ggF jet bin uncertainties in $H \rightarrow WW$

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ATLAS Higgs WG (N)NLO MC and Tools Workshop for LHC Run 2

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Motivation

- Theoretical uncertainty in ggF jet binning is a leading uncertainty on signal strength, μ
- Current prescription doesn't use latest calculations

Category	Source	Uncertainty, up (%)	Uncertainty, down (%)
Statistical	Observed data	+21	−21
Theoretical	Signal yield ($\sigma \cdot \mathcal{B}$)	+12	−9
Theoretical	WW normalisation	+12	−12
Experimental	Objects and DY estimation	+9	−8
Theoretical	Signal acceptance	+9	−7
Experimental	MC statistics	+7	−7
Experimental	W+jets fake factor	+5	−5
Theoretical	Backgrounds, excluding WW	+5	−4
Luminosity	Integrated luminosity	+4	−4
Total		+32	−29

ATLAS-CONF-2013-030

Difficulties with scale uncertainties in exclusive jet cross sections

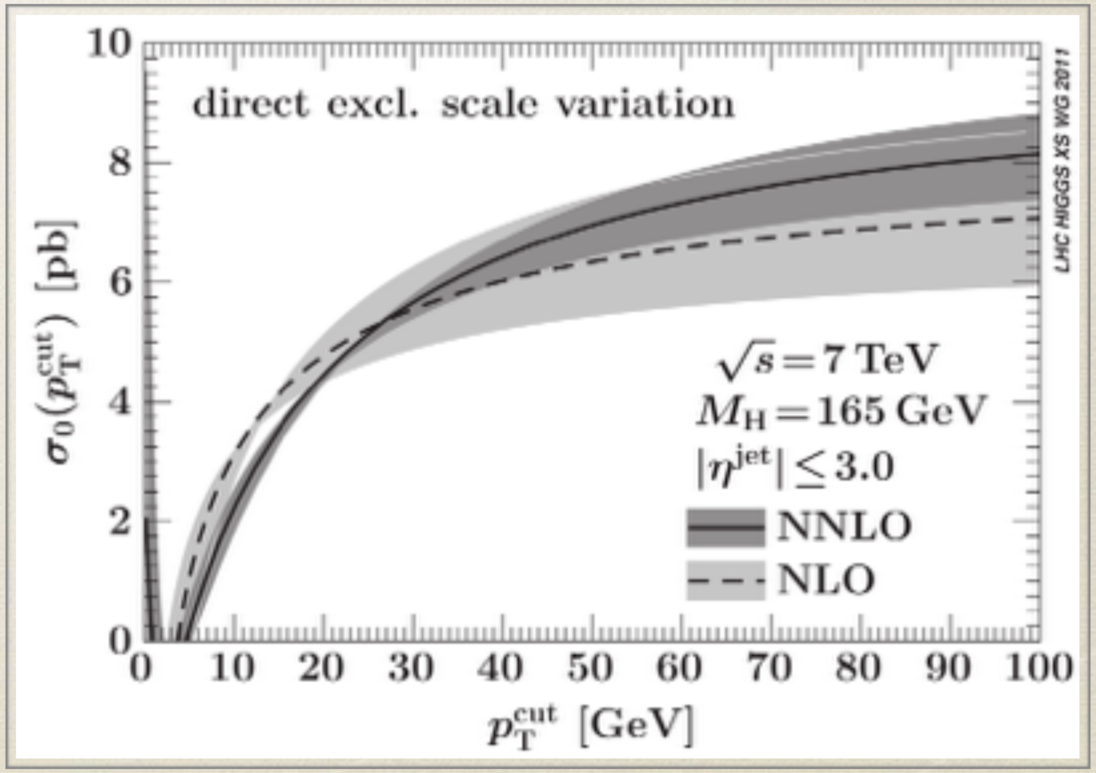
Based on §5.2 of YR2 (Stewart, Tackmann)

- restricting QCD radiation introduces Sudakov logarithms $L^2 = \ln^2(p_T^{\rm cut}/Q)$
- when $p_T^{\rm cut} \ll Q$ these are large, can overcome α_s suppression (would ideally resum)

$$\sigma_0(p_T^{\rm cut}) = \sigma_{\rm tot} - \sigma_{\geq 1}(p_T^{\rm cut})$$
$$= \sigma_B \left\{ \left[1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)\right] - \left[\alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \mathcal{O}(\alpha_s^3 L^6)\right] \right\}$$

- cancellations between series cause scale uncertainties to be underestimated, e.g. for ggF with √s = 7 TeV and jet p_T = 30 GeV

$$\sigma_0(p_T^{\rm cut}) = 3.32 \text{ pb} \left\{ \left[1 + 9.5\alpha_s + 35\alpha_s^2 + \mathcal{O}(\alpha_s^3)\right] - \left[4.7\alpha_s + 26\alpha_s^2 + \mathcal{O}(\alpha_s^3 L^6)\right] \right\}$$



- underestimation is important for H→WW ($p_T^{\rm cut}$= 25 GeV)
  - see "pinching" effect
- much work to develop methods to robustly probe higher order corrections

Two prescriptions (YR2)

- **Combined-inclusive** (Stewart, Tackmann)
  - inclusive cross sections have uncorrelated uncertainties
  - $\sigma_0 = \sigma_{\rm tot} - \sigma_{\geq 1}$ $\quad\sigma_1 = \sigma_{\geq 1} - \sigma_{\geq 2}$ $\quad\sigma_{\geq 2}$
  - this inflates uncertainties in exclusive cross sections
  - each component must be at same α_s accuracy
- **Jet veto efficiency** (Banfi, Salam, Zanderighi)
  - $\sigma_{\rm tot}$ and jet veto efficiencies have uncorrelated uncertainties
  - $\sigma_0 = \sigma_{\rm tot}\epsilon_0$ $\quad\sigma_1 = \sigma_{\rm tot}(1-\epsilon_0)\epsilon_1$ $\quad\sigma_{\geq 2} = \sigma_{\rm tot}(1-\epsilon_0)(1-\epsilon_1)$
  - use different definitions of jet veto efficiency to probe higher order corrections (each definition has equivalent accuracy in pQCD)
  - at fixed-order, actually gives larger uncertainties than **combined-inclusive** prescription, but can choose accuracy of each step independently $\Rightarrow$ use better calculations $\Rightarrow$ smaller uncertainties
  - in YR2 only split into σ_0 and $\sigma_{\geq 1}$ $\Rightarrow$ we extend to σ_0, σ_1 and $\sigma_{\geq 2}$

Current prescription

- **Combined-inclusive**
  - $\delta\sigma_{\text{tot}}$ from HXSWG (NNLO+NNLL+EWK)
  - $\delta\sigma_{\geq 1}$, $\delta\sigma_{\geq 2}$, f_i from HNNLO (NLO, LO)
  - standalone $\delta\sigma_{\geq 2}$ from MCFM (NLO)

NB: f_i are jet bin fractions

- Relative uncertainties in exclusive σ:
  - $\delta\sigma_0^2 = \frac{1}{f_0^2}\delta\sigma_{\text{tot}}^2 + \left(\frac{1}{f_0} - 1\right)^2 \delta\sigma_{\geq 1}^2$
  - $\delta\sigma_1^2 = \left(\frac{1-f_0}{f_1}\right)^2 \delta\sigma_{\geq 1}^2 + \left(\frac{1-f_0}{f_1} - 1\right)^2 \delta\sigma_{\geq 2}^2$
  - $\delta\sigma_{\geq 2}$ (from MCFM)

Proposed prescription

- **Jet veto efficiency**
  - $\delta\sigma_{\mathrm{tot}}$ from HXSWG (NNLO+NNLL+EWK)
  - $\delta\varepsilon_0$ from JetVHeto (NNLO+NNLL)
  - $\delta\varepsilon_1$ from MCFM (NNLO - see later for why)

NB: ε_0 is probability of no jets

NB: ε_1 is probability of no 2nd jet, given that we have a jet

- Relative uncertainties in exclusive σ:
  - $\delta\sigma_0^2 = \delta\sigma_{\mathrm{tot}}^2 + \delta\epsilon_0^2$
  - $\delta\sigma_1^2 = \delta\sigma_{\mathrm{tot}}^2 + \left(\frac{\epsilon_0}{1-\epsilon_0}\right)^2 \delta\epsilon_0^2 + \delta\epsilon_1^2$
  - $\delta\sigma_{\geq 2}^2 = \delta\sigma_{\mathrm{tot}}^2 + \left(\frac{\epsilon_0}{1-\epsilon_0}\right)^2 \delta\epsilon_0^2 + \left(\frac{\epsilon_1}{1-\epsilon_1}\right)^2 \delta\epsilon_1^2$
- Perform cross check with σ_1 (NLO+NLL')
  - Petriello, Liu - arXiv:1303.4405

Results

ε_0: 1st jet veto efficiency

* Three possible definitions

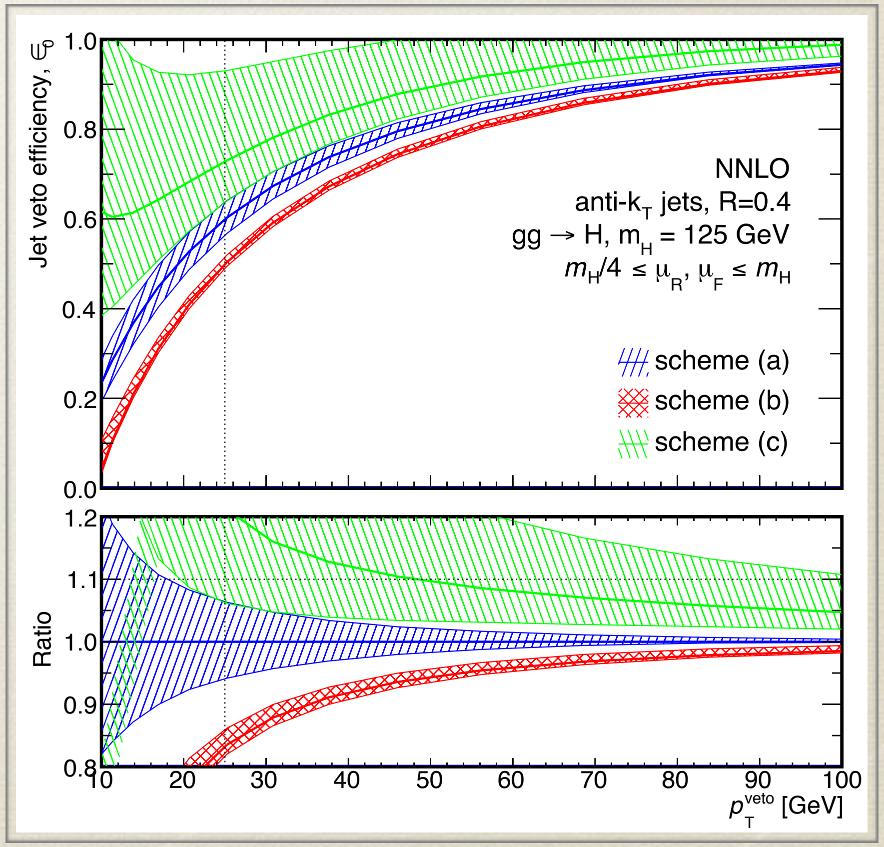
$$\epsilon_0^{(a)} = 1 - \frac{\sigma_{\geq 1}^{\mathrm{NLO}}}{\sigma_{\mathrm{tot}}^{\mathrm{NNLO}}} + \mathcal{O}(\alpha_s^3) \qquad \epsilon_0^{(b)} = 1 - \frac{\sigma_{\geq 1}^{\mathrm{NLO}}}{\sigma_{\mathrm{tot}}^{\mathrm{NLO}}} + \mathcal{O}(\alpha_s^3)$$

$$\epsilon_0^{(c)} = 1 - \frac{\sigma_{\geq 1}^{\mathrm{NLO}}}{\sigma_{\mathrm{tot}}^{\mathrm{LO}}} + \left(\frac{\sigma_{\mathrm{tot}}^{\mathrm{NLO}}}{\sigma_{\mathrm{tot}}^{\mathrm{LO}}} - 1\right) \frac{\sigma_{\geq 1}^{\mathrm{LO}}}{\sigma_{\mathrm{tot}}^{\mathrm{LO}}} + \mathcal{O}(\alpha_s^3)$$

* differ by NNNLO terms ⇒ probe higher order corrections

Banfi, Salam, Zanderighi - YR2

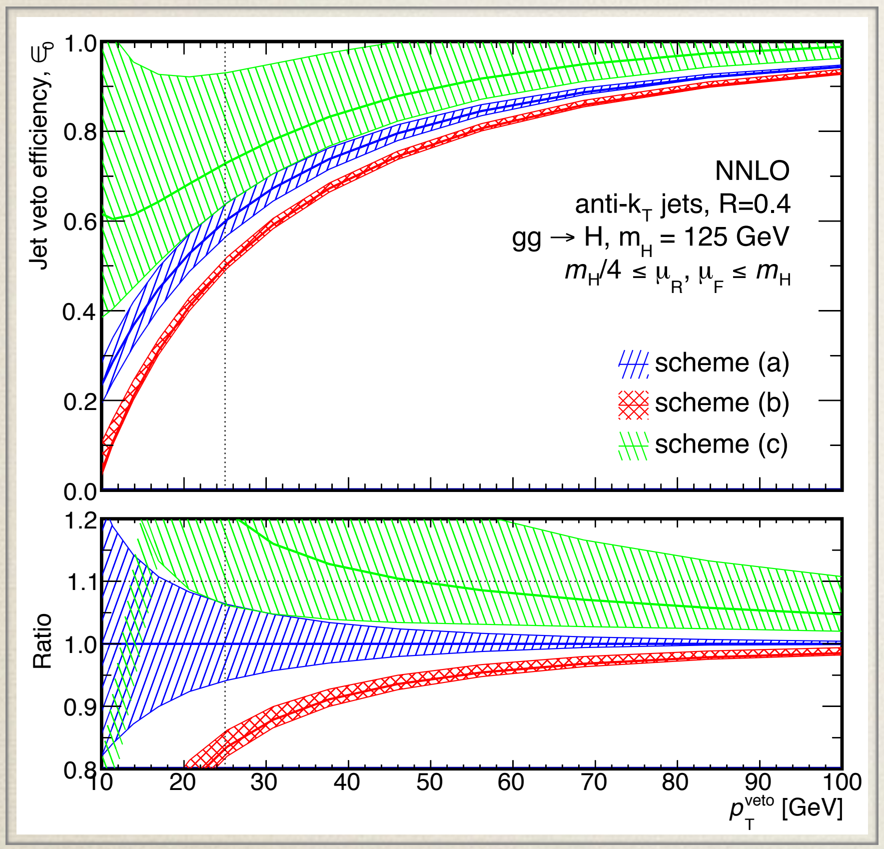
* These bands are scale variations of each scheme
* Use scheme (a) as central value
* Prescription takes uncertainty band to be envelope of scale uncertainties of scheme (a) and central values of schemes (b) and (c)
* Here, scheme difference dominates uncertainty
* Gives larger uncertainty than combined-inclusive
* Drell-Yan: schemes converge

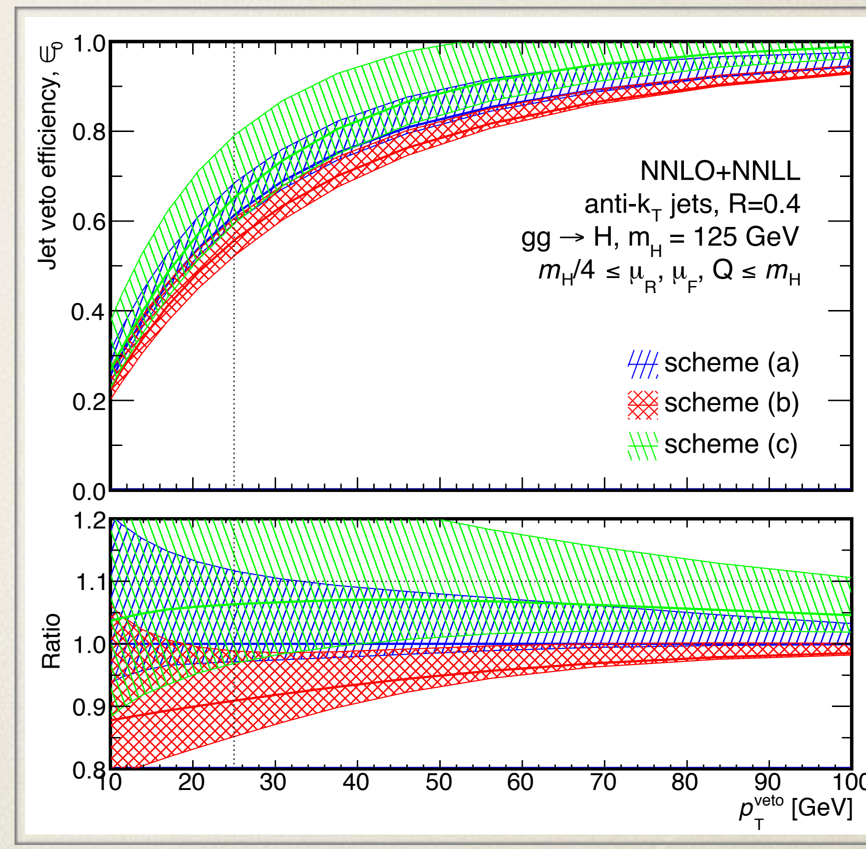


ε_0: 1st jet veto efficiency

- JetVHeto resums NNLL Sudakov logs to all orders of α_s
- Attached to 3 schemes individually
- Significant improvement in accuracy

Banfi, Monni, Salam, Zanderighi
PRL 109, 202001 (2012)



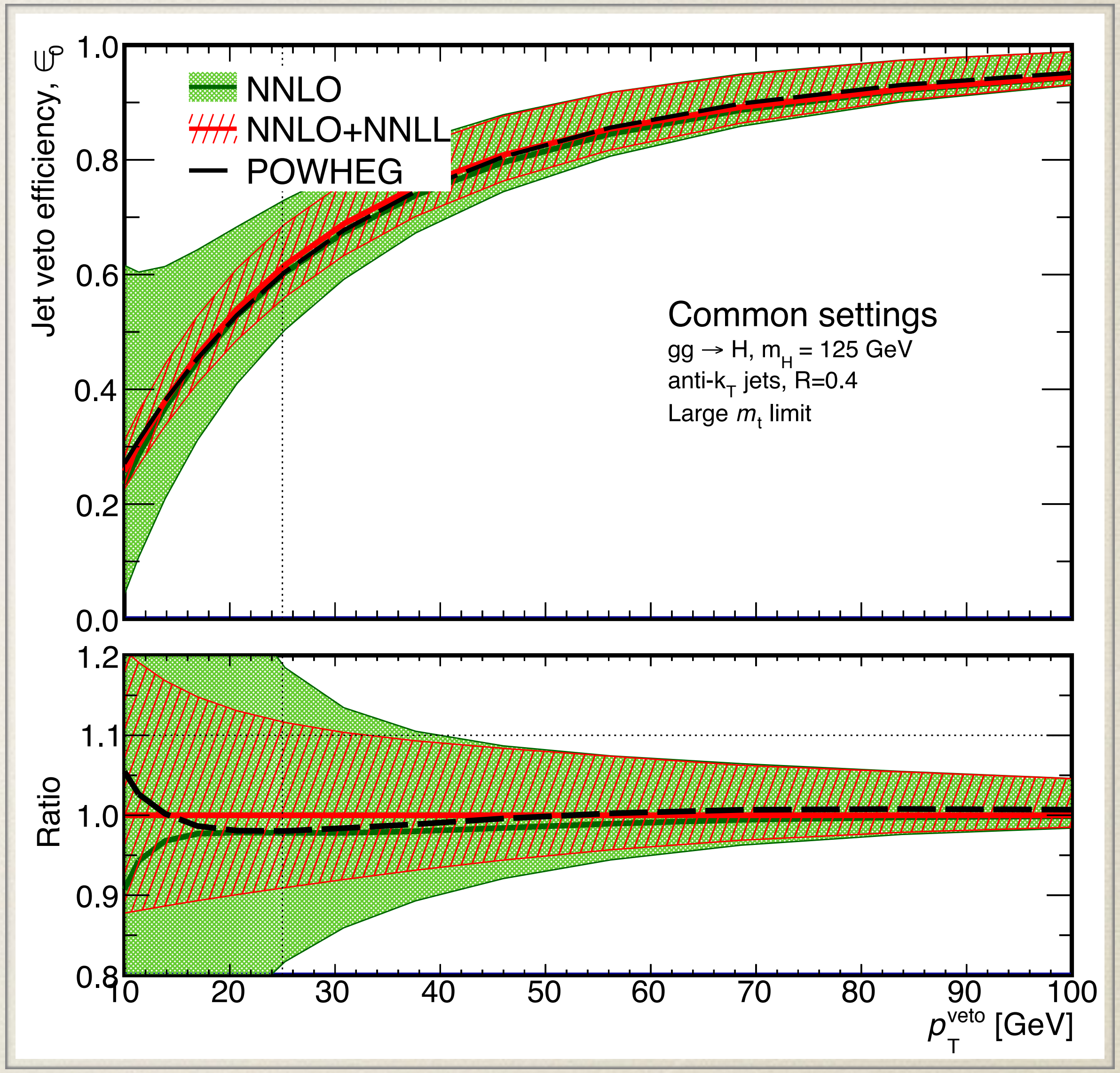


- Schemes are converging, and uncertainty is reduced
  - low bound is scheme (b), high bound is direct scale variation (now includes variation of resummation scale too)

ε_0: 1st jet veto efficiency

- Compared fixed order and resummed calculations to our MC setup (few changes for comparison)
  - Powheg (large m_t limit)
  - Pythia 8 (no hadronisation or MPI)
  - ATLAS UE tune

- Results are consistent
  - ⇒ allows us to reduce uncertainty by using resummation calculation



ε_1: 2nd jet veto efficiency

- Three analogous definitions of efficiency:

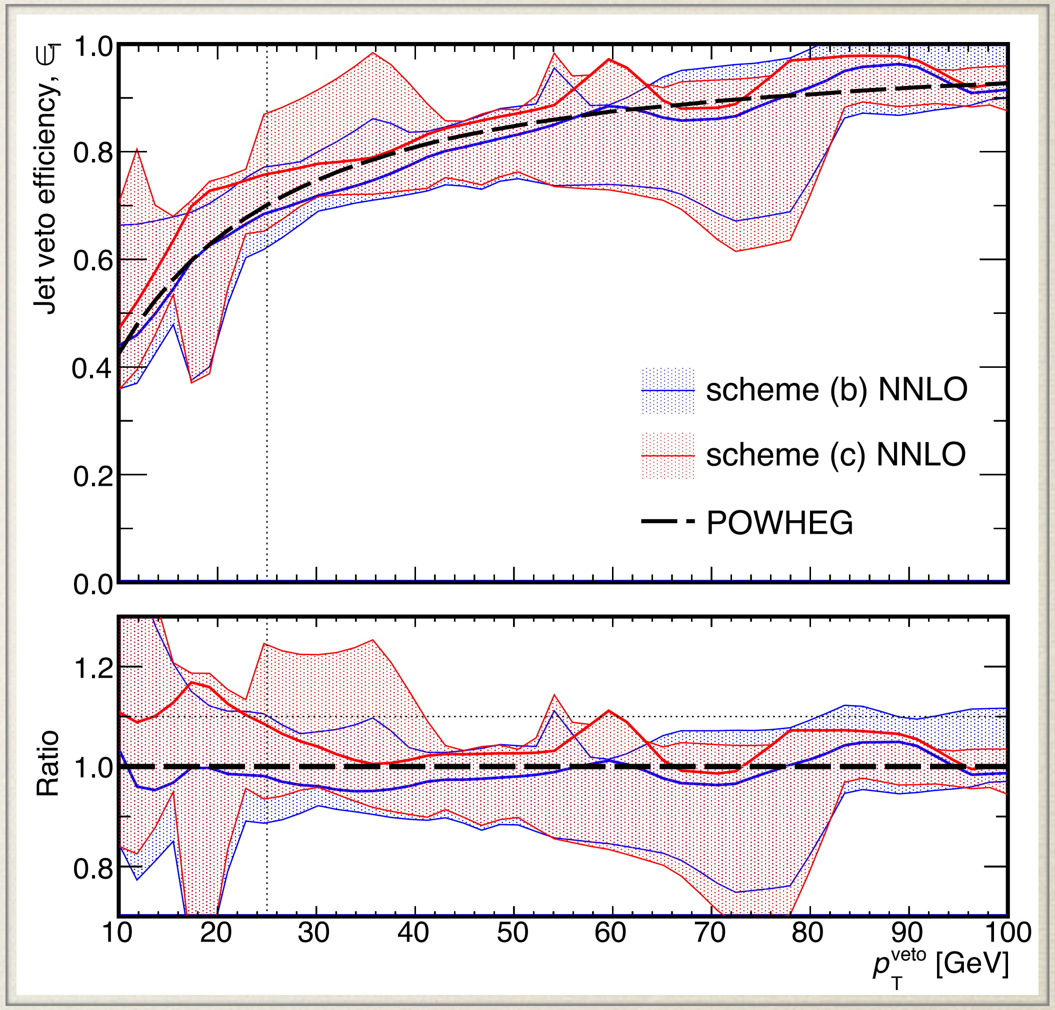
$$\epsilon_1^{(a)} = 1 - \frac{\sigma_{\geq 2}^{\rm NLO}}{\sigma_{\geq 1}^{\rm NNLO}} + \mathcal{O}(\alpha_s^3) \qquad \epsilon_1^{(b)} = 1 - \frac{\sigma_{\geq 2}^{\rm NLO}}{\sigma_{\geq 1}^{\rm NLO}} + \mathcal{O}(\alpha_s^3)$$

$$\epsilon_1^{(c)} = 1 - \frac{\sigma_{\geq 2}^{\rm NLO}}{\sigma_{\geq 1}^{\rm LO}} + \left(\frac{\sigma_{\geq 1}^{\rm NLO}}{\sigma_{\geq 1}^{\rm LO}} - 1\right)\frac{\sigma_{\geq 2}^{\rm LO}}{\sigma_{\geq 1}^{\rm LO}} + \mathcal{O}(\alpha_s^3)$$

- again, differ by NNNLO terms ⇒ probe higher order corrections
- $\sigma_{\geq 1}^{\rm NNLO}$ not available ⇒ cannot compute scheme (a)
  - come back to this later
- we can calculate everything else with MCFM
- let's look at schemes (b) and (c)

ε_1: 2nd jet veto efficiency

- Schemes (b) and (c) in better agreement with each other than seen with fixed-order ε_0 calculation because pQCD series is converging better
- Also reasonable agreement with Powheg
- Propose to
  - use MC for central value
  - take envelope of all scale variations around both schemes, since we don't have scheme (a)
- NB: precision of MCFM needs improving...



MCFM jobs by S. Diglio, D. Hall

ε_1: 2nd jet veto efficiency

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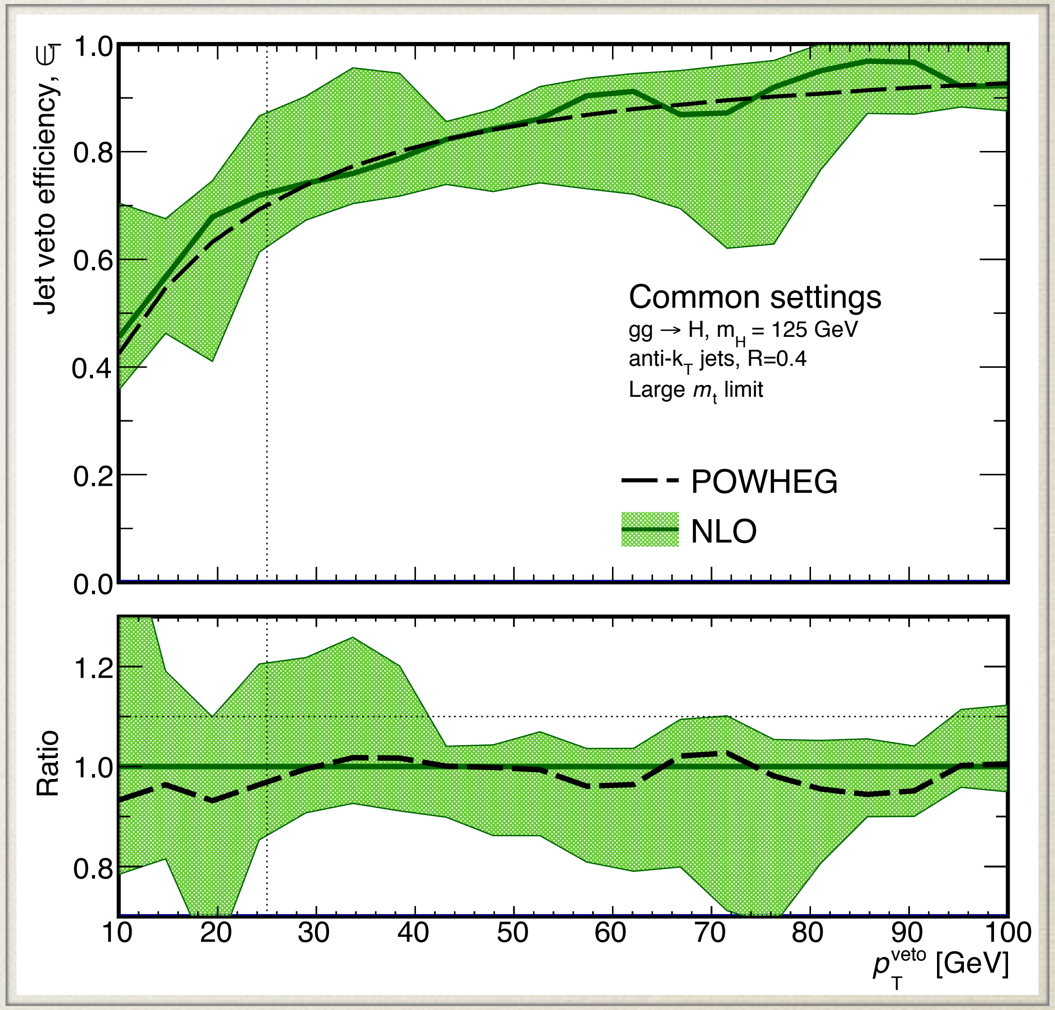


MCFM jobs by S. Diglio, D. Hall

Is (a) between (b) and (c)?

* H+1j NNLO calculation done for **gg-only** diagrams
  * Petriello et al. - arXiv:1302.6216
  * uses k_t jets with R=0.5 and p_T > 30 GeV
  * c.f. ATLAS anti-k_t R=0.4 with p_T > 25 GeV
* Can calculate (a), (b) and (c) with this setup

	σ [fb]
H+1j LO	2713
H+1j NLO	4377
H+1j NNLO	6177
H+2j LO	1008
H+2j NLO	1044

	ε_1
(a)	0.831
(b)	0.761
(c)	0.843

* find that (b) < (a) < (c)

Uncertainties in exclusive cross sections

- Propagate uncertainties to exclusive cross sections using equations on slides 5 & 6

	value	relative uncertainty
σ_{tot}	19.27	7.8%
$\sigma_{\geq 1}$	7.44	20.2%
$\sigma_{\geq 2}$	2.29	69.7%
σ_0	11.83	18.0%
σ_1	5.15	42.6%
$\sigma_{\geq 2}$	2.29	69.7%

Combined-inclusive
(current prescription)

	value	relative uncertainty
σ_{tot}	19.27	7.8%
ε_1	0.613	11.7%
ε_2	0.701	23.8%
σ_0	11.81	14.1%
σ_1	5.23	31.2%
$\sigma_{\geq 2}$	2.23	59.3%

Jet veto efficiency
(proposed prescription)

	value	relative uncertainty
σ_{tot}	19.27	7.8%
ε_1	0.613	21.5%
ε_2	0.701	23.8%
σ_0	11.81	22.9%
σ_1	5.23	42.3%
$\sigma_{\geq 2}$	2.23	65.8%

Jet veto efficiency
(fixed order results only - at request of Tackmann, et al.)

- JVE offers improvement over CI in 0, 1 jet bins (where majority of sensitivity lies)

Log-normal uncertainties

- In fitting code, we actually use log-normal uncertainties

$$\tilde{\sigma}_0 = \sigma_0 \cdot \exp(\delta\sigma_{\rm tot})^x \exp(\delta\epsilon_0)^y$$

$$\tilde{\sigma}_1 = \sigma_1 \cdot \exp(\delta\sigma_{\rm tot})^x \exp\left(\frac{-\epsilon_0}{1-\epsilon_0}\delta\epsilon_0\right)^y \exp(\delta\epsilon_1)^z$$

$$\tilde{\sigma}_{\geq 2} = \sigma_{\geq 2} \cdot \exp(\delta\sigma_{\rm tot})^x \exp\left(\frac{-\epsilon_0}{1-\epsilon_0}\delta\epsilon_0\right)^y \exp\left(\frac{-\epsilon_1}{1-\epsilon_1}\delta\epsilon_1\right)^z$$

  - where x, y, z are normally-distributed nuisance parameters

- Impact of each n.p. on signal strength, μ:
  - For CI: $x \Rightarrow \sigma_{\rm tot}$, $y \Rightarrow \sigma_{\geq 1}$, $z \Rightarrow \sigma_{\geq 2}$
  - For JVE: $x \Rightarrow \sigma_{\rm tot}$, $y \Rightarrow \varepsilon_0$, $z \Rightarrow \varepsilon_1$

Fits performed by Y. Hernandez Jimenez

	Combined inclusive			Jet veto efficiency		
	0 jet	1 jet	0+1 jet	0 jet	1 jet	0+1 jet
x	+15.4% −8.6%	+0% −0%	+7.1% −4.9%	+9.6% −5.4%	+8.8% −4.8%	+8.7% −5.7%
y	+15.1% −8.4%	+30.2% −16.3%	+4.0% −3.4%	+14.2% −8.0%	+19.5% −10.5%	+1.1% −0.9%
z	+0% −0%	+31.4% −16.6%	+10.9% −8.2%	+0% −0%	+17.4% −9.5%	+7.1% −5.0%

0+1 jet	CI	JVE
$\Delta\mu$	+13.6% −10.1%	+11.3% −7.6%
$\Delta\sigma_{\rm meas}$	+11.6% −8.9%	+7.2% −5.1%

Cross check with σ_1

- Recent NLO+NLL' calculation of σ_1
  - Petriello, Liu - YR3
- For ATLAS jets ($p_T > 25$ GeV, $R = 0.4$) and $m_H = 125$ GeV
  - $\sigma_1 = 5.55$ pb with 30% relative uncertainty
  - consistent with both prescriptions
    - CI: $\sigma_1 = 5.15$ pb
    - JVE: $\sigma_1 = 5.23$ pb

Extrapolation to other m_H

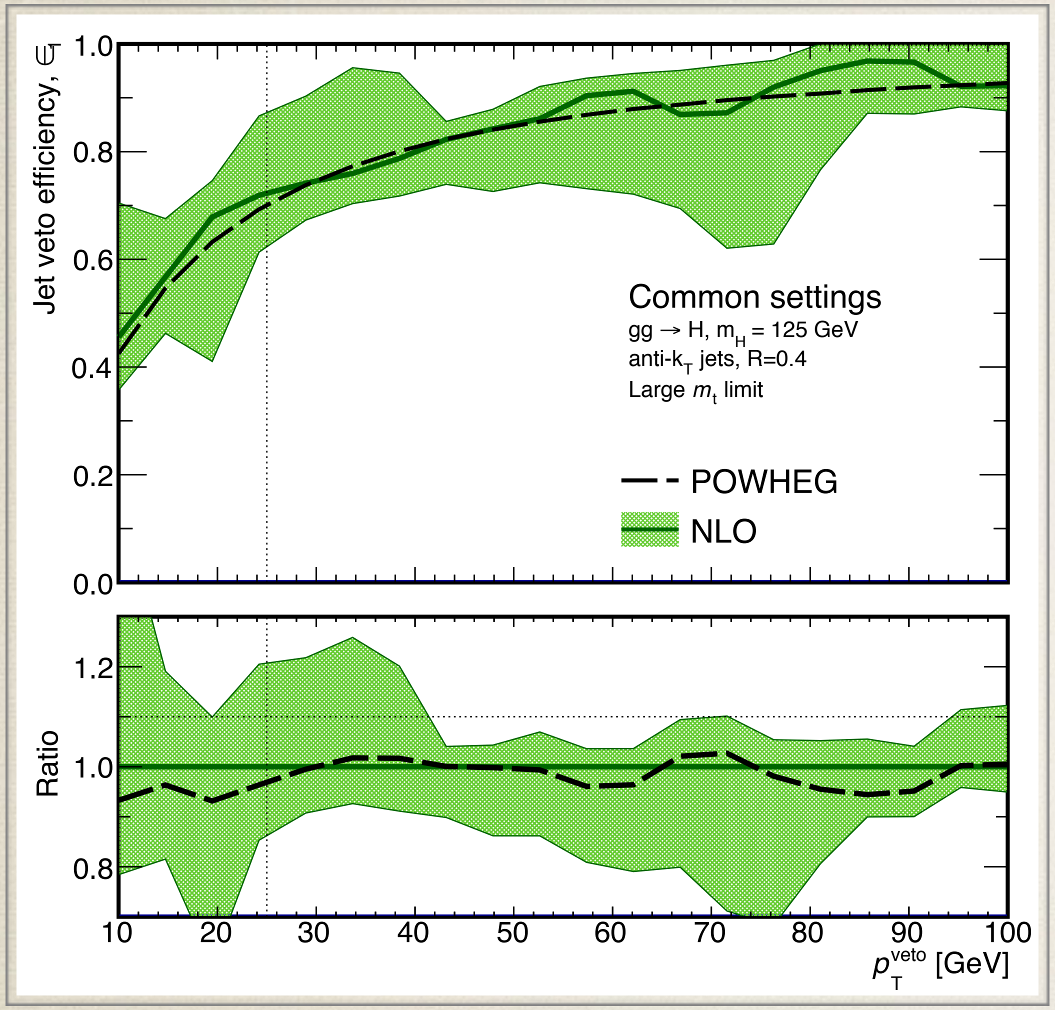
- We use same jet p_T threshold for both jet vetoes
  - $\varepsilon_0 = \varepsilon_0(\sqrt{s}, m_H, p_T^{veto})$
  - $\varepsilon_1 = \varepsilon_1(\sqrt{s}, m_H, p_T^{veto})$
- We can approximate $\delta\varepsilon_0$ and $\delta\varepsilon_1$ at other m_H values using our m_H=125 GeV sample by evaluating at different jet p_T thresholds
  - if $\Delta m_H \ll \sqrt{s}$, can approximate as a 2-scale problem
  - ε(8 TeV, m_H, 25 GeV) = ε(8 TeV, 125 GeV, 25 GeV*125 GeV/m_H)
- Use this to extrapolate over range 115 GeV < m_H < 140 GeV

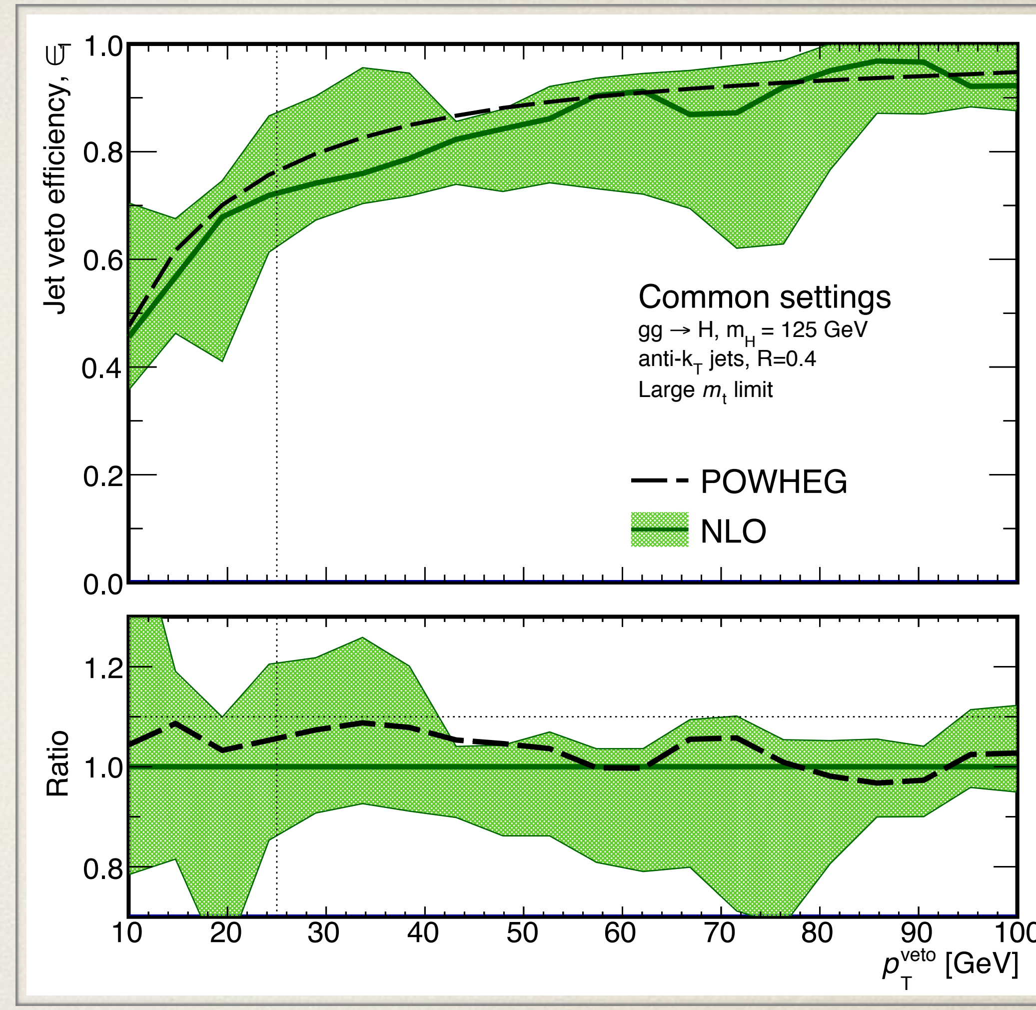
Summary

- ATLAS $H \rightarrow WW$ propose a switch from combined-inclusive prescription to jet veto efficiency prescription
- Allows us to use more advanced calculations
  - NNLO+NNLL ε_0 from JetVHeto
  - NLO H+2j from MCFM
- σ_1 consistent with latest resummation calculation (Petriello, Liu)
- Initial estimates show a significant reduction in the jet binning contribution to $\Delta\mu$ and $\Delta\sigma_{\mathrm{meas}}$
  - reduction in $\Delta\sigma_{\mathrm{meas}}$ particularly helpful in coupling measurements (e.g. ratios, λ_{WZ})

Backup slides

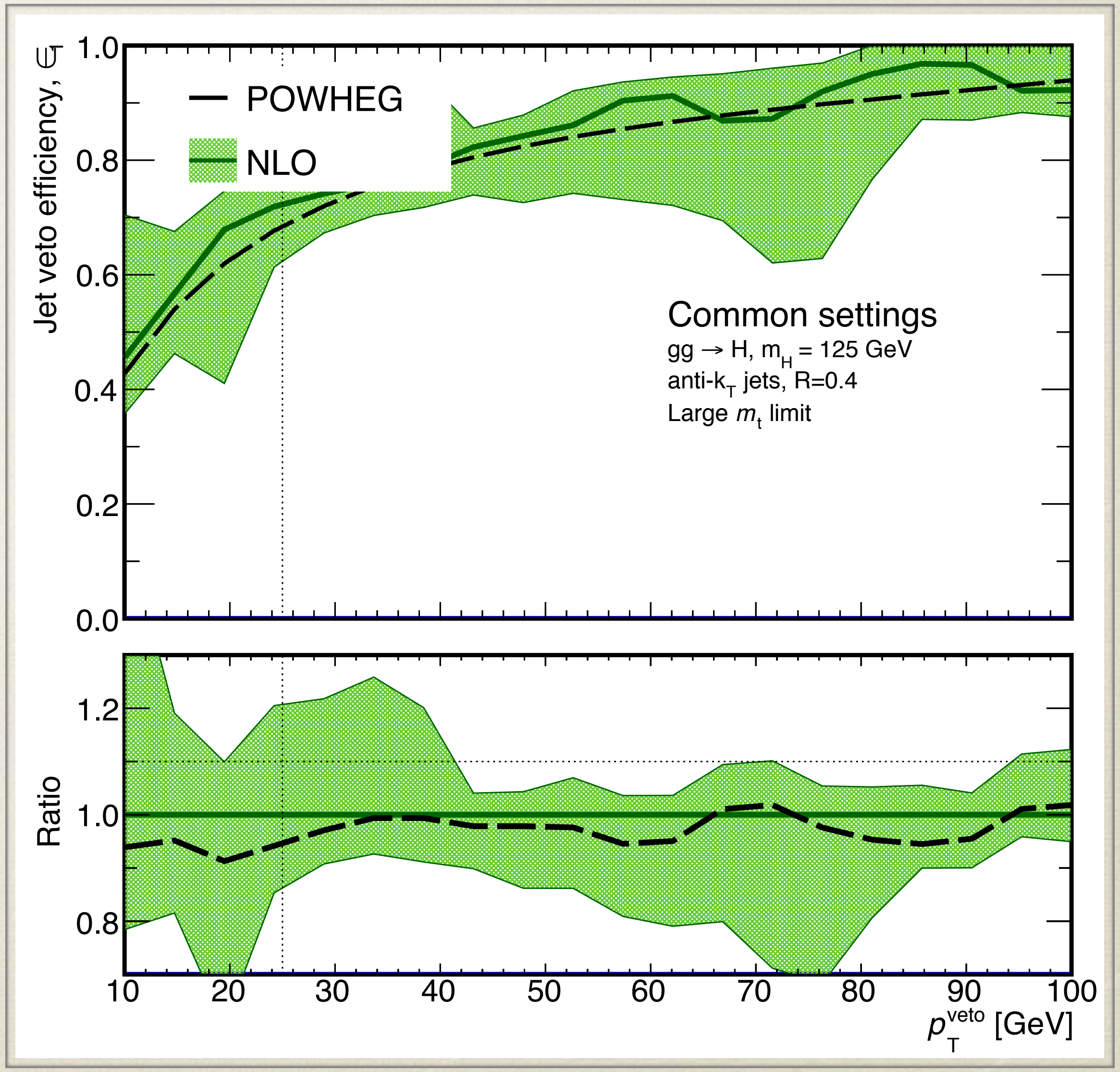
Hadronisation/MPI effects



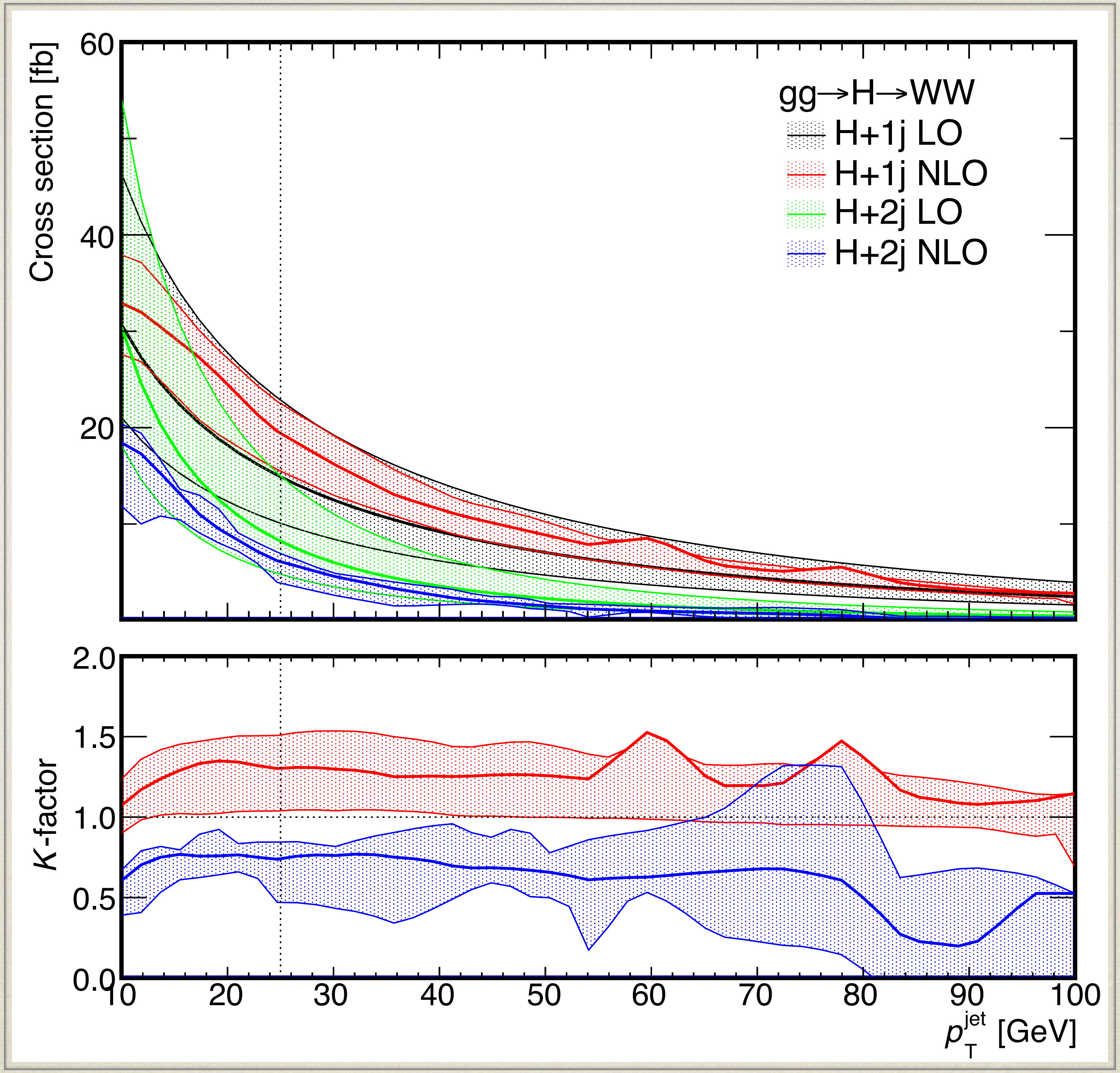


Compare to MiNLO

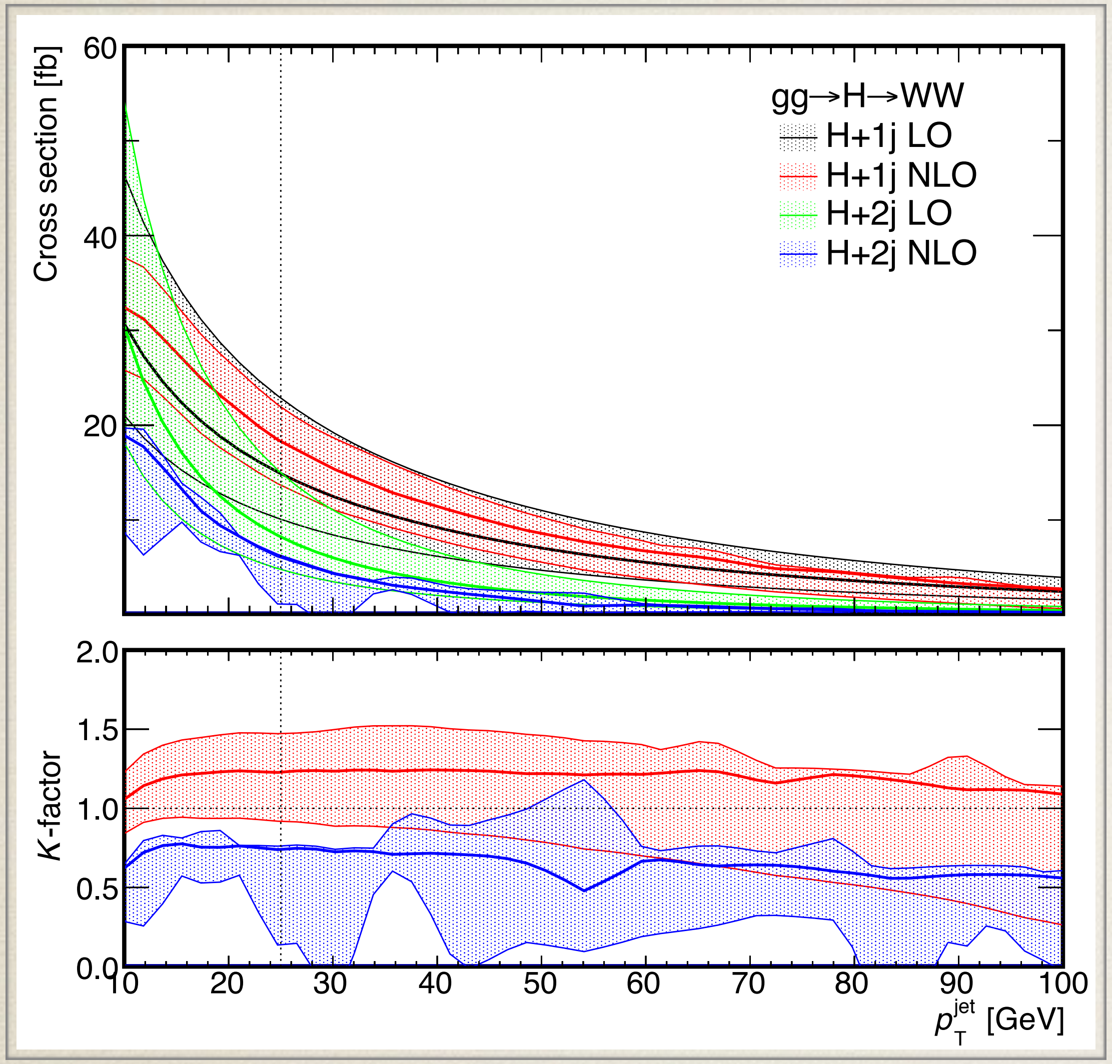
- Compare to ATLAS MiNLO H+1j sample
  - 2nd jet described by Powheg (modified Sudakov)
  - more accurate than relying on Pythia PS with standard sample
- very similar result

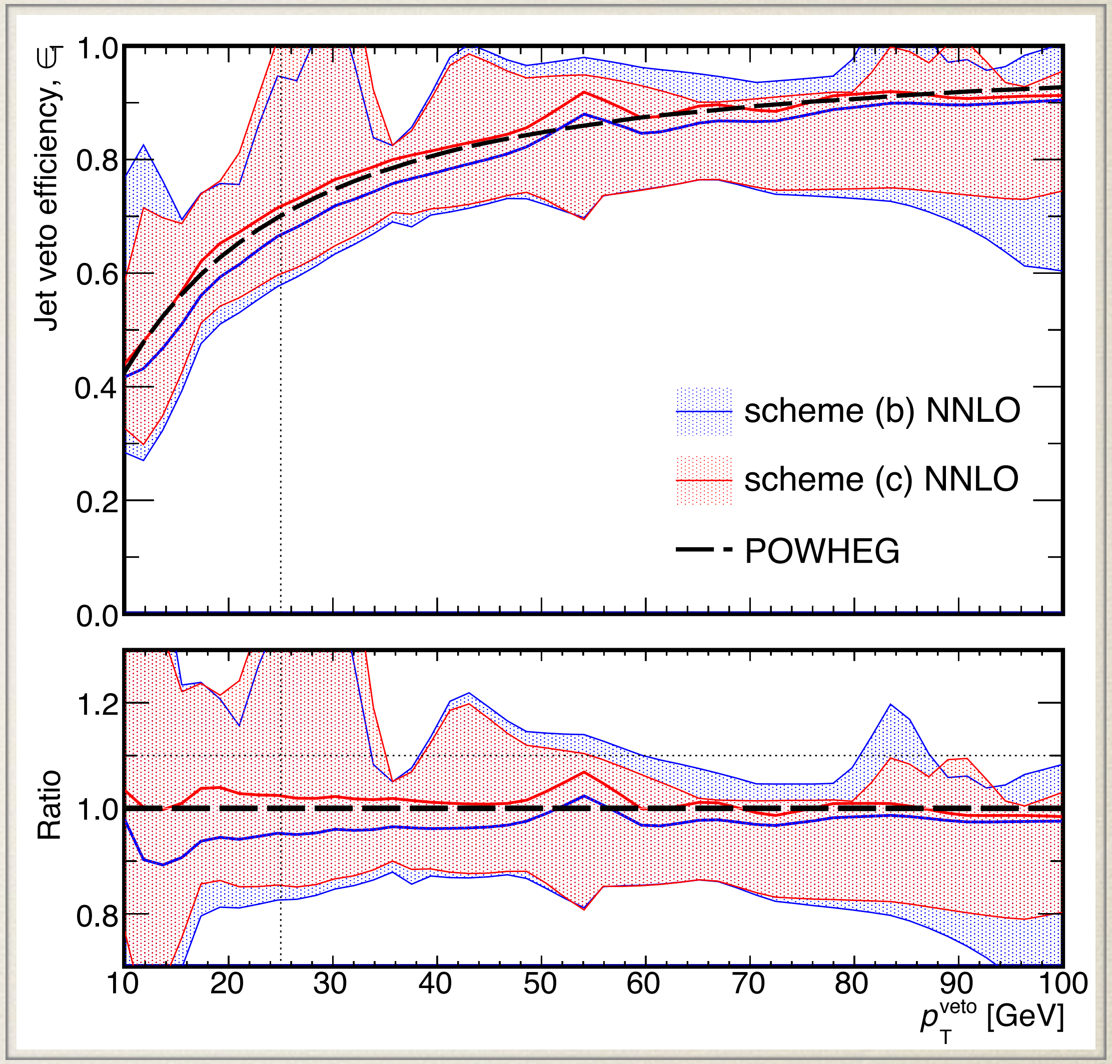


Cross sections used in ε_1



CTEQ6.6 PDFs (instead of CT10)





ε_1 at lower accuracy

- Possible to define ε_1 at lower accuracy:

$$\epsilon_1^{(a)} = 1 - \frac{\sigma_{\geq 2}^{\mathrm{LO}}}{\sigma_{\geq 1}^{\mathrm{NLO}}} + \mathcal{O}(\alpha_s^2) \qquad \epsilon_1^{(b)} = 1 - \frac{\sigma_{\geq 2}^{\mathrm{LO}}}{\sigma_{\geq 1}^{\mathrm{LO}}} + \mathcal{O}(\alpha_s^2)$$

- these differ by NNLO terms
- was done for ε_2
  - Gangal, Tackmann - arXiv:1302.5437
  - H+3j only known at LO
  - jet veto efficiency results shown to be consistent with combined-inclusive method