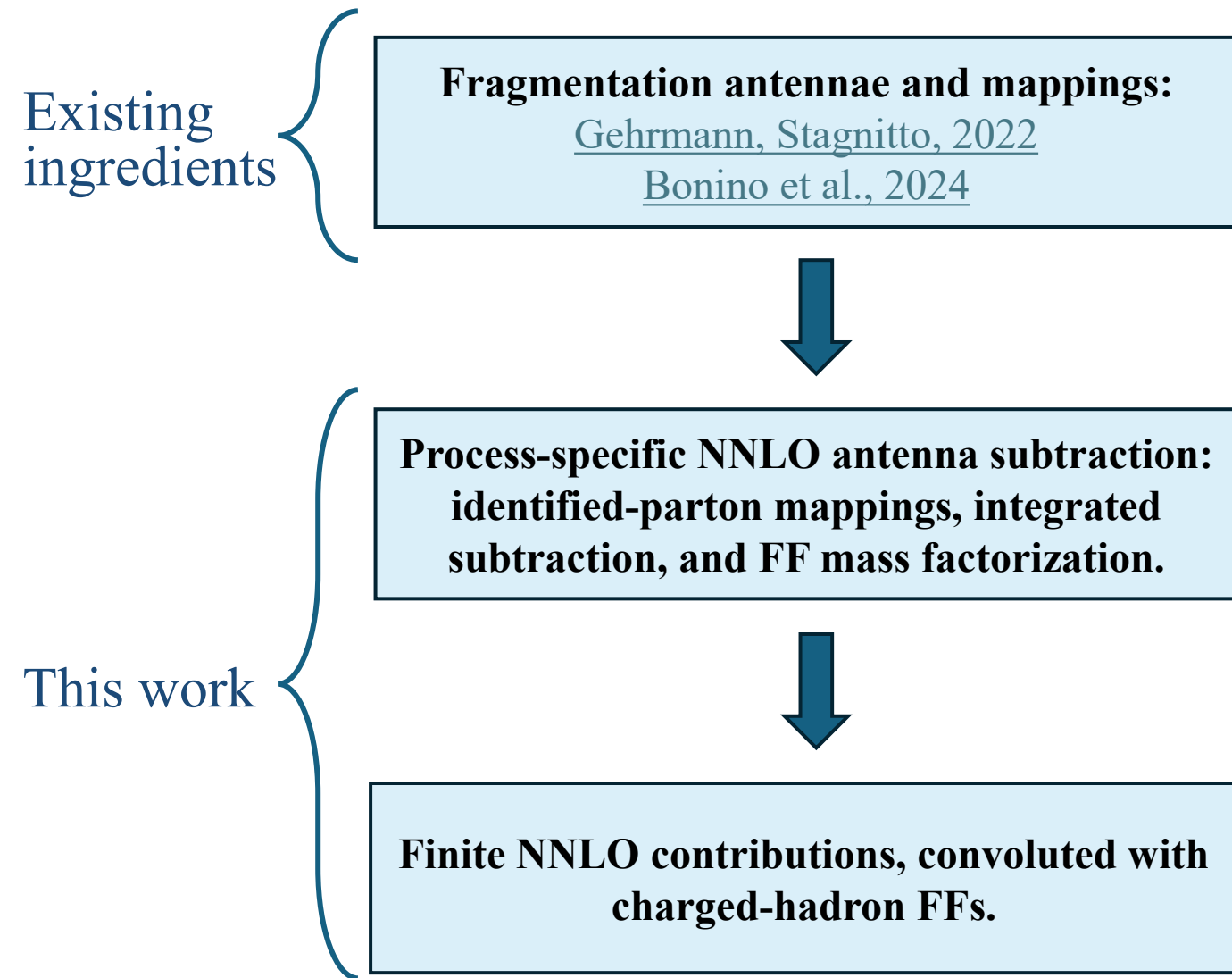
Four FF inputs, two complementary comparisons

Set	Fit order	Data and distinctive feature
BDSS23	NLO	SIA + SIDIS + pp; broad global fit.
NNFF1.1h	NLO	SIA + pp; collider reweighting.
NPC23	NLO	SIA + SIDIS + pp.
HAPS	NNLO	SIA + SIDIS; default NNLO input.

NPC23 already includes the ATLAS data.

- 1) **Fix the FF input; vary the hard-scattering order.**
- 2) **Fix the hard-scattering order; compare FF inputs.**

Assembling the NNLO prediction in NNLOJET



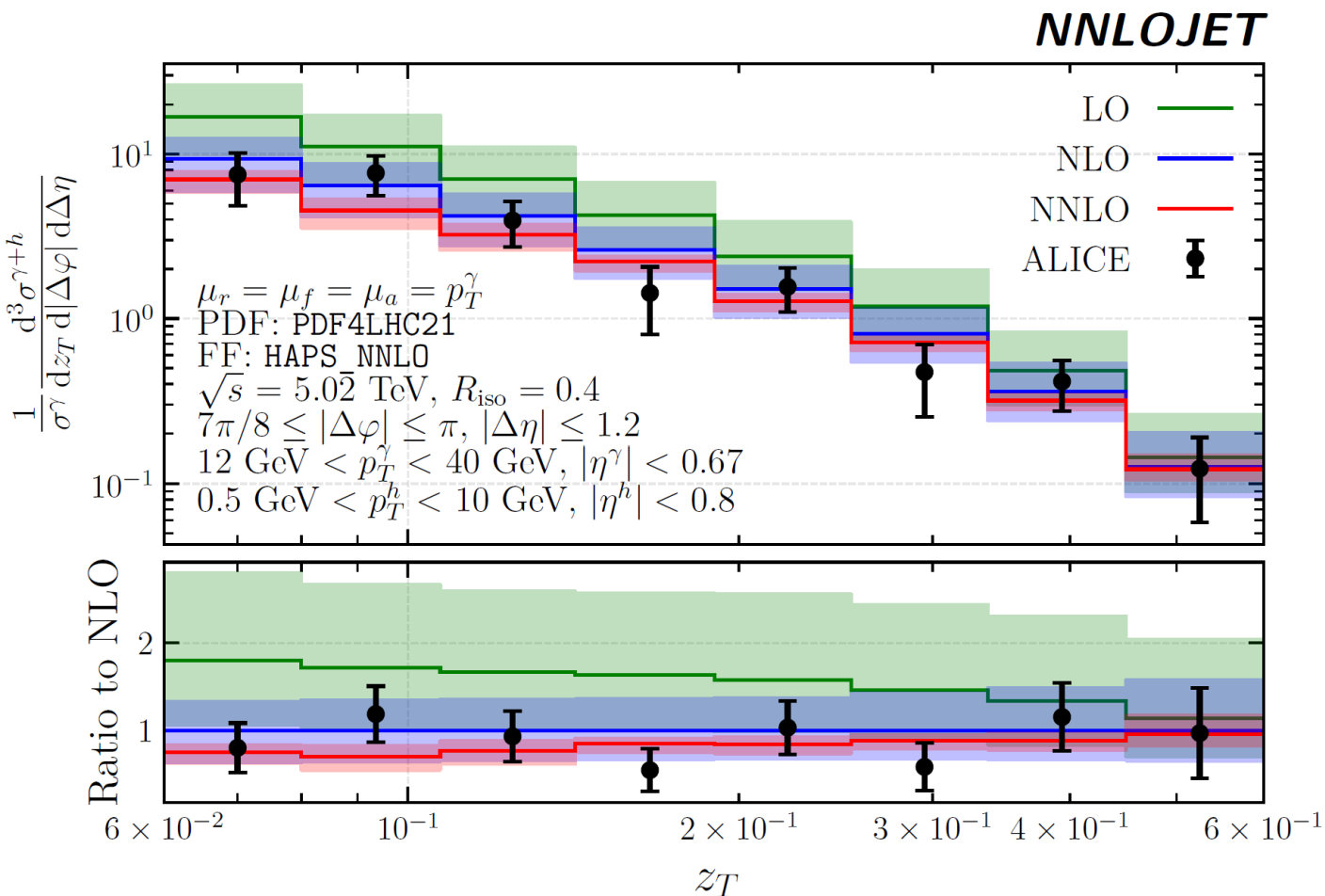
Validation

- Hybrid isolation suppresses photon-collinear configurations, avoiding photon FFs.
- Unresolved-limits tests and pole cancellation.
- Stability under variations of the technical infrared cut.
- Independent numerical validation at NLO with DIPHOX.

High Precision for Hard Processes 2026, Karlsruhe

ALICE: photon–hadron correlations

ALICE: z_T comparison through NNLO



➤ Recall:

$$z_T = \frac{p_T^h}{p_T^\gamma}$$

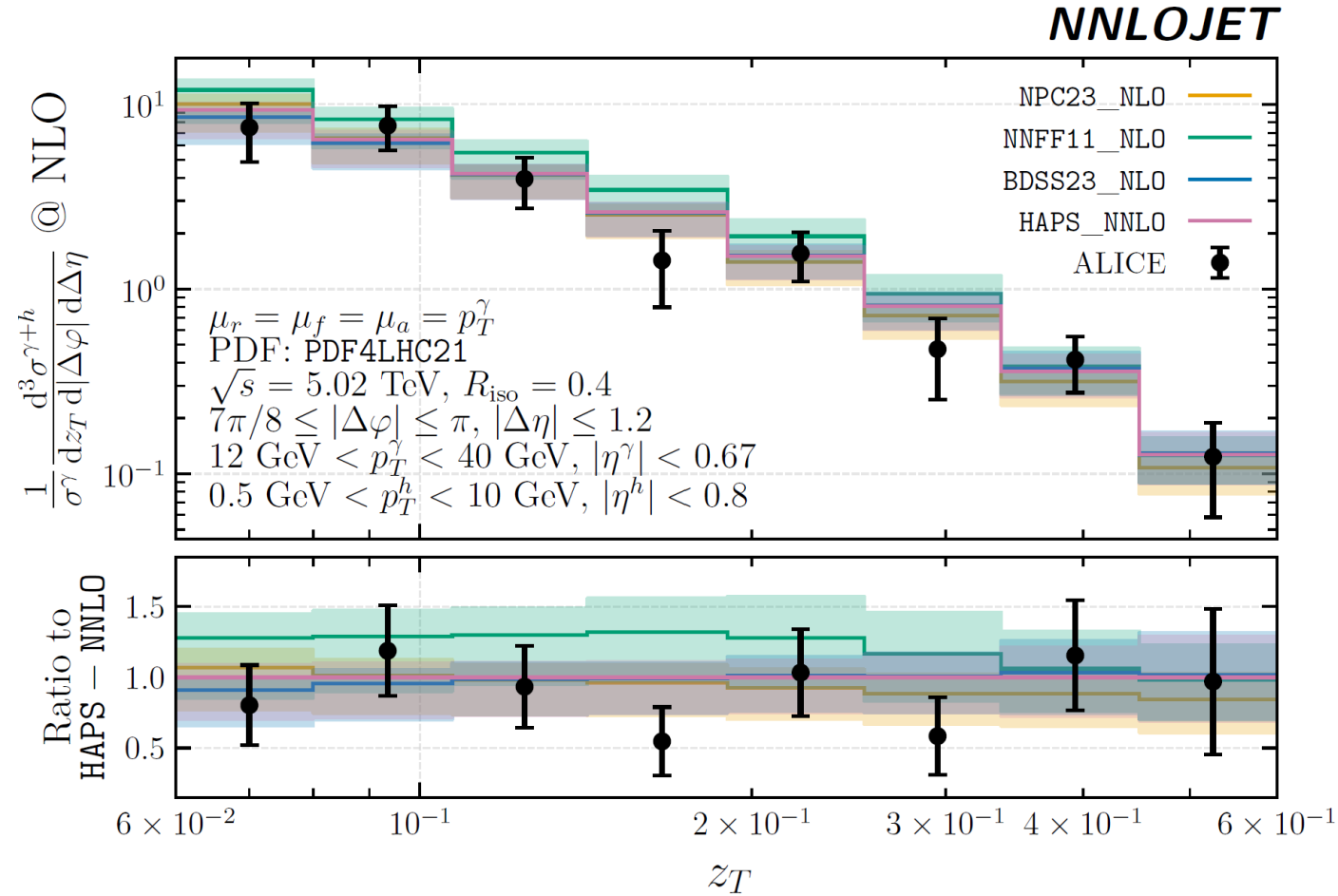
➤ NLO substantially reduces LO overshoot.

➤ NNLO gives smaller central shifts and a narrower scale dependence.

➤ Experimental uncertainties limit the discrimination between NLO and NNLO.

The gain here is perturbative stability

ALICE: FF sensitivity with NLO corrections



➤ BDSS23, NPC23 and HAPS give similar predictions.

➤ NNFF1.1h lies higher, but is compatible within uncertainties.

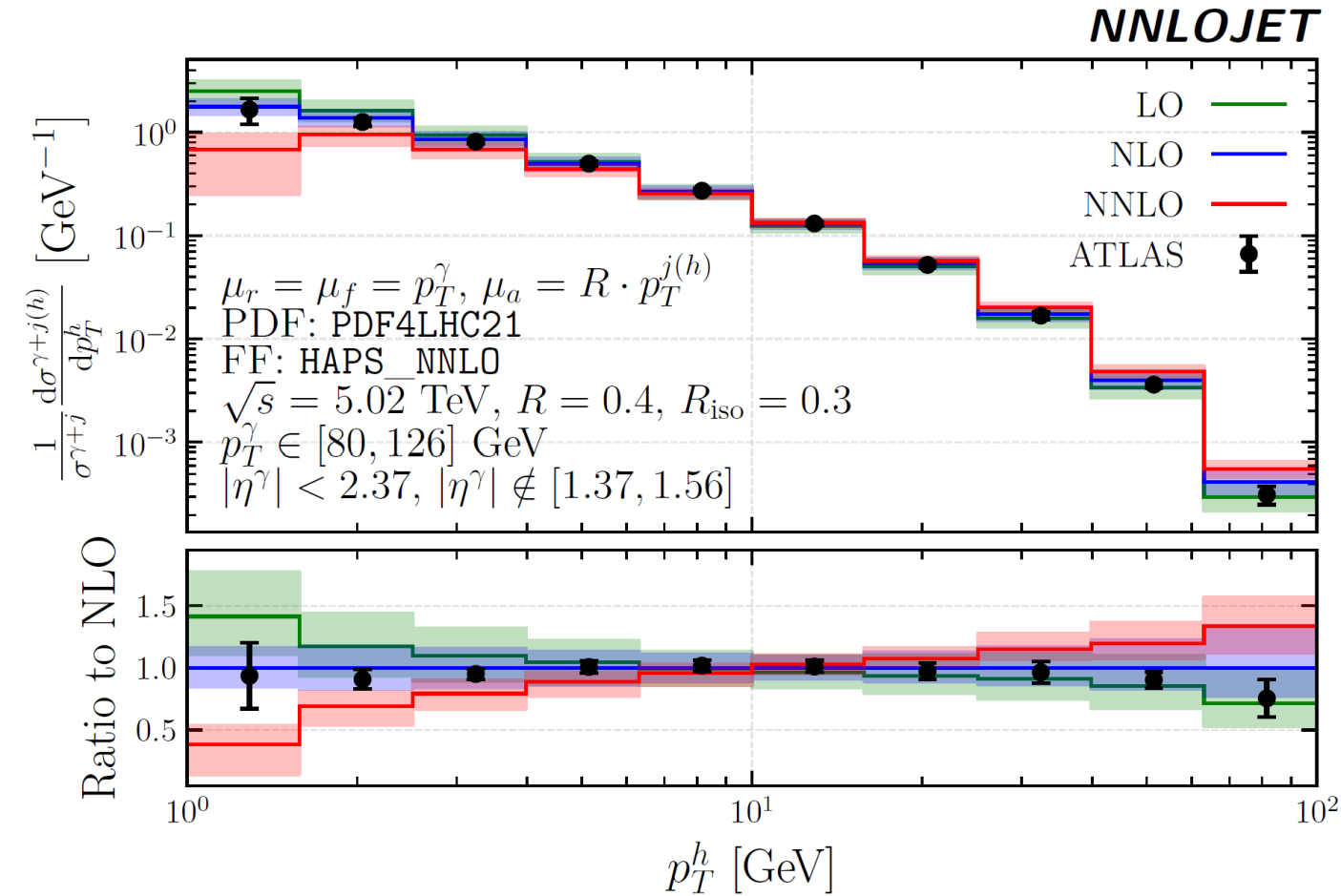
➤ Similar convolutions do not imply identical flavour-by-flavour FFs.

These ALICE data provide limited discrimination among the tested FF sets.

High Precision for Hard Processes 2026, Karlsruhe

ATLAS: hadrons in jets

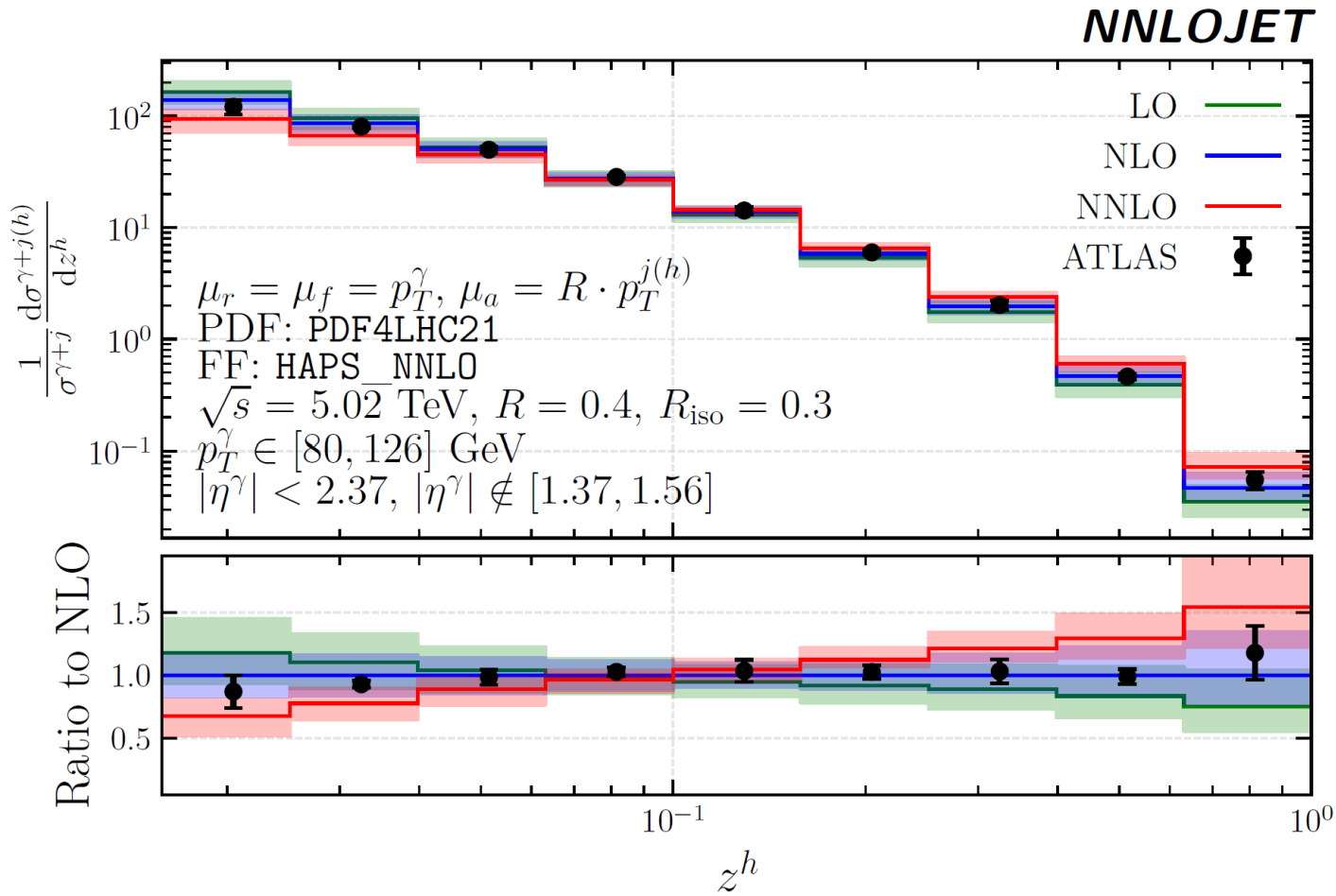
ATLAS: p_T^h comparison through NNLO



- The NLO prediction with the HAPS FF set already describes the data well.
- Low p_T^h : downward shift away from LO and NLO. Poor convergence in the small- z region.
- A fixed p_T^h bin receives contributions from different jet momenta and fragmentation fractions.

NNLO changes the shape and convergence depends on the kinematic region.

ATLAS: z^h comparison through NNLO



➤ Recall:

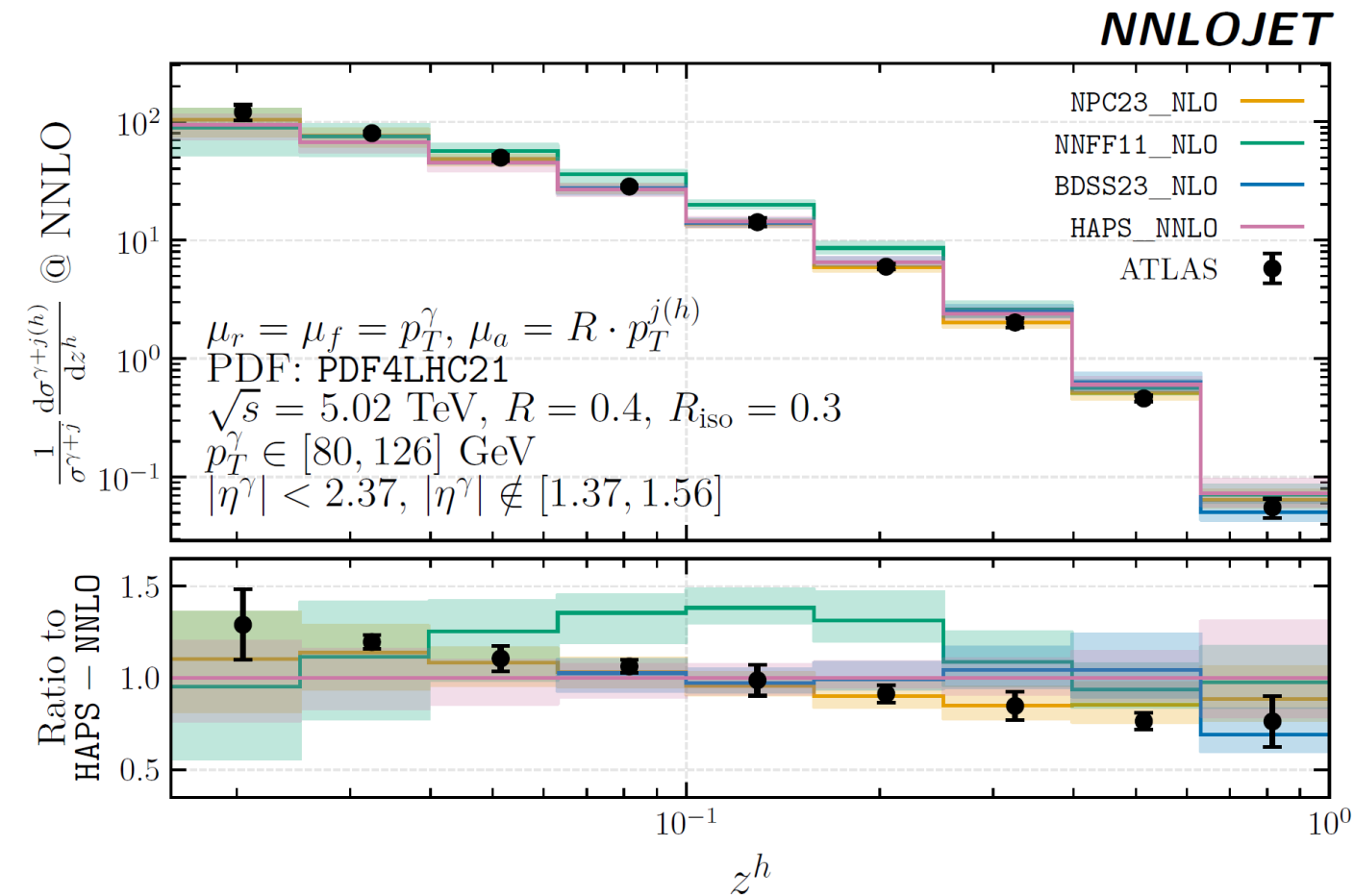
$$z^h = \frac{p_T^h}{p_T^{j(h)}} \cos \Delta R_{hj}$$

➤ NLO with HAPS_NNLO describes the data well. NNLO introduces additional shape changes.

➤ Small- z^h convergence is better than in the lowest- p_T^h bins, since harder hadrons can also contribute.

➤ A NNLO FF fit including these pp predictions could test the additional shape constraints.

ATLAS: FF sensitivity with NNLO Corrections



FF sensitivity remains at NNLO

- The FF sets produce distinguishable central shapes in intermediate z^h bins.
- NNFF1.1h overshoots for $0.06 < z^h < 0.25$.
- Prediction using NPC23 agrees well with data, but this set already included the ATLAS input.

A strong motivation to include these data in global NNLO fits.

High Precision for Hard Processes 2026, Karlsruhe

Summary and Conclusions

Summary

ALICE and ATLAS provide complementary tests

	ALICE: Photon + hadron	ATLAS: Photon + hadron inside a jet
NNLO effect	Smaller additional shift at NNLO, reduced scale uncertainty.	Significant shape changes, convergence varies across phase-space.
FF comparison	Predictions with the tested sets largely overlap	More pronounced spread across different FF sets.
Implication	A more stable perturbative reference for the measured yield.	Useful sensitivity for FF studies.

NNLO changes how photon-tagged data can be used

➤ New NNLO capability:

Fully differential NNLO QCD implementation for photon-associated charged-hadron production, implemented in NNLOJET.

➤ Phenomenology:

Improved perturbative stability for the ALICE selection; significant shape and FF dependence for the ATLAS selection.

➤ Outlook:

Our predictions provide the perturbative input to include photon-tagged fragmentation data in global FF analyses.

The same pp calculation also supplies the vacuum baseline for photon-tagged heavy-ion studies.

High Precision for Hard Processes 2026, Karlsruhe

Thank you for listening!