Jet vetoes in Higgs searches at the LHC

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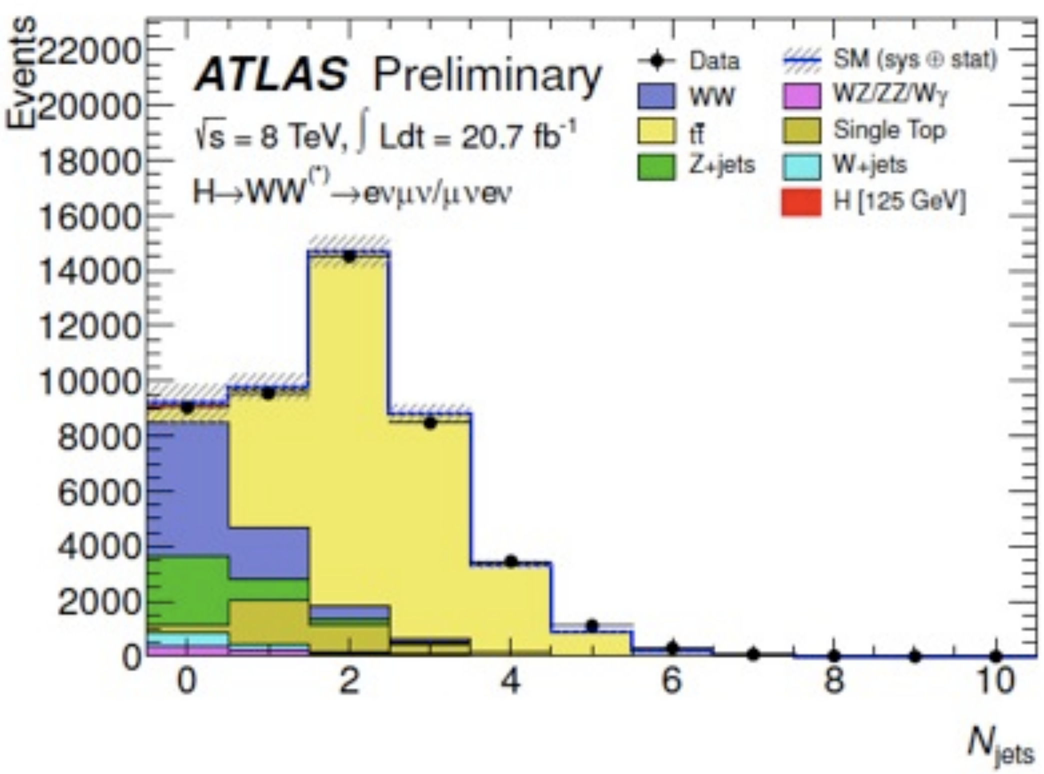
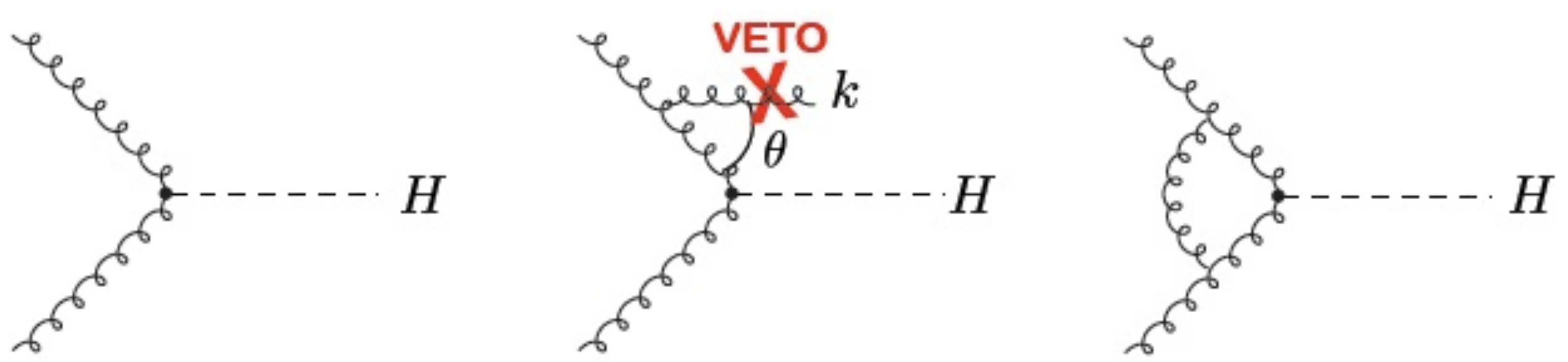
Searches in H ⟶ WW

- $H \to W^+W^- \to l^+\nu^- l^- \nu^+$ relevant for coupling and spin measurements
- Recent results show a $3.8\,\sigma$ (ATLAS) $/4\,\sigma$ (CMS) excess w.r.t. the background-only hypothesis in good agreement with the SM prediction
- Main background: $WW,\, W/Z\, +$ jets, $t\bar{t}, \ldots$
- Categorization according to lepton flavour and jet multiplicity to optimize sensitivity
- Additional bin-dependent selection cuts for further background reduction



The 0-jet bin

- 0-jet requirement suppresses high-p_t jets (*e.g.* b-jets from top decay)
- 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
- Vetoing QCD radiation gives rise to Sudakov logs.
  - *e.g.* emission of a soft ($\omega \ll M$) and collinear ($\theta \ll 1$) gluon



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

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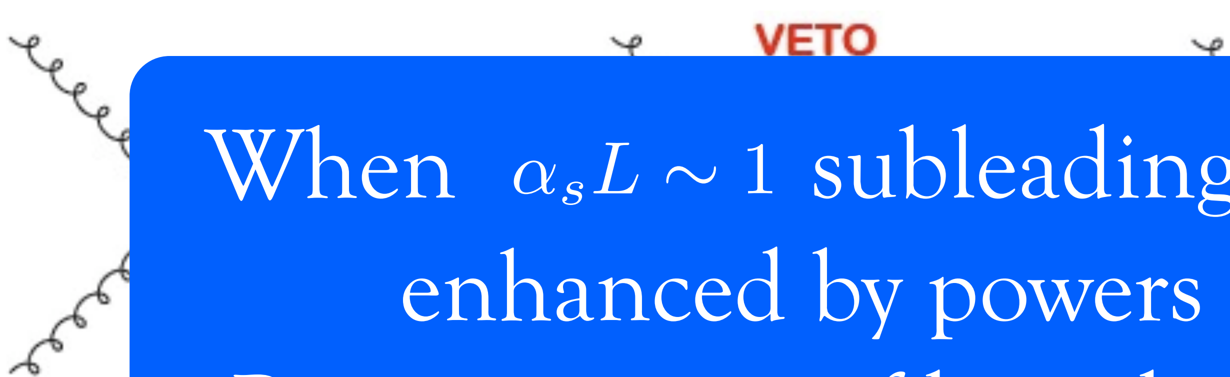

When $\alpha_s L \sim 1$ subleading terms are enhanced by powers of L .
Resummation of large logs needed

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Theoretical uncertainties in fixed-order

- LHC experiments choose $p_{\rm t,veto} \simeq 25-30\,{\rm GeV}$: over 90% reduction of background

- For such veto scales, logs. are not dramatically large: $\alpha_s \ln \frac{m_H}{p_{\rm t,veto}} \sim 0.2$

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

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

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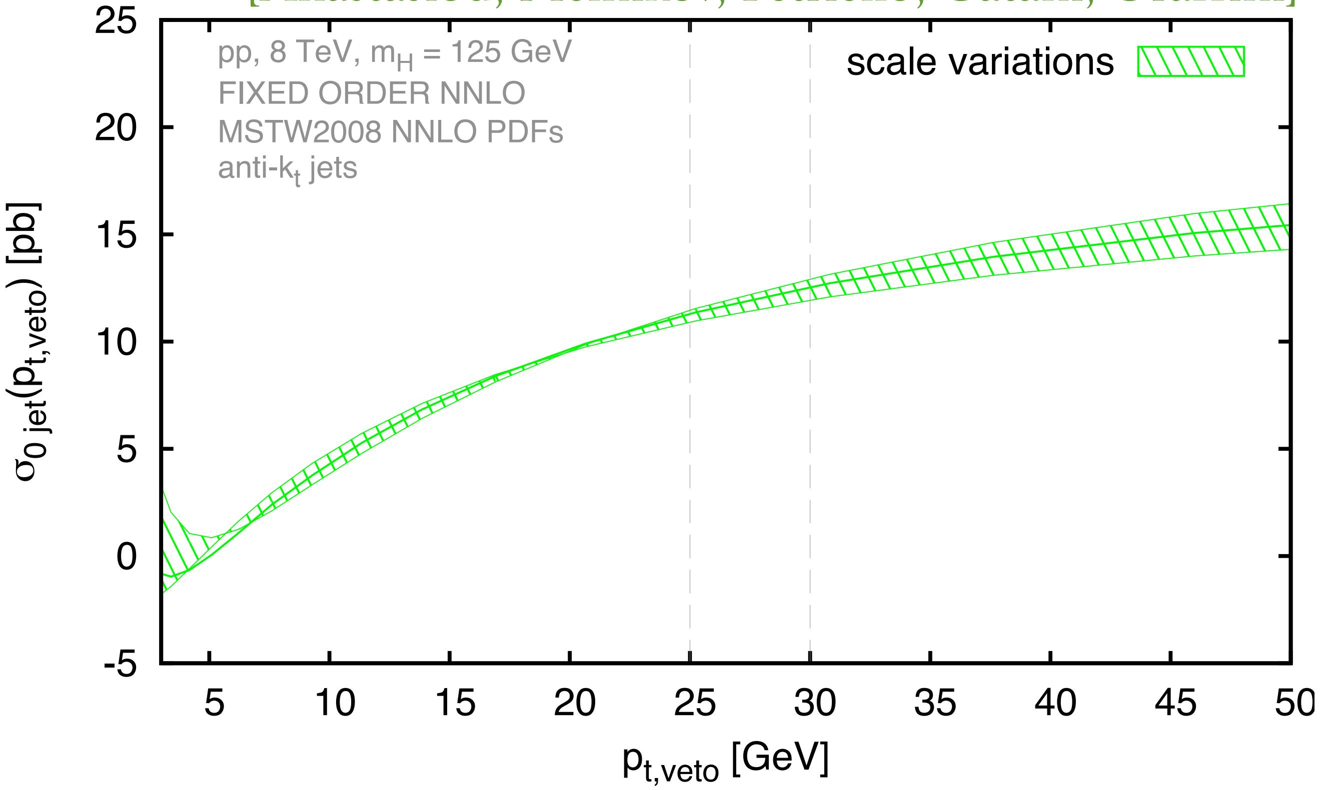
- Naive scale variations underestimate the th. uncertainty

[Anastasiou, Melnikov, Petriello; Catani, Grazzini]



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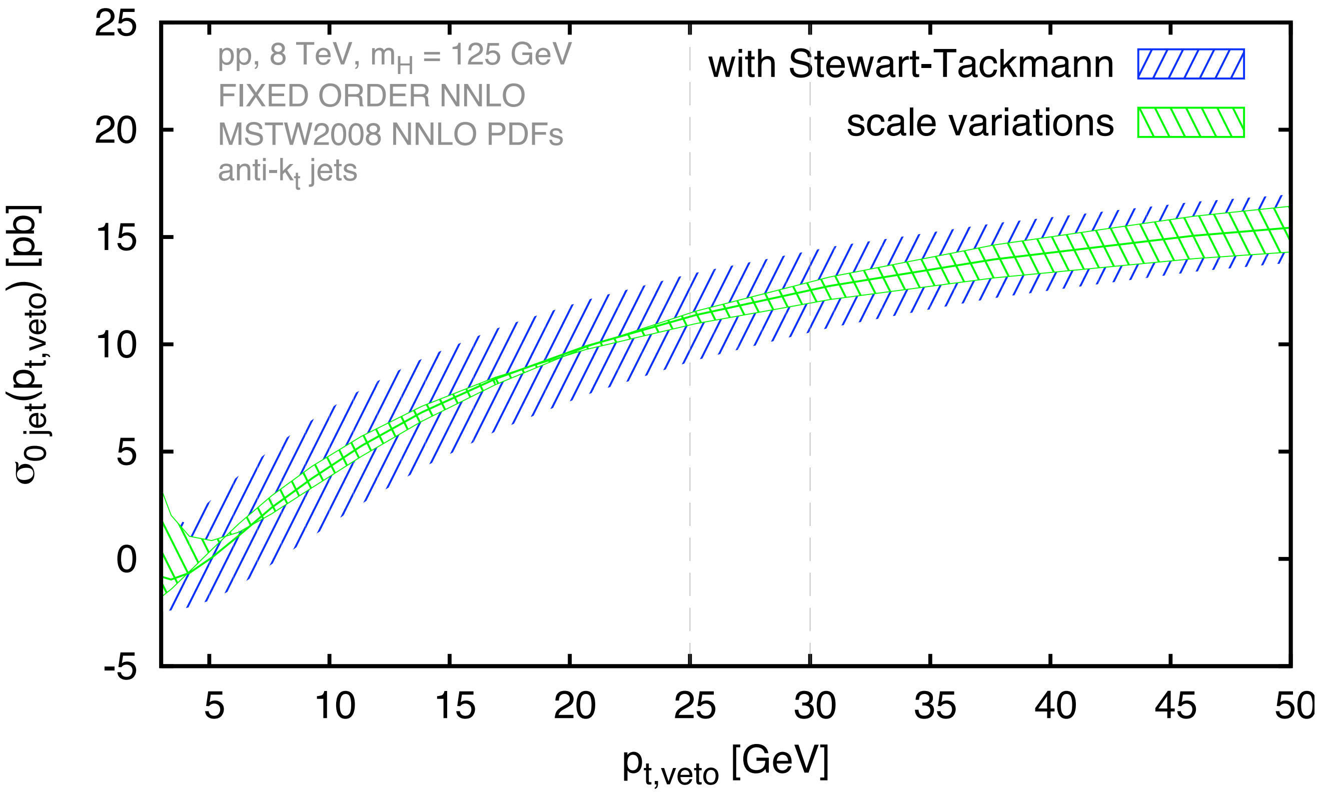
Can we rely on inclusive uncertainties ?



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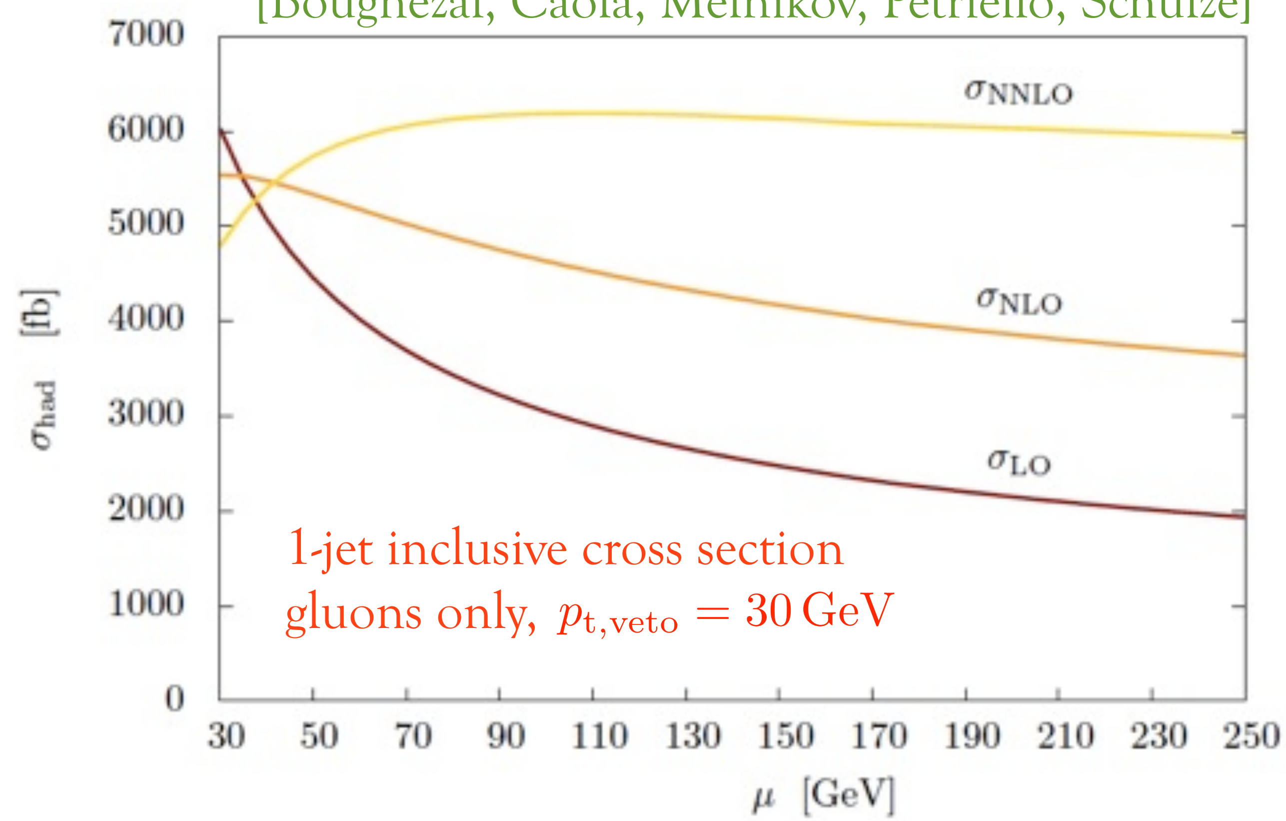
- Inclusive cross section $\sigma_{\geq 1jet}$ shows good convergence at low renormalisation scales

  $e.g.$

$$\mu \sim m_H/2$$

[Boughezal, Caola, Melnikov, Petriello, Schulze]



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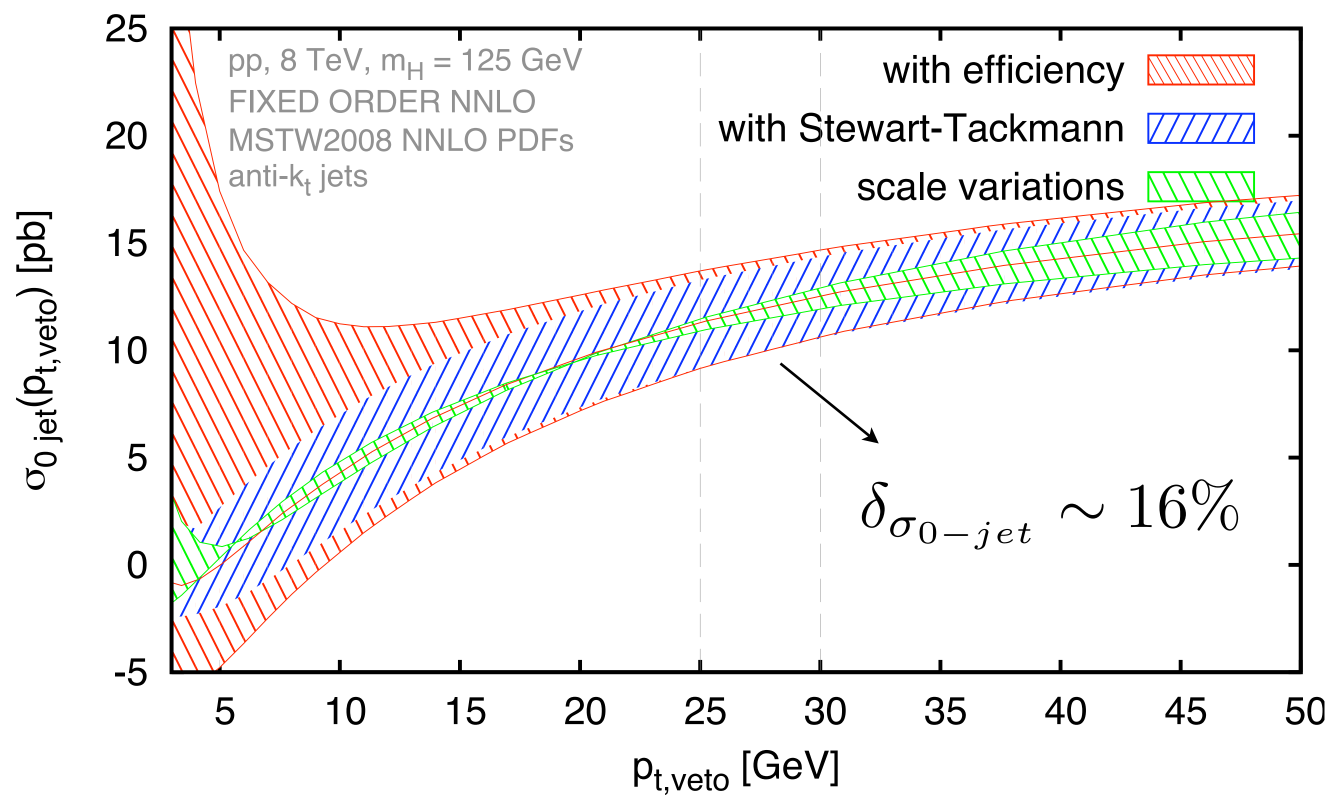

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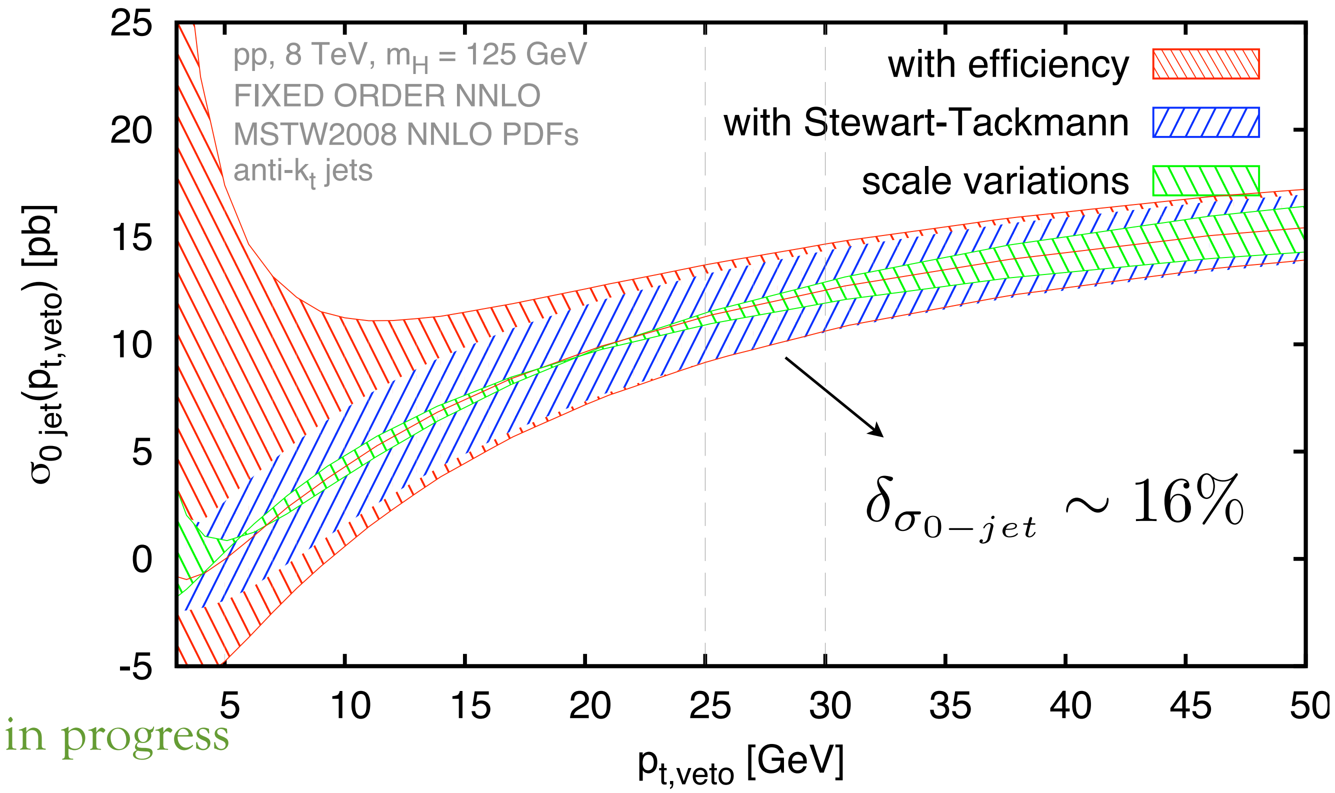
Resummation of large logs needed to improve error estimate



NLL: Banfi, Salam, Zanderighi ’12
NNLL : Banfi, PFM, Salam, Zanderighi;
Becher, Neubert ’12 ; Tackmann, Stewart, Walsh, Zuberi in progress

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

  - 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
    - Analytic expression for $\sigma_{0-jet}(p_{t,veto})$. Where $R' = -p_{t,veto}\frac{dR(p_{t,veto})}{dp_{t,veto}}$

Matching to fixed-order

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

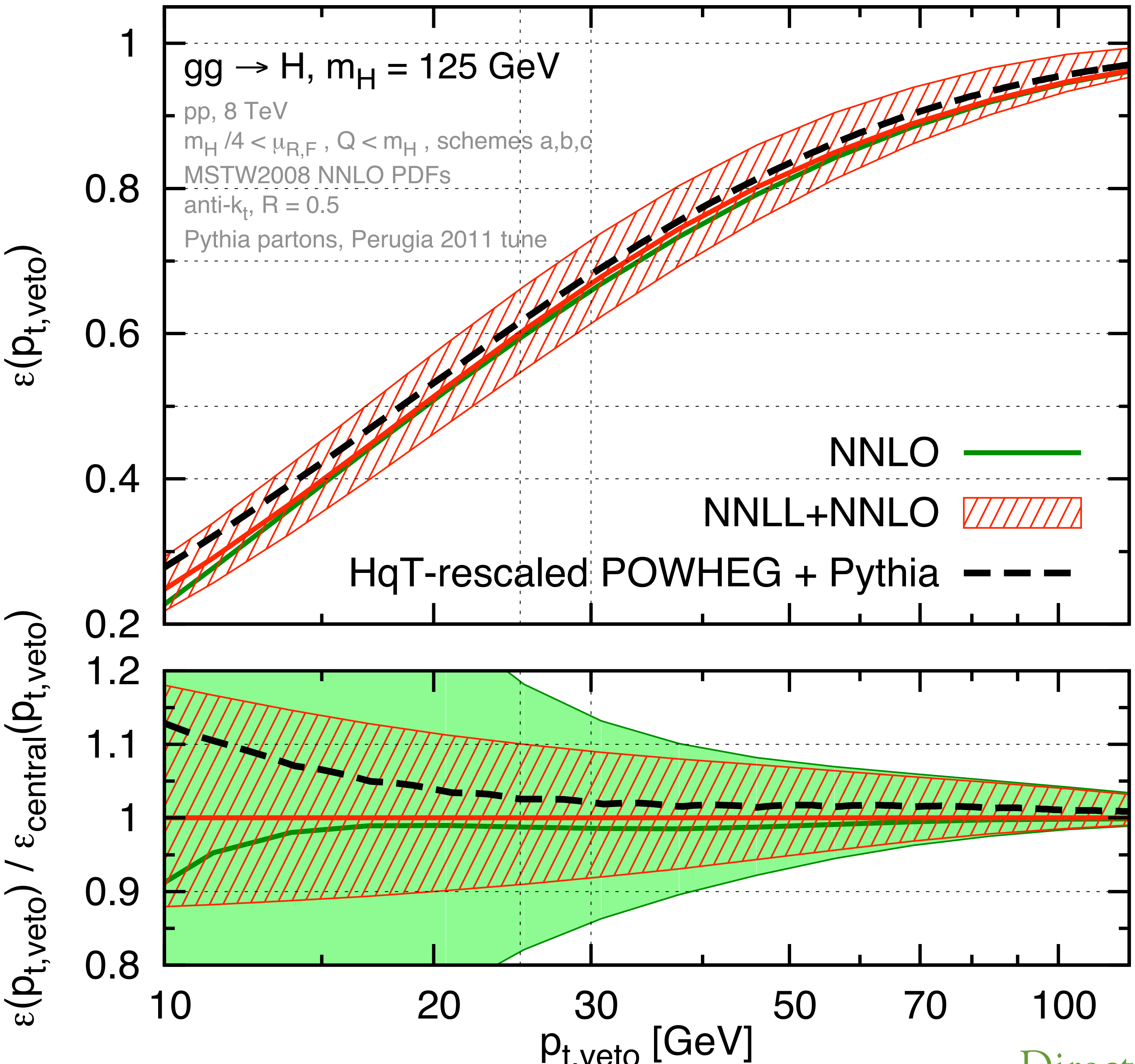
- Alternatively, one can obtain resummed predictions for the jet-veto efficiency and treat the resulting uncertainty with the efficiency method

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

    - The three schemes differ by subleading effects

    - Varying the scheme leads to an additional systematic uncertainty

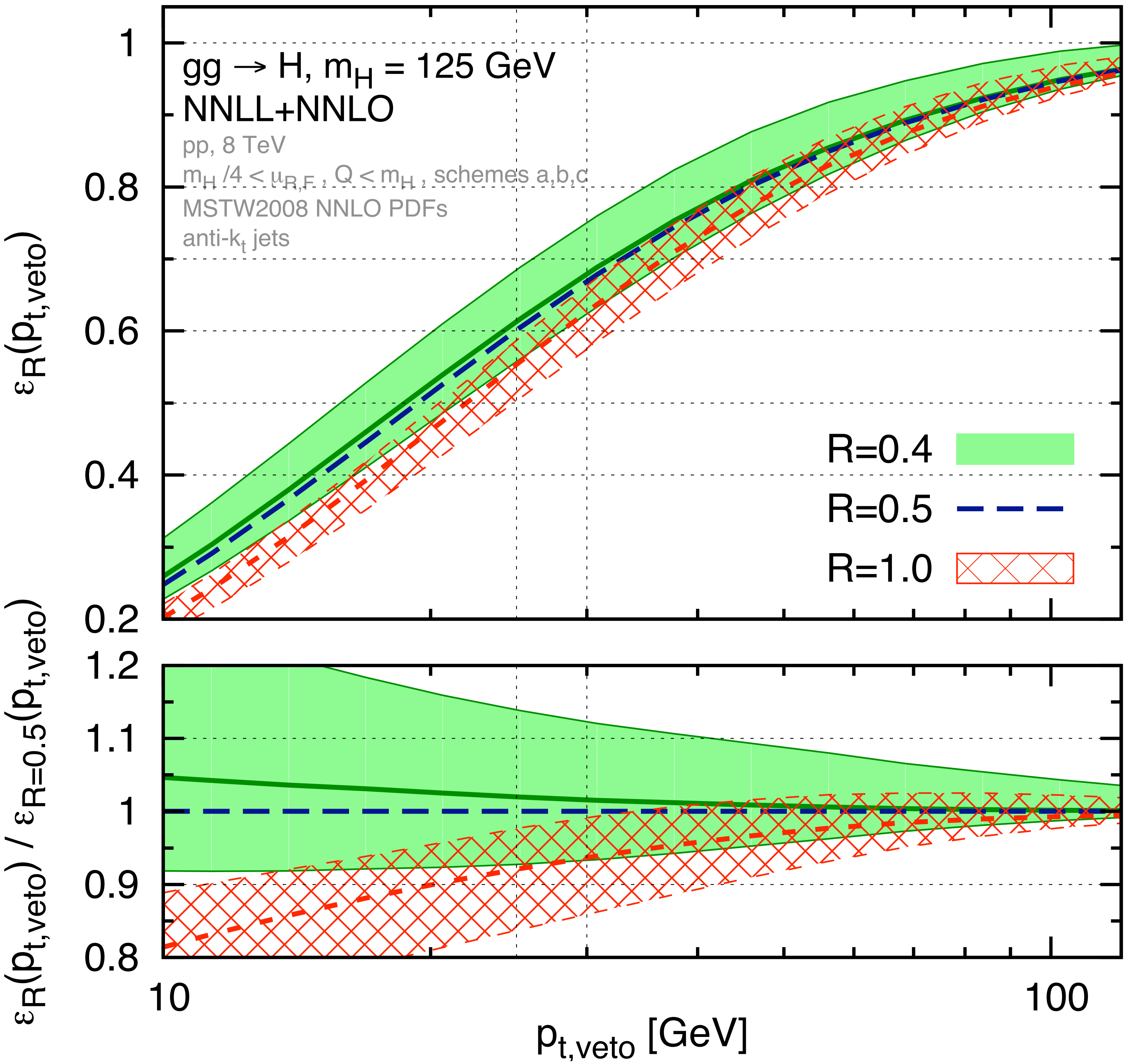
Comparison to MC



- Good agreement on central values with POWHEG+Pythia reweighted with HqT & HNNLO
- Uncertainties reduced from $\sim 15\%$ to $\sim 9\%$
- Hadronisation and UE corrections have a small impact ($\leq 1\%$)
- Corresponding error in the cross section $\sim 10\% - 11\%$

Direct predictions for the cross section can be also obtained without using the efficiencies

Choice of the jet radius R



- All-order terms of the form (*e.g.* $\mathcal{F}(R')$)

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

- For $R \ll 1$ they should be resummed

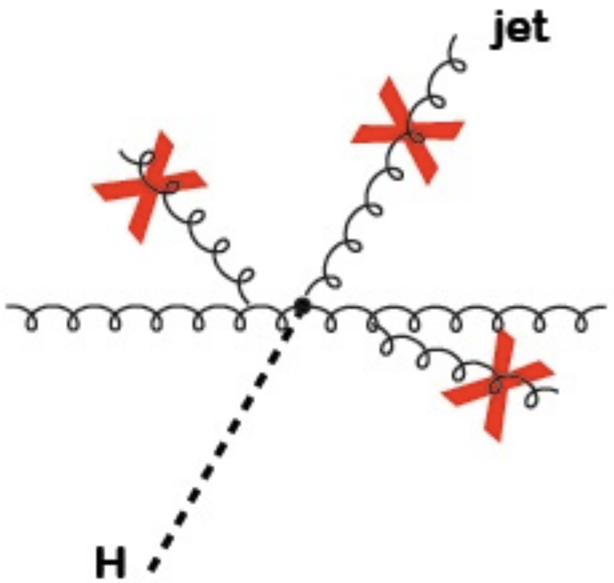
  [Tackmann, Walsh, Zuberi '12]

- Choosing $R \sim 1$ reduces the uncertainties

- Higher contamination from UE ($\sim R^2$) and pileup ... filtering can be used to reduce it

1-jet bin

- In the 0-jet sample all jets are vetoed. Cross section is sensitive to soft and collinear emissions everywhere in the phase space



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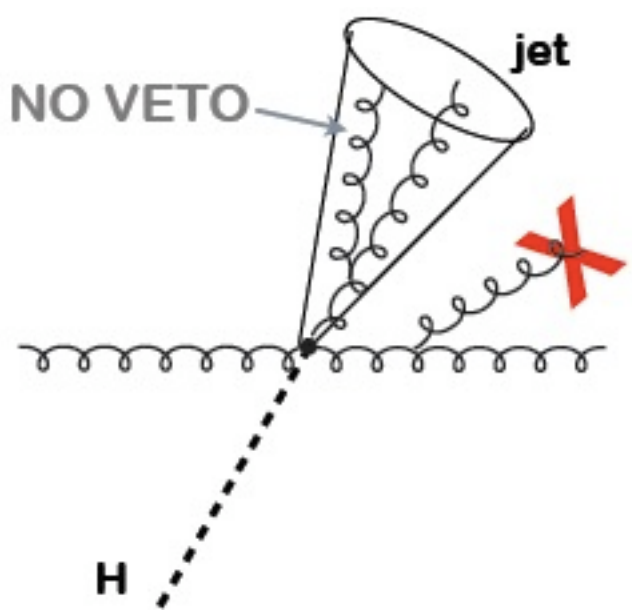
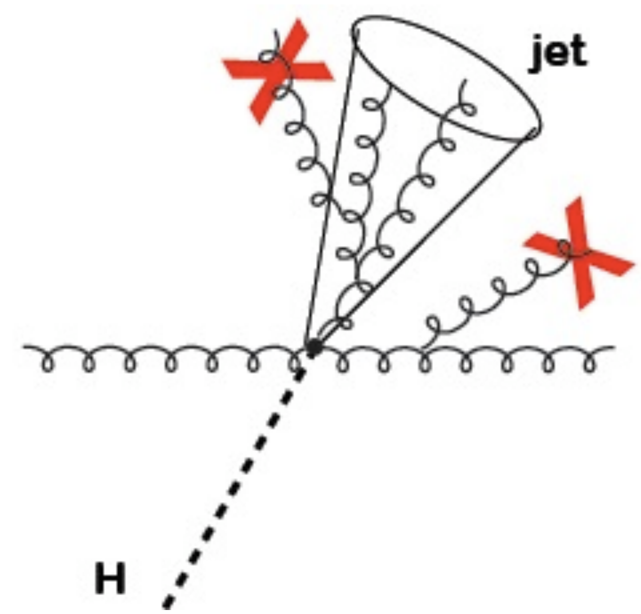
- This is not the case if we require to observe n jets.
  Cross section is insensitive to emissions which take place inside the tagged jets

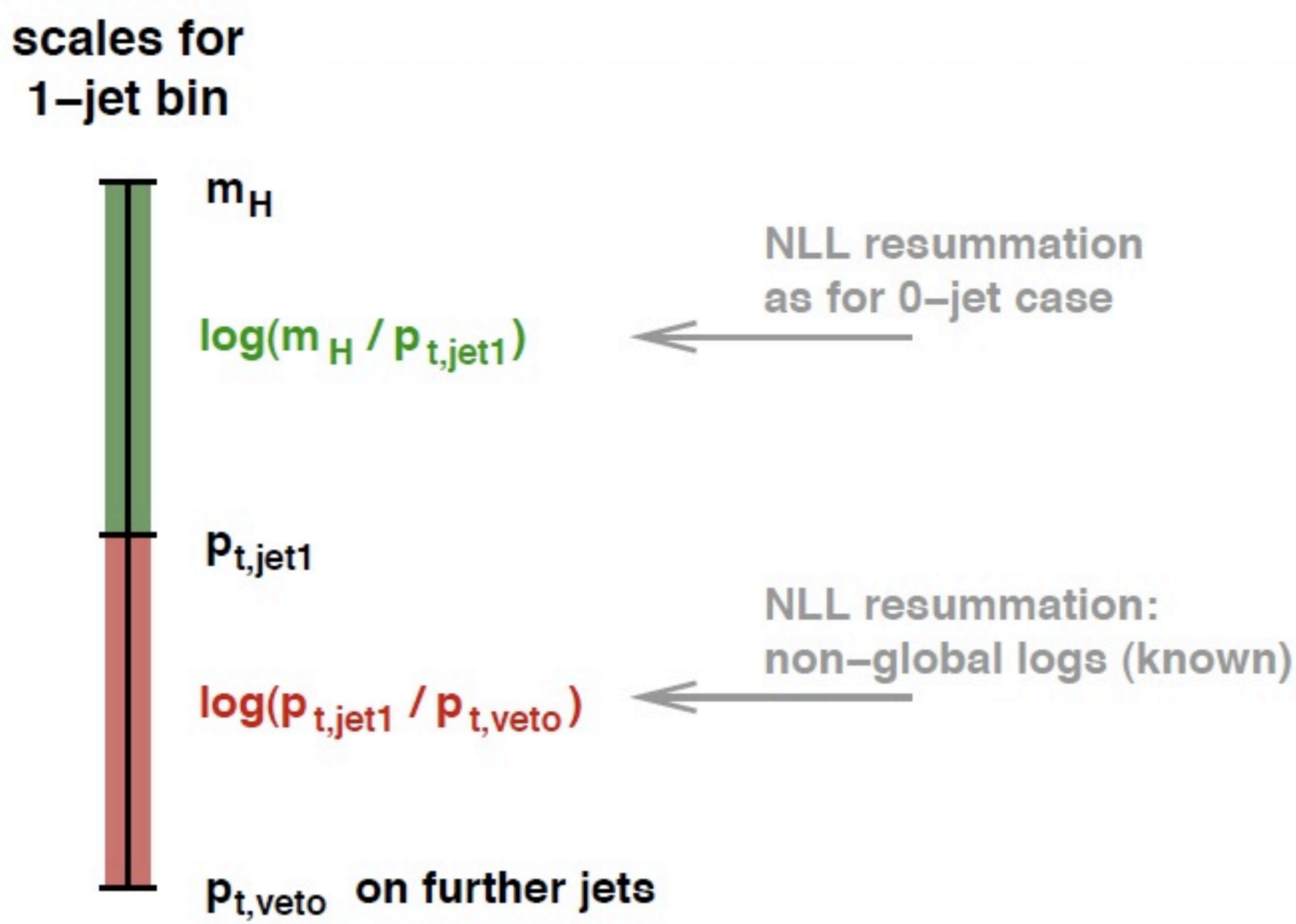




- A gluon splitting close to the jet boundary gives rise to a new family of large logarithms (non-global single logs) which require all-order treatment

[Dasgupta, Salam ’01; Appleby, Seymour ’02; Banfi, Dasgupta ’05]

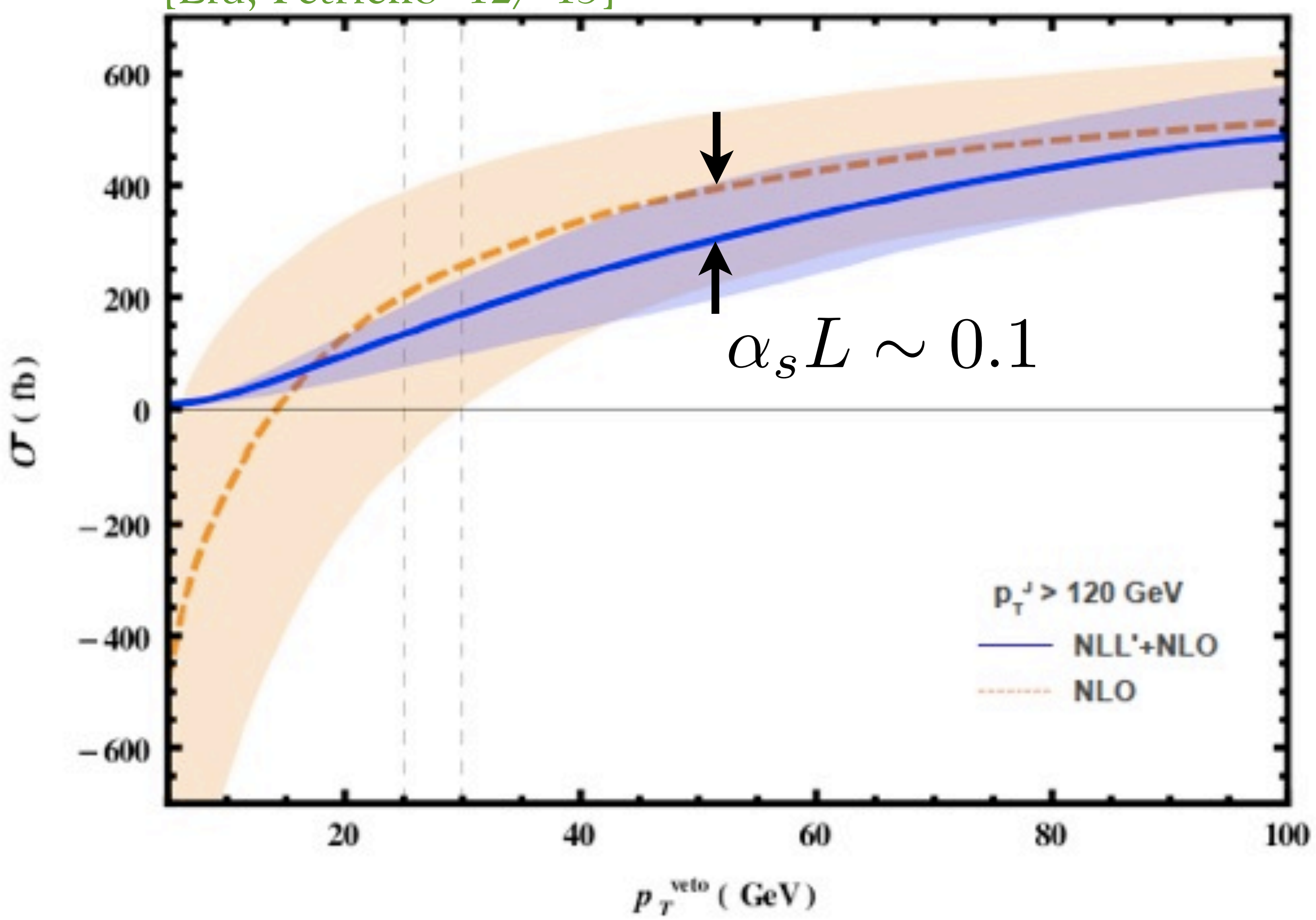
1-jet bin



- Three-scale problem
- More involved log structure
- Nested resummation required, with $p_{\mathrm{t,jet1}}$ integrated from $p_{\mathrm{t,veto}}$ to m_{H}

1-jet bin

[Liu, Petriello '12/'13]



- Global part of $\ln p_{t,jet}/p_{t,veto}$ recently resummed to NLL in the limit

$$p_{t,veto} \ll p_{t,jet} \sim m_{\mathrm{H}}$$

  - no $\ln \dfrac{m_{\mathrm{H}}}{p_{t,jet}}$
  - impact of non-global $\ln \dfrac{p_{t,jet}}{p_{t,veto}}$ estimated to be small

- Up to $\sim 25\%$ reduction w.r.t. NLO central value … large subleading corrections or matching effects ?

Fixed-order uncertainty with Stewart-Tackmann method

2-jet bin

- In the 2-jet bin VBF production becomes relevant

- Clean signal, *i.e.* two forward jets widely separated in rapidity and few extra gluon emissions (incoming quarks). VBF selection cuts are applied to isolate it

  2-jet bin used in $H \to WW$ searches

  But ggF/VFB separation relevant for other channels, *e.g.* $H \to \gamma\gamma$

- $\sim 25\%$ contamination from ggF (more radiation in the central region)

- It can be reduced by imposing a veto on extra (≥ 3) jets, but this makes uncertainties estimate less reliable

- Resummation desired, but extremely challenging !

  NLO studies matched to Parton-Showers are available, but hard to assess PS uncertainties

  [Campbell et al.; Frederix, Frixione]

2-jet bin

- Recent analysis for $H \to \gamma\gamma$ uses $p_{\rm t,Hjj} < 30\,{\rm GeV}$ and $\Delta\phi_{\rm H-jj} < 2.6\,{\rm rad}$ as jet vetoes
- Uncertainties with Stewart-Tackmann/Efficiency method

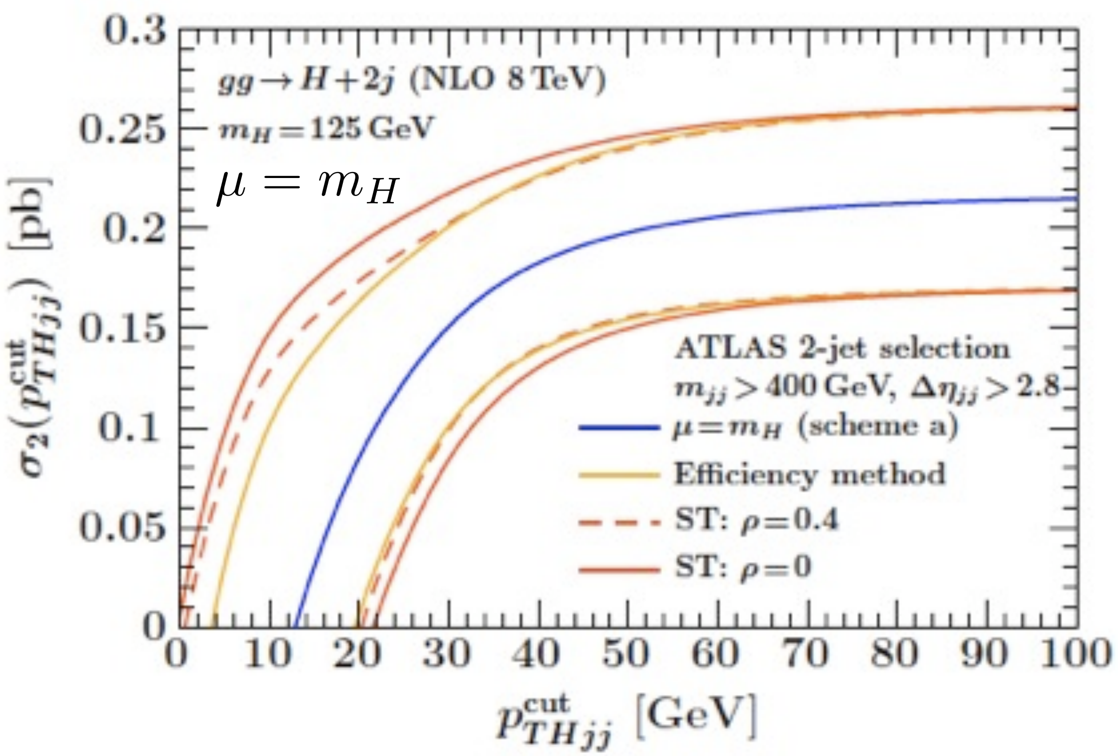
$$\sigma_{2\,\rm j}(p_{\rm t,Hjj} < p_{\rm t,Hjj}^{\rm cut}) = \sigma_{\geq 2j} - \sigma_{\geq 3j}(p_{\rm t,Hjj} > p_{\rm t,Hjj}^{\rm cut})$$

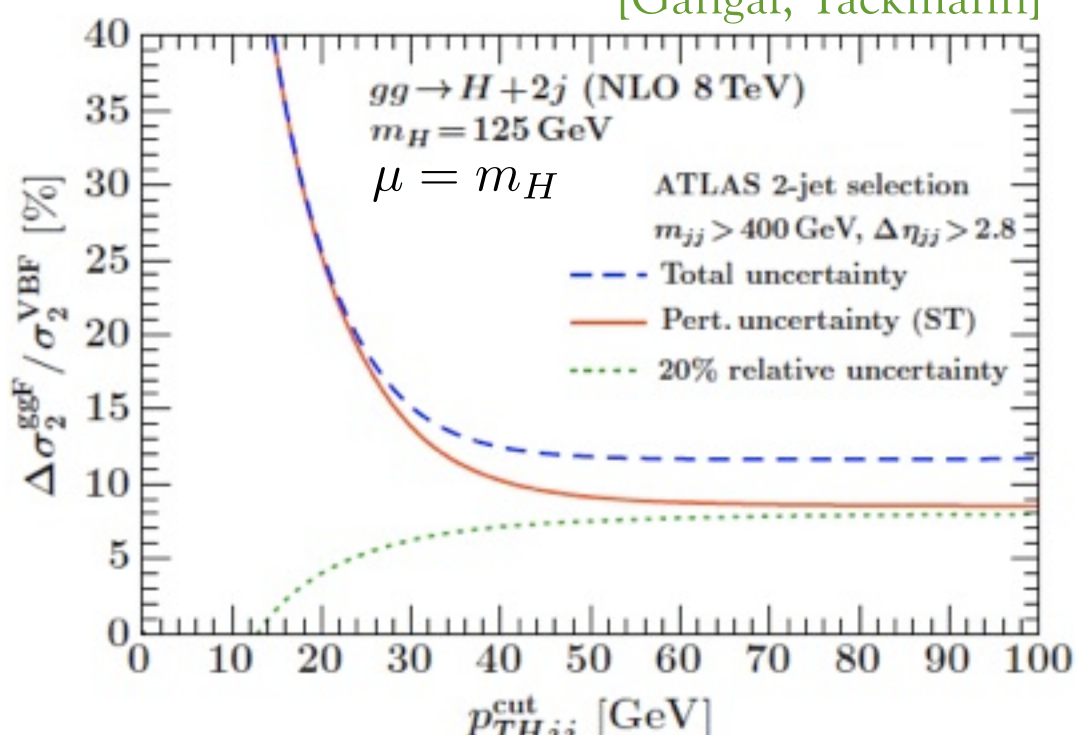
Known @ NLO [Campbell et al.; van Deurzen et al.]

Known @ LO: large relative uncertainty $\sim \mathcal{O}(70\%)$

- Very large uncertainty on the exclusive 2-jet cross section !

[Gangal, Tackmann]





Same conclusions apply to $\Delta\phi_{\rm H-jj}$

Conclusions

- Recent progress in resummation of observables involving jets allows for precise assessment of the theory uncertainty (+ efficiency method) in the 0-jet bin. The method can be applied to the production of any colour singlet (*e.g.* HW, WW, ...)
  Public code at: http://jetvheto.hepforge.org

    - Study of all-order small-R structure desirable

- Recent important progresses for the 1-jet bin. Non-global logarithms and nested resummation are still to be studied in detail

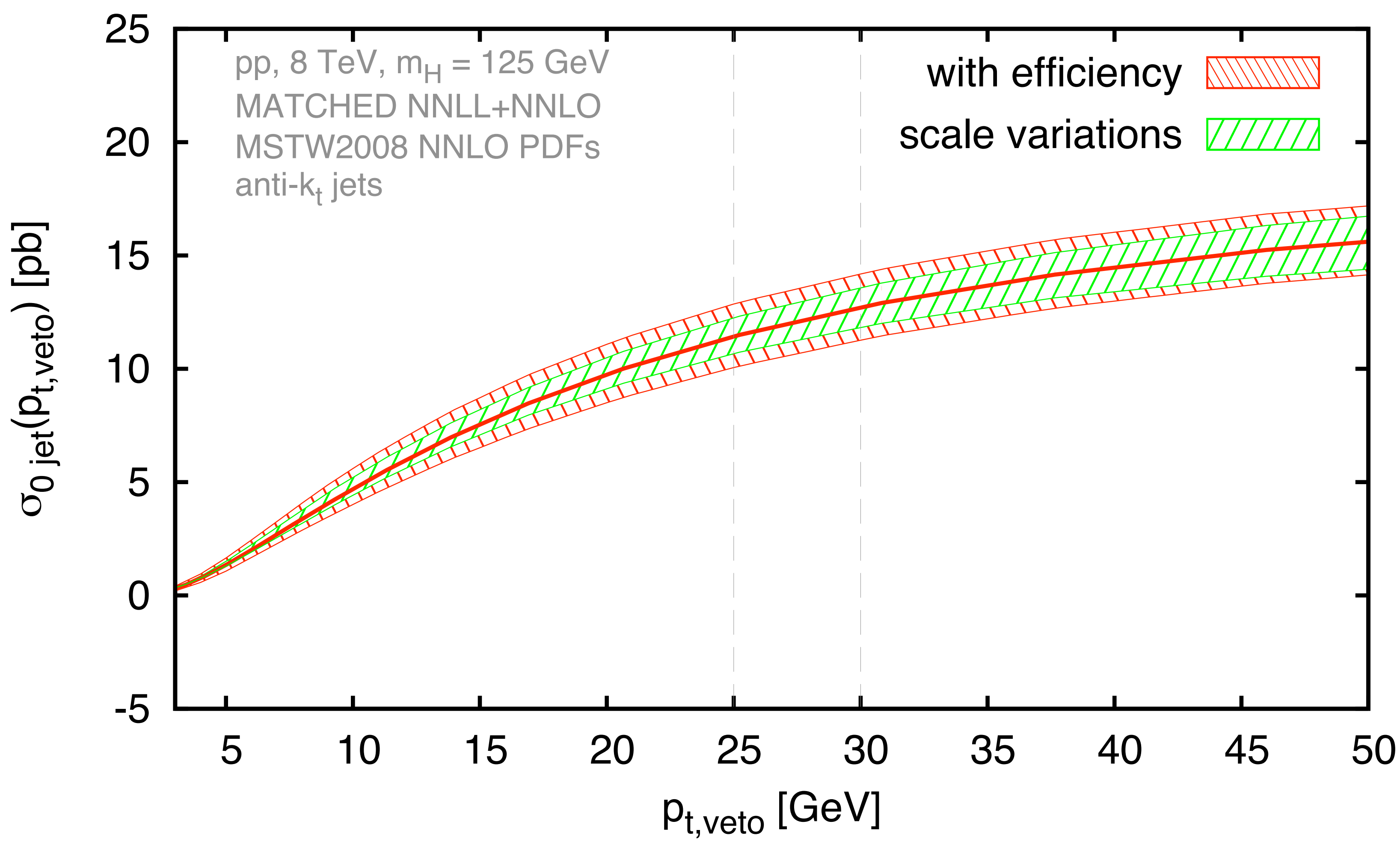
- The ggF contamination of VBF is still an open issue. H+3j@NLO desirable ? Several MC analyses currently ongoing using cut-based/multivariate techniques

Backup Slides

Uncertainties in the 0-jet cross section

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

single matching scheme in green band

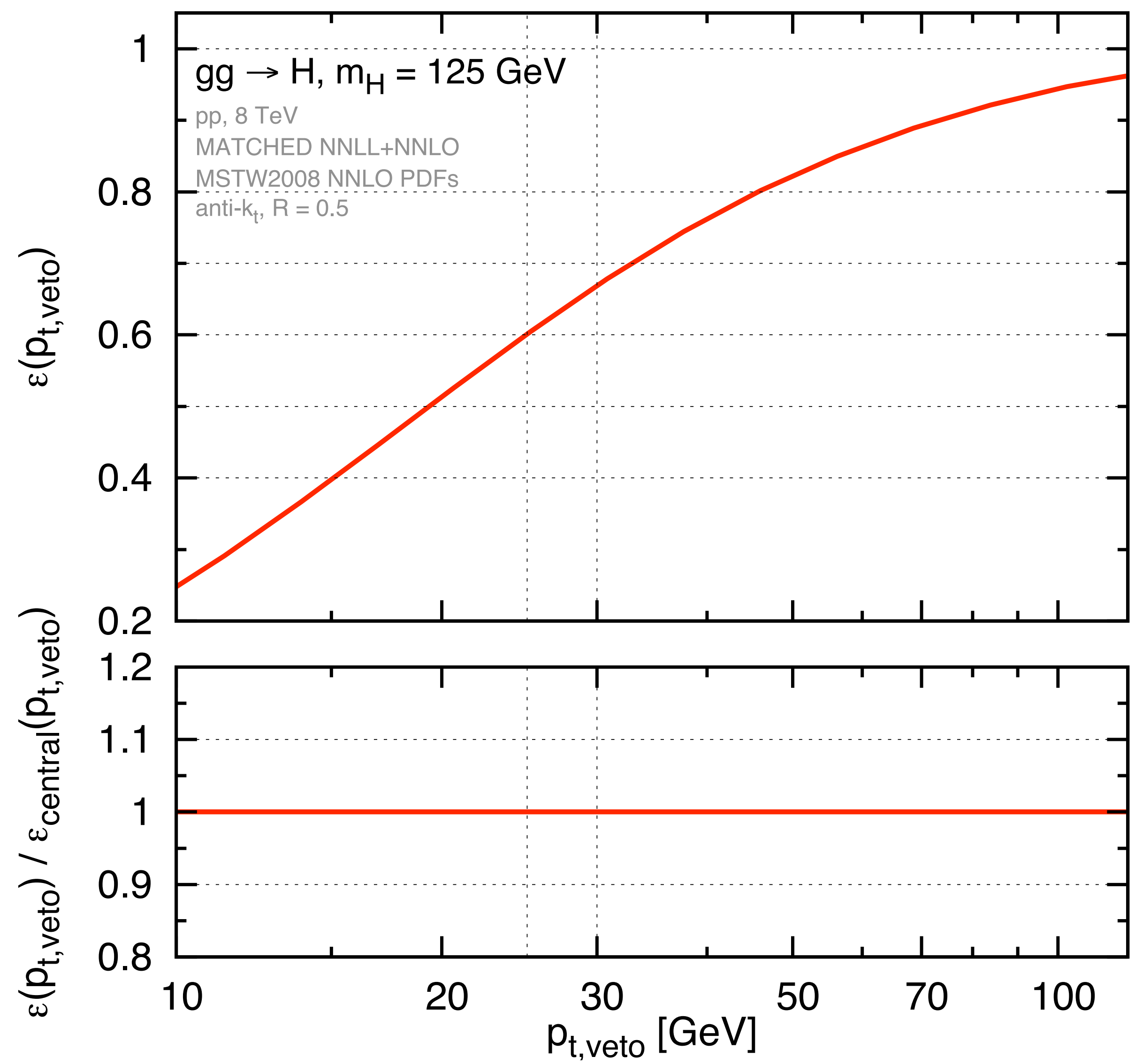


- Small difference mainly due to matching scheme uncertainty in efficiency method. Robust uncertainty estimate $\sim 10\% - 11\%$

Resummation uncertainties

- Central value: scheme (a) with

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



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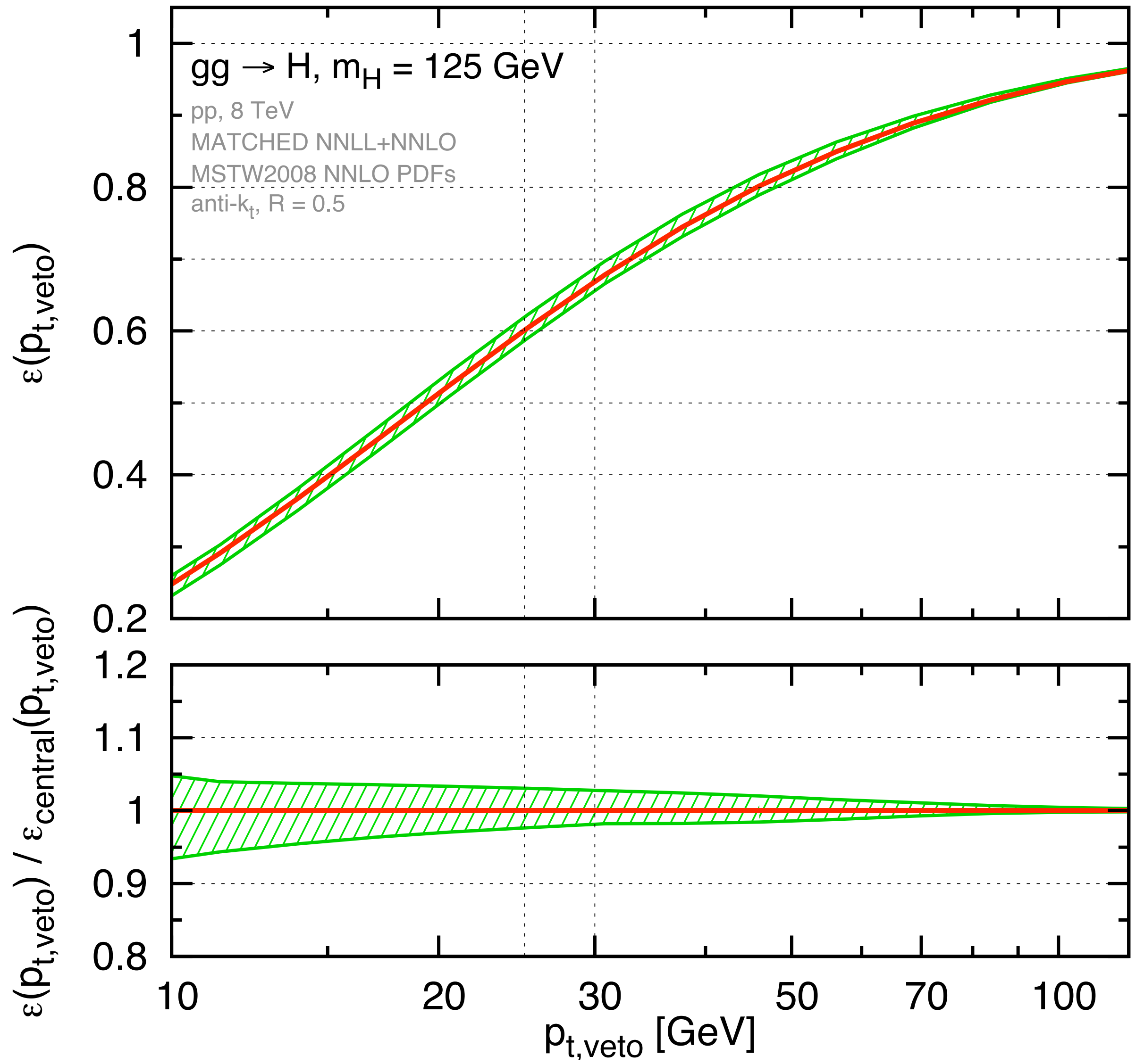

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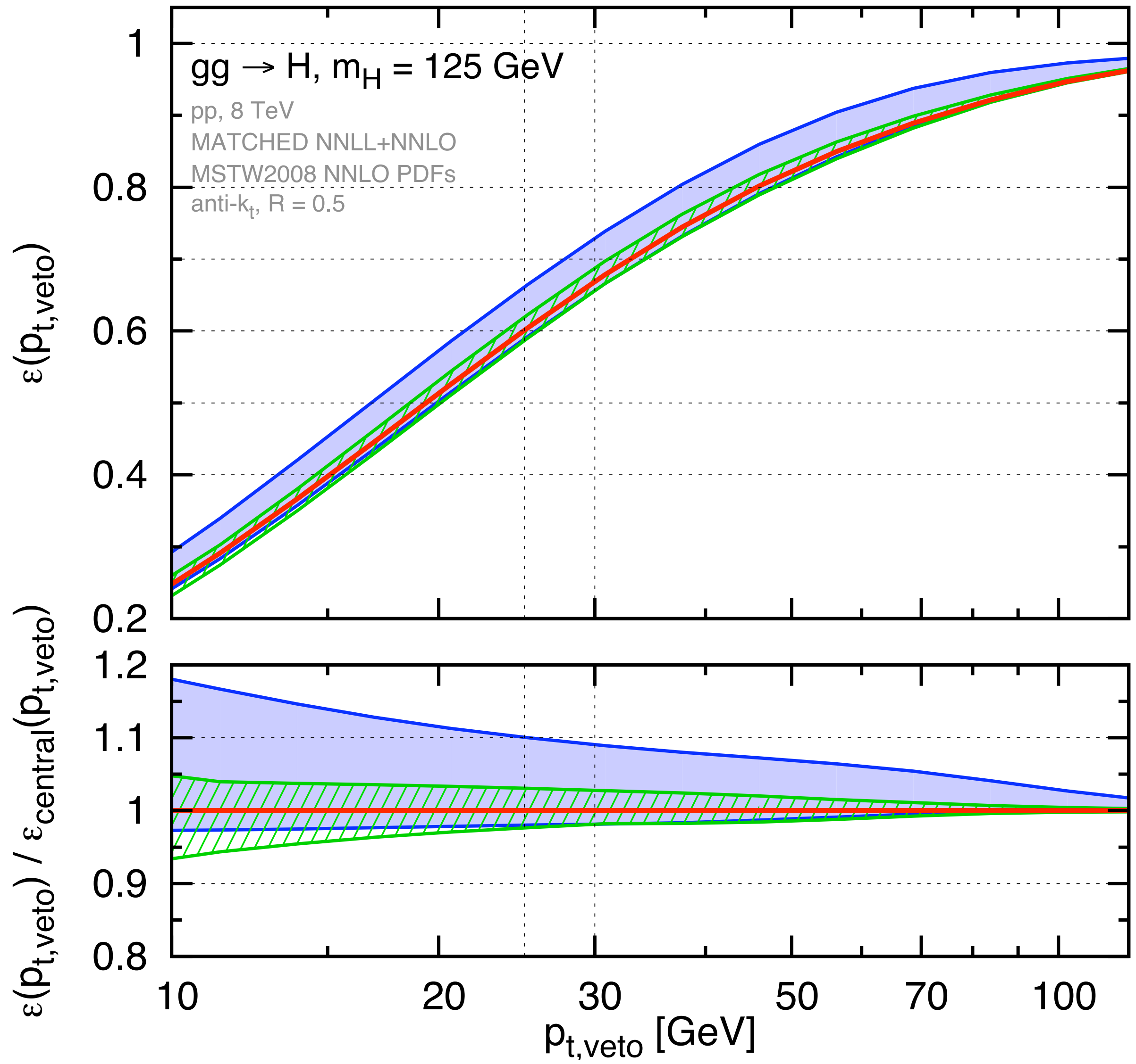

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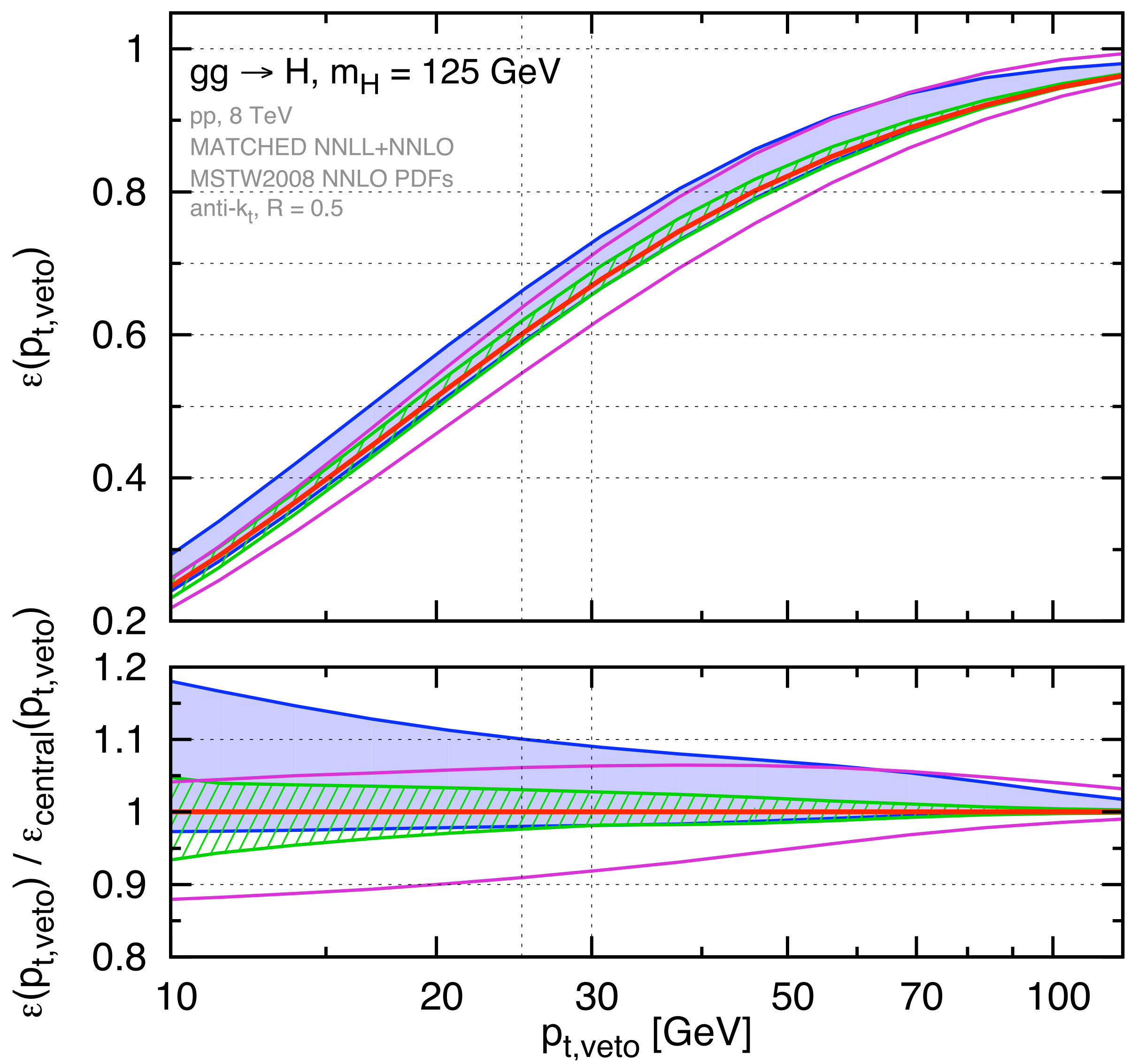

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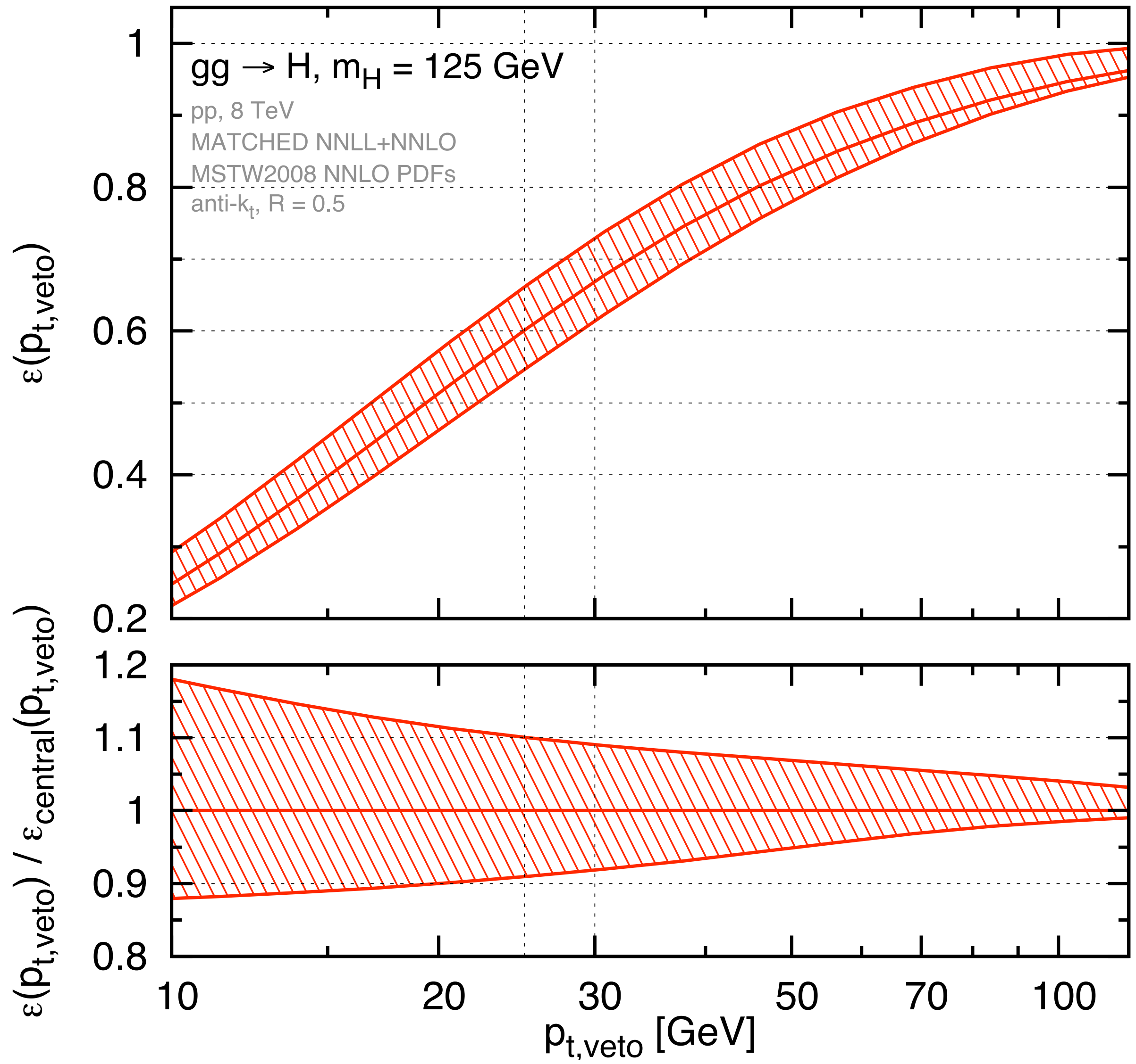
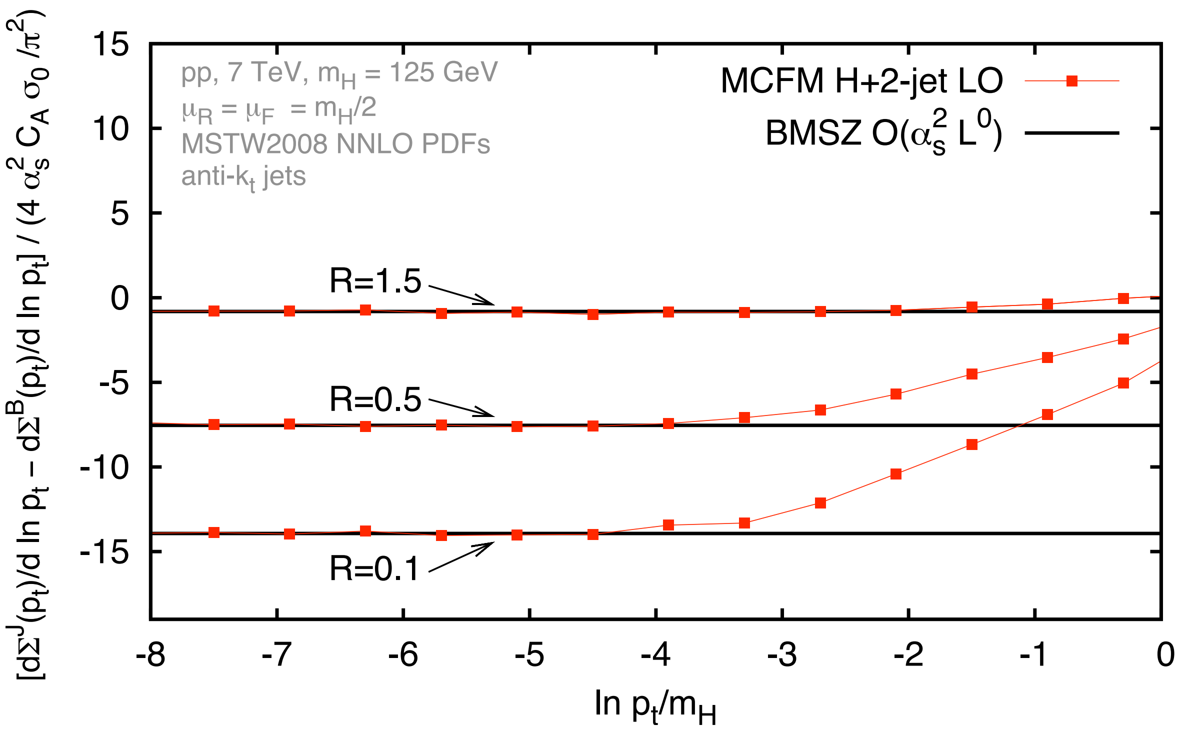
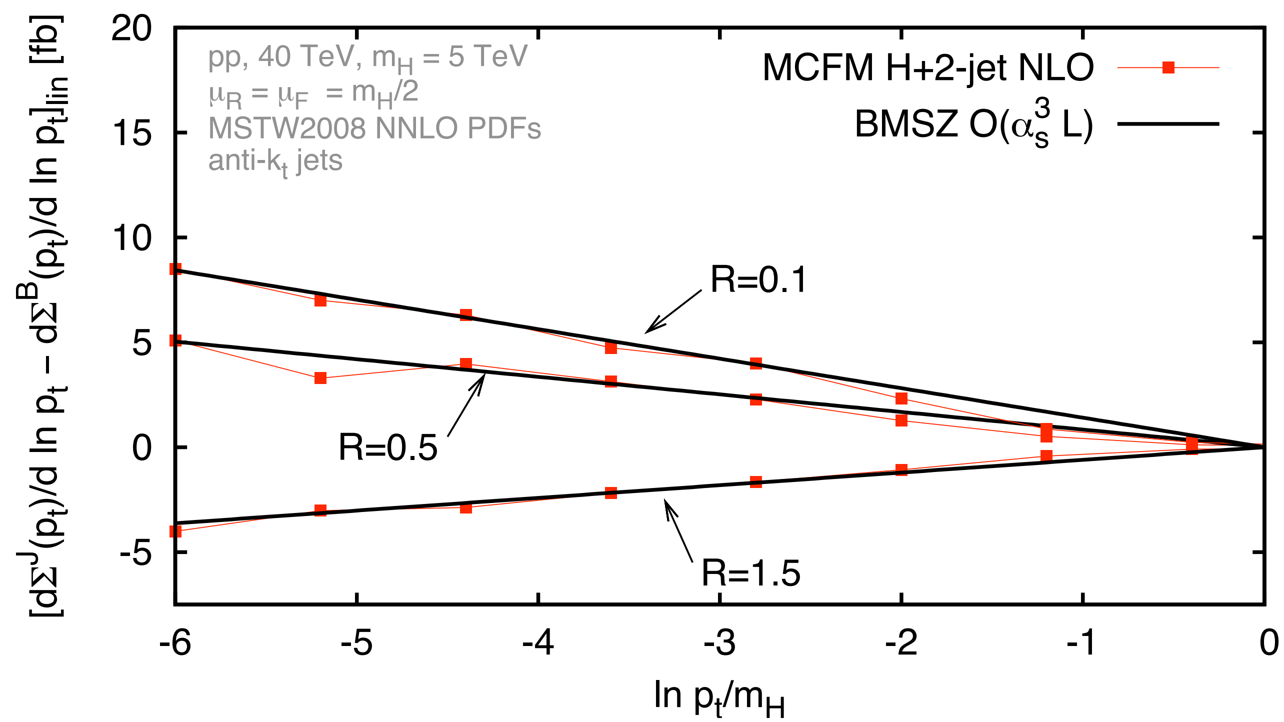
Total uncertainty = envelope



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 $p_{t,\text{Higgs}}$ and $p_{t,\text{veto}}$ at order $\mathcal{O}(\alpha_s^2)$ against MCFM's H+2j@LO

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

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

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

Covariance matrix

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

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

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

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

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

- 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 $|\Delta y| \leq R + \mathcal{O}(1/R)$

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

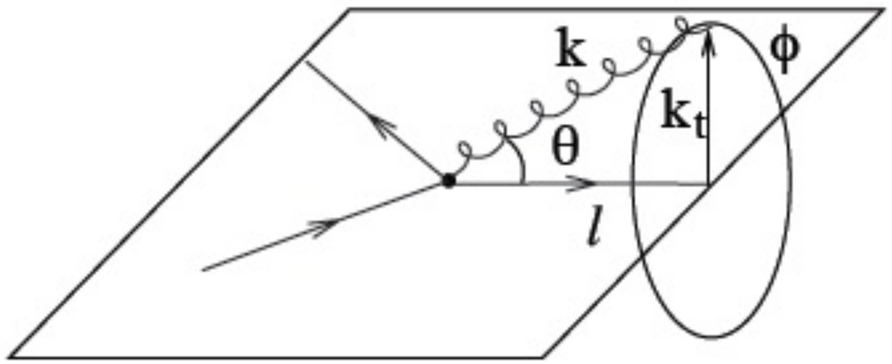
    - For $R \gtrsim \ln(M/p_{\rm t,veto}) \gg 1$ (boson-p_t) both emissions have $|y_i| \leq \ln \dfrac{M}{k_{t,1}}$

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

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

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