QCD effects in exclusive Higgs production

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Higgs Identification at KITP

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Outline

- Theory errors in experimental searches
- Brief discussion of inclusive cross sections, for purposes of comparison when cuts added
- Jet vetoes in VH, gluon-fusion

Effects of theory uncertainties

- CMS PAS HIG-11-024: (WW channel) "The overall signal efficiency uncertainty... is dominated by the theoretical uncertainty due to missing higher-order corrections"
- ATLAS CERN-PH-EP-2012-013 (γγ): uncertainties due to QCD scale variation one of the two dominant systematic effects (along with photon reconstruction+ID efficiency)

from G. Rolandi, HCP 2011

Source	Affected Processes	Typical uncertainty
PDFs+α_s (cross sections)	$gg \to H$, $t\bar{t}H$, $gg \to VV$	$\pm 8\,\%$
	VBF H, VH, VV@NLO	$\pm 4\,\%$
Higher-order uncertainties on cross sections	total inclusive $gg \to H$	$^{+12\,\%}_{-7\,\%}$
	inclusive "gg" $\to H + \geq 1$ jets	$\pm 20\,\%$
	inclusive "gg" $\to H + \geq 2$ jets	$\pm 20\%$ (NLO), $\pm 70\%$ (LO)
	VBF H	$\pm 1\,\%$
	associated VH	$\pm 1\,\%$
	$t\bar{t}H$	$^{+4\,\%}_{-10\,\%}$
	uncertainties specific to high mass Higgs boson, see Section 2.1	$\pm 30\%$
	V	$\pm 1\,\%$
	VV up to NLO	$\pm 5\,\%$
	$gg \to VV$	$\pm 30\,\%$
	$t\bar{t}$, incl. single top productions for simplicity	$\pm 6\,\%$
acceptance	acceptance for $H \to WW \to \ell\nu\ell\nu$ events	$\pm 2\%$
phenomenology	modelling of underlying event and parton showering	$\pm 10\,\%$
	fake lepton probability ($W + jets \to \ell\ell^{fake}$)	$\pm 40\%$
luminosities	ATLAS and CMS uncertainties on their luminosity measurements	$\pm 3.7\,\%$, $\pm 4.5\,\%$

Effects of theory uncertainties

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	13	-
1-jet incl. ggF signal ren./fact. scale	10	-
PDF model (signal only)	8	-
QCD scale (acceptance)	4	-
Jet energy scale and resolution	4	2
W+jets fake factor	-	5
WW theoretical model	-	5
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	26	-
2-jet incl. ggF signal ren./fact. scale	15	-
Parton shower/ U.E. model (signal only)	10	-
b-tagging efficiency	-	11
PDF model (signal only)	7	-
QCD scale (acceptance)	4	2
Jet energy scale and resolution	1	3
W+jets fake factor	-	5
WW theoretical model	-	3

systematics in the WW channel, from J. Qian

Inclusive cross sections

• How well do we know the inclusive gluon-fusion cross section? Receives several large corrections at higher orders

NLO in the EFT:

analytic continuation to time-like form factor

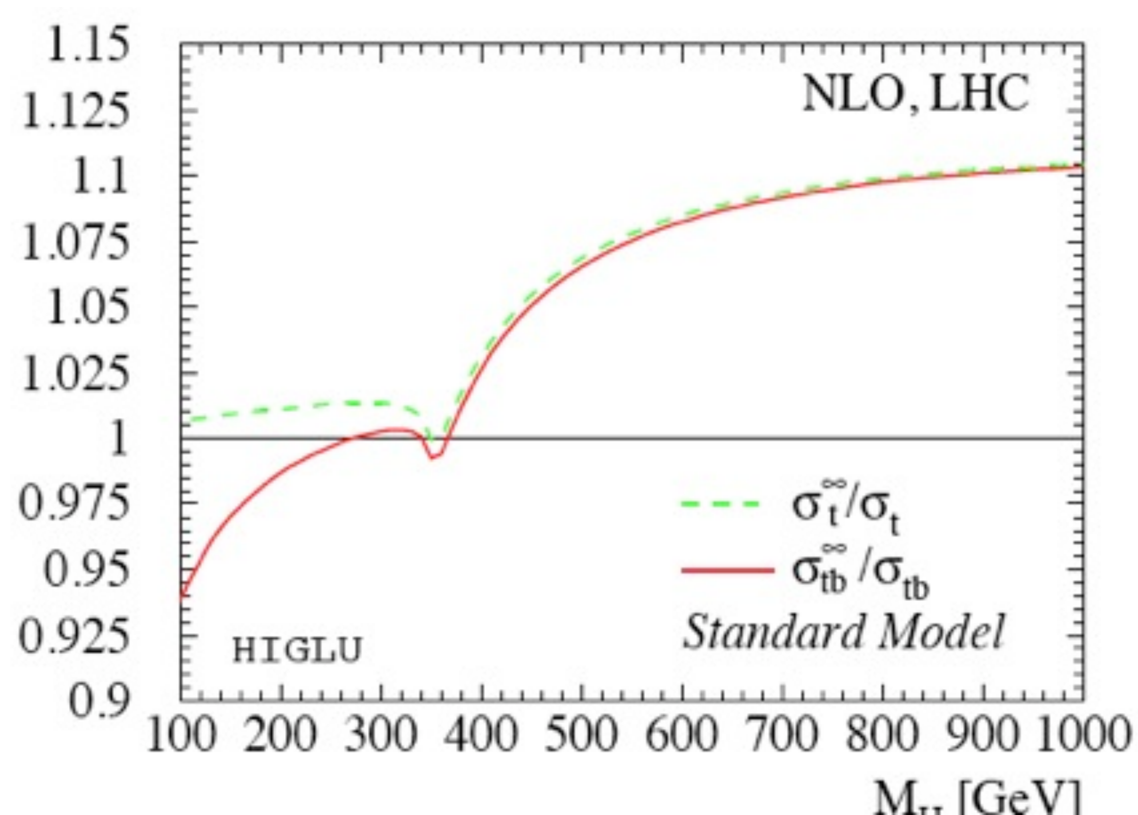
$z=M_H^2/(x_1 x_2 s)$

$$\Delta\sigma = \sigma_0 \frac{\alpha_s}{\pi}\left\{\left(\frac{11}{2}+\pi^2\right)\delta(1-z)+12\left[\frac{\ln(1-z)}{1-z}\right]_+ - 12z(-z+z^2+2)\ln(1-z) - 6\frac{(z^2+1-z)^2}{1-z}\ln(z) - \frac{11}{2}(1-z)^3\right\}$$

eikonal emission of soft gluons

Identical factors in full theory with $\sigma_0 \rightarrow \sigma_{LO,\text{ full theory}}$

$$\sigma_{NLO}^{approx} = \left(\frac{\sigma_{NLO}^{EFT}}{\sigma_{LO}^{EFT}}\right)\sigma_{LO}^{QCD}$$



Gluon-fusion: inclusive

Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about 6-15%)

S. Catani, D. De Florian, P. Nason, Grazzini (2003)

Partial N^3LO corrections known (considerably reduced scale dependence)

Moch, Vogt (2005)

Resummation of π^2 factors through appropriate matching condition

Ahrens, Becher, Neubert, Yang (2008)

Two-loop EW corrections are also known (effect is about O(5%))

U. Aglietti et al. (2004)
G. Degrassi, F. Maltoni (2004)
G. Passarino et al. (2008)

Mixed QCD-EW effects evaluated in EFT approach

Anastasiou, Boughezal, FP (2008)

EW effects for real radiation

W.Keung, FP, (2009)

Inclusive cross sections

m_H (GeV)	Cross Section (pb)	+Total %	-Total %	+Scale %	-Scale %	+(PDF+α_s) %	-(PDF+α_s) %
123.0	20.15	+14.7	-14.8	+7.2	-7.9	+7.5	-6.9
123.5	19.99	+14.7	-14.8	+7.2	-7.9	+7.5	-6.9
124.0	19.83	+14.7	-14.8	+7.2	-7.9	+7.5	-6.9
124.5	19.68	+14.7	-14.8	+7.2	-7.9	+7.5	-6.9
125.0	19.52	+14.7	-14.7	+7.2	-7.8	+7.5	-6.9
125.5	19.37	+14.7	-14.7	+7.2	-7.8	+7.5	-6.9
126.0	19.22	+14.7	-14.7	+7.2	-7.8	+7.5	-6.9
126.5	19.07	+14.7	-14.7	+7.2	-7.8	+7.5	-6.9
127.0	18.92	+14.6	-14.7	+7.1	-7.8	+7.5	-6.9

LHC Higgs XS working group

More in talk of M. Neubert

Imposing cuts: VH

- The difficulty comes when typical experimental cuts are imposed. Consider the VH channel as an example, and compare inclusive to exclusive

Inclusive NLO QCD: +30% (Han, Wllenbrock 1990)

NLO EW: +5-10% (Ciccolini, Dittmaier, Denner 2003)

NNLO QCD: 1-2% (Ferrera, Grazzini, Tramontano 2011)

However:

Categorization to take advantage of different S/B ratios:

- 3 E_T^{miss} categories for $ZH \to \nu\nu b\bar{b}$: 120 – 160, 160 – 200, >200 GeV
- 4 p_T^W categories for $WH \to \ell\nu b\bar{b}$: 0 – 50, 50 – 100, 100 – 200, >200 GeV;
- 4 p_T^Z categories for $ZH \to \ell\ell b\bar{b}$: 0 – 50, 50 – 100, 100 – 200, >200 GeV;

from J. Qian

Imposing cuts: VH

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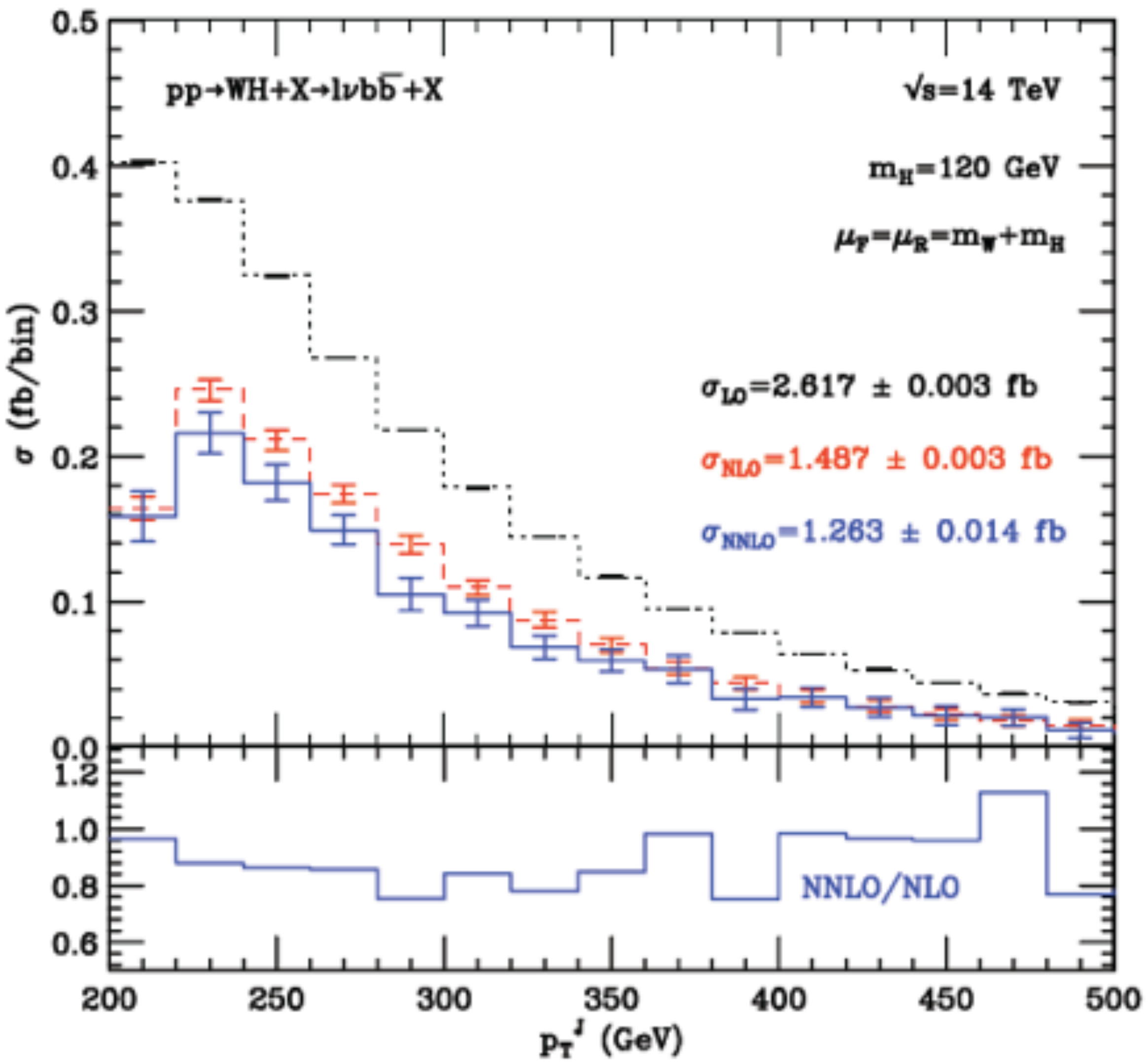

Ferrera, Grazzini, Tramontano 2011

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NNLO QCD: 1-2% (Ferrera, Grazzini, Tramontano 2011)

A 30% increase turns into a decrease of more than a factor of 2!

Imposing cuts: $\tau\tau$

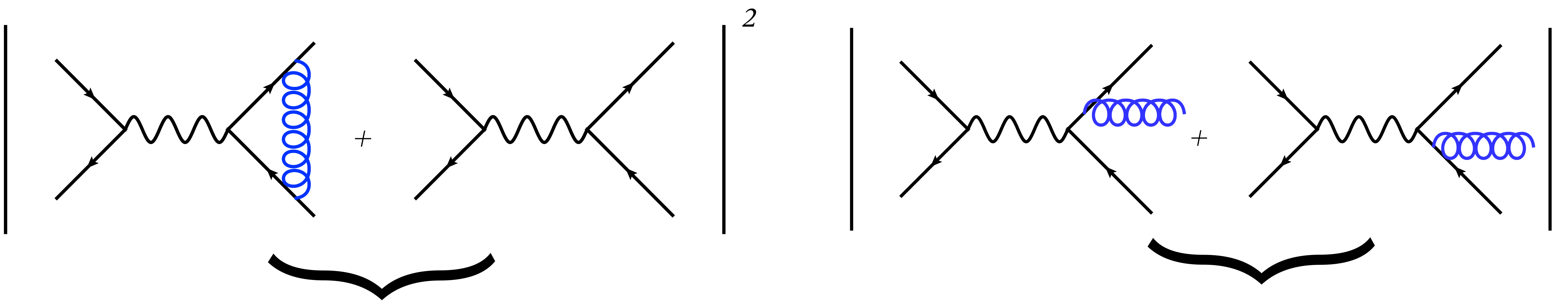
- The difficulty comes when typical experimental cuts are imposed. Consider the CMS $\tau\tau$ channel

- Categorization ($\mu\tau$, $e\tau$, $e\mu$, $\mu\mu$)
  - **VBF:** Require 2 jets above 30 GeV , $|\eta|<4.7$. The jets must have $\Delta\eta>3.5$ and $M_{jj}>500$ GeV. Jet veto in the gap between the jets and the tau products
  - **1 jet:** Requires at least one jet> 30 GeV. Veto events accepted by VBF category.

from M. Bachtis

Why are jet vetoes dangerous?

- Illustrate with simple example of $e^+e^- \rightarrow$ jets
- Infrared safety: must sum both virtual and real corrections

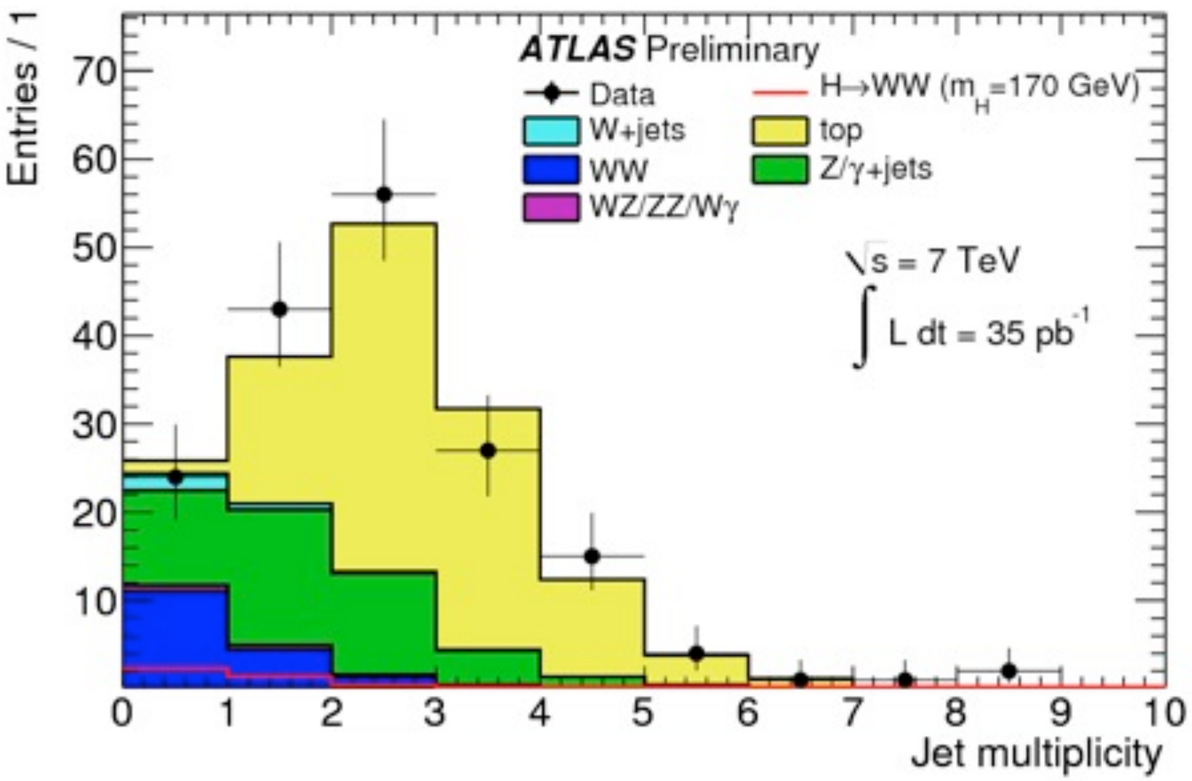


Virtual corrections: $-1/\varepsilon_{IR}^2$

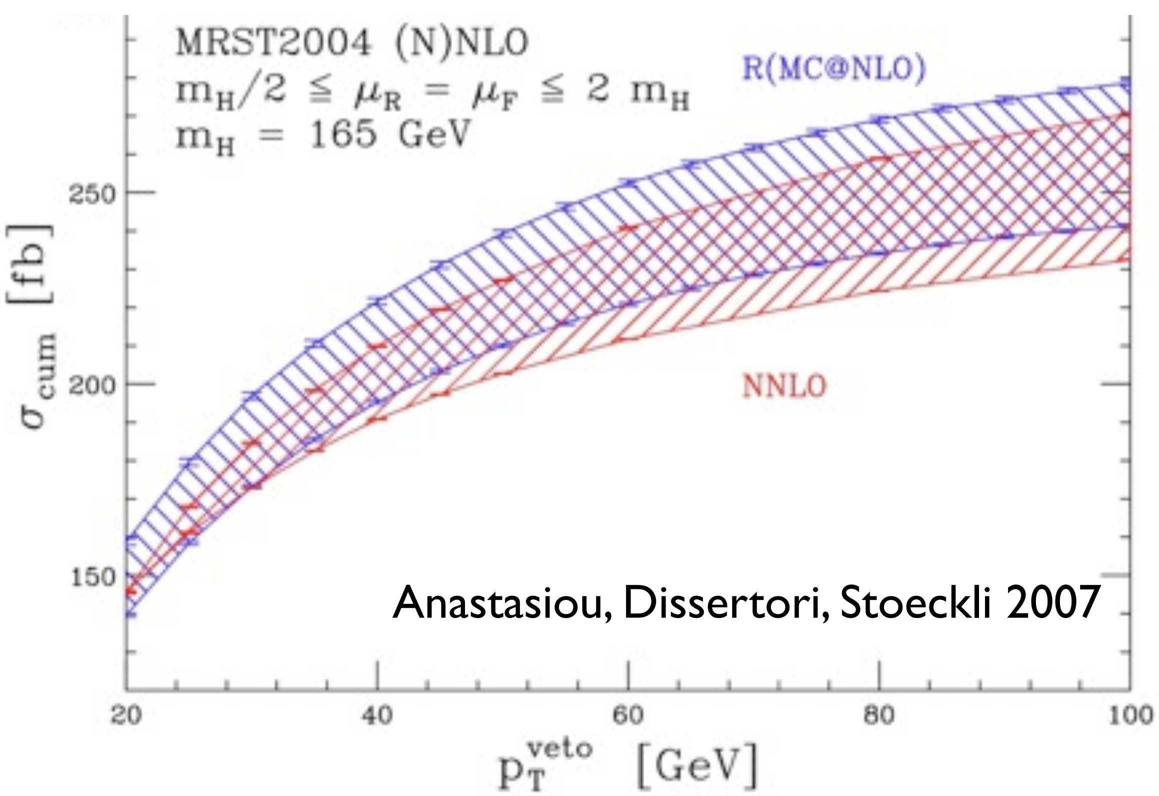
Real corrections: $1/\varepsilon_{IR}^2 - a \times \ln^2(Q/p_{T,cut})$

- Incomplete cancellation of IR divergences in presence of final state restrictions gives large logarithms of restricted kinematic variable
- Relevant log term for gluon-fusion Higgs searches: $6(\alpha_S/\pi)\ln^2(M_H/p_{T,veto}) \sim 1/2 \Rightarrow$ potentially a large correction

The jet-veto in gluon fusion



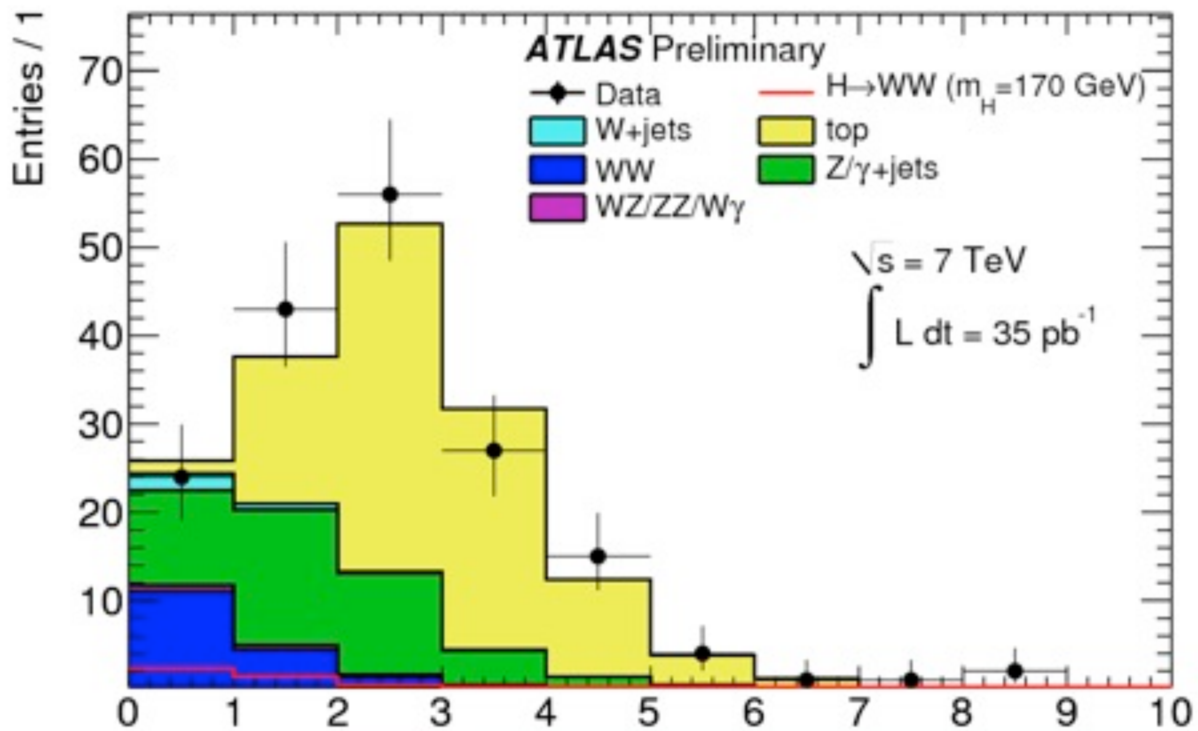
- Required in WW channel due to background composition; used in other channels also (γγ, ττ)
- 25-30 GeV jet cut used; restriction of radiation leads to large logs



Anastasiou, Dissertori, Stoeckli 2007

- Inclusive scale variation 10%; with a 25 GeV jet veto, 5-6%!
- Having $\Delta\sigma_{veto} < \Delta\sigma_{tot}$ doesn't seem correct; σ_{veto} has a more complicated structure and a larger expansion parameter, $\alpha_S \ln^2(m_H/p_{T,cut})$ rather than α_S

The jet-veto in gluon fusion



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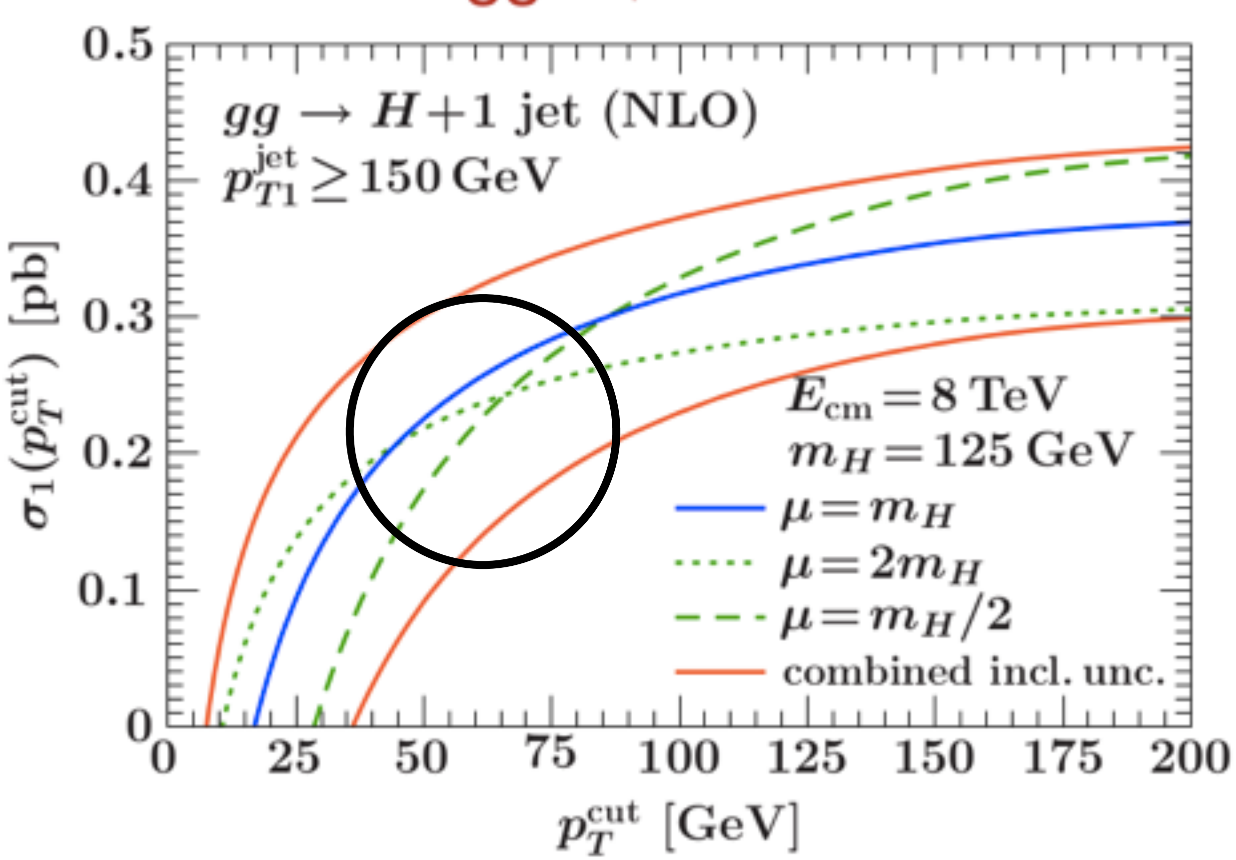
Higgs + 1 Jet



- Similar issue affects the H+1 jet bin; cross-over of scale variation bands near the experimental cut value

Cancellations

- Study of cross section structure (Stewart, Tackmann 2011)

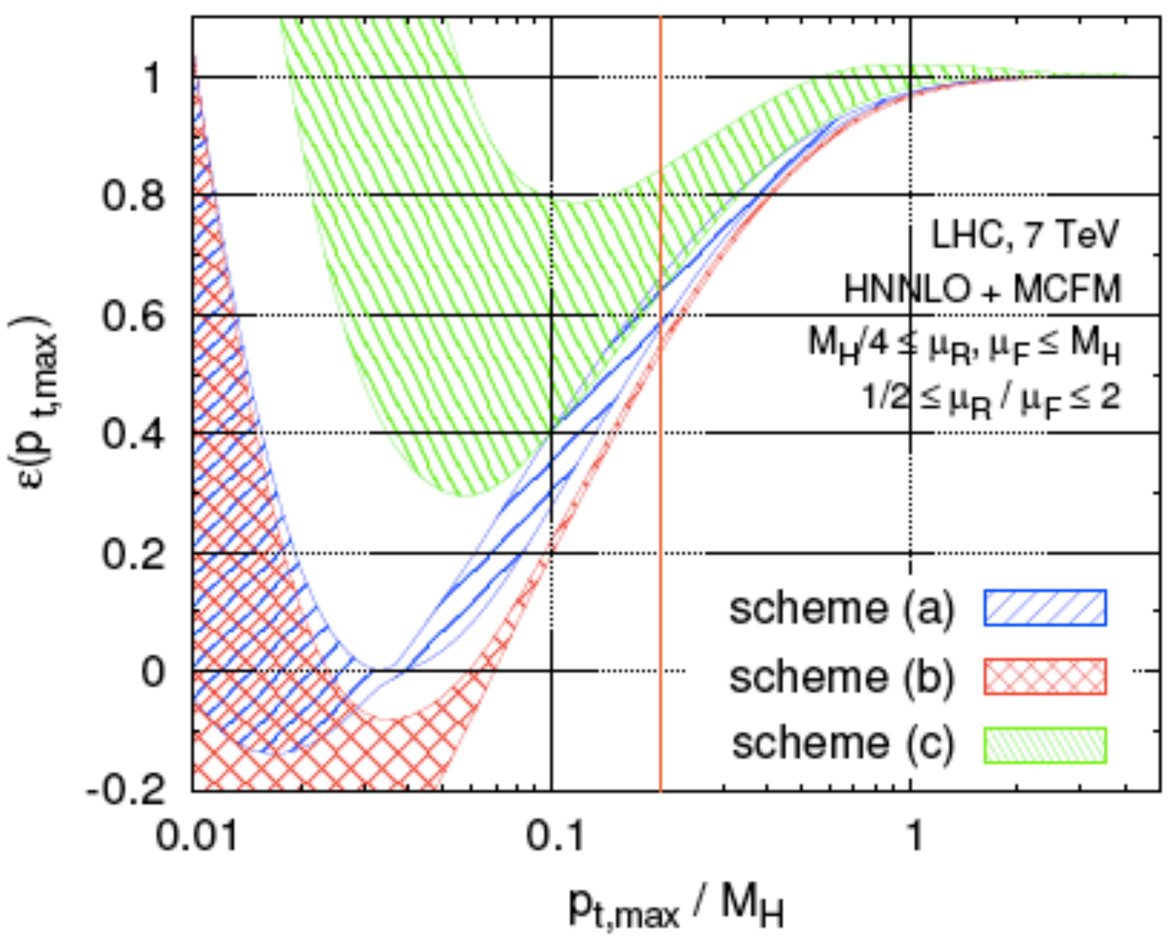
$$\sigma_0(p^{\rm cut}) = \sigma_{\rm total} - \sigma_{\geq 1}(p^{\rm cut})$$
$$\simeq \sigma_B\Big\{\big[1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)\big] - \big[\alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \mathcal{O}(\alpha_s^3 L^6)\big]\Big\}$$

$$\sigma_{\rm total} = (3.32\,{\rm pb})\big[1 + 9.5\,\alpha_s + 35\,\alpha_s^2 + \mathcal{O}(\alpha_s^3)\big]\,,$$
$$\sigma_{\geq 1}\big(p_T^{\rm jet} \geq 30\,{\rm GeV}, |\eta^{\rm jet}| \leq 3.0\big) = (3.32\,{\rm pb})\big[4.7\,\alpha_s + 26\,\alpha_s^2 + \mathcal{O}(\alpha_s^3)\big]\,.$$

- Accidental cancellation between large corrections to total cross section and logarithms, leading to reduced scale error. No reason to persist at higher orders

Explicit demonstration

- First further evidence: three ways of extending the calculation of the 0-jet event fraction that differ by $O(\alpha_S^3)$ w.r.t. leading order



Banfi, Salam, Zanderighi 2012

$$f_0^{(a)}(p_T^{\rm cut}) \equiv \frac{\Sigma^{(0)}(p_T^{\rm cut}) + \Sigma^{(1)}(p_T^{\rm cut}) + \Sigma^{(2)}(p_T^{\rm cut})}{\sigma^{(0)} + \sigma^{(1)} + \sigma^{(2)}}$$

$$f_0^{(b)}(p_T^{\rm cut}) = 1 - \frac{\sigma^{\rm NLO}_{\text{1-jet}}(p_T^{\rm cut})}{\sigma^{(0)} + \sigma^{(1)}}\,.$$

$$f_0^{(c)}(p_T^{\rm cut}) = 1 - \frac{\sigma^{\rm NLO}_{\text{1-jet}}(p_T^{\rm cut})}{\sigma^{(0)}} + \frac{\sigma^{(1)}}{(\sigma^{(0)})^2}\sigma^{\rm LO}_{\text{1-jet}}(p_T^{\rm cut})$$

- Gives results differing from 0.5 to 0.85 for a 30 GeV veto

Error prescription

- A solution using fixed-order results pointed out (Stewart, Tackmann 2011)

- In the limit of $\ln(m_H/p_{T,cut})$ large, σ_{tot} and $\sigma_{\geq 1}$ have independent expansions
- Gives expected result, that $\Delta\sigma_{veto} > \Delta\sigma_{tot}$
- The current prescription used in LHC analyses (phrased in terms of jet fractions)
- Leads to large uncertainties which limit experimental studies; any way to improve?

First consider *inclusive* jet cross sections

$$\sigma_{\rm total},\ \sigma_{\geq 1},\ \sigma_{\geq 2} \quad \Rightarrow \quad C = \begin{pmatrix} \Delta^2_{\rm total} & 0 & 0 \\ 0 & \Delta^2_{\geq 1} & 0 \\ 0 & 0 & \Delta^2_{\geq 2} \end{pmatrix}$$

Transform to *exclusive* jet cross sections

$$\sigma_0 = \sigma_{\rm total} - \sigma_{\geq 1}\,, \qquad \sigma_1 = \sigma_{\geq 1} - \sigma_{\geq 2}\,, \qquad \sigma_{\geq 2}$$

$$\Rightarrow \quad C = \begin{pmatrix} \Delta^2_{\rm total} + \Delta^2_{\geq 1} & -\Delta^2_{\geq 1} & 0 \\ -\Delta^2_{\geq 1} & \Delta^2_{\geq 1} + \Delta^2_{\geq 2} & -\Delta^2_{\geq 2} \\ 0 & -\Delta^2_{\geq 2} & \Delta^2_{\geq 2} \end{pmatrix}$$

cut	$\frac{\Delta\sigma_{\rm total}}{\sigma_{\rm total}}$	$\frac{\Delta\sigma_{\geq 1}}{\sigma_{\geq 1}}$	$\frac{\Delta\sigma_{\geq 2}}{\sigma_{\geq 2}}$	$\frac{\Delta\sigma_0}{\sigma_0}$	$\frac{\Delta\sigma_1}{\sigma_1}$
$p_T^{\rm cut} = 30\,{\rm GeV},\ \eta^{\rm cut} = 3$	10%	21%	45%	17%	29%

Resummation

- Significant recent efforts toward resumming logarithms associated with the jet veto

  H+0 jets through NNLL Banfi, Salam, Zanderighi, Monni; Becher, Neubert 2012

  'Clustering log' effects on H+0 jets Tackmann, Walsh, Zuberi 2012

  H+1 jet through NLL X. Liu, FP 2012

$$
\begin{aligned}
\sigma(p_T^{\text{cut}}) \quad &\sim \quad 1 \\
&+ \quad \alpha_s L^2 + \alpha_s L \; + \alpha_s \quad \textbf{NLO} \\
&+ \quad \alpha_s^2 L^4 + \alpha_s^2 L^3 + \alpha_s^2 L^2 + \alpha_s^2 L \; + \alpha_s^2 \quad \textbf{NNLO} \\
&+ \quad \alpha_s^3 L^6 + \alpha_s^3 L^5 + \alpha_s^3 L^4 + \alpha_s^3 L^3 + \alpha_s^3 L^2 + \cdots \\
& \qquad \textbf{LL} \qquad \textbf{NLL} \qquad \textbf{NNLL}
\end{aligned}
$$

$$L \equiv \ln \frac{p_T^{\text{cut}}}{m_H}$$

from S. Zuberi

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- Distance measures for H+1 jet, anti-k_T algortihm:

$$\rho_{ij} = \min(p_{T,i}^{-1}, p_{T,j}^{-1})\Delta R_{ij}/R,$$
$$\rho_i = p_{T,i}^{-1}.$$

$$\lambda \equiv p_T^{veto}/\sqrt{\hat{s}} \ll 1$$

$$\rho_{JJ} \lesssim \rho_J \sim 1\,, \quad \rho_{Js} \sim R^{-1}\,, \quad \rho_{Ja} \sim \rho_{Jb} \sim R^{-1}\log\lambda^{-1}\,,$$
$$\rho_{ss} \sim \rho_{aa} \sim \rho_{bb} \sim (\lambda R)^{-1}\,, \quad \rho_{sa} \sim \rho_{sb} \sim \rho_{ab} \sim (\lambda R)^{-1}\log\lambda^{-1}\,,$$
$$\rho_s \sim \rho_a \sim \rho_b \sim \lambda^{-1}\,.$$

R~0.4, λ~0.2

EFT approach (Becher, Neubert)

$p_s \sim m_H(\lambda,\lambda,\lambda)$

$p_{a,b} \sim m_H(\lambda^2,1,\lambda)$

$p_J \sim m_H(\lambda^2,1,\lambda)$ (along jet direction)

Radiation along the jet direction is combined first into a single state; soft radiation insensitive to details of collinear radiation

Resummation

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Soft and collinear radiation clustered separately

Resummation

- Significant recent efforts toward resumming logarithms associated with the jet veto

  H+0 jets through NNLL Banfi, Salam, Zanderighi, Monni; Becher, Neubert 2012

  'Clustering log' effects on H+0 jets Tackmann, Walsh, Zuberi 2012

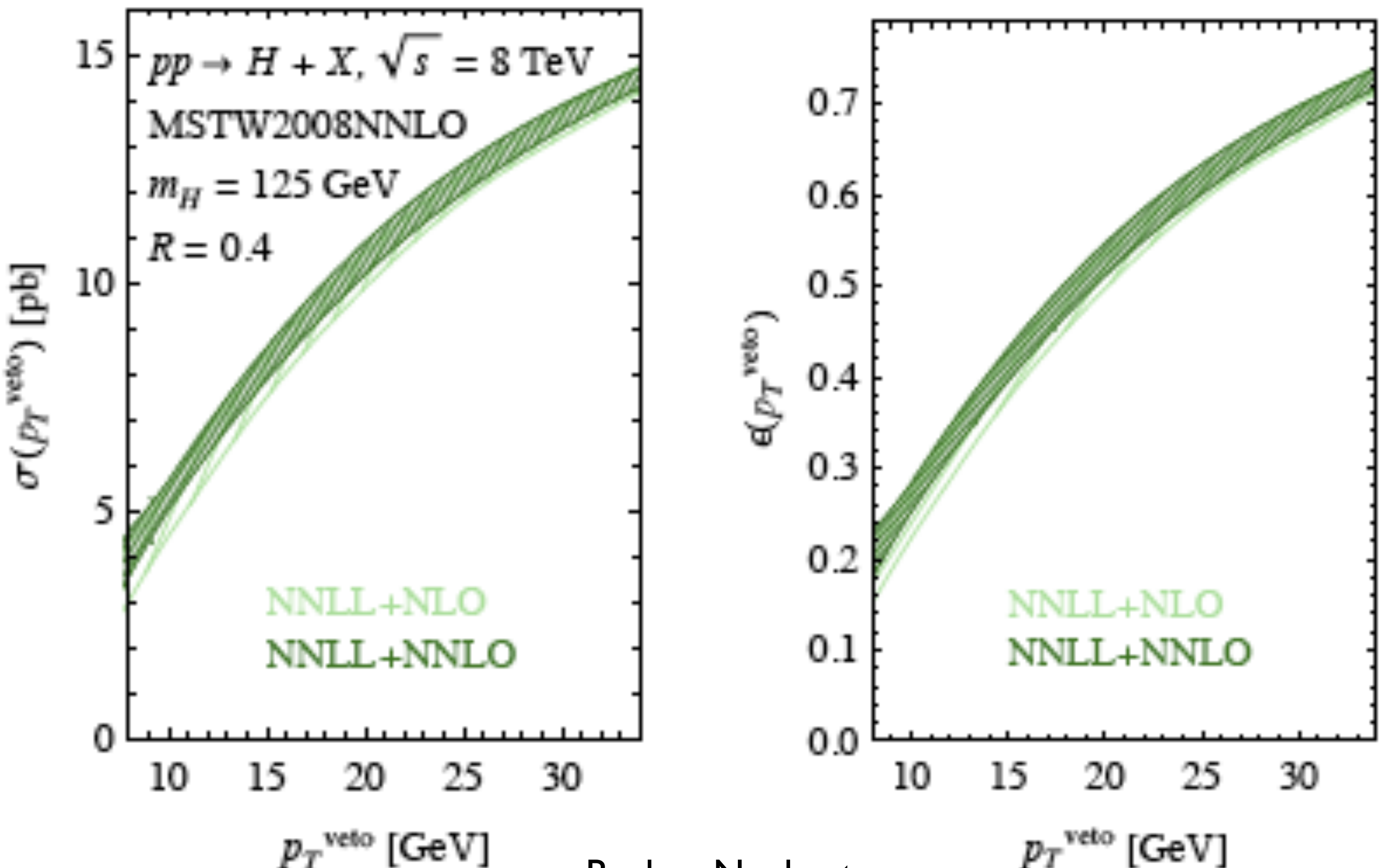
  H+1 (or more) jets through NLL X. Liu, FP 2012

- Can factorize radiation from soft, collinear, beam directions to establish the result:

$$\sigma(p_T^{\mathrm{cut}}) \sim H_{gg}(\mu)[B_a(\mu,\nu) \times B_b(\mu,\nu) \times S(\mu,\nu)] + \sigma_{ns} \qquad \text{(0-jet)}$$

$$\begin{aligned} d\sigma &= d\Phi_{H_c} d\Phi_{J_i} \mathcal{F}(\Phi_{H_c}, \Phi_{J_i}) \sum_{a,b} \int dx_a dx_b \frac{1}{2\hat{s}} (2\pi)^4 \delta^4\left(q_a + q_b - \sum_i^n q_{J_i} - \sum_c q_{H_c} \right) \\ &\times \sum_{\mathrm{spin}} \sum_{\mathrm{color}} \mathrm{Tr}(H \cdot S) \mathcal{I}_{a,i_a j_a} \otimes f_{j_a}(x_a) \mathcal{I}_{b,i_b j_b} \otimes f_{j_b}(x_b) \prod_i^n J_{J_i}(R), \end{aligned} \qquad \text{(H+n-jets)}$$

Numerical results, 0 jets



Becher, Neubert

Uncertainties from varying all scales separately and adding in quadrature

Numerical results, 0 jets

- Central value: scheme (a) with

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

- μ_R and μ_F variations

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

- Resummation scale (Q) variation

i.e.

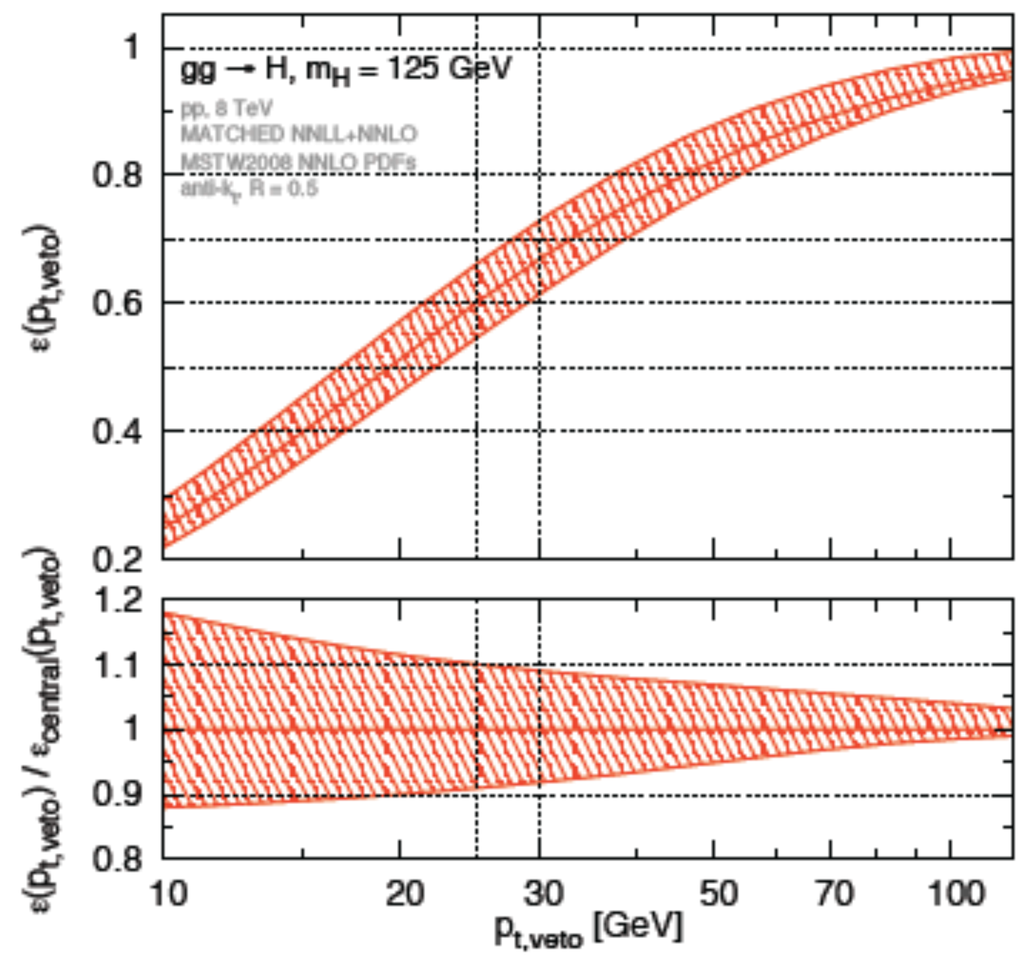
$$\ln \frac{M}{p_{t,veto}} \to \ln \frac{Q}{p_{t,veto}}$$

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

- Scheme (b) and (c) with

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

- Total uncertainty $\longleftrightarrow$ envelope



From P. Monni

Banfi, Monni, Salam, Zanderighi

Numerical results, 0 jets

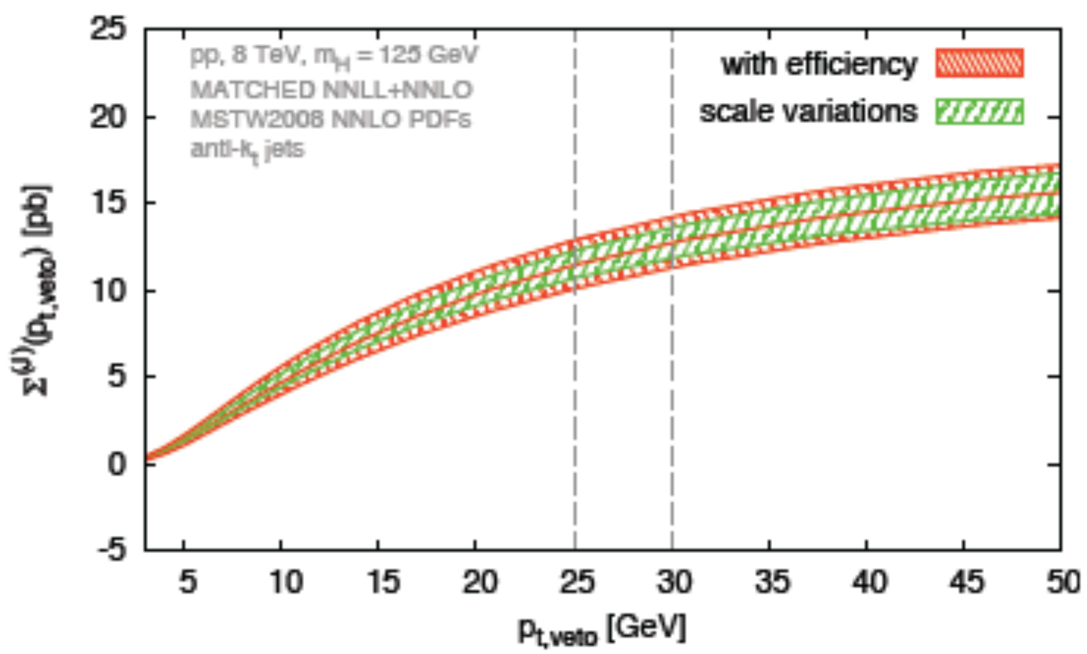
- Using jet-veto efficiencies to estimate the uncertainty @ NNLL+NNLO

- μ_R, μ_F and Q variations (green)

$$\delta_{\Sigma(J)} = 9\%$$

- With efficiencies (red)

$$\delta_{\Sigma(J)} = 11.5\%$$



From P. Monni

Banfi, Monni, Salam, Zanderighi

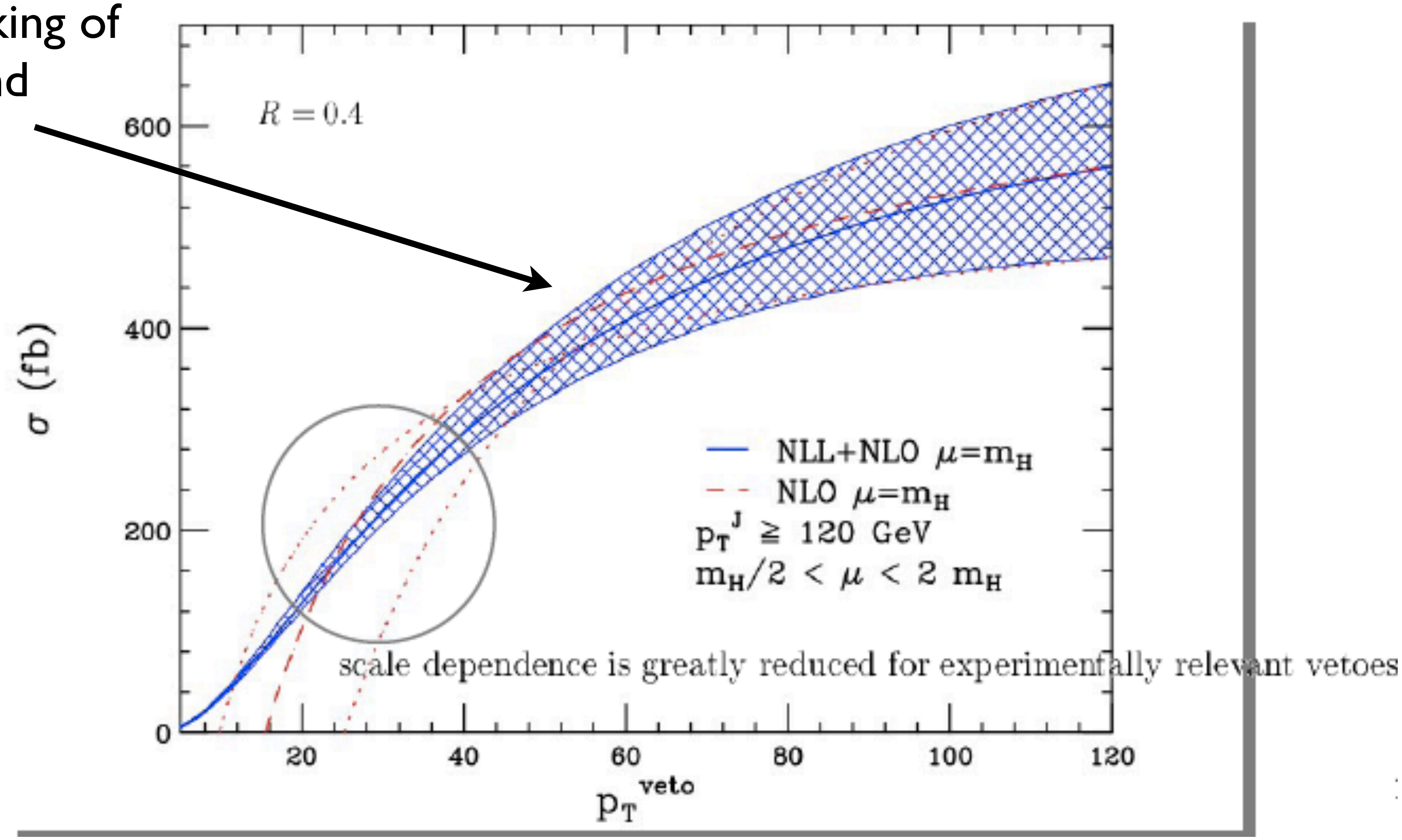
At fixed-order:

$$\delta_{\Sigma(J)} = 16.2\%$$

consistent with Stewart-Tackmann
in the region
$25\text{GeV} \leq p_{\text{t,veto}} \leq 30\text{GeV}$

Numerical results, 1 jet

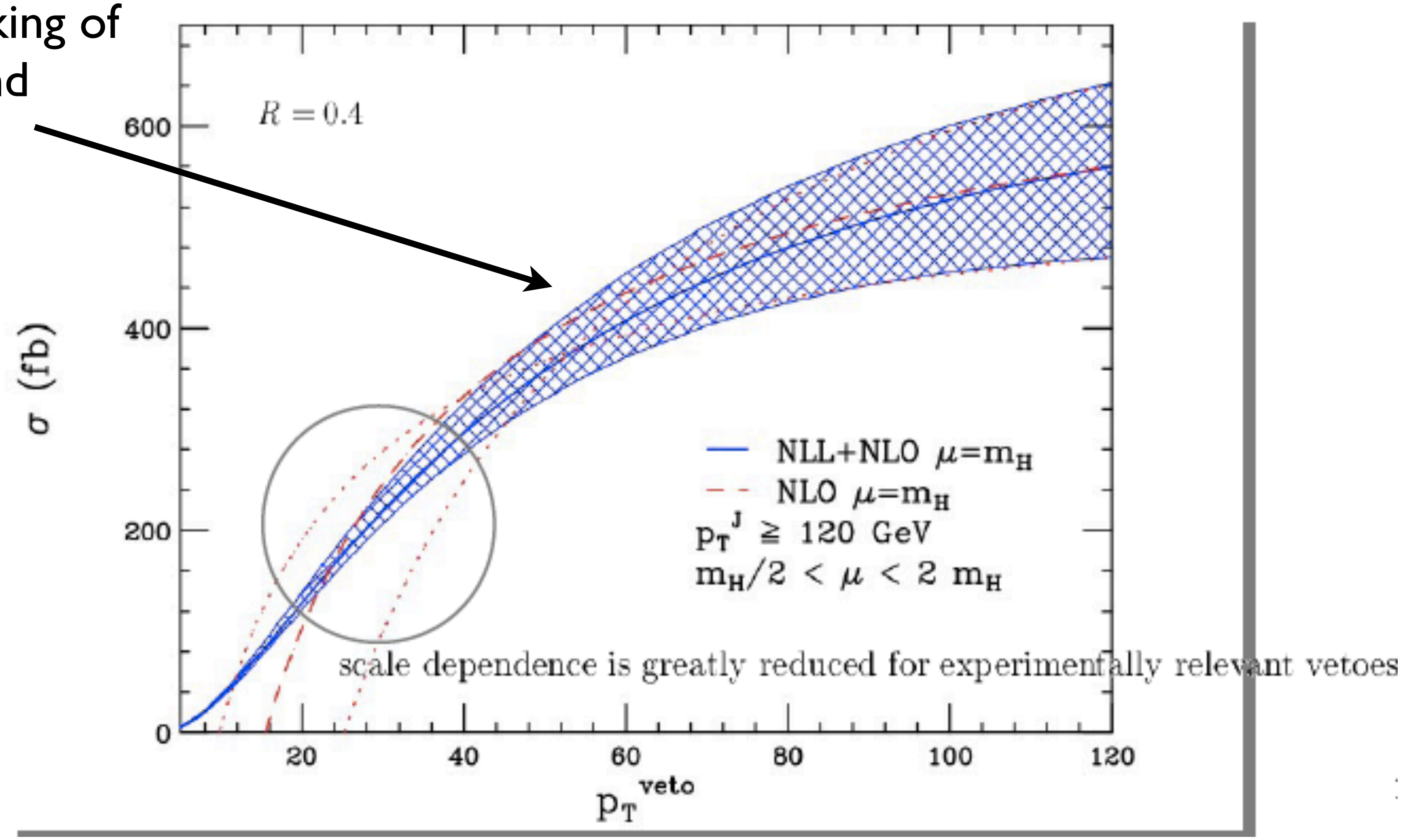
No artificial shrinking of scale-variation band



X. Liu, FP

Numerical results, 1 jet

No artificial shrinking of scale-variation band



X. Liu, FP

- Region where $p_{TJ} \gg p_{T,veto}$ accounts for between 30-50% of the spectrum; for $p_{TJ} \sim p_{T,veto}$ need new EFT with only soft+beam emissions

R dependence

- There is only a narrow window of parameter space where the resummation holds

$R \gg p_T^{cut}/m_H \quad \sigma \supset \alpha_s^n R^2$

Soft-collinear mixing.

$R \sim p_T^{cut}/m_H \quad \sigma \supset \alpha_s^n \ln^{n-1} R$

Clustering logarithms.

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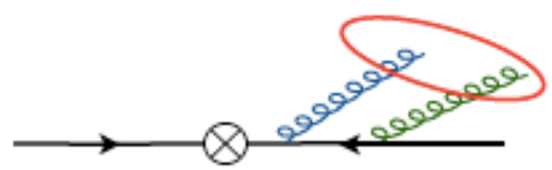

$$\delta\sigma_{SC} = -\sigma_{LO}\left(\frac{\alpha_s C_A}{\pi}\right)^2 \frac{2\pi^2}{3} R^2 \ln\frac{m_H}{p_T^{cut}}$$

From S. Zuberi

Tackmann, Walsh, Zuberi

Phenomenologically, R~0.4, $p_{T,veto}/m_H$~0.2→not the relevant limit

R dependence

- There is only a narrow window of parameter space where the resummation holds

$R \gg p_T^{cut}/m_H \quad \sigma \supset \alpha_s^n R^2$

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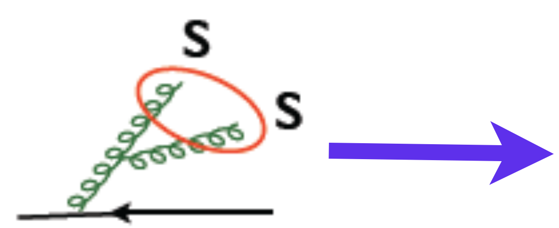


$$\frac{1}{\epsilon} \quad - \quad \frac{1}{\epsilon} R^{-2\epsilon} \sim \ln R$$

From S. Zuberi

Tackmann, Walsh, Zuberi

R dependence

- There is not a large window of parameter space where the resummation holds

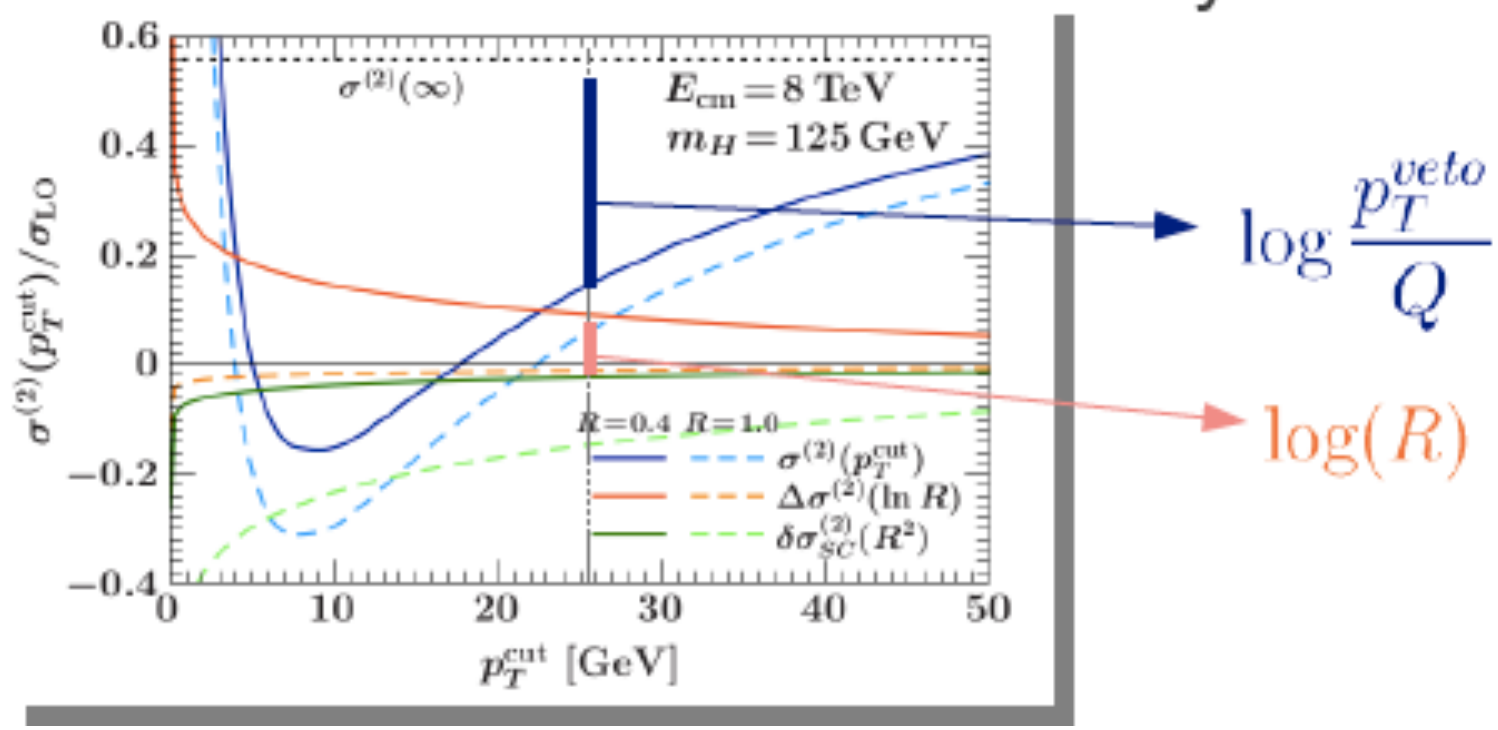
$R \gg p_T^{cut}/m_H \quad \sigma \supset \alpha_s^n R^2$

Soft-collinear mixing.

$R \sim p_T^{cut}/m_H \quad \sigma \supset \alpha_s^n \ln^{n-1} R$

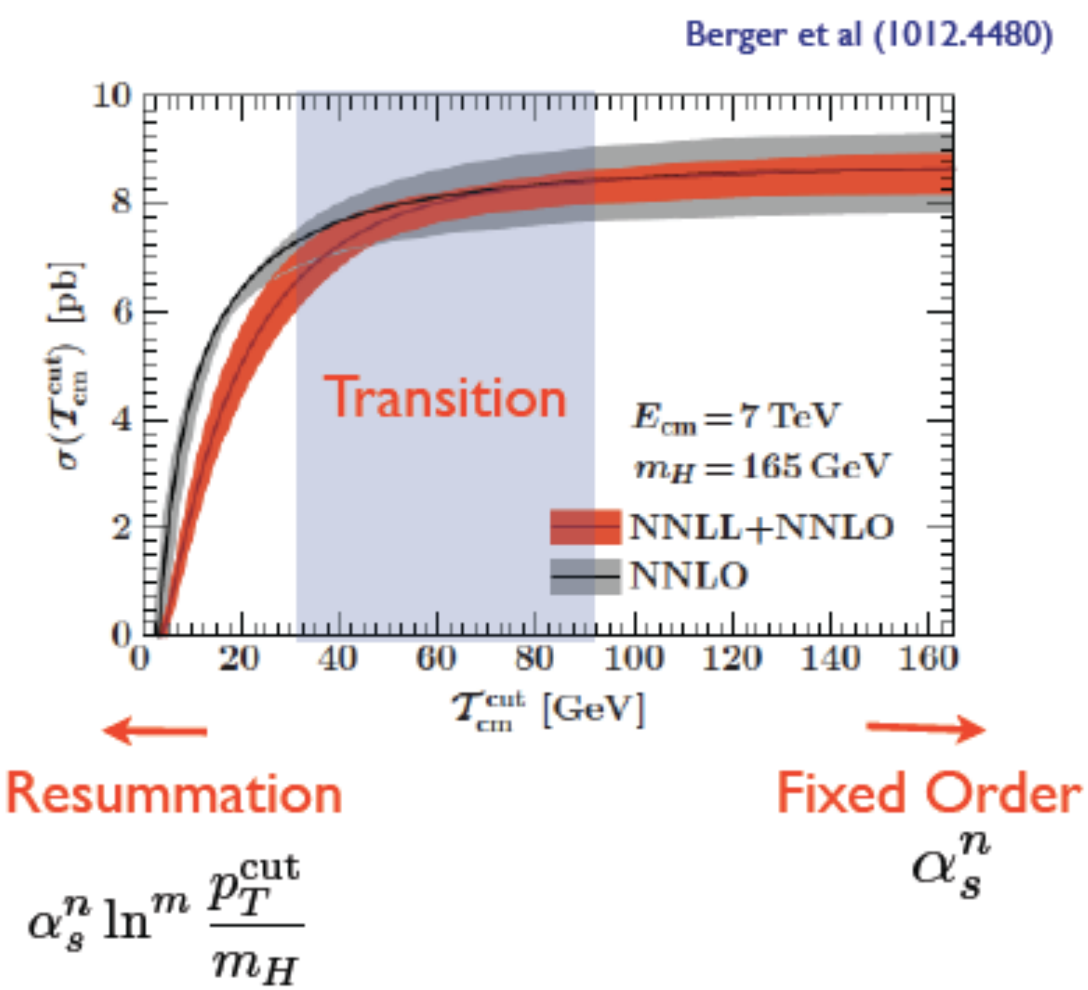
Clustering logarithms.

Moderate and well controlled for experimentally interesting R



Status

- Formalism well established for H+0 jet, 1-jet cross sections; some differences in how uncertainties are estimated by the various groups, more EFT development for the entire 1-jet bin spectrum
- A reduction of uncertainty from the current fixed-order estimates used, and experimentalists should stay tuned for updates



- The interesting region isn't dominated by either the resummation or the fixed-order results... progress on extending both frameworks needed
- Next steps: $\alpha_s^3 \ln^2 R \ln \lambda$ clustering terms
Tackmann, Walsh, Zuberi
- H+1 jet at NNLO Boughezal, Caola, Melnikov, FP, Schulze