Jet veto resummation

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Work in preparation with A. Banfi and G. Salam

based on

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The Zurich Phenomenology workshop: Higgs search confronts theory

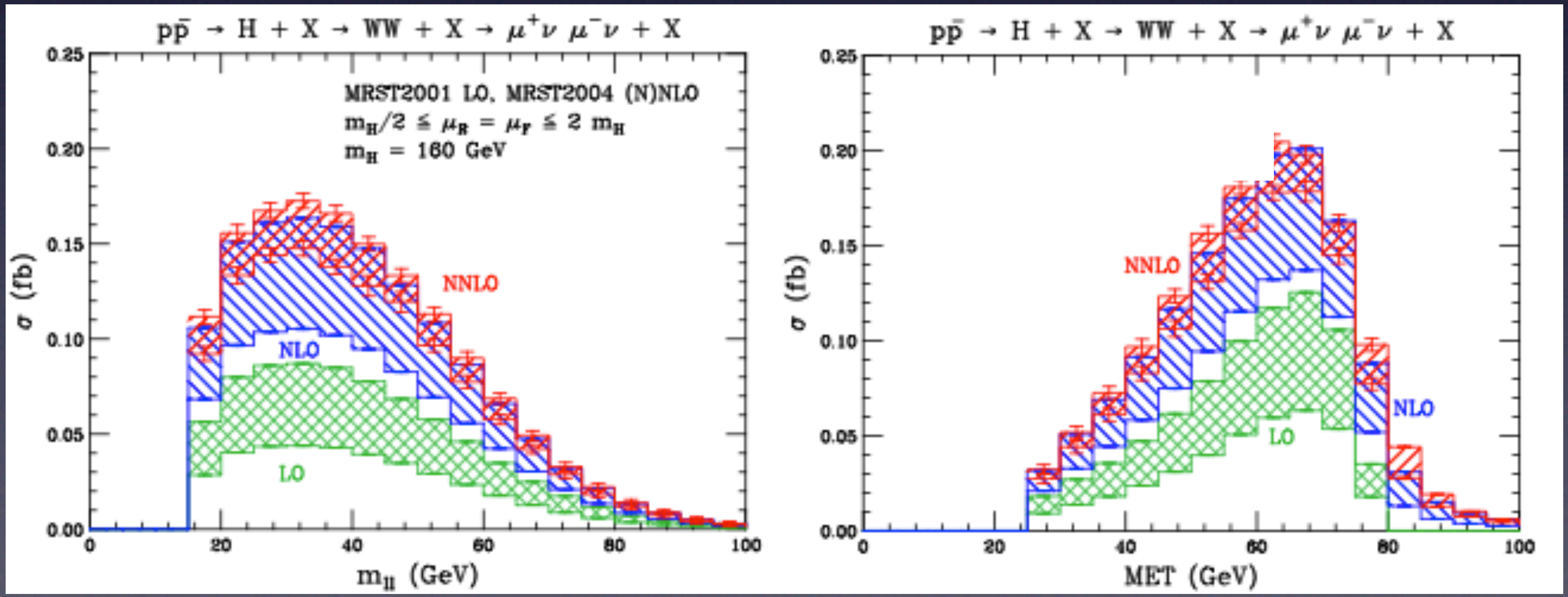
Zurich, 9-11th January 2012

Jet veto in Higgs searches

Kinematical cuts are needed to enhance the signal (Higgs) to background (top, WW, Z+jets, WW/ZZ/Zγ, W+jets, single top...) ratio

For instance, in H $\rightarrow$ WW $\rightarrow$ $l^+l^-\,\nu\nu$, most widely used cuts are on: ϕ_{ll}, m_{ll}, MET, $p_{t,lhard}$, $p_{t,lsoft}$ ... and $p_{t,jet}$

Most of these observables have constant K-factors, they barely affect the scale variation of the cross-section

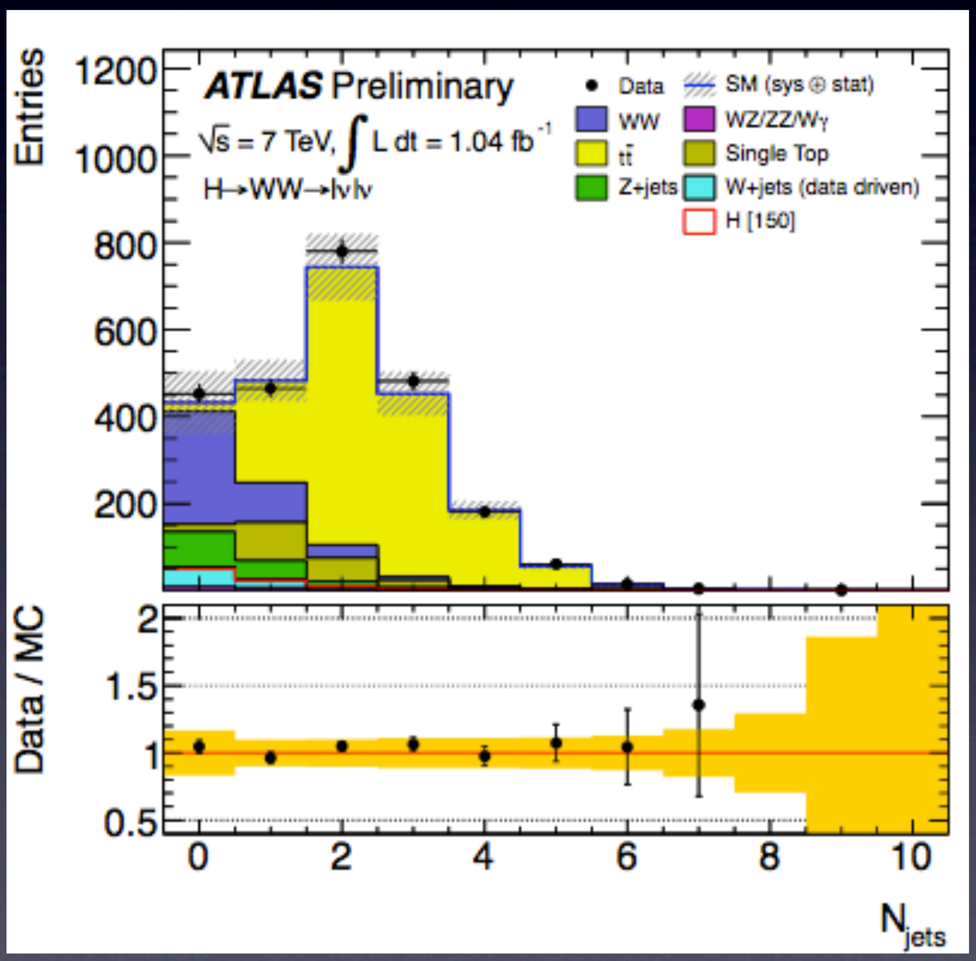


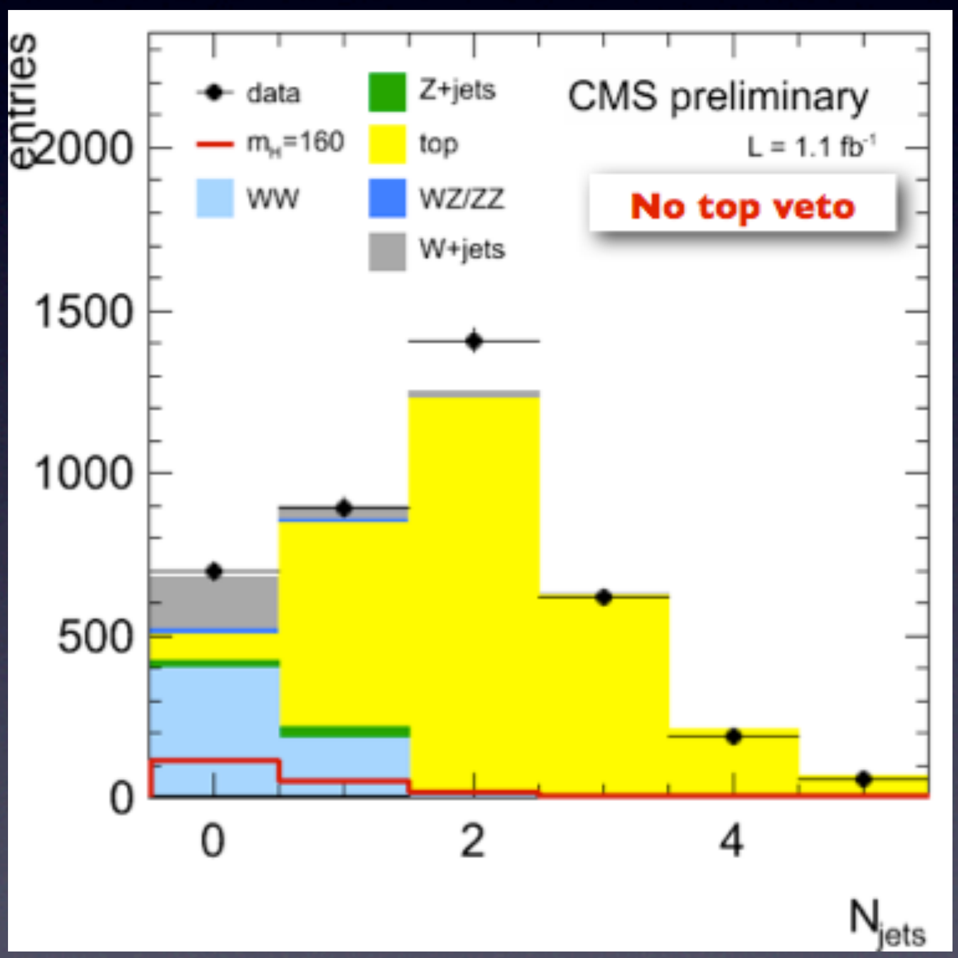
Anastasiou et al. ’09

This is in sharp contrast with the jet-veto, which is divergent for $p_{t,veto} \rightarrow 0$

Jet veto in Higgs searches

On the other hand, a jet veto essential to suppress large top background, experimental studies use $p_{t,\mathrm{veto}} \approx$ 20-30 GeV





Higgs production sensitivity can be maximized by studying the 0-,1-,2-jet bin cross-section separately, but this separation must be robust

Jet veto in Higgs searches

Breakout of the inclusive cross-section:
example Tevatron with m_H=160 GeV, $M_H/2 < \mu_R = \mu_F < 2\, M_H$

$$\frac{\Delta\sigma_{\rm tot}}{\sigma_{\rm tot}} = 66.5\%^{+5\%}_{-9\%} + 28.6\%^{+24\%}_{-22\%} + 4.9\%^{+78\%}_{-41\%} = [-14.3\%; +14.0\%]$$

0-jet 1-jet ≥2-jets

Anastasiou et al. '09

Update including NLO calculation of the 2-jet bin

$$\frac{\Delta\sigma_{\rm tot}}{\sigma_{\rm tot}} = 60\%^{+5\%}_{-9\%} + 29\%^{+24\%}_{-23\%} + 11\%^{+35\%}_{-31\%} = [-15.5\%; +13.8\%]$$

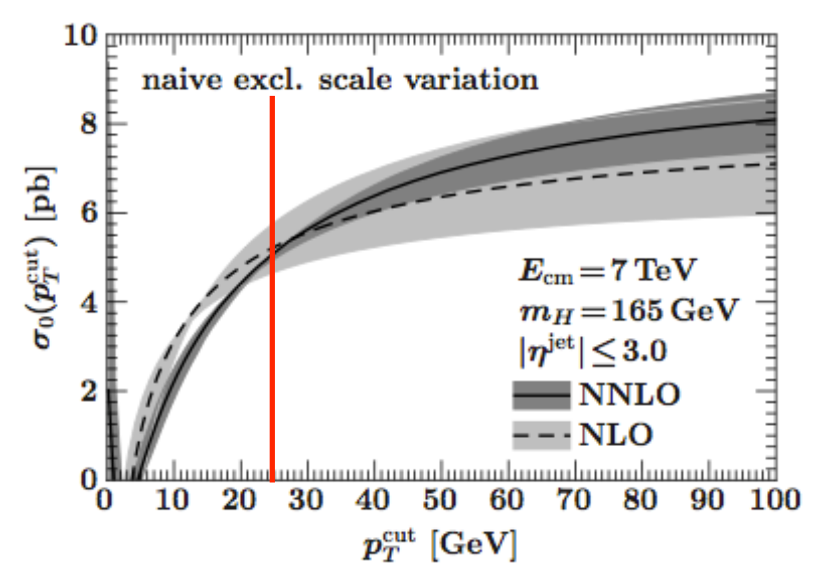
0-jet 1-jet ≥2-jets

Update by Campbell, Ellis, Williams '10

Events migrating to different jet-bins have a large impact on experimental analysis. Accurate predictions for jet-veto important.

Uncertainty on jet veto

Stewart and Tackman '11



- with p_T^{veto} much smaller error
- large positive correction (K-fact) and large negative logarithms

$$-\frac{2C_A\alpha_s}{\pi}\ln^2\frac{M_H}{\mathrm{p_T^{veto}}}$$

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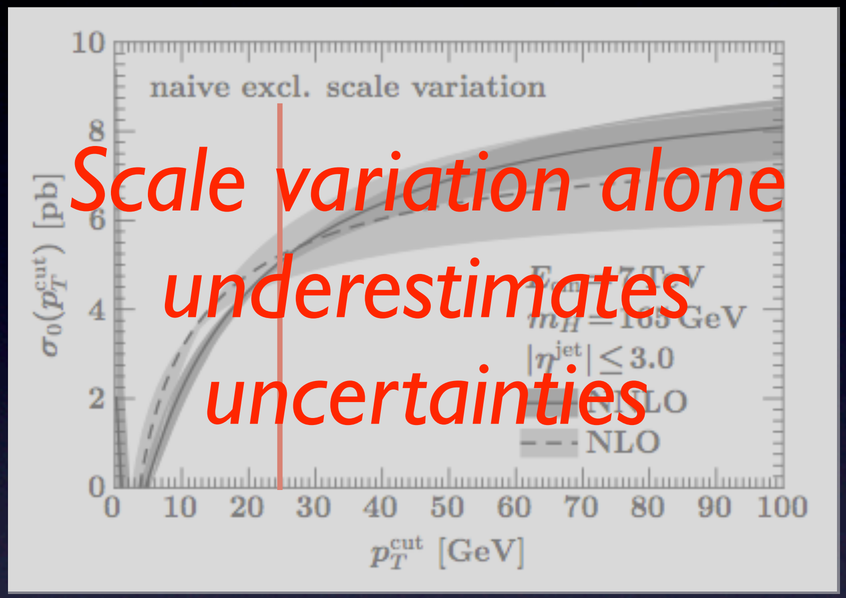

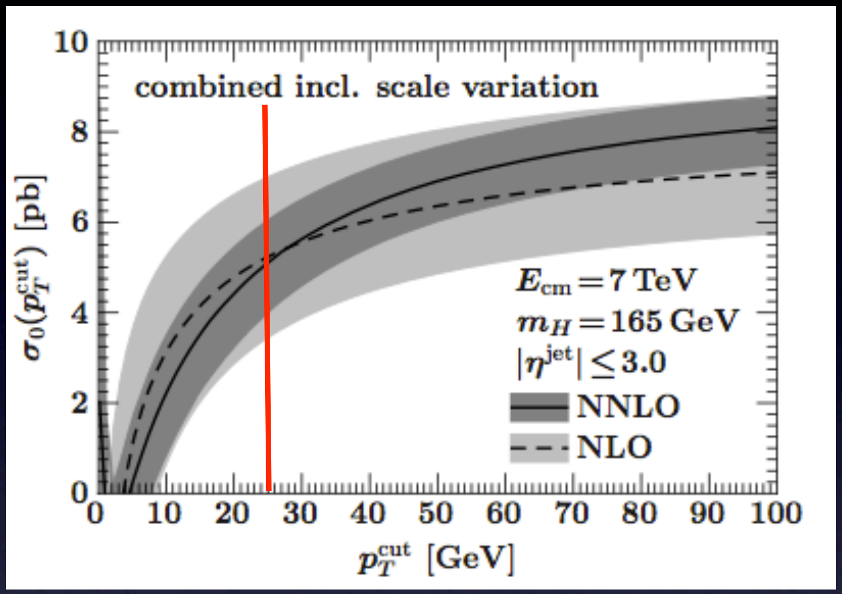

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$$-\frac{2C_A\alpha_s}{\pi}\ln^2\frac{M_H}{p_T^{veto}}$$

- with full correlations between jet bins

large K

large logarithms

$$\sigma_{0\,\mathrm{jets}} = \sigma_{\mathrm{tot}} - \sigma_{\geq 1\,\mathrm{jet}}$$

$$\Delta^2\sigma_{0\,\mathrm{jets}} = \Delta^2\sigma_{\mathrm{tot}} + \Delta^2\sigma_{\geq 1\,\mathrm{jet}}$$

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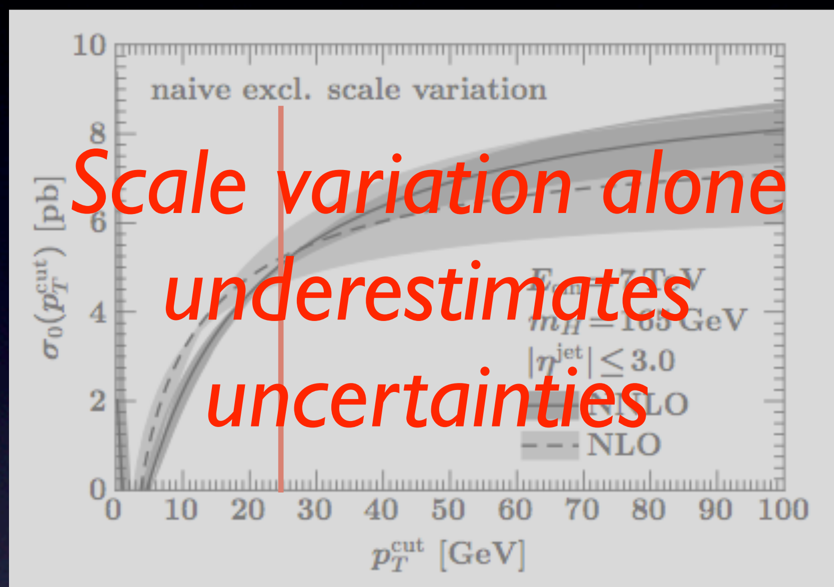

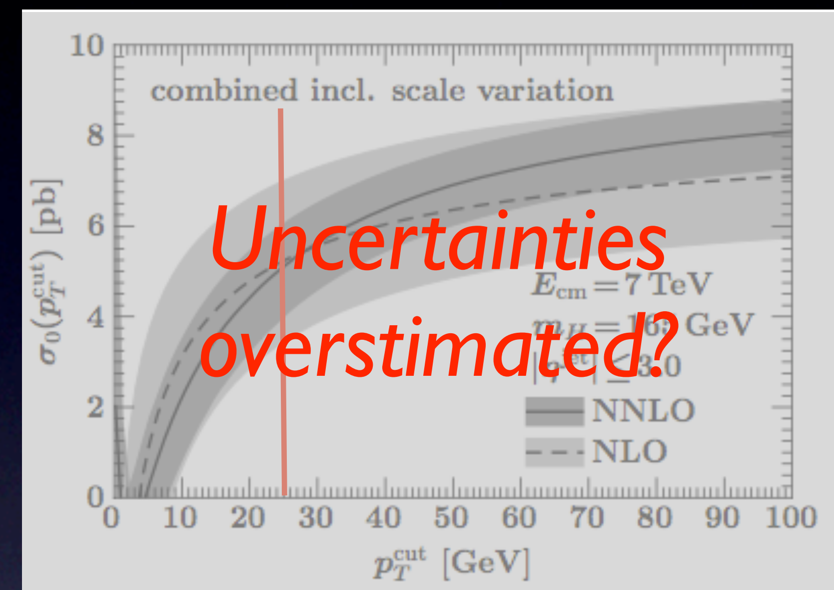

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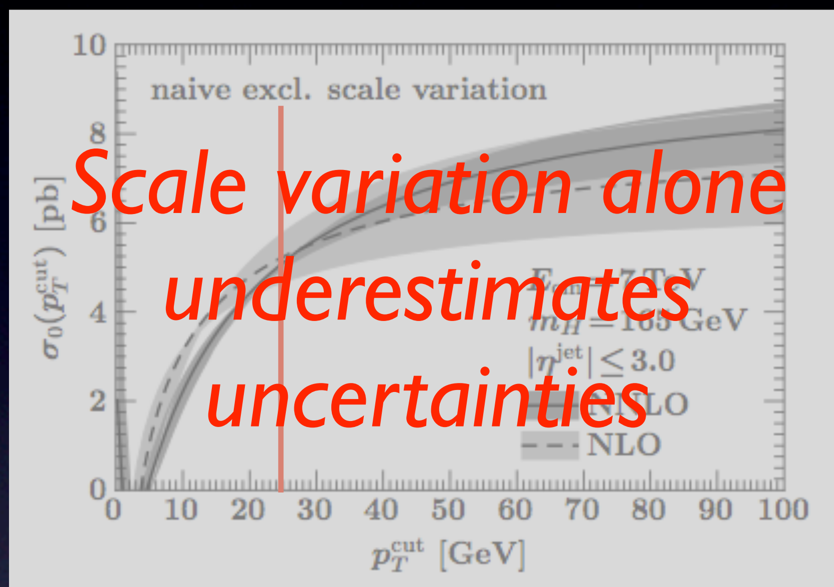

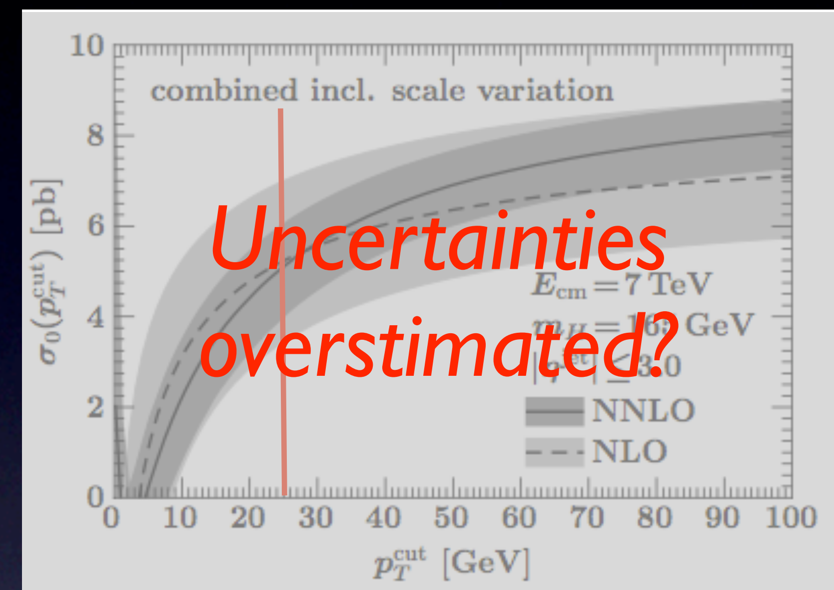

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Resummation only for related quantities exist ($p_{T,H}$, beam-thrust)

Bozzi, Catani, DeFlorian, Grazzini '03

Berger, Marcantonini, Stewart, Tackmann, Waalewijn '11

Jet-veto predictions

Currently available predictions for $p_{t,veto}$:

- Pure NNLO calculation, OK for largish $p_{t,veto}$ but divergent for small values

- MC predictions (Pythia, Herwig, MC@NLO, POWHEG . . .)

- POWHEG or MC@NLO re-weighted with HqT (that includes NNLO +NNLL for $p_{t,H}$)

- Also possible: similar gymnastic using beam thrust

This work:

☛ NLL + NNLO matched resummation for $p_{t,veto}$ itself

☛ comparison with other predictions (in progress)

Jet veto efficiency

Consider the production cross-section with a jet-veto

$$\Sigma(p_{\mathrm{t,veto}}) = \sum_N \int d\Phi_N \frac{d\sigma_N}{d\Phi_N} \Theta(p_{\mathrm{t,veto}} - p_{\mathrm{t,max}})$$

The observable considered in the following is the jet-veto efficiency

$$\boxed{\epsilon(p_{\mathrm{t,veto}}) \equiv \frac{\Sigma(p_{\mathrm{t,veto}})}{\sigma_{\mathrm{tot}}}}$$

We denote by $\Sigma_i (\mathrm{or}\, \sigma_i)$ the contributions $\mathcal{O}(\alpha_s^i)$ relative to the Born term

It is also useful to define

$$\bar{\Sigma}_i(p_{\mathrm{t,veto}}) = -\int_{p_{\mathrm{t,veto}}}^{\infty} dp_t \frac{d\Sigma_i(p_t)}{dp_t} \qquad \Sigma_i(p_{\mathrm{t,veto}}) = \sigma_i + \bar{\Sigma}_i(p_{\mathrm{t,veto}})$$

Resummation for jet-veto

A. Banfi, G. Salam, GZ '03-'04

Caesar is an automated tool to perform NLL resummation for suitable observables.
It first determines if an observable $V(k_1 \ldots k_n)$ is within its scope. If so, it determines numerically the input for the master resummation formula, and then evaluates it.

The jet veto is, trivially, in the scope of Caesar

Resummation for jet-veto

Suitable observables satisfy:

1) for a single soft emission, collinear to leg ℓ, V should behave as

$$V(\{p\},k) = d_\ell \left(\frac{k_t^{(\ell)}}{Q}\right)^{a_\ell} e^{-b_\ell \eta^{(\ell)}} g_\ell(\phi)$$

For the jet veto this is trivially satisfied with

$$a_\ell = d_\ell = g_\ell(\phi) = 1 \qquad b_\ell = 0 \qquad \ell = 1,2$$

A. Banfi, G. Salam, GZ '01, '03, '04

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3) the observable should be recursively IRC safe. Physically this means that if one scales all emissions in a uniform manner, the observable also scales in the same manner. Again this property is trivially satisfied

A. Banfi, G. Salam, GZ '01, '03, '04

Resummation for jet-veto

Last ingredient: compute the NLL effects due to multiple soft & collinear emissions that are well separated in rapidity

A resummation typically requires

1. to determine how the observable depend on multiple emissions
2. to factorize this dependence (e.g. traditional methods use Mellin/ Fourier transforms)

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- find a simple observable V_s which has the same double logs as the full observables and where factorization in trivial
- compute (numerically) the multiple emission functions that encodes the NLL difference between V and V_s

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Concretely

$$\boxed{V_s(\{p\}, k_1 \ldots k_N) = \max_i V(\{p\}, k_i)}$$

A. Banfi, G. Salam, GZ '01, '03, '04

Resummation for jet-veto

The NLL difference between V and V_s comes from the region where emissions are well-separated in rapidity (angular ordering)

In this limit, each emission leads to a jet, so $V = V_s$

There are no multiple emission effects, meaning that the resummation for the jet veto at NLL is a pure Sudakov form factor

Resummation for jet-veto

The NLL resummed result takes the very simple form

$$\Sigma_{\rm NLL}(p_{\rm t,veto}) = \int dx_1 dx_2 f\left(x_1, \mu_F \frac{p_{\rm t,veto}}{M}\right) f\left(x_2, \mu_F \frac{p_{\rm t,veto}}{M}\right) \cdot |\mathcal{M}_B|^2 e^{-R_B\left(\frac{p_{\rm t,veto}}{M}, \frac{\mu_R}{M}, \alpha_s(\mu_R)\right)} \delta(x_1 x_2 s - M^2)$$

$$R_Z\left(\frac{p_{\rm t,veto}}{M_Z}, \frac{\mu_R}{M_Z}, \alpha_s(\mu_R)\right) = 2C_F \int_{p_{\rm t,veto}^2}^{M_Z^2} \frac{dk_t^2}{k_t^2} \frac{\alpha_s^{\rm CMW}(k_t)}{\pi} \left(\frac{M_Z}{k_t} - \frac{3}{4}\right)$$

$$R_H\left(\frac{p_{\rm t,veto}}{M_H}, \frac{\mu_R}{M_H}, \alpha_s(\mu_R)\right) = 2C_A \int_{p_{\rm t,veto}^2}^{M_H^2} \frac{dk_t^2}{k_t^2} \frac{\alpha_s^{\rm CMW}(k_t)}{\pi} \left(\frac{M_H}{k_t} - \frac{11C_A - 4T_R N_f}{12 C_A}\right)$$

This is a pure $g_1(\alpha_s L)L$ and $g_2(\alpha_s L)$ in the exponent

Matching to fixed order

In order to have a reliable prediction everywhere, one needs to match resummation to fixed order results

The matching procedure should satisfy:

1. the matched results should be correct to NLL terms in the exponent and the matched expanded results should be correct to $\alpha_s^n L^{2n-2}$
2. the expansion should agree with fixed order up to NNLO
3. at the boundary the efficiency should satisfy

$$\boxed{\epsilon(p_{\mathrm{t,veto}}^{\mathrm{max}}) = 1 \qquad \left.\frac{d\epsilon(p_{\mathrm{t,veto}})}{dp_{\mathrm{t,veto}}}\right|_{p_{\mathrm{t,veto}}^{\mathrm{max}}} = 0}$$

Given these conditions there is freedom in the matching prescription (that can be used as a further handle on the estimation of the accuracy, an alternative could be an independent scale variation in num. and den.)

Three matching schemes

$$\Sigma_{\mathrm{logR}}(p_{\mathrm{t,veto}}) = \tilde{\Sigma}_{\mathrm{NLL}}(p_{\mathrm{t,veto}}) \exp\left[\frac{\Sigma_1(p_{\mathrm{t,veto}}) - \tilde{\Sigma}_{\mathrm{NLL},1}(p_{\mathrm{t,veto}})}{\sigma_0}\right] \times$$
$$\times \exp\left[\frac{\Sigma_2(p_{\mathrm{t,veto}}) - \tilde{\Sigma}_{\mathrm{NLL},2}(p_{\mathrm{t,veto}})}{\sigma_0} - \frac{(\Sigma_1(p_{\mathrm{t,veto}}))^2 - (\tilde{\Sigma}_{\mathrm{NLL},1}(p_{\mathrm{t,veto}}))^2}{2\sigma_0^2}\right]$$

❶ ~ resummation × exp. of fixed order cor. (common for event shapes)

$$\Sigma_{\mathrm{modR}}(p_{\mathrm{t,veto}}) =$$
$$\left(\frac{\tilde{\Sigma}_{\mathrm{NLL}}(p_{\mathrm{t,veto}})}{\sigma_0}\right)^Z \left[\sigma_0 + \Sigma_1(p_{\mathrm{t,veto}}) + \Sigma_2(p_{\mathrm{t,veto}}) - Z\left(\tilde{\Sigma}_{\mathrm{NLL},1}(p_{\mathrm{t,veto}}) + \tilde{\Sigma}_{\mathrm{NLL},2}(p_{\mathrm{t,veto}})\right)\right.$$
$$\left. - Z\frac{\tilde{\Sigma}_{\mathrm{NLL},1}(p_{\mathrm{t,veto}})}{\sigma_0}\left(\Sigma_1(p_{\mathrm{t,veto}}) - \frac{Z+1}{2}\tilde{\Sigma}_{\mathrm{NLL},1}(p_{\mathrm{t,veto}})\right)\right] \qquad Z = \left(1 - \frac{p_{\mathrm{t,veto}}}{p_{\mathrm{t,veto}}^{\mathrm{M}}}\right)^q$$

❷ ~ resummation + fixer order –expansion (common in DIS, or $p_{t,Z}$)

❸ ~ third scheme is analogous to the second one but one sets $\sigma_2 = 0$

Fixed order schemes

It is interesting to note that each scheme corresponds to a particular fixed order expression of the efficiency (all of which are the identical at NNLO)

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

keep all known terms

$$\epsilon^{(b)} \equiv \frac{\Sigma_0(p_{\mathrm{t,veto}}) + \Sigma_1(p_{\mathrm{t,veto}}) + \bar{\Sigma}_2(p_{\mathrm{t,veto}})}{\sigma_0 + \sigma_1}$$

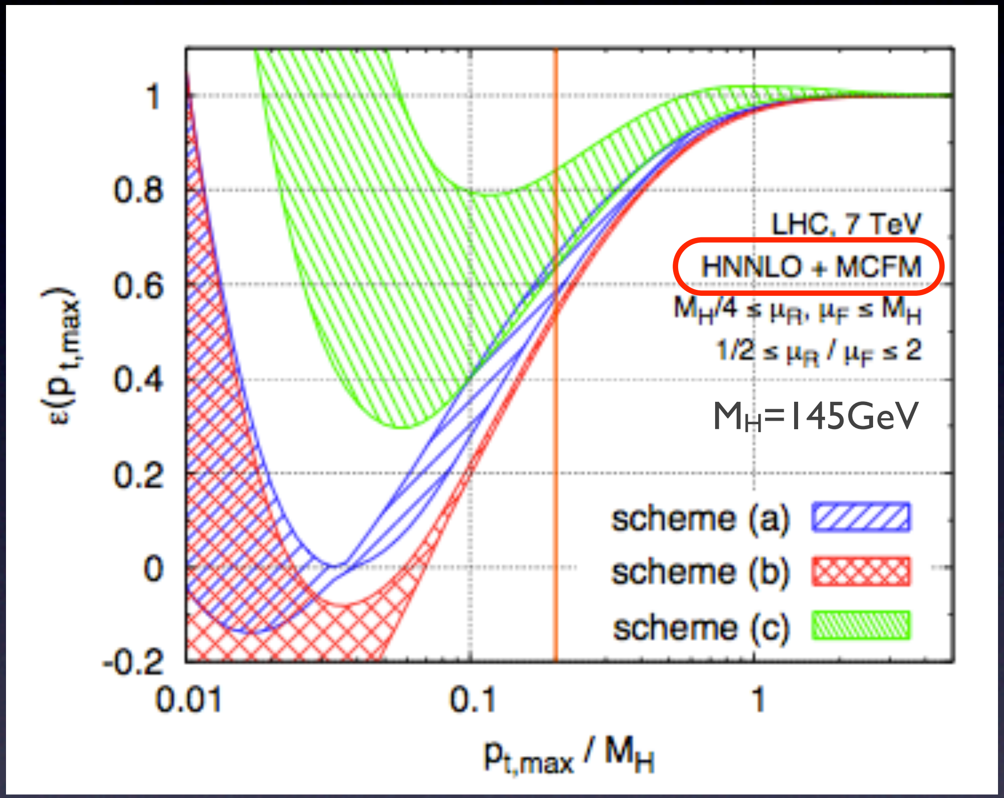
NLO expansion for $1-\epsilon$

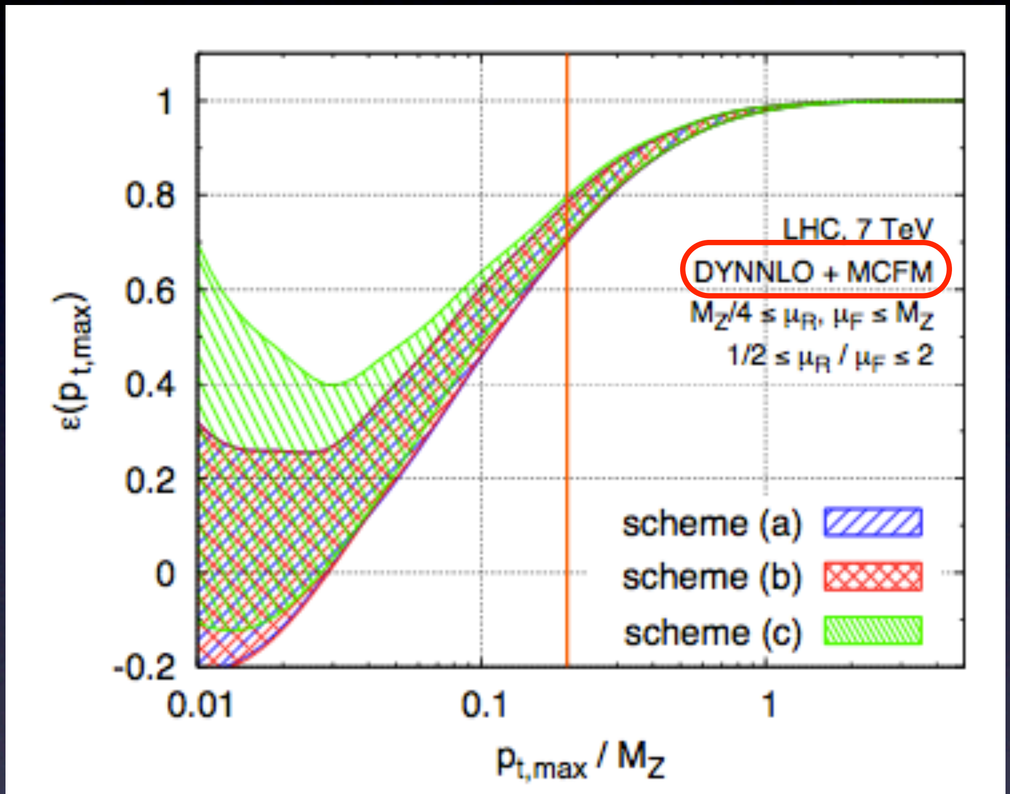
$$\epsilon^{(c)} \equiv 1 + \frac{\bar{\Sigma}_1(p_{\mathrm{t,veto}})}{\sigma_0} + \left(\frac{\bar{\Sigma}_2(p_{\mathrm{t,veto}})}{\sigma_0} - \frac{\sigma_1}{\sigma_0^2}\Sigma_1(p_{\mathrm{t,veto}})\right)$$

strict expansion

All these efficiencies differ by relative terms $\mathcal{O}(\alpha_s^3)$ not under control

Fixed order results



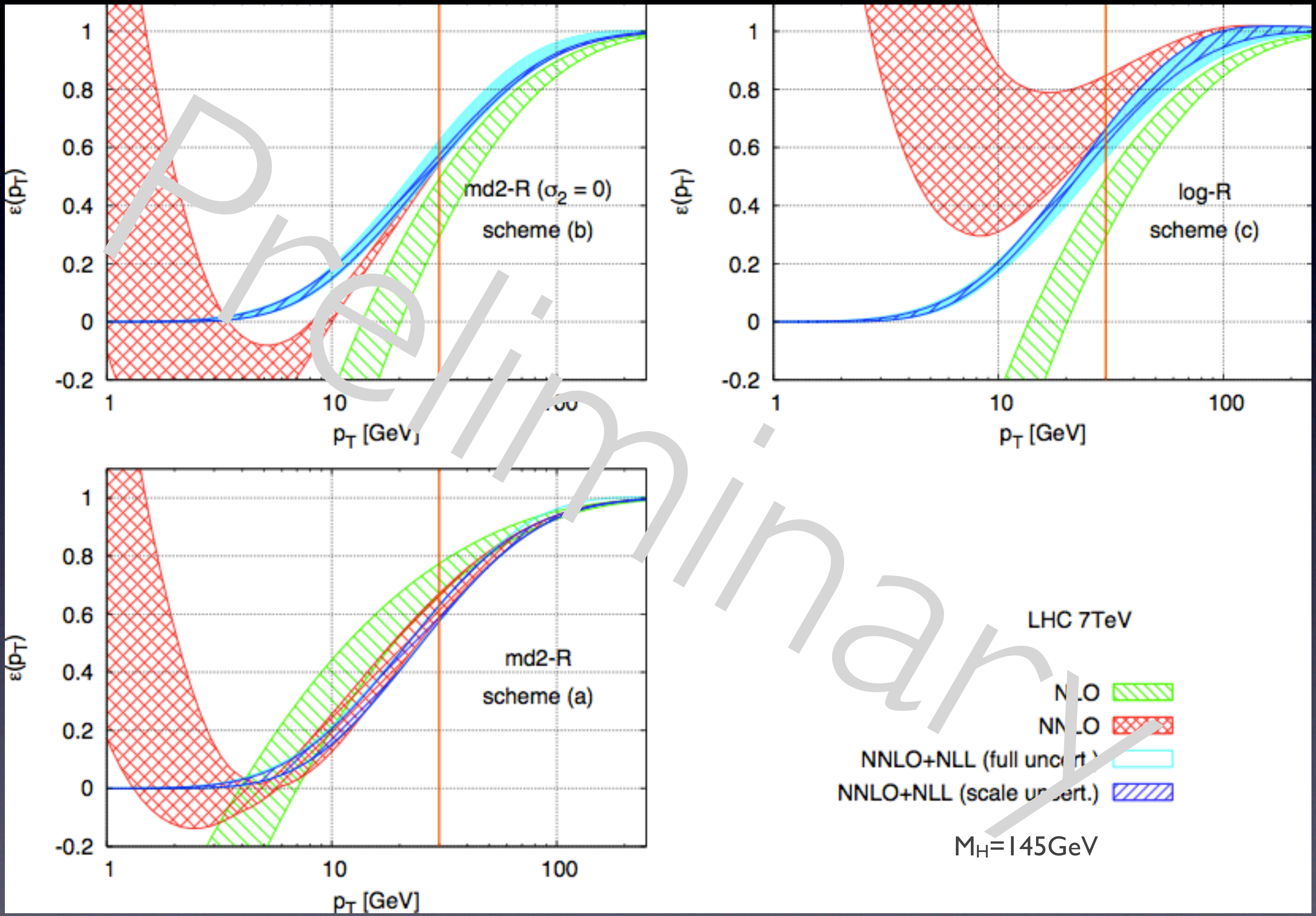


Large differences between schemes due to very large higher order corrections for Higgs production (for DY only modest differences)

Inclusive cross-sections

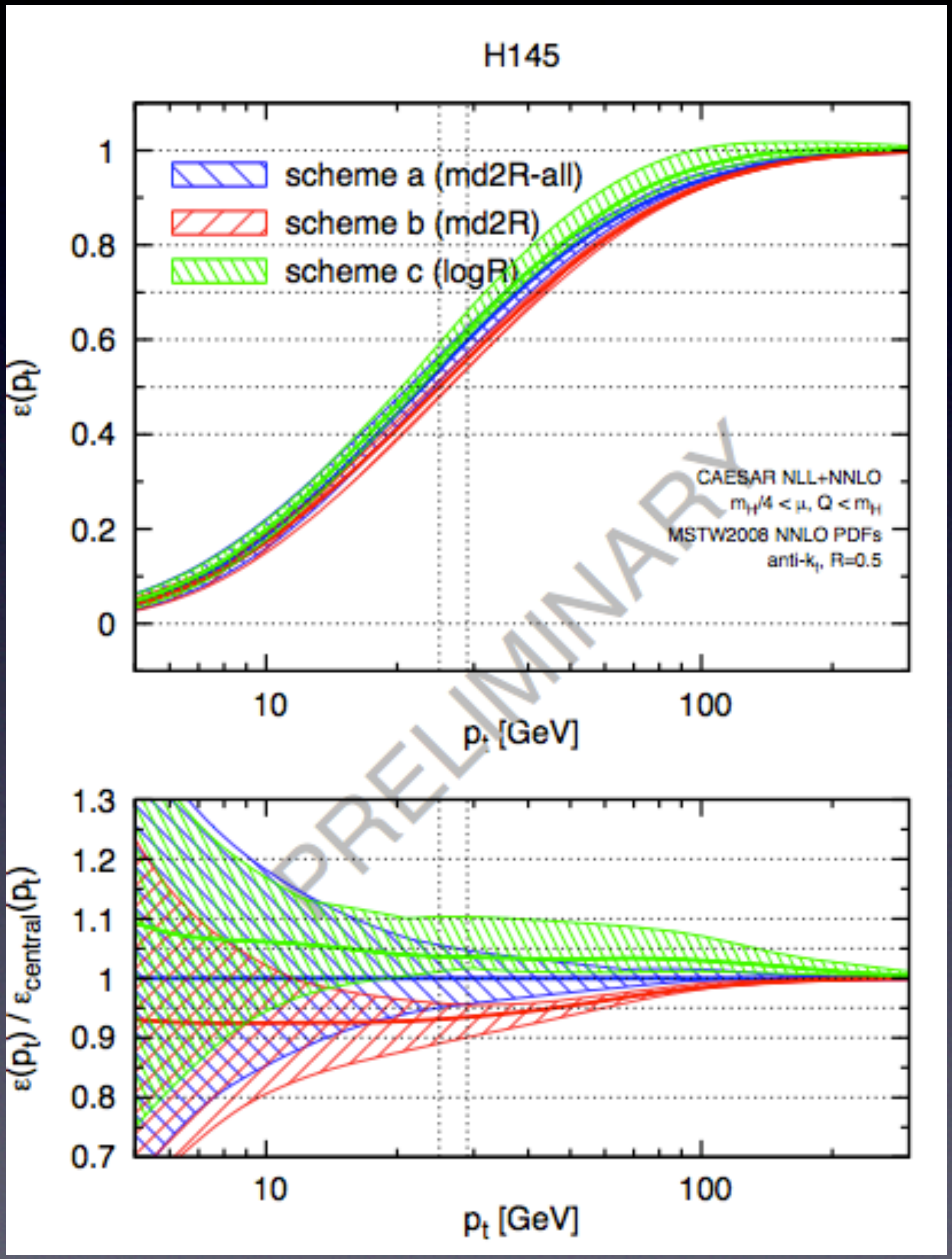
	LO	NLO	NNLO	c_1	c_2
Z [nb]	$22.84^{+2.07}_{-2.40}$	$28.6^{+0.8}_{-1.2}$	$28.6^{+0.4}_{-0.4}$	1.94	0.0
H [pb]	$3.94^{+1.01}_{-0.73}$	$8.53^{+1.86}_{-1.34}$	$10.5^{+0.8}_{-1.0}$	9.61	34

Matched NLL results



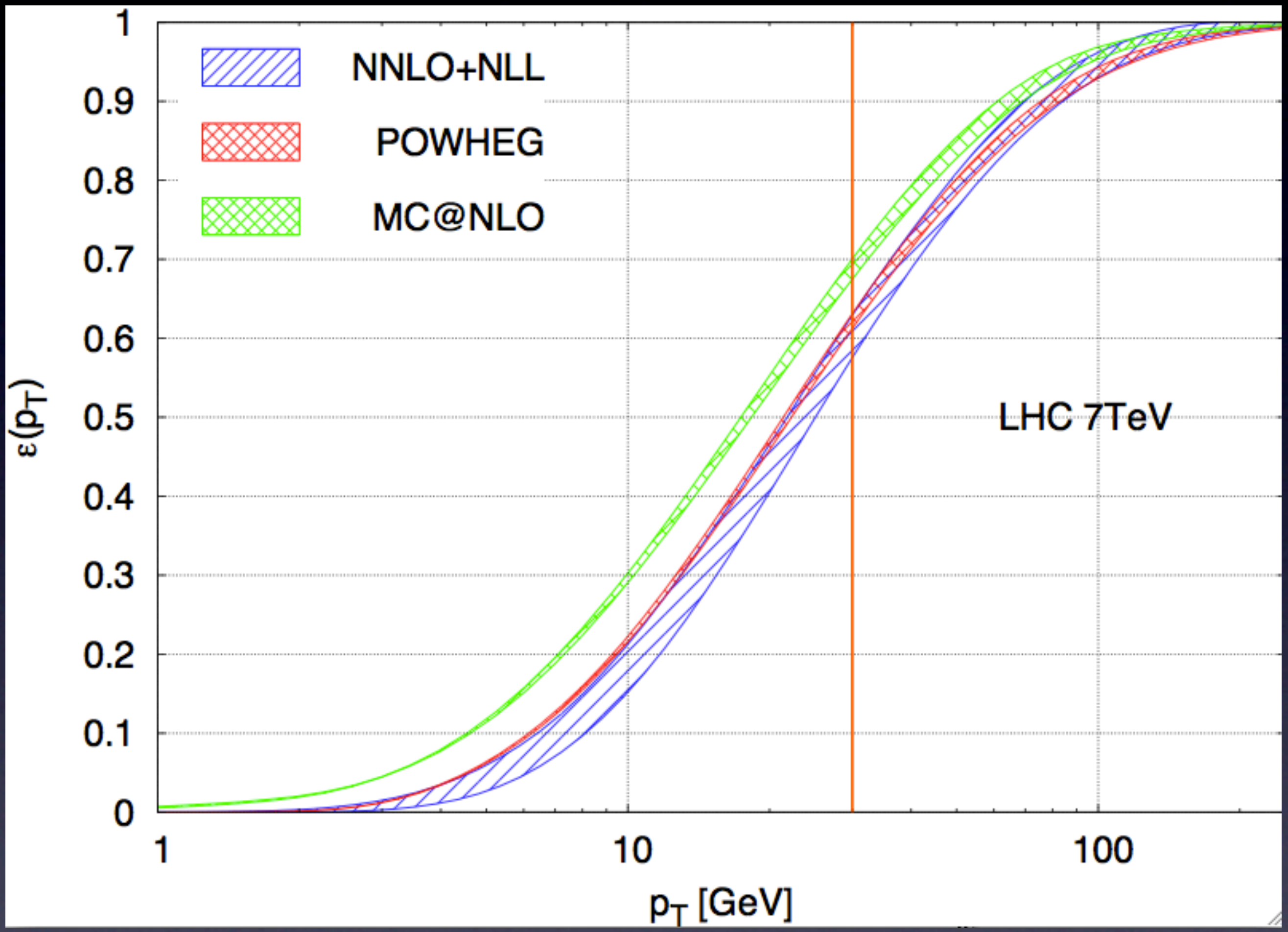
Full band obtained varying renormalization, factorization and resummation scales independently around $M_H/2$

Matched NLL results



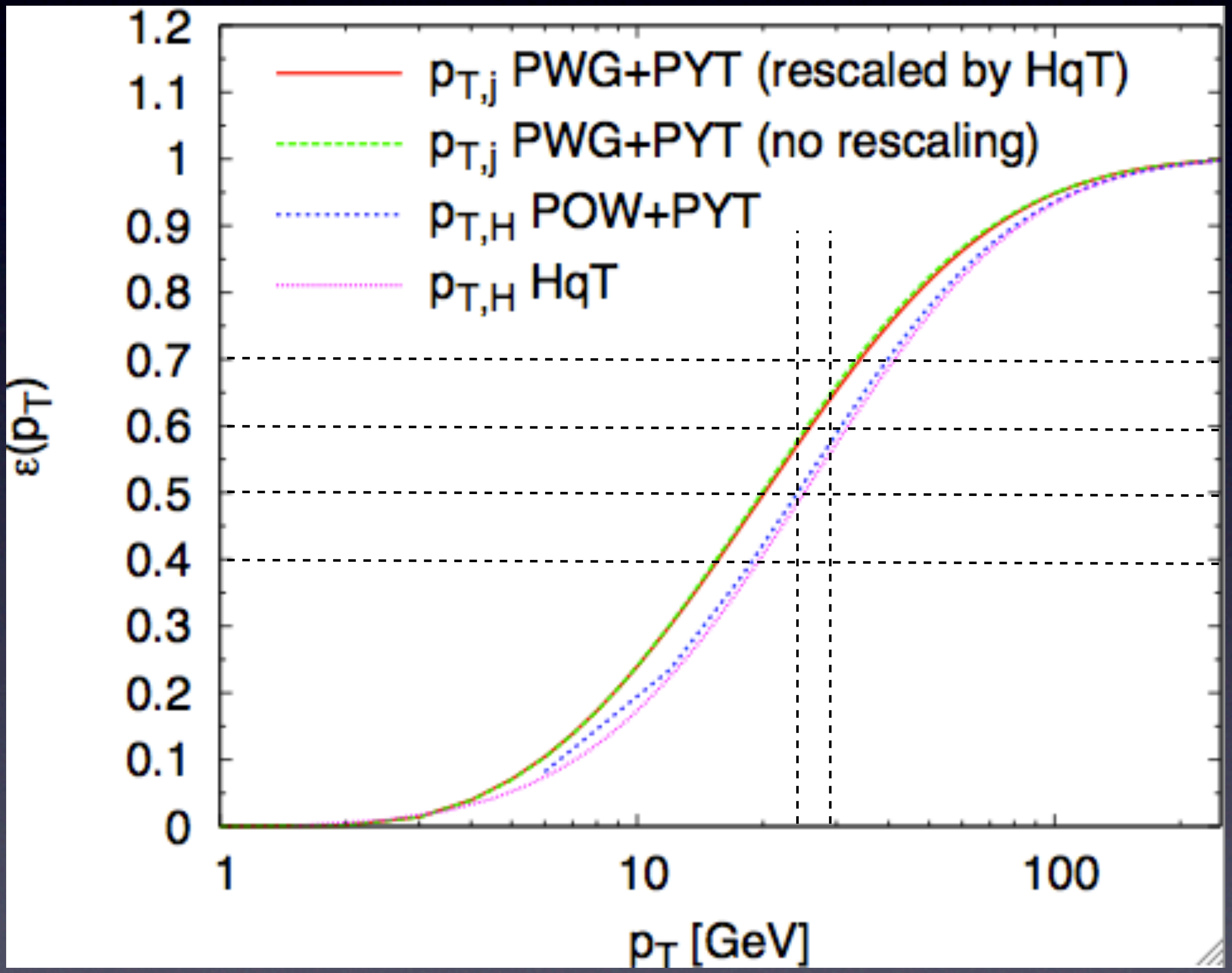
Comparison between the three schemes that are equivalent at NNLL

Comparison with MC



- NNLO+NLL band obtained by taking the envelope of full scale variation in scheme (a) + central scale for scheme (b) and (c)
- Good agreement with POWHEG, less so with MC@NLO
- Small uncertainties both in MC@NLO and POWHEG

HqT rescaling on PWG

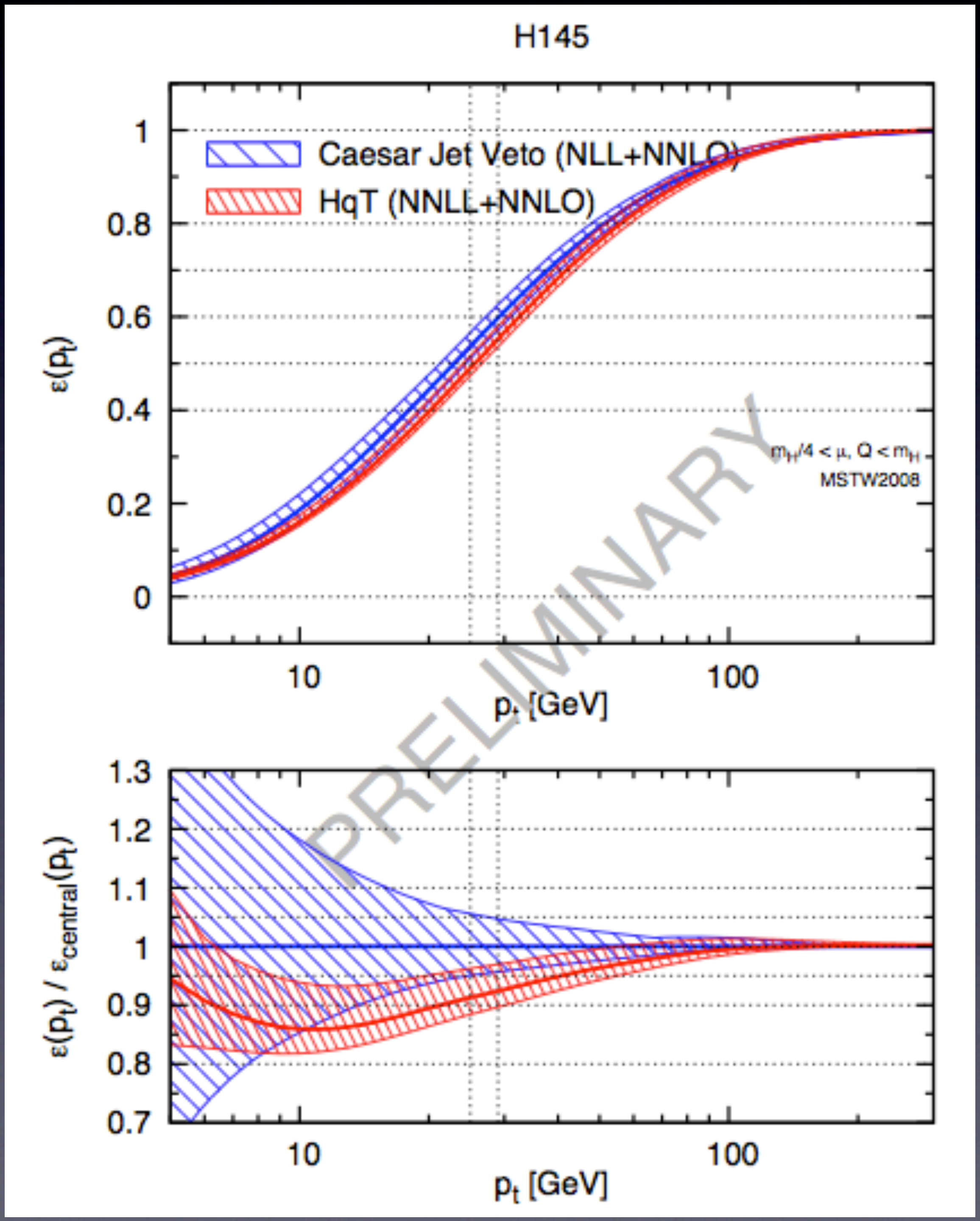


Look at central choices

$x_{\mu R} = x_{\mu F} = X_{res} = 0.5$

- Powheg agrees well with HqT
- Rescaling has a tiny effect
- Sizeable difference between $p_{t,veto}$ and $p_{t,H}$

$P_{t,\text{veto}}$ vs $P_{t,\text{Higgs}}$



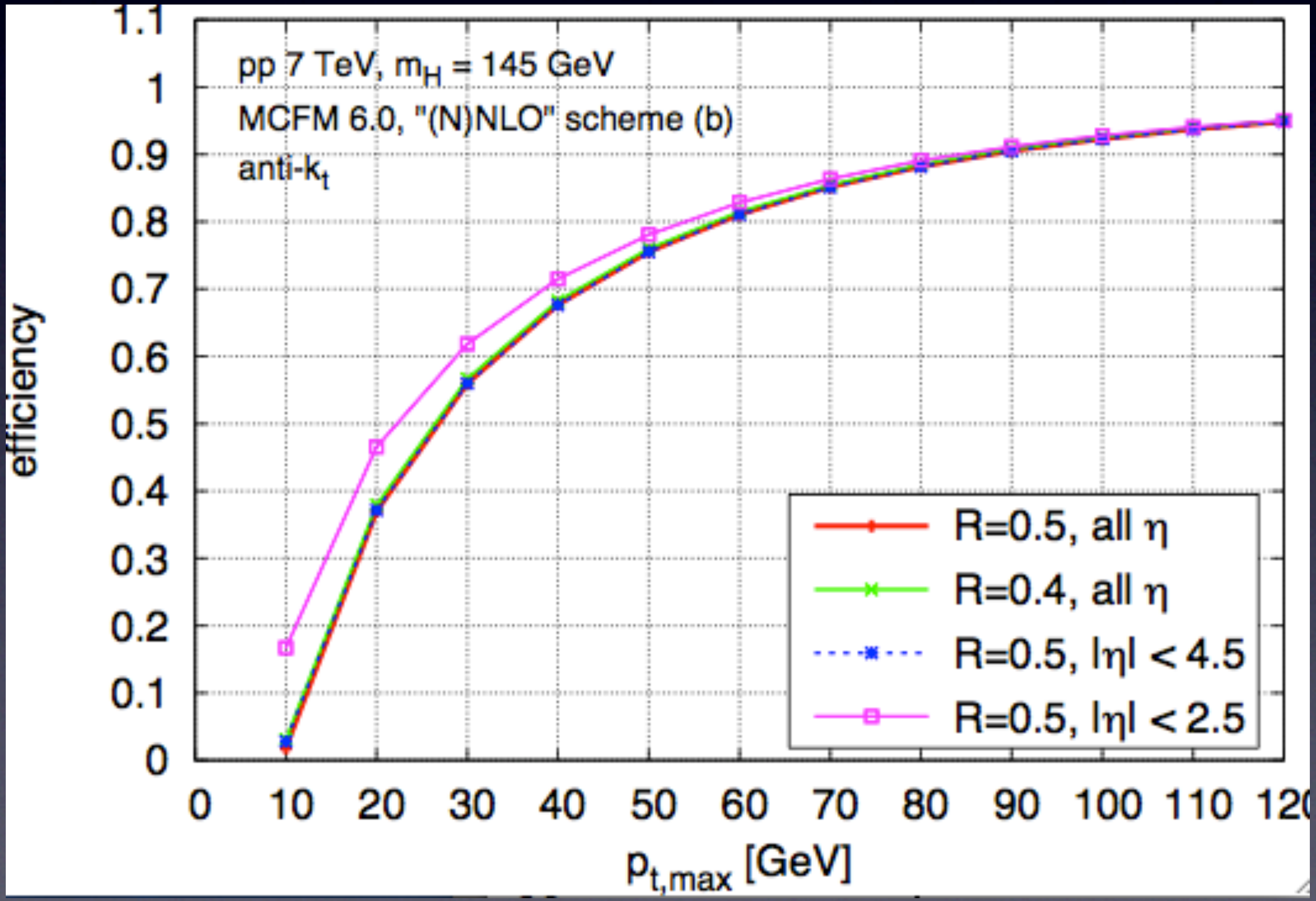
- In the p_t region of interest HqT and Caesar have similar uncertainties
- Difference between $p_{t,H}$ from HqT and $p_{t,\text{veto}}$ from Caesar is $\alpha_s^2 L$
- R-dependence of $p_{t,\text{veto}}$ result of the same order of magnitude as difference between HqT and Caesar (it is α_s^2 with a large "K-factor")

Conclusions

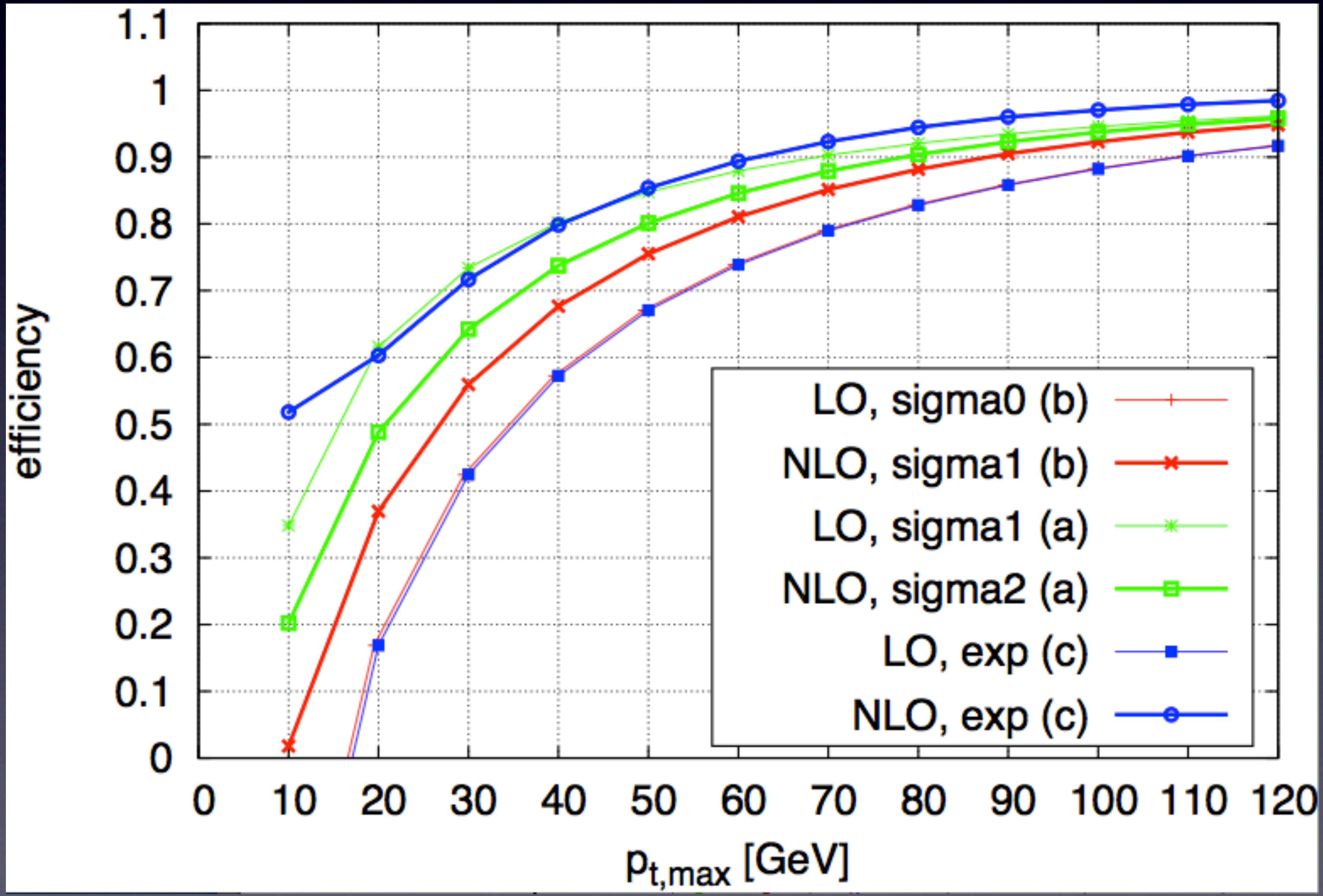
- ☛ a jet-veto enters all main current Higgs searches, solid theoretical predictions with reliable errors are highly desirable
- ☛ often accurate predictions for the Higgs p_t distribution are used to reweight Monte Carlo predictions for the jet-veto
- ☛ it is interesting that the jet-veto, that has never been resummed before, turns out to be a very simple observable
- ☛ we are in the process of understanding the impact of a NLL+NNLO calculation on central value and uncertainties. Preliminary results shown here. Final results and a full interpretation in progress
- ☛ natural to think also at a NNLL resummation. Unclear though how much uncertainties could be reduced (3 schemes equivalent at NNLL)

Extra Slides

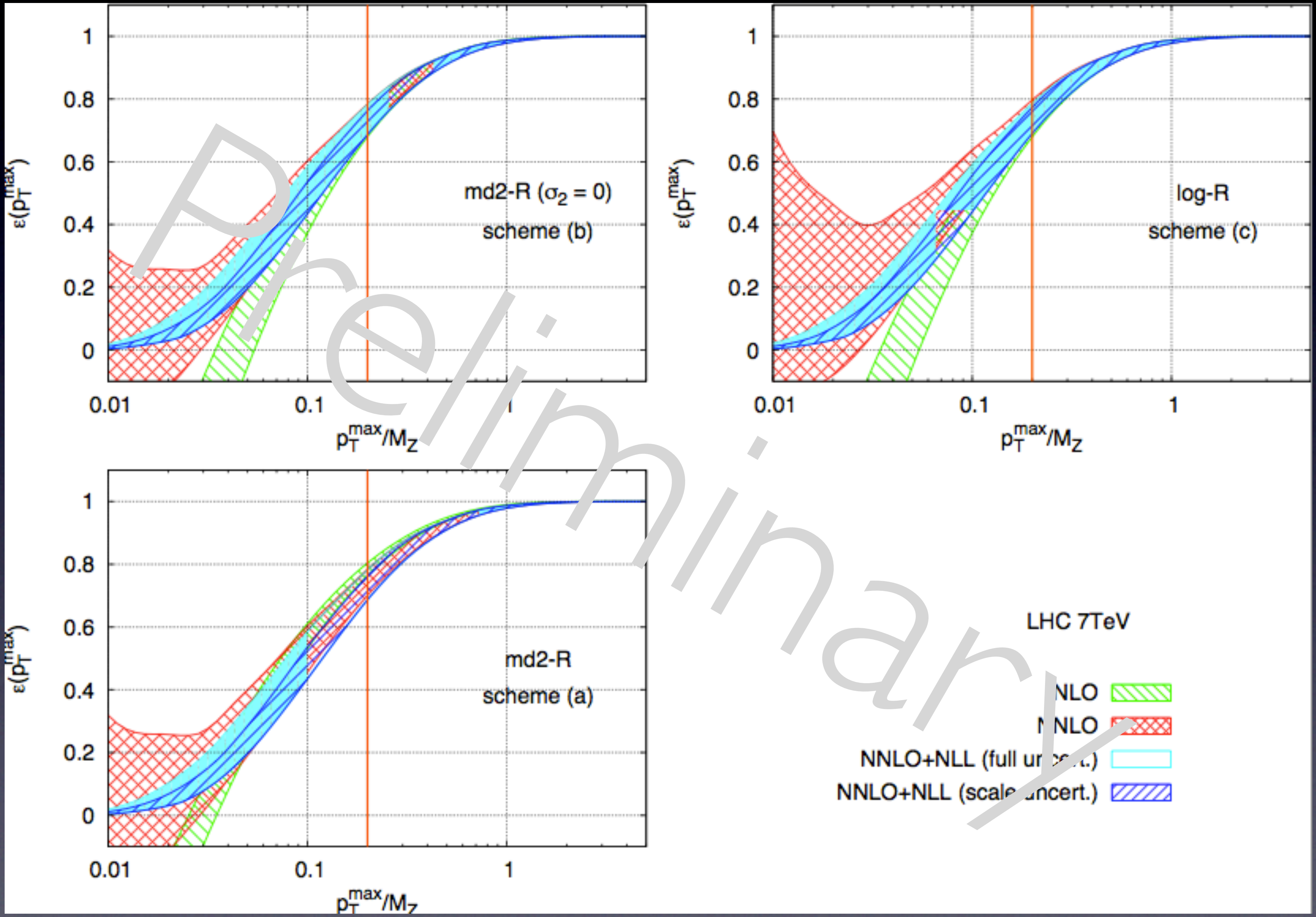
Impact of rapidity cut and change of R



Convergence of fixed order schemes



NLL+NNLO for DY



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