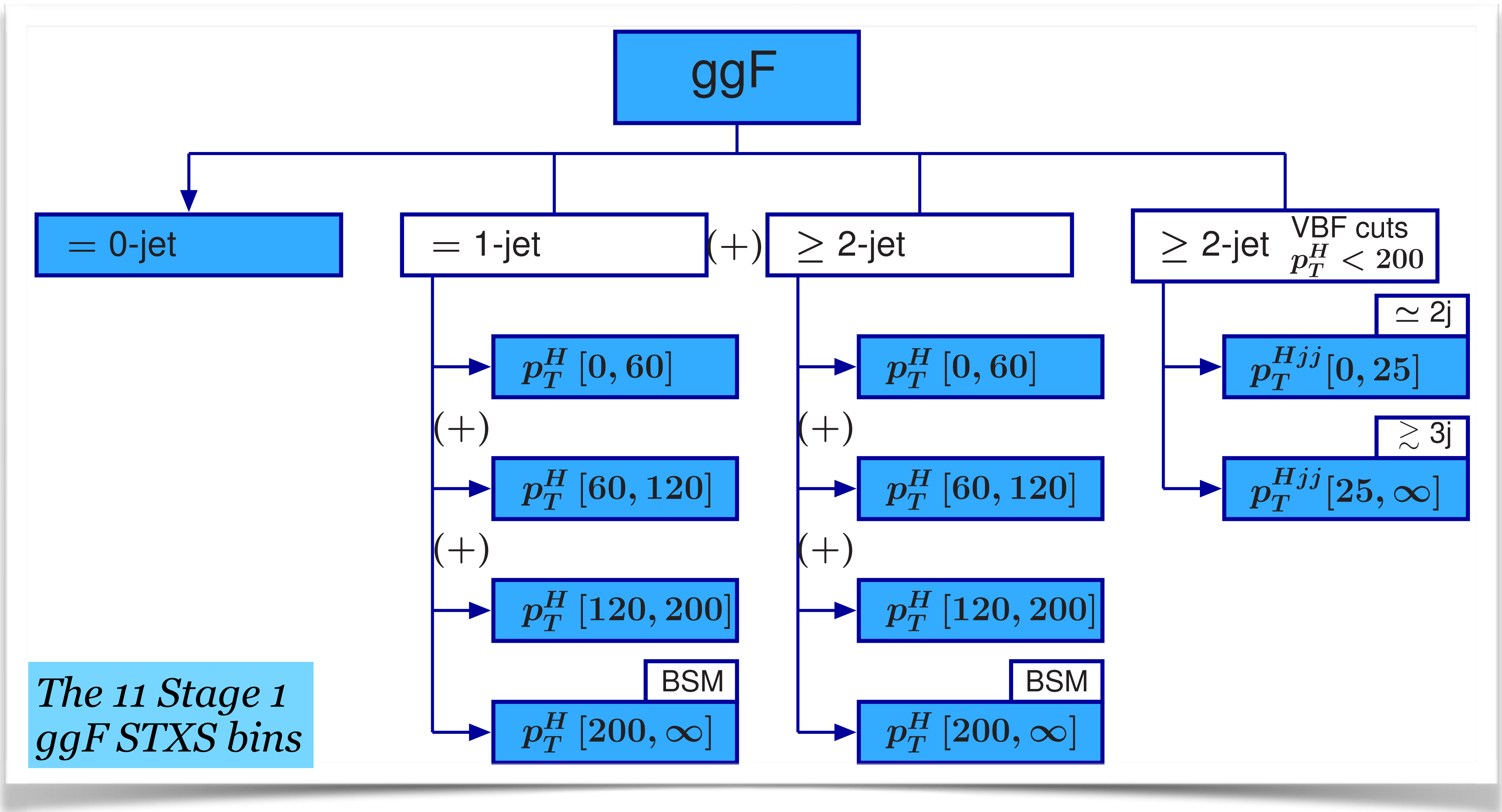
Towards common ATLAS/CMS prescription for $gg \rightarrow H$ perturbative uncertainties in kinematic regions

Fabrizio Caola, Dag Gillberg, Andrea Massironi, Pier Monni

Into + goal of today's meeting

- A long list of Higgs analyses of the current Run 2 dataset (~33 fb^{-1}) are in final stages
  - *Common, consistent approach for theoretical uncertainties for ggF urgently needed*
- Theoretical uncertainties enter a measurement at two levels:
  - They affect the estimated **acceptances** used in the measurements
    Typically quite small effect, but might be underestimated if one use a uncertainty scheme with too strong correlation (too simplified, i.e. to few uncertainty sources)
  - They affect the predicted cross section in a data-to-theory comparison
    (e.g. data/theory = μ or in κ measurement)
- Both ATLAS and CMS are measuring "Stage 1 simplified template cross sections" (STXS), which means the cross section after simultaneous selection criteria applied both to the number of jets and Higgs boson transverse momentum (see next page)
  - Perturbative uncertainties hence needed in particular for these regions
- Goal of today's meeting is to look at two proposed uncertainty schemes and hopefully be able to agree on a common scheme considered good enough to be used for the upcoming analyses
  - Feedback from theorists might result in revisions

Definition of the regions of interest



VBF topology

$m_{jj} > 400$ GeV

$\Delta y_{jj} > 2.8$

$p_{T,H} < 200$ GeV

then split using $p_{T,Hjj}$

- Jet definition:
  - Higgs decay products ignored
  - Jets built using anti-k_t R = 0.4 from all stable remaining particles (hadron jets)
  - Transverse momentum threshold: $p_T > 30$ GeV
  - RIVET implementation: svnweb.cern.ch/cern/wsvn/lhchiggsxs/repository/TemplateXS/

Pragmatic approach for evaluating theory uncertainty

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 using event weights (reweighing). For each uncertainty source:
   → Apply "+1-standard deviation" shifts depending on event kinematics
   → 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**

Same method as discussed in previous WG1 meeting:
https://indico.cern.ch/event/581691/

Example code for implementation for this method is available in backup slides

Test of uncertainty scheme using MC events

- Here extending the proposed scheme presented in last WG1 meeting in November
- Jet bin uncertainties evaluated according to the BLPTW scheme of YR4:

$p_T^{\mathrm{cut}} = 30$ 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

  - Accounts for uncertainties and migrations between the =0, =1 and >=2 jet bins
- Uncertainties also needed for:
  - Higgs p_T spectrum within a given jet bin
  - Quark mass treatment in ggF loop, if significant wrt QCD scale uncertainties
  - VBF region

Test of uncertainty scheme using MC events

- Here … vember
- Jet bi…

$p_T^{\mathrm{cut}} =$ …

$\sigma_{\geq 0}$

σ_0

$\sigma_{\geq 1}$

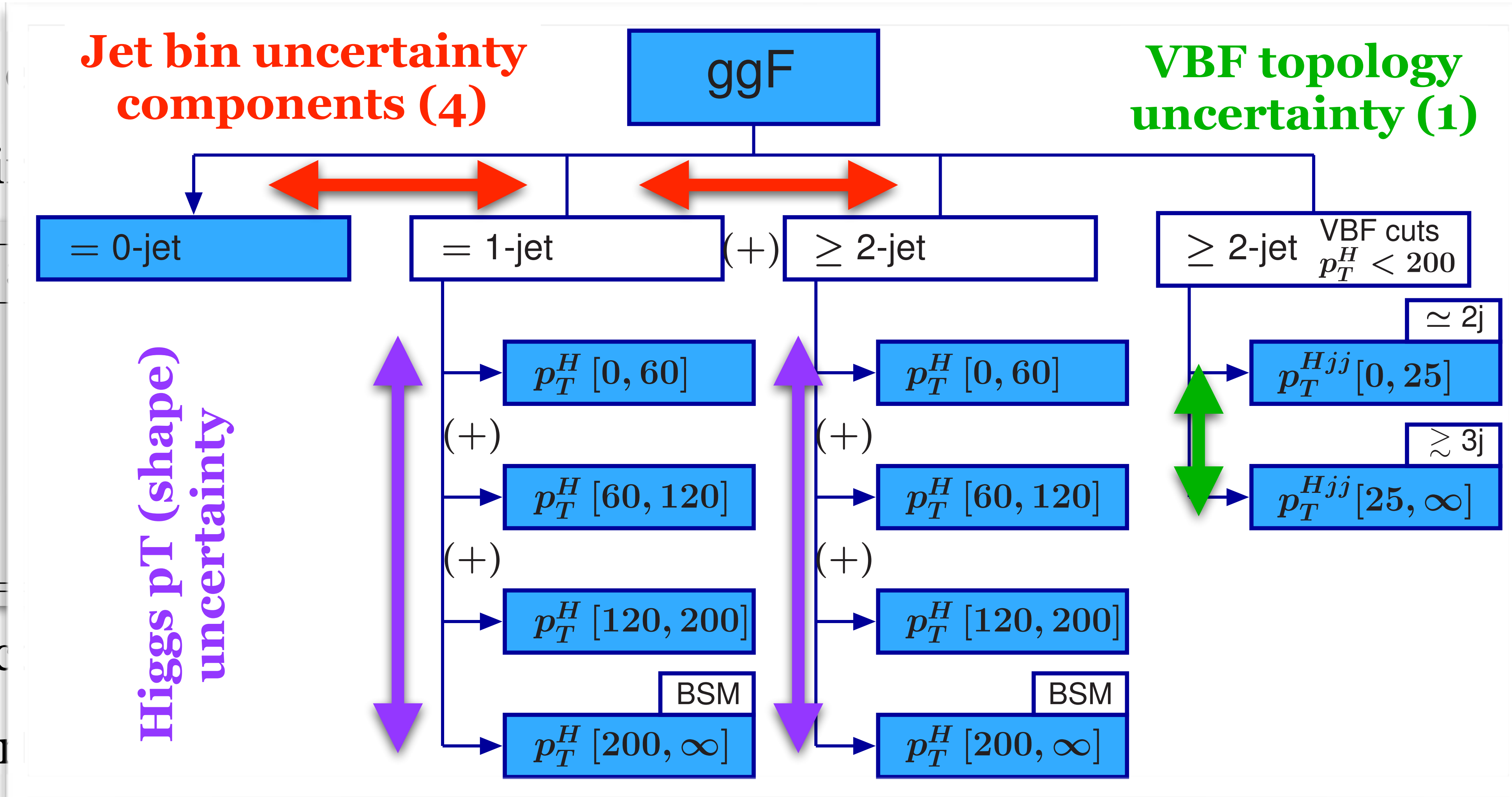
σ_1

$\sigma_{\geq 2}$

… split into 4 … rces

… on

… on



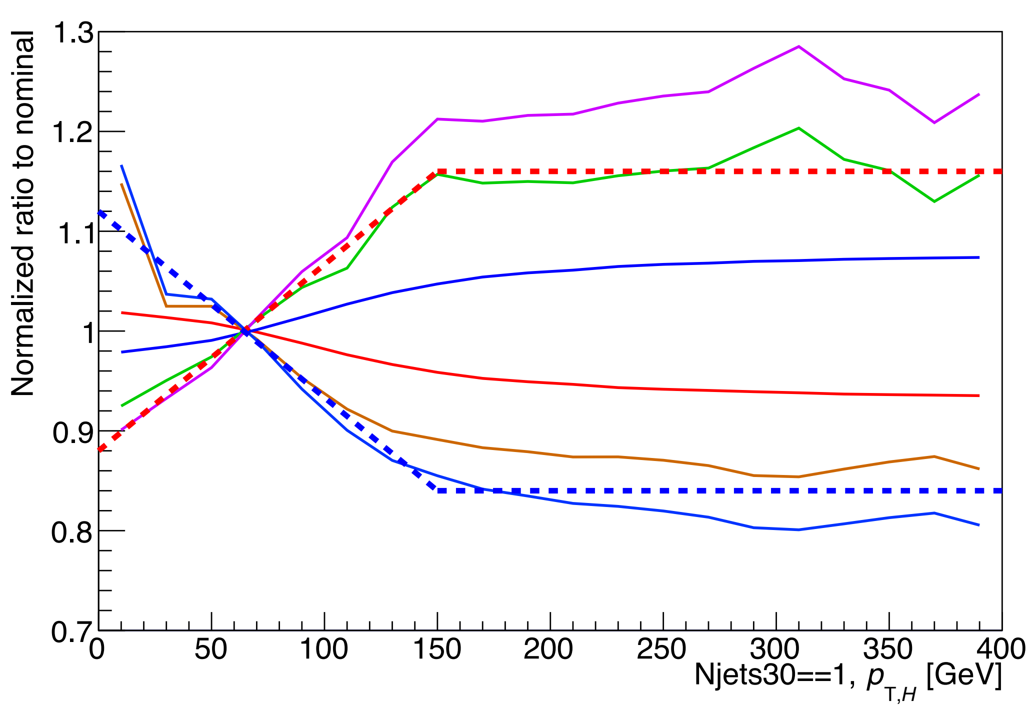
  - Ac… jet bins
- Uncer…
  - Higgs p_T spectrum within a given jet bin
  - Quark mass treatment in ggF loop, if significant wrt QCD scale uncertainties
  - VBF region

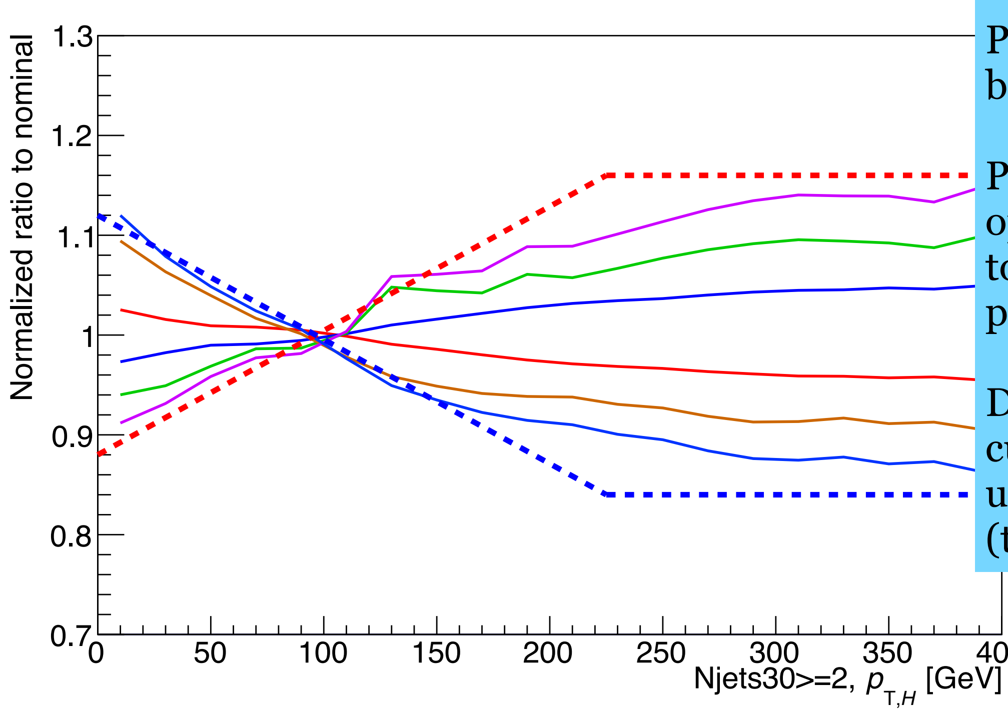
Uncertainty schemes & evaluation

- Two uncertainty schemes are discussed today
  - One scheme in the following slides, that provide smooth uncertainties as a function of Higgs p_{T}
  - A scheme developed specifically for STXS measurements (see talk by Kerstin)
  - Both schemes use the same jet bin uncertainties, but take different approaches to derive the Higgs p_{T} dependent uncertainty
  - Numerical values provided in separate slides for discussion (end of meeting)
- Size of perturbative p_{TH} uncertainties evaluated in both cases using scale variations in Powheg NNLOPS — which also is the MC used to provide the central-value kinematics (shape of distributions)
- Quark mass variations also studies and evaluated using event weights provided in Powheg NNLOPS
- First pass of VBF uncertainties evaluated using YR3 approach (used in Run-1) Alternative could be to use uncertainties from Gionata (?) with the ST procedure

“WG1 scheme”: $p_{T,H}$ uncertainty

- In the “WG1 scheme”, The Higgs pT uncertainty is derived within each jet bin from the shape change of the Higgs p_T introduced by QCD scale variations
- Three QCD scales are varied:
  1. Scale of the HNNLO input templates (used for NNLO reweihing)
  2. Renormalization scale of Powheg
  3. Factorization scale of Powheg
- Since jet bin uncertainties already provide a normalization uncertainty in each jet bin, only the shape change is considered





NNLO scale only
red/blue (inner)

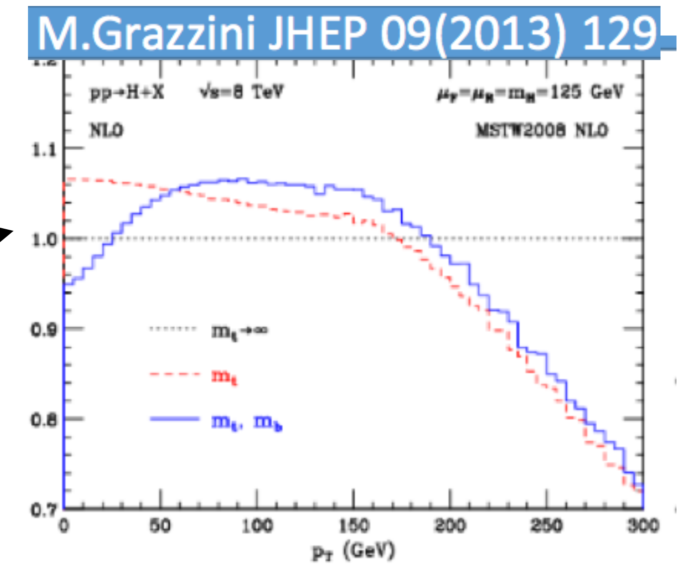
Powheg scales only:
brown/green

Powheg scales in opposite direction to NNLO scales
purple/blue (outer)

Dashed lines:
current assigned uncertainty
(too small?)

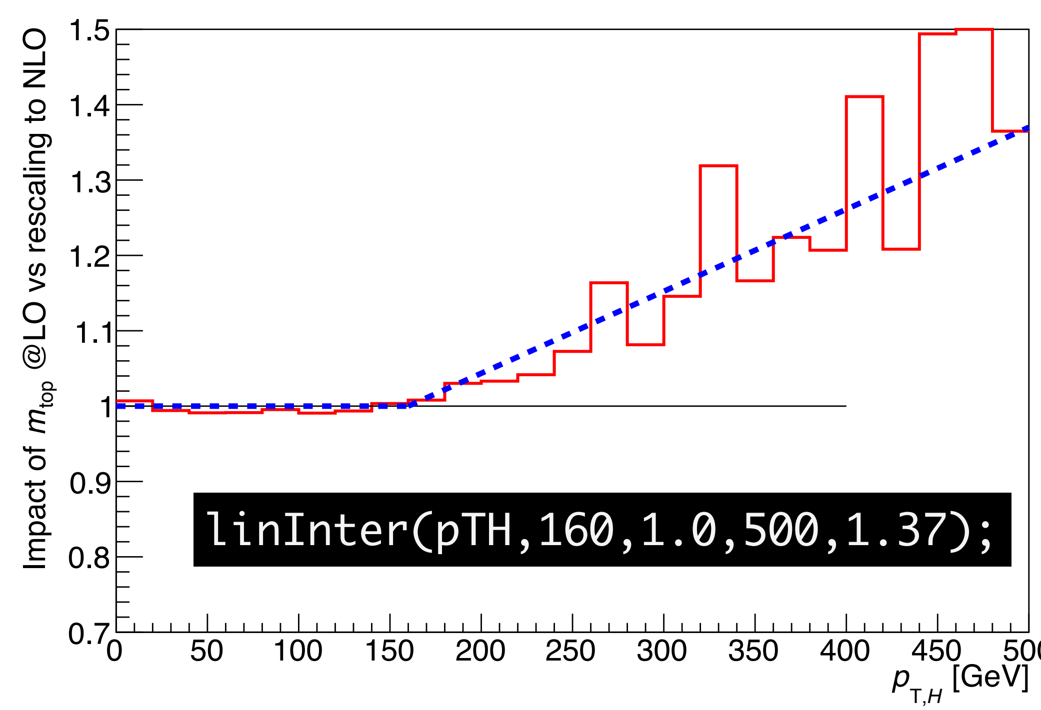
“WG1 scheme”: quark mass variations

- Can vary quark mass treatment in Powheg NNLOPS
- Default is finite top mass and b masses @NLO (scaled to NLO)
- Setting the top mass infinite results in change very similar to
- In discussion with Powheg authors, the proposed approach is to compare difference with finite quark masses at LO and NLO but details are not clear



(a) NLO

- Current idea
  - One uncertainty source from finite top mass @LO vs @NLO. Affect (very) high p_T region. See plot bottom right. qm_t
  - Second uncertainty from bottom mass treatment, if significant (might be negligible compare to pTH uncertainty): Check b@LO vs @NLO, and with/without *b* mass in the Sudakov exponent (bminlo)
  - Parametrize these uncertainties as function of Higgs boson p_T



VBF uncertainty

- Two options:
  - Use Run-1 approach documented in YR3, that use uncertainties from MCFM parametrized as a function of $\Delta\phi(H,jj)$ — which is correlated to the third jet pT, but found better modelled in MCFM (agree better with the MC used by ATLAS/CMS). And extension of the ST procedure is then used to calculate the total QCD uncertainty in the VBF region (even if not directly cutting on this variable).
    - Note: these uncertainties are from 8 TeV. Taken as relative uncertainties, this might still be OK.
    - Running this over truth events gives total QCD uncertainties of: 30.4% and 38%. Subtracting the QCD uncertainties from other sources
- Alternative option:
  - Use uncertainties from Gionata, or other prediction. Plug in to analysis using standard ST.
- Other ideas/alternatives ?

A first look at numbers (more during discussion part)

- Using ATLAS MC (Powheg NNLOPS) normalized to N3LO @mH = 125.09 GeV

Cross sections and fractional uncertainties

STXS	sig	stat	mu	res	mig01	mig12	pTH	qm_b	qm_top	Tot
Incl	48.52	+/- 0.00	+4.6%	+2.2%	+0.0%	-0.0%	-0.1%	-0.2%	+0.0%	+5.1%
FWDH	4.27	+/- 0.01	+4.4%	+1.8%	-0.5%	-0.4%	-0.5%	-0.6%	-1.5%	+5.1%
VBF1	0.27	+/- 0.00	+7.9%	+7.9%	+3.9%	+16.2%	-2.5%	-2.4%	+0.1%	+20.3%
VBF2	0.36	+/- 0.00	+7.9%	+7.9%	+3.9%	+16.2%	-0.9%	-1.1%	+0.2%	+20.1%
0J	27.25	+/- 0.03	+3.8%	+0.1%	-4.1%	+0.0%	+0.0%	-0.2%	+0.0%	+5.6%
1J_0-60	6.49	+/- 0.01	+5.3%	+4.6%	+8.1%	-6.9%	-4.5%	-4.0%	+0.0%	+14.1%
1J_60	4.50	+/- 0.01	+5.3%	+4.6%	+8.1%	-6.9%	+3.0%	+4.9%	+0.0%	+14.0%
1J_120	0.74	+/- 0.00	+5.3%	+4.6%	+8.1%	-6.9%	+14.0%	+5.0%	+0.5%	+19.6%
1J_200	0.15	+/- 0.00	+5.3%	+4.6%	+8.1%	-6.9%	+16.0%	+5.0%	+10.5%	+23.5%
2J_0-60	1.22	+/- 0.01	+7.9%	+7.9%	+3.9%	+16.2%	-7.4%	-7.2%	+0.0%	+22.5%
2J_60	1.86	+/- 0.01	+7.9%	+7.9%	+3.9%	+16.2%	-1.0%	-0.1%	+0.0%	+20.0%
2J_120	0.99	+/- 0.00	+7.9%	+7.9%	+3.9%	+16.2%	+6.8%	+5.0%	+0.6%	+21.7%
2J_200	0.42	+/- 0.00	+7.9%	+7.9%	+3.9%	+16.2%	+15.5%	+5.0%	+11.8%	+28.3%
=0J	30.12	+/- 0.03	+3.8%	+0.1%	-4.1%	+0.0%	+0.0%	-0.2%	-0.2%	+5.6%
=1J	12.92	+/- 0.02	+5.3%	+4.6%	+8.1%	-6.9%	-0.3%	+0.0%	+0.2%	+12.7%
>=2J	5.47	+/- 0.01	+7.9%	+7.9%	+3.9%	+16.1%	+0.1%	-0.7%	+1.1%	+20.0%
>=1J 60-200	9.09	+/- 0.01	+6.3%	+5.8%	+6.5%	+1.8%	+3.4%	+3.7%	+0.2%	+12.0%
>=1J 120-200	1.96	+/- 0.01	+6.9%	+6.6%	+5.6%	+7.0%	+9.6%	+5.0%	+0.6%	+17.0%
>=1J >200	0.58	+/- 0.00	+7.2%	+7.0%	+5.0%	+10.1%	+15.6%	+5.0%	+11.4%	+25.0%
>=1J >60	9.68	+/- 0.01	+6.3%	+5.9%	+6.4%	+2.3%	+4.2%	+3.8%	+0.8%	+12.4%
>=1J >120	2.54	+/- 0.01	+6.9%	+6.7%	+5.4%	+7.7%	+11.0%	+5.0%	+3.1%	+18.4%
>=1	18.40	+/- 0.02	+6.1%	+5.6%	+6.8%	-0.1%	-0.2%	-0.2%	+0.5%	+10.7%

The 11 ggF STXS bins

A first look at numbers (more during discussion part)

Cross sections and fractional uncertainties

STXS	sig	stat	mu	res	mig01	mig12	pTH	qm_b	qm_top	VBF	Tot
Incl	48.52	+/- 0.00	+4.6%	+2.2%	-0.0%	-0.0%	-0.1%	-0.2%	+0.2%	-0.0%	+5.1%
FWDH	4.29	+/- 0.05	+4.4%	+1.8%	-0.5%	-0.3%	-0.5%	-0.6%	+0.0%	+0.0%	+4.9%
VBF1	0.26	+/- 0.01	+7.9%	+7.9%	+3.9%	+16.1%	-2.6%	-2.4%	+0.1%	-32.0%	+37.9%
VBF2	0.35	+/- 0.01	+7.9%	+7.9%	+3.9%	+16.1%	-0.7%	-0.9%	+0.2%	+23.5%	+30.8%
0J	27.21	+/- 0.13	+3.8%	+0.1%	-4.1%	+0.0%	+0.0%	-0.2%	+0.0%	+0.0%	+5.6%
1J_0-60	6.53	+/- 0.06	+5.2%	+4.5%	+7.9%	-6.8%	-4.5%	-3.9%	+0.0%	+0.0%	+13.9%
1J_60	4.51	+/- 0.05	+5.2%	+4.5%	+7.9%	-6.8%	+3.1%	+4.9%	+0.0%	+0.0%	+13.8%
1J_120	0.72	+/- 0.02	+5.2%	+4.5%	+7.9%	-6.8%	+14.0%	+5.0%	+0.5%	+0.0%	+19.5%
1J_200	0.15	+/- 0.01	+5.2%	+4.5%	+7.9%	-6.8%	+16.0%	+5.0%	+10.6%	+0.0%	+23.5%
2J_0-60	1.23	+/- 0.02	+7.9%	+7.9%	+3.9%	+16.1%	-7.4%	-7.2%	+0.0%	+0.0%	+22.4%
2J_60	1.85	+/- 0.03	+7.9%	+7.9%	+3.9%	+16.1%	-1.0%	-0.1%	+0.0%	+0.0%	+20.0%
2J_120	0.98	+/- 0.02	+7.9%	+7.9%	+3.9%	+16.1%	+6.8%	+5.0%	+0.7%	+0.0%	+21.7%
2J_200	0.43	+/- 0.01	+7.9%	+7.9%	+3.9%	+16.1%	+15.5%	+5.0%	+12.0%	+0.0%	+28.4%
=0J	30.09	+/- 0.13	+3.8%	+0.1%	-4.1%	+0.0%	+0.0%	-0.2%	+0.0%	+0.0%	+5.6%
=1J	12.97	+/- 0.08	+5.2%	+4.5%	+7.9%	-6.8%	-0.3%	+0.0%	+0.2%	+0.0%	+12.5%
>=2J	5.47	+/- 0.05	+7.9%	+7.9%	+3.9%	+16.1%	+0.1%	-0.7%	+1.1%	-0.0%	+20.0%
>=1J 60-200	9.07	+/- 0.06	+6.2%	+5.8%	+6.4%	+1.9%	+3.4%	+3.7%	+0.1%	+0.1%	+11.9%
>=1J 120-200	1.93	+/- 0.03	+6.8%	+6.5%	+5.5%	+7.1%	+9.6%	+5.0%	+0.6%	+0.5%	+17.0%
>=1J >200	0.59	+/- 0.01	+7.2%	+7.0%	+5.0%	+10.1%	+15.6%	+5.0%	+11.5%	-0.0%	+25.1%
>=1J >60	9.66	+/- 0.07	+6.3%	+5.8%	+6.3%	+2.4%	+4.2%	+3.8%	+0.8%	+0.1%	+12.3%
>=1J >120	2.52	+/- 0.03	+6.9%	+6.6%	+5.4%	+7.8%	+11.0%	+5.0%	+3.2%	+0.4%	+18.4%
>=1	18.43	+/- 0.09	+6.0%	+5.5%	+6.7%	-0.0%	-0.2%	-0.2%	+0.4%	-0.0%	+10.6%

The 11 ggF STXS bins

BACKUP

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)

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

$p_T^{\text{cut}} = 30$ GeV	σ/pb	Δ_μ	Δ_φ	$\Delta_{\text{cut}}^{0/1}$	$\Delta_{\text{cut}}^{1/2}$	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

Test of uncertainty scheme using MC events

- Following slides present a test of propagating the jet bin uncertainties according to the results presented 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%
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QCD uncertainty split into 4 independent sources

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