Resummation effects in H and WW exclusive cross sections

P. F. Monni
Rudolf Peierls Centre for Theoretical Physics
University of Oxford

CERN - 17 December 2014

Exclusive cross sections

- Categorisation in jet multiplicities commonly used to differentiate sources of background of optimise sensitivity

- Recently there has been much progress on the fixed order (FO) front (N3LO, H+1J@NNLO, H+3J@NLO, WW@NNLO)

[Bonvini et al. 1303.3590 - 1404.3204; Anastasiou et al. 1403.4616 - 1411.3584; de Florian et al. 1408.6277]
[Boughezal et al. 1302.6216; Chen et al. 1408.5325]
[Cullen et al. 1307.4737]
[Gehrmann et al. 1408.5243]

- When tight phase space cuts (e.g. jet veto) on QCD radiation are present, the fixed-order prediction does not account for the correct Sudakov exponential suppression and diverges logarithmically

- Since FO is spoiled, one expects larger th. uncertainties. Often large (negative) Sudakov logarithms compensate large (positive) K-factors in exclusive cross sections (scale variation not a reliable uncertainty measure)

e.g. 0-jets cross section

$$\sigma_{0\mathrm{jet}}(p_{\mathrm{t,veto}}) = \sigma_{\mathrm{tot}} - \sigma_{\geq 1\mathrm{jet}}(p_{\mathrm{t,veto}})$$

- Possible solution to both problems: resummation of logarithmic terms to all orders

Uncertainties

- Accurate resummations available only for low jet multiplicities, i.e. 0, 1

  [Banfi et al. 1206.4998; Becher et al. 1307.0025; Stewart et al. 1307.1808; Liu et al. 1210.1906]
  [Jaiswal, Okui 1407.4537]

- Find a way to estimate the uncertainties even if resummation is not available
- Need for some general prescription for theory uncertainties that can
  - combine resummed (matched) and fixed order predictions for different jet bins
  - be used for any required jet multiplicity

- Some options are:
  - Combination of uncorrelated inclusive jet bin unc. (i.e. Stewart-Tackmann) [Stewart, Tackmann 1107.2117]
  - Uncorrelated unc. in jet rates and total cross section (i.e. JVE method) [Banfi, Salam, Zanderighi 1203.5773, + PM 1206.4998]
  - Use of yield and migration unc. from resummed jet bin cross sections (whenever available) [Boughezal, Liu, Petriello, Tackmann, Walsh 1312.4535]

Uncertainties

- Accurate resummations available only for low jet multiplicities, i.e. 0, 1

  [Banfi et al. 1206.4998; Becher et al. 1307.0025; Stewart et al. 1307.1808; Liu et al. 1210.1906]
  [Jaiswal, Okui 1407.4537]

- Find a way to estimate the uncertainties even if resummation is not available
- Need for some general prescription for theory uncertainties that can
  - combine resummed (matched) and fixed order predictions for different jet bins
  - be used for any required jet multiplicity

I will focus on this method in this talk

- Some options are:
  - Combination of uncorrelated inclusive jet bin unc. (i.e. Stewart-Tackmann) [Stewart, Tackmann 1107.2117]
  - Uncorrelated unc. in jet rates and total cross section (i.e. JVE method) [Banfi, Salam, Zanderighi 1203.5773, + PM 1206.4998]
  - Use of yield and migration unc. from resummed jet bin cross sections (whenever available) [Boughezal, Liu, Petriello, Tackmann, Walsh 1312.4535]

JVE method

- Need to disentangle Sudakov large logarithms from K factor due to hard physics in order to avoid cancellations
- Express the exclusive cross sections as products of jet veto efficiencies (JVE) and the total cross section

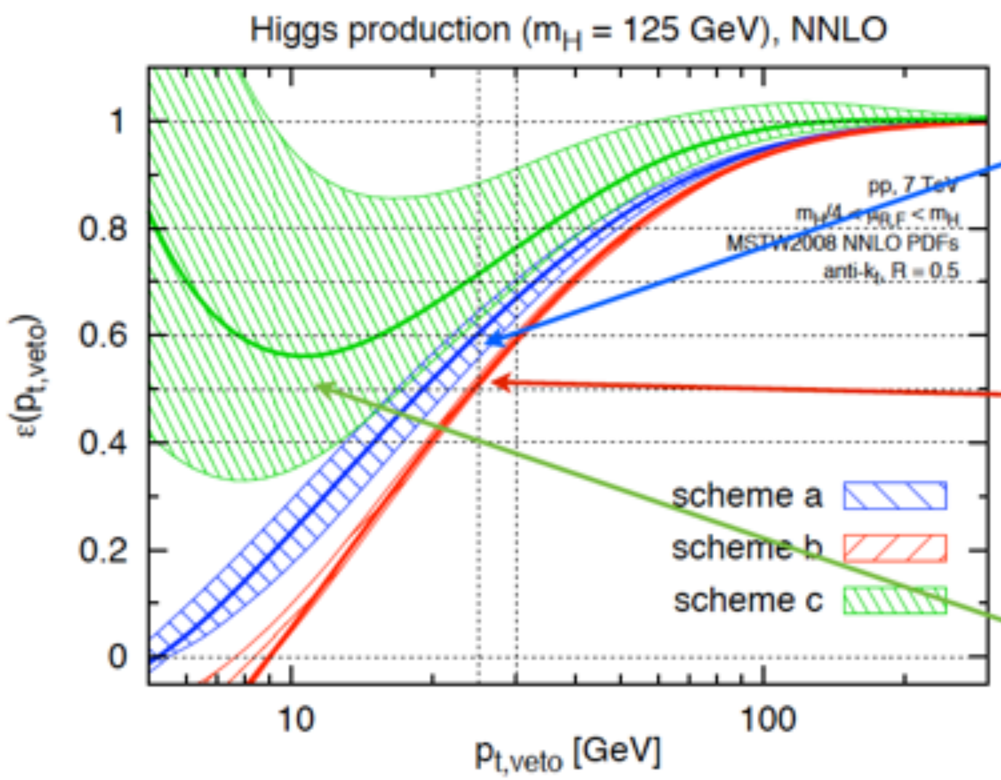
$$\begin{aligned}
\sigma_{0-\mathrm{jet}} &= \epsilon_0 \sigma_{\mathrm{tot}}, \\
\sigma_{1-\mathrm{jet}} &= \epsilon_1 (1-\epsilon_0) \sigma_{\mathrm{tot}}, \\
\sigma_{2-\mathrm{jet}} &= \epsilon_2 (1-\epsilon_1)(1-\epsilon_0) \sigma_{\mathrm{tot}}, \\
&\dots \\
\sigma_{\mathrm{n}-\mathrm{jet}} &= \epsilon_n (1-\epsilon_{n-1}) \dots (1-\epsilon_0) \sigma_{\mathrm{tot}}, \\
\sigma_{>\mathrm{n}-\mathrm{jet}} &= (1-\epsilon_n)(1-\epsilon_{n-1}) \dots (1-\epsilon_0) \sigma_{\mathrm{tot}}
\end{aligned}$$

- Observe that at small transverse momentum the effects due to hard physics cancel in the efficiencies, and contribute as a global K factor in the total cross section
- In this phase space region JVEs are dominated by large Sudakov logarithms, and their uncertainty can be considered as uncorrelated from the one in the total cross section (and uncorrelated with each other jet bin's uncertainty)

JVE method

- Scale variation uncertainty in the total cross section due to inclusive K factor effects
- Scale uncertainty in the JVE is mainly associated with miss higher order large logarithms
- Moreover, the spread between central values relative to all possible definitions for the JVE at a give perturbative order is considered as an additional systematic
  - Difference between schemes increases for slowly converging PT series

e.g. H+0-jets @ NNLO



$$\epsilon^{(a)}(p_{t,\mathrm{veto}}) = \frac{\sigma^{\mathrm{NNLO}}_{0-\mathrm{jet}}}{\sigma^{\mathrm{NNLO}}_{\mathrm{tot}}}$$

$$\epsilon^{(b)}(p_{t,\mathrm{veto}}) = 1 - \frac{\sigma^{\mathrm{NLO}}_{\geq 1-\mathrm{jet}}}{\sigma^{\mathrm{NLO}}_{\mathrm{tot}}}$$

$\epsilon^{(c)}(p_{t,\mathrm{veto}})$ = strict fixed order expansion

spread depends on inclusive K(NNLO/NLO)

spread depends on inclusive K(NLO/LO)

JVE method

- Error in the efficiency defined as the envelope of all these variations
- Final uncertainty in exclusive jet bin cross sections obtained by combining with the one in the total cross section
- Correlation between jet bins can be easily computed with any jet multiplicity

e.g. 2 jet-bins case

Fully correlated term (K factor effects on total cross section)

Fully anti-correlated term (migration effects due to jet bins separation)

$$\mathrm{Cov}[\sigma_{0-\mathrm{jet}}, \sigma_{\geq 1-\mathrm{jet}}] = \begin{pmatrix} \epsilon^2 \Delta^2 \sigma_{\mathrm{tot}} & \epsilon(1-\epsilon)\Delta^2 \sigma_{\mathrm{tot}} \\ \epsilon(1-\epsilon)\Delta^2 \sigma_{\mathrm{tot}} & (1-\epsilon)^2 \Delta^2 \sigma_{\mathrm{tot}} \end{pmatrix} + \begin{pmatrix} \sigma_{\mathrm{tot}}^2 \Delta^2 \epsilon & -\sigma_{\mathrm{tot}}^2 \Delta^2 \epsilon \\ -\sigma_{\mathrm{tot}}^2 \Delta^2 \epsilon & \sigma_{\mathrm{tot}}^2 \Delta^2 \epsilon \end{pmatrix}$$

Extension to any jet multiplicity in P. Monni's contribution to Les Houches '13 proceedings

- Resummation effects can be directly included in the JVE predictions when available

Jet Veto Resummation

- Resummation for the 0-jet cross section known to NNLL

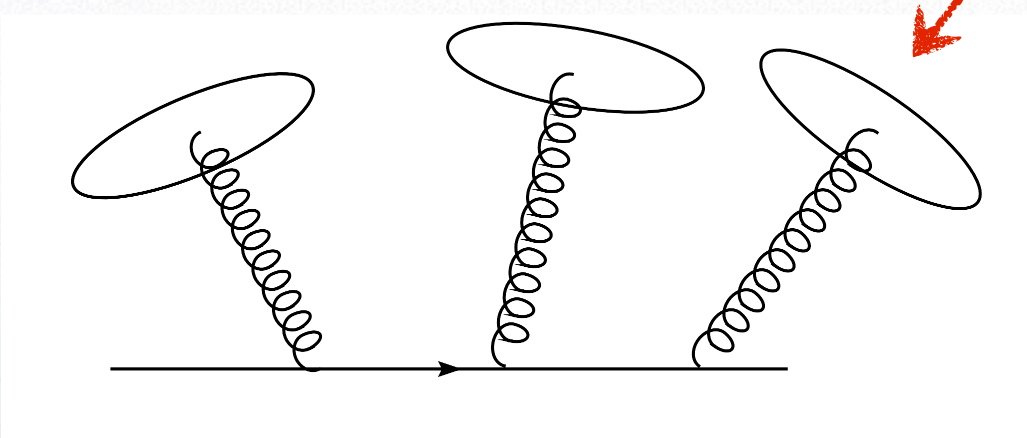
[Banfi, PM, Salam, Zanderighi 1206.4998]

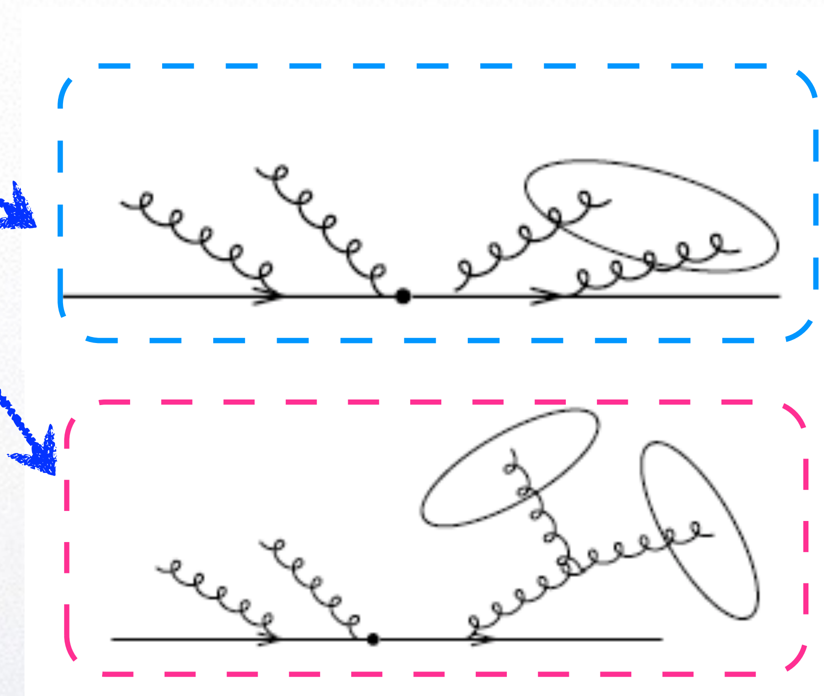
$$\Sigma(p_t) = \mathcal{L}(p_t)|\mathcal{M}_B|^2 e^{-R(p_t)} \mathcal{F}(R') \qquad R' = dR(p_t)/d\ln(m_H/p_t)$$

Sudakov Radiator, virtual corrections and parton luminosities

All-orders soft and collinear real radiation. Describes observable's behaviour in the presence of multiple emissions

$$\mathcal{F}(R') = 1 + \mathcal{O}(\text{NNLL})$$



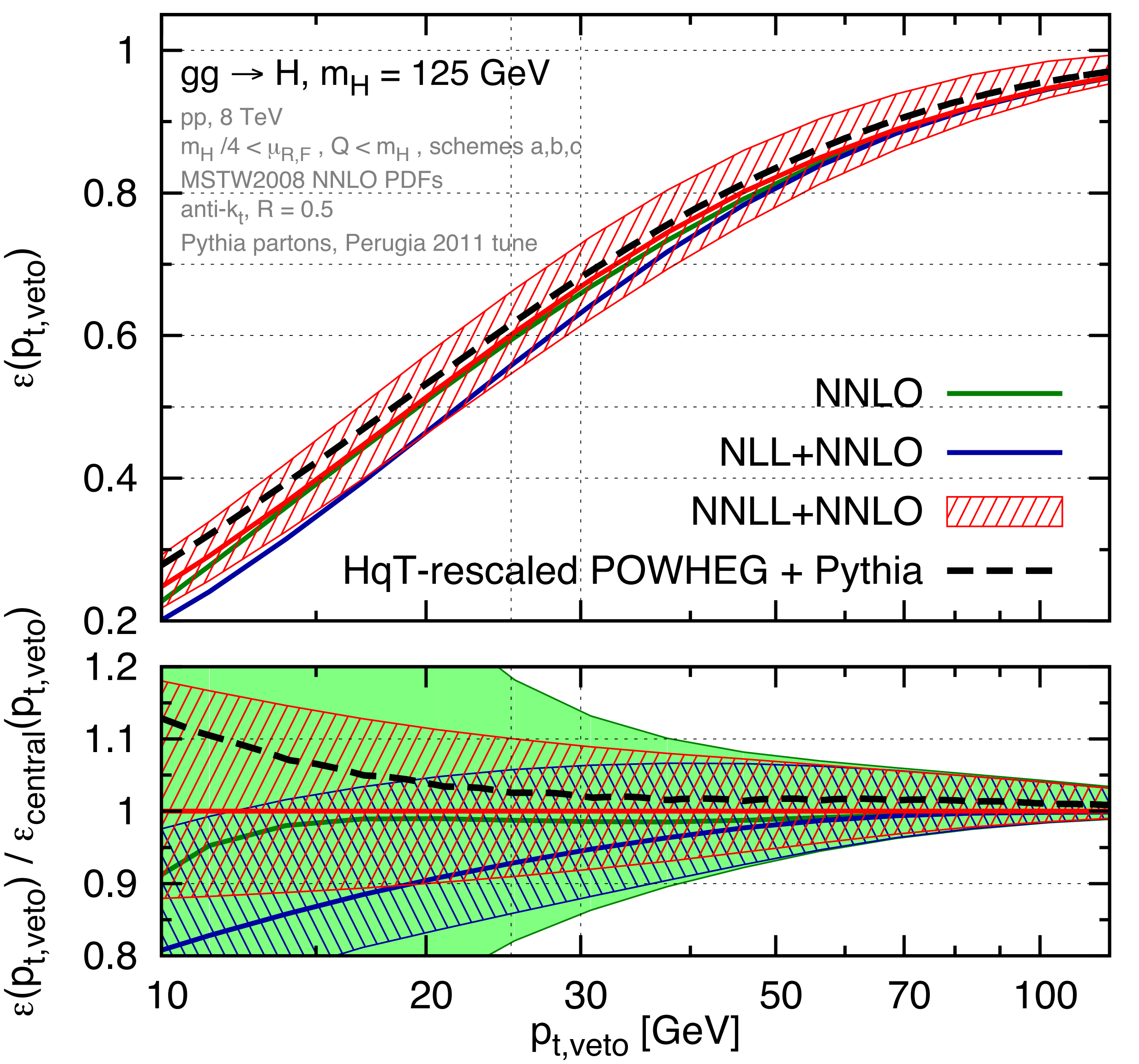


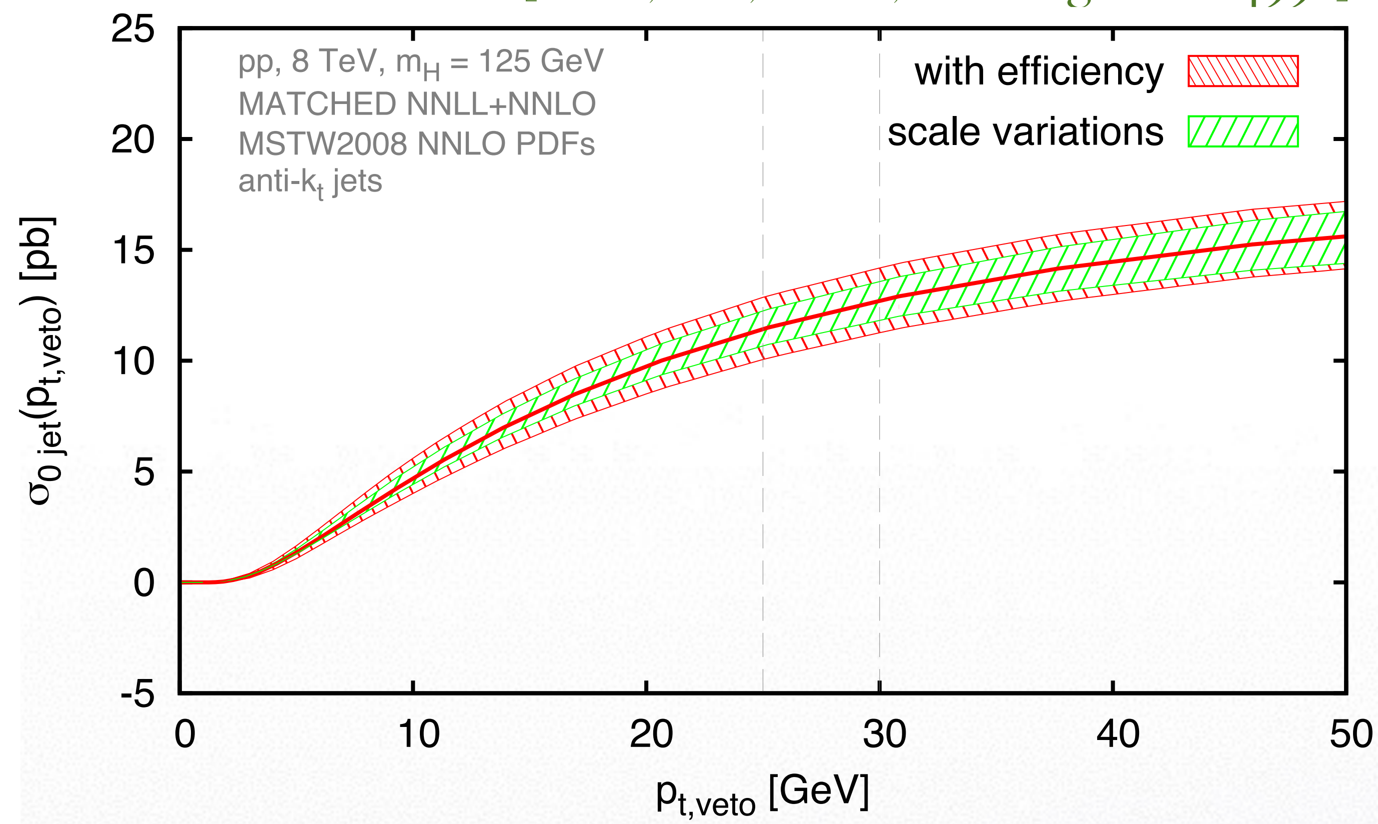
Alternative approaches in SCET lead to same results (see F. Tackmann's talk)

[Becher, Neubert, Rothen 1307.0025]

[Stewart, Tackmann, Walsh, Zuberi 1307.1808]

[Banfi, PM, Salam, Zanderighi 1206.4998]





- Uncertainty in the efficiency considerably reduced by resummation

e.g. $R = 0.4,\ p_{t,\mathrm{veto}} = 25\,\mathrm{GeV}$:

$\delta\sigma_{0-\mathrm{jet}} \sim 10\%$ [NNLL+NNLO]

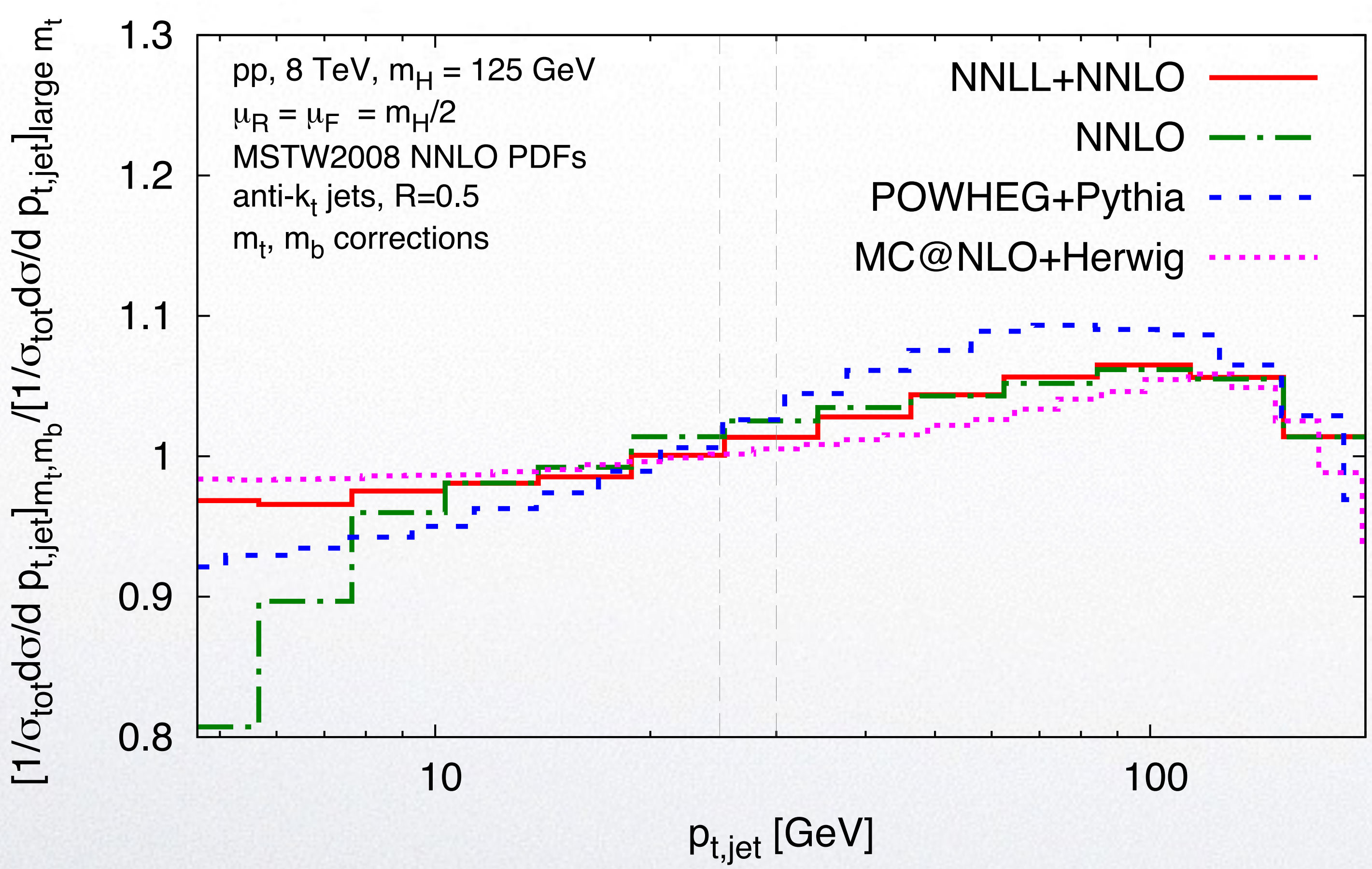
$\delta\sigma_{0-\mathrm{jet}} \sim 13.8\%$ [NNLL+NNLO + JVE method w $\sigma_{\mathrm{tot}}^{\mathrm{NNLO}}$]

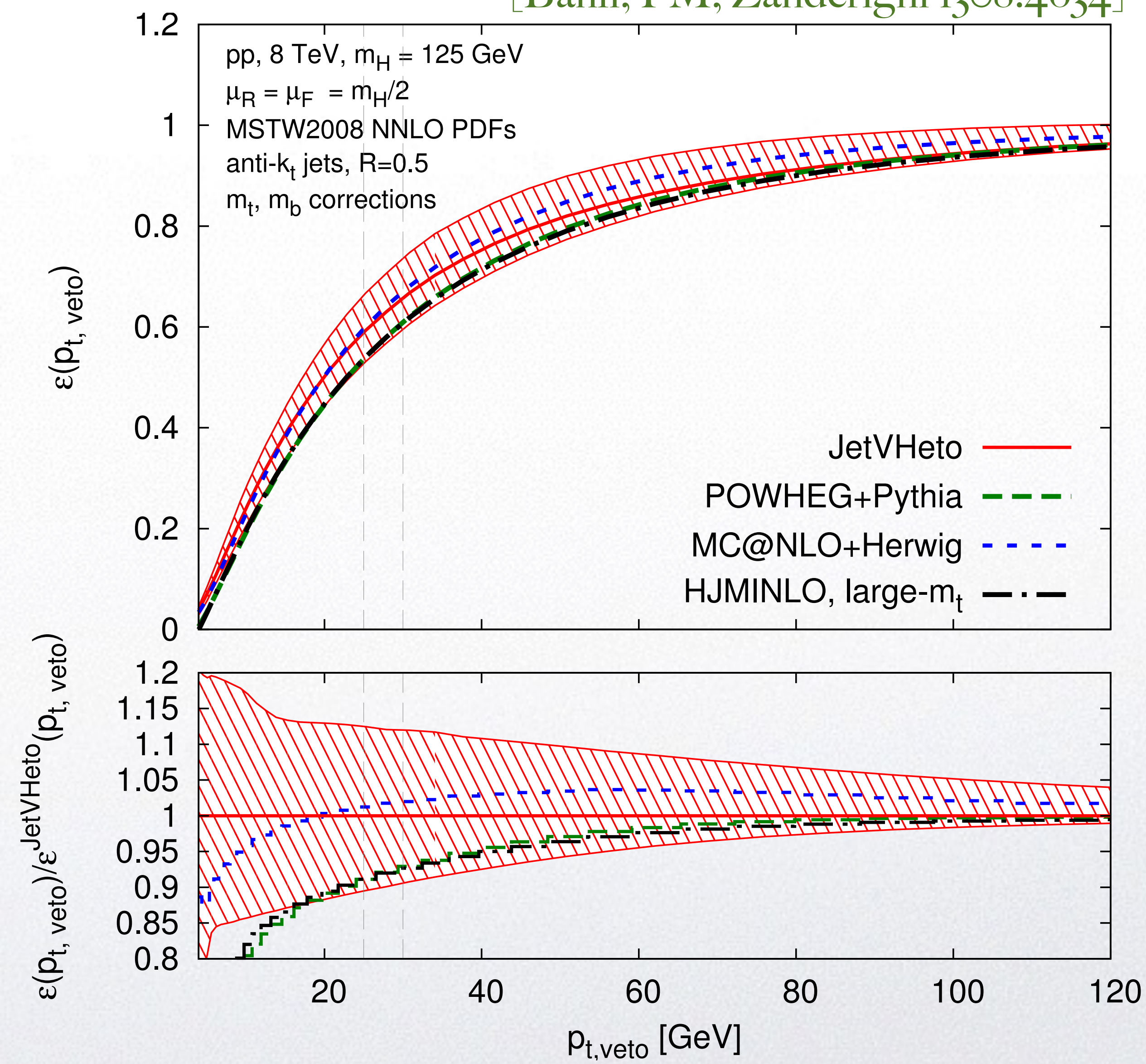
$\delta\sigma_{0-\mathrm{jet}} \sim 12.8\%$ [NNLL+NNLO + JVE method w $\sigma_{\mathrm{tot}}^{\mathrm{HXSWG}}$]

Quark masses effect

- Top and bottom quark masses introduce new regular logarithmic terms in the regime $m_b^2 \leq p_t^2 \leq m_H^2$, which can be treated as a remainder
- Moderate effects on both cross section and differential distributions
- Slightly larger theory uncertainties

[Banfi, PM, Zanderighi 1308.4634]





(see talks by G. Zanderighi and H. Sargsyan)

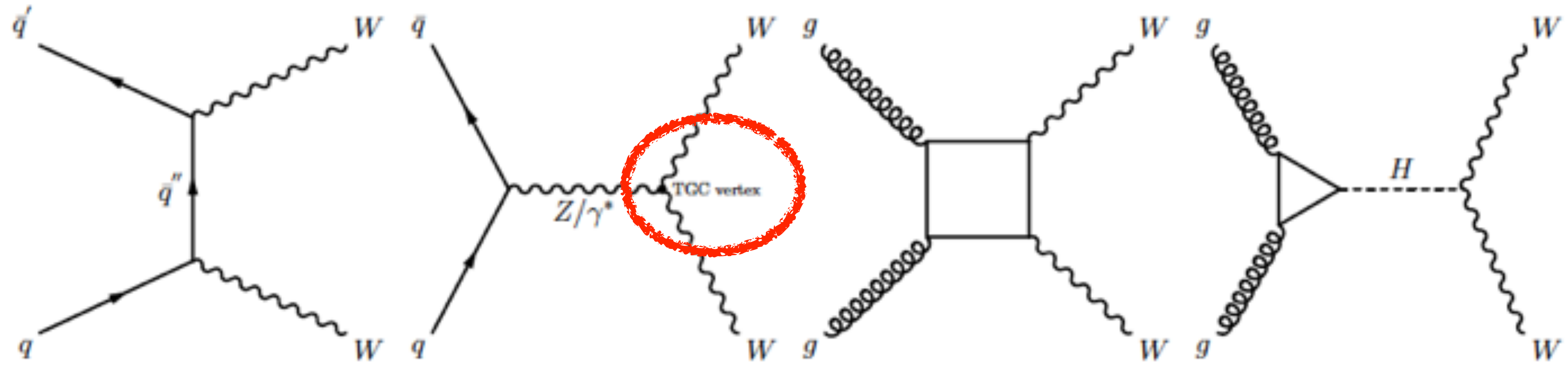
Summary H production

- JVE method: general prescription to treat jet bin uncertainties
  - Simple physical assumptions
  - Valid for any jet multiplicity
  - Allows one to combine fixed-order and resummed calculations

- Uncertainties for the 0-jet cross section under control, robust estimate with JVE method in agreement with pure scale variations for resummed cross section
- Further improvement achievable by combining the H+1J@NNLO and the total N3LO cross sections (calculations ongoing)
- Resummation and matching for both the zero jet cross section and efficiency implemented in the public code JetVHeto

http://jetvheto.hepforge.org

- Relevance of WW production at the LHC



- probe/test non-abelian structure of EW Standard Model
- Direct sensitivity to Triple Gauge Couplings (TGCs)
    - Deviations in total cross section and kinematic distributions can be due to anomalous TGCs or new states decaying into leptons + missing energy
- Important irreducible background for Higgs boson production (off-shell production)

- ATLAS & CMS performed analyses on both 7 and 8 TeV data

* includes formally NNLO gg → W W and gg → H → W W

$\sqrt{s}$	ATLAS σ [pb]	CMS σ [pb]	Theory* (MCFM) σ [pb]
7 TeV	$51.9^{+2.0+3.9+2.0}_{-2.0-3.9-2.0}$ [13]	$52.4^{+2.0+4.5+1.2}_{-2.0-4.5-1.2}$ [14]	$47.04^{+2.02+0.90}_{-1.51-0.66}$
8 TeV	$71.4^{+1.2+5.0+2.2}_{-1.2-4.4-2.1}$ [15]	$69.9^{+2.8+5.6+3.1}_{-2.8-5.6-3.1}$ [16]	$57.25^{+2.35+1.09}_{-1.60-0.80}$

- Systematic discrepancy of about 2.1 σ with the NLO prediction found by both experiments
- The tension seems to increase with the collider energy
- Tension not present for other di-boson channels (e.g. WZ, ZZ, $Z\gamma$, $W\gamma$)

ATLAS/CMS results

- ATLAS & CMS performed analyses on both 7 and 8 TeV data

* includes formally NNLO gg → W W and gg → H → W W

$\sqrt{s}$	ATLAS σ [pb]	CMS σ [pb]	Theory* (MCFM) σ [pb]
7 TeV	$51.9^{+2.0+3.9+2.0}_{-2.0-3.9-2.0}$ [13]	$52.4^{+2.0+4.5+1.2}_{-2.0-4.5-1.2}$ [14]	$47.04^{+2.02+0.90}_{-1.51-0.66}$
8 TeV	$71.4^{+1.2+5.0+2.2}_{-1.2-4.4-2.1}$ [15]	$69.9^{+2.8+5.6+3.1}_{-2.8-5.6-3.1}$ [16]	$57.25^{+2.35+1.09}_{-1.60-0.80}$

Larger discrepancy
with NLO.
Let's focus on this for a while...

- Systematic discrepancy of about 2.1 σ with the NLO prediction found by both experiments
- The tension seems to increase with the collider energy
- Tension not present for other di-boson channels (e.g. WZ, ZZ, $Z\gamma$, $W\gamma$)

Extrapolation to the total volume

- Measurements are carried out in a fiducial region, defined in an experiment-dependent way in order to optimise sensitivity
- The signal is then extrapolated to the inclusive phase space by means of MC event generators

Signal events in the fiducial region

$$\sigma(pp \to WW) = \frac{N_{\text{data}} - N_{\text{bg}}}{A_{WW} \times C_{WW} \times \mathscr{L} \times \text{Br}}$$

Integrated luminosity and branching ratios

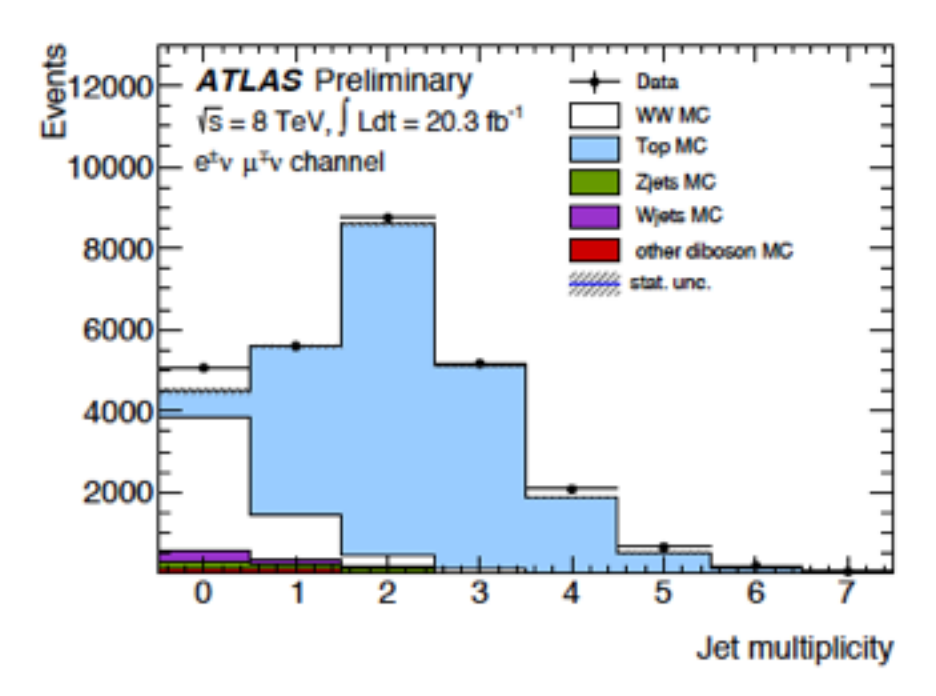
Kinematic and geometrical acceptance for the extrapolation from the fiducial to the total volume, i.e. efficiency of phase space cuts Simulated by MC generators

Detector and trigger acceptances and efficiencies, lepton reconstruction, missing phase space regions in the detector geometry, non-prompt leptons,...

- The above extrapolation requires a full control of the theory prediction and a robust assessment of the uncertainties associated with the MC generators in the fiducial region. Do we really understand so well the used tools ?
- Need to avoid that MC tool-dependent (e.g. shower, tune,...) effects propagate into the extrapolated total cross section

Possible theoretical issues

- Similar extrapolation methods from a fiducial to the total volume are used in other di-boson $(WZ, ZZ, Z\gamma, W\gamma)$ measurements, whose results are all consistent with the corresponding Standard Model predictions
- What's special in the WW channel ?
  - Unlike for other di-boson analyses, the WW fiducial volume requires a veto on extra jet activity, i.e. neglect events containing at least a jet with $p_{t,j} > p_{t,\mathrm{veto}}$
  - A jet veto is a necessary evil to suppress the large background due to top-pair production, leading to a sizeable loss of signal events



[ATLAS-CONF-2014-033]

Channels	$e\mu$	ee	$\mu\mu$
$m_{ll} > 10/15/15$ GeV	83042	4918726	8357583
$\lvert m_{ll} - m_Z \rvert > 0/15/15$ GeV	83042	412853	721978
$E_{\mathrm{T,\,Rel}}^{\mathrm{miss}} > 15/45/45$ GeV	52142	11594	19887
$p_{\mathrm{T}}^{\mathrm{miss}} > 20/45/45$ GeV	43718	5762	9152
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}}) < 0.6/0.3/0.3$	27591	2613	4291
Jet-veto requirement	5067	594	975

Theory status - fixed order

- At the fiducial level, a comparison to the NLO prediction (also including the NNLO channel $gg \to WW$) does not show any significant excess

MCFM

	ATLAS @ 8 TeV	$pp \to l^+l^-\nu\bar{\nu}$	$pp \to H \to l^+l^-\nu\bar{\nu}$	total
$e^+\mu^- + e^-\mu^+$	$377.8^{+6.9}_{-6.8}$(stat.)$^{+25.1}_{-22.2}$(syst.)$^{+11.4}_{-10.7}$(lumi.)	$332.4^{+4.7}_{-2.3}$	$9.8^{+0.0}_{-1.2}$	$342.2^{+4.7}_{-2.6}$
e^+e^-	$68.5^{+4.2}_{-4.1}$(stat.)$^{+7.7}_{-6.6}$(syst.)$^{+2.1}_{-2.0}$(lumi.)	$63.7^{+0.8}_{-0.4}$	$2.2^{+0.0}_{-0.2}$	$65.9^{+0.8}_{-0.4}$
$\mu^+\mu^-$	$74.4^{+3.3}_{-3.2}$(stat.)$^{+7.0}_{-6.0}$(syst.)$^{+2.3}_{-2.1}$(lumi.)	$69.3^{+0.9}_{-0.4}$	$2.4^{+0.0}_{-0.2}$	$71.7^{+0.9}_{-0.5}$

- NLO EW / NNLL threshold effects lead to a 2-3% correction at these energies

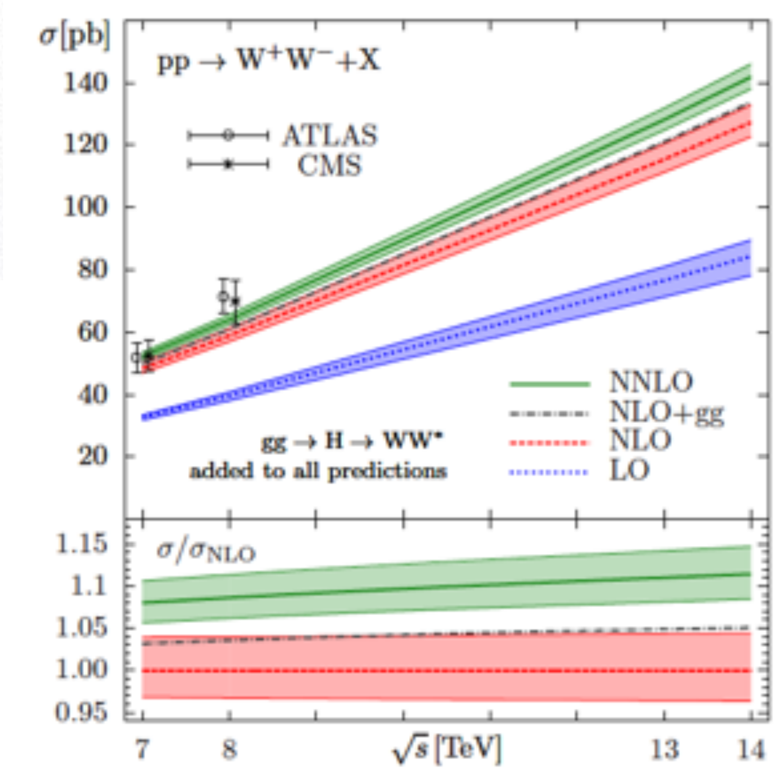
[Dawson et al. 1307.3249; Bierweiler et al. 1208.3147]

- NNLO corrections to the total cross section recently computed (not available yet for the fiducial cross section)

[Gehrmann et al. 1408.5243]

See M. Grazzini's talk

$\frac{\sqrt{s}}{\text{TeV}}$	σ_{LO}	σ_{NLO}	σ_{NNLO}	$\sigma_{gg\to H\to WW^*}$
7	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$	$3.25^{+7.1\%}_{-7.8\%}$
8	$35.50^{+2.4\%}_{-3.5\%}$	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$	$4.14^{+7.2\%}_{-7.8\%}$
13	$67.16^{+5.5\%}_{-6.7\%}$	$106.0^{+4.1\%}_{-3.2\%}$	$118.7^{+2.5\%}_{-2.2\%}$	$9.44^{+7.4\%}_{-7.9\%}$
14	$73.74^{+5.9\%}_{-7.2\%}$	$116.7^{+4.1\%}_{-3.3\%}$	$131.3^{+2.6\%}_{-2.2\%}$	$10.64^{+7.5\%}_{-8.0\%}$



Theory status - fixed order

- At the fiducial level, a comparison to the NLO prediction (also including the NNLO channel $gg \to WW$) does not show any significant excess

MCFM

	ATLAS @ 8 TeV	$pp \to l^+l^-\nu\bar{\nu}$	$pp \to H \to l^+l^-\nu\bar{\nu}$	total
$e^+\mu^- + e^-\mu^+$	$377.8^{+6.9}_{-6.8}$(stat.)$^{+25.1}_{-22.2}$(syst.)$^{+11.4}_{-10.7}$(lumi.)	$332.4^{+4.7}_{-2.3}$	$9.8^{+0.0}_{-1.2}$	$342.2^{+4.7}_{-2.6}$
e^+e^-	$68.5^{+4.2}_{-4.1}$(stat.)$^{+7.7}_{-6.6}$(syst.)$^{+2.1}_{-2.0}$(lumi.)	$63.7^{+0.8}_{-0.4}$	$2.2^{+0.0}_{-0.2}$	$65.9^{+0.8}_{-0.4}$
$\mu^+\mu^-$	$74.4^{+3.3}_{-3.2}$(stat.)$^{+7.0}_{-6.0}$(syst.)$^{+2.3}_{-2.1}$(lumi.)	$69.3^{+0.9}_{-0.4}$	$2.4^{+0.0}_{-0.2}$	$71.7^{+0.9}_{-0.5}$

- NLO EW / NNLL threshold effects lead to a 2-3% correction at these energies

[Dawson et al. 1307.3249; Bierweiler et al. 1208.3147]

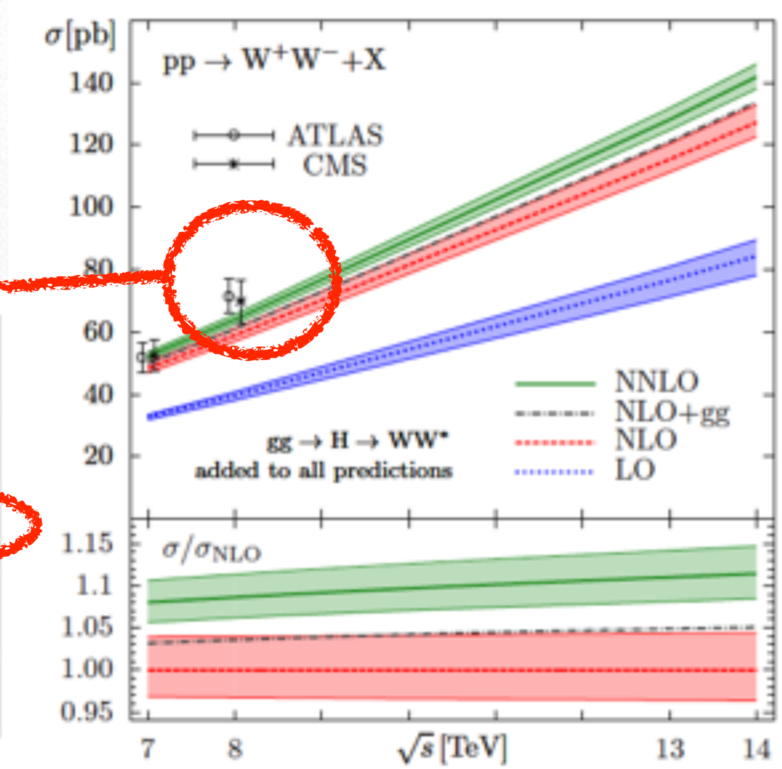
- NNLO corrections to the total cross section recently computed (not available yet for the fiducial cross section)

[Gehrmann et al. 1408.5243]

See M. Grazzini's talk

Still a ~ 1σ tension in ATLAS at 8 TeV

$\sqrt{s}$ TeV	σ_{LO}	σ_{NLO}	σ_{NNLO}	$\sigma_{gg\to H\to WW^*}$
7	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}$ [illegible]	$3.25^{+7.1\%}_{-7.8\%}$
8	$35.50^{+2.4\%}_{-3.5\%}$	54.77 [illegible]	$59.84^{+2.2\%}_{-1.9\%}$	$4.14^{+7.2\%}_{-7.8\%}$
13	$67.16^{+5.5\%}_{-6.7\%}$	$106.0^{+4.1\%}_{-3.2\%}$	$118.7^{+2.5\%}_{-2.2\%}$	$9.44^{+7.4\%}_{-7.9\%}$
14	$73.74^{+5.9\%}_{-7.2\%}$	$116.7^{+4.1\%}_{-3.3\%}$	$131.3^{+2.6\%}_{-2.2\%}$	$10.64^{+7.5\%}_{-8.0\%}$



Resummation effects

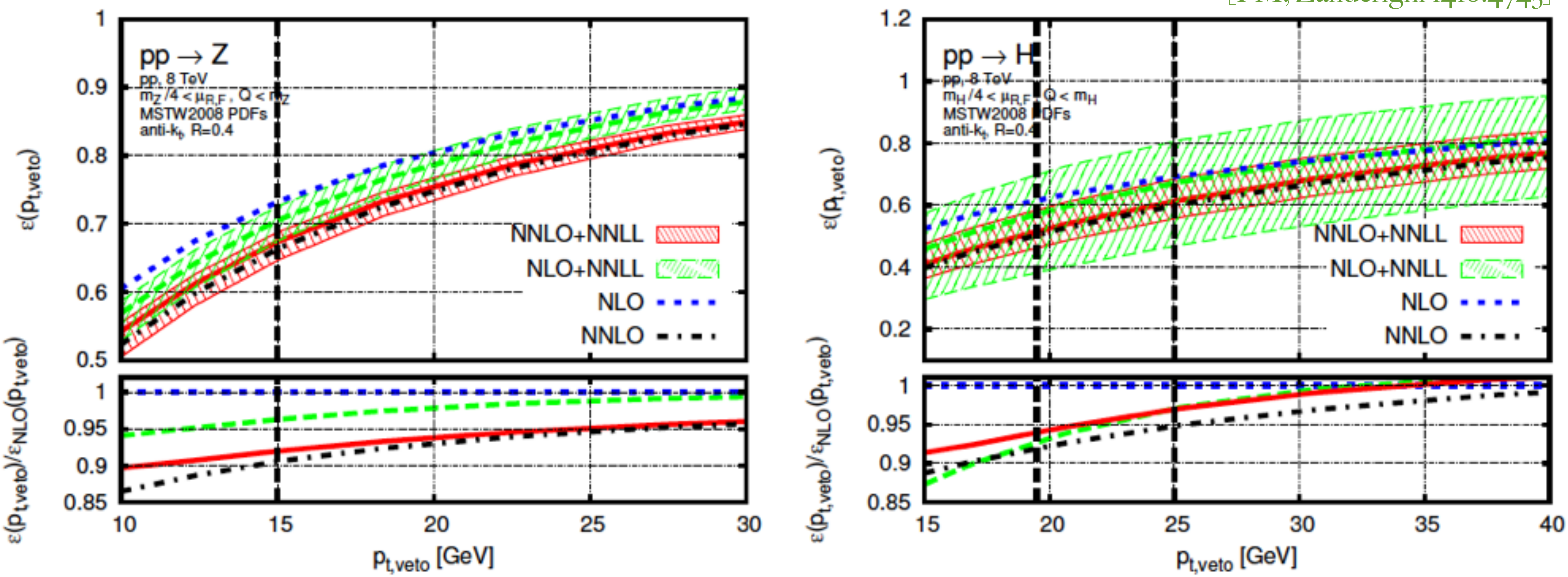
- In ATLAS analysis @ 8 TeV - fiducial signal simulated with:
  - POWHEG + Pythia for $q\bar{q} \to WW$ (9-11% suppression w.r.t. NLO result)
    [Melia et al. 1107.5051; Nason et al. 1311.1365]
  - GG2WW + Herwig for $gg \to WW$
    [Kauer, Passarino 1206.4803; Kauer 1310.7011]
- NNLL corrections known for $q\bar{q} \to WW$ only and matched to NLO
  [Jaiswal, Okui 1407.4537]

- Higher-order (NNLL+NNLO) corrections in the JVE can be estimated by looking at processes with similar radiation patterns
- e.g. for the jet veto efficiency in the $q\bar{q} \to WW$ channel, we can extract resummation effects from the Z production analysis
  - same initial state colour structure at Born level (quark initiated)
  - at sufficiently small $p_{t,\mathrm{veto}}$ Sudakov effects dominate the efficiency, and hard physics effects (virtual corrections, parton luminosities, EW parameters) largely cancel in the efficiency
  - In this phase space region, the only difference is the hard scale in the logs
- Similarly, effects in the efficiency for $gg \to WW$ can be estimated from Higgs production

Estimate of higher order and resummation effects

- An estimate of higher orders (NNLL+NNLO) corrections to the efficiency can be extracted from Z and H production

[PM, Zanderighi 1410.4745]



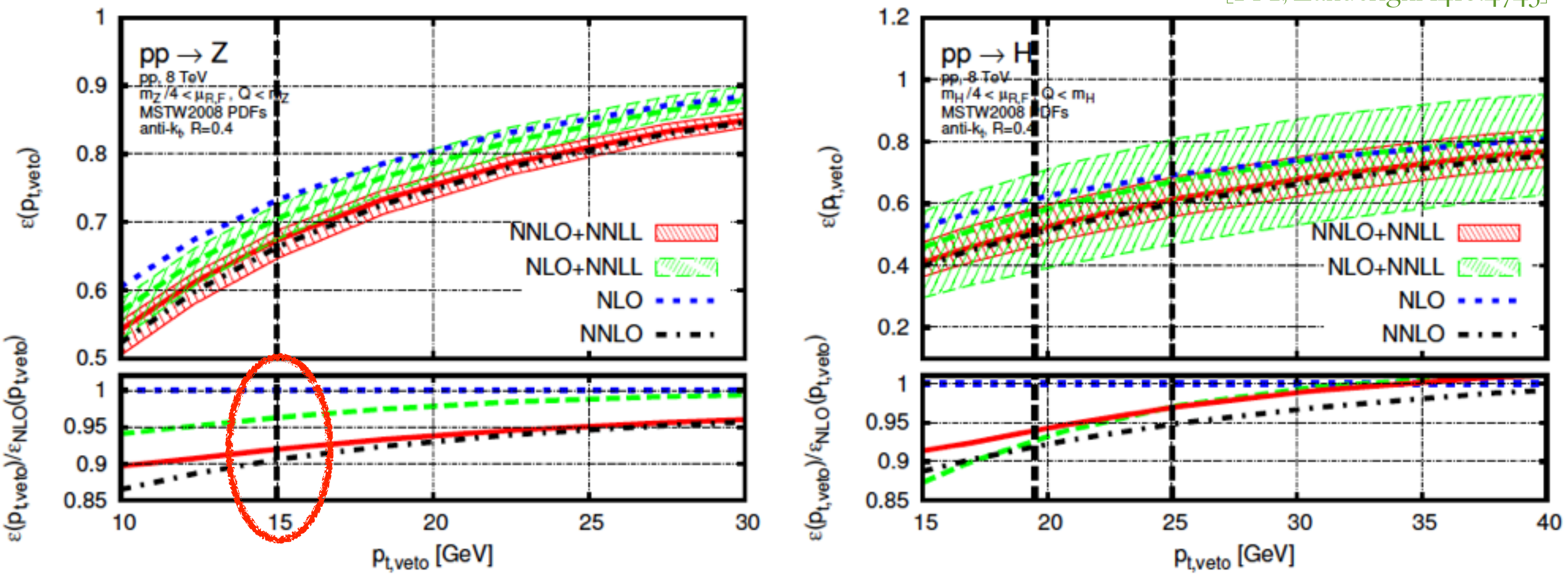
- Where, for the three contributing channels:

$q\bar{q} \to WW$ $\qquad$ $gg \to WW$ $\qquad$ $gg \to H \to WW$

$$p_{t,\mathrm{veto}}^{Z} = \frac{M_Z}{2M_W} p_{t,\mathrm{veto}}^{WW} \sim 15\,\mathrm{GeV} \qquad p_{t,\mathrm{veto}}^{H} = \frac{M_H}{2M_W} p_{t,\mathrm{veto}}^{WW} \sim 19.5\,\mathrm{GeV} \qquad p_{t,\mathrm{veto}}^{H} = 25\,\mathrm{GeV}$$

- An estimate of higher orders (NNLL+NNLO) corrections to the efficiency can be extracted from Z and H production

[PM, Zanderighi 1410.4745]



- Where, for the three contributing channels:

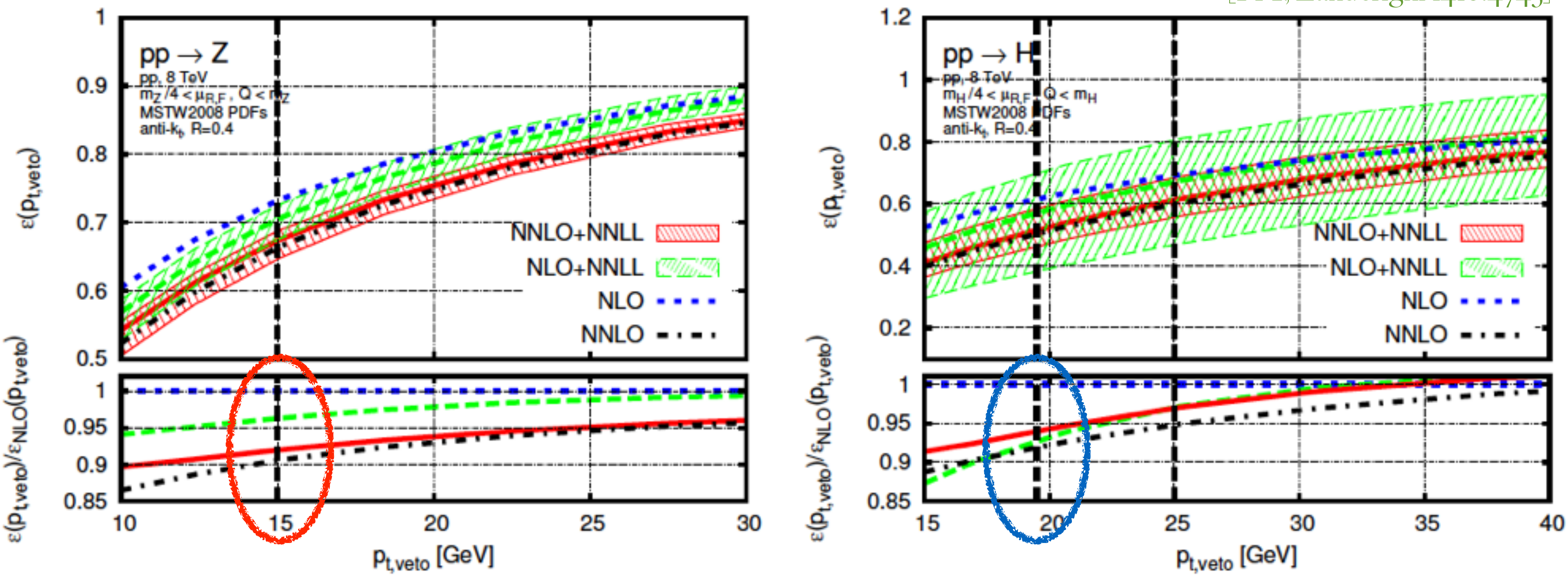
$q\bar{q} \to WW$ $\qquad gg \to WW$ $\qquad gg \to H \to WW$

$$p_{t,\mathrm{veto}}^{Z} = \frac{M_Z}{2M_W} p_{t,\mathrm{veto}}^{WW} \sim 15\,\mathrm{GeV} \qquad p_{t,\mathrm{veto}}^{H} = \frac{M_H}{2M_W} p_{t,\mathrm{veto}}^{WW} \sim 19.5\,\mathrm{GeV} \qquad p_{t,\mathrm{veto}}^{H} = 25\,\mathrm{GeV}$$

Estimate of higher order and resummation effects

- An estimate of higher orders (NNLL+NNLO) corrections to the efficiency can be extracted from Z and H production

[PM, Zanderighi 1410.4745]



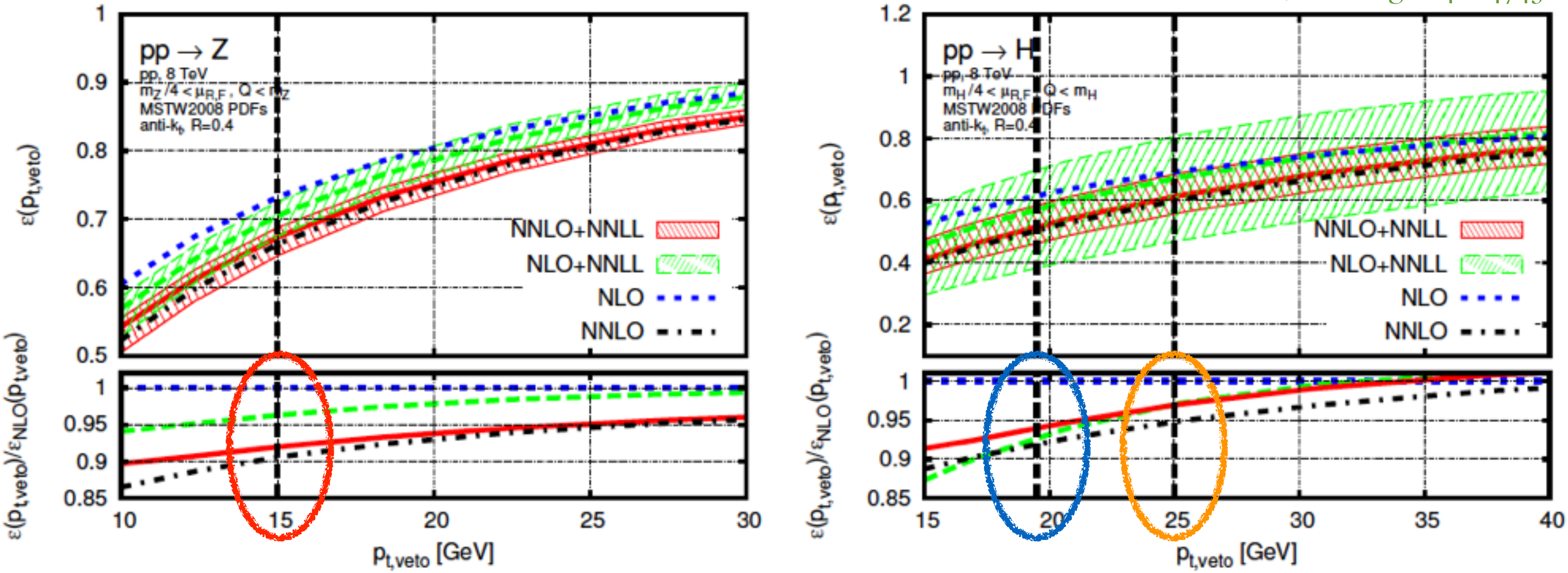
- Where, for the three contributing channels:

$q\bar{q} \to WW$	$gg \to WW$	$gg \to H \to WW$
$p^Z_{t,\rm veto} = \frac{M_Z}{2M_W} p^{WW}_{t,\rm veto} \sim 15\,\mathrm{GeV}$	$p^H_{t,\rm veto} = \frac{M_H}{2M_W} p^{WW}_{t,\rm veto} \sim 19.5\,\mathrm{GeV}$	$p^H_{t,\rm veto} = 25\,\mathrm{GeV}$

Estimate of higher order and resummation effects

- An estimate of higher orders (NNLL+NNLO) corrections to the efficiency can be extracted from Z and H production

[PM, Zanderighi 1410.4745]



- Where, for the three contributing channels:

$q\bar{q} \to WW$

$$p_{t,\text{veto}}^{Z} = \frac{M_Z}{2M_W} p_{t,\text{veto}}^{WW} \sim 15\,\text{GeV}$$

$gg \to WW$

$$p_{t,\text{veto}}^{H} = \frac{M_H}{2M_W} p_{t,\text{veto}}^{WW} \sim 19.5\,\text{GeV}$$

$gg \to H \to WW$

$$p_{t,\text{veto}}^{H} = 25\,\text{GeV}$$

- The enhancement due to the NNLO K factor is balanced by the Sudakov suppression in the fiducial cross section. The combined effect amounts to a moderate enhancement with respect to the NLO result
- Assuming that lepton efficiencies are not significantly affected by higher order corrections

$$\sigma^{\mathrm{th.}}_{\mathrm{fid.}} = \sum_{c\,\in\,\mathrm{channel}} \sigma^{(c),\mathrm{NLO}}_{\mathrm{fid.}} \times \frac{\epsilon^{(c),\mathrm{NNLL+NNLO}}(p^{(c)}_{\mathrm{t,veto}})}{\epsilon^{(c),\mathrm{NLO}}(p^{(c)}_{\mathrm{t,veto}})} \times \frac{\sigma^{(c),\mathrm{NNLO}}_{\mathrm{incl.}}}{\sigma^{(c),\mathrm{NLO}}_{\mathrm{incl.}}}$$

MCFM (assume NNLO does not change lepton acceptances)

As above

[Gehrmann et al. 1408.5243]

decay mode	$\sigma^{\mathrm{exp.}}_{\mathrm{fid.}}$ [fb]	$\sigma^{\mathrm{th.}}_{\mathrm{fid.}}$ [fb]
$e^+\mu^- + e^-\mu^+$	$377.8^{+6.9}_{-6.8}(\mathrm{stat.})^{+25.1}_{-22.2}(\mathrm{syst.})^{+11.4}_{-10.7}(\mathrm{lumi.})$	$357.9^{+14.4}_{-14.4}$
e^+e^-	$68.5^{+4.2}_{-4.1}(\mathrm{stat.})^{+7.7}_{-6.6}(\mathrm{syst.})^{+2.1}_{-2.0}(\mathrm{lumi.})$	$69.0^{+2.7}_{-2.7}$
$\mu^+\mu^-$	$74.4^{+3.3}_{-3.2}(\mathrm{stat.})^{+7.0}_{-6.0}(\mathrm{syst.})^{+2.3}_{-2.1}(\mathrm{lumi.})$	$75.1^{+3.0}_{-3.0}$

[PM, Zanderighi 1410.4745]

Uncertainties combined in quadrature

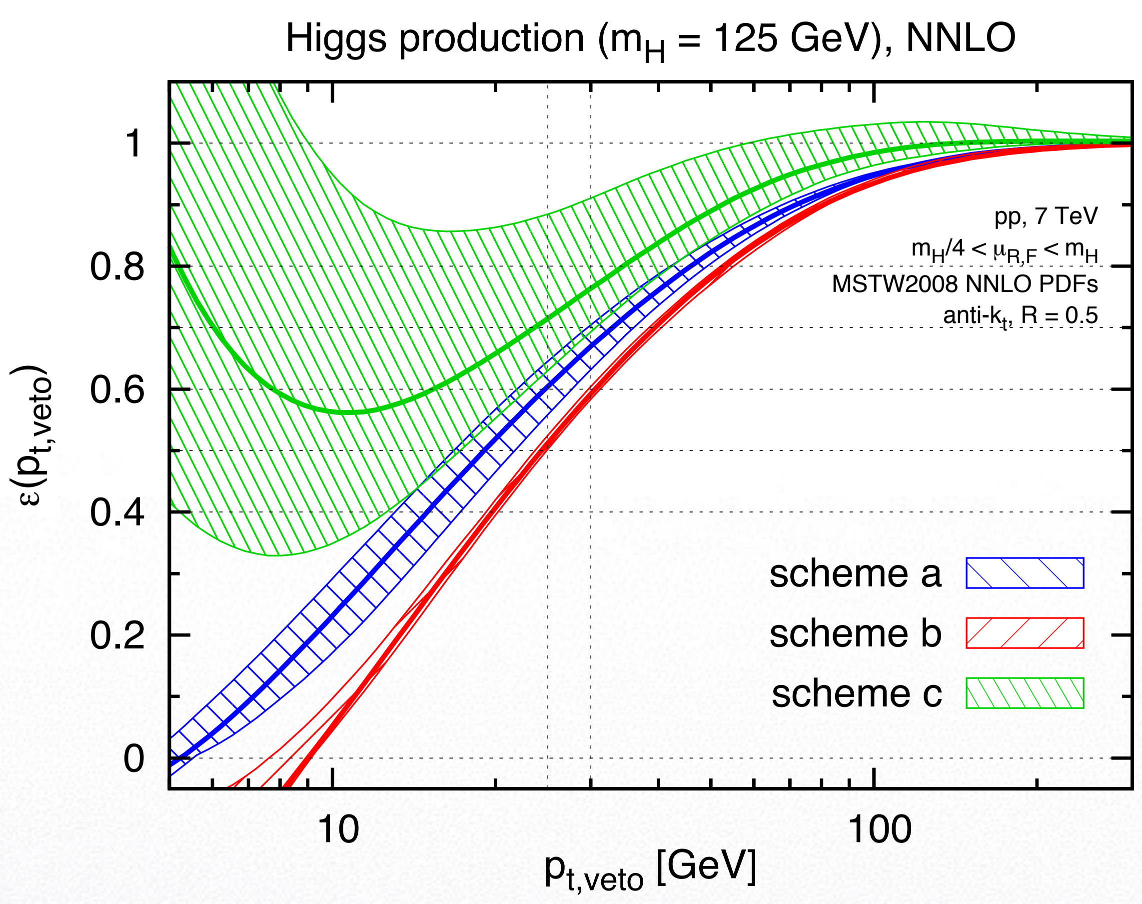
- Good agreement at the fiducial level.
- Carefull assessment of uncertainties necessary

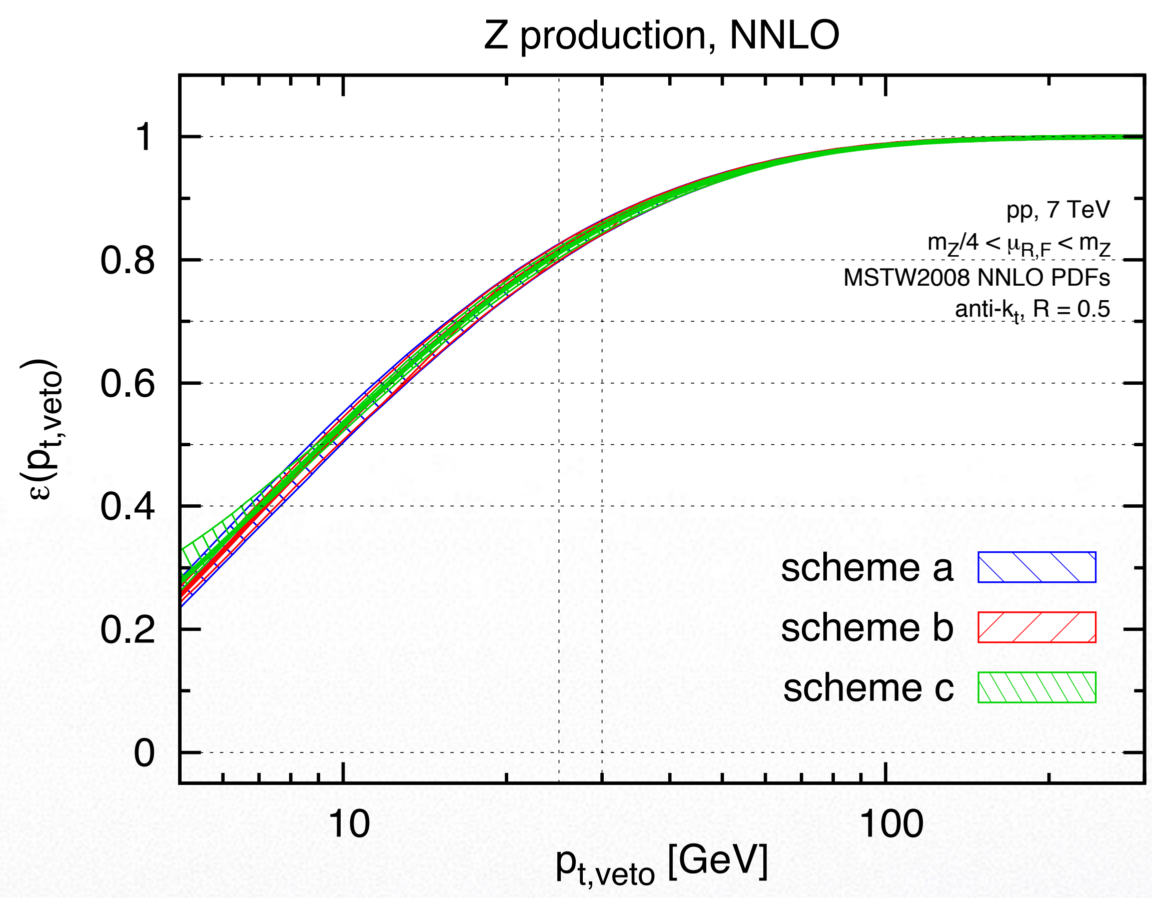
Summary WW production

- The discrepancy between the measured total cross section and the NLO prediction for ATLAS@8TeV is due to the MC generator used in the extrapolation procedure
    - Initial tension due to slightly underestimated JVE in POWHEG+Pythia and missing NNLO effects (see backup slides)
      [Meade, Ramani, Zeng 1407.4481; Jaiswal, Okui 1407.4537; PM, Zanderighi 1410.4745]
- For an extrapolation to be performed, a good understanding of the MC tools used, and a robust assessment of the uncertainties associated with them is required
- The (estimated) NNLL+NNLO corrections to the fiducial cross section bring the prediction in better agreement with measured data. The resulting extrapolated total cross section is in agreement with the NNLO prediction
- Full NNLL+NNLO analysis for all contributing channels desirable, now possible
- Similar effects could be present in some data-driven background estimates

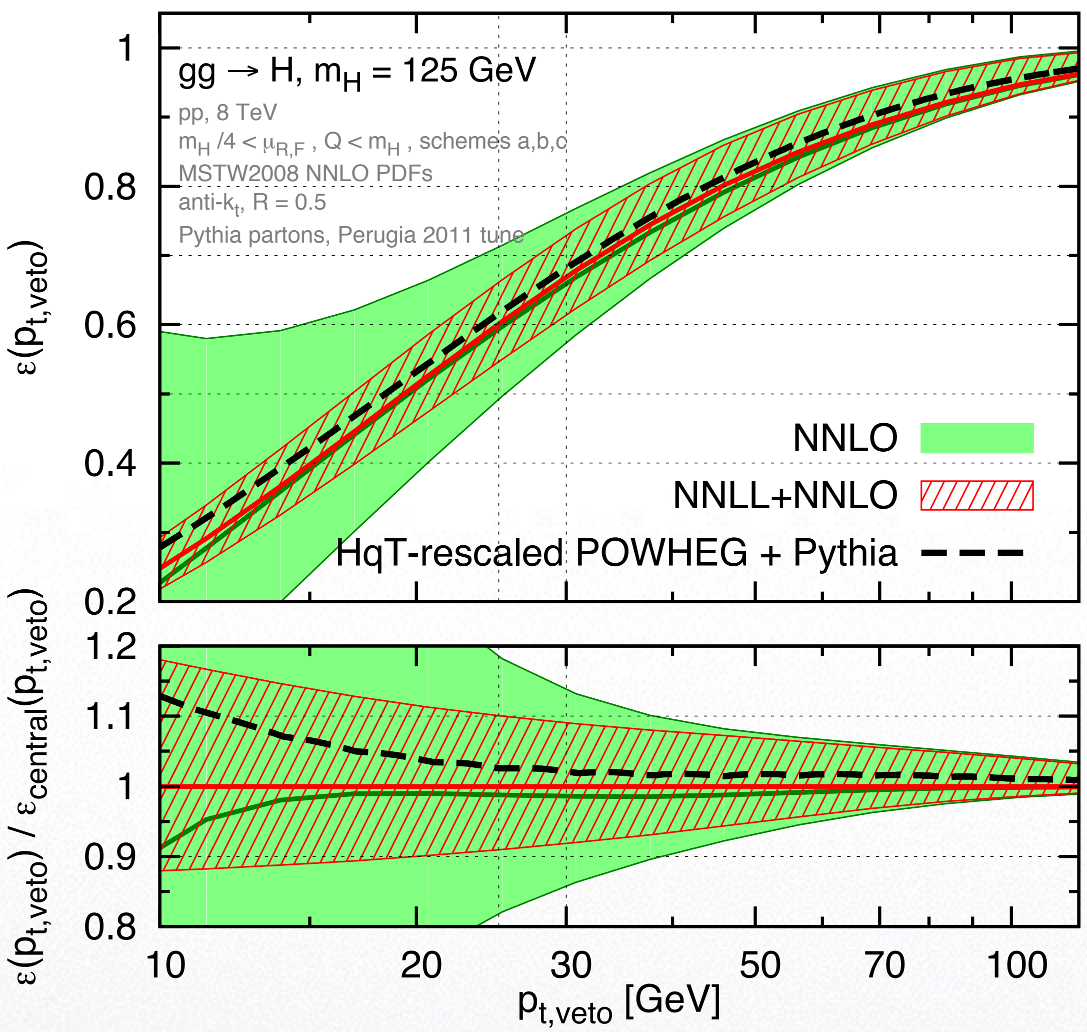
Back up slides

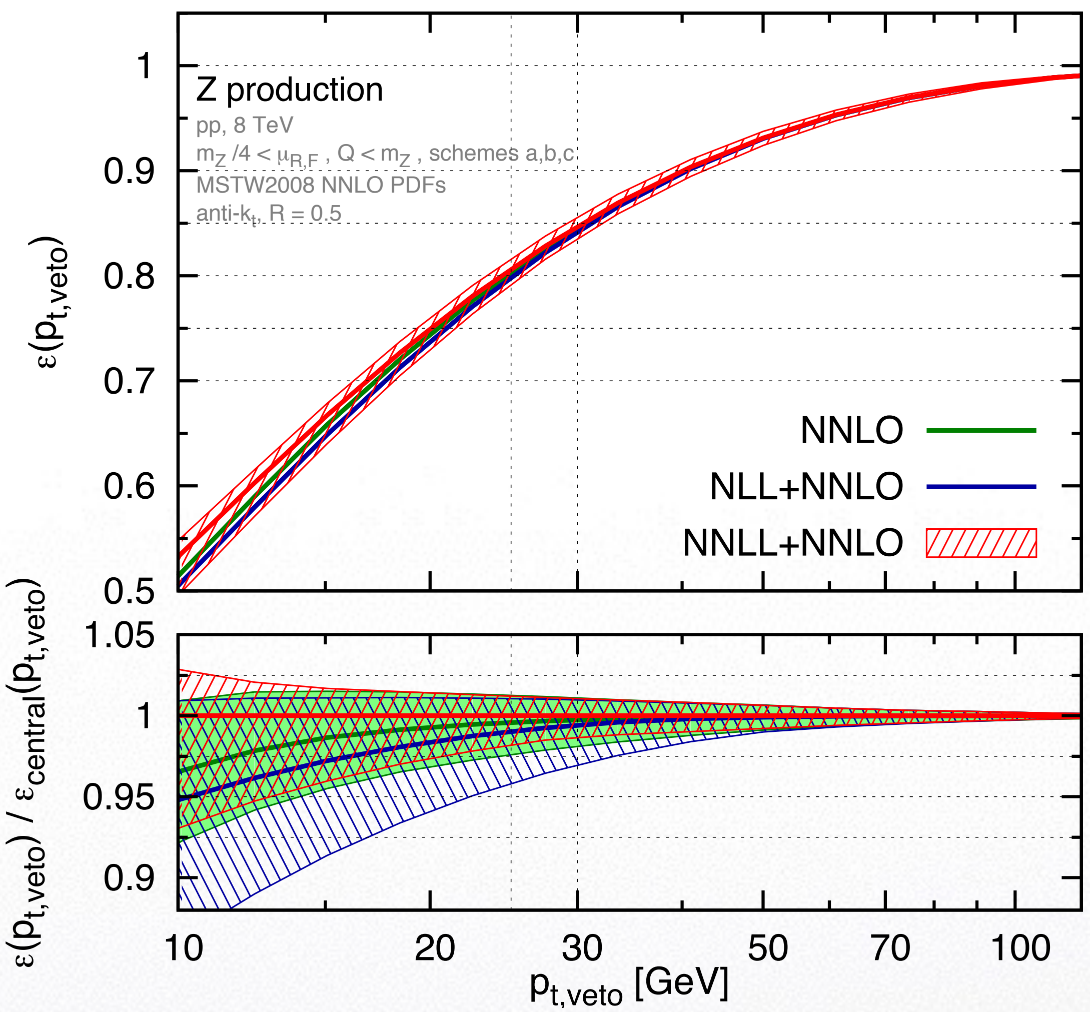
zero-jet efficiency at NNLO





- Large spread in the Higgs case (much radiation constrained, important Sudakov effects). Large uncertainty !
- Different schemes agree in the DY case (less QCD radiation, good convergence of the PT series)





- Uncertainty in the efficiency considerably reduced by resummation
- Central value in agreement with FO for $p_{t,\mathrm{veto}} \geq 20\,\mathrm{GeV}$

Jet veto treatment in WW experimental analyses

- The effect of the jet veto is simulated by computing a jet veto efficiency $\epsilon_{WW}^{\mathrm{MC}}$ with a number of tools (POWHEG+Pythia, MC@NLO + Herwig/Pythia, MadGraph + Pythia), and rescaling it with the ratio of data to MC jet veto efficiency for $Z/\gamma* \to \ell\ell$ with fiducial lepton selection criteria

$$\epsilon_{\mathrm{pred}}^{WW} = \frac{\epsilon_{Z/\gamma*}^{\mathrm{data}}}{\epsilon_{Z/\gamma*}^{\mathrm{MC}}} \epsilon_{WW}^{\mathrm{MC}}$$

- Jet veto efficiency is a problematic quantity, a misestimate could affect the extrapolation
- Is the MC jet veto efficiency fully reliable ?

Jet veto treatment in WW experimental analyses

- The effect of the jet veto is simulated by computing a jet veto efficiency $\epsilon_{WW}^{\mathrm{MC}}$ with a number of tools (POWHEG + Pythia, MC@NLO + Herwig/Pythia, MadGraph + Pythia), and rescaling it with the ratio of data to MC jet veto efficiency for $Z/\gamma* \to \ell\ell$ with fiducial lepton selection criteria

$$\epsilon_{\mathrm{pred}}^{WW} = \frac{\epsilon_{Z/\gamma*}^{\mathrm{data}}}{\epsilon_{Z/\gamma*}^{\mathrm{MC}}} \epsilon_{WW}^{\mathrm{MC}}$$

The correction factor reduces the experimental uncertainties due to Jet Energy Scale/Resolution

- Jet veto efficiency is a problematic quantity, a misestimate could affect the extrapolation
- Is the MC jet veto efficiency fully reliable ?

Jet veto treatment in WW experimental analyses

- The effect of the jet veto is simulated by computing a jet veto efficiency $\epsilon_{WW}^{\text{MC}}$ with a number of tools (POWHEG + Pythia, MC@NLO + Herwig/Pythia, MadGraph + Pythia), and rescaling it with the ratio of data to MC jet veto efficiency for $Z/\gamma* \to \ell\ell$ with fiducial lepton selection criteria

$$\epsilon_{\text{pred}}^{WW} = \frac{\epsilon_{Z/\gamma*}^{\text{data}}}{\epsilon_{Z/\gamma*}^{\text{MC}}} \epsilon_{WW}^{\text{MC}}$$

The correction factor reduces the experimental uncertainties due to Jet Energy Scale/Resolution

However, theory uncertainties in the ratio of two MC quantities could be hard to assess, and this could compromise the above reduction

- Jet veto efficiency is a problematic quantity, a misestimate could affect the extrapolation
- Is the MC jet veto efficiency fully reliable ?

Overview of results for ATLAS & CMS

- Fiducial signal efficiency simulated with different generators for the (dominant) $q\bar{q} \to WW$ channel*

$\sqrt{s}$	ATLAS (fiducials below) σ [pb]	CMS (no fiducials) σ [pb]	Theory (MCFM) σ [pb]
7 TeV	$51.9^{+2.0+3.9+2.0}_{-2.0-3.9-2.0}$ [13]	$52.4^{+2.0+4.5+1.2}_{-2.0-4.5-1.2}$ [14]	$47.04^{+2.02+0.90}_{-1.51-0.66}$
8 TeV	$71.4^{+1.2+5.0+2.2}_{-1.2-4.4-2.1}$ [15]	$69.9^{+2.8+5.6+3.1}_{-2.8-5.6-3.1}$ [16]	$57.25^{+2.35+1.09}_{-1.60-0.80}$

[13] ATLAS @ 7 TeV : MC@NLO + Herwig ++
[14] CMS @ 7 TeV: MadGraph + Pythia
[15] ATLAS @ 8 TeV : POWHEG + Pythia
[16] CMS @ 8 TeV: MadGraph + Pythia

ATLAS @ 7 TeV

	Measured σ^{fid}_{WW} (fb)	Predicted σ^{fid}_{WW} (fb)	Measured σ_{WW} (pb)	Predicted σ_{WW} (pb)
ee	$56.4 \pm 6.8 \pm 9.8 \pm 2.2$	54.6 ± 3.7	$46.9 \pm 5.7 \pm 8.2 \pm 1.8$	$44.7^{+2.1}_{-1.9}$
$\mu\mu$	$73.9 \pm 5.9 \pm 6.9 \pm 2.9$	58.9 ± 4.0	$56.7 \pm 4.5 \pm 5.5 \pm 2.2$	$44.7^{+2.1}_{-1.9}$
$e\mu$	$262.3 \pm 12.3 \pm 20.7 \pm 10.2$	231.4 ± 15.7	$51.1 \pm 2.4 \pm 4.2 \pm 2.0$	$44.7^{+2.1}_{-1.9}$
Combined	...	...	$51.9 \pm 2.0 \pm 3.9 \pm 2.0$	$44.7^{+2.1}_{-1.9}$

ATLAS @ 8 TeV

Channel	$\sigma^{\text{fiducial}}_{WW}$ [fb]
$e\mu$	$377.8^{+6.9}_{-6.8}$ (stat) $^{+25.1}_{-22.2}$ (syst) $^{+11.4}_{-10.7}$ (lumi)
ee	$68.5^{+4.2}_{-4.1}$ (stat) $^{+7.7}_{-6.6}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
$\mu\mu$	$74.4^{+3.3}_{-3.2}$ (stat) $^{+7.0}_{-6.0}$ (syst) $^{+2.3}_{-2.1}$ (lumi)

Channel	$\sigma^{\text{total}}_{WW}$ [pb]
$e\mu$	$71.4^{+1.3}_{-1.3}$ (stat) $^{+5.0}_{-4.4}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
ee	$68.6^{+4.2}_{-4.1}$ (stat) $^{+7.8}_{-6.7}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
$\mu\mu$	$68.6^{+3.1}_{-3.0}$ (stat) $^{+6.6}_{-5.6}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
Combined	$71.4^{+1.2}_{-1.2}$ (stat) $^{+5.0}_{-4.4}$ (syst) $^{+2.2}_{-2.1}$ (lumi)

* GG2WW everywhere for the $gg \to (H \to) WW$ channels

Overview of results for ATLAS & CMS

- Fiducial signal efficiency simulated with different generators for the (dominant) $q\bar{q} \to WW$ channel*

$\sqrt{s}$	ATLAS (fiducials below) σ [pb]	CMS (no fiducials) σ [pb]	Theory (MCFM) σ [pb]
7 TeV	$51.9^{+2.0+3.9+2.0}_{-2.0-3.9-2.0}$ [13]	$52.4^{+2.0+4.5+1.2}_{-2.0-4.5-1.2}$ [14]	$47.04^{+2.02+0.90}_{-1.51-0.66}$
8 TeV	$71.4^{+1.2+5.0+2.2}_{-1.2-4.4-2.1}$ [15]	$69.9^{+2.8+5.6+3.1}_{-2.8-5.6-3.1}$ [16]	$57.25^{+2.35+1.09}_{-1.60-0.80}$

[13] ATLAS @ 7 TeV : MC@NLO + Herwig + +
[14] CMS @ 7 TeV: MadGraph + Pythia
[15] ATLAS @ 8 TeV : POWHEG + Pythia
[16] CMS @ 8 TeV: MadGraph + Pythia

ATLAS @ 7 TeV

	Measured σ^{fid}_{WW} (fb)	Predicted σ^{fid}_{WW} (fb)	Measured σ_{WW} (pb)	Predicted σ_{WW} (pb)
ee	$56.4 \pm 6.8 \pm 9.8 \pm 2.2$	54.6 ± 3.7	$46.9 \pm 5.7 \pm 8.2 \pm 1.8$	$44.7^{+2.1}_{-1.9}$
$\mu\mu$	$73.9 \pm 5.9 \pm 6.9 \pm 2.9$	58.9 ± 4.0	$56.7 \pm 4.5 \pm 5.5 \pm 2.2$	$44.7^{+2.1}_{-1.9}$
$e\mu$	$262.3 \pm 12.3 \pm 20.7 \pm 10.2$	231.4 ± 15.7	$51.1 \pm 2.4 \pm 4.2 \pm 2.0$	$44.7^{+2.1}_{-1.9}$
Combined	…	…	$51.9 \pm 2.0 \pm 3.9 \pm 2.0$	$44.7^{+2.1}_{-1.9}$

ATLAS @ 8 TeV

Channel	$\sigma^{\text{fiducial}}_{WW}$ [fb]
$e\mu$	$377.8^{+6.9}_{-6.8}$ (stat) $^{+25.1}_{-22.2}$ (syst) $^{+11.4}_{-10.7}$ (lumi)
ee	$68.5^{+4.2}_{-4.1}$ (stat) $^{+7.7}_{-6.6}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
$\mu\mu$	$74.4^{+3.3}_{-3.2}$ (stat) $^{+7.0}_{-6.0}$ (syst) $^{+2.3}_{-2.1}$ (lumi)

Channel	$\sigma^{\text{total}}_{WW}$ [pb]
$e\mu$	$71.4^{+1.3}_{-1.3}$ (stat) $^{+5.0}_{-4.4}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
ee	$68.6^{+4.2}_{-4.1}$ (stat) $^{+7.8}_{-6.7}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
$\mu\mu$	$68.6^{+3.1}_{-3.0}$ (stat) $^{+6.6}_{-5.6}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
Combined	$71.4^{+1.2}_{-1.2}$ (stat) $^{+5.0}_{-4.4}$ (syst) $^{+2.2}_{-2.1}$ (lumi)

Larger discrepancy with NLO.
Let's focus on this for a while…

* GG2WW everywhere for the $gg \to (H \to)WW$ channels

Effect of jet veto in POWHEG + Pythia

- A parton shower matched to NLO is used to resum the relevant logarithms
  - competing effects tend to lower the fiducial cross section (i.e. average number of jets increases, out-of-jet radiation and MPI affect the leading jet's transverse momentum)

e.g. ATLAS 8 TeV fiducial setup - no gg contribution
POWHEG + Pythia 6.4.28 - Perugia tune 350

[PM, Zanderighi 1410.4745]

$pp \to l^+l^-\nu\bar{\nu}$ (no gg)	POWHEG (hadron)	POWHEG (NLO)	ratio
$e^+\mu^- + e^-\mu^+$	$295.2^{+4.8}_{-2.8}$	$323.0^{+6.0}_{-6.5}$	0.91
e^+e^-	$54.8^{+1.7}_{-0.7}$	$61.5^{+1.2}_{-1.3}$	0.89
$\mu^+\mu^-$	$59.5^{+1.7}_{-0.2}$	$66.9^{+1.3}_{-1.6}$	0.89

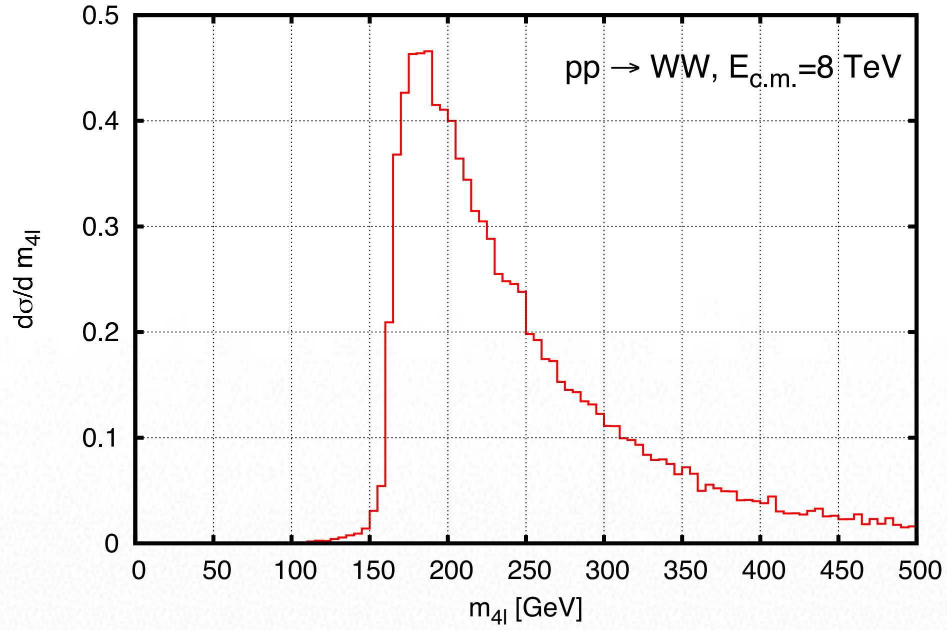
Fiducial cross section reduced by 9-11 %

- Too much suppression for a quark-initiated process with no extra QCD jets at tree level - need to understand where this comes from
- This can be due to a number of effects (e.g. shower tune dependence, uncontrolled sizeable higher order logarithmic effects)
- Need to validate this prediction against exact resummations in a more inclusive phase space region

[Meade, Ramani, Zeng 1407.4481; Jaiswal, Okui 1407.4537; PM, Zanderighi 1410.4745]

Resumation effects

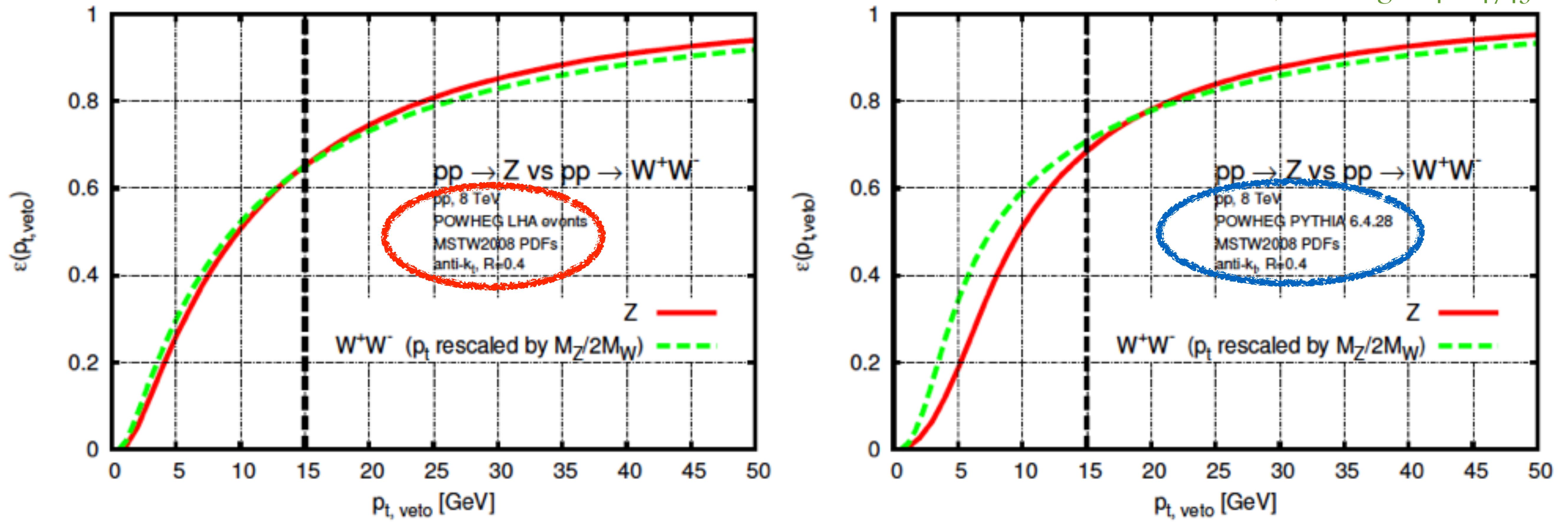
- First observe that the scale which appears in the large logarithms $\ln(M/p_{t,\mathrm{veto}})$ is the invariant mass of the colourless final state system (in general off-shell)



- The invariant mass spectrum is peaked at $M \sim 2M_W$ and steeply falls for higher values
- It is safe to assume that the cross section is dominated by $M \sim 2M_W$ - same applies to Z production with $M \sim M_Z$
- The dynamics in the low $p_{t,\mathrm{veto}}$ region is ruled by the large logarithms, so we can extract information from the DY/H production via the simple rescalings

- This correspondence can be tested in POWHEG itself by performing the rescaling at the Les Houches Events (LHE) level - good agreement at small $p_{t,\mathrm{veto}}$
- Shower and hadronization effects introduce non-logarithmic (perturbative and non-perturbative) effects that spoil the correspondence

[PM, Zanderighi 1410.4745]



- Similarly, effects in the efficiency for $gg \to WW$ can be estimated from Higgs production

- Jet veto efficiency for Z boson production known at NNLL+NNLO

[Banfi, PM, Salam, Zanderighi 1206.4998]

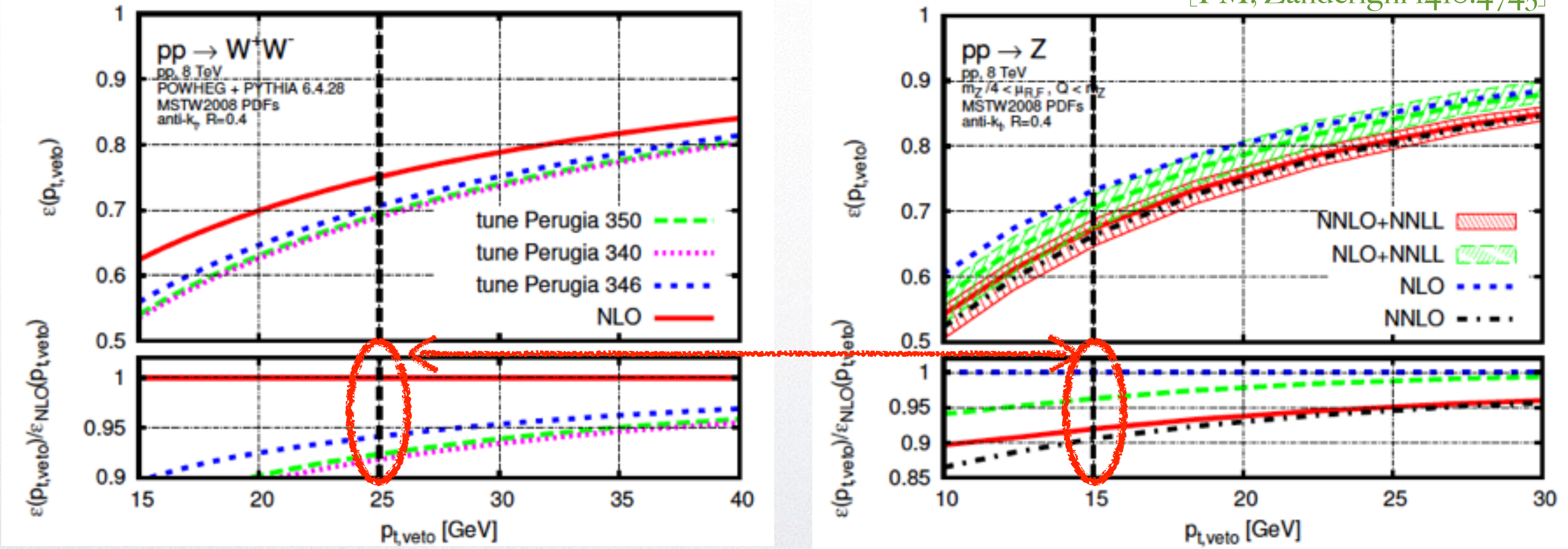
$$\Sigma(p_{\rm t}) = \mathcal{L}(p_{\rm t})|\mathcal{M}_{\rm B}|^2 e^{-R(p_{\rm t})}\mathcal{F}(R') \qquad \mathcal{F}(R') = 1 + \mathcal{O}(\text{NNLL})$$

Sudakov Radiator, virtual corrections and parton luminosities

All-orders soft and collinear real radiation. Describes observable behaviour in the presence of multiple emissions

- Compare to the efficiency for WW obtained with POWHEG in the $q\bar{q} \to WW$ channel

[PM, Zanderighi 1410.4745]



Resummation effects

- comparing to the NLO result, POWHEG + Pythia 's jet veto efficiency is 6-8% smaller (different results with different shower tunes)
- NNLL+NLO efficiency is reduced by 3-4% with respect to the NLO one
- NNLL+NNLO efficiency is reduced by 7-8% with respect to the NLO one

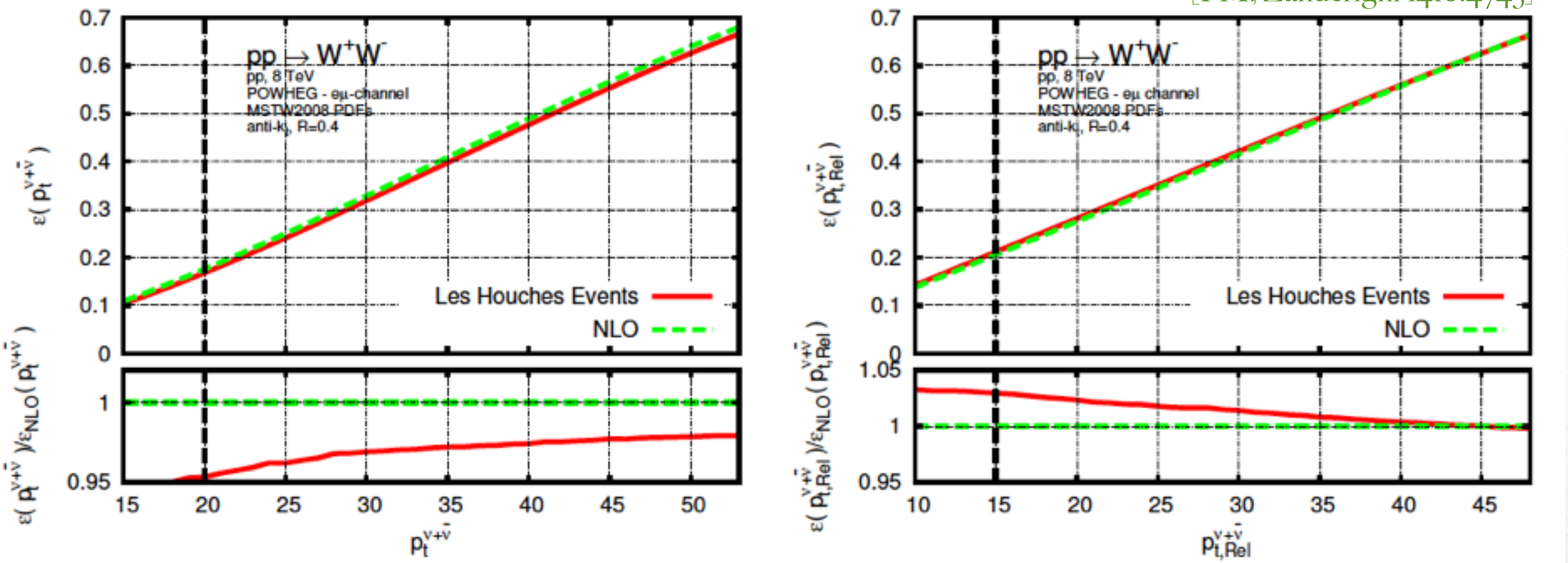
- At current values of the jet veto cut, POWHEG+Pythia accidentally mimics the NNLL +NNLO result for the jet veto efficiency
  - The resulting extrapolation to the inclusive phase space will be in better agreement with the NNLO total cross section

- This effect does not yet explain the 9-11% suppression observed for the fiducial cross section (efficiency) in comparison to NLO

Impact of leptonic cuts

- An extra source of suppression is present in POWHEG and has to do with the way the hardest emission is treated in the matching between NLO and parton shower
- Kinematic distributions of final state leptons change at the LHE level because of higher orders (unphysical ?) effects

[PM, Zanderighi 1410.4745]



- The overall effect amounts to a further 3% reduction of the fiducial cross section, leading to the initial 9-11%

The resulting systematic uncertainty can be studied/reduced by means of the hdamp parameter