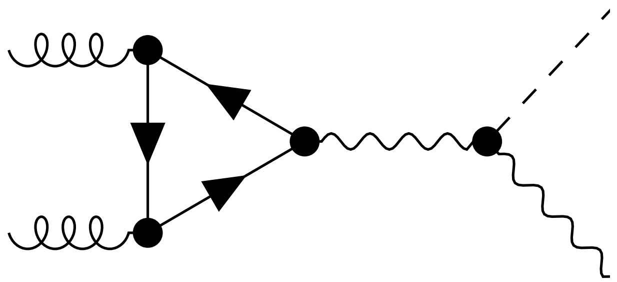
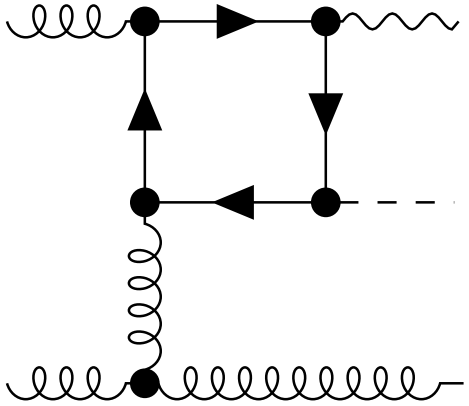




Modelling of loop-induced ZH production in ATLAS

19th workshop of the LHC Higgs Working Group

November 28, 2022

Philipp Windischhofer
University of Chicago

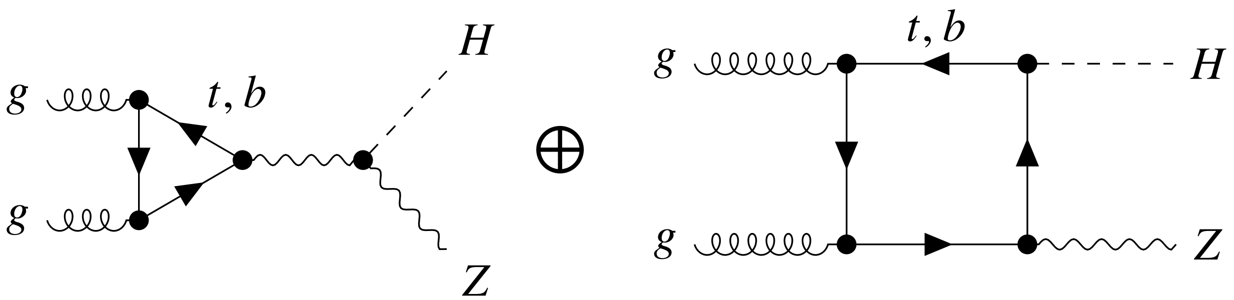
Introduction: loop-induced ZH

Leading contribution:

Loop-induced ZH ↔ gluon-induced ZH

↓ Loop suppression

↓ Large gluon luminosity



(Negative interference)

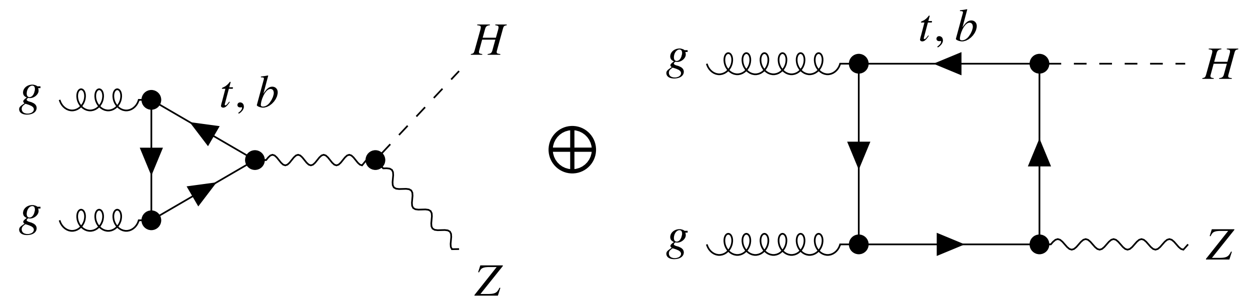
Introduction: loop-induced ZH

Leading contribution:

Loop-induced ZH ↔ gluon-induced ZH

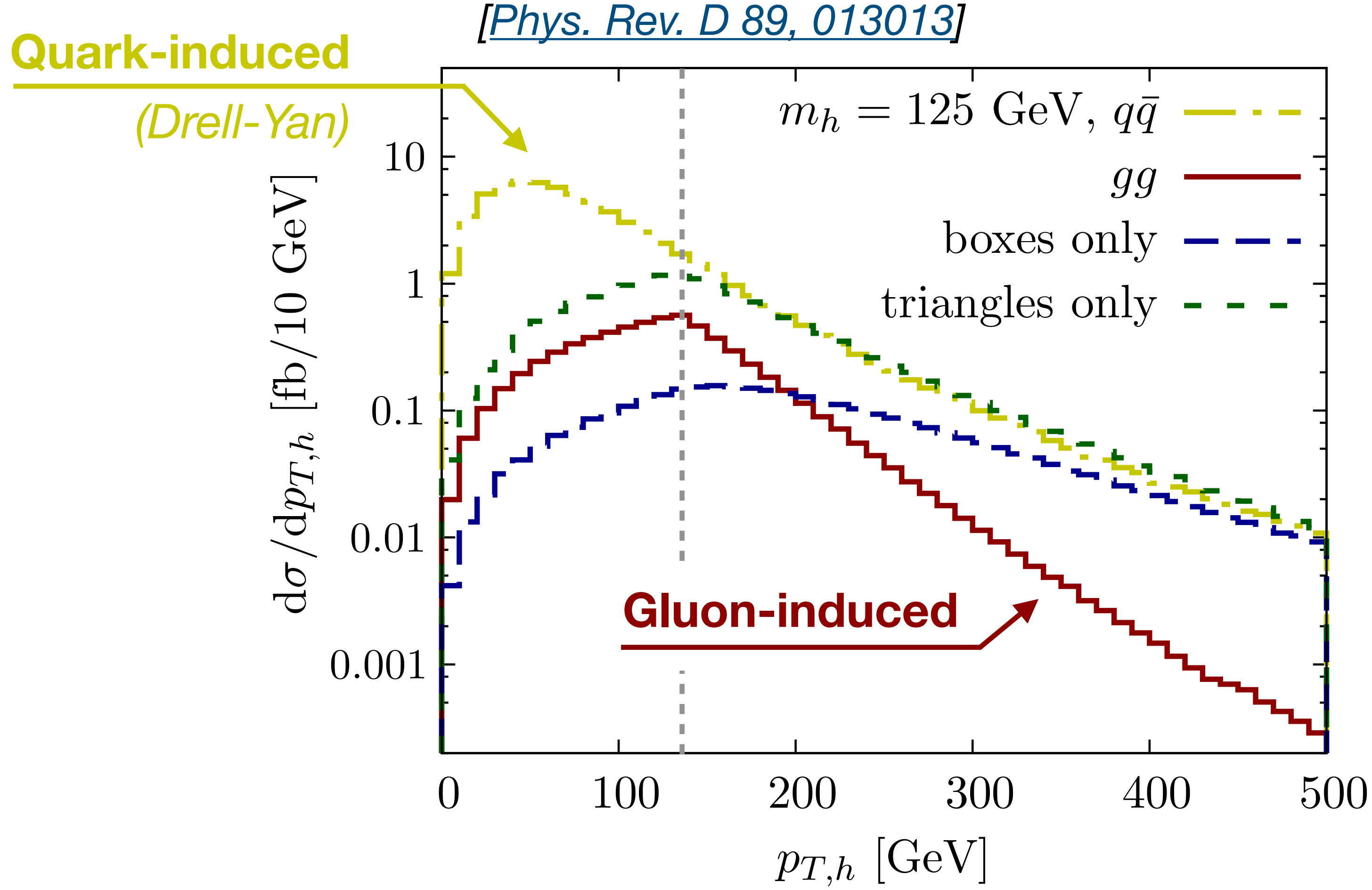
↓ Loop suppression

↓ Large gluon luminosity



(Negative interference)

[Phys. Rev. D 89, 013013]



Significant contribution to ZH cross-section around $p_{T,h} \approx m_t$

←

But: multi-scale loop integrals

→ *Lower perturbative accuracy than Drell-Yan*

[WG1 meeting] on recent theoretical advances

→ ***Important to consider** (and improve!) **for ZH measurements at the LHC***

Already [dominant] signal uncertainty in ATLAS Run 2 ZH measurement!

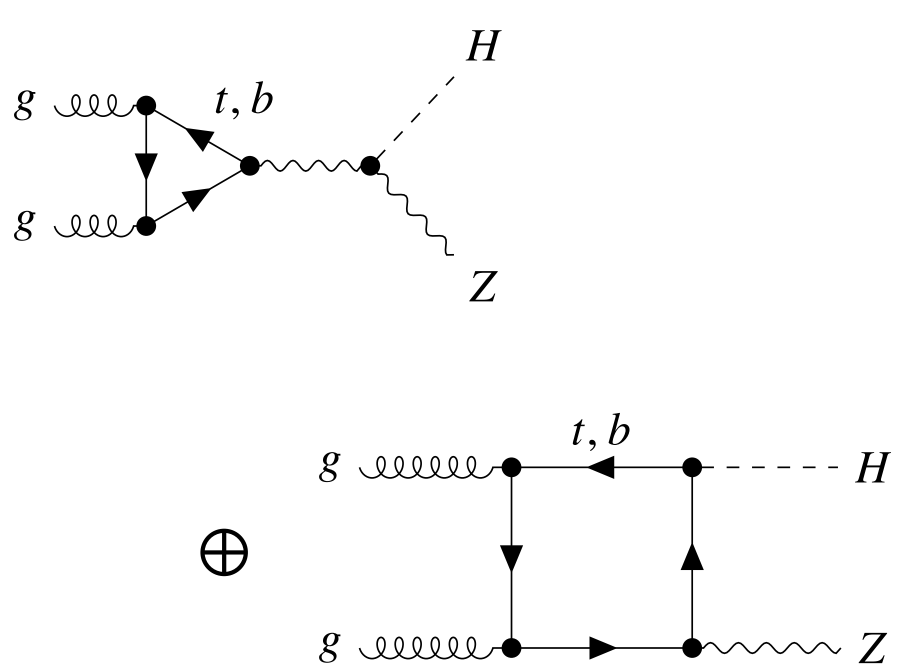
Loop-induced ZH 0+1j@LO

More information:
[ATL-PHYS-PUB-2022-055]

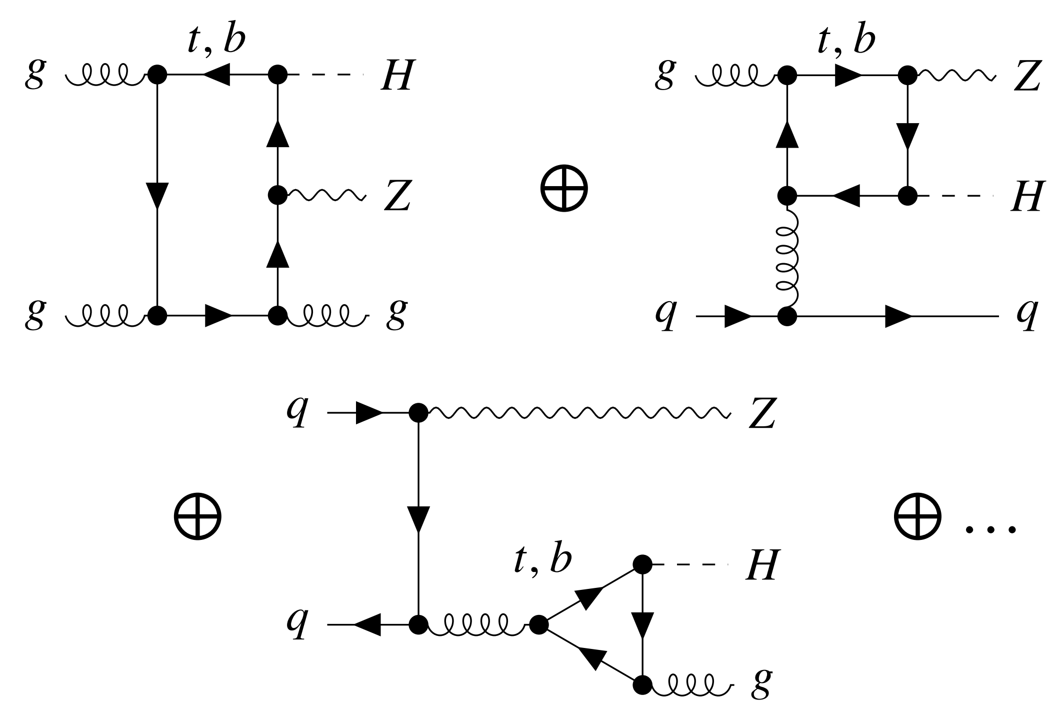
This talk: summary of work in ATLAS to **improve modeling** of **loop-induced ZH production** using **general-purpose Monte Carlo generators**:

Include leading jet emission into leading order matrix element

ZH + 0j@LO



ZH + 1j@LO



Non-gg initial states also contribute!
(see backup and Phys. Rev. D 92, 073006)

→ More accurate description of leading order process
(but no reduction in uncertainties!)

Used Monte Carlo generators

More information:
[ATL-PHYS-PUB-2022-055]

New 0+1j@LO calculations for loop-induced ZH: *integrated into ATLAS MC production*

SHERPA 2.2.8

Matrix element
from OPENLOOPS

MePS@NLO merging

Catani-Seymour parton shower

MADGRAPH_aMC@NLO 2.9.9

Matrix element computed
by MADLOOP

MLM merging

PYTHIA 8 parton shower

Existing 0j@LO setup: *used in previous ATLAS ZH measurements*

POWHEG-BOX v2

Matrix element evaluated by
`ggHZ` code

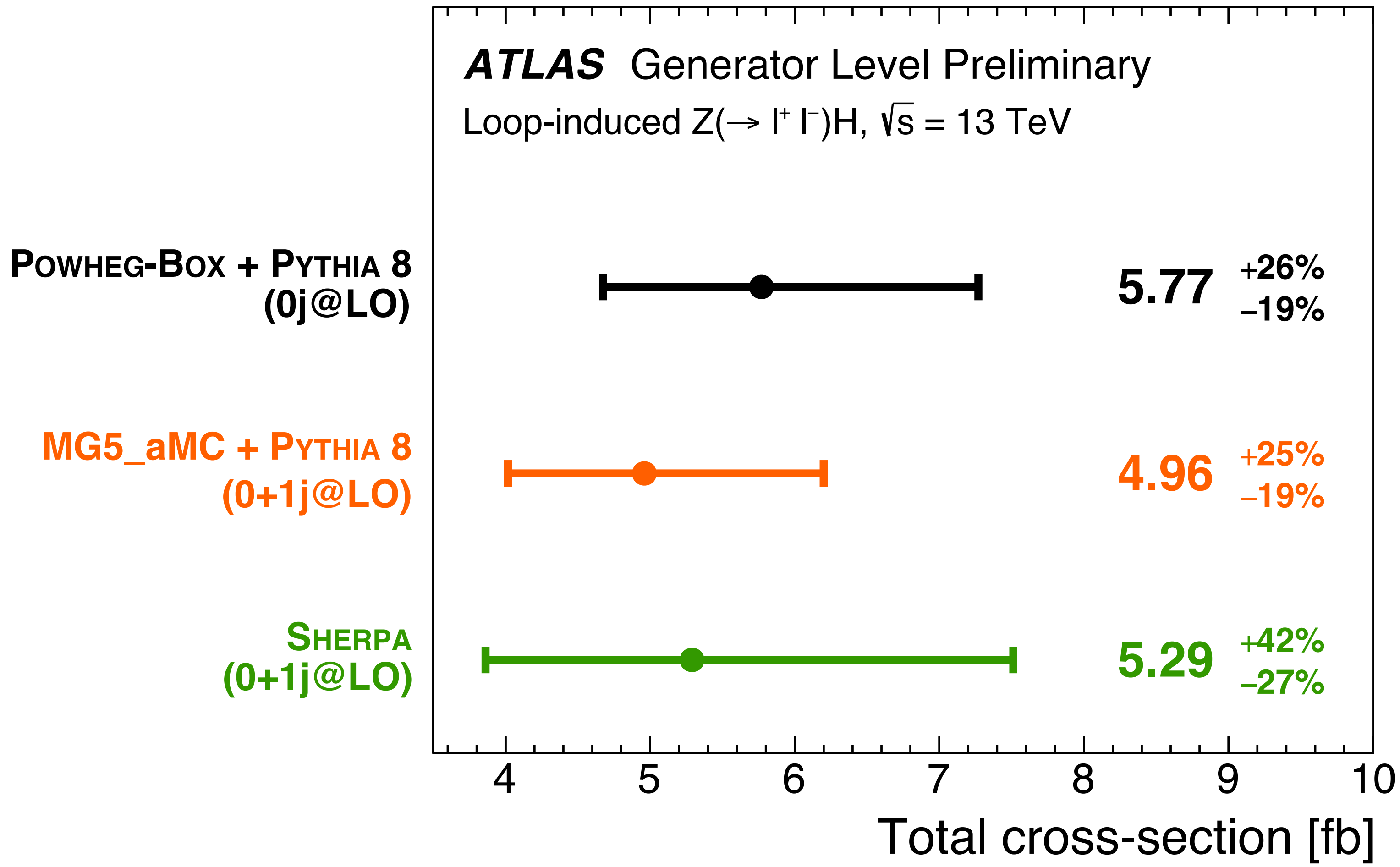
PYTHIA 8 parton shower

(All jets emitted by parton shower)

Comparison: total cross-section

In the following: focus on leptonic decay of Z boson (relevant for STXS)

$$(Z \to \ell^+\ell^-, \ell = e, \mu, \tau)$$



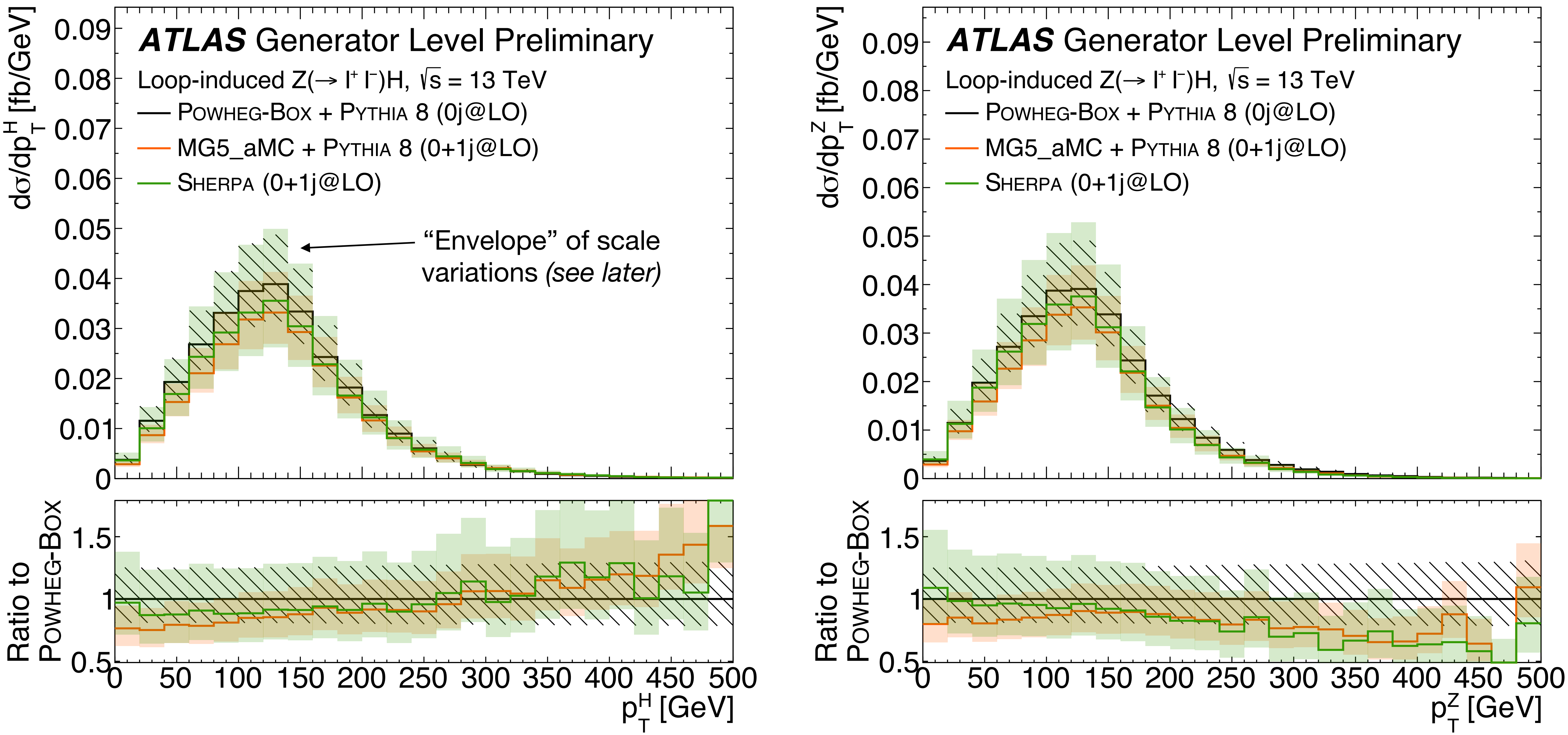
Total cross-sections compatible within uncertainties

Larger uncertainties for SHERPA compared to MG5_aMC (see later!)

Comparison: kinematic distributions

Focus on observables relevant for STXS measurements

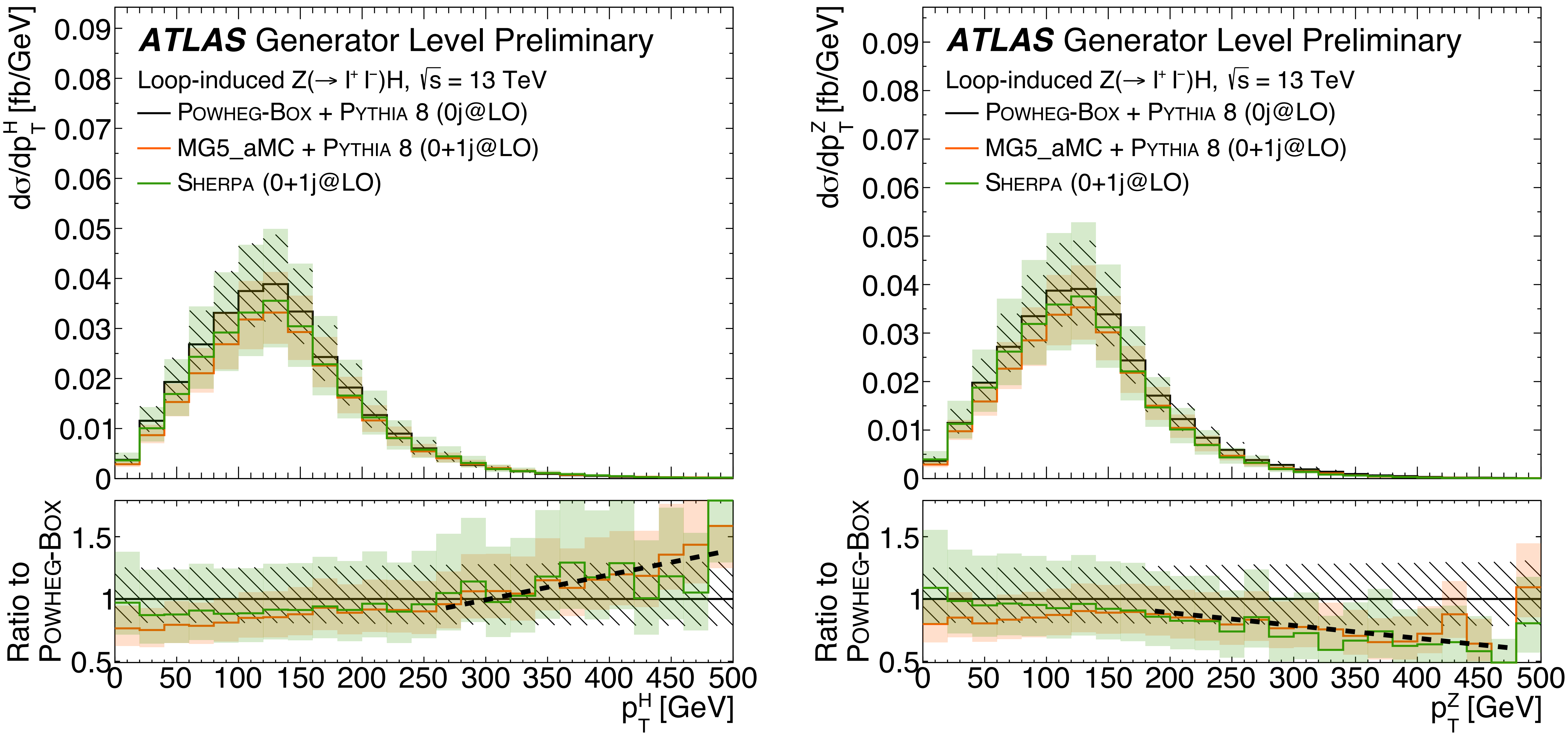
(Using generator truth information, no detector simulation)



Comparison: kinematic distributions

Focus on observables relevant for STXS measurements

(Using generator truth information, no detector simulation)

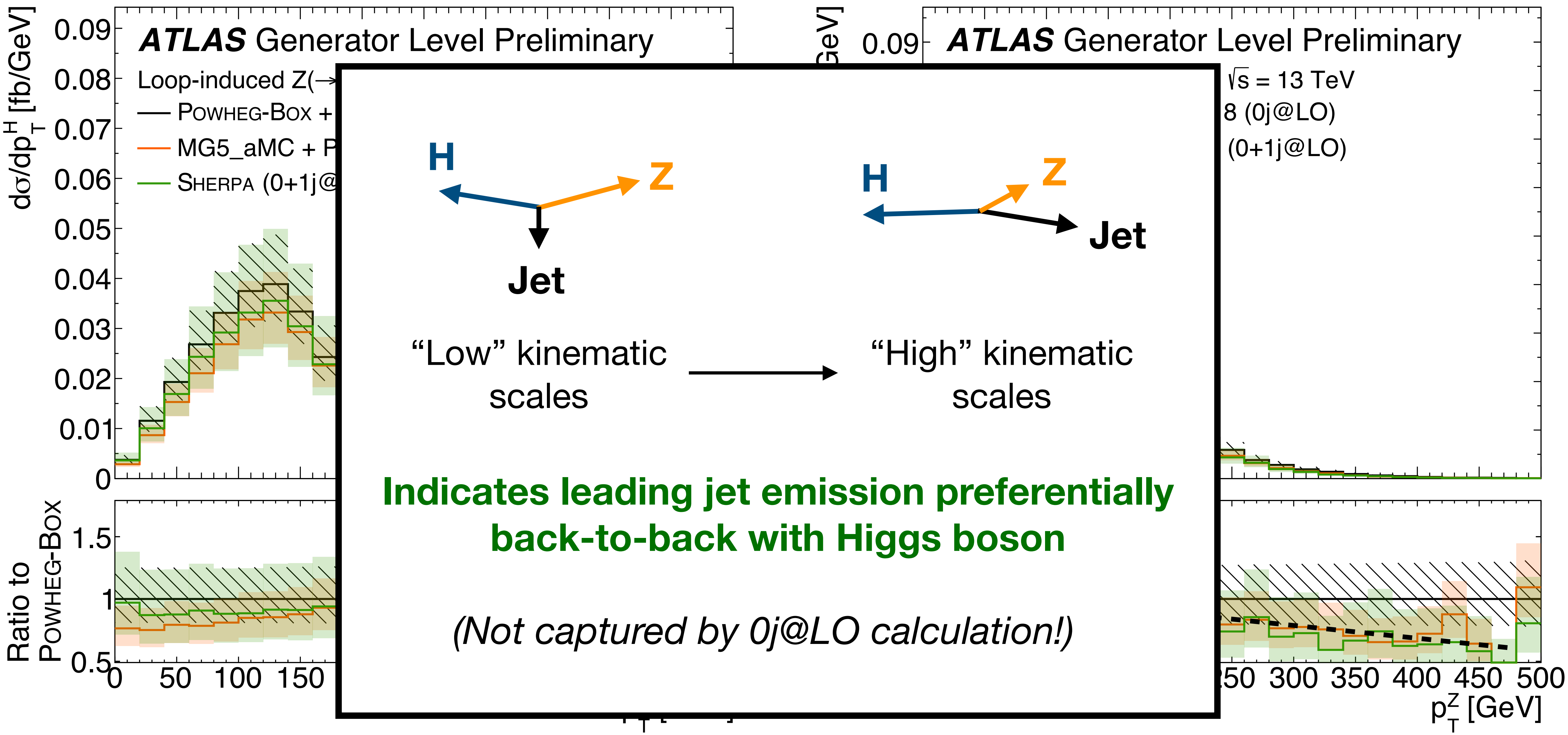


Consistent trends at high kinematic scales: harder p_T^H and softer p_T^Z spectrum w.r.t. 0j@LO calculation

Comparison: kinematic distributions

Focus on observables relevant for STXS measurements

(Using generator truth information, no detector simulation)



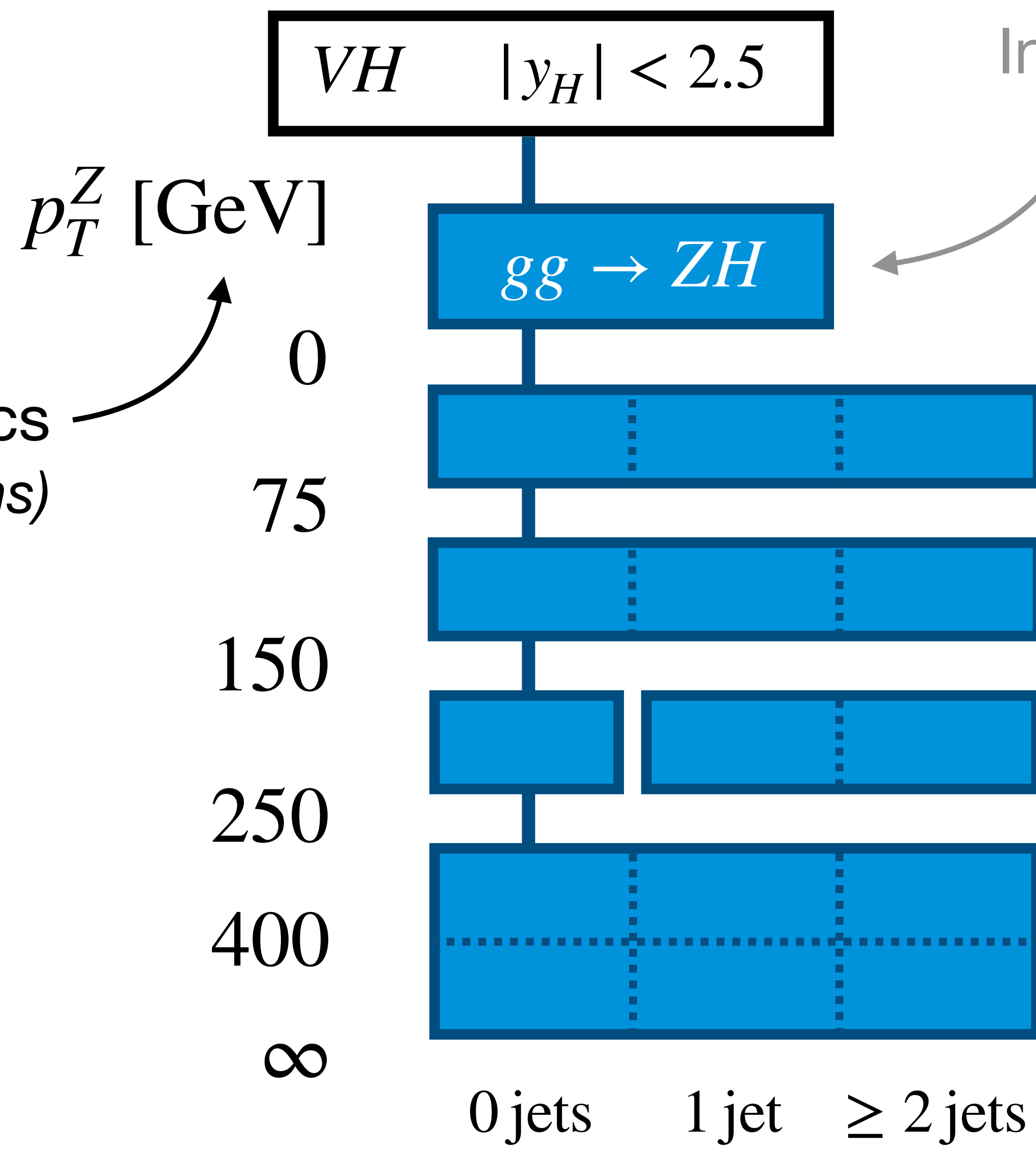
Consistent trends at high kinematic scales: harder p_T^H and softer p_T^Z spectrum w.r.t. 0j@LO calculation

Comparison: STXS

Fiducial cross-sections computed for Stage 1.2 STXS bins

Defined in terms of p_T^Z and n_{Jets}

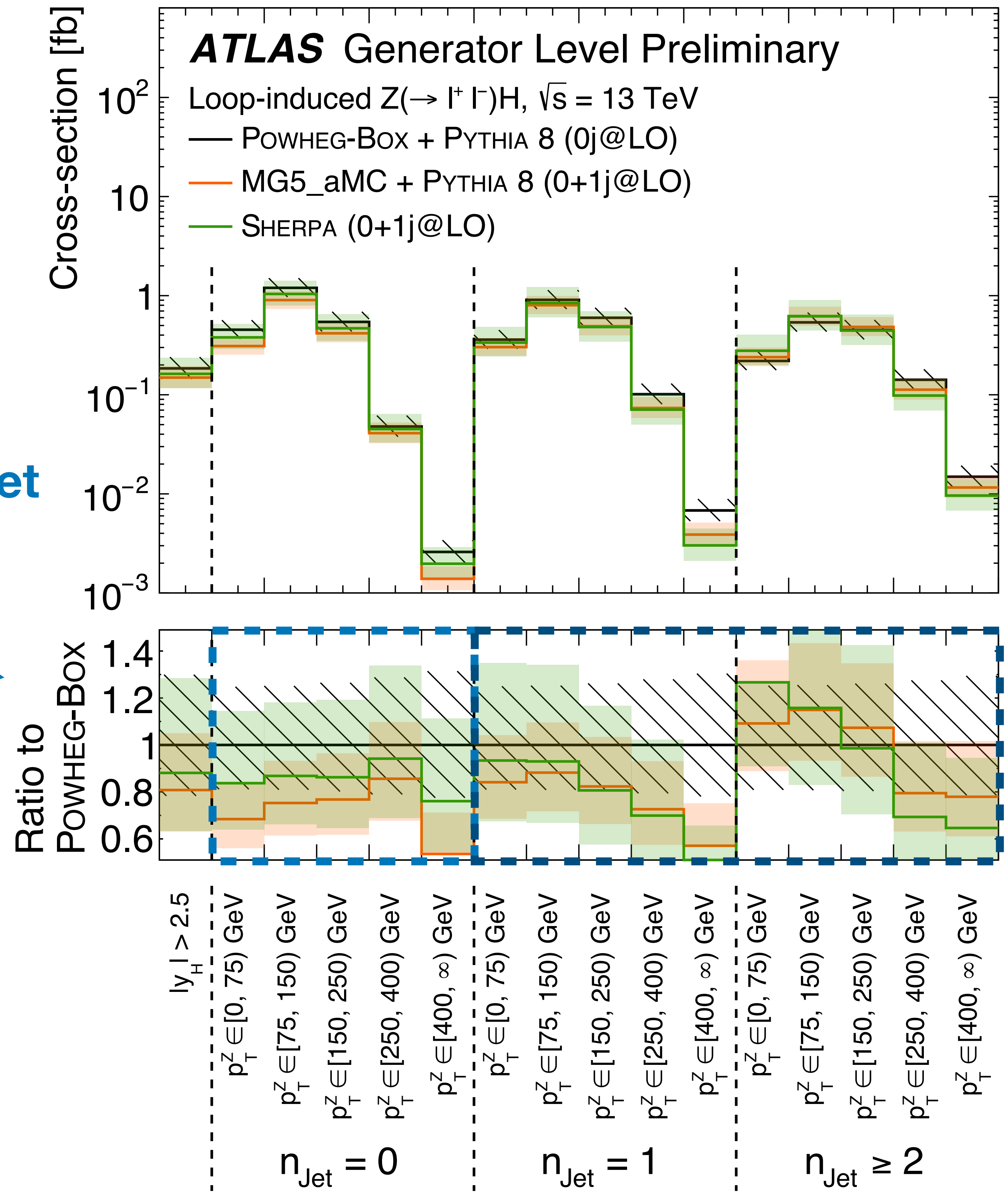
Instead: “loop-induced ZH”?
(Do we need do agree on a common definition?)



Truth Z boson kinematics
(including FSR photons)

Clustered with anti-k_T, R = 0.4
(excluding decay products of Z and Higgs bosons)

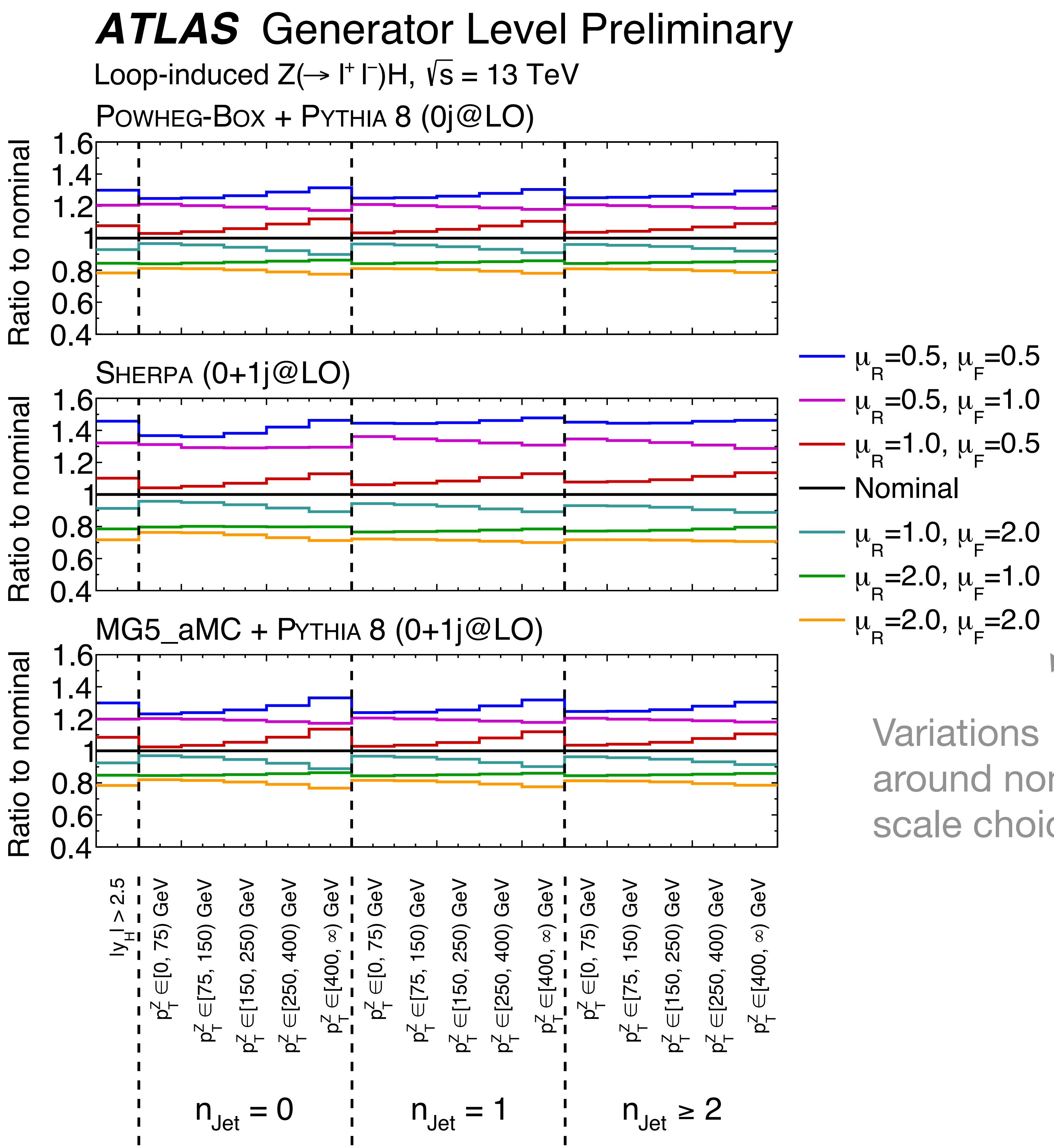
Comparison: STXS



Cross-section modification for 0 jet
(cf. slide 5)

Significant change in p_T^Z slope for ≥ 1 jet
(cf. slide 7)

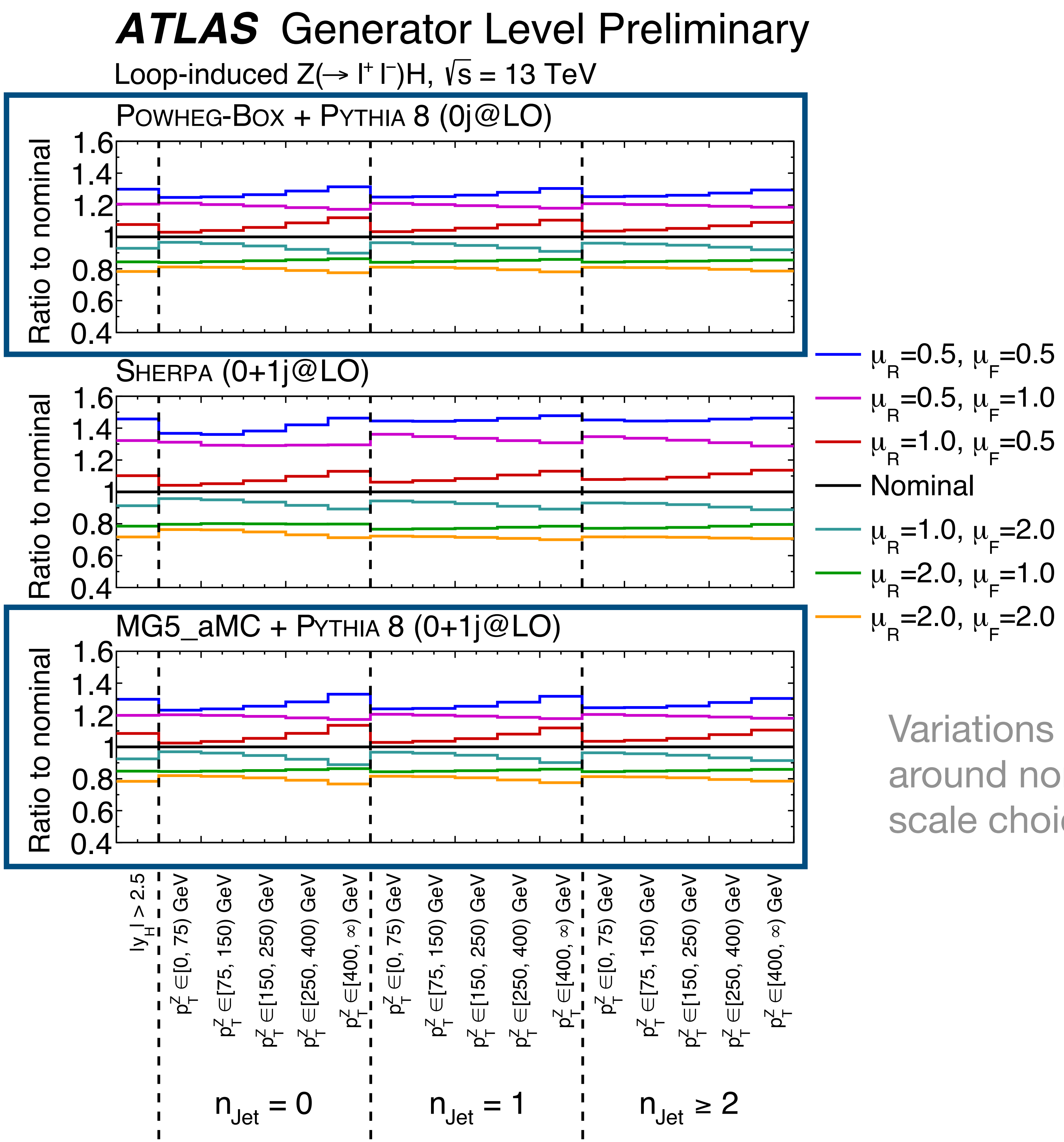
Comparison: scale variations



Variations around nominal scale choice

Comparison: scale variations

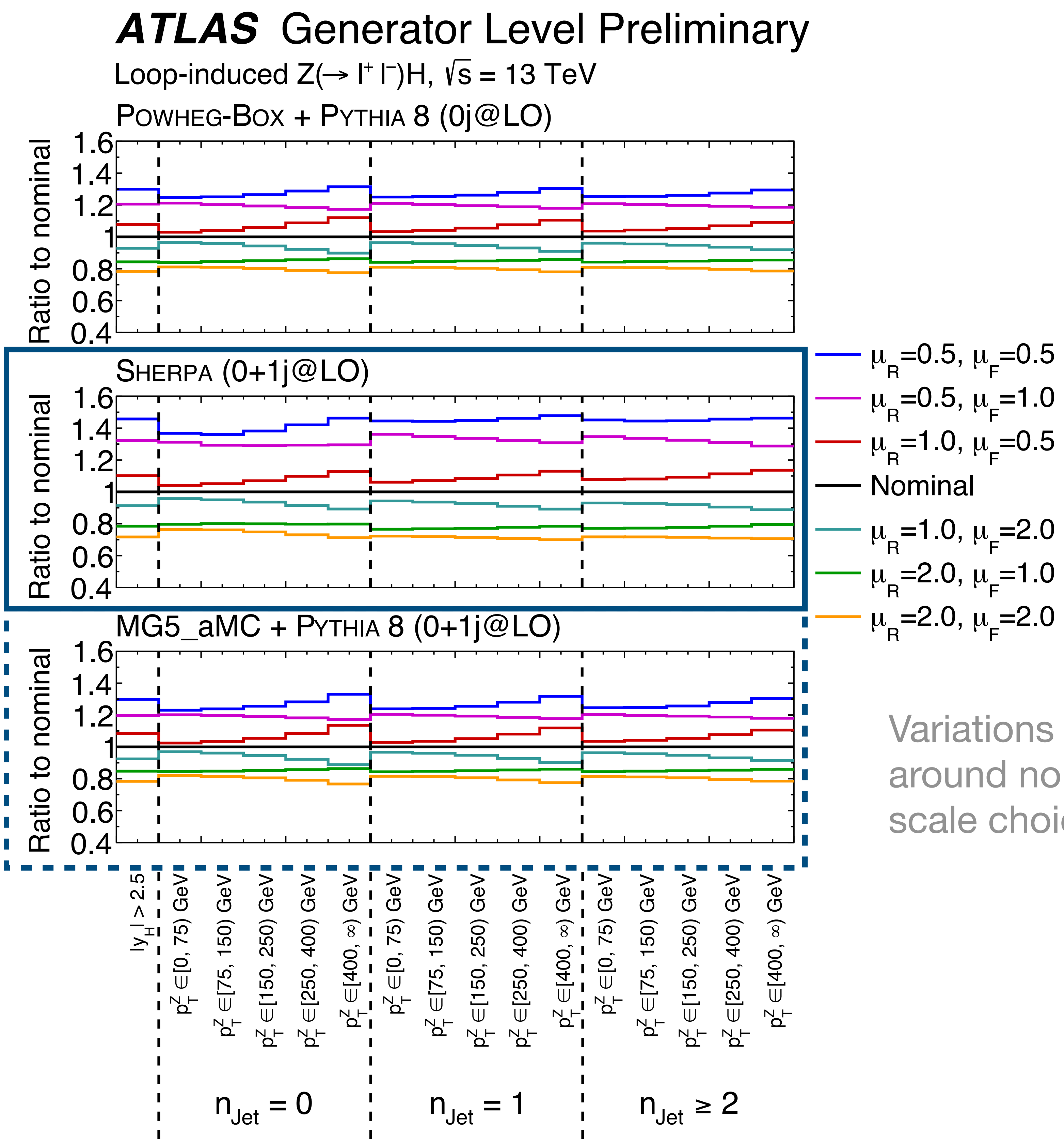
Similar impact for POWHEG-BOX (0j@LO) and MG5_aMC9 (0+1j@LO): **≈ 25%**



Variations around nominal scale choice

Comparison: scale variations

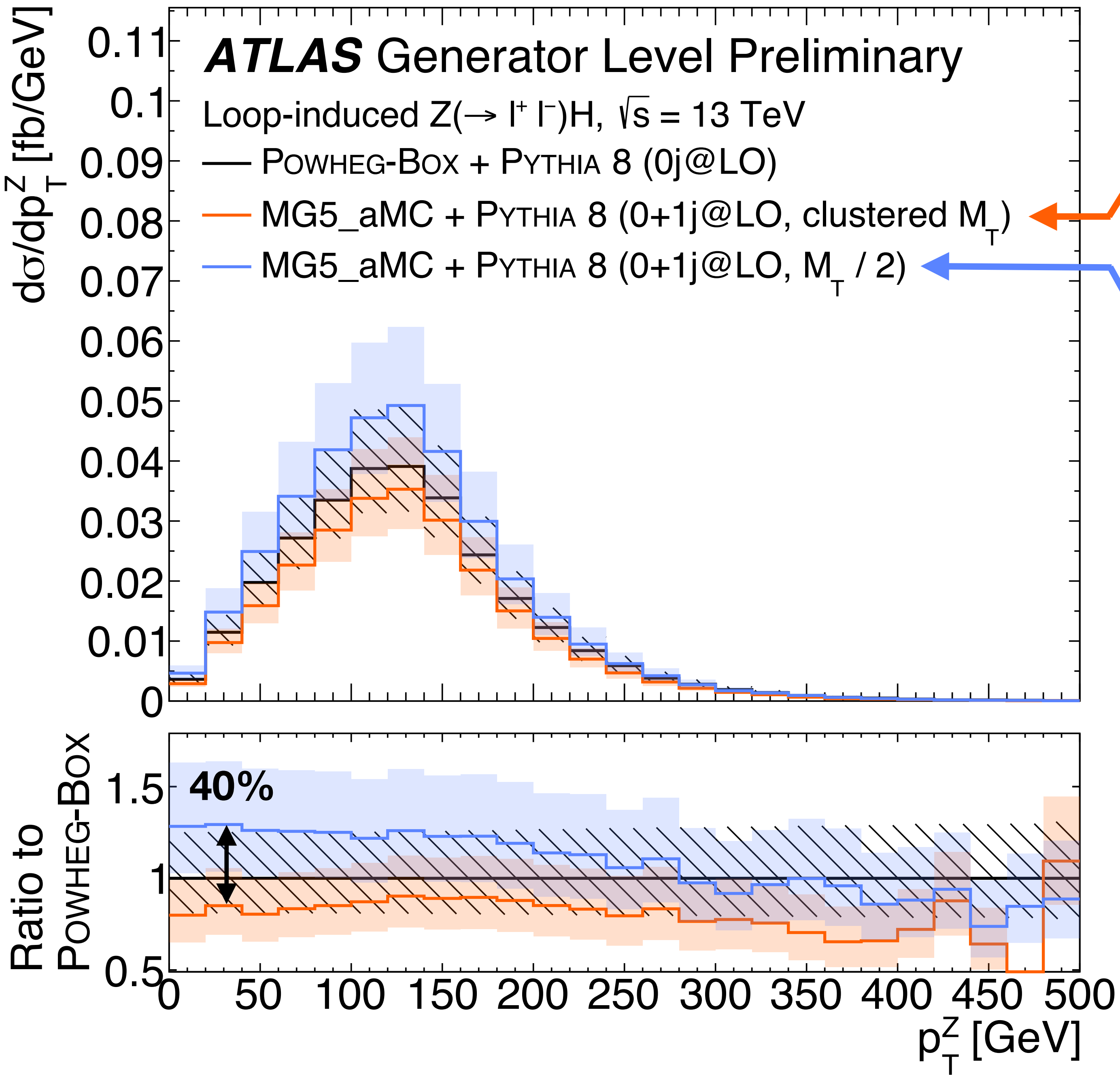
Significantly larger impact for SHERPA (0+1j@LO): ≈ **40%**



Variations around nominal scale choice

A closer look at MadGraph

Compare different *central* dynamic scale choices



Default scale choice *(used throughout):*

Transverse mass M_T after k_T-clustering of generated final state

Alternative scale choice:

$M_T/2$ directly computed on final state *(purely kinematic scale choice)*

Cross-sections predicted for different nominal scale choices not within each other's scale variations!

→ Do we need to take additional components into account?

Summary and outlook

Prepared new Monte Carlo setups for loop-induced ZH 0+1j@LO

Using available general-purpose generators;
fully integrated into ATLAS production system → immediately available

With respect to 0j@LO calculation: **modifies kinematics of Z and Higgs boson**

(Particular in boosted regime; important for future ZH measurements)

Significant **differences** in **impact of scale variations** between
SHERPA and MG5_aMC 0+1j@LO predictions

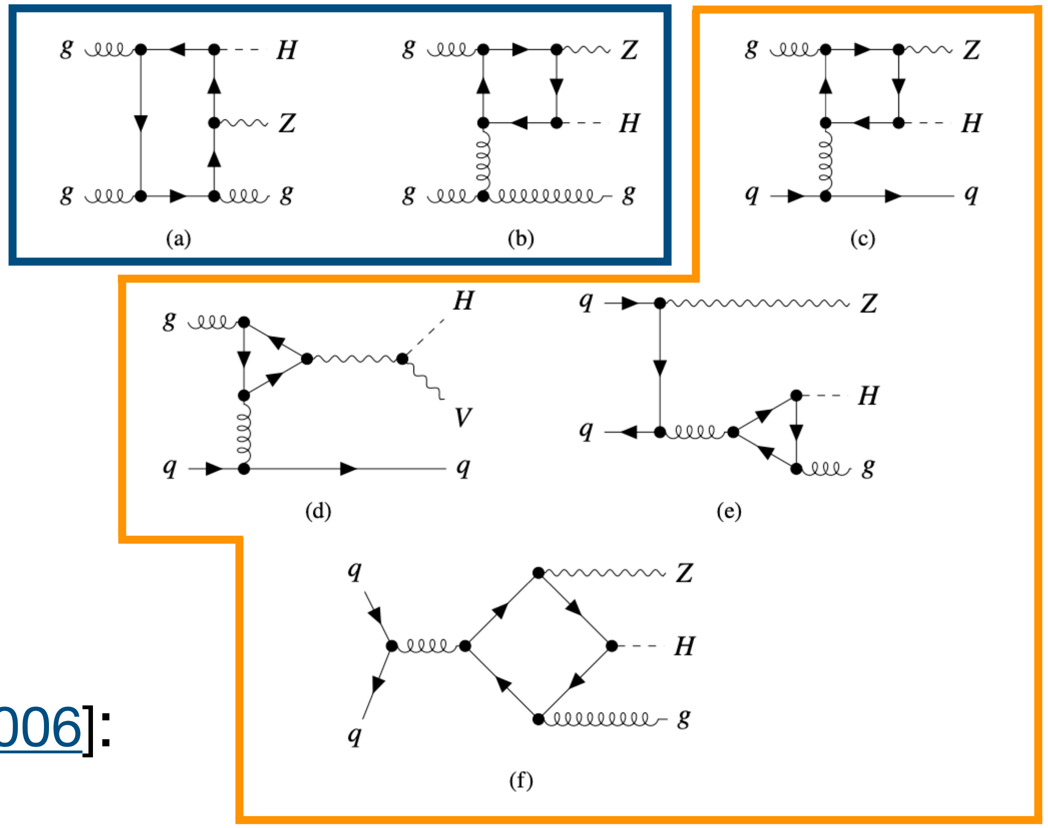
(Larger for SHERPA, but might be incomplete for MG5_aMC)

Let's discuss!

Many more details available in [ATL-PHYS-PUB-2022-055]

Backup

Definition of loop-induced ZH



Need a definition!

What is a good definition?

- Be theoretically well-defined:
  finite and gauge-invariant cross-section
- Be experimentally well-defined:
  group sub-processes with similar experimental signatures

Definition used here and e.g. also in [Phys. Rev. D 92, 073006]:

Take loop-induced ZH+jet to be composed of:

- Diagrams with closed quark loops and three external gluons
- Diagrams with closed quark loops and external quark line

Consequences / properties of this definition:

- Incudes non-gg initial states
- Includes all diagrams contributing a $|\text{Yukawa}|^2$ to the squared matrix element of pp → ZH+j at this order
- Diagrams overlap with NLO corrections to Drell-Yan ZH+jet

Details on generator setup

Generator versions

Process	ME generator	PS generator
Loop-ind. ZH 0+1j@LO	SHERPA (2.2.8p3)	SHERPA (2.2.8p3)
Loop-ind. ZH 0+1j@LO	MG5_aMC (2.9.9)	PYTHIA 8 (8.307)
Loop-ind. ZH 0j@LO	POWHEG-BOX v2 (ggHZ)	PYTHIA 8 (8.212)

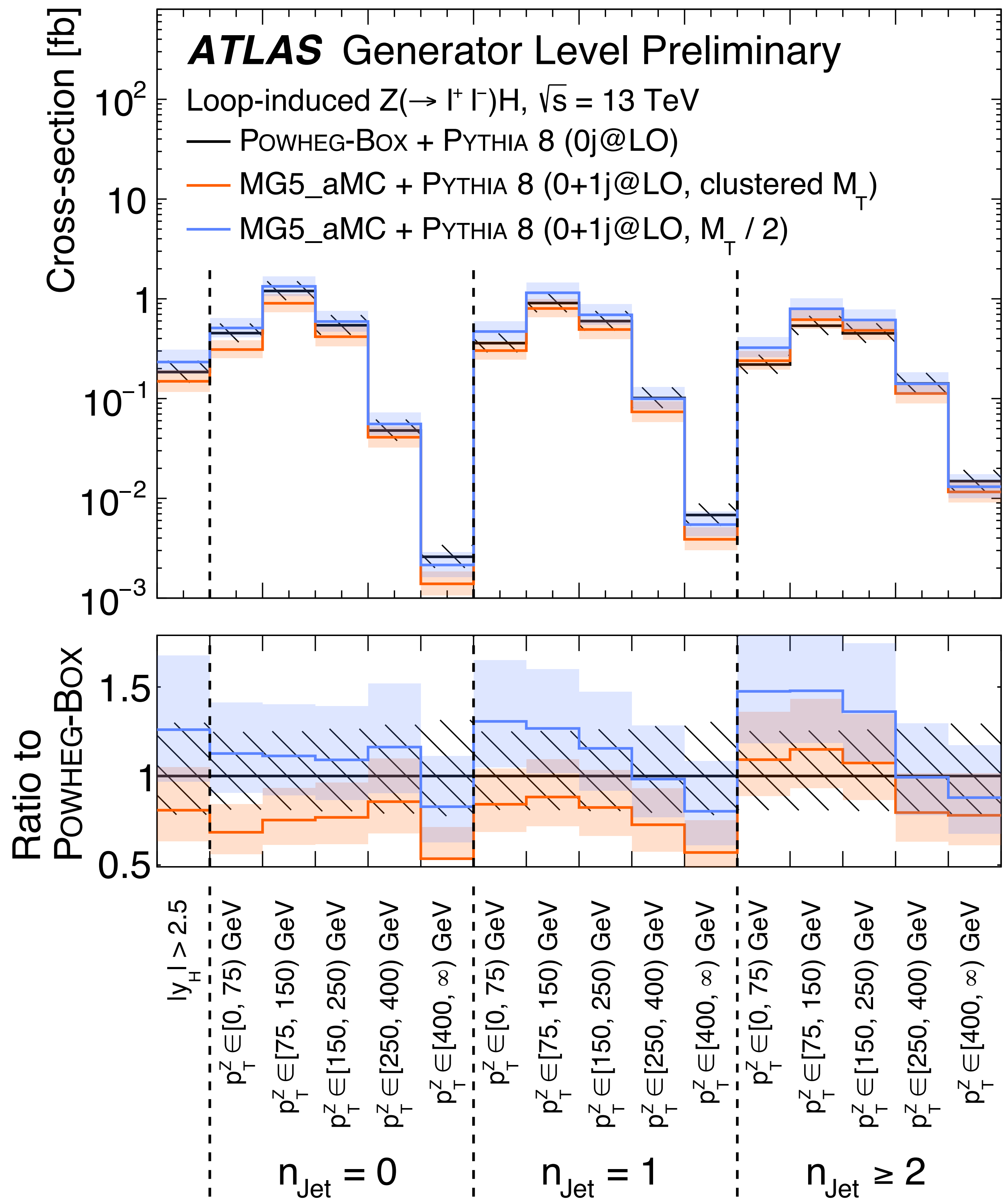
Dynamic scale choice

MG5_aMC: M_T computed after k_T-clustering

SHERPA: STRICT_METS, core scales set to M_T

$$M_T = \sum_i \sqrt{m_i^2 + p_{T,i}^2}$$

Scale choice for MG5_aMC



Default scale choice:

Transverse mass M_T after k_T-clustering of generated final state

Alternative scale choice:

$M_T/2$ directly computed on final state *(purely kinematic scale choice)*

$$M_T = \sum_i \sqrt{m_i^2 + p_{T,i}^2}$$

Significant differences between two scale choices; not within each other's scale uncertainties!