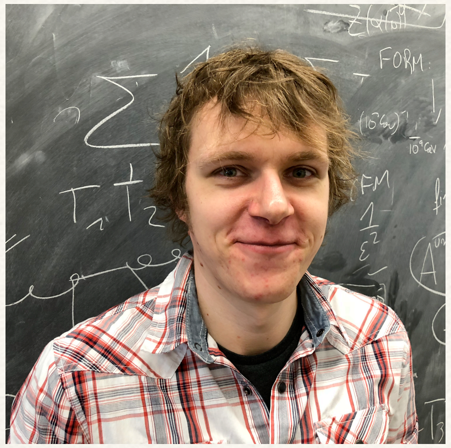


Crieff, June 2023

Jet Veto Resummation in MCFM

R. Keith Ellis,
IPPP, Durham

Jet-veto resummation at N^3LL_p+NNLO in boson production processes,
John M. Campbell, R. Keith Ellis, Tobias Neumann, Satyajit Seth, 2301.11768

MCFM (mcfm.fnal.gov)

- MCFM 10.3 (January 30th, 2023) contains about 350 processes at hadron-colliders evaluated at NLO.
- We have tried to improve the documentation by giving a web-page and a specimen input file for every process.
- Since matrix elements are calculated using analytic formulae, one can expect better performance, in terms of stability and computer speed, than fully numerical codes.
- In addition MCFM contains many processes evaluated at NNLO using both the jettiness and the q_T slicing schemes. Non-local slicing approaches for NNLO QCD in MCFM, Campbell, RKE and Seth 2202.07738
- NNLO results for $pp \to X$, require process $pp \to X+1$ parton at NLO, and two loop matrix elements for $pp \to X$, (all provided by other authors).
- MCFM also includes transverse momentum resummation at N^3LL+NNLO for W,Z,H,WW,ZZ,WH and ZH processes.

Fiducial qT resummation of color-singlet processes at N^3LL+NNLO, CuTe-MCFM 2009.11437, Becher and Neumann

Transverse momentum resummation at N^3LL+NNLO for diboson processes,Campbell, RKE, Neumann and Seth, 2210.10724

Web-page for every process, with specimen input files.

15:41 4G

1 $f(\text{-}p_1) + f(\text{-}p_2) \to W^+(\to \nu(p_3) + e^+(p_4))$

1.1 *W*-boson production, processes 1,6

These processes represent the production of a W boson which subsequently decays leptonically. This process can be calculated at LO, NLO, and NNLO. NLO calculations can be performed by dipole subtraction, zero-jettiness slicing and q_T-slicing. NNLO calculations can be performed by zero-jettiness slicing and q_T-slicing.

When `removebr` is true, the W boson does not decay.

Input files for these 6 possibilities, as used plots for 'Non-local slicing approaches for NNLO QCD in MCFM', ref. [1] are given in the link below.

1.2 Input files as used for NNLO studies, ref. [1]

- ./lo/input_W+.ini
- ./nlo/input_W+.ini
- ./nlo/input_W+_qt.ini
- ./nlo/input_W+_scet.ini
- ./nnlo/input_W+_qt.ini
- ./nnlo/input_W+_scet.ini

1.3 Input file for transverse momentum resummed cross-sections, ref. [2]

- input_W+.ini

1.4 Input files for jet-vetoed cross-sections, ref. [3]

- vetowp30nlo.ini
- vetowp30nnlo.ini
- vetowp30nnll.ini
- vetowp30n3ll.ini
- vetowp30nlomc.ini
- vetowp30nnlomc.ini

1.5 Plotter

nplotter_W_only.f is the default plotting routine.

1.6 Example input and output file(s)

input1.ini process1.out

References

[1] J.M. Campbell, R.K. Ellis and S. Seth, *Non-local slicing approaches for NNLO QCD in MCFM*, 2202.07738.

[2] T. Becher and T. Neumann, *Fiducial q_T resummation of color-singlet processes at N^3LL+NNLO*, JHEP **03** (2021) 199 [2009.11437].

[3] J.M. Campbell, R.K. Ellis, T. Neumann and S. Seth, *Jet-veto resummation at N^3LL_p+NNLO in boson production processes*, 2301.11768.

Example of Analytic loop amplitudes in MCFM

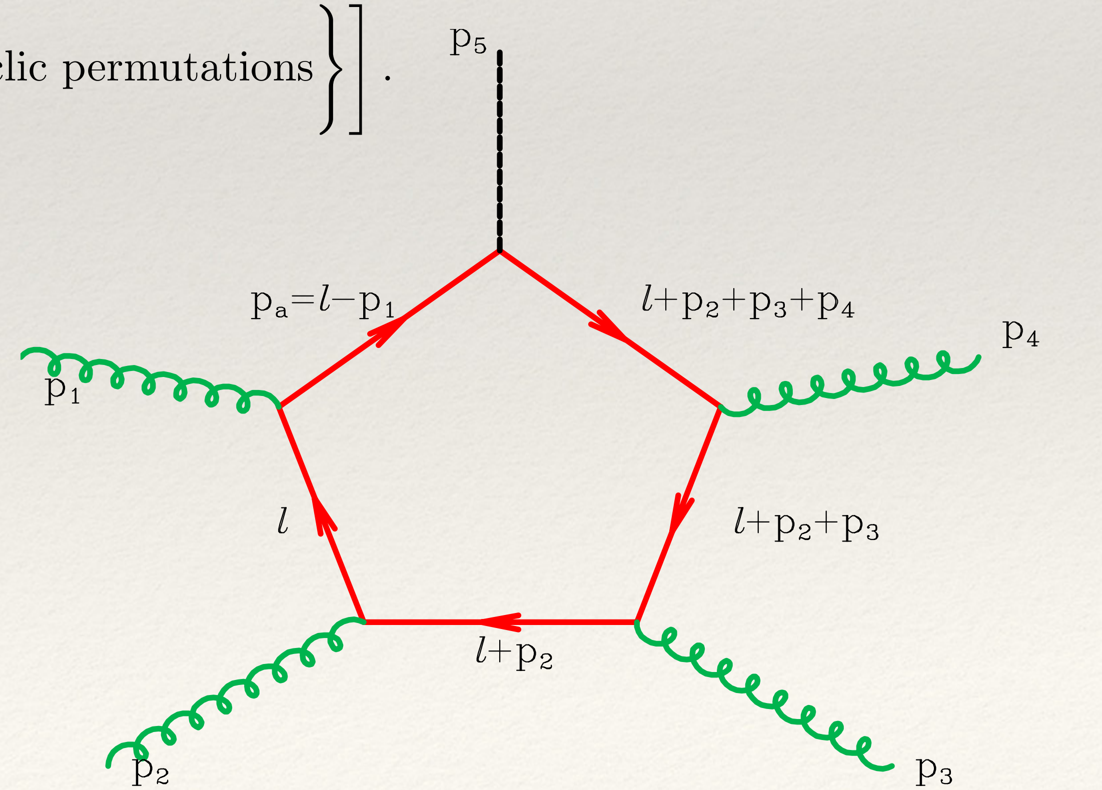
RKE and Seth, 1808.09292
Budge et al, 2002.04018

- Higgs boson plus four partons at one loop.

$$A_4(1_g^+,2_g^+,3_g^+,4_g^+;H) = m^2\Bigg[\Bigg\{\frac{4m^2-M_h^2}{\langle 1\,2\rangle\langle 2\,3\rangle\langle 3\,4\rangle\langle 4\,1\rangle}\Big[-\mathrm{tr}_+\{1\,2\,3\,4\}m^2E_0(p_1,p_2,p_3,p_4;m)$$
$$+\frac{1}{2}((s_{12}+s_{13})(s_{24}+s_{34})-s_{14}s_{23})D_0(p_1,p_{23},p_4;m)$$
$$+\frac{1}{2}s_{12}s_{23}D_0(p_1,p_2,p_3;m)$$
$$+(s_{12}+s_{13}+s_{14})C_0(p_1,p_{234};m)\Big]+2\frac{s_{12}+s_{13}+s_{14}}{\langle 1\,2\rangle\langle 2\,3\rangle\langle 3\,4\rangle\langle 4\,1\rangle}\Bigg\}$$
$$+\Bigg\{\text{3 cyclic permutations}\Bigg\}\Bigg].$$

- Used for the full NLO calculation of Higgs production with a jet.

- "Although the integration of the 2 → 3 amplitudes, …, is not time intensive, we preferred to use the analytic result … which saved about a factor of a 100 in the integration time of the gluonic one-loop 2 → 3 amplitudes." Bonciani et al, 2206.10490



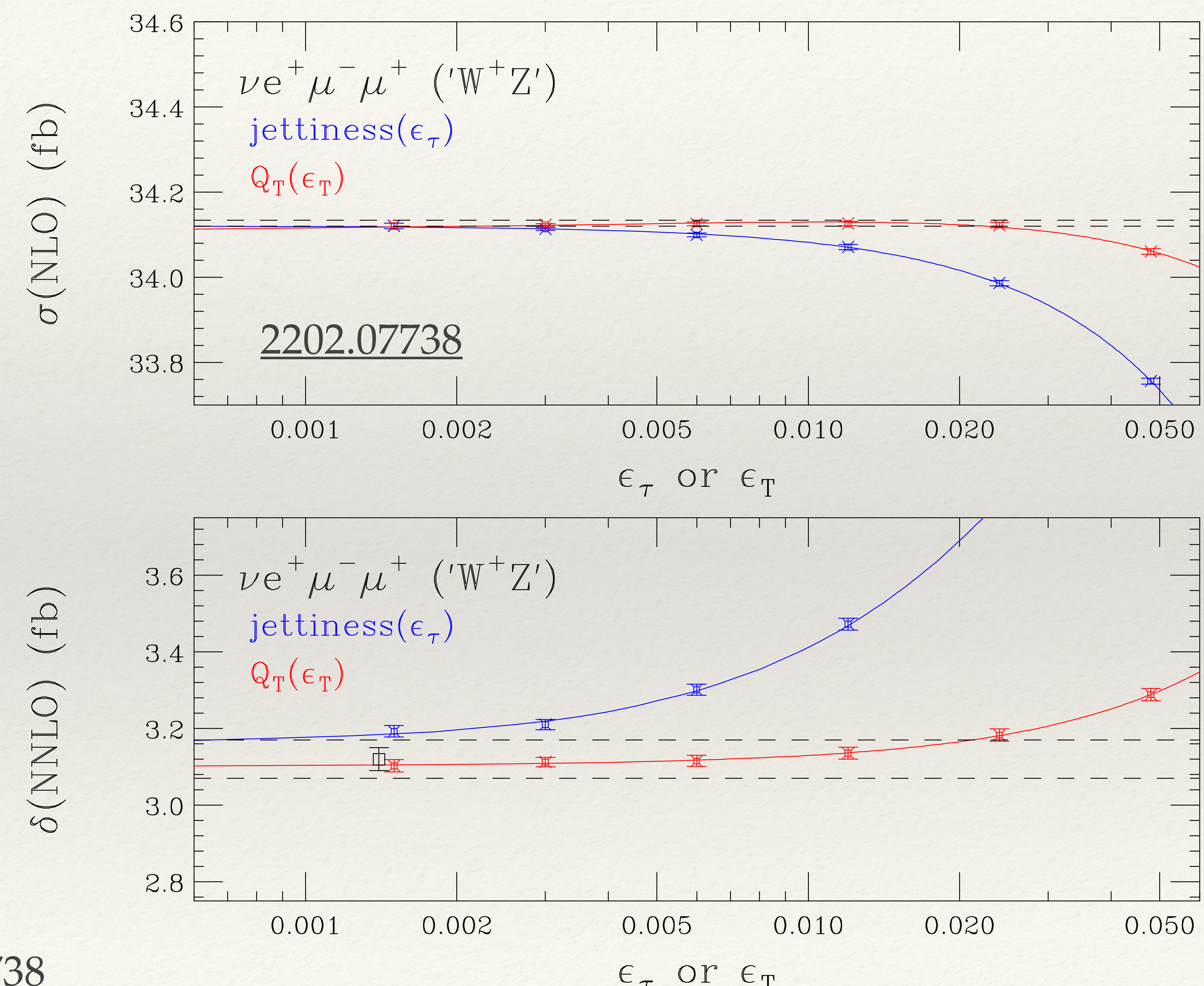
NNLO results

- In a recent paper (2202.07738) we tried to document all the processes calculated at NNLO.
- About 50% are available in MCFM.
- We use both q_T slicing and jettiness slicing.
- However I should note that in some cases N^{3}LO is now the start of the art (e.g. 1811.07906 ,2102.07607 2203.01565, 2209.06138)

Process	MCFM	Process	MCFM
$H+0$ jet [8–14]	✓ [15]	$W^\pm+0$ jet [16–18]	✓ [15]
Z/γ^*+0 jet [11, 17–19]	✓ [15]	ZH [20]	✓ [21]
$W^\pm\gamma$ [18, 22, 23]	✓ [24]	$Z\gamma$ [18, 25]	✓ [25]
$\gamma\gamma$ [18, 26–28]	✓ [29]	single top [30]	✓ [31]
$W^\pm H$ [32, 33]	✓ [21]	WZ [34, 35]	✓
ZZ [1, 18, 36–40]	✓	W^+W^- [18, 41–44]	✓
$W^\pm+1$ jet [45, 46]	[3]	$Z+1$ jet [47, 48]	[4]
$\gamma+1$ jet [49]	[5]	$H+1$ jet [50–55]	[6]
$t\bar{t}$ [56–61]		$Z+b$ [62]	
$W^\pm H$+jet [63]		ZH+jet [64]	
Higgs WBF [65, 66]		$H\to b\bar{b}$ [67–69]	
top decay [31, 70, 71]		dijets [72–74]	
$\gamma\gamma$+jet [75]		$W^\pm c$ [76]	
$b\bar{b}$ [77]		$\gamma\gamma\gamma$ [78]	
HH [79]		HHH [80]	

NNLO results: dependence on slicing procedure

- For most (but not all) processes the power corrections are smaller for Q_T slicing than for jettiness.
- Factor of two in the exponent difference between the leading form factors for q_T and jettiness
- removed by defining $\epsilon_T = q_T^{\text{cut}}/Q$ and $\epsilon_\tau = (\tau^{\text{cut}}/Q)^{\frac{1}{\sqrt{2}}}$



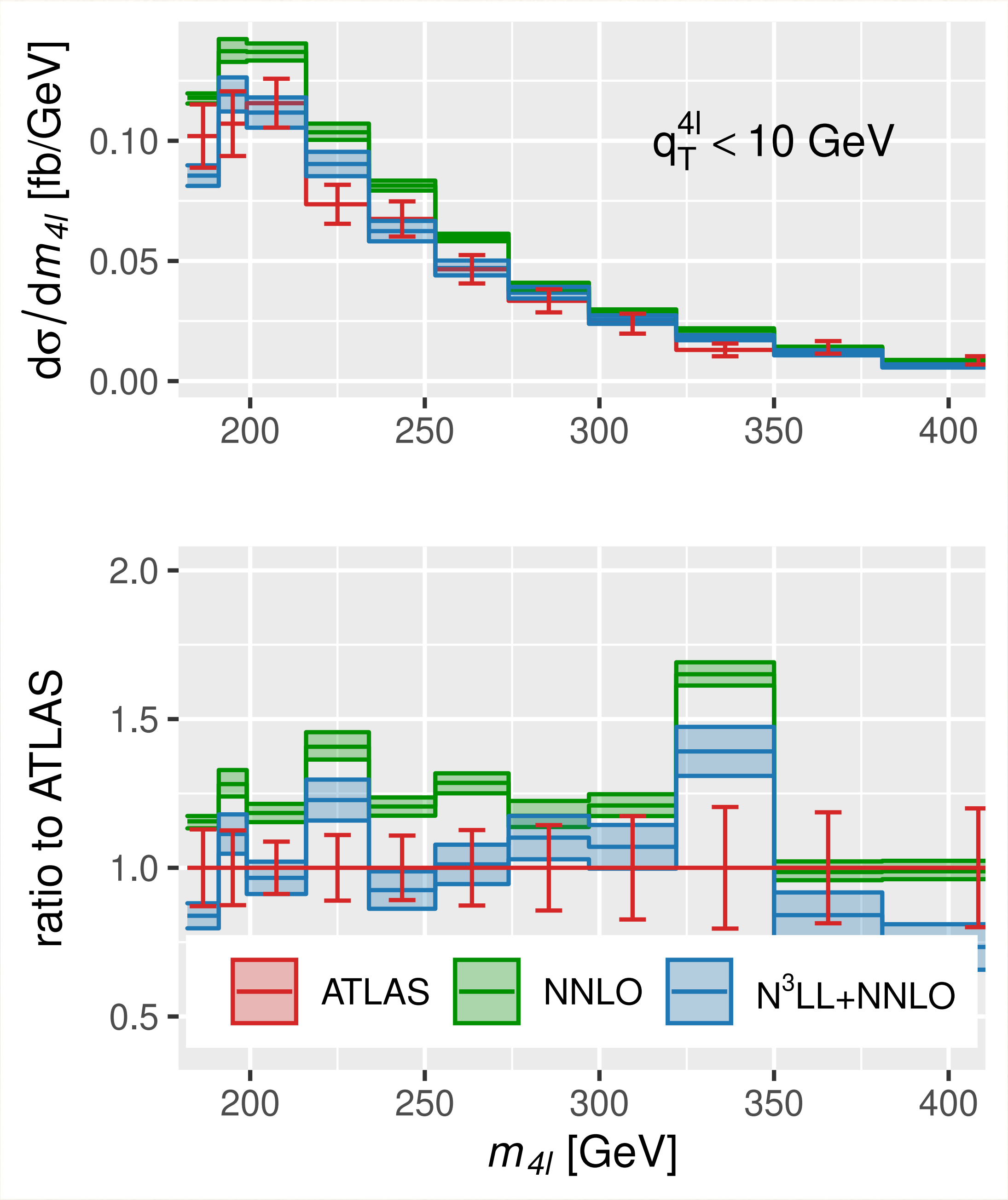
Campbell et al, 2202.07738

Example of q_T resummation in four lepton events(ZZ)

- ATLAS $\sqrt{s}$ = 13TeV, 139fb^{-1} data, 2103.01918

lepton cuts	$q_T^{\ell_1} > 20\,\text{GeV},\ q_T^{\ell_2} > 10\,\text{GeV},$ $q_T^{\ell_{3,4}} > 5\,\text{GeV},\ q_T^{e} > 7\,\text{GeV},$ $\lvert\eta^\mu\rvert < 2.7,\ \lvert\eta^e\rvert < 2.47$
lepton separation	$\Delta R(\ell, \ell') > 0.05$

- $m_{4l} > 182$ GeV to avoid Higgs region.
- Low q_T data, plotted as a function of m_{4l}
- Agreement with data improves as m_{4l} increases.



Fiducial q_T resummation of color singlet processes at N³LL+NNLO, Becher and Neumann, 2009.11437

Transverse momentum resummation at N³LL+NNLO for diboson processes, Campbell, RKE, Neumann and Seth, 2210.10724

Jet veto cross sections

This portion of the talk is intended to be complementary to (and complimentary of) the talk of Robert Szafron on Wednesday morning.

For initial studies see, for example, Becher et al, 1307.0025 , Stewart et al, 1307.1808

New ingredients for jet-veto resummation

- Important step in making SCET results for almost complete N^{3}LL available. For details of the missing piece, see later.
- Jets vetoed over all rapidity, (which is not the case experimentally).

The analytic two-loop soft function for leading-jet p_T

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Soft function
Abreu et al,
2204.03987

Prepared for submission to JHEP — CERN-TH-2022-118, ZU-TH 30/22

Quark and gluon two-loop beam functions for leading-jet p_T and slicing at NNLO

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Beam functions
Abreu et al,
2207.07037

Jet veto cross section

- Jets defined using sequential recombination jet algorithms, (n=1(anti-k_T), n=0(Cambridge-Aachen) n=-1(k_T);
- Jet vetos also generate large logarithms, as codified in factorization formula; however logarithms tend to be smaller than in transverse momentum resummation, since $p_T^{\text{veto}} \sim 25$ GeV;
- Beam and Soft functions for leading jet p_T recently calculated at two-loop order using an exponential regulator by Abreu et al.
- Jet veto cross sections are simpler than the p_T resummed calculation (No b space).

$$d_{ij} = \min(p_{Ti}^n, p_{Tj}^n)\, \frac{\sqrt{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}}{R}, \qquad d_{iB} = p_{Ti}^n$$

$$\frac{d^2\sigma(p_T^{veto})}{dM^2 dy} = \sigma_0 \left| C_V(-M^2,\mu) \right|^2$$
$$\left[\mathscr{B}_c(\xi_1, M, p_T^{veto}, R^2, \mu, \nu)\, \mathscr{B}_{\bar{c}}(\xi_2, M, p_T^{veto}, R^2, \mu, \nu) \times \mathscr{S}(p_T^{veto}, R^2, \mu, \nu) \right]$$

Rapidity regulator ν

Beam functions Abreu et al, 2207.07037

Soft function Abreu et al, 2204.03987

$$\xi_{1,2} = (M/\sqrt{s})\, e^{\pm y} \qquad \sigma_0 = \frac{4\pi\alpha^2}{3N_c M^2 s}$$

Refactorization

- Refactorize

$$\left[\mathscr{B}_q(\xi_1, Q, p_T^{veto}, R, \mu, \nu)\, \mathscr{B}_{\bar{q}}(\xi_2, Q, p_T^{veto}, R, \mu, \nu) \mathcal{S}(p_T^{veto}, R, \mu, \nu)\right]$$
$$= \left(\frac{Q}{p_T^{veto}}\right)^{-2F_{qq}(p_T^{veto},R,\mu)} e^{2h^F(p_T^{veto},\mu)}\, \bar{B}_q(\xi_1, p_T^{veto}, R, \mu)\, \bar{B}_{\bar{q}}(\xi_2, p_T^{veto}, R, \mu)$$

"Collinear anomaly"

"Collinear anomaly coefficient"

- In terms of reduced beam function jet vetoed cross section is now given by,

- $$\frac{d^2\sigma(p_T^{veto})}{dQ^2 dy} = \frac{d\sigma_0}{dQ^2}\, \bar{H}(Q, \mu, p_T^{veto}) \bar{B}_q(\xi_1, p_T^{veto}, R, \mu)\, \bar{B}_{\bar{q}}(\xi_2, p_T^{veto}, R, \mu) + \mathcal{O}(p_T^{veto}/Q)\,,$$

- The two pieces are separately RG invariant: $\frac{d}{d\mu}\bar{H}(Q, \mu, p_T^{veto}) = \mathcal{O}(\alpha_s^3)$

and $\frac{d}{d\mu}\bar{B}_q(\xi_1, p_T^{veto}, R, \mu)\, \bar{B}_{\bar{q}}(\xi_2, p_T^{veto}, R, \mu) = \mathcal{O}(\alpha_s^3)$

Collinear Anomaly

- In SCET the beam functions and the soft function have light-cone divergences which are not regulated by dimensional regularization;
- These are not soft divergences; they are due to gluons at large rapidity;
- This requires an additional regulator, which can be removed at the end of the calculation;
- However a vestige of this regulator remains. The product of the two beam functions depends on the large scale of the problem, Q ;
- This has been called the "collinear factorization anomaly" of SCET. Quantum effects modify a classical symmetry, $p \to \lambda p, \bar{p} = \bar{\lambda}\bar{p}$ with only $\lambda\bar{\lambda} = 1$ unbroken.

Becher, Neubert, 1007.4005

Needed information at each logarithmic accuracy.

- Defining Hard function for qqbar initiated process.

Approximation	Nominal order	Accuracy $\sim \alpha_s^n L_\perp^k$	$\Gamma_{\rm cusp}$	$\gamma_{\rm coll.}$	H
LL	α_s^{-1}	$2n \geq k \geq n+1$	Γ_0	tree	tree
NLL+LO	α_s^0	$2n \geq k \geq n$	Γ_1,	γ_0	tree
$\mathrm{N^2LL}$+NLO	α_s^1	$2n \geq k \geq \max(n-1,0)$	Γ_2	γ_1	1-loop
$\mathrm{N^3LL}$ +NNLO	α_s^2	$2n \geq k \geq \max(n-2,0)$	Γ_3	γ_2	2-loop

- $\bar{H}(Q,\mu,p_T^{veto}) = \left|C^V(-Q^2,\mu)\right|^2 e^{2h^F(p_T^{veto},\mu)} \left(\frac{Q}{p_T^{veto}}\right)^{-2F_{qq}(p_T^{veto},R,\mu)}$

- we have RGE equations,

- $\frac{d}{d\ln\mu} C^V(-Q^2,\mu) = \left[\Gamma^F_{\rm cusp}(\mu)\,\ln\frac{-Q^2}{\mu^2} + 2\gamma^q(\mu)\right] C^V(-Q^2,\mu)$

- $\frac{d}{d\ln\mu} F_{qq}(p_T^{veto},R,\mu) = 2\Gamma^F_{\rm cusp}(\mu)$

- $\frac{d}{d\ln\mu} h^F(p_T^{veto},\mu) = 2\Gamma^F_{\rm cusp}(\mu)\,\ln\frac{\mu}{p_T^{veto}} - 2\gamma^q(\mu)$

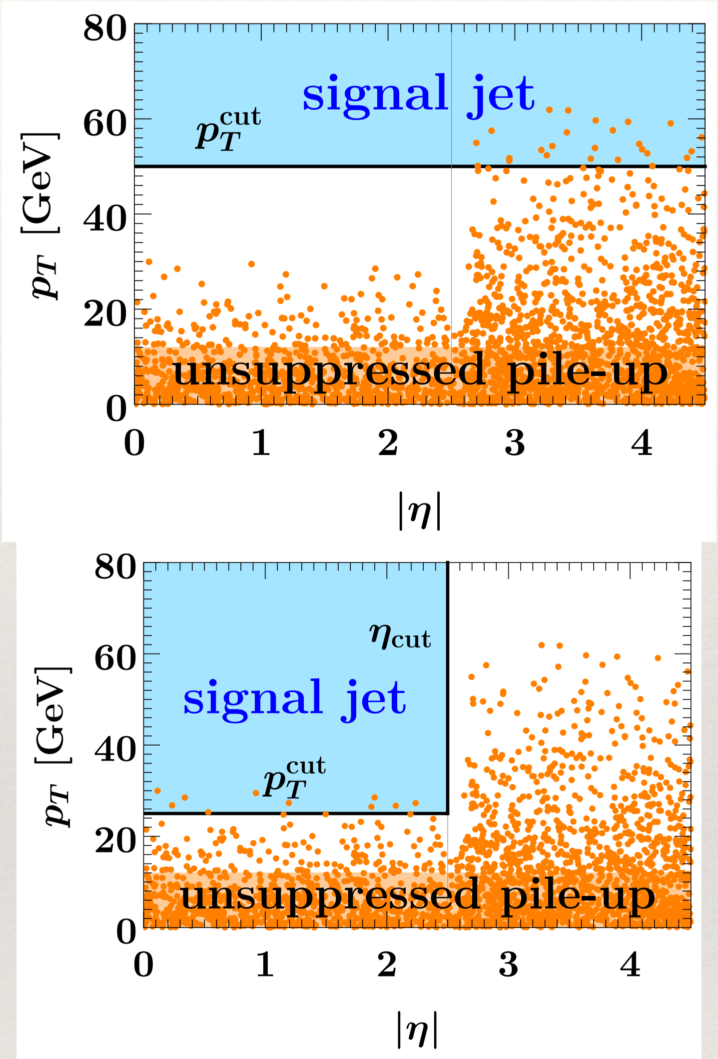
- $\frac{d}{d\mu}\bar{B}_q(\xi_1,p_T^{veto},R,\mu)\,\bar{B}_{\bar{q}}(\xi_2,p_T^{veto},R,\mu) = \mathcal{O}(\alpha_s^3)$

The second column indicates the nominal order when counting $L_\perp \sim 1/\alpha_s$. The third column states which logarithms are included. The last three columns show the necessary additional anomalous dimensions and hard function corrections in each successive order.

$$L_\perp = 2\ln(\mu/p_T^{veto})$$

Jet veto cross sections in a limited rapidity range

- Formula so far are valid for jet cross sections which are vetoed for all values of rapidity η_{cut}
- Experimental analyses perform jet cuts for $\eta < \eta_{\text{cut}}$
- In 1810.12911, three theoretical regions are identified
  - $\eta_{\text{cut}} \gg \ln(Q/p_T^{\text{veto}})$ (jet veto resummation as we are using it.)
  - $\eta_{\text{cut}} \sim \ln(Q/p_T^{\text{veto}})$ (η_{cut}-dependent beam functions)
  - $\eta_{\text{cut}} \ll \ln(Q/p_T^{\text{veto}})$ (collinear non-global logs)



Current theory calculation

Typical Experimental cuts

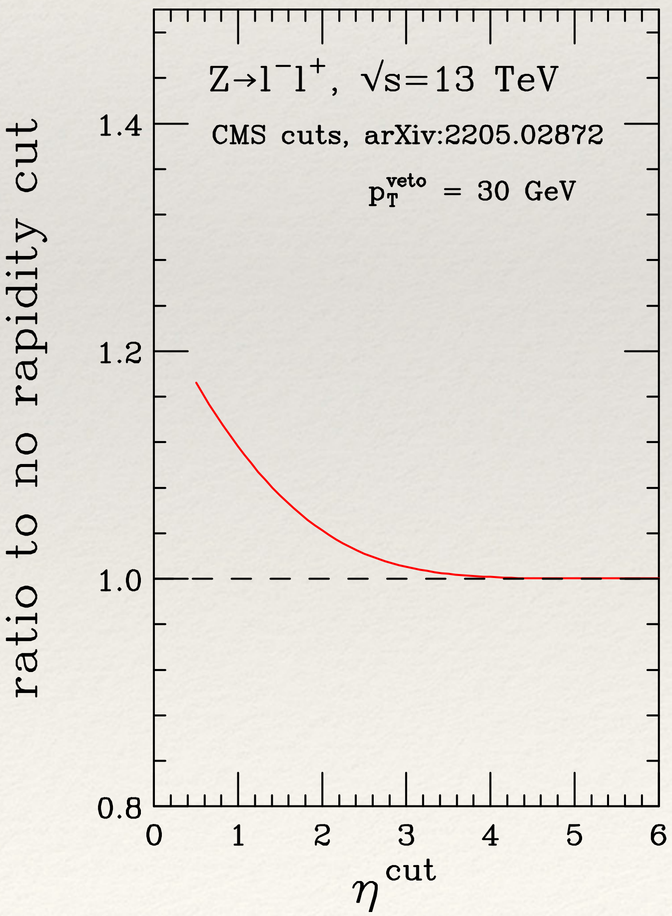
Figure taken from 1810.12911

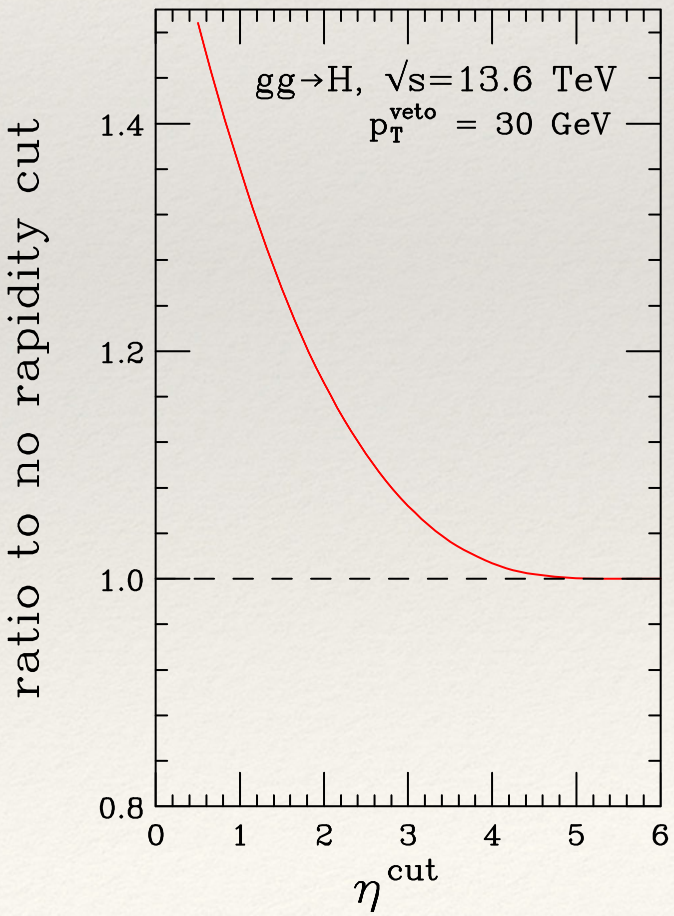
Strategy: determination where resummation is potentially important, before considering limited rapidity range resummation

Effects of rapidity cuts at fixed order

Process	Ref.	$y_{\rm cut}$
Higgs	–	no study
Z (CMS)	[38]	2.4
W (ATLAS)	[43]	4.4
WW (CMS)	[39]	4.5
WZ (ATLAS)	[44]	4.5
WZ (CMS)	[45]	2.5
ZZ (CMS)	–	no study

- The usual jet veto resummation imposes no cut on the jet rapidity, unlike the experimental analysis.
- To apply the theory we need $\eta_{\rm cut} \gg \ln(Q/p_T^{\rm veto})$
- We can address the potential impact by looking at fixed order.
- More important for Higgs (and WW and ZZ) than for Z.





Coefficient of Collinear Anomaly for $q\bar{q}$ case

$$F_{qq}(p_T^{\rm veto},\mu) = a_S F_{qq}^{(0)} + a_S^2 F_{qq}^{(1)} + a_S^3 F_{qq}^{(2)} + \dots\ , \quad a_S = \frac{\alpha_S}{4\pi}$$

$$F_{qq}^{(0)} = \Gamma_0^F L_\perp + d_1^{\rm veto}(R,F)$$

$$L_\perp = 2\ln\frac{\mu}{p_T^{\rm veto}}$$

$$F_{qq}^{(1)} = \frac{1}{2}\Gamma_0^F\beta_0 L_\perp^2 + \Gamma_1^F L_\perp + d_2^{\rm veto}(R,F)$$

$$F_{qq}^{(2)} = \frac{1}{3}\Gamma_0^F\beta_0^2 L_\perp^3 + \frac{1}{2}(\Gamma_0^F\beta_1 + 2\Gamma_1^F\beta_0)L_\perp^2 + (\Gamma_2^F + 2\beta_0 d_2^{\rm veto}(R,F))L_\perp + d_3^{\rm veto}(R,F)$$

Full N[3]LL will require knowledge of $d_3^{\rm veto}(R,F)$

$$d_1^{\rm veto}(R,F) = 0$$

$$d_2^{\rm veto}(R,B) = d_2^B - 32 C_B\, f(R,B)$$

$$\begin{aligned} f(R,B) = {} & C_B\Big(-\frac{\pi^2 R^2}{12} + \frac{R^4}{16}\Big) \\ & + C_A\left(c_L^A \ln R + c_0^A + c_2^A R^2 + c_4^A R^4 + \dots\right) \\ & + T_F n_f\left(c_L^f \ln R + c_0^f + c_2^f R^2 + c_4^f R^4 + \dots\right), \end{aligned}$$

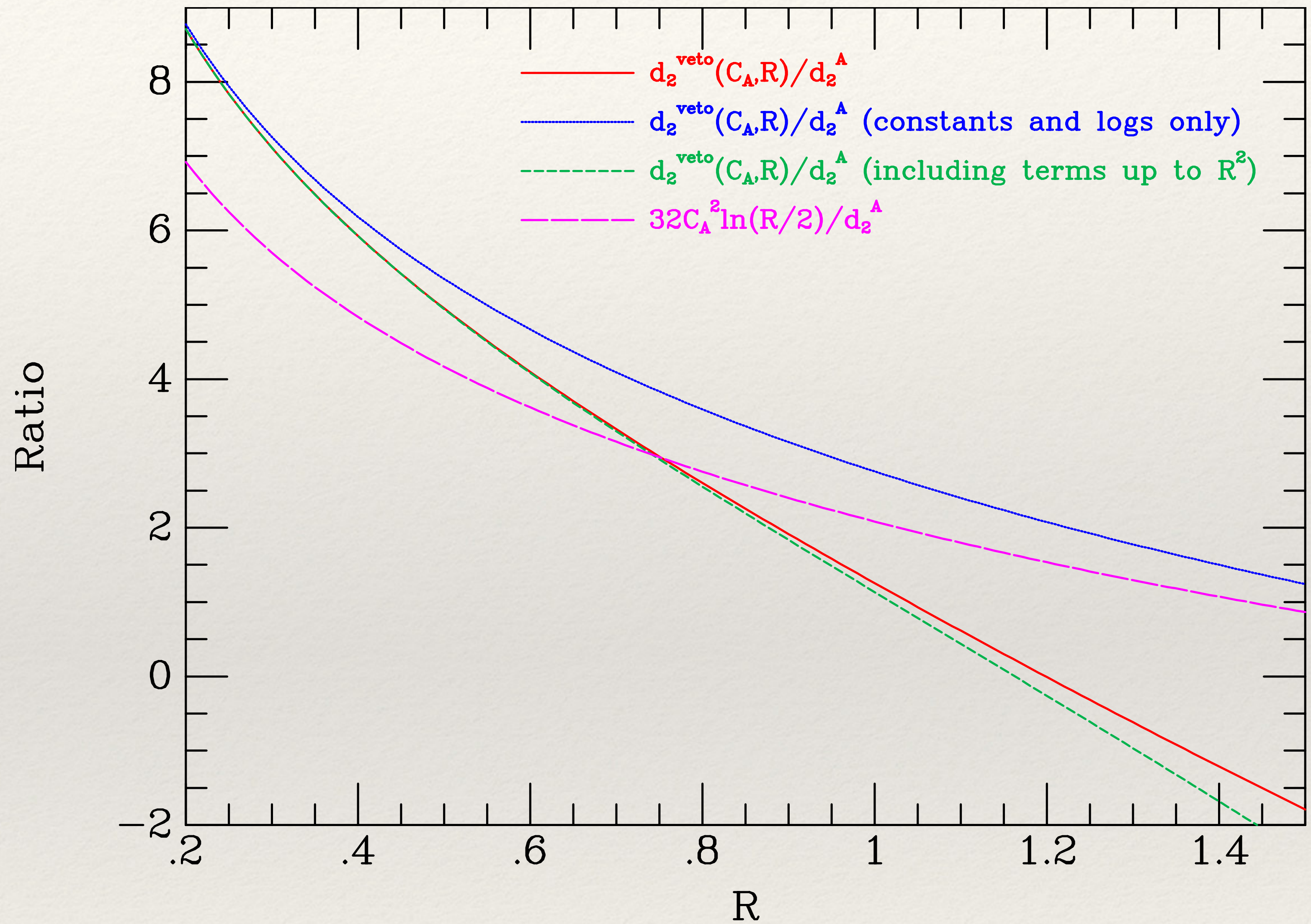
Coefficients c_i^A and c_i^f for $i < 10$, see 1307.0025

$$d_3^{\rm veto} \sim -8.3\times 64 C_B \ln^2(R/R_0) + O(\ln(R))$$

Log enhanced terms of $d_3^{\rm veto}$, see 1511.02886

Approximations to $d_2^{\rm veto}$

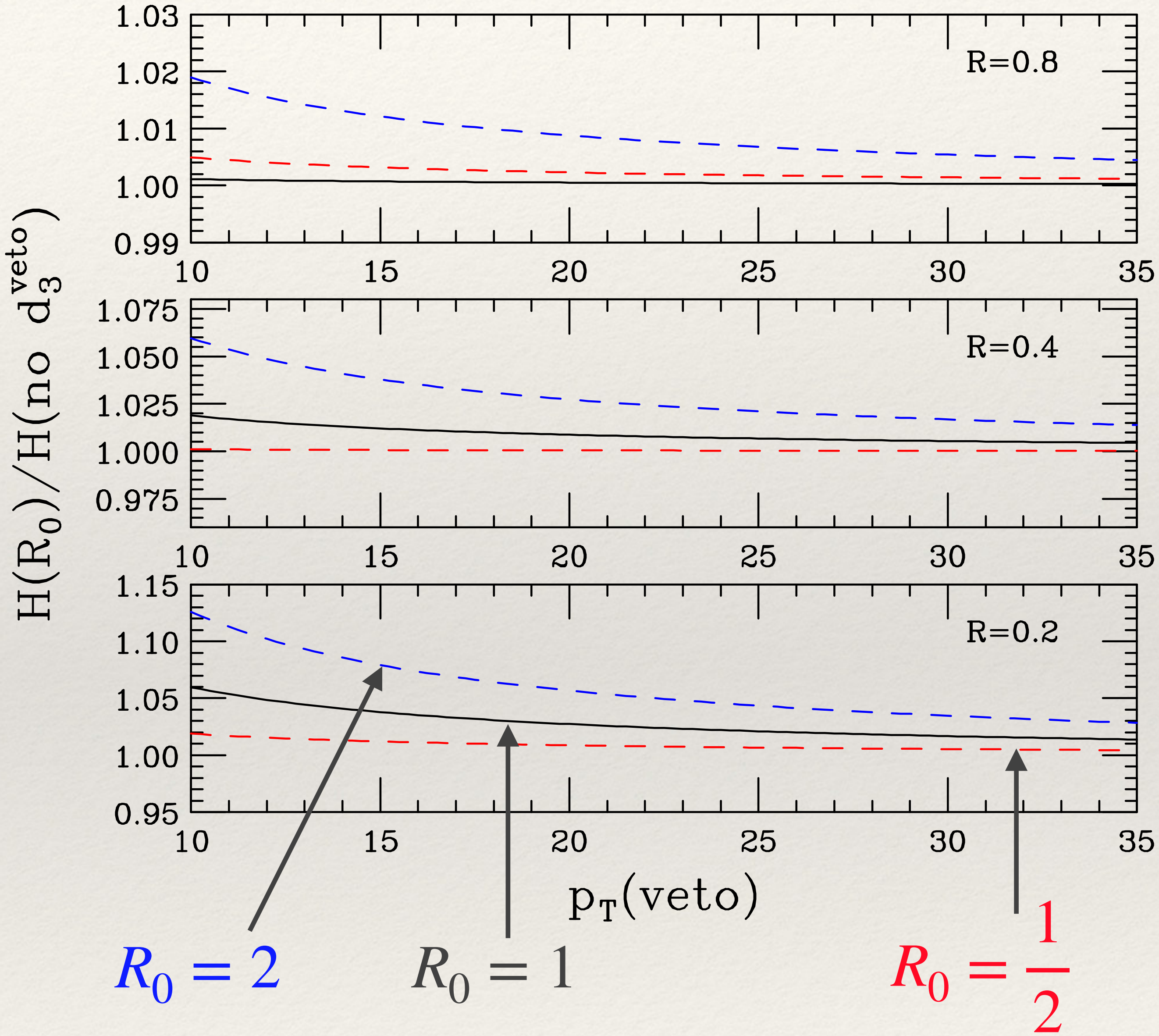
- Range of validity is $\frac{p_T^{\rm veto}}{Q} \ll R \ll \ln\left(\frac{Q}{p_T^{\rm veto}}\right)$
- At too small R terms of order $\ln^n R$ which are not covered by this factorization formula.
- At too large R, factorization formula breaks down.
- Results are presented as power series in R
- At $R \sim 0.4$ logarithmic approximation is about 20% too low.
- Results should be valid in a range around the experimentally preferred $R \sim 0.4 - 0.5$



Rescaled $d_2^{\rm veto}$ showing that limited number of terms in expansion is quite adequate for $R < 1$.

Estimated dependence on approximate d_3^{veto}

- Effect of R_0 dependence in approximate form for d_3^{veto}
- $d_3^{\text{veto}} \sim -8.3 \times 64 C_B \ln^2(R/R_0)$
- $\left(\frac{m_H}{p_T^{\text{veto}}}\right)^{-2\frac{\alpha_s(\mu)}{4\pi} d_3^{\text{veto}}}$
- In this approximation, d_3^{veto} gives an increase in the cross section.
- Estimate ~ ≤ 2.5 % at p_T^{veto}=25 GeV and $R = 0.4$

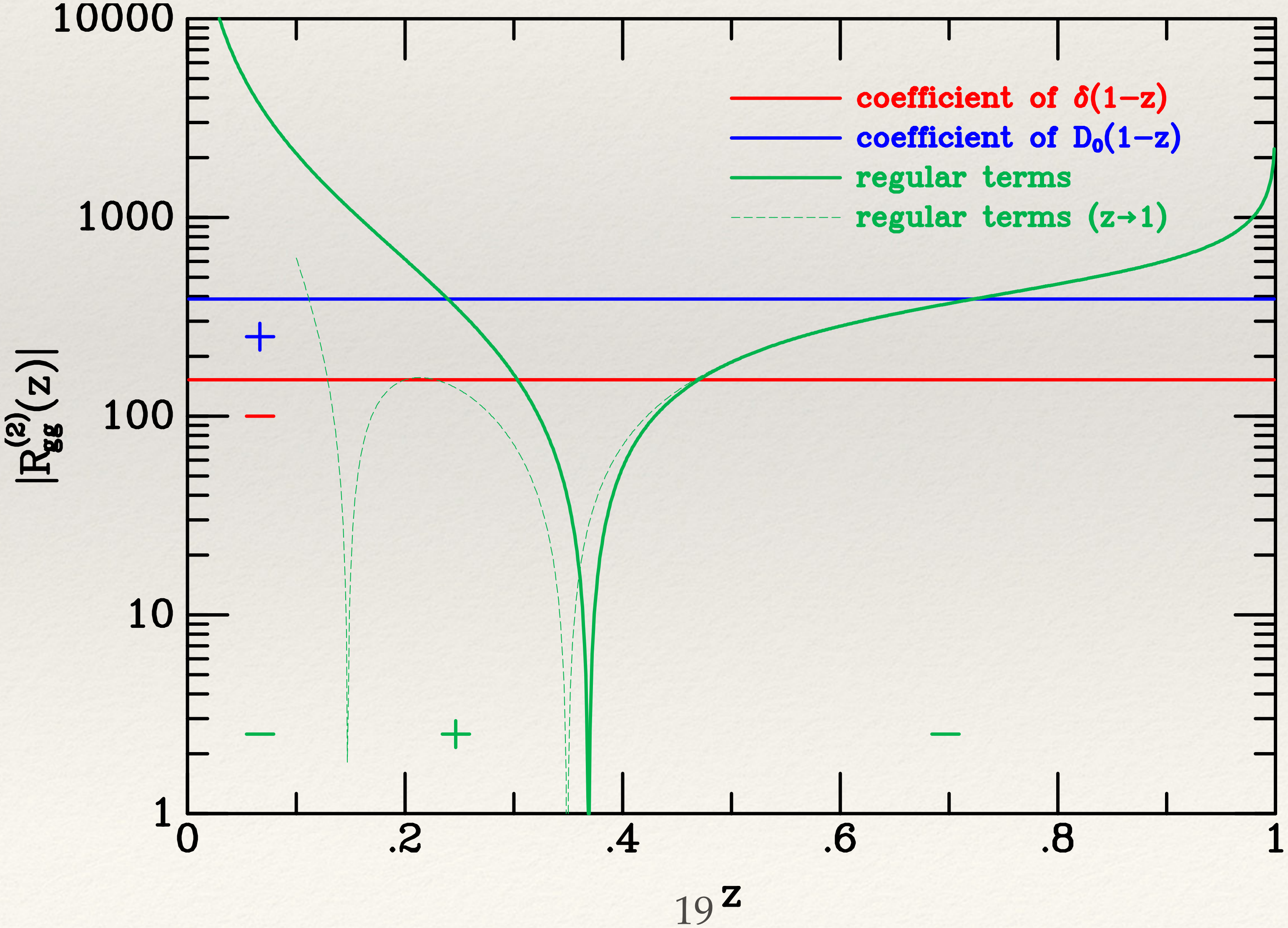


Suggestion is that error derived from $\frac{1}{2} < R_0 < 2$

Leading behavior derived from Banfi et al, 1511.02886

Reduced beam function kernels

- $\bar{I}_{ik}(z, p_T^{veto}, R, \mu) = \delta_{ik}\,\delta(1-z) + \frac{\alpha_s}{4\pi}\bar{I}_{ik}^{(1)}(z, p_T^{veto}, \mu) + \left(\frac{\alpha_s}{4\pi}\right)^2 \bar{I}_{ik}^{(2)}(z, p_T^{veto}, R, \mu) + O(\alpha_s^3)$
- $\bar{I}_{ik}^{(2)}(z, p_T^{veto}, R, \mu) = \left[2P_{ij}^{(1)}(x) \otimes P_{jk}^{(1)}(y) - \beta_0 P_{ik}^{(1)}(z)\right] L_\perp^2 + \left[-4P_{ik}^{(2)}(z) + \beta_0 R_{ik}^{(1)}(z) - 2R_{ij}^{(1)}(x) \otimes P_{jk}^{(1)}(y)\right] L_\perp + R_{ik}^{(2)}(z, R)$

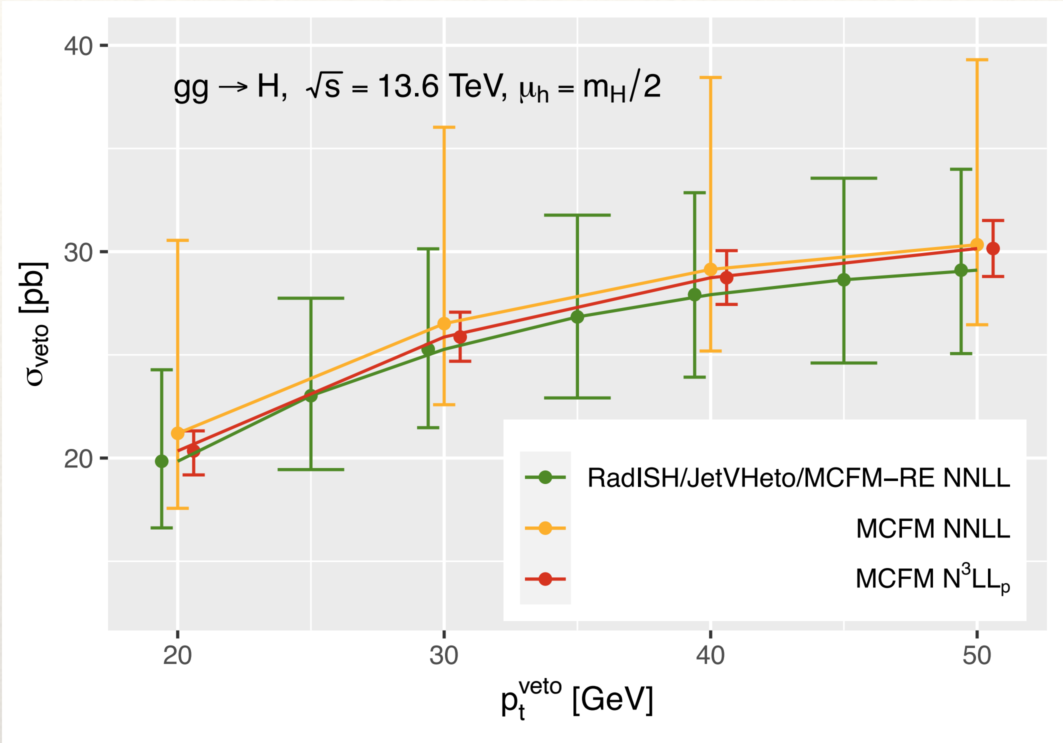


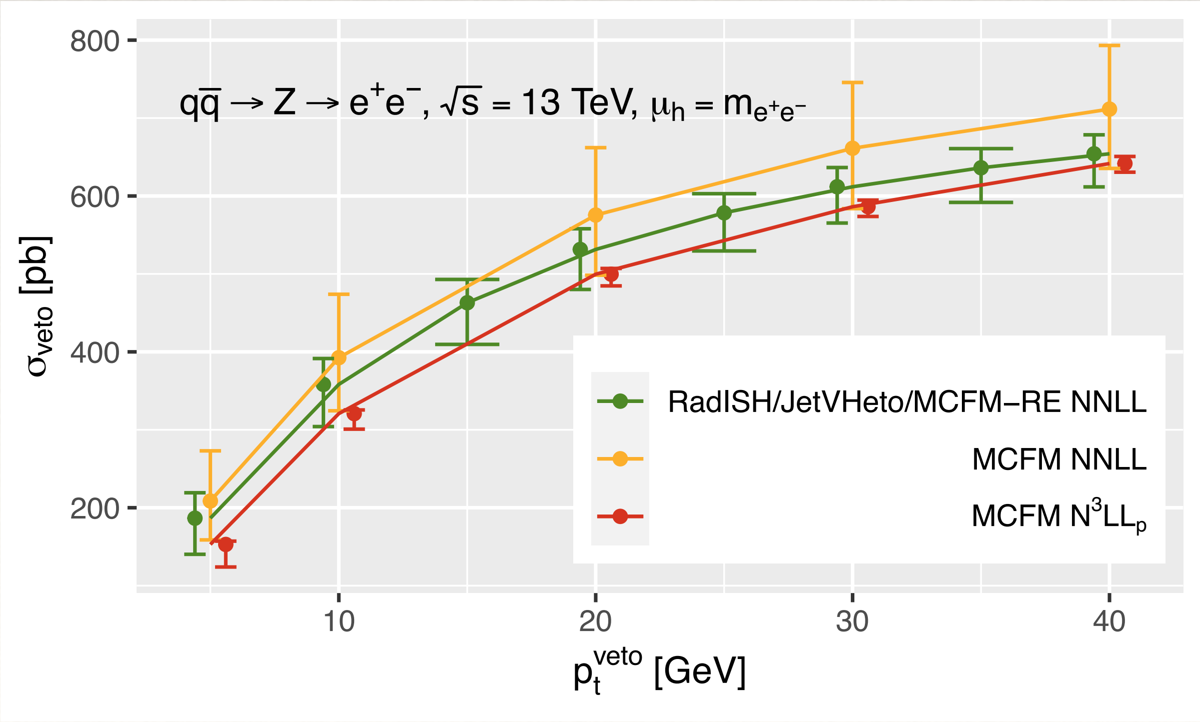
Phenomenological results in N^3LL_p

$N^3LL_p \equiv N^3LL$ with limited information on d_3^{veto}

Comparison with JetVHeto

- Public codes implementing resummation at NNLL are JetVHeto and RadISH.
- We have compared unmatched resummation with JetVHeto.
- MCFM agrees with JetVHeto, within errors
- N^3LL_p leads to considerable reduction in errors.





Error estimates

- Much discussion in the literature on the best method of error estimate, e.g. estimate error in jet-veto efficiency. The procedure we follow is:-
    - For the resummation (fixed-order) parts we vary both the resummation (factorization) and hard (renormalization) scales by a factor of two about their central values, adding the excursions in quadrature to obtain the total scale uncertainty.
    - For the resummation we re-introduce the rapidity scale, by writing the collinear anomaly factor as follows.

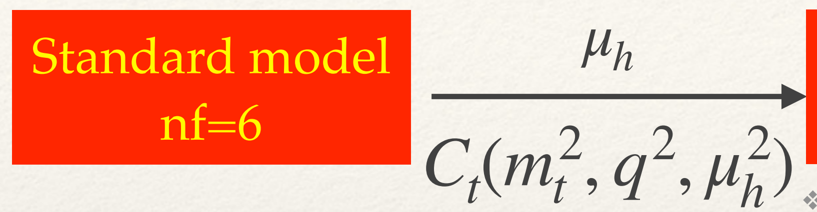
$$\left(\frac{Q}{p_T^{veto}}\right)^{-2F_{ii}(p_T^{veto},R,\mu)} = \left(\frac{Q}{\nu}\right)^{-2F_{ii}(p_T^{veto},R,\mu)} \left(\frac{\nu}{p_T^{veto}}\right)^{-2F_{ii}(p_T^{veto},R,\mu)}$$

    - For $\nu \sim p_T^{veto}$ the second factor can be expanded since it does not contain a large logarithm. We vary the rapidity scale ν in the range $[p_t^{veto}/2, 2p_t^{veto}]$ for gluon-initiated processes and in the range $[p_T^{veto}/6, 6p_T^{veto}]$ for quark-initiated processes.
    - The parameter R_0 in d_3^{veto} is varied between 0.5 and 2.

Jet veto in Higgs production

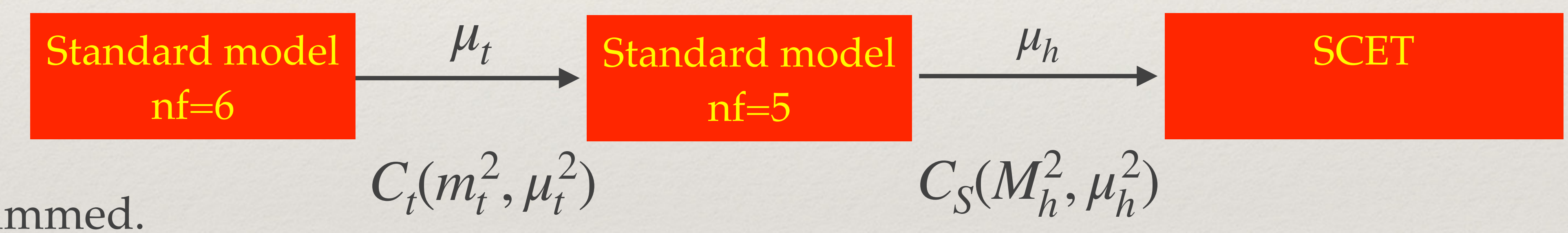
One-step vs Two-step matching for Higgs production

- **One step matching,** power corrections in m_t/m_h retained but logarithms not resumed.



- One step procedure notes that $\rho = (m_h/m_t)^2 \approx 1/2$ is not large in a logarithmic sense, $\alpha_s \ln(1/\rho) = 0.07$.

- **Two step matching,** logarithms m_t/m_hresummed.

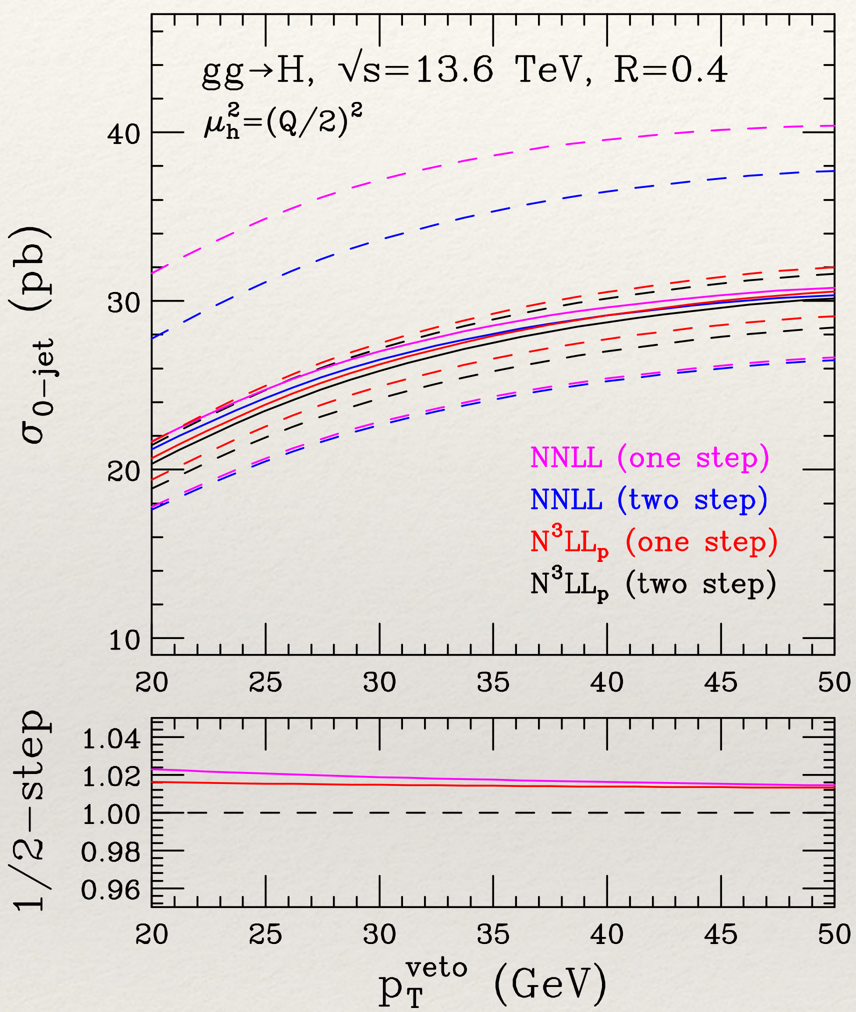


- Two step matching can restore most of the important mass effects by re-scaling the two-step result by the exact leading order result;

- With care, the two-step procedure gives a result that is only smaller than the one-step result by about 1%. $1 + (a+b)\alpha_s \neq (1 + a\alpha_s)(1 + b\alpha_s)$

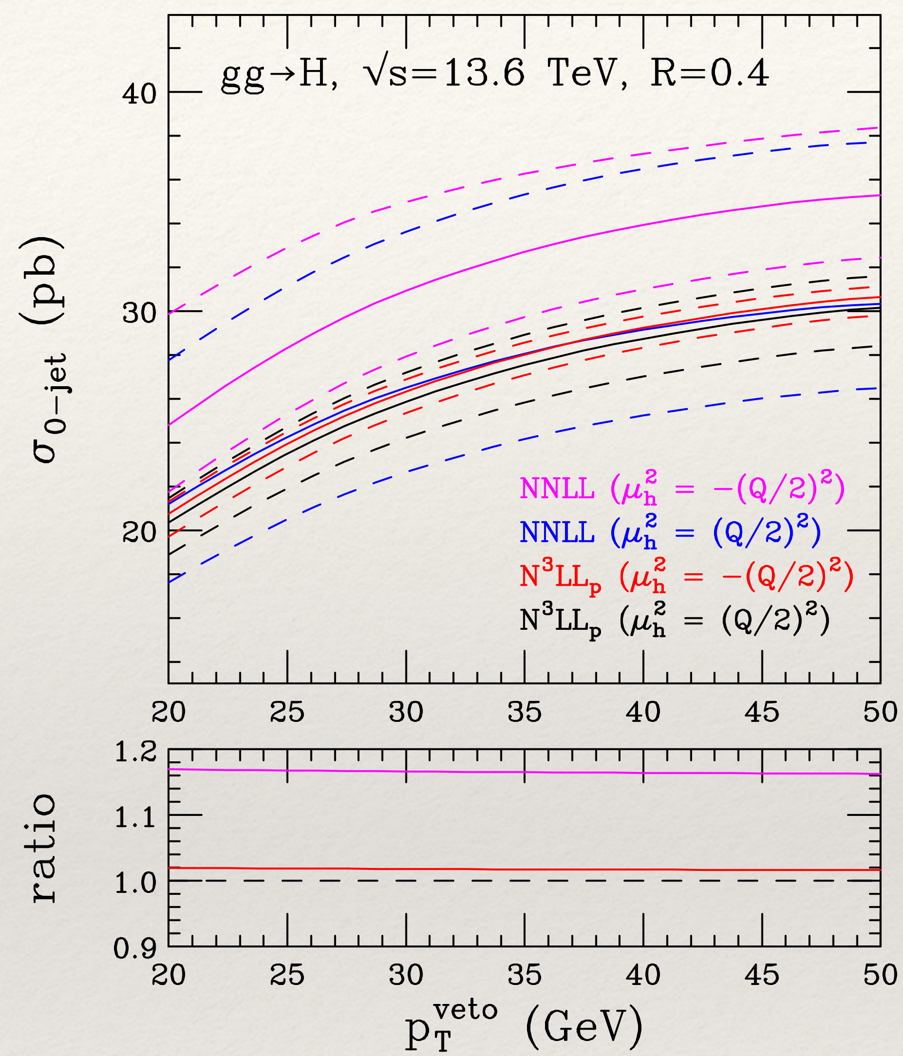
- Bigger differences can be found if higher order effects are not controlled.

Detailed assumptions for Higgs production



- One-step scheme results in cross section which is only 1.6% larger at N^3LL_p

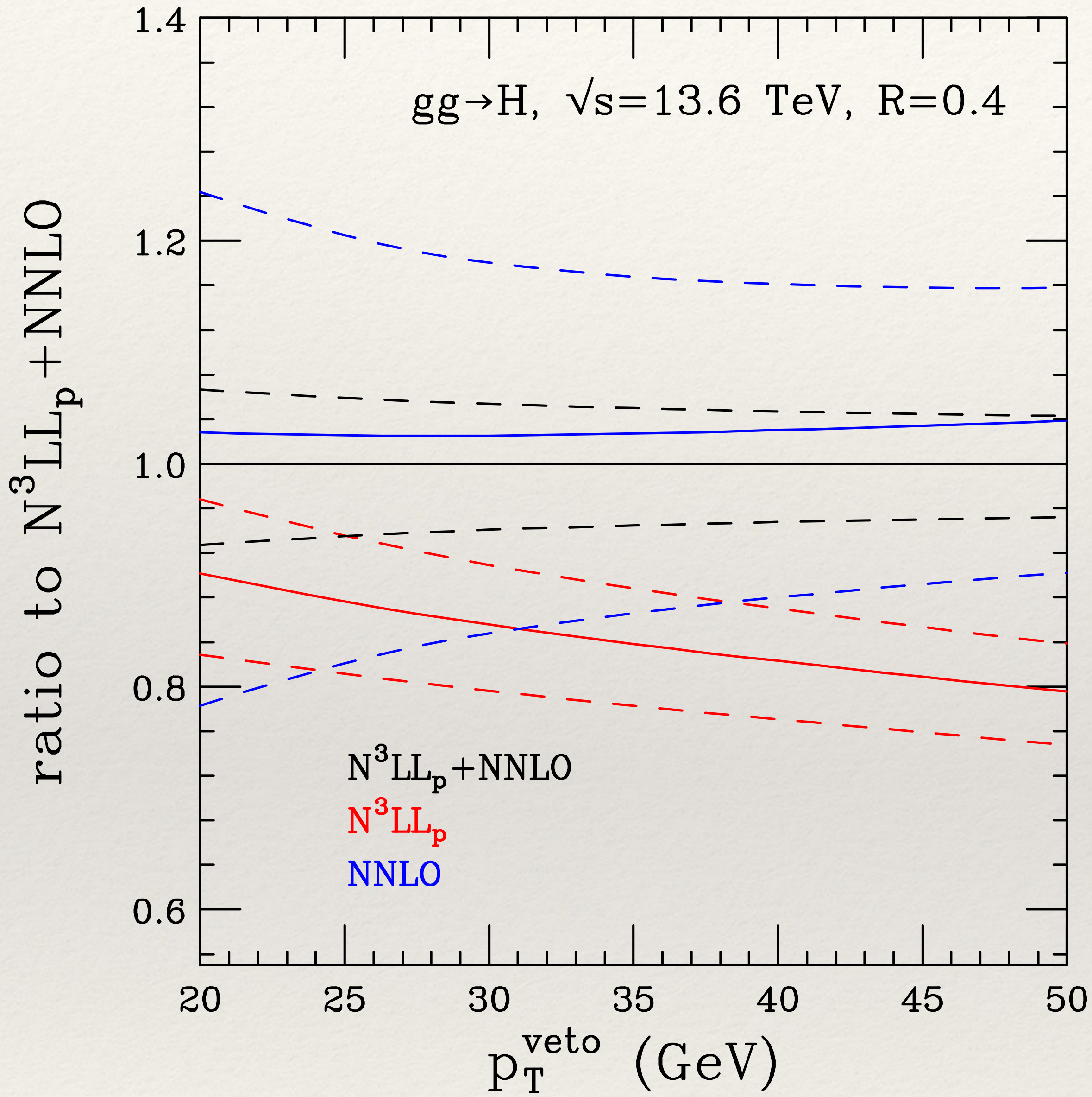
We use one-step scheme

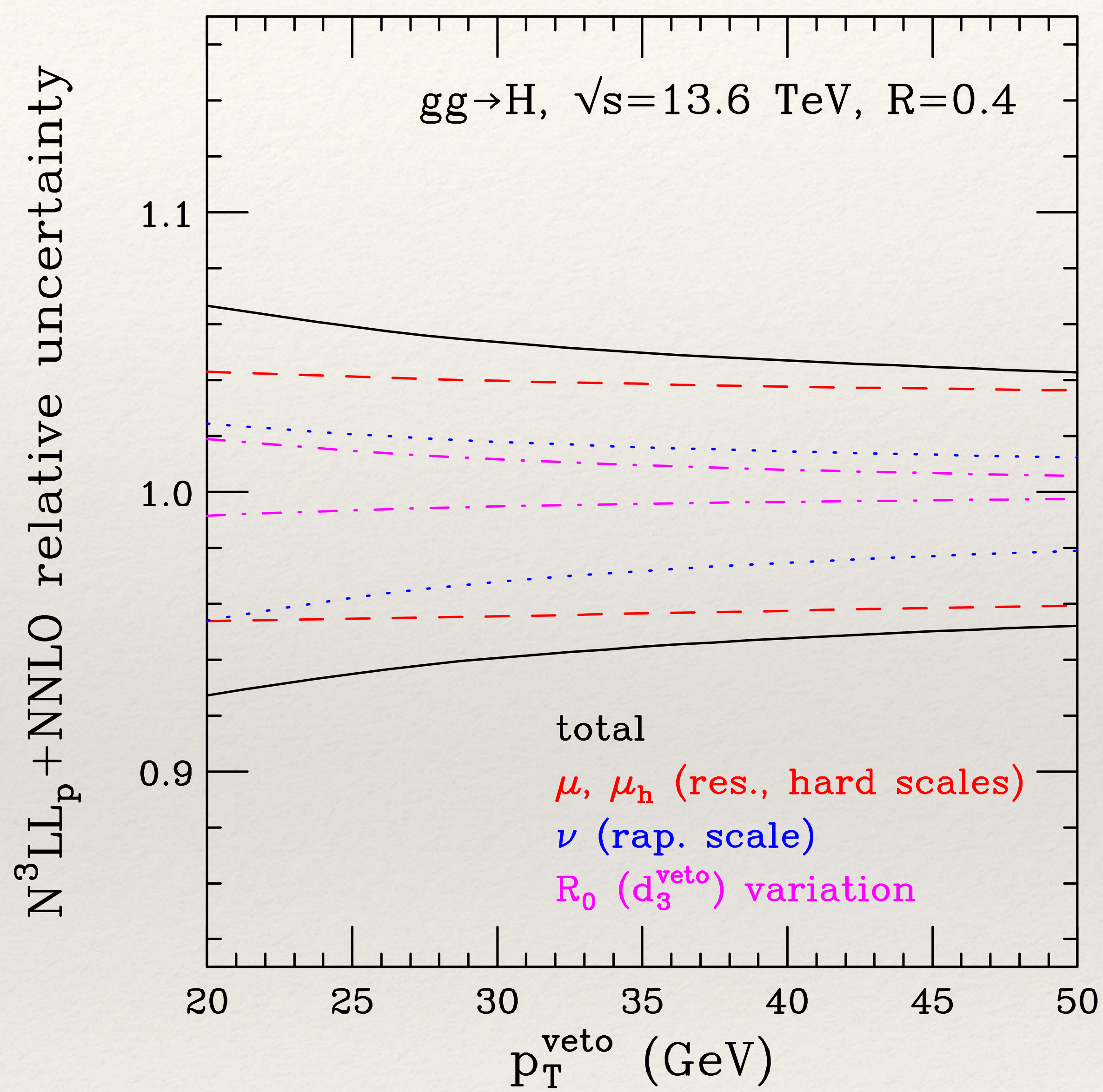


- At NNLL, the resummation of the π^2 terms enhances the cross-section by 17%. However, at N^3LL_p accuracy, this resummation only leads to a small increase of 2% in the cross-section.

We use spacelike μ_h

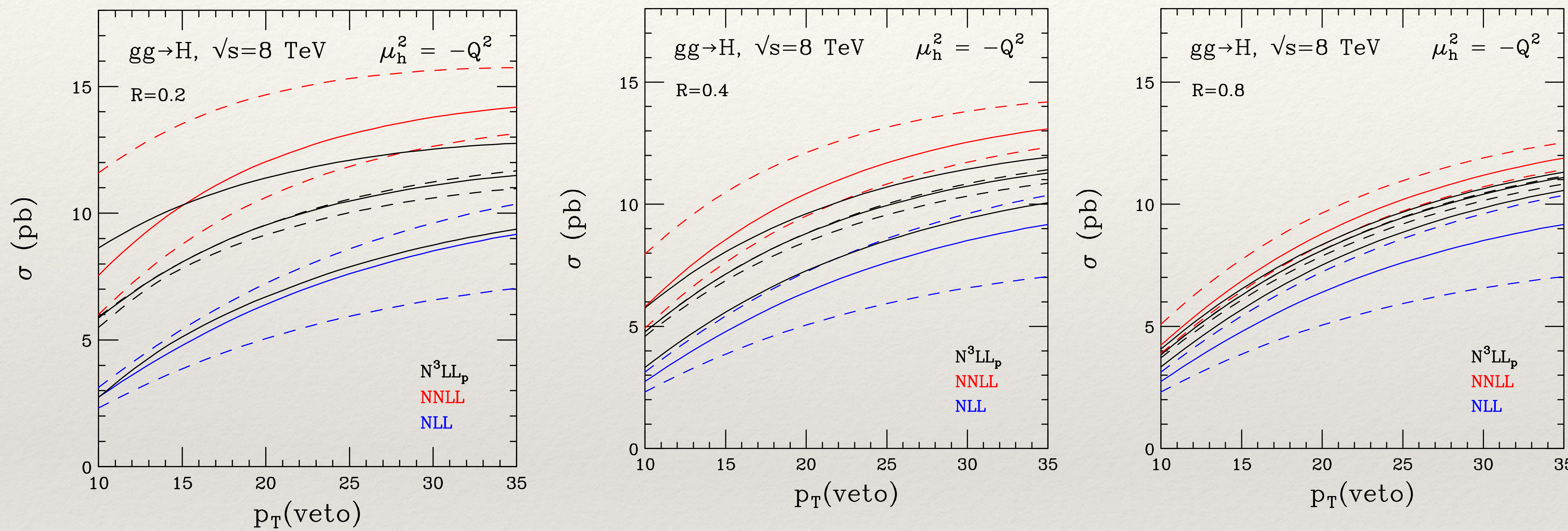
Comparison of NNLO, N^3LL_p and N^3LL_p+NNLO predictions for Higgs production.





- After matching agreement between NNLO and N^3LL_p but with smaller errors for N^3LL_p
- Our estimate of uncertainty on partially known d_3^{veto} contributes in a small way to the overall error budget.

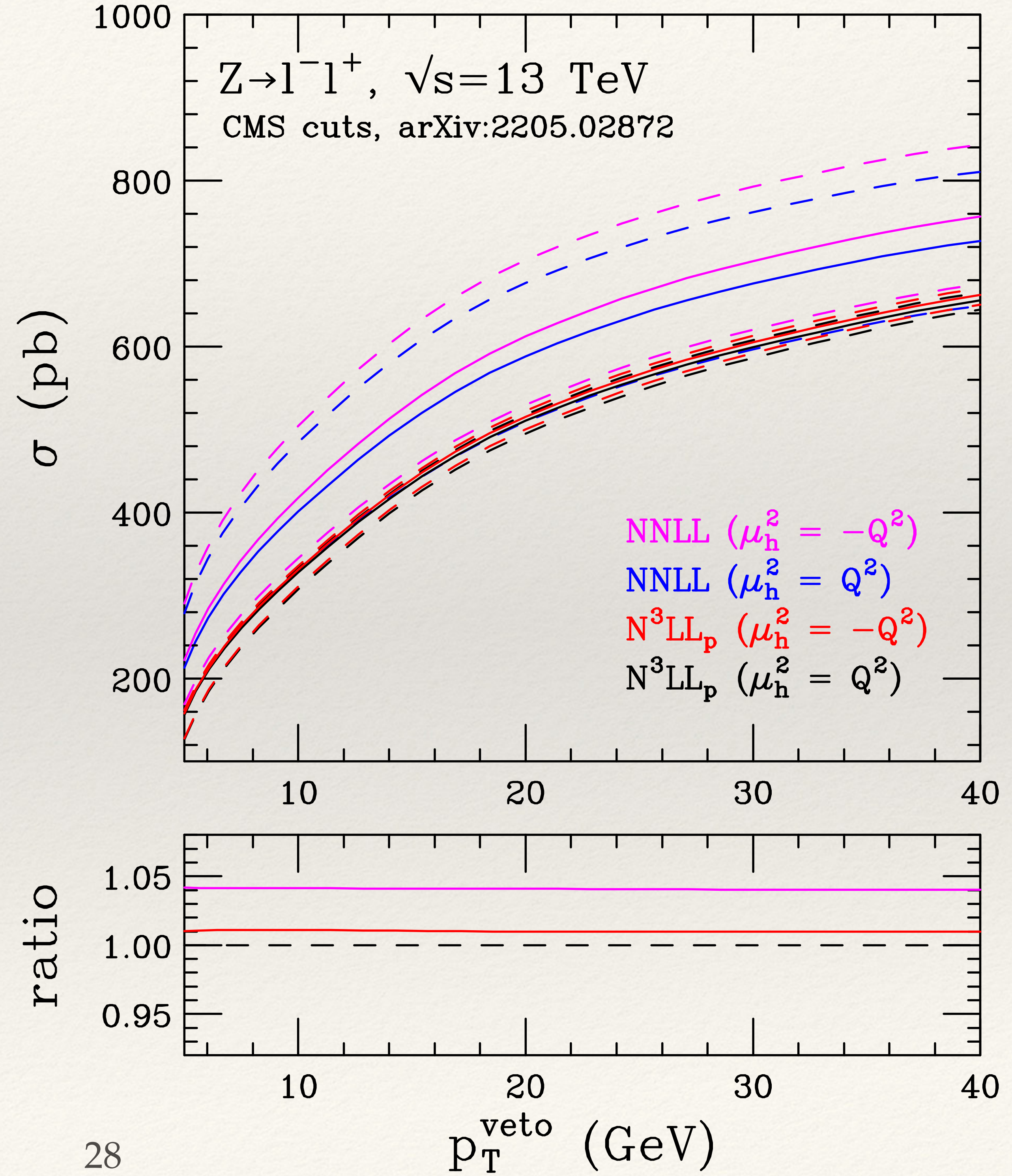
Jet-veto in Higgs production



- Uncertainties estimated by varying renormalization and factorization and rapidity scales by $2, \frac{1}{2}$ and adding in quadrature;
- In the main the perturbative series is well-behaved at moderate R and successive orders lie with in the band of the preceding order with modestly decreasing uncertainty.

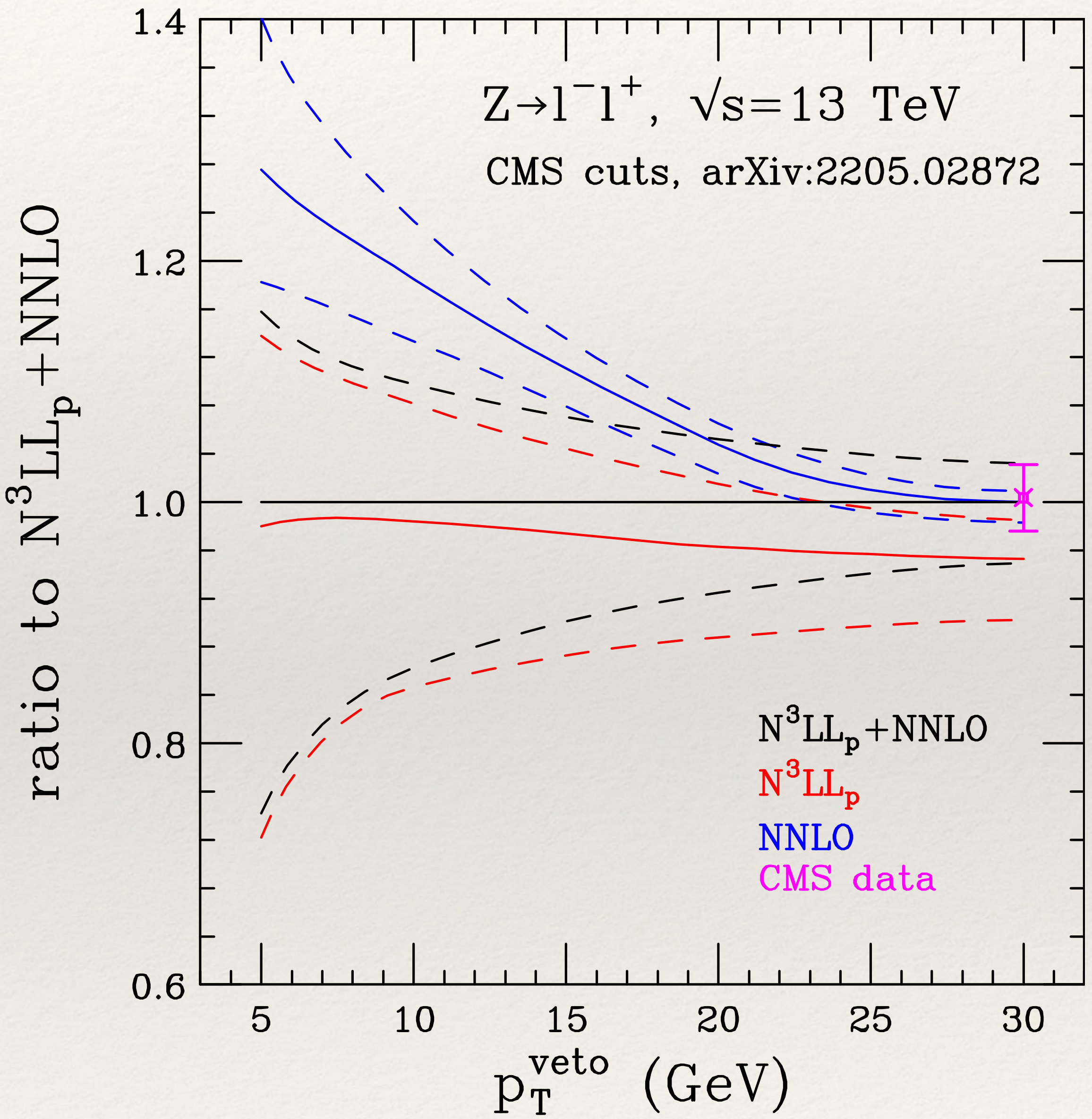
Z-production

- Time-like hard scale choice $\mu_h^2 = -q^2$ can resum certain π^2 contributions using a complex strong coupling.
- After resummation the results do not depend strongly on the choice of hard scale;
- The difference is 4% and NNLL and 1% at N^3LL_p.
- So we always will work with space-like scale choices in the following.



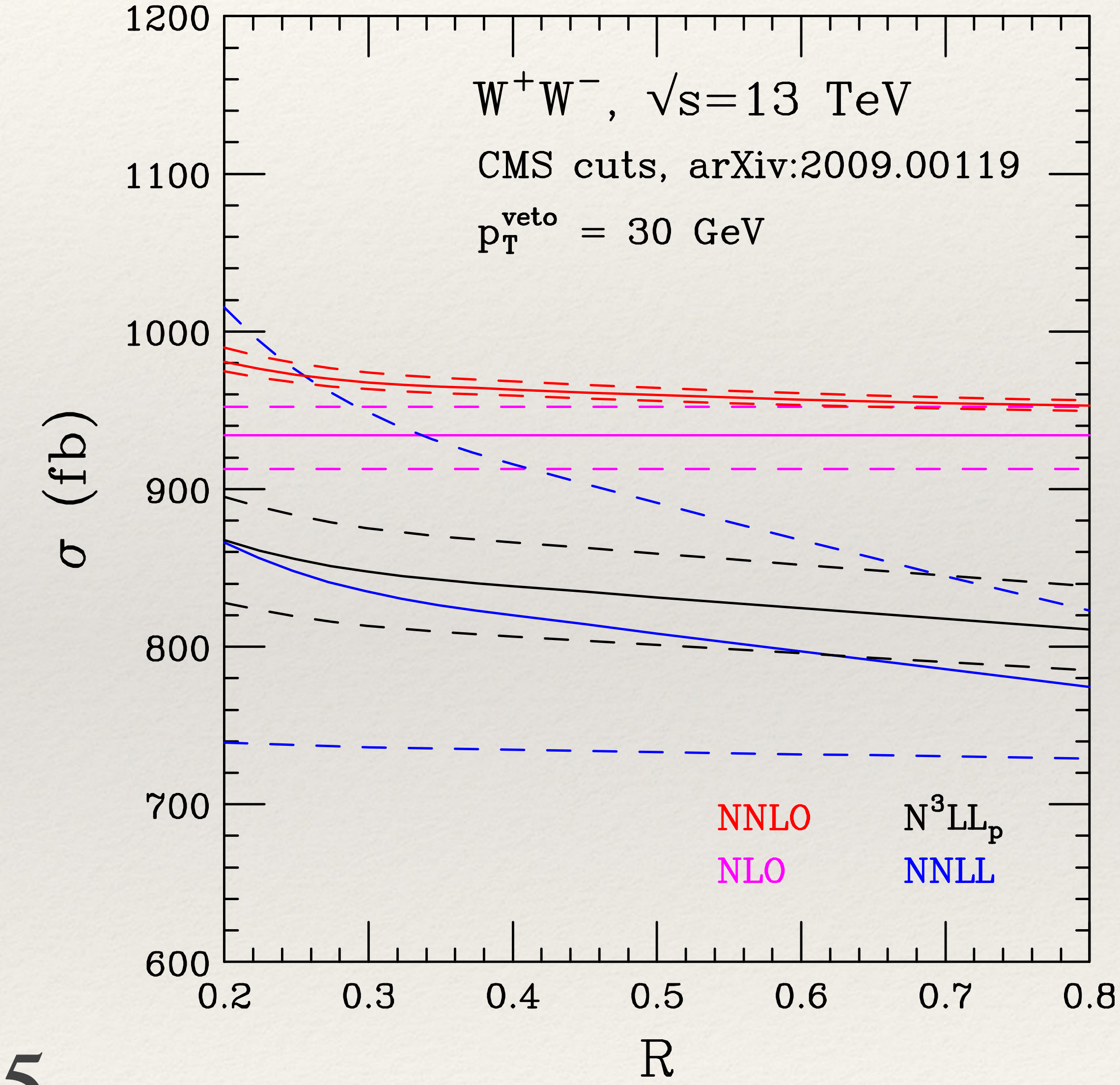
Jet veto in Z production

- At $p_T^{\rm veto} \sim 25-30$ all calculations agree within errors.
- However error estimates differ between NNLO and N^{3}LL +NNLO.
- For $p_T^{\rm veto} = 30$ GeV, $(\ln(Q/p_T^{\rm veto} = 1.1) \ll (\eta_{\rm cut} = 2.4)$
- As expected at (unphysically) small $p_T^{\rm veto}$ resummed calculations show deviations from fixed order.
- Jet veto resummation probably not so necessary at $p_T^{veto} \sim 30\,$GeV, for W or Z production.

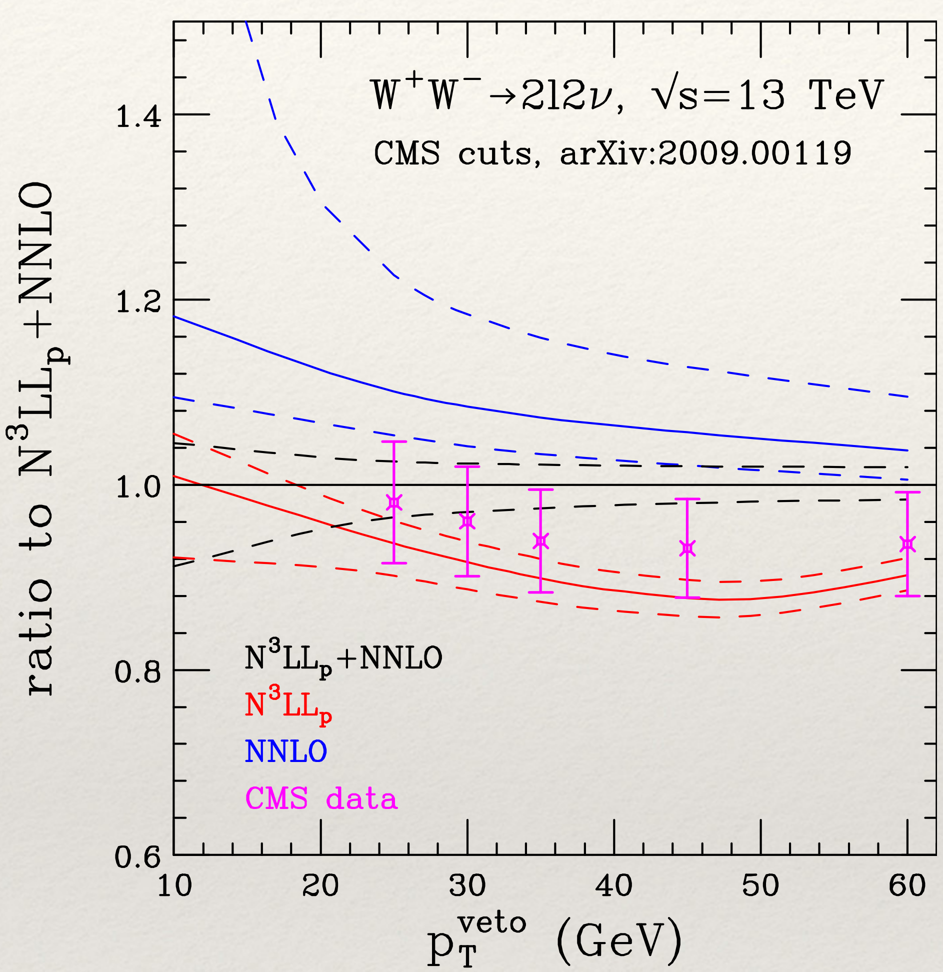


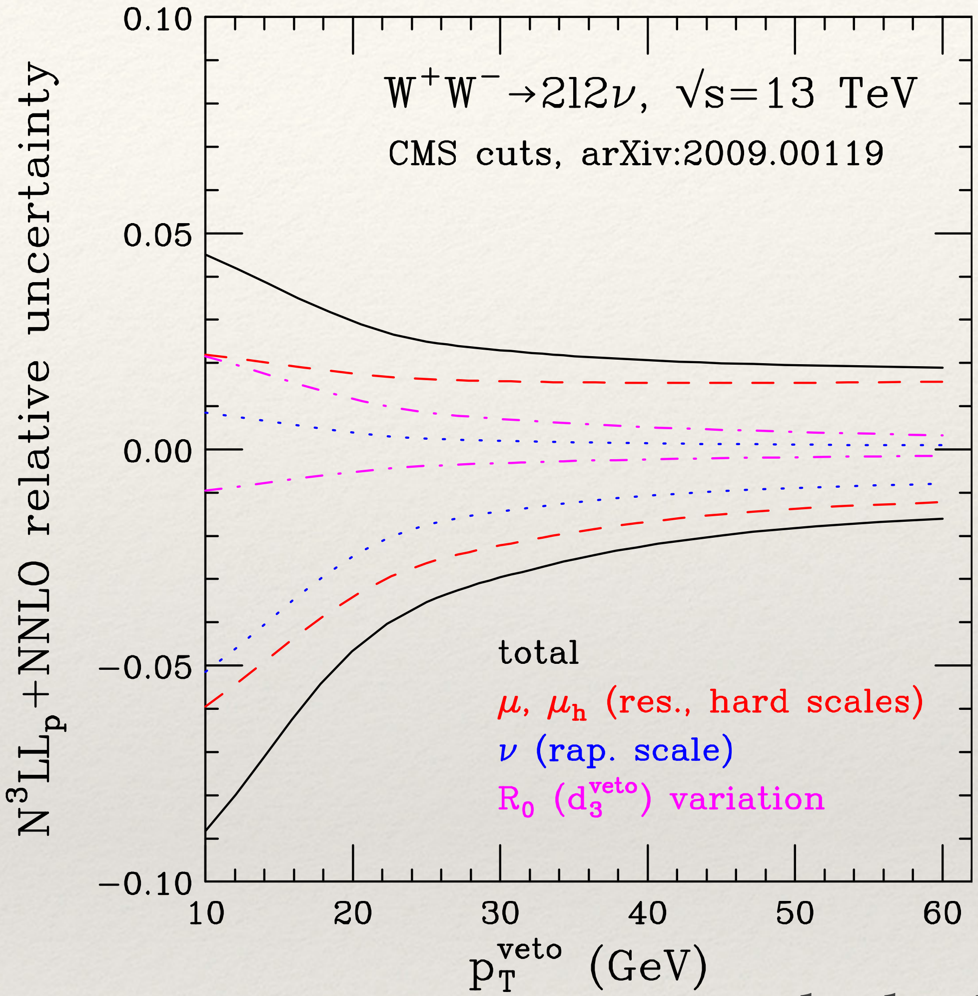
Jet veto in W^+W^- production

- Evidence that neither NNLO nor N^3LL is sufficient, especially around $p_T^{\text{veto}} = 25 - 30\text{GeV}$
- R dependence is modest (zero at NLO!)
- $|\eta_{\text{cut}}| < 4.5$, so we can argue that $(\ln(Q/p_T^{\text{veto}}) = 1.3 - 2.2) \ll 4.5$



W+W- production

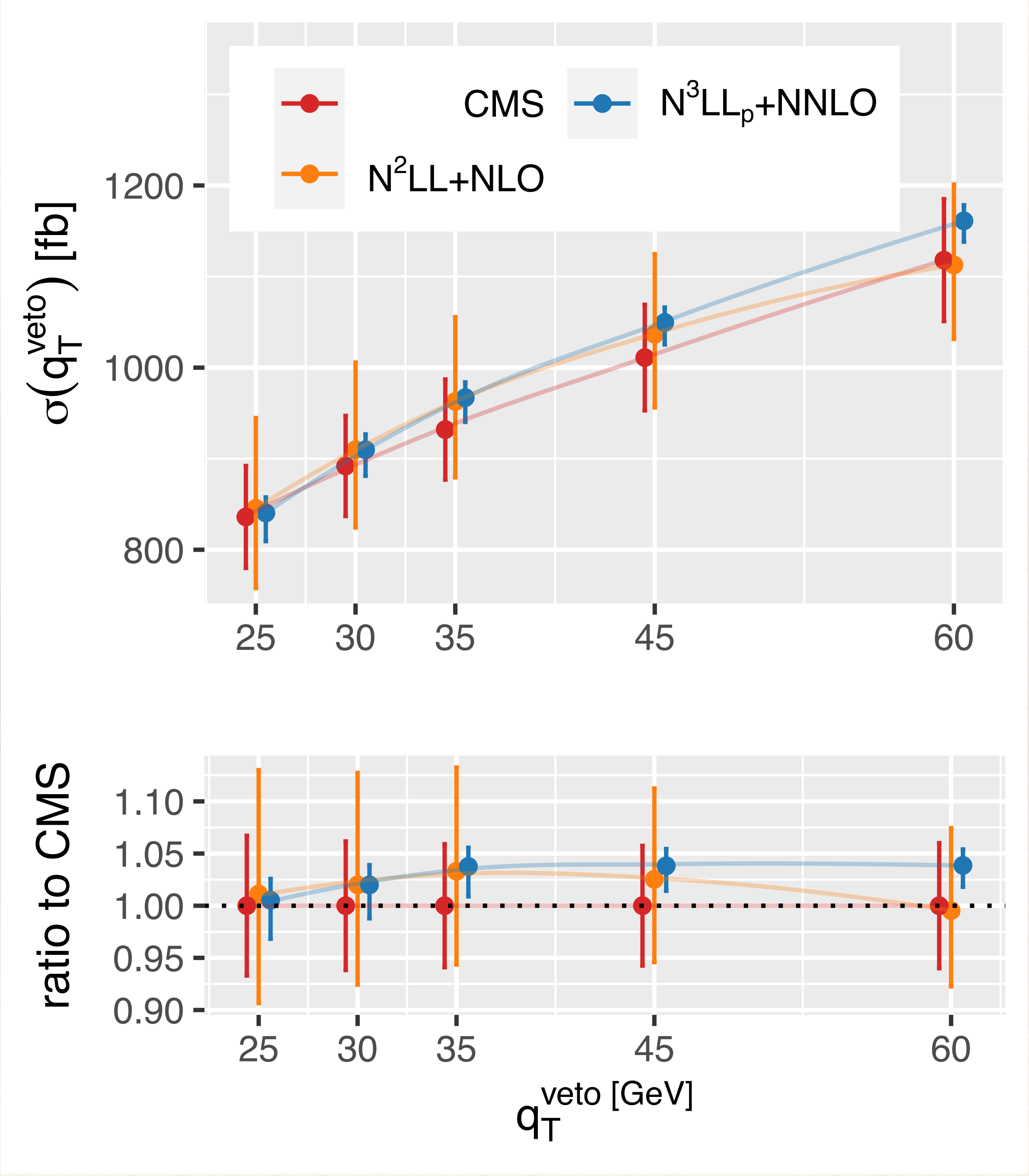




- The effect of matching is substantial; fixed order only appropriate at the highest values of p_T^{veto}.
- R_0 variation, which estimates the contribution of d_3^{veto}, contributes in a small way to total error budget.

Jet veto in W^+W^- production vs data

- Errors improve going from N^2LL +NNLO to N^3LL+NNLO
- Theoretical errors smaller than experimental.
- CMS data taken from 2009.00119



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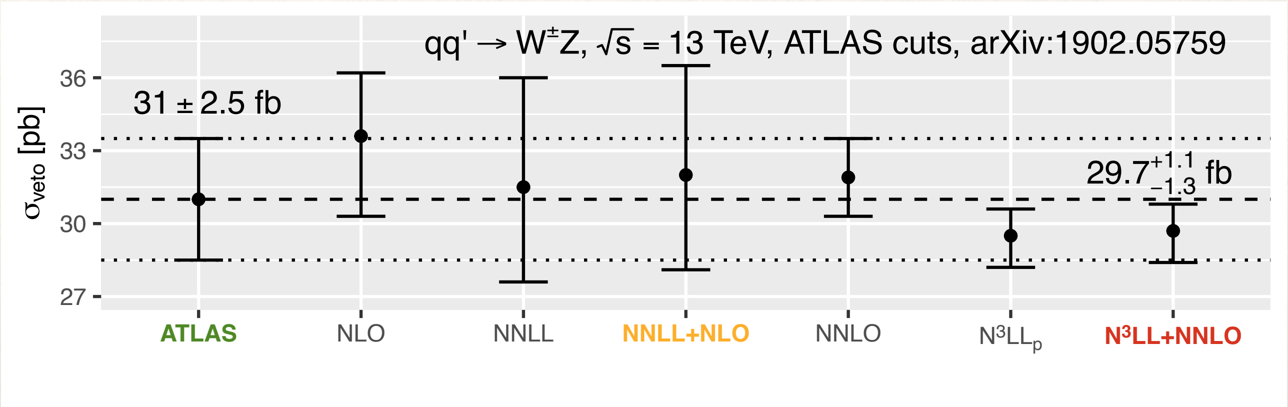
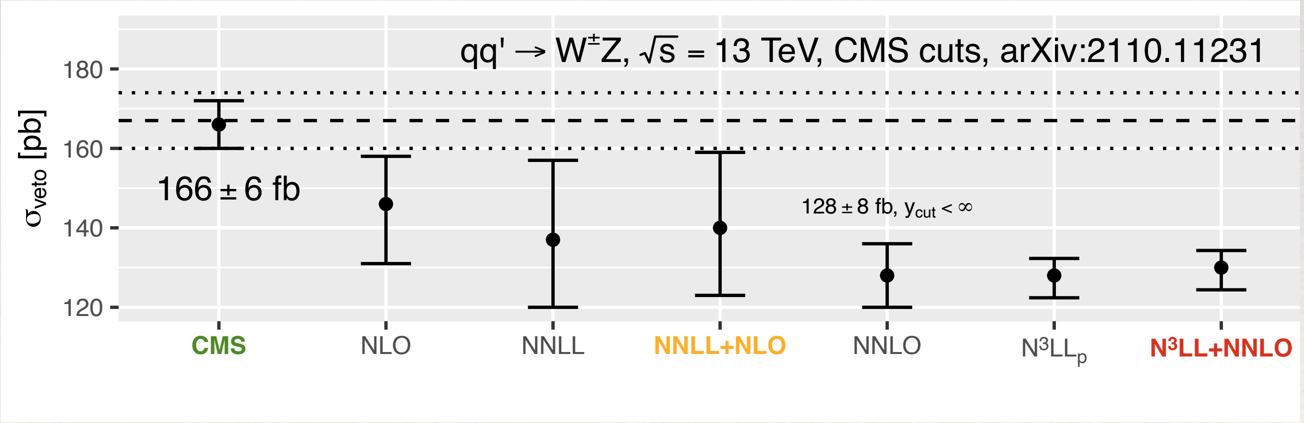
WZ production in ATLAS and CMS

- ATLAS: 36 fb^{-1} ,p_T>25GeV, | y | <4.5, R=0.4.

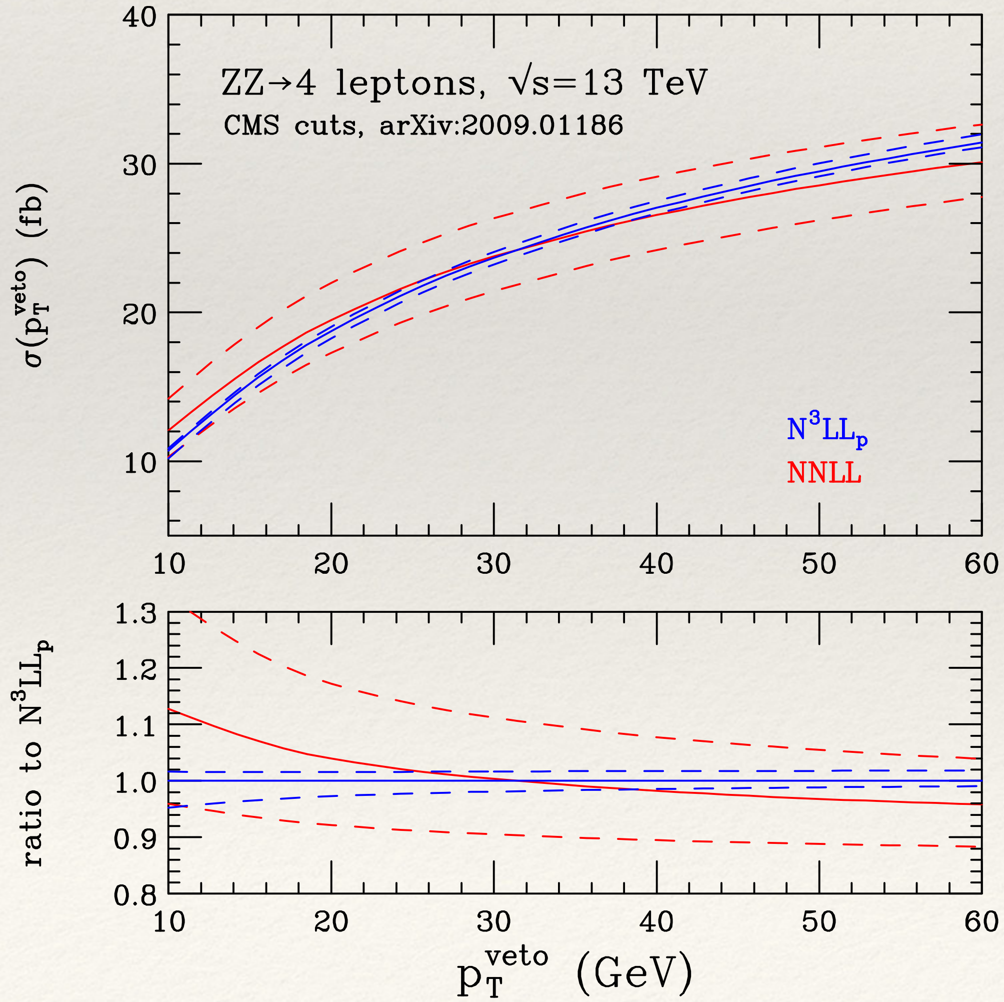


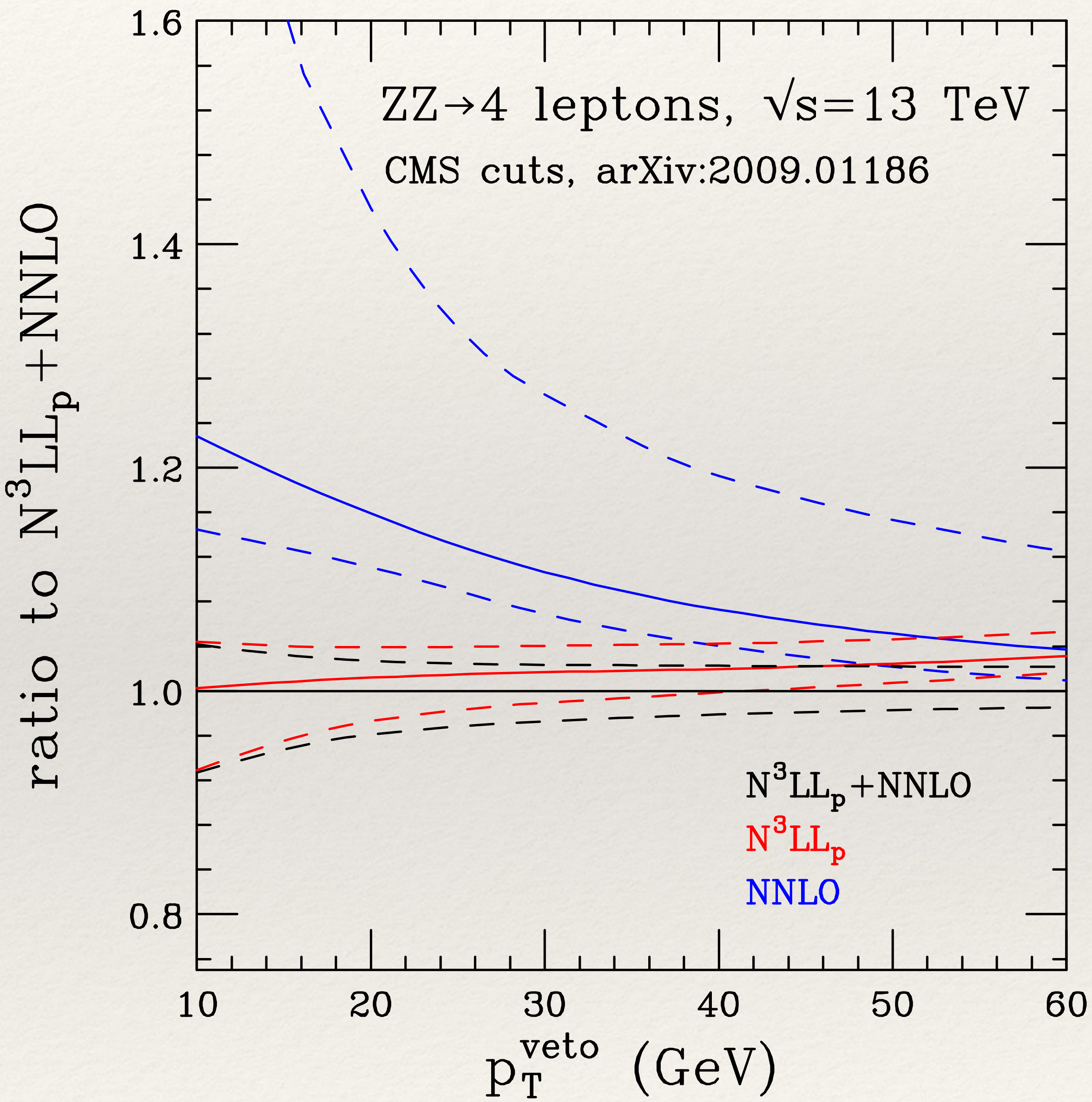
- CMS: 137 fb^{-1},Neither NNLO nor N^{3}LL+NNLO in good agreement.
- $\ln(Q/p_T^{veto})$=2.3 and y_{cut}=2.5, jet-veto resummation with veto over all rapidities may not be appropriate.
- The limited rapidity range requires a more sophisticated theoretical treatment.



ZZ production

- No experimental measurements with jet-vetos.





Conclusion

- We have presented resummed cross sections at N^3LL_p +NNLO for all color singlet final state processes with a jet veto, $p_T^{\rm veto}$, at all rapidities.
- We have compared our predictions with the available data;
- Resummation is essential for the description of jet-vetoed cross sections in Higgs production and for vector boson pair production.
- The fine-grained experimental study of vector boson pair processes where the resummation effects will be crucial is, in the main, still to come;
- Our work and the MCFM code can serve as a tool for testing and validating general purpose shower Monte Carlo programs.

Backup

Solution to RGE equations

$$\frac{d}{d\ln\mu} C(Q\,\mu) = \left[\Gamma_{\text{cusp}}(\mu)\ \ln\frac{Q^2}{\mu^2}\right] C(Q\,\mu)$$

- Traditional solution to the LL equation

$$C(Q,\mu) = \exp\left[2S(Q,\mu)\right] C(Q,Q) \qquad \frac{d}{d\ln\mu} S(Q,\mu) = -\Gamma_{\text{cusp}}(\alpha_S(\mu))\ln\frac{\mu}{Q}$$

$$S(Q,\mu) = -\int_Q^{\mu} \frac{d\mu'}{\mu'}\,\Gamma_{\text{cusp}}(\alpha_S(\mu'))\ \ln\frac{\mu'}{Q}$$

- We can write solution in terms of running coupling

- $$S(Q,\mu) = -\int_{\alpha_S(Q)}^{\alpha_S(\mu)} d\alpha \frac{\Gamma_{\text{cusp}}(\alpha)}{\beta(\alpha)} \int_{\alpha_S(Q)}^{\alpha} \frac{d\alpha'}{\beta(\alpha')}, \qquad \frac{d\alpha_S}{d\ln\mu} = \beta(\alpha_S)$$

$$S(Q,\mu) \to \frac{\Gamma_0}{4\pi k_0^2}\frac{1}{\alpha_S(Q)}\left(\frac{r - r\ln r - 1}{r}\right) \text{ where } r = \alpha_S(\mu)/\alpha_S(Q)$$

- We recover the double log, setting

$$\beta(\alpha_S) = -k_0\alpha_S^2 \text{ and } \frac{1}{r} = 1 - k_0\alpha_S(Q)\ln(Q/\mu)$$