Resummation for jet veto in $H \longrightarrow WW$

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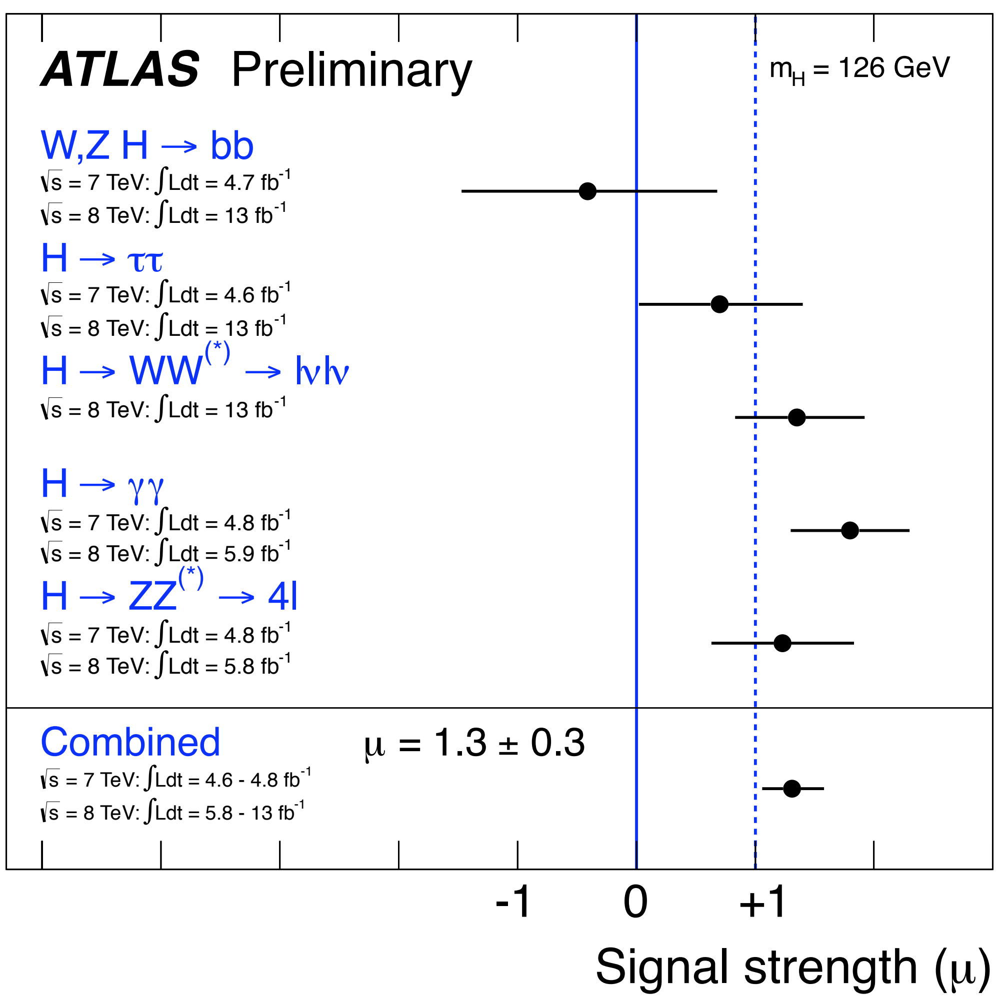
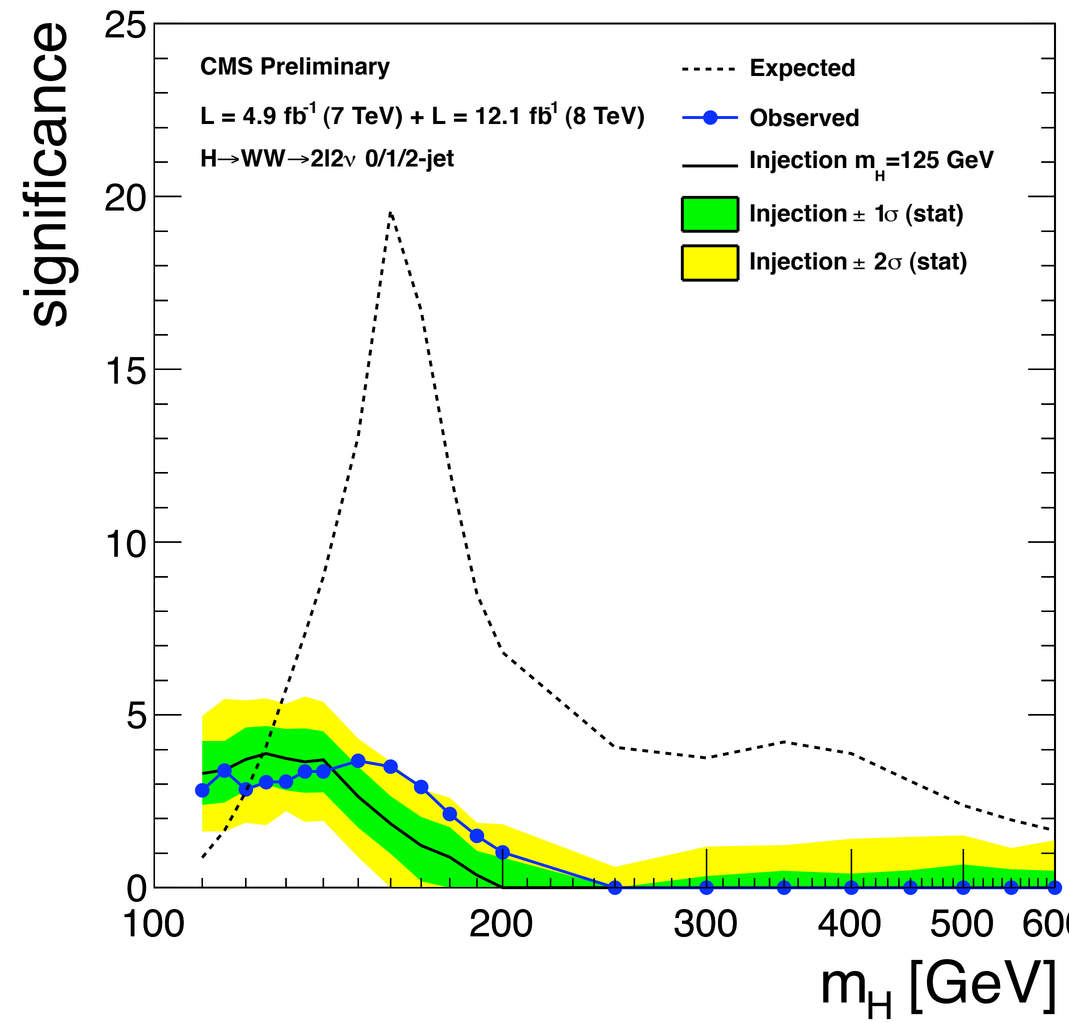
Searches in H⟶WW

- $H \to W^+W^- \to l^+\nu^- l^-\nu^+$ channel relevant for coupling measurements

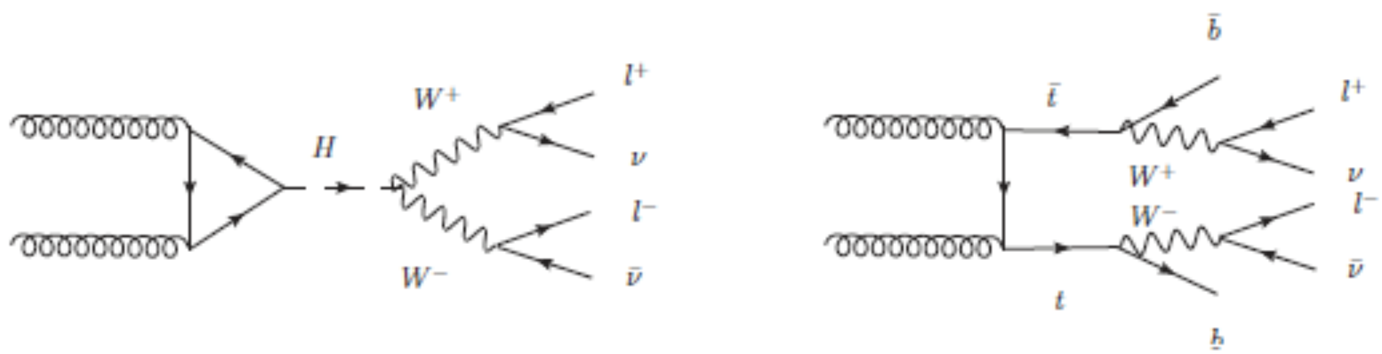




- Recent results from CMS show a $3.1\,\sigma$ excess w.r.t. the background-only hypothesis ($4.1\,\sigma$ is expected assuming the SM prediction)

Jet Veto in Higgs searches

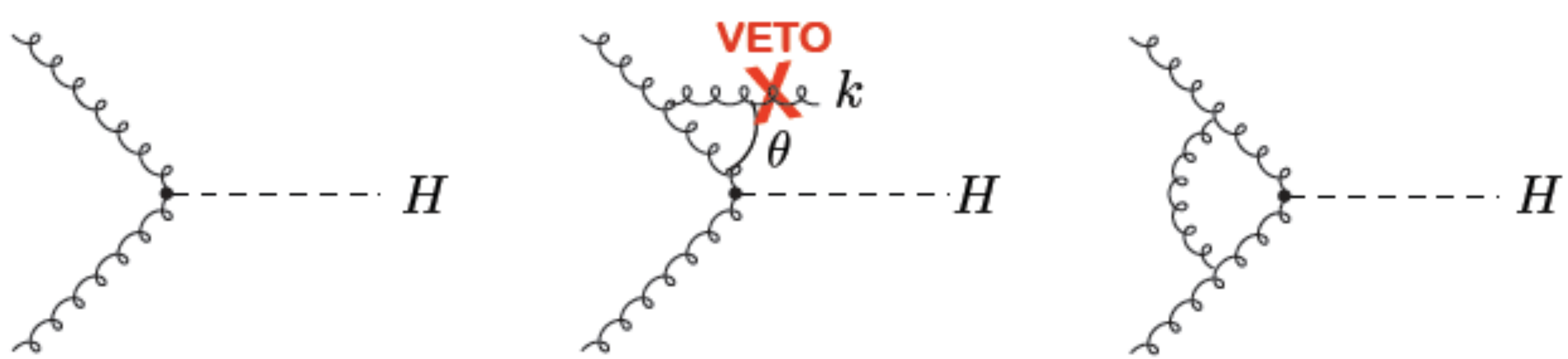
- Main background: WW, W/Z + jets, $t\bar{t}$, ...
- Categorization according to lepton flavour and jet multiplicity to optimize sensitivity
- Imposing a veto (0-jet bin) on p_t of jets massively suppresses the background from $t\bar{t}$ production



- Additional topological cuts on leptons for further background reduction
- Often in practice aggressive cuts give rise to large logarithms

The 0-jet bin

- To extract couplings, we need to know the fraction of signal events (mainly $gg \to H$) that survives the veto $p_{t,veto}$ on the ISR
- Normal veto scales $p_{t,veto} \sim 25 - 30\,\mathrm{GeV} \ll M$ may lead to large logarithms
  - *e.g.* emission of a soft ($\omega \ll M$) and collinear ($\theta \ll 1$) gluon



$$\sigma_{0-jet} \simeq \sigma_0 \left(1 + C_A \frac{\alpha_s}{\pi} \int \frac{d\omega}{\omega} \frac{d\theta^2}{\theta^2} \left(\Theta(p_{t,veto} - \omega\theta) - 1\right)\right) \simeq \sigma_0 \left(1 - 2C_A \frac{\alpha_s}{\pi} \ln^2 \frac{M}{p_{t,veto}} + \ldots\right)$$

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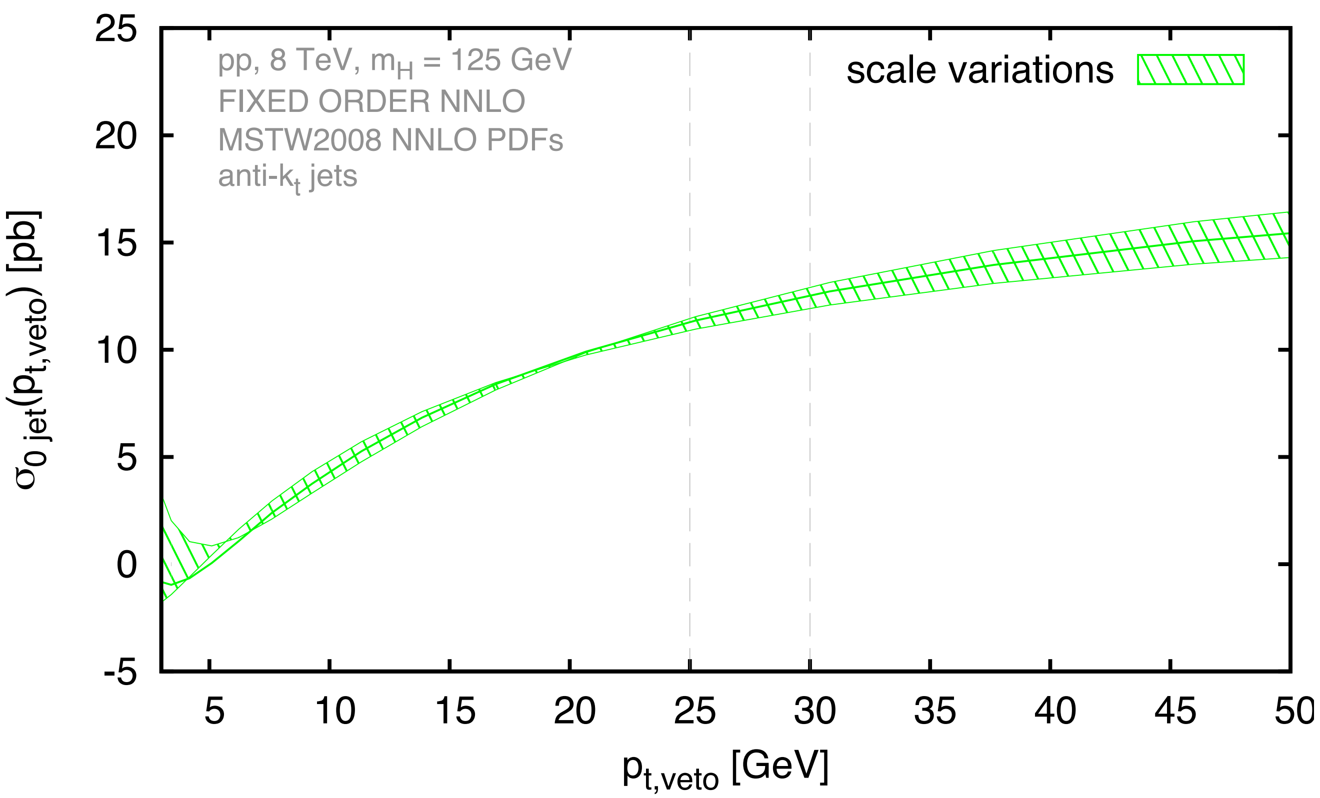
→ Problems for fixed-order perturbation theory !

Theoretical uncertainties in fixed-order

- Huge cancellations in σ_{0-jet} between large K-factor (σ_{tot}) and large Sudakov logs ($\sigma_{\geq 1jet}$)

$$\sigma_{0-jet} = \sigma_{tot} - \sigma_{\geq 1jet} \sim \sigma_0 \left(K - 2C_A \frac{\alpha_s}{\pi} \ln^2 \frac{M}{p_{t,veto}} \right)$$

- Naive scale variation underestimates the th. uncertainty



- NNLO fixed-order prediction
  [Anastasiou et al. '04; Grazzini et al. '07]

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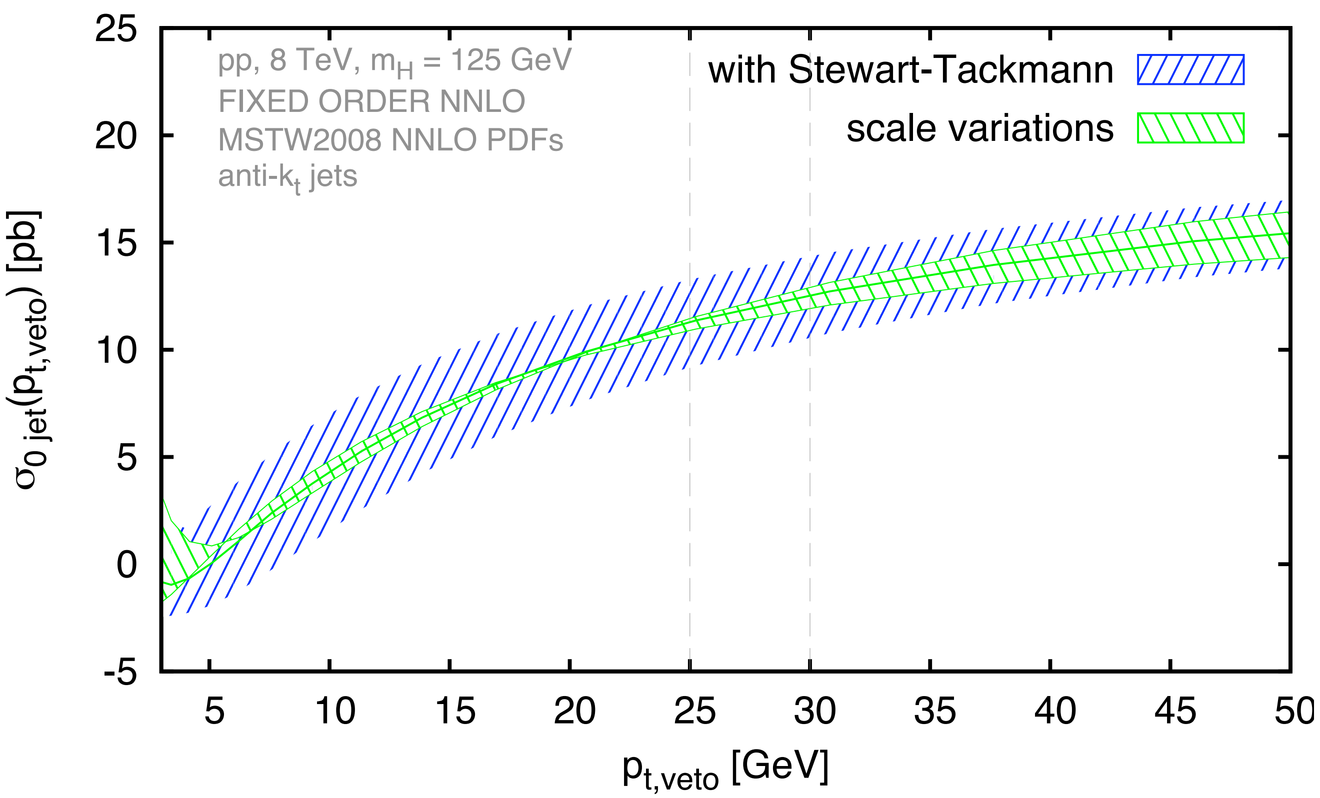
- Stewart-Tackmann '11: treat uncertainties in σ_{tot} and $\sigma_{\geq 1jet}$ as uncorrelated and combine inclusive bin uncertainties in quadrature



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- Banfi et al. '12: use jet-veto efficiency

  - large K-factor effects in σ_{tot}

  - Sudakov suppression in $\epsilon = \sigma_{0-jet}/\sigma_{tot}$:
    K factor effects largely cancel in the ratio

  - Treat jet-veto efficiency and total cross section uncertainties as uncorrelated.

Theoretical uncertainties in fixed-order

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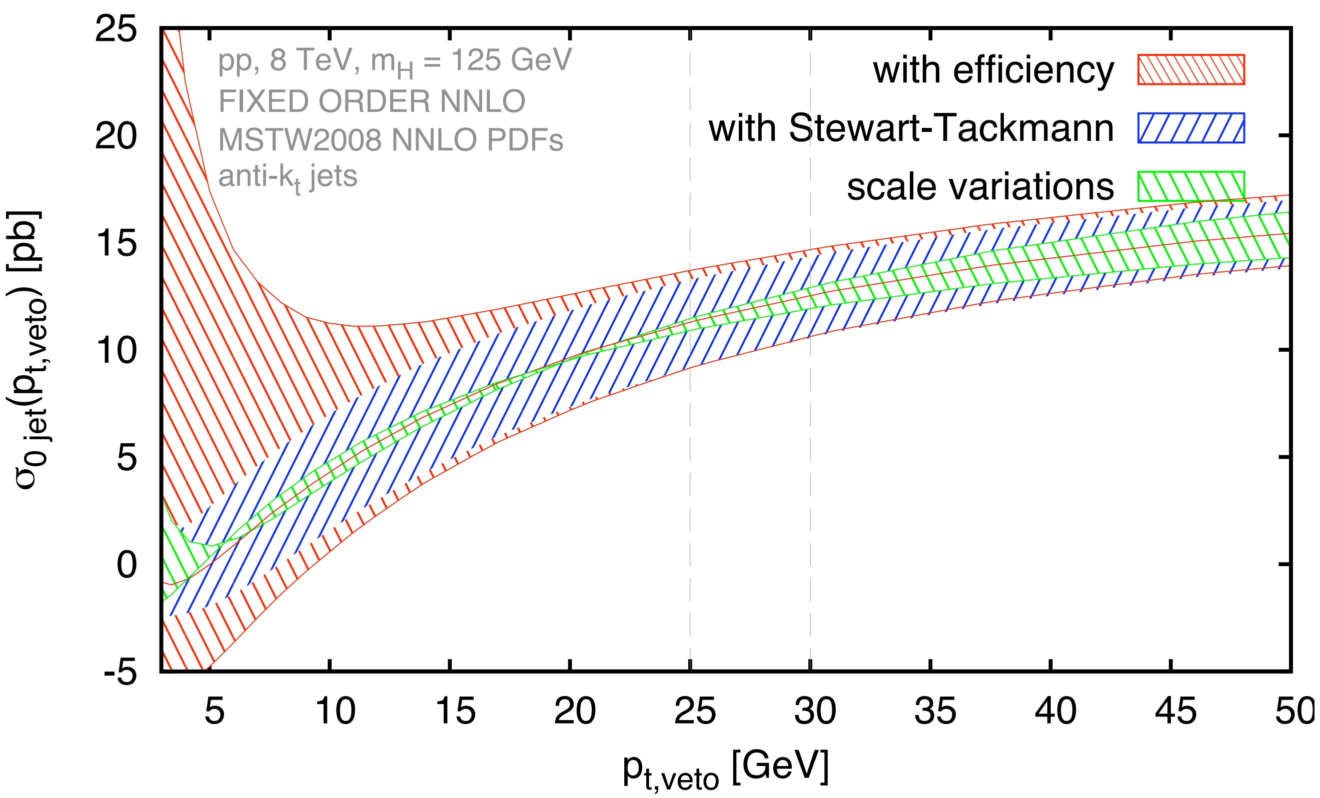

- Three possible definitions of efficiency at NNLO (in general n + 1 schemes at N^nLO)

- Use them jointly with scale variation

Uncert. $\sim 16\%$

Resummation of jet-veto logarithms

- How to improve uncertainty estimate ? Need to resum Sudakov logarithms
- Resummation of large logarithms:
    - NNLL resummation for related quantities (Higgs p_t and beam thrust)
      [Bozzi et al. '03; Becher et al. '10, Berger et al. '11]
    - NLL resummation for $\ln M/p_{t,veto}$
      [Banfi, Salam, Zanderighi '12]
    - NNLL resummation for $\ln M/p_{t,veto}$
        - CAESAR-like approach [Banfi, PFM, Salam, Zanderighi '12]
        - SCET approach
          [Becher, Neubert '12]

Initial disagreement between the two results now fixed.
The two groups agree on the NNLL result !
SCET factorisation beyond NNLL queried by Tackmann et al. '12

Resumming large logarithms

- Automated resummation for a jet observable can be carried out under some applicability conditions (*i.e.* rIRC safety, continuous globalness)

[Banfi, Salam, Zanderighi '01/'02]

- Resummation structure for $\sigma_{0-jet}(p_{t,veto})$ remarkably simple:

$$\sigma_{0-jet}(p_{t,veto}) = \qquad |M_B|^2 e^{-R(p_{t,veto})}$$

  - Double logarithms exponentiate: Sudakov factor
    - Encodes soft-collinear virtual contributions at scales larger than $p_{t,veto}$
    - Obtained from a single dressed (up to $\mathcal{O}(\alpha_s^3)$) gluon emission
    - Identical to boson-p_t resummation up to NNLL (not beyond!)

[Bozzi et al. '03; Becher, Neubert '10]

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$$\sigma_{0-jet}(p_{t,veto}) = \mathcal{L}(p_{t,veto})|M_B|^2 e^{-R(p_{t,veto})}$$

  - Double logarithms exponentiate: Sudakov factor
  - Luminosity pre-factor $\mathcal{L}(p_{t,veto})$ contains:
    - parton luminosity evaluated at $\mu_F \simeq p_{t,veto}$
    - hard virtual corrections to the Born up to $\mathcal{O}(\alpha_s(\mu_R))$
    - collinear coefficient functions up to $\mathcal{O}(\alpha_s(p_{t,veto}))$

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$$\sigma_{0-jet}(p_{t,veto}) = \mathcal{L}(p_{t,veto})|M_B|^2 e^{-R(p_{t,veto})}\mathcal{F}(R')$$

$$R' = -p_{t,veto}\frac{dR(p_{t,veto})}{dp_{t,veto}}$$

  - Double logarithms exponentiate: Sudakov factor

  - Luminosity pre-factor $\mathcal{L}(p_{t,veto})$

  - Multiple emission function $\mathcal{F}(R')$: encodes the single logarithmic (up to NNLL) contribution from arbitrarily many soft and/or collinear emissions

    - Result fully analytic. Explicit dependence on jet radius at NNLL

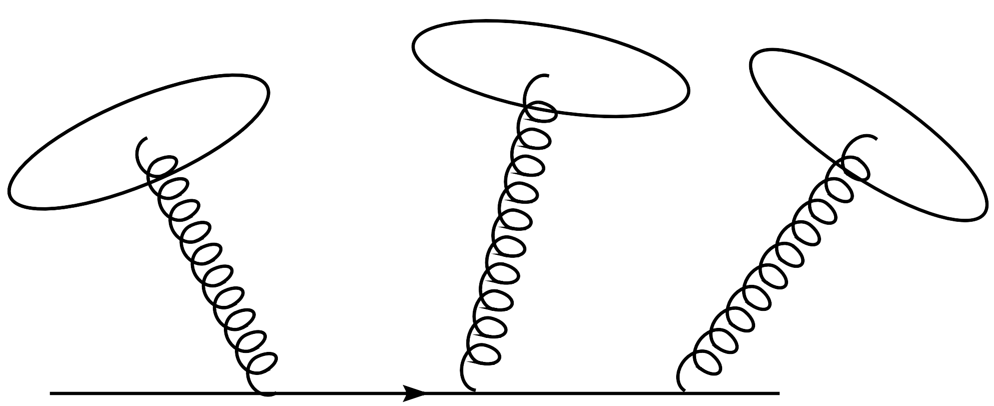
All-order structure to NNLL

- Multiple emissions @ NLL: as $p_{t,veto} \to 0$ the emissions are independent and widely separated in rapidity (single-log accuracy), so no clustering occurs.

[Banfi, Salam, Zanderighi '12]

  - each emission gives a jet, only the hardest is vetoed

  - Information contained in Sudakov factor, yielding $\mathcal{F}(R') = 1$ @ NLL



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[Banfi, Salam, Zanderighi '12]

- Multiple emissions @ NNLL: two non-trivial NNLL corrections

  - any number of emissions + 2 gluons cluster into one jet

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

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- Multiple emissions @ NNLL: two non-trivial NNLL corrections

  - any number of emissions + 1 gluon splits into two jets

$$\mathcal{F}_{\rm correl} = \frac{\alpha_s(p_{t,veto})}{\pi} R'(p_{t,veto}) \left(\frac{-131 + 12\pi^2 + 132\ln 2}{72} C_A + \frac{23 - 24\ln 2}{72} n_f \right) \ln\frac{1}{R} + \quad \cdots$$

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Result checked with MCFM's H+2j@NLO up to $\mathcal{O}(\alpha_s^3)$

Good agreement for different R values.

Matching to fixed-order

- Resummation provides a direct handle to estimate the impact of missing Sudakov logarithms (*i.e.* resummation scale variation)

- Alternatively, one can obtain resummed predictions for the jet-veto efficiency and treat the resulting uncertainty with the efficiency method

    - Define three matching schemes to NNLL+NNLO in one to one correspondence with the three schemes for the FO efficiency

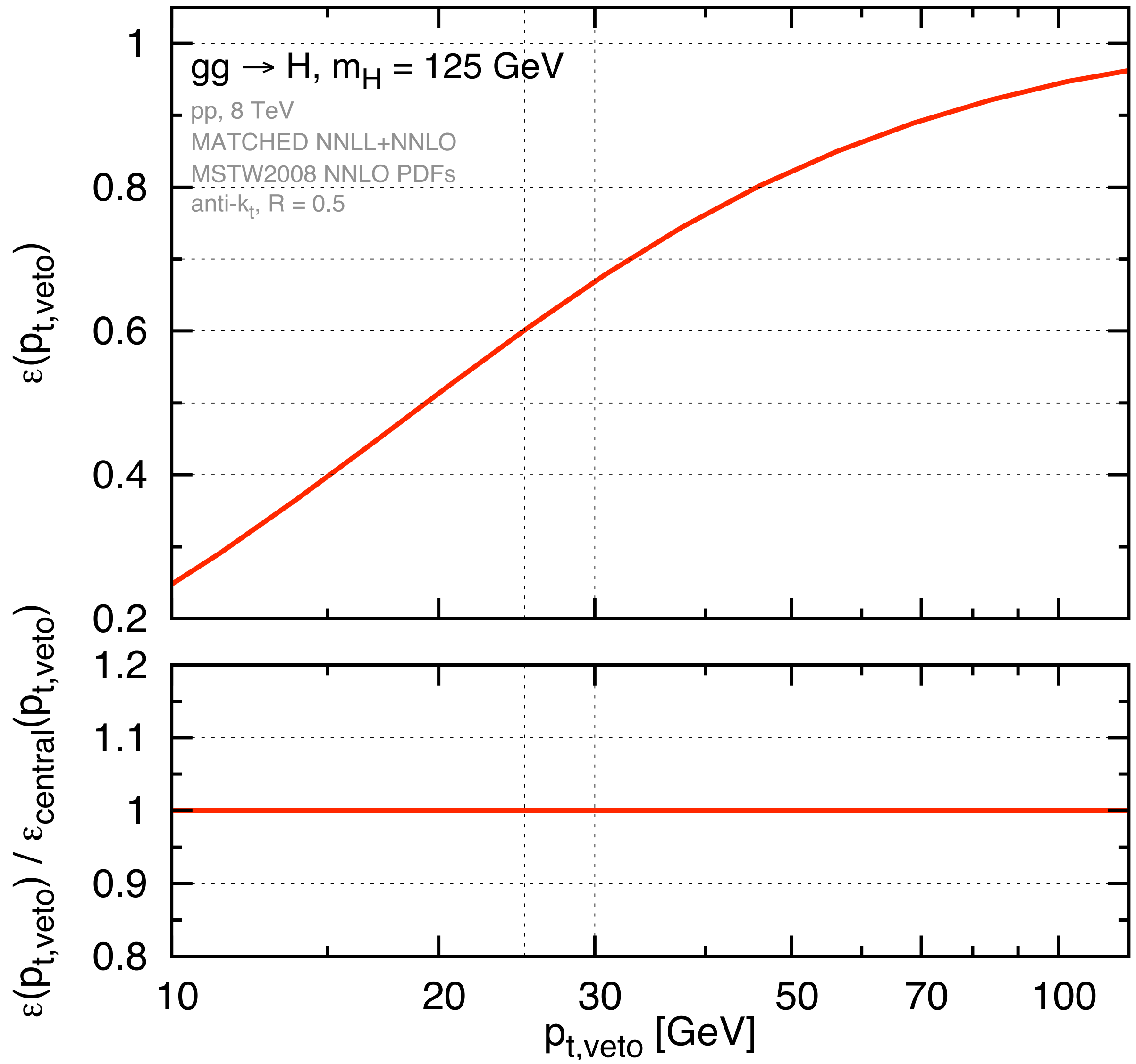
    - The three schemes differ by subleading effects

    - Varying the scheme leads to an additional systematic uncertainty

Resummation uncertainties

- Central value: scheme (a) with

$$\mu_R = \mu_F = Q = M/2$$



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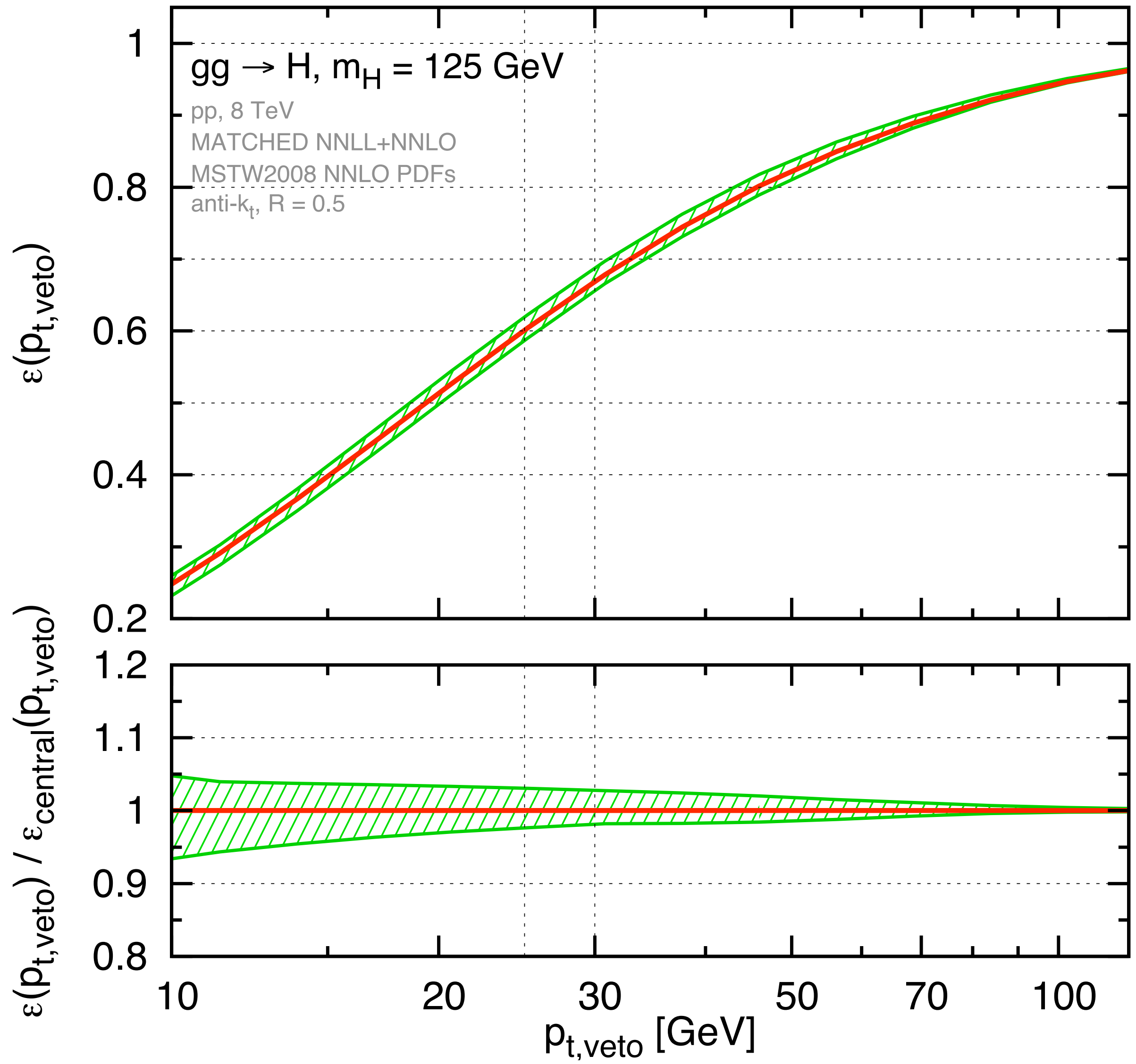
- μ_R and μ_F variations

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



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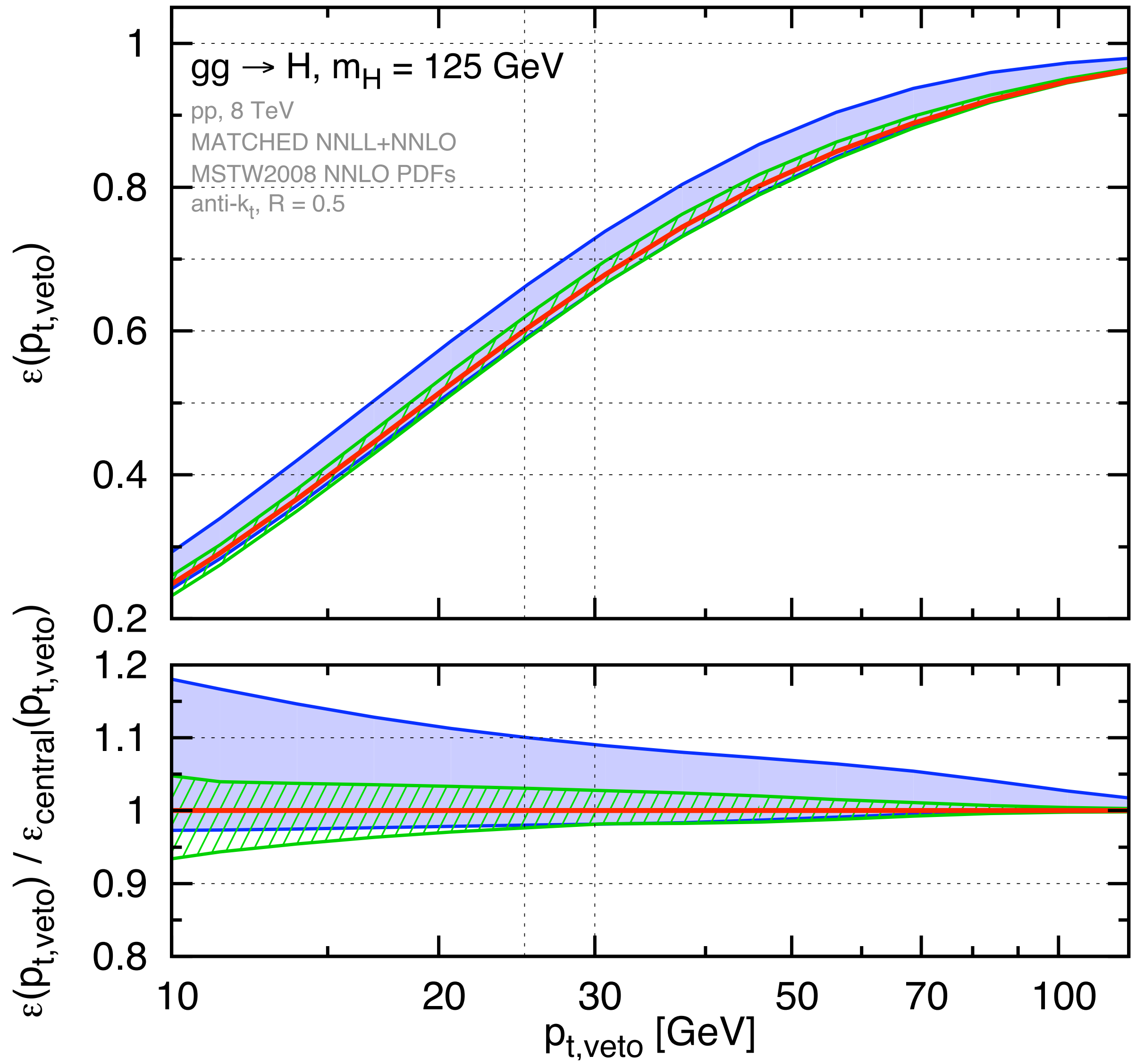
- Resummation scale (Q) variation

i.e.

$$\ln \frac{M}{p_{t,veto}} \to \ln \frac{Q}{p_{t,veto}}$$

$$\frac{M}{4} \le Q \le M \qquad \mu_{R,F} = M/2$$



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- Schemes (b) and (c) with

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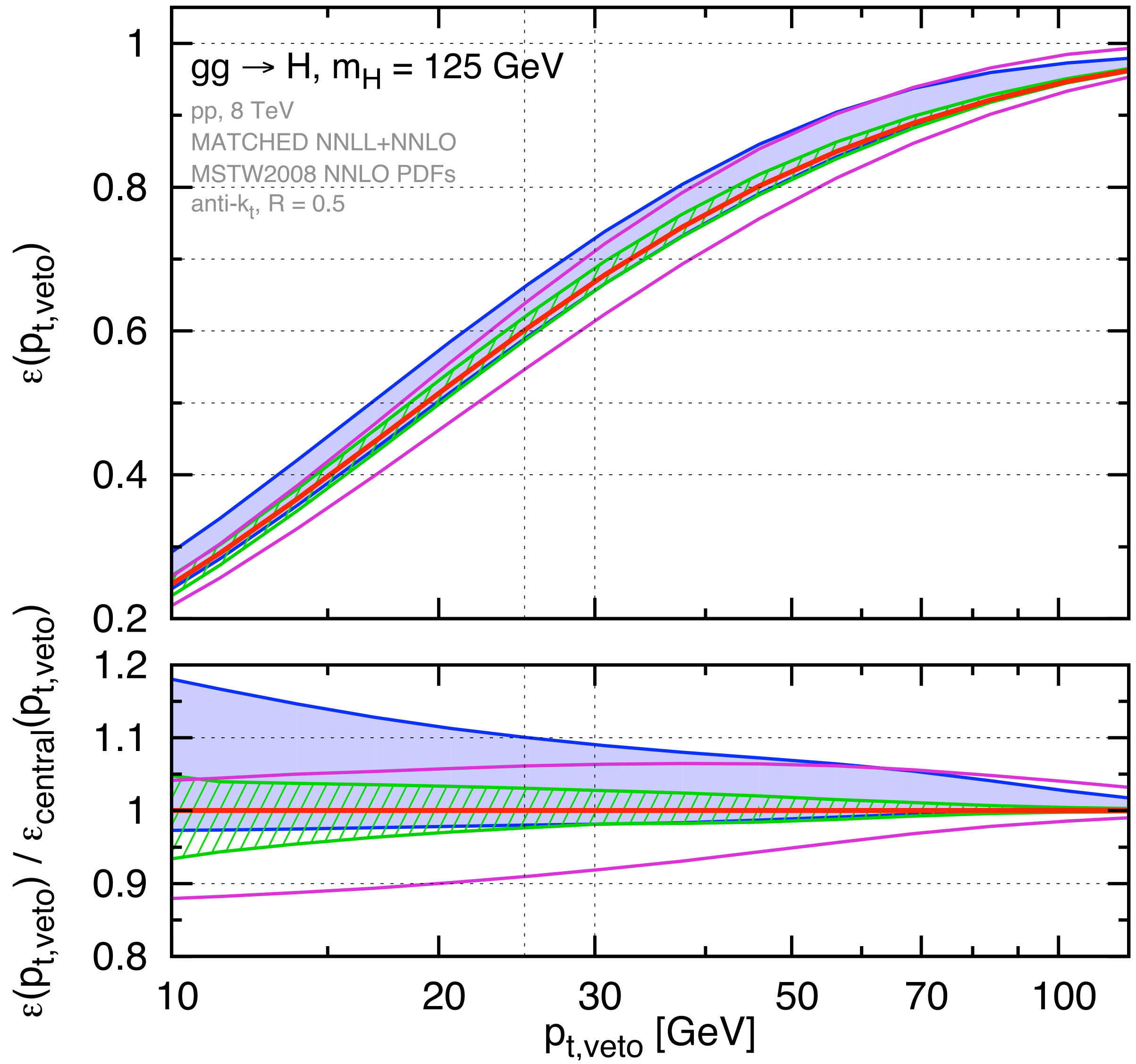

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- Schemes (b) and (c) with

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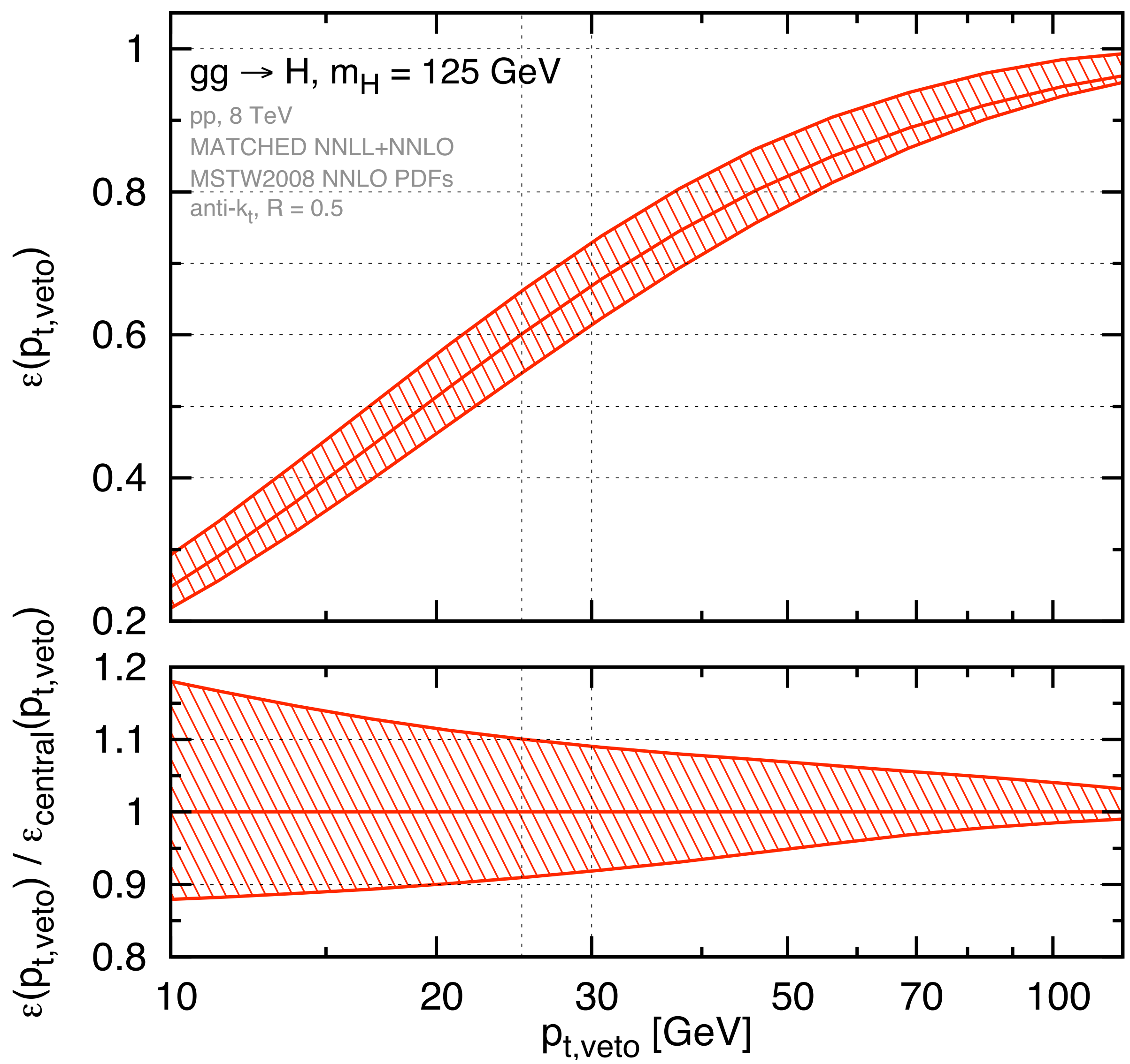
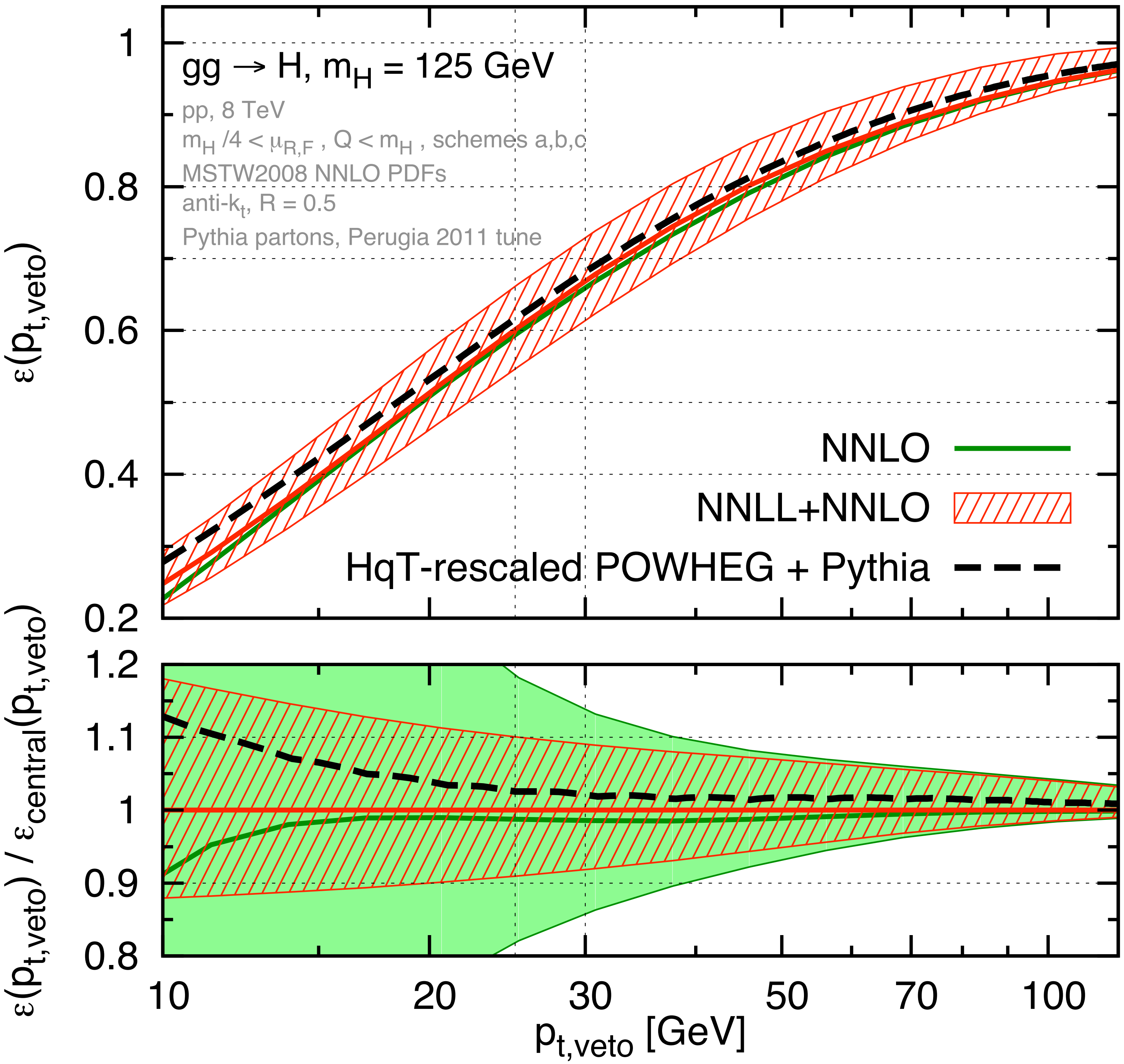
Total uncertainty = envelope

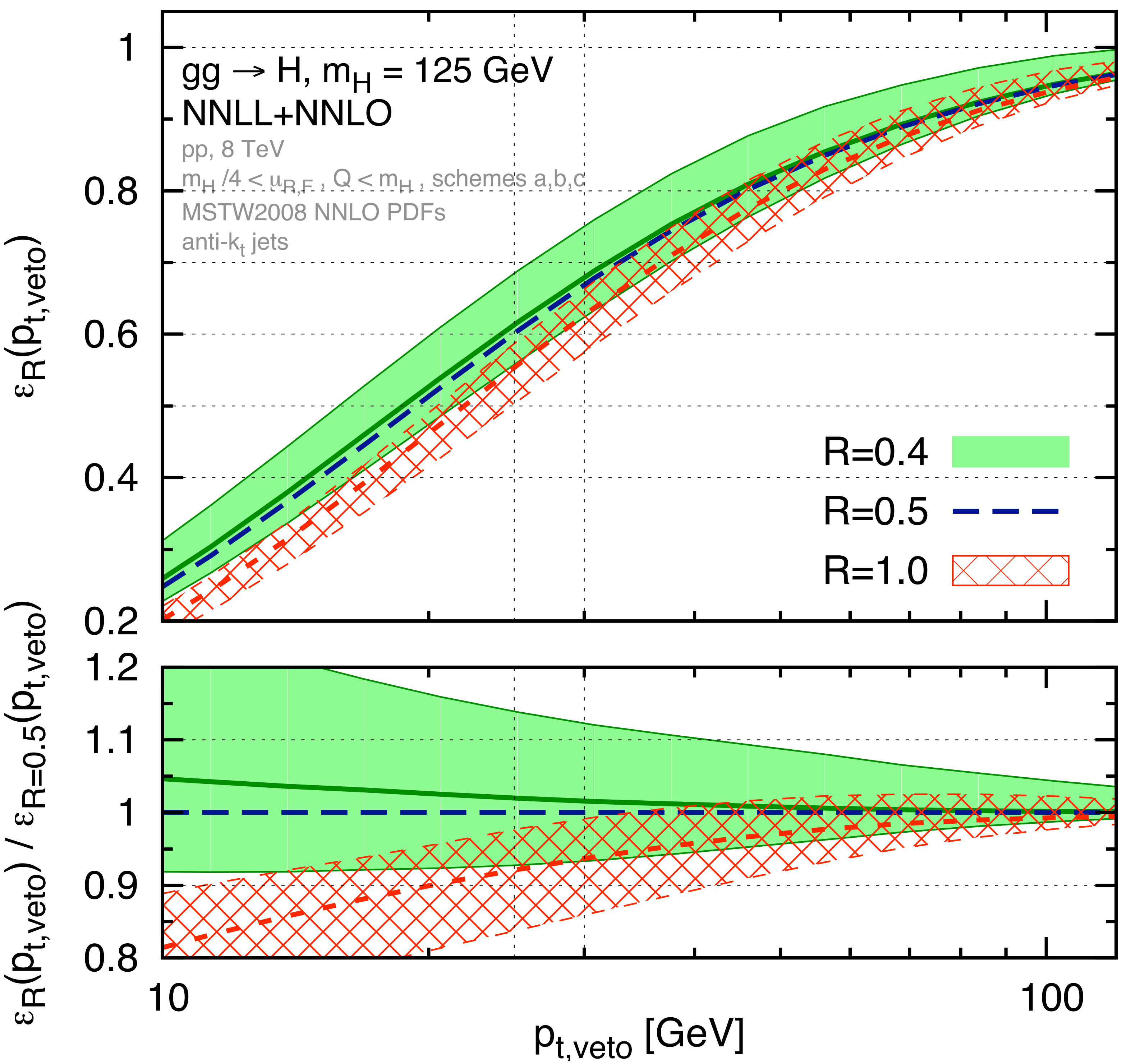


Comparison to NNLO & MC



- NNLL reduces FO uncertainties from $\sim 15\%$ to $\sim 9\%$ (still large because of R-dep. terms)
- Good agreement on central values
- Nice agreement with POWHEG+Pythia reweighted with HqT
- MC uncertainties smaller (harder to estimate)

Choice of the jet radius R



- All-order terms of the form (*e.g.* $\mathcal{F}_{\rm correl}$)

$$\alpha_s^n \ln^{n-1} \frac{1}{R}$$

- For $R \ll 1$ they become large ... and should be resummed

[Tackmann, Walsh, Zuberi '12]

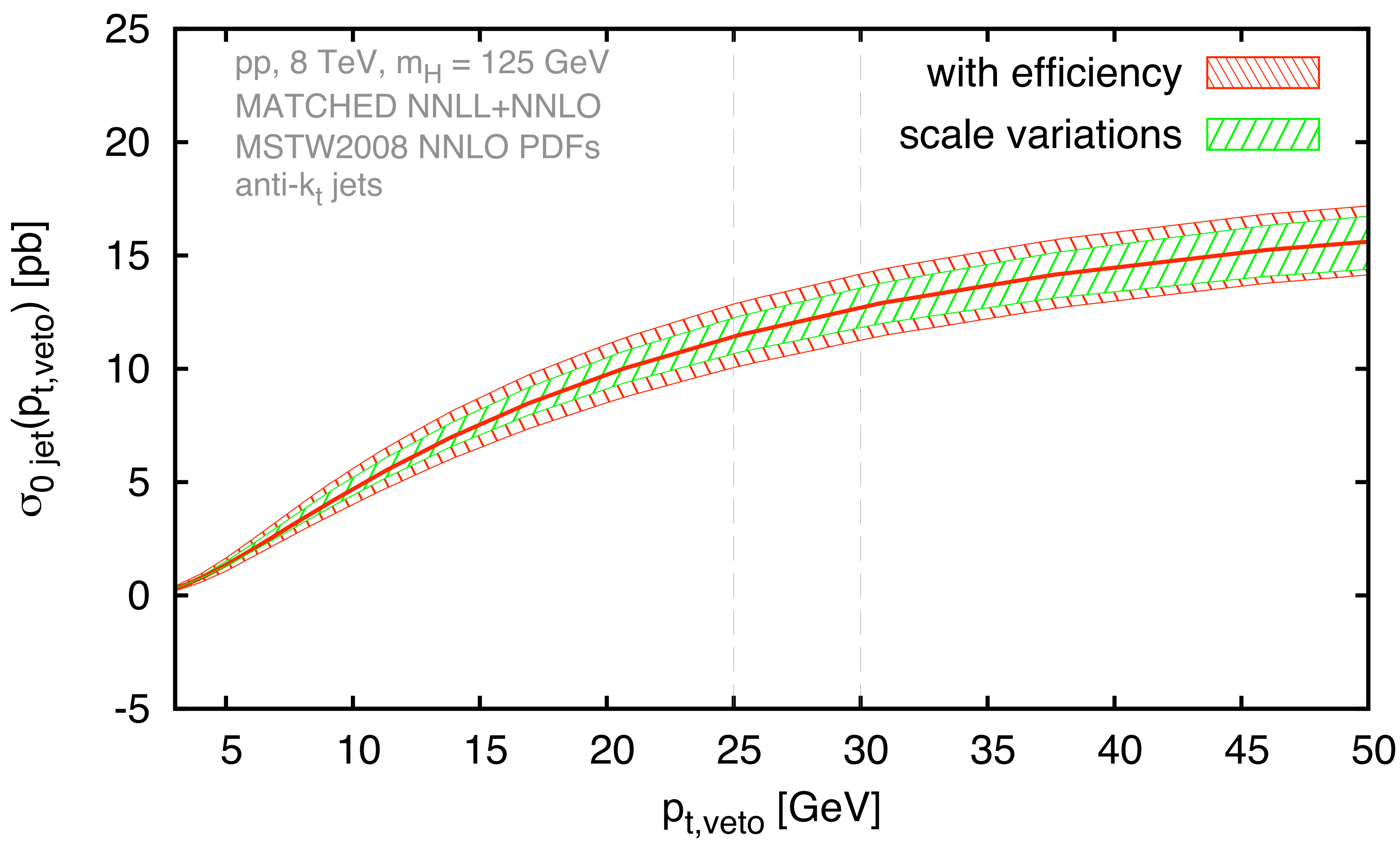
- Choosing $R \sim 1$ reduces the uncertainties

- Higher contamination from UE ($\sim R^2$) and pileup ... filtering ?

Uncertainties of the 0-jet cross section

- Use resummation (with or without efficiencies) to obtain direct predictions for the exclusive 0-jet cross section

single matching scheme in green band



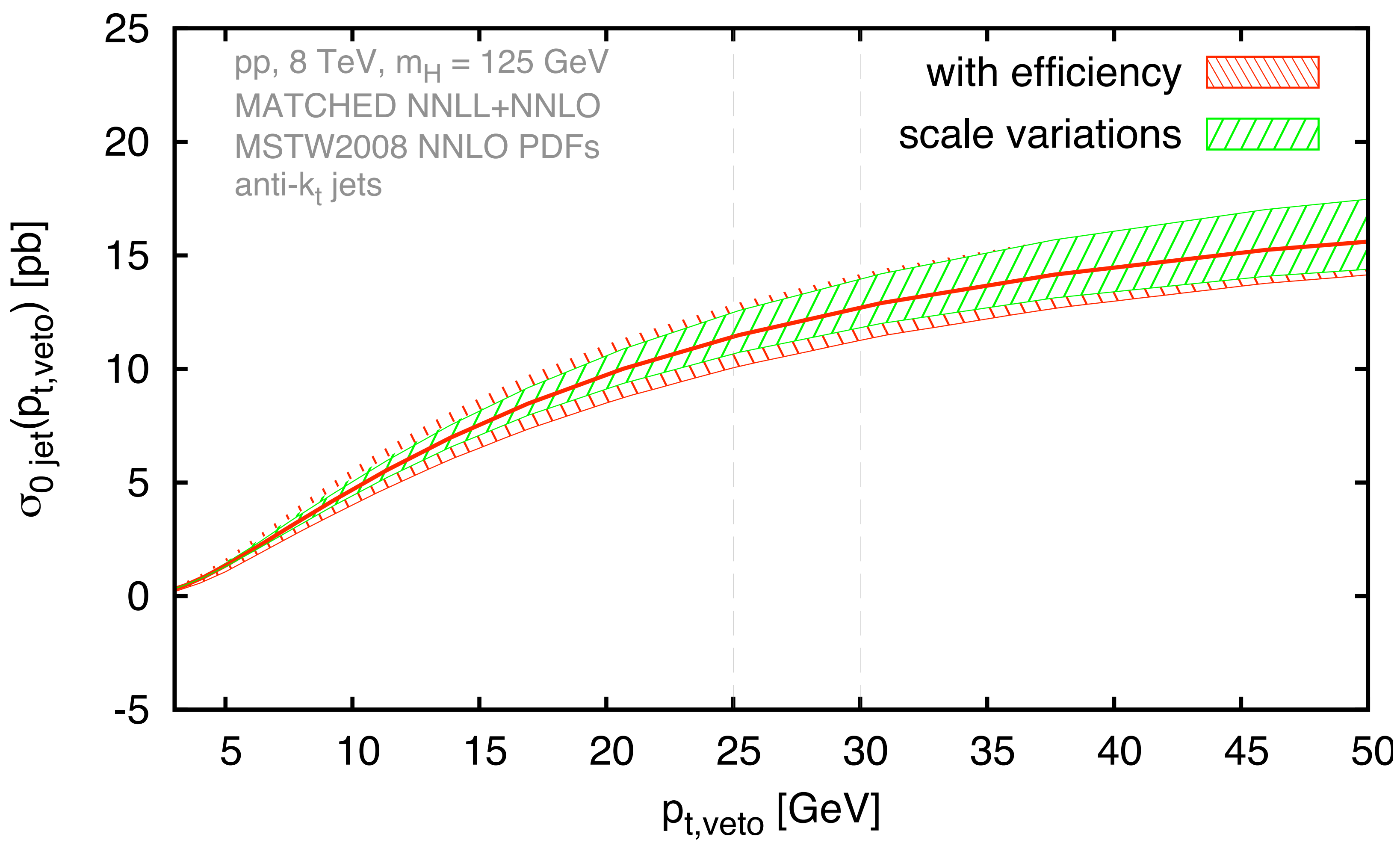
- Small difference mainly due to matching scheme uncertainty in efficiency method

Uncertainties of the 0-jet cross section

- Use resummation (with or without efficiencies) to obtain direct predictions for the exclusive 0-jet cross section

two matching schemes

in green band



- Robust uncertainty estimate $\sim 10\% - 11\%$

Public code at: http://jetvheto.hepforge.org

Conclusions

- Recent progress in resummation of observables involving jets allows for precise assessment of the theory uncertainty (+ efficiency method) in the 0-jet bin
    - Correlation with the inclusive 1-jet bin can be computed too
- Some questions still open :
    - large NNLL + NNLO uncertainty → H+1jet@NNLO desirable
      Recently first developments on Sudakov resummation
    - choose larger R values jointly with jet substructure techniques ?
- The method presented can be extended easily to include rapidity cuts and it can be applied to the production of any colour singlet (*e.g.* HW, WW, ...)

Backup Slides

Covariance matrix

- Stewart-Tackmann: $\sigma_{0-\mathrm{jet}} = \sigma_{\mathrm{tot}} - \sigma_{\geq 1-\mathrm{jet}}$, with σ_{tot} and $\sigma_{\geq 1-\mathrm{jet}}$ uncorrelated, gives the covariance matrix

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

- Jet-veto efficiency: $\sigma_{0-\mathrm{jet}} = \sigma_{\mathrm{tot}}\,\epsilon$, with σ_{tot} and ϵ uncorrelated, gives

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

$$\mathrm{Cov}_{\mathrm{BMSZ}} = \mathrm{Cov}_{\mathrm{ST}} + (1-\epsilon)\Delta^2\sigma_{\mathrm{tot}} \begin{pmatrix} 2\epsilon & 1 \\ 1 & 0 \end{pmatrix}$$

- Consistency with the Stewart-Tackmann procedure in the region where the fixed-order is reliable ($\epsilon \lesssim 1$)

Large R limit

- As $R \to \infty$ one would (wrongly) expect to recover the boson-p_t result (whole radiation clustered into a single jet)

- *e.g.* NNLL correction at $\mathcal{O}(\alpha_s^2 L)$
  - $\mathcal{F}_{\rm correl}$ vanishes smoothly in this limit
  - subtleties arise with two independent emissions ($\mathcal{F}_{\rm indep}$)
    - For $1 \ll R \ll \ln(M/p_{\rm t,veto})$ (jet-veto case) the first emission's rapidity is bounded by $|y_1| \leq \ln M/k_{t,1}$ while $|\Delta y| \leq R + \mathcal{O}(1/R)$

$$\mathcal{F}_{\rm indep} = -2C_A^2 \frac{\alpha_s^2}{\pi^2} R\,\zeta_3 + \mathcal{O}\left(\frac{\alpha_s^2 L}{R}\right) \qquad \text{N}^3\text{LL}$$

    - For $R \gtrsim \ln(M/p_{\rm t,veto}) \gg 1$ (boson- p_t) both emissions have $|y_i| \leq \ln \dfrac{M}{k_{t,1}}$

$$\mathcal{F}_{\rm indep} = -4C_A^2 \frac{\alpha_s^2}{\pi^2}\,\zeta_3 \ln\frac{M}{p_t} + \mathcal{O}\left(\alpha_s^2\right) \qquad \text{NNLL!}$$

Jet-veto efficiency at NNLO

- We define three different prescriptions to express the efficiency at $\mathcal{O}(\alpha_s^2)$

$$\varepsilon^{(a)}(p_{\mathrm{t,veto}}) = \frac{\Sigma_0(p_{\mathrm{t,veto}}) + \Sigma_1(p_{\mathrm{t,veto}}) + \Sigma_2(p_{\mathrm{t,veto}})}{\sigma_0 + \sigma_1 + \sigma_2},$$

$$\varepsilon^{(b)}(p_{\mathrm{t,veto}}) = \frac{\Sigma_0(p_{\mathrm{t,veto}}) + \Sigma_1(p_{\mathrm{t,veto}}) + \bar{\Sigma}_2(p_{\mathrm{t,veto}})}{\sigma_0 + \sigma_1},$$

$$\varepsilon^{(c)}(p_{\mathrm{t,veto}}) = 1 + \frac{\bar{\Sigma}_1(p_{\mathrm{t,veto}})}{\sigma_0} - \frac{\sigma_1}{\sigma_0^2}\bar{\Sigma}_1(p_{\mathrm{t,veto}}) + \frac{\bar{\Sigma}_2(p_{\mathrm{t,veto}})}{\sigma_0}$$

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

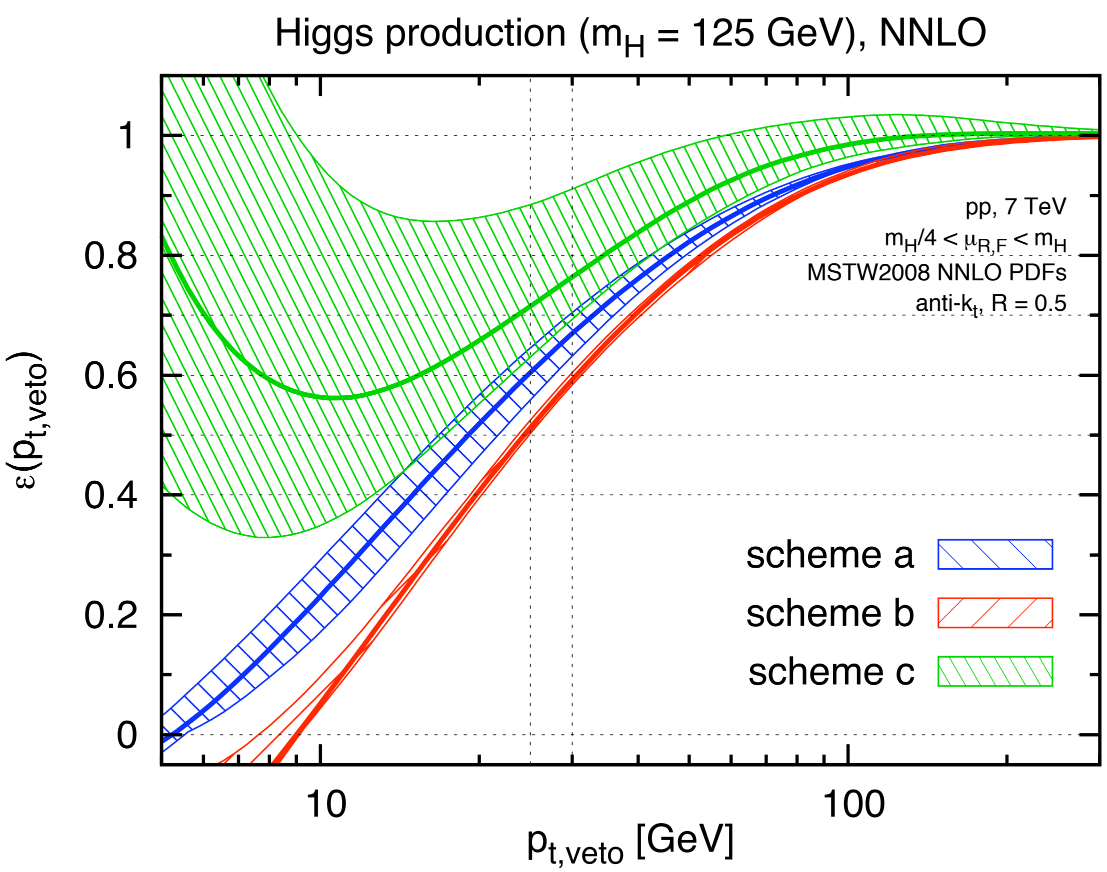
- The three schemes differ by terms of order $\mathcal{O}(\alpha_s^3)$ which are beyond the current PT accuracy

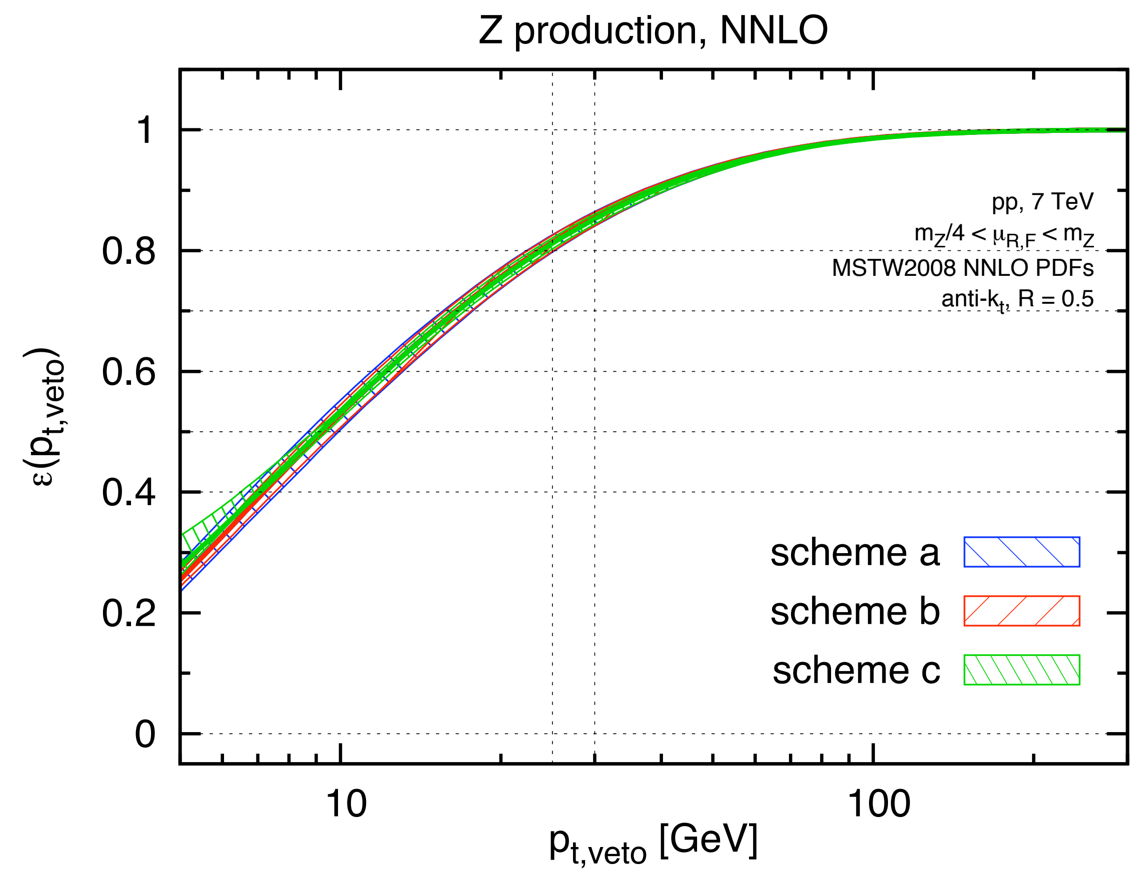
- Varying the scheme gives an additional handle to estimate the uncertainty

Jet-veto efficiency at NNLO

- Compare Higgs production and Drell-Yan

[HNNLO, DYNNLO, MCFM]



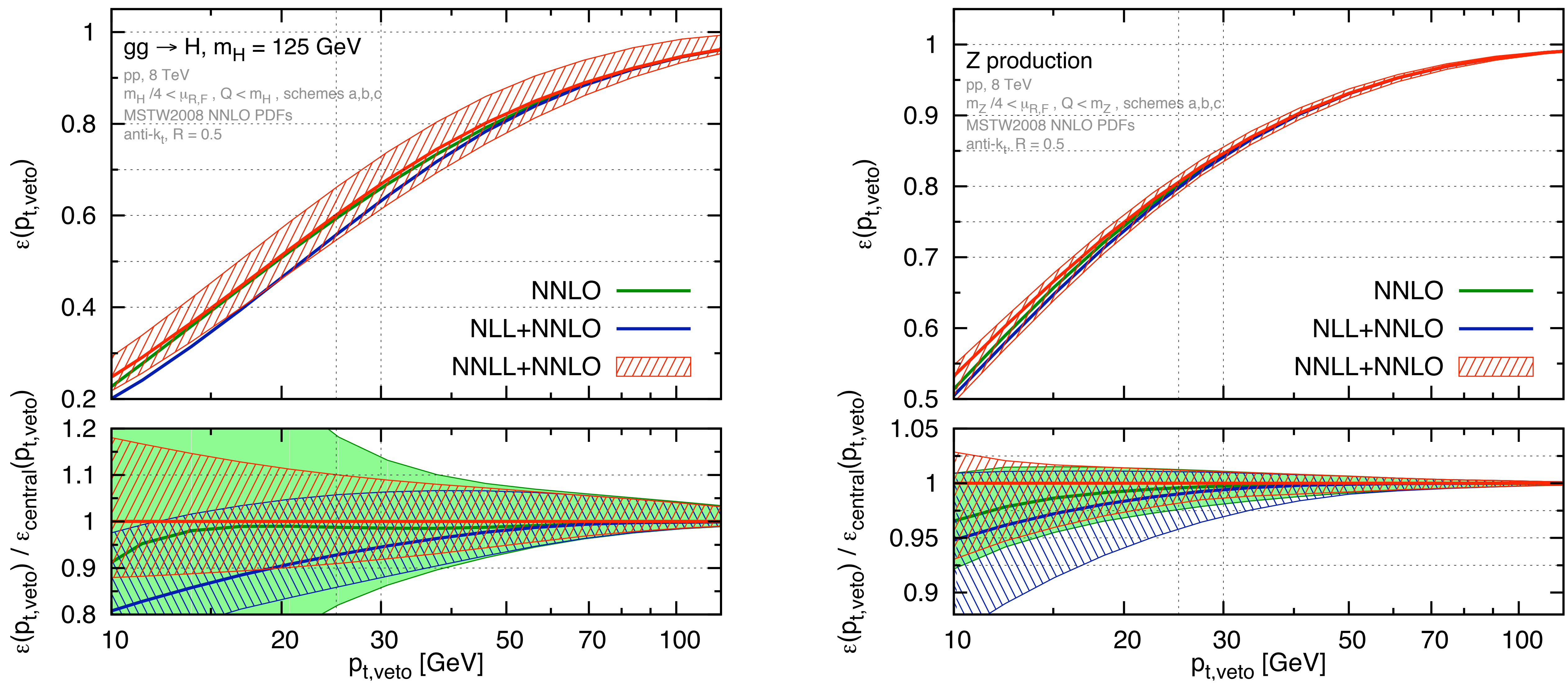


- In Z production, the 3 schemes lead to similar results, indicating a good convergence of the PT series

- In Higgs production the 3 prescriptions differ significantly at common veto scales

Comparison with N(N)LO

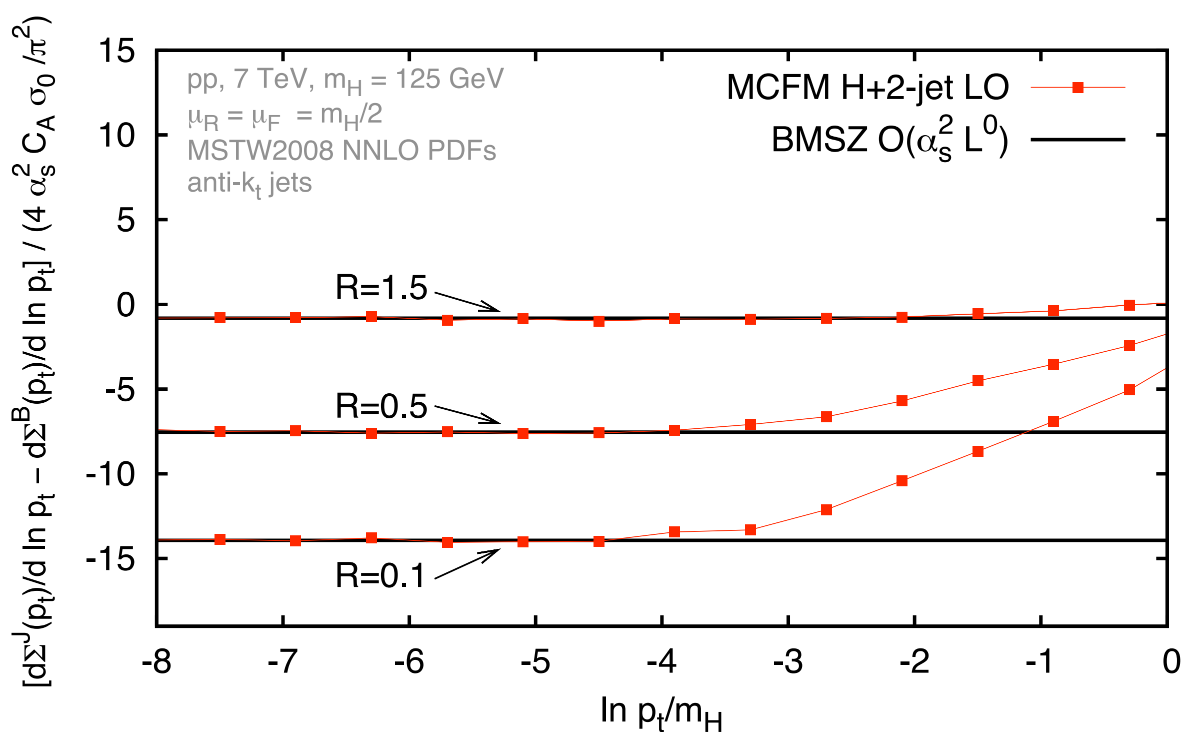
[HNNLO, DYNNLO, MCFM]

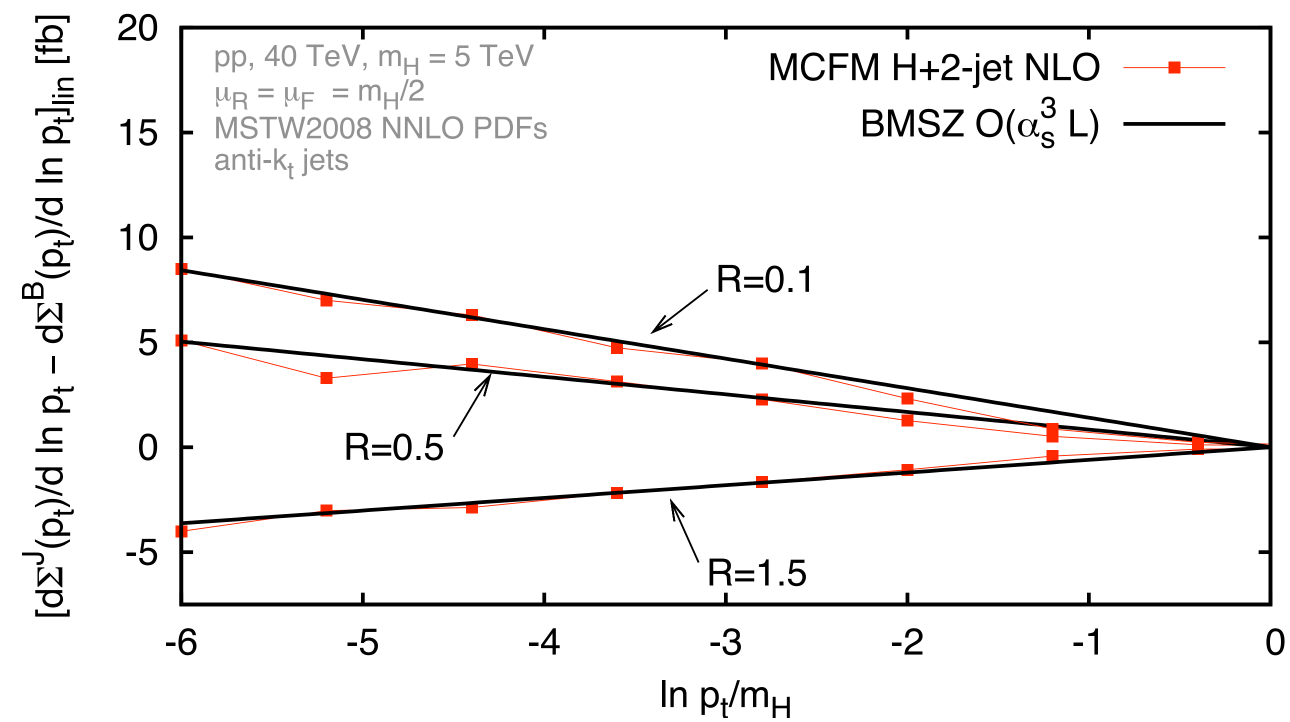


- Large NNLL corrections in H and DY
- NNLL resummation reduces uncertainty from $\sim$ 15% to $\sim$ 9%
- NNLL + NNLO uncertainty band $\sim$ as broad as NLL+NNLO one (R-dep.)

Check against fixed order

- Check the difference with boson-p_t distribution by comparing expansion of the resummation to MCFM [Campbell, Ellis, Williams '10]





- Difference between log-distributions in $p_{t,\mathrm{Higgs}}$ and $p_{t,\mathrm{veto}}$ at order $\mathcal{O}(\alpha_s^2)$ against MCFM's H+2j@LO

$$\Delta\left(\frac{d\Sigma_2(p_t)}{d\ln p_t}\right) \sim \alpha_s^2 L^0$$

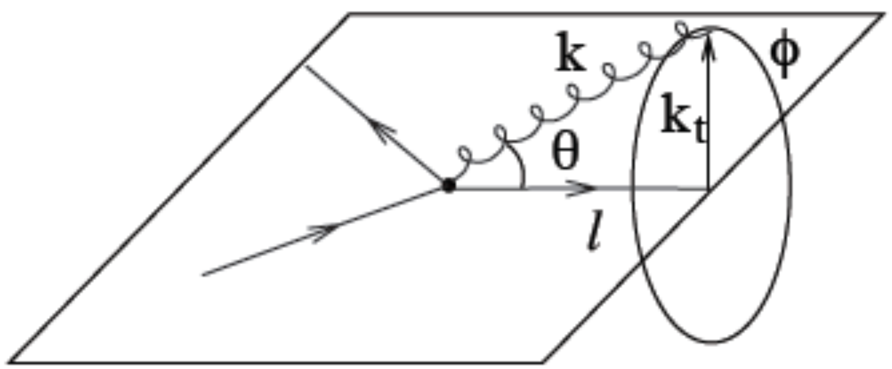
- Difference between log-distributions in $p_{t,\mathrm{Higgs}}$ and $p_{t,\mathrm{veto}}$ at order $\mathcal{O}(\alpha_s^3)$ against MCFM's H+2j@NLO

$$\Delta\left(\frac{d\Sigma_3(p_t)}{d\ln p_t}\right) \sim \alpha_s^3 L^2 + \alpha_s^3 L + \alpha_s^3 L^0$$

Applicability conditions

- A given observable can be parametrised as follows for a single soft and collinear gluon is emitted off a hard (Born) leg l

$$V(\{p\},k) = d_l \left(\frac{k_t}{Q}\right)^{a_l} e^{-b_l \eta} g_l(\phi)$$



- *continuous globalness* : uniform dependence on k_t, independently of the emission direction ($a_1 = a_2 = a_3 = ... = a$)

- *recursive Infrared and Collinear (rIRC) safety* : extra emissions do not introduce different soft/collinear scaling

$$[\lim_{\bar{v}\to 0}, \lim_{\zeta\to 0}] \frac{1}{\bar{v}} V(\{p\}, \bar{v}k_1, \bar{v}k_2, ..., \zeta\bar{v}k_n) = 0$$