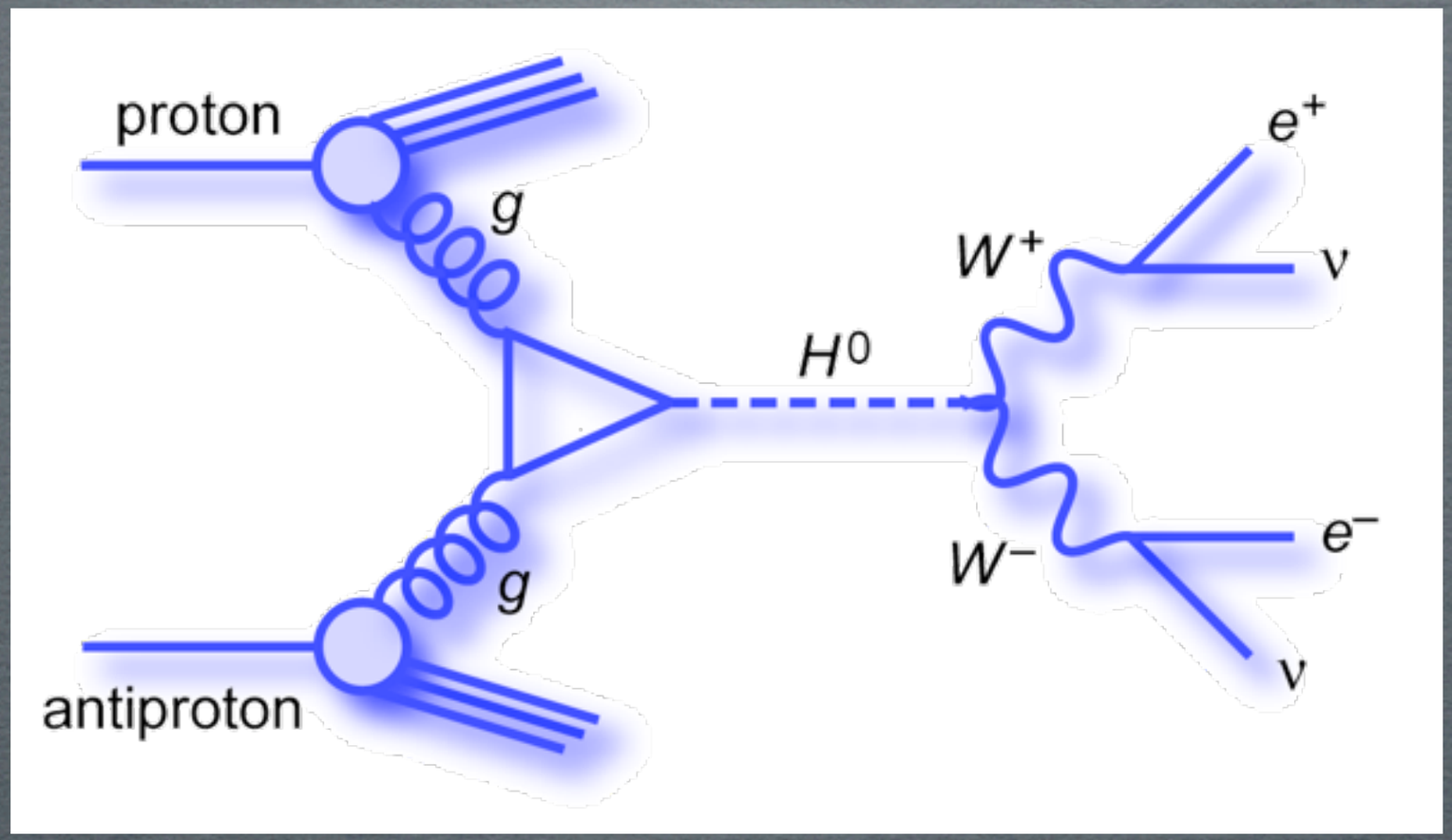
Jet-veto efficiencies at all orders in QCD



Andrea Banfi
University of Freiburg

In collaboration with
Gavin Salam and Giulia Zanderighi

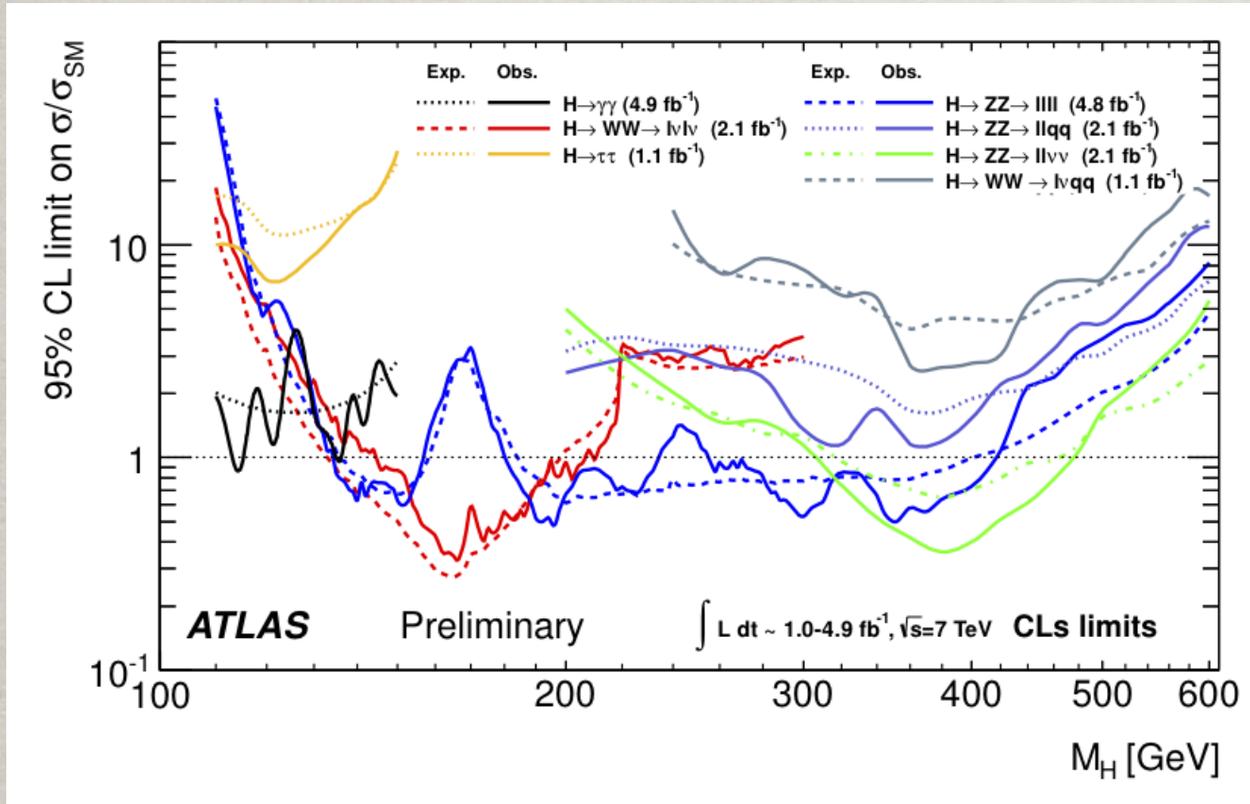
Outline

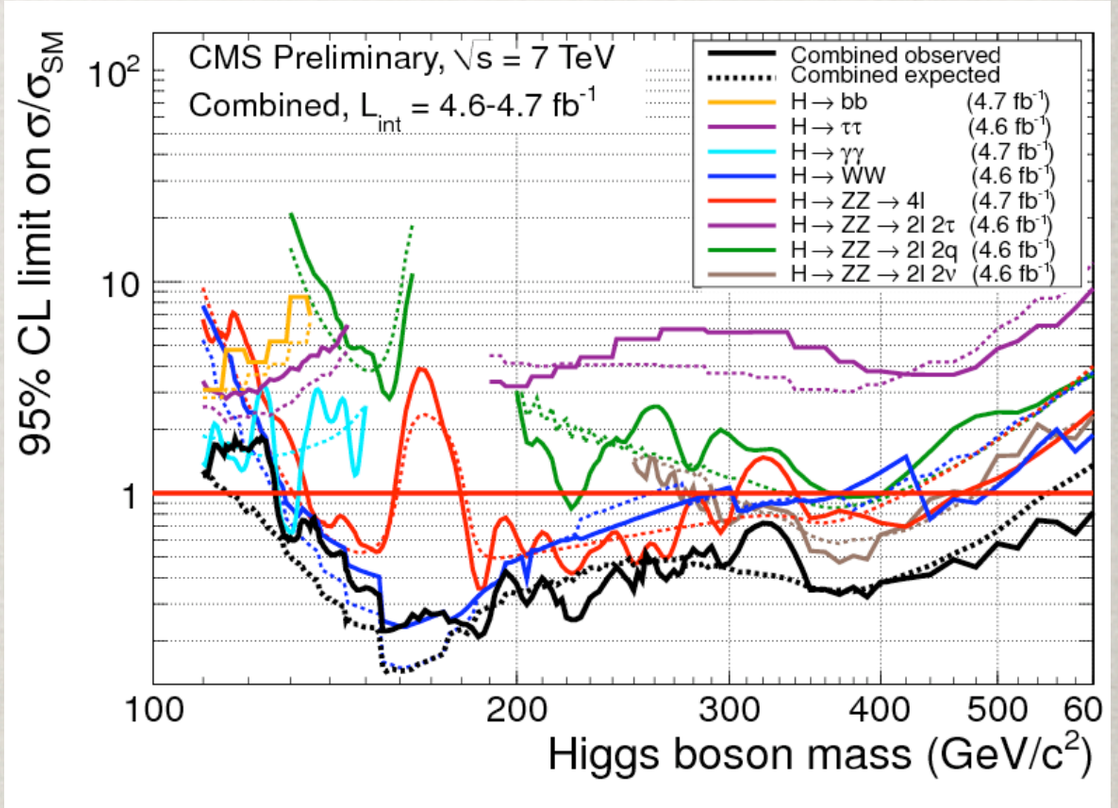
- Why jet-veto efficiencies in Higgs searches
- QCD predictions for jet-veto efficiencies
  - Fixed order calculations
  - NLL resummation
- Comparisons with other theoretical approaches
  - NNLL transverse momentum resummation (HqT)
  - Parton shower MC (POWHEG + PYTHIA)
- Missing theoretical ingredients (multi-jet configurations, NNLL resummation, etc.)

[Fresh from the press: AB Salam Zanderighi arXiv:1203.5773]

Low-mass Higgs searches

- Experimental data collected so far at the LHC give us hints that the Standard Model Higgs can be light

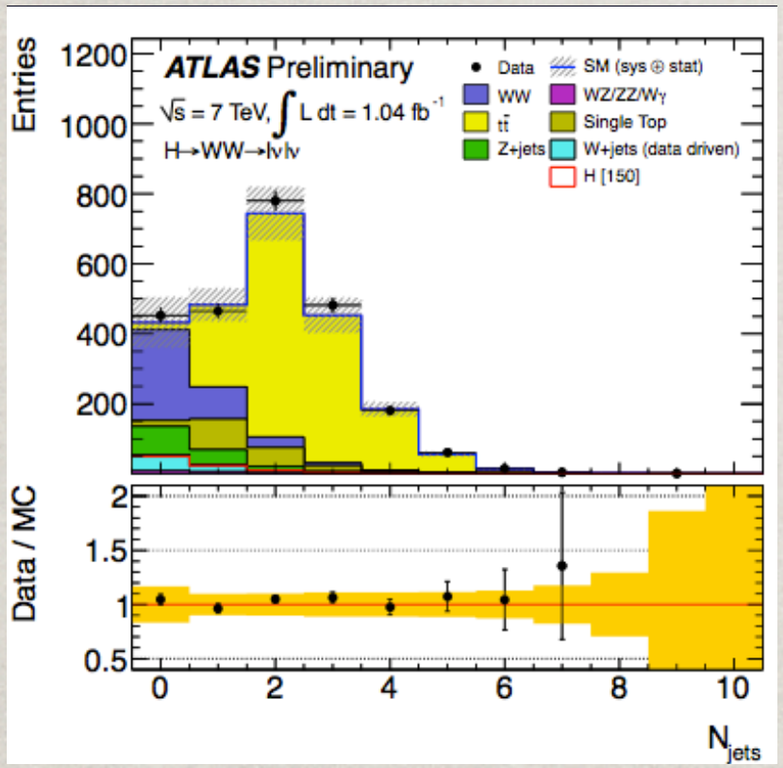


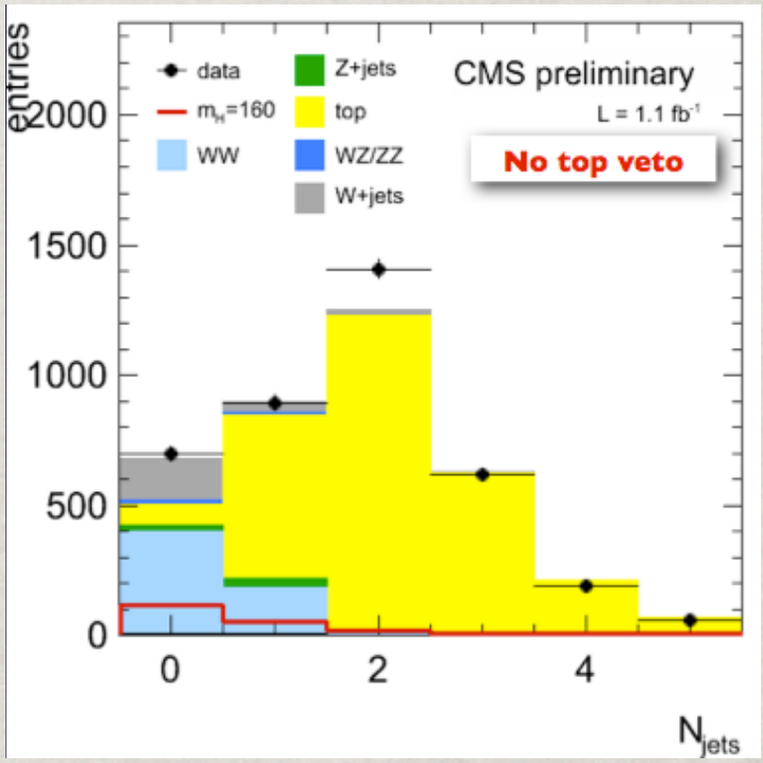


- One of the channels that is sensitive to a low-mass Higgs is $H \to WW^*$
- In case of a discovery, this channel will be crucial to determine the nature of the Higgs, e.g. its coupling to SM particles

Jet-veto cross sections

- In order to suppress the background from coloured particles (top), it is useful to separate events with different jet multiplicities



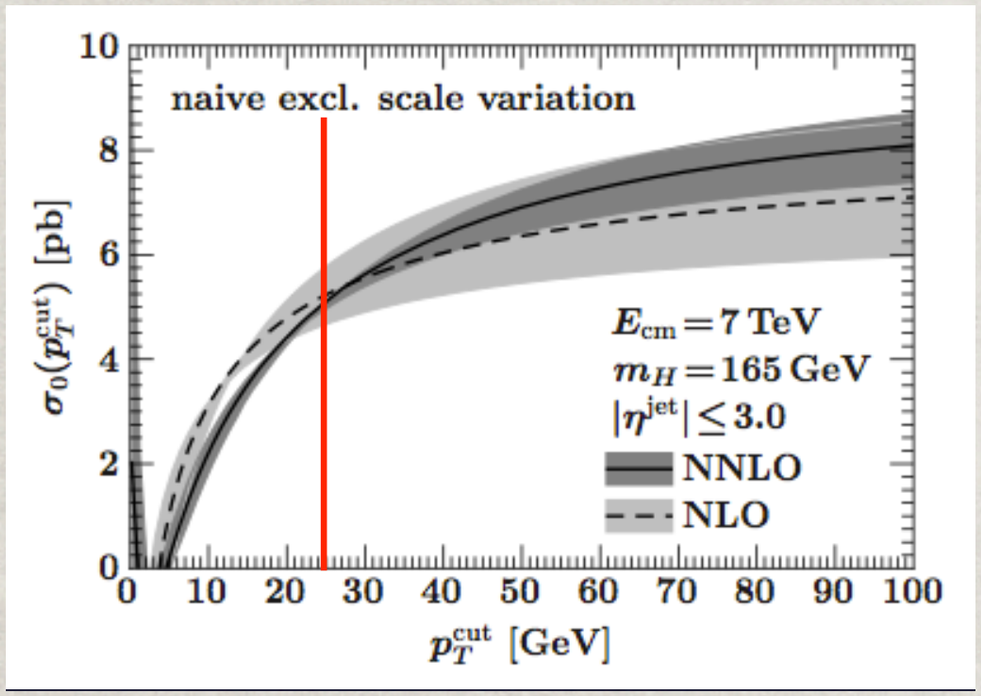


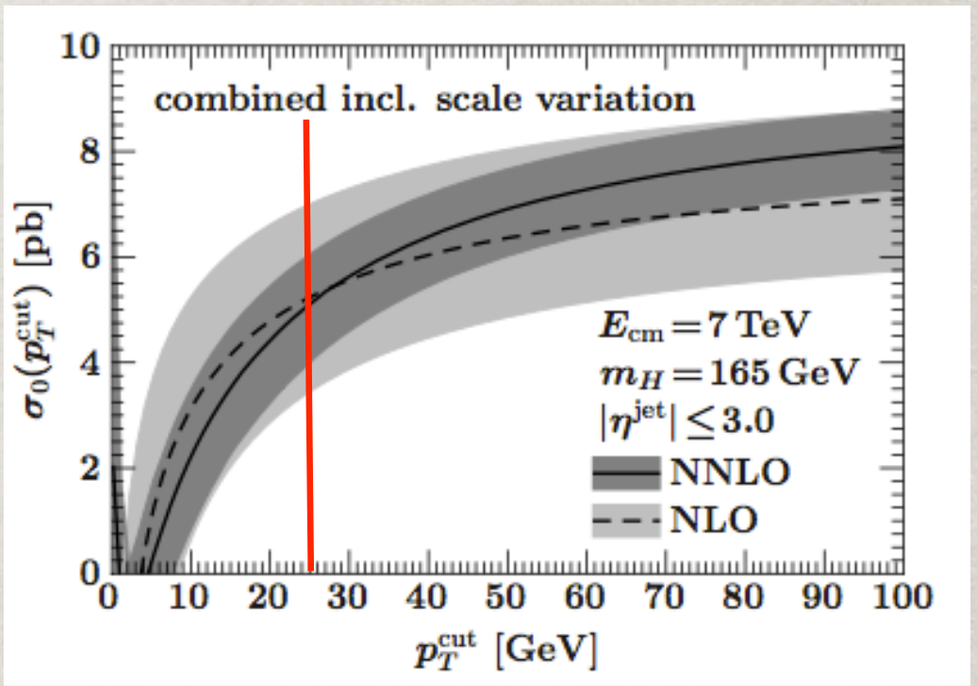
- In particular, the 0-jet bin is the least contaminated by W's from top-antitop production
- The 0-jet cross section, the quantity we want to compute with high accuracy, is the cross section for Higgs production with no jets with $p_t > p_{t,\mathrm{veto}}$

Jet-veto uncertainties

- The most obvious way to estimate jet-veto cross sections is via QCD fixed order calculations, nowadays NNLO

[Anastasiou Melnikov Petriello '05, Catani Grazzini '07]





- $\sigma[0\,\text{jets}]$ is affected by cancellation between large K-factor and large logarithms $\Rightarrow$ scale variations underestimate uncertainty

[Stewart Tackmann '11]

$$\sigma[0\,\text{jets}] = \sigma[\text{inclusive}] - \sigma[\geq 1\ \text{jet}] \sim \sigma_0 \left(K - 2C_A \frac{\alpha_s}{\pi} \ln^2 \frac{M_H}{p_T^{\text{cut}}} \right)$$

- Assuming that the K-factor and the logs are uncorrelated gives

$$\Delta\sigma^2[0\,\text{jets}] = \Delta\sigma^2[\text{all jets}] + \Delta\sigma^2[\geq 1\ \text{jet}]$$

Jet-veto efficiencies

- An alternative way to account for different sources of uncertainties is to consider the jet-veto efficiency
- The efficiency $\epsilon(p_{t,\mathrm{veto}})$ is the fraction of events in which all jets have $p_t < p_{t,\mathrm{veto}}$

$$\sigma[0\,\mathrm{jets}] = \sigma[\mathrm{inclusive}] \times \epsilon(p_{t,\mathrm{veto}})$$

large K-factor

large logarithms

- Uncertainties in $\sigma[\mathrm{inclusive}]$ reflect our ignorance of NNNLO terms in the perturbative expansion
- Uncertainties in $\epsilon(p_{t,\mathrm{veto}})$, especially at low $p_{t,\mathrm{veto}}$, are related to missing logarithms $\ln(M_H/p_{t,\mathrm{veto}})$ of Sudakov origin
- In the following we will concentrate on the jet-veto efficiency and consider uncertainties of $\sigma[\mathrm{inclusive}]$ and $\epsilon(p_{t,\mathrm{veto}})$ uncorrelated

Efficiencies at NNLO

- Fixed-order jet-veto efficiencies have extra source of uncertainties related to how they are defined in terms of basic cross sections

$$\sigma[\text{inclusive}] \equiv \sigma = \sigma_0 + \sigma_1 + \sigma_2$$

$$\sigma[0\text{ jets}] \equiv \Sigma(p_{t,\text{veto}}) = \sigma_0 + \Sigma_1(p_{t,\text{veto}}) + \Sigma_2(p_{t,\text{veto}})$$

$$\Sigma_i(p_{t,\text{veto}}) = \sigma_i + \bar{\Sigma}_i(p_{t,\text{veto}}) \qquad \bar{\Sigma}_i(p_{t,\text{veto}}) = -\int_{p_{t,\text{veto}}}^{\infty} dp_t \, \frac{d\Sigma_i}{dp_t}$$

- We propose three schemes for $\epsilon(p_{t,\text{veto}})$, equivalent at NNLO

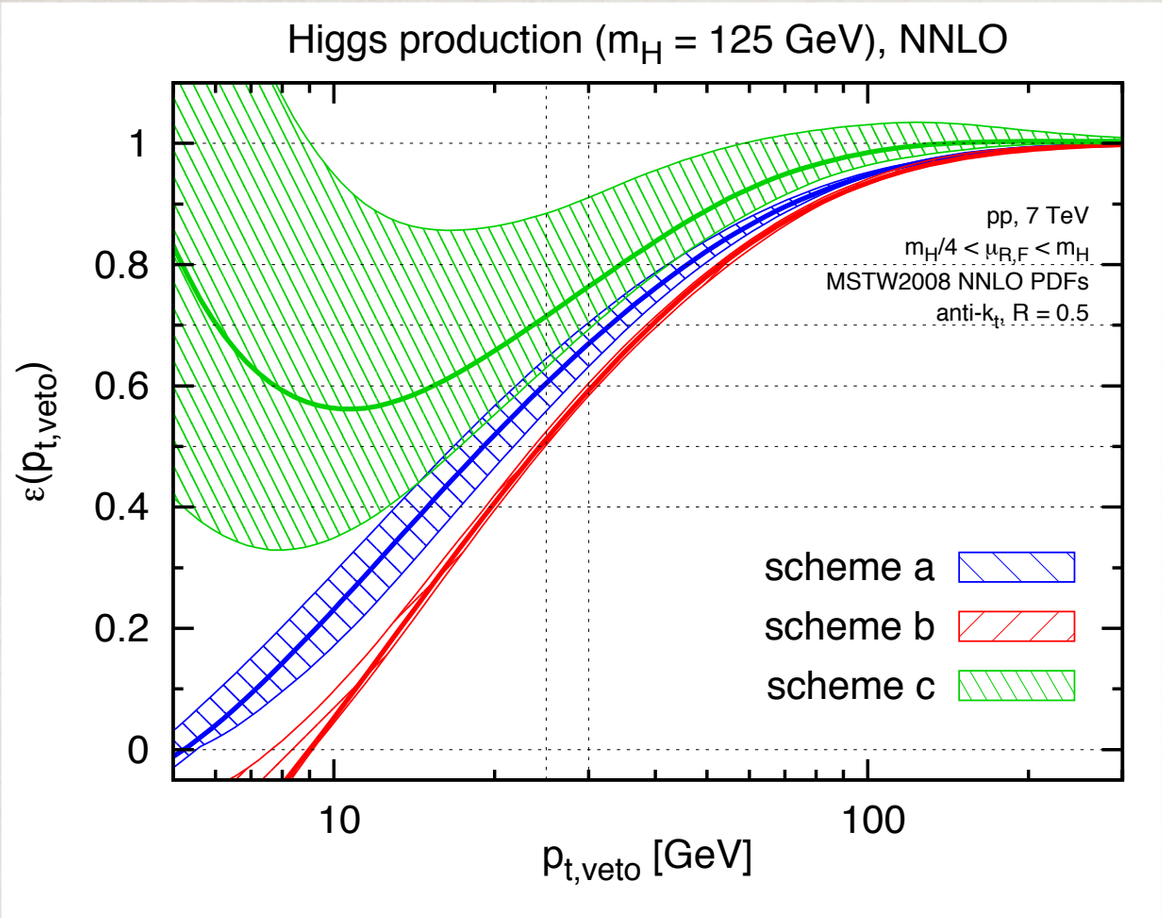
$$\epsilon^{(a)}(p_{t,\text{veto}}) = \frac{\sigma_0 + \Sigma_1(p_{t,\text{veto}}) + \Sigma_2(p_{t,\text{veto}})}{\sigma_0 + \sigma_1 + \sigma_2} \longleftrightarrow \text{Naive definition}$$

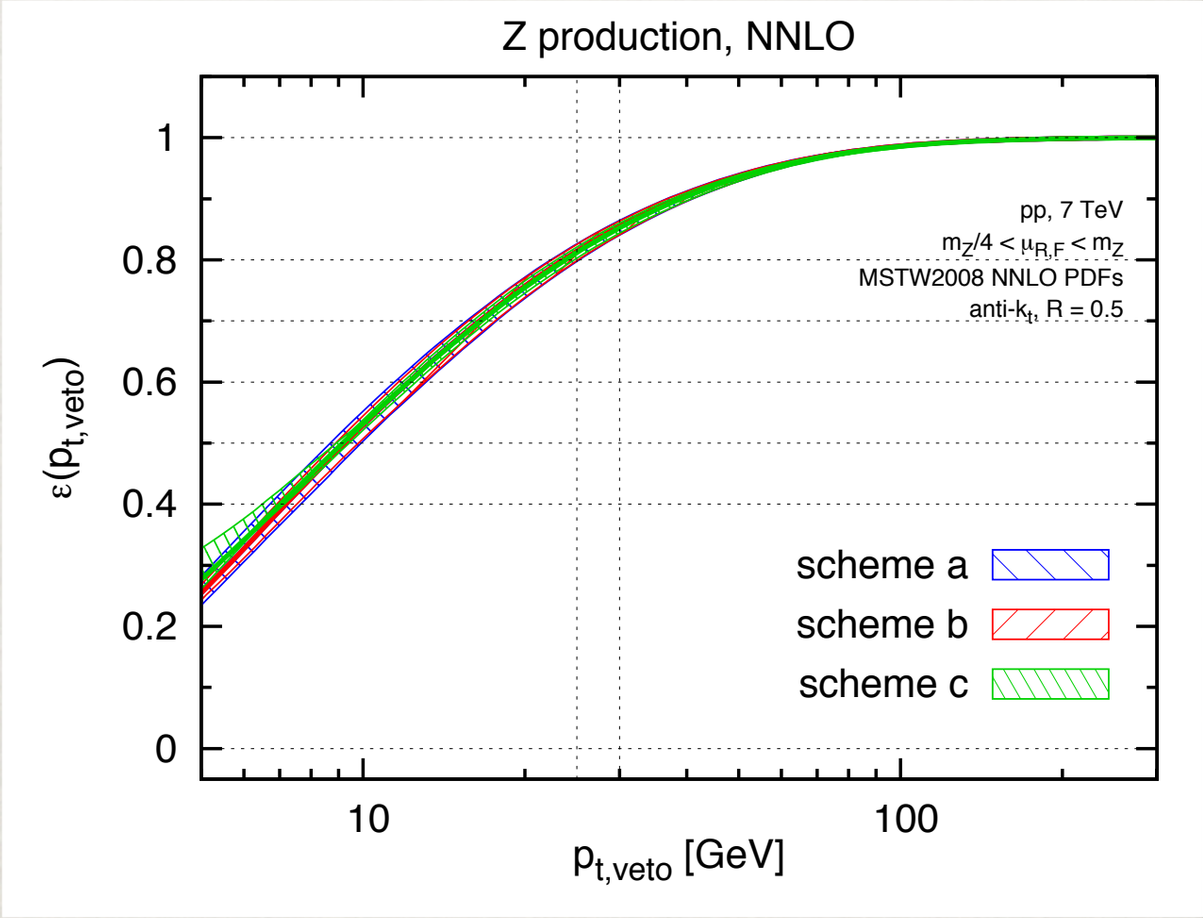
$$\epsilon^{(b)}(p_{t,\text{veto}}) = \frac{\sigma_0 + \Sigma_1(p_{t,\text{veto}}) + \bar{\Sigma}_2(p_{t,\text{veto}})}{\sigma_0 + \sigma_1} \longleftrightarrow 1 - \frac{\sigma_{\text{NLO}}[1\text{ jet}]}{\sigma_{\text{NLO}}[\text{all jets}]}$$

$$\epsilon^{(c)}(p_{t,\text{veto}}) = 1 + \left(1 - \frac{\sigma_1}{\sigma_0}\right)\frac{\bar{\Sigma}_1(p_{t,\text{veto}})}{\sigma_0} + \frac{\bar{\Sigma}_2(p_{t,\text{veto}})}{\sigma_0} \longleftrightarrow \text{Strict fixed order expansion of } \epsilon(p_{t,\text{veto}})$$

NNLO uncertainties

- For Higgs the three schemes differ significantly at the reference values $p_{t,\mathrm{veto}} = 25 - 30\,\mathrm{GeV}$ (ATLAS - CMS)





- In Z production, our control case, the 3 schemes give similar results, due to a better convergence of the PT series for σ[inclusive]
- Part of the uncertainty in Higgs production can be removed via an all-order resummation of large logarithmic contributions

NLL resummation

- Resummation is a reorganisation of the PT series for $\epsilon(p_{t,\mathrm{veto}})$ that gives a physically sensible answer for any value of $p_{t,\mathrm{veto}}$

$$\epsilon(p_{t,\mathrm{veto}}) = \exp[\underbrace{Lg_1(\alpha_s L)}_{\mathrm{LL}} + \underbrace{g_2(\alpha_s L)}_{\mathrm{NLL}} + \underbrace{\alpha_s g_3(\alpha_s L)}_{\mathrm{NNLL}} + \ldots]$$

Here $L = \ln(M_B/p_{t,\mathrm{veto}})$, with M_B the boson (Higgs, Z) mass

- The jet-veto efficiency is just the cumulative distribution in the transverse momentum $p_{t,\mathrm{jet}}$ of the leading jet $\Rightarrow$ within the scope of the Computer Automated Expert Semi-Analytical Resummer (CAESAR)

[AB Salam Zanderighi '05]

- Given a subroutine that computes a function $V(k_1, \ldots, k_n)$ of final state momenta $k_1, \ldots, k_n$ (e.g. $p_{t,\mathrm{jet}}$), CAESAR
  - checks whether $V(k_1, \ldots, k_n)$ is resummable at NLL accuracy
  - performs the NLL resummation using a general master formula

NLL JET-VETO EFFICIENCY

- Since $p_{t,\mathrm{jet}}$ satisfies CAESAR's applicability conditions, the jet-veto efficiency, at NLL accuracy, can be written in the form

$$\epsilon(p_{t,\mathrm{veto}}) \sim \mathcal{L}(p_{t,\mathrm{veto}})\, e^{-R(p_{t,\mathrm{veto}})}\, \mathcal{F}(R') \qquad R' = -\, p_{t,\mathrm{veto}}\, \frac{dR(p_{t,\mathrm{veto}})}{dp_{t,\mathrm{veto}}}$$

- The Sudakov exponent $R(p_{t,\mathrm{veto}})$ embodies virtual corrections at a scale larger than $p_{t,\mathrm{veto}}$

$$R(p_{t,\mathrm{veto}}) = 2C \int_{p_{t,\mathrm{veto}}^2}^{M_B^2} \frac{dk_t^2}{k_t^2} \frac{\alpha_s^{\mathrm{CMW}}(k_t)}{\pi} \left[\ln \frac{M_B}{k_t} + B\right] \qquad \begin{aligned} C &= \quad C_A \quad \text{or} \quad C_F \\ B &= -\frac{4\pi\beta_0}{C_A} \quad \text{or} \quad -\frac{3}{4} \end{aligned}$$

- $\mathcal{F}(R')$, a pure NLL function, accounts for the effect of multiple soft and collinear emissions: $\mathcal{F}(R') = 1$ for a perfectly factorisable observable $V(k_1, \ldots, k_n) = \max_i \{V(k_i)\}$
- In the NLL limit $p_{t,\mathrm{veto}} \to 0$ emissions are widely separated in rapidity, no recombination occurs and $p_{t,\mathrm{jet}} = \max_i \{k_{ti}\} \Rightarrow \mathcal{F}(R') = 1$ $\epsilon(p_{t,\mathrm{veto}})$ is a pure Sudakov form factor

Resummation uncertainties

- Uncertainties in resummed calculations are estimated via
  - "traditional" variation of renormalisation and factorisation scales, which we pick up in the range

$$\frac{M_B}{4} \leq \mu_F, \mu_R \leq M_B \qquad \frac{1}{2} \leq \frac{\mu_R}{\mu_F} \leq 2$$

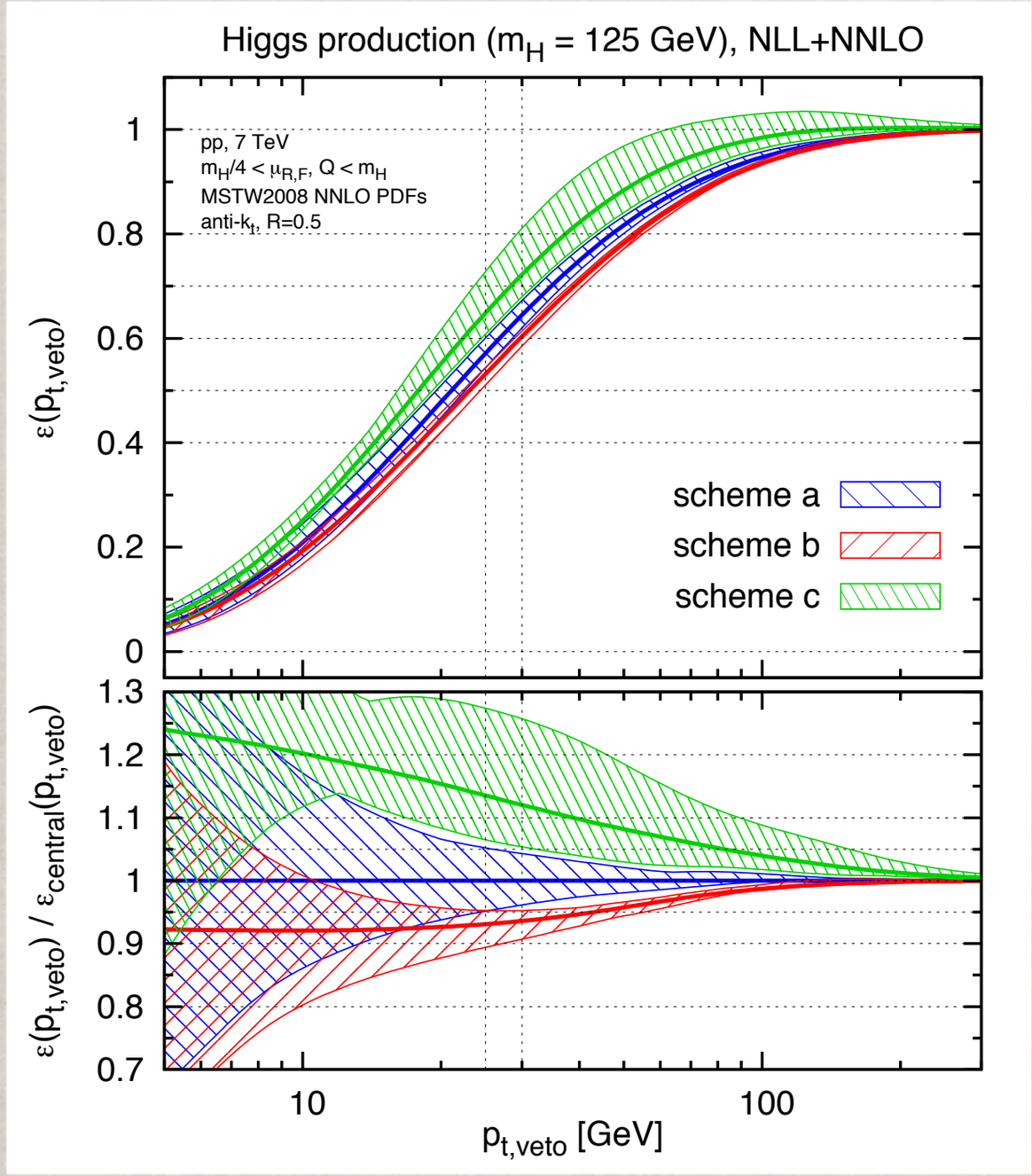
  - resumming $L = \ln(Q/p_{t,\mathrm{veto}})$ and letting $M_B/4 \leq Q \leq M_B$

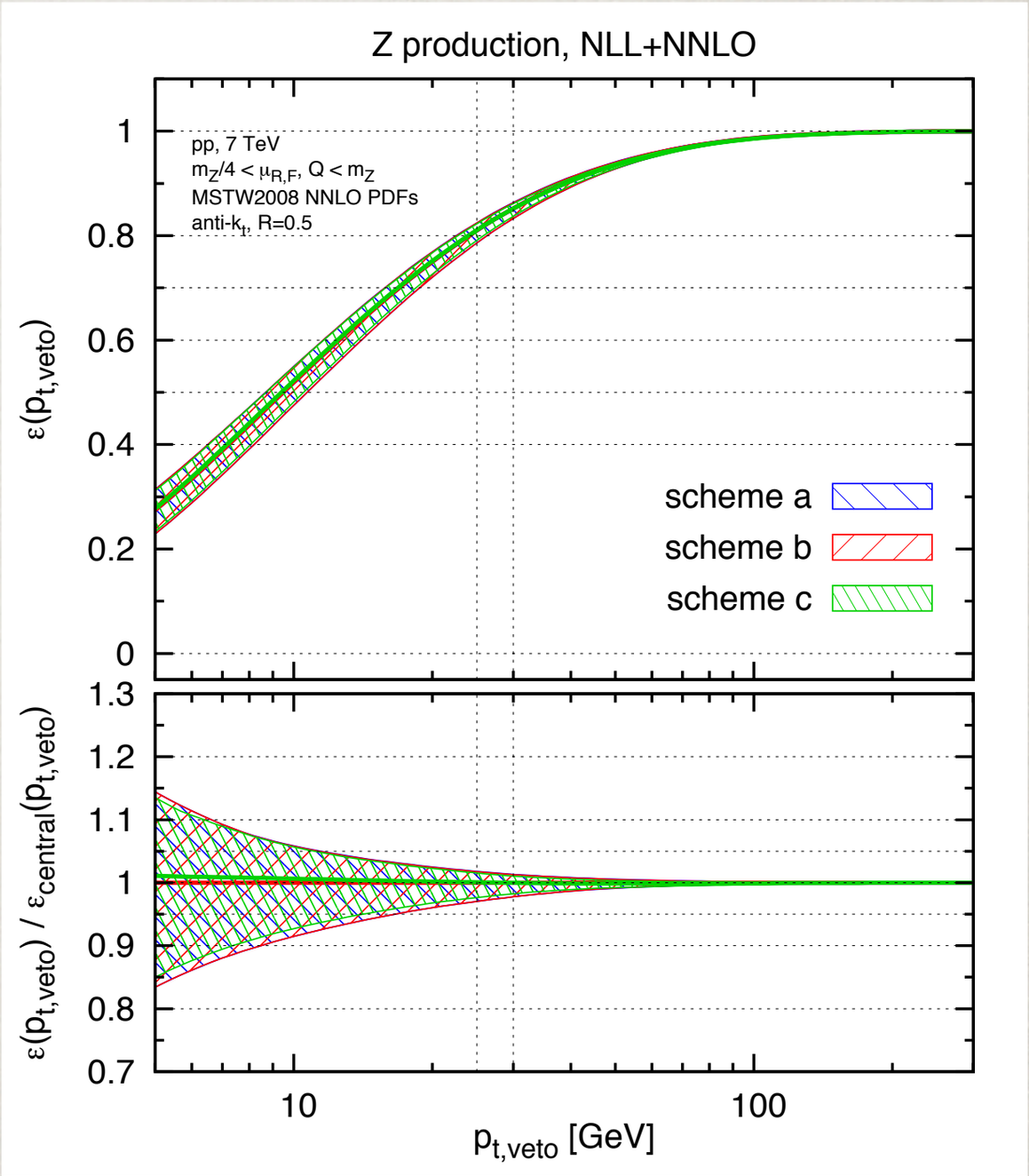
- Resummed calculations are unphysical for large $p_{t,\mathrm{veto}} \Rightarrow$ matching to fixed order needed
- Variation of matching schemes gives an extra handle we can use to estimate theoretical uncertainties

[AB Salam Zanderighi arXiv:1203.5773]

Matching to fixed order

- We propose three different matchings that correspond to the three schemes a, b, and c adopted for $\epsilon(p_{t,\mathrm{veto}})$ at fixed order

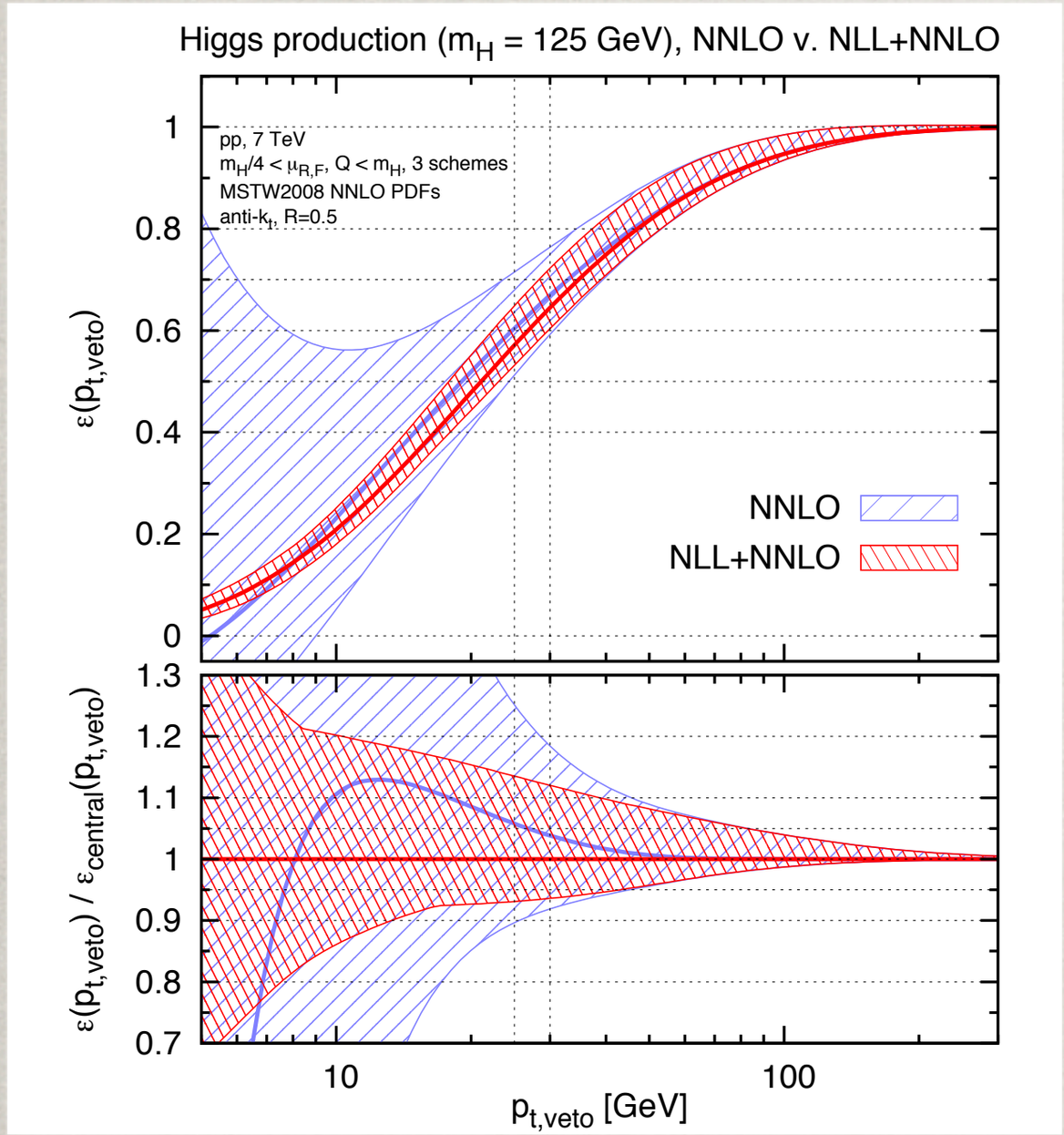


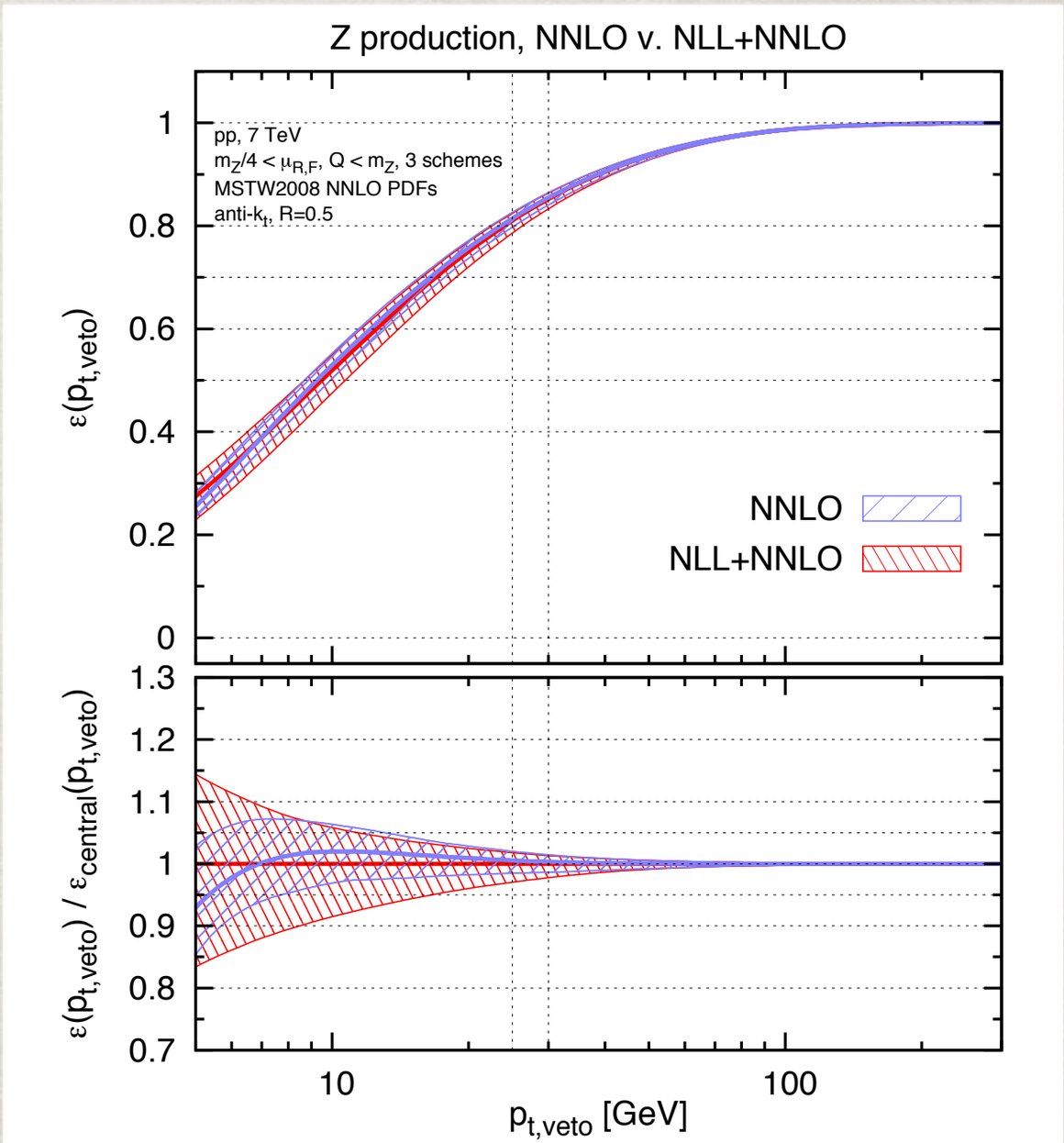


- Total uncertainty: scale variations + central value of schemes b, c

Comparison to NNLO

- NLL+NNLO gives in general a lower efficiency with respect to pure NNLO, with 50% reduction of uncertainty at $p_{t,\mathrm{veto}} = 25\,\mathrm{GeV}$

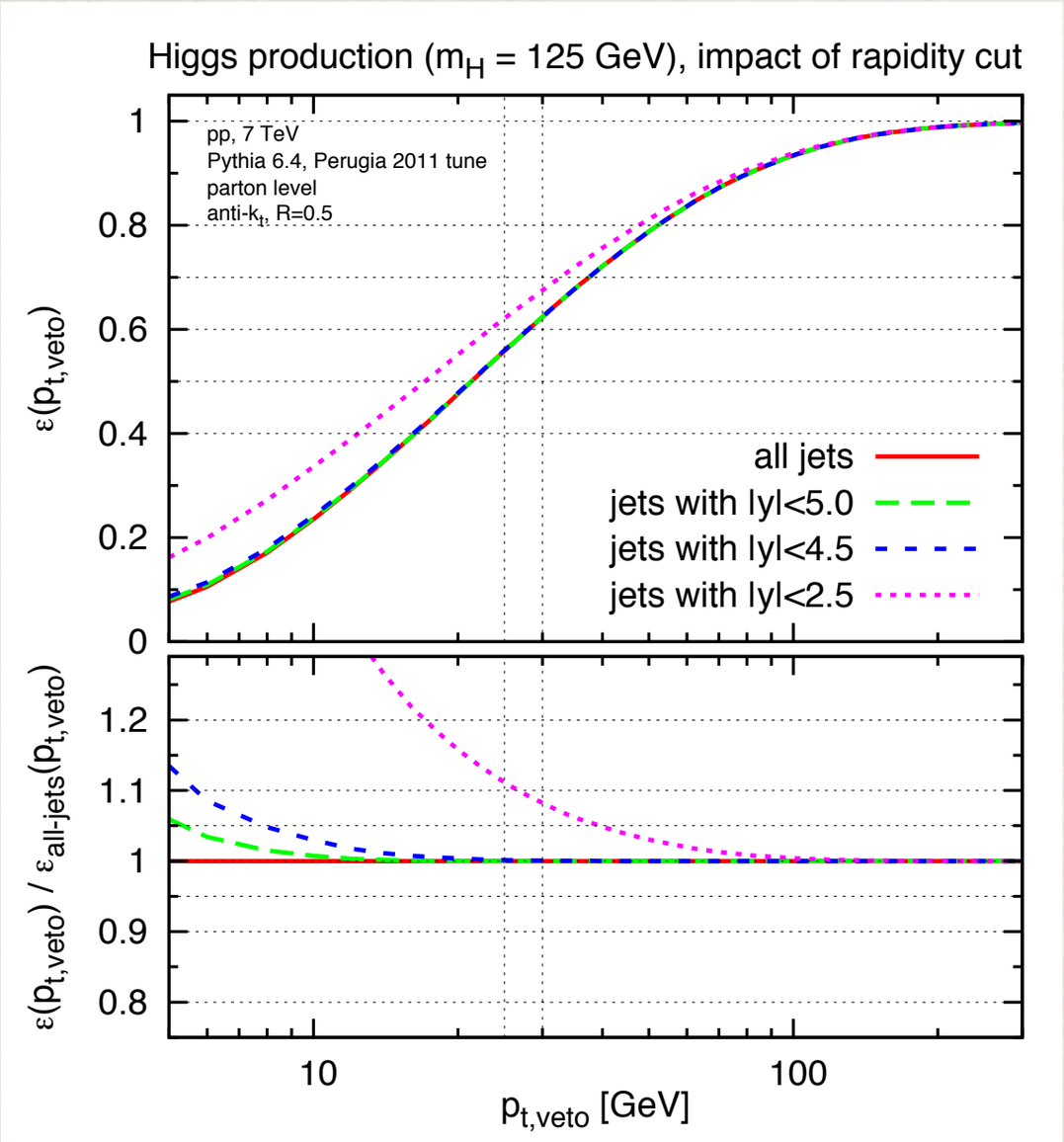


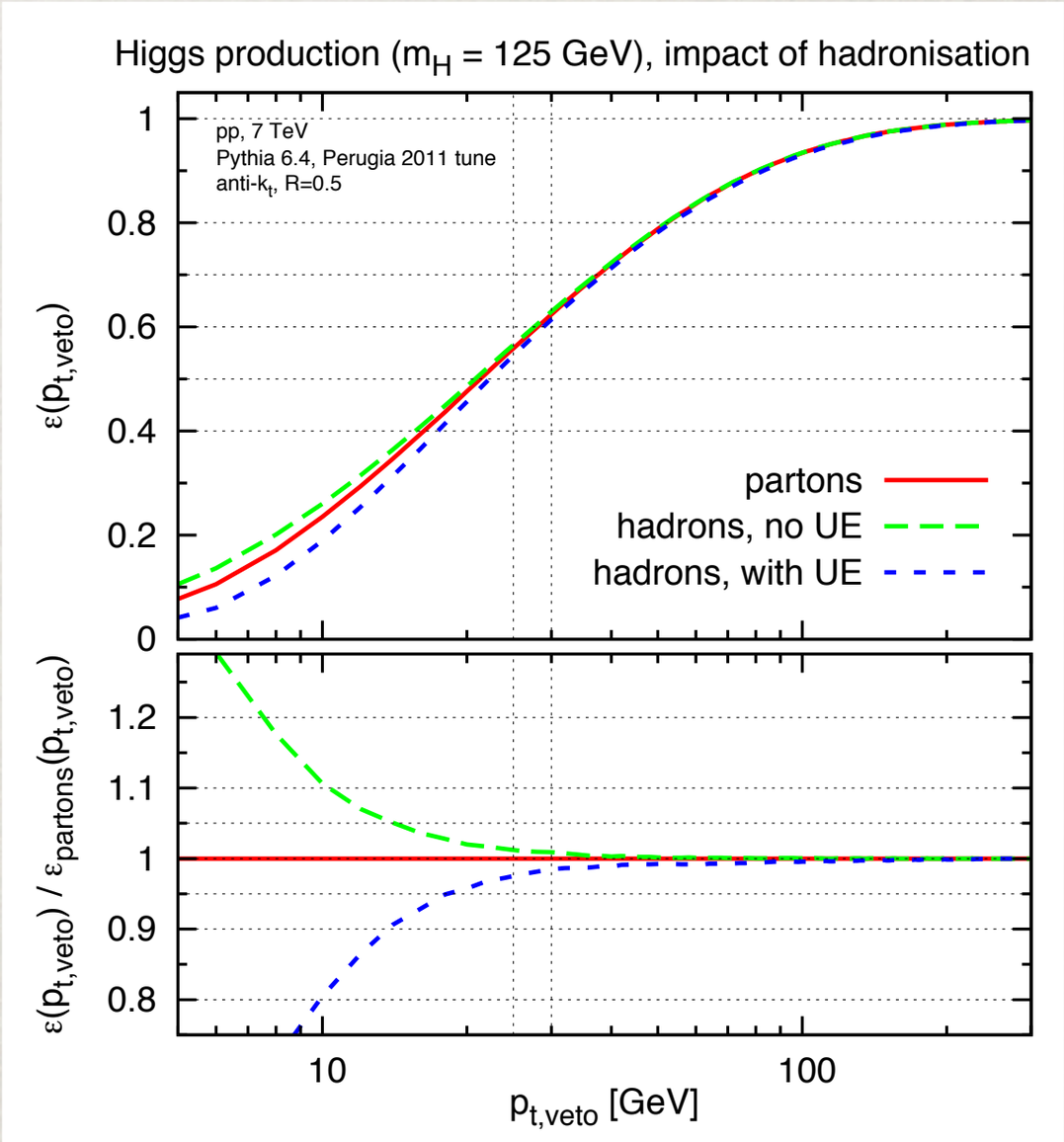


- Difference among schemes is NNNLL, only moderate improvement expected from NNLL at intermediate $p_{t,\mathrm{veto}}$

Real-life issues

- Our resummed calculation considers partonic jets, detected at all possible rapidities (jet-veto efficiency is global)



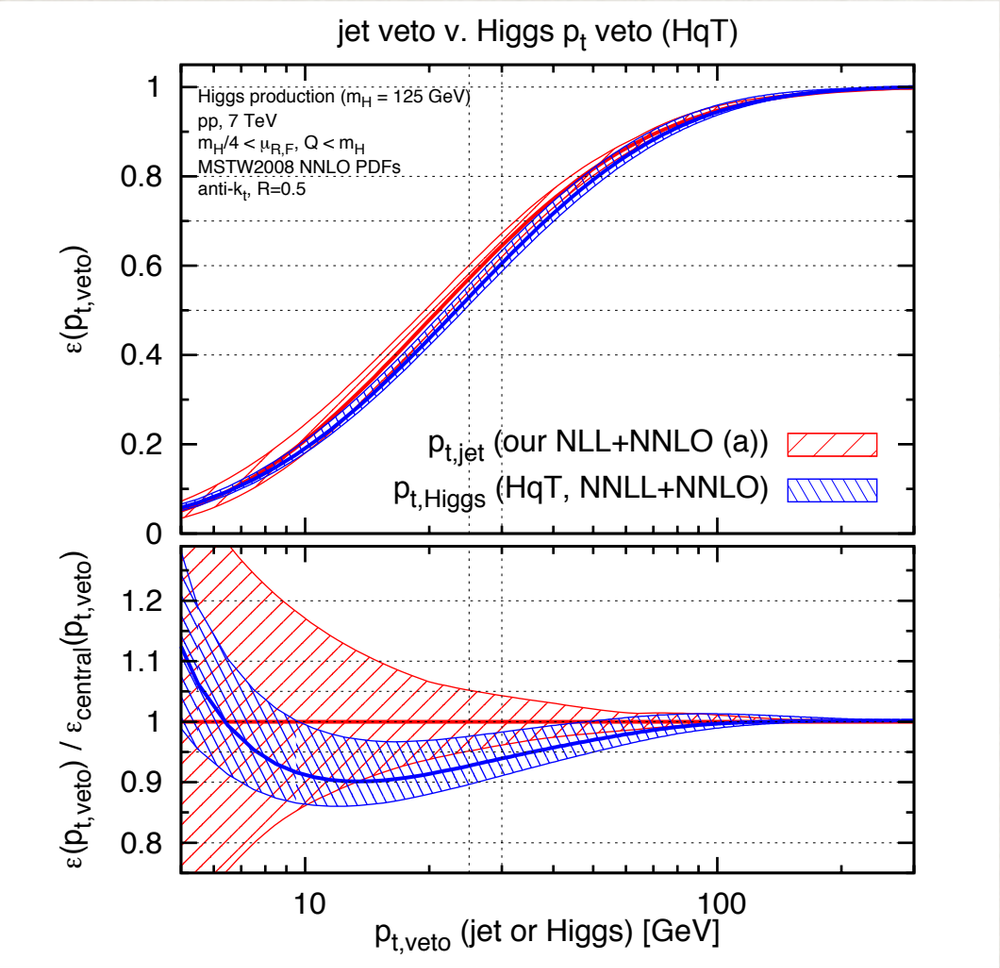


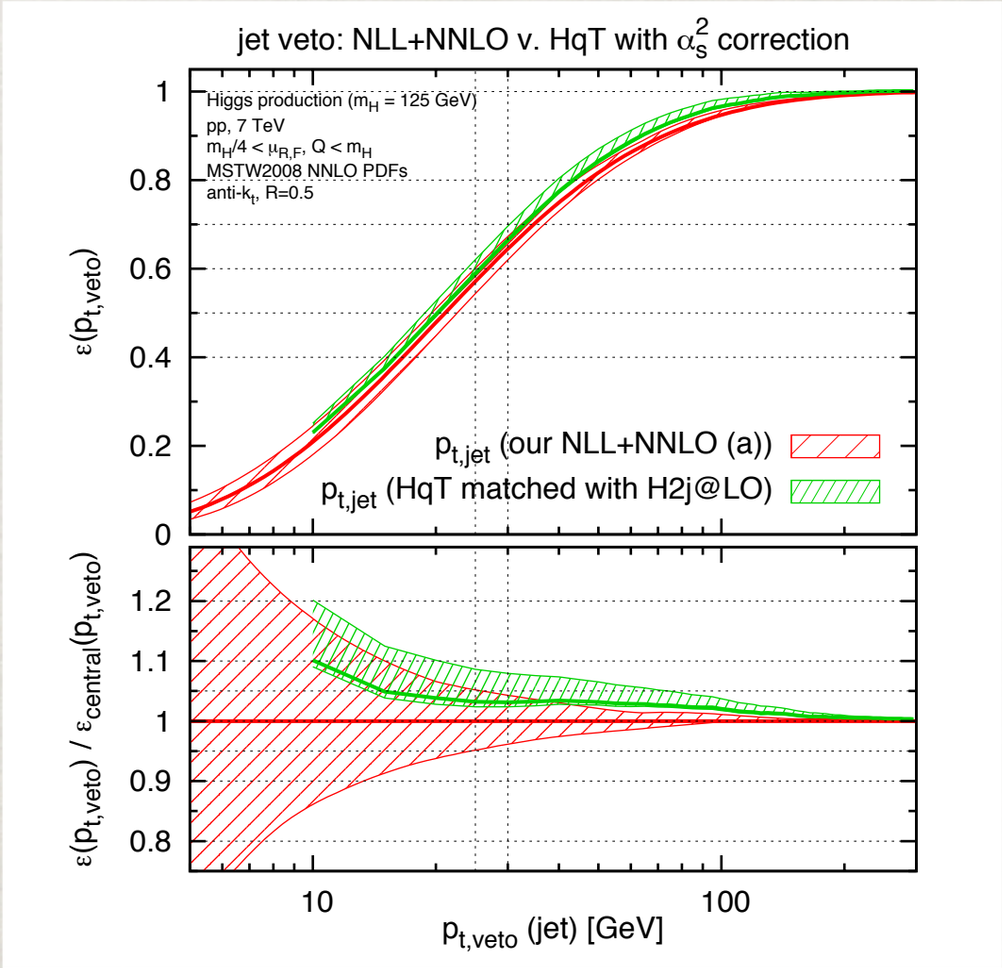
- Hadronisation and finite acceptance corrections are much less than theoretical uncertainties in the reference region

Comparison with HqT

- The observable used for validation of MC event genereators is the Higgs p_t, for which we have NNLL+NNLO (HqT)

[Bozzi Catani de Florian Grazzini '03]

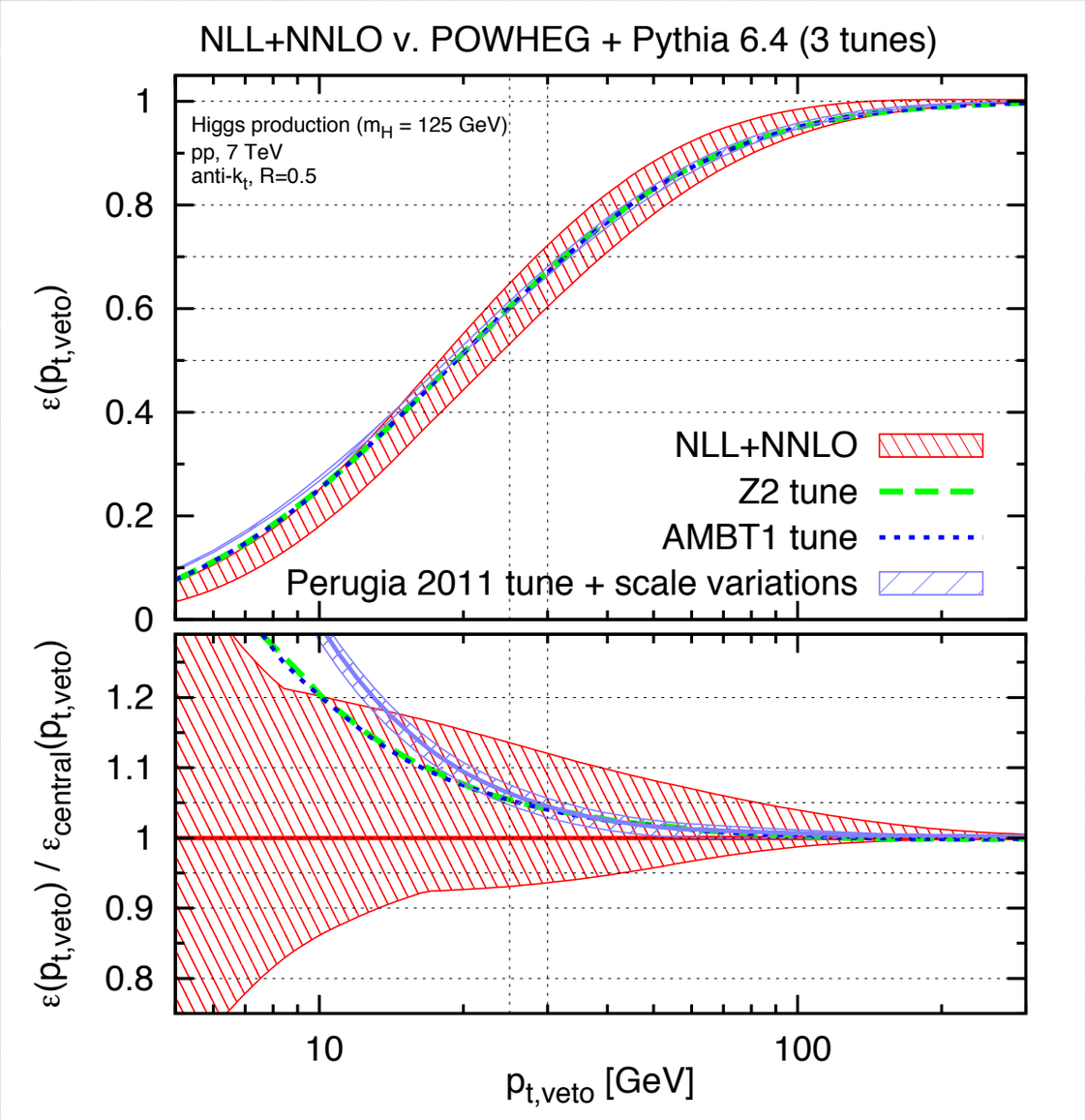


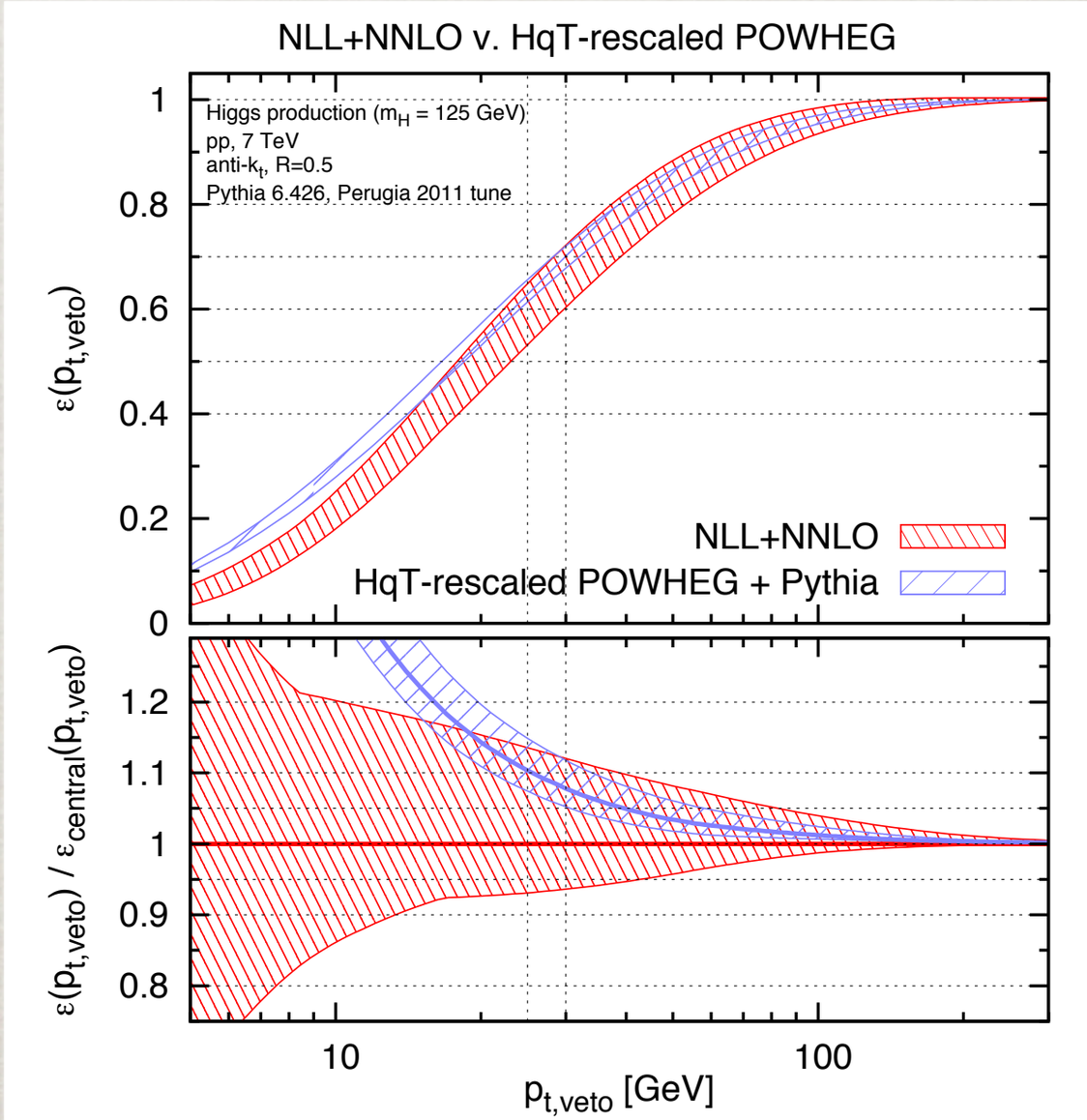


- In the reference region, size of uncertainties of NNLL Higgs p_t and NLL jet veto is comparable $\Rightarrow$ matching corrections dominate
- Consistency between our resummation and NNLL Higgs p_t with addition of NNLL corrections from Higgs+2jet@NLO

Comparison with MC

- Experimental analyses use POWHEG+PYTHIA, rescaled so that it agrees with HqT resummation [Alioli Nason Oleari Re '09]





- Overall agreement within uncertainties in the reference region, although our resummation gives lower efficiency

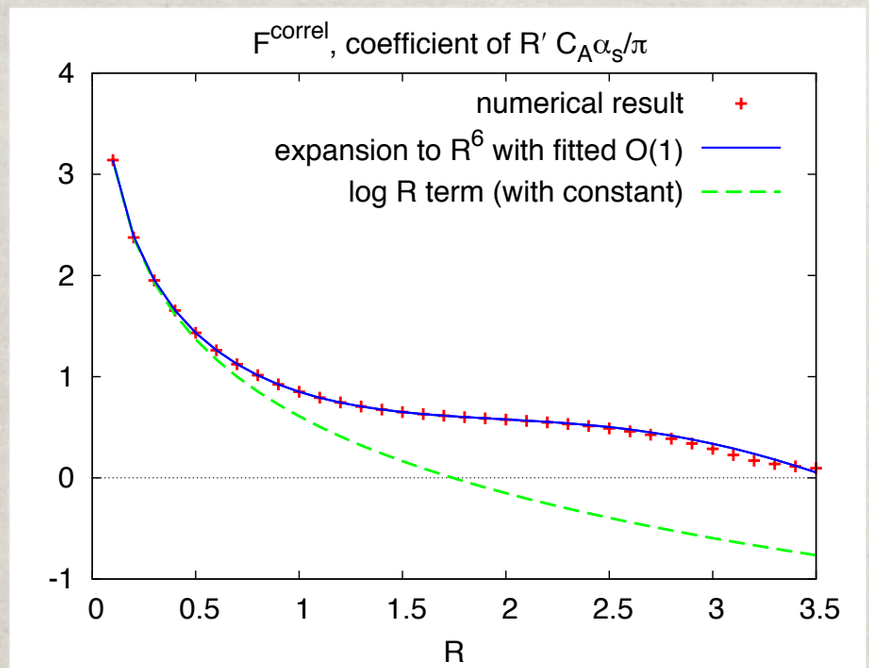
Towards NNLL

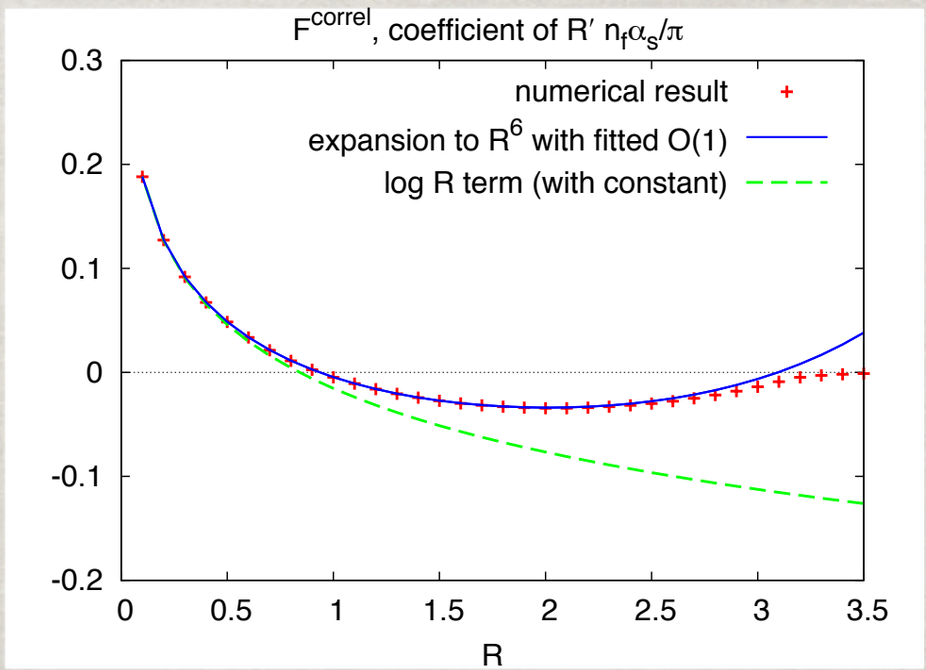
- Using CAESAR's approach we can compute the only NNLL corrections that depend on the jet radius R

$$\epsilon(p_{t,\mathrm{veto}}) \sim e^{-R_{\mathrm{NNLL}}(p_{t,\mathrm{veto}})}\,(1+\mathcal{F}_{\mathrm{correl}}+\mathcal{F}_{\mathrm{indep}})$$

- $\mathcal{F}_{\mathrm{correl}}$ accounts for the effects of two partons coming from the splitting of a soft gluon

$$\mathcal{F}_{\mathrm{correl}} = R'\alpha_s(p_{t,\mathrm{veto}}) \times \Big[C_A\,F_A(R) + n_f\,F_f(R)\Big]$$





- $\mathcal{F}_{\mathrm{indep}}$ accounts for two independent emissions that are clustered into the same jet

$$\mathcal{F}_{\mathrm{indep}} = R'\,\frac{C\alpha_s(p_{t,\mathrm{veto}})}{\pi}\left(-\frac{\pi^2R^2}{12}+\frac{R^4}{16}\right)$$

Conclusions

- We have argued that uncertainties on total Higgs cross-section and jet-veto efficiency are uncorrelated
- We have introduced fixed-order prescriptions as extra handles to estimate theoretical uncertainties for jet-veto efficiencies
- Fixed-order uncertainties are in general reduced by matching NNLO to NLL resummation (performed with CAESAR)
- In the reference region ($p_{t,\mathrm{veto}} \sim 20 - 30\,\mathrm{GeV}$) resummation does not have a huge impact, matching corrections are important
- NNLO+NLL predictions for the efficiency are consistent with those obtained with other theoretical tools (HqT+MCFM, POWHEG+PYTHIA)
- Issues that should be addressed (corrections of order 5%)
  - Impact of NLO corrections to H+2jets
  - Relation between Higgs p_t and jet-veto at NNLL

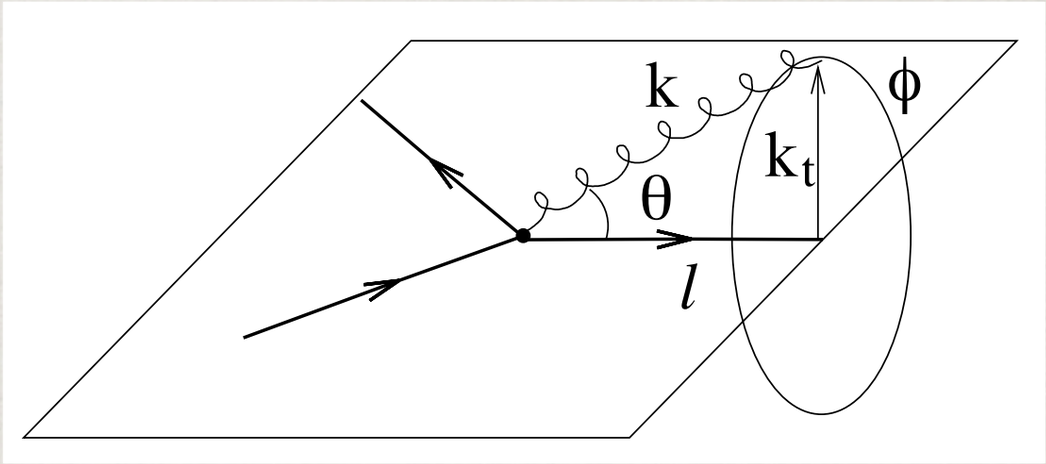
EXTRA SLIDES

NLL resummability

An observable $V(k_1, \ldots, k_n)$ is resummable at NLL accuracy if

- After a single emission k, soft and collinear to any hard leg ℓ, the observable behaves as

$$V(k) = d_\ell \left(\frac{k_t}{Q}\right)^{a_\ell} e^{-b_\ell \eta^{(\ell)}} g_\ell(\phi)$$



For $V(k) = p_{t,\mathrm{jet}}/M_B$ we have $a_\ell = d_\ell = g_\ell = 1$ and $b_\ell = 0$

- V is continuously global, sensitive to emissions in the whole of the phase space $\Rightarrow$ satisfied since $p_{t,\mathrm{jet}} \sim k_t$ everywhere
- V is recursively IR and collinear safe, a non-trivial condition on the observable's scaling with multiple emissions $\Rightarrow$ also satisfied for $p_{t,\mathrm{jet}}$, which can then be resummed with CAESAR