Partial N3LL + NNLO Resummed Predictions for the Drell-Yan Process in Rapidity Dependent Jet Veto Observables

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The University of Manchester

Aims of Analysis

- Produce partial N3LL + NNLO phenomenological predictions in the Drell-Yan process for two jet veto variables

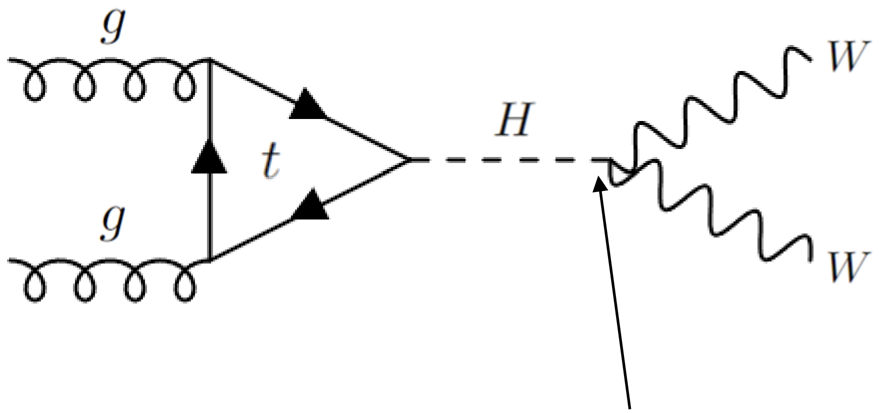
- Demonstrate the benefit of resumming logarithms in these jet veto variables by comparing to fixed-order (FO) predictions

Jet Vetoes

Class of observable used to separate final states by number of final state jets. A common jet veto is the leading jet transverse momentum P_{Tj}.

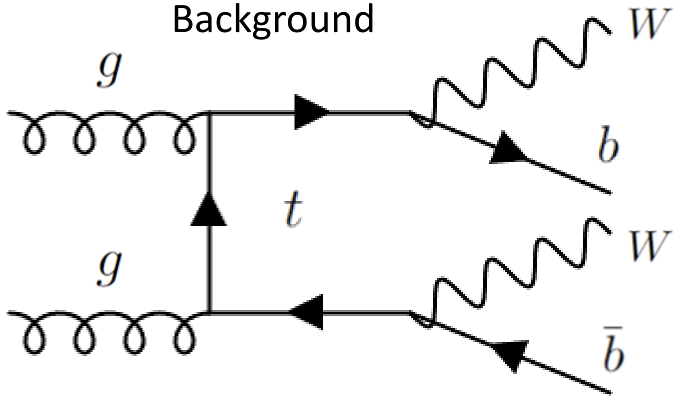
Can separate hard processes, cut out background events and study QCD radiation. For example:

Signal



Same initial states, final states differ by number of jets.

Background



Can be used to study Higgs coupling

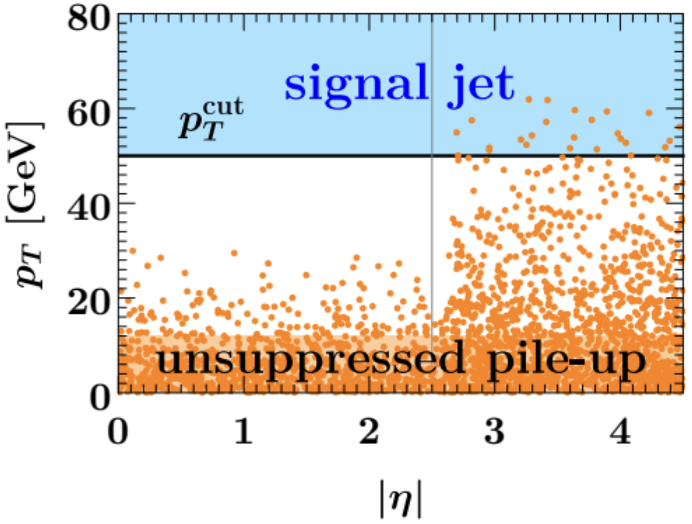
Can be removed with by imposing a veto on jets.

Rapidity Dependent Jet Vetoes

Useful to control the tightness of the P_T cut depending on kinematics of jet.

Due to a lack of tracking information, high rapidity, low P_T jets are hard to resolve experimentally.

A rapidity dependent jet veto allows tighter P_T cuts in central rapidites and looser P_T cuts at forward rapidities to remove sensitivity to these low P_T jets.



Michel, Pietrulewicz, Tackman, arXiv:1810.12911

$$\tau_f^{jet} = \underset{j\in J}{Max} \mid p_{Tj} \mid f\left(Y, y_j\right)$$

Rapidity of hard system

Rapidity of jet

Rapidity Dependent Jet Vetoes

Study two of these based on different weighing functions.

Tackmann, Walsh, Zuberi, arXiv:1206.4312

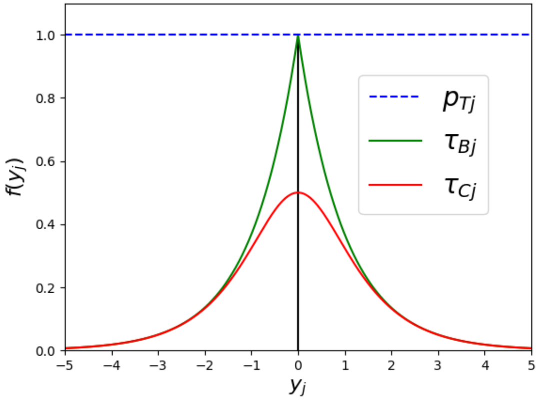
Gangal, Stahlhofen, Tackmann, arXiv:1412.4792

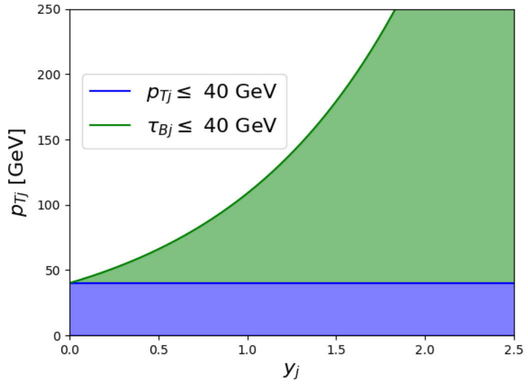
$$\tau_B : f_B\left(Y, y_j\right) = e^{-|y_j - Y|}$$

$$\tau_C : f_C\left(Y, y_j\right) = \frac{1}{2\cosh\left(y_j - Y\right)}$$

τ_B is tighter at central rapidities than τ_C but they are equivalent at forward rapidities.

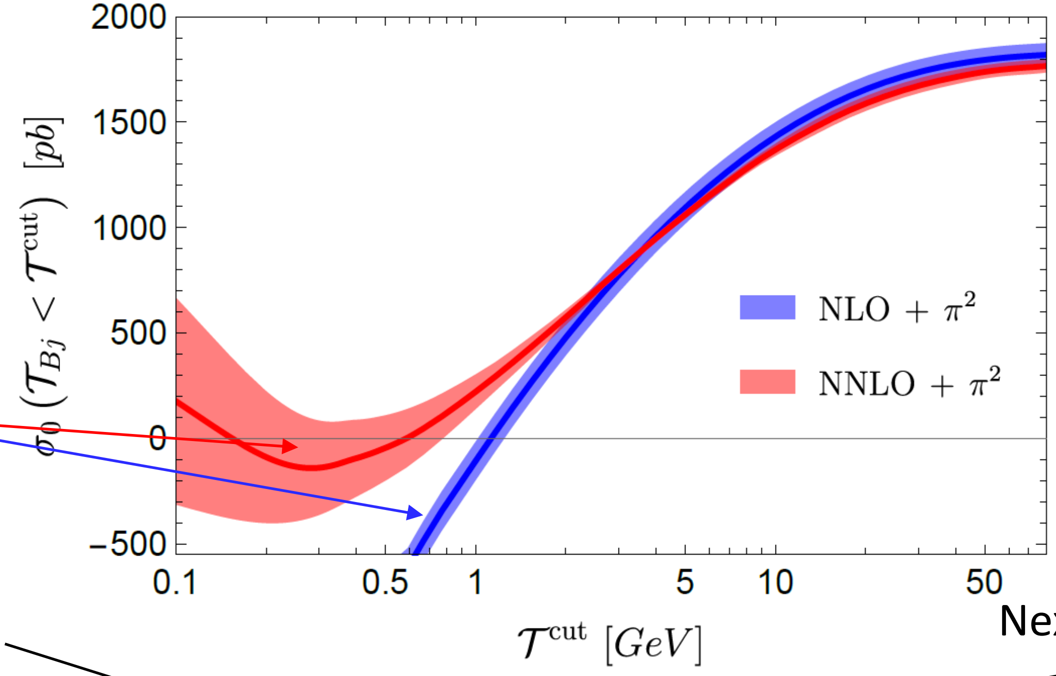
These jet vetoes are more inclusive of QCD radiation due to tight veto being over smaller range. Allows QCD radiation to be studied from a different point of view.





Large Logarithms in Jet Vetoes

Often tight cuts on jet veto variables required. Leads to large logarithms in the FO predictions in τ_{Cut} / Q :



Unphysical prediction due to large logarithms

Leading Log (LL)

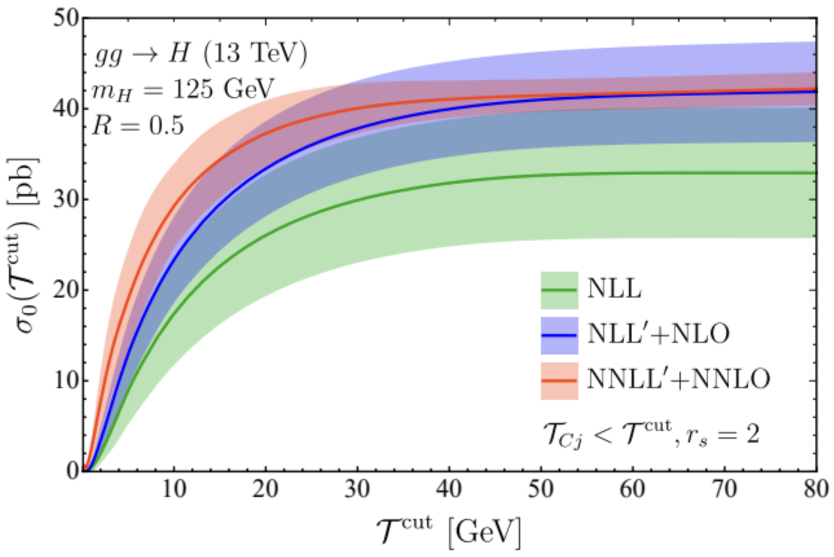
Next to Next to Leading Log (NNLL)

$$\mathcal{O}(\alpha_s^n) : c_1 \alpha_s^n \ln^m \left(\frac{\mathcal{T}_{cut}}{Q}\right) + c_2 \alpha_s^n \ln^{m-1} \left(\frac{\mathcal{T}_{cut}}{Q}\right) + c_3 \alpha_s^n \ln^{m-2} \left(\frac{\mathcal{T}_{cut}}{Q}\right) + \ldots + c_{m+1} \alpha_s^n$$

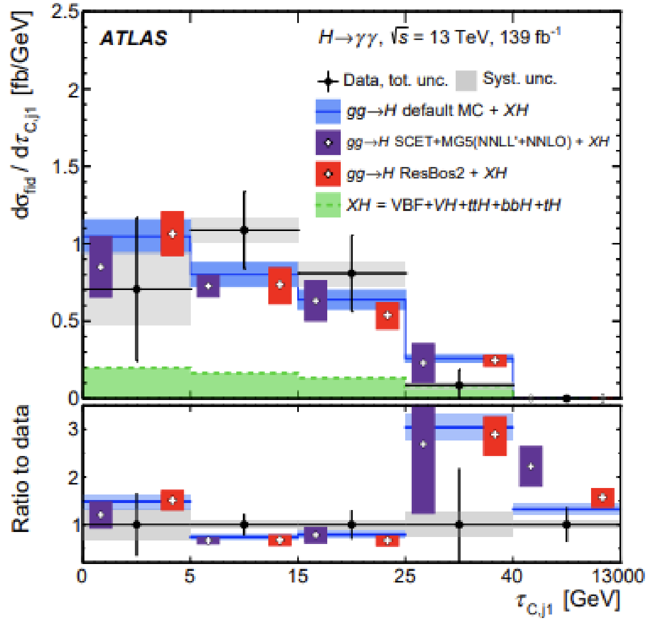
Next to Leading Log (NLL)

Jet Veto Resummation Example: Higgs

Resummation of large logarithms in rapidity dependent jet vetoes for Higgs production has been produced and compared with experimental data.



Gangal, Gaunt, Tackmann, Vryonidou, arXiv:2003.04323

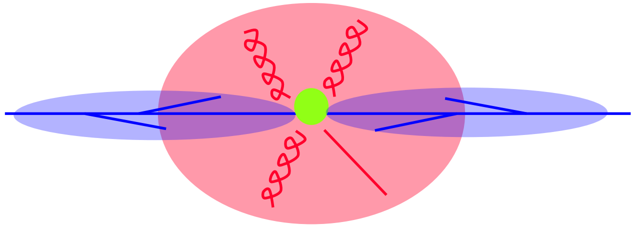


ATLAS collaboration, arXiv:2202.00487

Factorisation in Jet Vetoes

The below τ_{Cut} cross section can be factorised as follows for $\tau_{\text{Cut}} << Q$:

$$H_{q\bar{q}}(Q,\mu)\, B_q(Q\mathcal{T}^{\text{cut}}, R, \mu)\, B_{\bar{q}}(Q\mathcal{T}^{\text{cut}}, R, \mu)\, S(\mathcal{T}^{\text{cut}}, R, \mu)$$



Tackmann, Walsh, Zuberi, arXiv:1206.4312
Gangal, Stahlhofen, Tackmann, arXiv:1412.4792
Gangal, Gaunt, Tackmann, Vryonidou, arXiv:2003.04323

Logarithms can be thought to come from each function in factorised cross section:

$$\ln^2\left(\frac{\mathcal{T}^{\text{cut}}}{Q}\right) = 2\ln^2\left(\frac{Q}{\mu}\right) - \ln^2\left(\frac{Q\mathcal{T}^{\text{cut}}}{\mu^2}\right) + 2\ln^2\left(\frac{\mathcal{T}^{\text{cut}}}{\mu}\right)$$

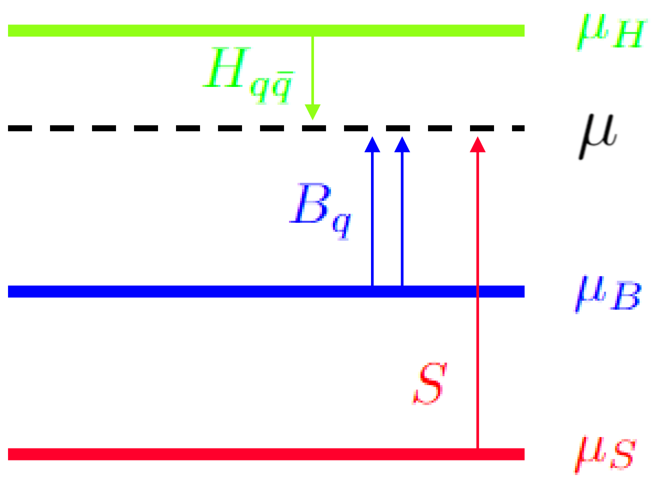
Resummation in Jet Vetoes

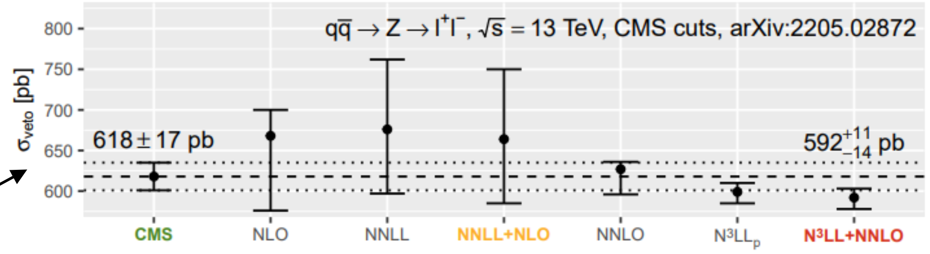
Can sum the logarithms by solving the RGE's of the functions in the factorisation formula.

Evolve all the scales to a common scale.

The goal precision is NNLL' + π^2 (partial N^{3}LL).

The result is matched to the FO + π^2 cross section. The final precision is NNLL' + NNLO + π^2 (n.b. State of the art for P_T veto is also partial N3LL).





Drell-Yan Ptj resummation at partial N3LL + NNLO compared with experimental data.

Campbell, Ellis, Neumann, Seth, arXiv:2301.11768

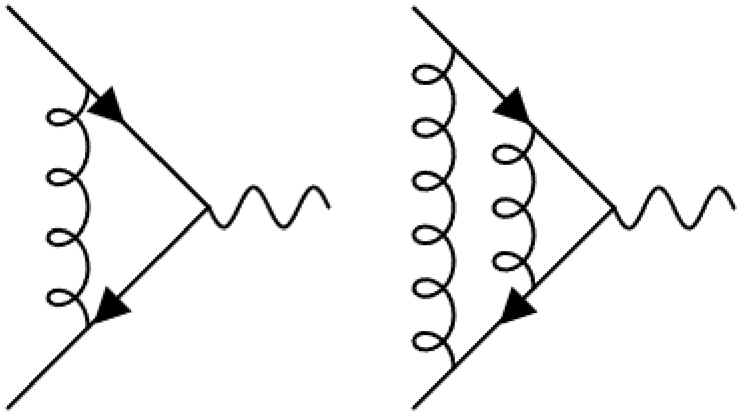
Choice of Scales

For a particular value of τ_{Cut}, need to choose the beam, soft and hard scales.

Hard scale chosen to sum time-like logarithms (π^2 resummation):

$$\mu_H = -i\mu_{\text{FO}}$$

Form of processes resummed by π^2 resummation →



See e.g. Ahrens, Becher, Neubert, Yang, arXiv:0808.3008,0809.4283

The factorisation scale is generally taken to be equal to the beam scale.

Choice of Scales

Non-perturbative region

$\mathcal{T}_{\rm cut} \sim \Lambda_{\rm QCD}$

'Freezing scale' → $\mu_0 > \Lambda_{\rm QCD}$

$\mu_S \sim \mu_0$

$\mu_B \sim \sqrt{\mu_S \mu_0}$

→

Resummation region (Canonical scaling)

$\mathcal{T}_{\rm cut} << Q$

$\mu_S \sim \mathcal{T}_{\rm cut}$

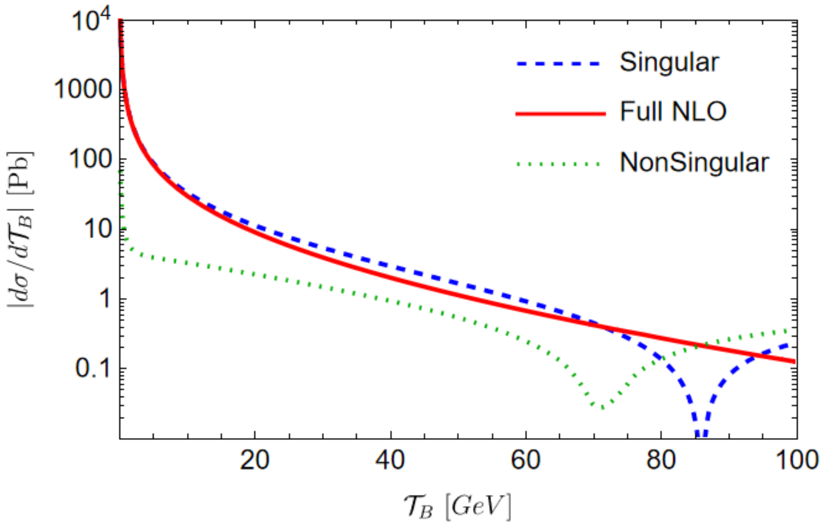
$\mu_B \sim \sqrt{Q\mathcal{T}_{\rm cut}}$

→

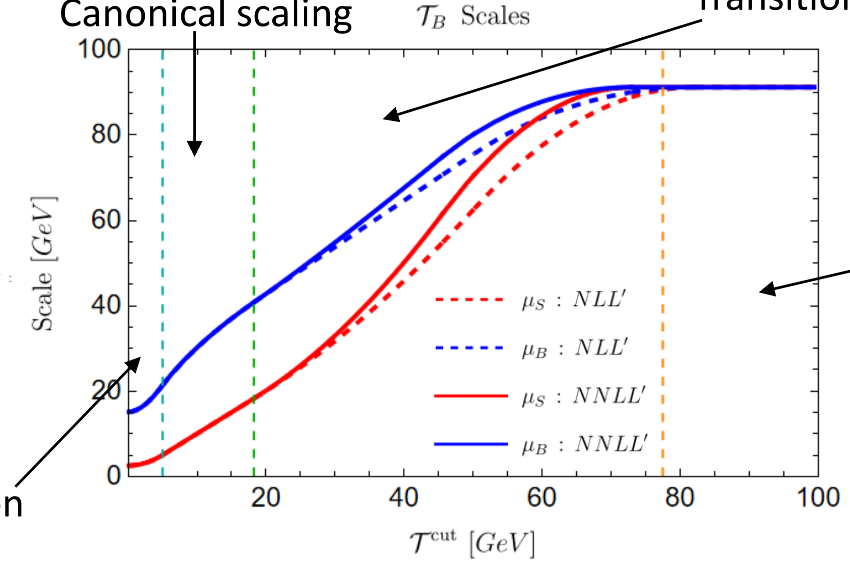
Fixed-order region

$\mathcal{T}_{\rm cut} \sim Q \sim \mu_{\rm FO}$

$\mu_S, \mu_B \sim Q \sim \mu_{\rm FO}$



Used to determine →



Scale Variations

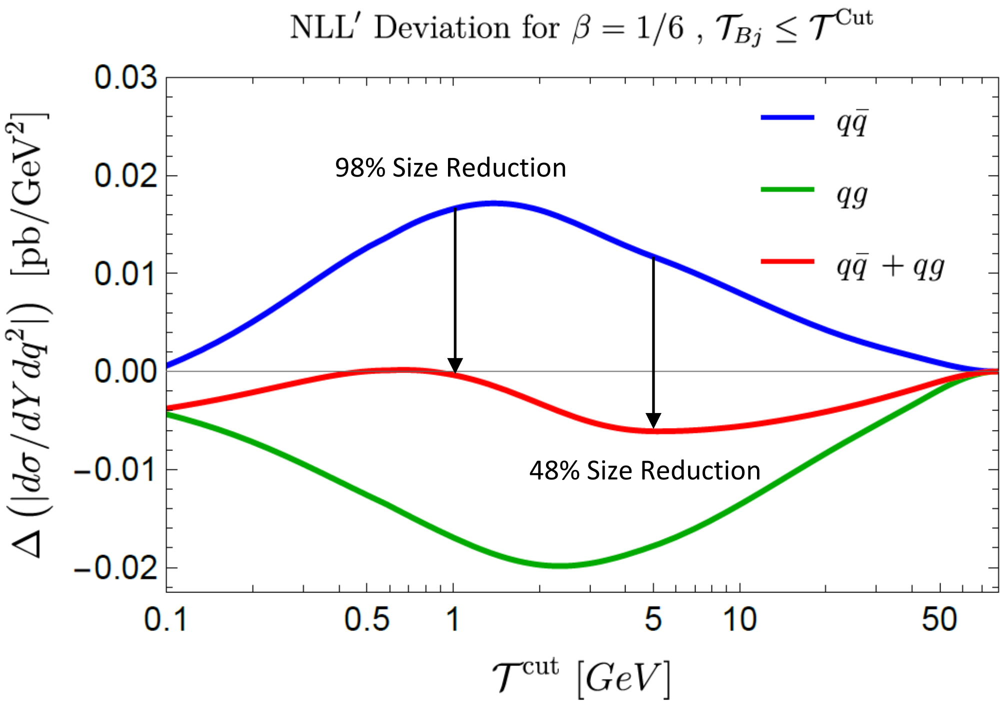
Standard FO variations are used:

$$\mu_{\rm FO} = \{\tfrac{1}{2}M_Z, M_Z, 2M_Z\}$$

Profile scales are varied using two parameters (α,β) that lead to ~2 variation in the beam and soft scales and variation in the canonical beam scaling.

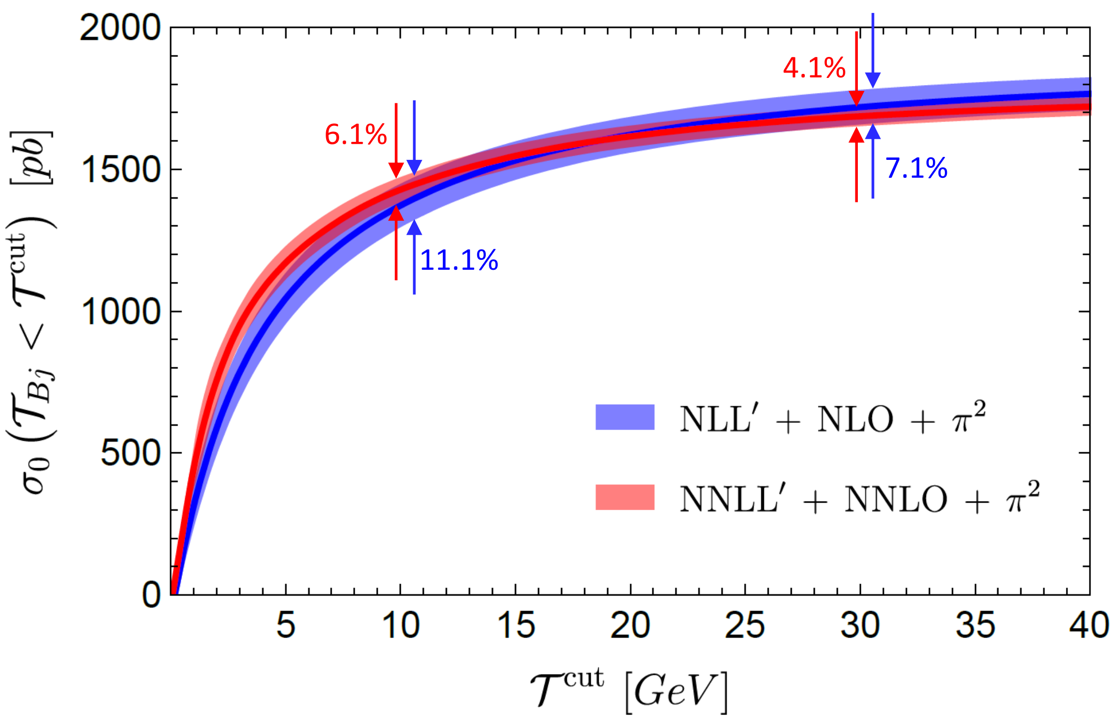
Cancellation between the $q\bar{q}$ and qg channel variations led to only the maximally deviating channel's scales being varied.

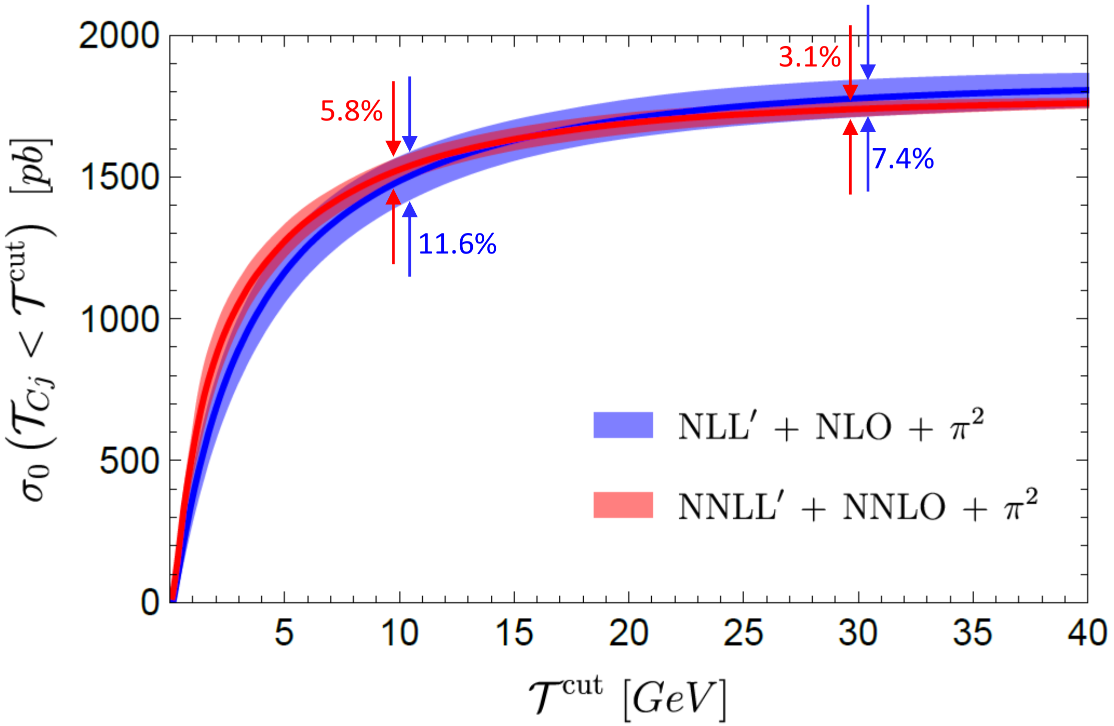
This cancellation was larger for NLL' than NNLL'.



Jet Veto Predictions for Drell-Yan

$R = 0.5 \qquad 80\text{GeV} \le Q \le 100\text{GeV}$



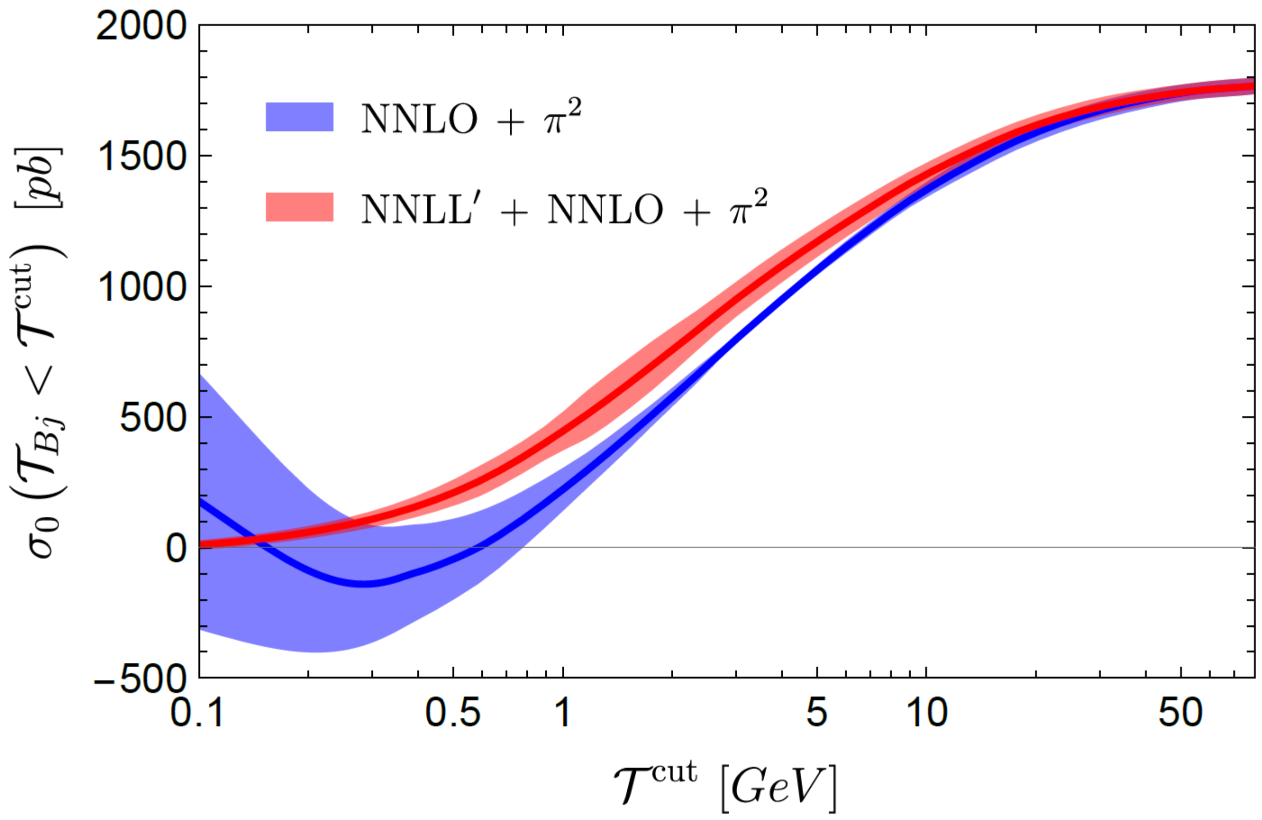


Jet Veto Predictions for Drell-Yan

Fixed-order prediction becomes inconsistent with resummed prediction at $\tau_{Cut} \sim 10$ GeV.

Other hard processes at larger Q will have larger logarithms for given τ_{Cut} .

Expect fixed-order predictions to become inconsistent at larger $\tau_{Cut.}$



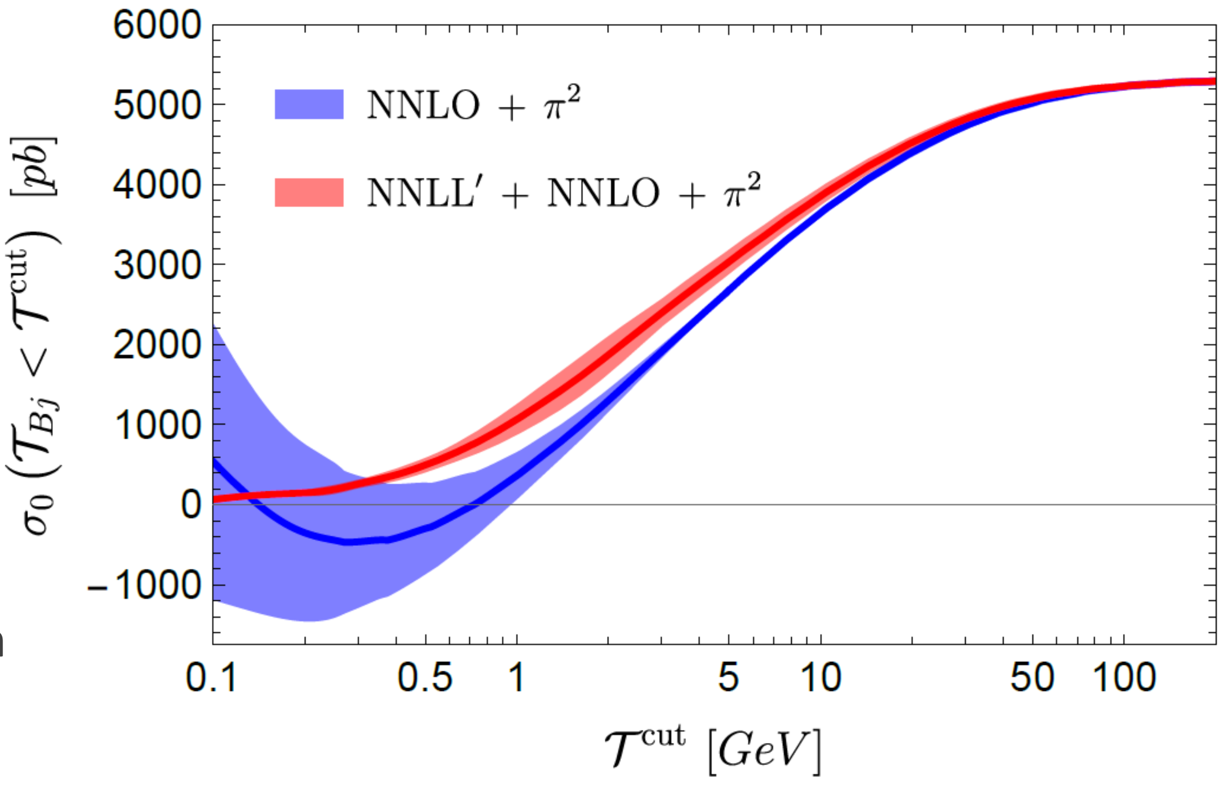
Jet Veto Predictions for Heavy Z

Repeated for artificial on-shell heavy Z boson production with a mass of 200 GeV.

Motivated by WW and WZ productions, where Q ~ 200 GeV, and have similar QCD structure.

Partonic channel cancellations again removed by using scale variations from maximally deviating partonic channel.

Fixed-order prediction becomes inconsistent with resummed prediction at τ_{Cut} ~ 20 GeV.



Theory Nuisance Parameters

How can we check our “max channel” uncertainties are reasonable estimates?

Use alternative method to calculate theory uncertainties: Theory nuisance parameters (TNPs).

Higher order structure can be recursively found from renormalization group equations. E.g. for 3-loop soft function:

$$\mu \frac{d}{d\mu} \ln S_q \left(\mathcal{T}^{\text{cut}}, R, \mu\right) = 4\Gamma^q_{\text{cusp}} \left[\alpha_s(\mu)\right] \ln \frac{\mathcal{T}^{\text{cut}}}{\mu} + \gamma^q_S \left[\alpha_s(\mu), R\right]$$

Expand in α_s →

$$\mu \frac{d}{d\mu} S_q^{(3)} = 4\Gamma_2^q + \gamma^q_{S2} + 4\beta_0 S_q^{(2)} + 2\beta_1 S_q^{(1)}$$

TNP approach developed by Cridge, Marinelli, Tackmann, see talk by Tackmann at SCET 2024 and talk by Marinelli at QCD@LHC 2024

Theory Nuisance Parameters

Unknown values in higher order structure are boundary constants from integration and anomalous dimensions.

$$F\left(\alpha_s\right) = 1 + \sum_{n=1} \left(\frac{\alpha_s}{4\pi}\right)^n F_n \qquad \gamma\left(\alpha_s\right) = \sum_{n=0} \left(\frac{\alpha_s}{4\pi}\right)^{n+1} \gamma_n$$

Implement the higher order structure and vary boundary constant and anomalous dimension values of these to estimate theory uncertainties.

$$F_n\left(\theta_n\right) = 4C_r\left(4C_A\right)^{n-1}(n-1)!\theta_n$$

$$\gamma_n\left(\theta_n\right) = 2C_r\left(4C_A\right)^n\theta_n$$

Leading colour factors and order normalisation

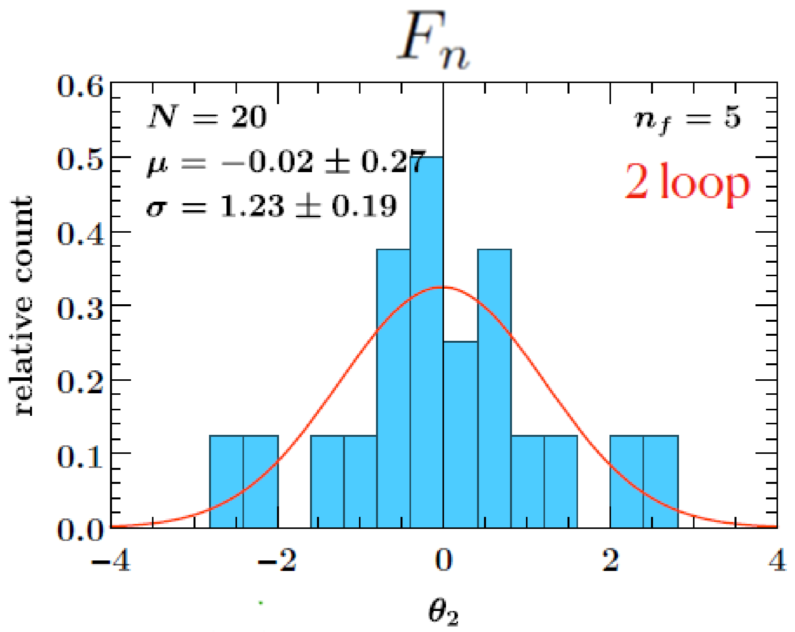
Nuisance parameter to vary

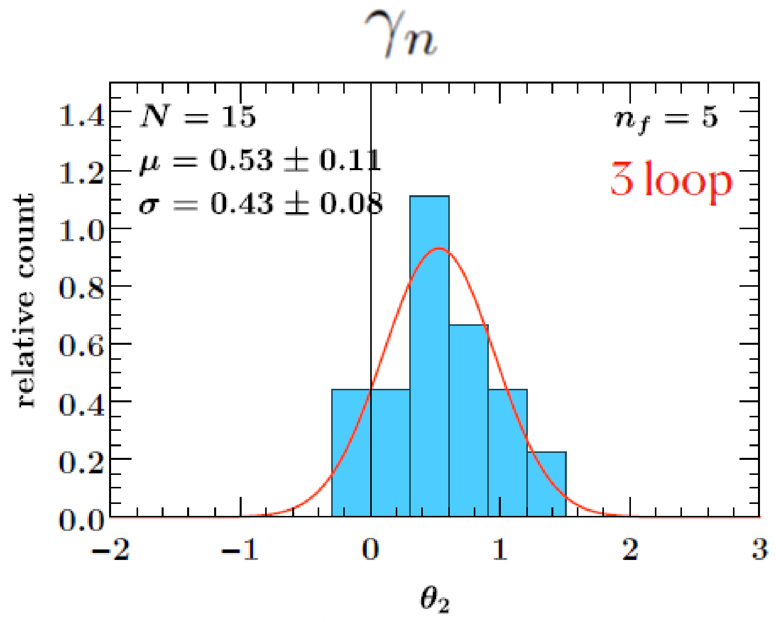
In this implementation a rough estimate of the theory uncertainties size is desired, only include higher order structure related to TNPs to simplify calculation.

TNP approach developed by Cridge, Marinelli, Tackmann, see talk by Tackmann at SCET 2024 and talk by Marinelli at QCD@LHC 2024

Theory Nuisance Parameters

Figures taken from talk by Marinelli at QCD@LHC 2024





Form gaussian distributions, vary TNPs by ±1 centred at 0.

TNP approach developed by Cridge, Marinelli, Tackmann, see talk by Tackmann at SCET 2024 and talk by Marinelli at QCD@LHC 2024

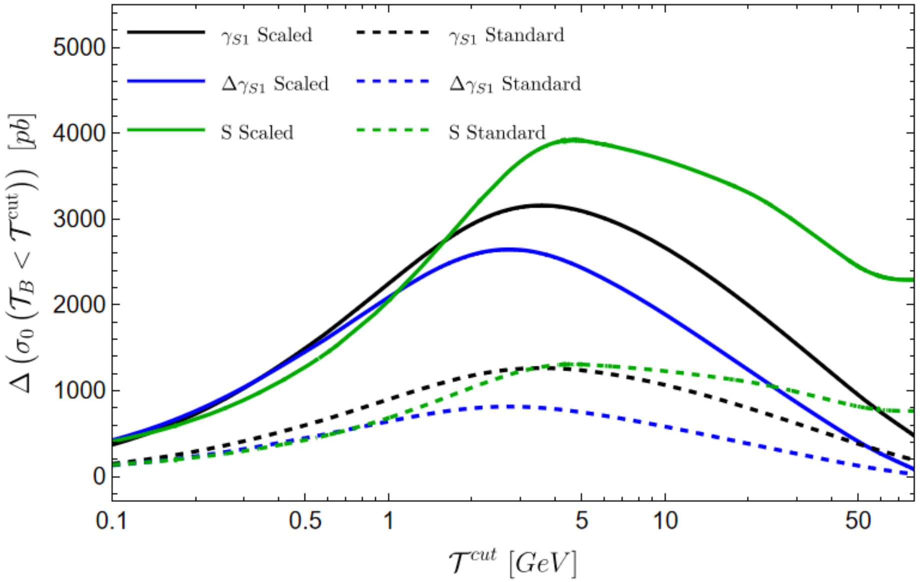
Theory Nuisance Parameters

Found ±1 TNP variation not appropriate at NLL' for some nuisance parameters.

Comparing with known size (at NLL' all TNP used have known true values, not true for NNLL') alter variation when appropriate.

Alioli, Walsh, arXiv:1311.5234
Tackmann, Walsh, Zuberi: 1206.4312

PRELIMINARY



Soft variations larger due to clustering corrections and dominate NLL' TNP uncertainty

$$\gamma_S^q[\alpha(\mu), R] = \gamma_{G,S}^q[\alpha(\mu)] + \Delta\gamma_S^q[\alpha(\mu), R]$$

TNP approach developed by Cridge, Marinelli, Tackmann, see talk by Tackmann at SCET 2024 and talk by Marinelli at QCD@LHC 2024

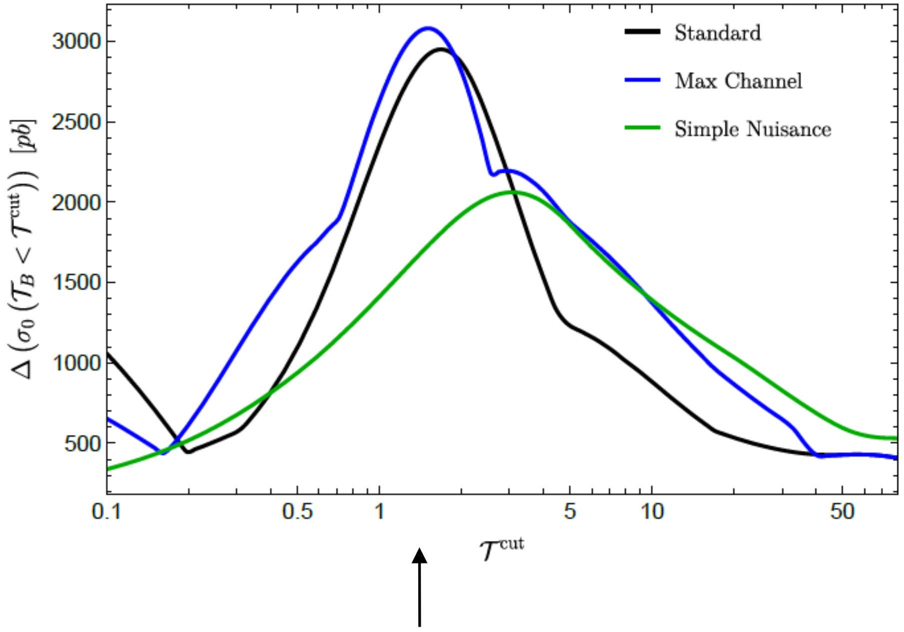
Theory Nuisance Parameters

At NLL', uncertainty with new variations and only most dominant TNP uncertainties was much larger than scale variation uncertainties.

At NNLL' produced various estimates based on NLL' implementation.

NLL' scale variations largely underestimate uncertainties, NNLL' scale variations slightly overestimates but of order of TNP approach.

PRELIMINARY



Most conservative NNLL' TNP uncertainty prediction

TNP approach developed by Cridge, Marinelli, Tackmann, see talk by Tackmann at SCET 2024 and talk by Marinelli at QCD@LHC 2024.

Summary

- Produced cutting edge NLL′ + NLO + π^2 and NNLL′ + NNLO + π^2 predictions for τ_B and τ_c
- Demonstrated the need to perform resummation when tight cuts on τ_B and τ_c produce unphysical FO predictions
- Producing theory uncertainties via theory nuisance parameters to test the theory uncertainty implementation
- The next key step is to compare these high precision results against experimental data

Additional: Parameter Values

Description	Parameter	Value	Unit
Z boson mass	M_Z	91.1876	GeV
Z boson width	Γ_Z	2.4952	GeV
Centre of mass energy	E_{COM}	13	TeV
Jet Radius	R	0.5	N/A
Sin squared of weak mixing angle	$\sin^2(\theta_W)$	0.22301383694753507	N/A
Fine structure constant	α_{EM}	0.0075652121285480845	N/A
NLO strong coupling at M_Z	$\alpha_s^{\text{NLO}}(M_Z)$	0.120	N/A
NNLO strong coupling at M_Z	$\alpha_s^{\text{NNLO}}(M_Z)$	0.118	N/A

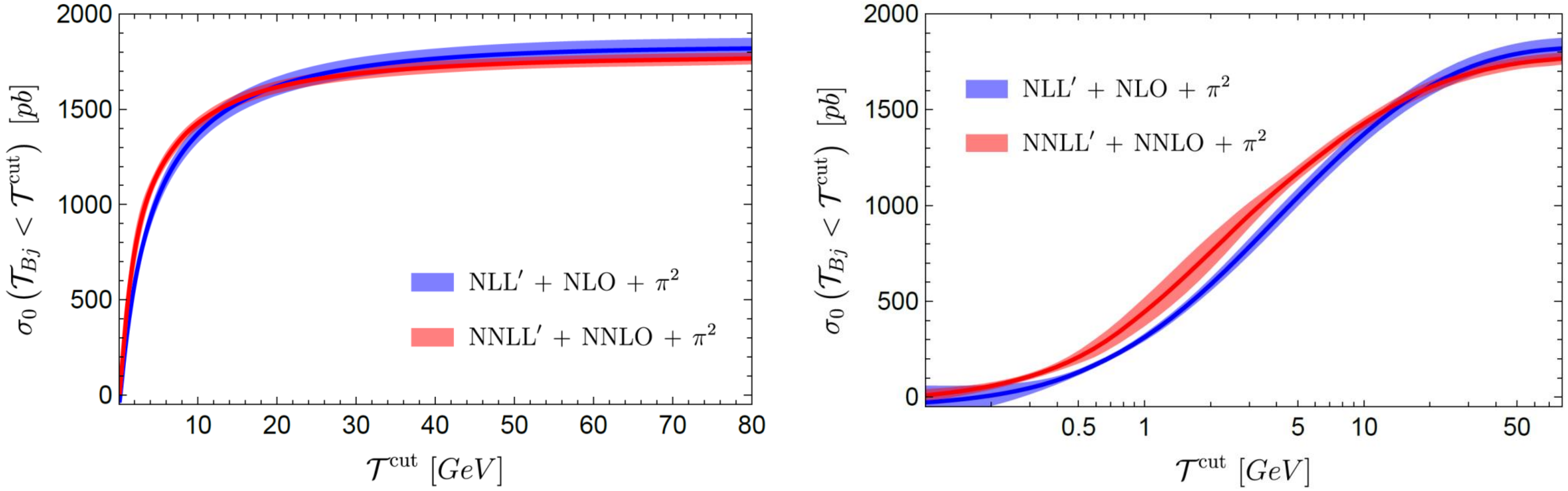
PDF Set for NLL’ + NLO: MSHT20nlo_as120

PDF Set for NNLL’ + NNLO: MSHT20nnlo_as118

Additional: Table of Results

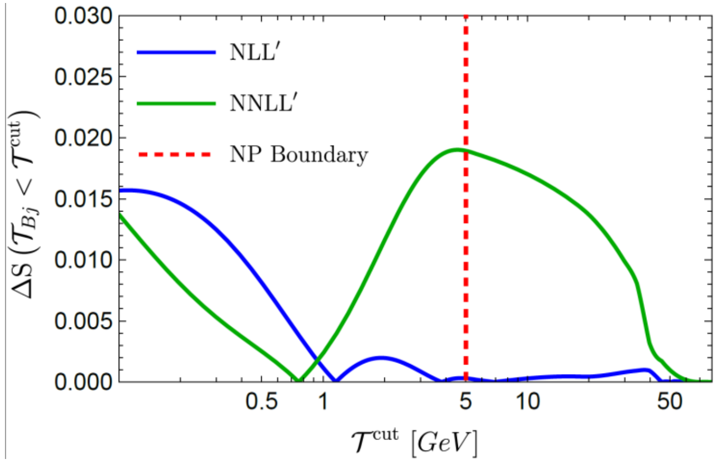
	$\sigma_0\left(\mathcal{T}_{B_j} < \mathcal{T}^{\text{cut}}\right)$ [pb] $(r_s = 1)$	$\sigma_0\left(\mathcal{T}_{C_j} < \mathcal{T}^{\text{cut}}\right)$ [pb] $(r_s = 2)$
NLO		
$\mathcal{T}^{\text{cut}} = 10$ GeV	$1431.40 \pm 68.48\,(4.78\%)$	$1544.24 \pm 65.89\,(4.27\%)$
$\mathcal{T}^{\text{cut}} = 30$ GeV	$1736.71 \pm 59.42\,(3.42\%)$	$1785.10 \pm 57.38\,(3.21\%)$
NNLO		
$\mathcal{T}^{\text{cut}} = 10$ GeV	$1369.47 \pm 28.50\,(2.08\%)$	$1484.16 \pm 24.64\,(1.66\%)$
$\mathcal{T}^{\text{cut}} = 30$ GeV	$1672.43 \pm 34.54\,(2.07\%)$	$1730.45 \pm 19.94\,(1.15\%)$
$\text{NLL}' + \text{NLO}$		
$\mathcal{T}^{\text{cut}} = 10$ GeV	$1372.27 \pm 47.71\,(3.48\%)$	$1486.13 \pm 54.03\,(3.64\%)$
$\mathcal{T}^{\text{cut}} = 30$ GeV	$1718.99 \pm 51.05\,(2.97\%)$	$1777.50 \pm 53.67\,(3.08\%)$
$\text{NNLL}' + \text{NNLO}$		
$\mathcal{T}^{\text{cut}} = 10$ GeV	$1428.09 \pm 29.08\,(2.04\%)$	$1526.03 \pm 33.12\,(2.17\%)$
$\mathcal{T}^{\text{cut}} = 30$ GeV	$1686.84 \pm 31.75\,(1.88\%)$	$1739.81 \pm 19.16\,(1.10\%)$
$\text{NLL}' + \text{NLO}$ Max Channel		
$\mathcal{T}^{\text{cut}} = 10$ GeV	$1372.27 \pm 76.43\,(5.57\%)$	$1486.13 \pm 86.27\,(5.80\%)$
$\mathcal{T}^{\text{cut}} = 30$ GeV	$1718.99 \pm 60.84\,(3.54\%)$	$1777.50 \pm 65.78\,(3.70\%)$
$\text{NNLL}' + \text{NNLO}$ Max Channel		
$\mathcal{T}^{\text{cut}} = 10$ GeV	$1428.09 \pm 43.87\,(3.07\%)$	$1526.03 \pm 44.07\,(2.89\%)$
$\mathcal{T}^{\text{cut}} = 30$ GeV	$1686.84 \pm 34.85\,(2.07\%)$	$1739.81 \pm 27.30\,(1.57\%)$

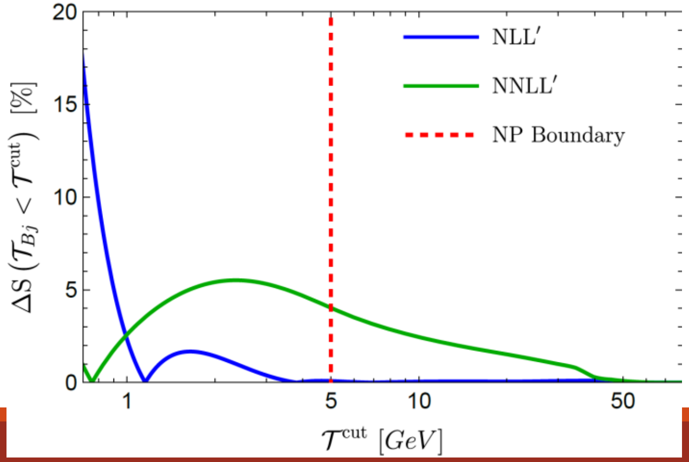
Additional: Standard Scale Variations



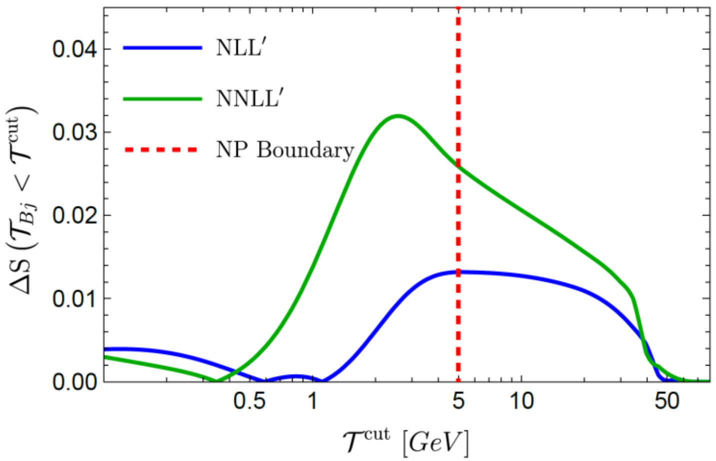
Additional: Soft Function Deviations

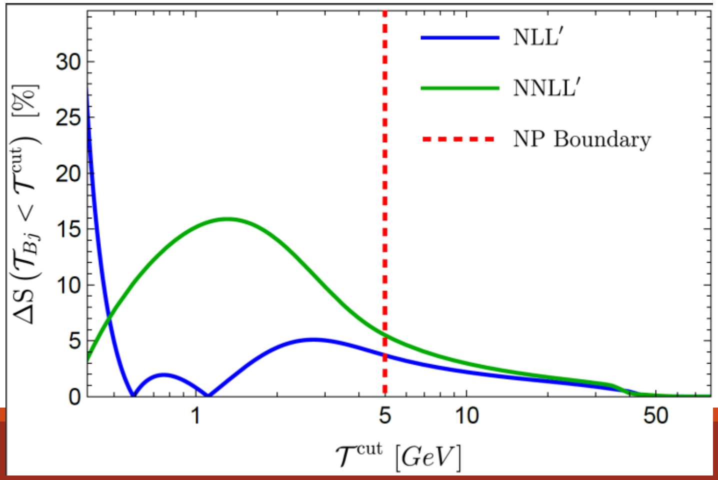
alpha = 1



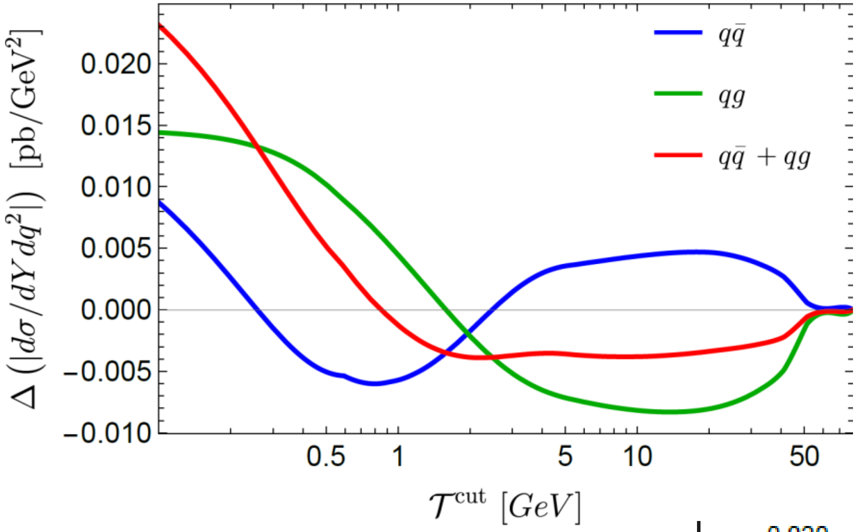


alpha = -1

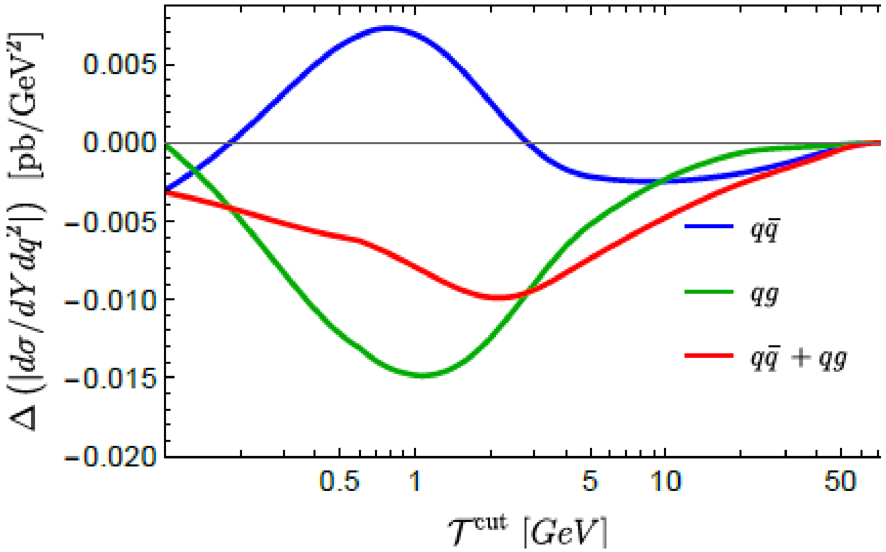




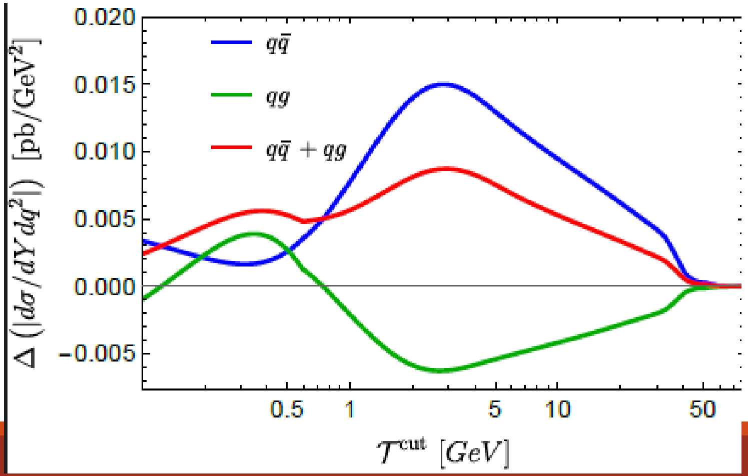
Additional: Channel Cancellations



NLL’ alpha = 1

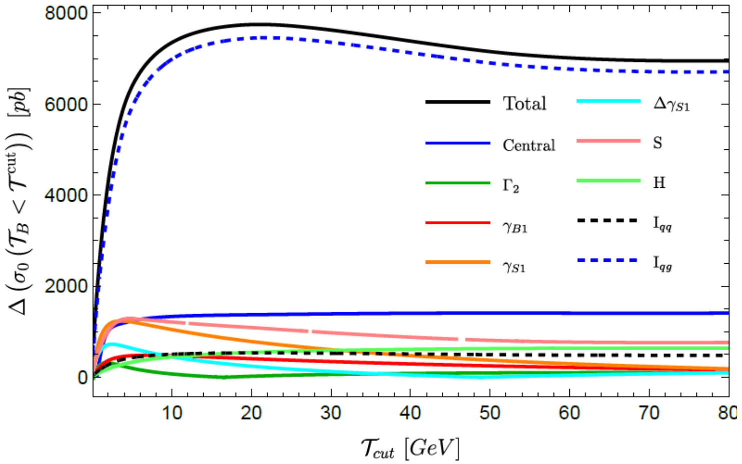


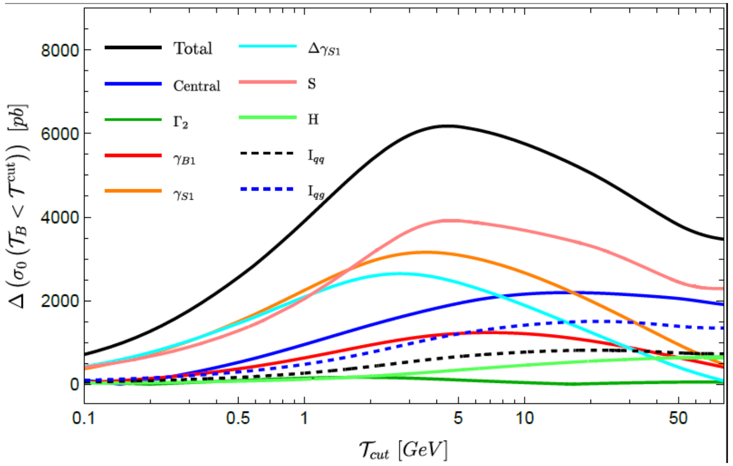
NNLL’ beta = 1/6

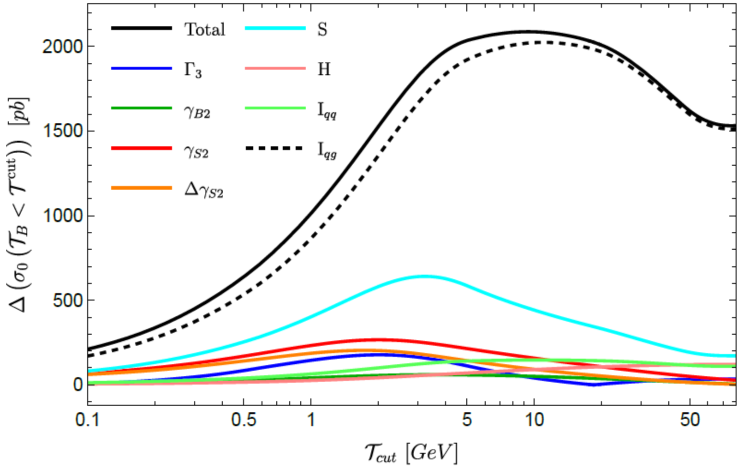


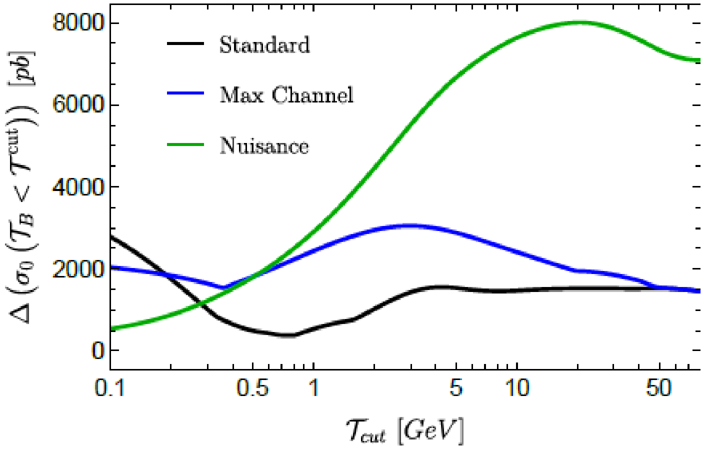
NNLL’ alpha = 1

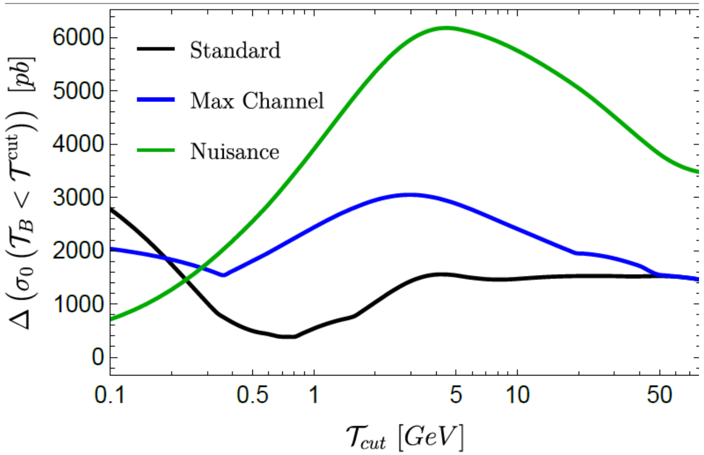
Additional: TNPs



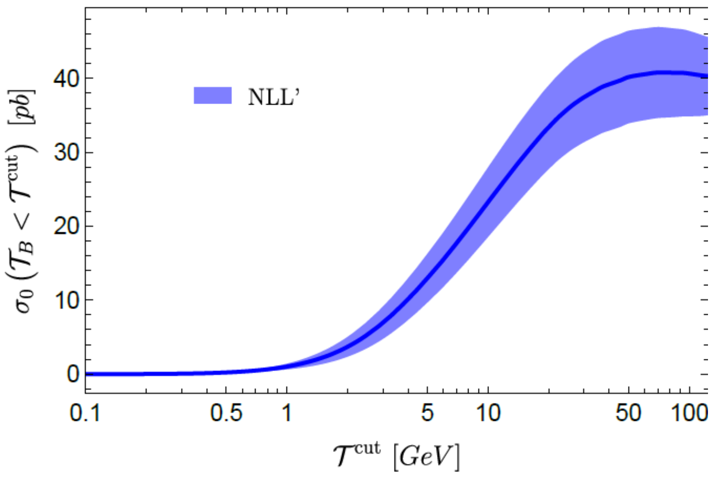


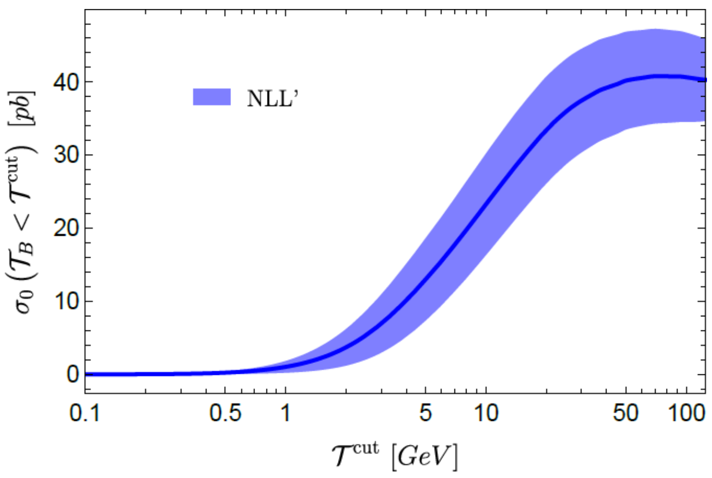


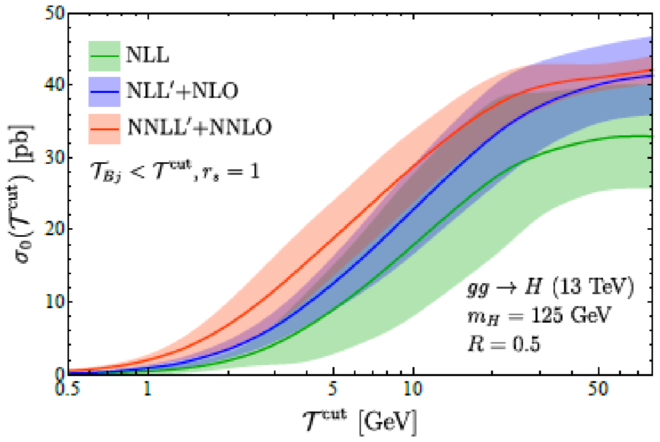




Additional: TNPs







Gangal, Gaunt, Tackmann, Vryonidou, arXiv:2003.04323