Higgs Production with a Jet Veto at NNLL+NNLO

Frank Tackmann

Massachusetts Institute of Technology

Discussion with LHC Higgs working group
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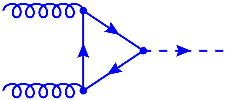
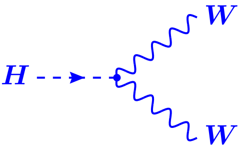
with Iain Stewart, Carola Berger,
Claudio Marcantonini, Wouter Waalewijn

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

- Dominant production: $gg \to H$

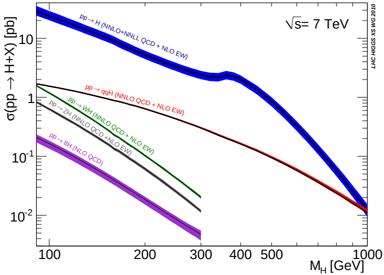


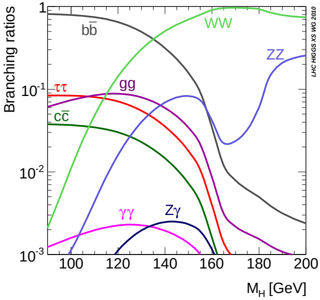
- Dominant decay for $m_H \gtrsim 130\,\mathrm{GeV}$
  $H \to WW$



$\Rightarrow$ Important early discovery channel at LHC

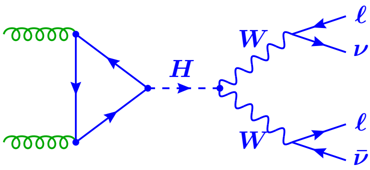
$\Rightarrow$ Dominant channel in Tevatron exclusion





$H \to WW$ vs. $t\bar{t} \to WWb\bar{b}$

1



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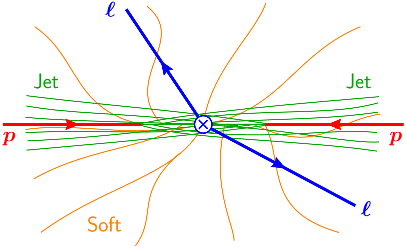

to

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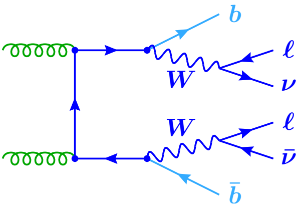

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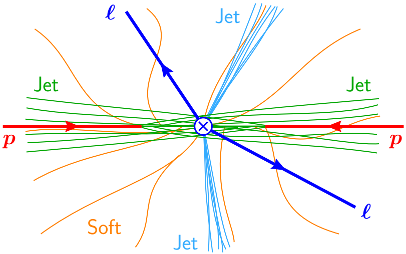


⇒ Veto events with central jets, measure $pp \to H(\to WW) + 0$ jets

How to Veto Jets

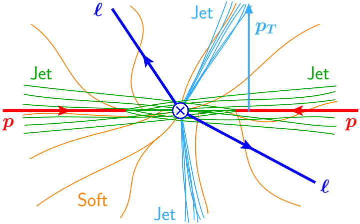
Conventional: Jet algorithm ($\eta < \eta^{\rm cut}$)

- Search for jets and require $p_T^{\rm jet} < p_T^{\rm cut}$

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

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

- Complicated phase-space restrictions



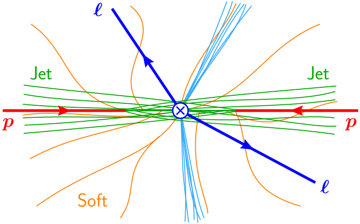
Alternative: Event shape

- Measure beam thrust of each event

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

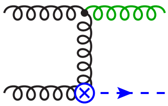
  and require $\mathcal{T}_{\rm cm} < \mathcal{T}_{\rm cm}^{\rm cut}$

- Nice for analytic higher-order calculations



Large Logarithms from Jet Veto

Even if hard signal process $gg \to H$ contains no jets,
jet veto affects cross section by restricting hadronic ISR



$\Rightarrow$ t-channel singularities produce double logarithms

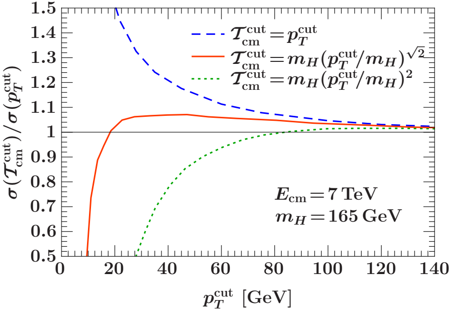
$$\sigma(p_T^{\mathrm{cut}}) \propto 1 - \frac{3\alpha_s}{\pi}\, 2\ln^2 \frac{p_T^{\mathrm{cut}}}{m_H} + \cdots \qquad \sigma(\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}}) \propto 1 - \frac{3\alpha_s}{\pi} \ln^2 \frac{\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}}}{m_H} + \cdots$$

Appropriate correspondence

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

- Exact for leading double logarithms
- NNLO spectra agree to 7%

$\Rightarrow$ $\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}} \simeq 10\ \mathrm{GeV}$ corresponds to $p_T^{\mathrm{cut}} \simeq 20\ \mathrm{GeV}$



Perturbative Structure of Cross Section

$$\sigma_{\text{0-jet}} = 1$$
$$+ \alpha_s L^2 + \alpha_s L + \alpha_s n_1(p_T^{\text{cut}})$$
$$+ \alpha_s^2 L^4 + \alpha_s^2 L^3 + \alpha_s^2 L^2 + \alpha_s^2 L + \alpha_s^2 n_2(p_T^{\text{cut}})$$
$$+ \alpha_s^3 L^6 + \alpha_s^3 L^5 + \alpha_s^3 L^4 + \alpha_s^3 L^3 + \alpha_s^3 L^2 + \alpha_s^3 L + \alpha_s^3 n_3(p_T^{\text{cut}})$$
$$+ \vdots + \vdots + \vdots + \vdots + \vdots + \vdots + \ddots$$

Jet-Veto Logarithms can easily get large

$$L^2 = 2\ln^2 \frac{p_T^{\text{cut}}}{m_H} \quad \text{or} \quad L^2 = \ln^2 \frac{\mathcal{T}_{\text{cm}}^{\text{cut}}}{m_H}$$
$$= 9, \ldots, 4 \qquad \text{for} \quad p_T^{\text{cut}} = 20, \ldots, 40\,\text{GeV},\ m_H = 165\,\text{GeV}$$

Pert. structure is *very* different for inclusive and 0-jet cross sections

- Inclusive cross section: dominated by n_i terms (logarithms vanish $L = 0$)
- 0-jet cross section: dominated by logarithmic terms $\alpha_s^n L^m$

$\Rightarrow$ Scale uncertainties for each are practically unrelated

Fixed-Order Perturbation Theory

$$\sigma_{\text{0-jet}} = 1$$

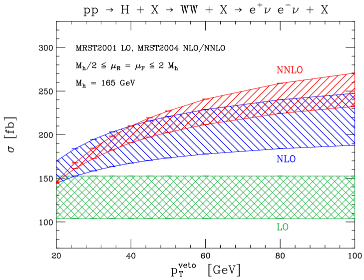
$$+ \alpha_s L^2 + \alpha_s L + \alpha_s n_1(p_T^{\text{cut}}) \qquad \text{NLO}$$

$$+ \alpha_s^2 L^4 + \alpha_s^2 L^3 + \alpha_s^2 L^2 + \alpha_s^2 L + \alpha_s^2 n_2(p_T^{\text{cut}}) \qquad \text{NNLO}$$

$$+ \alpha_s^3 L^6 + \alpha_s^3 L^5 + \alpha_s^3 L^4 + \alpha_s^3 L^3 + \alpha_s^3 L^2 + \alpha_s^3 L + \alpha_s^3 n_3(p_T^{\text{cut}})$$

$$+ \vdots + \vdots + \vdots + \vdots + \vdots + \vdots + \ddots$$

- FEHiP, HNNLO: Fully differential NNLO cross section known numerically [Anastasiou, Melnikov, Petriello; Grazzini]
- FO scale only appears in $\alpha_s(\mu)$
  $\longrightarrow$ does not probe logarithms
- FO expansion breaks down at small p_T^{cut}
  Apparent convergence at small p_T^{cut} comes from cancellation between large positive K factor (virtual corrections) and large negative logs at this order



[Anastasiou et al.]

Resummation of Logarithms

$$\sigma_{\text{0-jet}} = 1$$

$+ \alpha_s L^2$	$+ \alpha_s L$	$+ \alpha_s n_1(p_T^{cut})$					NLO
$+ \alpha_s^2 L^4$	$+ \alpha_s^2 L^3$	$+ \alpha_s^2 L^2$	$+ \alpha_s^2 L$	$+ \alpha_s^2 n_2(p_T^{cut})$			NNLO
$+ \alpha_s^3 L^6$	$+ \alpha_s^3 L^5$	$+ \alpha_s^3 L^4$	$+ \alpha_s^3 L^3$	$+ \alpha_s^3 L^2$	$+ \alpha_s^3 L$	$+ \alpha_s^3 n_3(p_T^{cut})$	
$+ \vdots$	$+ \vdots$	$+ \vdots$	$+ \vdots$	$+ \vdots$	$+ \vdots$	$+ \ddots$	
LL	NLL	NNLL		N^{3}LL			

Initial-state parton shower resums LL

- Pythia/Herwig is LL (maybe a bit NLL from tuning)
- MC@NLO, POWHEG: combine fixed NLO with parton-shower LL

Resummation of Logarithms

$$\sigma_{\text{0-jet}} = 1$$

$+\ \alpha_s L^2$	$+\ \alpha_s L$	$+\ \alpha_s n_1(p_T^{\mathrm{cut}})$					NLO
$+\ \alpha_s^2 L^4$	$+\ \alpha_s^2 L^3$	$+\ \alpha_s^2 L^2$	$+\ \alpha_s^2 L$	$+\ \alpha_s^2 n_2(p_T^{\mathrm{cut}})$			NNLO
$+\ \alpha_s^3 L^6$	$+\ \alpha_s^3 L^5$	$+\ \alpha_s^3 L^4$	$+\ \alpha_s^3 L^3$	$+\ \alpha_s^3 L^2$	$+\ \alpha_s^3 L$	$+\ \alpha_s^3 n_3(p_T^{\mathrm{cut}})$	
$+\ \vdots$	$+\ \vdots$	$+\ \vdots$	$+\ \vdots$	$+\ \vdots$	$+\ \vdots$	$+\ \ddots$	
LL	NLL	NNLL		N^{3}LL			

Initial-state parton shower resums LL

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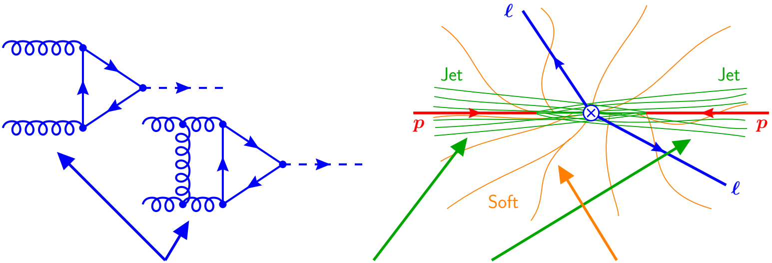
Our calculation: NNLL+NNLO

- Using $\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}}$ and SCET as tool for resummation $\longrightarrow$ two orders beyond PS
- $n_{1,2}(\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}})$ numerically from FEHiP $\longrightarrow$ reproduce full NNLO

Factorization Theorem for Beam Thrust



$$\frac{\mathrm{d}\sigma^{\mathrm{s}}}{\mathrm{d}\mathcal{T}_{\mathrm{cm}}} = H_{gg}(\mu) \int \mathrm{d}t_a \mathrm{d}t_b \, B_g(t_a, \mu) \, B_g(t_b, \mu) \, S_B^{gg}\Big(\mathcal{T}_{\mathrm{cm}} - \frac{t_a + t_b}{m_H}, \mu\Big)$$

Function	contains	at the scale
Hard H_{gg}	hard virtual radiation	$\lvert\mu_H\rvert \simeq m_H$
Beam B_g	virtual & real energetic ISR	$\mu_B \simeq \sqrt{\mathcal{T}_{\mathrm{cm}} m_H}$
Soft S_B^{gg}	virtual & real soft radiation	$\mu_S \simeq \mathcal{T}_{\mathrm{cm}}$

Summation of Jet-Veto Logarithms

Logarithms are split apart by factorization

$$\frac{\mathrm{d}\sigma^s}{\mathrm{d}\mathcal{T}_{\mathrm{cm}}} = H_{gg}(\mu) \int \mathrm{d}t_a \mathrm{d}t_b\, B_g(t_a, \mu)\, B_g(t_b, \mu)\, S_B^{gg}\Big(\mathcal{T}_{\mathrm{cm}} - \frac{t_a + t_b}{m_H}, \mu\Big)$$

$$\ln^2 \frac{\mathcal{T}_{\mathrm{cm}}}{m_H} = 2\ln^2 \frac{m_H}{\mu} \quad - \quad \ln^2 \frac{\mathcal{T}_{\mathrm{cm}} m_H}{\mu^2} \quad + \quad 2\ln^2 \frac{\mathcal{T}_{\mathrm{cm}}}{\mu}$$

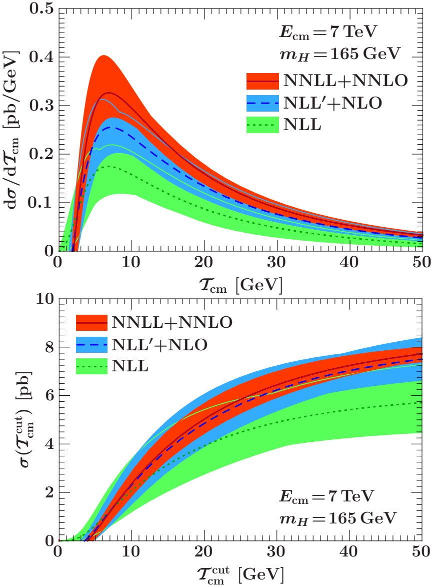
$$\Rightarrow \quad |\mu_H| \simeq m_H \qquad \mu_B \simeq \sqrt{\mathcal{T}_{\mathrm{cm}} m_H} \qquad \mu_S \simeq \mathcal{T}_{\mathrm{cm}}$$

- Each function is computed in perturbation theory at its own scale (where it has no large logarithms): $H_{gg}(\mu_H)$, $B_g(\mu_B)$, $S_B^{gg}(\mu_S)$
- RG evolution to common scale μ resums all logarithms

Perturbation theory at *each scale* contributes to scale uncertainties

- Jet-veto introduces sensitivity to smaller scales $\alpha_s(\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}})$ or $\alpha_s(p_T^{\mathrm{cut}})$
- Separate variation of each scale directly probes large logarithms

Results for Beam Thrust Spectrum and Cumulant



$gg \to H$ production cross section for $m_H = 165\,\mathrm{GeV}$ at the LHC

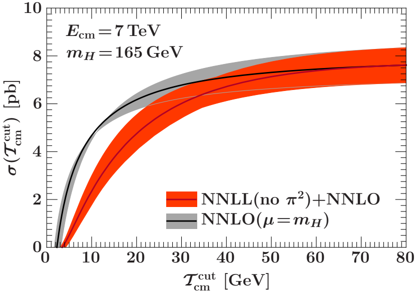
Differential beam-thrust spectrum

- Most events at small $\mathcal{T}_{cm}$
- Large tail from ISR (incoming gluons radiate a lot)

Perturbative corrections are important

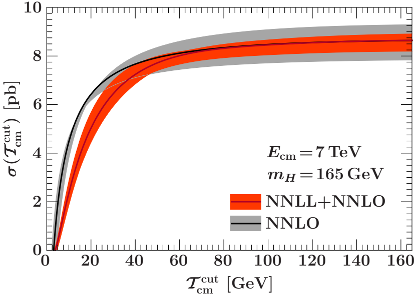
- Large K factors ($\sim$ 2-3) at fixed order are reduced by log+π^2 summation
- Good convergence at higher orders: Theory bands overlap (from separate μ_H, μ_B, μ_S variation)

Results at Large $\mathcal{T}_{\mathrm{cm}}$



At large $\mathcal{T}_{\mathrm{cm}}$ (no jet veto)

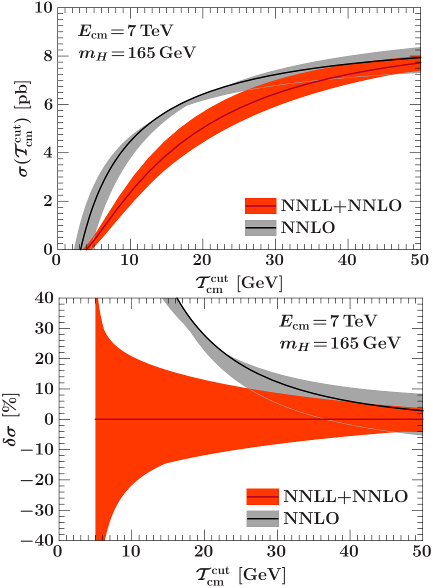
- Exactly reproduce central value and uncertainties of fixed NNLO (using $\mu_{\mathrm{FO}} = m_H$)



NNLL+NNLO with π^2 summation (default) vs. fixed NNLO (using $\mu_{\mathrm{FO}} = m_H/2$)

- Central values agree at large $\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}}$
- π^2 summation reduces scale uncertainty in total cross section (to 4% at LHC)

Results at Small $\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}}$ (0-Jet Region)



Compare NNLL+NNLO to NNLO only

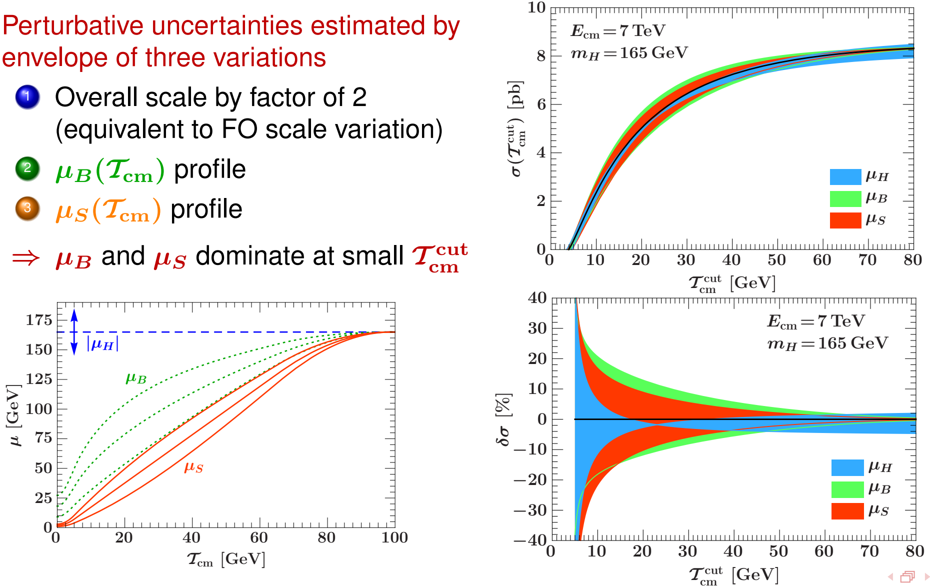
- NNLO alone is not reliable for small $\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}}$
- Jet-veto logarithms are important: Central value including NNLL lower than NNLO (partly accounted for by parton shower)
- Scale uncertainty at NNLL+NNLO is $10 - 20\%$

Individual Scale Uncertainties

Perturbative uncertainties estimated by envelope of three variations

1. Overall scale by factor of 2 (equivalent to FO scale variation)
2. $\mu_B(\mathcal{T}_{\rm cm})$ profile
3. $\mu_S(\mathcal{T}_{\rm cm})$ profile

$\Rightarrow$ μ_B and μ_S dominate at small $\mathcal{T}_{\rm cm}^{\rm cut}$



How Can the Results Be Used?

Directly using $\mathcal{T}_{\mathrm{cm}}$ to implement the jet veto?

- Event shape sums over particles $\longrightarrow$ pile-up and UE are problematic
- Perhaps summing over (mini-)jets instead

Use $\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}}$ as a proxy for p_T^{cut}

- Reweight the partonic beam-thrust spectrum in Monte Carlo to partonic NNLL+NNLO results (then add hadronization, UE, ...)
  - Improves 0-jet phase-space region with higher-order resummation
  - At the same time produces correct inclusive NNLO cross section
- Use reweighted sample to analyze jets with a standard p_T^{cut} method
- Similarly, use MC to translate the NNLL+NNLO uncertainty band for $\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}}$ into an uncertainty for p_T^{cut}
  - Uncertainties in p_T^{cut} might be a bit smaller
  - Not identical to directly resumming p_T^{cut} but still much better than relying on fixed-order uncertainties

Summing over Different Jet Bins

$$\sigma_{\rm incl} = \underbrace{\int_0^{\mathcal{T}_{\rm cm}^{\rm cut}} d\mathcal{T}_{\rm cm} \frac{d\sigma}{d\mathcal{T}_{\rm cm}}}_{\sigma_0(\mathcal{T}_{\rm cm}^{\rm cut})} + \underbrace{\int_{\mathcal{T}_{\rm cm}^{\rm cut}}^{m_H} d\mathcal{T}_{\rm cm} \frac{d\sigma}{d\mathcal{T}_{\rm cm}}}_{\sigma_{\geq 1}(\mathcal{T}_{\rm cm}^{\rm cut})}$$

Dependence on $\mathcal{T}_{\rm cm}^{\rm cut}$ cancels between $\sigma_0(\mathcal{T}_{\rm cm}^{\rm cut})$ and $\sigma_{\geq 1}(\mathcal{T}_{\rm cm}^{\rm cut})$

- Large logarithms and uncertainties are caused by the “boundary” $\mathcal{T}_{\rm cm}^{\rm cut}$ $\rightarrow$ cancel in the sum

Theory error matrix $= \begin{pmatrix} \delta_0^2 & \delta_0 \delta_{\geq 1}\, \rho_{0,\geq 1} \\ \delta_0 \delta_{\geq 1}\, \rho_{0,\geq 1} & \delta_{\geq 1}^2 \end{pmatrix} \approx \begin{pmatrix} \delta_0^2 & -\delta_0^2 \\ -\delta_0^2 & \delta_0^2 + \delta_{\rm incl}^2 \end{pmatrix}$

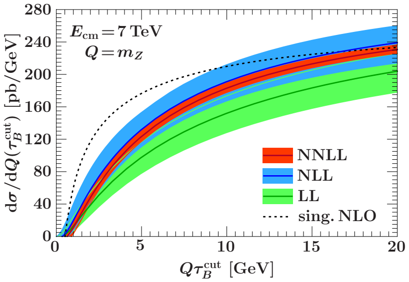
Repeats when splitting $\sigma_{\geq 1} = \sigma_1 + \sigma_{\geq 2}$

- σ_1 will have an uncertainty from lower and upper boundary

Using Existing Data

MC reweighting procedure can be tested with identical analysis for Drell-Yan

- Uncertainties in Drell-Yan turn out to be much smaller [arXiv:1005.4060]



Using data to reduce jet-veto uncertainties?

- Dividing $H + 0$ jets by $W/Z + 0$ jets is unlikely to help (incoming quarks instead of gluons)
- Unfortunately there is no other color singlet dominantly produced by gg (At least none that I could think of)
- Maybe $gg \to q\bar{q}\gamma$ or $gq \to q\gamma$ can help?

Theory Plans

- Similar calculation can be carried out for $H + 1$ jet (using cut on "1-jettiness"). This is already work in progress.
- Calculation of irreducible background $pp \to WW + 0$ jets at NNLL+NLO using beam thrust is straightforward
- Calculation of $H + 0$ jet cross section at one higher order ($\mathrm{N^3LL}$) is feasible. "Only" requires a doable 2-loop calculation. This will help to reduce the perturbative uncertainties.

$\Rightarrow$ What is most important to you? What else would be useful?

Backup Slides

$H \to WW$ Signal and Backgrounds at LHC

Expected $WW \to e\nu\mu\nu$ events in $1\,\mathrm{fb}^{-1}$ [ATLAS arXiv:0901.0512]

Cut	$H \to WW$	$t\bar{t} \to WWb\bar{b}$	WW	$Z \to \tau\tau$	$W+$ jets
Lepton selection	166	6501	718	4171	209
$p_T^{\mathrm{miss}} > 30\,\mathrm{GeV}$	148	5617	505	526	182
$Z \to \tau\tau$ rejection	146	5215	485	164	150
Central jet veto	62	15	238	32	76
b-jet veto	62	7	238	31	76
$M_T < 600\,\mathrm{GeV}$, $\Delta\phi_{\ell\ell} < \pi/2$	50.6 ± 2.5	2.3 ± 1.6	85.4 ± 2.7	< 1.7	38 ± 38

- Central jet veto essential to eliminate huge $t\bar{t} \to WWb\bar{b}$ background
- Main irreducible background from $pp \to WW$

Theory Uncertainties Used at Tevatron

Relative uncertainties for $W^+W^- \to \ell^\pm \ell'^\mp$ [CDF numbers from arXiv:1007.4587]

	$pp \to WW$	$gg \to H + 0$ jets	$gg \to H + 1$ jets
Scale		7.0% (HNNLO)	23.5% (HNNLO)
PDF Model		7.6%	17.3%
Total	6.0% (MCFM)		

- Theory uncertainties are taken from fixed-order calculations
  - Do not take into account large logarithms $\longrightarrow$ likely underestimated
- Uncertainties in exclusive jet cross section are different from inclusive cross section
  - Uncertainty for $pp \to WW$ (and other) background(s) should also be evaluated for each jet multiplicity separately

General Structure of the Cross Section

$$\frac{d\sigma}{d\tau} = \underbrace{C^{-1}\delta(\tau) + \sum_k C^k \left[\frac{\ln^k \tau}{\tau}\right]_+}_{\text{singular}} + \underbrace{\frac{d\sigma^{\rm ns}}{d\tau}}_{\text{nonsingular}} \quad \text{with} \quad \tau = \frac{\mathcal{T}_{\rm cm}}{m_H}$$

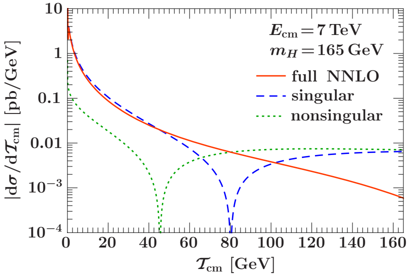
Singular (log-enhanced) terms

- Dominant contribution at small τ

⇒ Resummed to NNLL using SCET

Nonsingular terms

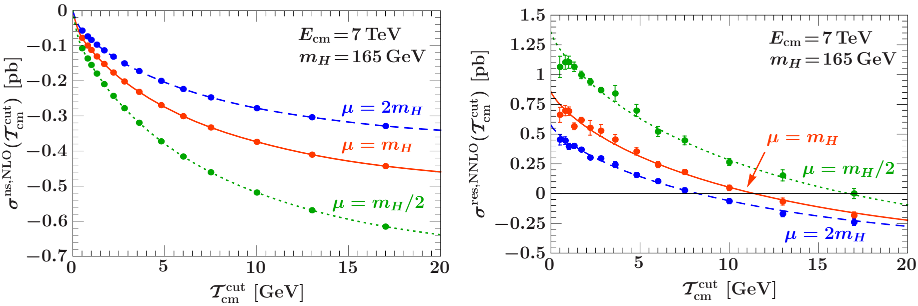
- Suppressed by $\mathcal{O}(\tau)$ relative to singular ones



- Required to reproduce full fixed-order cross section at large τ

⇒ Obtained numerically from FEHiP to NNLO

Nonsingular Corrections

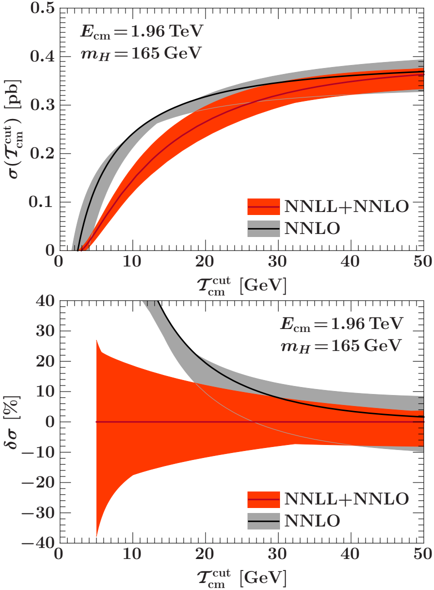


$$\sigma^{ns,NLO}(\tau^{cut}) = \sigma^{NLO}(\tau^{cut}) - \sigma^{s,NNLL}(\tau^{cut})\big|_{NLO}$$

$$\sigma^{res,NNLO}(\tau^{cut}) = \sigma^{NNLO}(\tau^{cut}) - \sigma^{s,NNLL}(\tau^{cut})\big|_{NNLO}$$

- σ^{NLO} and σ^{NNLO} numerically from FEHiP [Anastasiou, Melnikov, Petriello]
- NNLO $C^{-1}\delta(\tau)$ term is not part of $\sigma^{s,NNLL}$
  - Obtained from intercept at $\tau^{cut} = 0$ and added to singular
  - Proper treatment requires 2-loop hard, beam, soft functions

Results for the Tevatron



Compare NNLL+NNLO to NNLO only

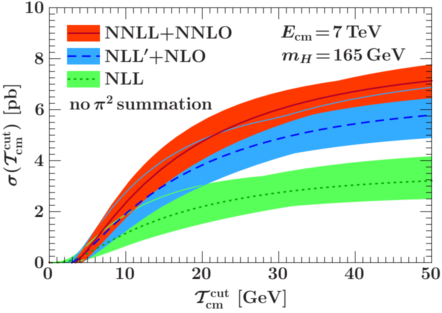
- Fixed-order expansion is not reliable in 0-jet region at small $\mathcal{T}_{cm}$
- Summation of jet-veto logarithms is necessary for reliable predictions and estimation of uncertainties
- Scale uncertainty at NNLL+NNLO is $10 - 20\%$

Current Tevatron Higgs limits

- Lower central value partly accounted for by parton shower
- Theory uncertainty $\sim 20\%$ much larger than currently used 7%

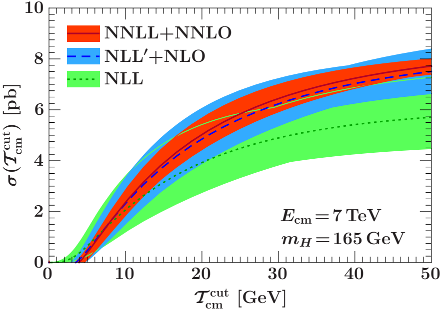
π^2 Summation

without π^2 summation



⇒

including π^2 summation



Hard virtual corrections contain large $\ln^2(-1 - \mathrm{i}0) = -\pi^2$ terms

[Magnea, Sterman; Eynck, Laenen, Magnea; Ahrens, Becher, Neubert, Yang]

$$H_{gg}(m_H, \mu_H) \propto 1 - \frac{\alpha_s(\mu_H) C_A}{2\pi} \ln^2 \frac{-m_H^2 - \mathrm{i}0}{\mu_H^2} + \cdots$$

- Can be summed along with double logarithms by taking $\mu_H = -\mathrm{i}\, m_H$

⇒ Convergence improves significantly when including π^2 summation