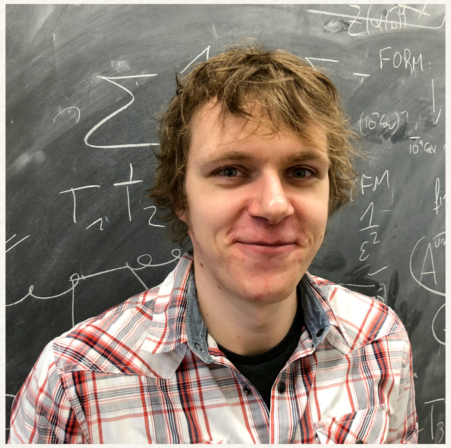


Milan, June 2023

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

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.

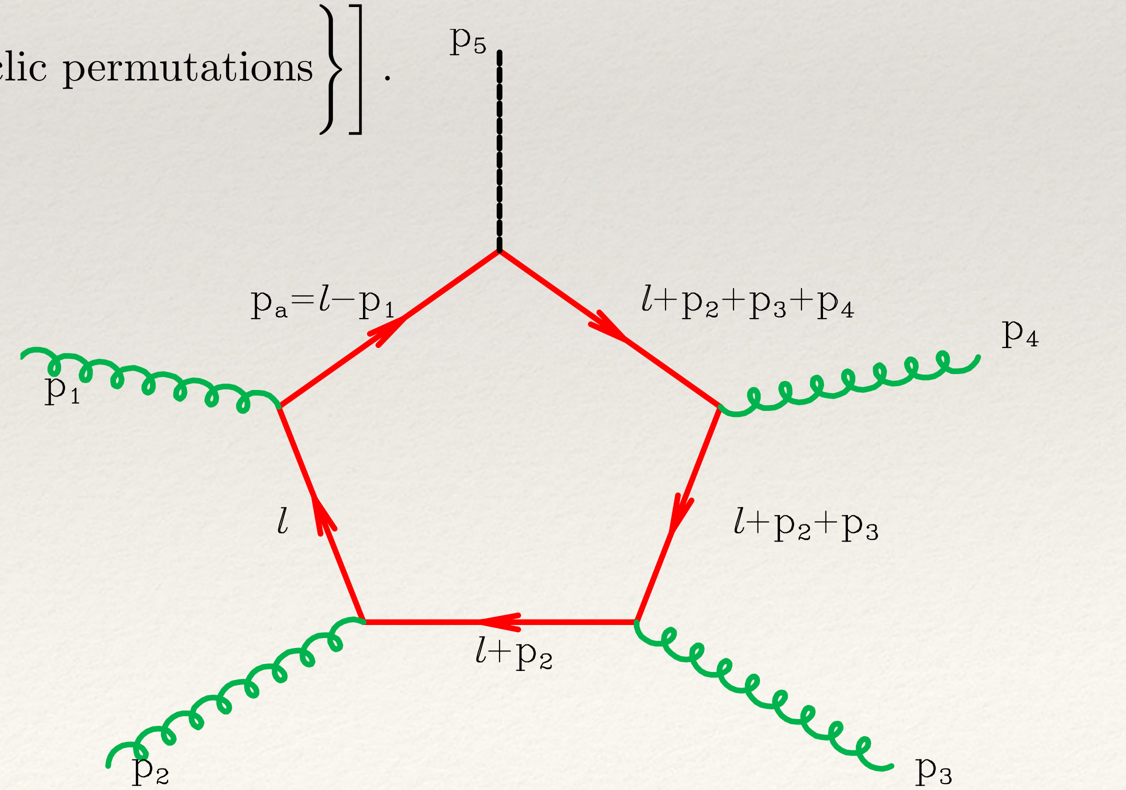
Example of Analytic loop amplitudes in MCFM

RKE and Seth, 1808.09292
Budge et al, 2002.04018

- Higgs boson plus four partons at one loop.

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

- 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



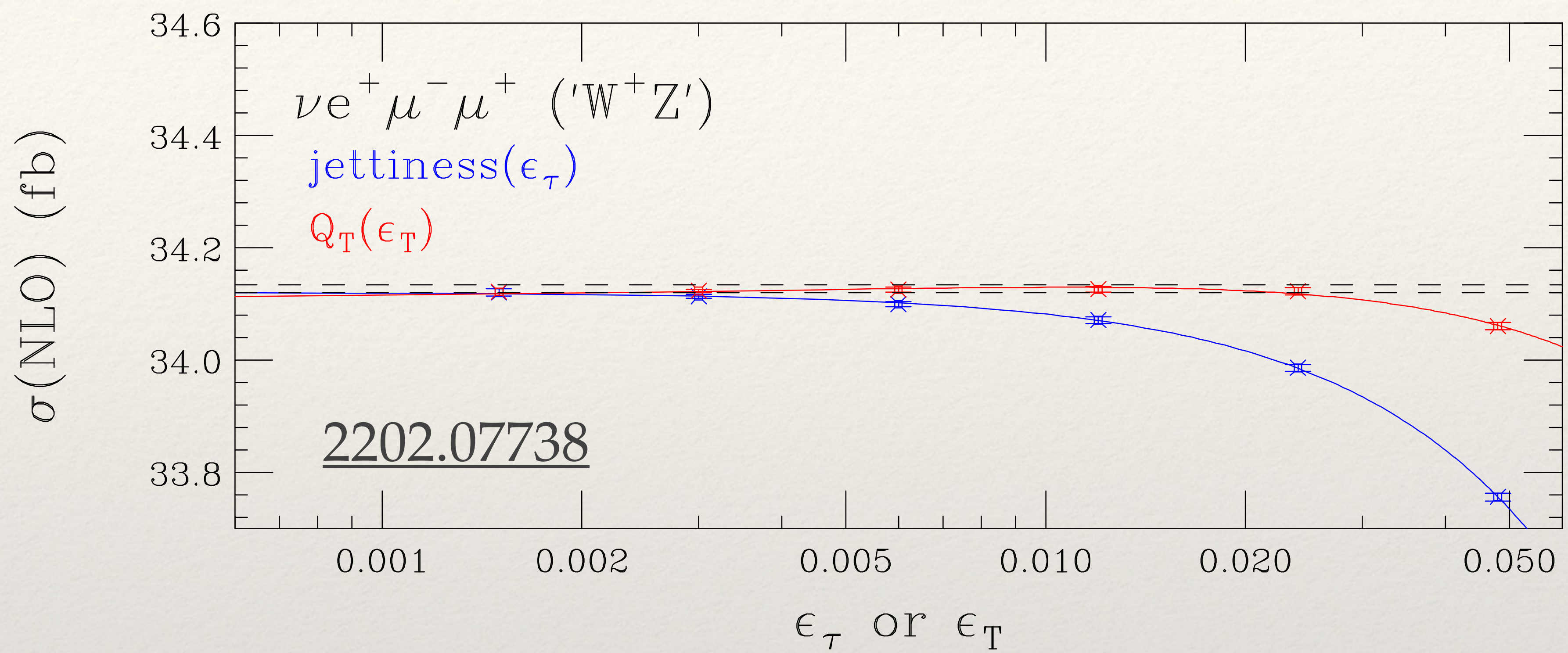
NNLO results

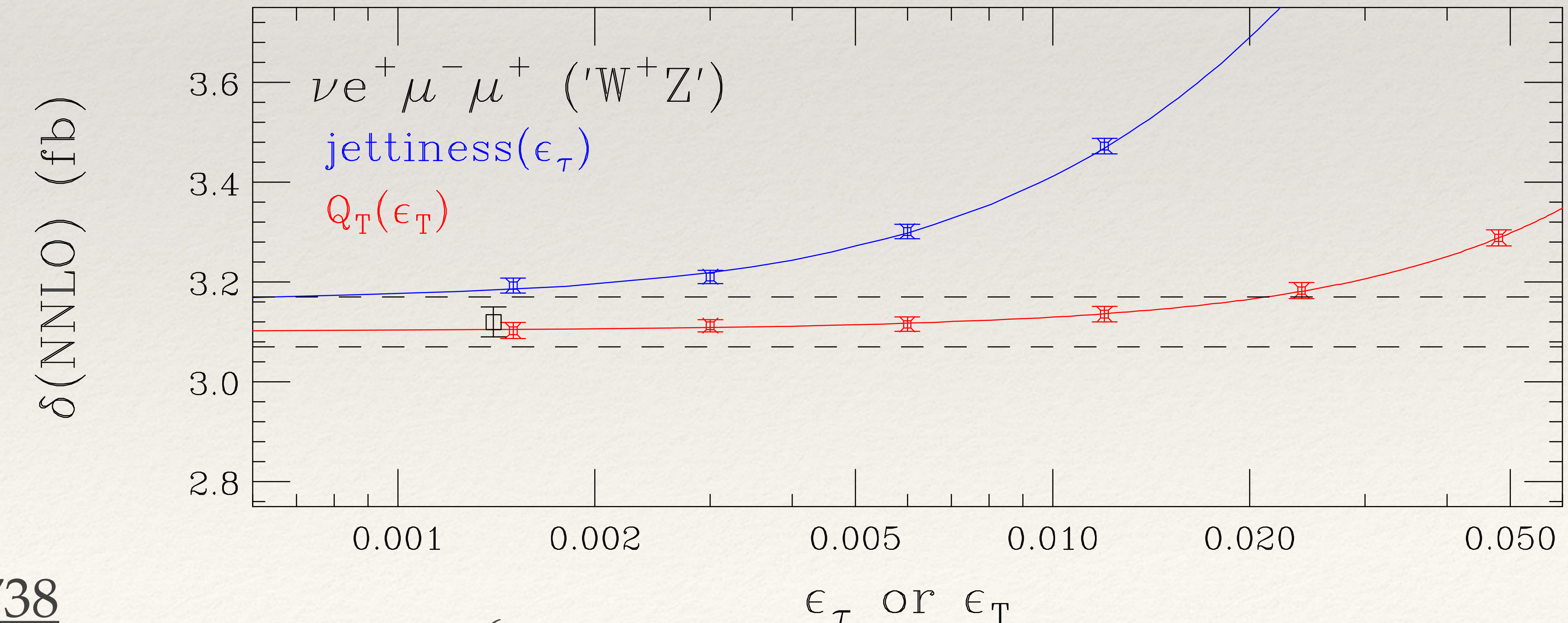
- In a recent paper (2202.07738) we tried to document all the processes calculated at NNLO.
- About 50% are available in MCFM.
- We use both q_T slicing and jettiness slicing.
- However I should note that in some cases N^{3}LO is now the start of the art (e.g. 1811.07906 ,2102.07607 2203.01565, 2209.06138)

Process	MCFM	Process	MCFM
$H + 0$ jet [8–14]	✓ [15]	$W^\pm + 0$ jet [16–18]	✓ [15]
$Z/\gamma^* + 0$ 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 $\epsilon_\tau = (\tau^{\text{cut}}/Q)^{\frac{1}{\sqrt{2}}}$





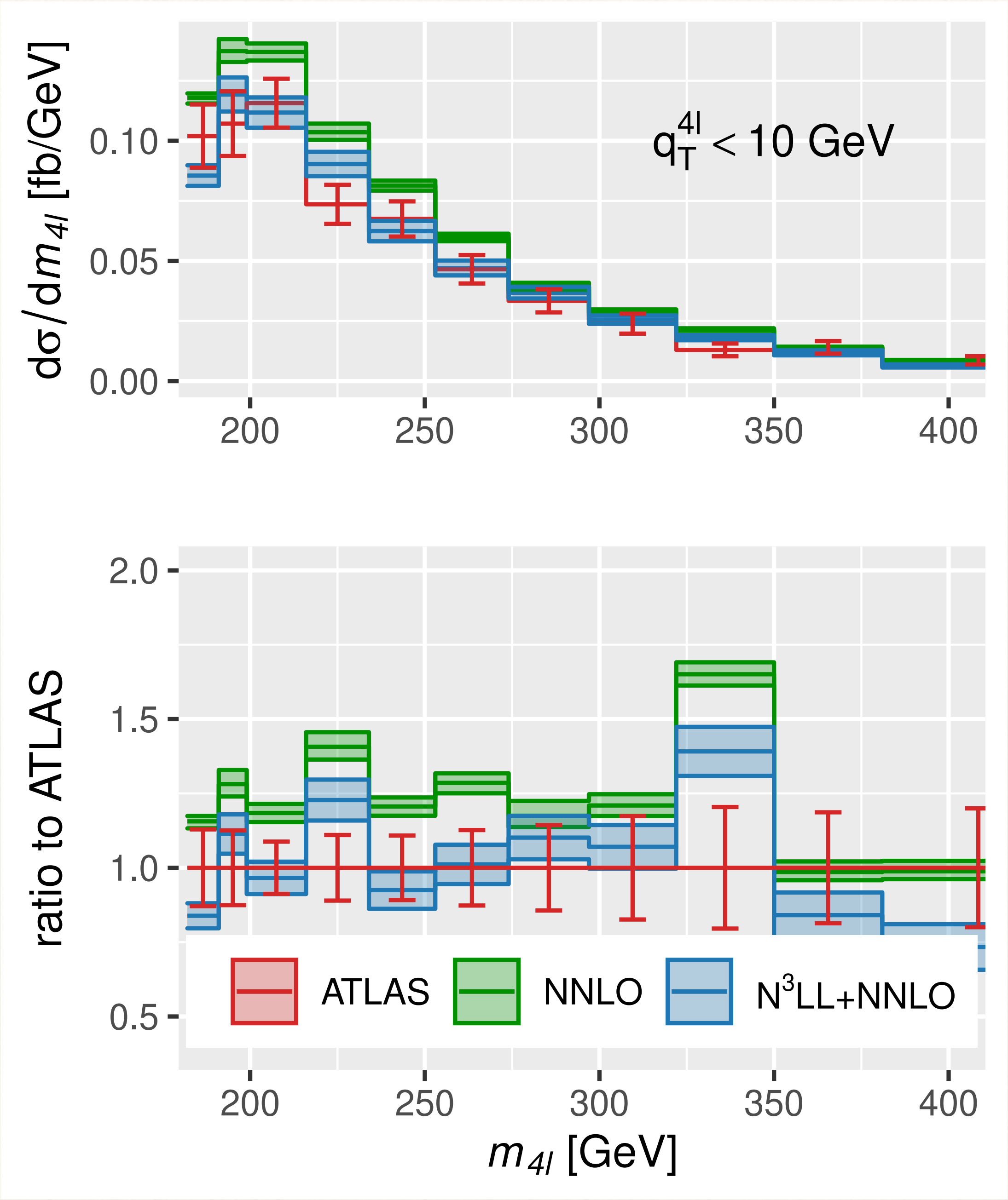
Campbell et al,2202.07738

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 N^{3}LL+NNLO, Becher and Neumann, 2009.11437

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

Jet veto cross sections

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

Soft function
Abreu et al,
2204.03987

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[b]*Higgs Centre for Theoretical Physics, School of Physics and Astronomy, The University of Edinburgh, Edinburgh EH9 3FD, Scotland, United Kingdom*
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Quark and gluon two-loop beam functions for leading-jet p_T and slicing at NNLO

Beam functions
Abreu et al,
2207.07037

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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 $p_T^{\rm veto} \sim 25$ 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).

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

Rapidity regulator ν

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

Beam functions Abreu et al, 2207.07037

Soft function Abreu et al, 2204.03987

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

Refactorization

- Refactorize

$$\left[\mathcal{B}_q(\xi_1, Q, p_T^{veto}, R, \mu, \nu)\, \mathcal{B}_{\bar{q}}(\xi_2, Q, p_T^{veto}, R, \mu, \nu) \mathcal{S}(p_T^{veto}, R, \mu, \nu)\right]$$

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

"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.

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

Approximation	Nominal order	Accuracy $\sim \alpha_s^n L_\perp^k$	Γ_{cusp}	$\gamma_{\text{coll.}}$	H
LL	α_s^{-1}	$2n \geq k \geq n+1$	Γ_0	tree	tree
NLL+LO	α_s^0	$2n \geq k \geq n$	$\Gamma_1,$	γ_0	tree
N^2LL+NLO	α_s^1	$2n \geq k \geq \max(n-1,0)$	Γ_2	γ_1	1-loop
N^3LL +NNLO	α_s^2	$2n \geq k \geq \max(n-2,0)$	Γ_3	γ_2	2-loop

- we have RGE equations,

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

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

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

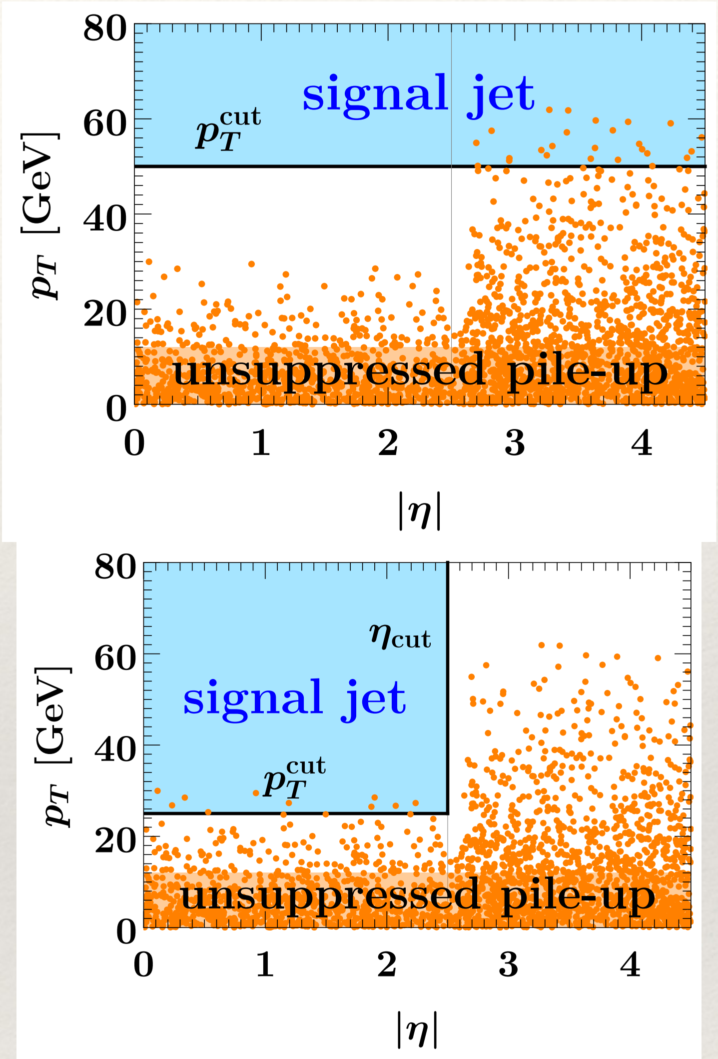
- $$\frac{d}{d\mu}\bar{B}_q(\xi_1,p_T^{veto},R,\mu)\,\bar{B}_{\bar{q}}(\xi_2,p_T^{veto},R,\mu) = \mathcal{O}(\alpha_s^3)$$

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 $\eta_{\rm cut}$
- Experimental analyses perform jet cuts for $\eta < \eta_{\rm cut}$
- In 1810.12911, three theoretical regions are identified
  - $\eta_{\rm cut} \gg \ln(Q/p_T^{\rm veto})$ (jet veto resummation as we are using it.)
  - $\eta_{\rm cut} \sim \ln(Q/p_T^{\rm veto})$ ($\eta_{\rm cut}$-dependent beam functions)
  - $\eta_{\rm cut} \ll \ln(Q/p_T^{\rm veto})$ (collinear non-global logs)



Current theory calculation

Typical Experimental cuts

Figure taken from 1810.12911

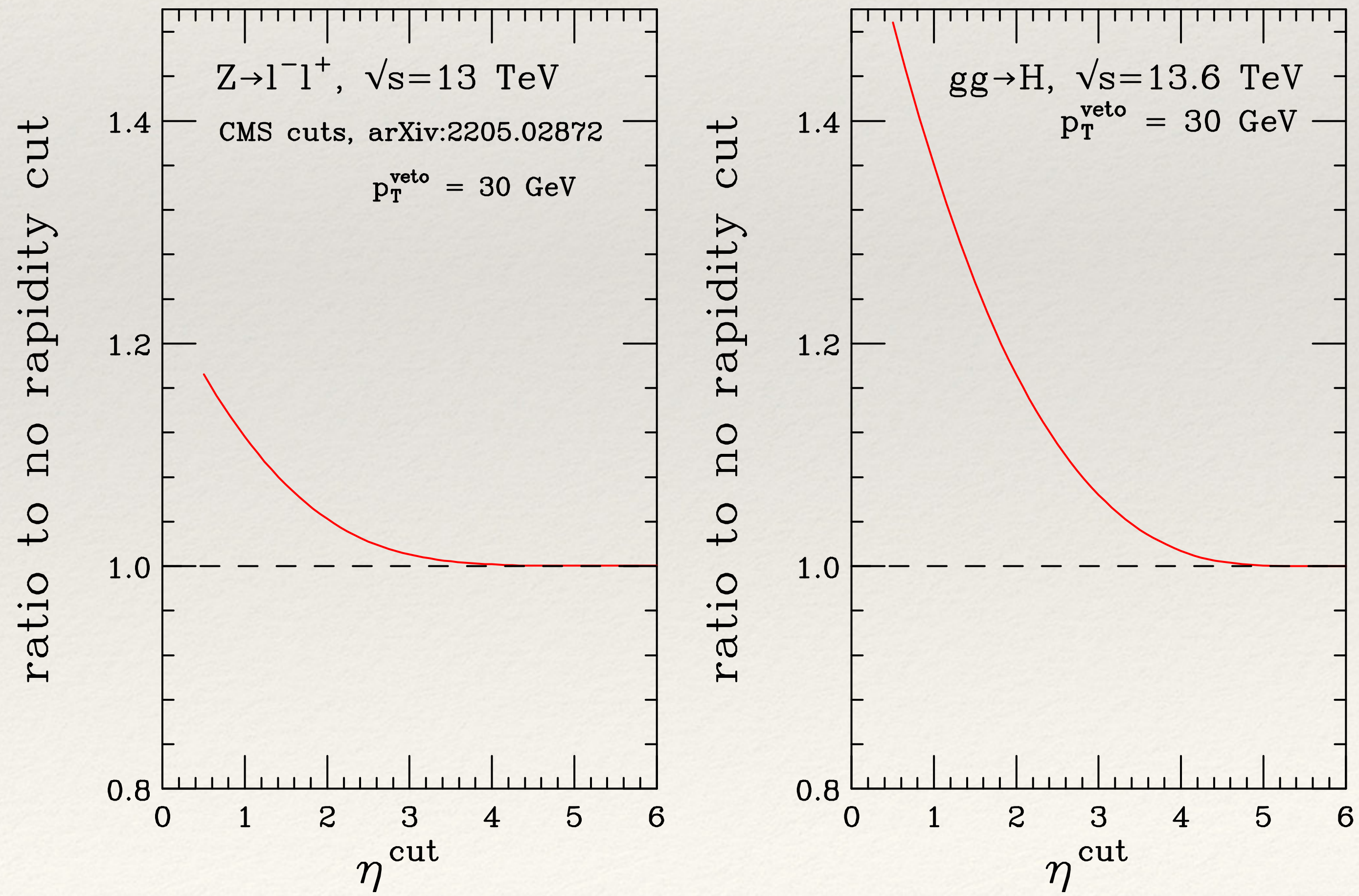
Strategy: determination where resummation is potentially important, before considering limited rapidity range resummation

Effects of rapidity cuts at fixed order

- The usual jet veto resummation imposes no cut on the jet rapidity, unlike the experimental analysis.

Process	Ref.	y_{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

- To apply the theory we need $\eta_{\text{cut}} \gg \ln(Q/p_T^{\text{veto}})$
- 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

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

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

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

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

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

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

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

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

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

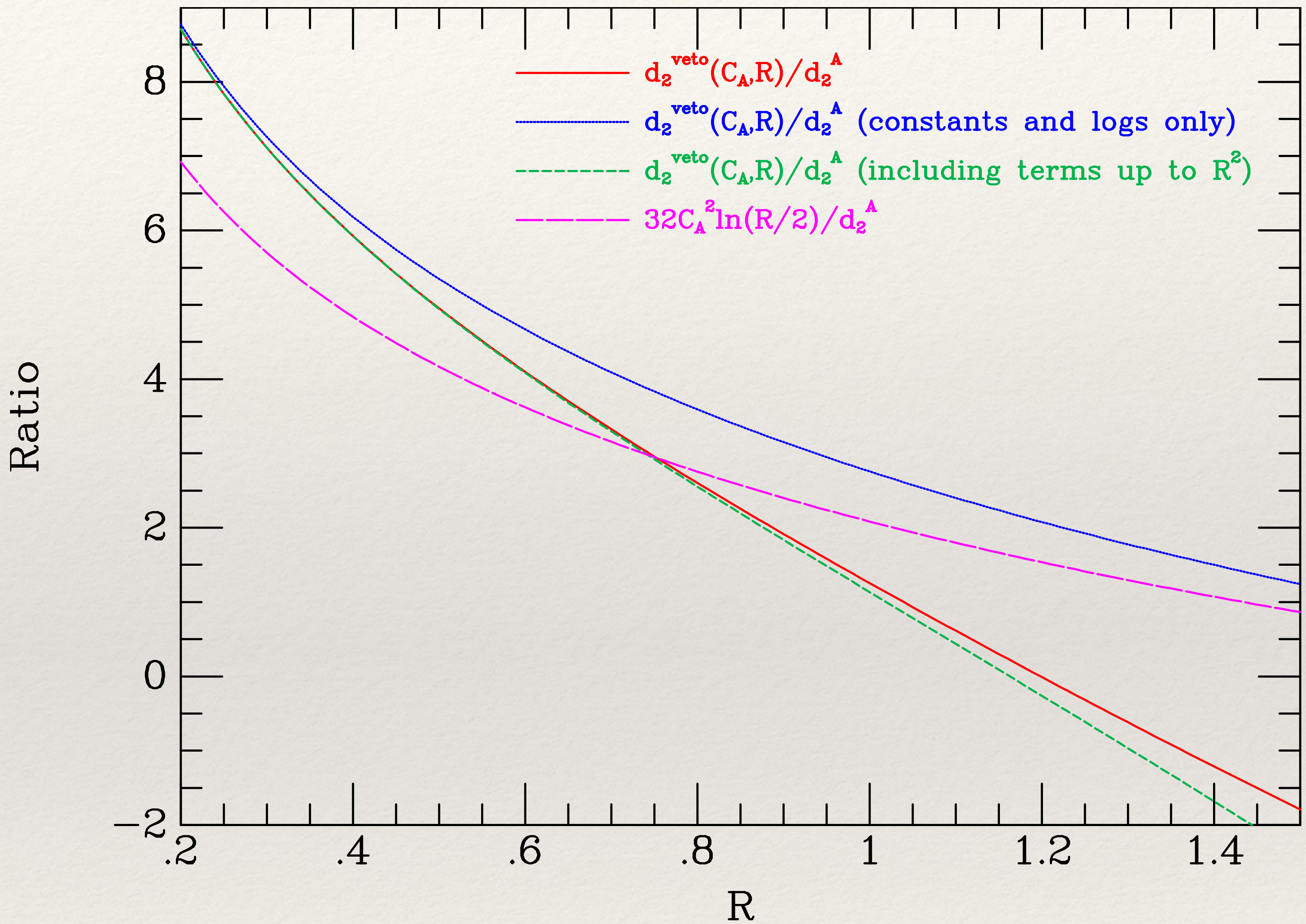
Coefficients c_i^A and c_i^f for $i < 10$, see 1307.0025

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

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

Approximations to d_2^{veto}

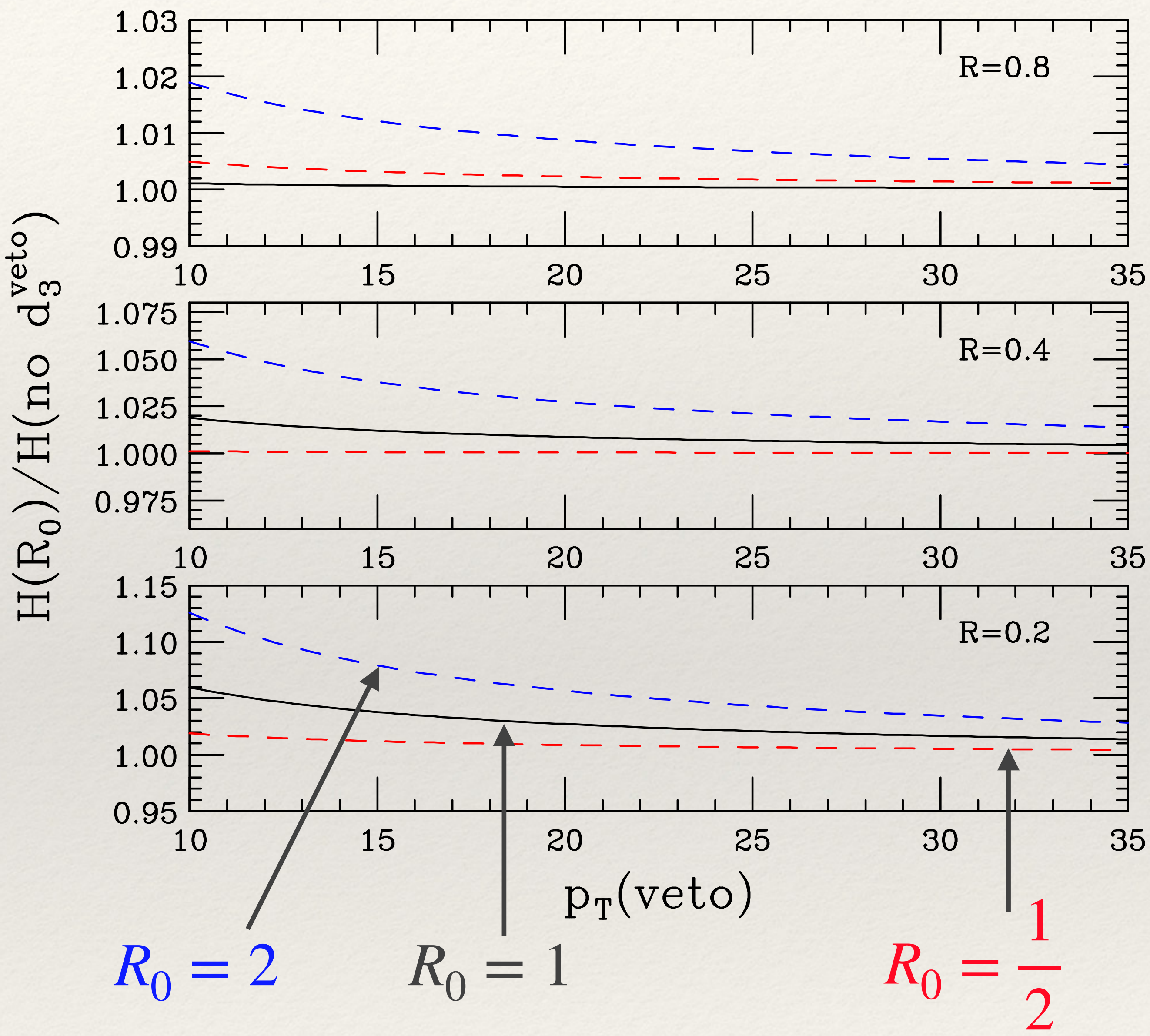
- Range of validity is $\frac{p_T^{\text{veto}}}{Q} \ll R \ll \ln\left(\frac{Q}{p_T^{\text{veto}}}\right)$
- At too small R terms of order $\ln^n R$ which are not covered by this factorization formula.
- At too large R, factorization formula breaks down.
- Results are presented as power series in R
- 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^{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 ~ $\leq 2.5\ \%$ at p_T^{veto}=25 GeV and $R = 0.4$

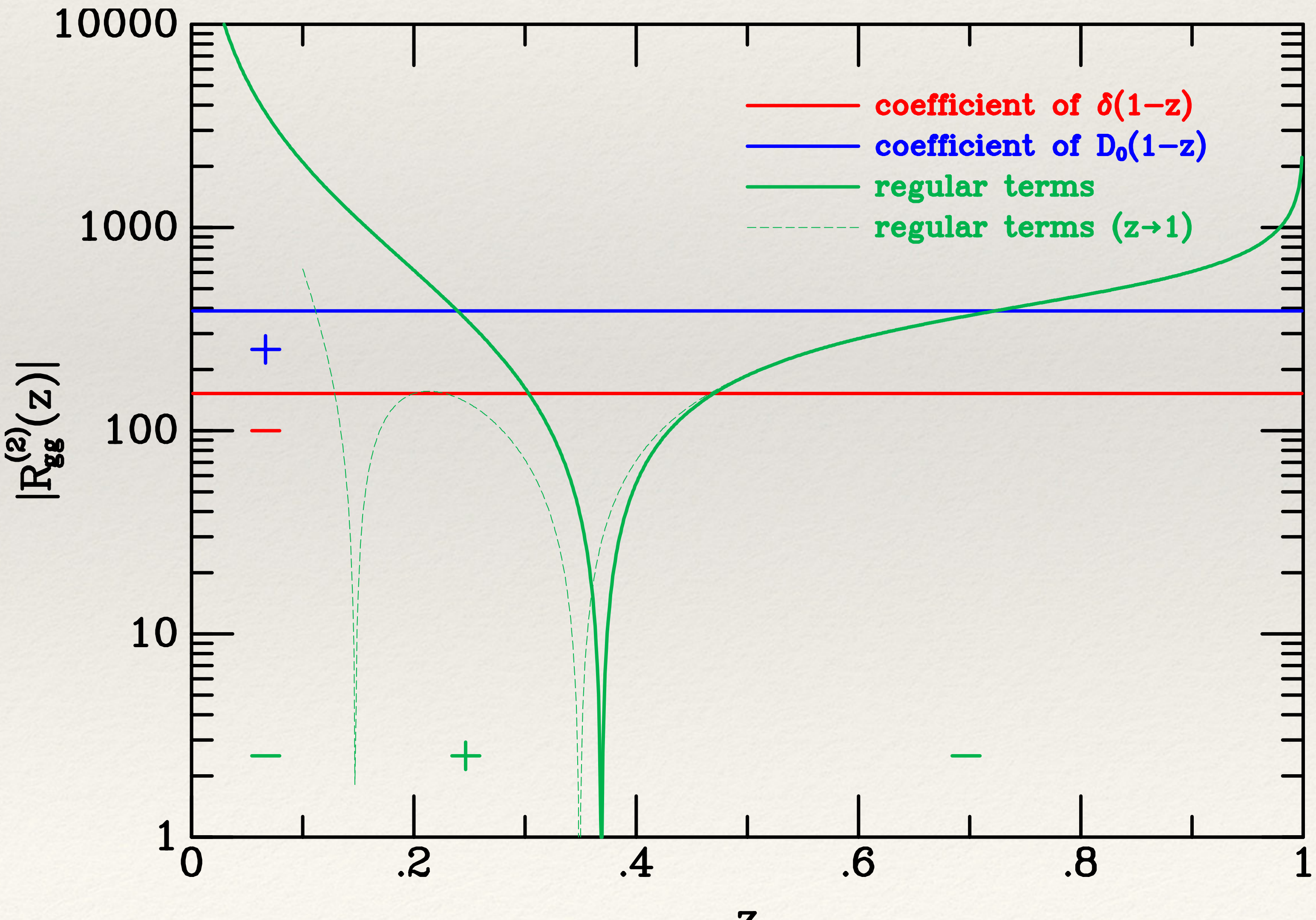


Suggestion is that error derived from $\frac{1}{2} < R_0 < 2$

Leading behavior derived from Banfi et al, 1511.02886

Reduced beam function kernels

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

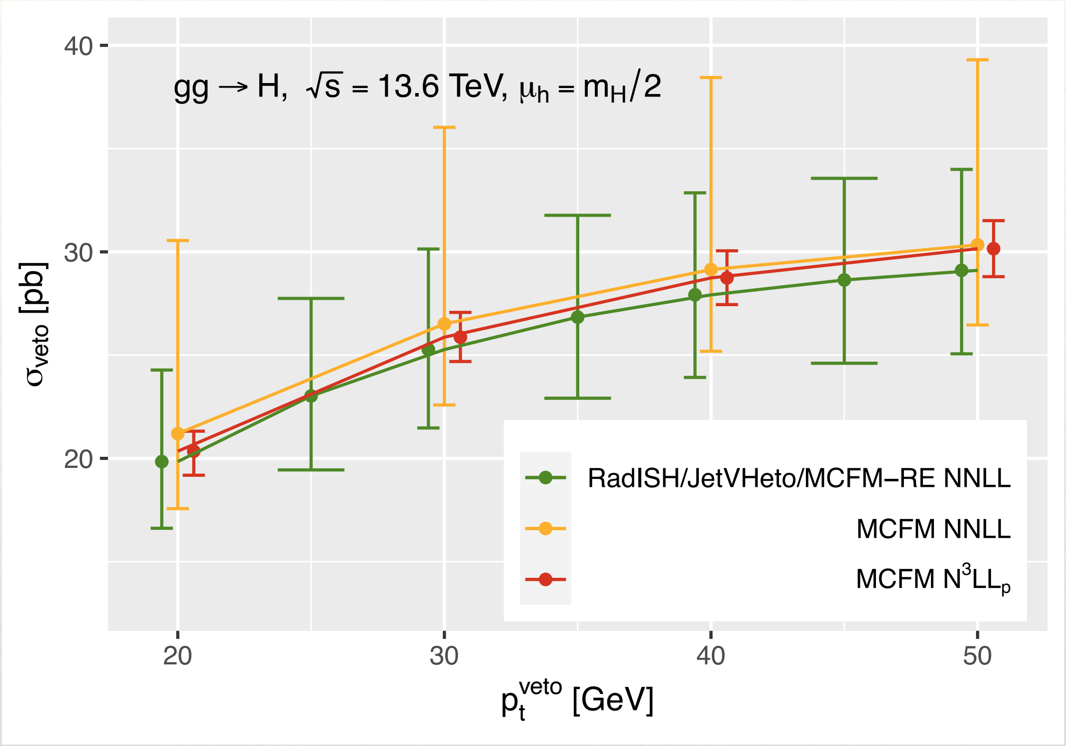


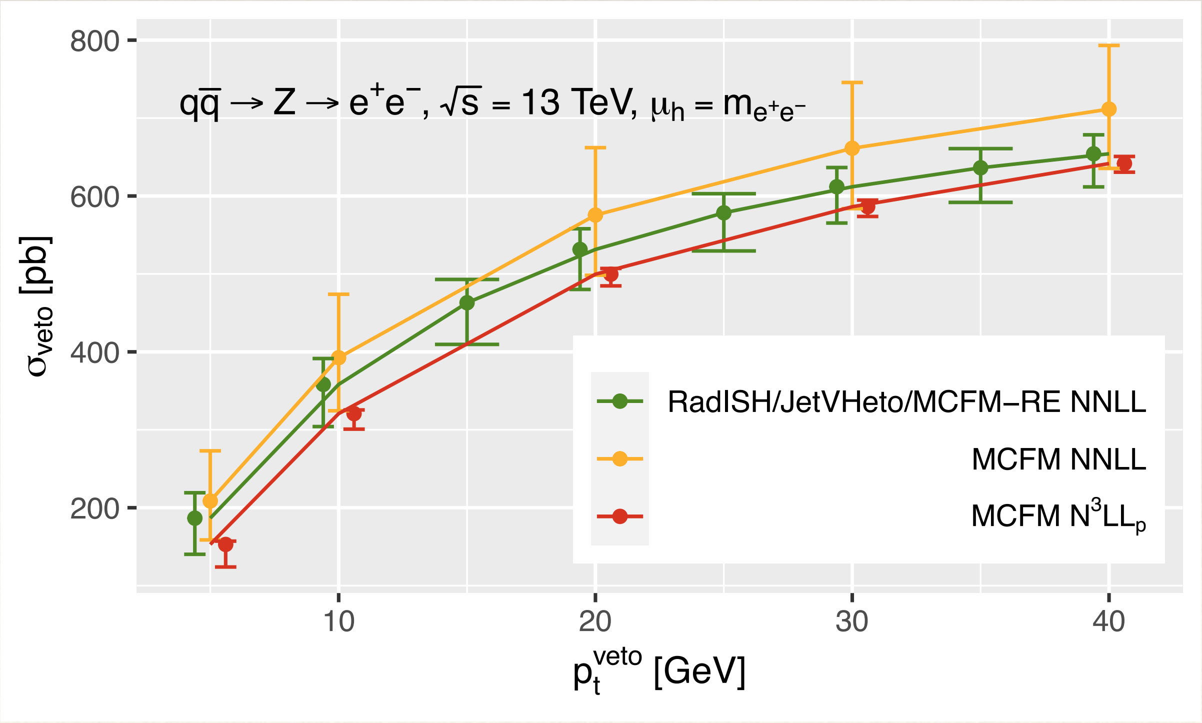
Phenomenological results in N^3LL_p

$N^3LL_p \equiv N^3LL$ 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.

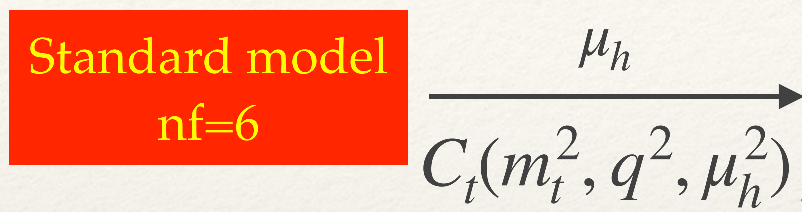
$$\left(\frac{Q}{p_T^{veto}}\right)^{-2F_{ii}(p_T^{veto},R,\mu)} = \left(\frac{Q}{\nu}\right)^{-2F_{ii}(p_T^{veto},R,\mu)} \left(\frac{\nu}{p_T^{veto}}\right)^{-2F_{ii}(p_T^{veto},R,\mu)}$$

  - 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

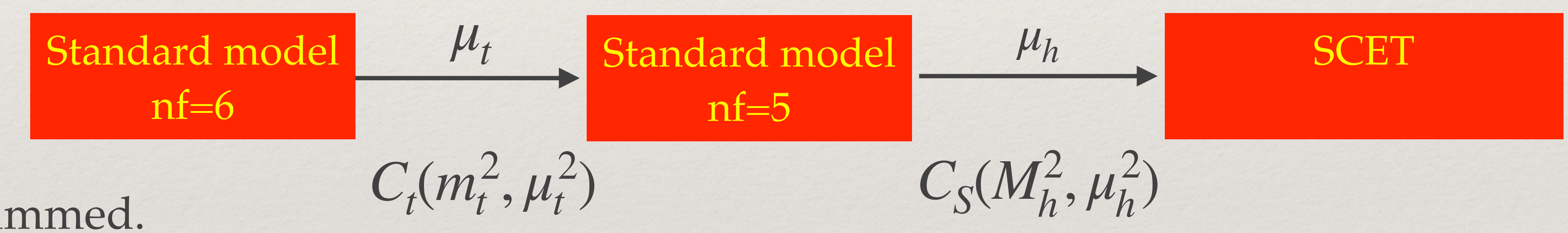
One-step vs Two-step matching for Higgs production

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



- 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_h resummed.

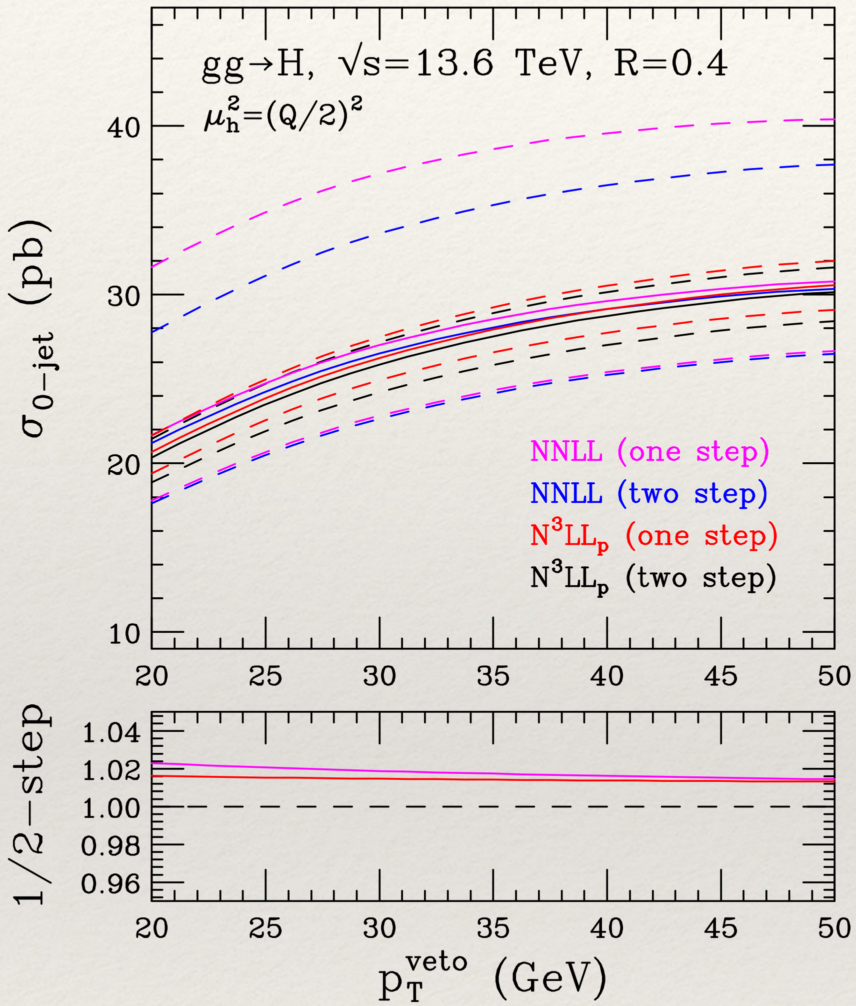


- Two step matching can restore most of the important mass effects by re-scaling the two-step result by the exact leading order result;

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

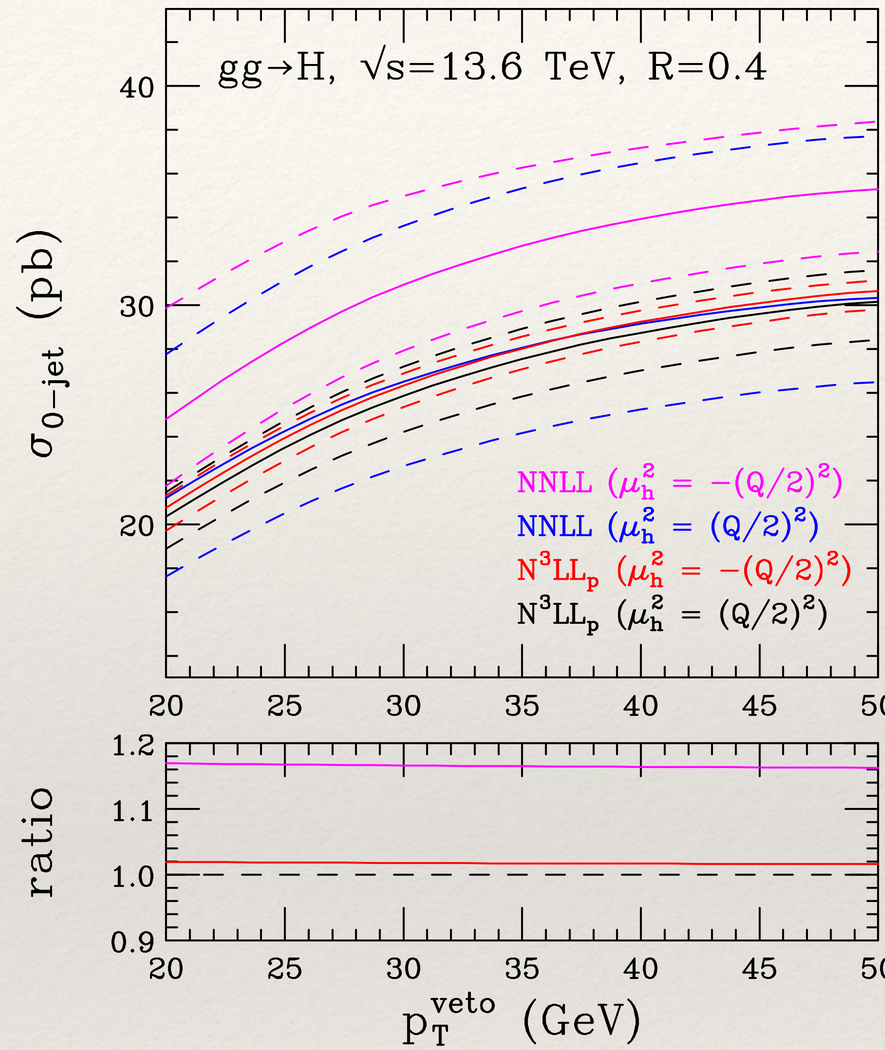
- Bigger differences can be found if higher order effects are not controlled.

Detailed assumptions for Higgs production



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

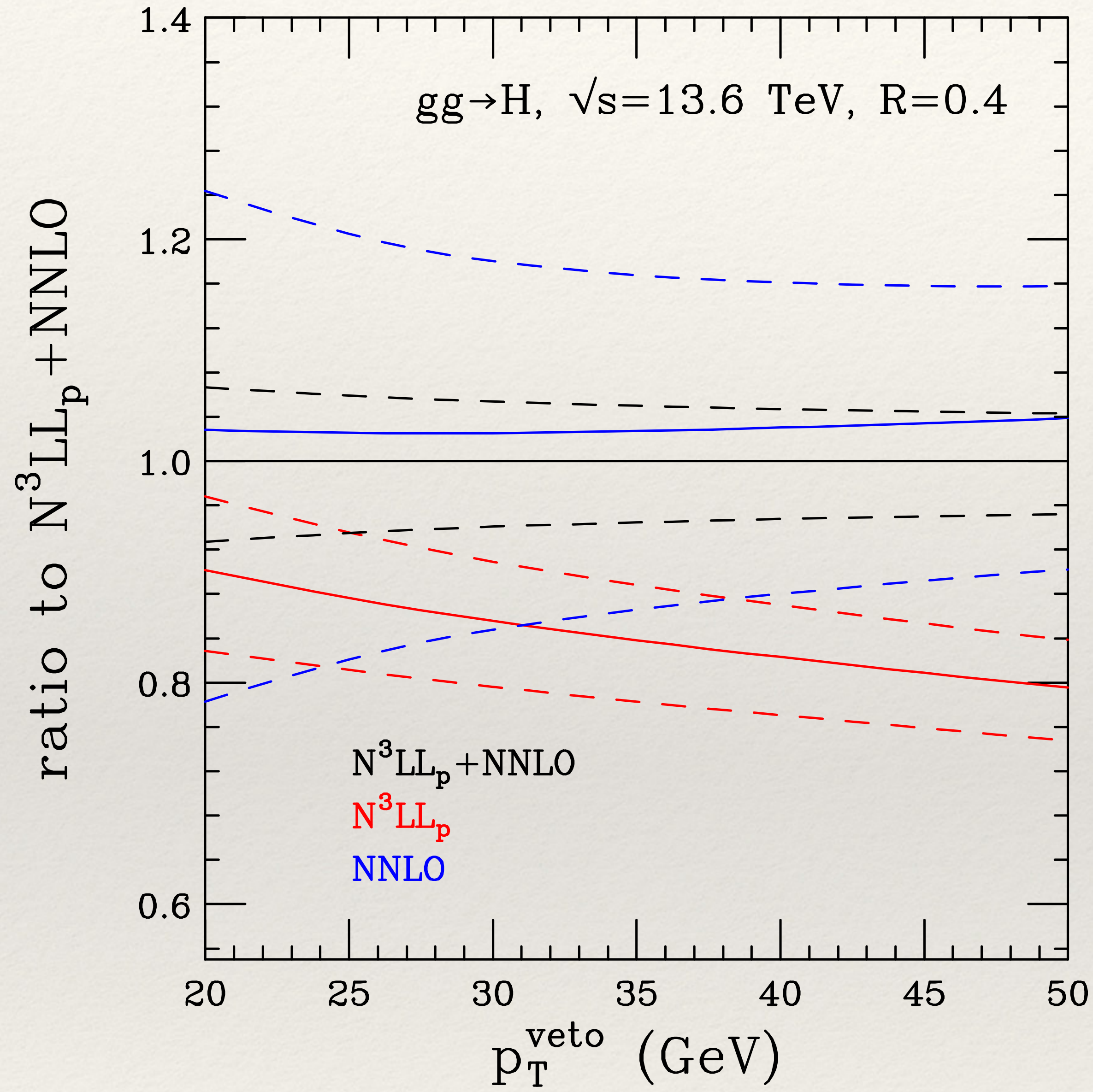
We use one-step scheme

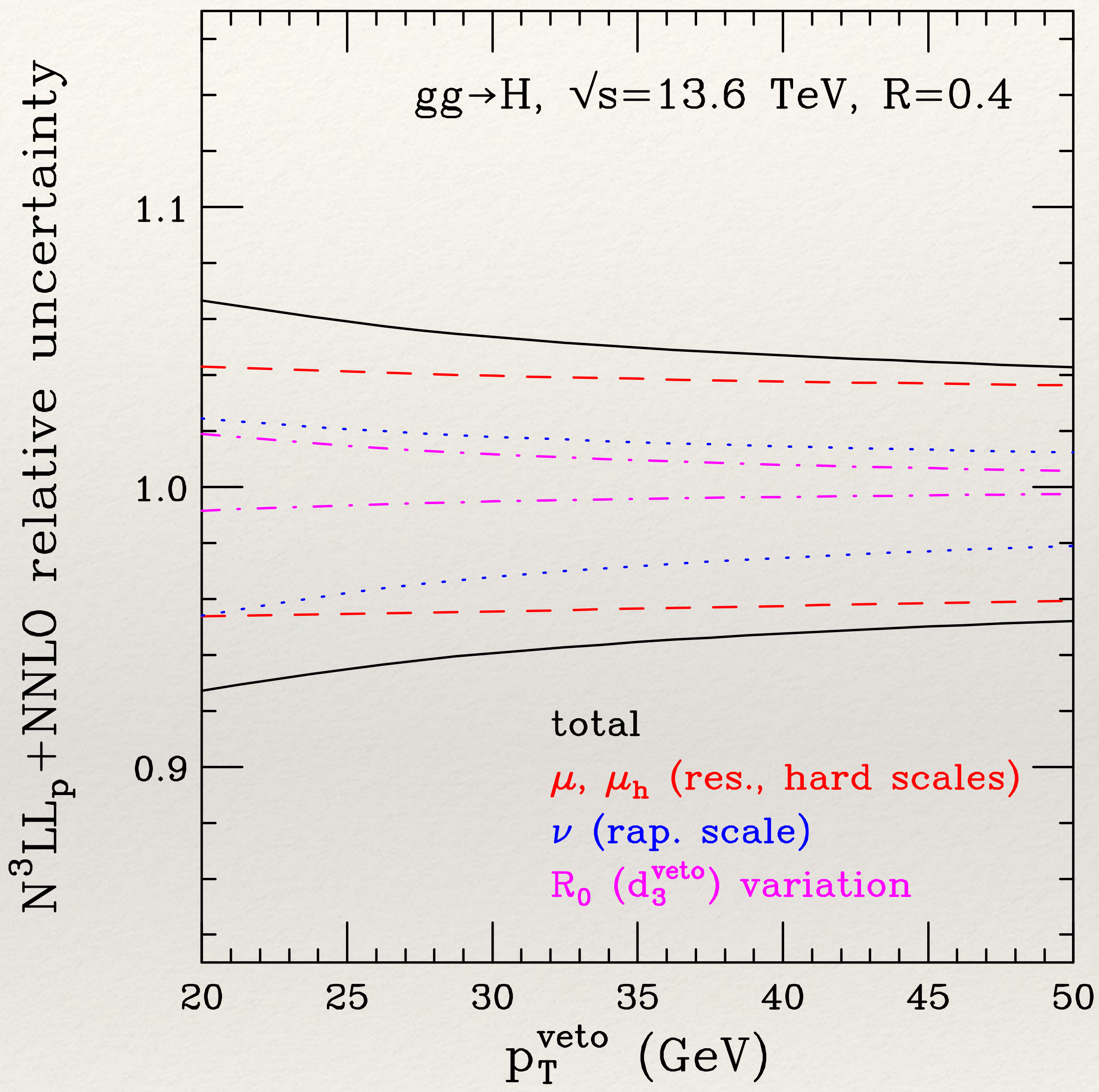


- At NNLL, the resummation of the π^2 terms enhances the cross-section by 17%. However, at N^3LL_p accuracy, this resummation only leads to a small increase of 2% in the cross-section.

We use spacelike μ_h

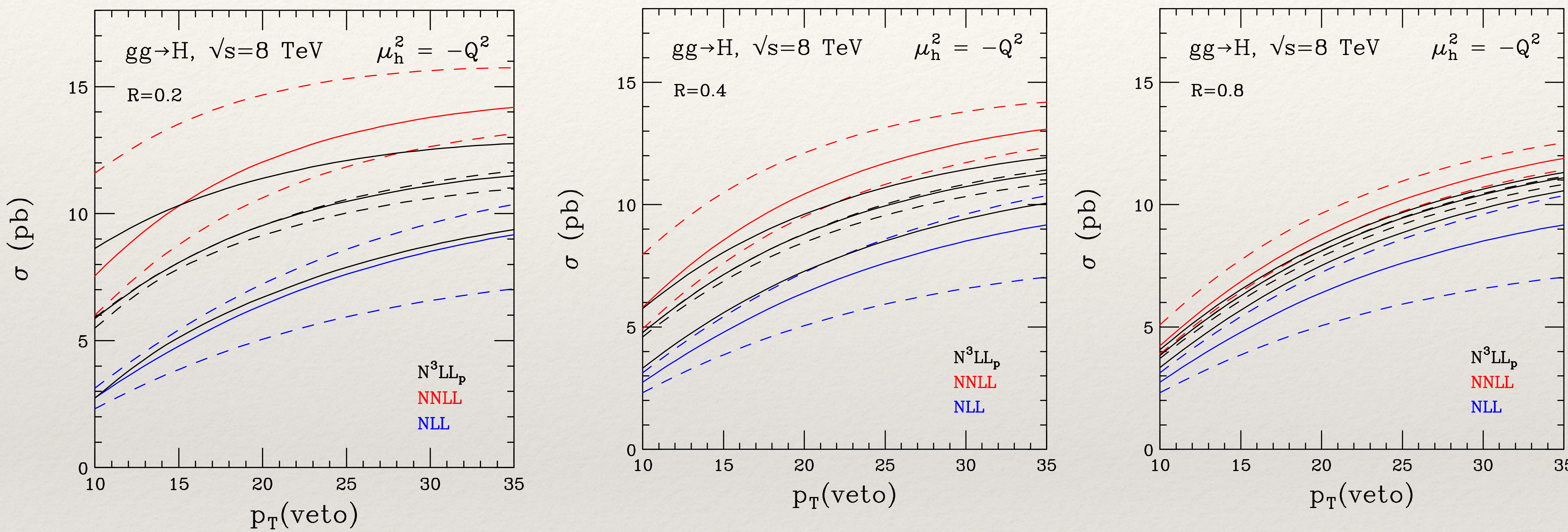
Comparison of NNLO, N^3LL_p and N^3LL_p+NNLO predictions for Higgs production.





- 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.

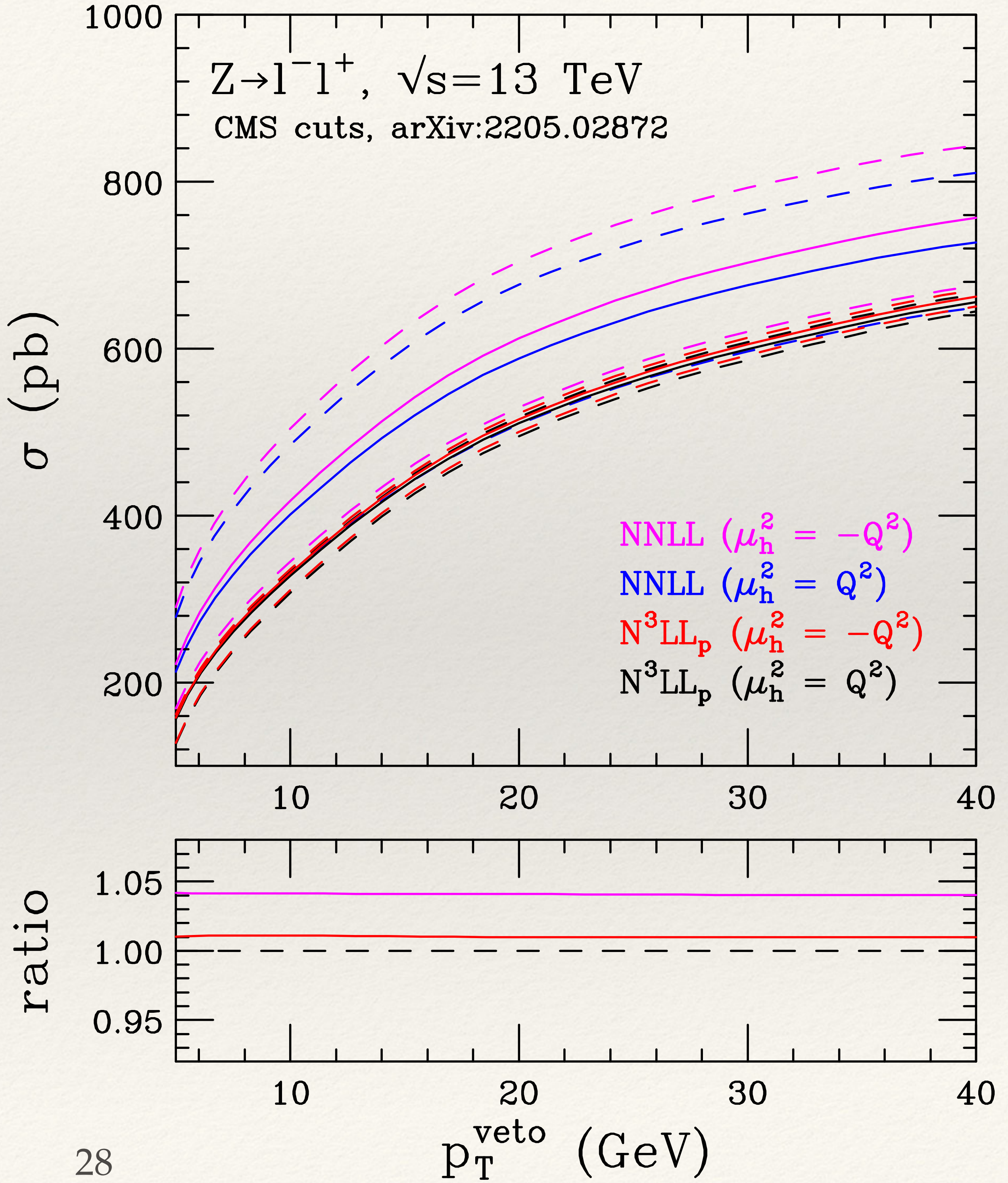
Jet-veto in Higgs production



- 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.

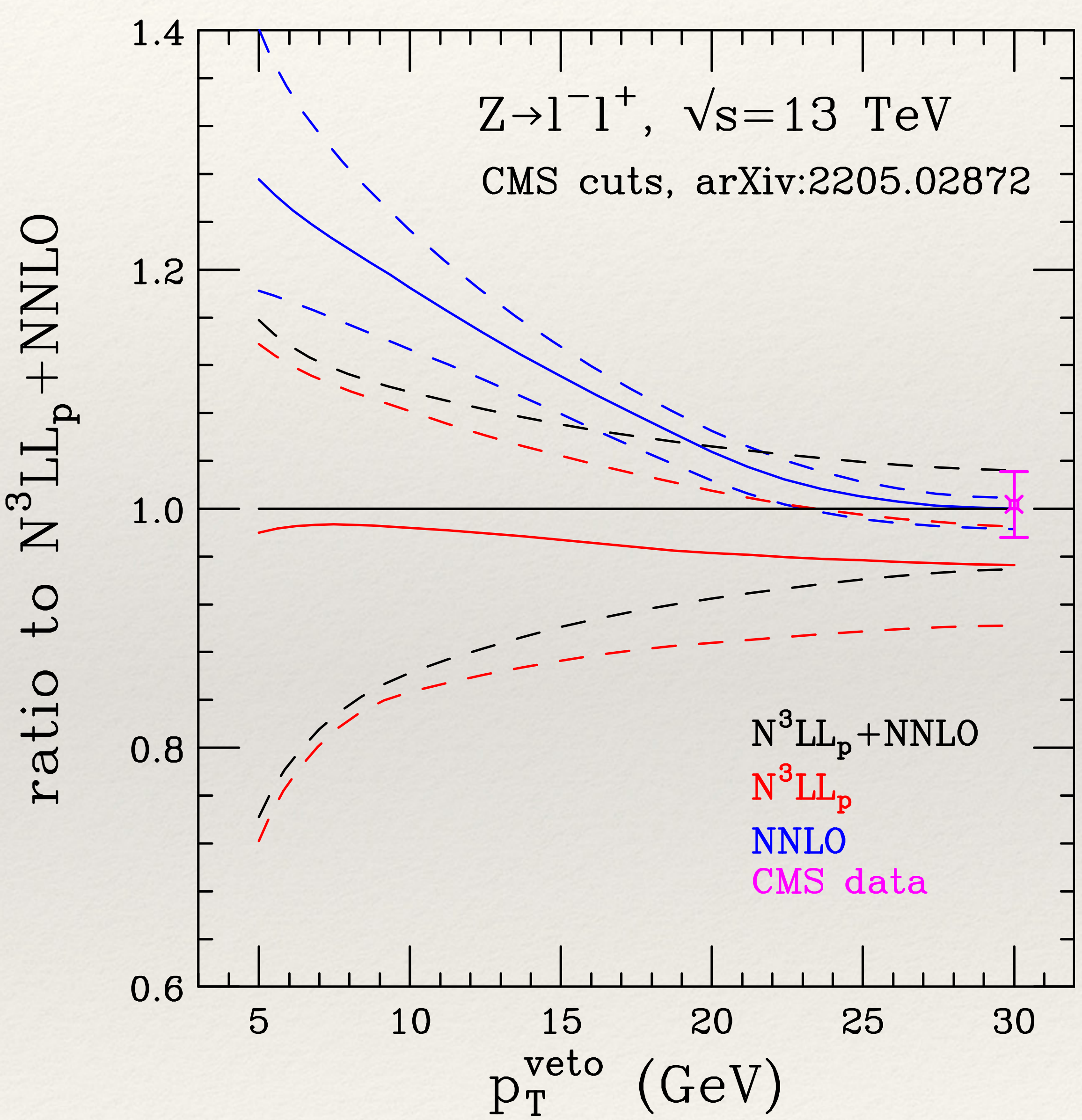
Jet veto in Z-production

- 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.



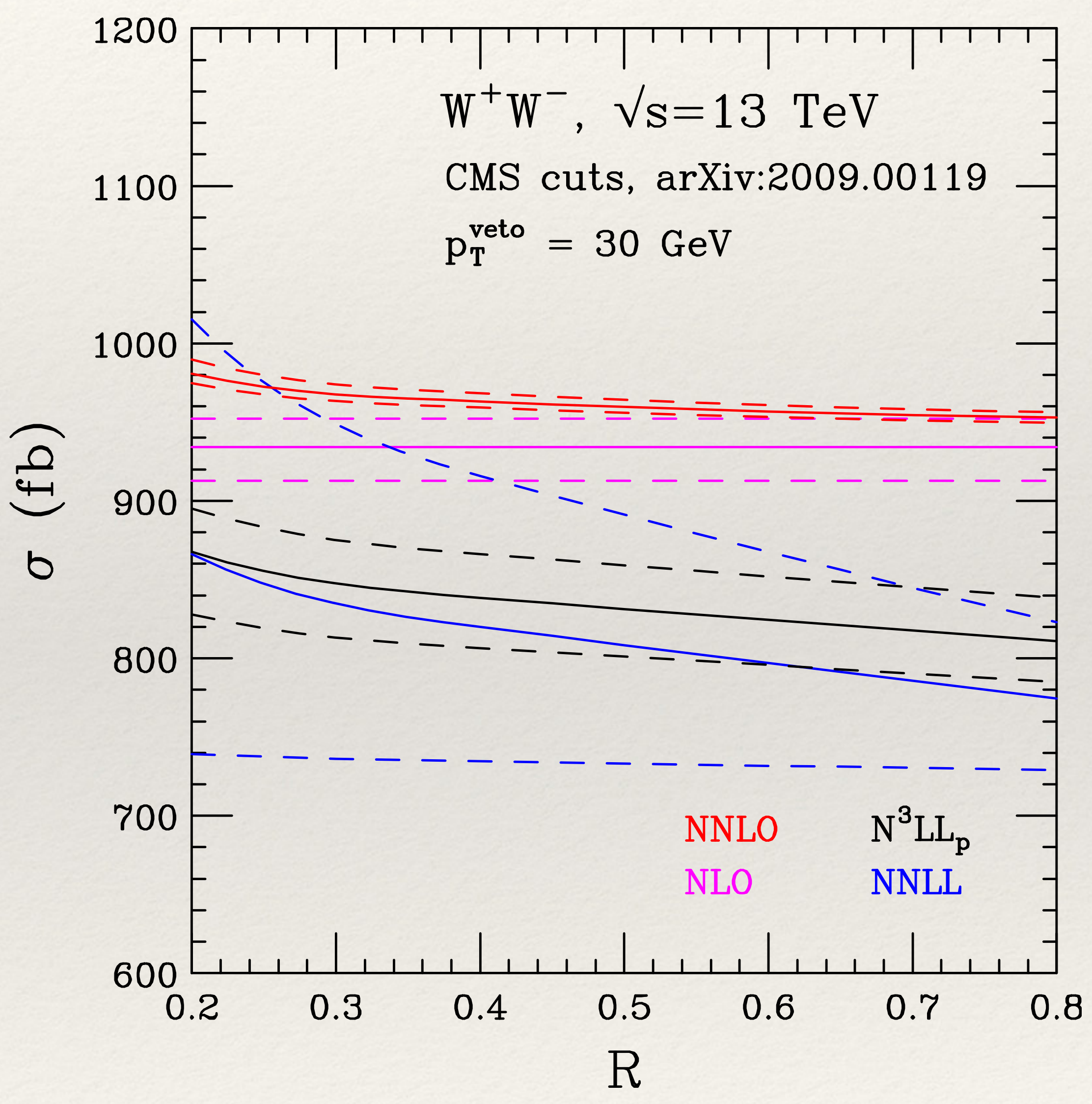
Jet veto in Z production

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

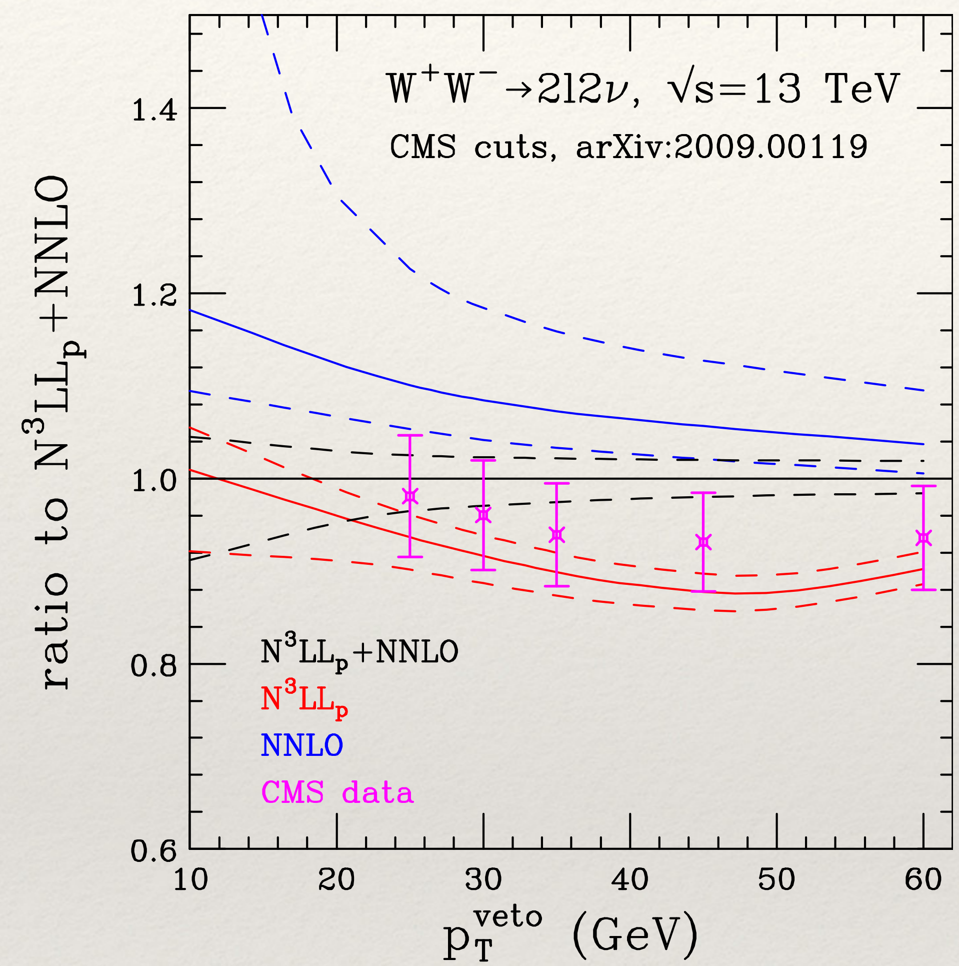


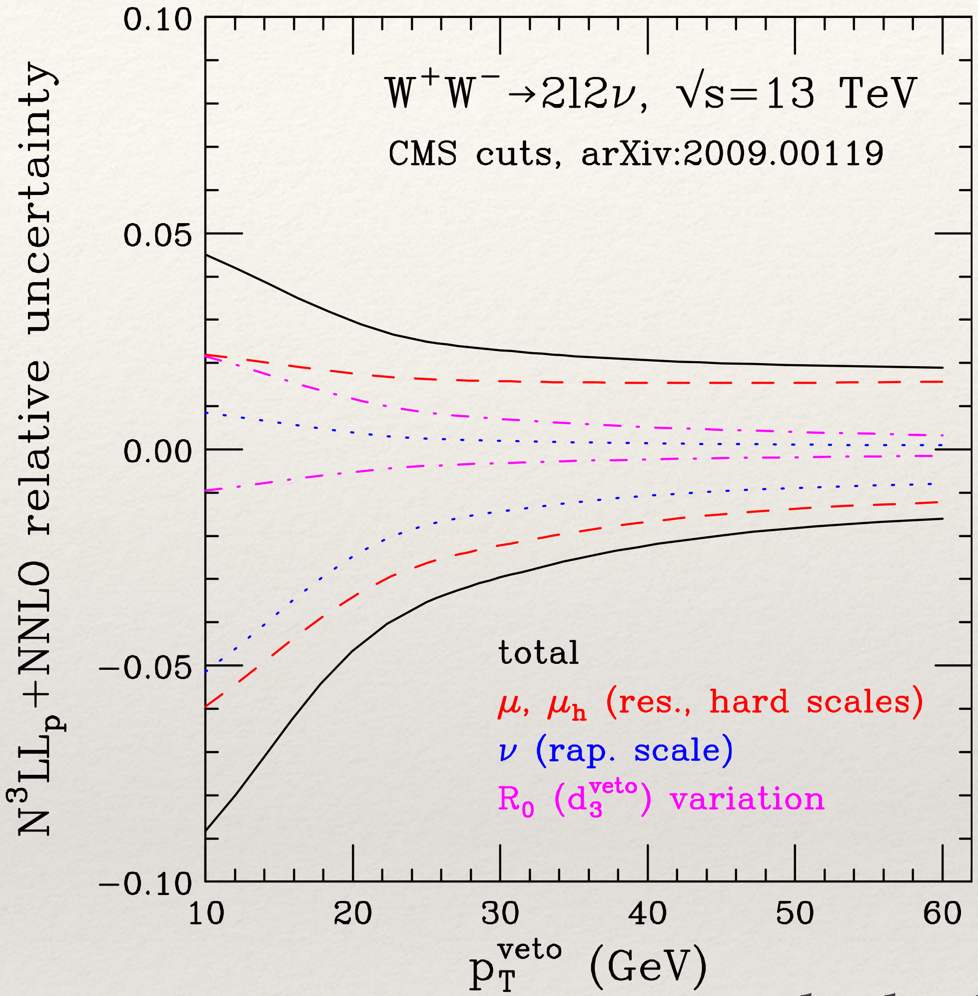
Jet veto in W^+W^- production

- Often performed to eliminate top background.
- 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

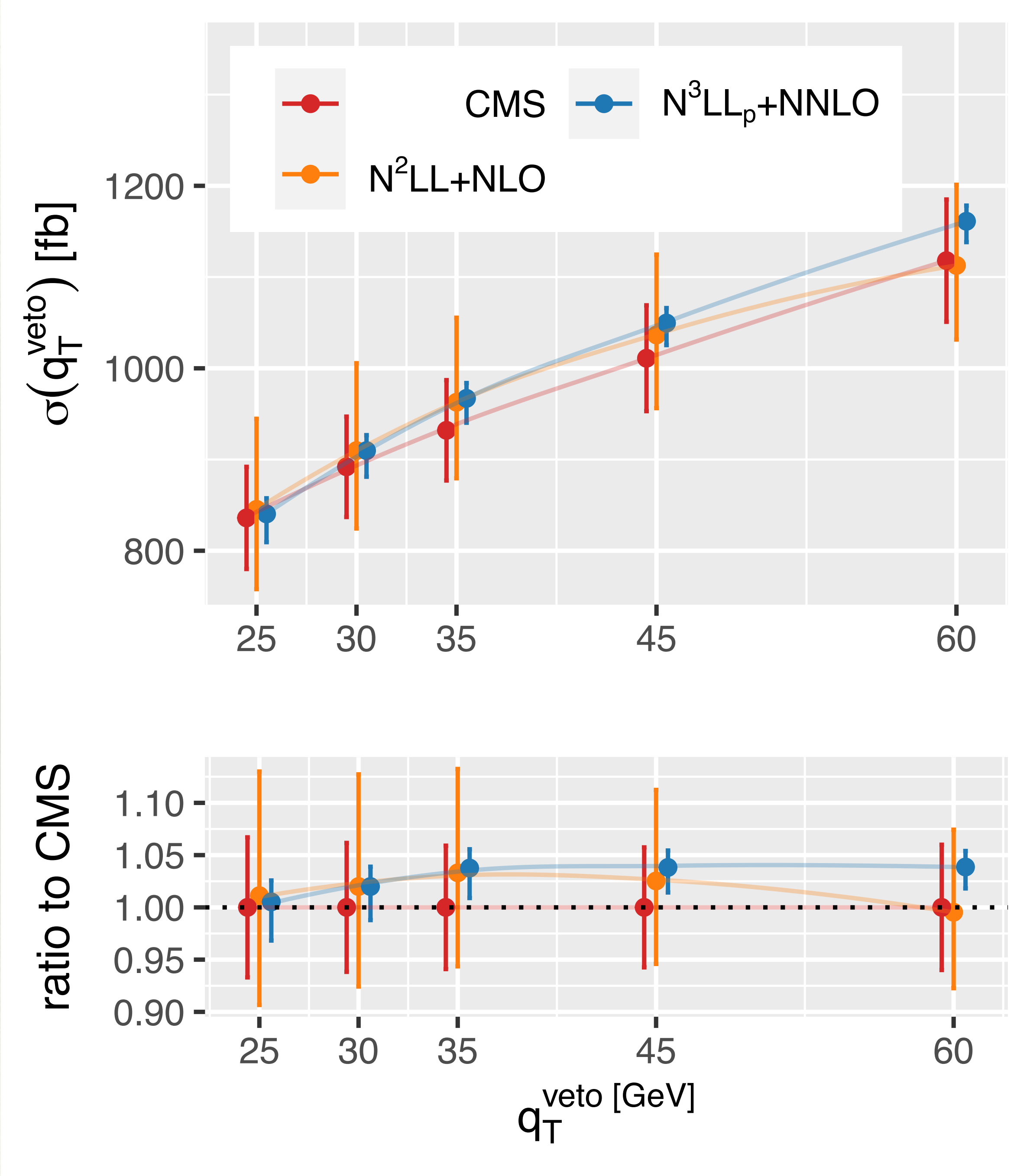




- The effect of matching is substantial; fixed order only appropriate at the highest values of p_T^{veto}.
- R_0 variation, which estimates the contribution of d_3^{veto}, contributes in a small way to total error budget.

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

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



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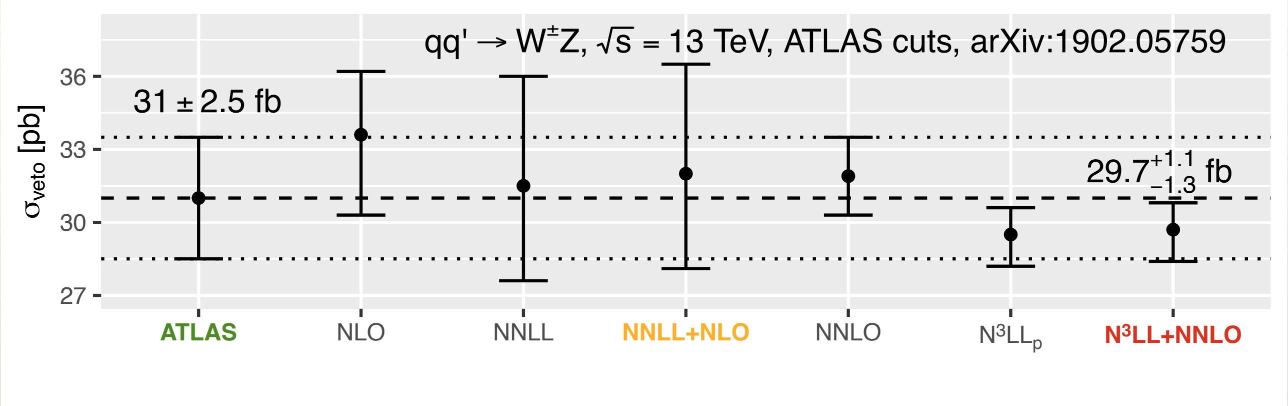
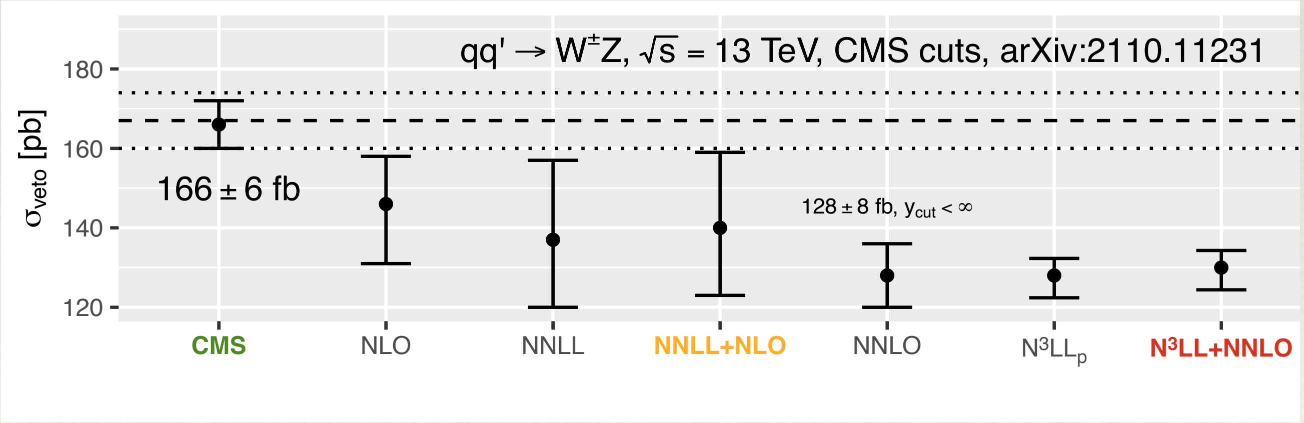
WZ production in ATLAS and CMS

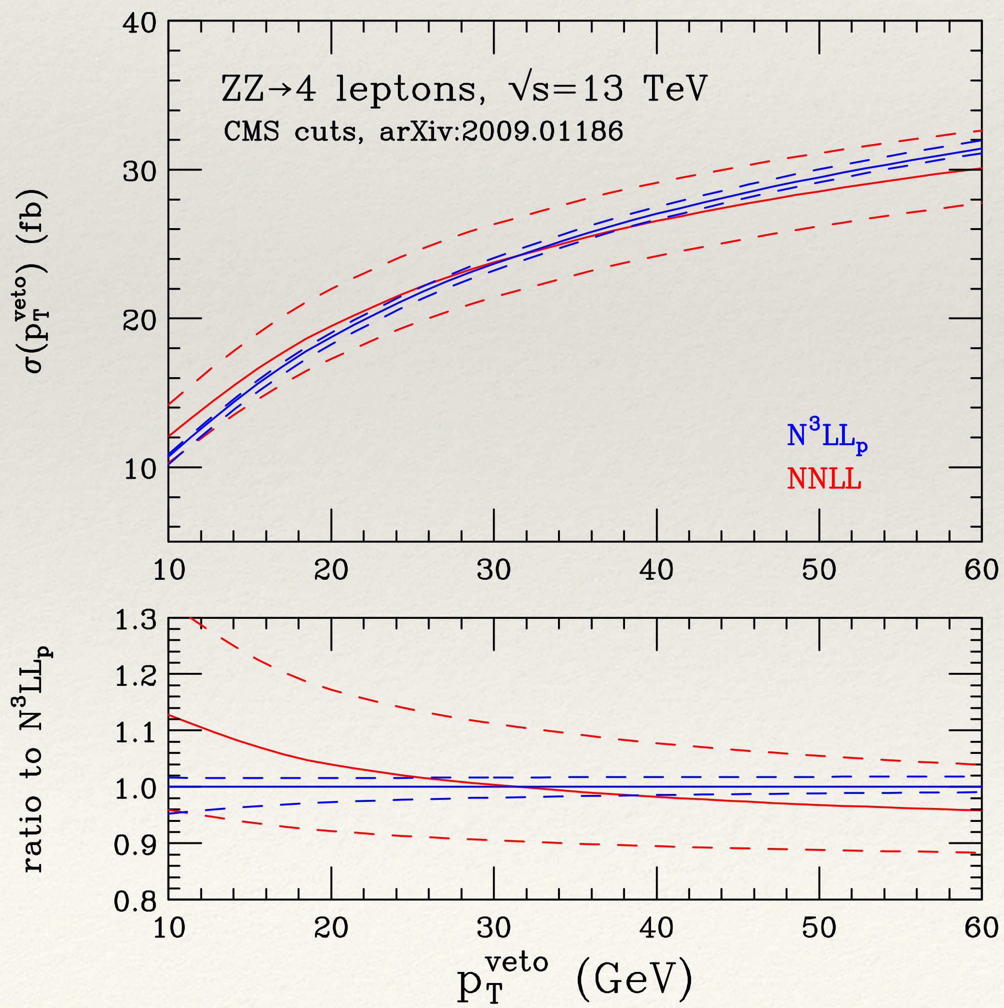
- ATLAS: 36 fb-1 ,p_T>25GeV, | y | <4.5, R=0.4.
- CMS: 137 fb-1,Neither NNLO nor N3LL+NNLO in good agreement.
- $\ln(Q/p_T^{veto})$=2.3 and y_{cut}=2.5, jet-veto resummation with veto over all rapidities may not be appropriate.
- The limited rapidity range requires a more sophisticated theoretical treatment.

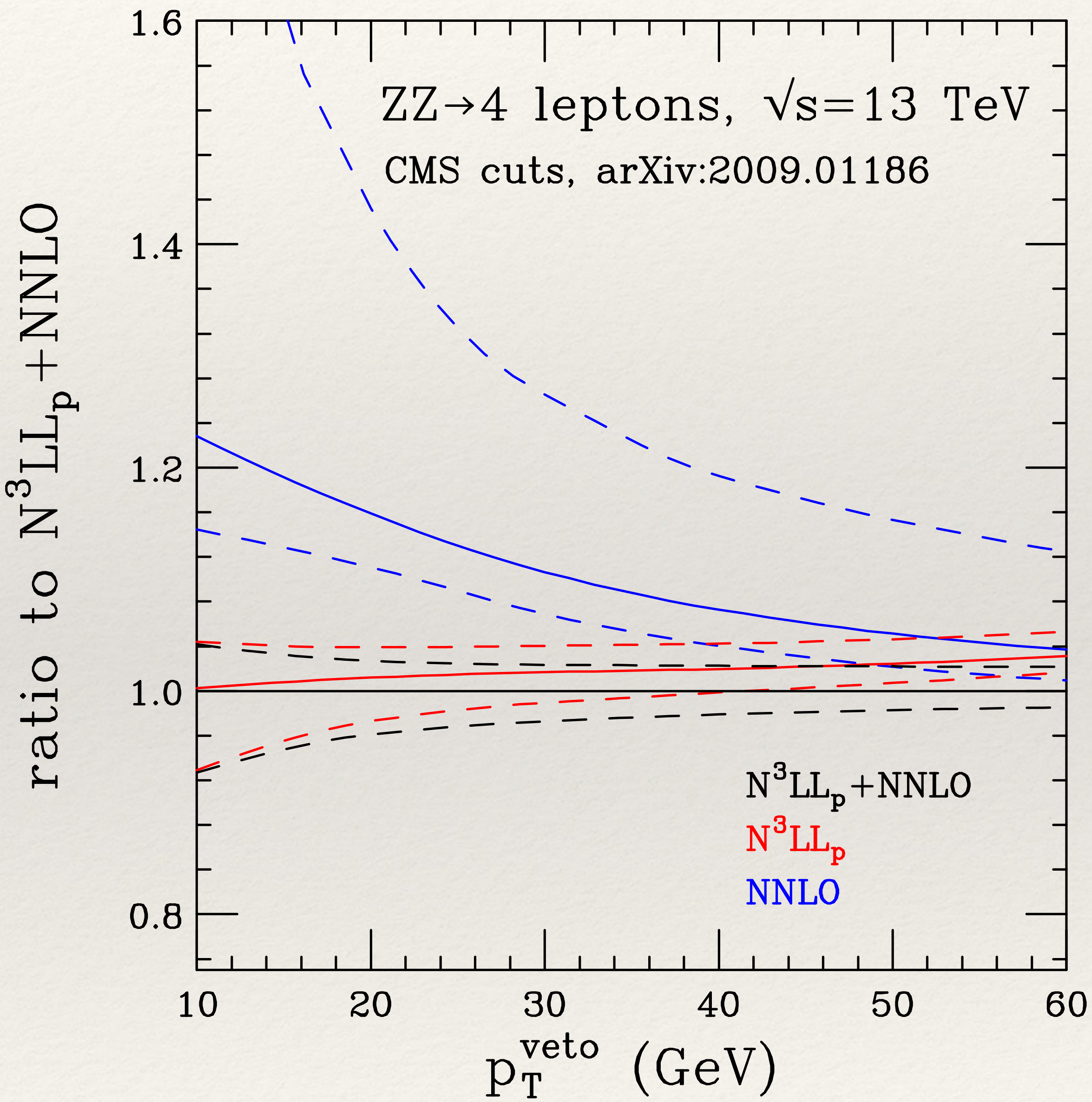




ZZ production

- 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^{veto}, over 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;
- Matching reduces the theoretical error (Higgs) and contributes significantly to full N^3LL_p +NNLO results(W^+W^-);
- 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

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