Jet Vetoes with a Jet Rapidity Cut.

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Introduction.

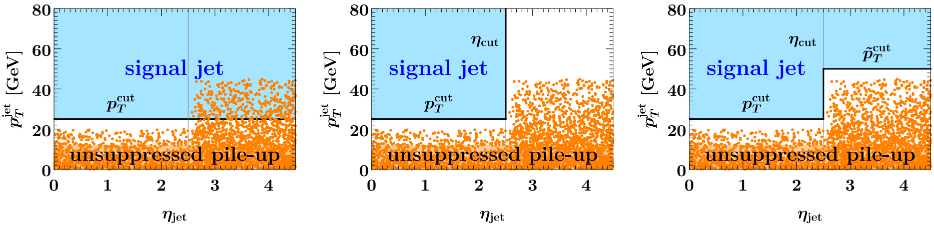
Motivation.

Jet binning & jet vetoes, $p_T^{\mathrm{jet}} < p_T^{\mathrm{cut}}$, ...

- Reduce backgrounds, increase sensitivity to production channels

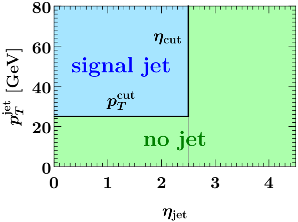
... with a jet rapidity cut, $\eta_{\mathrm{jet}} < \eta_{\mathrm{cut}}$

- Pile-up hinders jet reconstruction at forward rapidities and small p_T^{jet}
  - Realistically the veto is loosened to $\tilde{p}_T^{\mathrm{cut}} > p_T^{\mathrm{cut}}$ for $\eta_{\mathrm{jet}} > \eta_{\mathrm{cut}}$



Question: Can we quantify the impact of η_{cut}, $\tilde{p}_T^{\mathrm{cut}}$?
Can we systematically incorporate it into resummed predictions?

No Veto Beyond the Rapidity Cut.



Standard jet veto resummation: $p_T^{\mathrm{cut}} \gg Q e^{-\eta_{\mathrm{cut}}}$.

- Standard jet veto resummation assumes $\eta_{\mathbf{cut}} = \infty$

  [Banfi, Monni, Salam, Zanderighi '12]
  [Becher, Neubert, Rothen '12, '13]
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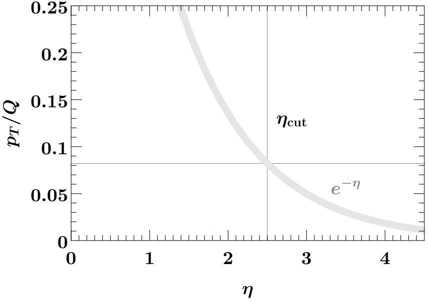

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- Energetic emissions ($E \sim Q$) with $\eta \gtrsim \eta_{\rm cut}$ have

$$p_T \sim E e^{-\eta} \lesssim Q e^{-\eta_{\rm cut}}$$

- ▶ New scale for finite $\eta_{\rm cut}$

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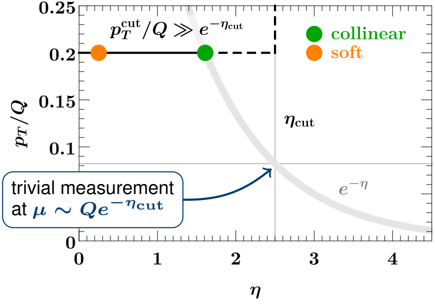

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▸ New scale for finite $\eta_{\rm cut}$

$$\sigma_0(p_T^{\rm cut}, \eta_{\rm cut}) = H_\kappa(\Phi) \times B_a(\omega_a, p_T^{\rm cut}, R) \times B_b(\omega_b, p_T^{\rm cut}, R) \times S_\kappa(p_T^{\rm cut}, R)$$

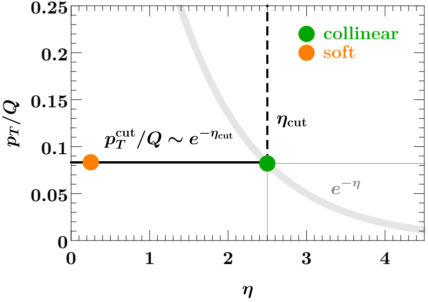
$$\times \left[1 + \mathcal{O}\left(\frac{p_T^{\rm cut}}{Q}, R^2, \frac{Q e^{-\eta_{\rm cut}}}{p_T^{\rm cut}}\right)\right]$$

$\mathcal{I}_{ij}(\omega, p_T^{\rm cut}, R) \otimes f_j$

▸ Standard jet veto resummation works, up to $\mathcal{O}\left(\frac{Q e^{-\eta_{\rm cut}}}{p_T^{\rm cut}}\right)$

- Naive power counting: $\eta_{\rm cut} = \begin{cases} 4.5 \\ 2.5 \end{cases} \Rightarrow \frac{125\,\mathrm{GeV}\, e^{-\eta_{\rm cut}}}{25\,\mathrm{GeV}} = \begin{cases} 6\% \\ 41\% \end{cases}$

$\eta_{\rm cut}$ dependent beam functions: $p_T^{\rm cut} \sim Q e^{-\eta_{\rm cut}}$.



$$\begin{aligned}\sigma_0(p_T^{\rm cut}, \eta_{\rm cut}) &= H_\kappa(\Phi) \\ &\times B_a(\omega_a, p_T^{\rm cut}, \eta_{\rm cut}, R) \\ &\times B_b(\omega_b, p_T^{\rm cut}, \eta_{\rm cut}, R) \\ &\times S_\kappa(p_T^{\rm cut}, R) \\ &\times \left[1 + \mathcal{O}\left(\frac{p_T^{\rm cut}}{Q}, R^2, e^{-\eta_{\rm cut}}\right)\right]\end{aligned}$$

- Absorb the $\eta_{\rm cut}$ dependence into an additive correction:

$$\mathcal{I}_{ij}(\omega, p_T^{\rm cut}, \eta_{\rm cut}, R, \mu, \nu) = \mathcal{I}_{ij}(\omega, p_T^{\rm cut}, R, \mu, \nu) + \Delta\mathcal{I}_{ij}\left(\frac{\omega e^{-\eta_{\rm cut}}}{p_T^{\rm cut}}, R\right)$$

- Calculated all $\Delta\mathcal{I}_{ij}$ at $\mathcal{O}(\alpha_s)$, $\mathcal{O}(\alpha_s^2 \ln R)$
- Useful: factorizing the $\alpha_s^2 \ln R$ piece into

primary emission $\otimes$ semi-inclusive jet function

[Kang, Ringer, Vitev '16]

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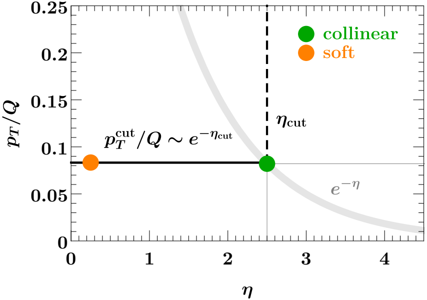

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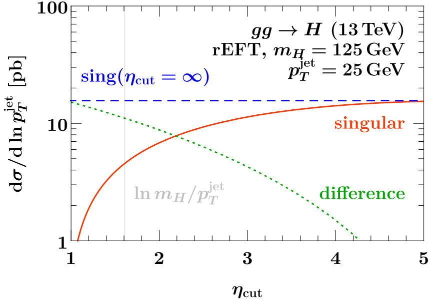

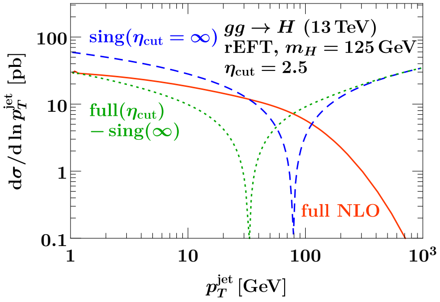

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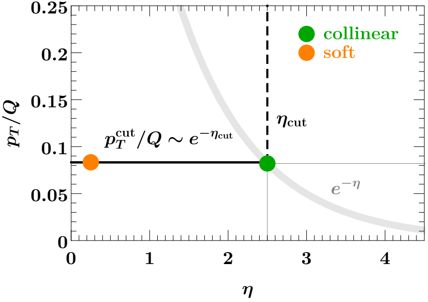

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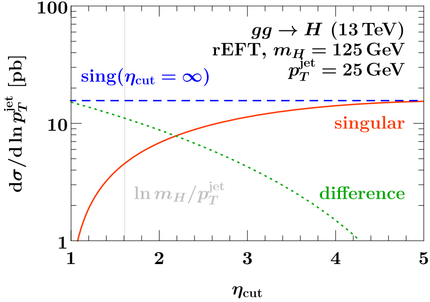
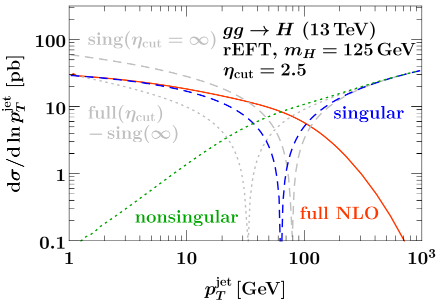
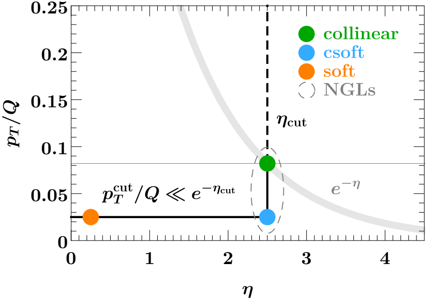




Refactorization for tight vetoes: $p_T^{\rm cut} \ll Q e^{-\eta_{\rm cut}}$



- Soft-collinear and collinear modes have the same angular resolution, but different energies:

$$p_T^{\rm cut} e^{\eta_{\rm cut}} \ll Q$$

- ▶ Intrinsic nonglobal structure
- Analogous to a narrow jet with $m_J \sim p_T^J R$ and an outside veto
  [Kolodrubetz, Pietrulewicz, Stewart, Tackmann, Waalewijn '16: "Regime 3"]

$$B_i(\omega, p_T^{\rm cut}, \eta_{\rm cut}, R) = B_i^{(\rm cut)}(\omega e^{-\eta_{\rm cut}}) \times \mathcal{S}_i^{(\rm cut)}(p_T^{\rm cut}, \eta_{\rm cut}, R) \times \left[1 + \mathcal{B}_i^{(\rm NG)}\left(\frac{p_T^{\rm cut}}{\omega e^{-\eta_{\rm cut}}}, R\right)\right] \times \left[1 + \mathcal{O}\left(\frac{p_T^{\rm cut}}{\omega e^{-\eta_{\rm cut}}}\right)\right]$$

[Hornig, Kang, Makris, Mehen '17 → talk by Y. Makris]

- Calculated $B_i^{(\rm cut)}$, $\mathcal{S}_i^{(\rm cut)}$ at $\mathcal{O}(\alpha_s)$ (agrees with Hornig et al.) and $\mathcal{O}(\alpha_s^2 \ln R)$
- ▶ Going beyond LL would require an all-order treatment of NGLs
  [Hatta, Ueda; Caron-Huot; Larkoski, Moult, Neill; Becher, Neubert, Rothen, Shao '13 - '16]

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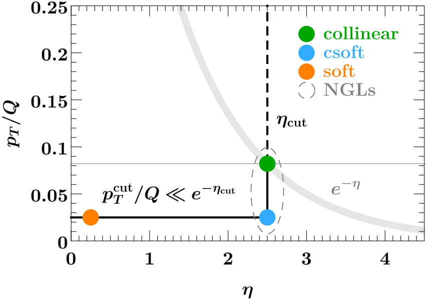

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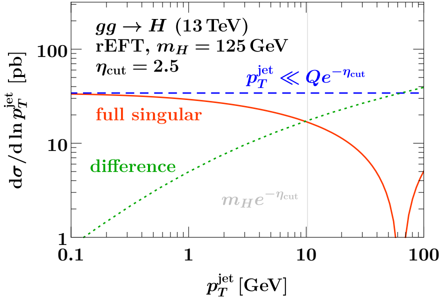
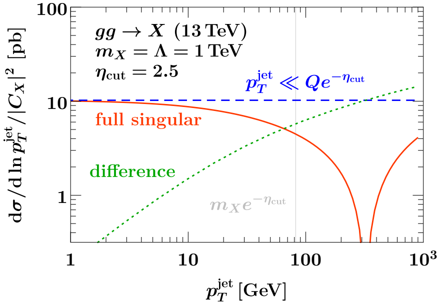
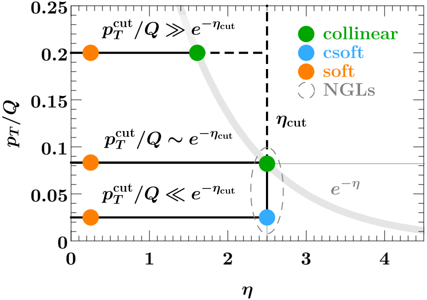




Summary: no veto beyond the rapidity cut.



- Standard setup receives corrections
  $$\mathcal{O}\Big(\frac{Qe^{-\eta_{\rm cut}}}{p_T^{\rm cut}}\Big)$$
- Can seamlessly* incorporate these into the beam function

  *at the cost of a more involved measurement
- Refactorization for $p_T^{\rm cut} \ll Qe^{-\eta_{\rm cut}}$ mostly irrelevant for realistic vetoes

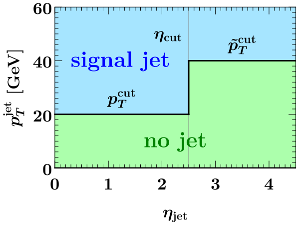
▶ Use these ingredients as building blocks for the step-like veto

Note: $p_T^{\rm cut} \sim Qe^{-\eta_{\rm cut}}$ is relevant for Higgs analyses, if $\eta_{\rm cut} = 2.5$

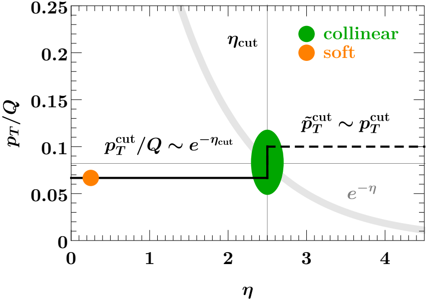
- Our setup in this regime differs from the one of Hornig et al.

▶ Can describe this regime without having to think about NGLs

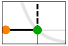
Step-like Jet Vetoes.



Collinear resolves the step: $p_T^{\mathrm{cut}} \sim Q e^{-\eta_{\mathrm{cut}}} \sim \tilde{p}_T^{\mathrm{cut}}$.



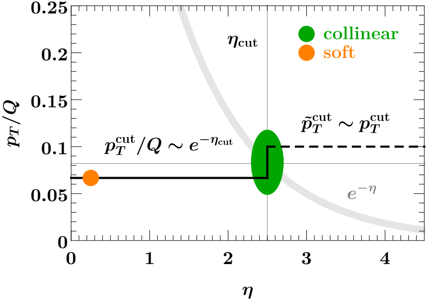
$$
\begin{aligned}
&\sigma_0(p_T^{\mathrm{cut}}, \tilde{p}_T^{\mathrm{cut}}, \eta_{\mathrm{cut}}) \\
&= H_\kappa(\Phi) \\
&\quad \times B_a(\omega_a, p_T^{\mathrm{cut}}, \tilde{p}_T^{\mathrm{cut}}, \eta_{\mathrm{cut}}, R) \\
&\quad \times B_b(\omega_b, p_T^{\mathrm{cut}}, \tilde{p}_T^{\mathrm{cut}}, \eta_{\mathrm{cut}}, R) \\
&\quad \times S_\kappa(p_T^{\mathrm{cut}}, R) \\
&\quad \times \left[1 + \mathcal{O}\left(\frac{p_T^{\mathrm{cut}}}{Q}, \frac{\tilde{p}_T^{\mathrm{cut}}}{Q}, R^2\right)\right]
\end{aligned}
$$

- Direct extension of η_{cut} dependent beam functions ()
- At $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2 \ln R)$:

$$
\begin{aligned}
\Delta\mathcal{I}_{ij}(\omega, p_T^{\mathrm{cut}}, \tilde{p}_T^{\mathrm{cut}}, \eta_{\mathrm{cut}}, R) = &+ \Delta\mathcal{I}_{ij}(\omega, p_T^{\mathrm{cut}}, \eta_{\mathrm{cut}}, R) \\
&- \Delta\mathcal{I}_{ij}(\omega, \tilde{p}_T^{\mathrm{cut}}, \eta_{\mathrm{cut}}, R)
\end{aligned}
$$

(This measurement decomposition does not hold for the full two-loop piece.)

Collinear resolves the step: $p_T^{\rm cut} \sim Q e^{-\eta_{\rm cut}} \sim \tilde{p}_T^{\rm cut}$.



$$\sigma_0(p_T^{\rm cut}, \tilde{p}_T^{\rm cut}, \eta_{\rm cut})$$
$$= H_\kappa(\Phi)$$
$$\times B_a(\omega_a, p_T^{\rm cut}, \tilde{p}_T^{\rm cut}, \eta_{\rm cut}, R)$$
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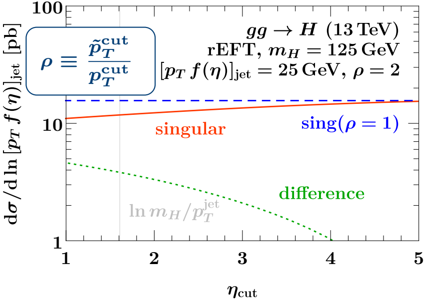
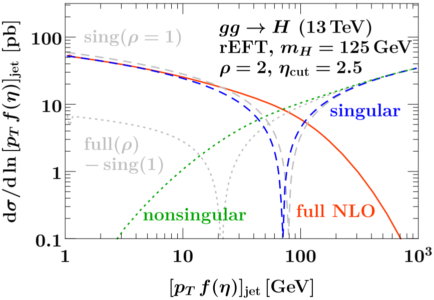
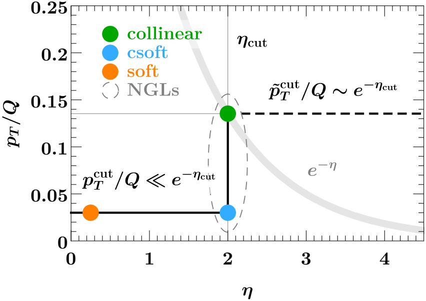
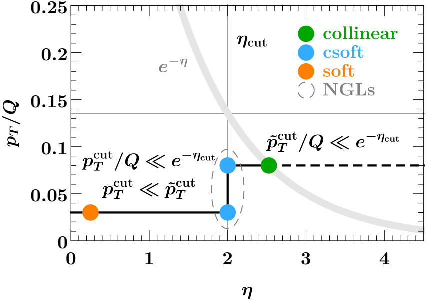
$$\times S_\kappa(p_T^{\rm cut}, R)$$
$$\times \Big[1 + \mathcal{O}\Big(\frac{p_T^{\rm cut}}{Q}, \frac{\tilde{p}_T^{\rm cut}}{Q}, R^2\Big)\Big]$$









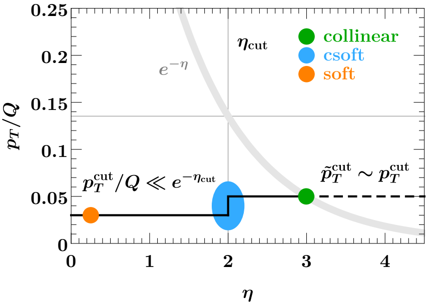
$$B_i^{\rm (cut)}(\omega e^{-\eta_{\rm cut}}, \tilde{p}_T^{\rm cut}) \times \mathcal{S}_i^{\rm (cut)}(p_T^{\rm cut}, \eta_{\rm cut}, R) \times \left[1 + \mathcal{B}_i^{\rm (NG)}\left(\frac{p_T^{\rm cut}}{\omega e^{-\eta_{\rm cut}}}, \frac{p_T^{\rm cut}}{\tilde{p}_T^{\rm cut}}, R\right)\right]$$

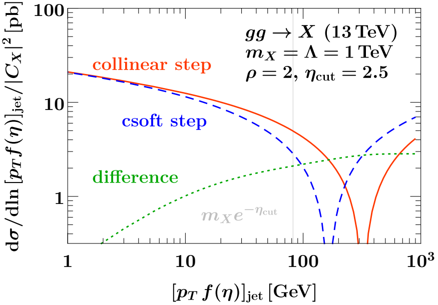
- NGLs entangle collinear and soft-collinear contributions

$$B_i(\tilde{p}_T^{\rm cut}, R) \times \frac{\mathcal{S}_i^{\rm (cut)}(p_T^{\rm cut}, \eta_{\rm cut}, R)}{\mathcal{S}_i^{\rm (cut)}(\tilde{p}_T^{\rm cut}, \eta_{\rm cut}, R)} \times \left[1 + \mathcal{S}_i^{\rm (NG)}\left(\frac{p_T^{\rm cut}}{\tilde{p}_T^{\rm cut}}, R\right)\right]$$

- NGLs within soft-collinear sector

CSoft resolves the step: $p_T^{\rm cut} \sim \tilde{p}_T^{\rm cut} \ll Q e^{-\eta_{\rm cut}}$.





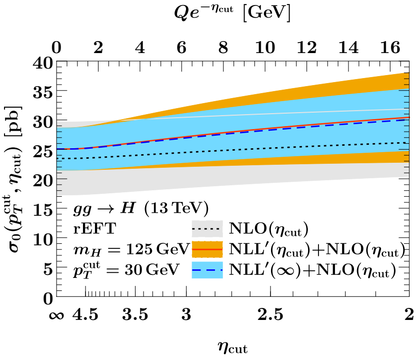
- Soft-collinear function $\mathcal{S}_i(p_T^{\rm cut}, \tilde{p}_T^{\rm cut}, \eta_{\rm cut}, R)$, computed to $\mathcal{O}(\alpha_s^2 \ln R)$
  - $\nu_S = \sqrt{p_T^{\rm cut}\tilde{p}_T^{\rm cut}}\, e^{+\eta_{\rm cut}}$ resums all logs of $p_T^{\rm cut}/Qe^{-\eta_{\rm cut}}$ and $\tilde{p}_T^{\rm cut}/Qe^{-\eta_{\rm cut}}$
  - Full two-loop $\mathcal{S}_i$ could be obtained by numerical calculation with `SoftSERVE` [Bell, Rahn, Talbert → see talk by G. Bell on Wednesday]
  - All other ingredients are already known to NNLL′, regime is
  - Can also infer presence of $\mathcal{S}_i$ from consistency:

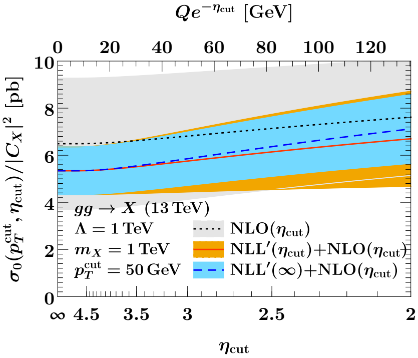
100 % NGL free

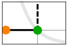
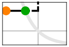
$$-2\gamma_{\nu,B} = 4\Gamma_{\rm cusp} \ln \frac{\tilde{p}_T^{\rm cut}}{\mu} \neq 4\Gamma_{\rm cusp} \ln \frac{p_T^{\rm cut}}{\mu} = \gamma_{\nu,S}$$

Results.

Comparing different treatments of the rapidity cut.





- NLL′$(\eta_{\rm cut})$+NLO$(\eta_{\rm cut})$ use $\eta_{\rm cut}$ dependent beam functions ()
- Same RG structure as for $\eta_{\rm cut} = \infty$ ()

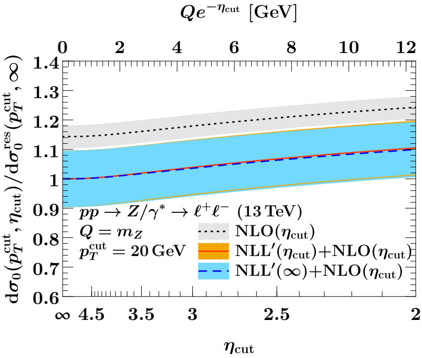
▸ Use known profile-scale setup to estimate resummation uncertainties*

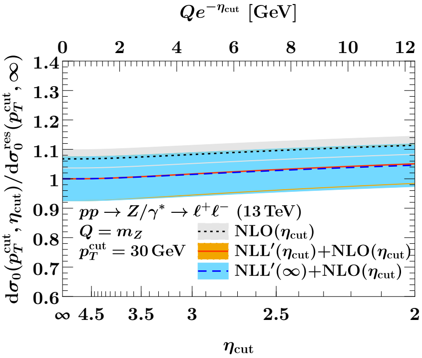
[Stewart, Tackmann, Walsh, Zuberi '13]

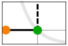
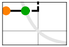
*Fixed-order results use ST uncertainties [Stewart, Tackmann '11]

- Total uncertainty estimate is $\Delta^2_{\rm tot} = \Delta^2_\mu (+\Delta^2_\varphi) + \Delta^2_{\rm res}$

Comparing different treatments of the rapidity cut.





- NLL′(η_{cut})+NLO(η_{cut}) use η_{cut} dependent beam functions ()
- Same RG structure as for $\eta_{\mathrm{cut}} = \infty$ ()
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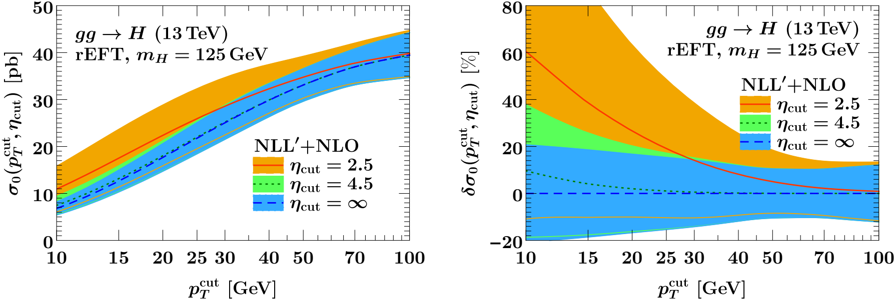
NLL′ predictions for finite η_{cut}: gluon fusion



$\sigma_0(p_T^{cut}, \eta_{cut})$ [pb], $gg \to H$ (13 TeV), rEFT, $m_H = 125$ GeV

η_{cut}	$p_T^{cut} = 25$ GeV	$p_T^{cut} = 30$ GeV
2.5	$25.9 \pm 3.7_\mu \pm 1.5_\varphi \pm 5.0_{res}$ (24.7%)	$28.6 \pm 3.9_\mu \pm 1.6_\varphi \pm 4.5_{res}$ (21.5%)
4.5	$22.0 \pm 2.0_\mu \pm 1.0_\varphi \pm 2.7_{res}$ (16.0%)	$25.2 \pm 2.2_\mu \pm 1.2_\varphi \pm 2.7_{res}$ (14.6%)
∞	$21.8 \pm 1.8_\mu \pm 1.0_\varphi \pm 2.6_{res}$ (15.4%)	$25.1 \pm 2.1_\mu \pm 1.1_\varphi \pm 2.6_{res}$ (14.2%)

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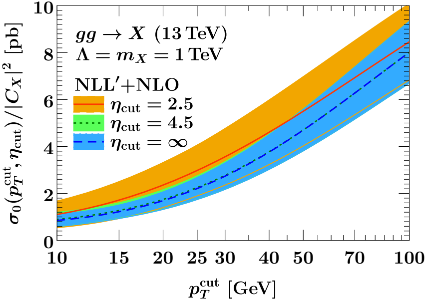
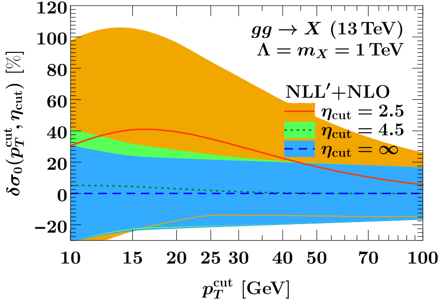
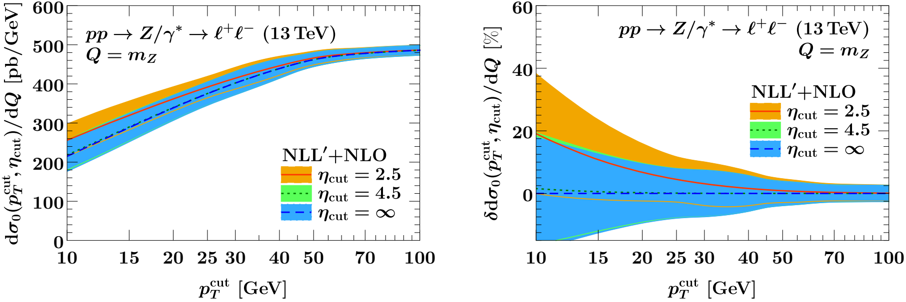




	$\sigma_0(p_T^{\rm cut}, \eta_{\rm cut})/\lvert C_X\rvert^2$ [pb], $gg \to X$ (13 TeV), $\Lambda = m_X = 1$ TeV	
$\eta_{\rm cut}$	$p_T^{\rm cut} = 50$ GeV	$p_T^{\rm cut} = 100$ GeV
2.5	$3.6 \pm 0.7_\mu \pm 0.2_\varphi \pm 0.9_{\rm res}$ (33.9%)	$5.5 \pm 0.8_\mu \pm 0.2_\varphi \pm 1.2_{\rm res}$ (26.8%)
4.5	$2.8 \pm 0.4_\mu \pm 0.1_\varphi \pm 0.4_{\rm res}$ (21.3%)	$4.7 \pm 0.5_\mu \pm 0.1_\varphi \pm 0.7_{\rm res}$ (19.0%)
∞	$2.7 \pm 0.4_\mu \pm 0.1_\varphi \pm 0.4_{\rm res}$ (20.7%)	$4.7 \pm 0.5_\mu \pm 0.1_\varphi \pm 0.7_{\rm res}$ (18.9%)

NLL′ predictions for finite η_{cut}: Drell-Yan.



η_{cut}	$\mathrm{d}\sigma_0(p_T^{\mathrm{cut}}, \eta_{\mathrm{cut}})/\mathrm{d}Q$ [pb/GeV], $pp \to Z/\gamma^* \to \ell^+\ell^-$ (13 TeV), $Q = m_Z$ $p_T^{\mathrm{cut}} = 20$ GeV	$p_T^{\mathrm{cut}} = 25$ GeV
2.5	$361 \pm 22_\mu \pm 22_{\mathrm{res}}$ (8.6%)	$392 \pm 23_\mu \pm 15_{\mathrm{res}}$ (6.9%)
4.5	$339 \pm 23_\mu \pm 22_{\mathrm{res}}$ (9.4%)	$375 \pm 25_\mu \pm 16_{\mathrm{res}}$ (7.9%)
∞	$339 \pm 23_\mu \pm 22_{\mathrm{res}}$ (9.5%)	$375 \pm 25_\mu \pm 16_{\mathrm{res}}$ (7.9%)

Conclusion.

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Jet vetoes with a jet rapidity cut:

- Standard jet veto resummation is correct up to $\mathcal{O}\Big(\frac{Qe^{-\eta_{\mathrm{cut}}}}{p_T^{\mathrm{cut}}}\Big)$
- Now incorporated into the resummation, in a systematical way:
  - a sharp cut on identified jets at η_{cut}
  - a step in the jet veto at η_{cut}
- Experimentally relevant regimes are free of NGLs

▸ Improved description of real-life jet vetoes

▸ This analysis paves the way to precision predictions
for experimentally clean jet-based observables

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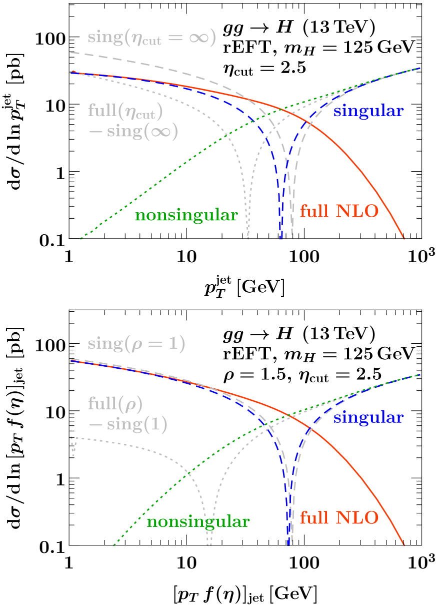
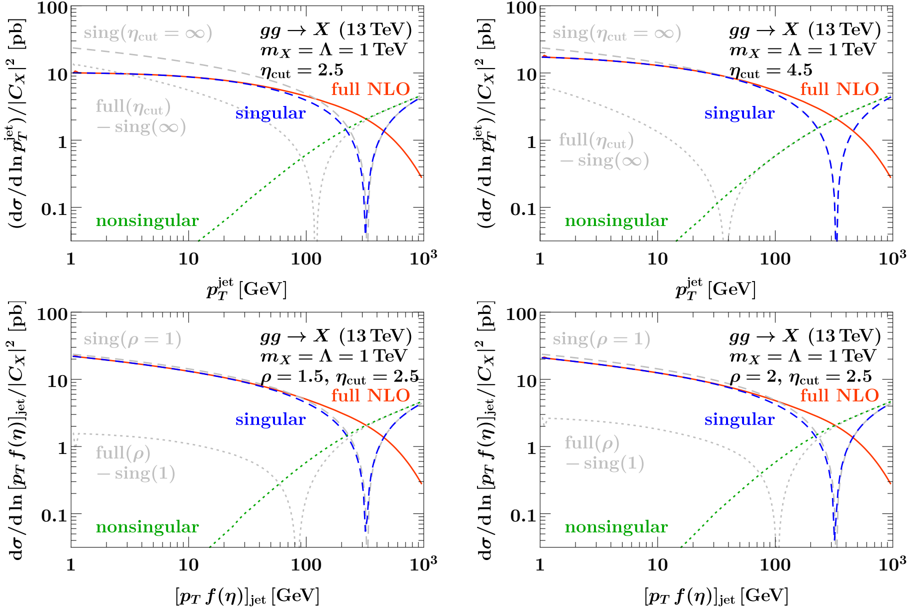
Thank you for your attention!

Backup.

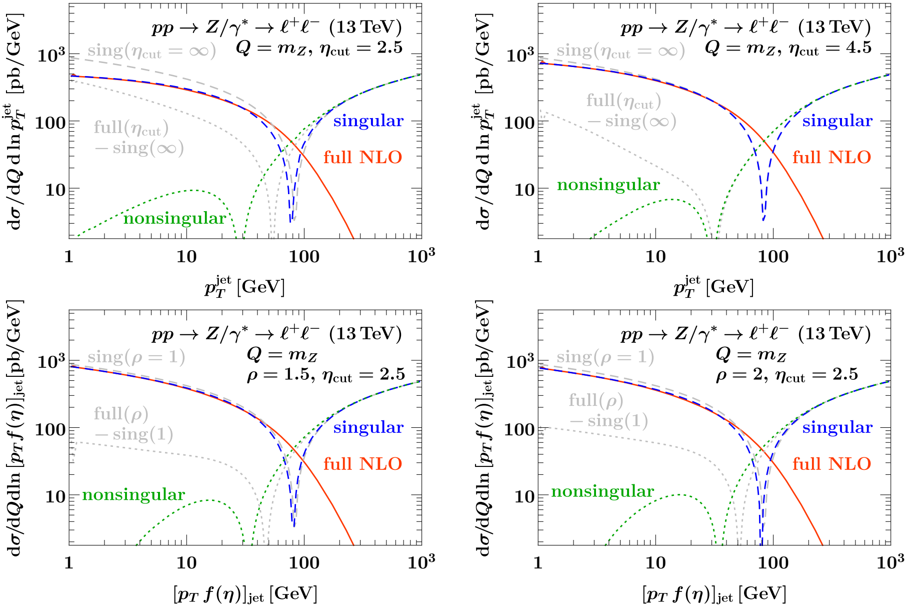
Full QCD comparison: $gg \to H$



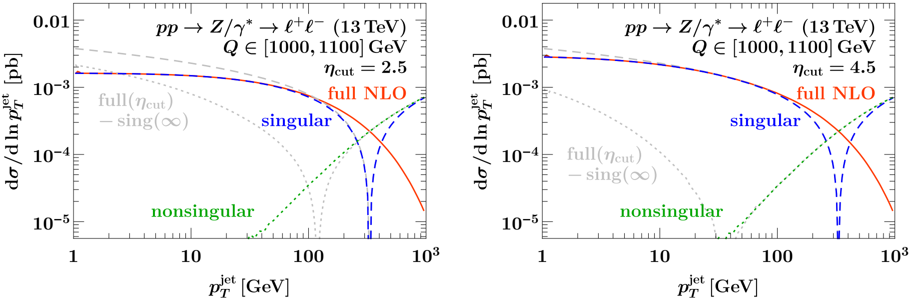
Full QCD comparison: $gg \to X$



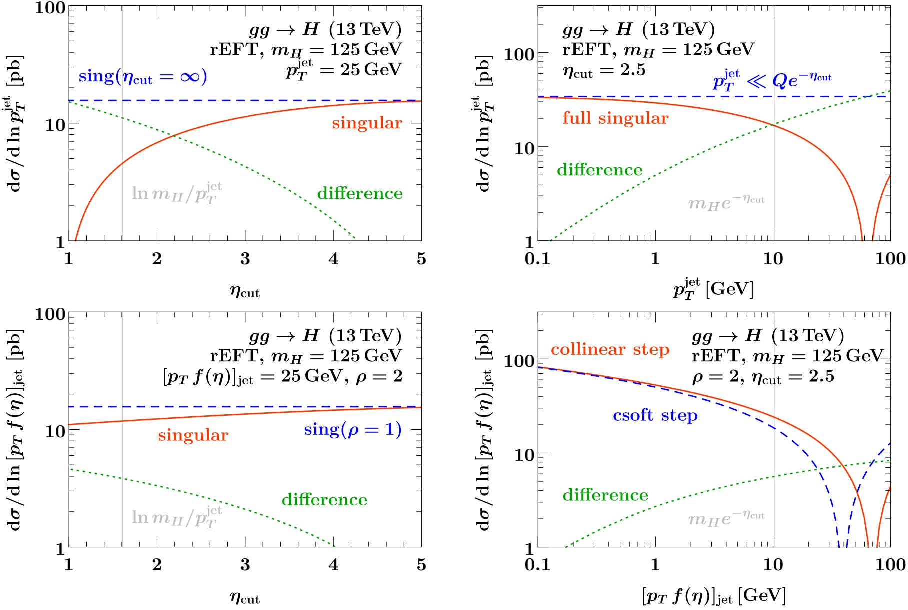
Full QCD comparison: Drell-Yan at $Q = m_Z$



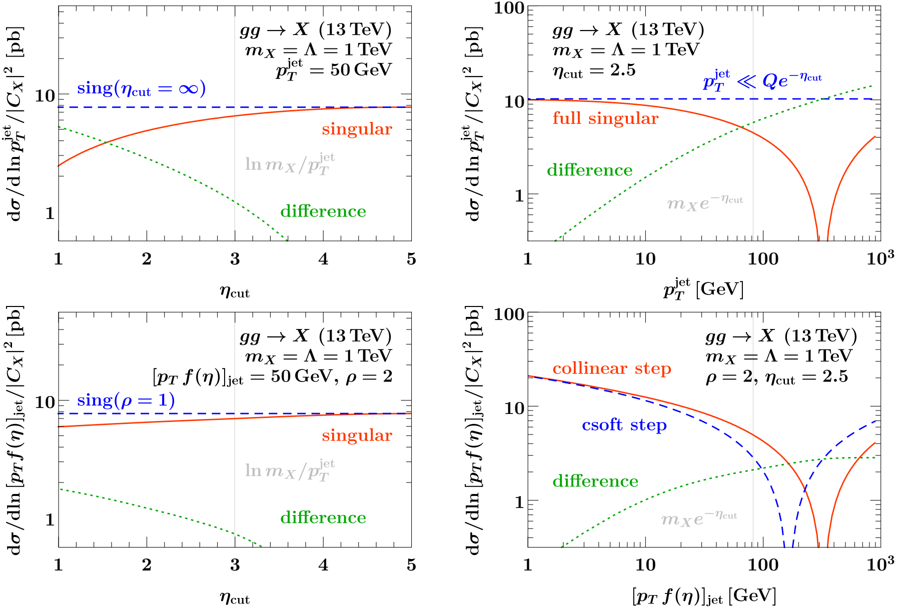
Full QCD comparison: Drell-Yan at high masses.



Detailed regime comparison: $gg \to H$



Detailed regime comparison: $gg \to X$



Detailed regime comparison: Drell-Yan at $Q = m_Z$