Higgs Production with a Jet Veto at NNLL+NNLO

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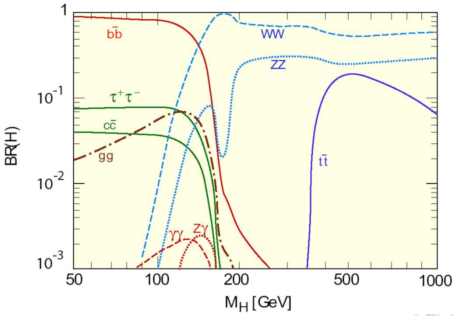
UCSD

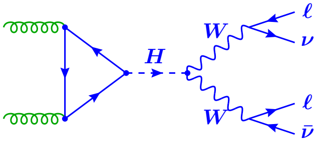
Boston Jet Physics Workshop
January 12-14, 2011

In collaboration with: Carola Berger, Claudio Marcantonini,
Iain Stewart and Frank Tackmann

arXiv:1012.4480

Higgs at LHC and Tevatron





$gg \to H \to WW \to \ell\bar{\nu}\bar{\ell}\nu$

- Strong discovery potential, dominant channel in Tevatron exclusion for $m_H \gtrsim 130\,\mathrm{GeV}$

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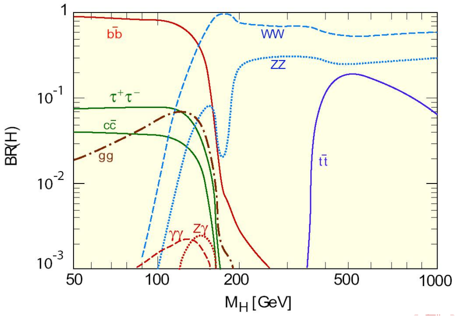
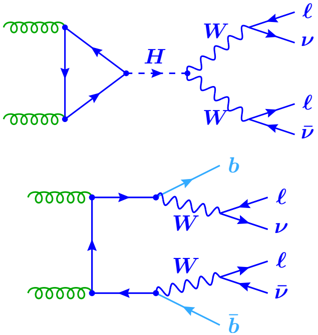




$gg \to H \to WW \to \ell\bar{\nu}\bar{\ell}\nu$

- Strong discovery potential, dominant channel in Tevatron exclusion for $m_H \gtrsim 130\,\mathrm{GeV}$
- Large $\sim 40:1$ background from $t\bar{t} \to WWb\bar{b}$
- Cannot reconstruct Higgs invariant mass ($\nu\bar{\nu}$)

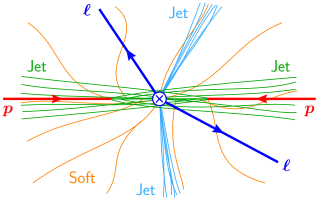
Higgs at LHC and Tevatron

Use jet veto to remove $t\bar{t}$ background

- Throw out events with a jet with $p_T^{\mathrm{jet}} > p_T^{\mathrm{cut}}$

  Tevatron: $p_T^{\mathrm{cut}} \simeq 20\,\mathrm{GeV}$

  LHC: $p_T^{\mathrm{cut}} \simeq 25\,\mathrm{GeV}$



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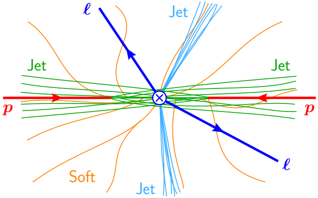
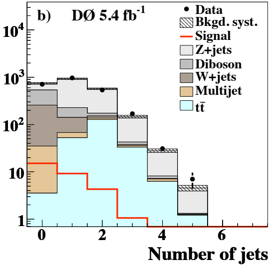


Tevatron excludes $m_H \simeq 165\,\mathrm{GeV}$ at 95% CL

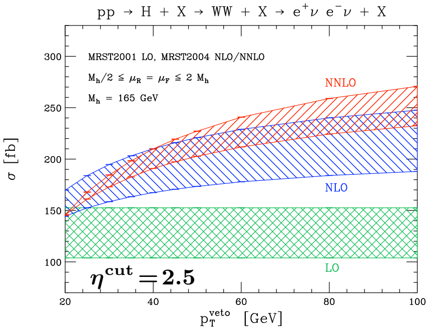
- Includes channels with jets
- Sensitivity dominated by 0-jet sample
- Exclusion requires reliable theory predictions
  Recently some discussion on theory uncert:
  - Large K-factor: vary μ by factor of 3
  - PDF set uncertainty

[Baglio, Djouadi (arXiv:1003.4266)]



[DØ (arXiv:1001.4481)]

$gg \to H \to WW$ with 0 Jets



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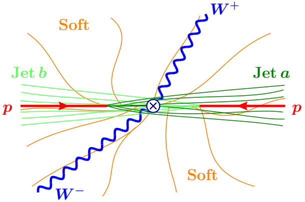

Jet veto restricts
initial-state radiation

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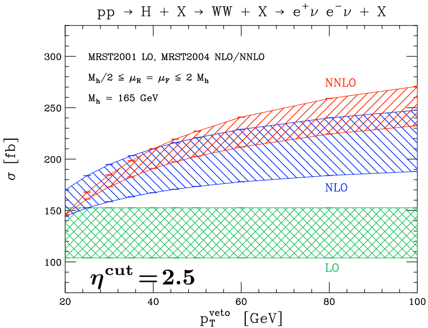

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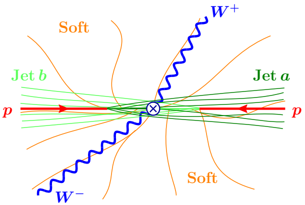

Jet veto restricts initial-state radiation

Jet veto leads to large double logarithms (if $p_T^{cut} \ll m_H$)

$$\sigma(p_T^{cut}) \propto 1 - \frac{2\alpha_s C_A}{\pi} \ln^2 \frac{p_T^{cut}}{m_H} + \dots$$

[Extracted from Catani, de Florian, Grazzini (hep-ph/0111164)]

- Need to be summed for reliable predictions *and* uncertainties

Large Jet Veto Logarithms

Cross section with jet veto p_T^{cut} [with $L = \ln(p_T^{\mathrm{cut}}/m_H)$]

$$\begin{aligned}\sigma = \sigma_0\{1 &+ \alpha_s[c_{12}L^2 + c_{11}L + c_{10} + n_1(p_T^{\mathrm{cut}})] \\ &+ \alpha_s^2[c_{24}L^4 + c_{23}L^3 + c_{22}L^2 + c_{21}L + c_{20} + n_2(p_T^{\mathrm{cut}})] \\ &+ \alpha_s^3[c_{36}L^6 + c_{35}L^5 + c_{34}L^4 + c_{33}L^3 + \dots] \\ &+ \dots\}\end{aligned}$$

Nonsingular terms $n_i(p_T^{\mathrm{cut}})$

- Suppressed by $\mathcal{O}(p_T^{\mathrm{cut}}/m_H)$ relative to singular terms
  e.g. $p_T^{\mathrm{cut}}/m_H \ln(p_T^{\mathrm{cut}}/m_H)$

Different calculations:

- Fixed order: LO, NLO, NNLO, …

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- Fixed order: LO, NLO, NNLO, ...
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- Resummed: LL, NLL, NLL′, NNLL

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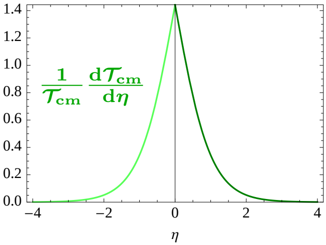
Beam Thrust

We want to sum jet veto logs to higher order

- Phase space is complicated for jet algorithm
  $\rightarrow$ Use beam thrust:

$$\mathcal{T}_{\mathrm{cm}} = \sum_k |\vec{p}_{kT}| e^{-|\eta_k|} = \sum_k (E_k - |p_k^z|)$$

- Central jet veto: $\mathcal{T}_{\mathrm{cm}} \leq \mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}} \ll m_H$
- $\mathcal{T}_{\mathrm{cm}}$ has no jet algorithm dependence



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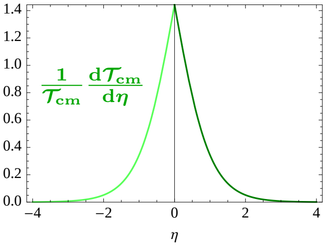
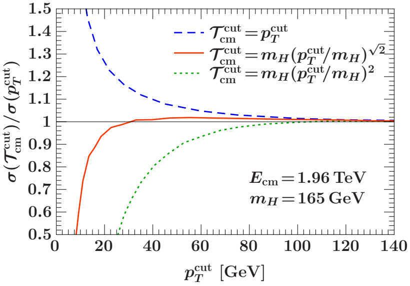


Compare to jet algorithm veto p_T^{cut}

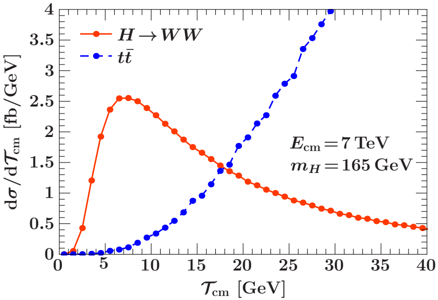
- Exact for LL results

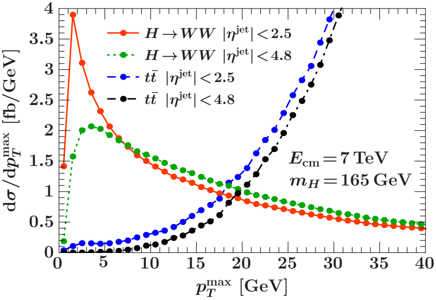
$$\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}} \simeq m_H \left(\frac{p_T^{\mathrm{cut}}}{m_H}\right)^{\sqrt{2}}$$

- Correspondence at NNLO within 3% for Tevatron and 7% for LHC
  [Using FEHiP: Anastasiou, Petriello, Melnikov]



Higgs vs. $t\bar{t}$ background using Pythia





- Lepton selection cuts from Atlas study [arXiv:0901.0512]
  Don't affect Higgs shape, affect $t\bar{t}$ shape by $5\% - 20\%$
- Hadronization is included, multiple parton interactions are not

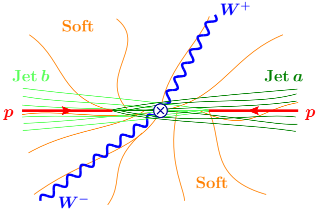
Beam Thrust Factorization Theorem

Sum large $\alpha_s^n \ln^m(\mathcal{T}_{\rm cm}/m_H)$ using:

Factorization theorem for $\mathcal{T}_{\rm cm} \ll m_H$

[Stewart, Tackmann, WW (arXiv:0910.0467)]

Derived using Soft-Collinear Effective Theory



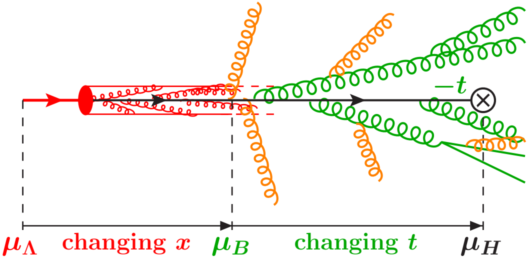
$$\frac{d\sigma}{d\mathcal{T}_{\rm cm}} = H_{gg}(m_t, m_H, \mu) \int dY \int dt_a\, B_i(t_a, x_a, \mu) \int dt_b\, B_j(t_b, x_b, \mu)$$
$$\times S_B\Big(\mathcal{T}_{\rm cm} - \frac{e^{-Y} t_a + e^{Y} t_b}{m_H}, \mu\Big)\Big[1 + \mathcal{O}\Big(\frac{\Lambda_{\rm QCD}}{m_H}, \frac{\mathcal{T}_{\rm cm}}{m_H}\Big)\Big]$$

H	hard function	virtual hard corrections	$\mu_H \simeq -i m_H$
B	beam function	virtual & real energetic ISR	$\mu_B \simeq \sqrt{\mathcal{T}_{\rm cm} m_H}$
S	soft function	virtual & real soft radiation	$\mu_S \simeq \mathcal{T}_{\rm cm}$

- Each function depends on only one scale $\rightarrow$ use RGE to sum large logs
- Sum large π^2 terms in the hard function $\rightarrow$ improves convergence

Physical Picture of the Initial State

Measurement sets scale at which PDF is probed, $\mu_B \simeq \sqrt{\mathcal{T}_{\rm cm} m_H}$



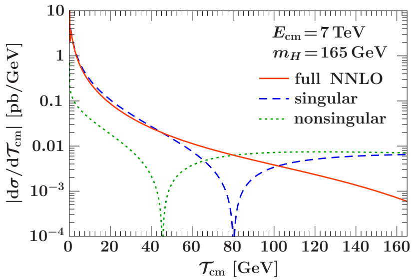
$\mu < \mu_B$: on-shell partons inside proton

- ISR described by PDF evolution, redistributes the momentum fraction x

$\mu > \mu_B$: off-shell partons inside incoming jet

- Colliding parton emits collinear and soft ISR
  builds up jet of size t, where $-t$ is transverse virtuality of colliding parton
- Wide angle emissions described by fixed-order corrections at $\mu \simeq \mu_B$
- Small angle emissions summed by evolution: changes t, not x or flavor

Cross Section at NNLL+NNLO



Nonsingular terms in our analysis

$$\sigma^{\text{ns,NNLO}}(\mathcal{T}_{\rm cm}) = \sigma^{\text{NNLO}}(\mathcal{T}_{\rm cm}) - \sigma^{\text{s,NNLO}}(\mathcal{T}_{\rm cm})$$

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- Cancellation between singular and nonsingular for large $\mathcal{T}_{\rm cm}$

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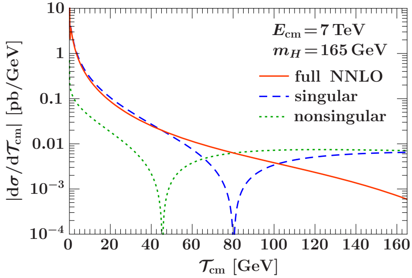

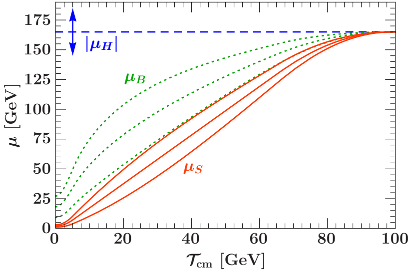

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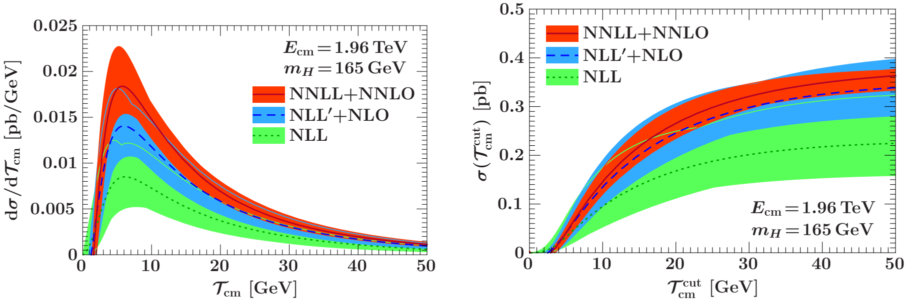
  $\rightarrow$ turn resummation off earlier using profile functions
  [Ligeti, Stewart, Tackmann (arXiv:0807.1926) Abbate et. al. (arXiv:1006.3080)]

Estimating uncertainties

- Take the envelope of varying μ_H, μ_B and μ_S separately

Higgs Production for Small $\mathcal{T}_{\mathrm{cm}}$

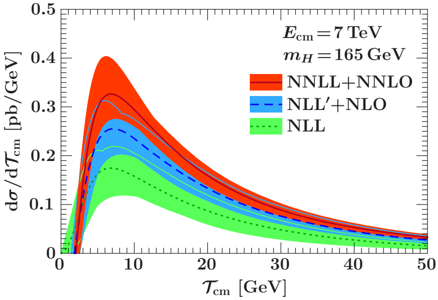
Tevatron:

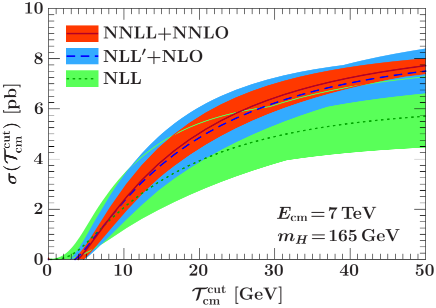


- Leptonic decay not included (multiply by branching ratio)
- Radiation peaked at small $\mathcal{T}_{\mathrm{cm}} \sim 5\,\mathrm{GeV}$
- Large perturbative corrections
- Resummed perturbation series converges (within uncertainty bands)
- Perturbative uncertainty dominates over hadronization corrections for Higgs (peak is perturbative)

Higgs Production for Small $\mathcal{T}_{\mathrm{cm}}$

LHC at $\mathbf{7\ TeV}$:





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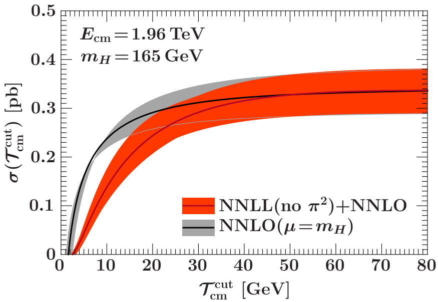
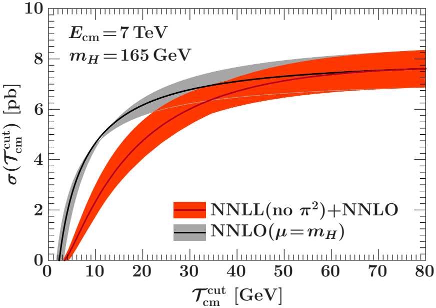


LHC at $7\ \mathrm{TeV}$:



No π^2 resummation and evaluating NNLO at $\mu = m_H$

- NNLL+NNLO merges with the NNLO for large $\mathcal{T}_{\mathrm{cm}}$

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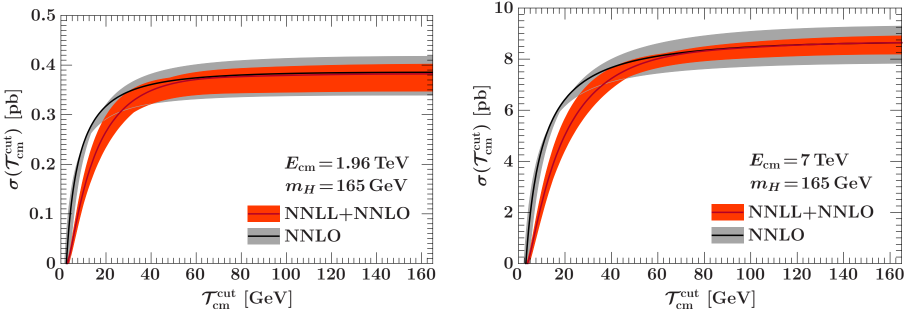


No π^2 resummation and evaluating NNLO at $\mu = m_H$

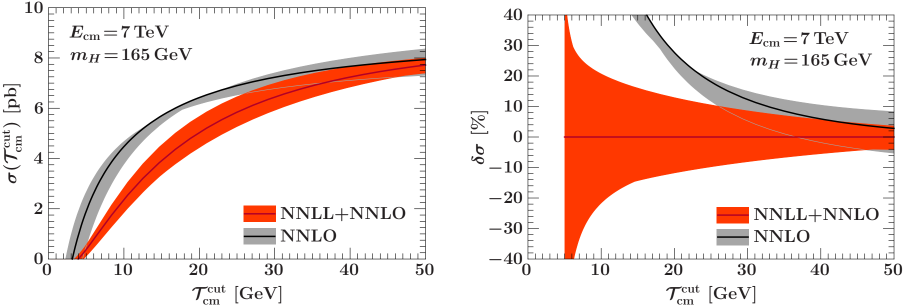
- NNLL+NNLO merges with the NNLO for large $\mathcal{T}_{\mathrm{cm}}$

With π^2 resummation and evaluating NNLO at $\mu = m_H/2$

- Increases the cross section
- π^2 resummation and evaluating at $\mu = m_H/2$ have very similar effect!
- Reduces uncertainties at large $\mathcal{T}_{\mathrm{cm}}$. Tevatron: $^{+5\%}_{-9\%}$, LHC: $^{+3\%}_{-5\%}$

Comparison to Fixed Order

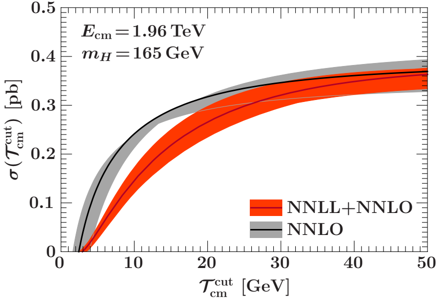
LHC at $7\,\mathrm{TeV}$:

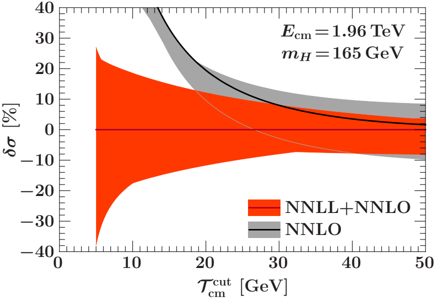


- NNLO evaluated at conventional $\mu = m_H/2$
- Central values differ by $\sim 25\%$ at $\mathcal{T}_{\rm cm}^{\rm cut} = 20\,\mathrm{GeV}$
  $> 50\%$ at $\mathcal{T}_{\rm cm}^{\rm cut} = 10\,\mathrm{GeV}$
- NNLO scale variation underestimates uncertainty for small $\mathcal{T}_{\rm cm}^{\rm cut}$
- Resummation is important for reliable predictions & uncertainties

Implications for Tevatron Higgs exclusion

Tevatron:





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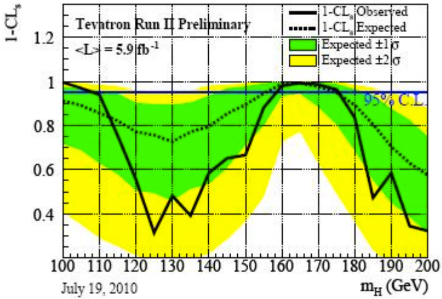
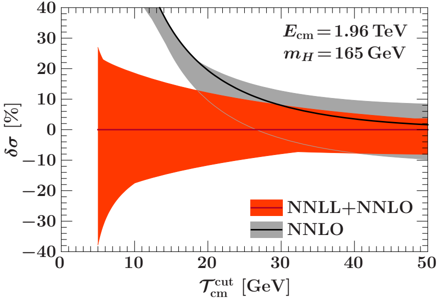


[CDF+DØ (arXiv:1007.4587)]



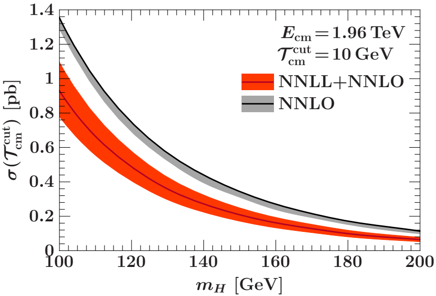
- Tevatron uses $\pm 7\%$ scale uncertainty at $p_T^{\rm cut} \simeq 20\,\mathrm{GeV}$ from NNLO

  [Anastasiou, Dissertori, Grazzini, Stöckli, Webber (arXiv:0905.3529)]

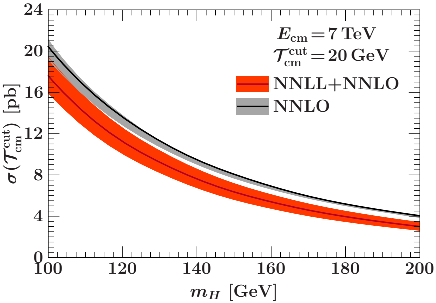
  compared to $\pm 20\%$ at $\mathcal{T}_{\rm cm}^{\rm cut} \simeq 10\,\mathrm{GeV}$ uncertainty from our NNLL+NNLO
- Reweighting parton shower (LL) with NNLO might improve central value but cannot yield better uncertainties than NNLL+NNLO

m_H dependence

Tevatron:



LHC at 7 TeV:



- Using representative cut $\mathcal{T}_{\rm cm}^{\rm cut} = 10\,\mathrm{GeV}$ for Tevatron
  $20\,\mathrm{GeV}$ for LHC
- Smaller m_H $\to$ smaller logs $\to$ effect of resummation smaller (relatively)
- Resummation remains important for reliable predictions & uncertainties

Conclusions

- Jet veto needed to remove $t\bar{t}$ background in $H \to WW \to \ell\nu\ell\bar{\nu}$.
- Strong jet veto leads to large logs in the cross section
  $\to$ logs must be summed for reliable predictions *and* uncertainties
- Beam thrust $\mathcal{T}_{\mathrm{cm}}$
  - easier phase space restrictions than jet algorithm
    $\to$ can sum beyond leading log
  - no jet algorithm dependence
  - good correspondence with p_T^{cut}
- Large perturbative uncertainties $(\sim 20\%)$ should be taken into account in Tevatron Higgs bound, and will weaken it

Thank you!

Theoretical Uncertainty is Important

CDF: $H \to W^+W^- \to \ell^\pm \ell'^\mp$ with no associated jet channel relative uncertainties (%)

Contribution	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet	$gg \to H$	WH	ZH	VBF
Cross Section :											
Scale								7.0			
PDF Model								7.6			
Total	*6.0*	*6.0*	*6.0*	10.0					**5.0**	**5.0**	10.0
Acceptance :											
Scale (leptons)								1.7			
Scale (jets)	*0.3*							1.5			
PDF Model (leptons)								2.7			
PDF Model (jets)	*1.1*							5.5			
Higher-order Diagrams		*10.0*	*10.0*	10.0		10.0			**10.0**	**10.0**	**10.0**
$\not{E}_T$ Modeling					19.5						
Conversion Modeling						10.0					
Jet Fake Rates											
(Low S/B)							22.0				
(High S/B)							25.0				
Jet Energy Scale	*2.6*	*6.1*	*3.4*	*26.0*	*17.5*	*3.1*		*5.0*	*10.5*	*5.0*	*11.5*
Lepton ID Efficiencies	*3.0*	*3.0*	*3.0*	*3.0*	*3.0*			*3.0*	*3.0*	*3.0*	*3.0*
Trigger Efficiencies	*2.0*	*2.0*	*2.0*	*2.0*	*2.0*			*2.0*	*2.0*	*2.0*	*2.0*
Luminosity	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*			*3.8*	*3.8*	*3.8*	*3.8*
Luminosity Monitor	*4.4*	*4.4*	*4.4*	*4.4*	*4.4*			*4.4*	*4.4*	*4.4*	*4.4*