ggF Stage 1.2 Uncertainty scheme

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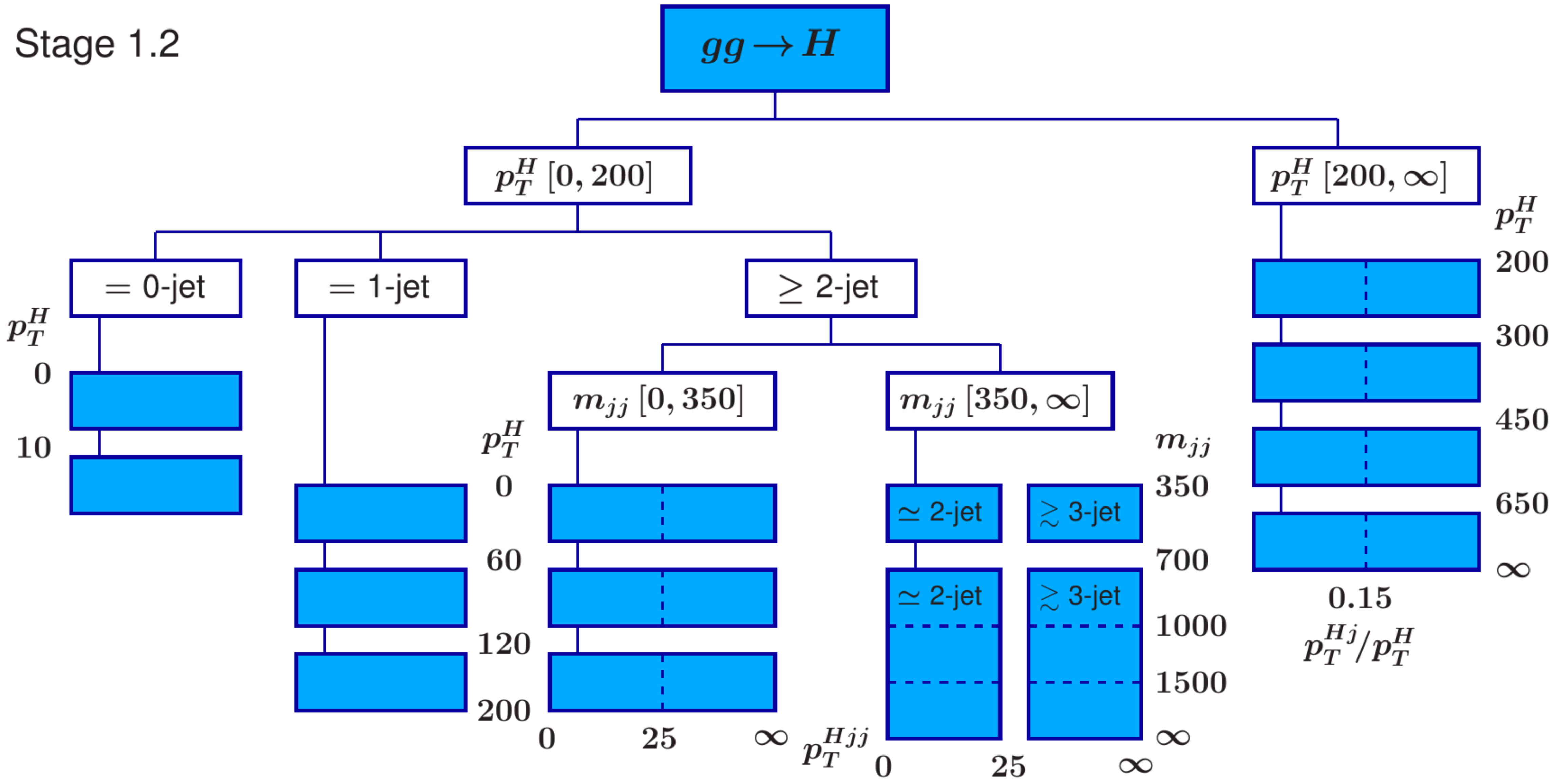
Introduction

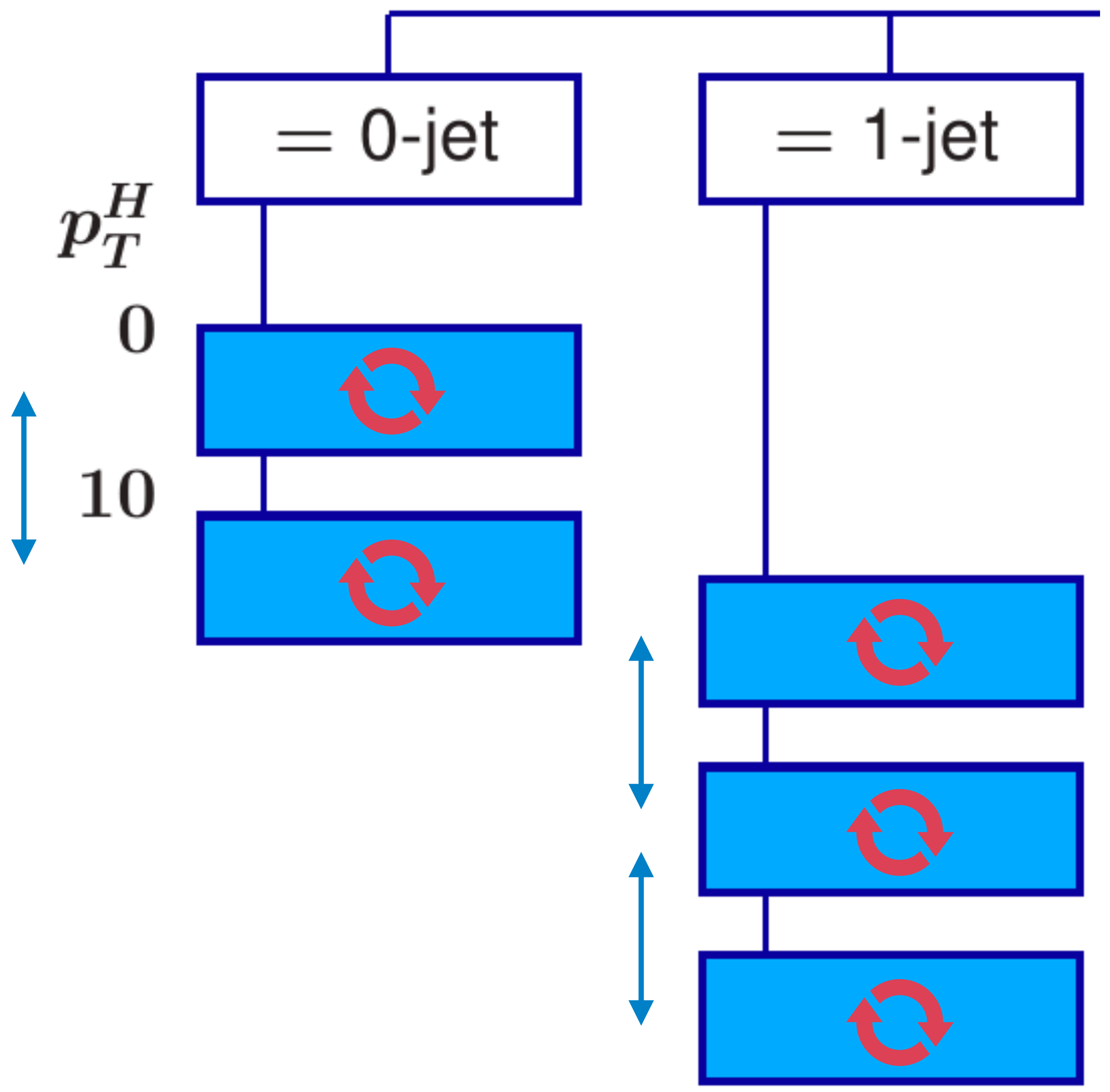
- STXS measurements are very common in the Higgs group + provide a convenient way to parametrize the uncertainties
    - STXS recommendations have two parts - bin definition + associated uncertainty
- Other production modes - Finalized with their respective uncertainties
    - qq2Hqq - Link, Link
    - VH-lep - Link, Link
    - ttH - Link
- ggF Stage 1.2 had a preliminary systematic scheme
    - Tons of work put into the defining a new scheme - ~ year long collaboration with people from ATLAS, CMS & theorists all involved
    - Collaborations across various LHC XS WGs!
- Results documented @ Link, working on releasing a LHC HWG document



Uncertainty scheme - ggF

- Couple of **key ingredients** that need to be defined for such a scheme:
  - **Common default MC** - ATLAS: Powheg & CMS: MG5 - Both with NNLOPS reweighing
    - Talks on harmonizing this even further for Run 3
  - **List of NPs to parametrize the uncertainty**
    - All stakeholders need to agree on this - defines how to correlate the systematics
    - Many meetings within the LHC XS WG - Finalized a common scheme @ Link
  - The method to numerically evaluate impacts across bin boundaries
    - Year long collaboration on the methodology - an evolution of the ST method settled as the main choice - used for other production modes as well
    - Final numbers evaluated by applying this methodology - can be updated as better calculations come
  - Systematics impacting the acceptance - shapes within an STXS bin
    - Largely agreed to leave this up to each analysis as there are too many possibilities
    - But there is proposal on how to cover for this - Not covered in this talk

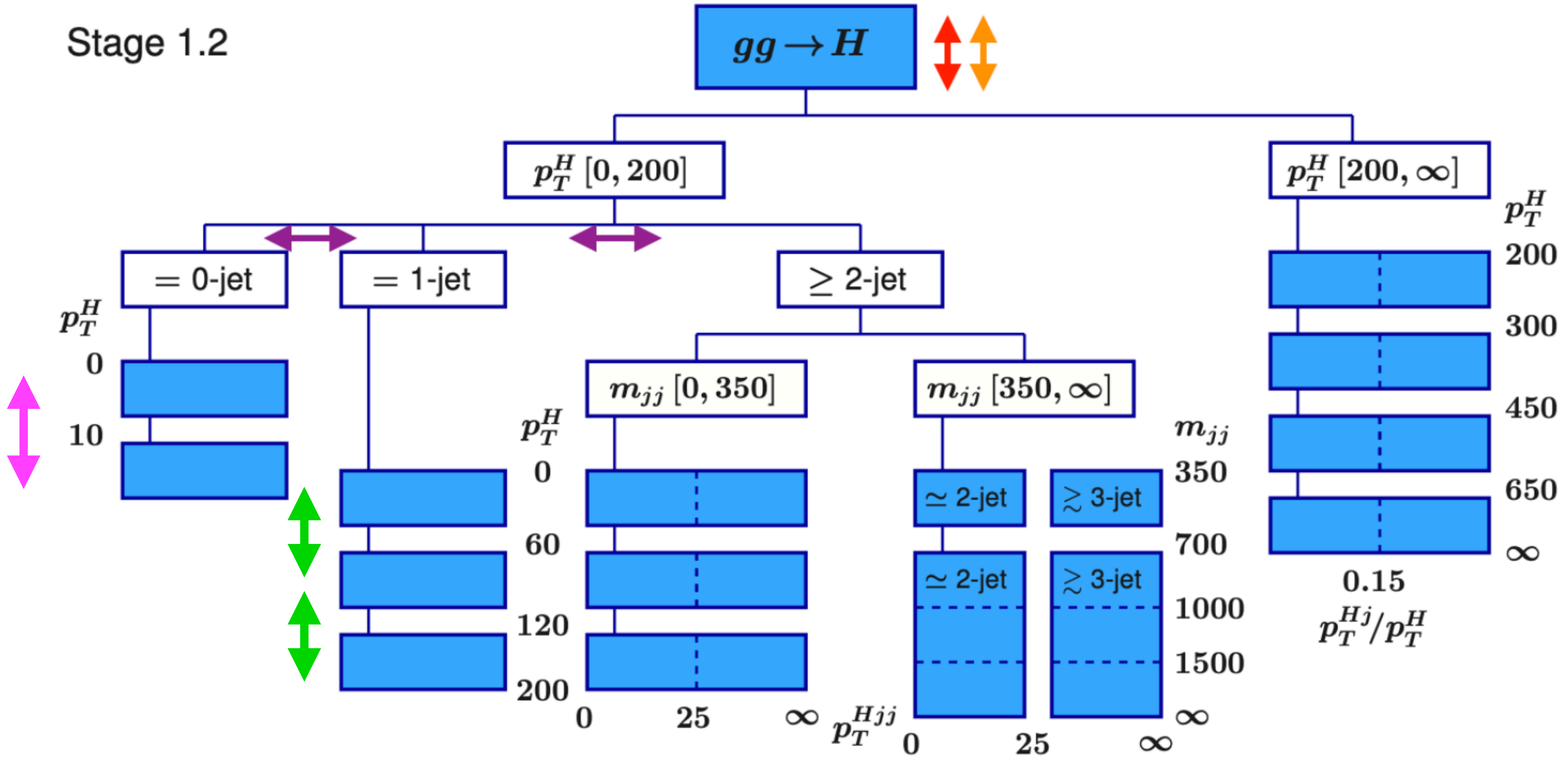
Stage 1.2



Parameter Scheme

NP scheme

- Final decision from discussions documented @ Link
  - This is an evolution of the Stage 1 theory scheme with many common parts taken directly
- Overall, 18 NPs have been decided upon to parameterize the uncertainties



Overall yield and jet migration (4 NPs):

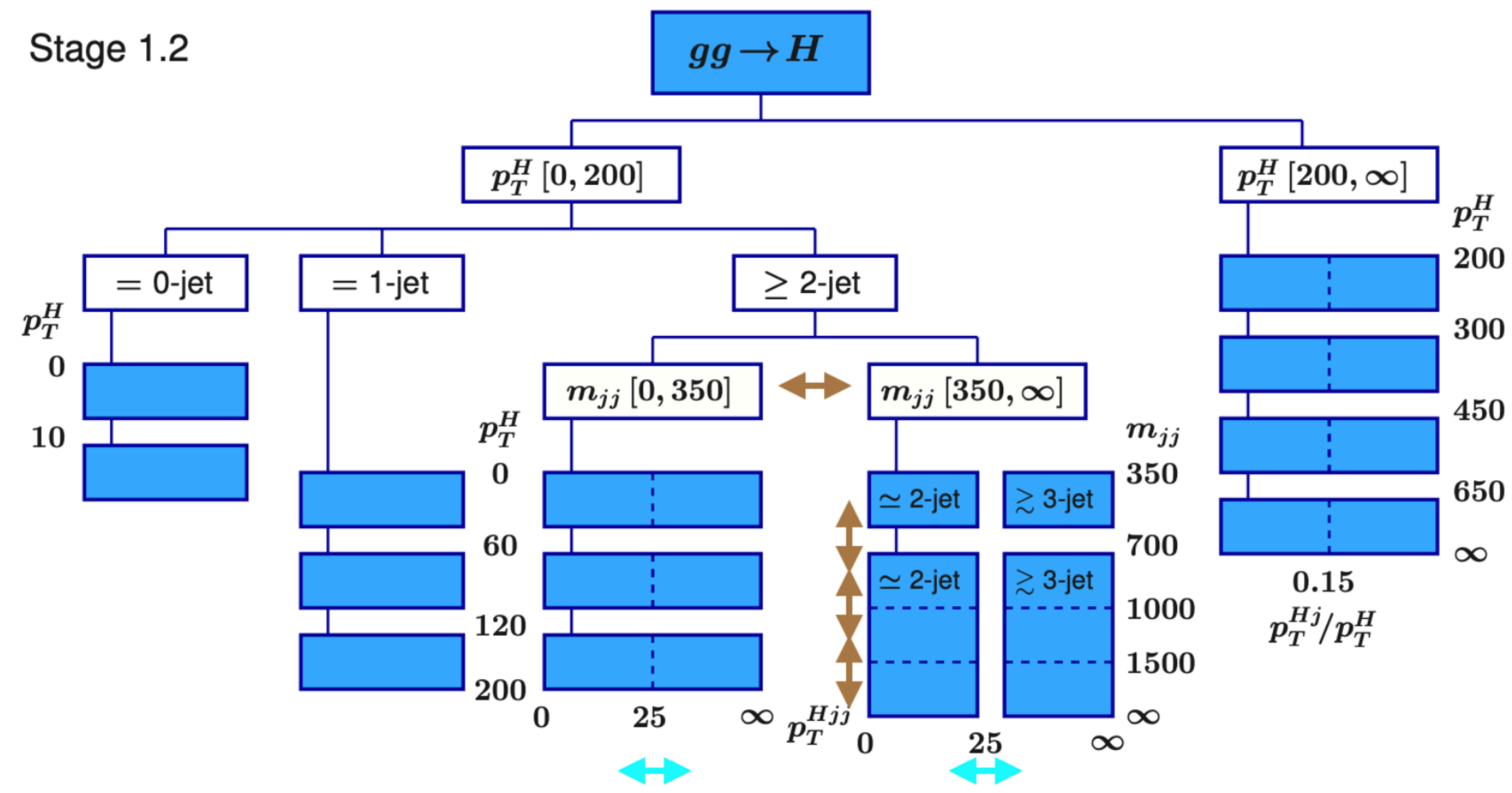
- 1 NP for overall fixed-order effects
- 1 NP for overall resummation effects
- 1 NP for 0-1 jet bin migration
- 1 NP for 1-2 jet bin migration

pTH migrations (3 NPs):

- 1 NP for p_T^H migration in 0 jet
- 2 NP for p_T^H migration at the 60/120 boundary Correlated across 1-2 jet bins

No change from Stage 1 for these NPs

NP scheme



m_{JJ} and p_T^{Hjj} migration (5 NPs):
4 NP for new m_{JJ} bins
1 NP for p_T^{Hjj} variations

New m_{JJ} bins added

p_T^{Hjj} sys now impacts the full 2J phase space

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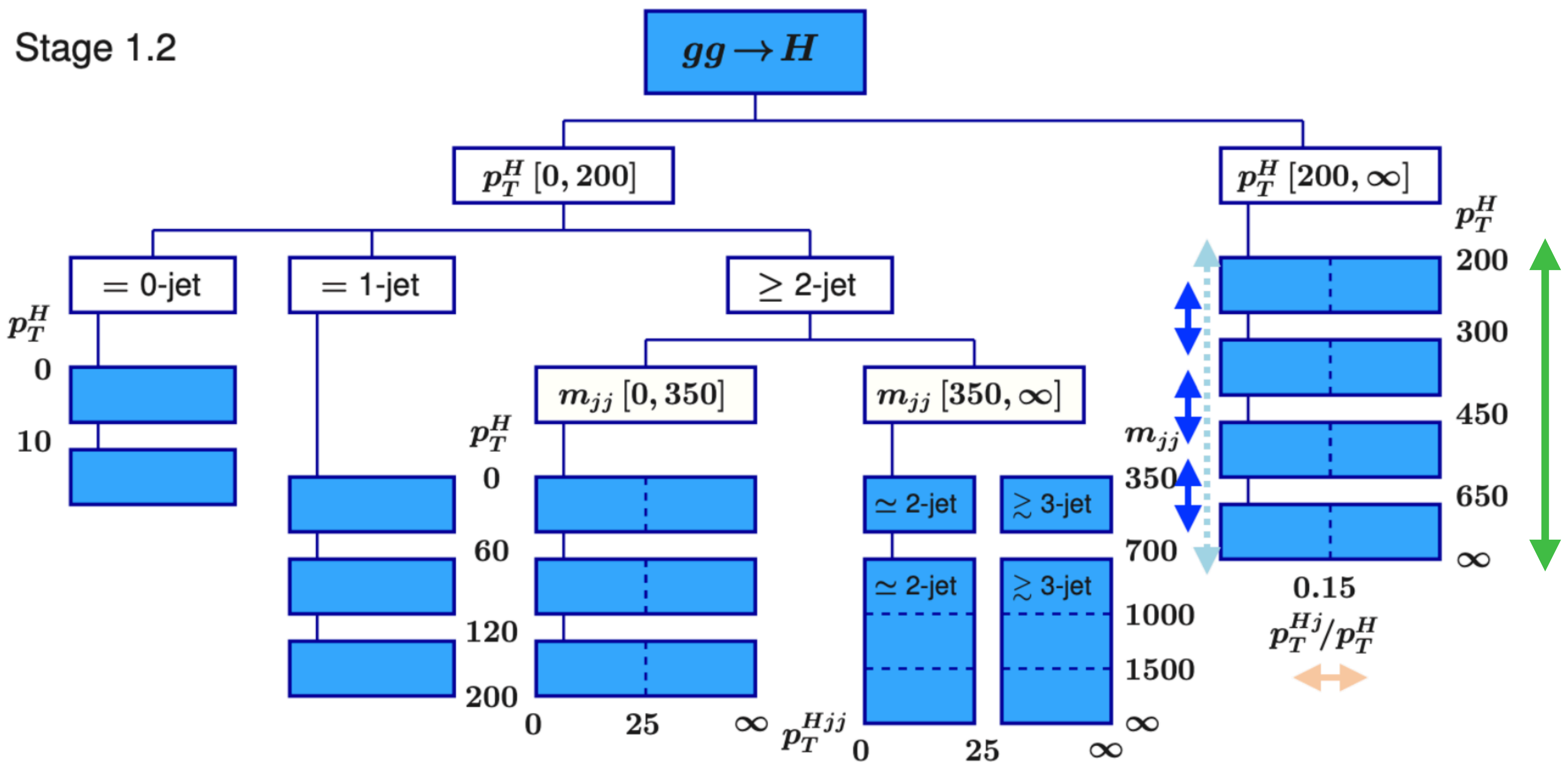


High p_T^H migration (6 NPs)
1 NP for overall XS variation
3 NP for new p_T^H bins
1 NP for p_T^{Hj}/p_T^H variations
1 NP for top mass scheme

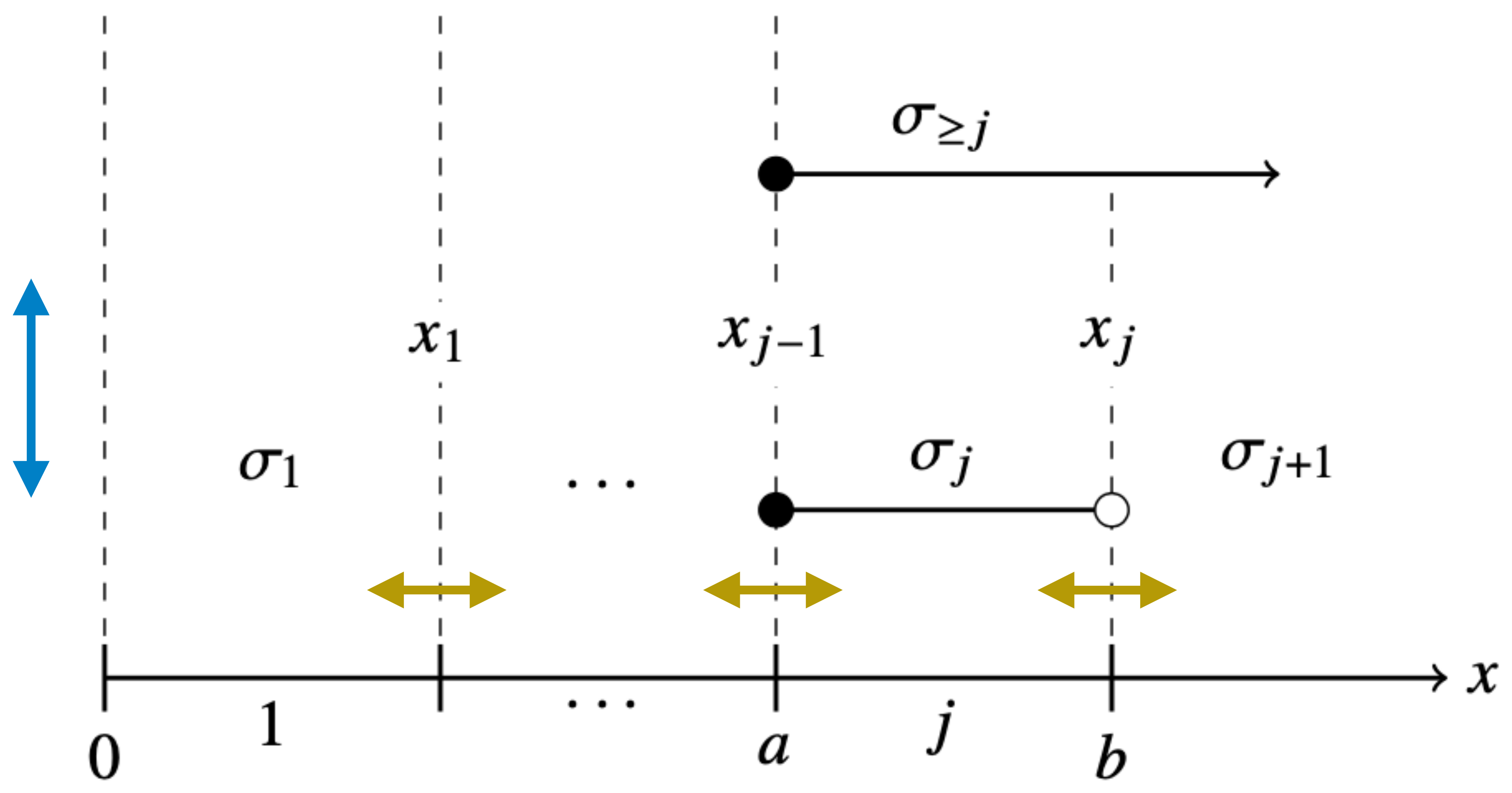
Previously one NP for full region
Now take dedicated state of art predictions and factorize out the various effects

Uncertainty evaluation

Long range ST method

- Many ways to evaluate - all involve **varying** the muR & muF scales and using the XS variations
- Build upon the ST method to remove some of its limitations - **LR ST method collaboratively developed**
  - Evaluate the yield variations inclusively and replace with better calculation if available
  - Distribute the migration sys across all ‘higher’ bins
- Leads to **double counting** - if we apply the same method in $m_{JJ}>350$ and $m_{JJ}>700$, double counting in the upper region
  - Introduce ρ scaling param to prevent this - no clear way to estimate this correlation theoretically
  - Nominal choice of $\rho = 0.5$ chosen to ensure that total variation is ~ equal to the scale variations in that bin

Bin definitions



Long range ST method

Take the max scale variation inclusive region and apply as yield NP for all bins

$$\theta^{y}(j)\left\{\delta^{y} = \max|\Delta_{\mu}|/\sigma \quad \text{(Replaced by state-of-the-art number when available)},\right.$$

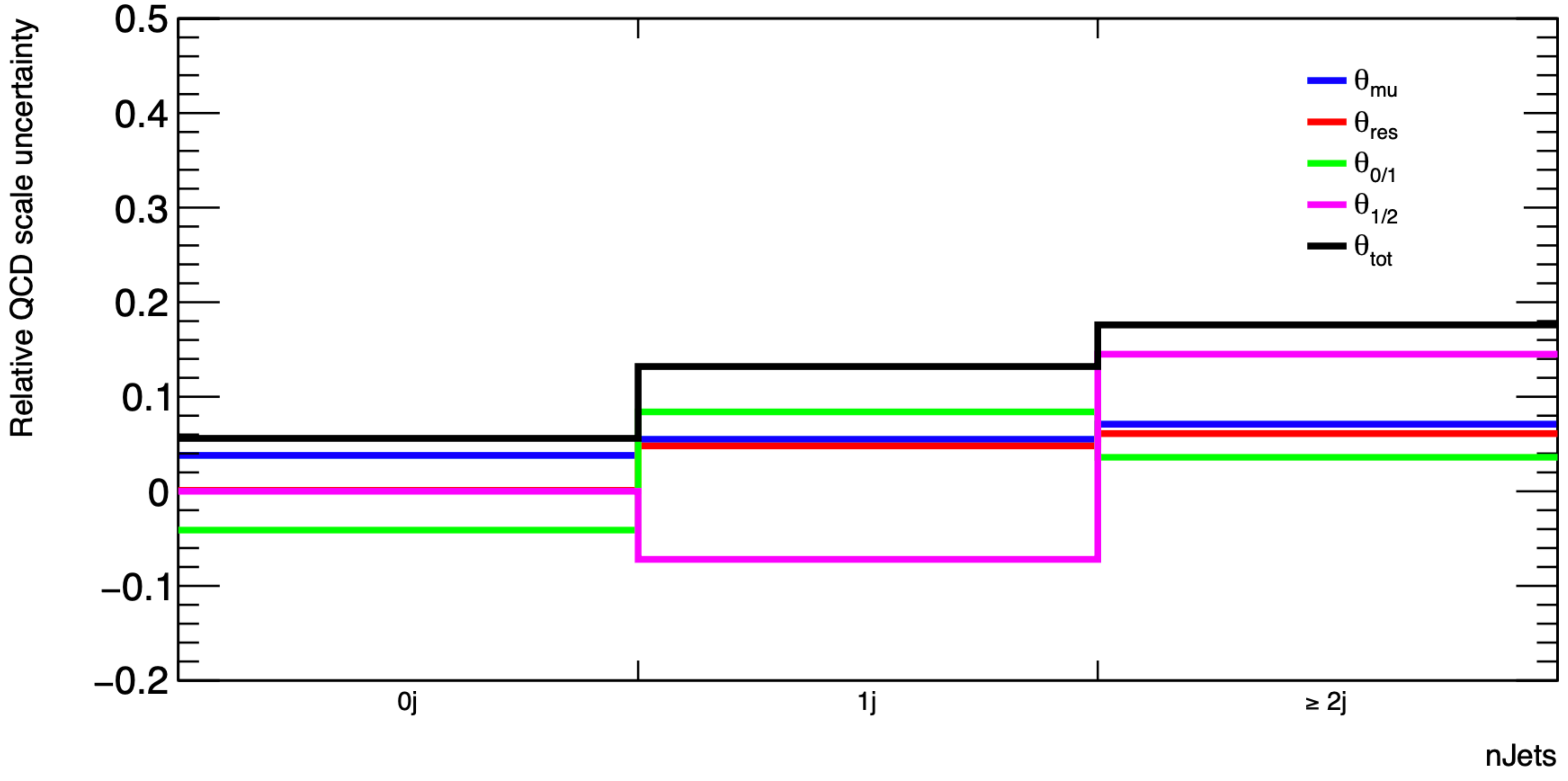
$$\theta^{\text{mig}}_{x_k}(j)\begin{cases}0 & : j < k\\ \rho\times\left(\delta_k^{-} \equiv -\max|\Delta_{\mu,\geq k+1}|/\sigma_k\right) & : j = k\\ \rho\times\left(\delta_k^{+} \equiv +\max|\Delta_{\mu,\geq k+1}|/\sigma_{\geq k+1}\right) & : j \geq k+1\end{cases}$$

Take the max scale variation in ≥ k+1 region and apply as migration NP between k and ≥ k+1 bins

Inclusive and Jet migrations

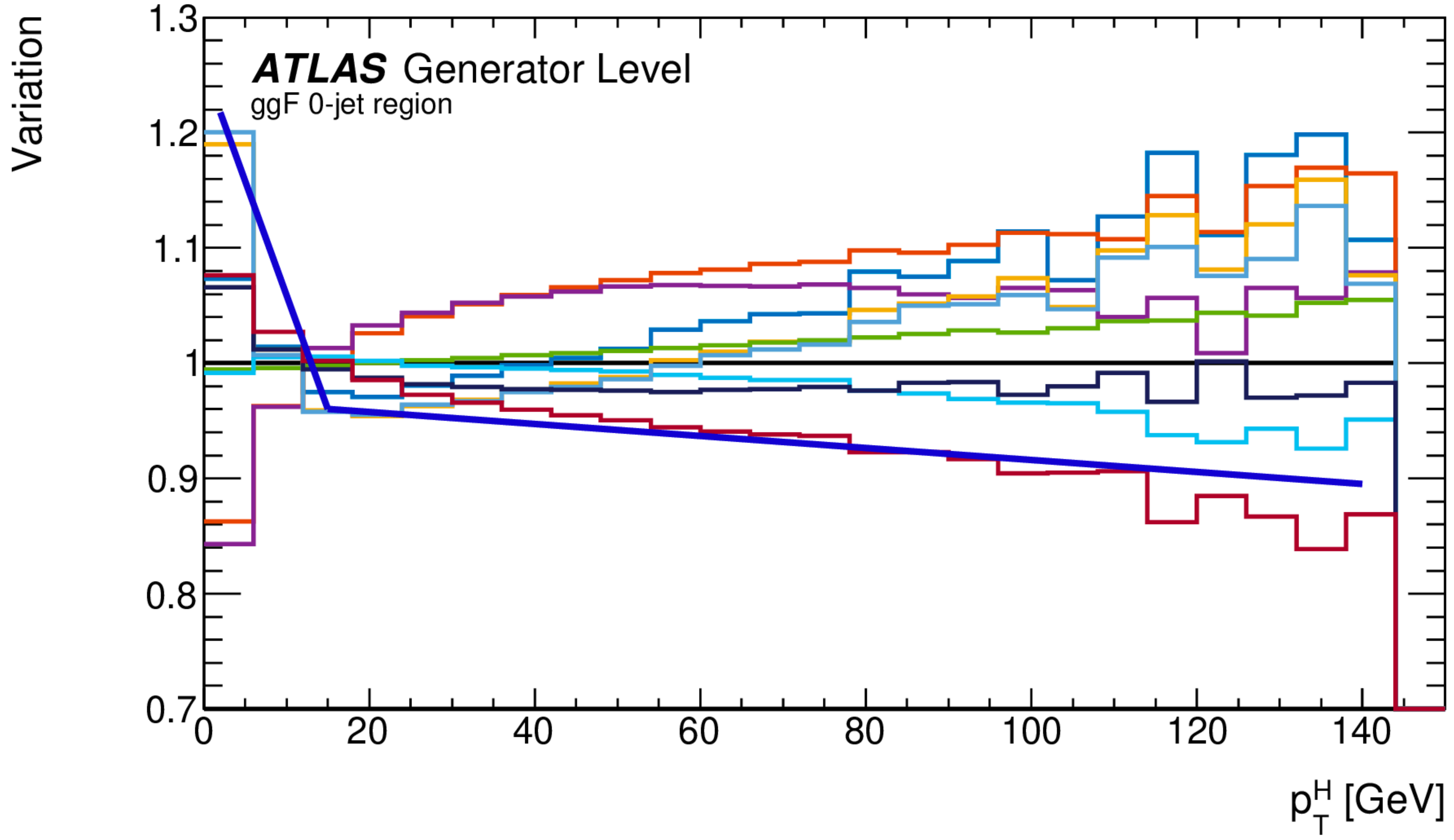
- No change from the Stage 1 scheme
- Use BLPTW method from the YR4
  - These end up being the ‘yield’ uncertainties when we evaluate other uncertainties

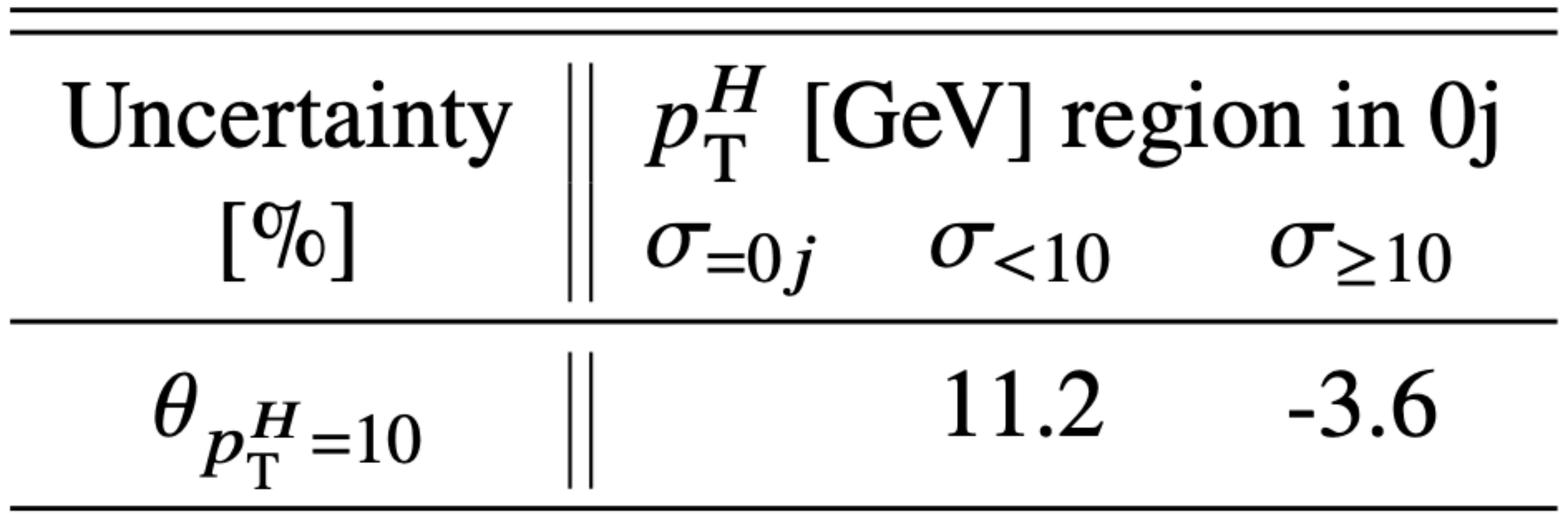
Uncertainty [%]	jet bin σ_0	σ_1	$\sigma_{\geq 2}$
θ_μ	3.8	5.2	7.9
θ_{res}	0.1	4.5	7.9
$\theta_{0/1}$	-4.2	7.9	3.9
$\theta_{1/2}$	-	-6.8	16.1
Total	5.6	12.5	19.9



Low p_T^H region - 0 jet topology

- Scheme developed a few years ago - approved as part of the Stage 1.1 scheme - Link
  - Envelop of HNNLO NNLOPS/muR/muF scale taken as the sys
- No application of long range method - only one bin boundary
  - Dominant effects are from low p_T resummation
  - Care taken to ensure that uncertainty in the regions are in line with calculations

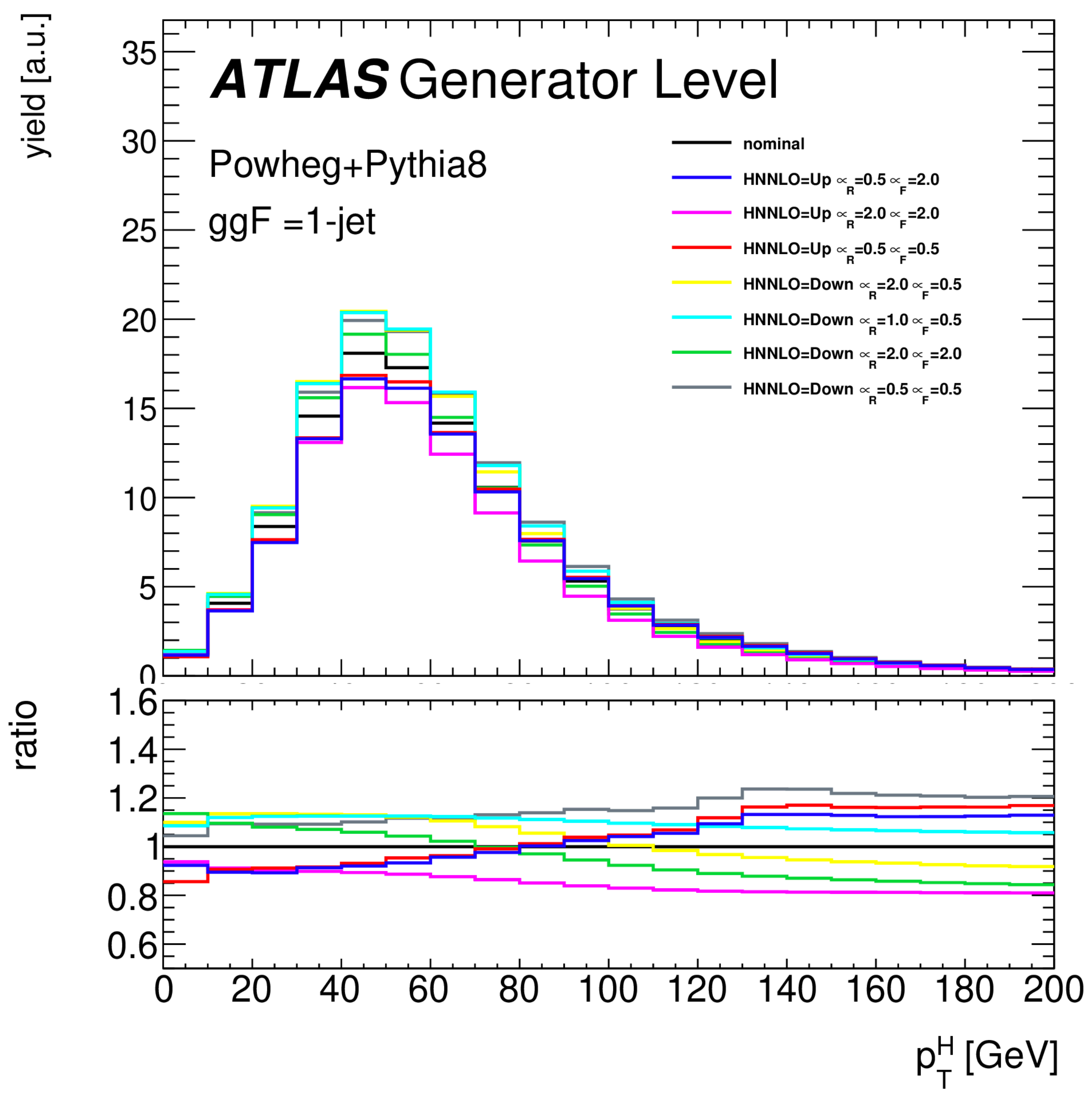


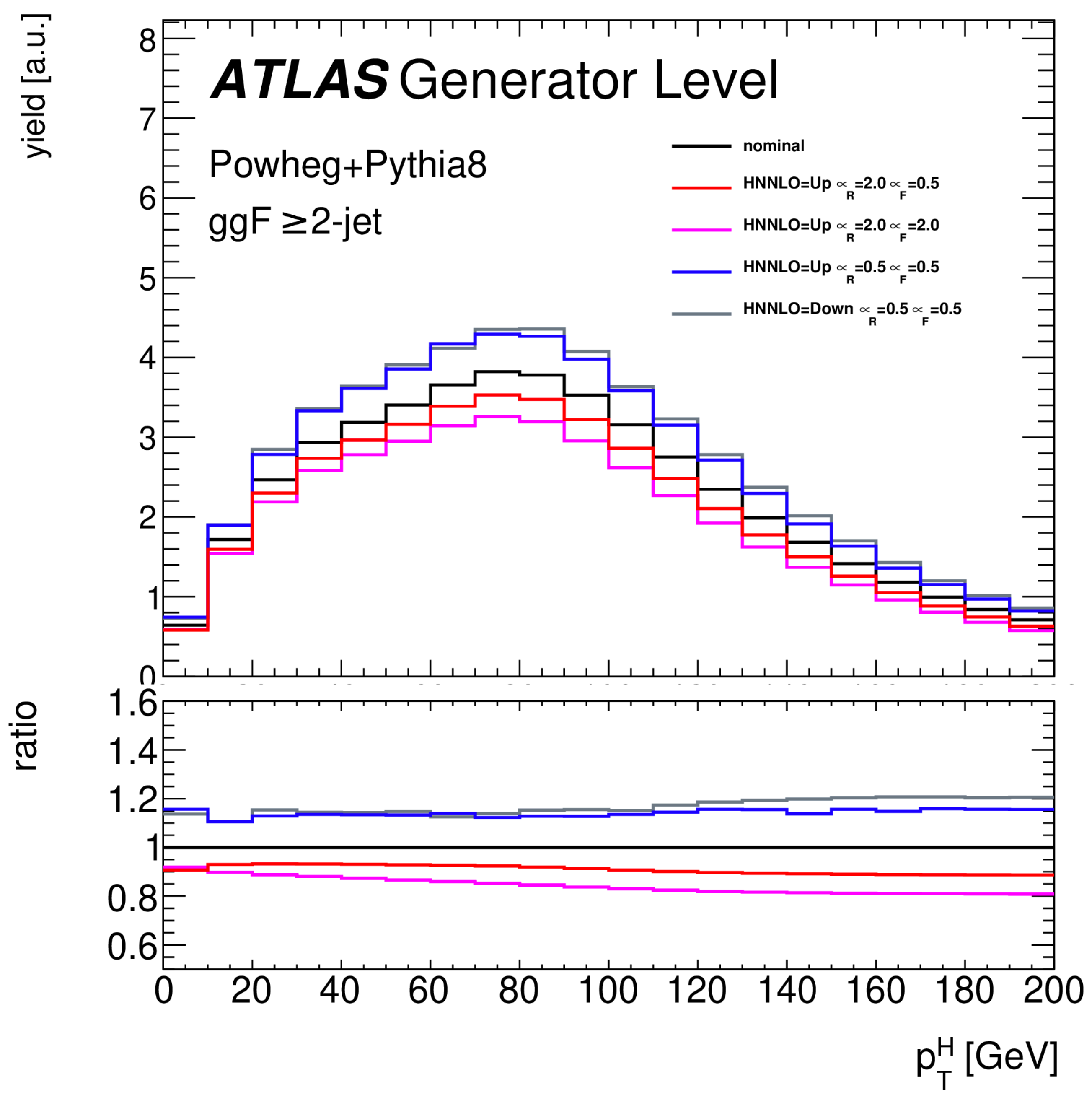


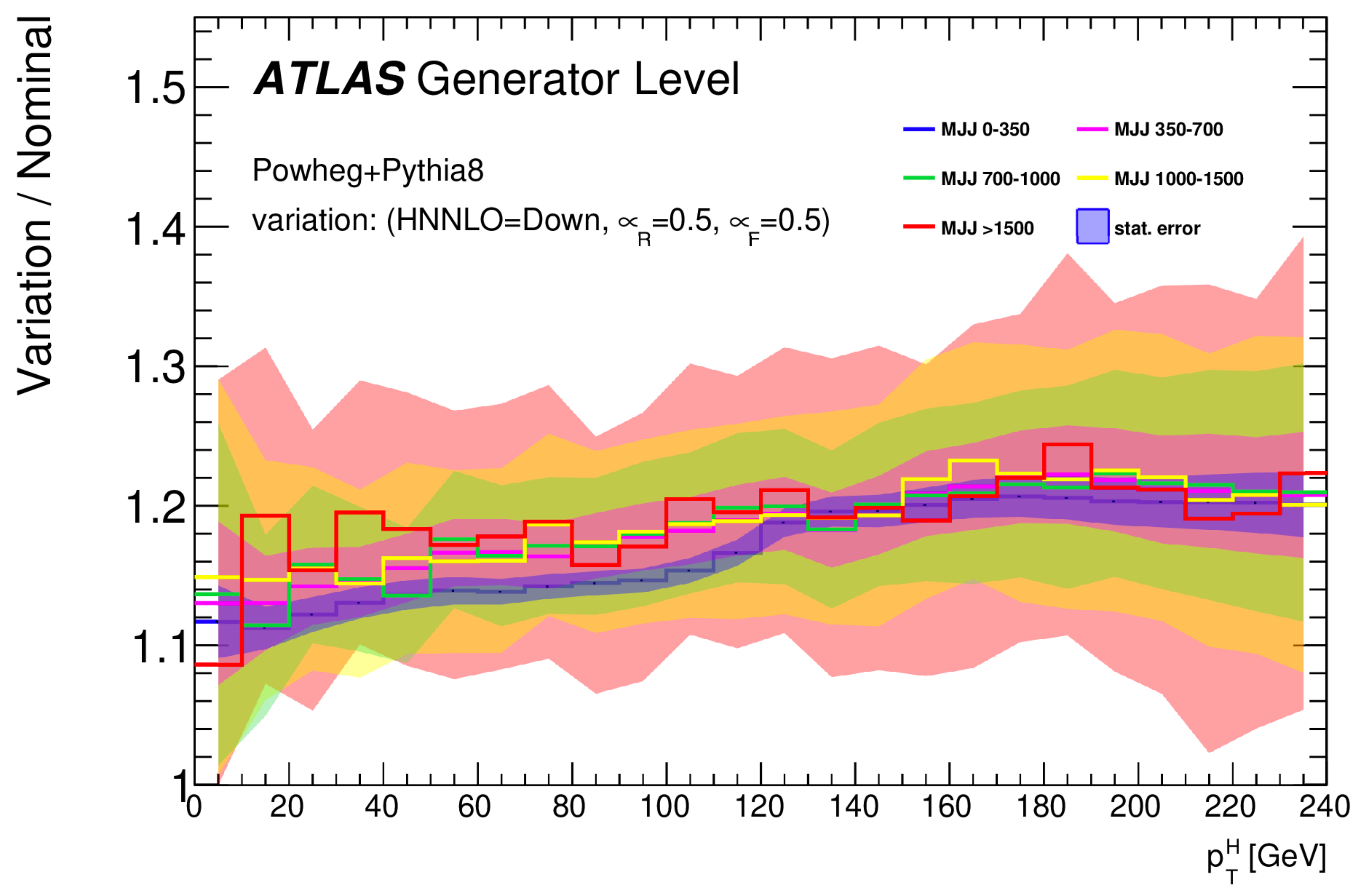
Uncertainty [%]	p_T^H [GeV] region in 0j $\sigma_{=0j}$	$\sigma_{<10}$	$\sigma_{\geq 10}$
$\theta_{p_T^H=10}$		11.2	-3.6

Low p_T^H region - 1/2 jet topology

- Similar as 0 jet - but dominant uncertainty source expected to be covered by muR/muF/HNNLO variations
- Following a similar procedure to Stage 1 scheme - but applying LR ST method in the middle
- Also checked the scale variations in m_{jj} bins - consistent within the statistical error
  - Assume for now, p_T^H uncertainty is independent of m_{jj}





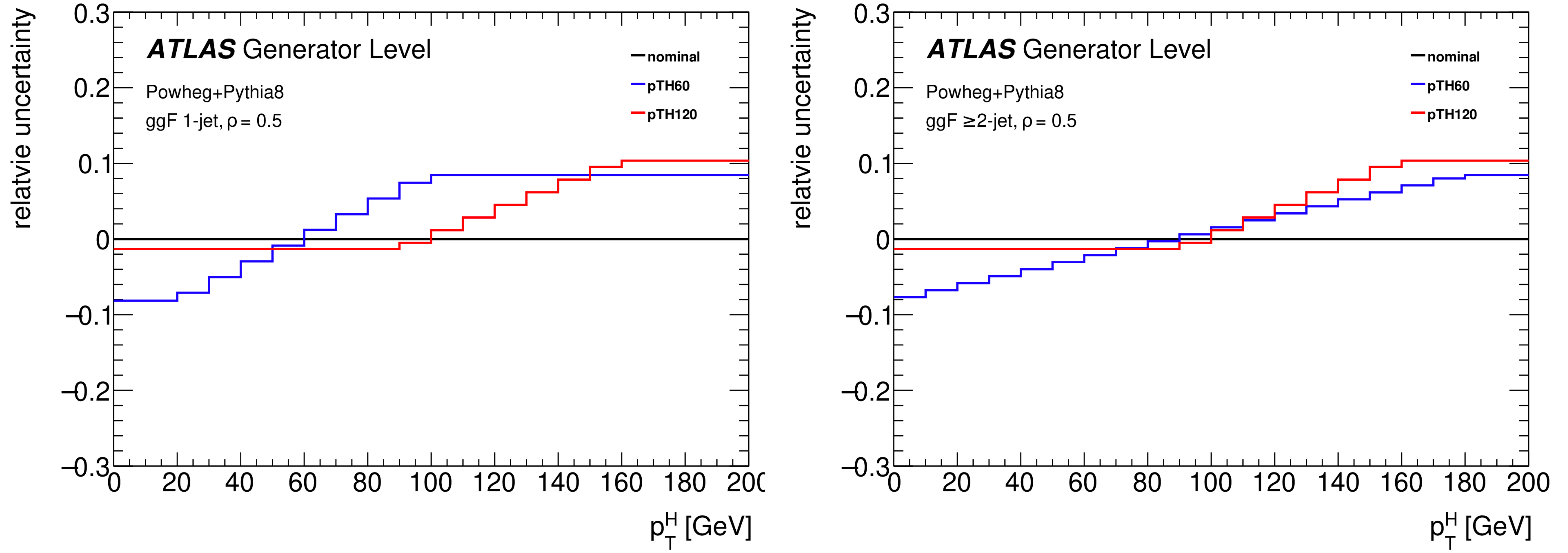


Low p_T^H region - 1/2 jet topology

- **Derive** the results in ≥ 1 jet region
  - Since p_T^H shape changes in jet regions, apply a different **smoothing** function to distribute the XS impact evenly across p_T^H
- Only place where smoothing is applied - p_T^H is typically correlated with acceptance effects due to analysis selection
  - Smoothing allows to get the impact of these acceptance effects
  - Non-trivial to parameterize other variables once p_T^H has been smoothed - **tackle in the next iteration** of the scheme

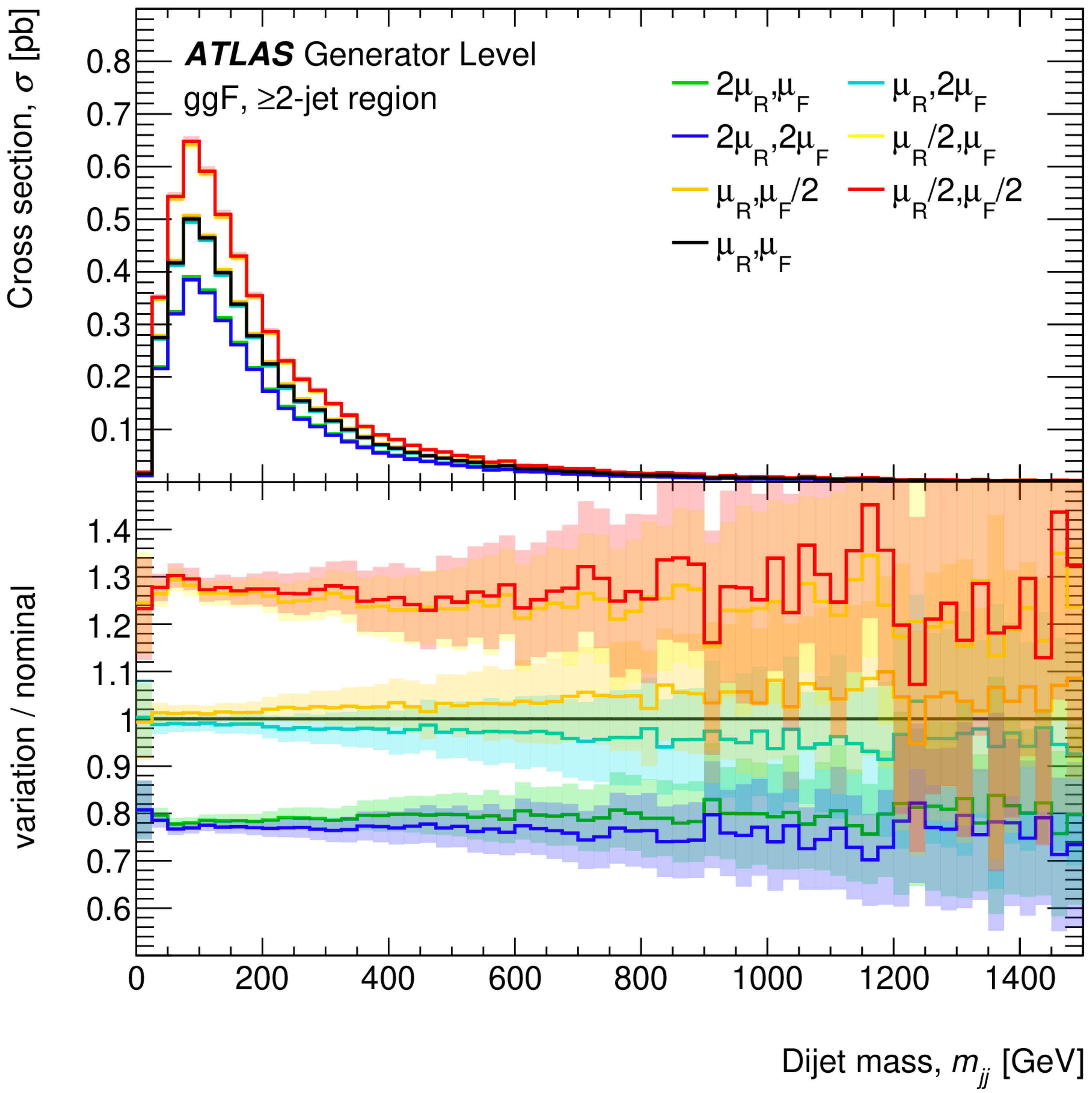
Uncertainty [%]	Powheg NNLOPS			
	p_T^H [GeV] region			
	$\sigma_{\geq 1}$	$\sigma_{[0,60)}$	$\sigma_{[60,120)}$	$\sigma_{[120,200)}$
$\boxed{\theta_y}$	13.1	13.1	13.1	13.1
$\theta_{p_T^H=60}$		-8.1	+7.6	+7.6
$\theta_{p_T^H=120}$			-2.9	+10.3
Total	13.1	15.4	15.5	18.3

To be replaced with the BLPTW



2 Jet region - m_{jj}

- Uncertainties for m_{jj} are a simple application of the long range method
  - Scale variation from FxFx used as it is NLO @ 2j
- Cross-checked results with NNLOPS, MG5 H+2J and Hjj MiNLO
- Ensured that migration uncertainties cancel out when applied to NNLOPS

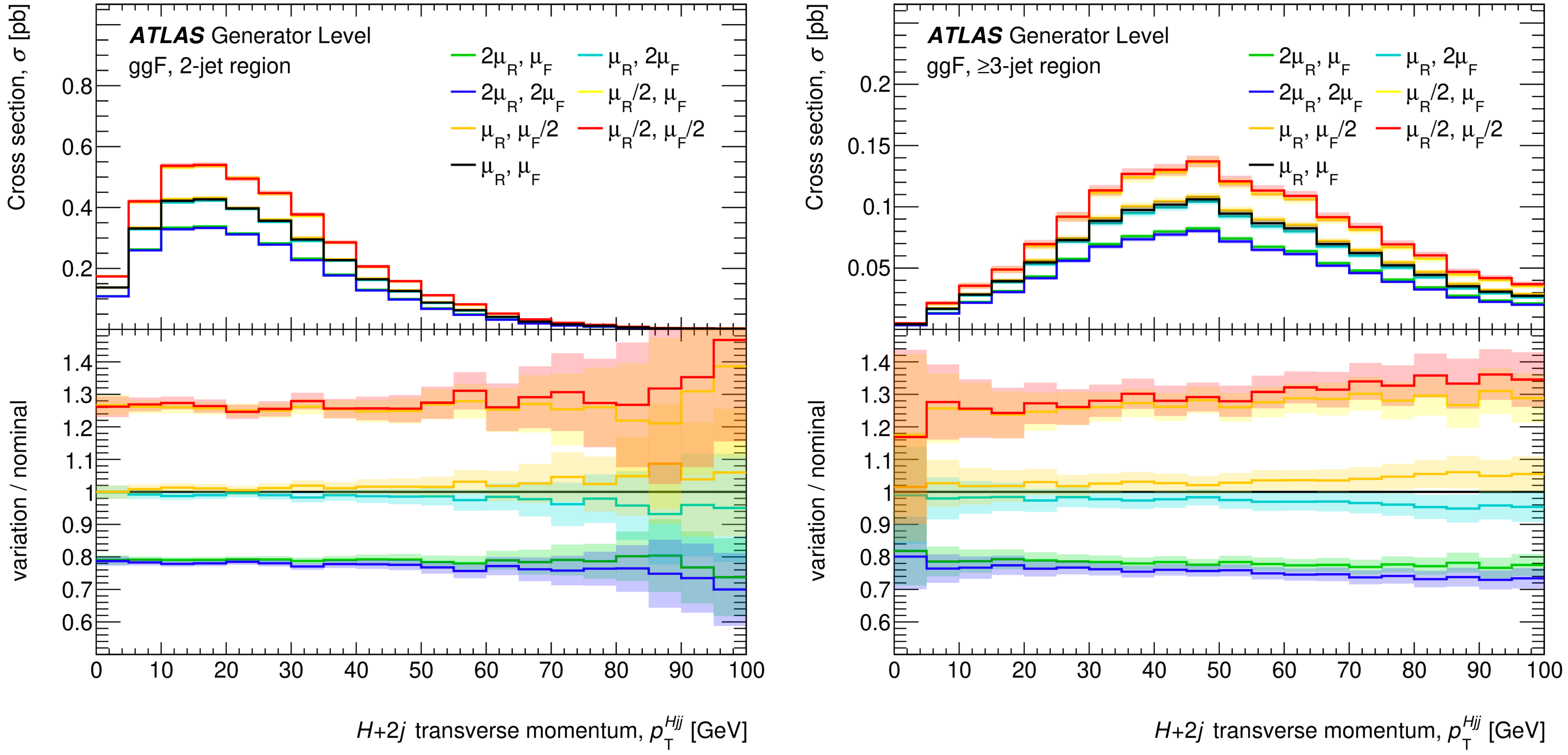


	$H+0,1,2j$ MG5_aMC@NLO (FxFx)					
Uncertainty [%]	m_{jj} [GeV] region					
	$\sigma_{\geq 2j}$	$\sigma_{<350}$	$\sigma_{[350,700)}$	$\sigma_{[700,1000)}$	$\sigma_{[1000,1500)}$	$\sigma_{\geq 1500}$
$\boxed{\theta_y}$	23.0	23.0	23.0	23.0	23.0	23.0
$\theta_{m_{jj}=350}$		-2.9	+11.8	+11.8	+11.8	+11.8
$\theta_{m_{jj}=700}$			-5.7	+12.4	+12.4	+12.4
$\theta_{m_{jj}=1000}$				-11.1	+12.6	+12.6
$\theta_{m_{jj}=1500}$					-6.8	+13.0
Total	23.0	23.2	26.5	30.7	32.0	33.9

2 Jet region - p_T^{Hjj}

- p_T^{Hjj} is an indirect probe for N_{jet} (p_T^j > 30 GeV) - there is significant leakage at the p_T^{Hjj} = 25 GeV boundary
  - Consistently found the same behaviour across generators
  - Need a better probe for $N_{jet} = 2 \leftrightarrow N_{jet} \geq 3$ migrations

- Leads to an artificial **increase** in the systematic in the lower bin



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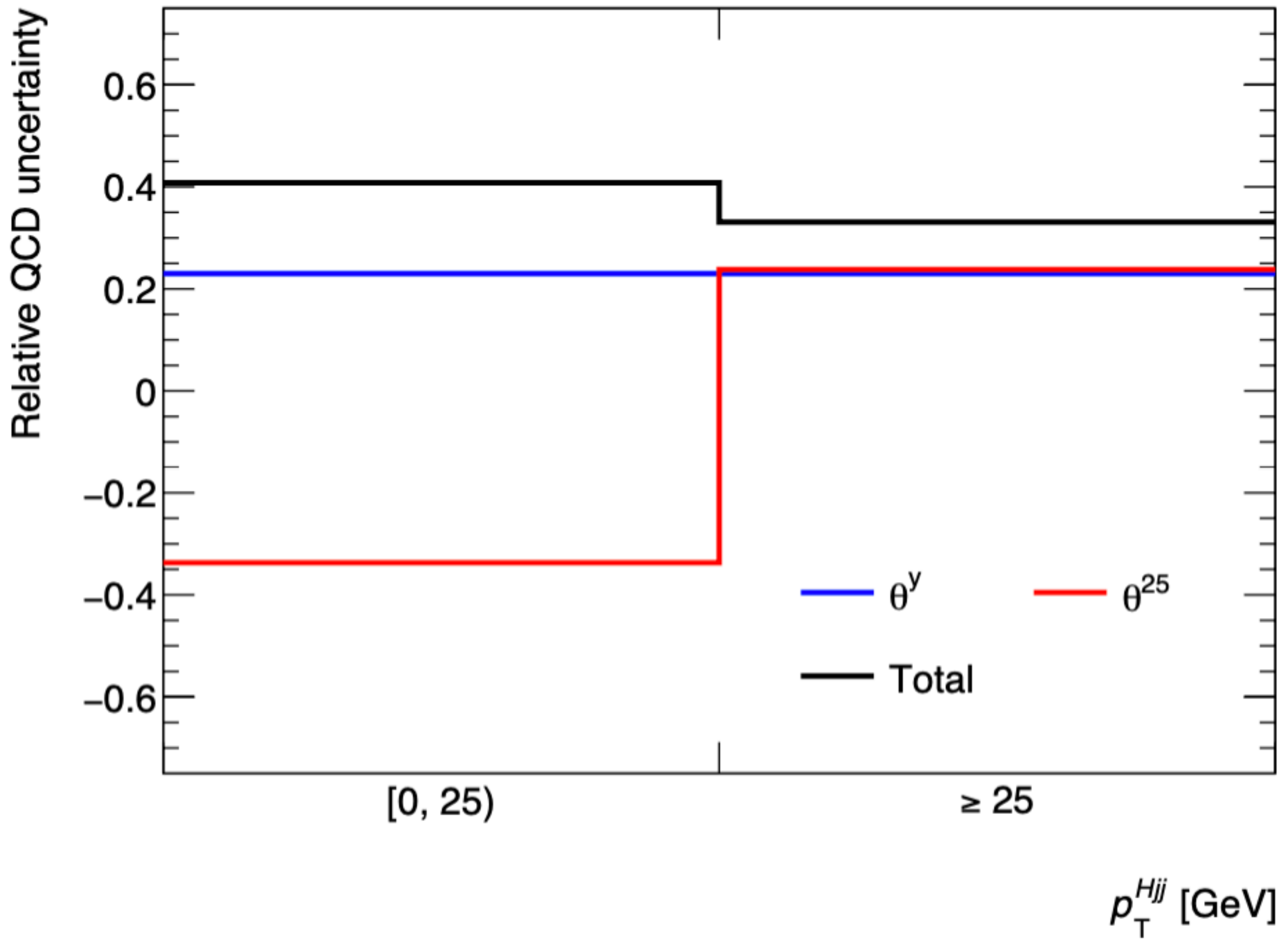
	$H + 0, 1, 2j$ MG5_aMC@NLO (FxFx)	
Composition [%]	p_T^{Hjj} [GeV] region	
	$\sigma_{<25}$	$\sigma_{\geq 25}$
$N_{jet} = 2$	91	9
$N_{jet} \geq 3$	55	45

2 Jet region - p_T^{Hjj}

- Due to differences in the p_T^{Hjj} shape at NLO (FxFx) vs LO (NNLOPS), the impact in the upper bin increased to O(30%) ensure the migration uncertainty cancel out overall
- Cross-checked results with NNLOPS, MG5 H+2J and Hjj MiNLO
- ρ set to 1 as there is only one bin

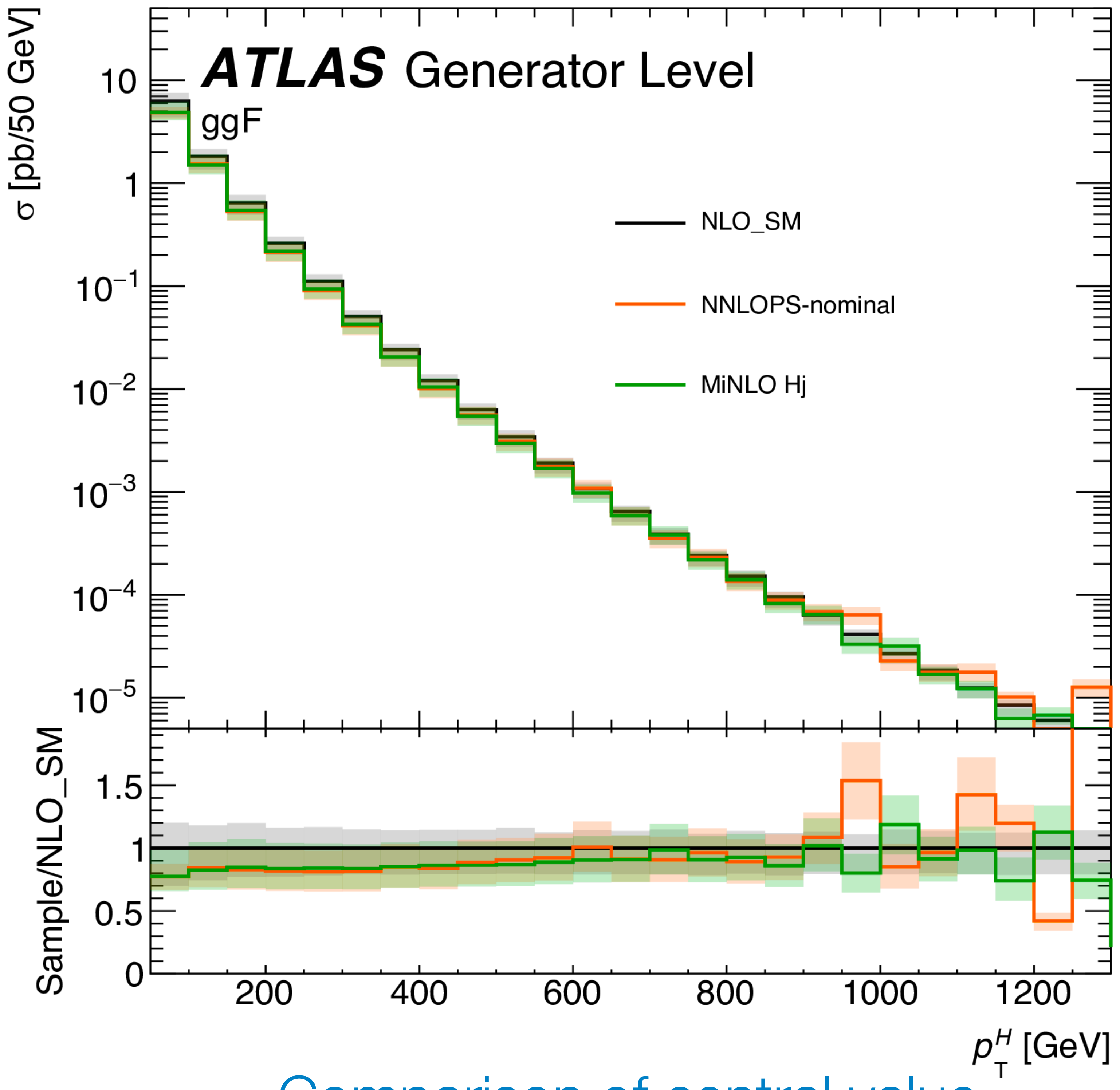
	$H+0,1,2j$ MG5_aMC@NLO (FxFx)		
Uncertainty [%]	p_T^{Hjj} [GeV] region		
	$\sigma_{\geq 2j}$	$\sigma_{<25}$	$\sigma_{\geq 25}$
$\boxed{\theta^y}$	23.0	23.0	23.0
θ^{25}		-33.7	$\boxed{+30.0}$
Total	23.0	40.8	37.8

Increased from 23.8% to 30% to account for relative XS difference in PP8 + NNLOPS wrt MG5 FxFx

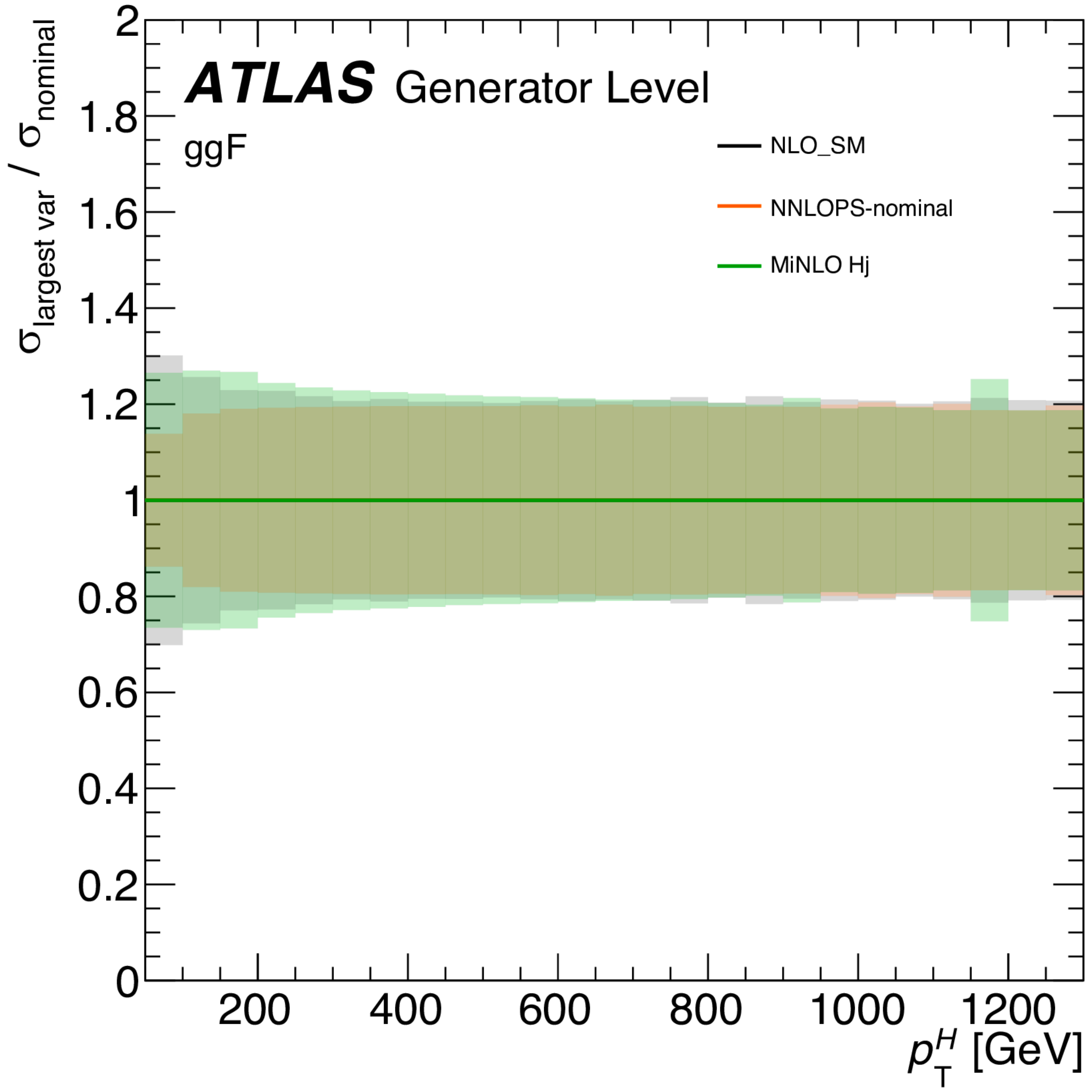


High p_T^H region - Scale variation

- Significant improvements to the uncertainty scheme in $p_T^H > 200$ GeV region
- Dedicated theoretical calculations and associated QCD scale uncertainty - 1802.00349
- Matthias Kerner & Stephen Jones extended and provided results in the needed binning
  - Ensured that these results are consistent with the NNLOPS results
- Very recently found that the top mass effect was overestimated - numbers will be updated ASAP



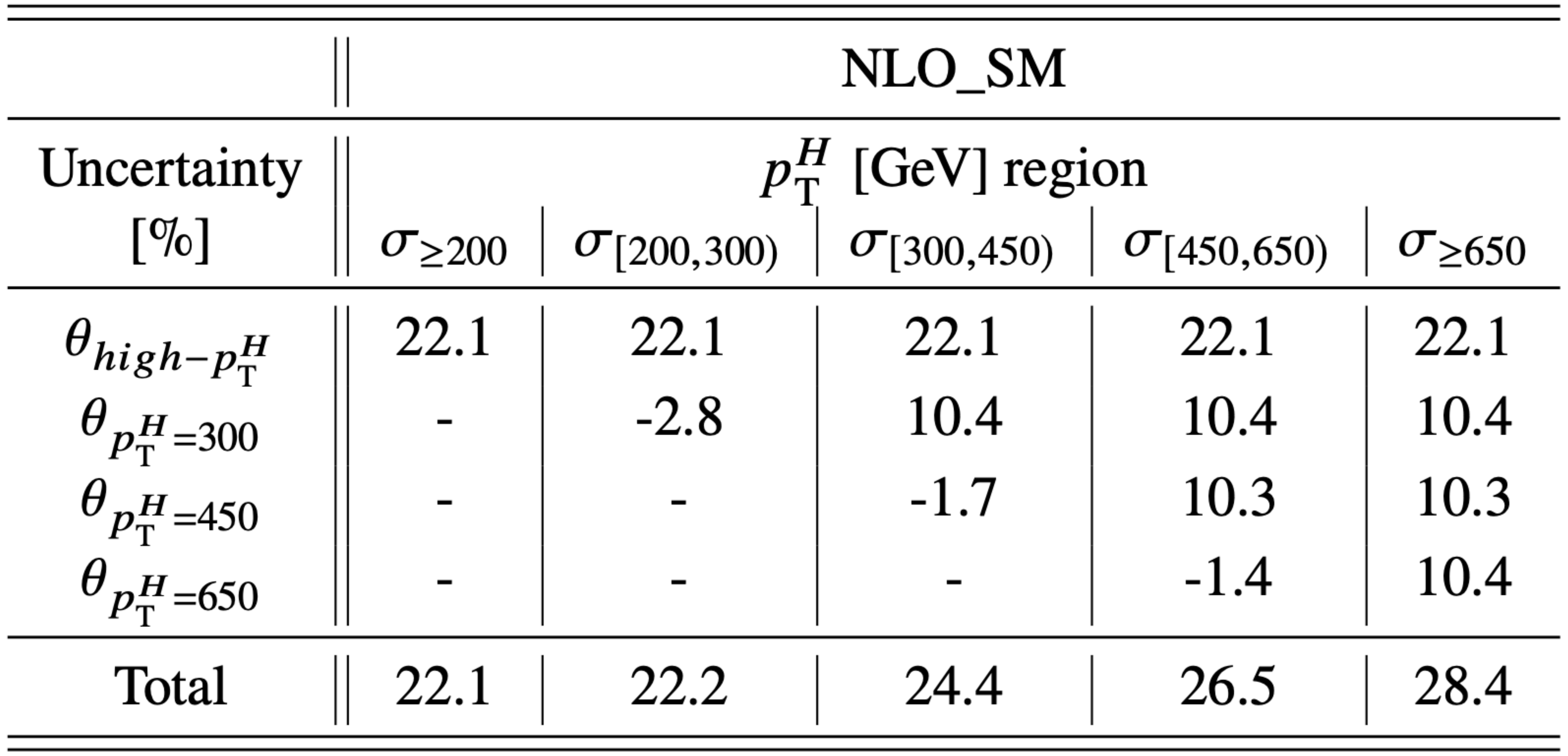
Comparison of central value



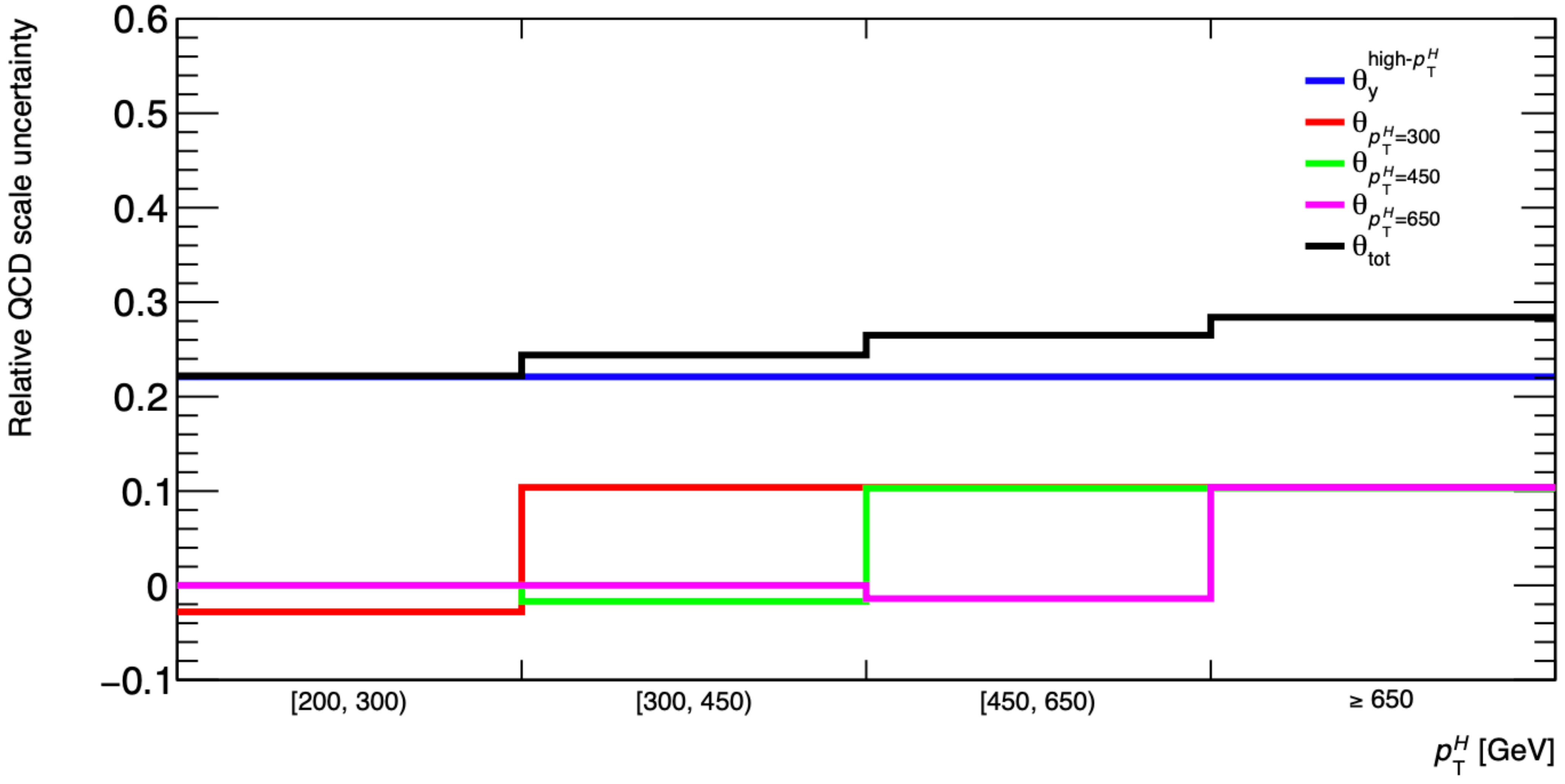
Comparison of uncertainty band

High p_T^H region - Scale variation

- Afterwards a normal application of the long range method
- In this case, yield migration is kept as a separate NP
  - BLPTW is not expected to cover this region

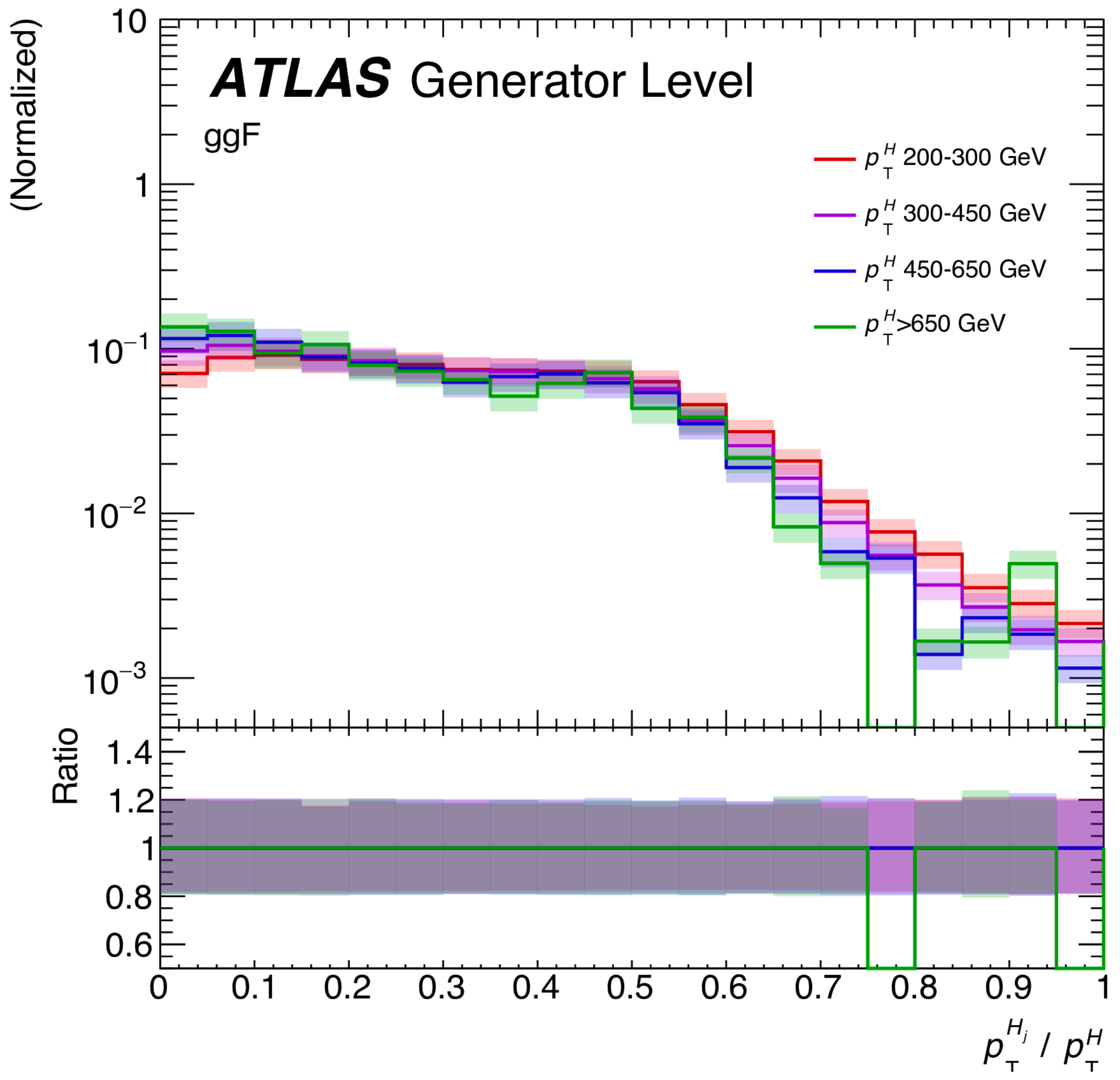


	NLO_SM				
Uncertainty [%]	p_T^H [GeV] region				
	$\sigma_{\geq 200}$	$\sigma_{[200,300)}$	$\sigma_{[300,450)}$	$\sigma_{[450,650)}$	$\sigma_{\geq 650}$
$\theta_{high-p_T^H}$	22.1	22.1	22.1	22.1	22.1
$\theta_{p_T^H=300}$	-	-2.8	10.4	10.4	10.4
$\theta_{p_T^H=450}$	-	-	-1.7	10.3	10.3
$\theta_{p_T^H=650}$	-	-	-	-1.4	10.4
Total	22.1	22.2	24.4	26.5	28.4

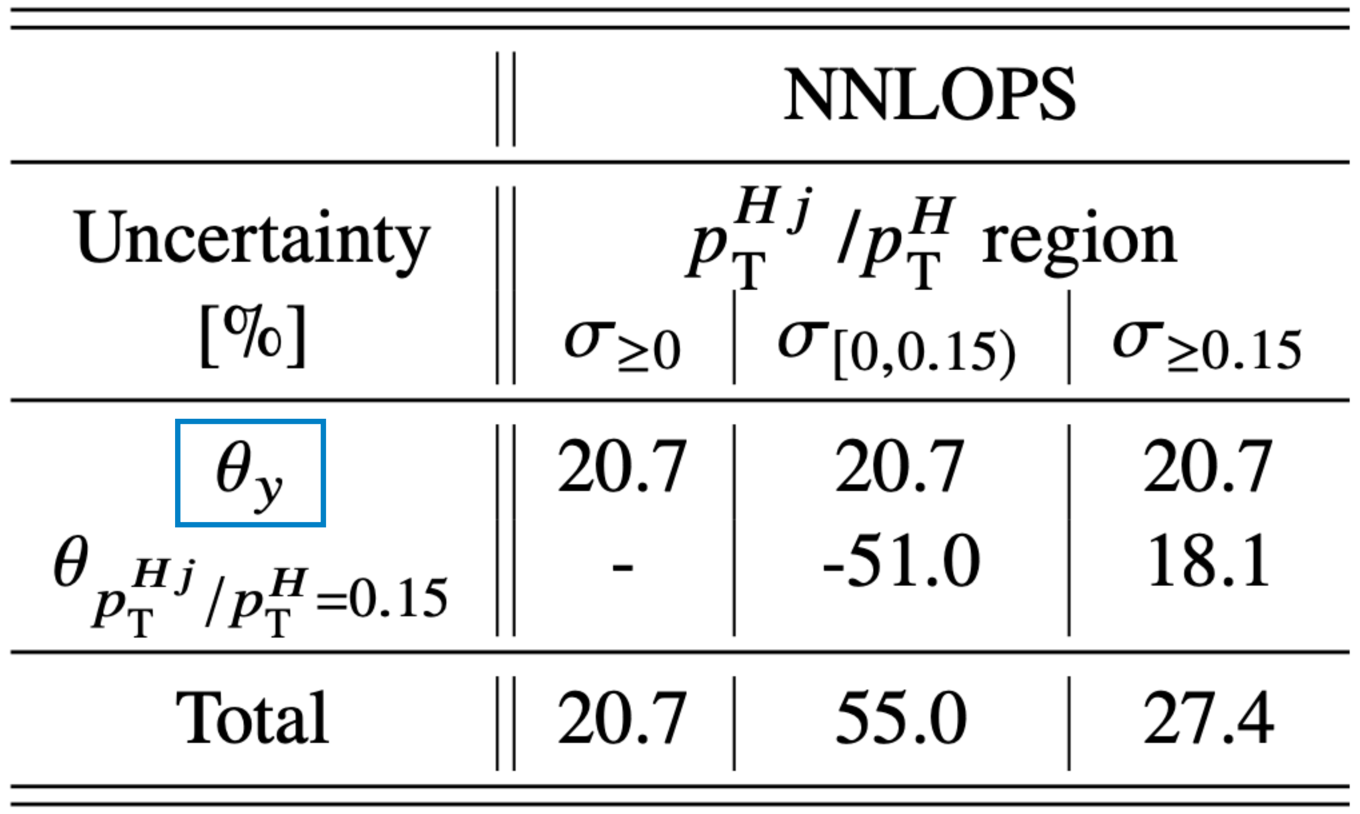


High p_T^H region - p_T^{Hj}/p_T^H

- p_T^{Hj}/p_T^H to account for $N_{jet} = 1$ <-> $N_{jet} \geq 2$ migration
  - Similar to p_T^{Hjj} probing $N_{jet} = 2$ <-> $N_{jet} \geq 3$ at lower p_T^H
  - Checked to ensure cut at 0.15 is a good probe for this effect
- ρ set to 1 as there is only one bin
- Results cross-checked with MG FxFx sample



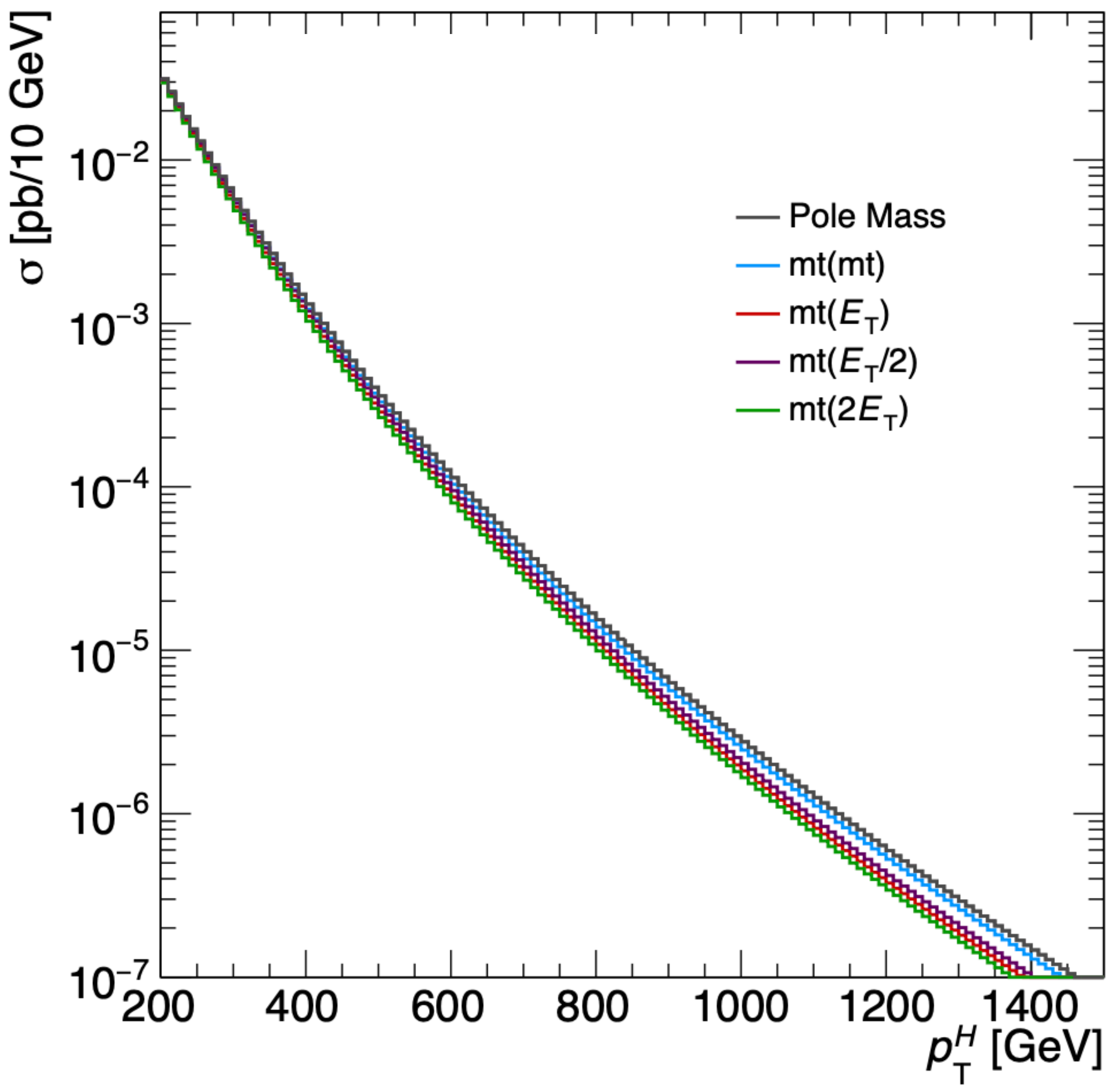
pTHj/pTH variations are not pTH dependant



Uncertainty [%]	NNLOPS		
	p_T^{Hj}/p_T^H region		
	$\sigma_{\geq 0}$	$\sigma_{[0,0.15)}$	$\sigma_{\geq 0.15}$
θ_y	20.7	20.7	20.7
$\theta_{p_T^{Hj}/p_T^H=0.15}$	-	-51.0	18.1
Total	20.7	55.0	27.4

High p_T^H region - top mass scheme

- Various calculations show that top mass scheme can lead to different prediction in the high p_T^H region - source of uncertainty
- Calculations with MSbar and pole mass only available at LO - Michael Spira
  - Calculations of other processes show ~2x reduction in the difference between these schemes at NLO
  - Take half of the difference for Higgs p_T^H as a systematic uncertainty
- Independent from the previous high p_T^H calculation - not impacted by the top mass issue



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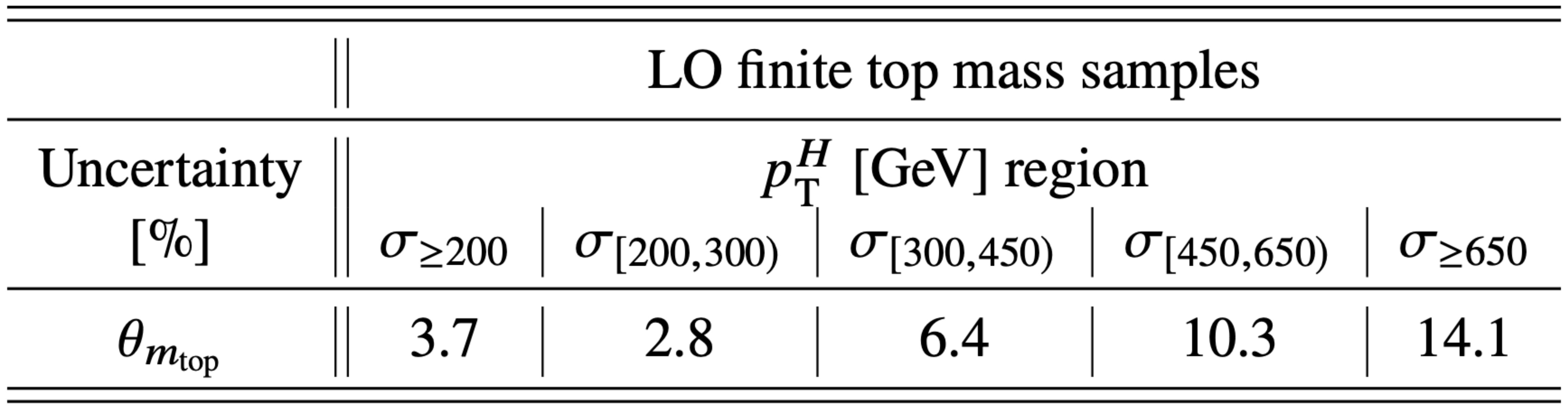


	LO finite top mass samples				
Uncertainty	p_T^H [GeV] region				
[%]	$\sigma_{\geq 200}$	$\sigma_{[200,300)}$	$\sigma_{[300,450)}$	$\sigma_{[450,650)}$	$\sigma_{\geq 650}$
$\theta_{m_{\text{top}}}$	3.7	2.8	6.4	10.3	14.1

Conclusion

- Significant work has been invested in defining the uncertainty scheme for the ggF Stage 1.2 STXS scheme
  - Collaborative effort between ATLAS, CMS and theorists!

- Complete version of both the nuisance parameter scheme and the associated numbers available!
  - Small update to come for the high pT scheme
  - Results documented @ Link which can be implemented by the analyses
- Plan to document these results in a LHC HWG note!

- Potential improvements to the scheme in the future
  - Account for systematics variations across multiple dimensions
  - Smooth parameterization across variables
  - Harmonization of the acceptance/with-bin uncertainties across ATLAS & CMS

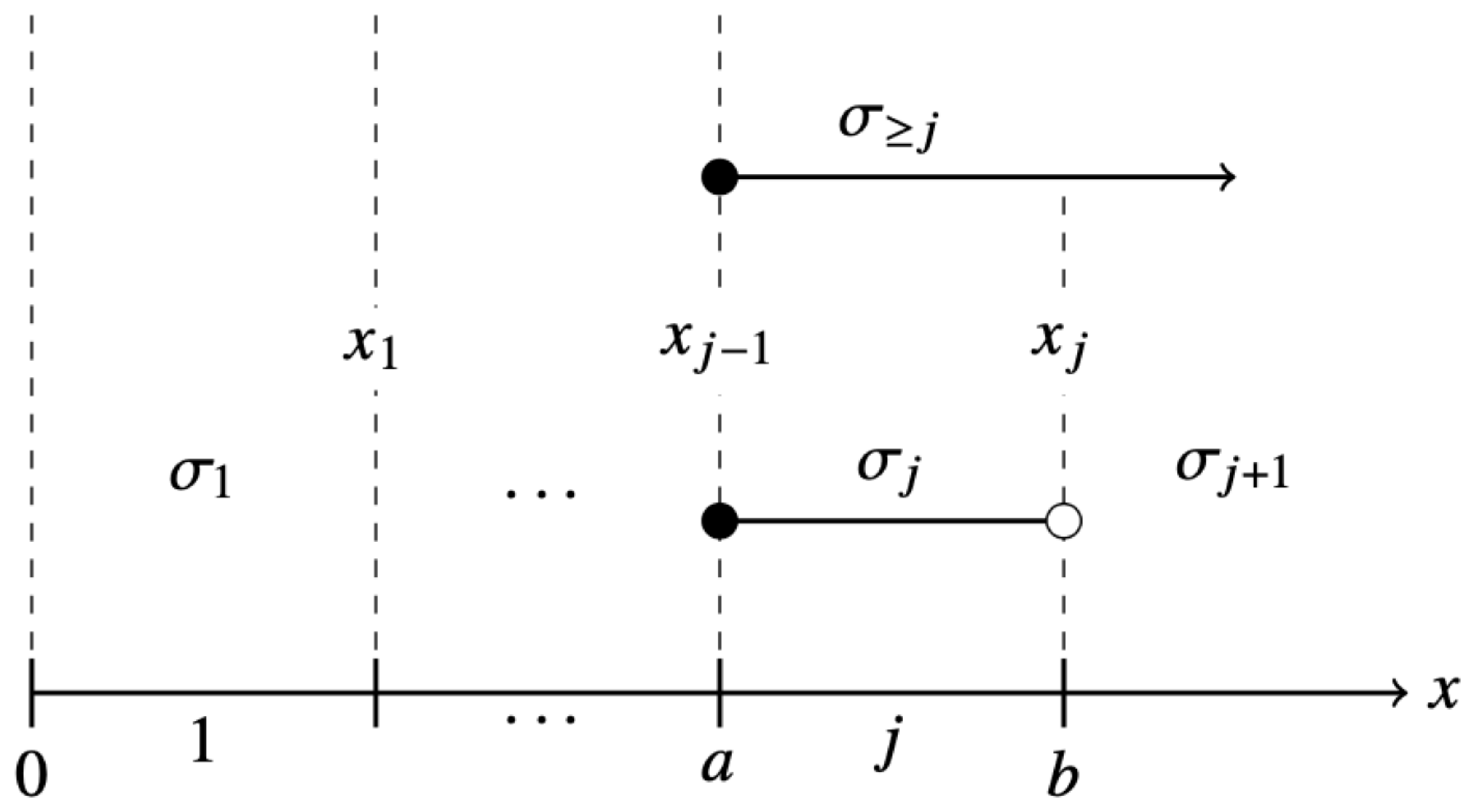
- However, next main critical uncertainty to tackle is the shower uncertainty
  - It is the leading systematic across many analyses - impact will get even large with more data!
  - Need a consistent and unified approach to parametrize this uncertainty

Backup

Evaluating the uncertainty

- Many ways - all involve varying the renormalization & factorization scale and using the XS variations in some NP scheme
- Our current go-to is the ST method - One NP for overall yield variation and other NP for migration between categories
  - Removes the accidental cancellation of scale variations

Bin definitions



ST method

$$\theta^{y}(j)\begin{cases}0 & : j<k\\ +\max|\Delta_{\mu,\geq k}|/\sigma_j & : j=k\\ 0 & : j\geq k+1\end{cases}$$

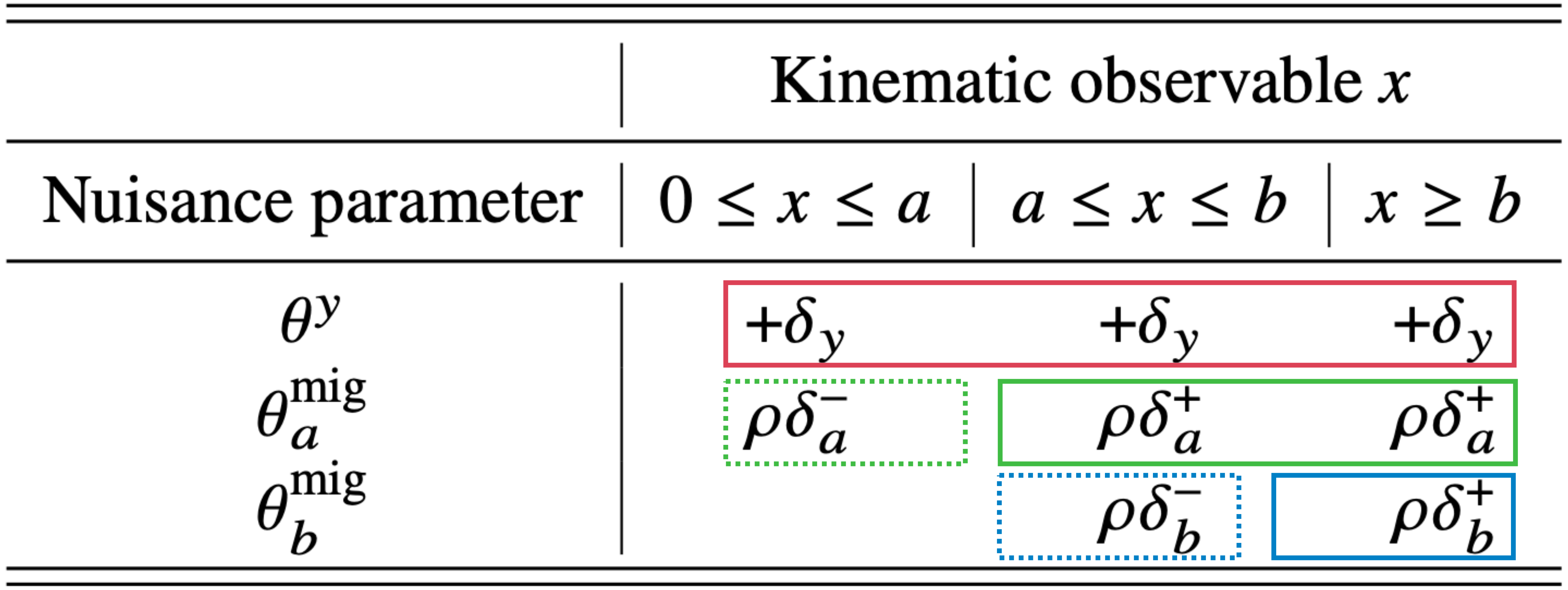
Take the max scale variation in ≥ k region and apply as yield NP in k bin

$$\theta^{\mathrm{mig}}_{x_k}(j)\begin{cases}0 & : j<k\\ -\max|\Delta_{\mu,\geq k+1}|/\sigma_j & : j=k\\ +\max|\Delta_{\mu,\geq k+1}|/\sigma_j & : j=k+1\\ 0 & : j\geq k+2\end{cases}$$

Take the max scale variation in ≥ k+1 region and apply as migration NP in k and k+1 bin

- But this method breaks down in the case of many or small bin width - unphysical blow up of uncertainty if XS is small
- For continuous variables, like pTH, it makes no sense that migration will be only between two neighbouring bins

Long range ST method



	Kinematic observable x		
Nuisance parameter	$0 \leq x \leq a$	$a \leq x \leq b$	$x \geq b$
θ^{y}	$+\delta_{y}$	$+\delta_{y}$	$+\delta_{y}$
$\theta_{a}^{\mathrm{mig}}$	$\rho\delta_{a}^{-}$	$\rho\delta_{a}^{+}$	$\rho\delta_{a}^{+}$
$\theta_{b}^{\mathrm{mig}}$		$\rho\delta_{b}^{-}$	$\rho\delta_{b}^{+}$

ρ chosen to remove the overlap between x > a and x > b uncertainty values

θ^{y} as the max scale variation in the inclusive x region - $\delta_{y} = \mathrm{max}(\Delta_{\mu})/\sigma$

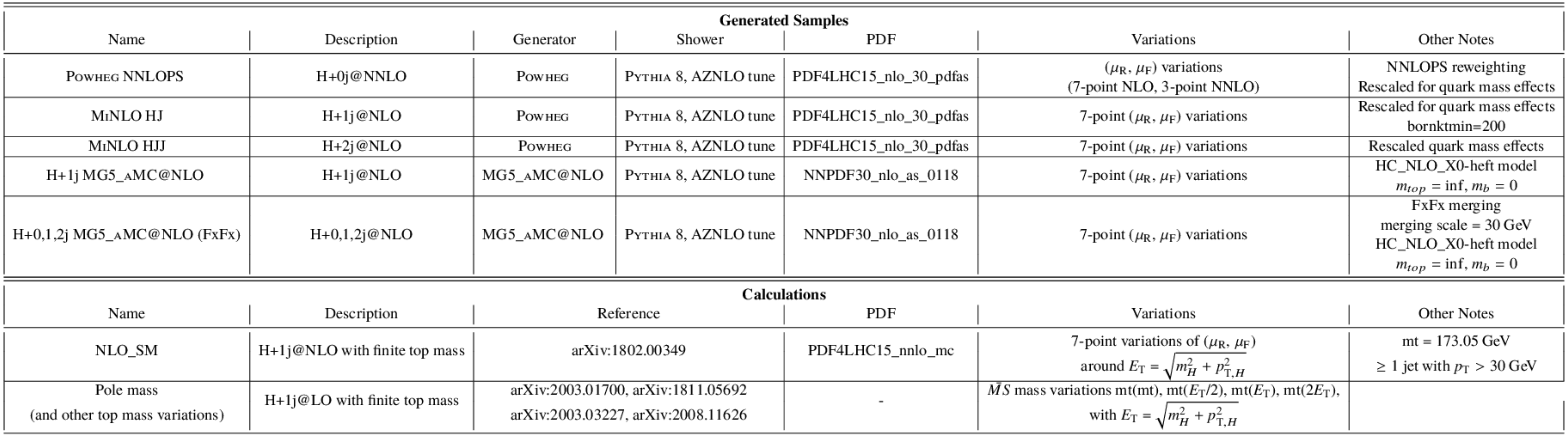
$\theta_{a}^{\mathrm{mig}}$ as the max scale variation in the x > a region. First bin as the negative of this value as the uncertainty

$$\delta_{a}^{+} = \mathrm{max}(\Delta_{x>a})/\sigma_{x>a}$$
$$\delta_{a}^{-} = -\,\mathrm{max}(\Delta_{x>a})/\sigma_{x<a}$$

$\theta_{b}^{\mathrm{mig}}$ as the max scale variation in the x > b region. Second bin as the negative of this value, with no sys applied to the first bin

$$\delta_{b}^{+} = \mathrm{max}(\Delta_{x>b})/\sigma_{x>b}$$
$$\delta_{b}^{-} = -\,\mathrm{max}(\Delta_{x>b})/\sigma_{a<x<b}$$

Samples used for theory sys



Generated Samples

Name	Description	Generator	Shower	PDF	Variations	Other Notes
Powheg NNLOPS	H+0j@NNLO	Powheg	Pythia 8, AZNLO tune	PDF4LHC15_nlo_30_pdfas	(μ_R, μ_F) variations (7-point NLO, 3-point NNLO)	NNLOPS reweighting Rescaled for quark mass effects
MiNLO HJ	H+1j@NLO	Powheg	Pythia 8, AZNLO tune	PDF4LHC15_nlo_30_pdfas	7-point (μ_R, μ_F) variations	Rescaled for quark mass effects bornktmin=200
MiNLO HJJ	H+2j@NLO	Powheg	Pythia 8, AZNLO tune	PDF4LHC15_nlo_30_pdfas	7-point (μ_R, μ_F) variations	Rescaled quark mass effects
H+1j MG5_aMC@NLO	H+1j@NLO	MG5_aMC@NLO	Pythia 8, AZNLO tune	NNPDF30_nlo_as_0118	7-point (μ_R, μ_F) variations	HC_NLO_X0-heft model m_{top} = inf, m_b = 0
H+0,1,2j MG5_aMC@NLO (FxFx)	H+0,1,2j@NLO	MG5_aMC@NLO	Pythia 8, AZNLO tune	NNPDF30_nlo_as_0118	7-point (μ_R, μ_F) variations	FxFx merging merging scale = 30 GeV HC_NLO_X0-heft model m_{top} = inf, m_b = 0

Calculations

Name	Description	Reference	PDF	Variations	Other Notes
NLO_SM	H+1j@NLO with finite top mass	arXiv:1802.00349	PDF4LHC15_nnlo_mc	7-point variations of (μ_R, μ_F) around $E_T = \sqrt{m_H^2 + p_{T,H}^2}$	mt = 173.05 GeV ≥ 1 jet with $p_T > 30$ GeV
Pole mass (and other top mass variations)	H+1j@LO with finite top mass	arXiv:2003.01700, arXiv:1811.05692 arXiv:2003.03227, arXiv:2008.11626	-	$\bar{M}S$ mass variations mt(mt), mt($E_T/2$), mt(E_T), mt($2E_T$), with $E_T = \sqrt{m_H^2 + p_{T,H}^2}$	

Acceptance effects + uncovered variables

Acceptance effect + other variables

- Almost all uncertainty numbers are applied flat in a STXS bin
  - If analysis selection shapes the acceptance or ML algorithm uses the variable, the uncertainty will factorize
  - Many other QCD sensitive variables not covered by this scheme
  - This leads to an underestimation
- Way around it - provide one scale variation (e.g. muF = muR = 0.5) as part of the implementation of the scheme
- To avoid 'significant' double counting, normalize scale variation in STXS bin to remove overall XS
  - Provided as one additional NP

- This proposal has some still has double counting
  - If NP is pulled/constrained/ranked highly - ask analysis to do detailed checks & make decisions on an case-by-case level
  - Leave this up to the collaboration to define how to implement this