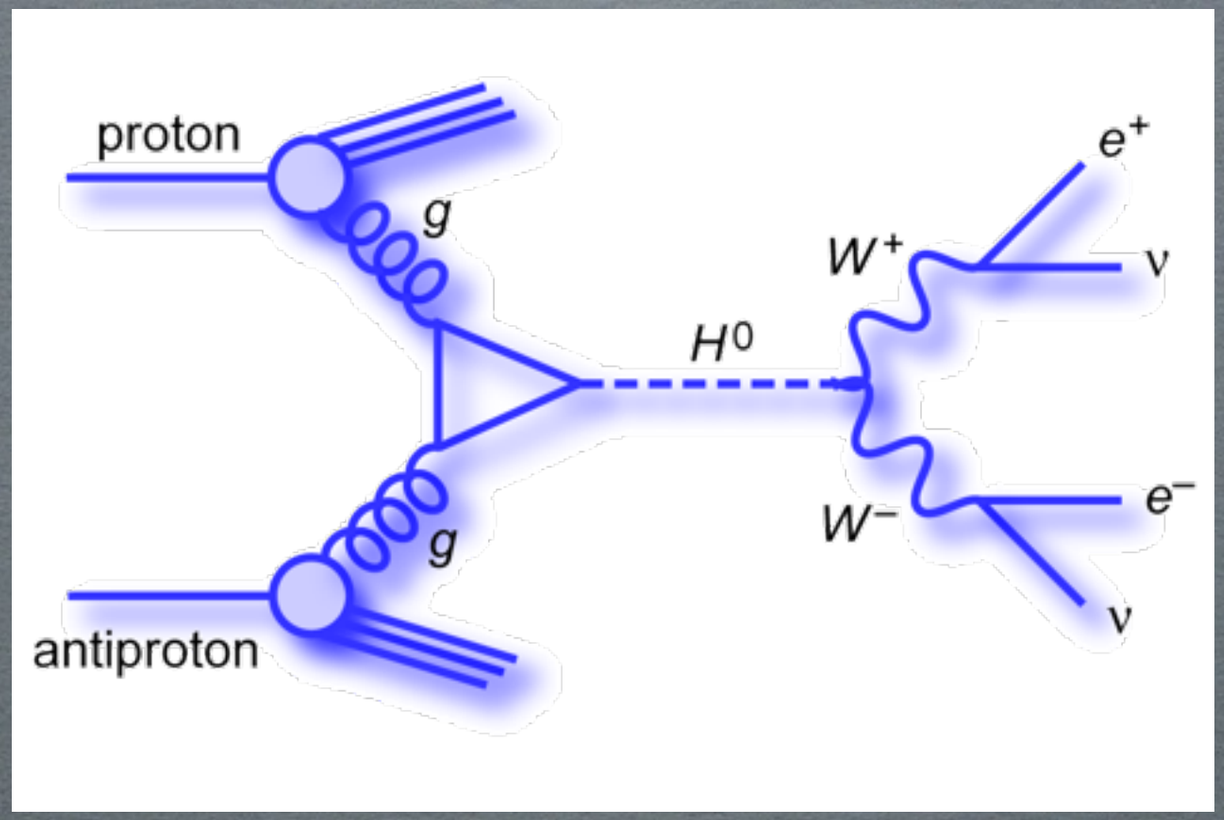
Jet-veto uncertainties and differential cross sections



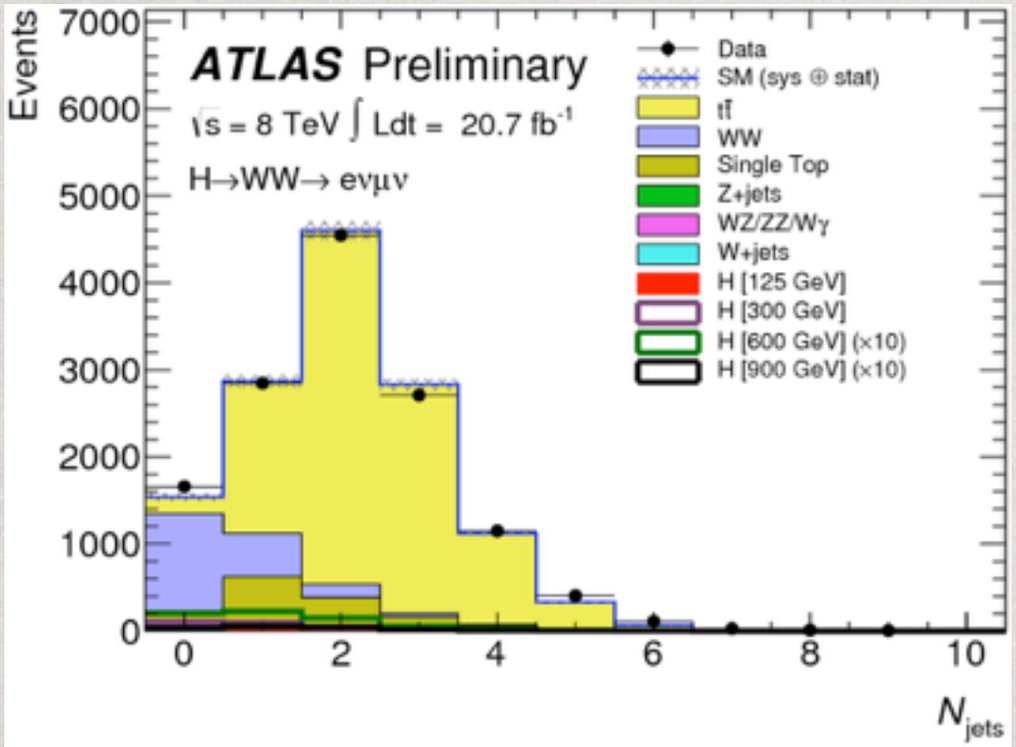
Andrea Banfi

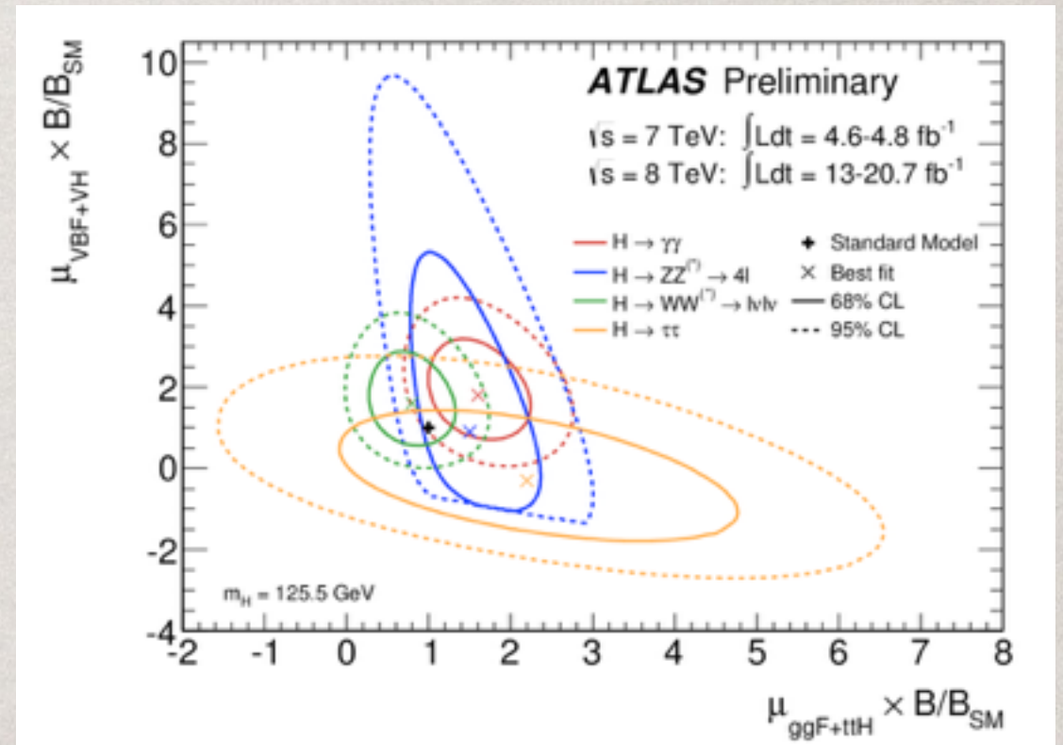
University of Sussex

SM@LHC 2015 - GGI Florence

Jet-veto cross sections: why?

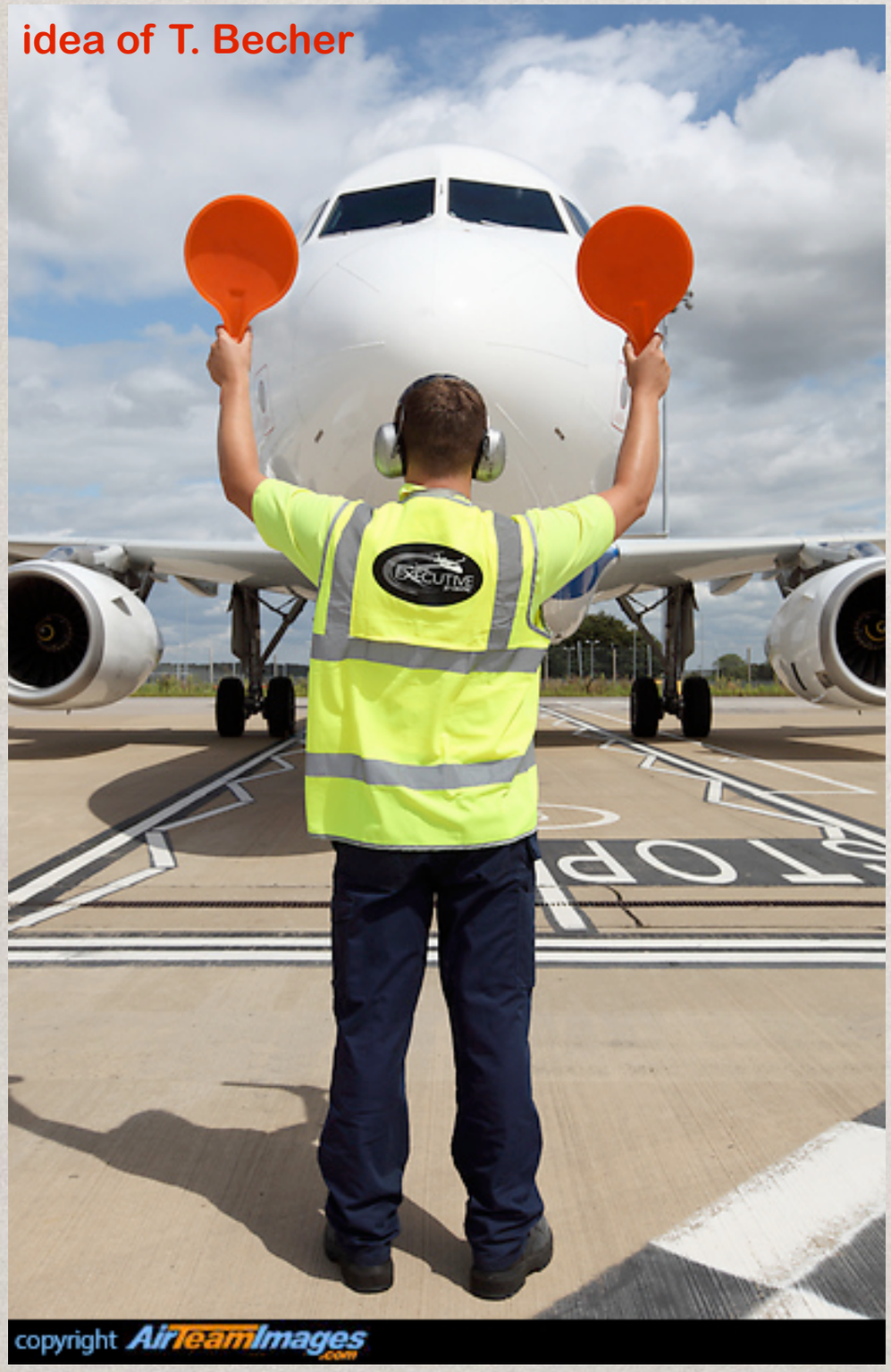
- Experimental analyses involving the Higgs select exclusive jet samples



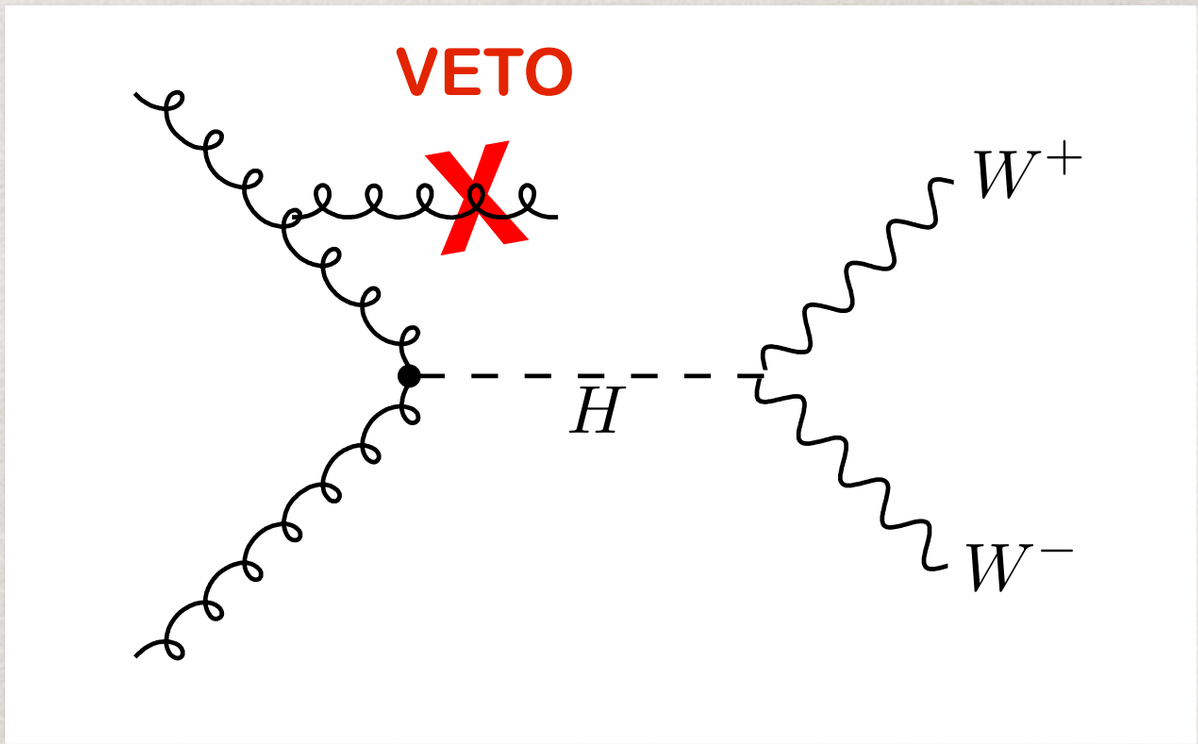


- $H \to WW$: the zero-jet bin is least contaminated by huge top-antitop background
- Two-jet exclusive samples needed to separate VFB from gluon fusion

The zero-jet cross section



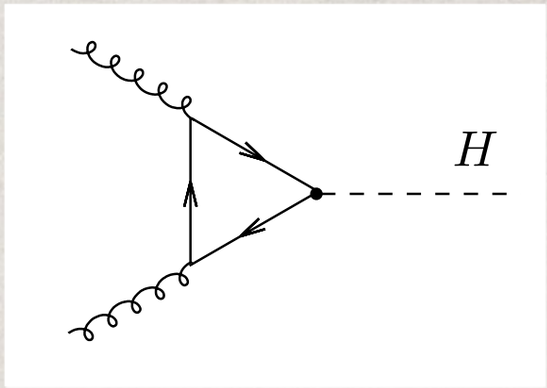
- zero-jet cross section $\Leftrightarrow$ jet veto condition, all jets have $p_{\mathrm{t,jet}} < p_{\mathrm{t,veto}}$



Higgs plus zero-jets at fixed order

- The Higgs cross section in gluon fusion has been computed at very high accuracy

$$d\sigma_{\geq 0-\mathrm{jet}} \sim \alpha_s^2 \left(1 + \underbrace{\alpha_s}_{\mathrm{NLO}} + \underbrace{\alpha_s^2}_{\mathrm{NNLO}} + \ldots \right)$$

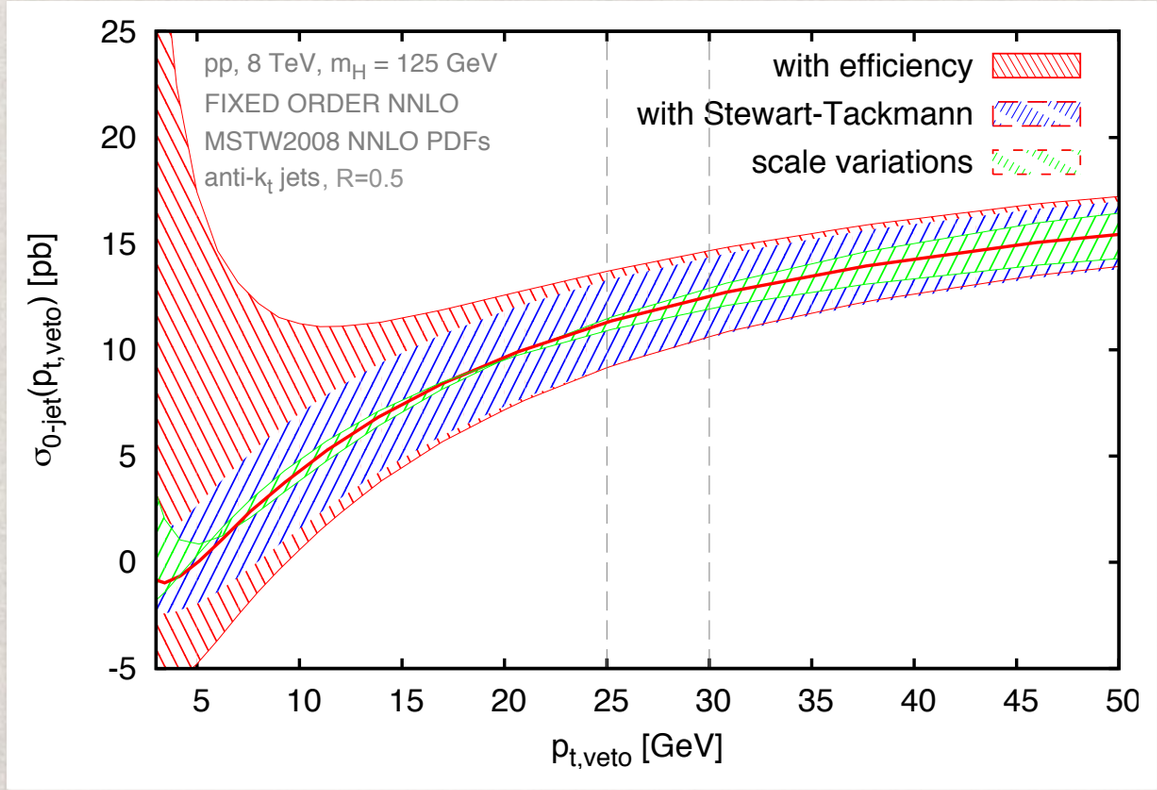


finite m_t, m_b	NLO	[Spira et al. NPB 453 (1995) 17]
large- m_t	NNLO	[Anastasiou Melnikov Petriello NPB 724 (2005) 197] [Catani Grazzini PRL 98 (2007) 222002]
large-m_W	QCD-EW	[Anastasiou Boughezal Petriello JHEP 04 (2009) 003]

- These calculations are implemented in computer codes (FEHiP, HNNLO) producing exclusive events $\Rightarrow$ directly compute $\sigma_{0-\mathrm{jet}}$ at NNLO
- The total cross section σ_{tot} is know also to NNNLO, with theoretical uncertainties of order 3% [Anastasiou et al. 1503.0605]
- Higgs+1jet is known at NNLO $\Rightarrow$ compute $\sigma_{0-\mathrm{jet}}$ at NNNLO [F. Caola's talk at Moriond]

Need for resummation

- At fixed-order, various ways of treating uncertainties (scale variations, Stewart-Tackmann, efficiency method) give different results



- Resummation of large logarithms $\ln(m_H/p_{\mathrm{t,veto}})$ needed to have stable predictions in the region considered at the LHC $p_{\mathrm{t,veto}} \simeq 25 - 30\,\mathrm{GeV}$

NNLL+NNLO resummations

- NNLL resummation matched to NNLO is implemented in the code JetVHeto
  http://jetvheto.hepforge.org/

[AB Monni Salam Zanderighi PRL 109 (2012) 202001]

- The same result has been obtained by two groups in the framework of Soft-Collinear Effective Theory (SCET)

[Becher Neubert JHEP 07 (2012) 108]
[Becher Neubert Rothen JHEP 10 (2013) 125]
[Stewart Tackmann Walsh Zuberi PRD89 (2014) 054001]

Further improvements:

- Ingredients beyond NNLL accuracy

[Becher Neubert Rothen JHEP 10 (2013) 125]
[Stewart Tackmann Walsh Zuberi PRD89 (2014) 054001]

- Effect of top and bottom masses in loops

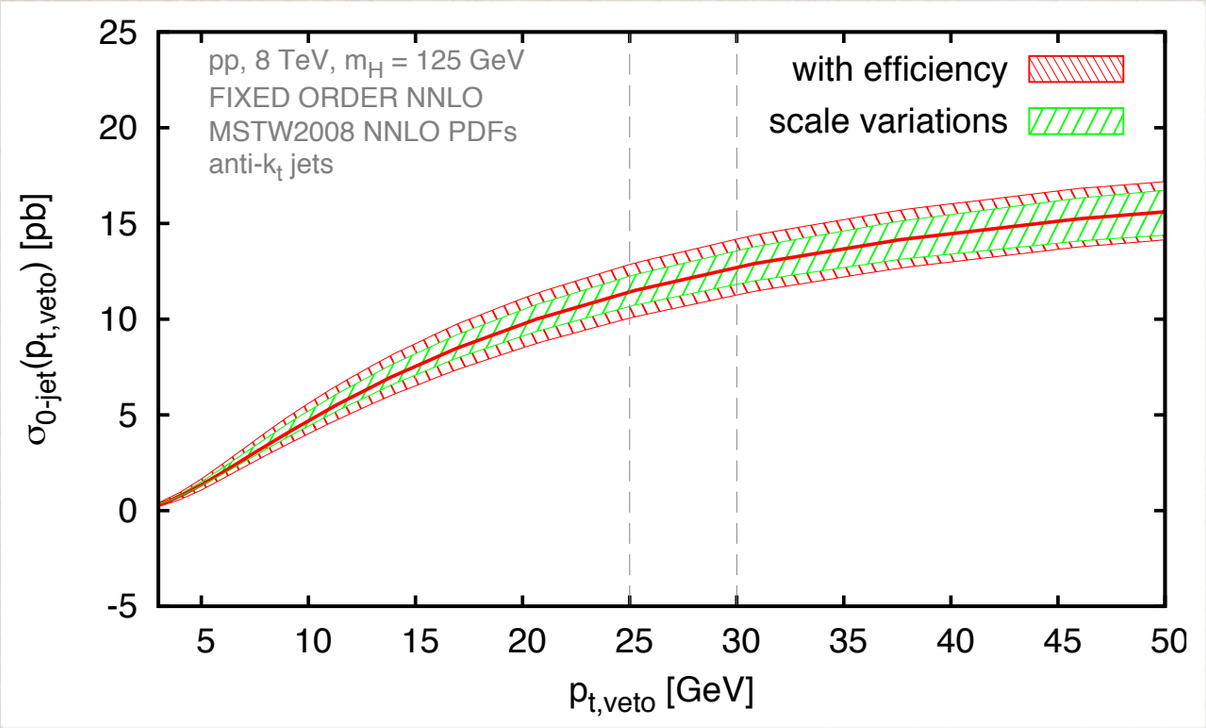
[AB Monni Zanderighi JHEP 01 (2014) 097]

- Resummation of large logarithms induced by small jet radius

[Dasgupta Dreyer Salam Soyez JHEP 04 (2015) 039]

Uncertainties: JVE method

- Jet-veto efficiency (JVE) method for theoretical uncertainties
  - Compute the zero-jet cross section from $\sigma_{0-\mathrm{jet}} = \epsilon(p_{\mathrm{t,veto}})\,\sigma_{\mathrm{tot}}$
  - Treat uncertainties in σ_{tot} and $\epsilon(p_{\mathrm{t,veto}})$ as uncorrelated



e.g. $R = 0.4,\ p_{\mathrm{t,veto}} = 25\,\mathrm{GeV}$:

$\delta\sigma_{0-\mathrm{jet}} \sim 10\%$ [NNLL+NNLO]

$\delta\sigma_{0-\mathrm{jet}} \sim 13.8\%$ [NNLL+NNLO + JVE $\sigma_{\mathrm{tot}}^{\mathrm{NNLO}}$]

$\delta\sigma_{0-\mathrm{jet}} \sim 12.8\%$ [NNLL+NNLO + JVE $\sigma_{\mathrm{tot}}^{\mathrm{HXSWG}}$]

- Uncertainties still sizeable at NNLL+NNLO, need to improve predictions by including σ_{tot} at NNNLO and Higgs+1jet@NNLO

[Anastasiou Duhr Dulat Herzog Mistleberger 1503.0605]

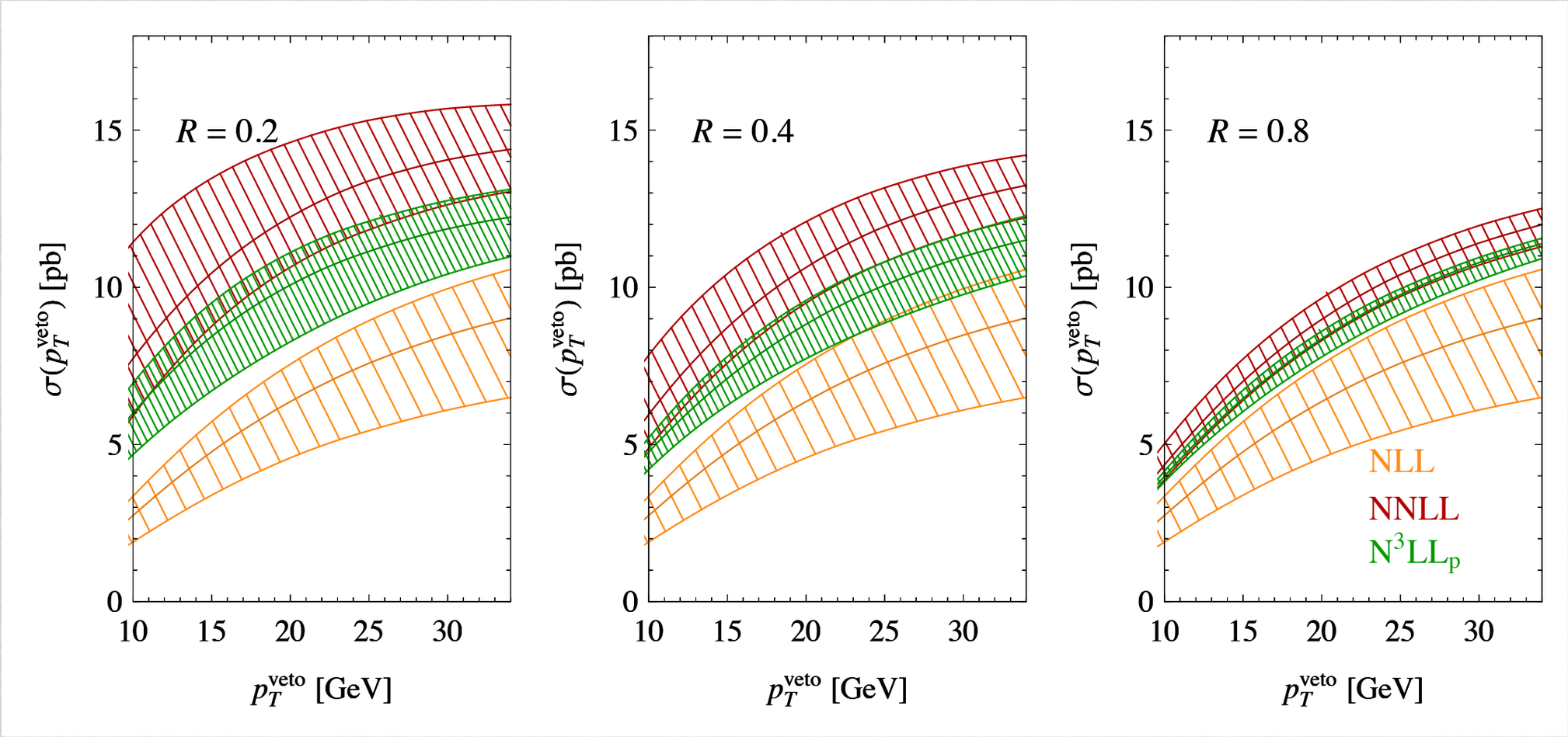
[F. Caola's talk at Moriond]

Uncertainties: NNNLLp predictions

- NNNLLp predictions include terms beyond NNLL

[Becher Neubert Rothen JHEP 10 (2013) 125]

- Uncertainties in $\sigma_{0-\mathrm{jet}}$: variation of all scales by a factor of two around m_H and estimate of missing NNNLL R-dependent terms

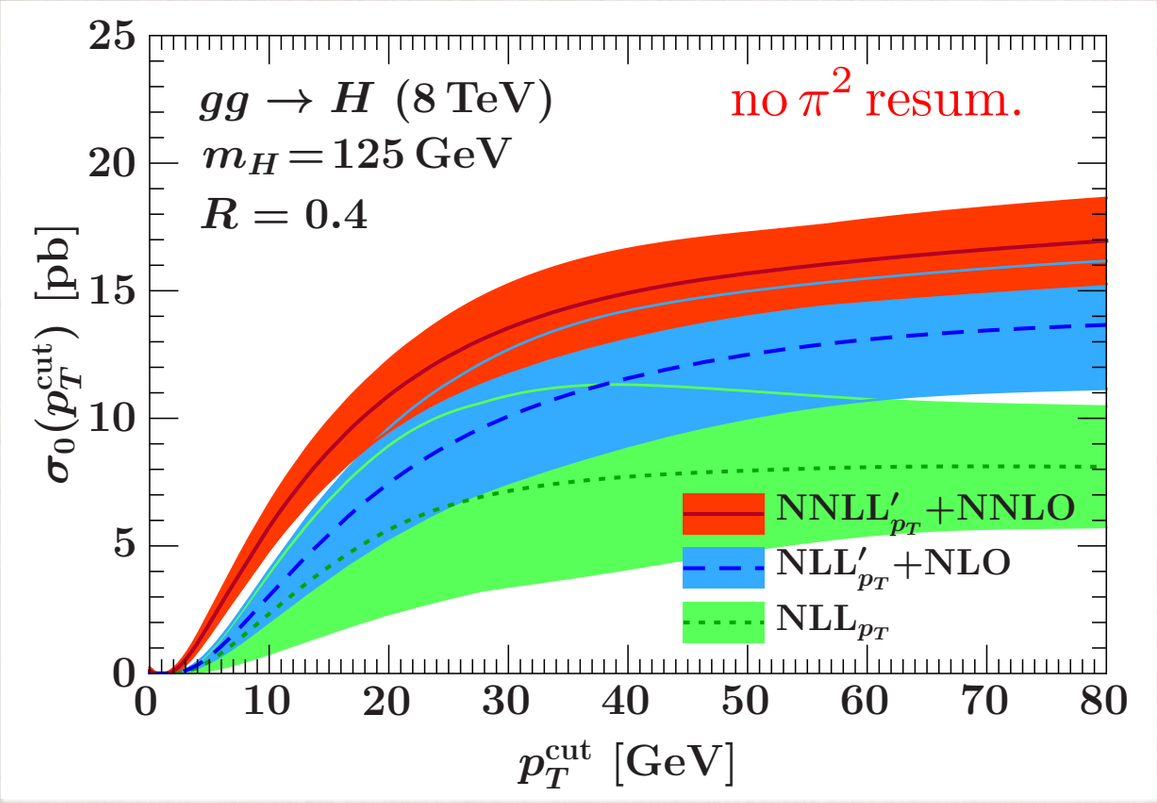


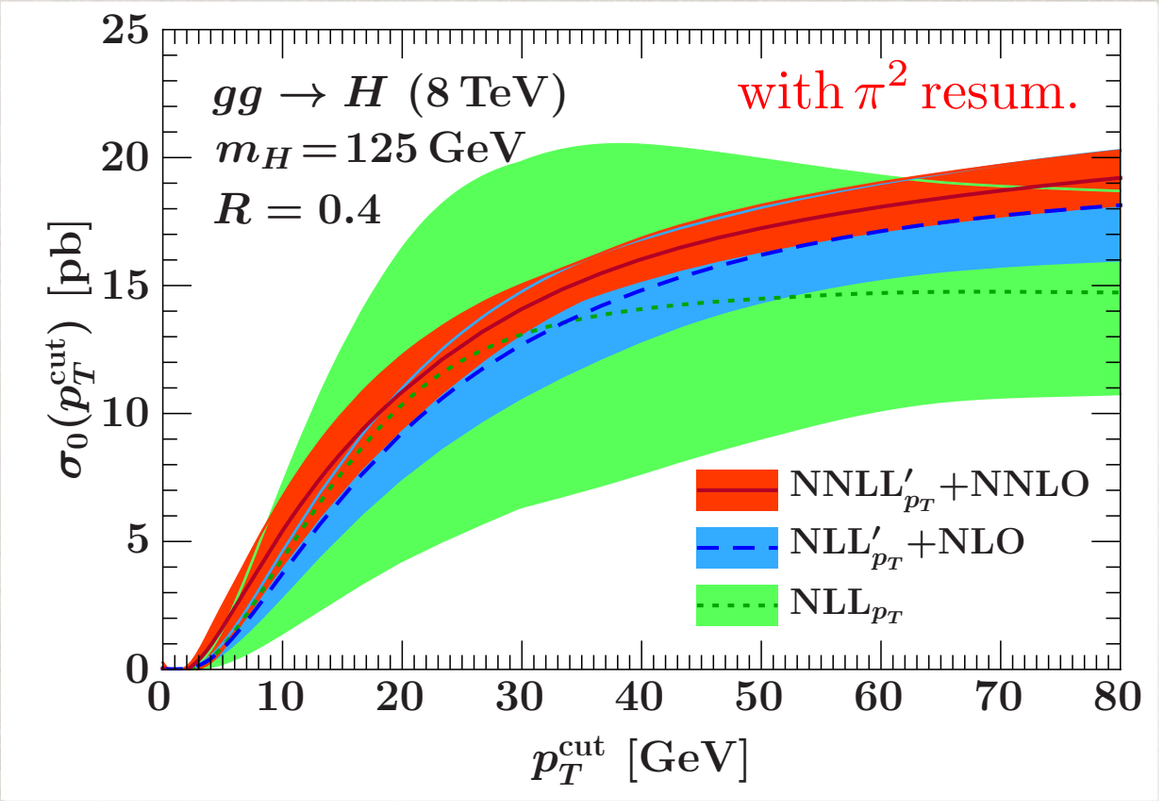
$$\text{e.g. } R = 0.4,\ p_{\mathrm{t,veto}} = 25\,\mathrm{GeV} : \delta\sigma_{0-\mathrm{jet}} \sim 9\%$$

Results include resummation of π^2 in virtual corrections: total cross section different from $\sigma_{\mathrm{tot}}^{\mathrm{HXSWG}}$

Uncertainties: NNLL'+NNLO

- Uncertainties on $\sigma_{0-\mathrm{jet}}$ are evaluated by varying all scales around m_H with profiling functions [Stewart Tackmann Walsh Zuberi PRD89 (2014) 054001]
- Theory uncertainty reduced by performing π^2 resummation





e.g. $R = 0.4$, $p_{\mathrm{t,veto}} = 25\,\mathrm{GeV}$:

$$\delta\sigma_{0-\mathrm{jet}} \sim 12.8\% \overset{\pi^2\,\mathrm{res.}}{\to} \delta\sigma_{0-\mathrm{jet}} \sim 9.6\%$$

Zero-jet summary

LHC $\sqrt{s} = 8\,\mathrm{TeV}$ MSTW2008NNLO

	$\sigma_{0-\mathrm{jet}}(25\,\mathrm{GeV}, R = 0.4)\,[\mathrm{pb}]$	$\sigma_{0-\mathrm{jet}}(30\,\mathrm{GeV}, R = 0.5)\,[\mathrm{pb}]$	
BMSZ	11.81 ± 1.51	12.86 ± 1.47	large-m_t
B'NR	$11.25^{+0.77\ (+0.65)}_{-1.25\ (-1.15)}$	n/a	large-m_t
STWZ'	$12.67 \pm 1.22_{\mathrm{pert}}(\pm 0.46_{\mathrm{clust}})$	$13.85 \pm 0.87_{\mathrm{pert}}(\pm 0.24_{\mathrm{clust}})$	large-m_t
BMZ	11.59 ± 1.72	12.64 ± 1.79	exact m_t, m_b

- All results are compatible within uncertainties
- Theoretical uncertainties are between 10% and 15%
- Inclusion of mass effects increases the uncertainty

Comparing the various approaches is difficult because of different values of σ_{tot}

Across jet bins with JVE

- The JVE method can be generalised to arbitrary jet multiplicities

$$\sigma_{0-\mathrm{jet}} = \epsilon\,\sigma_{\mathrm{tot}} \quad \sigma_{1-\mathrm{jet}} = \epsilon_1(1-\epsilon)\sigma_{\mathrm{tot}} \quad \sigma_{\geq 2-\mathrm{jets}} = (1-\epsilon_1)(1-\epsilon)\sigma_{\mathrm{tot}}$$

- Uncertainties in the efficiency require considering different schemes to define the efficiency in terms of total cross sections
- The method does not need modification when resummed predictions become available
- The correlation matrix $\mathrm{Cov}[\sigma_{\mathrm{tot}}, \sigma_{\geq 1-\mathrm{jet}}, \sigma_{\geq 2-\mathrm{jets}}]$ can be computed by considering $\sigma_{\mathrm{tot}}, \epsilon, \epsilon_1$ as uncorrelated

[Les Houches proceedings 1405.1067]

Across jet bins with BLPTW

- Combination of resummed predictions and fixed-oder for different jet multiplicities [Boughezal Liu Petriello Tackmann Walsh JHEP 10 (2013) 125]

$$\sigma_{\rm tot} = \sigma_0(p_T^{\rm cut}) + \sigma_1(\underbrace{[p_T^{\rm cut}, \infty]}_{\text{range of } p_{TJ}}; p_T^{\rm cut}) + \sigma_{\geq 2}(p_T^{\rm cut})$$

NNLL'+NNLO

[Stewart Tackmann Walsh Zuberi PRD89 (2014) 054001]

- Problem: the one-jet cross section can be resummed only for $p_{TJ} \gg p_T^{\rm cut}$

NLL'+NLO

$$\sigma_1([p_T^{\rm cut}, \infty]; p_T^{\rm cut}) = \sigma_1([p_T^{\rm cut}, p_T^{\rm off}]; p_T^{\rm cut}) + \sigma_1([p_T^{\rm off}, \infty]; p_T^{\rm cut})$$

[Liu Petriello PRD87 (2013) 014018, PRD87 (2013) 094027]

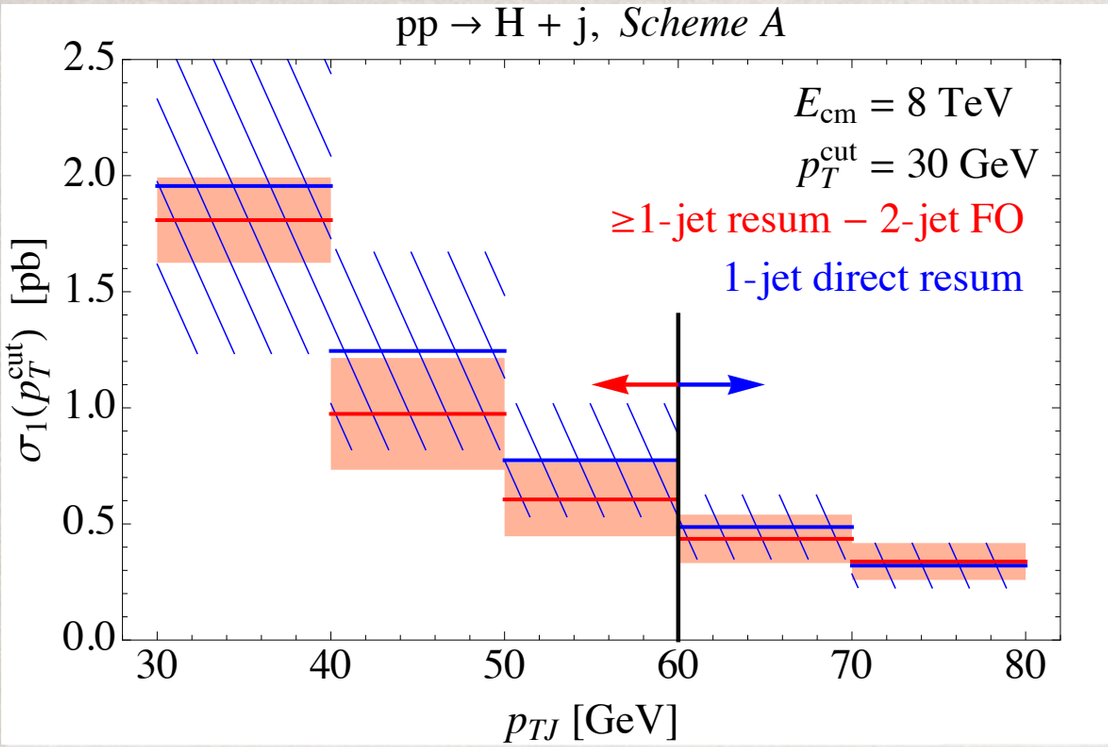
$$\sigma_1([p_T^{\rm cut}, p_T^{\rm off}]; p_T^{\rm cut}) = [\sigma_0(p_T^{\rm off}) - \sigma_0(p_T^{\rm cut})] - [\sigma_{\geq 2}(p_T^{\rm cut}, p_T^{\rm cut}) - \sigma_{\geq 2}(p_T^{\rm cut}, p_T^{\rm off})]$$

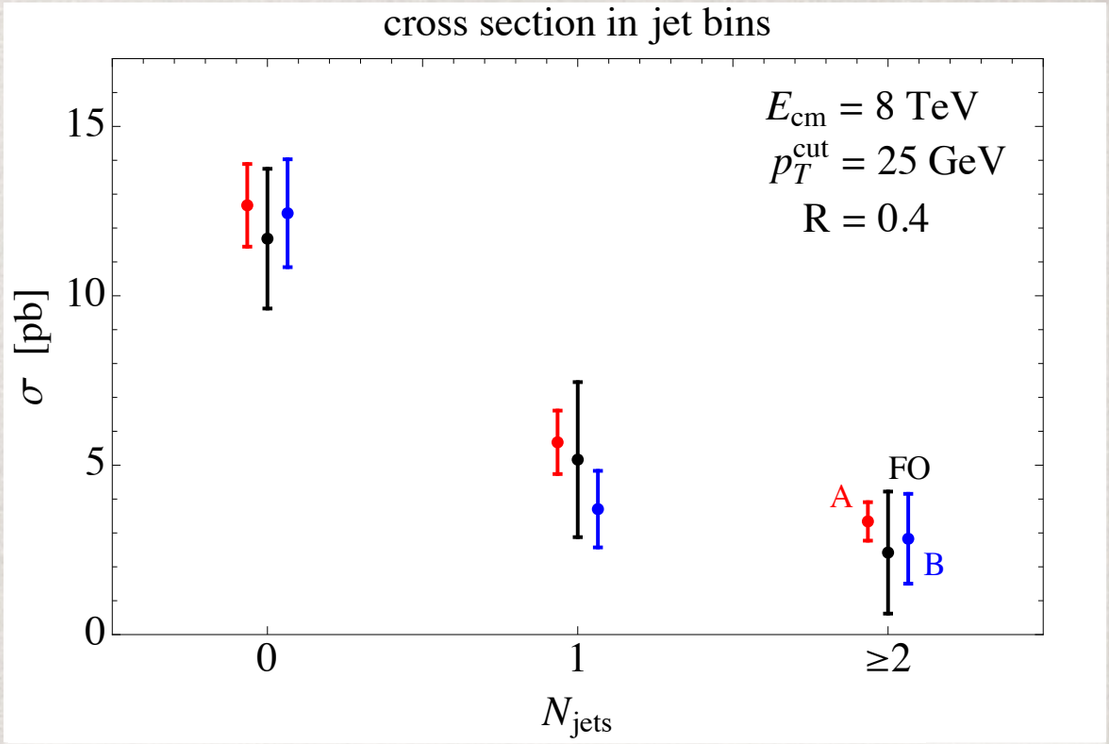
NNLL'+NNLO

NLO

H+1jet cross section

- Considerable reduction of theoretical uncertainties with resummation





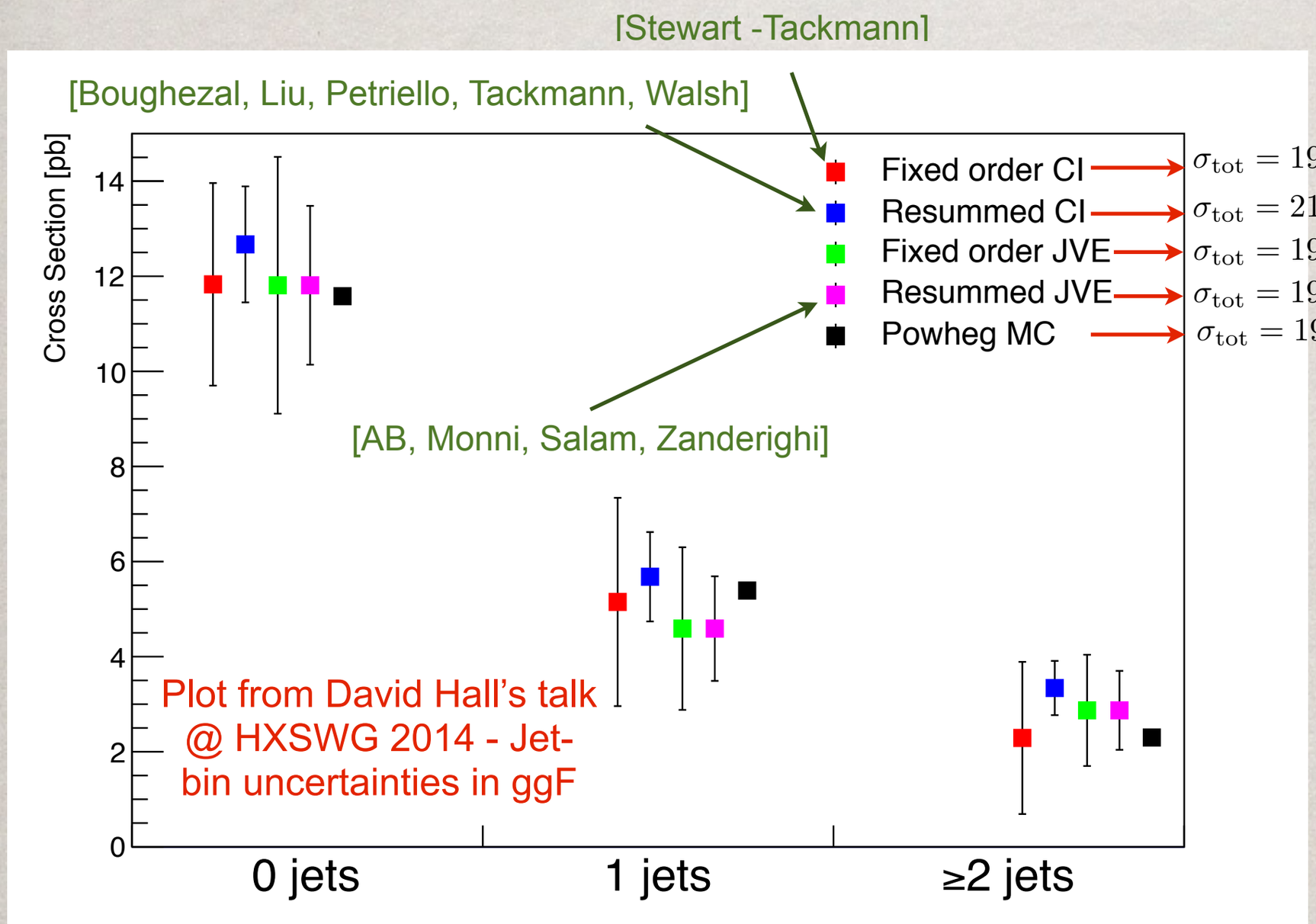
$$\text{e.g. } R = 0.4,\ p_{\mathrm{t,veto}} = 25\,\mathrm{GeV}:\ \delta\sigma^{\mathrm{NLO}}_{1-\mathrm{jet}} \sim 40\% \rightarrow \delta\sigma^{\mathrm{BLPTW}}_{1-\mathrm{jet}} \sim 16.5\%$$

Also here the total cross section includes π^2 resummation and differs from HXSWG

Uncertainties at the LHC

- Comparison among different methods

$$\mathrm{anti-k_t\ \ jets,\ R = 0.4,\ p_{t,veto} = 25\ GeV}$$



$\sigma_{\mathrm{tot}} = 19.27 \pm 1.5\,\mathrm{pb}$ (NNLO)

$\sigma_{\mathrm{tot}} = 21.69 \pm 1.49\,\mathrm{pb}$ (NNLO + π^2 resummation)

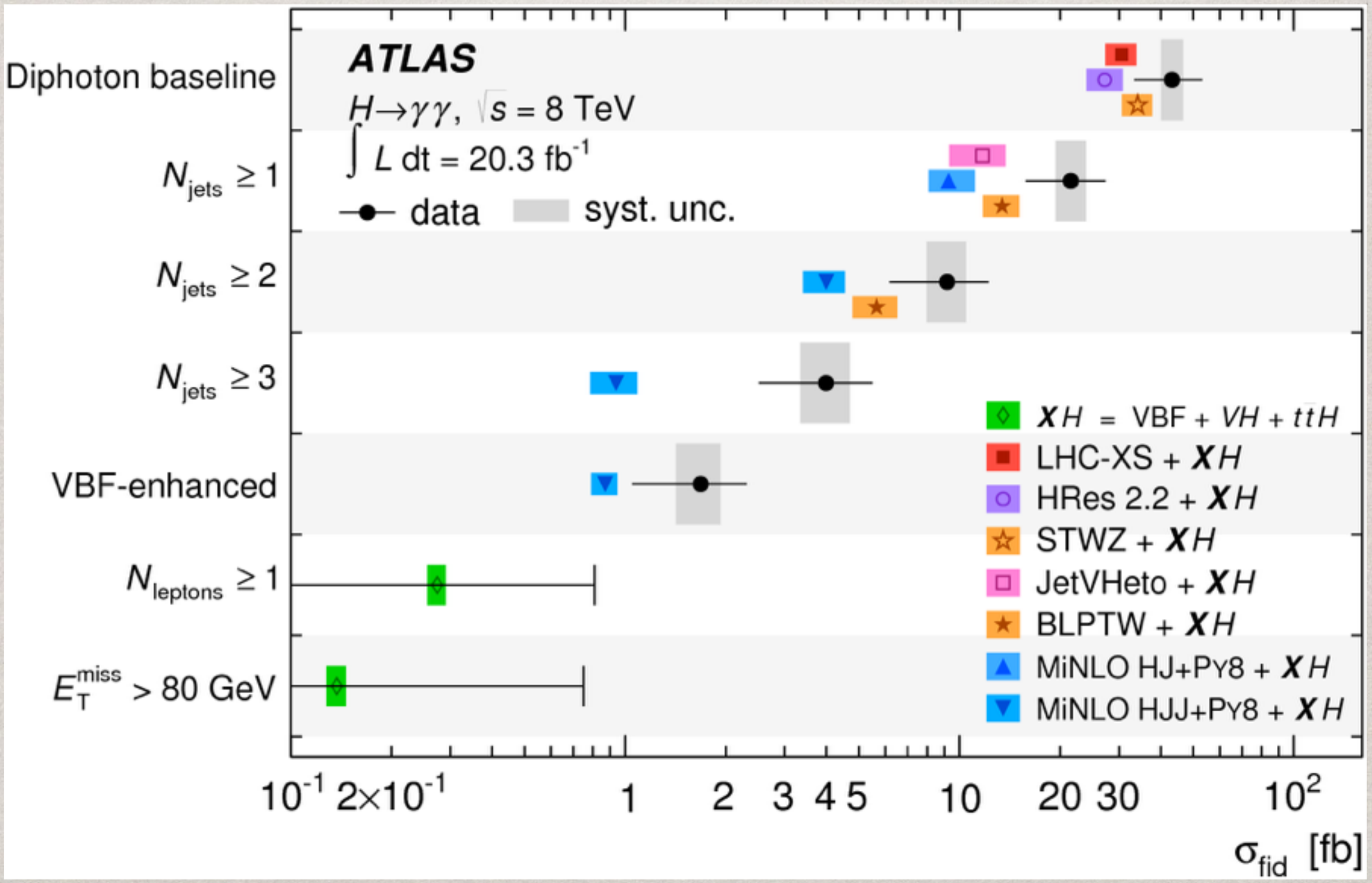
$\sigma_{\mathrm{tot}} = 19.27 \pm 1.5\,\mathrm{pb}$ (NNLO)

$\sigma_{\mathrm{tot}} = 19.27 \pm 1.5\,\mathrm{pb}$ (NNLO)

$\sigma_{\mathrm{tot}} = 19.5 \pm 1.5\,\mathrm{pb}$ (HXSWG)

Comparision to data

- Cross section in different bins have been measured by ATLAS in $H \to \gamma\gamma$

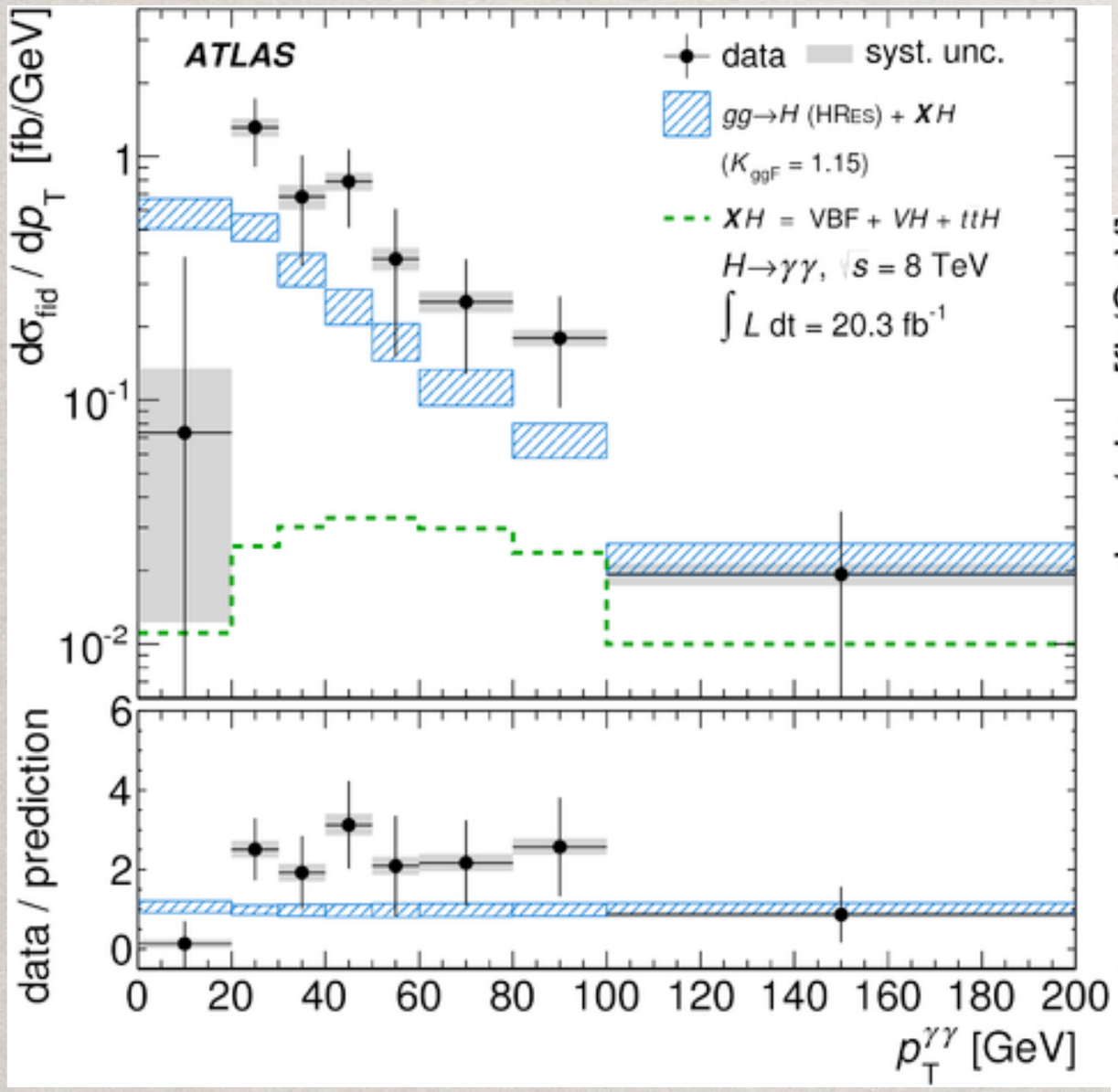


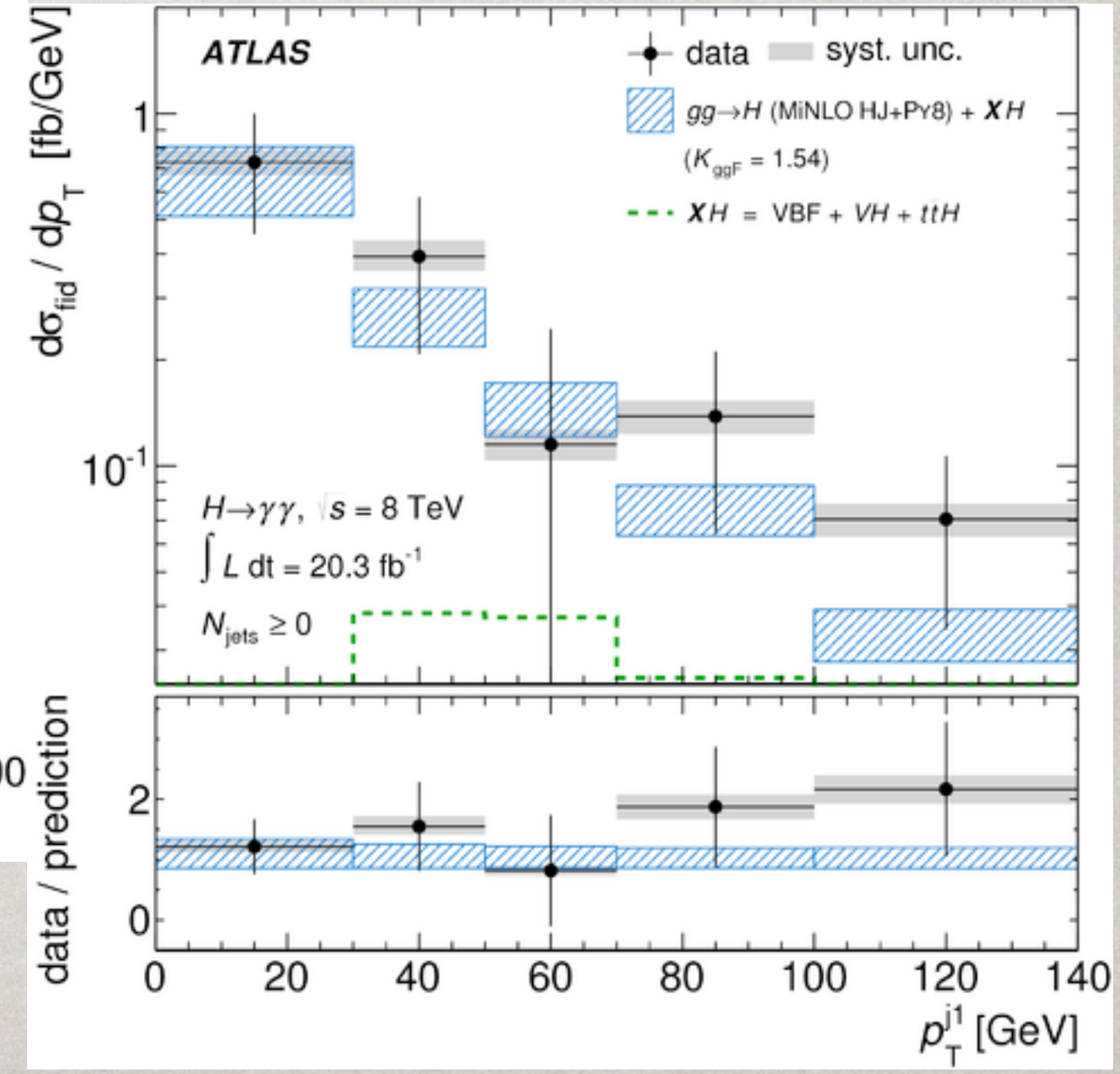
Room for improvements

- Zero-jet cross section
  - NNLL+NNNLO including the most recent results for the total Higgs cross section and Higgs+1jet [Anastasiou Duhr Dulat Herzog Mistleberger 1503.0605] [F. Caola's talk at Moriond]
  - include resummation of $\alpha_s^n \ln^n R$ [Dasgupta Dreyer Salam Soyez JHEP 04 (2015) 039]
  - combine recent results for two-loop beam and soft function to compute the two-loop constant and reach NNLL'+NNNLO [Boughezal Liu Petriello 1504.02540]
  - use MADGRAPH interface to be differential in Higgs decay products [Becher Frederix Neubert Rothen 1412.8408]
- One-jet cross section
  - use Higgs+1jet@NNLO to obtain NLL'+NNLO results
  - incorporate Higgs+1jet@NNLO in fixed-order uncertainty estimates with the efficiency method

Differential cross sections

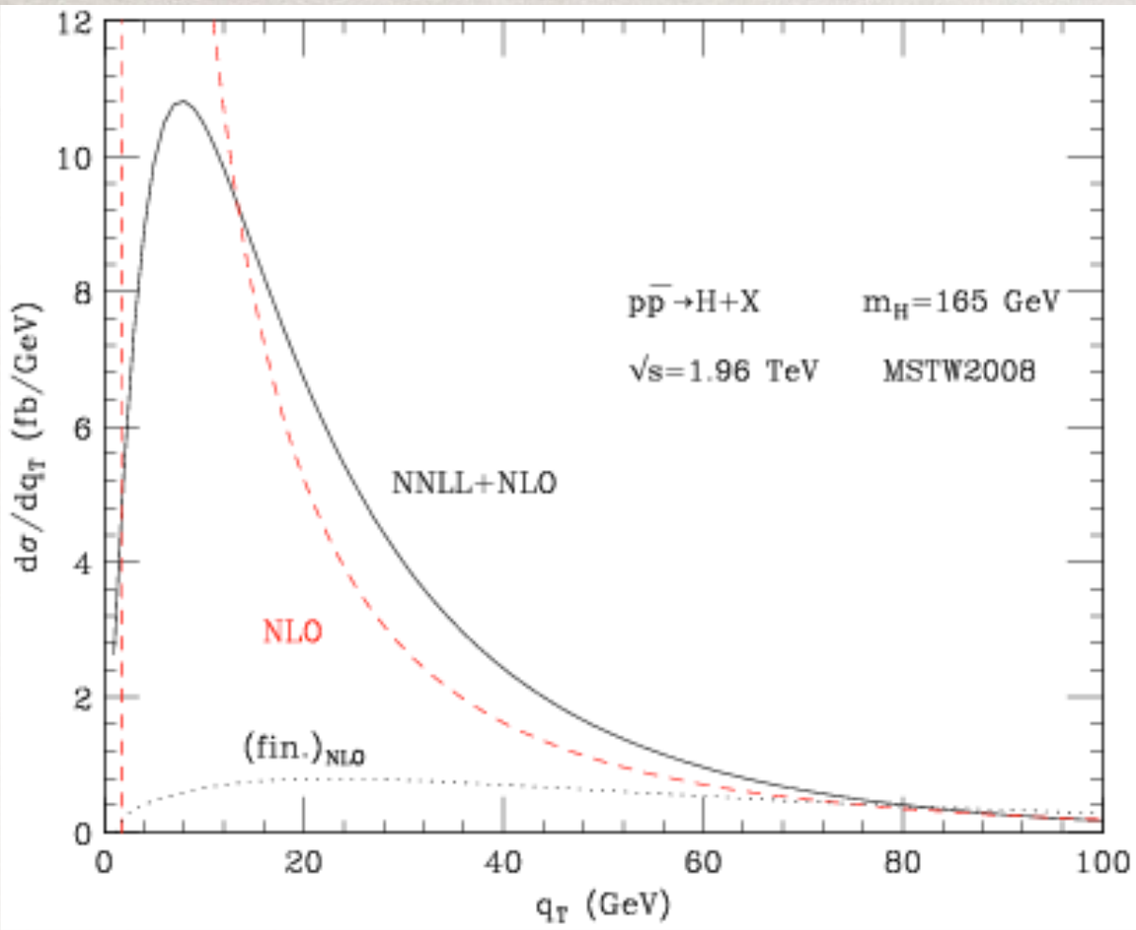
- With currently available LHC data it is possible to have access to a number of differential cross sections

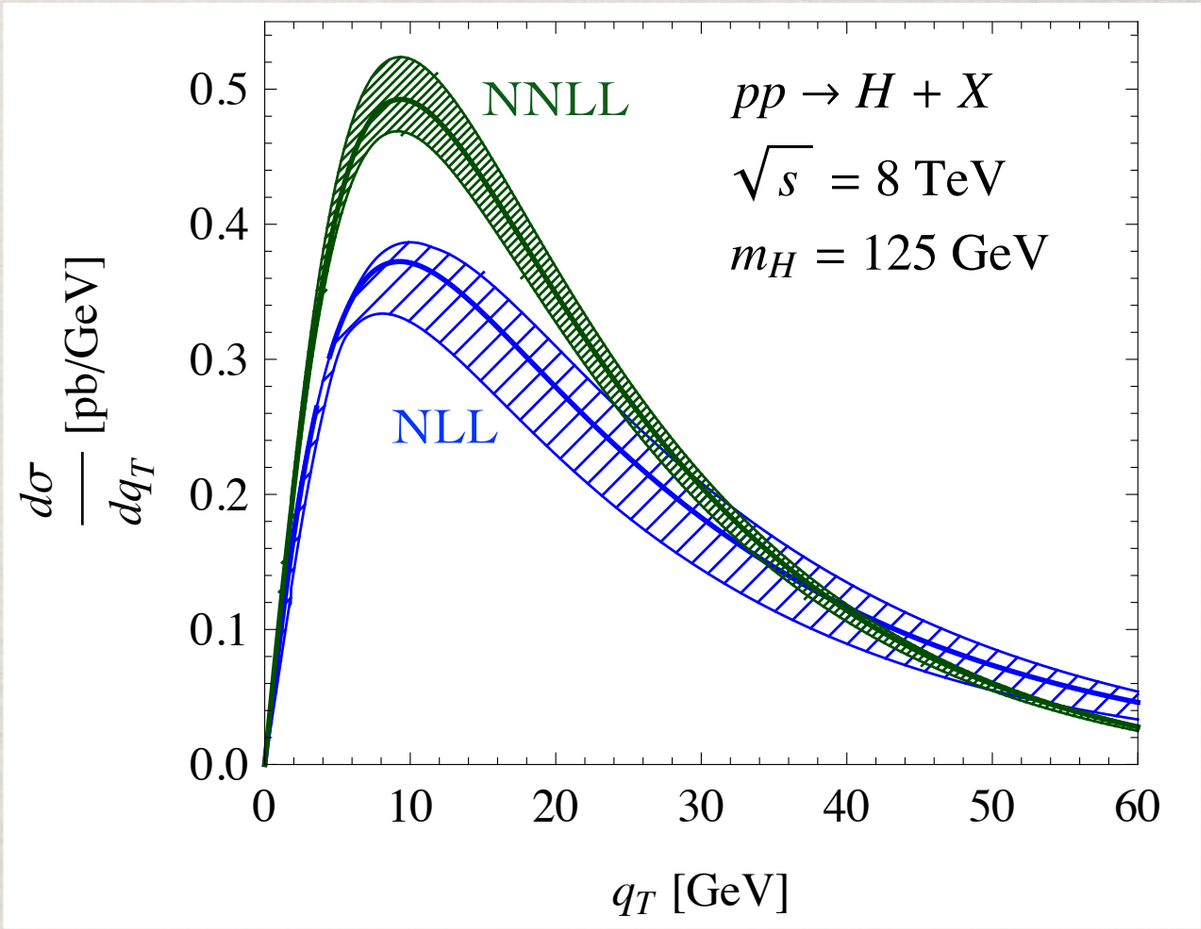




Higgs pt distribution

- The Higgs transverse momentum distribution suffers from the presence of large logarithms $\ln(m_H/p_{tH})$





- These logarithms have been resummed at NNLL+NNLO accuracy

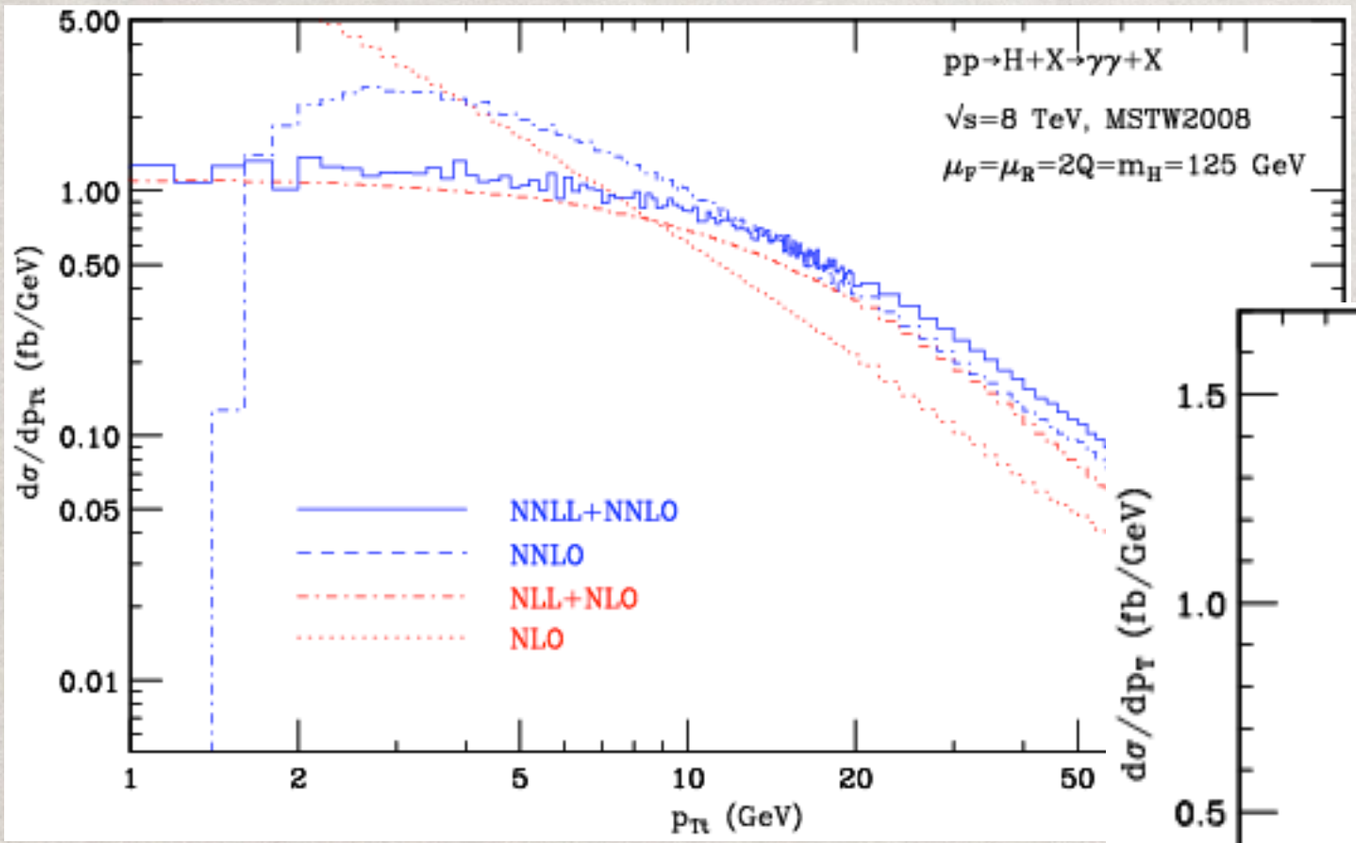
[De Florian Ferrera Grazzini Tommasini JHEP 11 (2011) 064]

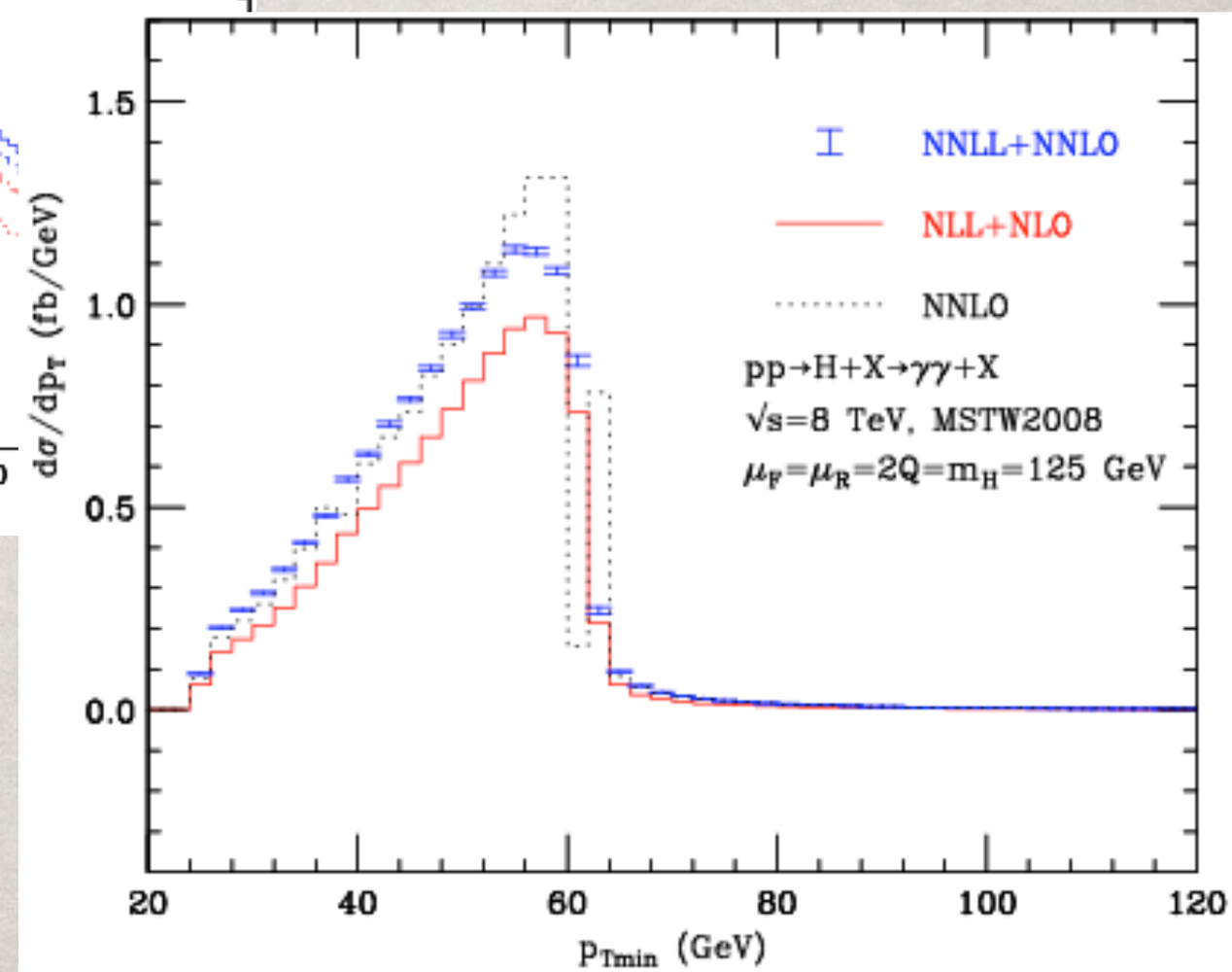
[Becher Neubert Wilhelm JHEP 05 (2013) 110]

More exclusive distributions

- With the program HRes it is possible to compute differential distributions in the decay products of the Higgs

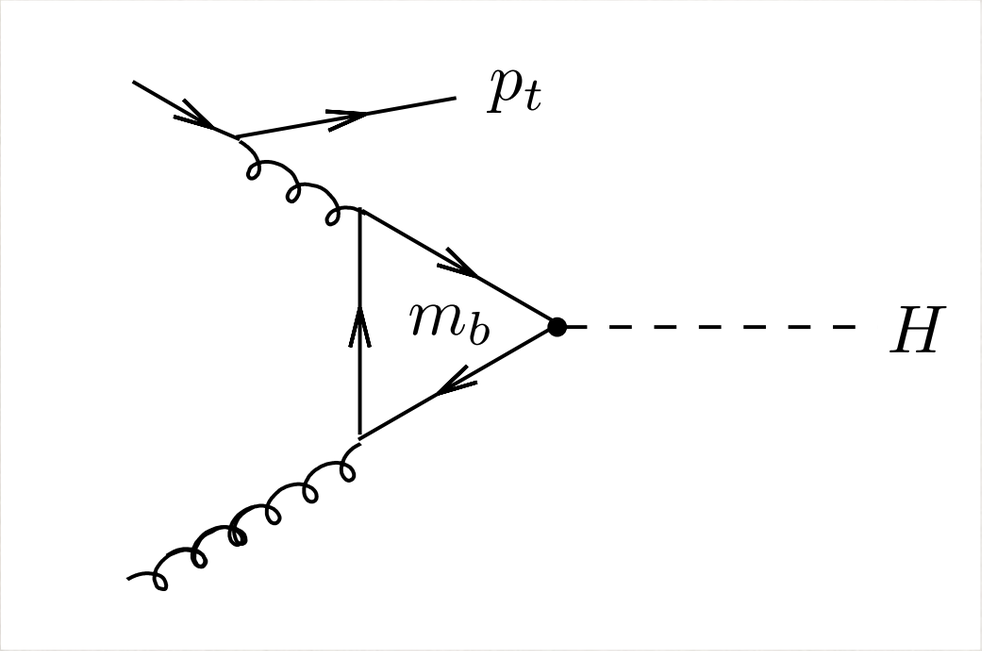
[De Florian Ferrera Grazzini Tommasini JHEP 06 (2012) 132]





Non-factorising corrections

- Collinear emissions can resolve a bottom loop for $m_b \ll p_t \ll m_H$



$$M_{qg\to Hq} \sim \frac{m_b}{p_t}\left[\ln^2\left(\frac{m_H^2}{m^2}\right) - \ln^2\left(\frac{m_b^2}{p_t^2}\right)\right]$$

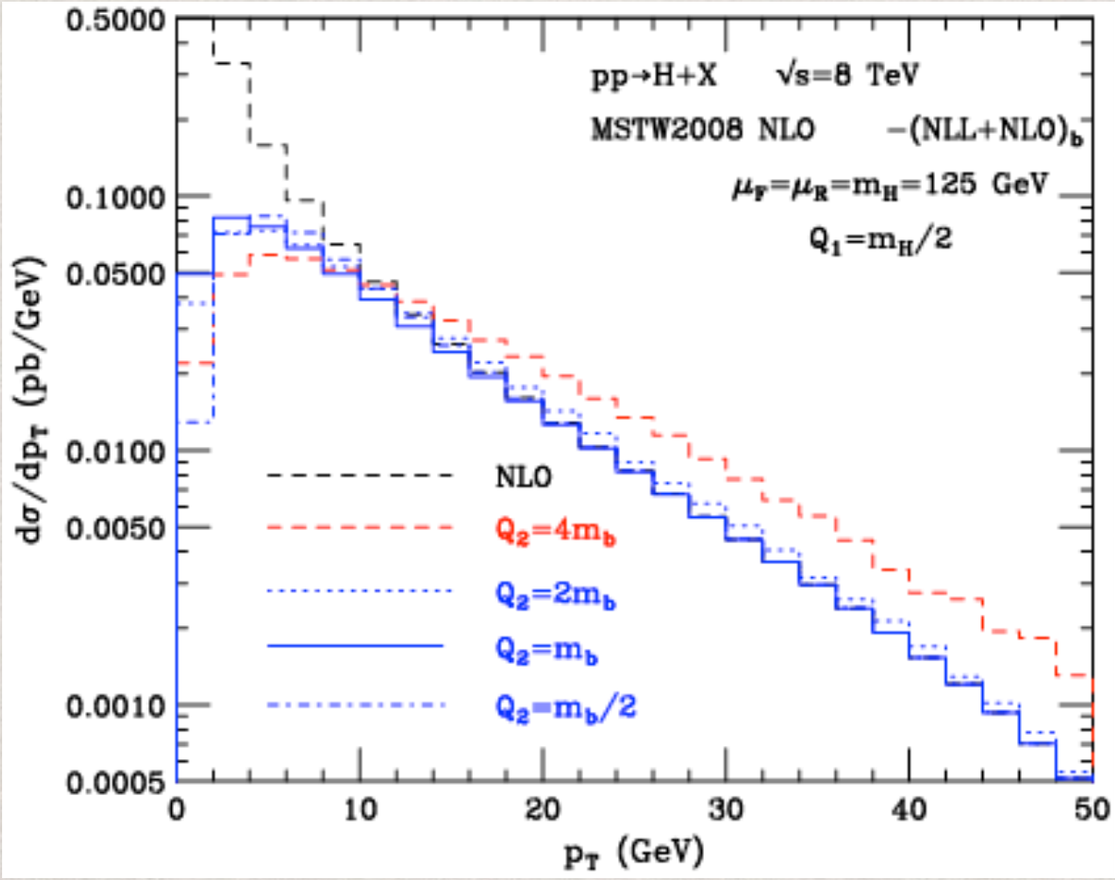
factorising non-factorising

- Non-factorising contributions due to soft gluons cancel in the in interference with the top loop

[AB Monni Zanderighi JHEP 01 (2014) 097]

Impact of non-factorising terms

- There are various ways to deal with non-factorising terms



- They spoil factorisation for $p_T \gtrsim m_b \Rightarrow$ stop the resummation at $p_T \gtrsim m_b$ with a low choice of the resummation scale Q_2

[Grazzini Sargsyan JHEP 09 (2013) 129]

Impact of non-factorising terms

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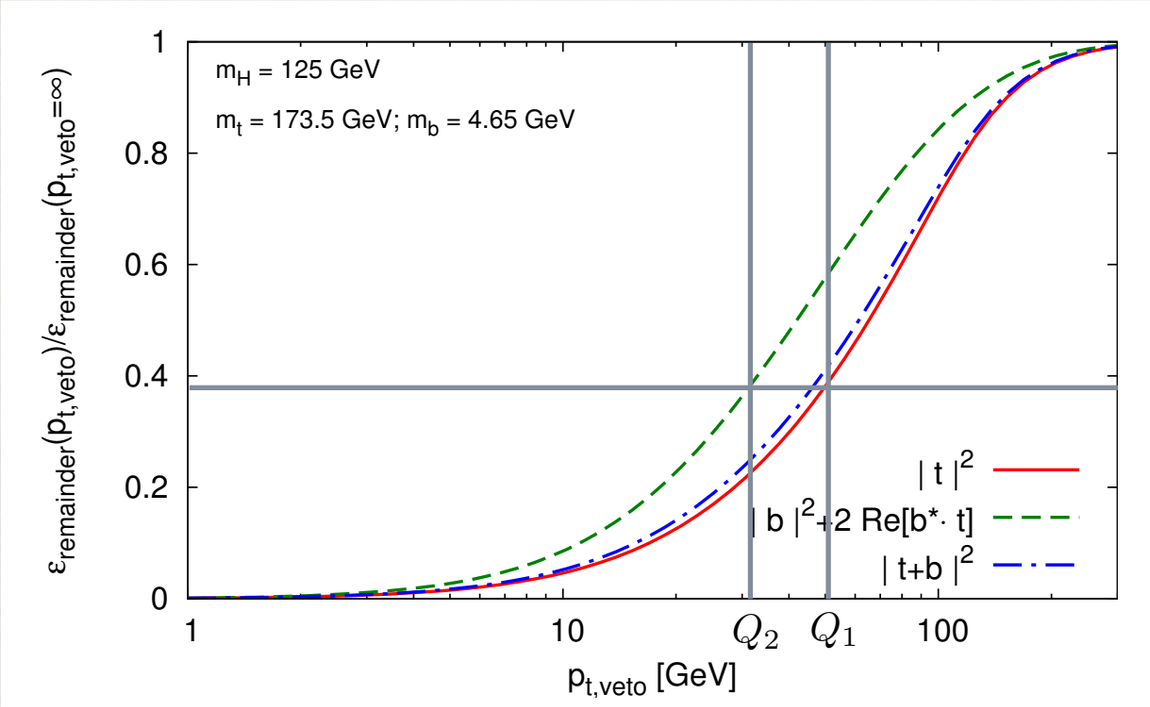
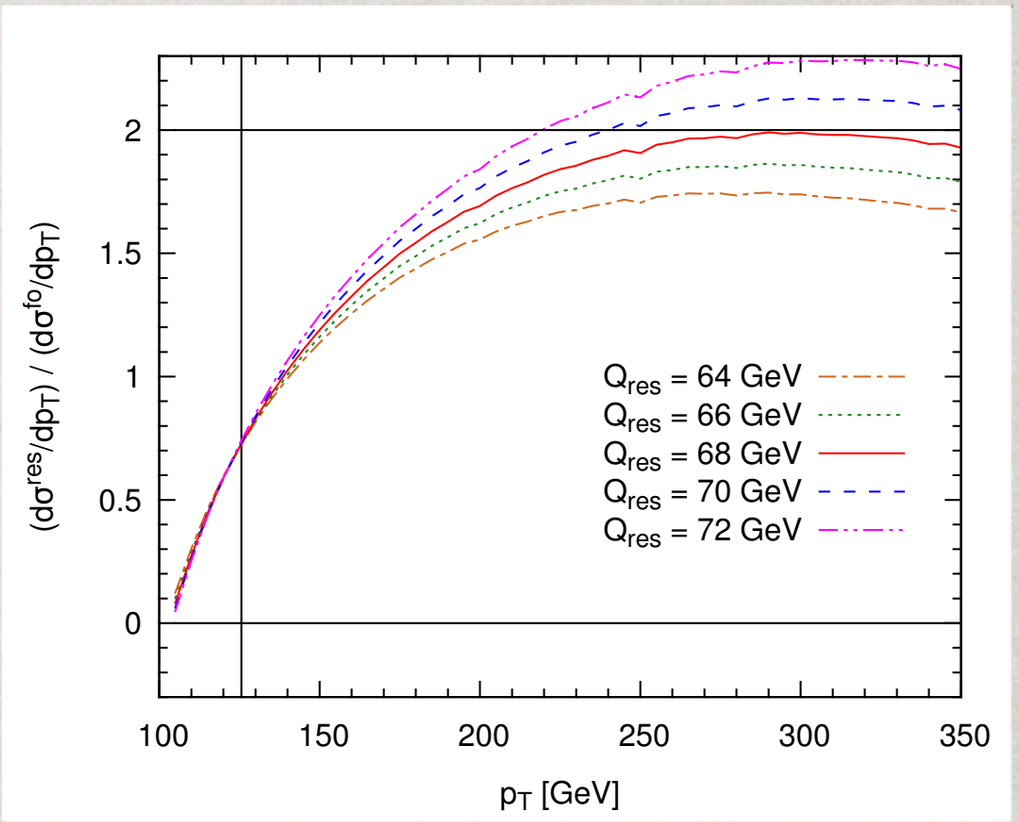




- The phase space for non-factorising terms is limited to $m_b \ll p_t \ll m_H$, so their effect is more in the fixed order region
  - Stop the resummation when they start to become important

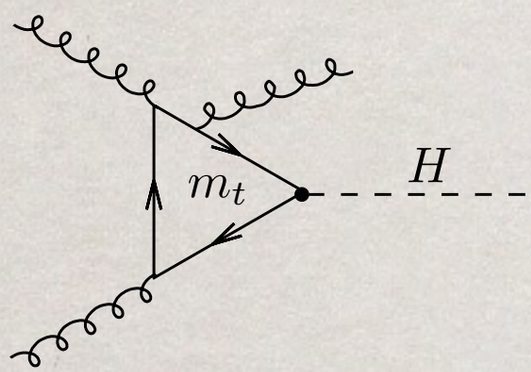
    [AB Monni Zanderighi JHEP 01 (2014) 097]
  - Choose the range in resummation scale so that the resummation is not too different from the fixed order at high p_t

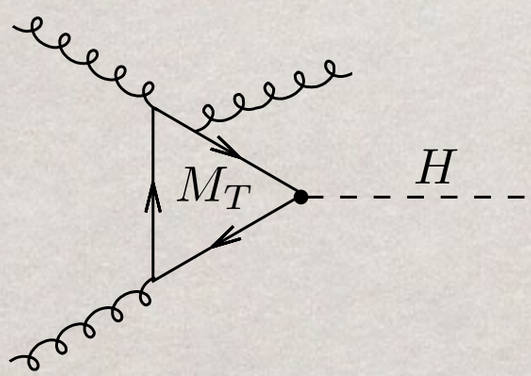
    [Harlander Mantler Wiesemann 1409.0531]

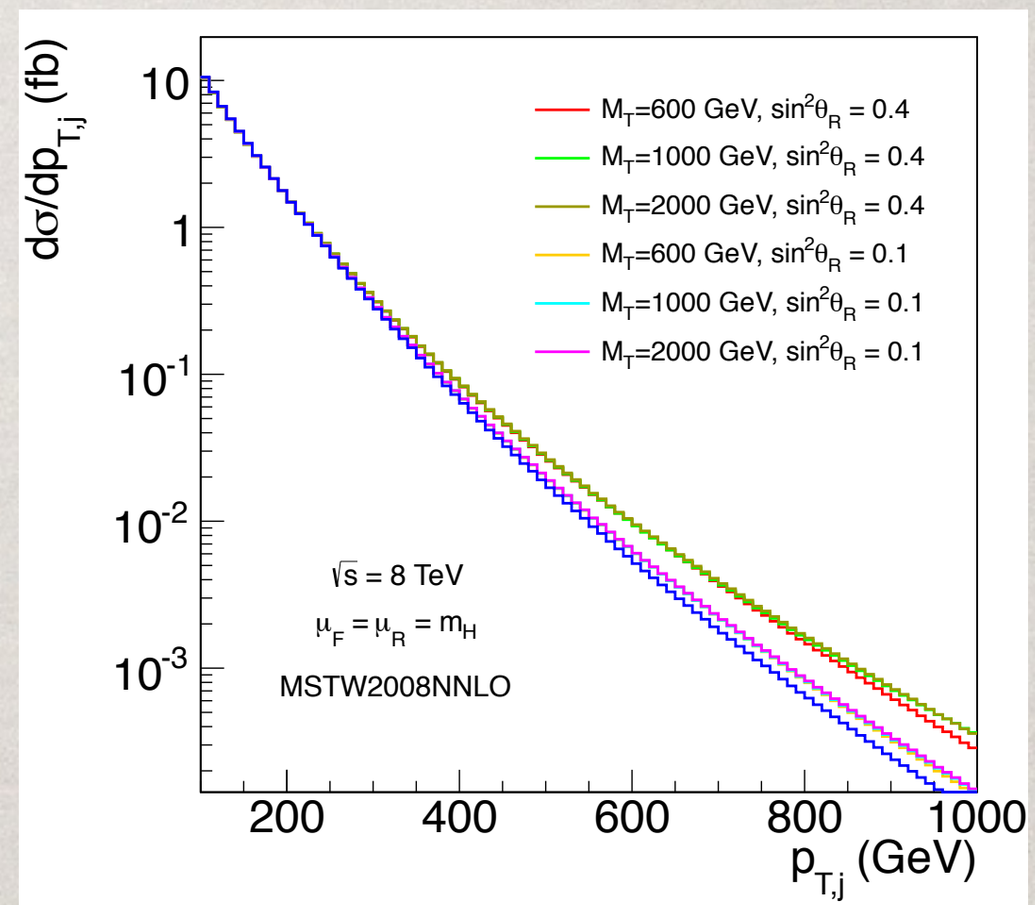
Finite masses at high pt

- A high-p_t gluon can resolve a top partner running in the loop, e.g. a heavy composite top or a stop

[AB Martin Sanz JHEP 08 (2014) 053]
[Azatov Paul JHEP 01 (2014) 014]
[Grojean Salvioni Schlaffler Weiler JHEP 05 (2014) 022]
[Schlaffler Spannowsky Tacheuchi Weiler Wymant EPJC 74 (2014) 10]







- Need perturbative control on the tail of jet-p_t distribution, where $\ln(p_{\mathrm{t,j}}/m_t)$ is large $\Rightarrow$ strong case for Higgs+1jet@NLO with full mass dependence

Highlights

- Higgs cross section with zero jets
  - Three different procedures that agree at NNLL+NNLO accuracy
  - All predictions give an uncertainty of order 10-13%
  - Including π^2resummation reduces scale uncertainties
- Uncertainties across jet bins
  - JVE method can be generalised to an arbitrary jet multiplicity
  - New BLPTW method that takes advantage of resummation of the exclusive one-jet cross section
- Effects of finite masses in loops
  - inclusion of top and bottom mass effects gives a larger uncertainty in the jet-veto cross section, of order 14% $\Rightarrow$ Higgs+1jet@NLO needed
  - Strategies needed to minimise the effect of the resummation at high p_t

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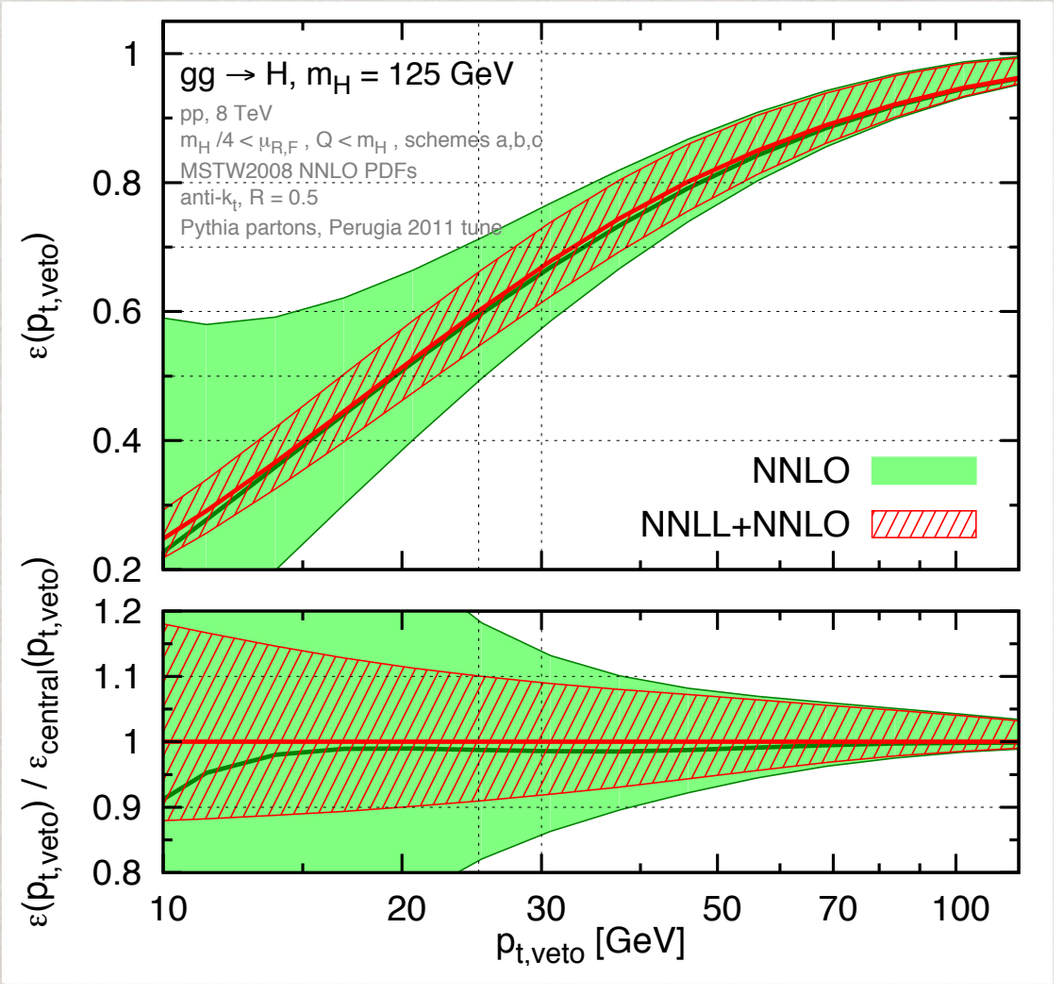
Thank you for your attention!

Extra

Predictions for jet-veto efficiency

- Uncertainties of the jet-veto efficiency: independent variation of all scales by a factor two around $m_H/2$, and of schemes to match NNLL to NNLO



- Reduction of theoretical uncertainty from NNLO to NNLL+NNLO
- Uncertainty would be further reduced with a larger jet radius

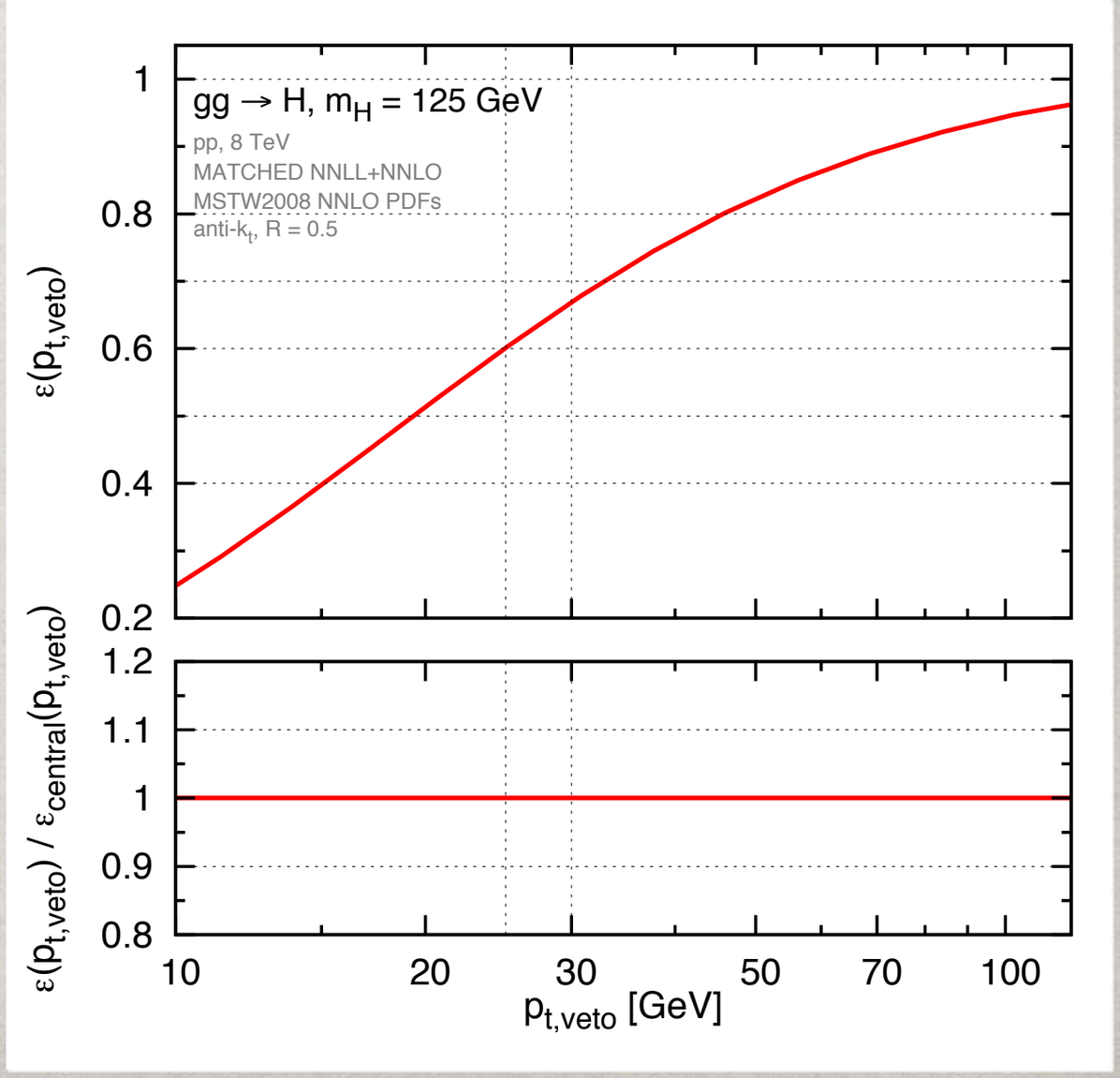
Theoretical uncertainties

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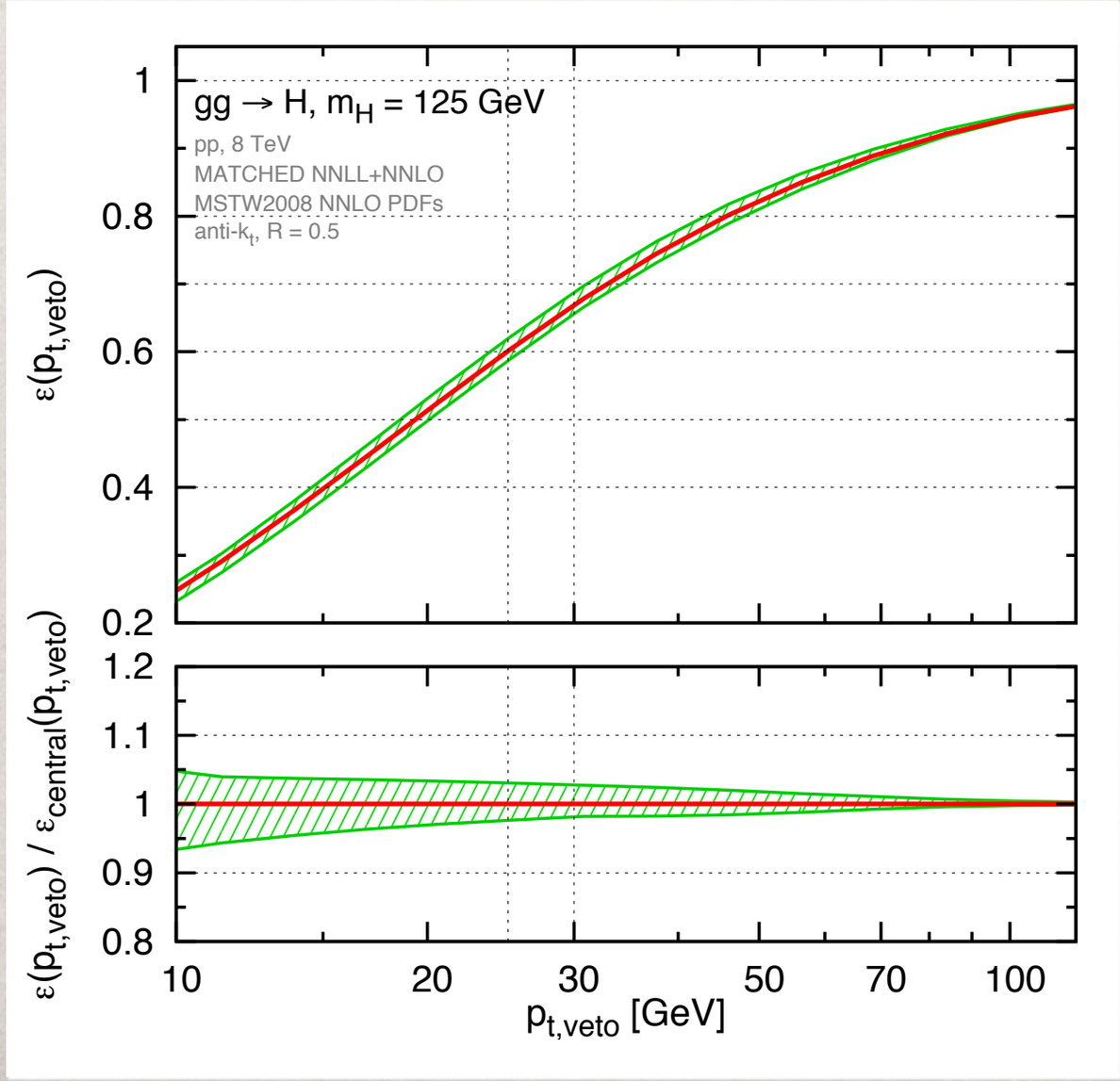
$$\frac{m_H}{4} \leq \mu_R, \mu_F \leq m_H \qquad \frac{1}{2} \leq \frac{\mu_R}{\mu_F} \leq 2$$



Theoretical uncertainties

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[AB Monni Salam Zanderighi '12]

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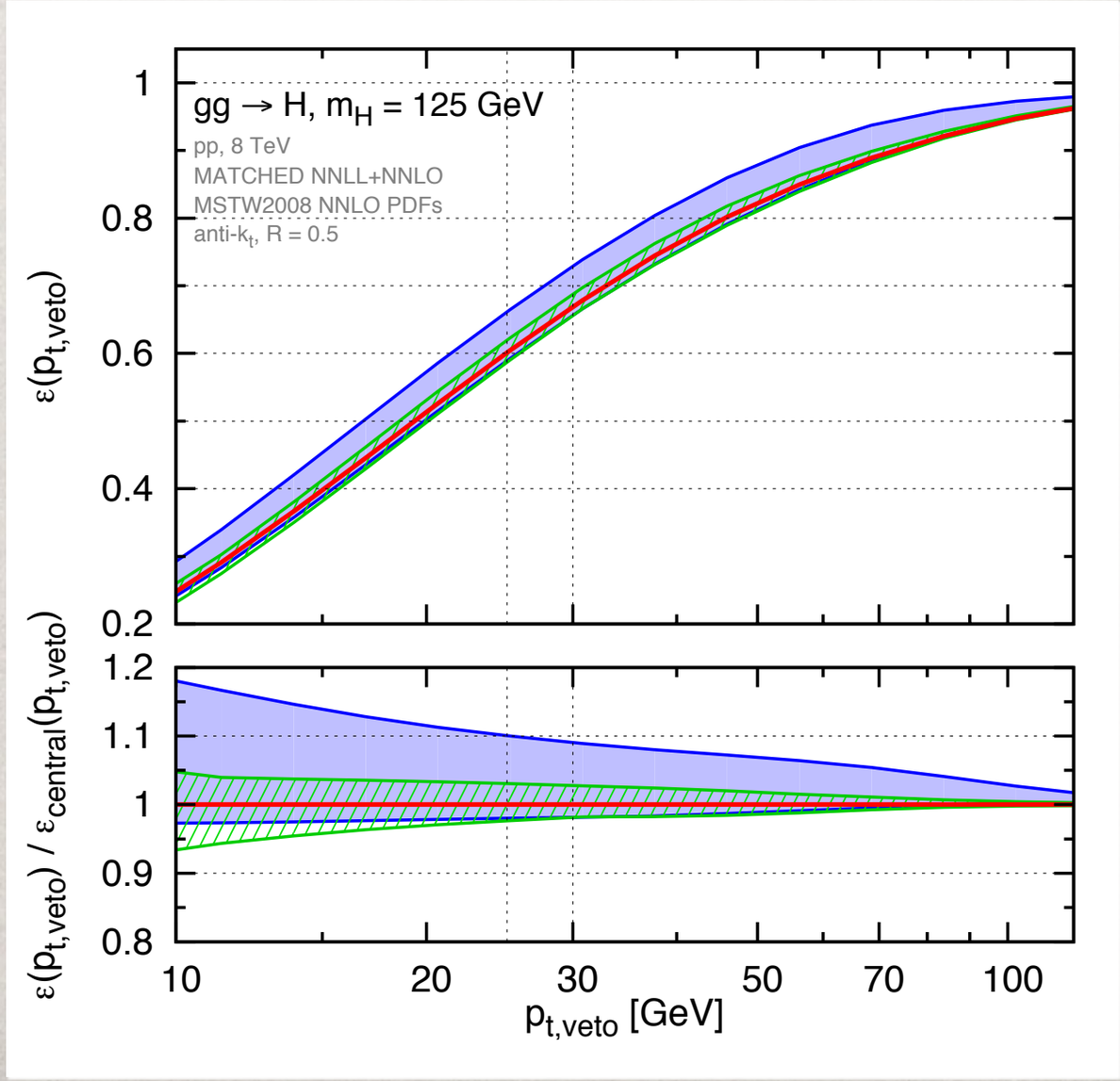

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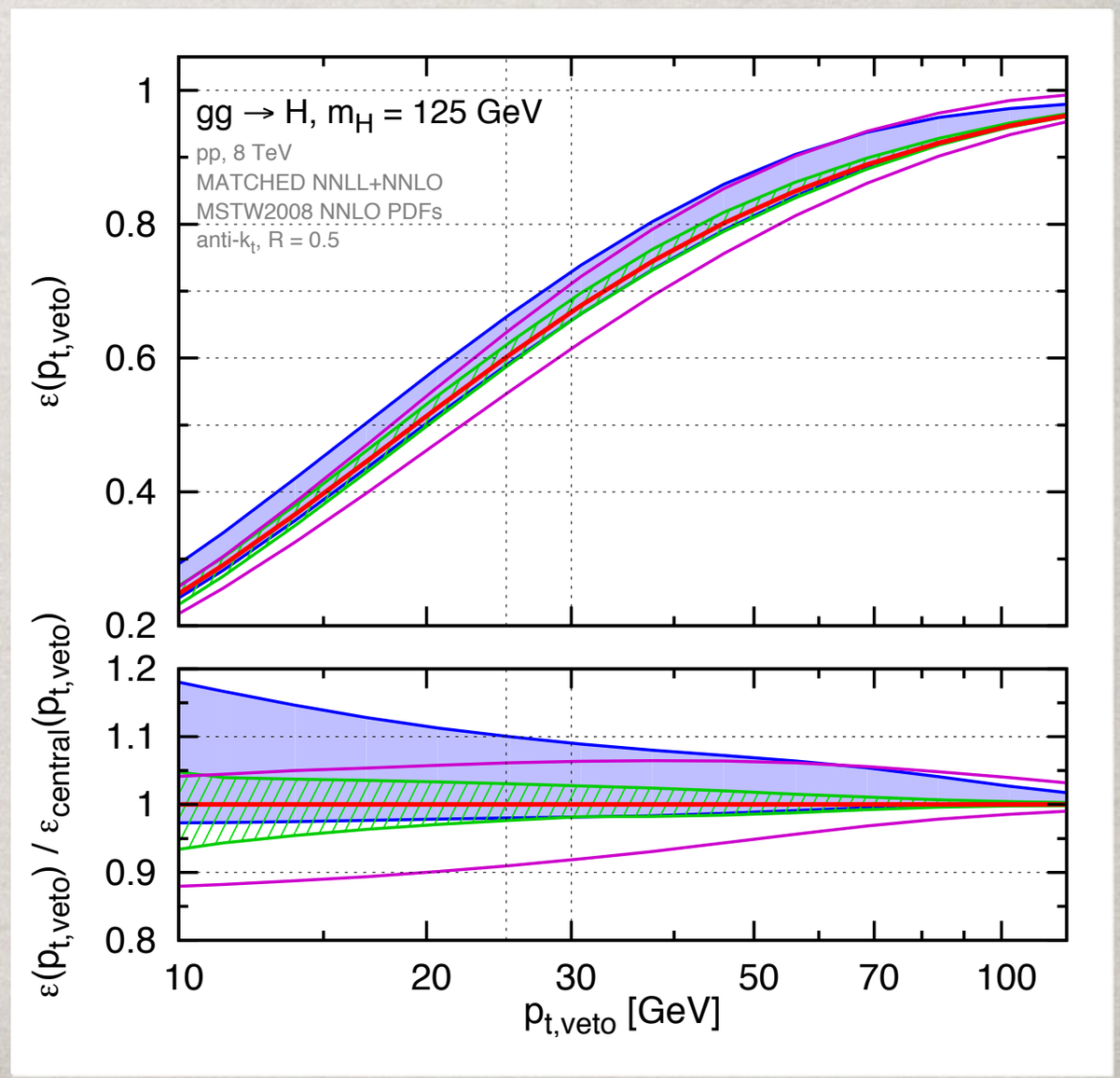

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