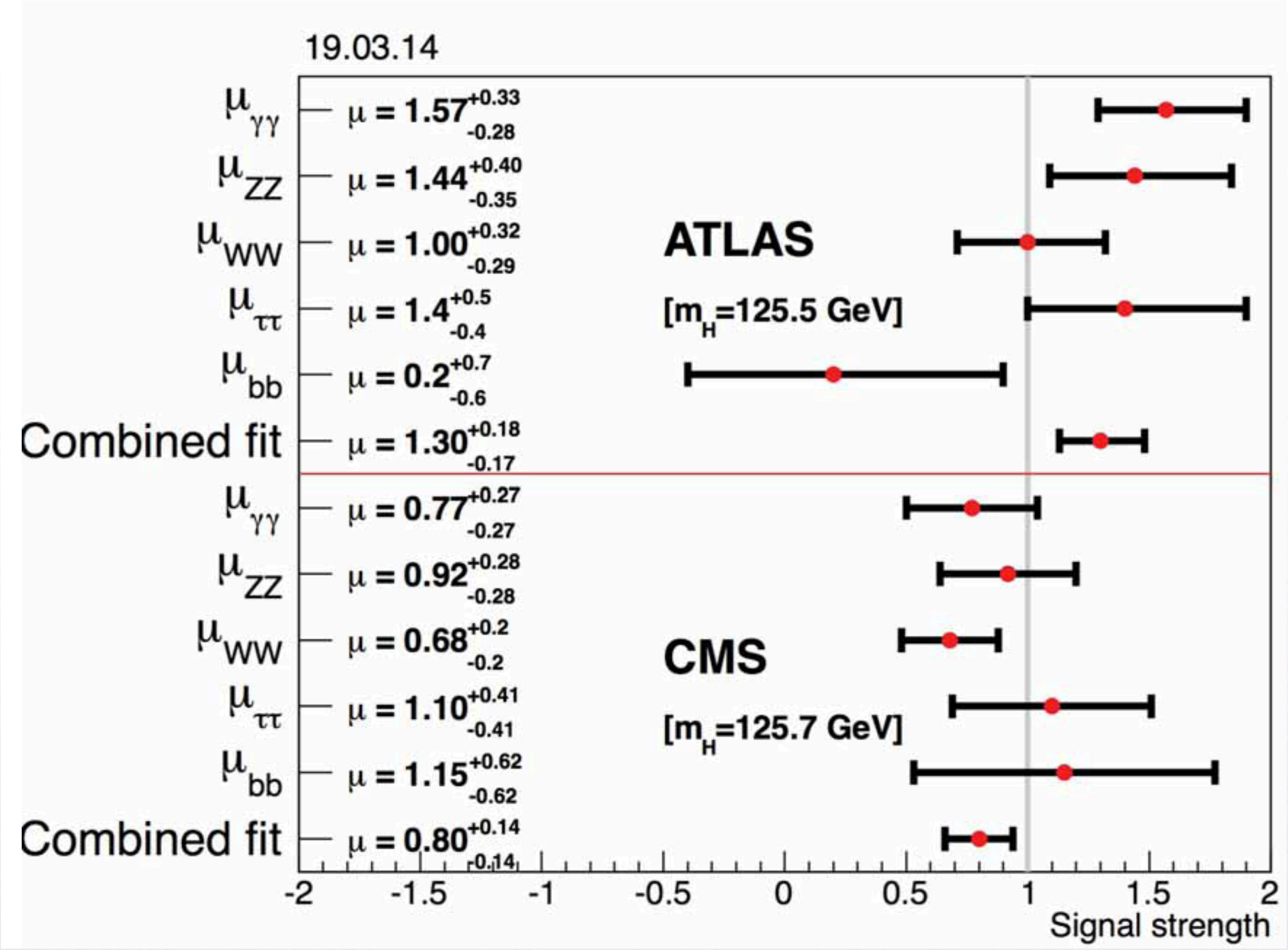
Jet-binning Uncertainties in H+jets

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

LPTHE, Paris 6th June 2014

Vetoing jets

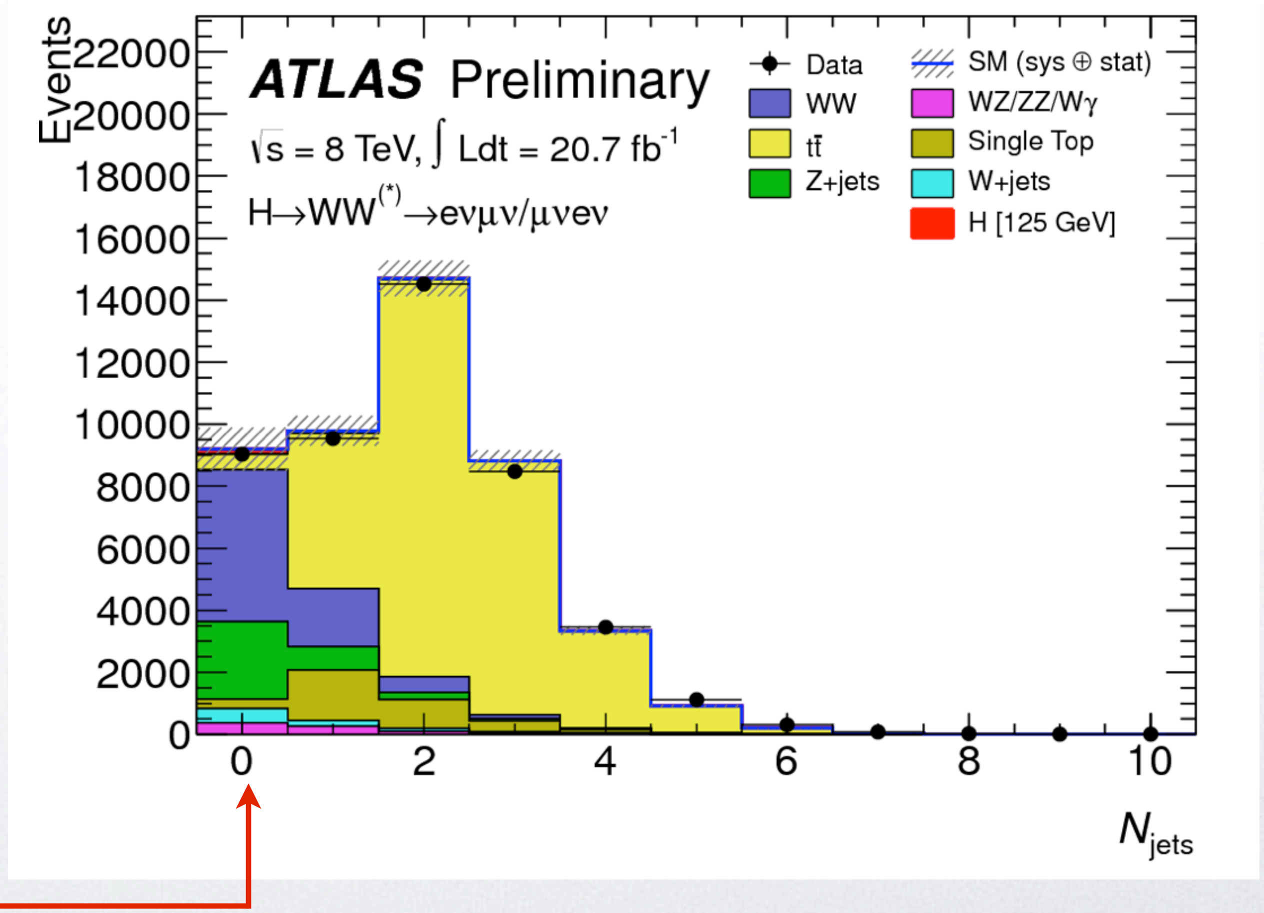
- Jet vetoes are used in several analyses to reduce background due to coloured particles production and improve sensitivity
- e.g. measurement of Higgs boson coupling to vector bosons HW^+W^-



Vetoing jets

- Jet vetoes are used in several analyses to reduce background due to coloured particles production and improve sensitivity
- e.g. measurement of Higgs boson coupling to vector bosons HW^+W^-

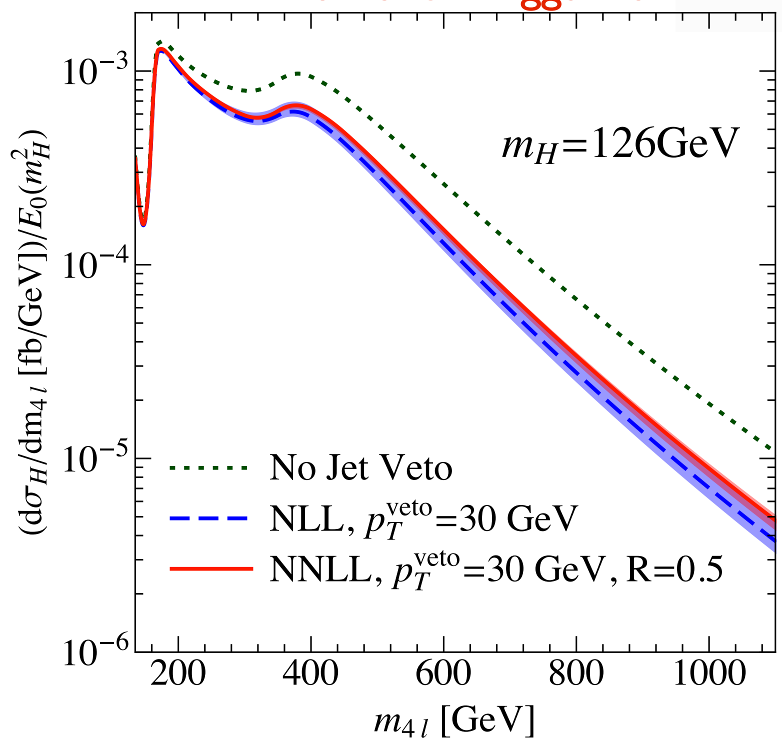
- bkg composition changes with jet multiplicity
- vetoing any jet activity (i.e. no jets with $p_{t,j} \geq 25-30\,\mathrm{GeV}$) leads to a massive suppression of W^+W^- coming from $t\bar{t}$ decay (production rate 100 times as large)



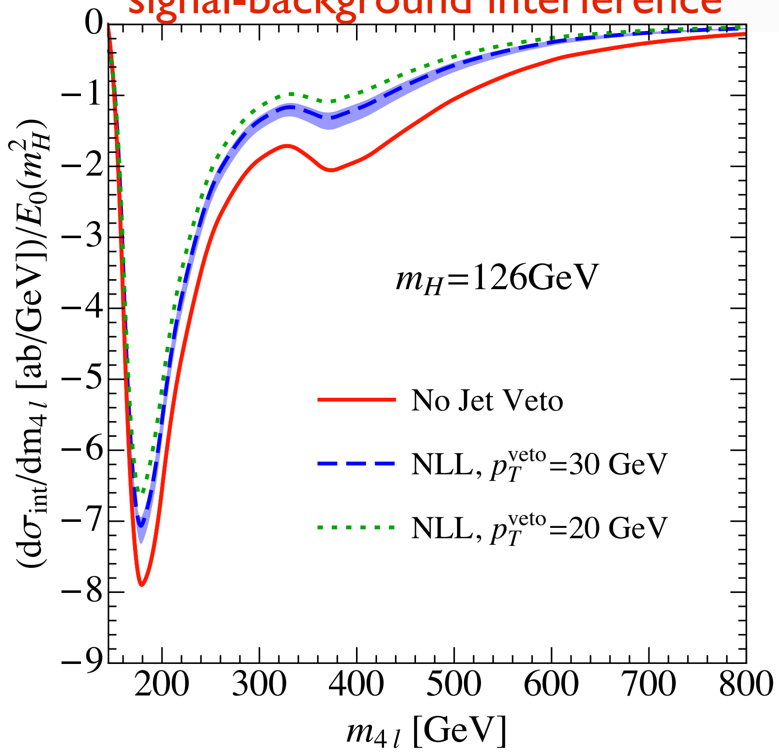
Vetoing jets

- Enhancement in total cross section in off-shell production of $H \to VV$ allows for a precise measurement of Γ_H
- Latest CMS measurement $\Gamma_H/\Gamma_{SM} < 4.2$ in $H \to ZZ$
  [Kauer, Passarino '12, Caola, Melnikov '13, Campbell, Ellis, Williams '13]
- Approach also extended to $H \to W^+W^-$ [Campbell, Ellis, Williams '13]
- Conclusions change if a jet veto is applied on $H \to W^+W^-$ [Moult, Stewart '14]

off-shell Higgs XS



signal-background interference



- A veto on extra jets suppresses both signal and signal-background interference in the off-shell region
- Sudakov suppressions weakens the bounds on the Higgs width by about factor of two
- ZZ channel not affected

Why resummation ?

- Requiring the QCD radiation to be confined at the boundary of its phase space (large gap between scales) leads to an exponential (Sudakov) suppression of the corresponding cross section

- The latter is not accounted for in Fixed Order (FO) calculations, which diverges logarithmically in these kinematical regimes
  e.g. 0-jet bin: $\ln p_{\mathrm{t,veto}}/m_H$; 1-jet bin: $\ln p_{\mathrm{t,veto}}/p_{\mathrm{t,j}}$, $\ln p_{\mathrm{t,j}}/m_H$; ...

  Integrated over the allowed jet's phase space

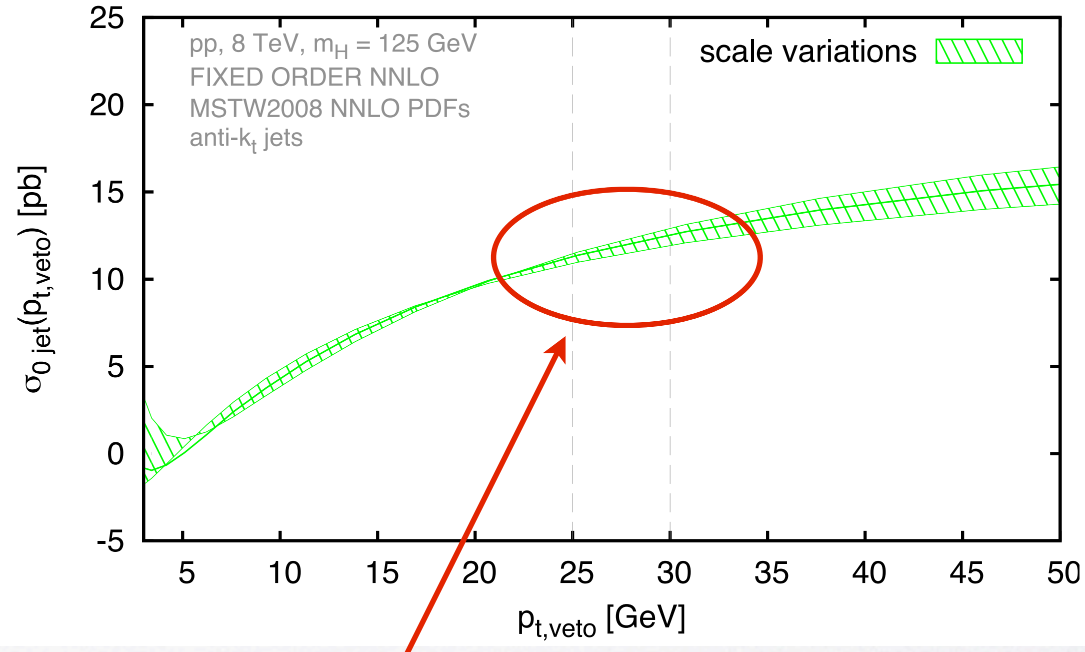
- In order to know the precise fraction of signal events surviving the veto, the correct Sudakov suppression must be restored

- The correct behaviour is obtained by resumming the large logarithms to all orders in the strong coupling constant

Why resummation ?

- Large Sudakov logarithms compensate large K-factor in exclusive cross sections when the renormalization scale is varied
- As a result, the FO scale variation underestimates the actual theory uncertainty

e.g. Higgs + no-jets cross section @ NNLO
[Anastasiou et al. '04]



- Scale uncertainty smaller than the one in the total cross section. The cancellation is dramatic for veto scales used in ATLAS & CMS analyses

Overview of the talk

- In this talk:
  - improved predictions for the zero-jet cross section in (on-shell) Higgs boson production (relevant for $H \to W^+W^- \to l^+\nu l^-\bar{\nu}$)
  - general prescription to assess theory uncertainty in exclusive jet bins even if the resummation of large logarithms is not available.
  - size of corrections to the heavy quark effective theory in Higgs and leading-jet transverse momentum distributions

- The results/techniques presented here can be applied to the production of any colour singlet in hadronic collisions (e.g. Z, W^+W^-, ...)
- Although only the signal is discussed here, similar attention is required for many background reactions too

Sudakov resummation (heavy-top case)

- The resummed cross section has similar structures for the $p_{\mathrm{t,H}}$ and $p_{\mathrm{t,veto}}$ spectra

$$\Sigma(p_{\mathrm{t}}) = \mathcal{L}(p_{\mathrm{t}})|\mathcal{M}_{\mathrm{B}}|^2 e^{-R(p_{\mathrm{t}})} \mathcal{F}(R') \qquad R' = dR(p_{\mathrm{t}})/d\ln(m_H/p_{\mathrm{t}})$$

Sudakov Radiator, virtual corrections and parton luminosities

[Grazzini, de Florian '01]
[Becher, Neubert '11]

- Parton luminosities are evaluated at $\mu_F \sim p_{\mathrm{t,veto}}$, i.e. no emissions above this scale

- The Sudakov form factor accounts for the radiation suppression at transverse momentum scales larger than $p_{\mathrm{t,veto}}$

- Identical for $p_{\mathrm{t,H}}$ and $p_{\mathrm{t,veto}}$ up to NNLL order

Sudakov resummation (heavy-top case)

- The resummed cross section has similar structures for the $p_{t,\mathrm{H}}$ and $p_{t,\mathrm{veto}}$ spectra

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

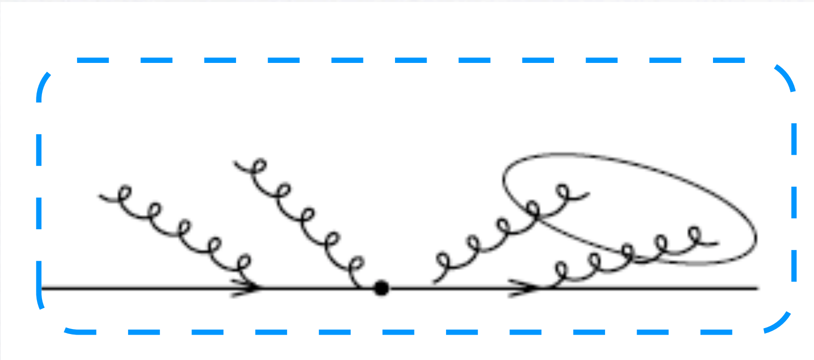
[Banfi, Salam, Zanderighi '12]
[Banfi, PM, Salam, Zanderighi '12]

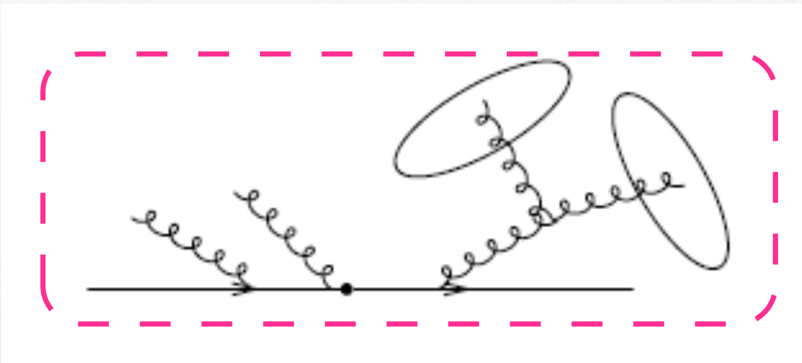
All-orders soft and collinear real radiation. Describes observable behaviour in the presence of multiple emissions

- for $p_{t,\mathrm{H}}$: $$\mathcal{F}(R') = e^{-R'\gamma_E} \frac{\Gamma(1-R'/2)}{\Gamma(1+R'/2)} + \mathcal{O}(\mathrm{NNLL})$$

- for $p_{t,\mathrm{veto}}$: $$\mathcal{F}(R') = 1 + \mathcal{O}(\mathrm{NNLL})$$

  - No clustering at NLL !
  - Dependence on jet-radius pops in at NNLL: clustering of independent emissions & correlated emissions clustered into two separate jets





NNLL structure confirmed in:
[Becher, Neubert, Rothen '13].
Also used in
[Tackmann, Stewart, Walsh, Zuberi '13]

Theory uncertainties

- After matching to FO, the resummed 0-jet cross section on its own allows one to control separately both K-factor and Sudakov effects, and to estimate reliably the theory uncertainty
- Since resummation is not available for arbitrary jet multiplicities, a more general approach to uncertainty assessment is highly desirable
- Different solutions are available:
  - Efficiency method
    [Banfi, Salam, Zanderighi '12; + PM '12]
  - Combination of yield and migration uncertainties
    [Boughezal, Liu, Petriello, Tackmann, Walsh '13]
  - Stewart-Tackmann (treat inclusive cross sections as uncorrelated)
    [Stewart, Tackmann '11]

The efficiency method

- Exclusive cross sections suffer from cancellations between large Sudakov and K-factor induced terms at commonly used renormalization scales
- Idea: to a large extent separate Sudakov (logarithms) effects from K-factor (normalization) effects
- Express the exclusive jet bin cross sections as

$$\sigma_{0j} = \epsilon_0 \sigma_{tot}, \;\; \sigma_{1j} = (1-\epsilon_0)\epsilon_1 \sigma_{tot}, \;\; \sigma_{2j} = (1-\epsilon_0)(1-\epsilon_1)\epsilon_2 \sigma_{tot}, \;\; \ldots$$

- Assume that uncertainties in total cross section (normalization, K-factor effects) and those in the efficiencies (logarithms/shape, Sudakov effects) are fully uncorrelated
- Covariance matrix between jet bins can be obtained once the errors in the total cross section and efficiencies are known [see Les Houches '13 proceedings]

The efficiency method

- Exclusive cross sections suffer from cancellations between large Sudakov and K-factor induced terms at commonly used renormalization scales

- Idea: to a large extent separate Sudakov (logarithms) effects from K-factor (normalization) effects

- Express the exclusive jet bin cross sections as

$$\sigma_{0j} = \epsilon_0 \sigma_{tot}, \;\; \sigma_{1j} = (1-\epsilon_0)\epsilon_1 \sigma_{tot}, \;\; \sigma_{2j} = (1-\epsilon_0)(1-\epsilon_1)\epsilon_2 \sigma_{tot}, \;\; \ldots$$

ϵ_2: [Campbell et al. '06 - '10] Known to NLO

ϵ_1: [Liu, Petriello '13] [Boughezal et al. '13] Known to NLO + NLL (NNLO ongoing)

σ_{tot}: [Anastasiou, Melnikov, Petriello '04] [Anastasiou et al. '14] Known to NNLO (N3LO ongoing)

ϵ_0: [Banfi, Salam, PM, Zanderighi '12] Known to NNLO+NNLL

- It be easily extended to higher jet multiplicities. Currently the only method that works seamlessly for resummed and fixed-order calculations

The efficiency method

- Uncertainty in the total cross section can be estimated by using standard scale variation (no cancellations here). Vary independently μ_R and μ_F by a factor of two in either direction, while keeping $1/2 < \mu_R/\mu_F < 2$

- For efficiencies, scale plain variation is not reliable

- Observe that at a given FO, several equivalent definitions for the efficiency are possible (differ by subleading terms)

e.g. Higgs + 0-jets bin @ NNLO

$$\epsilon^{(a)} = \frac{\sigma^{\mathrm{NNLO}}_{0-\mathrm{jet}}}{\sigma^{\mathrm{NNLO}}_{\mathrm{tot}}} \qquad \epsilon^{(b)} = 1 - \frac{\sigma^{\mathrm{NNLO}}_{\geq 1-\mathrm{jet}}}{\sigma^{\mathrm{NLO}}_{\mathrm{tot}}}$$

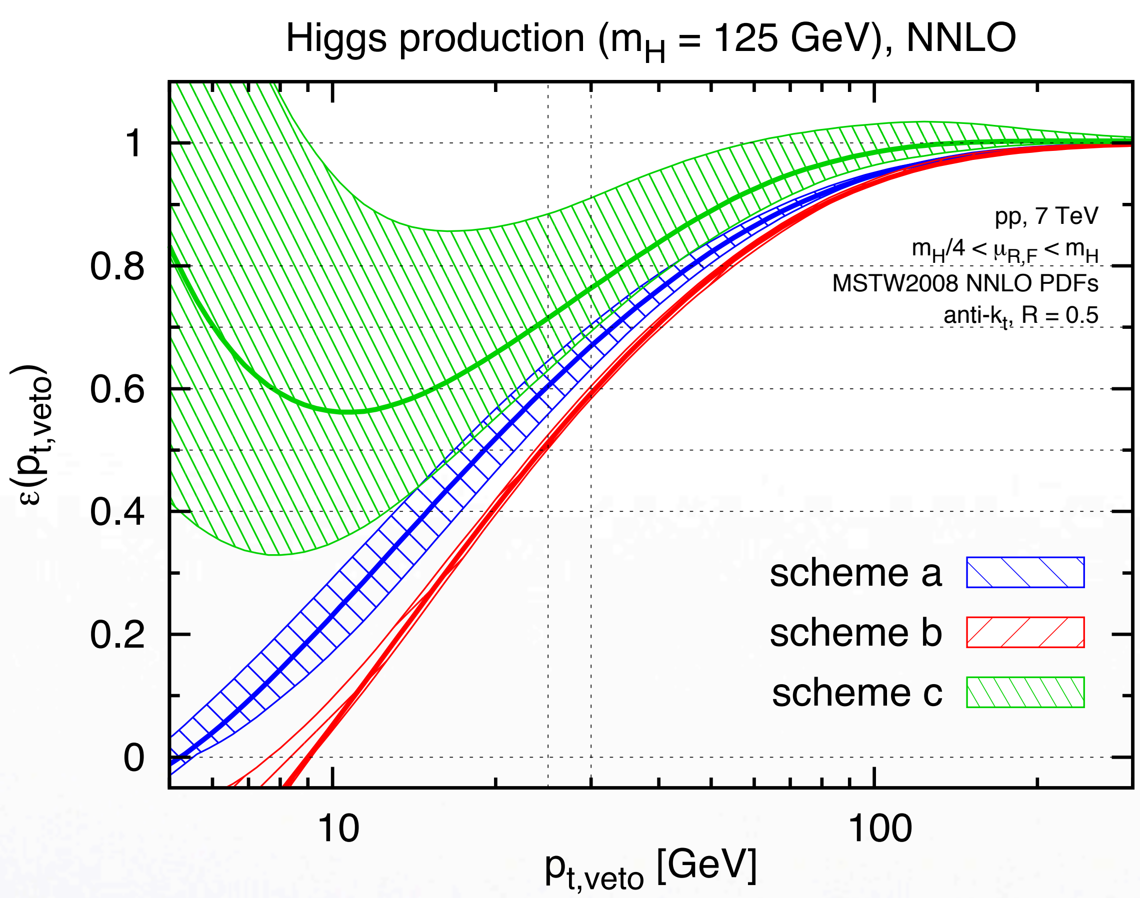
$\epsilon^{(c)} =$ strict fixed order expansion

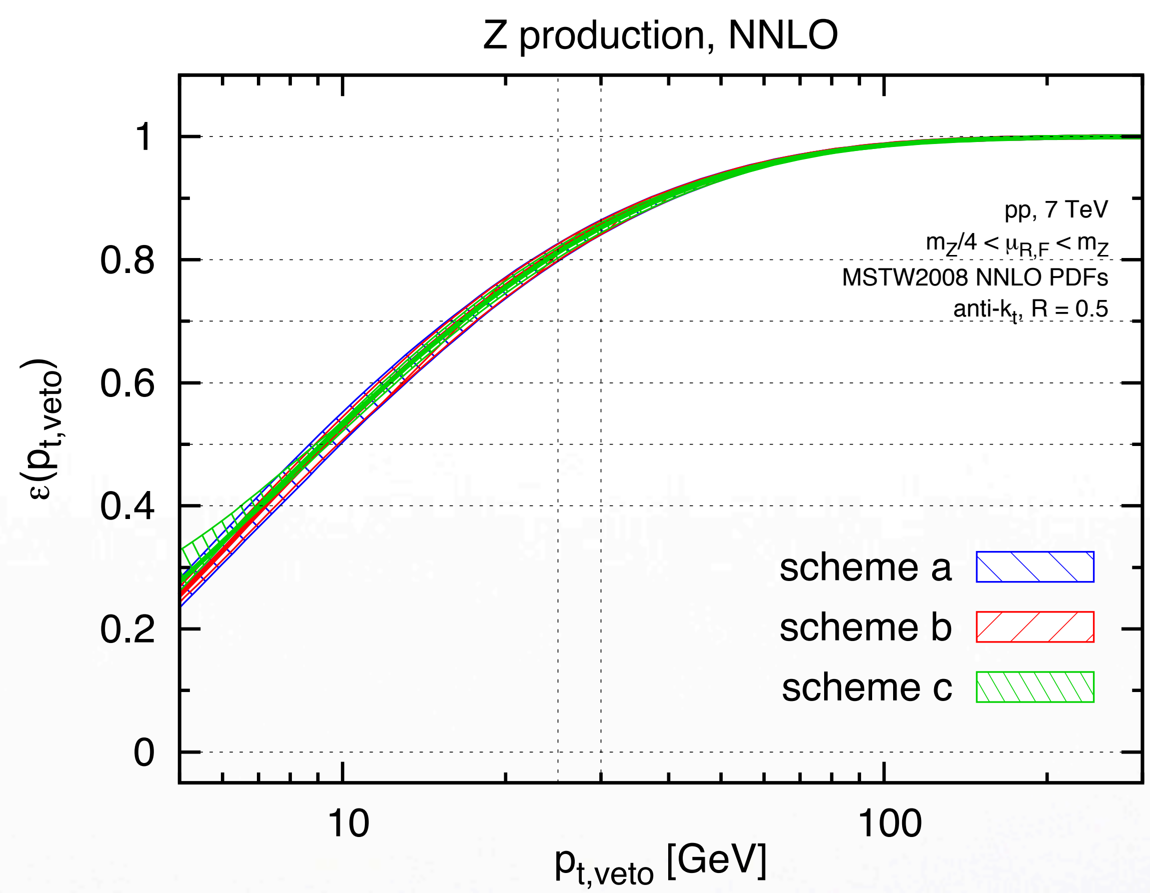
- For each FO efficiency scheme, define a corresponding resummation scheme whenever resummation is available

The efficiency method

- Uncertainty in the total cross section can be estimated by using standard scale variation (no cancellations here). Vary independently μ_R and μ_F by a factor of two in either direction, while keeping $1/2 < \mu_R/\mu_F < 2$
- For efficiencies, scale plain variation is not reliable
- Observe that at a given FO, several equivalent definitions for the efficiency are possible (differ by subleading terms)
- Uncertainty obtained as follows:
  - vary μ_R and μ_F as for the total cross section
  - when resummation is available, for central μ_R and μ_F vary the resummation scale Q by a factor of two
  - for central scales choice, vary efficiency scheme and take the envelope

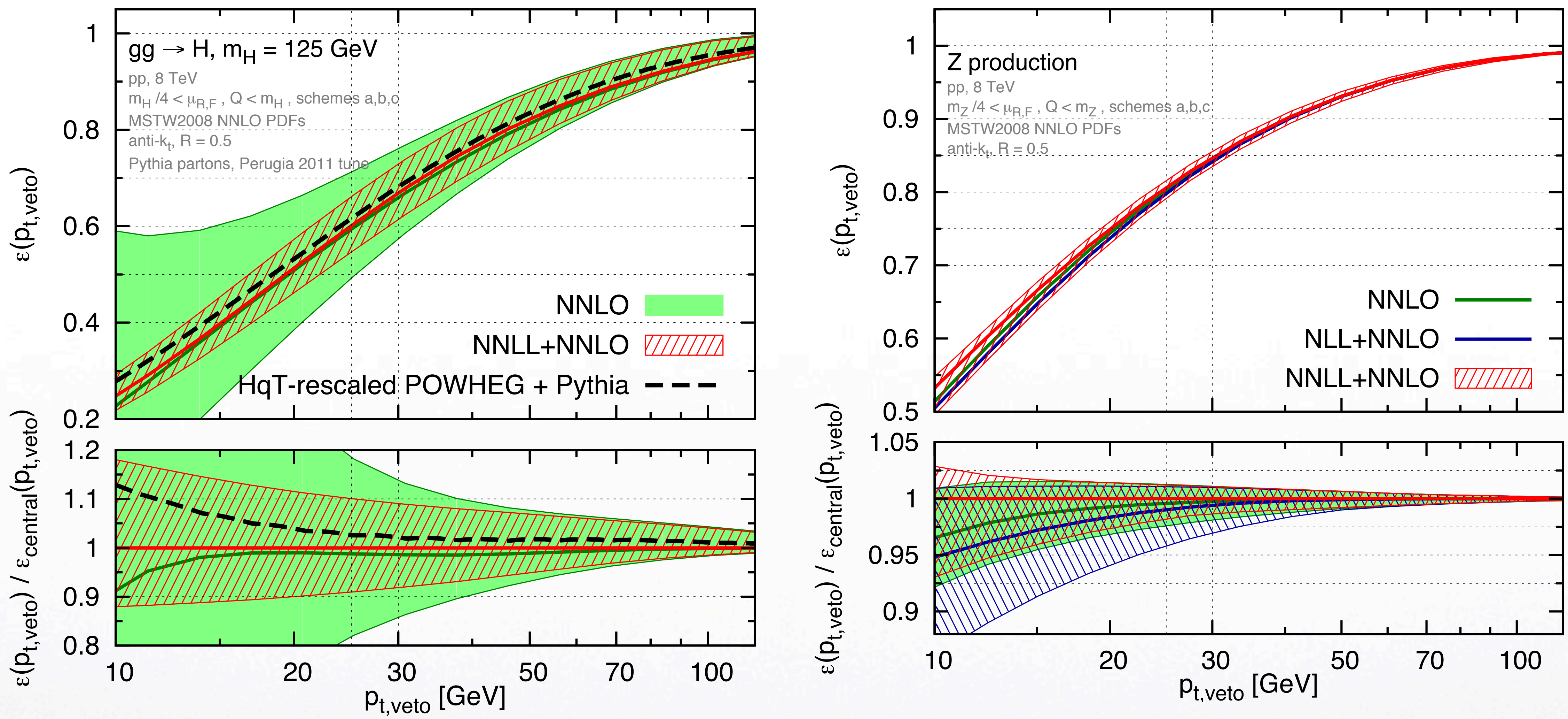
zero-jet efficiency at NNLO





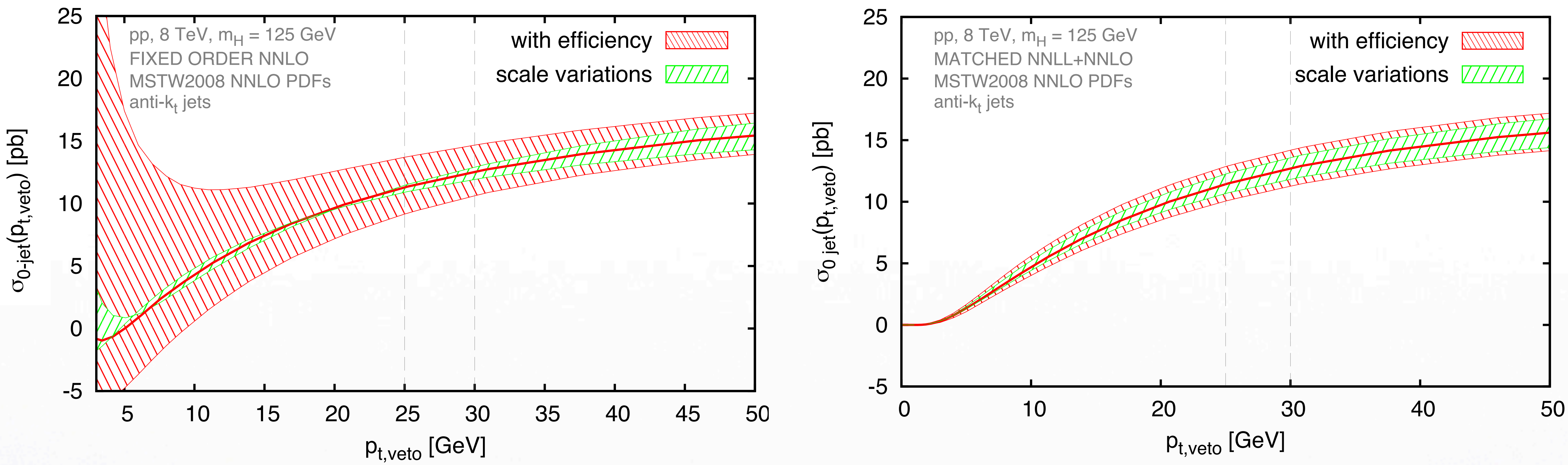
- Large spread in the Higgs case (much radiation constrained, important Sudakov effects). Large uncertainty !
- Different schemes agree in the DY case (less QCD radiation, good convergence of the PT series)

zero-jet efficiency at NNLO+NNLL



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

zero-jet cross section at NNLO+NNLL

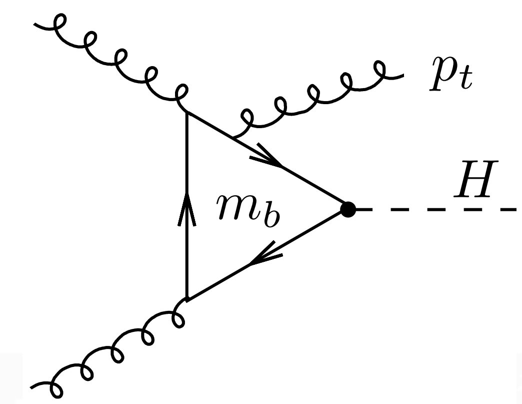


- At FO the large uncertainty band reflects the unreliability of the FO prediction at low veto scales
- When resummation is included, the efficiency method uncertainty is marginally larger than the one obtained with scales (μ_R, μ_F, Q) variation

Method not overly conservative

Exact treatment of quark masses

- When quark masses m_b, m_t are taken into account, new non-factorizing logarithmic terms pop up in the regime $m_b^2 << p_{\rm t}^2 << m_H^2$



e.g. including top and bottom quarks at relative order $\mathcal{O}(\alpha_s)$

- soft limit (squared amplitude)

$$\sim (m_b/m_H)^4 \ln^4(m_b^2/p_{\rm t}^2)$$

non-factorizing terms completely cancel in the top-bottom interference

- collinear limit (squared amplitude)

$$\sim (m_b m_t)^2/m_H^4 \ln^2(m_b^2/p_{\rm t}^2) \ln^2(m_t^2/p_{\rm t}^2)$$

interference terms survive and give a dominant contribution

- These new terms vanish for $p_{\rm t} \leq m_b$, so that the standard factorization of soft and collinear singularities is preserved as $p_{\rm t} \to 0$

No factorization breaking ! Just a larger remainder...

Implementation of mass effects

- In the region $p_t \sim 25-30$ GeV the logarithms $\ln(p_{\rm t}/m_b)$ should be resummed. All-order structure so far unknown. Phase-space suppression kills them at high $p_{\rm t}$
- They can be formally treated as a finite remainder that vanishes when $p_{\rm t} \to 0$
- As any remainder, the non-factorizing terms are thus computed at fixed-order and matched to the resummed calculation [Banfi, PM, Zanderighi '13]

It contains power suppressed terms and "non-factorizing" logs $\ln(p_{\rm t}/m_b)$

Resummation of logarithms $\ln(m_H/p_{\rm t})$ as in the large-m_t limit

$$\Sigma(p_{\rm t}) \sim C(\alpha_s, \mu_R, \mu_F, Q, m_H, m_b, m_t) \boxed{e^{-R(p_{\rm t})}\mathcal{F}(R')} + \boxed{\text{remainder}}$$

Prefactor contains coefficient functions as in the heavy-top limit and full virtual corrections with both top and bottom quarks running in the loop.
It contains large logarithms $\ln(m_H/m_b)$

Results for no-jet cross section

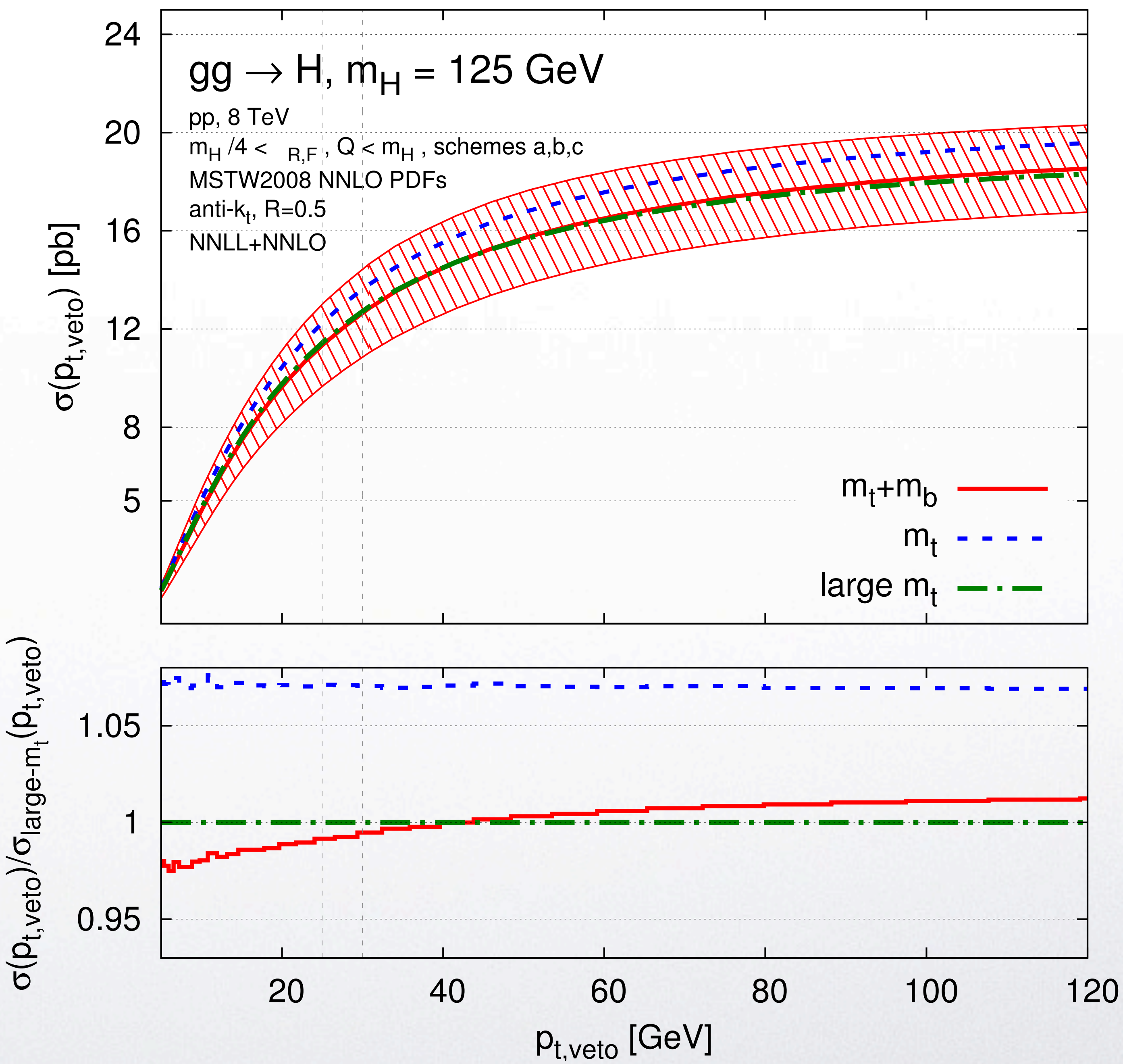
The enhanced remainder when including bottom quarks would require a smaller resummation scale for the bottom-induced contribution (about 30 GeV).

However, its impact is within the uncertainty band obtained with the efficiency method, so one can use a single resummation scale as in the heavy-top case

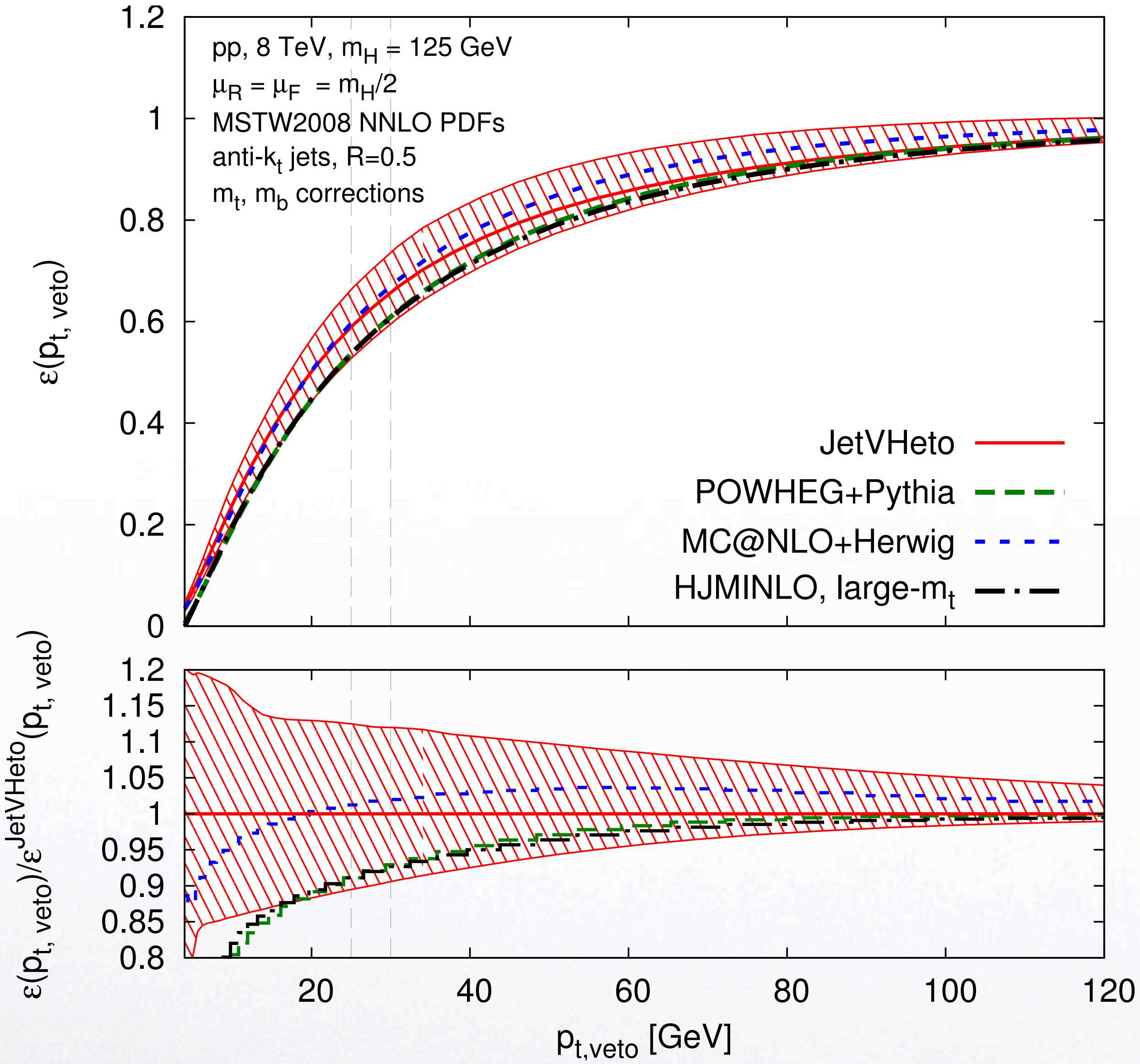
The effect of top-quark amounts to an over-all rescaling whilst the bottom quark distorts the shape of the spectrum.

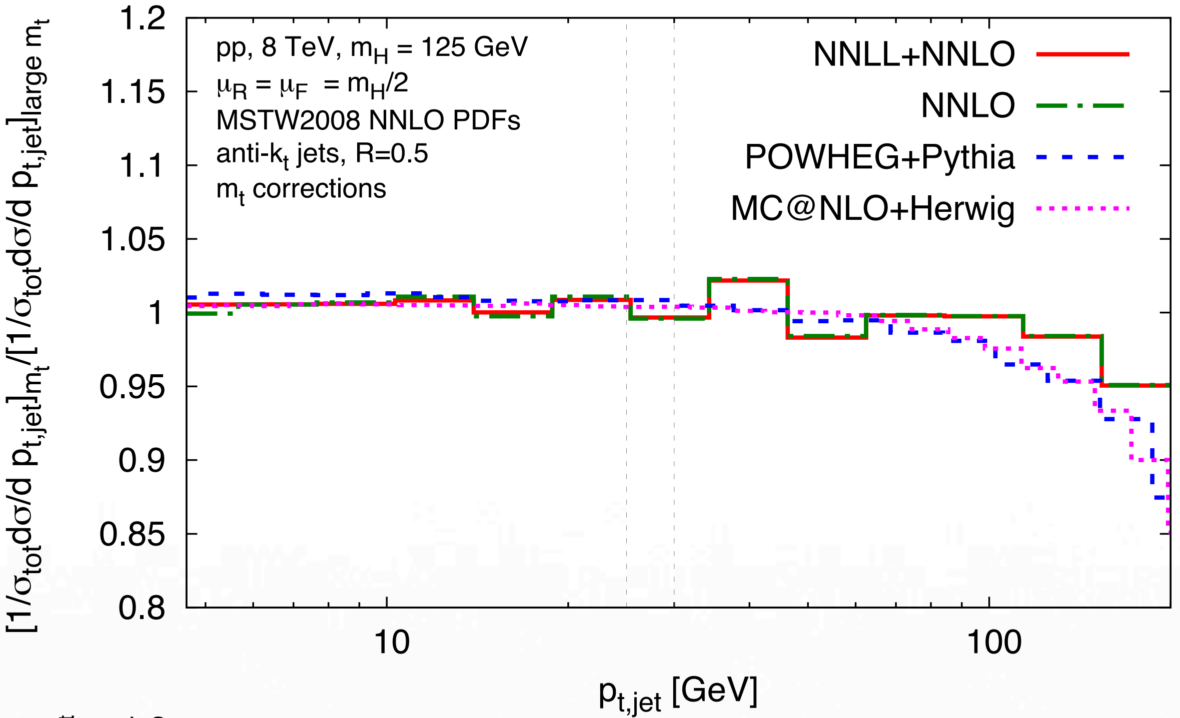
The total effect is small: $\sim 3\%$ at small transverse momentum and $\leq 2\%$ in the high-$p_{t,\mathrm{veto}}$ region

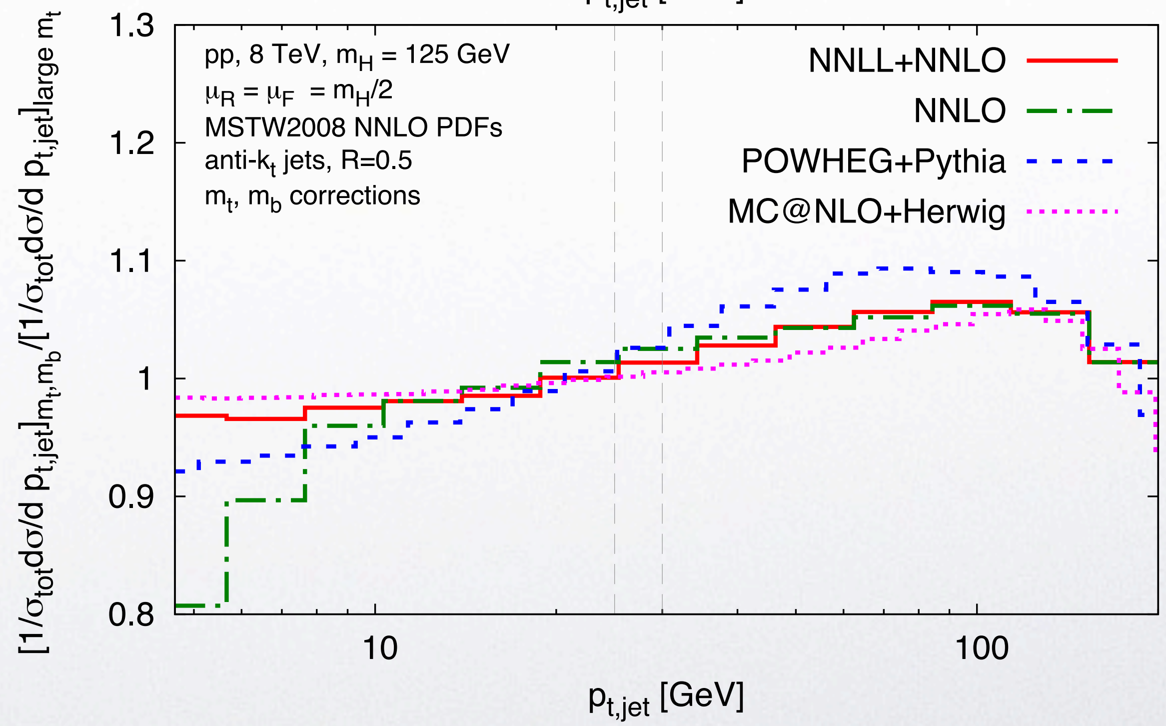
Uncertainty band obtained with the efficiency method, i.e. errors on jet-veto efficiency and total cross section treated as totally uncorrelated



Comparison to Monte Carlo







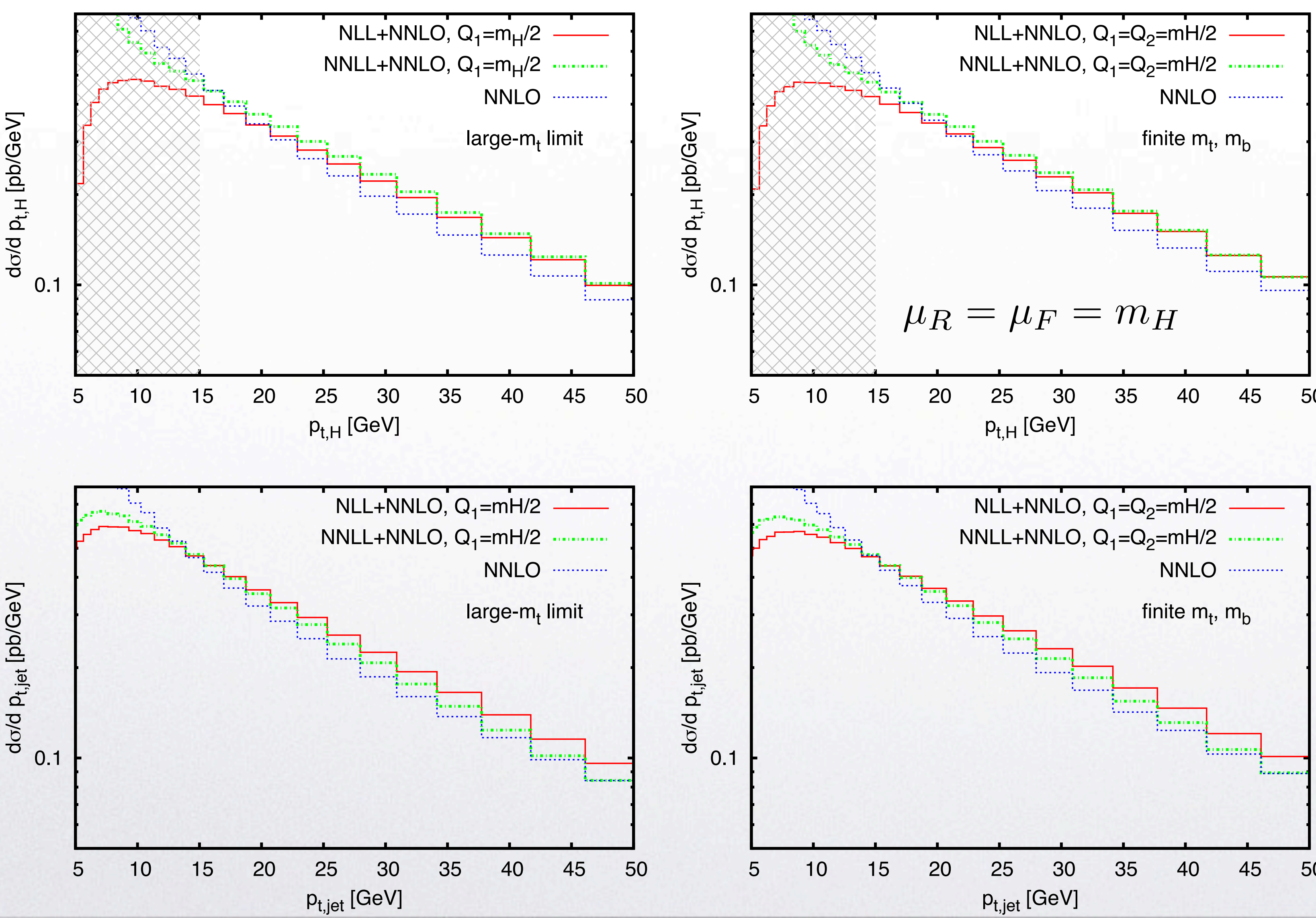
Good agrement with MC generators.
MC@NLO agrees better with the NNLL+NNLO prediction

Implementations in event generators :
MC@NLO, Herwig, POWHEG
[Frixione et al., Corcella et al., Bagnaschi et al.]

NNLO distributions obtained with hnnlo-v2.0

Comparison between leading-jet and Higgs p_t

- Similar impact on $p_{t,\mathrm{H}}$ and $p_{t,\mathrm{veto}}$ distributions
- NNLO corrections not known with exact mass treatment (here obtained as the heavy top result rescaled by the Born correction factor) : $\mathcal{O}(\alpha_s^2)$ mismatch between matched and FO distributions, instead of $\mathcal{O}(\alpha_s^3)$ in the heavy-top limit



Analytical study of the impact of heavy quark masses on Higgs transverse momentum spectrum previously studied in [Harlander, Neumann, Ozeren, Wiesemann '12] [Mantler, Wiesemann '12].

Alternative prescription for the treatment of bottom quark contribution in Higgs transverse momentum spectrum proposed in [Grazzini, Sargsyan '13], i.e. turn off resummation and use fixed-order for $p_{t,\mathrm{H}} \geq m_b$

Large impact previously observed due to large remainders in the matching to NLO, rather than to physical effects.

Conclusions

- The presence of a veto on jets demands resummation of large logarithms
- Uncertainty are reduced by a factor of two in the region of experimental interest for the zero-jet efficiency (cross section)
- Efficiency method is a robust and general method to assess uncertanties in any jet bin analyses. Extension to high jet multiplicities straightforward.
- The code JetVHeto [http://jetvheto.hepforge.org] computes NNLL+NNLO (NLO differential) predictions for both Higgs and leading-jet transverse momentum cross sections and zero-jet efficiency
- Exact treatment of heavy quark masses included in v-2.0. Impact moderate on both Higgs and leading-jet transverse momentum distributions.