Theoretical uncertainties on cross sections in jet bins

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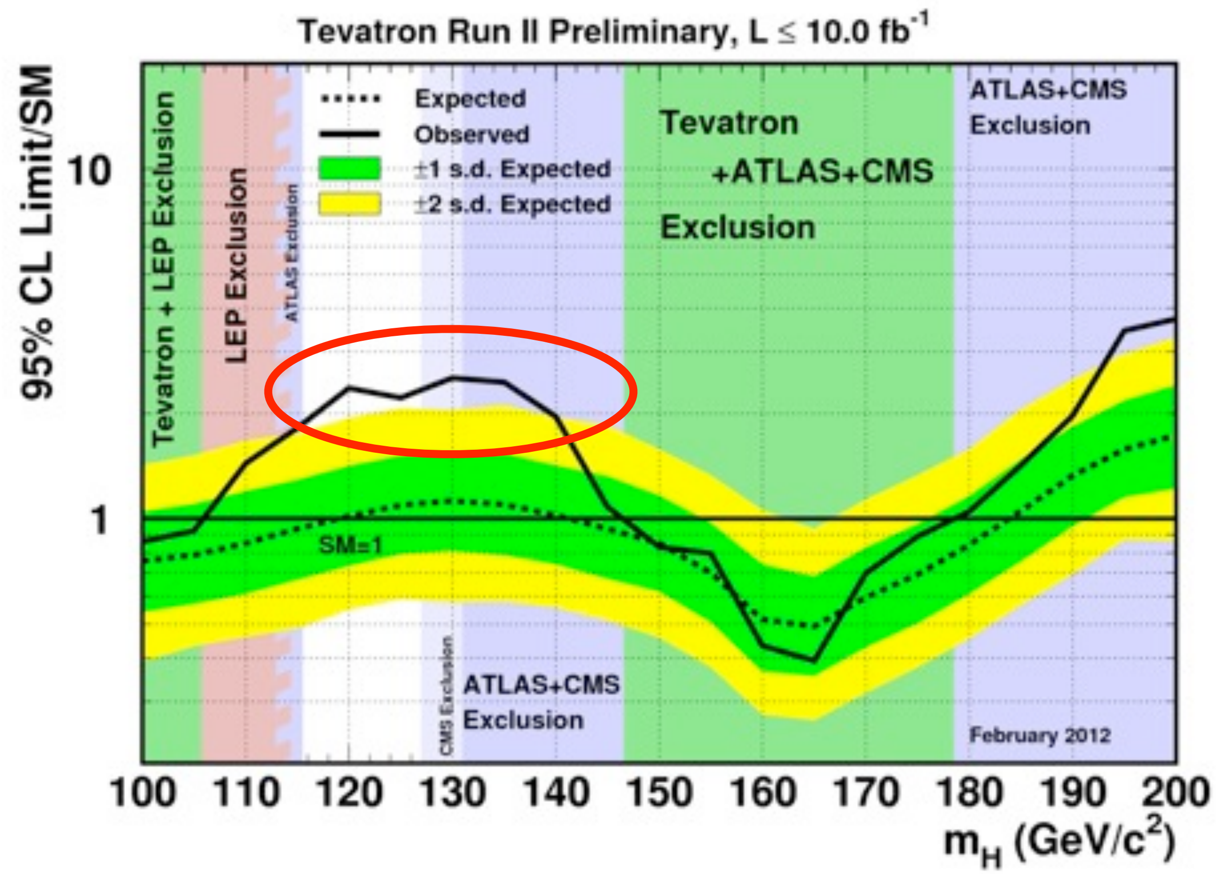
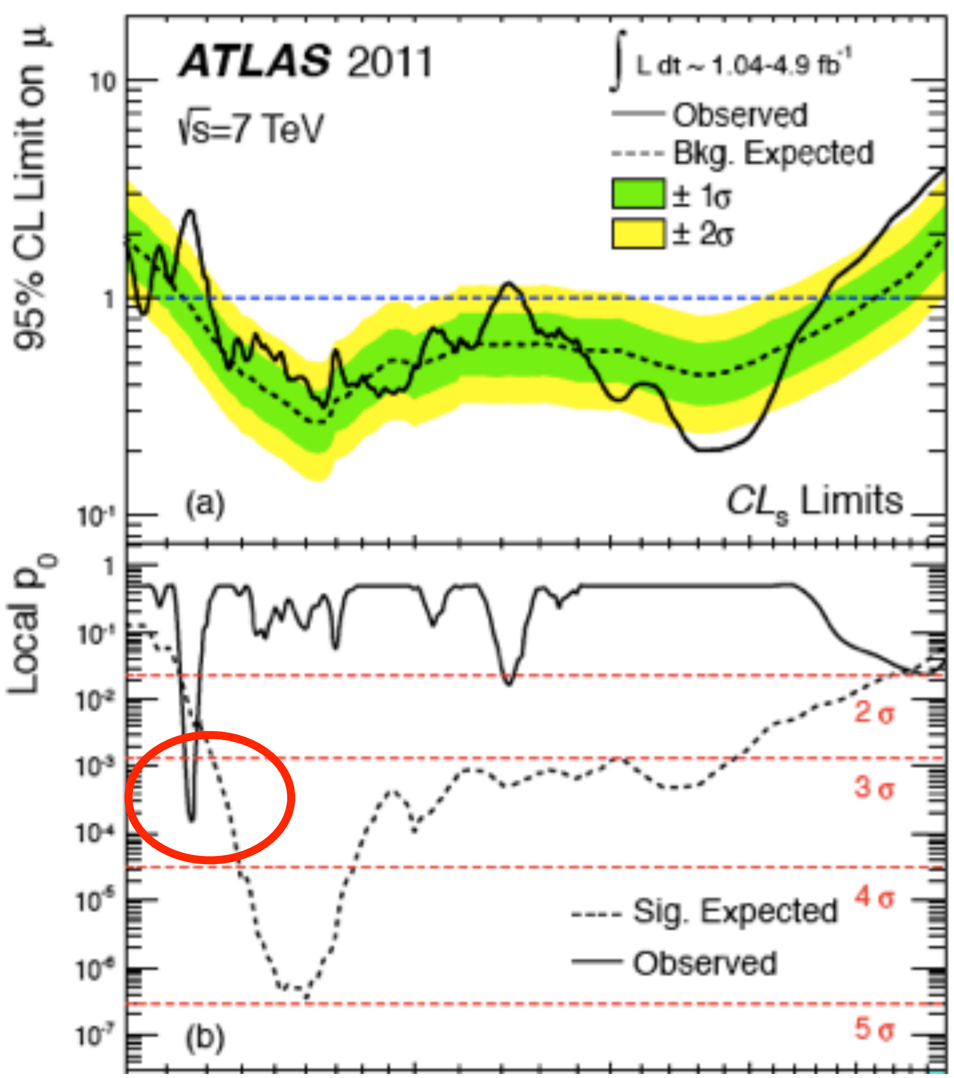
Outline

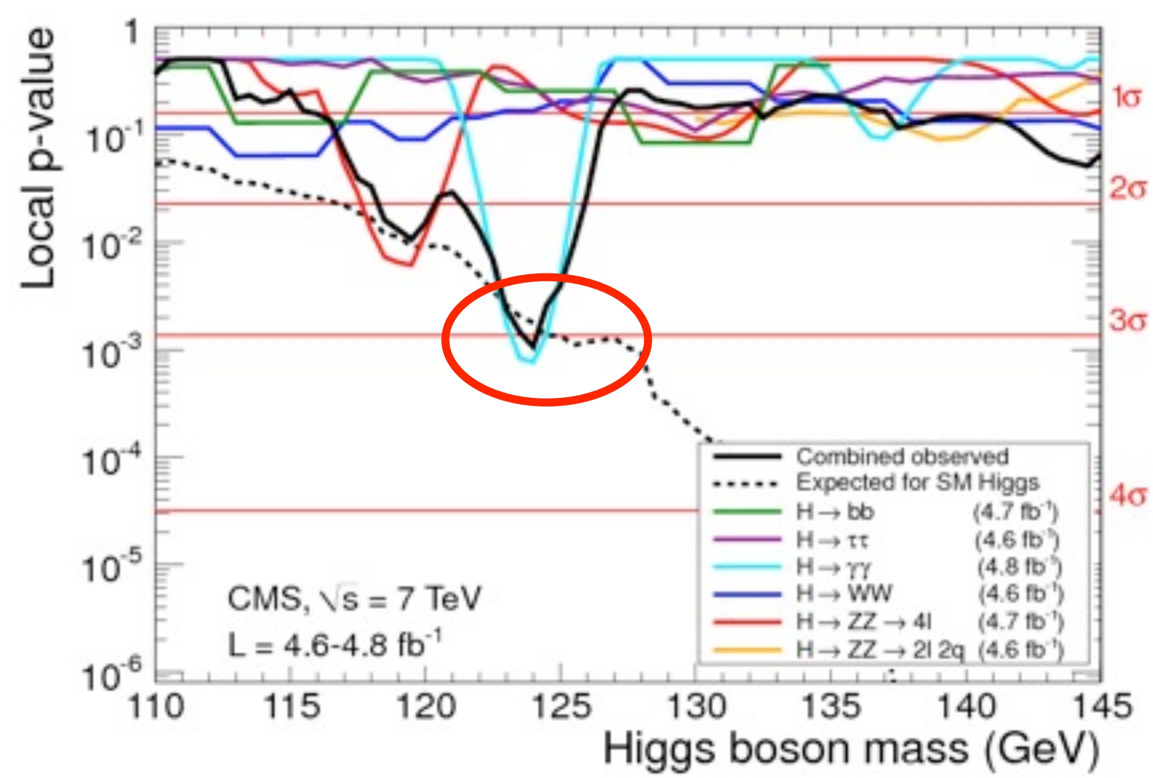
- Will focus on Higgs as an example of a search needing jet vetos
- Intro: why are jet vetos needed and dangerous
- Past ways for estimating theoretical uncertainties
- New calculations and results

The Higgs search today

- Tevatron excess driven by bbar channel
- LHC primarily γγ



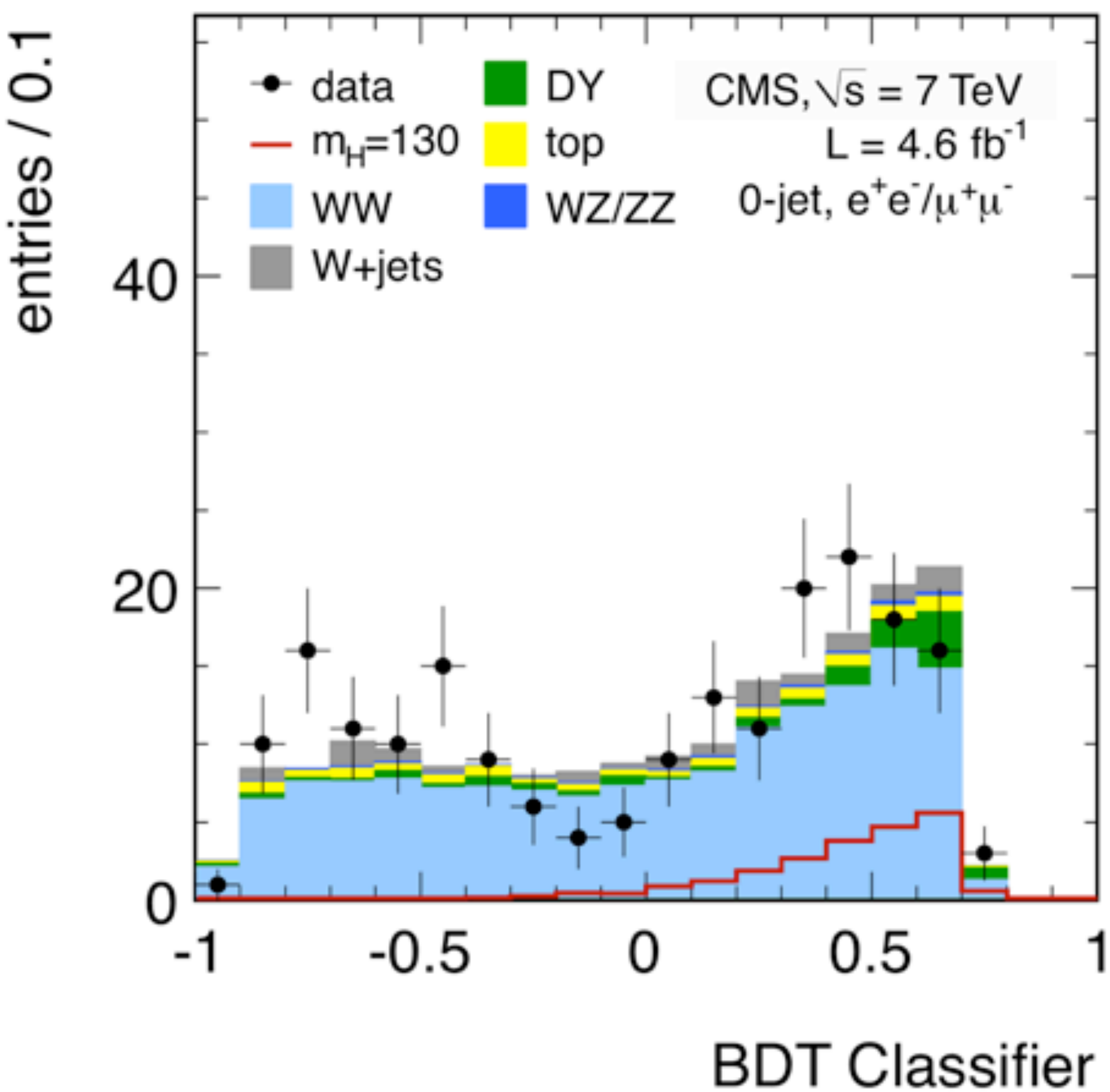




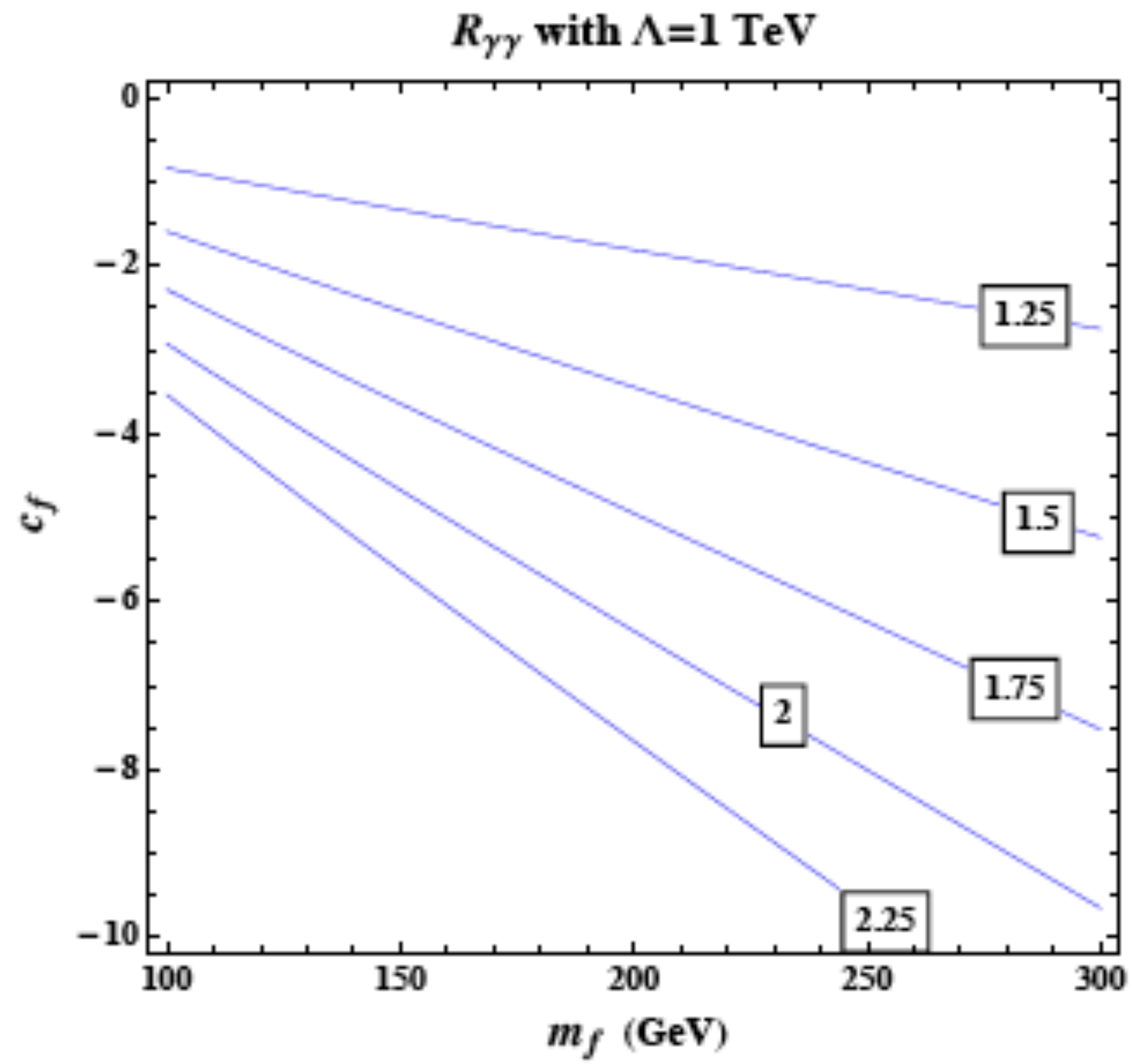
Theoretical uncertainties on cross sections in jet bins

F. Petriello

The need for accurate theory



Discovery is not a simple peak in many channels; detailed knowledge of signal shape desirable



(Carena, Low, Wagner; from C. Wagner, MCTP 2012)

Precision measurement of Higgs properties will be critical in mapping out underlying theory

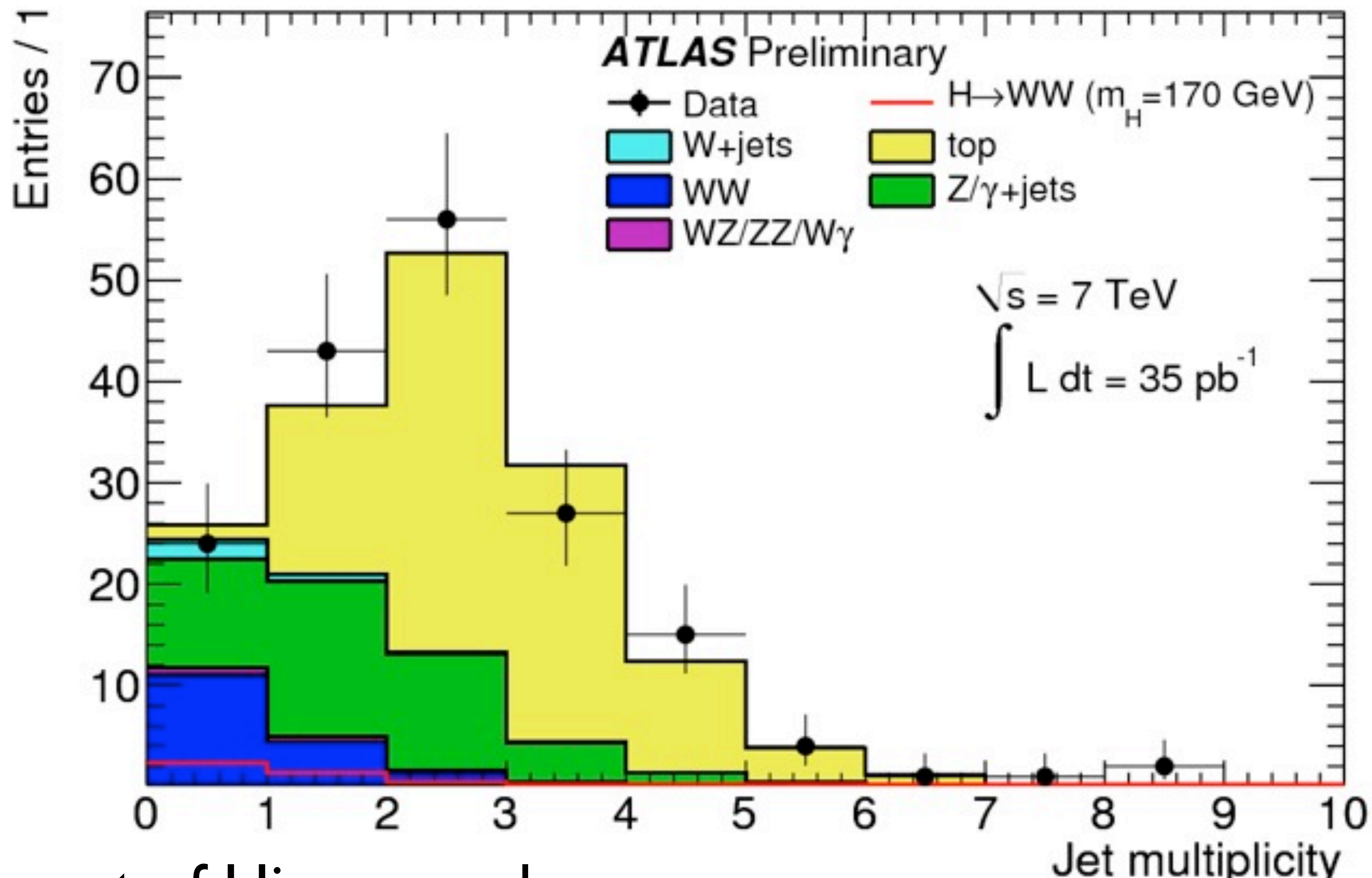
Effects of theory uncertainties

- 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 ($\gamma\gamma$): 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	$\pm 3.7\,\%$, $\pm 4.5\,\%$

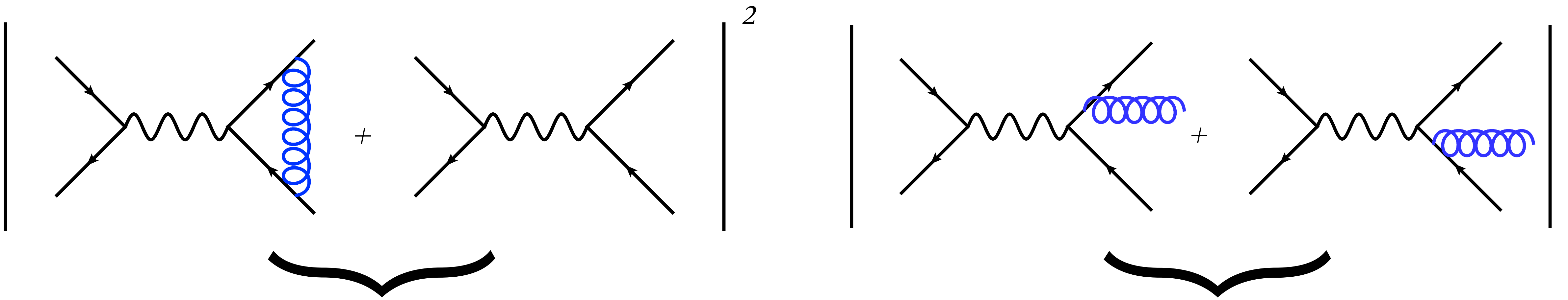
Why jet vetoes?



- Vital component of Higgs searches
- Required in WW channel due to background composition
- 0,1-jet bins WW continuum
- 2-jet bin ttbar
- 25 GeV (ATLAS) or 30 GeV jet cut (CMS)

Why are jet vetoes dangerous?

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



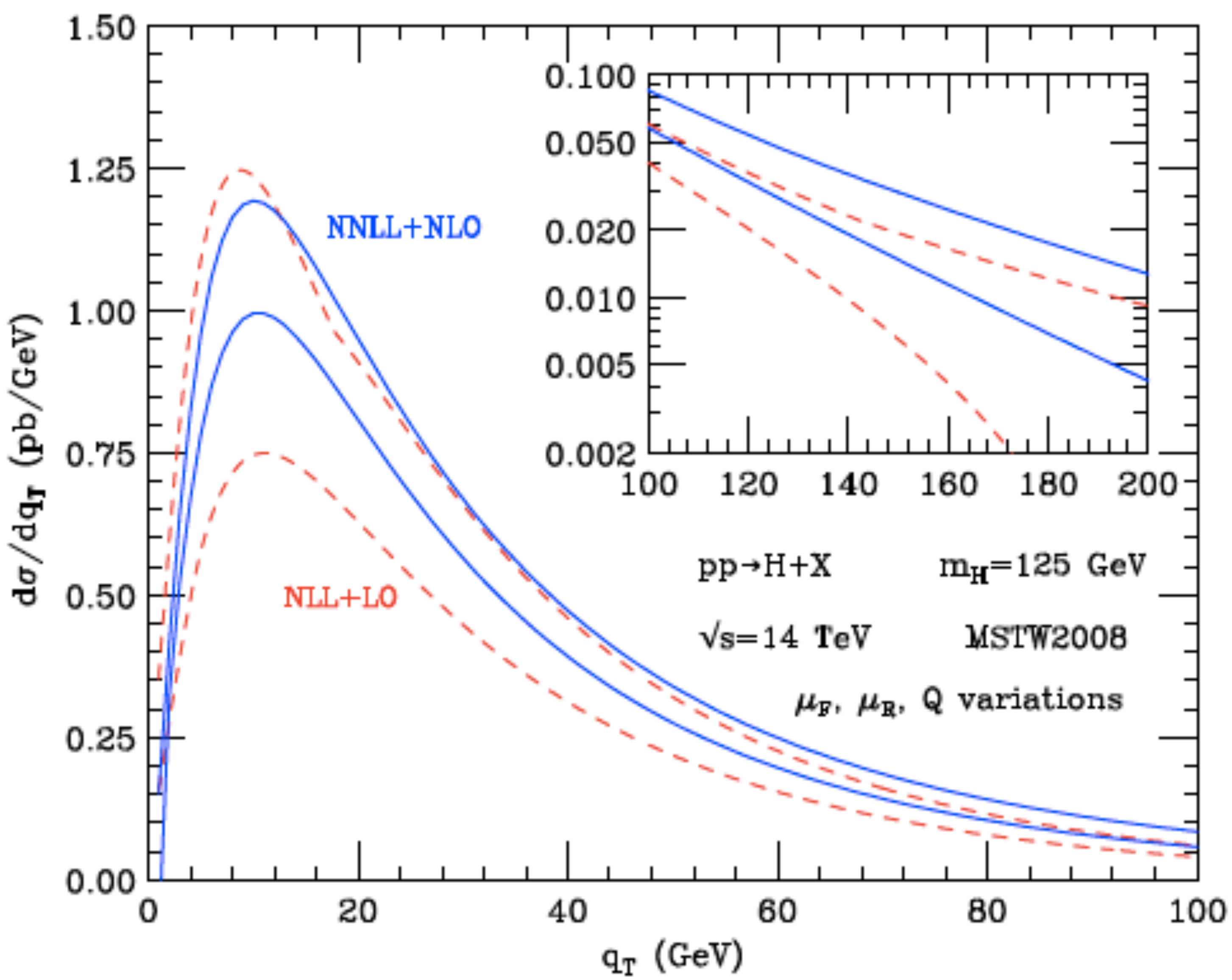
Virtual corrections: $-1/\varepsilon_{IR}$

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

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

Other variables

- The jet-vetoed cross section dependence on the jet algorithms makes it difficult to study with standard analytic resummation techniques
- Often rely on other, simpler variables which behave similarly for intuition



- p_T of the Higgs is the same as a jet veto through relative order $O(\alpha_S)$
- Known to NNLL+NLO in HqT

de Florian, Ferrera, Grazzini, Tommasini 2011

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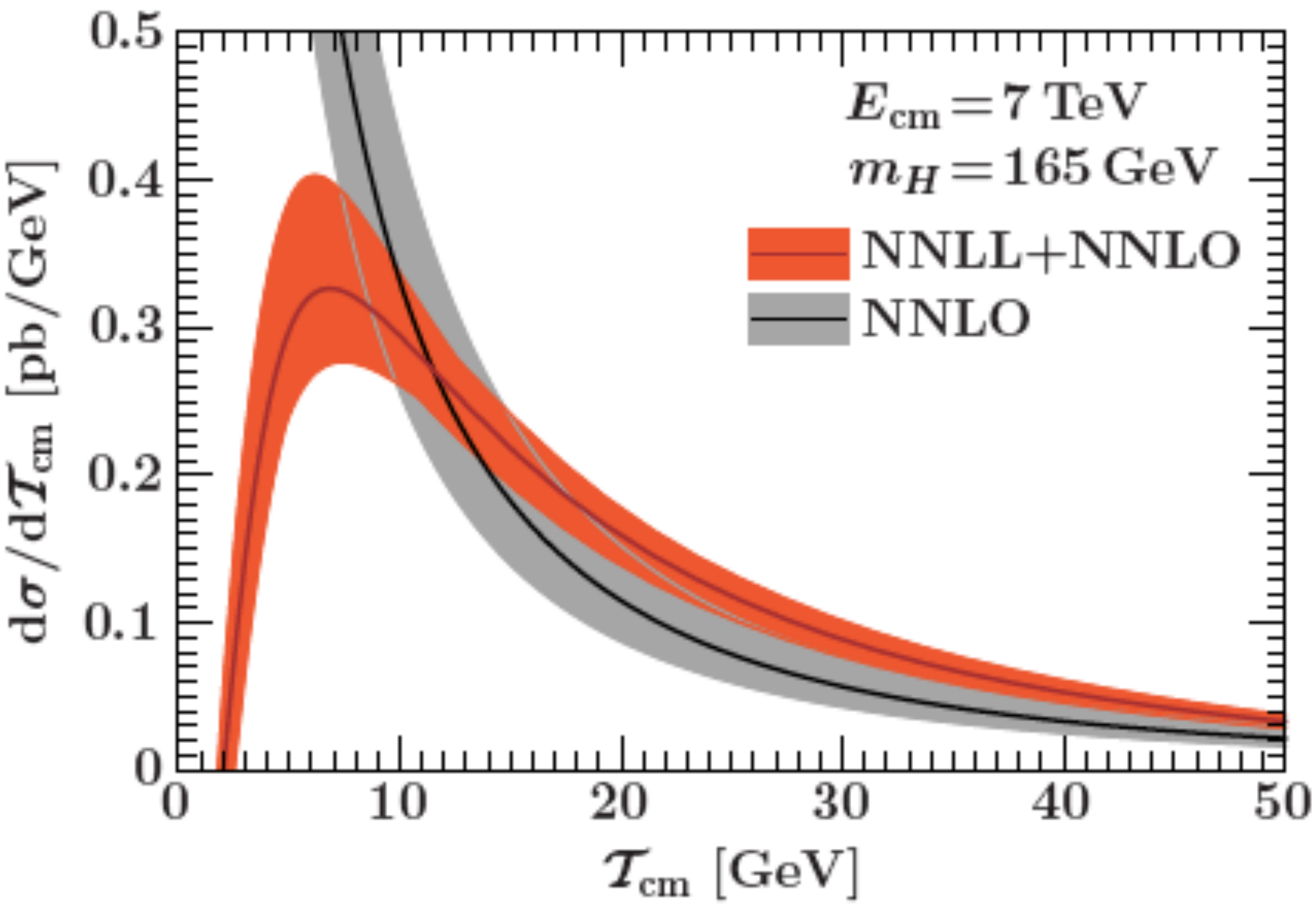
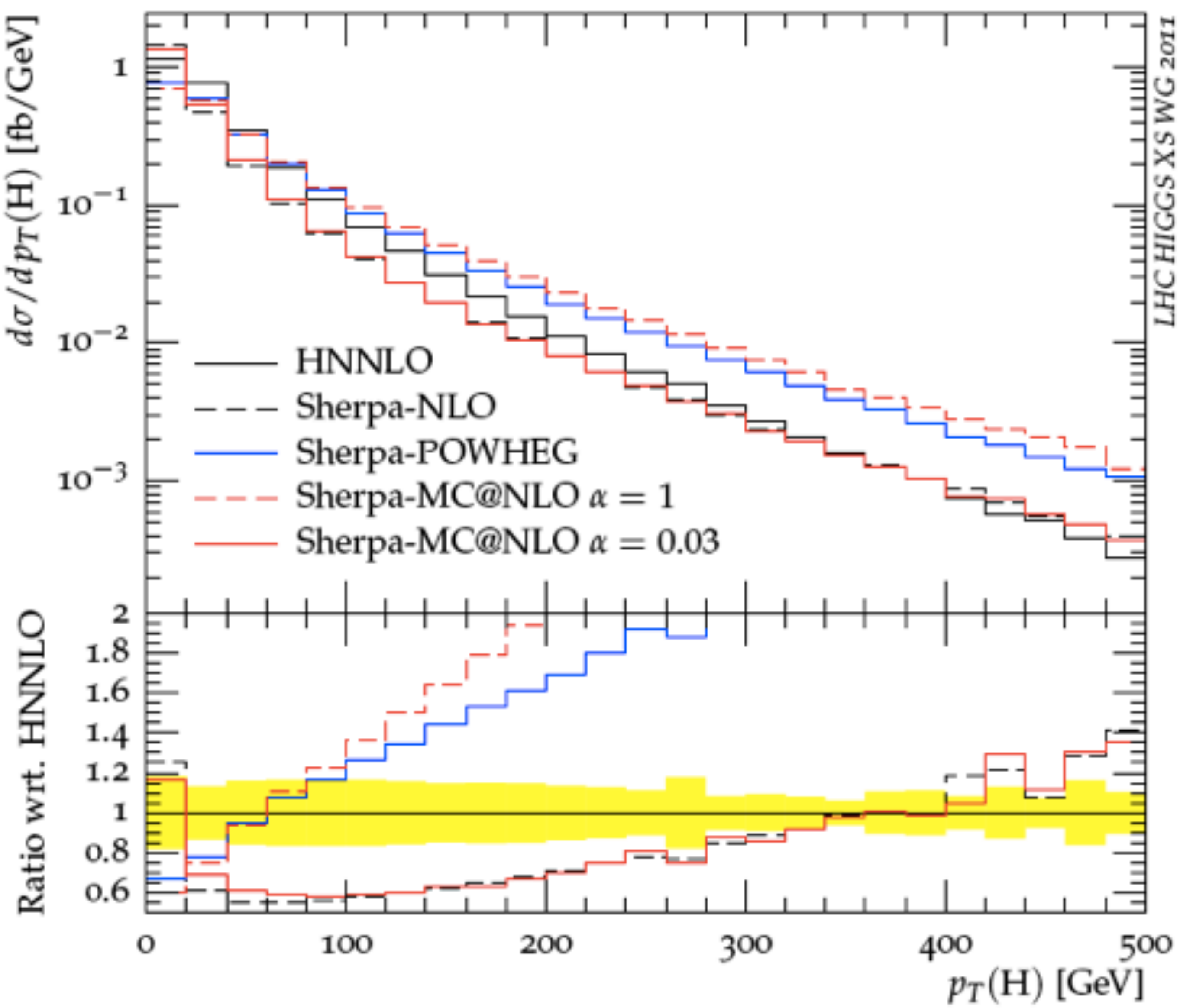


$$\mathcal{T}_{cm} = \sum_k |\vec{p}_{kT}|\, e^{-|\eta_k|}$$

- Beam thrust qualitatively similar in that it vetoes hard, central jets
- Known to NNLL Berger, Marcantonini, Stewart, Tackmann, Waalewijn 2010

Standard tools

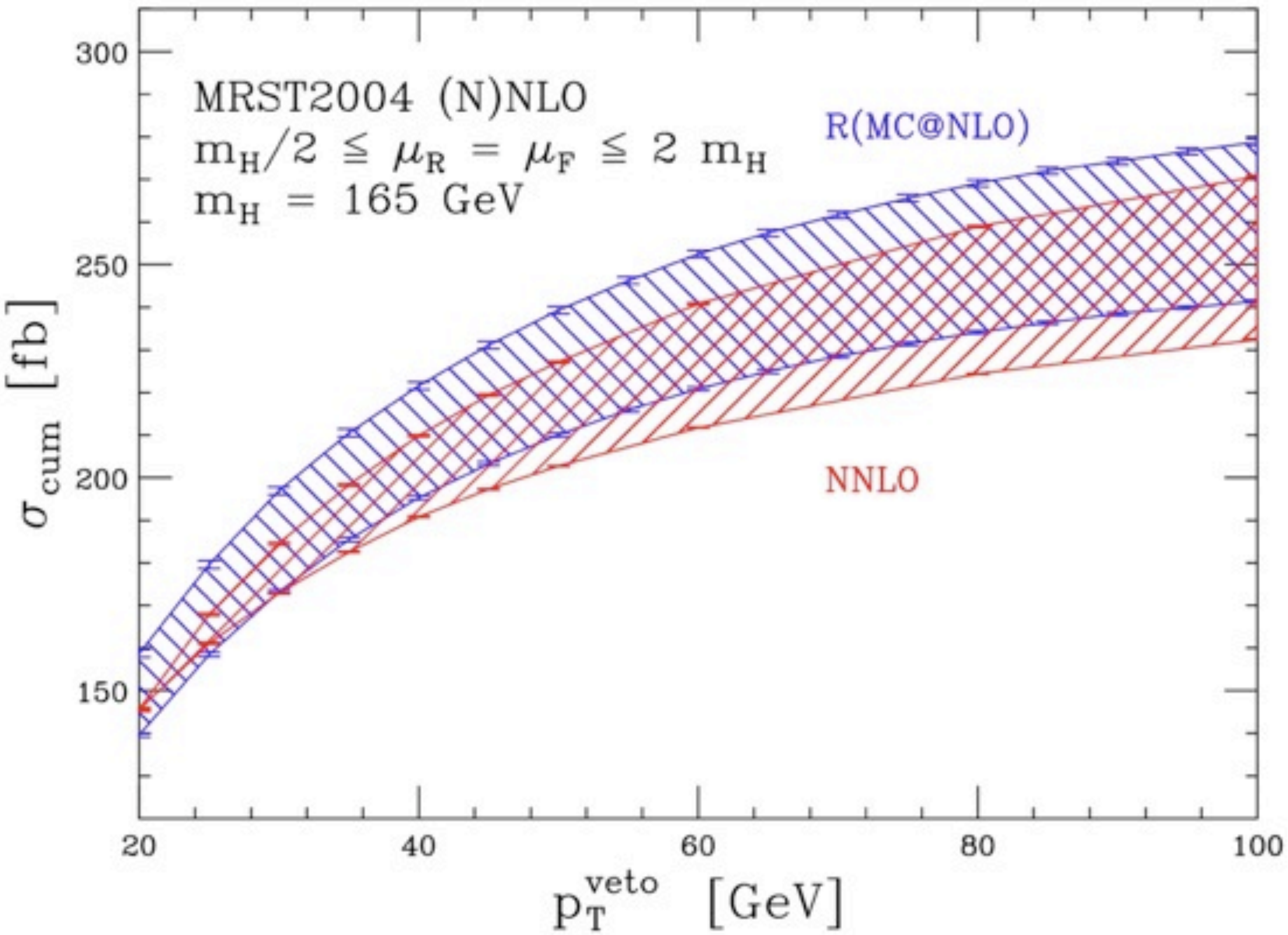
- Experimental studies typically use NLO+PS tools such as POWHEG or MC@NLO to get efficiencies for jet bins
- These can have very large uncertainties for exactly the interesting variables



Grazzini, Hoeth, Krauss, FP, Schoenherr, Siegert 2012

- What exactly is stuck up in the exponent in the various codes modifies the pT spectrum
- Matching to HqT needed to ameliorate these differences
- Furthermore, often rely on fixed-order QCD to estimate theoretical error (argued in literature that 25-30 GeV suitably described by fixed-order)

Fixed-order scale variation



Anastasiou, Dissertori, Stoeckli, Webber 2008

- 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

Cancellations

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

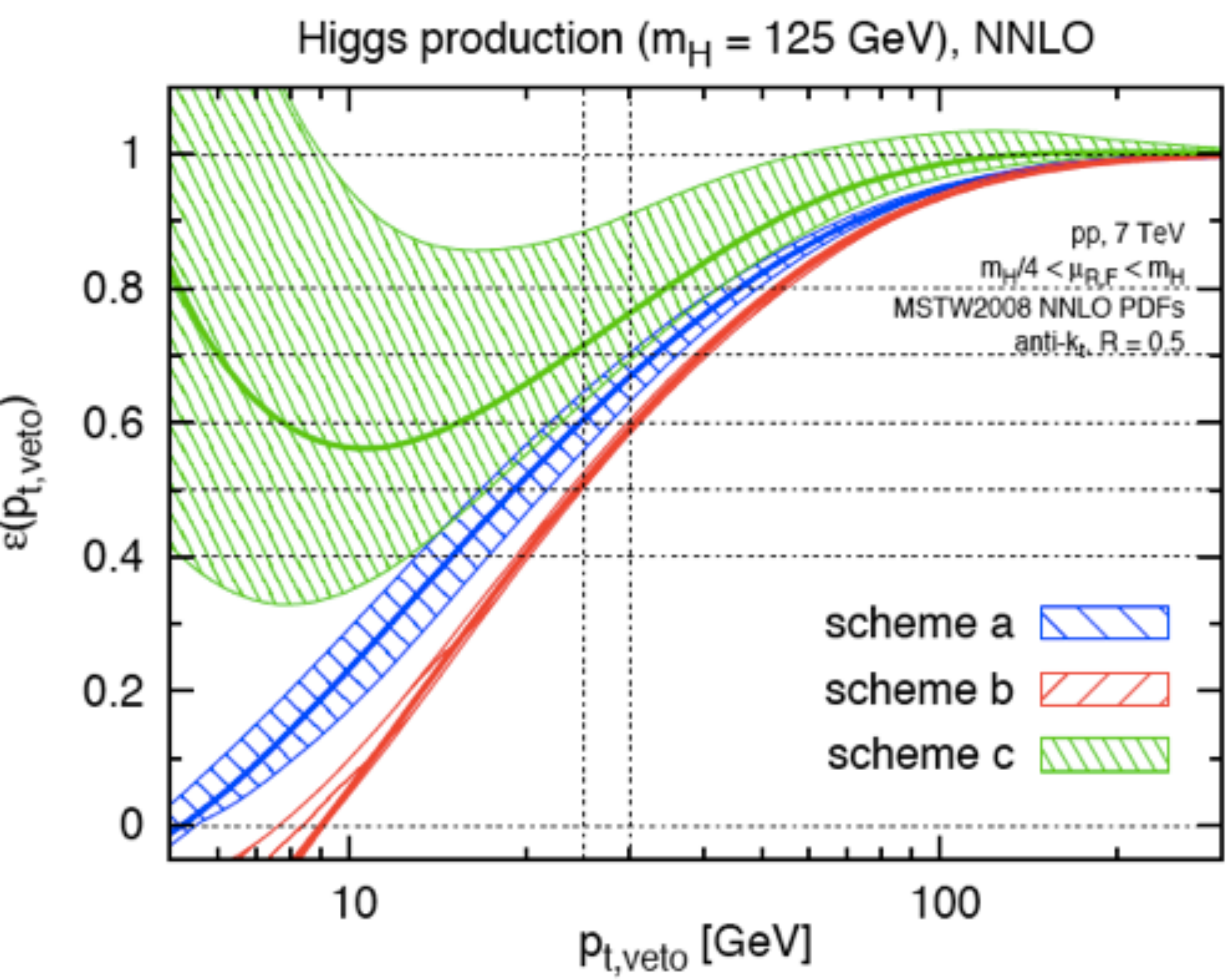
$$\sigma_0(p^{\mathrm{cut}}) = \sigma_{\mathrm{total}} - \sigma_{\geq 1}(p^{\mathrm{cut}})$$
$$\simeq \sigma_B\Big\{\big[1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)\big] - \big[\alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \mathcal{O}(\alpha_s^3 L^6)\big]\Big\}$$

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

- Jet-vetoed cross section is the difference between two cross sections with large corrections ($C_A\pi^2$ and threshold logs for inclusive, jet-veto logs for $\sigma_{\geq 1}$)
- 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

- 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

$$\epsilon^{(a)}(p_{t,\text{veto}}) \equiv \frac{\Sigma_0(p_{t,\text{veto}}) + \Sigma_1(p_{t,\text{veto}}) + \Sigma_2(p_{t,\text{veto}})}{\sigma_0 + \sigma_1 + \sigma_2}$$

(keep all known terms in top and bottom)

$$\epsilon(p_{t,\text{veto}}) = 1 - \frac{\sigma^{\text{NLO}}_{\text{1-jet}}(p_{t,\text{veto}})}{\sigma_0 + \sigma_1}$$

(perturbative series for jet-vetoed results really begins at relative $O(\alpha_S)$ w.r.t. inclusive)

$$\epsilon^{(c)}(p_{t,\text{veto}}) \equiv 1 + \frac{\bar{\Sigma}_1(p_{t,\text{veto}})}{\sigma_0} + \left(\frac{\bar{\Sigma}_2(p_{t,\text{veto}})}{\sigma_0} - \frac{\sigma_1}{\sigma_0^2}\bar{\Sigma}_1(p_{t,\text{veto}})\right)$$

(strict expansion to $O(\alpha_S^2)$)

- Give results differing from 0.5 to 0.85 for a 25-30 GeV cuts

Error prescription

- A solution to better estimate error 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)

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

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

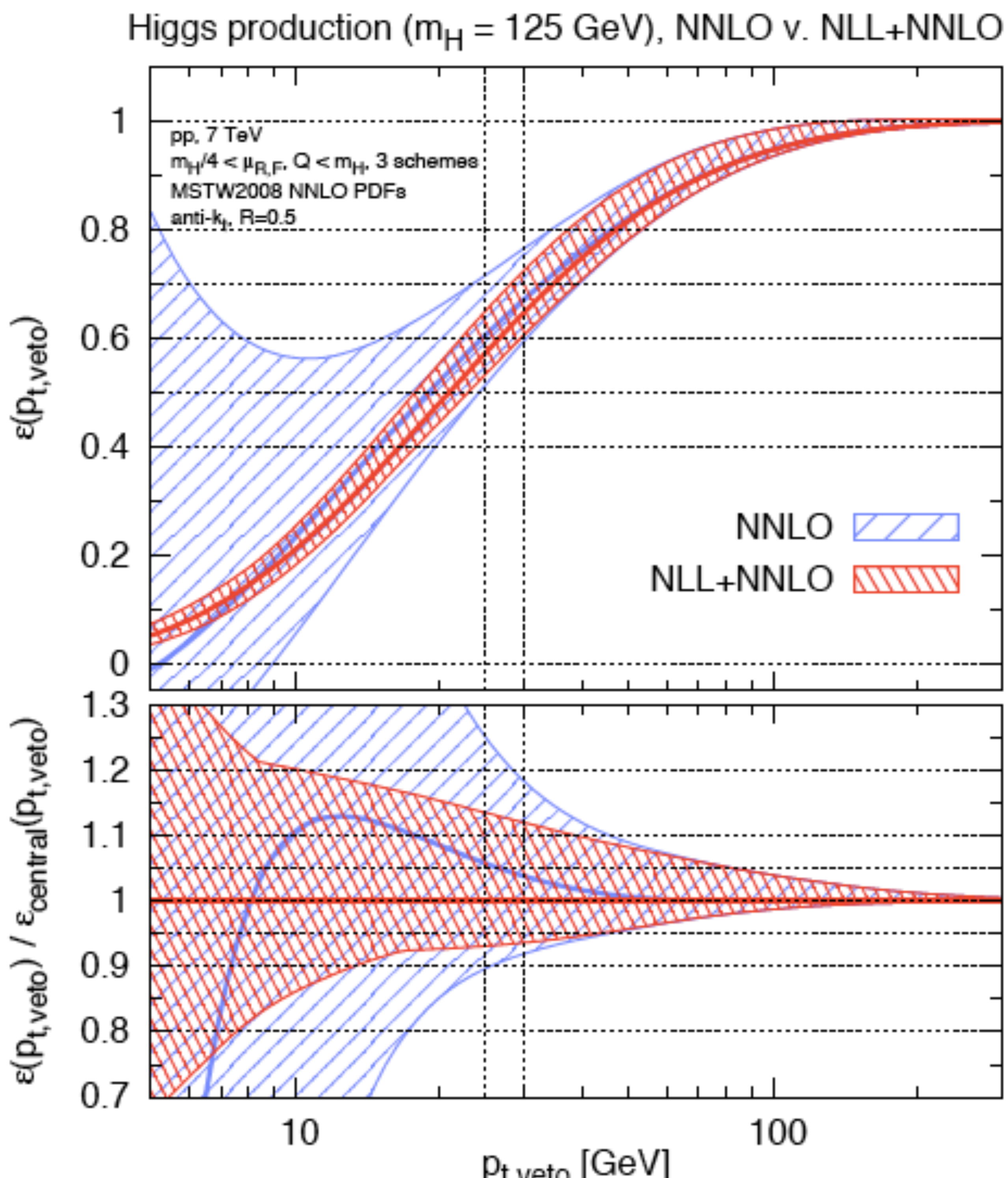
$$\Rightarrow \quad C = \begin{pmatrix} \Delta^2_{\rm total} + \Delta^2_{\geq 1} & -\Delta^2_{\geq 1} & 0 \\ \Delta^2_{\geq 1} & \Delta^2_{\geq 1} + \Delta^2_{\geq 2} & -\Delta^2_{\geq 2} \\ 0 & -\Delta^2_{\geq 1} & \Delta^2_{\geq 2} \end{pmatrix}$$

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%

NLL resummation for jet veto

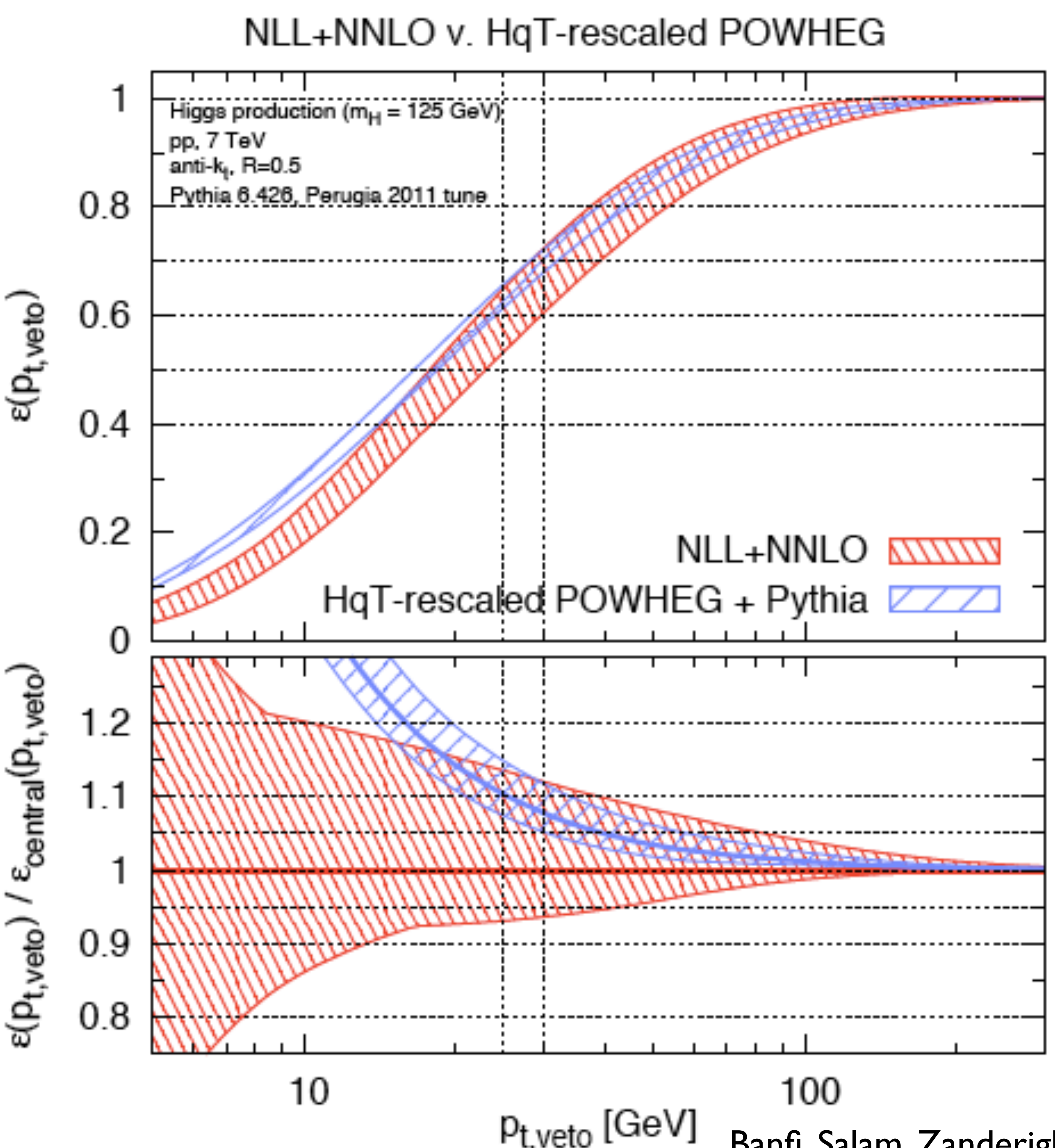
- Very recent numerical NLL resummation of the jet-vetoed cross section

Banfi, Salam, Zanderighi 2012



- Errors not much reduced from those estimated using previous prescription (error defined here as a combination of usual scale variation, and the envelope of methods a, b, c from before)

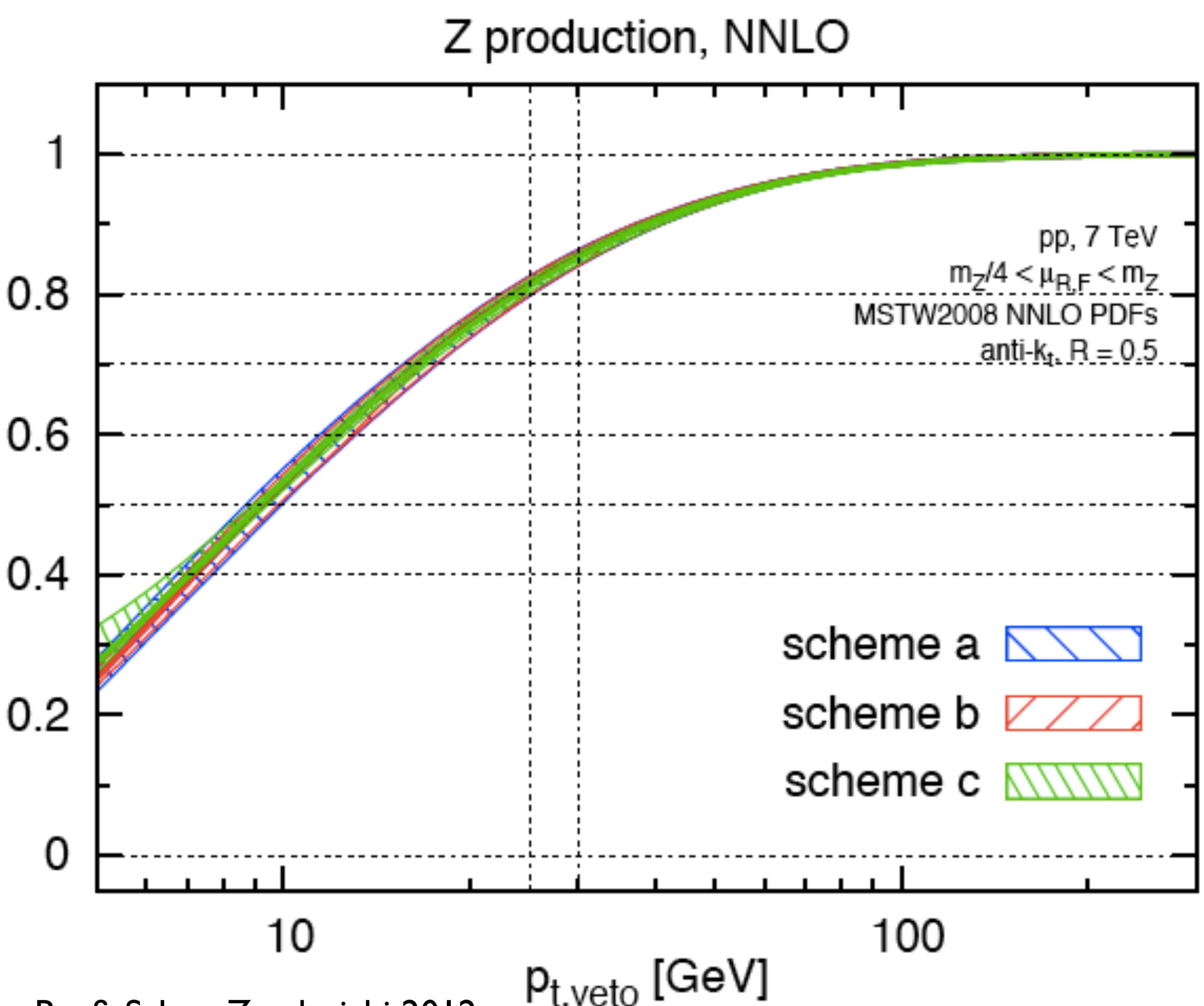
NLL resummation for jet veto



Banfi, Salam, Zanderighi 2012

- Can't use HqT reweighted POWHEG to estimate uncertainty!
- Central also value off by 10-15%; this should enter experimental studies

Data tests of calculations



Banfi, Salam, Zanderighi 2012

- The same issues do not affect W/Z production; both C_F instead of C_A as for Higgs, and tiny NLO→NNLO shift for W/Z
- Worth thinking about top, which is gg-initiated (although with a much better behaved inclusive cross section)

Conclusions

- Have discussed new work on how to treat jet vetos theoretically
- Better way to estimate uncertainty on fixed-order results
- New NLL resummation of the jet-vetoed Higgs signal; should propagate to experimental studies
- Worth thinking about cross-checks in other channels

Jet fractions

- Can be easily translated to be in terms of fractions of events in 0, 1, 2 jet bins

$$
\begin{aligned}
\delta(f_0)^2 &= \left(\frac{1}{f_0} - 1\right)^2 \left(\delta^2_{\rm total} + \delta^2_{\geq 1}\right), \\
\delta(f_1)^2 &= \delta^2_{\rm total} + \left(\frac{1 - f_0}{f_1}\right)^2 \delta^2_{\geq 1} + \left(\frac{1 - f_0}{f_1} - 1\right)^2 \delta^2_{\geq 2}, \\
\rho(f_0, \sigma_{\rm total}) &= \left[1 + \frac{\delta^2_{\geq 1}}{\delta^2_{\rm total}}\right]^{-1/2}, \\
\rho(f_1, \sigma_{\rm total}) &= -\frac{\delta_{\rm total}}{\delta(f_1)}, \\
\rho(f_0, f_1) &= -\left(1 + \frac{1 - f_0}{f_1} \frac{\delta^2_{\geq 1}}{\delta^2_{\rm total}}\right)\left(\frac{1}{f_0} - 1\right) \frac{\delta^2_{\rm total}}{\delta(f_0)\delta(f_1)}.
\end{aligned}
$$