

Higgs and Jet Vетos  
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Beam Thrust as Jet Veto  
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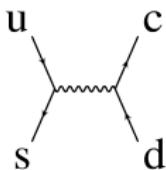
Cross Section at NNLL+NNLO  
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0-Jet Higgs Production  
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# Higgs Production with a Jet Veto at NNLL+NNLO

Wouter Waalewijn

UCSD

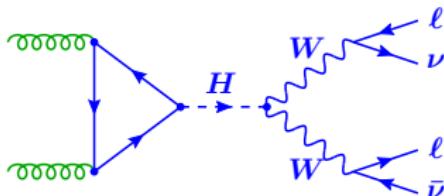
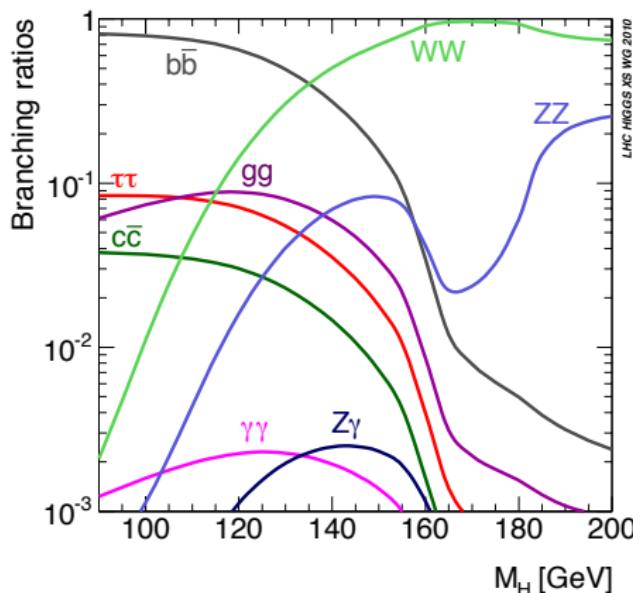


SCET Workshop  
March 6-8, 2011

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

arXiv:1012.4480

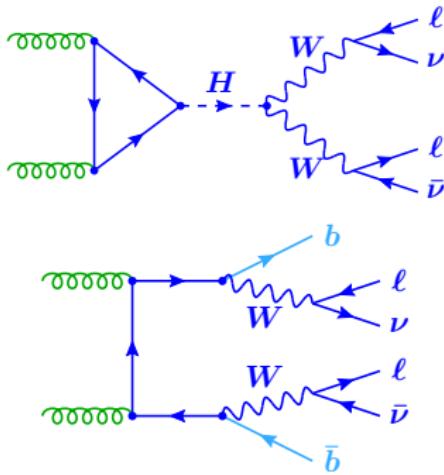
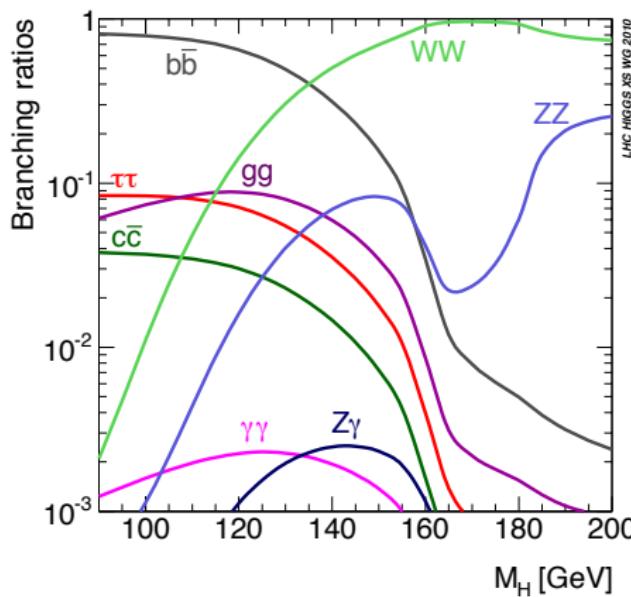
# Higgs at LHC and Tevatron



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

- Strong discovery potential at the LHC for  $m_H \gtrsim 130$  GeV
- Dominant channel in Tevatron exclusion

# Higgs at LHC and Tevatron



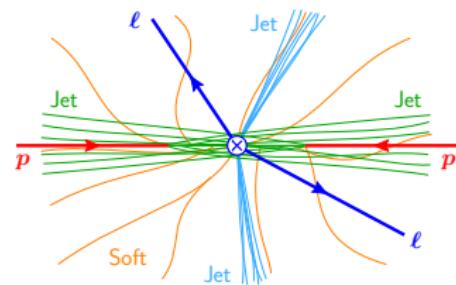
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- Strong discovery potential at the LHC for  $m_H \gtrsim 130$  GeV
- Dominant channel in Tevatron exclusion
- Large  $\sim 20 - 40 : 1$  background from  $t\bar{t} \rightarrow WWb\bar{b}$

# Higgs at LHC and Tevatron

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

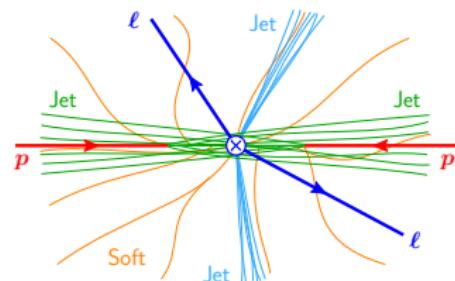
- ▶ Throw out events with a jet with  $p_T^{\text{jet}} > p_T^{\text{cut}}$
- Tevatron:  $p_T^{\text{cut}} \simeq 20 \text{ GeV}$
- LHC:  $p_T^{\text{cut}} \simeq 25 \text{ GeV}$
- ▶  $b$ -tagging is not sufficient



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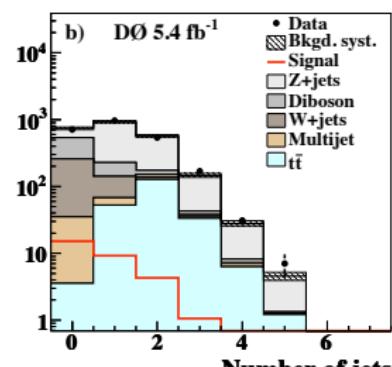


Tevatron excludes  $m_H \simeq 165 \text{ GeV}$  at 95% CL

- ▶ Includes channels with jets
- ▶ Largest sensitivity from 0-jet sample
- ▶ Exclusion requires reliable theory predictions  
 There is some discussion on theory uncert:

- ▶ Large K-factor: vary  $\mu$  by factor of 3
- ▶ PDF set uncertainty

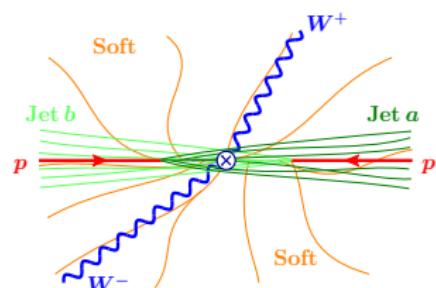
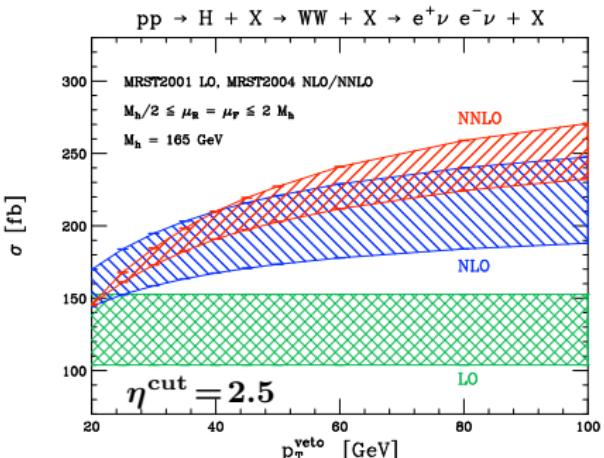
[Baglio, Djouadi (arXiv:1003.4266)]



[DØ (arXiv:1001.4481)]

# $gg \rightarrow H \rightarrow WW$ with 0 Jets

0-jet cross section has been calculated up to NNLO

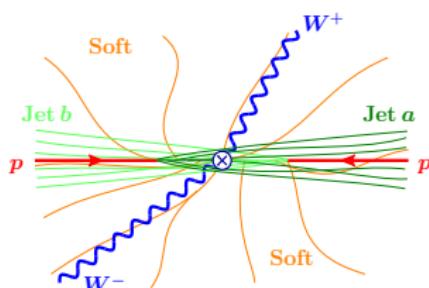
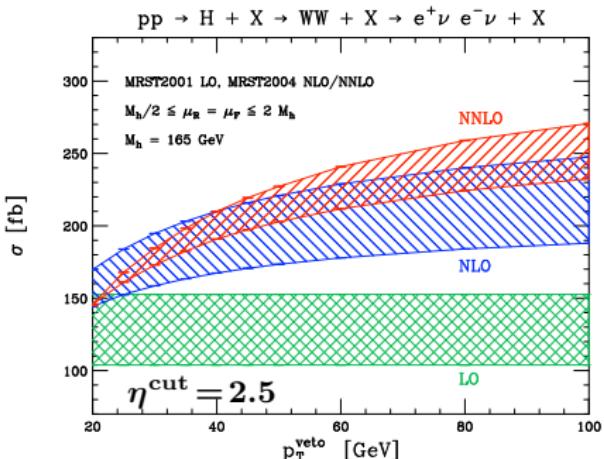


Jet veto restricts  
initial-state radiation

[Anastasiou, Dissertori, Stöckli (arXiv:0707.2373)]

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Jet veto restricts  
initial-state radiation

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

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

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

# Large Jet Veto Logarithms

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

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

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

- ▶ Suppressed by  $\mathcal{O}(p_T^{\text{cut}}/m_H)$  relative to singular terms

e.g.  $\frac{p_T^{\text{cut}}}{m_H} \ln \frac{p_T^{\text{cut}}}{m_H}$ ,  $\frac{p_T^{\text{cut}}}{m_H}$ .

Different calculations:

- ▶ Fixed order: LO, NLO, NNLO, ...

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Different calculations:

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- ▶ Monte Carlo: Parton-shower, MC@NLO
- ▶ Resummed: LL, NLL, NLL', NNLL

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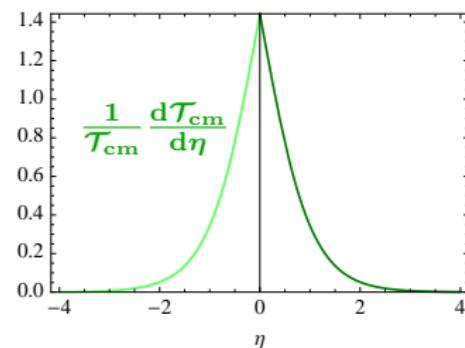
# Beam Thrust

We want to sum jet veto logs to higher order

- Phase space is complicated for jet algorithm  
→ Use beam thrust:

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

- Central jet veto:  $\mathcal{T}_{\text{cm}} \leq \mathcal{T}_{\text{cm}}^{\text{cut}} \ll m_H$



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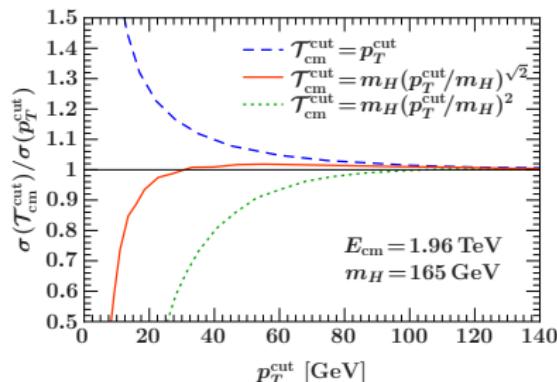
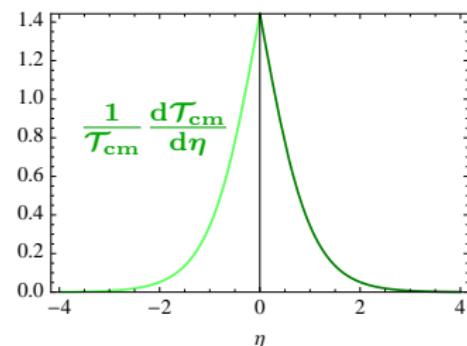
Compare to jet algorithm veto  $p_T^{\text{cut}}$

$$\sigma(\mathcal{T}_{\text{cm}}^{\text{cut}}) = \sigma_0 \left( 1 - \frac{\alpha_s C_A}{\pi} \ln^2 \frac{\mathcal{T}_{\text{cm}}^{\text{cut}}}{m_H} + \dots \right)$$

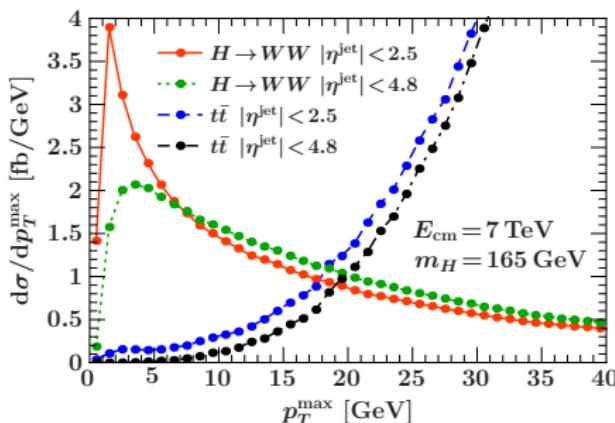
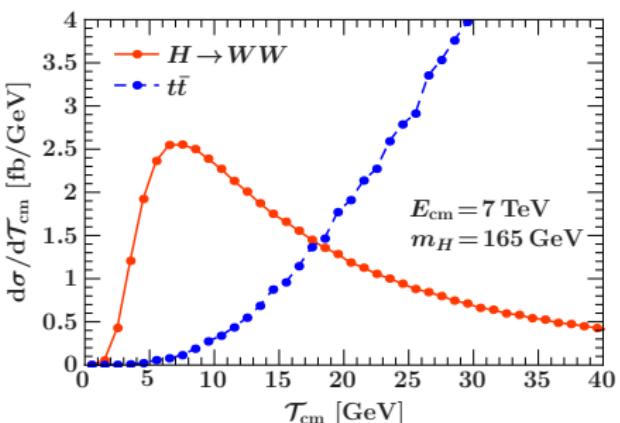
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- $\mathcal{T}_{\text{cm}}^{\text{cut}} \simeq m_H (p_T^{\text{cut}} / m_H)^{\sqrt{2}}$   
correspondence works well at NNLO

[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%
- ▶ No underlying event
- ▶ Correspondence looks more like  $T_{cm}^{\text{cut}} \simeq p_T^{\text{cut}}$

# Factorization Theorem for $\mathcal{T}_{\text{cm}} \ll m_H$

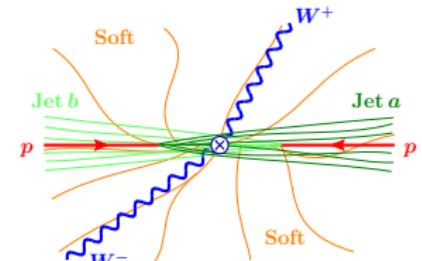
- Separate singular/nonsingular cross section:

$$\frac{d\sigma}{d\mathcal{T}_{\text{cm}}} = \frac{d\sigma^s}{d\mathcal{T}_{\text{cm}}} + \frac{d\sigma^{\text{ns}}}{d\mathcal{T}_{\text{cm}}}$$

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

$$\begin{aligned} \frac{d\sigma^s}{d\mathcal{T}_{\text{cm}}} &= H_{gg}(m_t, m_H, \mu) \int dY \int dt_a B_g(t_a, x_a, \mu) \int dt_b B_g(t_b, x_b, \mu) \\ &\times S_B^{gg} \left( \mathcal{T}_{\text{cm}} - \frac{e^{-Y} t_a + e^Y t_b}{m_H}, \mu \right) \end{aligned}$$

where  $x_{a,b} = (m_H/E_{\text{cm}}) e^{\pm Y}$ . [Stewart, Tackmann, WW (arXiv:0910.0467)]



$H$	hard function	$\mu_H \simeq -im_H$
$B$	beam function	$\mu_B \simeq \sqrt{\mathcal{T}_{\text{cm}} m_H}$
$S$	soft function	$\mu_S \simeq \mathcal{T}_{\text{cm}}$

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

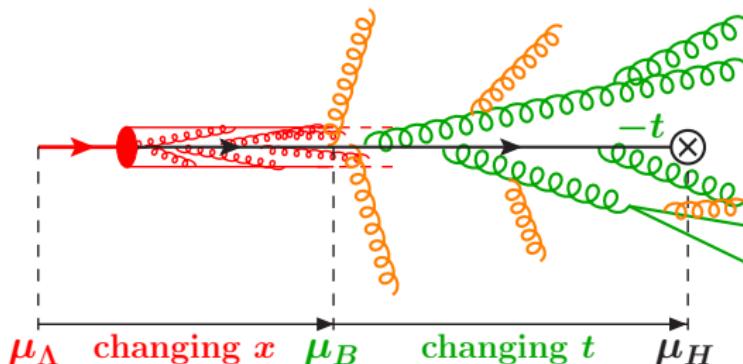
[Parisi, Sterman, Magnea, Eynck, Laenen. For Higgs: Ahrens, Becher, Neubert, Yang]

# Gluon Beam Function

Measures momentum fraction  $x$  and transverse virtuality  $-t$  of colliding gluon

$$B_g(t, x, \mu) = \sum_j \int \frac{d\xi}{\xi} \mathcal{I}_{gj}\left(t, \frac{x}{\xi}, \mu\right) f_j(\xi, \mu) \left[1 + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{t}\right)\right]$$

- ▶ Evaluate at  $\mu_B \simeq \sqrt{t}$  to avoid large logarithms



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$$\mathcal{I}_{gg}^{(1)} = \begin{array}{c} \text{Diagram of } \mathcal{I}_{gg}^{(1)} \text{ showing two gluon-gluon vertices with momenta } p, \alpha \text{ and } p, \beta \text{ and a central vertex with momenta } p - \ell, \sigma \text{ and } p - \ell, \rho. \end{array} + Z_{gg}^{f(1)} \quad \mathcal{I}_{gq}^{(1)} = \begin{array}{c} \text{Diagram of } \mathcal{I}_{gq}^{(1)} \text{ showing a gluon-gluon vertex with momenta } p, \alpha \text{ and a quark-gluon vertex with momenta } p, \beta \text{ and a central vertex with momenta } p - \ell, \sigma \text{ and } p - \ell, \rho. \end{array} + Z_{gq}^{f(1)}$$

$$\mathcal{I}_{gg}^{(1)}(t, z, \mu) = \frac{\alpha_s(\mu) C_A}{2\pi} \theta(z) \left[ \frac{2}{\mu^2} \left( \frac{\ln t/\mu^2}{t/\mu^2} \right)_+ \delta(1-z) + \frac{1}{\mu^2} \left( \frac{1}{t/\mu^2} \right)_+ P_{gg}(z) + \delta(t) \mathcal{I}_{gg}^\delta(z) \right]$$

$$\mathcal{I}_{gq}^{(1)}(t, z, \mu) = \frac{\alpha_s(\mu) C_F}{2\pi} \theta(z) \left[ \frac{1}{\mu^2} \left( \frac{1}{t/\mu^2} \right)_+ P_{gq}(z) + \delta(t) \mathcal{I}_{gq}^\delta(z) \right]$$

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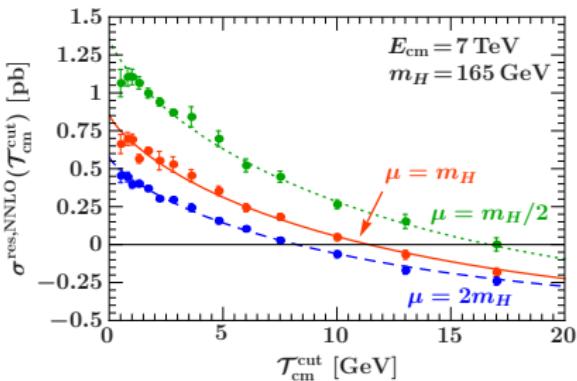
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Comparison with literature:

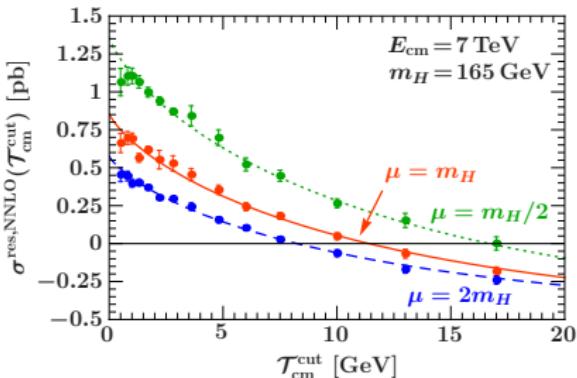
- [Fleming, Leibovich, Mehen (hep-ph/0607121)] calculated  $\mathcal{I}_{gg}$  in moment space:  
 $\mathcal{I}_{gg}^\delta$  differs by  $\pi^2$  term
- [Mantry, Petriello (arXiv:0911.4135)] calculated  $\mathcal{I}_{gj}(t, z, y, \mu)$ :  
 $\mathcal{I}_{gg}$  agrees,  $\mathcal{I}_{gq}^\delta$  differs ( $y \rightarrow 0$  does not change the renormalization)

# Extracting the NNLO Constant and Nonsingular



$$\begin{aligned}\sigma^{\text{NNLO}} = & \sigma_0 \{ 1 + \alpha_s [c_{12} L^2 + c_{11} L + c_{10} + n_1(T_{\text{cm}}^{\text{cut}})] \\ & + \alpha_s^2 [c_{24} L^4 + c_{23} L^3 + c_{22} L^2 + c_{21} L + c_{20} + n_2(T_{\text{cm}}^{\text{cut}})] \}\end{aligned}$$

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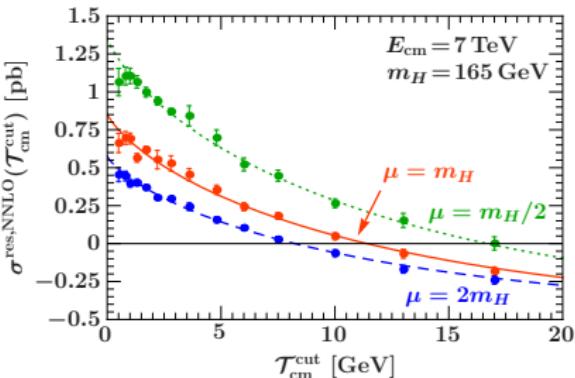


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►  $c_{20}$  only partly known:

$$\begin{aligned}c^\pi: & \pi^2 \text{ resummation}, \quad c^\mu: \mu \text{ variation of NLO}, \quad c^x: H^{(1)} S^{(1)} + \dots \\ \sigma^{\text{res}}(\mathcal{T}_{\text{cm}}^{\text{cut}}) \equiv & \sigma^{\text{NNLO}}(\mathcal{T}_{\text{cm}}^{\text{cut}}) - \sigma^{\text{NNLL}}(\mathcal{T}_{\text{cm}}^{\text{cut}}) \Big|_{\text{NNLO}} - c^\pi - c^\mu \\ = & c^\delta + c^x - c^\pi - c^\mu + \sigma^{\text{ns,NNLO}}(\mathcal{T}_{\text{cm}}^{\text{cut}})\end{aligned}$$

# Extracting the NNLO Constant and Nonsingular



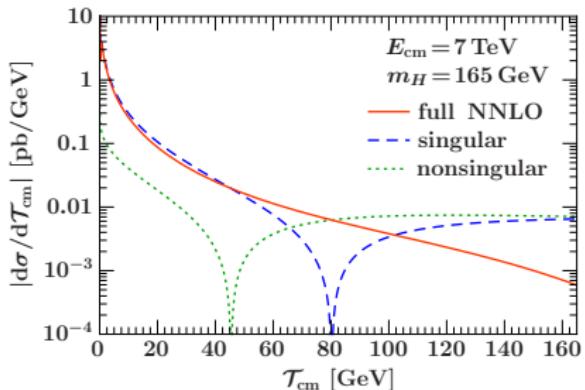
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- $\sigma^{\text{res}}$  is constant for  $T_{cm}^{\text{cut}} \rightarrow 0$ , so FEHIP has the right logs
- $H^{(2)} + S^{(2)} + 2B^{(2)} \sim c^\delta \ll c_{20}$  Negligible!

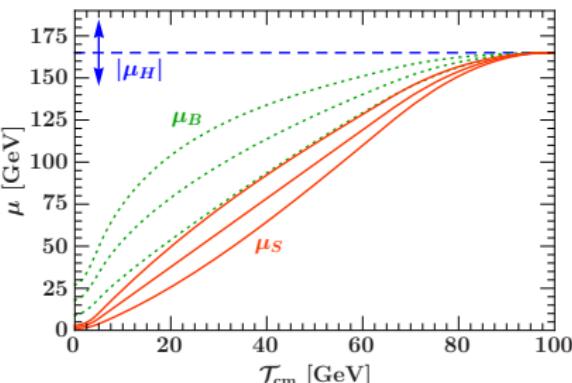
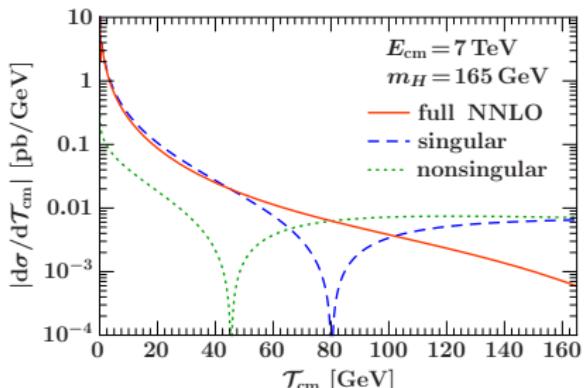
# Nonsingular Cross Section and Scale Choice



## Nonsingular cross section

- ▶ Suppressed by  $\mathcal{O}(T_{\text{cm}}/m_H)$ , included up to NNLO
- ▶ Cancellation between singular and nonsingular for large  $T_{\text{cm}}$

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- ▶ Suppressed by  $\mathcal{O}(T_{cm}/m_H)$ , included up to NNLO
- ▶ Cancellation between singular and nonsingular for large  $T_{cm}$ 
  - turn resummation off earlier using profile functions  
[Ligeti et al. (arXiv:0807.1926) Abbate et al. (arXiv:1006.3080)]

## Estimating uncertainties

- ▶ Take the envelope of varying  $\mu_H$ ,  $\mu_B$  and  $\mu_S$  separately

# Cross Section at NNLL+NNLO

$$\frac{d\sigma^{\text{NNLL+NNLO}}}{d\mathcal{T}_{\text{cm}}} = \frac{d\sigma^{\text{NNLL}}}{d\mathcal{T}_{\text{cm}}} + \frac{d\sigma^\delta}{d\mathcal{T}_{\text{cm}}} + \frac{d\sigma^{\text{ns,NNLO}+\pi^2}}{d\mathcal{T}_{\text{cm}}}$$

- ▶ NNLL now includes two-loop H, B and S except for constants
- ▶ Sum of constants  $c^\delta$  was extracted numerically and is negligible  
At NNLL' it multiplies a Sudakov, so we take:

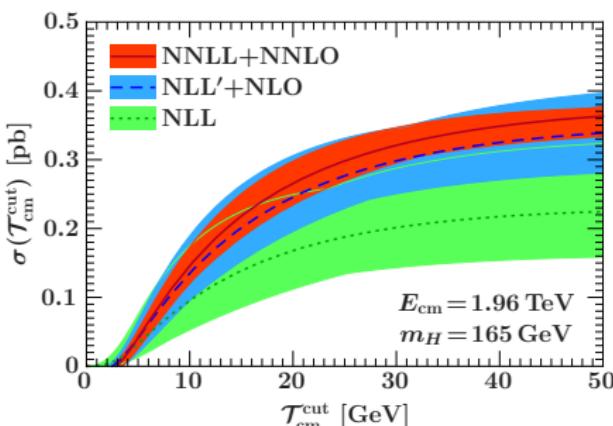
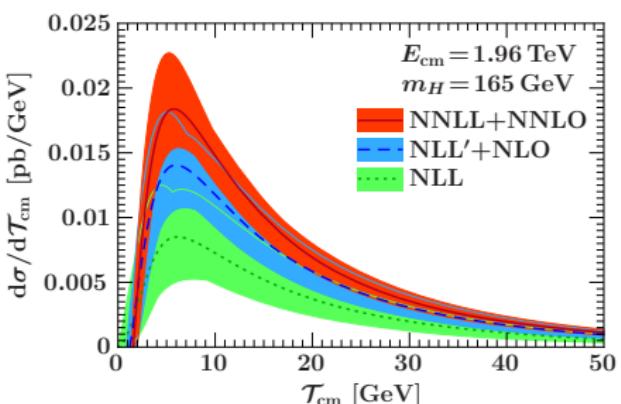
$$\frac{d\sigma^\delta}{d\mathcal{T}_{\text{cm}}} = c^\delta(\mu_{\text{ns}}) U_H(\mu_H, \mu) U_B^g(\mu_B, \mu) \otimes U_B^g(\mu_B, \mu) \otimes U_S(\mu_S, \mu)$$

- ▶ We also include  $\pi^2$  resummation for the nonsingular
  - ▶ Preserve cancellation between sing. and nonsing. for large  $\mathcal{T}_{\text{cm}}$
  - ▶ Subleading factorization theorems include leading hard function

$$\frac{d\sigma^{\text{ns,NNLO}+\pi^2}}{d\mathcal{T}_{\text{cm}}} = U_H(-i\mu_{\text{ns}}, \mu_{\text{ns}}) \left[ \frac{d\sigma^{\text{ns,NNLO}}}{d\mathcal{T}_{\text{cm}}} - \frac{\alpha_s C_A}{2\pi} \pi^2 \frac{d\sigma^{\text{ns,NLO}}}{d\mathcal{T}_{\text{cm}}} \right]$$

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

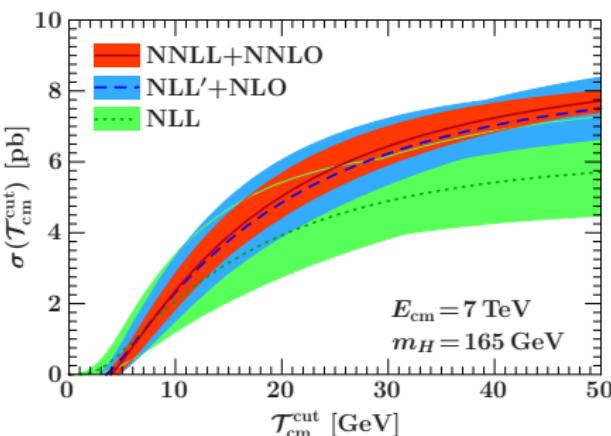
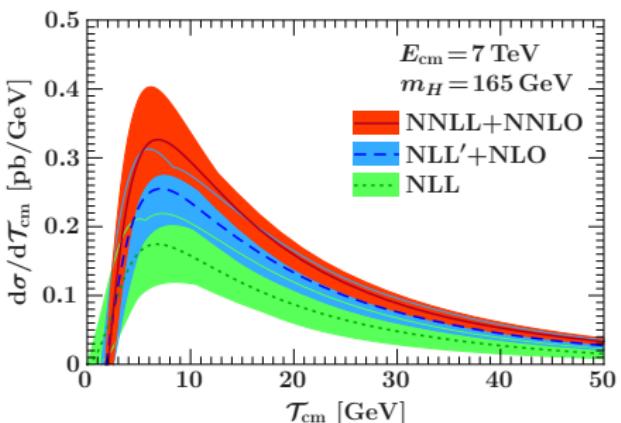
Tevatron:



- Leptonic decay not included (multiply by branching ratio)
- Spectrum peaked at small  $\mathcal{T}_{\text{cm}} \sim 5 \text{ GeV}$
- Large perturbative corrections
- Resummed perturbation series converges

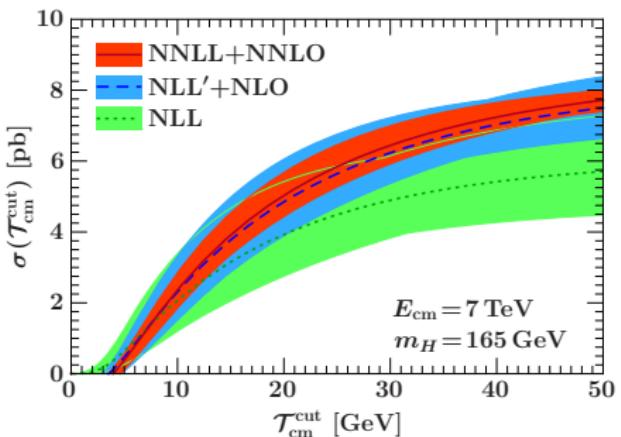
# Higgs Production for Small $\mathcal{T}_{\text{cm}}$

LHC at 7 TeV:

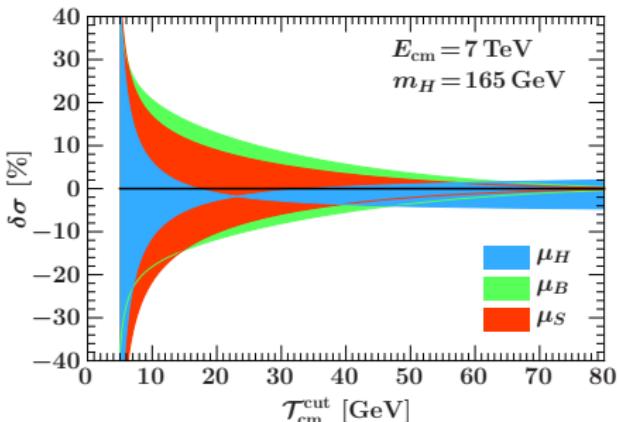


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# Some Details

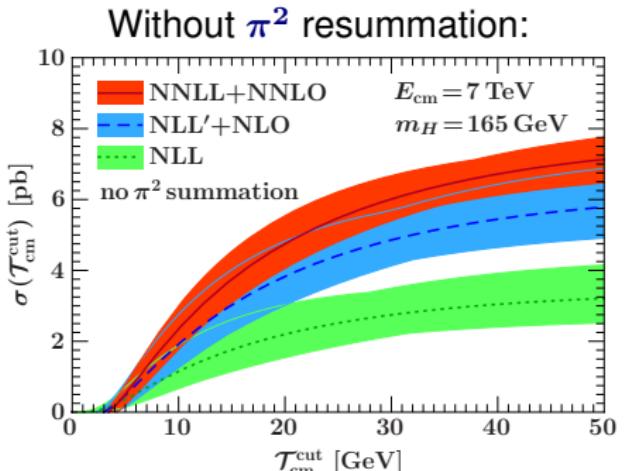
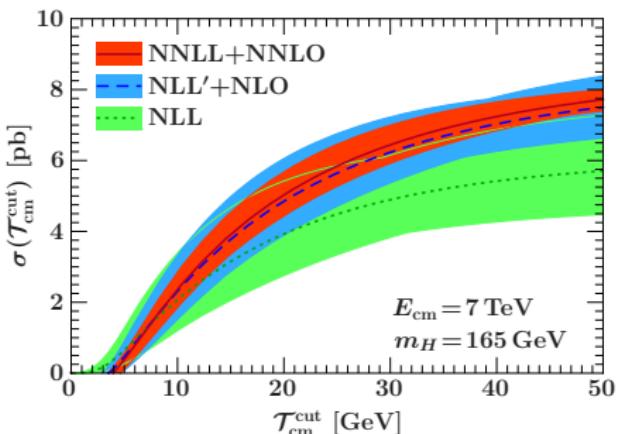


## Relative scale variations at NNLL:



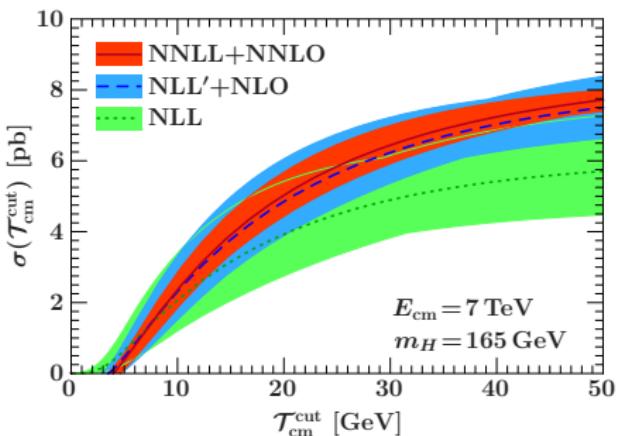
- ▶ Uncertainties are envelope of independent scale variations
- One scale variation dominates:  $\mu_S$ ,  $\mu_B$  at small  $\mathcal{T}_{\text{cm}}^{\text{cut}}$ ,  $\mu_H$  at large  $\mathcal{T}_{\text{cm}}^{\text{cut}}$

# Some Details

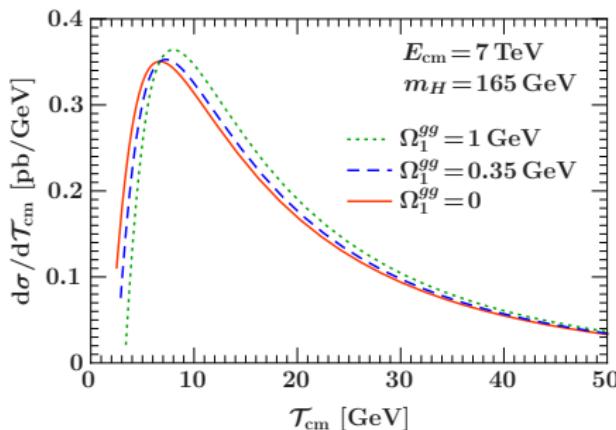


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- ▶ Summing large  $\pi^2$  terms in the hard function improves convergence

# Some Details



Including nonperturbative corrections:



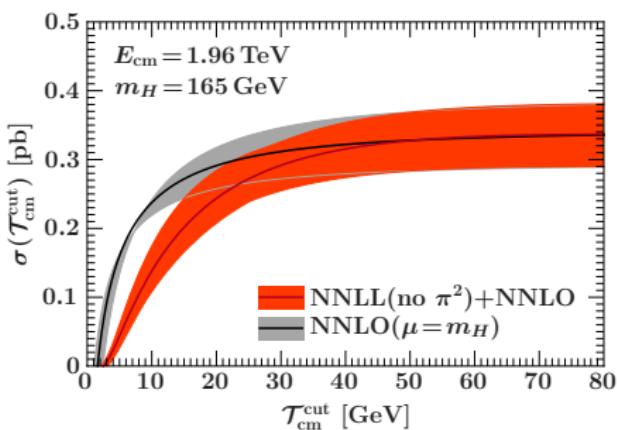
- Uncertainties are envelope of independent scale variations  
One scale variation dominates:  $\mu_S$ ,  $\mu_B$  at small  $\mathcal{T}_{\text{cm}}^{\text{cut}}$ ,  $\mu_H$  at large  $\mathcal{T}_{\text{cm}}^{\text{cut}}$
- Summing large  $\pi^2$  terms in the hard function improves convergence
- Nonperturbative corrections from the soft function

$$S_B^{gg}(k, \mu_S) = S_{\text{pert}}^{gg}(k, \mu_S) - 2\Omega_1^{gg} \frac{dS_{\text{pert}}^{gg}(k, \mu_S)}{dk} + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{k^3}\right)$$

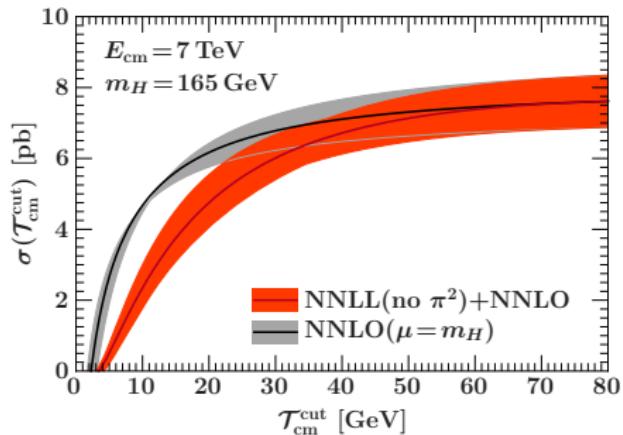
Hadronization corrections small → peak is perturbative

# Higgs Production for Large $\mathcal{T}_{\text{cm}}$

Tevatron:



LHC at 7 TeV:

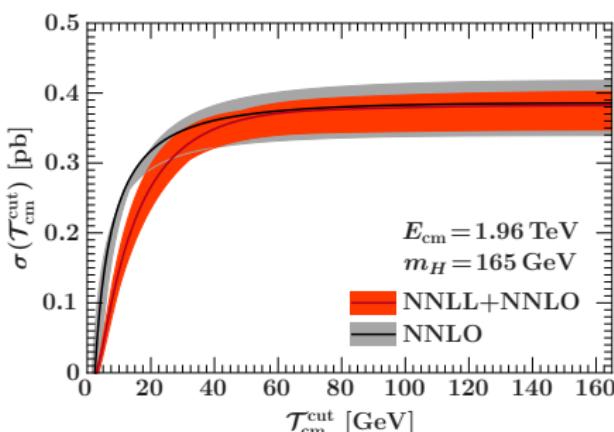


No  $\pi^2$  resummation and evaluating NNLO at  $\mu = m_H$

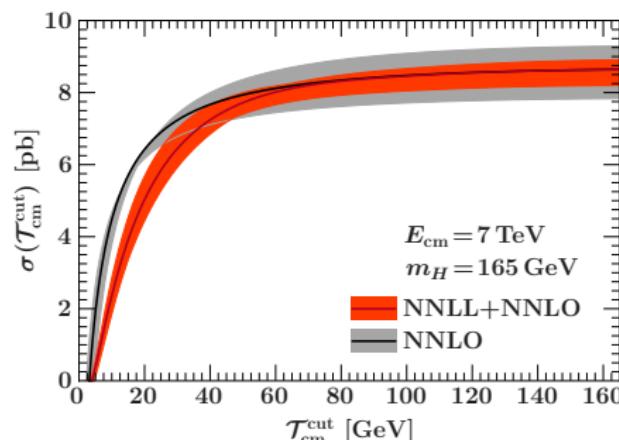
- ▶ NNLL+NNLO merges with the NNLO for large  $\mathcal{T}_{\text{cm}}$

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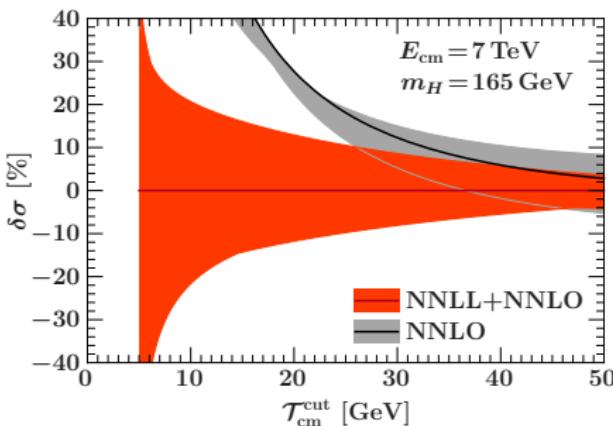
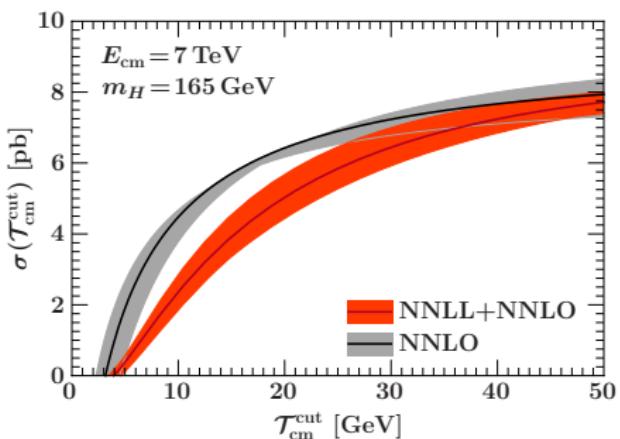
- ▶ NNLL+NNLO merges with the NNLO for large  $\mathcal{T}_{\text{cm}}$

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

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

# Comparison to Fixed Order

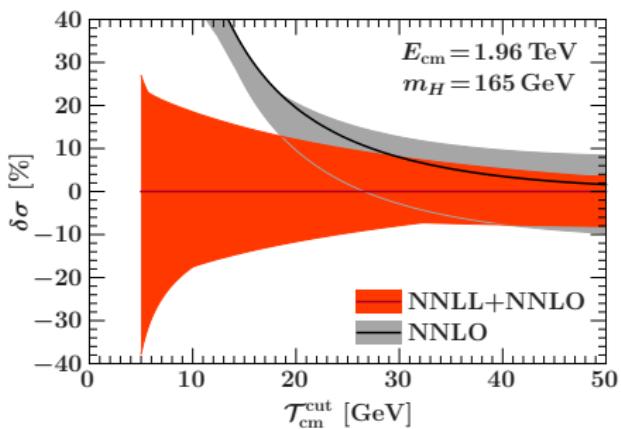
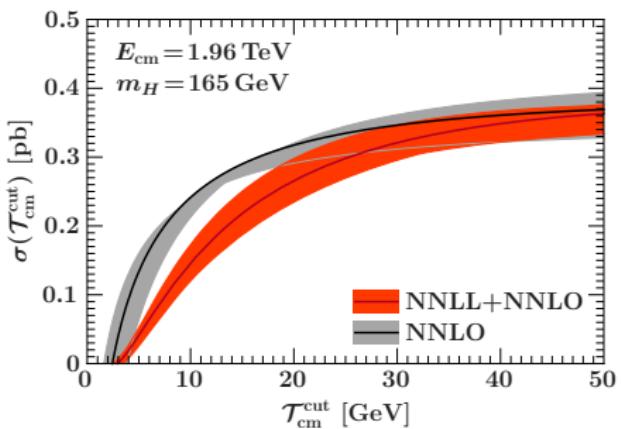
LHC at 7 TeV:



- ▶ NNLO evaluated at conventional  $\mu = m_H/2$
- ▶ Central values differ significantly for small  $\mathcal{T}_{\text{cm}}^{\text{cut}}$
- ▶ NNLO scale variation underestimates uncertainty for small  $\mathcal{T}_{\text{cm}}^{\text{cut}}$
- ▶ Resummation is important for reliable predictions & uncertainties

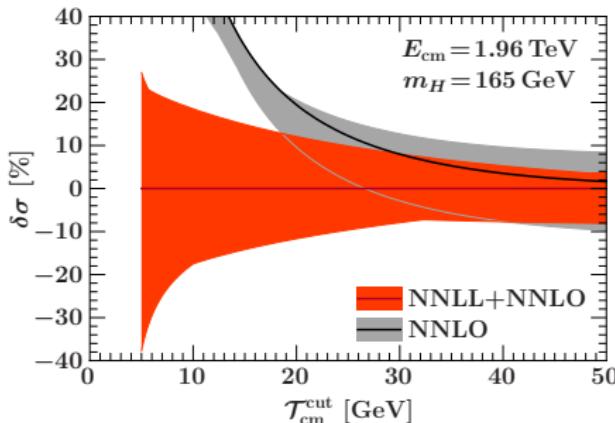
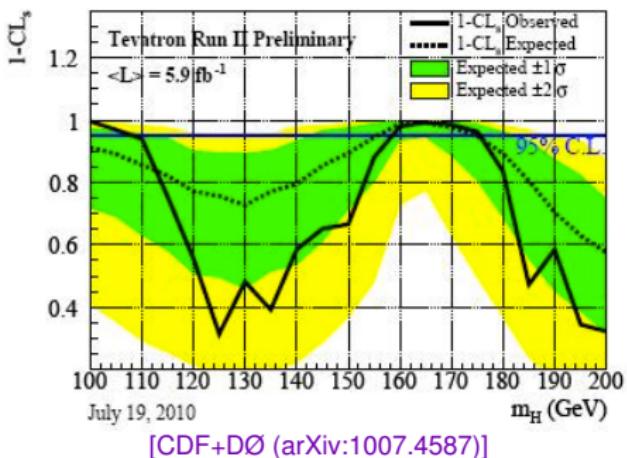
# Implications for Tevatron Higgs exclusion

Tevatron:



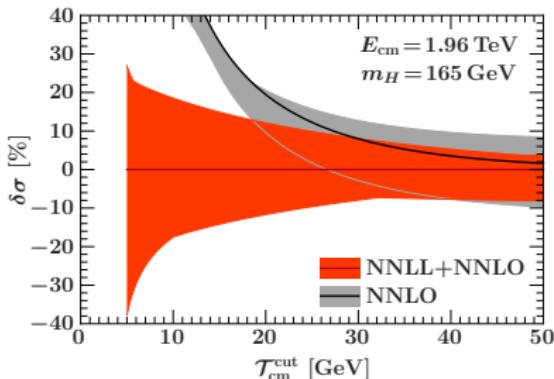
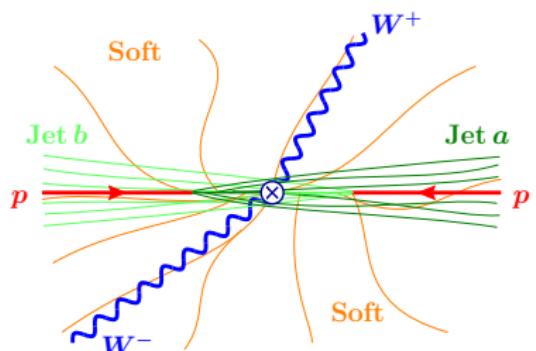
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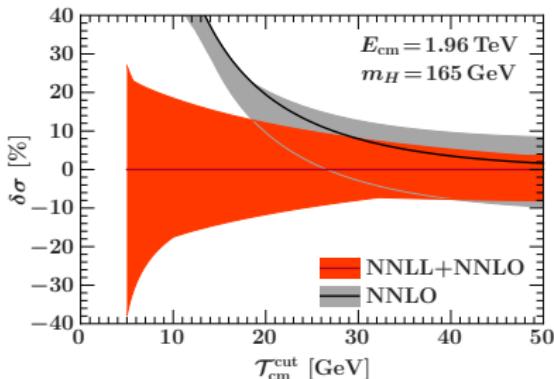
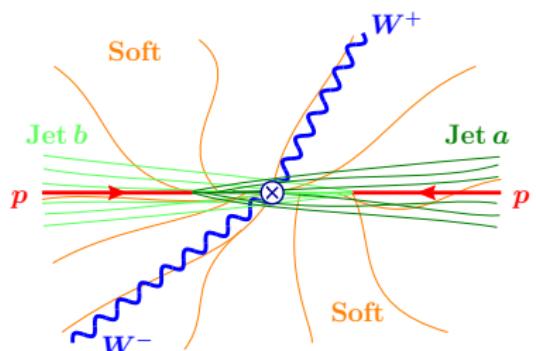
- ▶ Tevatron uses 7% scale uncertainty at  $p_T^{\text{cut}} \simeq 20 \text{ GeV}$  from NNLO  
 [Anastasiou, Dissertori, Grazzini, Stöckli, Webber (arXiv:0905.3529)]  
 compared to 15 – 20% at  $p_T^{\text{cut}} \lesssim 20 \text{ GeV}$  from our NNLL+NNLO
- ▶ Reweighting parton shower (LL) with NNLO might improve central value  
 but cannot yield better uncertainties than NNLL+NNLO

# Conclusions



- ▶ Jet veto needed to remove  $t\bar{t}$  background in  $H \rightarrow WW \rightarrow \ell\nu\ell\bar{\nu}$ .
- ▶ Strong jet veto leads to large logs in the cross section
  - logs must be summed for reliable predictions *and* uncertainties
- ▶ Beam thrust  $T_{cm}$  has easier phase space restrictions than jet algorithm
  - we resum the jet veto logs to NNLL+NNLO
- ▶ Larger scale uncertainties (15 – 20%) should be taken into account in Tevatron Higgs bound, and will weaken it

# Conclusions



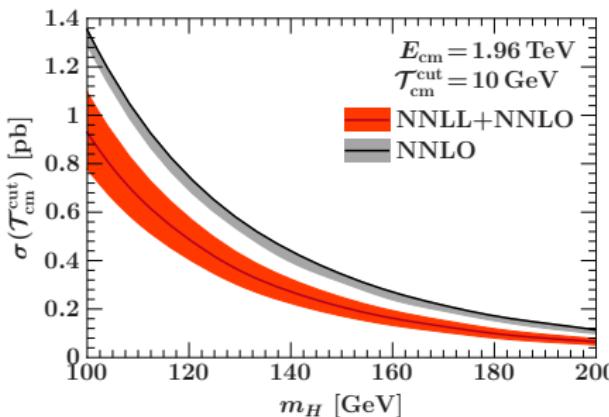
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Thank you!

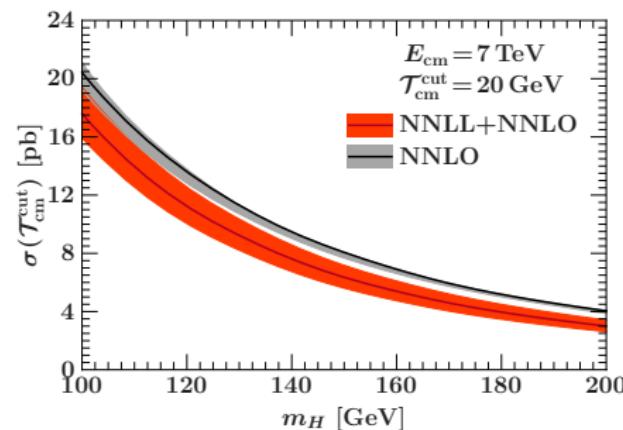
# Backup slides

# $m_H$ dependence

Tevatron:



LHC at 7 TeV:



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

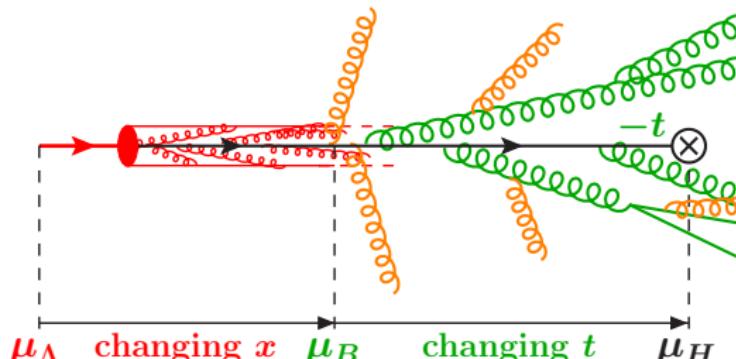
# Theoretical Uncertainty is Important

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

Contribution	$WW$	$WZ$	$ZZ$	$t\bar{t}$	DY	$W\gamma$	$W+\text{jet}$	$gg \rightarrow H$	$WH$	$ZH$	$VBF$
<b>Cross Section :</b>											
Scale								7.0			
PDF Model								7.6			
Total	6.0	6.0	6.0	10.0					<b>5.0</b>	<b>5.0</b>	10.0
<b>Acceptance :</b>											
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			<b>10.0</b>	<b>10.0</b>	<b>10.0</b>
$\cancel{E}_T$ 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

# Physical Picture of the Initial State

Measurement sets scale at which PDF is probed,  $\mu_B \simeq \sqrt{T_{\text{cm}} m_H}$



$\mu < \mu_B$ : 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