Investigations of a common ggF uncertainty prescription for different kinematic regions

Dag Gillberg
with feedback from several

Desired from the experimental side

- Highly desired to have a common, reasonable prescription for (ggF) theory uncertainties that can be applied consistently across different Higgs analyses
  - Several analyses ($H \rightarrow WW$ in particular) target N_{jets} bins
  - Other analyses target $p_{\mathrm{T,H}}$ bins
  - Most analyses have analysis categories targeting VBF
  - In a combined analysis (e.g. kappa fit), we need to assess theory uncertainties on all these regions **simultaneously**
- QCD uncertainties in these regions are partially correlated
  - In experimental uncertainty, partial correlation is typically addressed by splitting the full uncertainty into separate uncertainty sources, that are fully uncorrelated wrt each other, but fully correlated across kinematic bins (See talk by Kerstin for general treatment)
  - Fully analogous to Hessian PDF error sets (100 error sets → 100 uncertainty sources, uncorrelated wrt each other)

Uncertainty schemes on the market that deals with uncertainty correlation

- Stewart-Tackmann method (STWZ, BLPTW)
  - Several versions
  - Original method (ST-FO) assumes uncertainties on inclusive jet bins uncorrelated
    Used by ATLAS and CMS in Run-1 (all analyses, but ATLAS $H \to$WW)
  - Section in YR4 on resummed ST — current recommended method from ST team
    most complete jet bin result: uncertainties for 0, 1 and ≥2 jet bins
- Jet veto efficiency method
  - Assumes uncertainties on jet veto efficiencies are uncorrelated
  - Used by ATLAS $H \to WW$ in Run-1, with results from both 0-jet-veto & 1-jet-veto
  - For YR4: results with
    JVE @ N^3LO, providing uncertainty for 0⟷1 jet migration: 0 and ≥1 jet bins
- Use uncertainties from MC generators
  - Several MC generators now come with multiple event weights corresponding to variations of parameters
  - E.g. PDF uncertified provided as weights
  - QCD scale weights provided by many generators, but not clear if it's possible to use them to get meaningful uncertainties for **migration** across jet bins and pT regions …

Uncertainty propagation through MC sample

1. Start with MC generator believed to have adequate modelling of the kinematics
2. Normalize it to the best available cross section (YR4: N^3LO)
3. Propagate the uncertainties according to an uncertainty scheme
    1. Apply "+1-standard deviation" shifts of each theory uncertainty, source-by-source, to the MC sample as event weights corresponding to
       $d\sigma_{varied} / d\sigma_{nominal}$
       depending on the kinematic of the given event
       → one new prediction per uncertainty source
       (can do the same for -1 sigma)
4. For any given observable, take the difference between the shifted and nominal prediction separately for each uncertainty source and add in quadrature to construct the total uncertainty band
5. Compare prediction to state-of-the art (analytical) predictions
   → **hope to see state-of-the-art predictions falling within assigned uncertainty band**

Test of uncertainty scheme using MC events

- Following slides present a test of propagating the jet bin uncertainties according to the results presentedd by BLPTW in YR4
- This can easily be adopted to other uncertainty scheme (such as JVE), but BLPTW was chosen since it was the most complete scheme (there is not one-jet-veto result @ 13 TeV)
- Note that this goes beyond what the uncertainties are designed for
  - They are designed to provide uncertainties for jet bins: 0, 1, 2 jets or any combination thereof
  - Here I test what happens to regions split by other observables (pTH, VBF) when propagating the uncertainties parametrized by the number of jets

$p_T^{\rm cut} = 30$ GeV	σ/pb	Δ_μ	Δ_φ	$\Delta_{\rm cut}^{0/1}$	$\Delta_{\rm cut}^{1/2}$	total pert. unc.
$\sigma_{\geq 0}$	47.41±2.40	4.6%	2.0%	-	-	5.1%
σ_0	29.51±1.65	3.8%	0.1%	4.1%	-	5.6%
$\sigma_{\geq 1}$	17.90±1.88	6.0%	5.2%	6.8%	-	10.5%
σ_1	11.94±1.58	5.5%	4.8%	8.4%	7.2%	13.2%
$\sigma_{\geq 2}$	5.96±1.05	7.1%	6.1%	3.6%	14.5%	17.6%

QCD uncertainty split into 4 independent sources

normalization

resummation

0⟷1 jet migration

1⟷2 jet migration

Technical implementation
Uncertainty propagation through MC sample

```
// enum for QCD scale uncertainty source
enum ggF_qcdUncSource { yield=1, res=2, cut01=3, cut12=4 };

// Event weight for propagation of QCD scale uncertainty
// Input: Number of truth (particle) jets with pT>30 GeV, built excluding the Higgs decay
// Number of sigma variation (+1 for "up", -1 for "down")
double getJetBinUncertaintyWeight(ggF_qcdUncSource source, int Njets30, double Nsig=+1.0) {

  // Cross sections in the =0, =1, and >=2 jets of Powheg ggH after reweighing scaled to  sigma(N3LO)
  static vector<double> sig({30.26,13.12,5.14});

  // BLPTW absolute uncertainties in pb
  static vector<double> yieldUnc({ 1.12, 0.66, 0.42});
  static vector<double> resUnc  ({ 0.03, 0.57, 0.42});
  static vector<double> cut01Unc({-1.22, 1.00, 0.21});
  static vector<double> cut12Unc({    0,-0.86, 0.86});

  // account for missing EW+quark mass effects by scaling BLPTW total cross section to sigma(N3LO)
  double sf = 48.52/47.4;

  int jetBin = (Njets30 > 1 ? 2 : Njets30);
  if ( source == yield ) return 1.0 + Nsig*yieldUnc[jetBin]/sig[jetBin]*sf;
  if ( source == res   ) return 1.0 + Nsig*resUnc[jetBin]/sig[jetBin]*sf;
  if ( source == cut01 ) return 1.0 + Nsig*cut01Unc[jetBin]/sig[jetBin]*sf;
  return 1.0 + Nsig*cut12Unc[jetBin]/sig[jetBin]*sf;
}
```

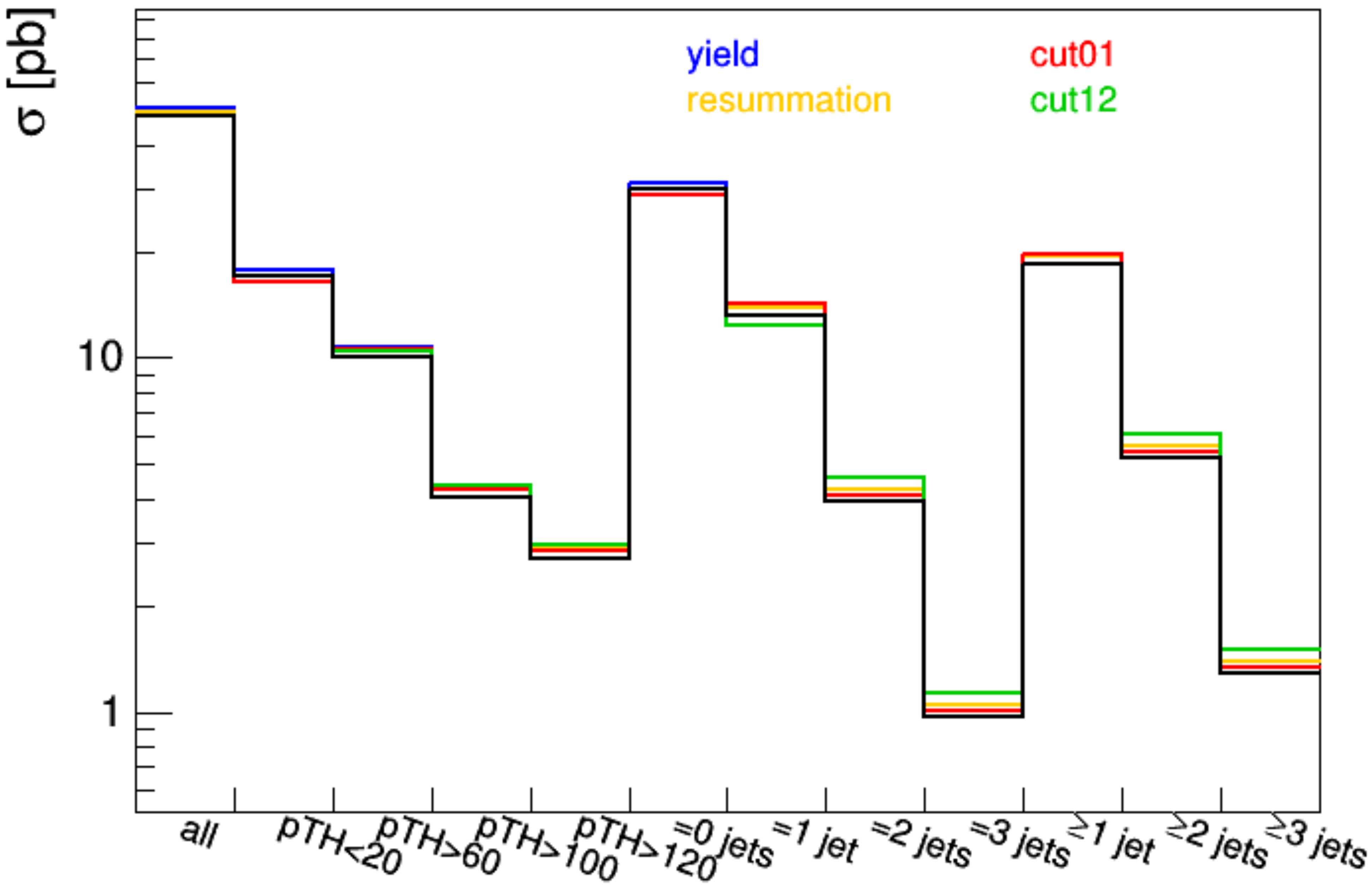
This code returns a weight equal to the relative change in cross section.
E.g. 1.2 if the uncertainty is +20% (Gaussian assumption).
Uncertainty parametrized vs N_{jets} (p_{T}>30 GeV) according to YR4 writeup (STWZ).
The code is similar for the JVE prescription.

Technical implementation (2)
Uncertainty propagation through MC sample

```
// enum for QCD scale uncertainty source
enum ggF_qcdUncSource { yield=1, res=2, cut01=3, cut12=4 };

// Event loop -- this method gets called for each event
void execute() {

  // access the number of jets of the event
  int Njets30 = event.jets30().size();

  // access any observable
  double observable = event.getObservable();

  // access nominal event weight
  double weight_nom = event.getNominalWeight();

  // Fill nominal histogram, weighted by nominal event weight
  histogam_nominal->Fill(observable,weight_nom);

  // Fill histograms shifted by +1 sigma of each QCD uncertainty
  // here yield, resummation, cut01, cut12
  histo_QCDyield_up -> Fill( observable, weight_nom*getJetBinUncertaintyWeight(yield,Njets30,+1.0) );
  histo_QCDres_up   -> Fill( observable, weight_nom*getJetBinUncertaintyWeight(res,Njets30,+1.0)   );
  histo_QCDcut01_up -> Fill( observable, weight_nom*getJetBinUncertaintyWeight(cut01,Njets30,+1.0) );
  histo_QCDcut12_up -> Fill( observable, weight_nom*getJetBinUncertaintyWeight(cut12,Njets30,+1.0) );
}
```

Uncertainty propagated with event weights, just as for PDF uncertainties.
(e.g. PDF4LHC15, Hessian error sets)

Results from propagating BLPTW uncertainties to NNLOPS MC

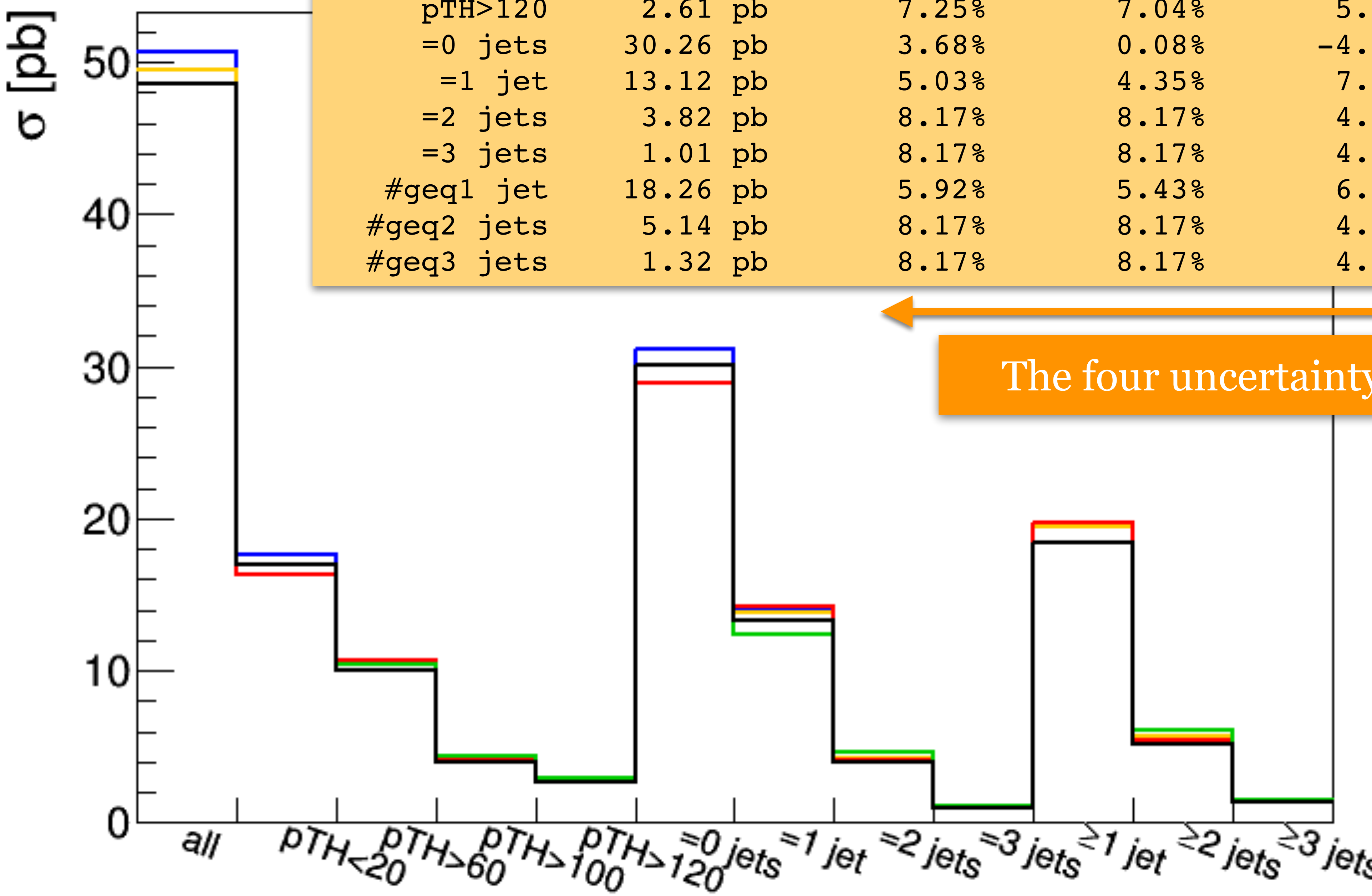


Results from propagating BLPTW uncertainties to NNLOPS MC

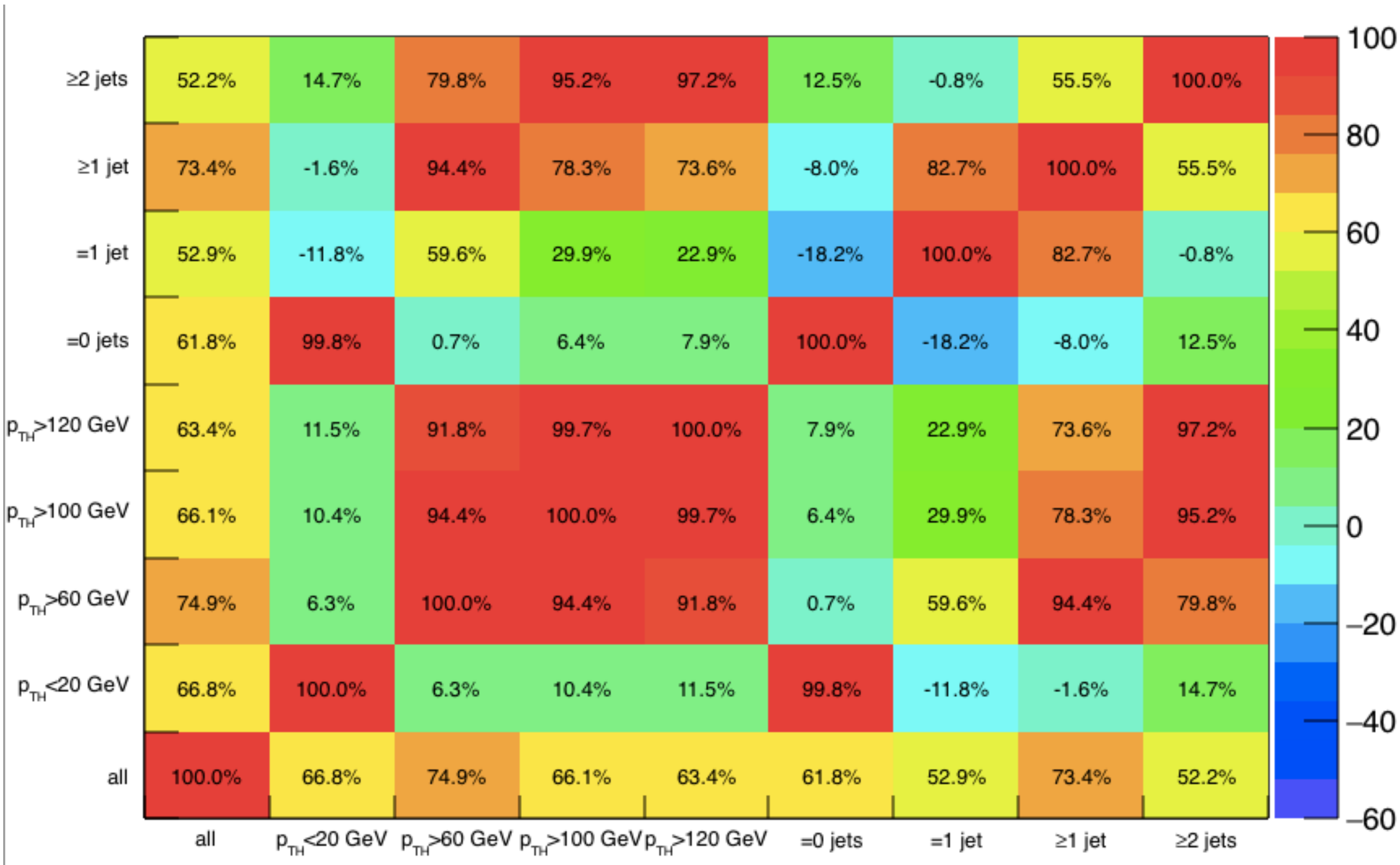
Region	xsec	mu unc.	res unc.	cut01 unc.	cut12 unc.	tot unc.
incl	48.52 pb	4.53%	2.09%	-0.01%	0.00%	4.99%
pTH<20	17.06 pb	3.76%	0.26%	-3.70%	-0.10%	5.28%
pTH>60	9.96 pb	6.30%	5.80%	5.74%	3.44%	10.87%
pTH>100	3.90 pb	7.05%	6.80%	5.33%	8.44%	13.98%
pTH>120	2.61 pb	7.25%	7.04%	5.13%	9.87%	15.03%
=0 jets	30.26 pb	3.68%	0.08%	-4.04%	0.00%	5.46%
=1 jet	13.12 pb	5.03%	4.35%	7.62%	-6.55%	12.05%
=2 jets	3.82 pb	8.17%	8.17%	4.08%	16.73%	20.74%
=3 jets	1.01 pb	8.17%	8.17%	4.09%	16.73%	20.74%
#geq1 jet	18.26 pb	5.92%	5.43%	6.63%	0.00%	10.41%
#geq2 jets	5.14 pb	8.17%	8.17%	4.08%	16.73%	20.74%
#geq3 jets	1.32 pb	8.17%	8.17%	4.09%	16.73%	20.74%

The four uncertainty sources

addition in quadrature

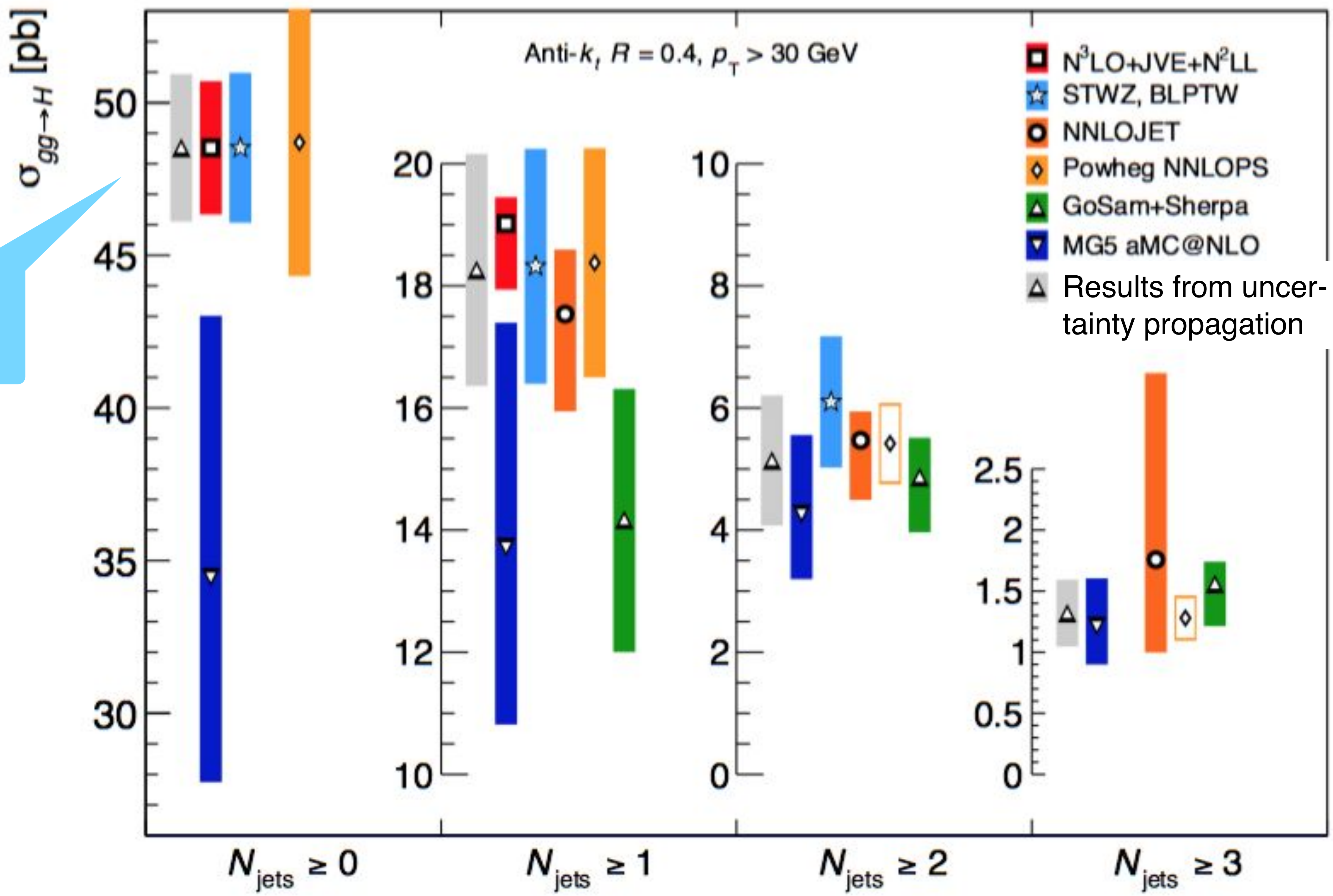


Uncertain correlations between different kinematic regions (constructed from table on prev. page)

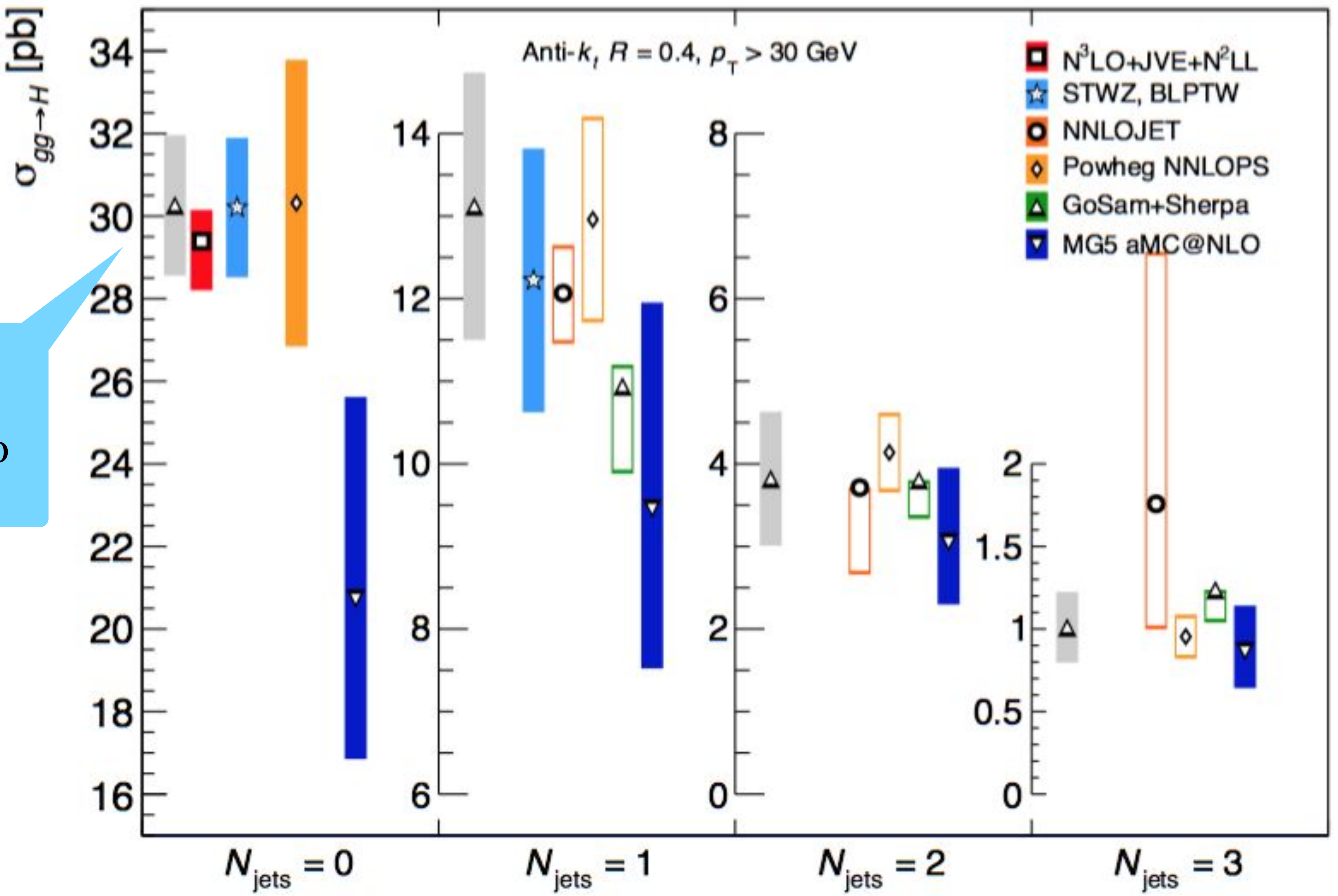


Comparison with state-of-the-art

Normalized to N3LO

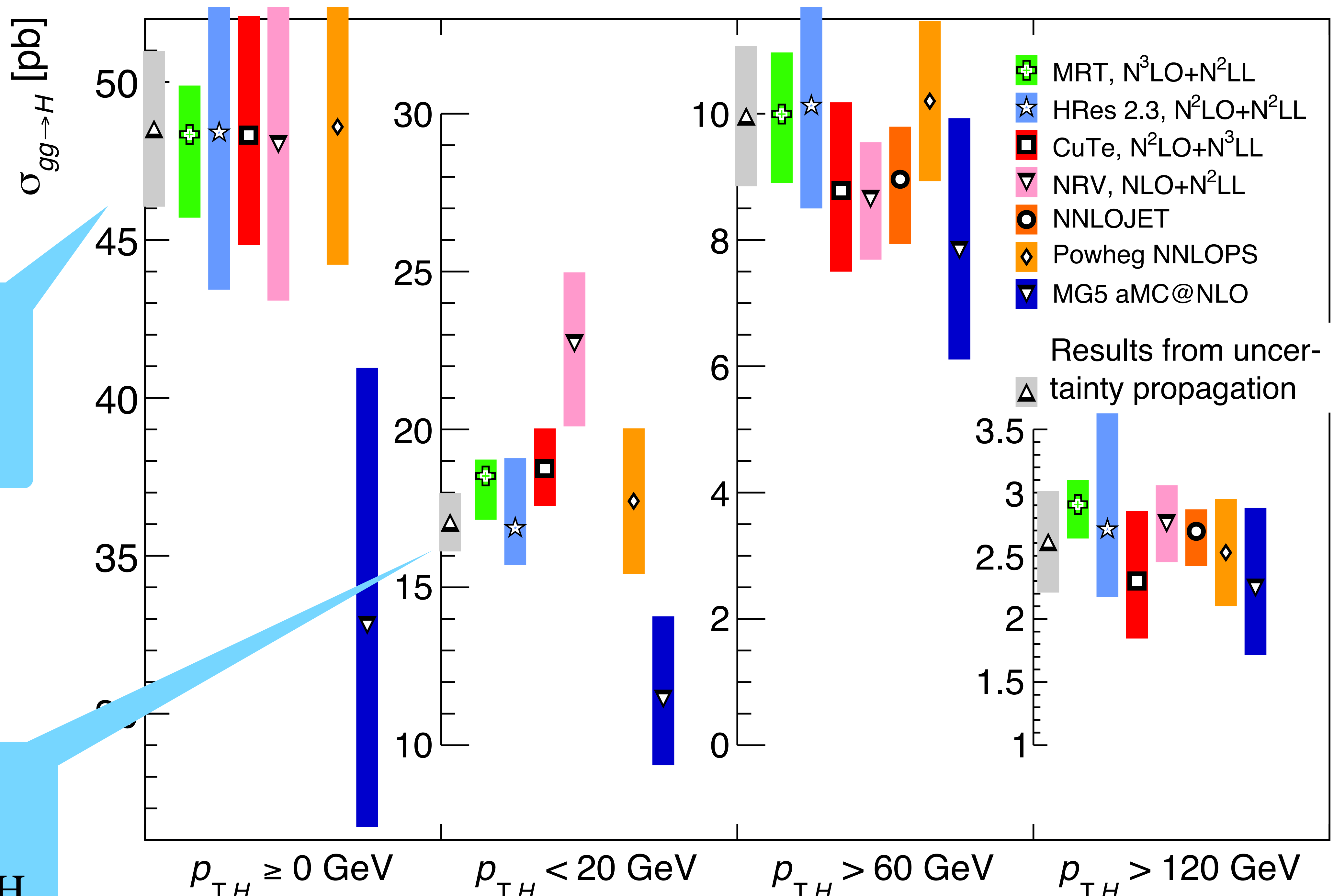


Comparison with state-of-the-art



Inclusive predictions Normalized to N3LO

Comparison with state-of-the-art



Inclusive predictions Normalized to N³LO

Very small uncertainty at very low pTH.

Shortcomings of the method

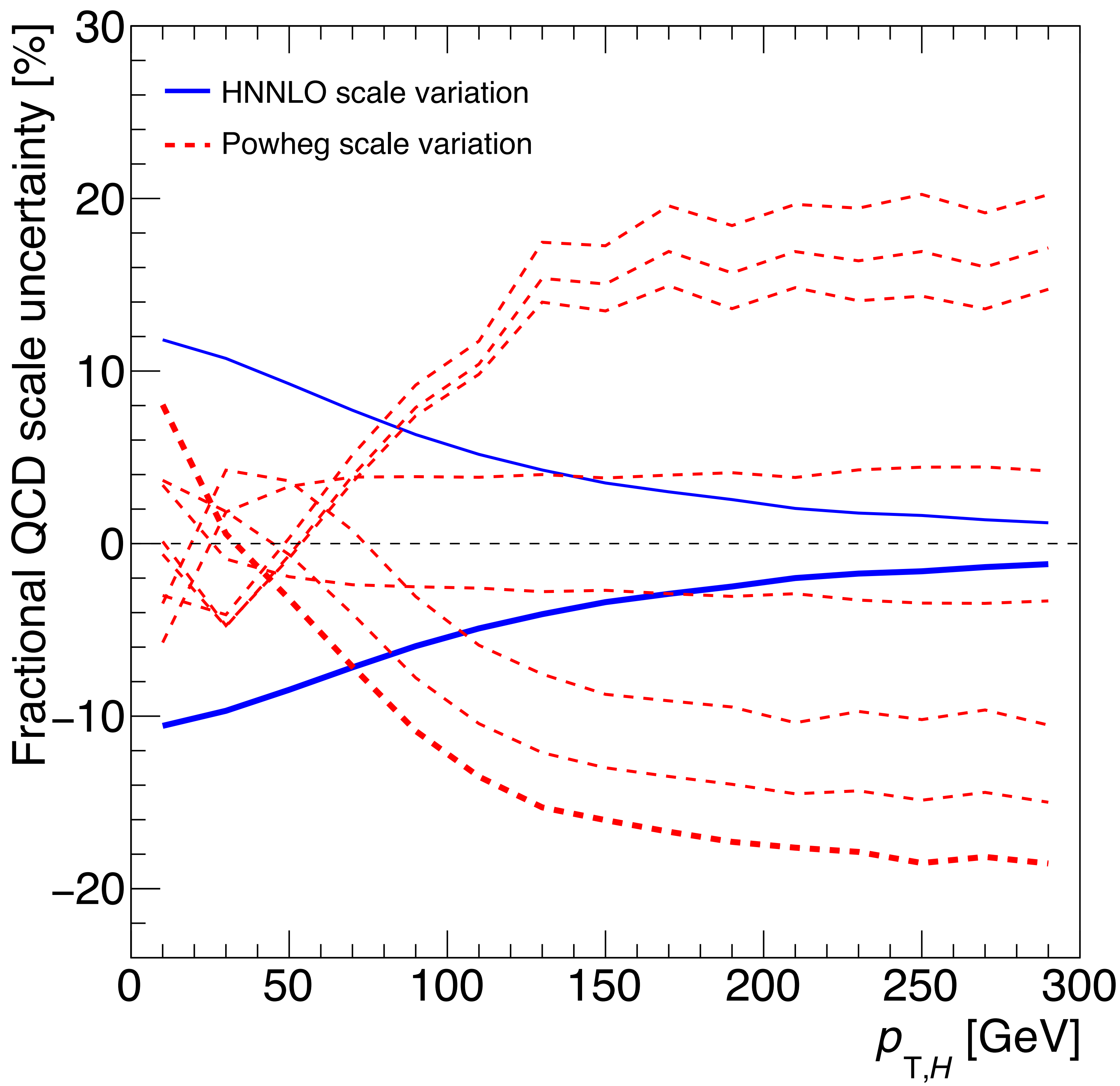
- Discontinuity
  - The results here are parametrized vs N_{jets}
  - This means that when propagating uncertainties to a $p_{\text{T,jet}}$ variable, one will introduce a jump a the p_{T} boundary corresponding to the N_{jets} splitting
  - This issue can be avoided by parametrizing the uncertainty as smooth functions of e.g. $p_{\text{T,j1}}$, $p_{\text{T,j2}}$ etc instead of N_{jets}.
- Also note, the results presented here will have the same uncertainty in a given $p_{\text{T,jet}}$ bin (e.g. all pT,H regions inside a pT, jet bin has the same relative uncertainty)
- Not addressing VBF topology uncertainty yet, but should be fairly straight forward to add on top, e.g. using ST

Summary

- Presented results from straw man test of a common way to propagate theory uncertainties
  - Hope is to find common method to assign a QCD uncertainties that should be valid for jet bins (up two 2 jets inclusive), and hopefully also assign reasonable uncertainties in regions based on (modest) $p_{T,H}$ cuts
  - Could act as a "base" uncertainty for all analyses, that might need to be appended with additional uncertainties in more difficult phase space regions (e.g. low p_{TH} used in $H \rightarrow \mu\mu$)
- Certainly room for improvement to the method

Backup

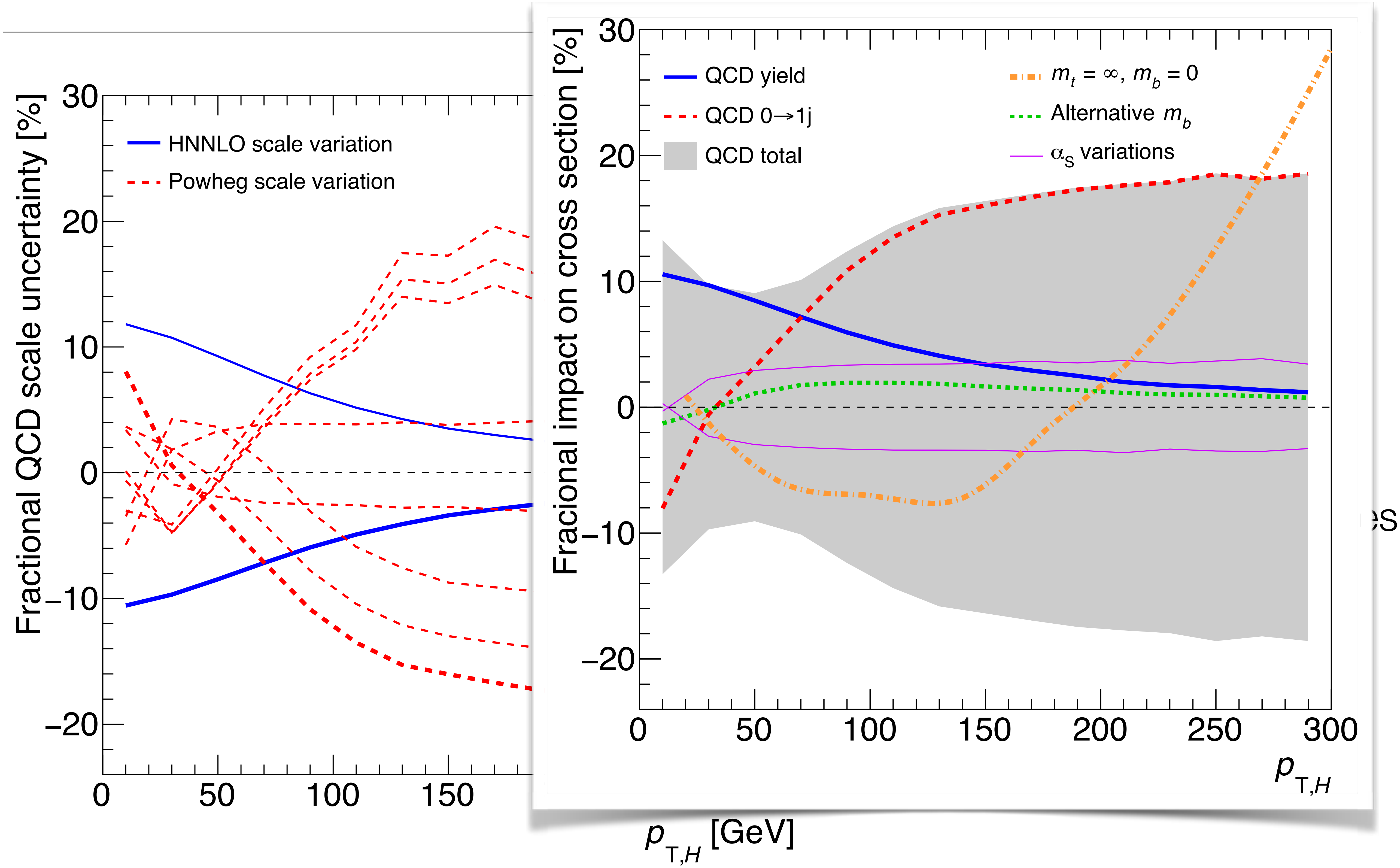
Look at uncertainty from Powheg NNLOPS provided as event weights



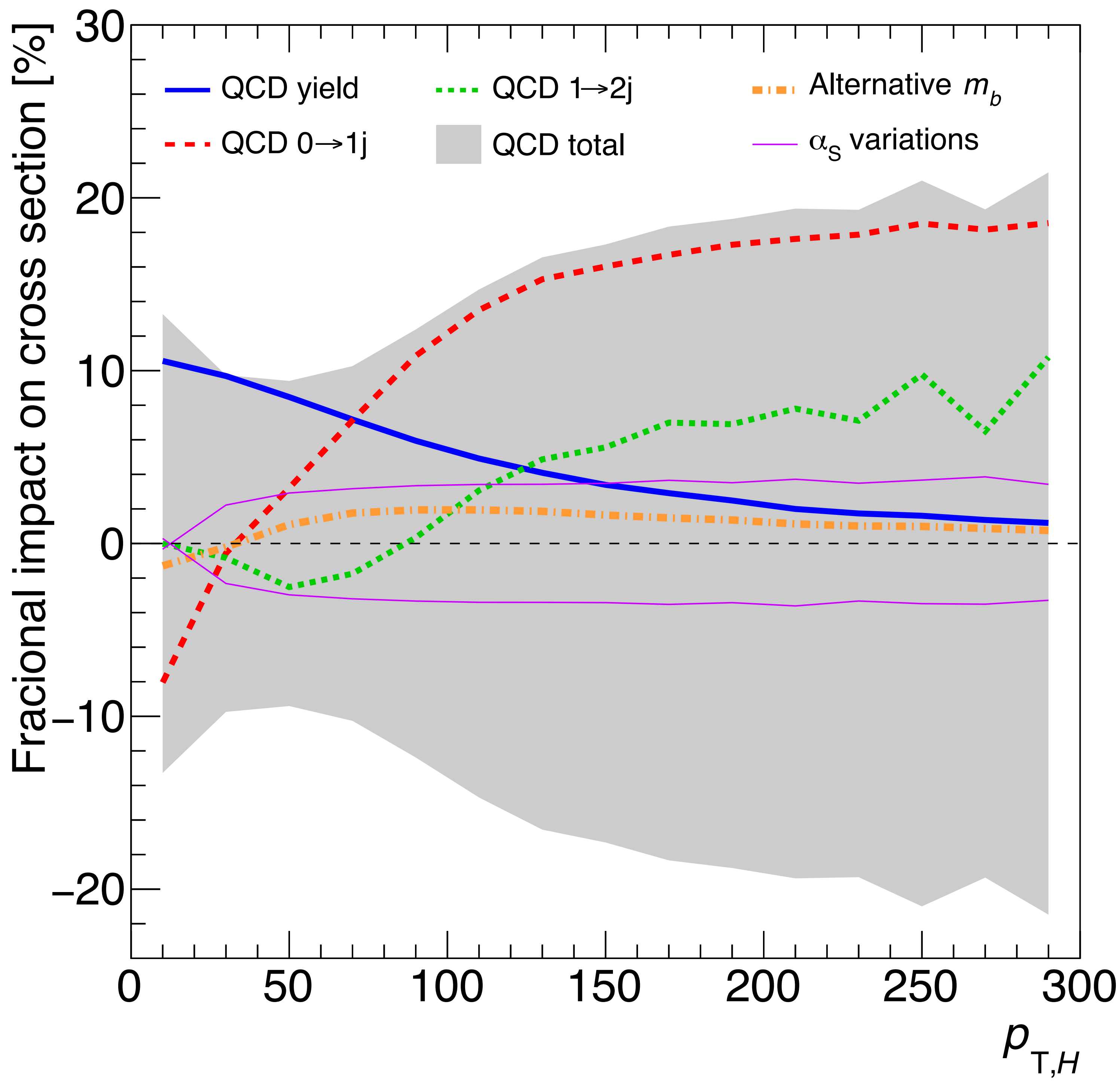
Powheg NNLOPS
has weights corresponding
to the Powheg scale (red)
and to the NNLO piece,
that's taken from HNNLO

I took the largest variations (bolded) and treated them as uncorrelated uncertainty sources (nuisance parameters)

Look at uncertainty from Powheg NNLOPS provided as event weights



Propagating BLPTW uncertainties to an observable



Jet bin uncertainties and correlation

- The “main” Higgs (coupling) results are extracted in combined fits using multiple Higgs decay channels and several kinematic regions simultaneously
  - ➡ We don’t just need the SM ggF uncertainty in a kinematic region, but also uncertainty correlation between different bins
  - ➡ In experimental analyses, this is typically achieved by splitting the total uncertainty into independent (Hessian) components(/sources) treated with an associated nuisance parameter in the fit
- Nice section in YR4 discusses this:
  General treatment of theory uncertainties between kinematic bins
- Two contributions also touch on this topic:
  - JVE @ N3LO, providing uncertainty for 0⟷1 jet migration: 0 and ≥1 jet bins
  - STWZ, BLPTW, providing uncertainties for the 0, 1 and ≥2 jet bins

$p_T^{\mathrm{cut}} = 30$ GeV	σ/pb	Δ_μ	Δ_φ	$\Delta_{\mathrm{cut}}^{0/1}$	$\Delta_{\mathrm{cut}}^{1/2}$	total pert. unc.
$\sigma_{\geq 0}$	47.41±2.40	4.6%	2.0%	-	-	5.1%
σ_0	29.51±1.65	3.8%	0.1%	4.1%	-	5.6%
$\sigma_{\geq 1}$	17.90±1.88	6.0%	5.2%	6.8%	-	10.5%
σ_1	11.94±1.58	5.5%	4.8%	8.4%	7.2%	13.2%
$\sigma_{\geq 2}$	5.96±1.05	7.1%	6.1%	3.6%	14.5%	17.6%

QCD uncertainty split into 4 independent sources
normalization
resummation
0⟷1 jet migration
1⟷2 jet migration