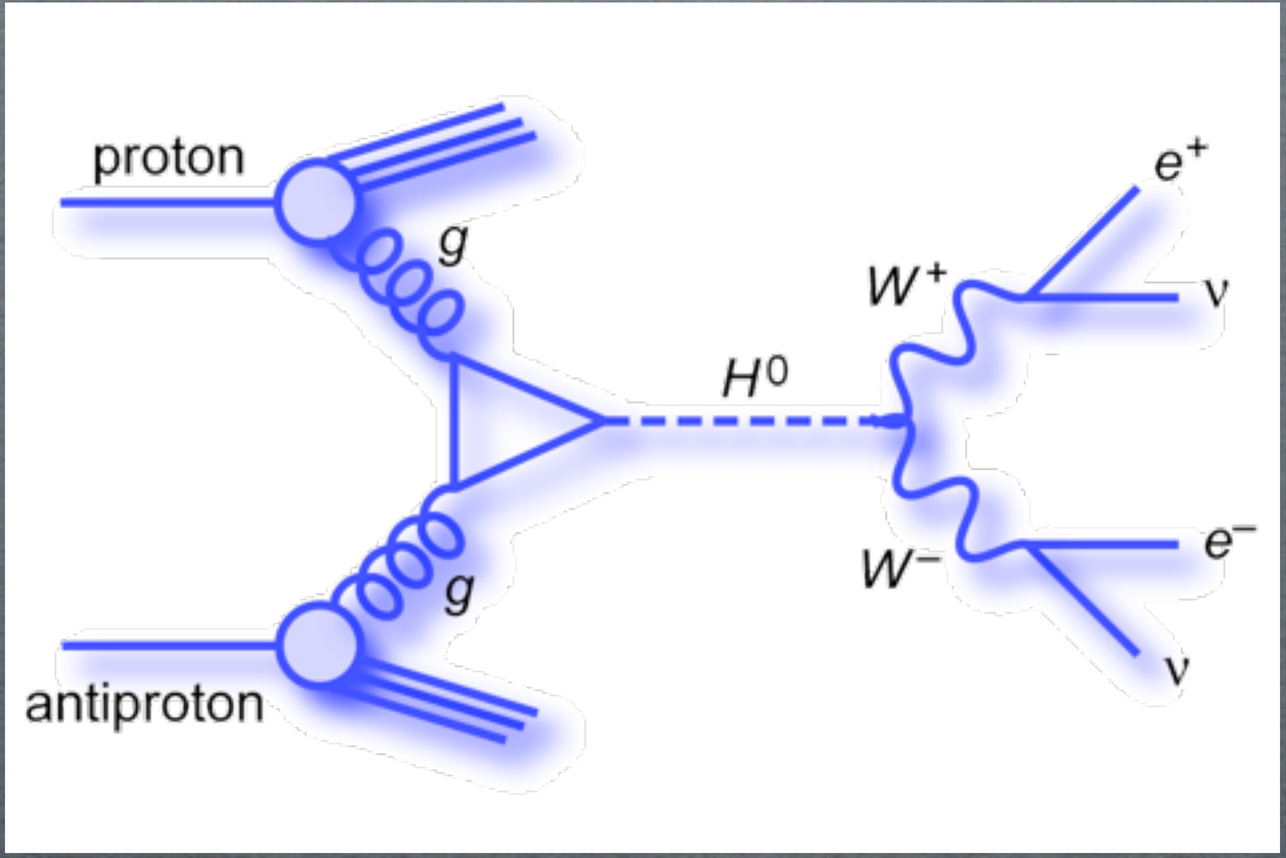
Higgs production with a jet veto
(including mass effects)



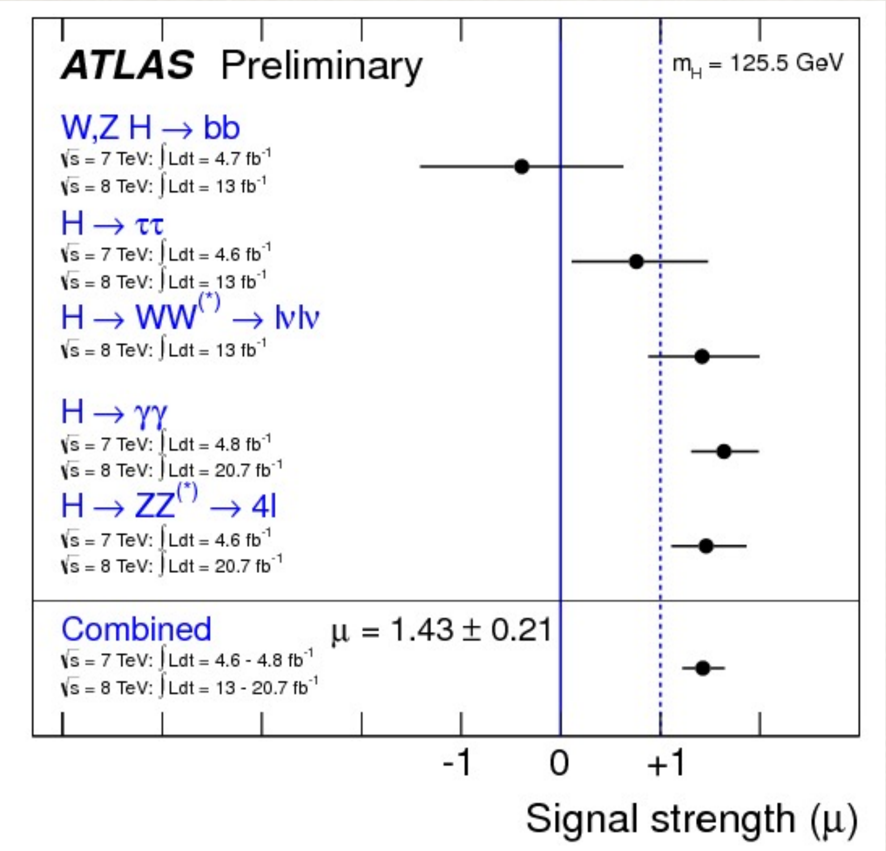
Andrea Banfi

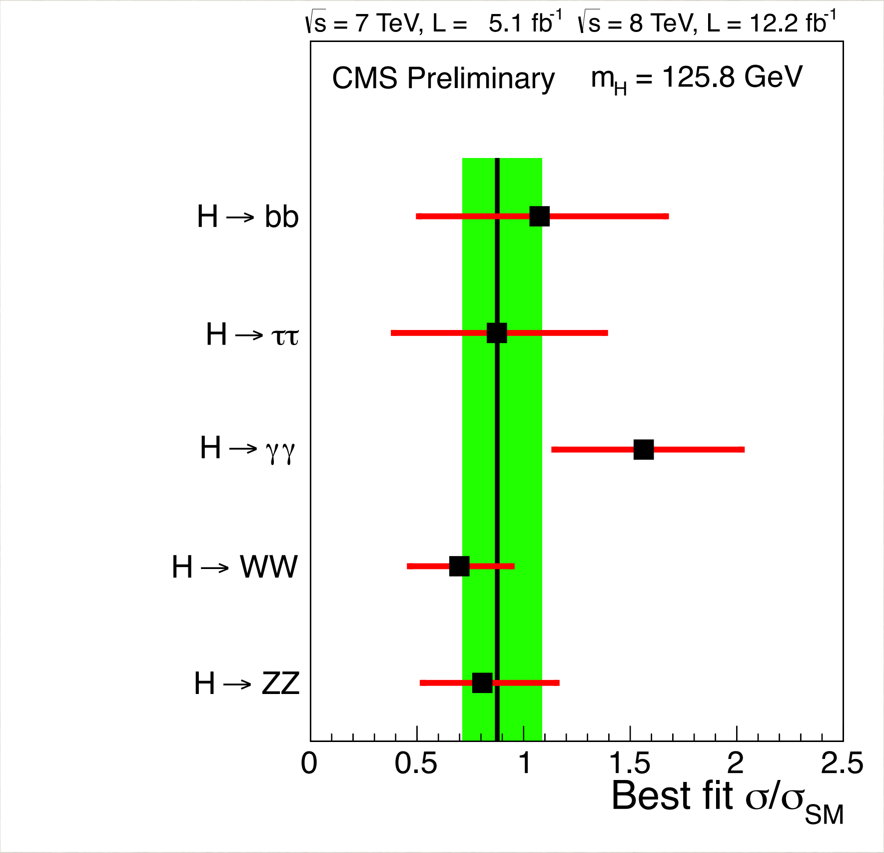
University of Sussex

Resummation and parton showers - IPPP Durham

Higgs characterisation

- Precision calculations are required to establish the nature of the125-GeV Higgs boson recently found at the LHC

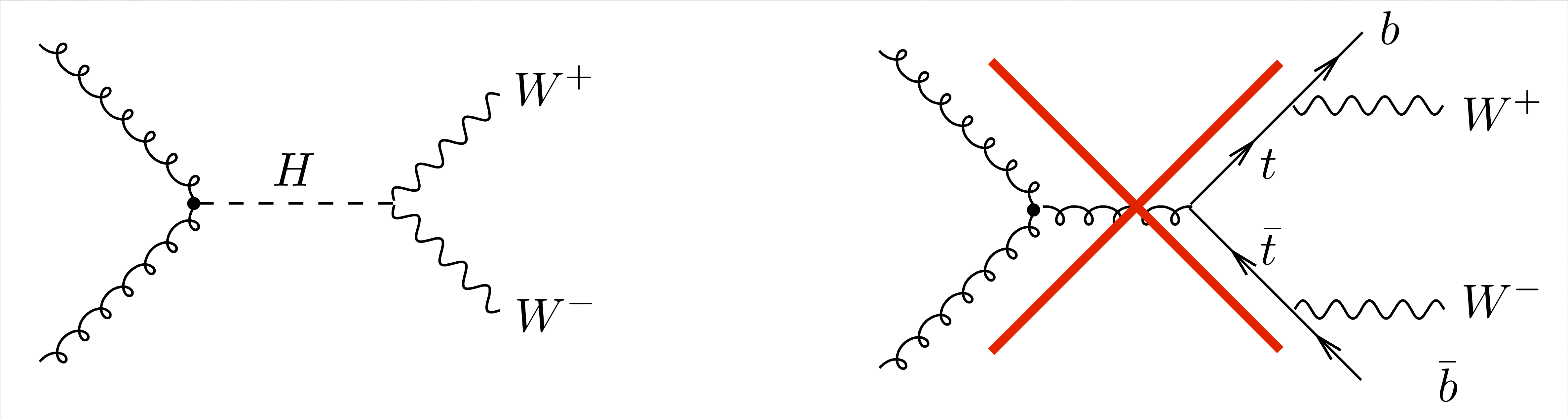




- In particular, calculations describing accurately the experimental setup for each Higgs decay channel are needed

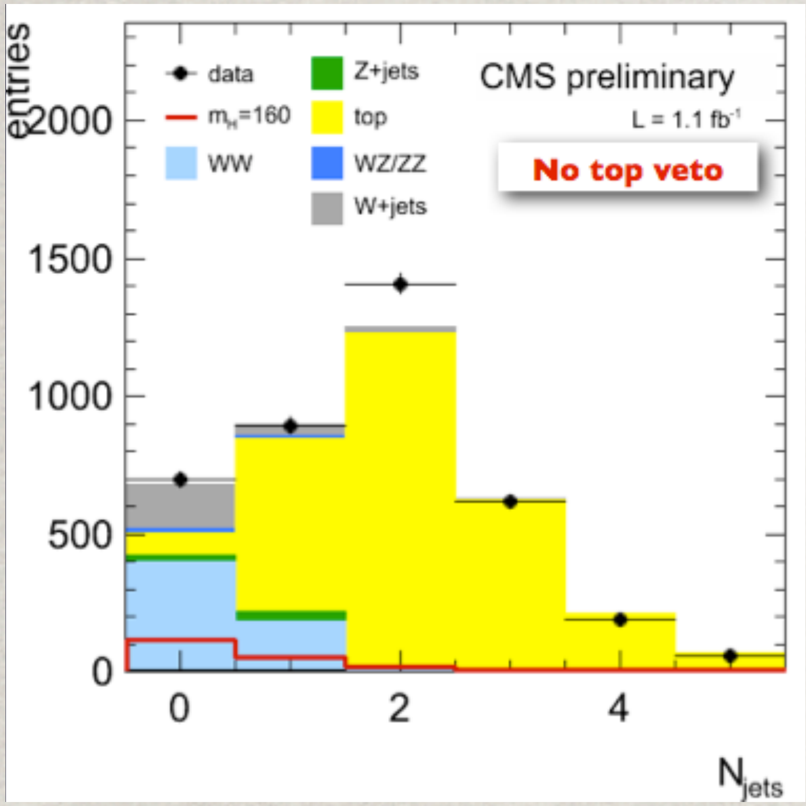
WW channel: jet-veto needed

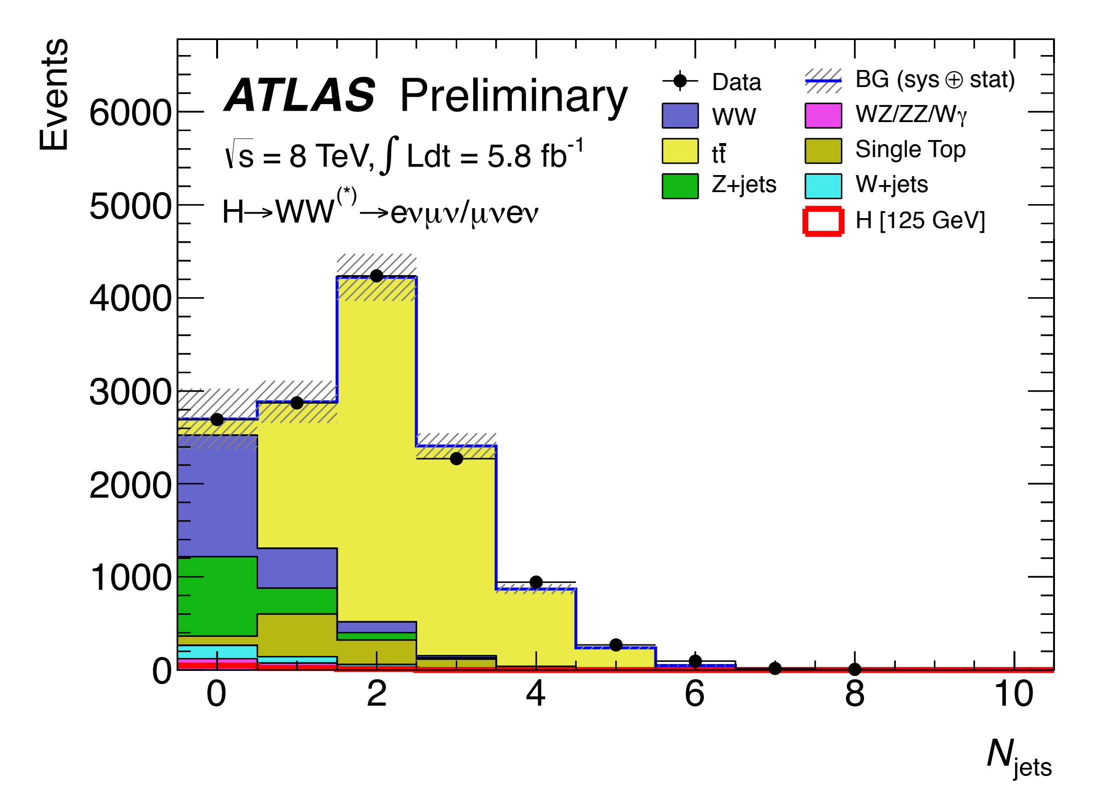
- Higgs decaying into WW suffers from a huge background from top-antitop production



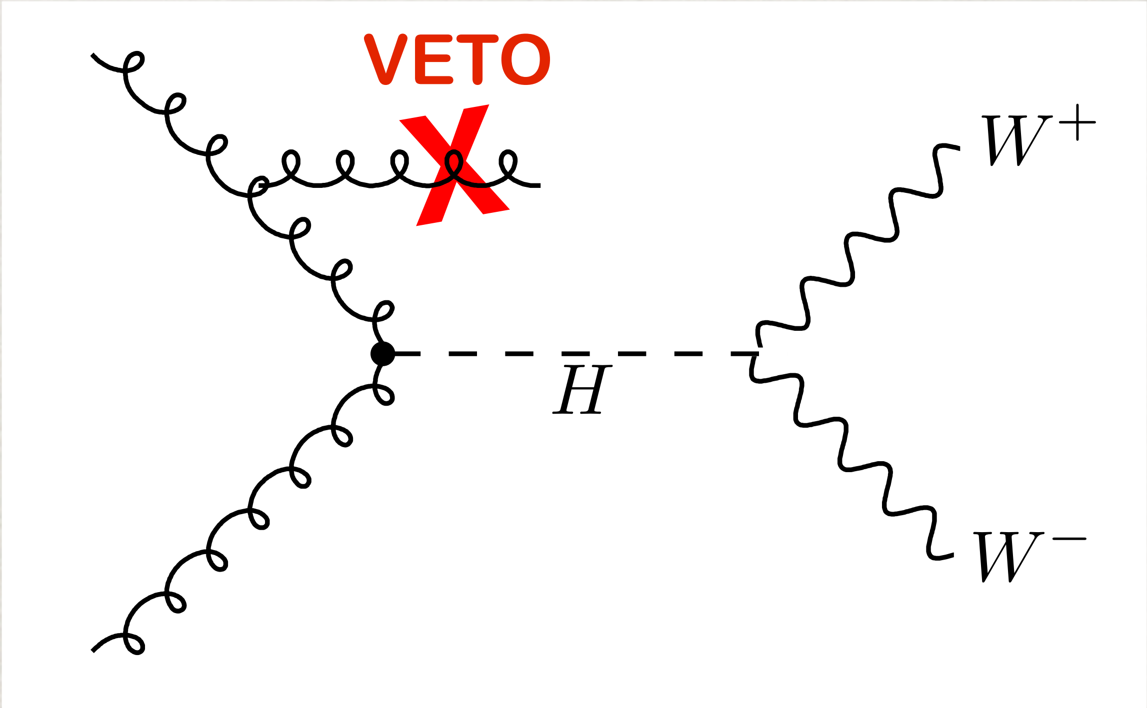
- Each top quark decays into a b-jet $\Rightarrow$ veto events with jets in the final state

The zero-jet cross section





We require that there are no jets with transverse momentum larger than $p_{\mathrm{t,veto}}$



This works well: the zero-jet cross section $\sigma_{0-\mathrm{jet}}$ is least contaminated by huge (yellow) top-antitop background

All-order 0-jet cross section

- The 0-jet cross section contains logarithms that become large when $p_{\mathrm{t,veto}} \ll m_H$

$$\sigma_{0-\mathrm{jet}} \simeq \sigma_0 \left(1 - 2C_A \frac{\alpha_s(m_H)}{\pi} \ln^2 \frac{m_H}{p_{\mathrm{t,veto}}} + \dots \right)$$

All-order 0-jet cross section

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$$\sigma_{0-\mathrm{jet}} \simeq \sigma_0 \left(1 - 2C_A \frac{\alpha_s(m_H)}{\pi} \ln^2 \frac{m_H}{p_{\mathrm{t,veto}}} + \dots \right)$$

- Finiteness of $\sigma_{0-\mathrm{jet}}$ is recovered after resummation of large logarithms $\Rightarrow$ reorganisation of the PT series for $\alpha_s L \sim 1$

$$L = \ln(m_H/p_{\mathrm{t,veto}})$$

$$\sigma_{0-\mathrm{jet}} \sim \sigma_0 \exp\left[\underbrace{L g_1(\alpha_s L)}_{\mathrm{LL}} + \underbrace{g_2(\alpha_s L)}_{\mathrm{NLL}} + \underbrace{\alpha_s g_3(\alpha_s L)}_{\mathrm{NNLL}} + \dots\right]$$

All-order 0-jet cross section

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$$\sigma_{0-\mathrm{jet}} \simeq \sigma_0 \left(1 - 2C_A \frac{\alpha_s(m_H)}{\pi} \ln^2 \frac{m_H}{p_{\mathrm{t,veto}}} + \dots \right)$$

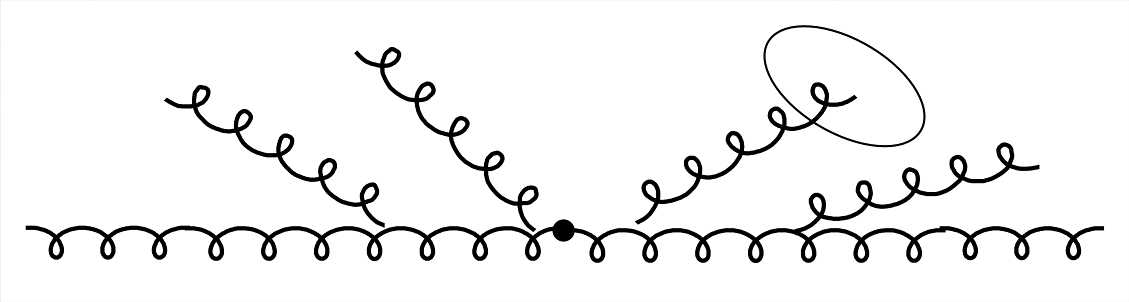
- Finiteness of $\sigma_{0-\mathrm{jet}}$ is recovered after resummation of large logarithms $\Rightarrow$ reorganisation of the PT series for $\alpha_s L \sim 1$

$$\sigma_{0-\mathrm{jet}} \sim \sigma_0 \, e^{\overbrace{Lg_1(\alpha_s L)}_{\mathrm{LL}}} \times \left(\overset{1}{\underbrace{G_2(\alpha_s L)}_{\mathrm{NLL}}} \overset{+}{+} \overset{\alpha_s}{\underbrace{\alpha_s G_3(\alpha_s L)}_{\mathrm{NNLL}}} \overset{+\dots}{+\dots} \right)$$

NLL resummation

- NLL resummation can be obtained automatically with CAESAR, the Computer Automated Expert Semi-Analytical Resummer

[AB Salam Zanderighi '03]



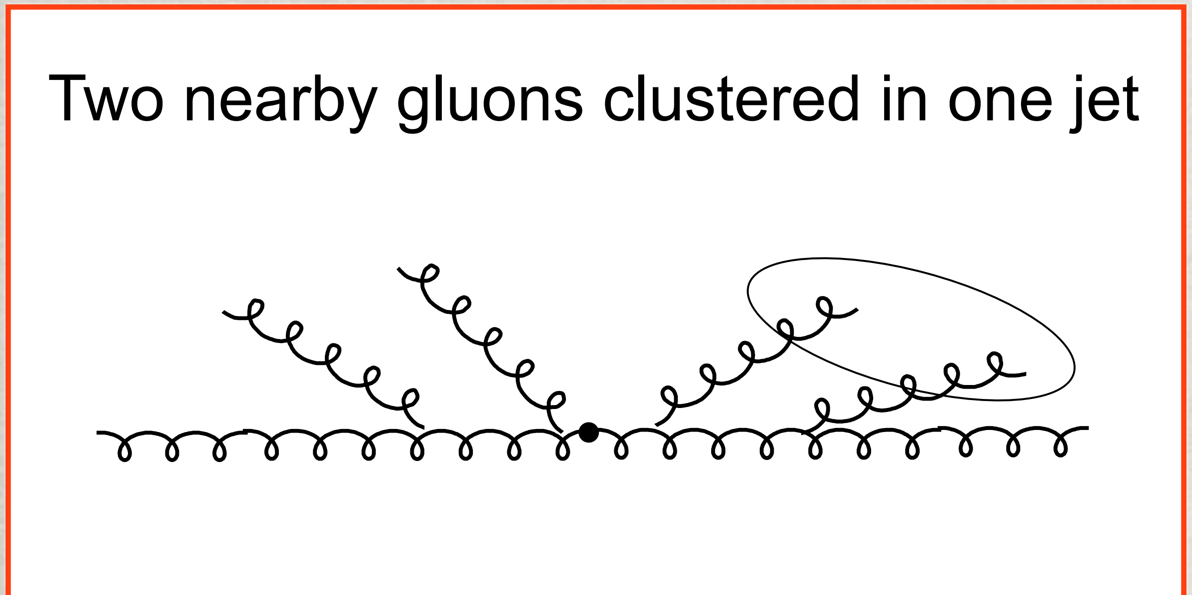
- At NLL accuracy, relevant soft and collinear emissions are widely separated in rapidity $\Rightarrow$ no recombinations can occur [AB Salam Zanderighi '12]

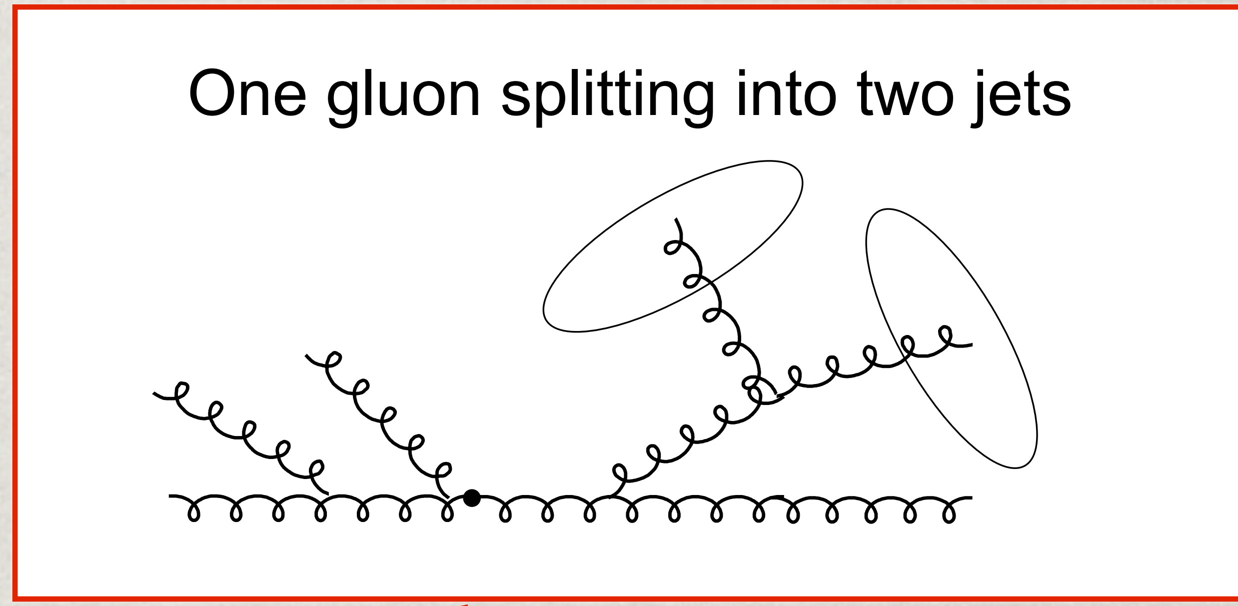
- No jets = no gluons $\Rightarrow$ $\sigma_{0-\mathrm{jet}}$ is just a Sudakov form factor

$$\sigma_{0-\mathrm{jet}} \sim \sigma_0 \, e^{\overbrace{\underbrace{Lg_1(\alpha_s L)}_{\mathrm{LL}} + \underbrace{g_2(\alpha_s L)}_{\mathrm{NLL}}}}$$

NNLL resummation

- At NNLL, we have extra contributions from gluon emission $\Rightarrow$ non trivial dependence on the jet radius [AB Monni Salam Zanderighi '12]



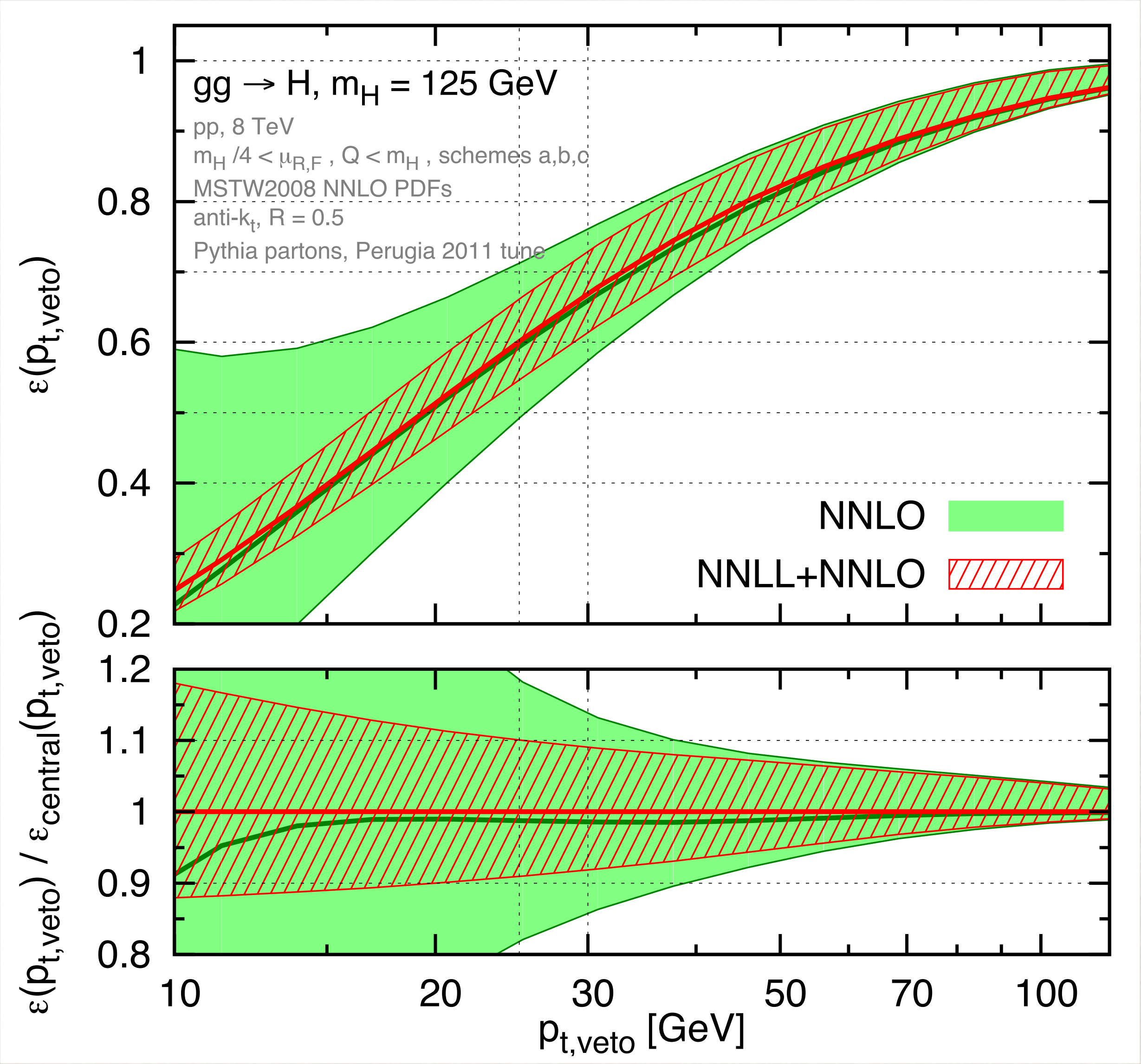


$$\sigma_{0-\mathrm{jet}} \sim \sigma_0 \times \left(1 + \underbrace{f(R)\alpha_s^2(p_{\mathrm{t,veto}})L}_{\mathrm{NNLL}} \right) \times e^{\underbrace{Lg_1(\alpha_s L)}_{\mathrm{LL}} + \underbrace{g_2(\alpha_s L)}_{\mathrm{NLL}} + \underbrace{\alpha_s g_3(\alpha_s L)}_{\mathrm{NNLL}} + \dots}$$

- NNLL Sudakov exponent taken from Higgs p_t distribution [Catani et al. '06, Becher Neubert '11]
- Correction $f(R)$ from real radiation only $\Rightarrow$ computed with a Monte Carlo [AB Salam Zanderighi '12]
- Note: $f(R) \sim \ln R$ due to collinear singularity in gluon splitting

Comparison to NNLO

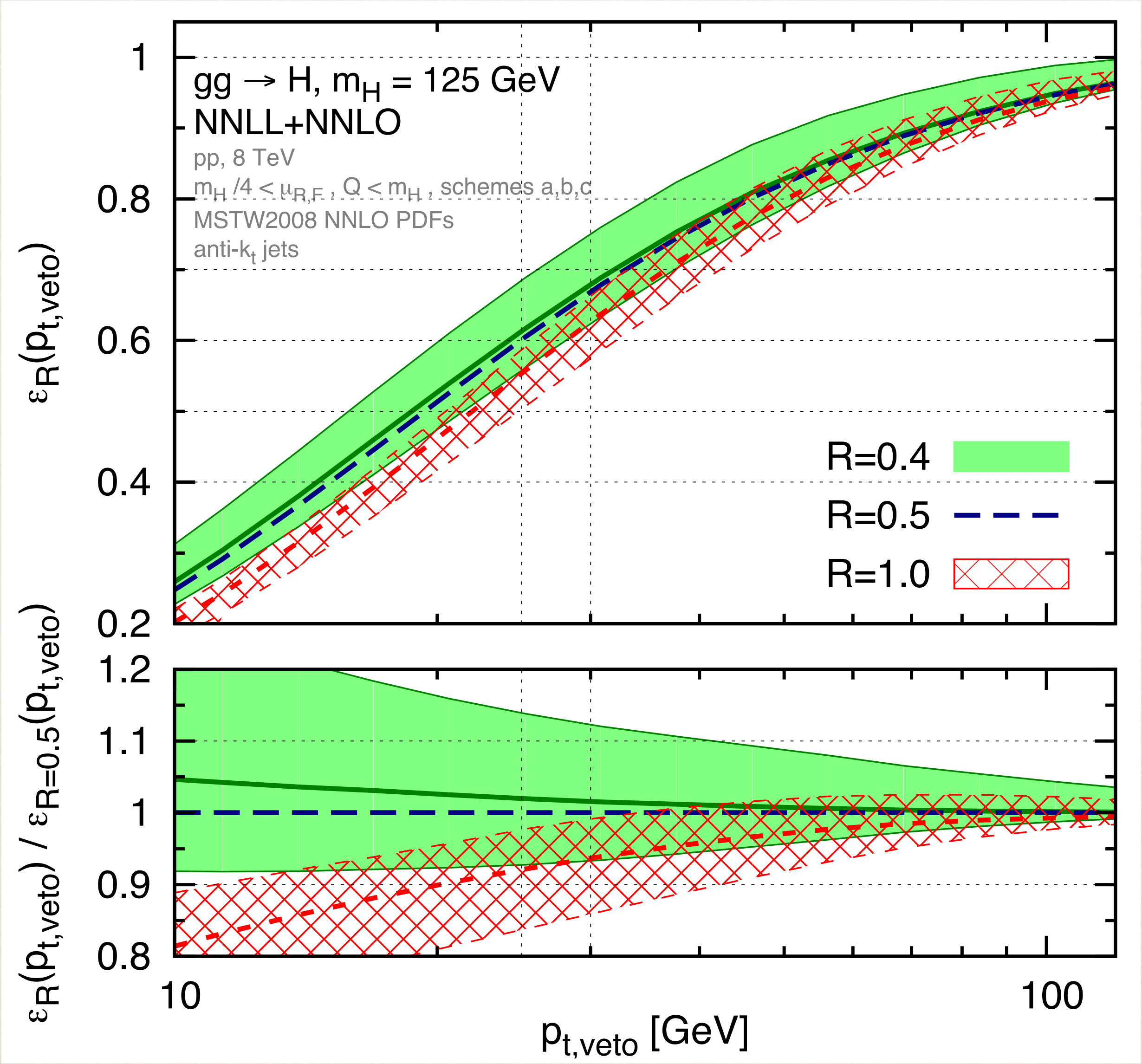
- We present results for the jet-veto efficiency $\epsilon(p_{\rm t,veto}) = \sigma_{0-\rm jet}(p_{\rm t,veto})/\sigma_{\rm tot}$



- Central values of NNLO and NNLL+NNLO are in good agreement
- Resummation reduces uncertainties by a factor two with respect to NNLO

Effect of jet radius

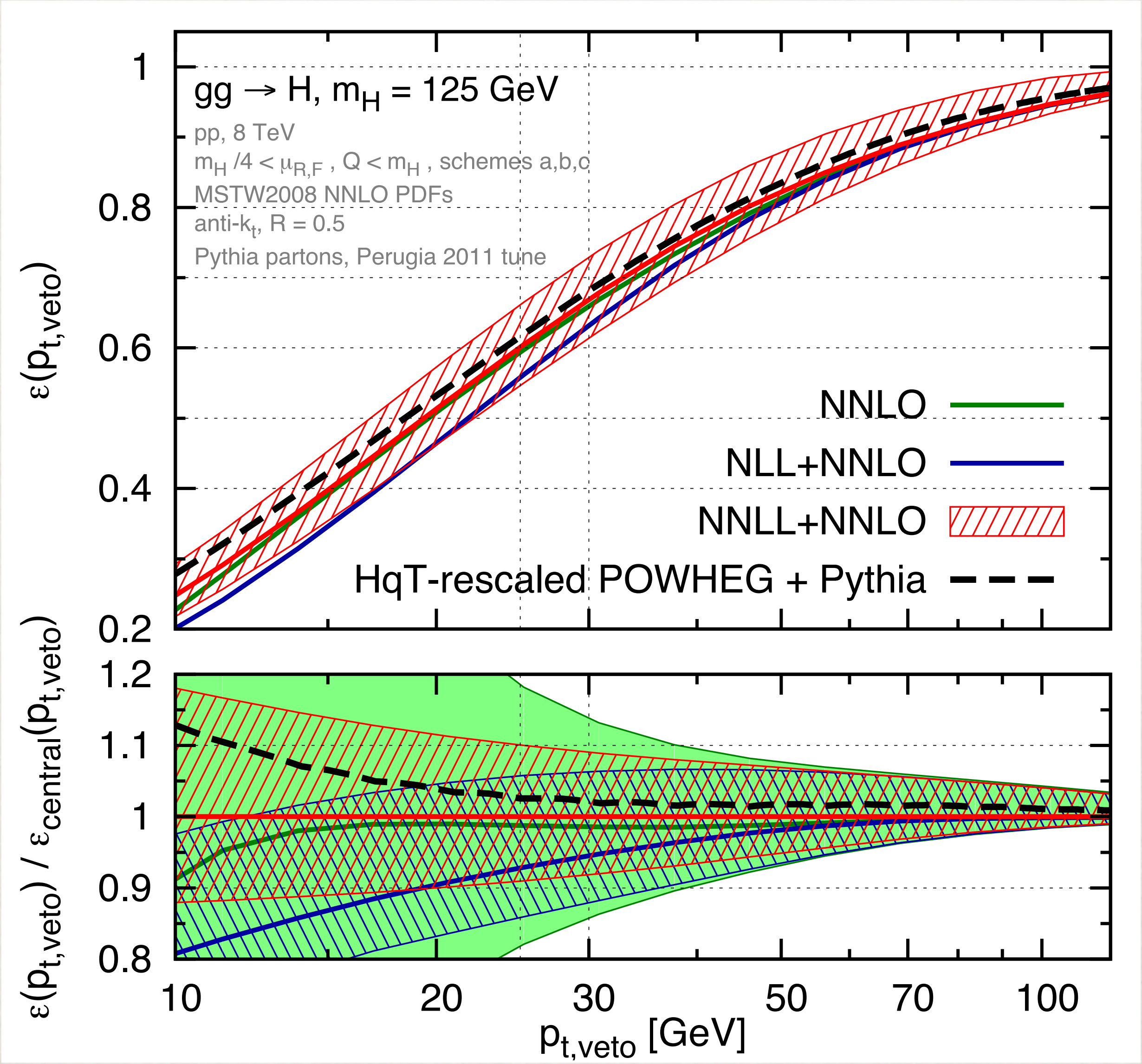
- We present results for the jet-veto efficiency $\epsilon(p_{\mathrm{t,veto}}) = \sigma_{0-\mathrm{jet}}(p_{\mathrm{t,veto}})/\sigma_{\mathrm{tot}}$



- A larger jet-radius gives smaller theoretical uncertainties
- Note: larger jet-radius ⇒ more contamination from underlying event

Comparison to Monte Carlo

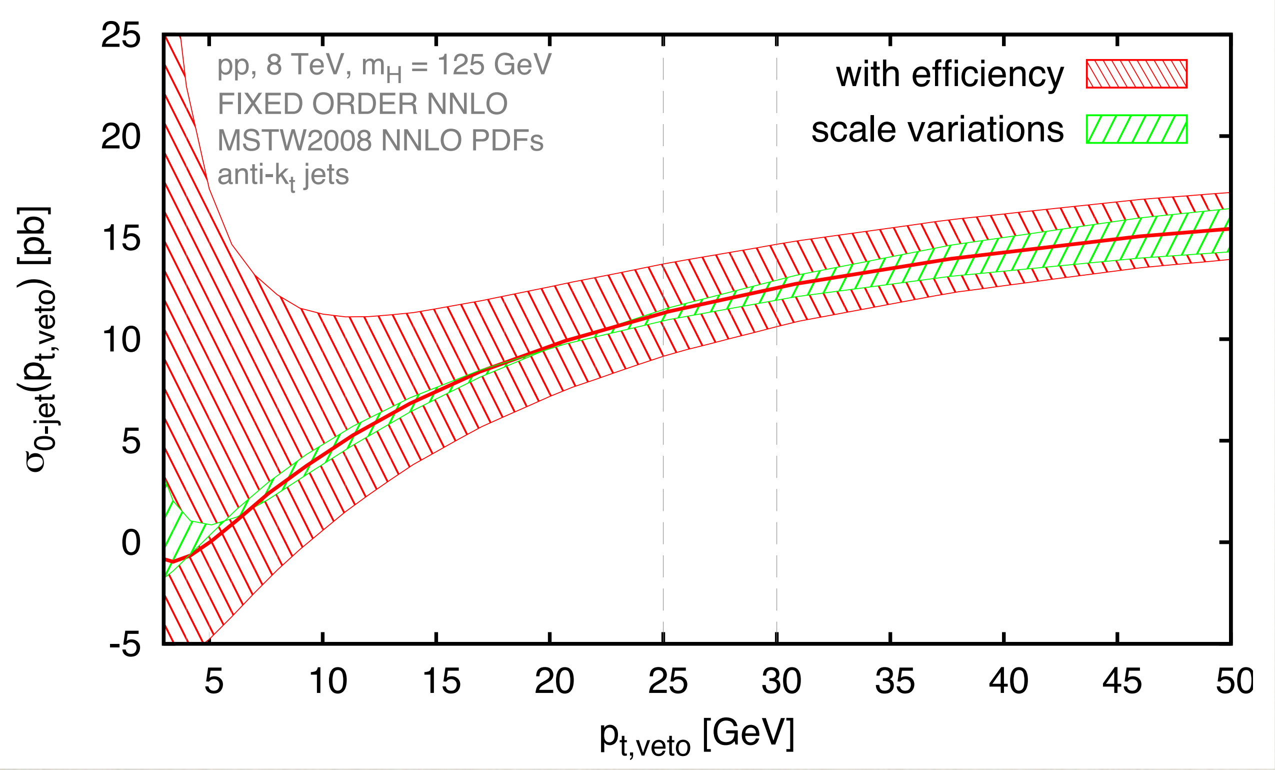
- We present results for the jet-veto efficiency $\epsilon(p_{\mathrm{t,veto}}) = \sigma_{0-\mathrm{jet}}(p_{\mathrm{t,veto}})/\sigma_{\mathrm{tot}}$

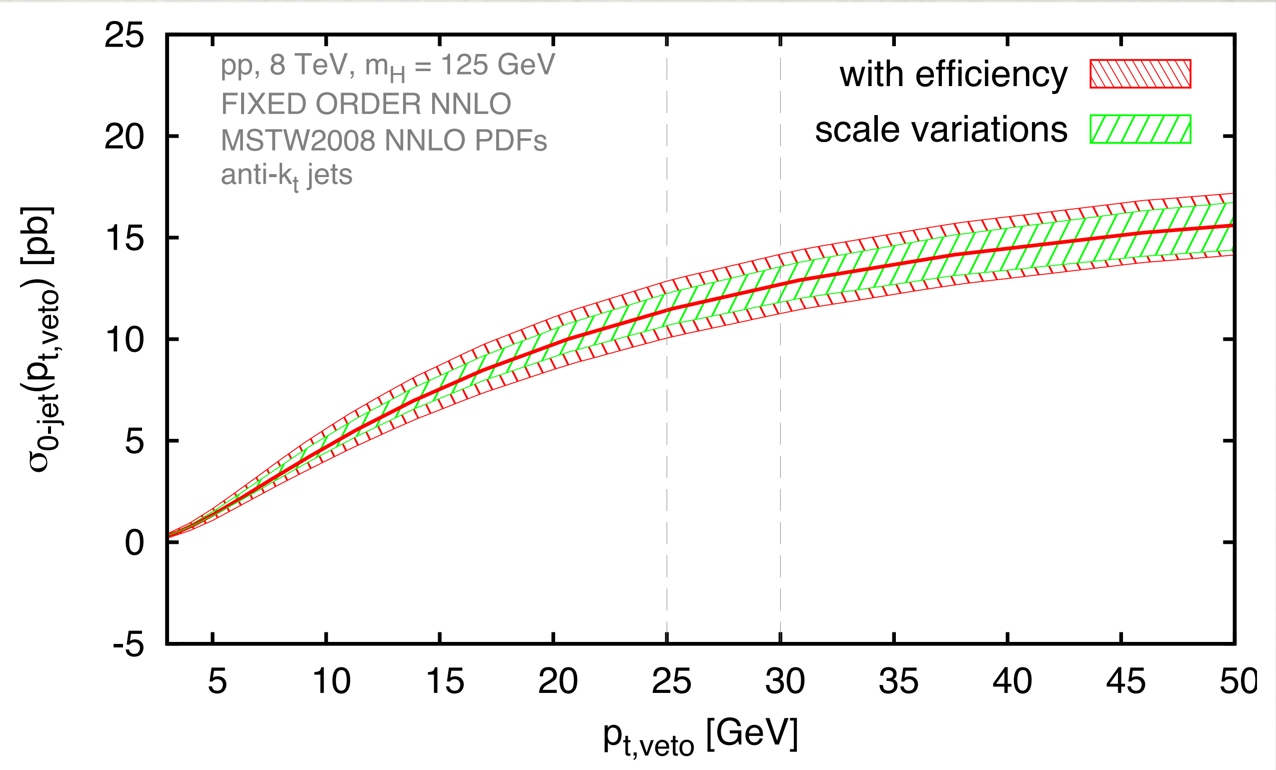


- Central value agrees with POWHEG+PYTHIA (rescaled so as to agree with Higgs NNLL+NNLO transverse momentum distribution)

Uncertainties in the 0-jet bin

- We have developed a new uncertainty method for $\sigma_{0-\text{jet}} = \epsilon\,\sigma_{\text{tot}}$, treating the efficiency ϵ and the total cross section σ_{tot} as uncorrelated
- The efficiency method makes full use of resummed results, as opposed to the currently used Stewart-Tackmann method, which is tied to fixed order





- At NNLO, in the region $p_{t,\text{veto}} \ll m_H$, the efficiency method gives a much larger error than scale variations, which vanish spuriously
- Adding NNLL, uncertainty for $p_{t,\text{veto}} = 25 - 30\,\text{GeV}$ reduces to 11%

Jet-veto resummation: outlook

- The code JetVHeto to perform the resummation and matching to NNLO is available at http://jetvheto.hepforge.org/
- Our results have been independently confirmed by two different groups in the framework of Soft-Collinear Effective Theory (SCET)

[Becher Neubert '12, Becher Neubert Rothen '13, Stewart Tackmann Walsh Zuberi '13]

Recent improvements:

- Effect of top and bottom masses in loops

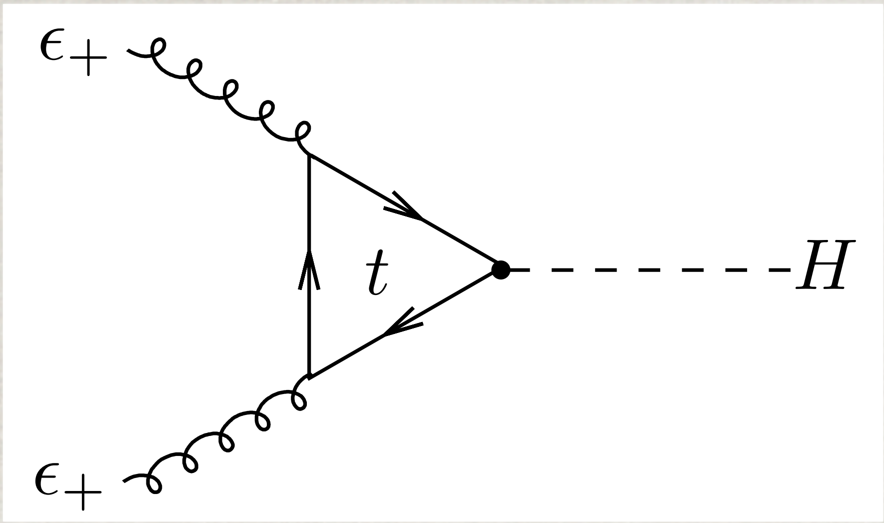
[AB Monni Zanderighi, in preparation]

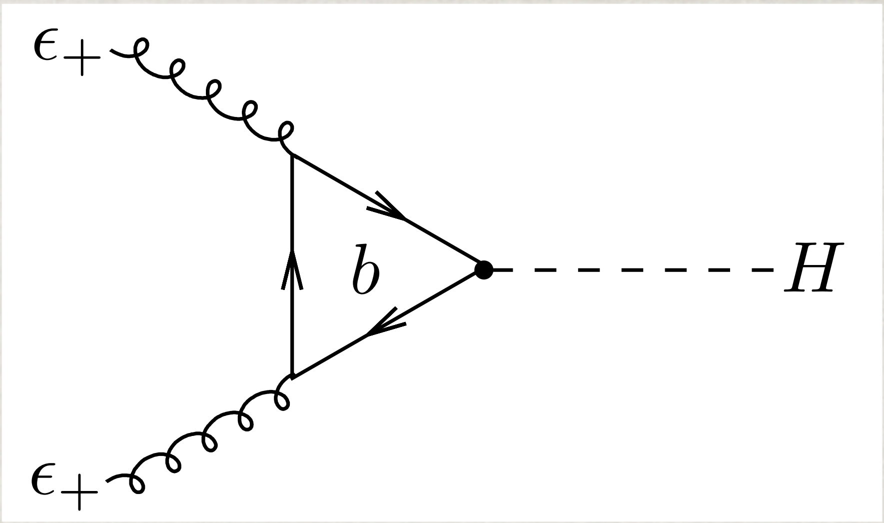
- Calculations beyond NNLL accuracy

[Becher Neubert Rothen '13, Stewart Tackmann Walsh Zuberi '13]

Finite-mass effects in loops

- The predictions presented so far were computed in the limit $m_t \to \infty$
- For finite masses, top and bottom loops have different behaviours





Top loop: $m_H \ll m_t$

The amplitude M_{++} has a well-behaved expansion in powers of (m_H/m_t)

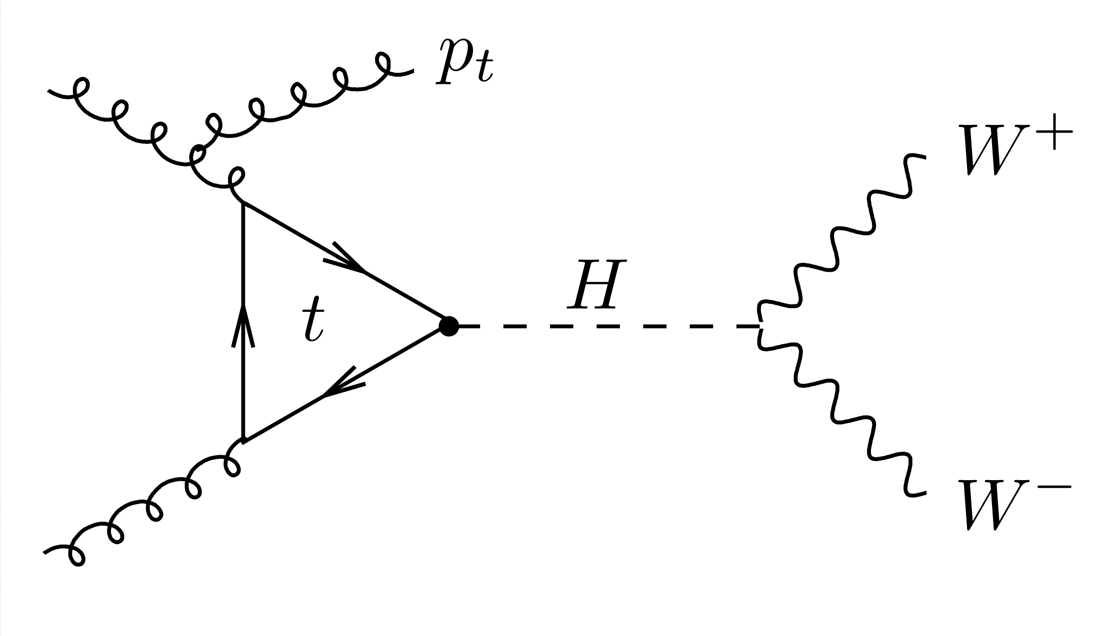
Bottom loop: $m_b \ll m_H$

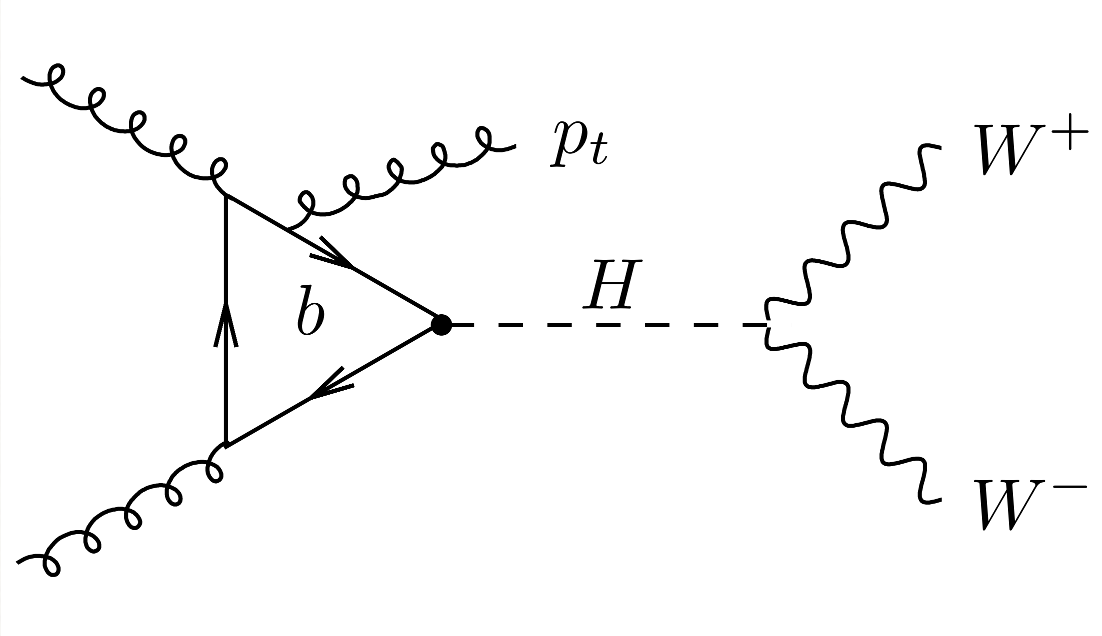
$$M_{++} \sim \left(\frac{m_b}{m_H}\right) \ln^2\left(\frac{m_b^2}{m_H^2}\right)$$

The loop momentum becomes soft giving the usual double-log

Masses and soft factorisation

- Top and bottom loops have also different behaviours with respect to factorisation of soft emissions in the region $p_{\mathrm{t,veto}} = 25 - 30\,\mathrm{GeV}$





Top loop: $p_t \ll m_H \ll m_t$

Soft gluons cannot resolve the top loop $\Rightarrow$ factorisation OK

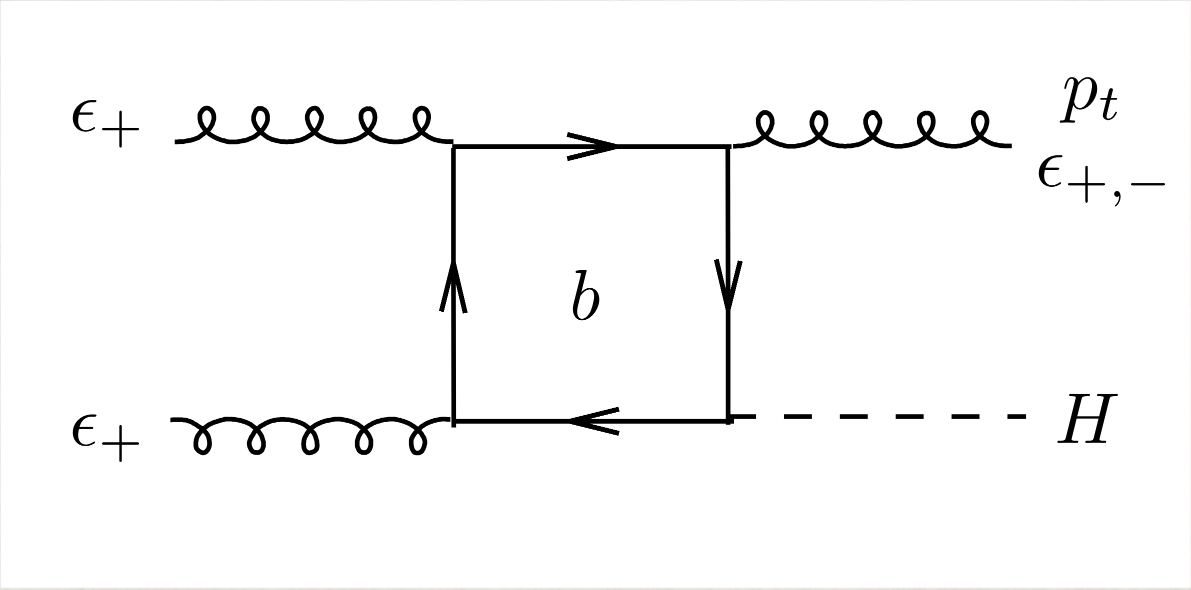
Bottom loop: $m_b \ll p_t \ll m_H$

Soft gluons can resolve a bottom loop $\Rightarrow$ factorisation breaking?

Non-factorising corrections (I)

- Emission of a soft gluon does not factorise from the lowest order amplitude

[for the amplitude see Baur Glover '90]



$$\frac{1}{p_t} \times \text{Born}$$

$$M_{+++} \sim \frac{m_b}{p_t}\left[\ln^2\left(\frac{m_b^2}{m_H^2}\right) + \ln^2\left(\frac{m_b^2}{p_t^2}\right)\right] \qquad M_{++-} \sim \frac{m_b}{p_t}\left[\ln^2\left(\frac{m_b^2}{m_H^2}\right) - \ln^2\left(\frac{m_b^2}{p_t^2}\right)\right]$$

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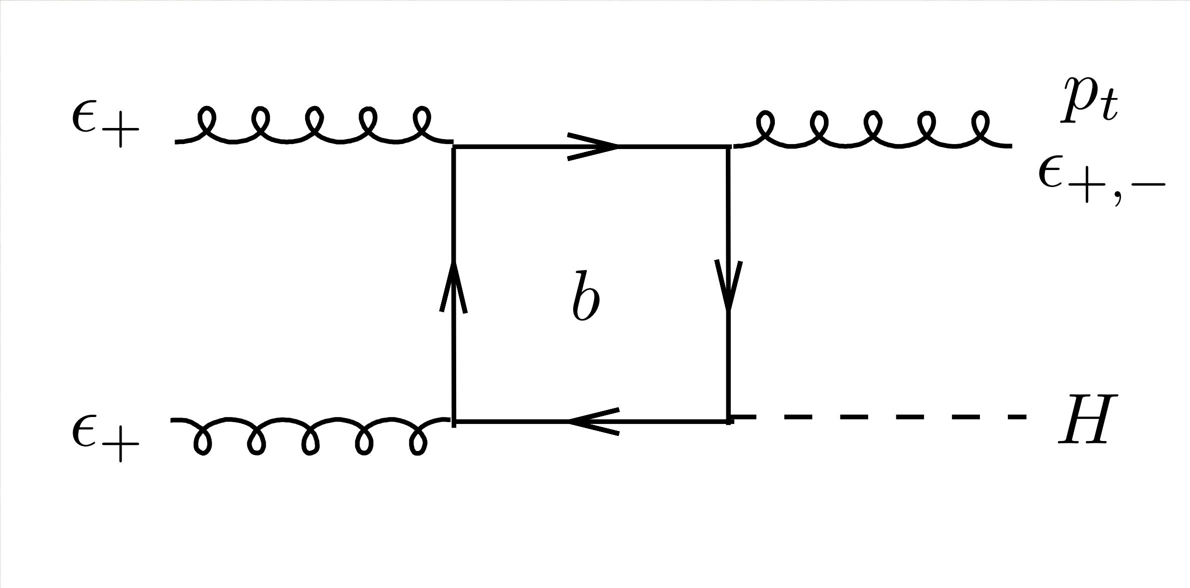

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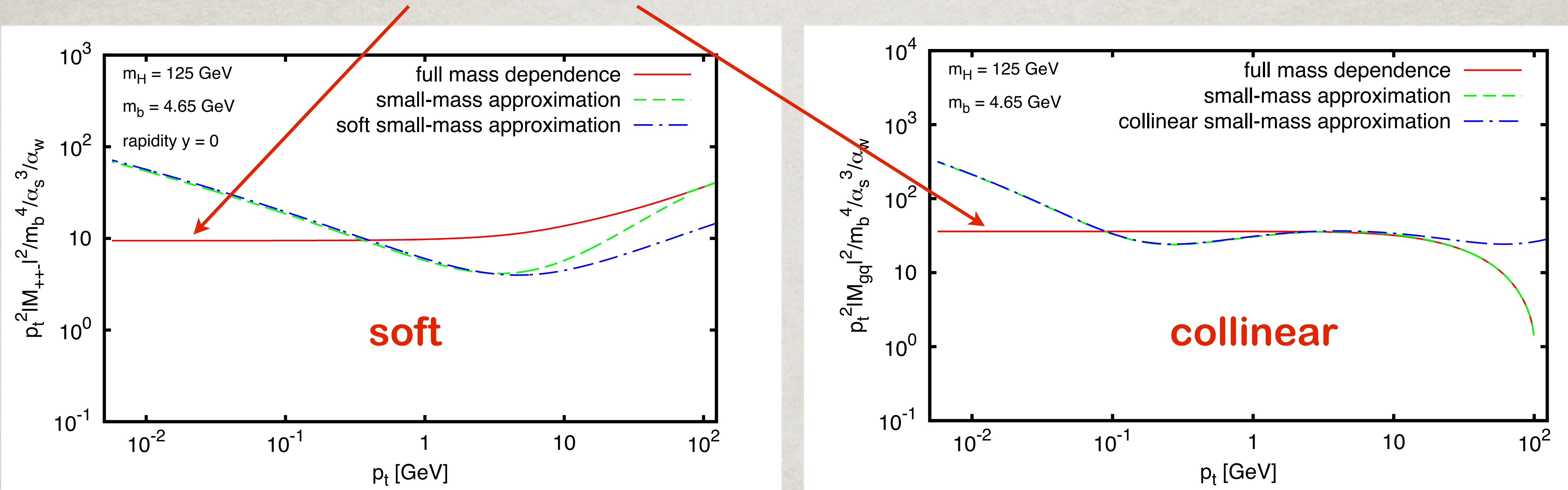
- Non-factorising terms in the soft limit
  - depend on the helicity of the soft gluon
  - have opposite signs $\Rightarrow$ cancel in interference with the top loop
- Note: non-factorising terms arise also in the hard collinear limit

[see also Grazzini Sargsyan '13]

Non-factorising corrections (II)

- We investigate the impact of non-factorising corrections by studying $p_t^2 |M|^2$ (constant behaviour = factorisation)

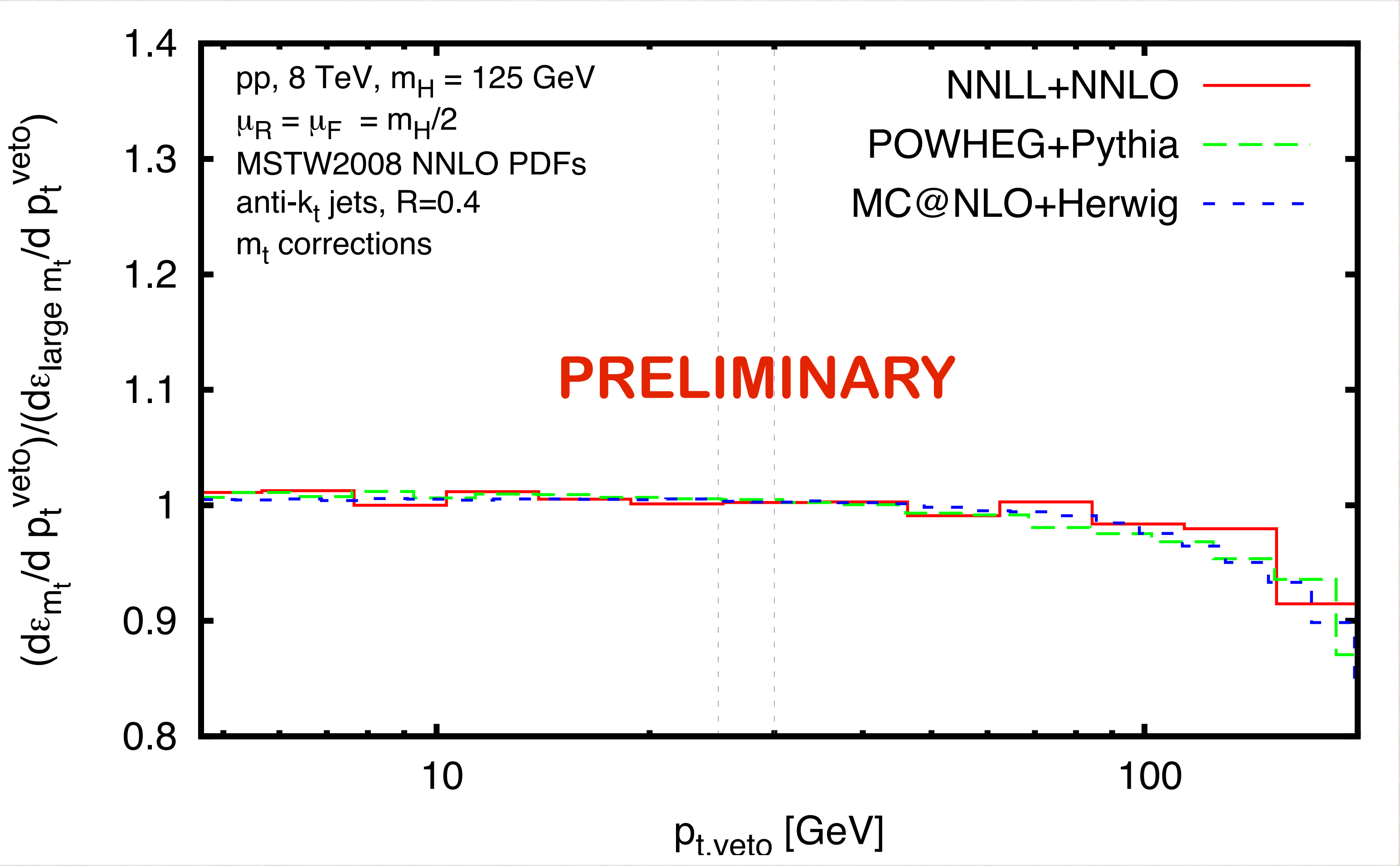


- The region in which $\ln^2(p_t/m_b)$ dominate never overlaps with the soft region, and hardly with the collinear region

- We then consider non-factorising corrections as a remainder, vanishing smoothly for $p_{\mathrm{t,veto}} \to 0 \Rightarrow$ automatically implemented through matching

Comparison to MC: top

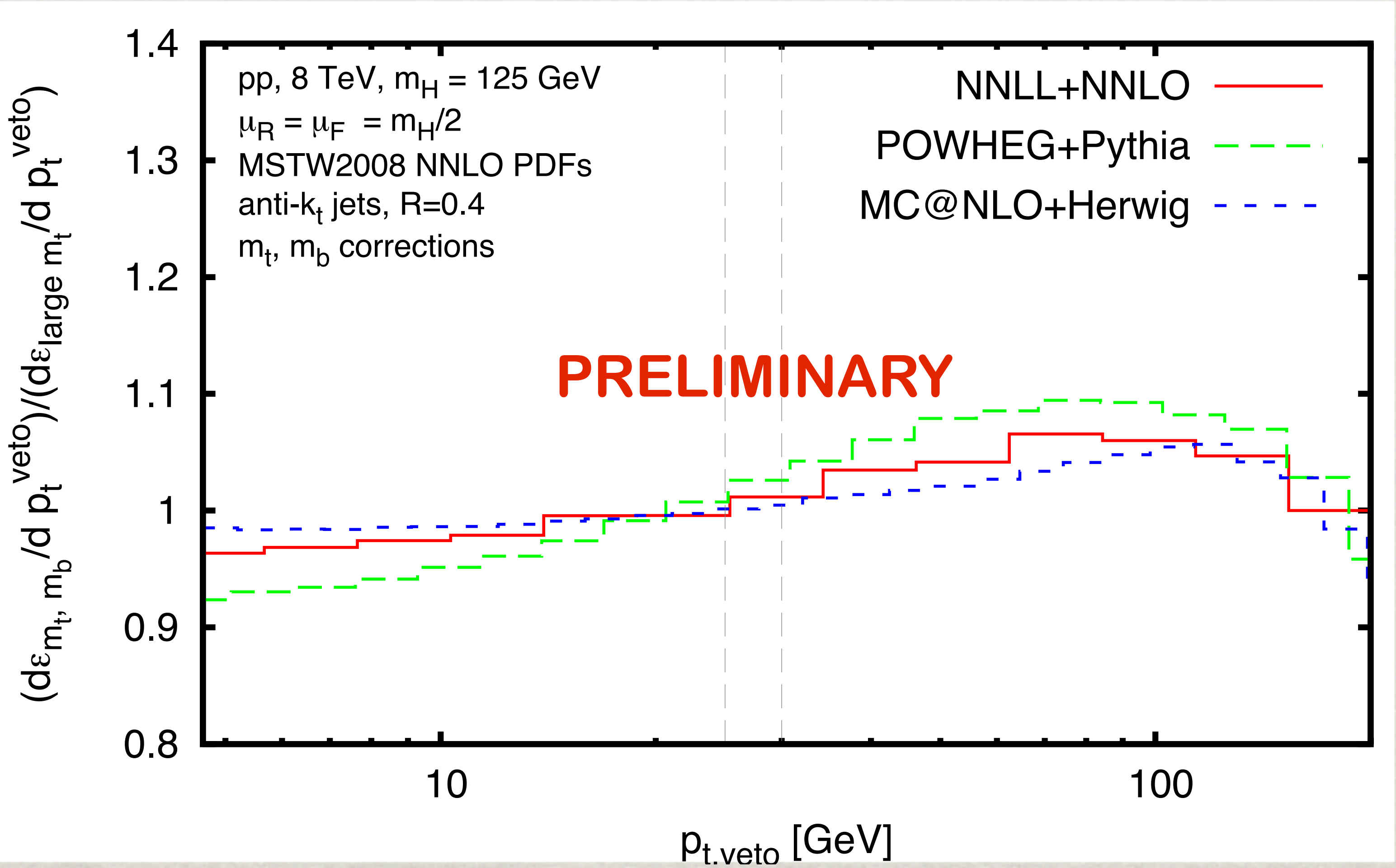
- We consider the ratio of $d\epsilon/dp_t$ over its limit for $m_t \to \infty$



- Finite-m_t corrections: excellent agreement between resummation and Monte Carlo

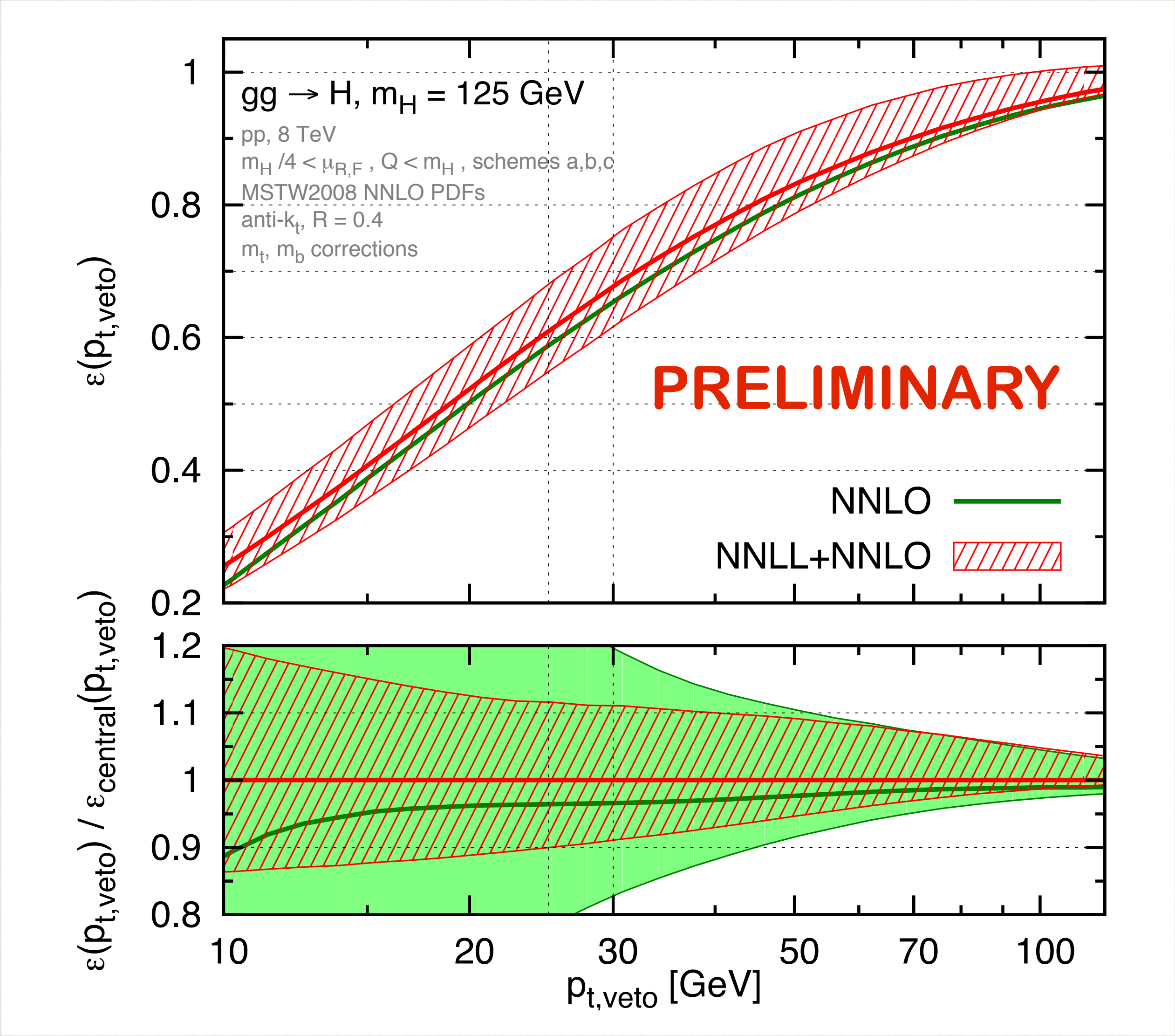
Comparison to MC: bottom

- We consider the ratio of $d\epsilon/dp_t$ over its limit for $m_t \to \infty$



- Finite-m_b corrections: different implementations of mass corrections lead to differences up to 5%
- POWHEG overestimates finite-mass effects, whereas MC@NLO tends to underestimate them

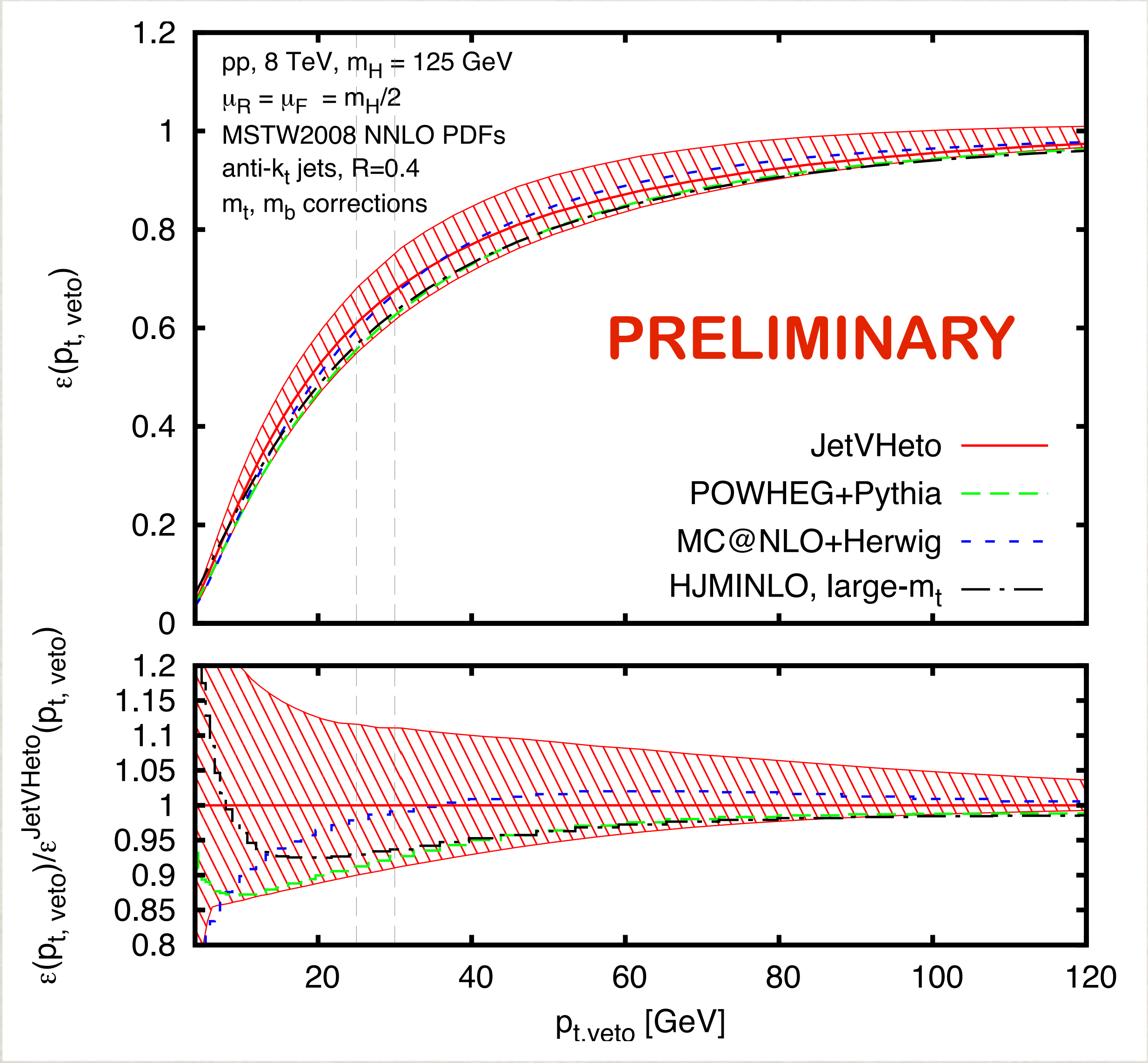
Results for the efficiency



- Larger discrepancy between central values of NNLO and NNLL+NNLO with respect to $m_t \to \infty$ case
- Larger uncertainty in the efficiency $\Rightarrow$ error on $\sigma_{0-\mathrm{jet}}$ around 13-14%
- Is there a case for resummation of $\ln(p_{\mathrm{t,veto}}/m_b)$ at all orders?

Comparison to Monte Carlo

- We compare the jet-veto efficiency to different Monte Carlo predictions

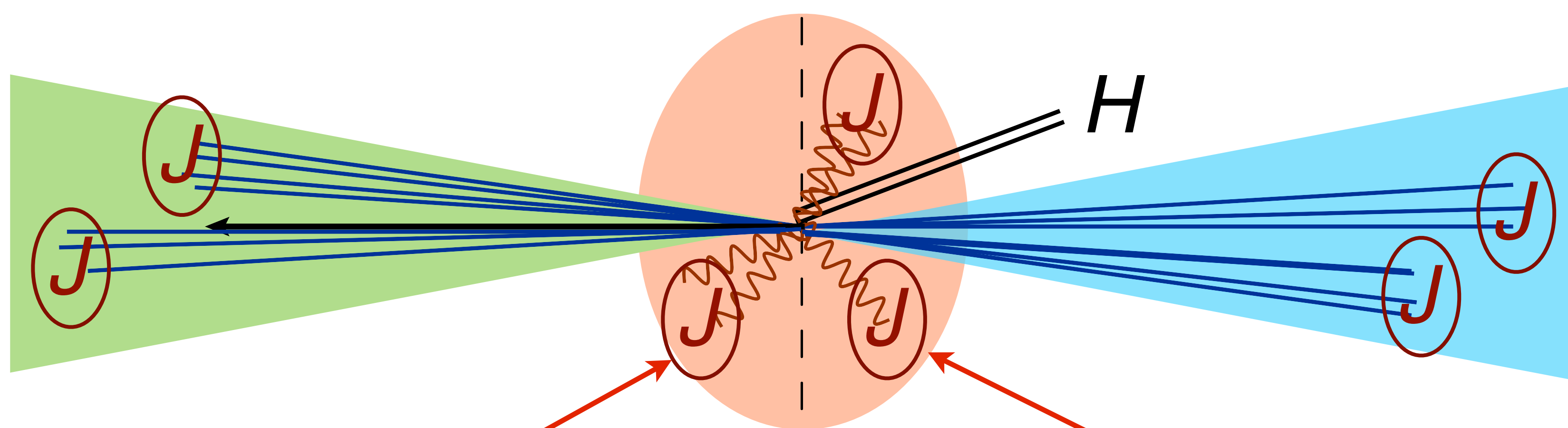


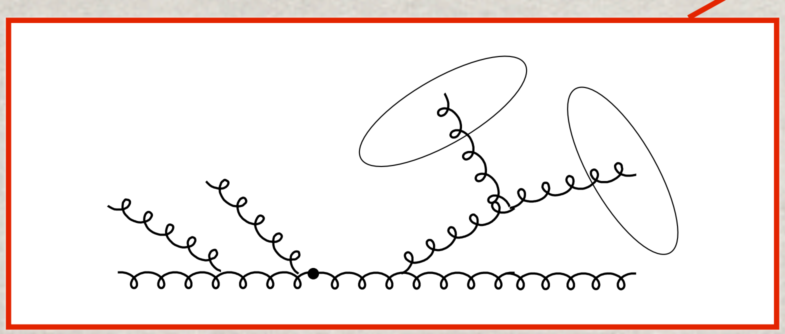
- All Monte Carlo results are within resummation uncertainty band
- In the region $p_{\mathrm{t,veto}} = 25 - 30\,\mathrm{GeV}$ NNLL+NNLO results are in better agreement with MC@NLO

All-order factorisation

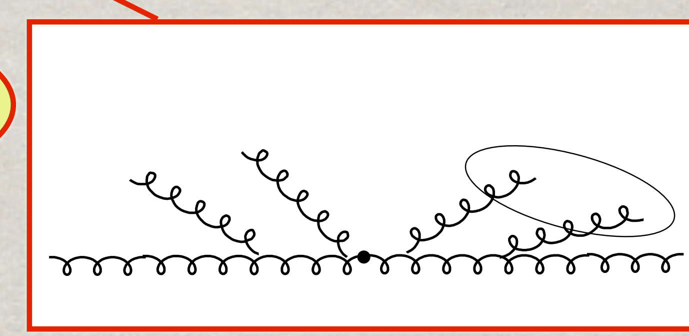
- Very recently, an all-order factorisation formula in SCET has been proposed for the zero-jet cross section [Becher Neubert '12, Becher Neubert Rothen '13]

$$\sigma_{0-\text{jet}} \sim \sigma_0 \times \mathcal{B}_c(p_{\text{t,veto}}) \otimes \mathcal{B}_{\bar{c}}(p_{\text{t,veto}}) \otimes \mathcal{H}(p_{\text{t,veto}}, m_H)$$





$$\mathcal{H} \sim \left(\frac{p_{\text{t,veto}}}{m_H}\right)^{d[\alpha_s(p_{\text{t,veto}})]}$$



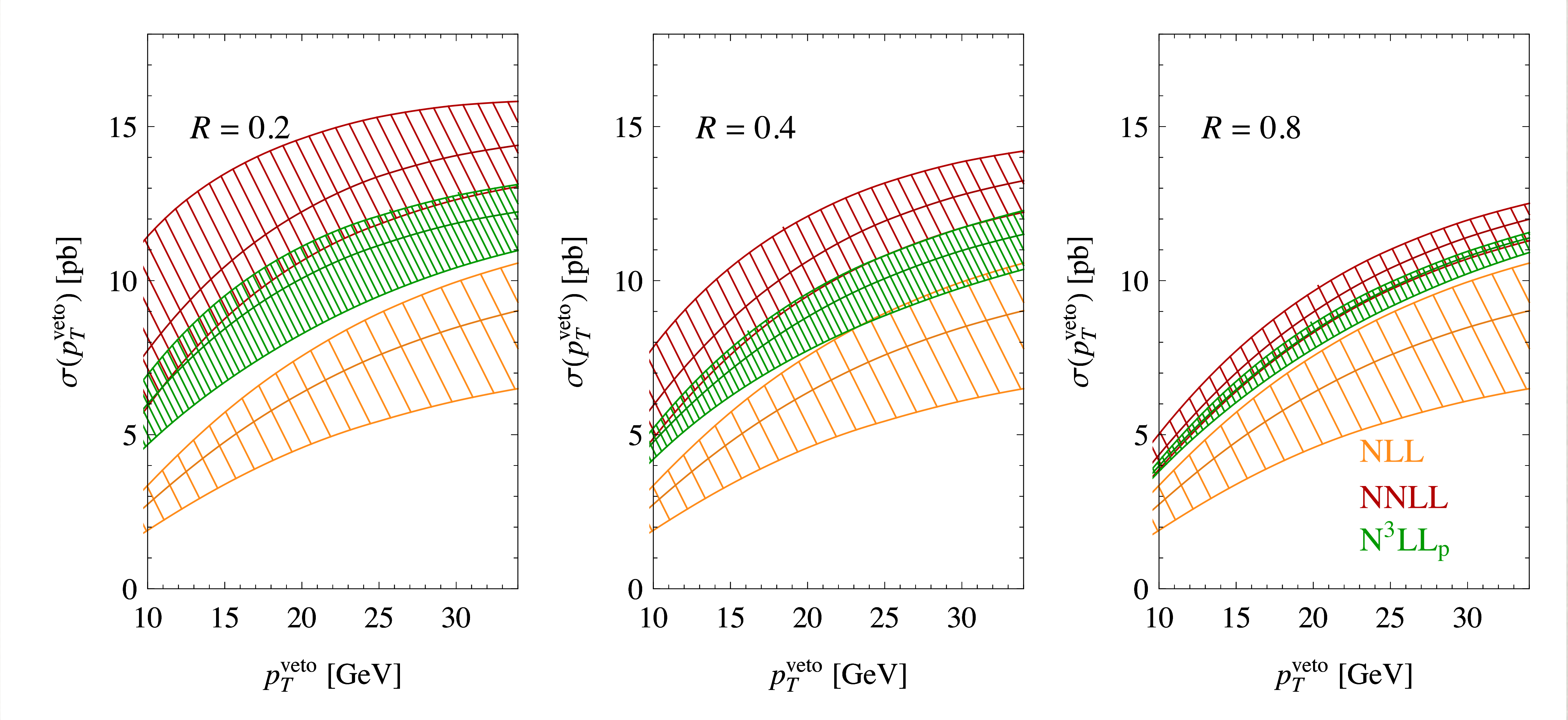
- Jet-clustering effects are part of a so-called "collinear anomaly" and are shown to exponentiate

The NNLLp approximation

- NNLLp predictions include terms beyond NNLL

[Becher Neubert Rothen '13]

  - Numerical estimate of hard and beam functions $\mathcal{H}, \mathcal{B}_c, \mathcal{B}_{\bar{c}}$ at two loops
  - Estimate of the size of the three-loop collinear anomaly $d_3(R)$



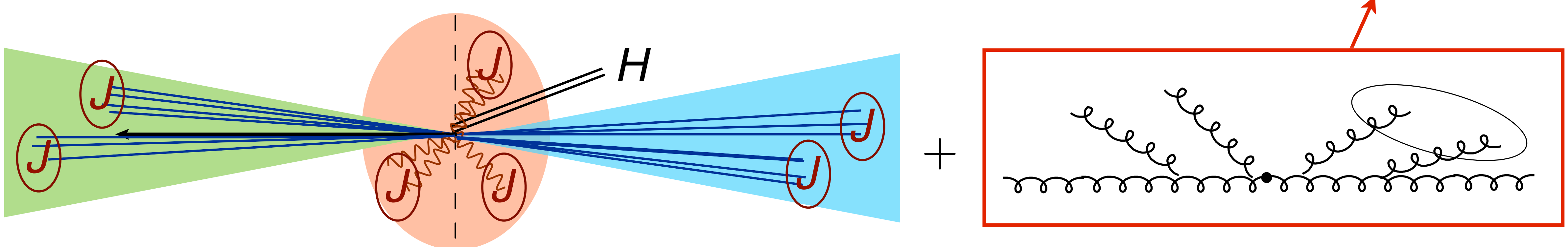
- At small radius, large $\ln R$ corrections spoil the convergence even of resummed predictions at high logarithmic accuracy

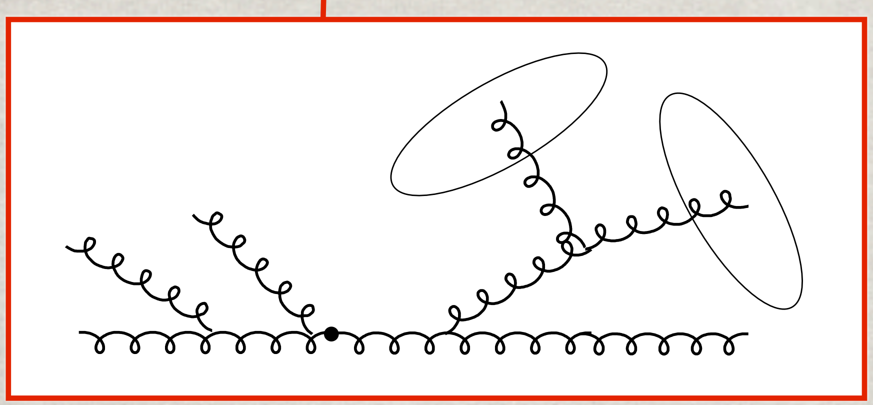
Alternative factorisation

- An alternative approach uses SCET-II to resum the 0-jet cross section

[Stewart Tackmann Walsh Zuberi '13]

$$\sigma_{0-\text{jet}} \sim \sigma_0 \times \mathcal{B}_c(p_{\text{t,veto}}) \otimes \mathcal{B}_{\bar{c}}(p_{\text{t,veto}}) \otimes \mathcal{H}(p_{\text{t,veto}}, m_H) + \sigma_0^{R_{\text{sub}}}(p_{\text{t,veto}}, R)$$





Factorisation is incomplete: clustering of two nearby gluons is not exponentiated

- New NNLL' predictions containing exact two-loop dependence of the zero-jet cross section on $\ln R$

Conclusions

- We have three equivalent NNLL resummations for the Higgs cross section with zero jets
  - Banfi-Monni-Salam-Zanderighi: QCD resummation, publicly available in the code JetVHeto http://jetvheto.hepforge.org/
  - Becher-Neubert: all-order factorisation formula in SCET
  - Stewart-Tackmann-Walsh-Zuberi: SCET-II, no all-order factorisation
- New version of JetVHeto contains top and bottom mass effects
- BN and STWZ have improved predictions containing some NNNLL terms
- There are two new cases for resummation
  - Logarithmically enhanced mass effects $\ln(p_{\mathrm{t,jet}}/m_b)$
  - Large $\ln R$ corrections induced by small jet radius

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Thank you for your attention!

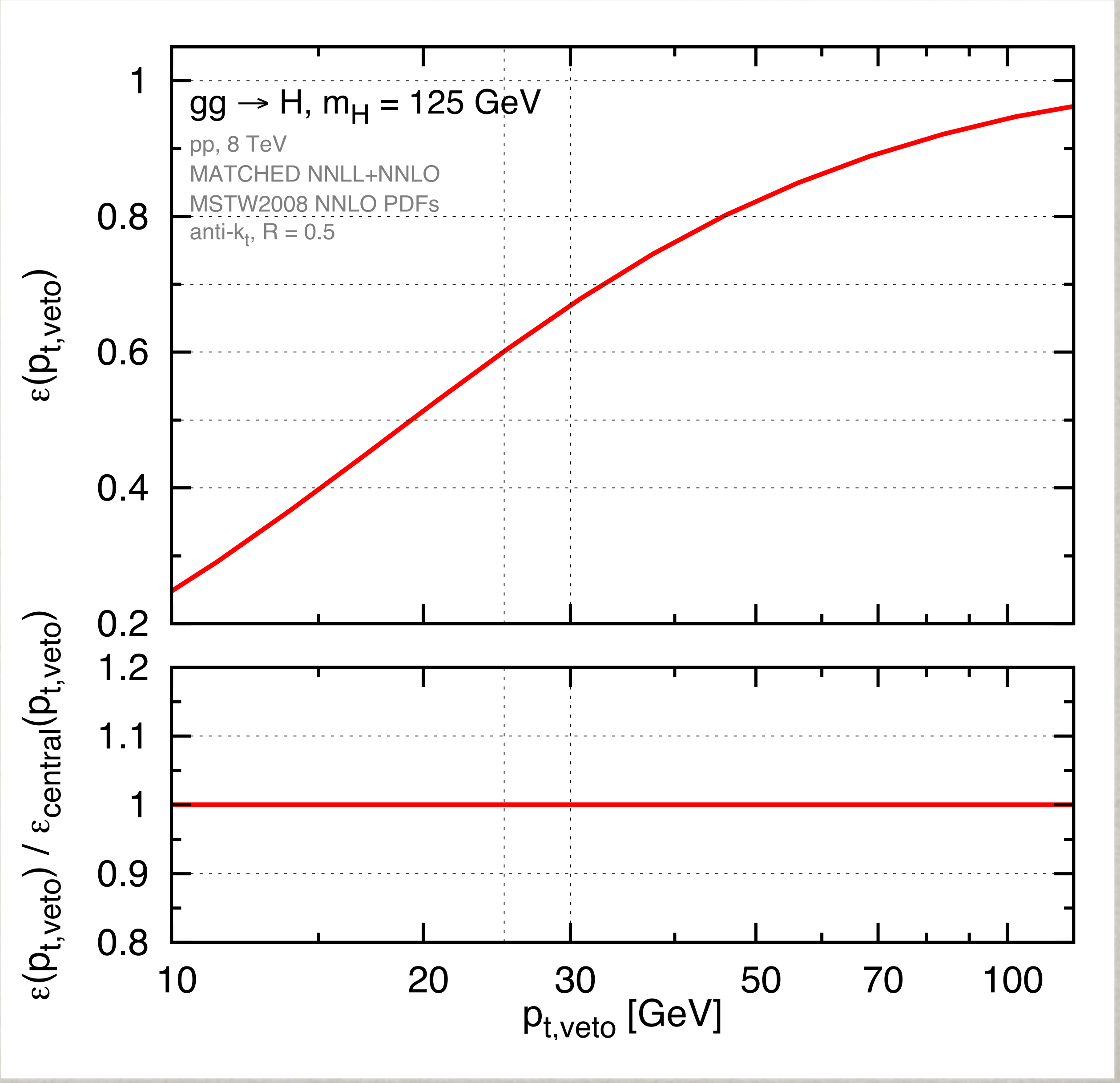
Extra

Theoretical uncertainties

- We have combined the NNLL resummation with NNLO, using three matching schemes (a), (b) and (c) [AB Monni Salam Zanderighi ’12]

- Central value: scheme (a) with $\mu_R = \mu_F = Q = m_H/2$

  Q is the resummation scale: $\ln(m_H/p_{\mathrm{t,veto}}) \to \ln(Q/p_{\mathrm{t,veto}})$



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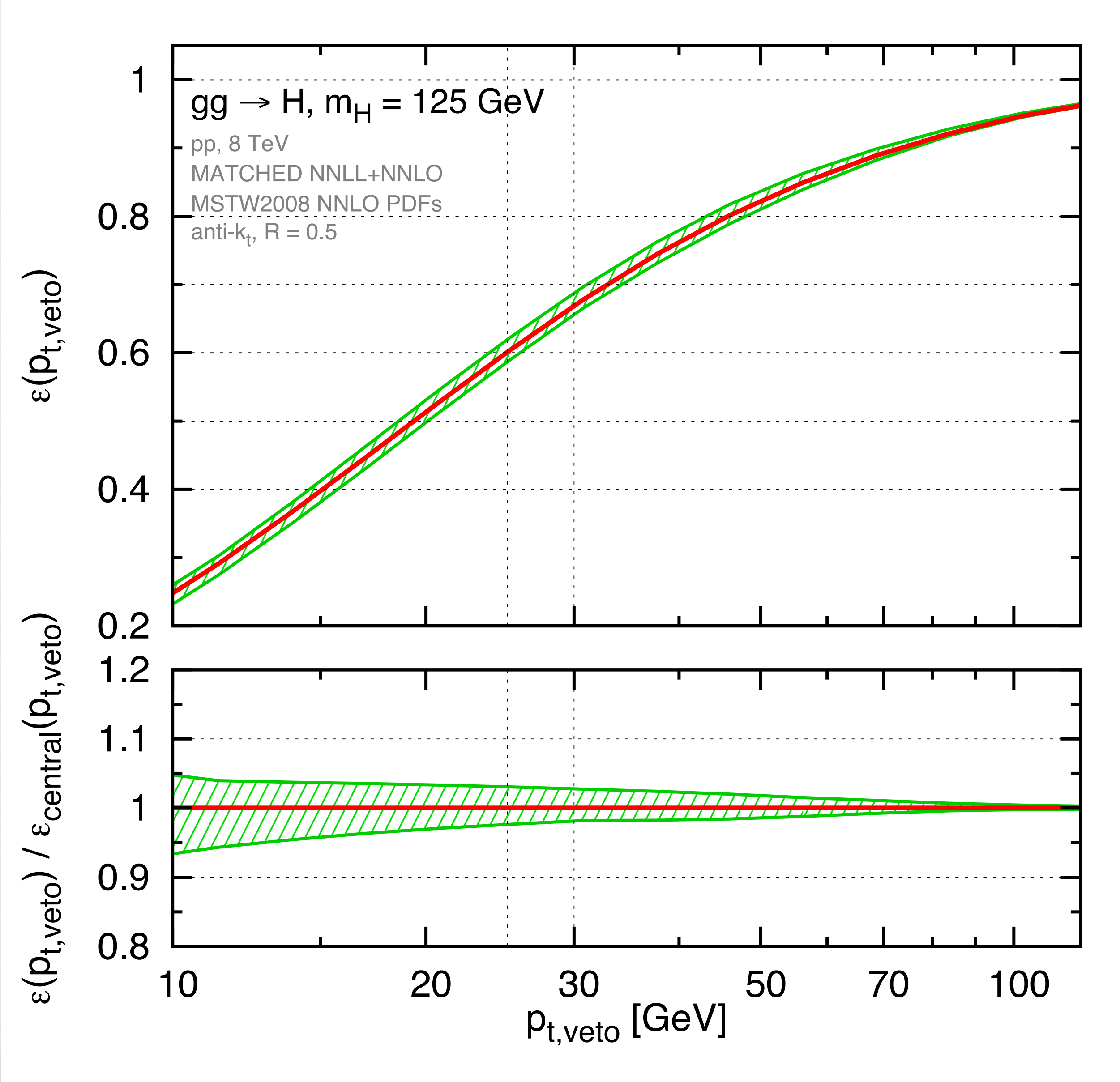
- Variation of μ_R, μ_F with $Q = m_H/2$

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



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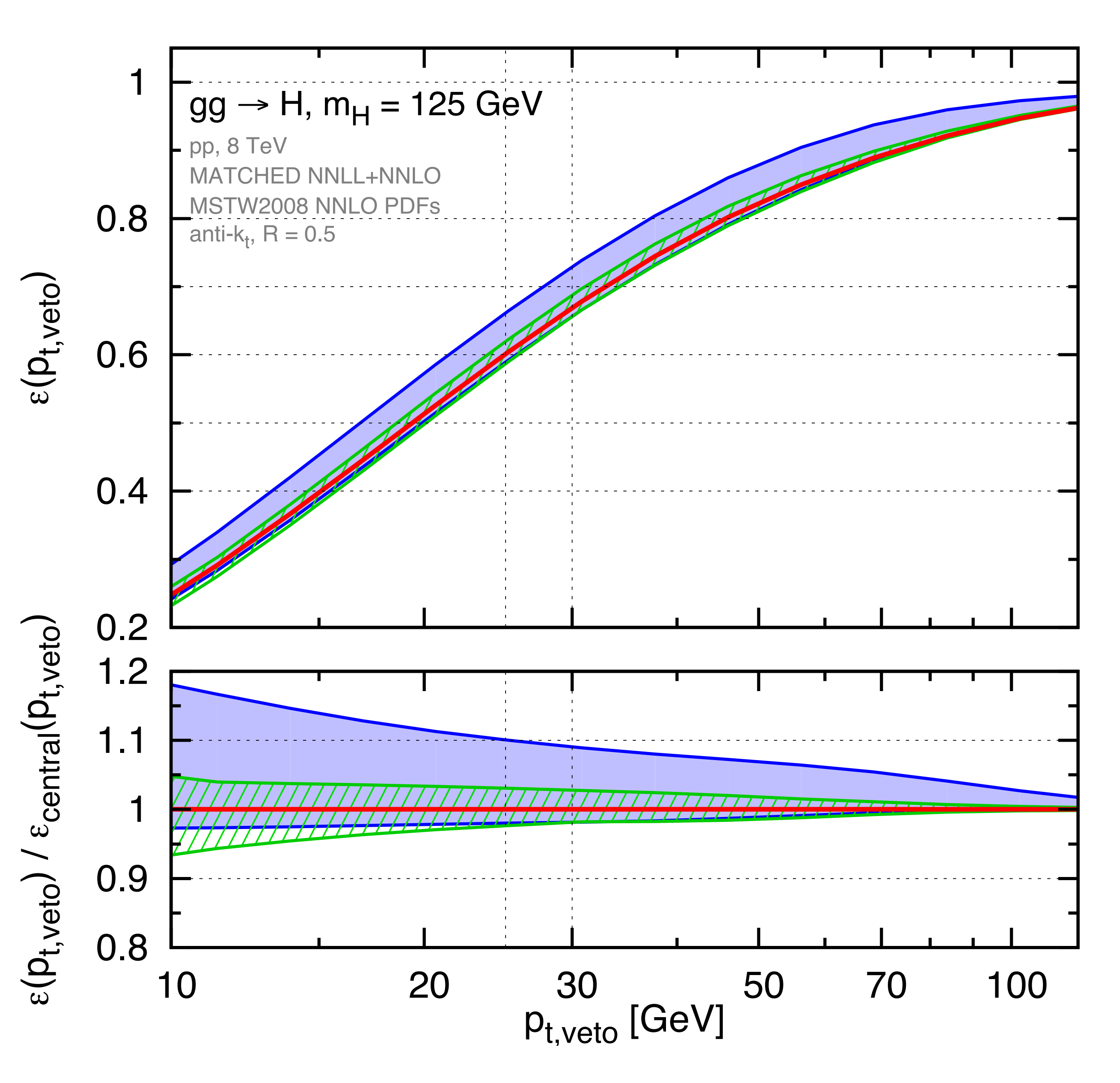
- Variation of Q with $\mu_R, \mu_F = m_H/2$

$$\frac{m_H}{4} \leq Q \leq m_H$$



Theoretical uncertainties

- We have combined the NNLL resummation with NNLO, using three matching schemes (a), (b) and (c)

[AB Monni Salam Zanderighi '12]

- Central value: scheme (a) with $\mu_R = \mu_F = Q = m_H/2$

  Q is the resummation scale: $\ln(m_H/p_{\mathrm{t,veto}}) \to \ln(Q/p_{\mathrm{t,veto}})$

- Variation of μ_R, μ_F with $Q = m_H/2$

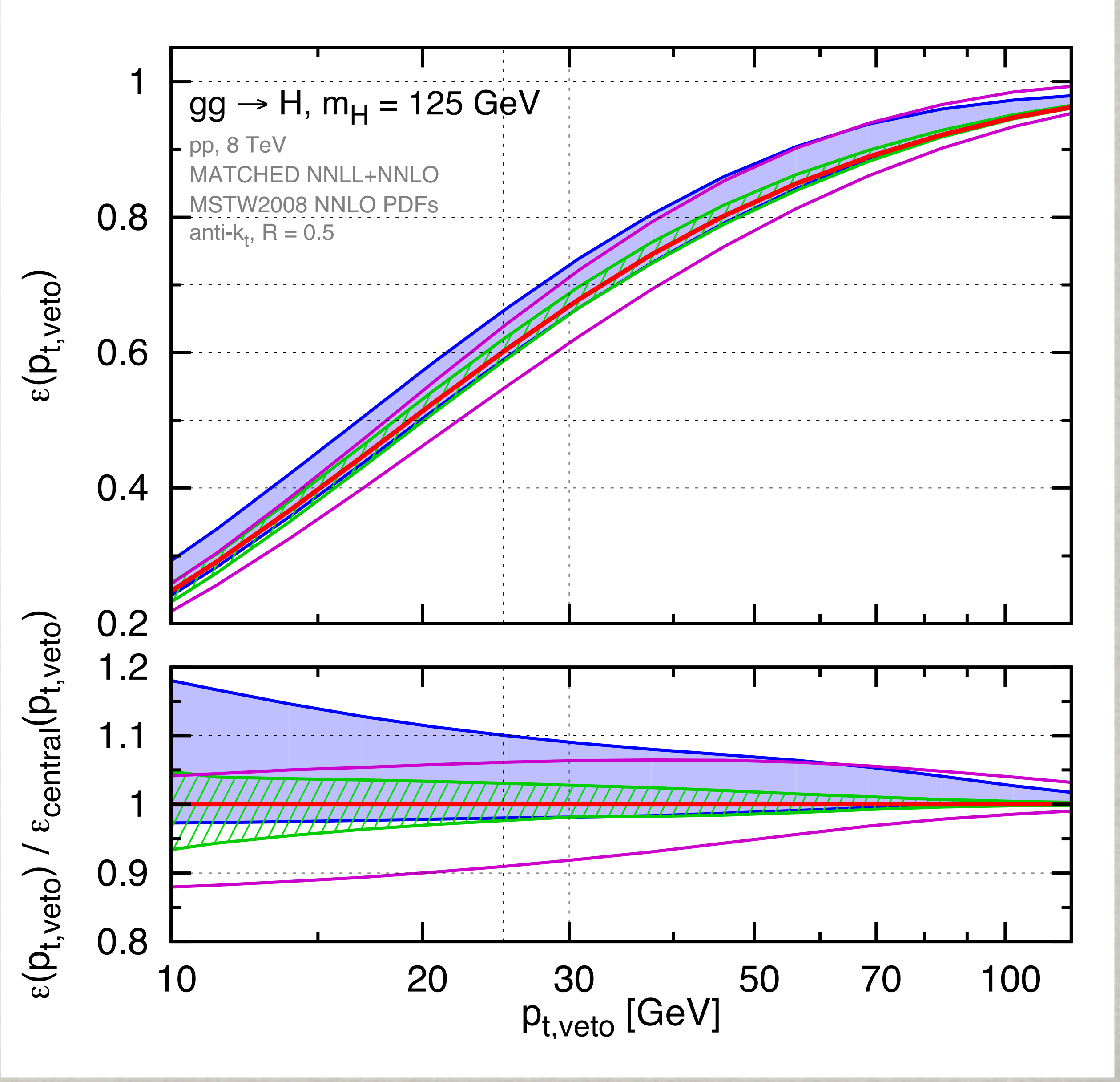
$$\frac{m_H}{4} \leq \mu_R, \mu_F \leq m_H \qquad \frac{1}{2} \leq \frac{\mu_R}{\mu_F} \leq 2$$

- Variation of Q with $\mu_R, \mu_F = m_H/2$

$$\frac{m_H}{4} \leq Q \leq m_H$$

- Schemes (b) and (c) with

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



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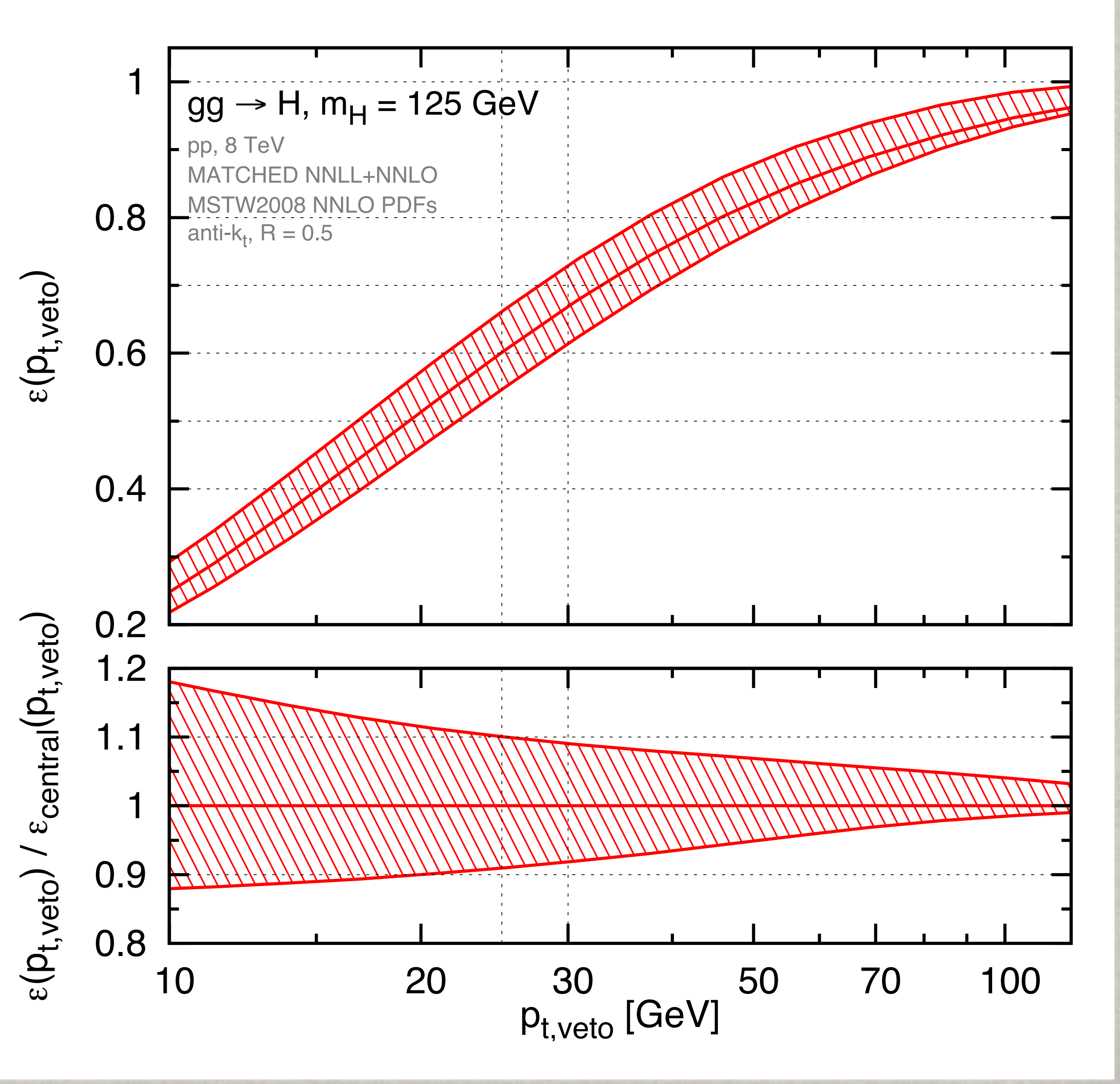
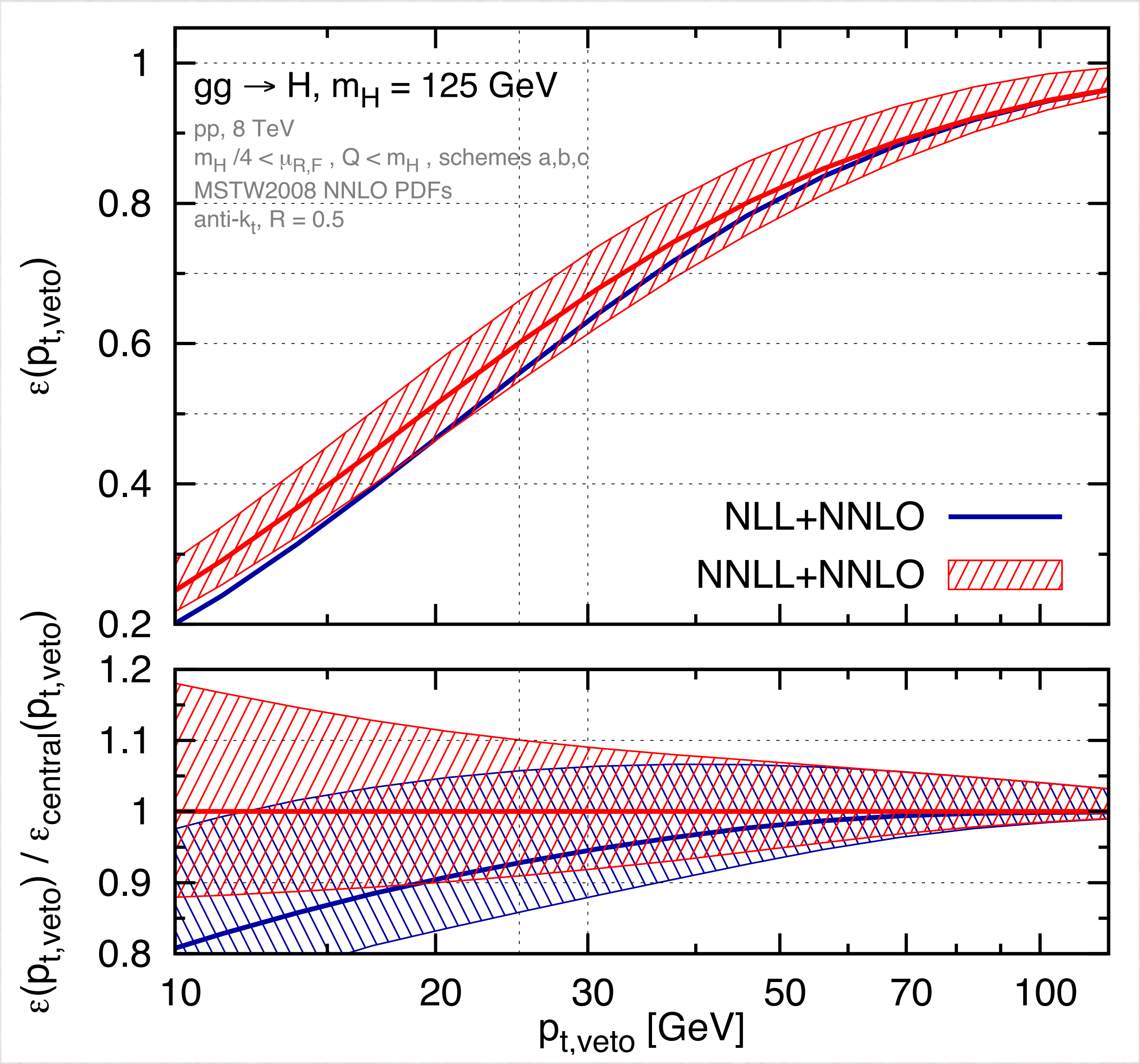
- Total uncertainty: envelope



Comparison to NNL

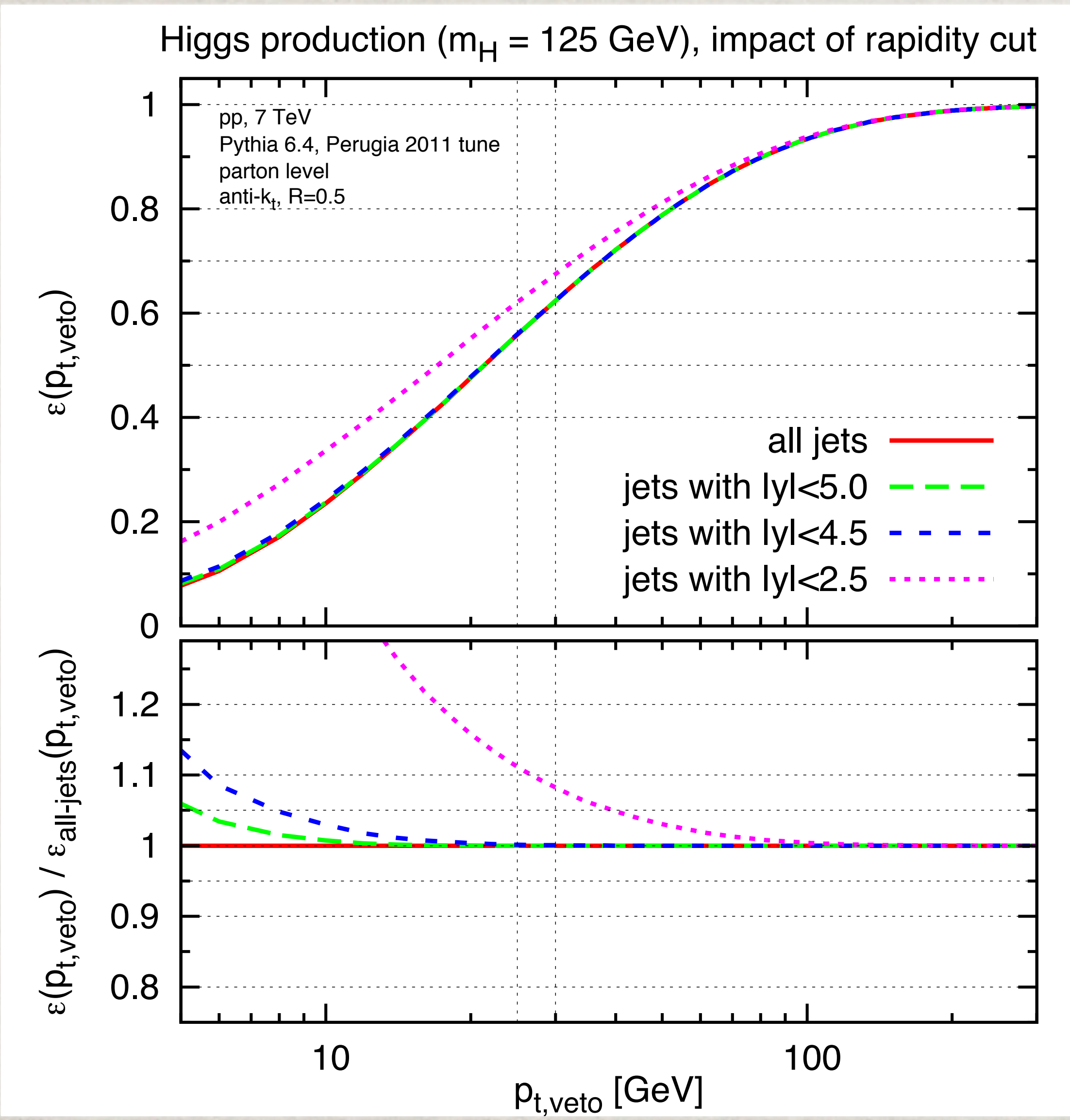
- We present results for the jet-veto efficiency $\epsilon(p_{\mathrm{t,veto}}) = \sigma_{0-\mathrm{jet}}(p_{\mathrm{t,veto}})/\sigma_{\mathrm{tot}}$

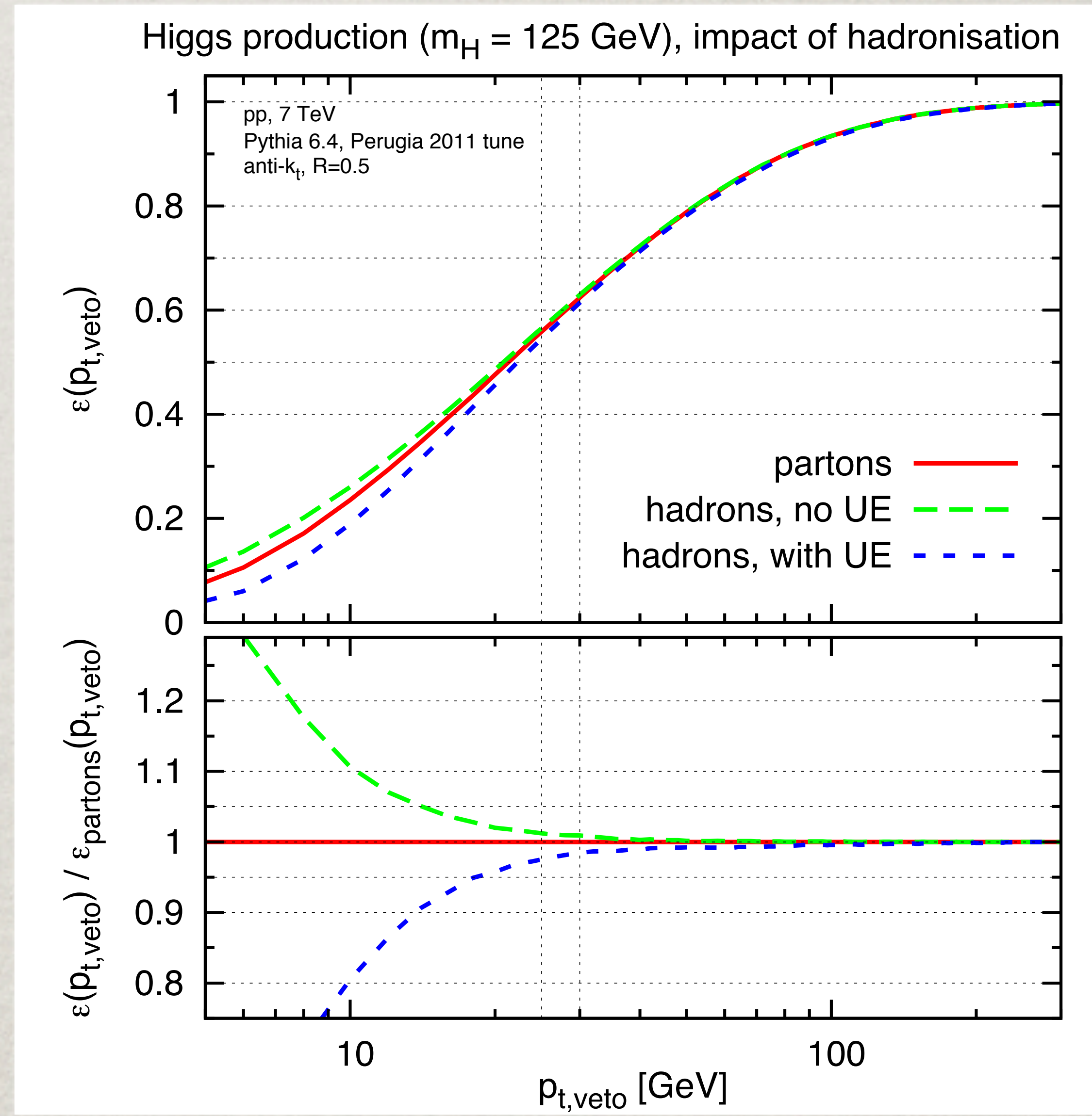


- No significant reduction of uncertainties from NLL to NNLL
- Large NNLL corrections induced by the small jet radius

Real life issues

- We present results for the jet-veto efficiency $\epsilon(p_{\rm t,veto}) = \sigma_{0-\rm jet}(p_{\rm t,veto})/\sigma_{\rm tot}$

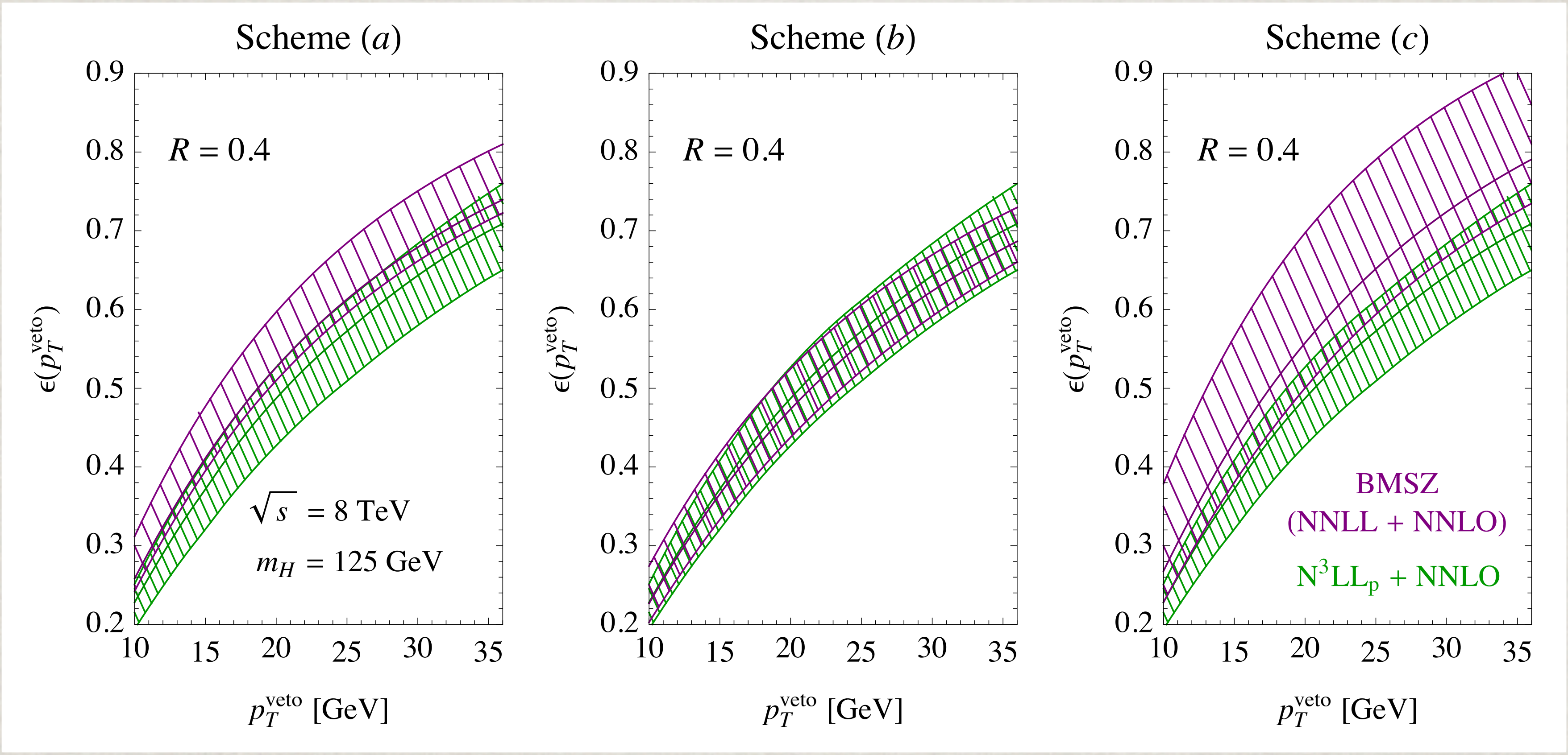




- Finite rapidity, hadronisation and underlying event effects are negligible in the region of interest at the LHC $p_{\rm t,veto} \simeq 25 - 30\,\rm GeV$

Comparing NNLLp with JetVHeto

- The NNLLp+NNLO results have been compared to the output of JetVHeto



- Matching scheme (a) is the reference scheme used by BMSZ to obtain central value and scale uncertainties
- NNLLp+NNLO does not agree with reference scheme (a)
- Note however: NNLLp is expected to give a lower efficiency than NNLL