Recent developments in q_T subtraction

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Subtracting Infrared Singularities Beyond NLO

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Universität Zürich[UZH]

FNSNF SWISS NATIONAL SCIENCE FOUNDATION

Outline

- Introduction
- q_T subtraction
- The MATRIX project
- Most recent results: $pp \to HH+X$ at NNLO
- Beyond colour singlet: heavy-quark production
- Summary & Outlook

NNLO methods

Broadly speaking there are two approaches that we can follow:

- Organise the calculation from scratch so as to cancel all the singularities
  - sector decomposition — T. Binoth, G.Heinrich (2000,2004); C.Anastasiou, K.Melnikov, F.Petriello (2004)
  - antenna subtraction — A. & T. Gehrmann, N. Glover (2005)
  - "colourful" subtraction — G, Somogyi, Z. Trocsanyi, V. Del Duca (2005, 2007)
  - join subtraction and sector decomposition — M.Czakon (2010,2011); R.Boughezal, K.Melnikov, F.Petriello (2011); F.Caola, K.Melnikov, R.Rontsch (2017)
- Start from an inclusive NNLO calculation (sometimes obtained through resummation) and combine it with an NLO calculation for n+1 parton process
  - q_T subtraction — S.Catani, MG (2007)
  - "N-jettiness" method — R.Boughezal, C.Focke,X.Liu, F.Petriello (2015); F.Tackmann et al. (2015)
  - recently introduced "Born projection" method for VBF — M.Cacciari, F.Dreyer, A.Karlberg, G.Salam,G.Zanderighi (2015)

...and then we need the relevant two-loop amplitudes !

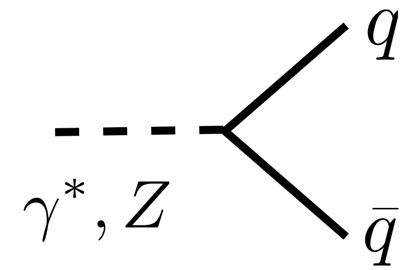
C.Anastasiou, F.Caola, M.Czakon, T.Gehrmann, N.Glover, M.Jaquier, A. Koukoutsakis
C.Oleari, K.Melnikov, L.Tancredi, M.E. Tejeda-Yeomans, A. von Manteuffel and many others

Our method

S. Catani, MG (2007)

To make the discussion simpler, let us consider $e^+e^- \to 2$ jets as an example

→ Same LO topology after crossing



Consider the two-jet rate:

$$R^{LO}_{\text{2jets}} = 1$$

At LO all events are two-jet like

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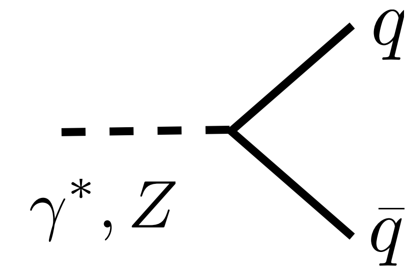

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$$R^{NLO}_{\rm 2jets} = 1 - R^{LO}_{3jets}$$

At NLO all events are two-jet like except those that contribute to the LO three-jet rate

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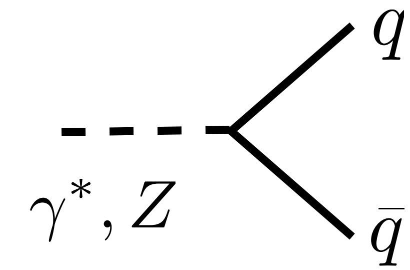

Consider the two-jet rate:

$$R_{2\mathrm{jets}}^{LO} = 1$$

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$$R_{2\mathrm{jets}}^{NNLO} = 1 - R_{3jets}^{NLO} - R_{4jets}^{LO}$$

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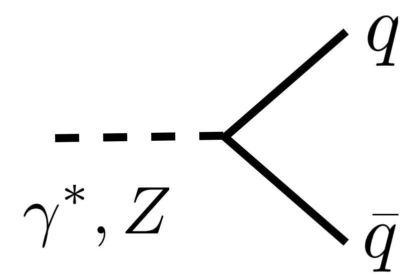

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At NNLO all events are two-jet like except those that contribute to the NLO three-jet rate and to the LO four jet rate

→ $R^{N^nLO}_{2\text{jets}}$ **can be obtained through a $N^{n-1}LO$ computation !**

See e.g. NNLO calculation of A_{FB}

S.Catani, M.H.Seymour (1999)

Can this idea be extended to hadron collisions ? It was !

Computation of Higgs cross section with a jet veto up to NNLO

S. Catani, D. de Florian, MG (2001)

Jet veto: cut on jets with $p_T > p_T^{\rm veto}$

$$\sigma_{\rm veto}^{LO} = \sigma_{\rm tot}^{LO}$$

$$\sigma_{\rm veto}^{NLO} = \sigma_{\rm tot}^{NLO} - \sigma_{p_T^{\rm jet} > p_T^{\rm veto}}^{LO}$$

$$\sigma_{\rm veto}^{NNLO} = \sigma_{\rm tot}^{NNLO} - \sigma_{p_T^{\rm jet} > p_T^{\rm veto}}^{NLO}$$

→ (N)NLO computation can be done by having the (N)NLO total cross section and the (N)LO cross section for H+jet

Does it work for general cuts ? Yes !

Example: $H \to \gamma\gamma$

$p_T^\gamma > 20\,{\rm GeV}$

$|y^\gamma| < 2.5\ {\rm GeV}$

$E_T^{R=0.3} < 6\,{\rm GeV}$

photon isolation

$$d\sigma^{NNLO} = d\sigma^{NNLO}_{\{p_T^\gamma > 20\,{\rm GeV},\,|y^\gamma|<2.5\}} - d\sigma^{NLO}_{\{p_T^\gamma > 20\,{\rm GeV},\,|y^\gamma|<2.5;\,E_T^{R=0.3}>6\,{\rm GeV}\}}$$

Inclusive cross section to be computed up to NNLO (no free lunch !)

H+jet cross section to be computed up to NLO

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Inclusive cross section to be computed up to NNLO (no free lunch !)

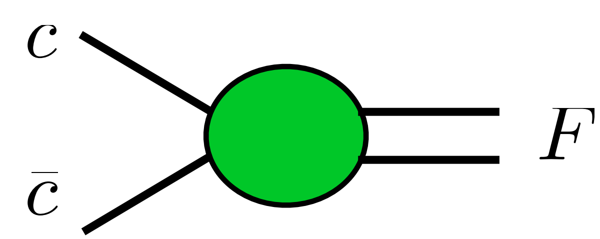
H+jet cross section to be computed up to NLO

The q_T subtraction method

S. Catani, MG (2007)

Let us consider a more general class of processes: the production of colourless high-mass systems F in hadron collisions (F may consist of lepton pairs, vector bosons, Higgs bosons......)

At LO it starts with $c\bar{c} \to F$



Strategy: start from NLO calculation of F+jet(s) and observe that as soon as the transverse momentum of the F $q_T \neq 0$ one can write:

$$d\sigma^{F}_{(N)NLO}|_{q_T \neq 0} = d\sigma^{F+\text{jets}}_{(N)LO}$$

Define a counterterm to deal with singular behaviour at $q_T \to 0$

But.....
the singular behaviour of $d\sigma^{F+\text{jets}}_{(N)LO}$ is well known from the resummation program of large logarithmic contributions at small transverse momenta

G. Parisi, R. Petronzio (1979)
J. Collins, D.E. Soper, G. Sterman (1985)
S. Catani, D. de Florian, MG (2000)

choose $d\sigma^{CT} \sim d\sigma^{(LO)} \otimes \Sigma^F(q_T/Q)$

where $\Sigma^F(q_T/Q) \sim \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1} \frac{Q^2}{q_T^2}$

Then the calculation can be extended to include the $q_T = 0$ contribution:

$$d\sigma^F_{(N)NLO} = \mathcal{H}^F_{(N)NLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$

where I have subtracted the truncation of the counterterm at (N)LO and added a contribution at $q_T = 0$ to restore the correct normalization

The function $\mathcal{H}^F$ can be computed in QCD perturbation theory

$$\mathcal{H}^F = 1 + \left(\frac{\alpha_S}{\pi}\right) \mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)} + \ldots\ldots.$$

Let's focus on Higgs production (F=H)

The function $\mathcal{H}^H$ can be computed in QCD perturbation theory as follows

$$\mathcal{H}^H = 1 + \left(\frac{\alpha_S}{\pi}\right)\mathcal{H}^{H(1)} + \left(\frac{\alpha_S}{\pi}\right)^2\mathcal{H}^{H(2)} + ...$$

S. Catani, MG (2011)

consider integral of q_T distribution up to an arbitrary small Q_0

$$\int_0^{Q_0^2} dq_T^2 \frac{d\hat{\sigma}_{H\,ab}}{dq_T^2}(q_T, M, \hat{s} = M^2/z) \equiv z\sigma_H^{(0)} \hat{R}^H_{ggab}(z, M/Q_0)$$

Up to $\mathcal{O}(\alpha_S^2)$ the coefficients of the logarithmic expansion in $l_0 = \ln M_H^2/Q_0^2$ are all known

D. de Florian, MG (2000)

$$\hat{R}^{(1)}_{gg\leftarrow ab}(z, M/Q_0) = l_0^2\, \Sigma^{H(1;2)}_{gg\leftarrow ab}(z) + l_0\, \Sigma^{H(1;1)}_{gg\leftarrow ab}(z) + \mathcal{H}^{H(1)}_{gg\leftarrow ab}(z) + \mathcal{O}(Q_0^2/M^2)$$

$$\hat{R}^{(2)}_{gg\leftarrow ab}(z, M/Q_0) = l_0^4\, \Sigma^{H(2;4)}_{gg\leftarrow ab}(z) + l_0^3\, \Sigma^{H(2;3)}_{gg\leftarrow ab}(z) + l_0^2\, \Sigma^{H(2;2)}_{gg\leftarrow ab}(z)$$
$$+ l_0 \left(\Sigma^{H(2;1)}_{ggab}(z) - 16\zeta_3 \Sigma^{H(2;4)}_{ggab}(z)\right) + \left(\mathcal{H}^{H(2)}_{ggab}(z) - 4\zeta_3\, \Sigma^{H(2;3)}_{ggab}(z)\right) + \mathcal{O}(Q_0^2/M^2)$$

The only missing one is $\mathcal{H}^{H(2)}_{gg\leftarrow ab}(z)$

Total cross section q_T distribution

solve this equation to obtain the $\mathcal{H}^{H(2)}_{gg\leftarrow ab}(z)$

$$\int_0^{Q_0^2} dq_T^2 \frac{d\hat{\sigma}_{H\,ab}}{dq_T^2}(q_T, M; z) = \hat{\sigma}^H_{ab}(z) - \int_{Q_0^2}^{\infty} dq_T^2 \frac{d\hat{\sigma}_{H\,ab}}{dq_T^2}(q_T, M; z)$$

Use available analytical NLO results

C.Glosser, C.Schmidt (2003)

For a generic $pp \to F + X$ process:

- At NLO we need a LO calculation of $d\sigma^{F+\mathrm{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{LO}$ and $\mathcal{H}^{F(1)}$

  - the counterterm $d\sigma^{CT}_{LO}$ requires the resummation coefficients $A^{(1)}, B^{(1)}$ and the one loop anomalous dimensions

  - the general form of $\mathcal{H}^{F(1)}$ is known

D. de Florian, MG (2000)
G. Bozzi, S. Catani, D. de Florian, MG (2005)

- At NNLO we need a NLO calculation of $d\sigma^{F+\mathrm{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{NLO}$ and $\mathcal{H}^{F(2)}$

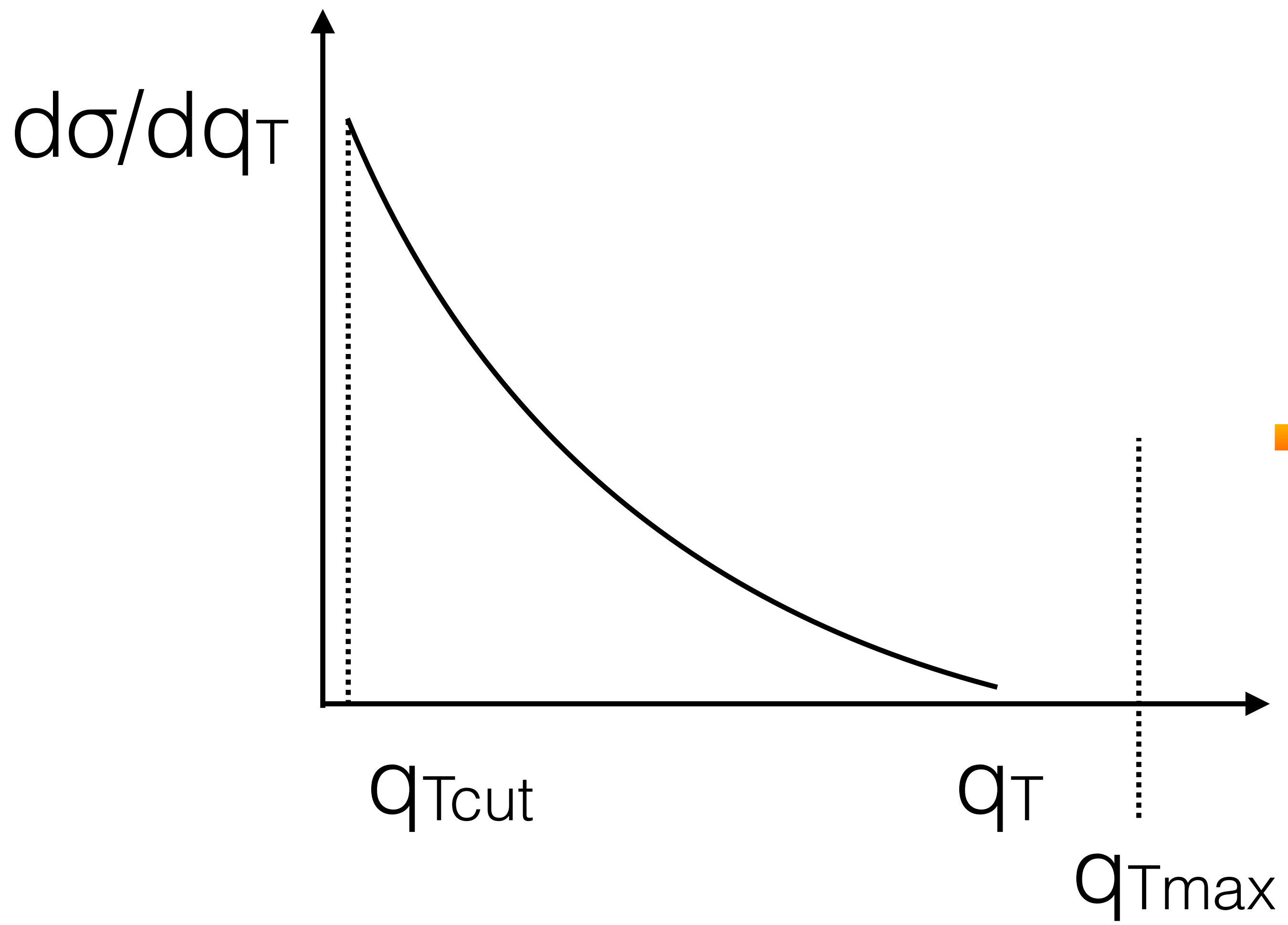
  - the counterterm $d\sigma^{CT}_{NLO}$ depends also on the resummation coefficients $A^{(2)}, B^{(2)}$ and on the two loop anomalous dimensions

  - we have computed $\mathcal{H}^{F(2)}$ for Higgs and vector boson production !

S. Catani, MG (2007)
S. Catani, L. Cieri, G.Ferrera, D. de Florian, MG (2009)

→ **this is enough to compute NNLO corrections for *any* process in this class provided F+jet is known up NLO and the two loop amplitude for $c\bar{c} \to F$ is known**

Subtraction or slicing ?



Slicing: integrate $d\sigma_{CT}$ from q_{Tcut} to ∞ (unitarity) (e.g. MATRIX)

→ Logarithmic terms in q_{Tcut}/Q that cancel those coming from the integral of the F+jet contribution

(Non-local) subtraction: map an event in the real contribution to a counter event at q_T=0

(e.g. first versions of DYNNLO and HNNLO)

But: the counter term is integrated only up to the kinematical boundary q_{Tmax} (practically irrelevant at the LHC but relevant for VH at the Tevatron !)

q_T subtraction vs Born projection

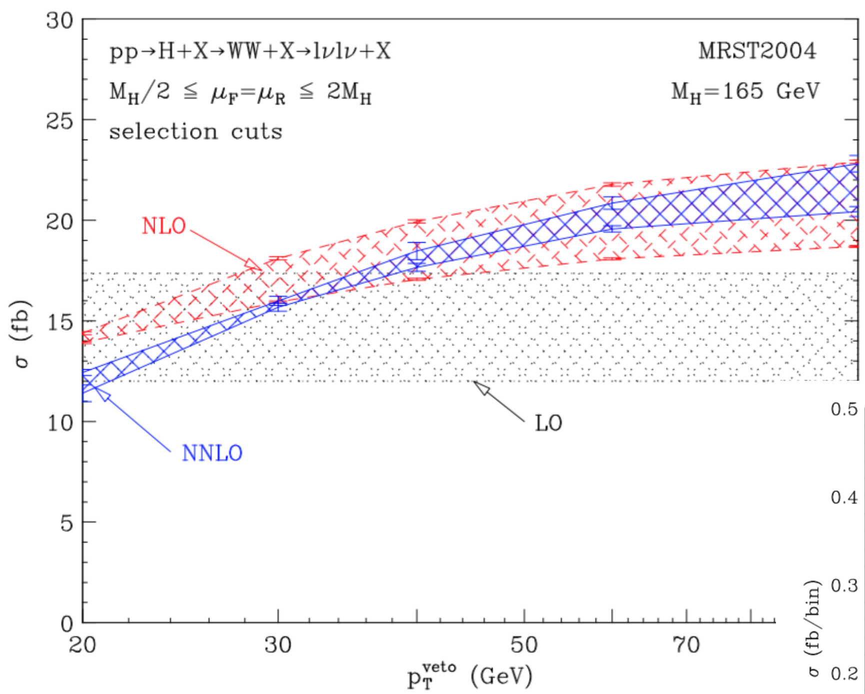
Suppose we have only one variable q_T (neglect rapidity.....)

$$d\sigma \sim H\delta(q_T) + \left(d\sigma^R - d\sigma^{CT}\right)$$ q_T subtraction

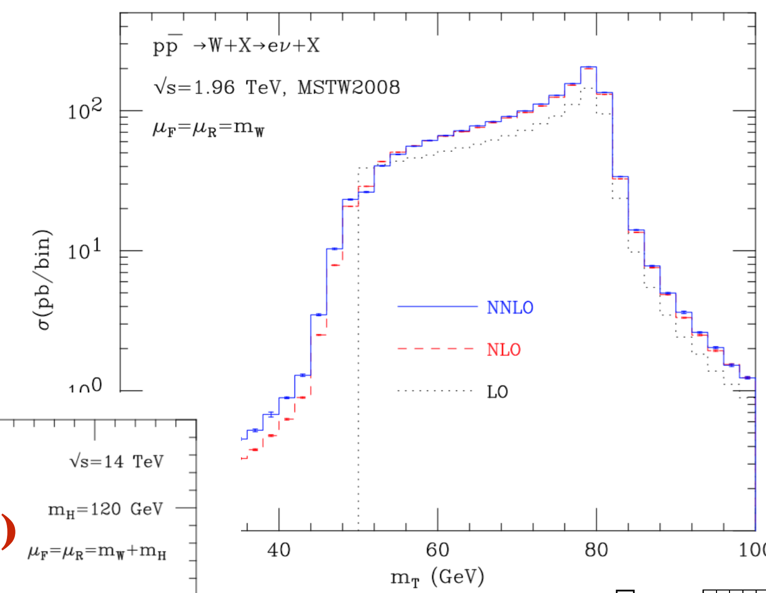
$$d\sigma \sim \sigma_{\rm tot}\delta(q_T) + \left(d\sigma^R\right)_+$$ Born projection

Available implementations

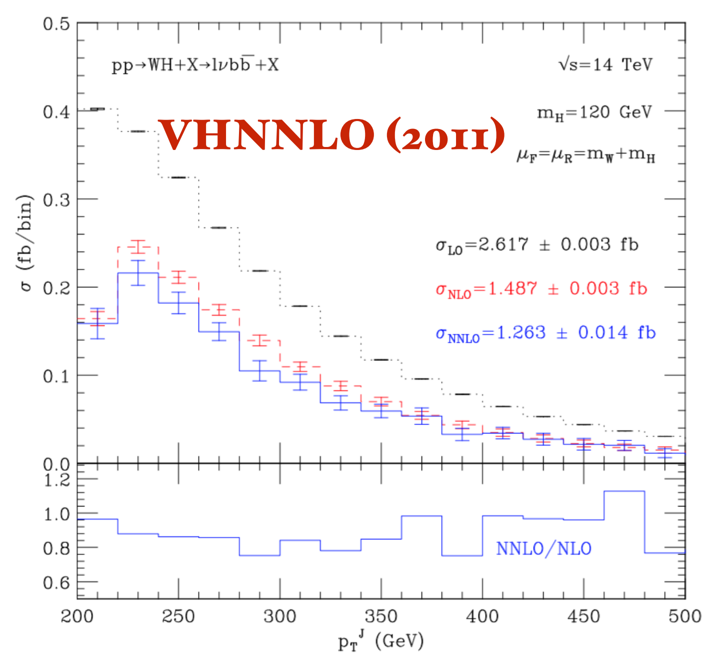
HNNLO (2008)



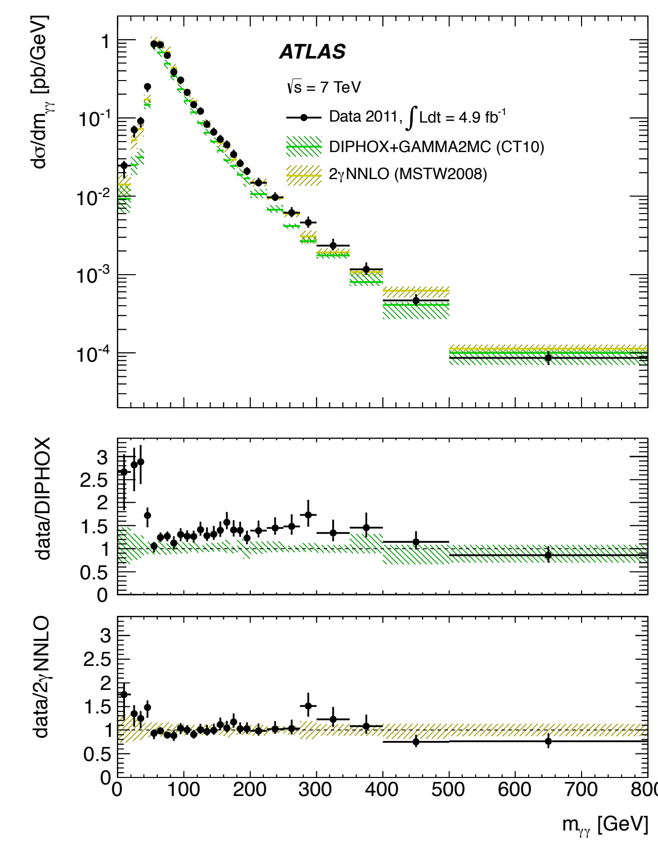
DYNNLO (2009)



VHNNLO (2011)



2γNNLO (2011)

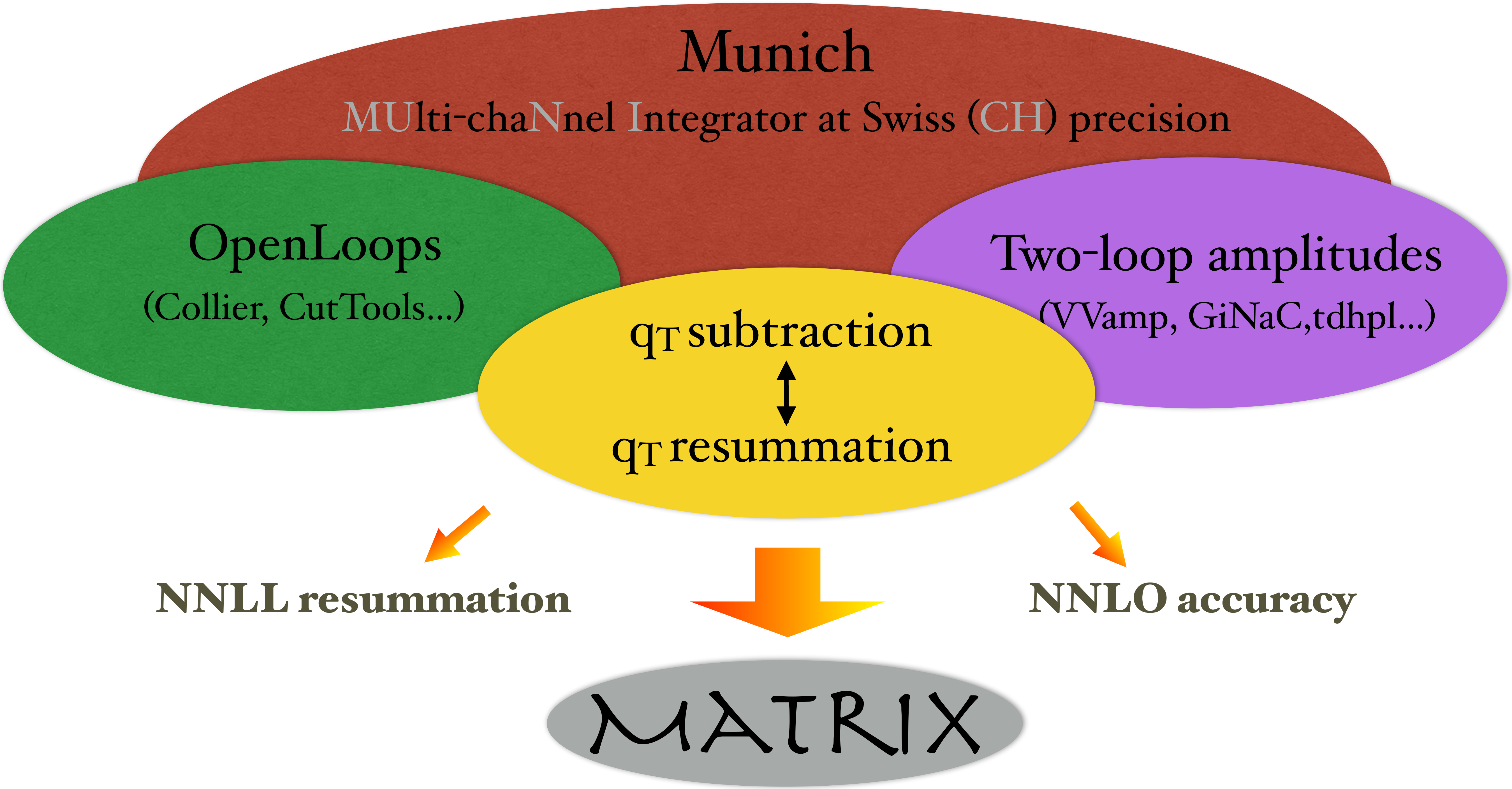


Up to now building up NNLO codes has been a craftsman work !

Generality of the method suggests that a single implementation in a general purpose program could be more efficient

The MATRIX project

S.Kallweit, D.Rathlev, M.Wiesemann, MG + (H.Sargsyan, J.Mazzitelli.....)



Munich Automates qT subtraction and Resummation to Integrate X--sections

Status

- $pp \to Z/\gamma^*$ $(\to l^+l^-)$ ✅
- $pp \to W(\to l\nu)$ ✅
- $pp \to H$ ✅
- $pp \to \gamma\gamma$ ✅
- $pp \to W\gamma \to l\nu\gamma$ ✅
- $pp \to Z\gamma \to l^+l^-\gamma$ ✅
- $pp \to ZZ(\to 4l)$ ✅
- $pp \to WW \to (l\nu l'\nu')$ ✅
- $pp \to ZZ/WW \to ll\nu\nu$ ✅
- $pp \to WZ \to l\nu ll$ ✅
- $pp \to HH$ (✅) not in public release

First public release out in November 2017

S.Kallweit, M.Wiesemann, MG (2017)

Stability of the subtraction procedure

$$d\sigma^{F}_{(N)NLO} = \mathcal{H}^{F}_{(N)NLO} \otimes d\sigma^{F}_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$

The q_T subtraction counterterm is non-local → the difference in the square bracket is evaluated with a cut-off r_{cut} on the ratio $r = q_T/Q$

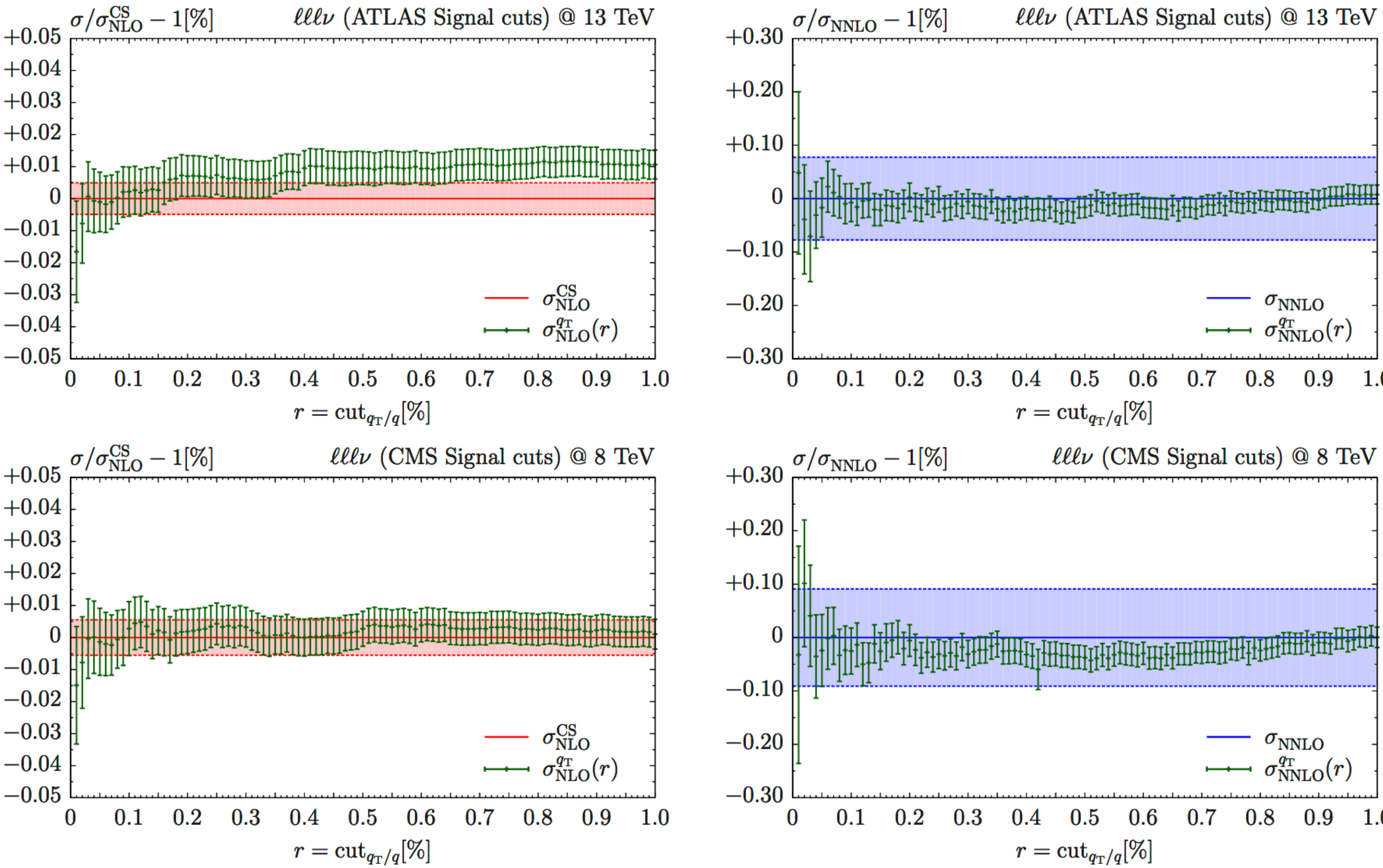
In MATRIX q_T subtraction indeed works as a slicing method

It is important to monitor the dependence of our results on r_{cut}

MATRIX allows for a simultaneous evaluation of the NNLO cross section for different values of r_{cut}

The dependence on r_{cut} is used by the code to provide an estimate of the systematic uncertainty in any NNLO run

Stability: the easy case



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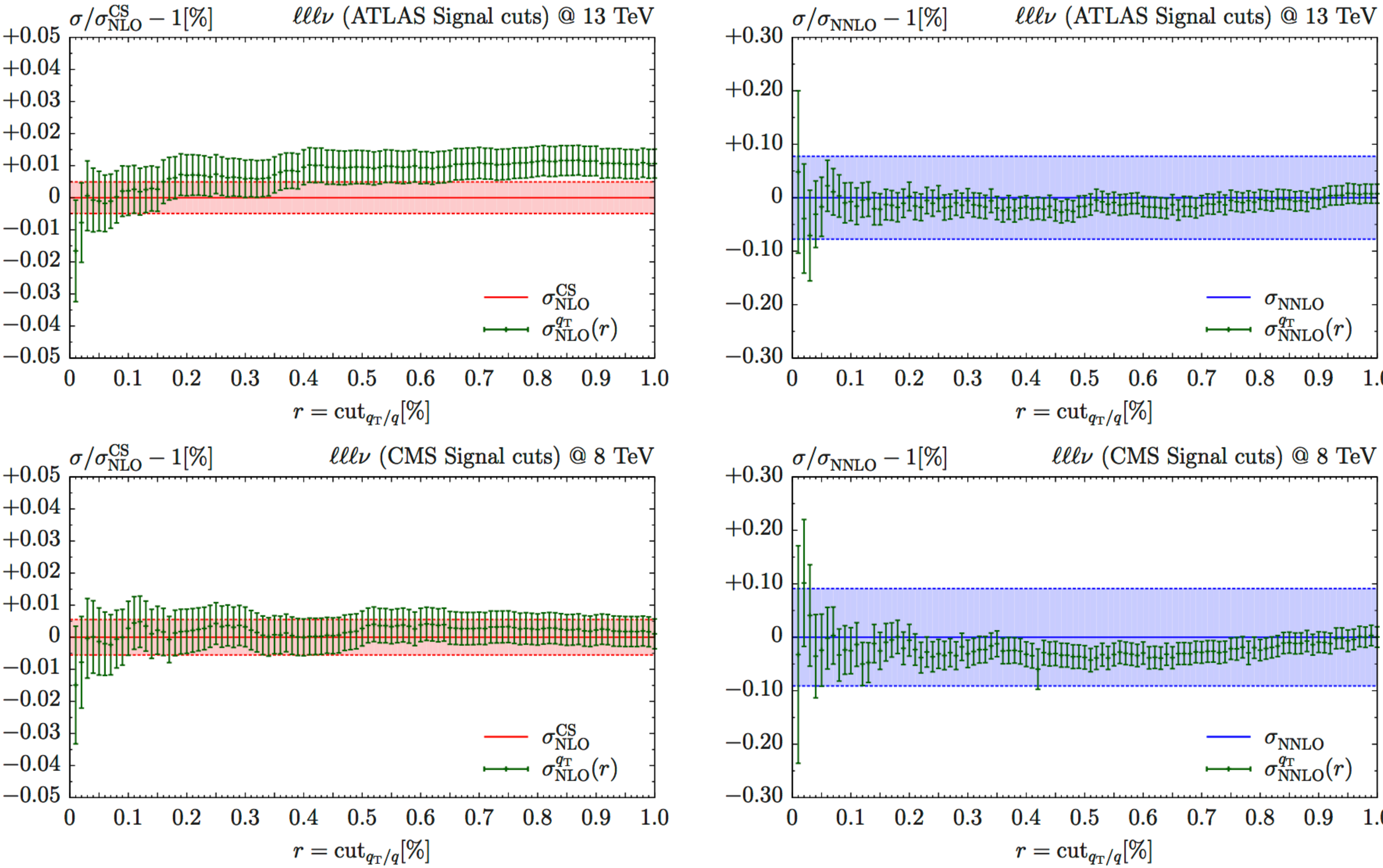


...but life is not always so easy !

The extraplation

We introduce an automatic extrapolation procedure to obtain the best result for the NNLO cross section with a solid estimate of its systematic uncertainty

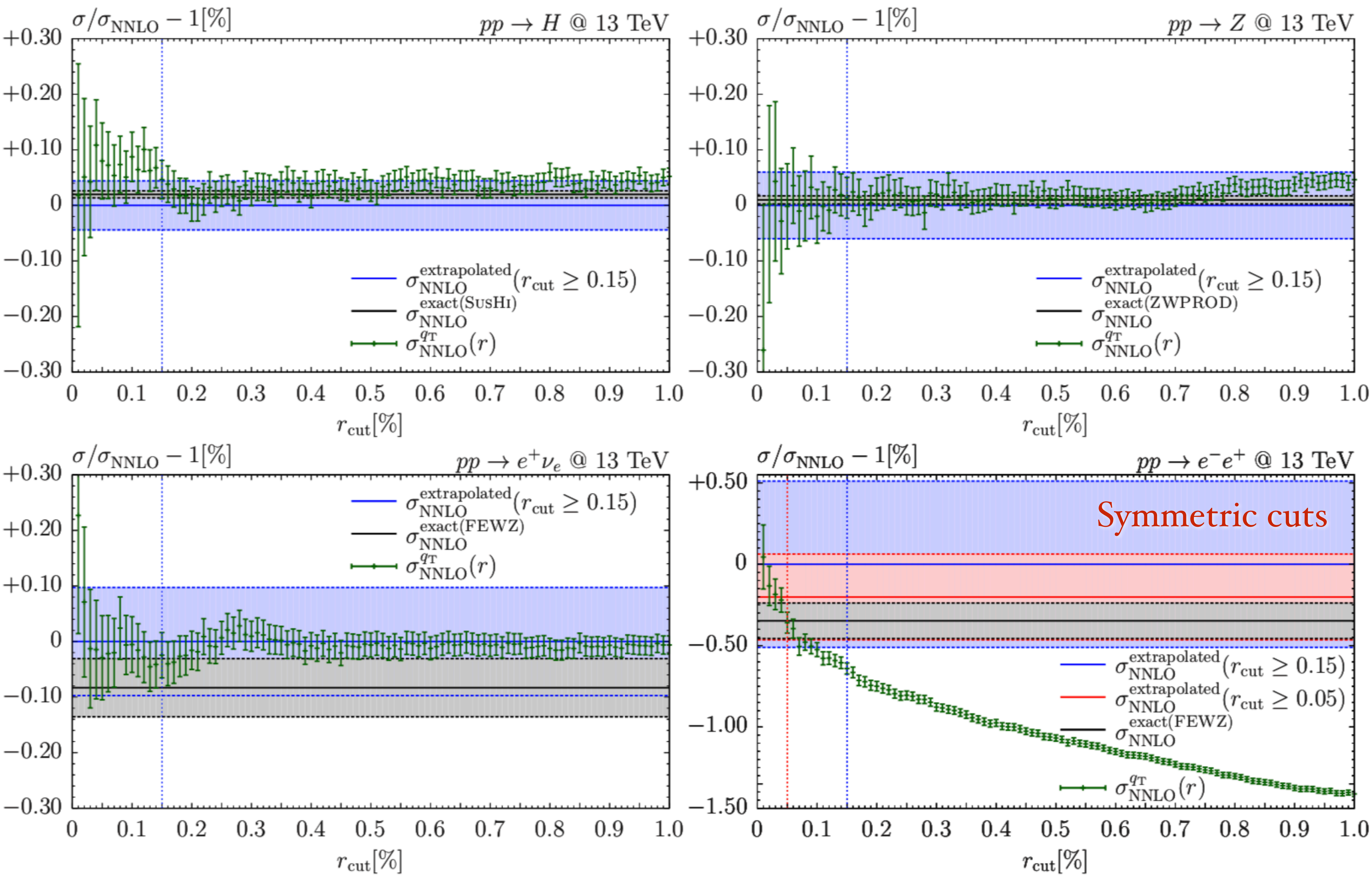
We use a simple quadratic least χ^2 fit

Two options: start from a minimum r_{cut}=0.15% (default) and from r_{cut}=0.05%

Repeat the fit by varying the upper limit of r_{cut} and assign an uncertainty by comparing the difference between the results

Introduce a lower limit to the uncertainty as half of the difference between the best fit and the cross section evaluated at the minimum r_{cut}=0.15% (0.05%)

Stability plots



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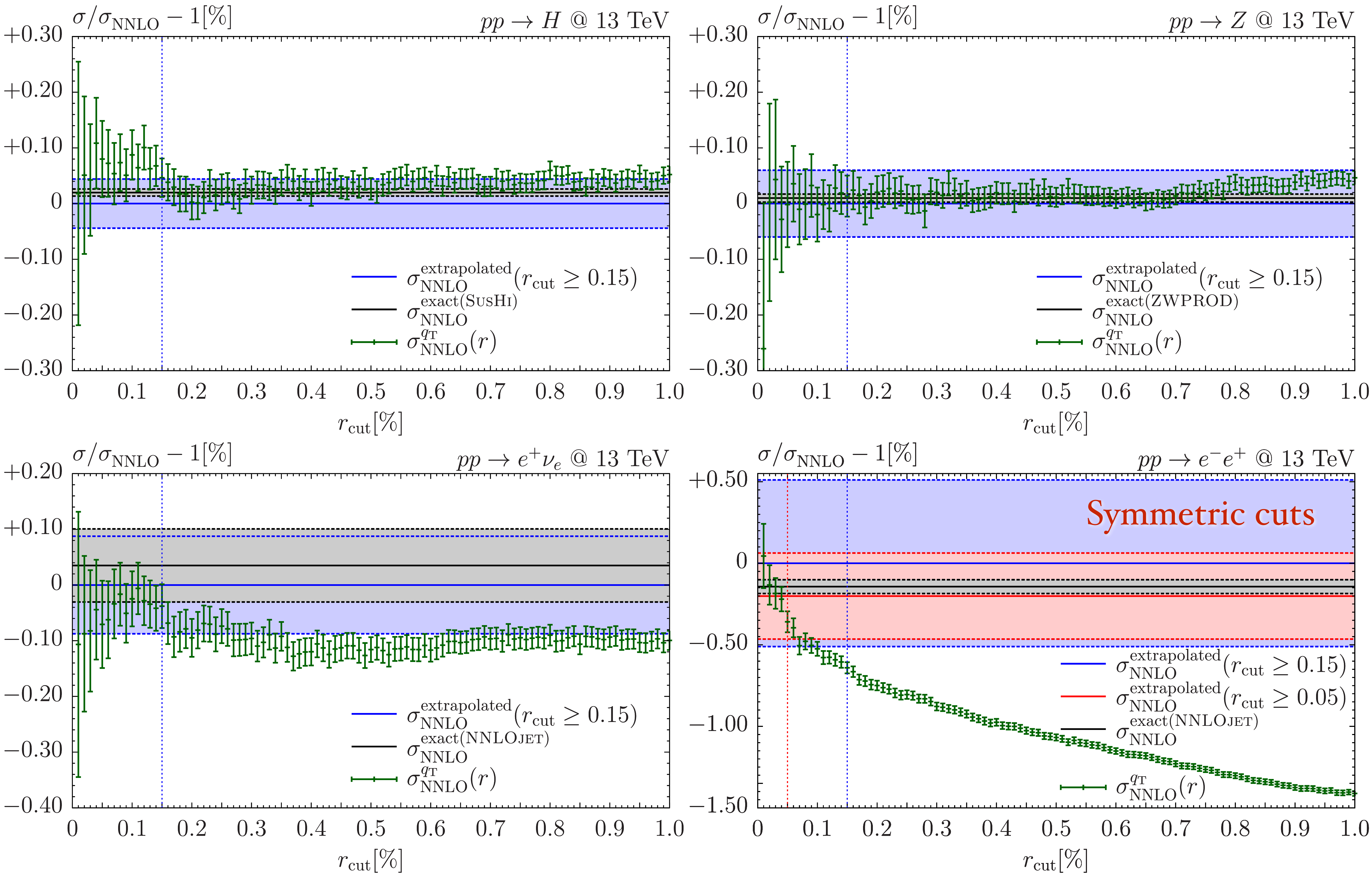

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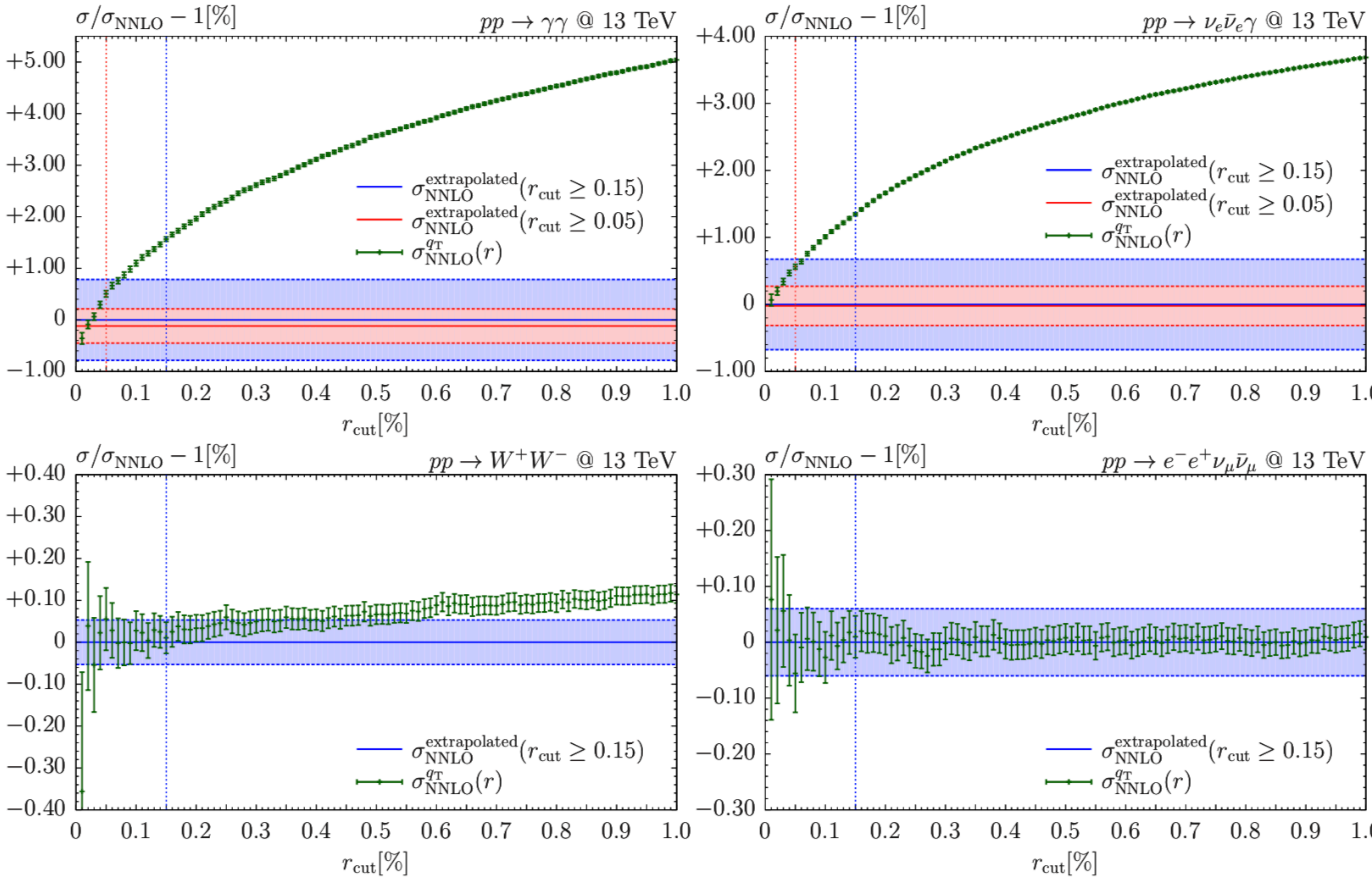
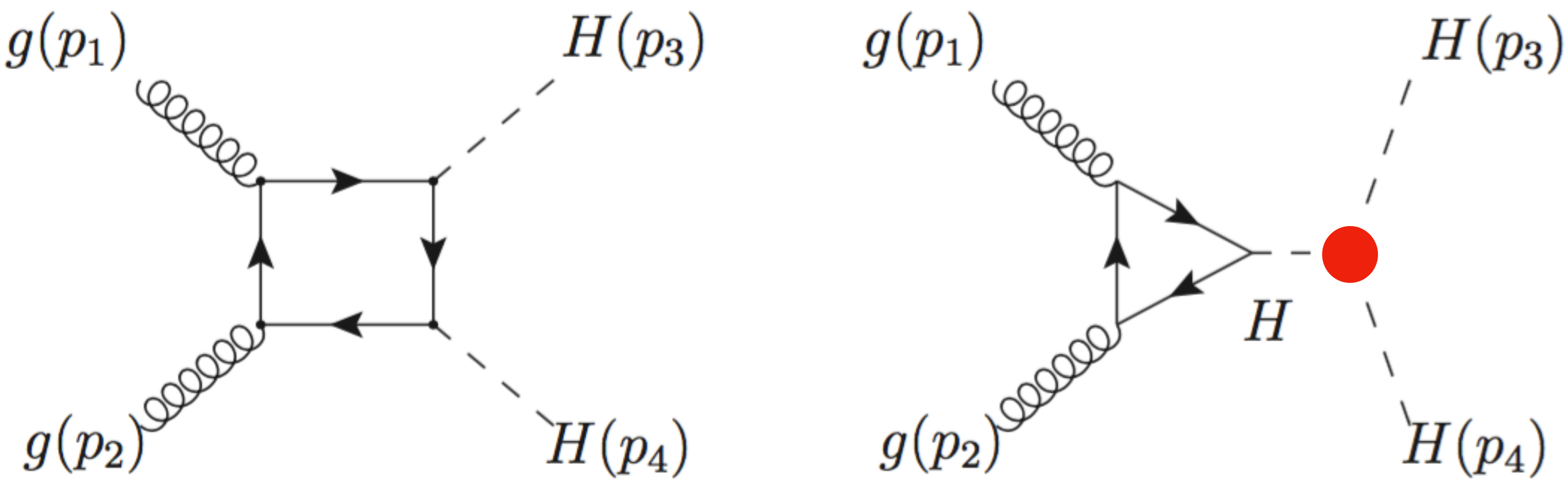


Most recent results: HH

HH



Large cancellations and small available phase space makes rate very small

It is the process that gives direct access to the Higgs self coupling λ

Up to very recently QCD corrections at NLO and NNLO known only in the large-m_{top} approximation

S.Dawson,S.Dittmaier,M.Spira (1998)
D. de Florian, J.Mazzitelli (2013)

NNLL resummation available

D. de Florian, J.Mazzitelli (2015)

Main issue: large-m_{top} approximation known not to work so well

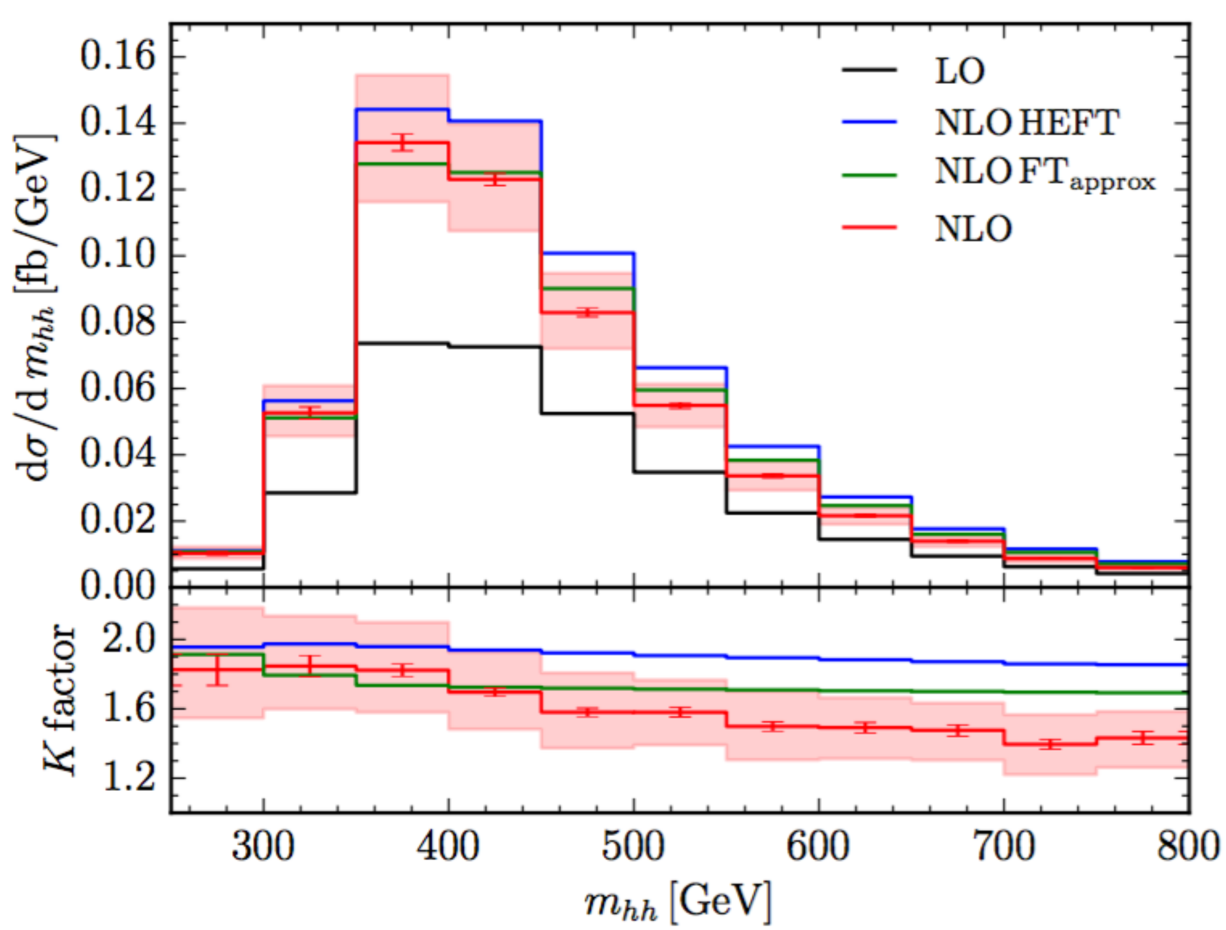
J.Grigo et al. (2013)

HH

Recent breakthrough: exact NLO calculation completed

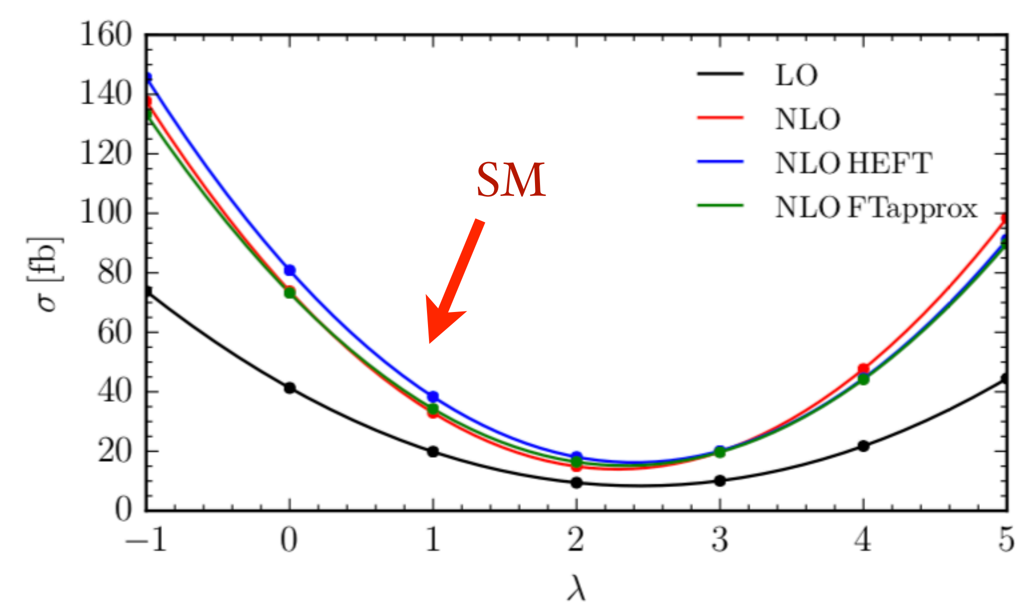
S.Borowka et al (2016)

Multi scale two-loop integrals evaluated numerically



Accurate predictions must account for exact NLO

Promising for other important multi scale NLO calculations



HH

G.Heinrich, S.Jones, S.Kallweit, M.Kerner, J.Lindert,MG (2018)

Approximate NNLO calculation recently presented combining the most advanced perturbative information available at present

NNLO$_{\text{FTapprox}}$ Combine exact double real emission amplitudes with suitably reweighted single real and double virtual contributions

- Start from exact NLO

- At NNLO:

  - use exact double-real one loop amplitudes

  - use real-virtual and double virtual HEFT amplitudes reweighed with

$$\mathcal{R}(ij \to HH + X) = \frac{\mathcal{A}^{\text{Born}}_{\text{Full}}(ij \to HH + X)}{\mathcal{A}^{(0)}_{\text{HEFT}}(ij \to HH + X)}$$

HH

G.Heinrich, S.Jones, S.Kallweit, M.Kerner, J.Lindert,MG (2018)

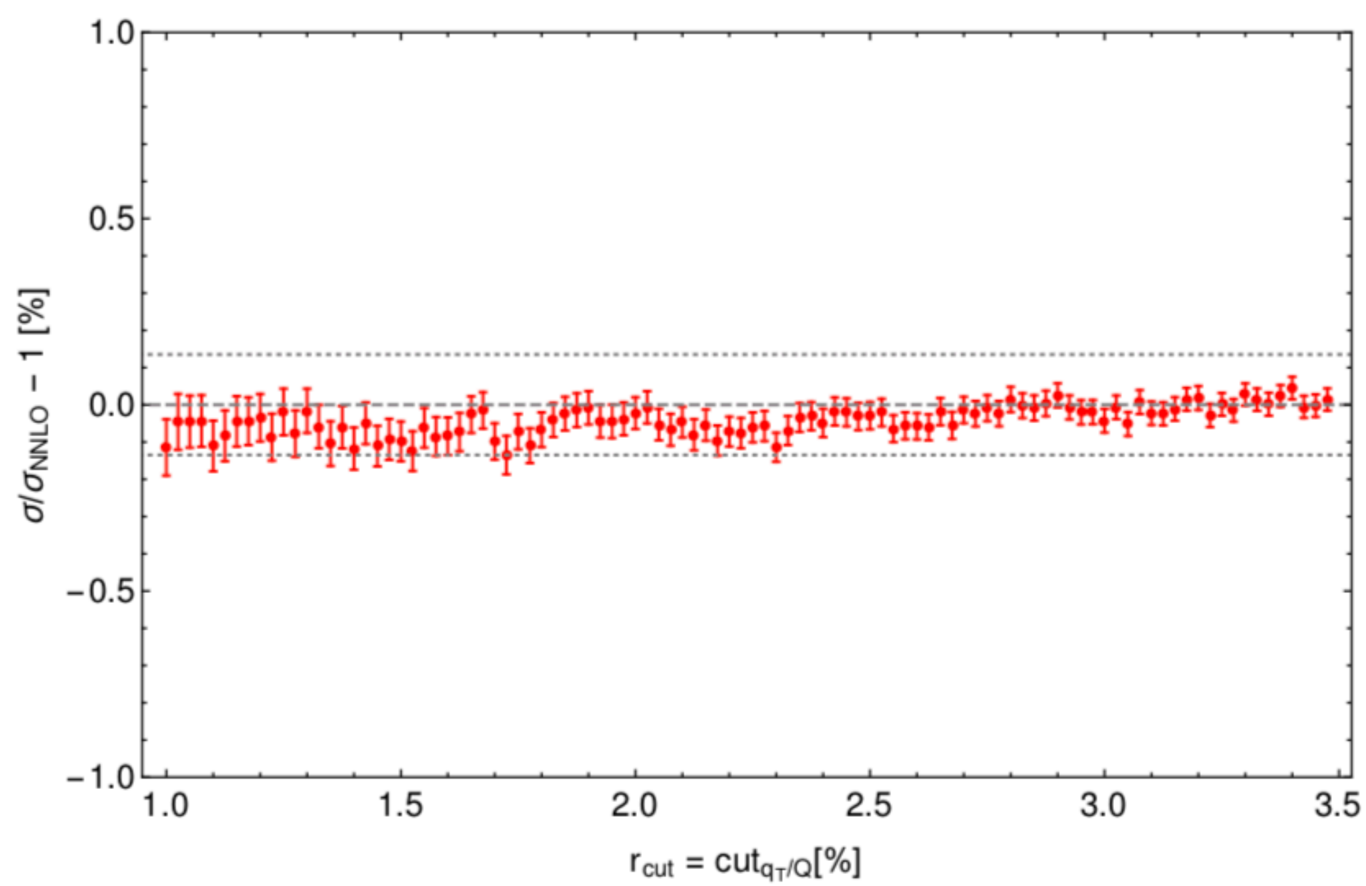
Numerical stability: the double real contribution requires $gg \to HHgg$ six point integrals to be evaluated in the unresolved region

Quadrupole precision prohibitive (10s/phase space point)

➡ Switch to (reweighted) HEFT amplitudes below a given α_{cut}

Set $\alpha_{cut}=10^{-4}$ but check the independence of the results by varying α_{cut} 10^{-3} and 10^{-5}

r_{cut} stability at the few per mille level



HH

G.Heinrich, S.Jones, S.Kallweit, M.Kerner, J.Lindert,MG (2018)

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
$\text{NLO}_{\text{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
$\text{NNLO}_{\text{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$	$1337^{+4.1\%}_{-5.4\%}$
$\text{NNLO}_{\text{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$154.2^{+0.7\%}_{-3.8\%}$	$1406^{+0.5\%}_{-2.8\%}$
$\text{NNLO}_{\text{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$
M_t unc. $\text{NNLO}_{\text{FTapprox}}$	$\pm 2.6\%$	$\pm 2.7\%$	$\pm 3.4\%$	$\pm 4.6\%$
$\text{NNLO}_{\text{FTapprox}}/\text{NLO}$	1.118	1.116	1.096	1.067

Uncertainty from finite m_{top} effects down to the few percent level

Beyond colour singlets

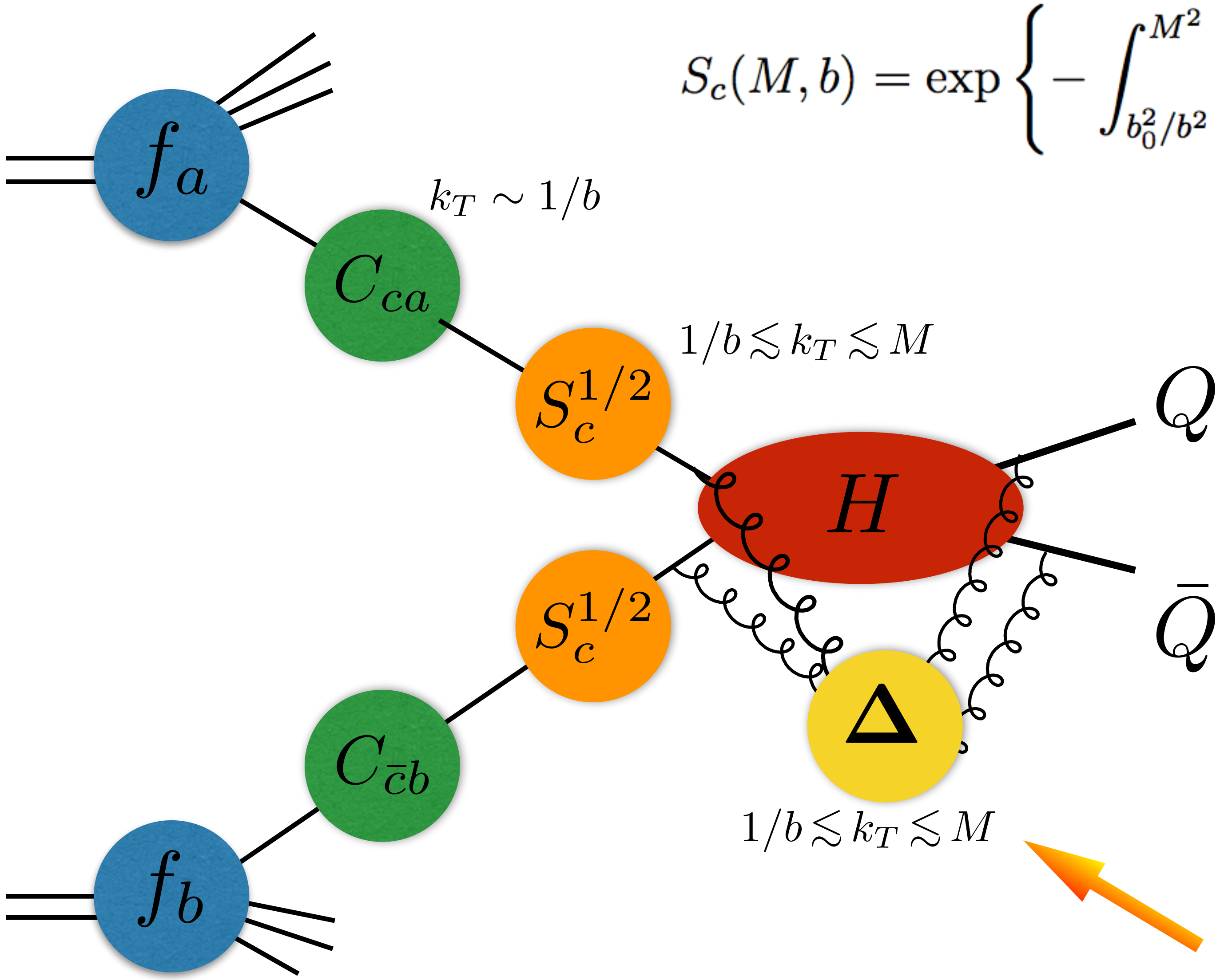
The case of heavy-quark production

S.Catani, A.Torre, MG (2014)

$$\frac{d\sigma^{(\mathrm{sing})}(P_1,P_2;\mathbf{q_T},M,y,\mathbf{\Omega})}{d^2\mathbf{q_T}\;dM^2\;dy\;d\mathbf{\Omega}} = \frac{M^2}{2P_1\cdot P_2}\sum_{c=q,\bar{q},g}\left[d\sigma^{(0)}_{c\bar{c}}\right]\int\frac{d^2\mathbf{b}}{(2\pi)^2}\;e^{i\mathbf{b}\cdot\mathbf{q_T}}\;S_c(M,b)$$

$$\times\sum_{a_1,a_2}\int_{x_1}^{1}\frac{dz_1}{z_1}\int_{x_2}^{1}\frac{dz_2}{z_2}\left[(\mathbf{H}\,\mathbf{\Delta})\,C_1C_2\right]_{c\bar{c};a_1a_2}\;f_{a_1/h_1}(x_1/z_1,b_0^2/b^2)\;f_{a_2/h_2}(x_2/z_2,b_0^2/b^2)$$

$$S_c(M,b)=\exp\left\{-\int_{b_0^2/b^2}^{M^2}\frac{dq^2}{q^2}\left[A_c(\alpha_S(q^2))\;\ln\frac{M^2}{q^2}+B_c(\alpha_S(q^2))\right]\right\}$$



C coefficients embody collinear radiation at scale 1/b

S_c embodies soft and flavour conserving collinear radiation in the region $1/b < k_T < M$

H^F includes hard radiation at scales $k_T \sim M$

Additional radiative factor of purely soft origin (starts to contribute at NLL)

The case of heavy-quark production

S.Catani, A.Torre, MG (2014)

$$(\mathbf{H}\,\mathbf{\Delta})_{c\bar{c}} = \frac{\langle\, \widetilde{\mathcal{M}}_{c\bar{c}\to Q\bar{Q}} \,|\, \mathbf{\Delta} \,|\, \widetilde{\mathcal{M}}_{c\bar{c}\to Q\bar{Q}} \,\rangle}{\alpha_S^2(M^2)\ |\mathcal{M}^{(0)}_{c\bar{c}\to Q\bar{Q}}(p_1, p_2; p_3, p_4)|^2}$$

$|\, \widetilde{\mathcal{M}}_{c\bar{c}\to Q\bar{Q}} \,\rangle$ subtracted virtual amplitude

$$\mathbf{\Delta}(\mathbf{b}, M; y_{34}, \phi_3) = \mathbf{V}^\dagger(b, M; y_{34})\ \ \mathbf{D}(\alpha_S(b_0^2/b^2); \phi_{3b}, y_{34})\ \mathbf{V}(b, M; y_{34})$$

$$\mathbf{V}(b, M; y_{34}) = \overline{P}_q\ \exp\left\{ -\int_{b_0^2/b^2}^{M^2} \frac{dq^2}{q^2}\, \mathbf{\Gamma}_t(\alpha_S(q^2); y_{34}) \right\}$$

$\alpha_S^n L^m$ terms $\quad n \geq m$

soft anomalous dimension

$\mathbf{\Gamma}_t^{(1)}$ and $\mathbf{\Gamma}_t^{(2)}$ directly related to singular structure of $|\mathcal{M}_{c\bar{c}\to Q\bar{Q}}\rangle$

M.Neubert et al. (2009)

$\mathbf{D}(\alpha_S; \phi_{3b}, y_{34})$ embodies azimuthal correlations at scale 1/b

$$\langle\, \mathbf{D}(\alpha_S; \phi_{3b}, y_{34})\rangle_{\text{av.}} = 1$$

Beyond colour singlets: top-quark production

R.Bonciani, S.Catani, H.Sargsyan and A.Torre , MG (2015)

The q_T subtraction method can be extended to heavy-quark production

We have used this method to compute ttbar production at NLO and to include all the off-diagonal partonic channels at NNLO

σ(pb)	NLO	$O(\alpha_S^4)_{qg}$	$O(\alpha_S^4)_{qq+qq'}$
q_T subtraction	226.2(1)	-2.25(5)	1.51(3)
Top++	226.3	-2.253	1.48

pp, 8 TeV

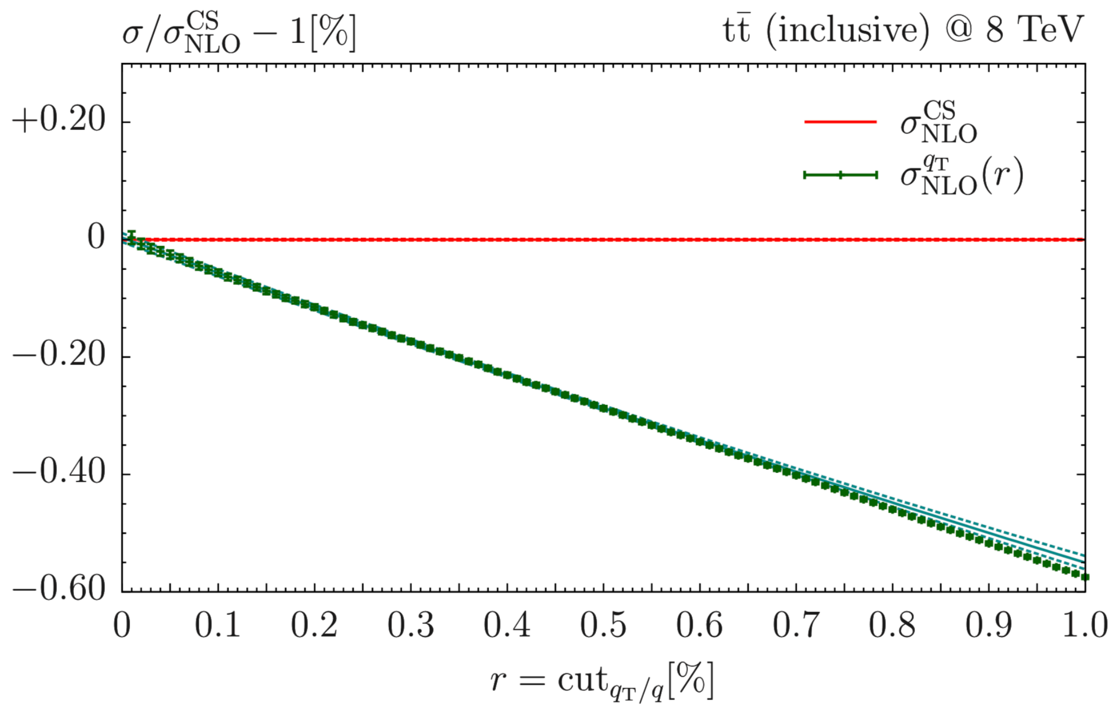
σ(fb)	NLO	$O(\alpha_S^4)_{qg}$	$O(\alpha_S^4)_{qq+qq'}$
q_T subtraction	7083(3)	-61.5(5)	1.33(1)
Top++	7086	-61.53	1.33

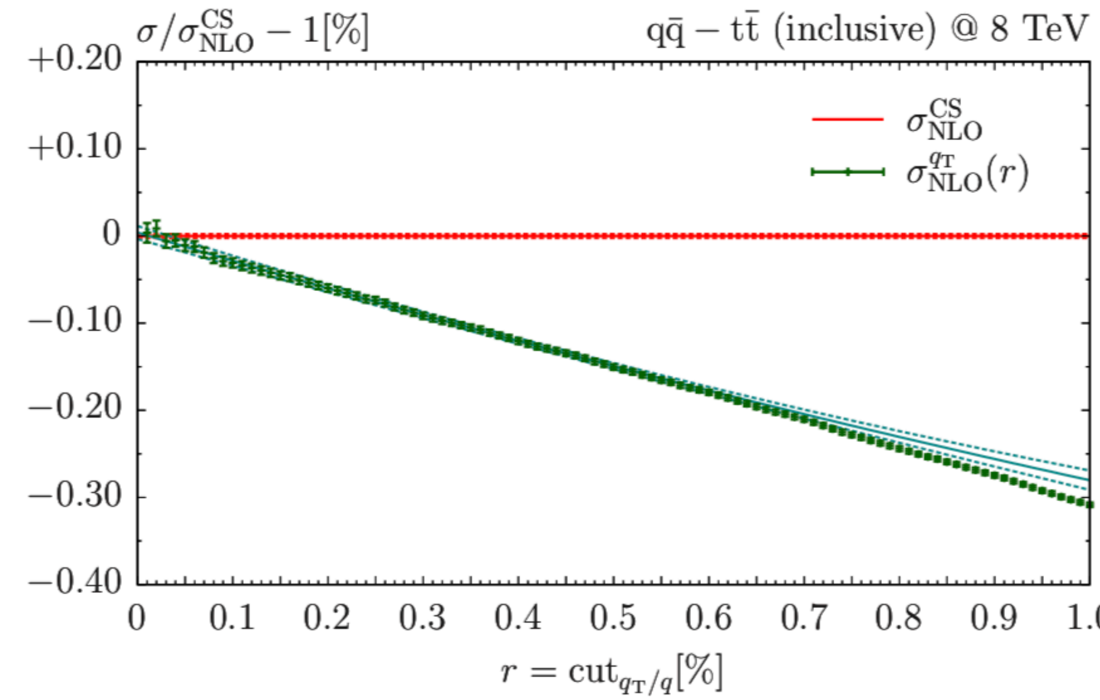
ppbar, 2 TeV

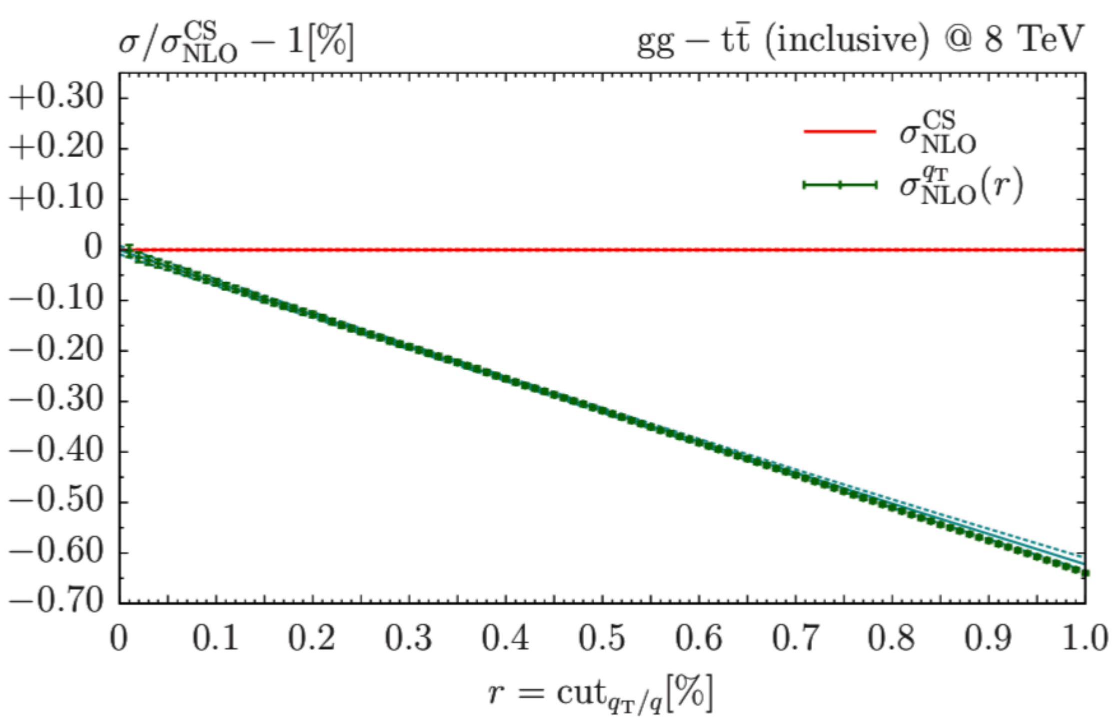
But: the r_{cut} dependence is larger in this case

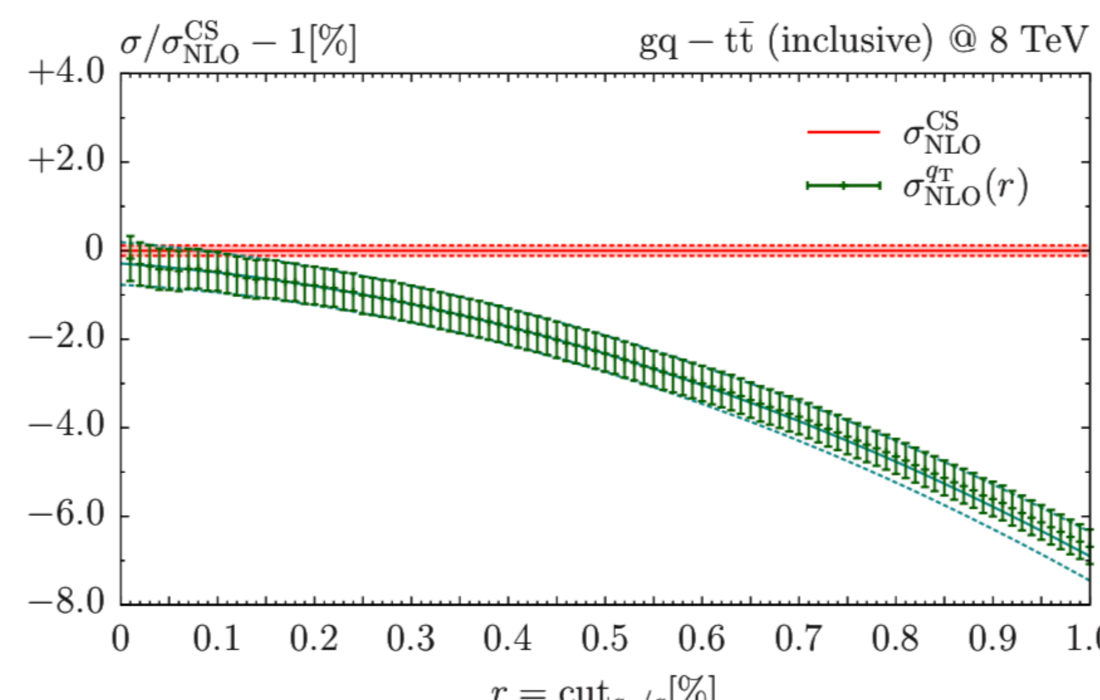
Beyond colour singlets: top-quark production

S.Catani, S.Devoto, J.Mazzitelli, S.Kallweit,H.Sargsyan,MG (in progress)





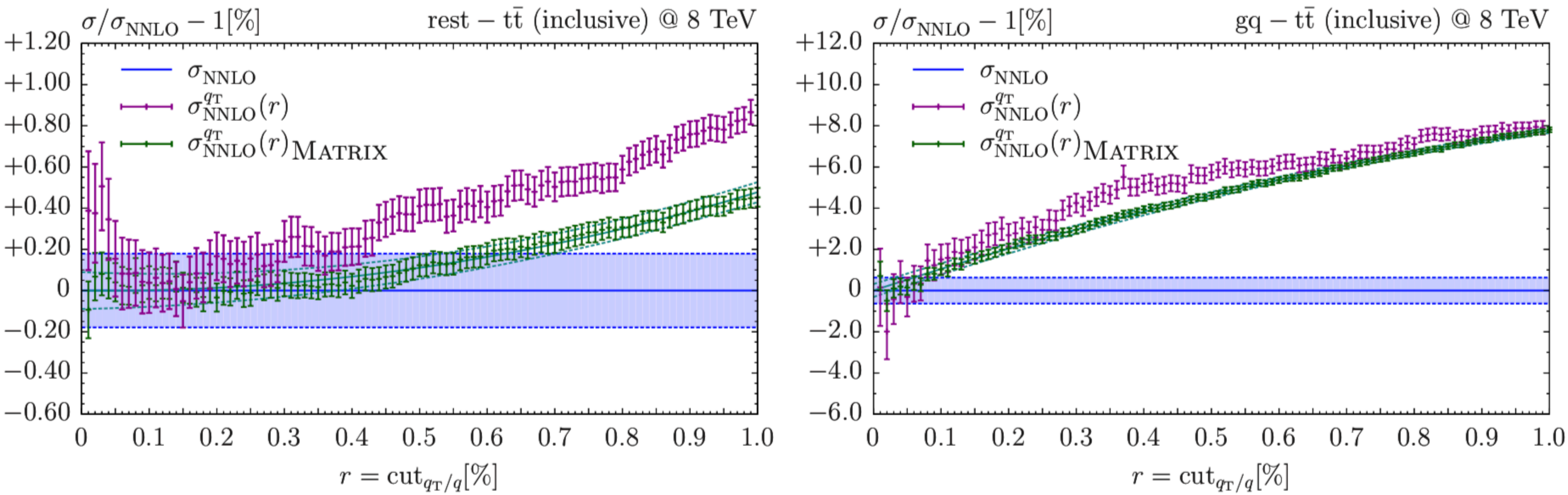




Beyond colour singlets: top-quark production

S.Catani, S.Devoto, J.Mazzitelli, S.Kallweit,H.Sargsyan,MG (in progress)

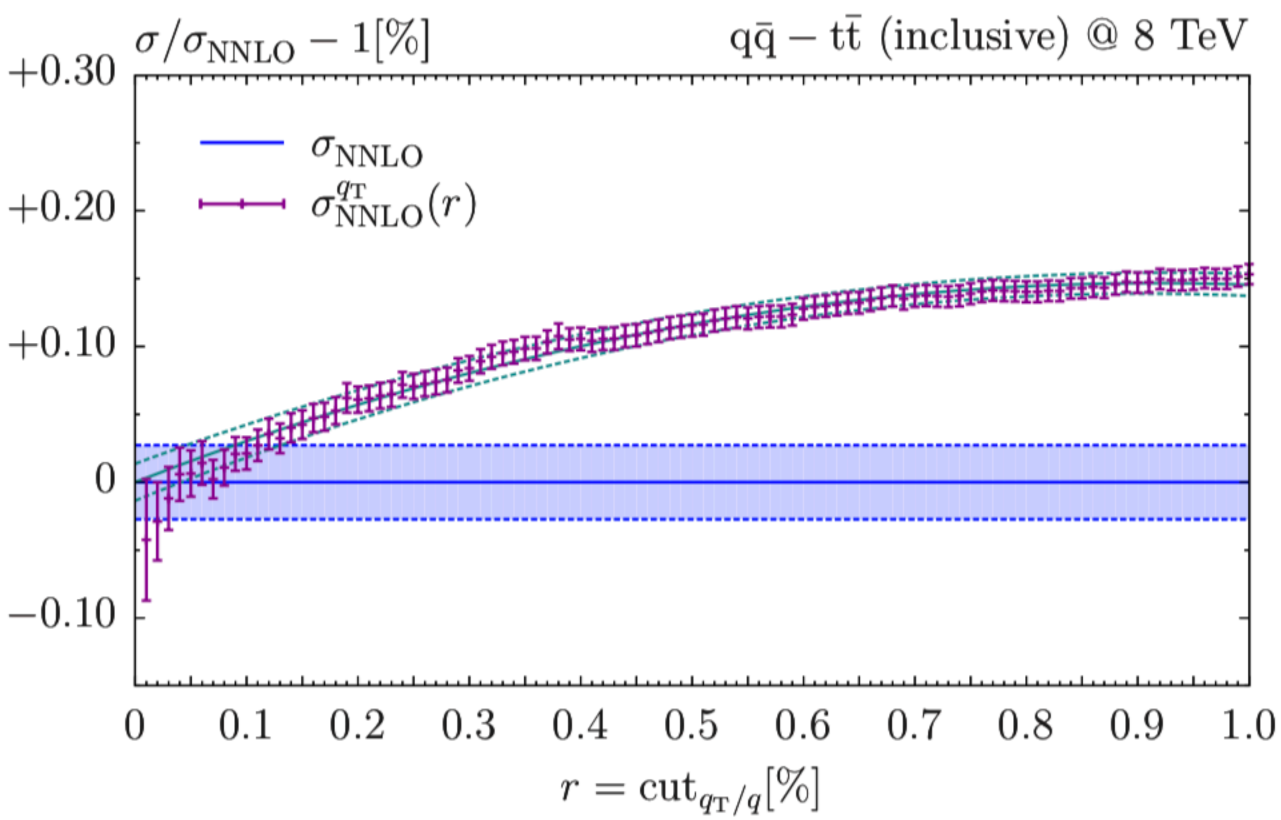
r_{cut} stability: off-diagonal channels

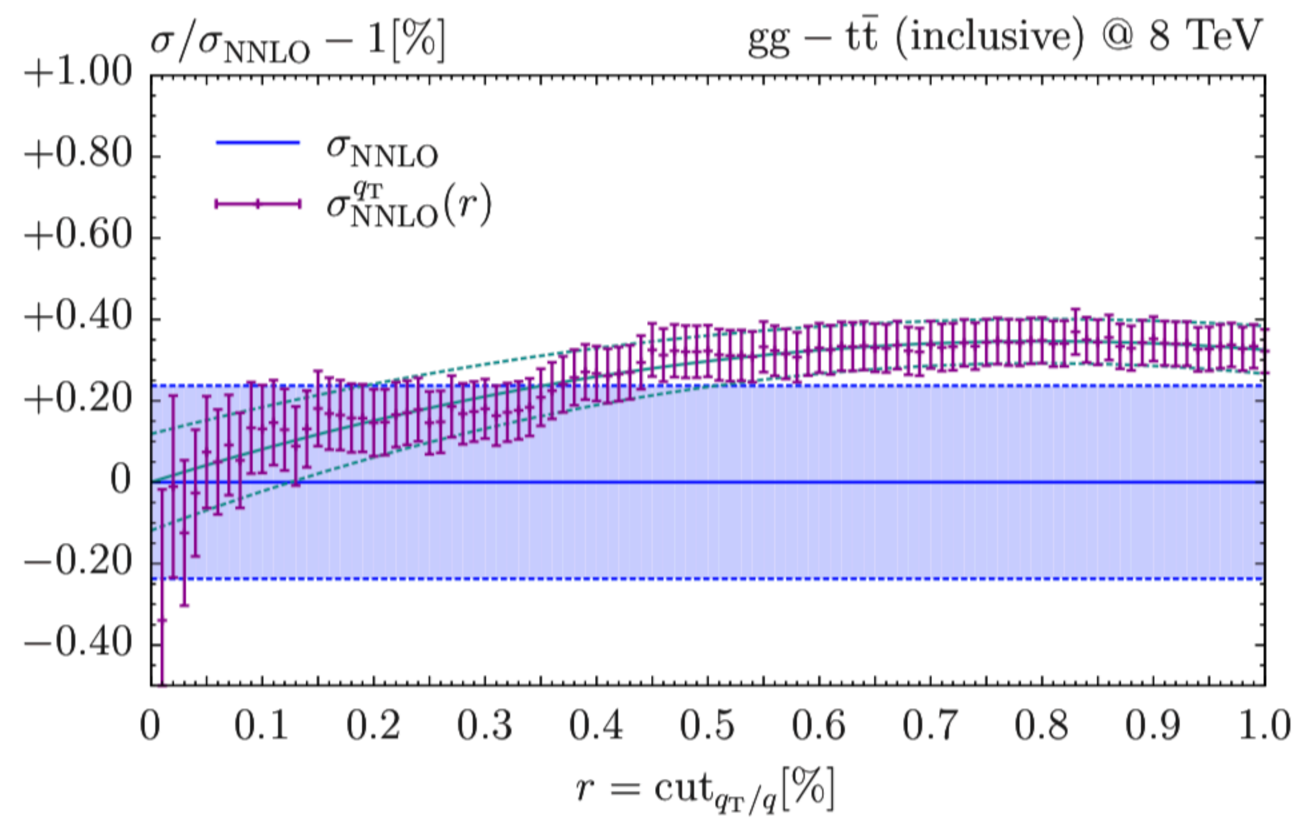


Beyond colour singlets: top-quark production

S.Catani, S.Devoto, J.Mazzitelli, S.Kallweit,H.Sargsyan,MG (in progress)

r_{cut} stability: diagonal channels





Summary & Outlook

- The q_T subtraction method has been used to perform a number of important NNLO calculations where a coloured singlet final state is produced in hadron collisions
- The calculations were implemented in numerical codes which are to a large extent independent from each other
- We provide a new NNLO parton level generator which implements all these calculations in a unique framework and includes all the vector-boson pair production processes

→ MATRIX

- The program combines the MUNICH Monte Carlo framework with amplitudes from Openloops and q_T subtraction and will eventually include transverse-momentum resummation at NNLL

Summary & Outlook

- MATRIX encompasses all the previous codes in a single general framework
- First public version including single vector and Higgs boson production and all the diboson processes has been released
- Non-trivial applications to loop induced processes: HH production
- Some items on our to do list:

  - NLO gg in WW and ZZ
  - inclusion of processes with a heavy-quark pair
  - Include EW corrections
  - Include anomalous couplings

Thank you !

Backup

process (`${process_id}`)	σ_{LO}	σ_{NLO}	σ_{loop} ($\sigma_{\mathrm{loop}}/\Delta\sigma^{\mathrm{ext}}_{\mathrm{NNLO}}$)	$\sigma^{r_{\mathrm{cut}}}_{\mathrm{NNLO}}$	$\sigma^{\mathrm{extrapolated}}_{\mathrm{NNLO}}$	K_{NLO}	K_{NNLO}
$pp \to H$ (`pph21`)	$15.42(0)^{+22\%}_{-17\%}$ pb	$30.26(1)^{+20\%}_{-15\%}$ pb	—	$39.93(3)^{+11\%}_{-10\%}$ pb	$39.93(3)^{+11\%}_{-10\%}$ pb	$+96.2\%$	$+32.0\%$
$pp \to Z$ (`ppz01`)	$43.32(0)^{+12\%}_{-13\%}$ nb	$54.20(1)^{+3.1\%}_{-4.9\%}$ nb	—	$56.01(3)^{+0.84\%}_{-1.1\%}$ nb	$55.99(3)^{+0.84\%}_{-1.1\%}$ nb	$+25.1\%$	$+3.31\%$
$pp \to W^-$ (`ppw01`)	$60.15(0)^{+13\%}_{-14\%}$ nb	$75.95(2)^{+3.3\%}_{-5.3\%}$ nb	—	$78.36(3)^{+0.98\%}_{-1.2\%}$ nb	$78.33(8)^{+0.98\%}_{-1.2\%}$ nb	$+26.3\%$	$+3.14\%$
$pp \to W^+$ (`ppwx01`)	$81.28(1)^{+13\%}_{-14\%}$ nb	$102.2(0)^{+3.4\%}_{-5.3\%}$ nb	—	$105.8(1)^{+0.93\%}_{-1.3\%}$ nb	$105.8(1)^{+0.93\%}_{-1.3\%}$ nb	$+25.7\%$	$+3.52\%$
$pp \to e^-e^+$ (`ppeex02`)	$592.8(1)^{+14\%}_{-14\%}$ pb	$699.7(2)^{+2.9\%}_{-4.5\%}$ pb	—	$728.4(3)^{+0.48\%}_{-0.72\%}$ pb	$732.7(3.4)^{+0.43\%}_{-0.79\%}$ pb	$+18.0\%$	$+4.72\%$
$pp \to \nu_e\bar{\nu}_e$ (`ppnenex02`)	$2876(0)^{+12\%}_{-13\%}$ pb	$3585(1)^{+3.0\%}_{-4.9\%}$ pb	—	$3705(2)^{+0.86\%}_{-1.1\%}$ pb	$3710(2)^{+0.85\%}_{-1.1\%}$ pb	$+24.6\%$	$+3.48\%$
$pp \to e^-\bar{\nu}_e$ (`ppenex02`)	$2972(0)^{+14\%}_{-15\%}$ pb	$3674(1)^{+3.1\%}_{-5.2\%}$ pb	—	$3772(2)^{+0.89\%}_{-0.94\%}$ pb	$3768(3)^{+0.90\%}_{-0.93\%}$ pb	$+23.6\%$	$+2.57\%$
$pp \to e^+\nu_e$ (`ppexne02`)	$3964(0)^{+14\%}_{-14\%}$ pb	$4855(1)^{+3.0\%}_{-5.1\%}$ pb	—	$4986(2)^{+0.88\%}_{-0.95\%}$ pb	$4986(3)^{+0.88\%}_{-0.95\%}$ pb	$+22.5\%$	$+2.70\%$
$pp \to \gamma\gamma$ (`ppaa02`)	$5.592(1)^{+10\%}_{-11\%}$ pb	$25.75(1)^{+8.8\%}_{-7.5\%}$ pb	$2.534(1)^{+24\%}_{-17\%}$ pb (17.4%)	$40.86(2)^{+8.7\%}_{-7.2\%}$ pb	$40.28(30)^{+8.7\%}_{-7.0\%}$ pb	$+361\%$	$+56.4\%$
$pp \to e^-e^+\gamma$ (`ppeexa03`)	$1469(0)^{+12\%}_{-12\%}$ fb	$2119(1)^{+2.9\%}_{-4.6\%}$ fb	$16.02(1)^{+24\%}_{-18\%}$ fb (8.14%)	$2326(1)^{+1.2\%}_{-1.3\%}$ fb	$2316(5)^{+1.1\%}_{-1.2\%}$ fb	$+44.3\%$	$+9.29\%$
$pp \to \nu_e\bar{\nu}_e\gamma$ (`ppnenexa03`)	$63.61(1)^{+2.7\%}_{-3.5\%}$ fb	$98.75(2)^{+3.3\%}_{-2.7\%}$ fb	$2.559(2)^{+26\%}_{-19\%}$ fb (17.3%)	$114.7(1)^{+3.2\%}_{-2.6\%}$ fb	$113.5(6)^{+2.9\%}_{-2.4\%}$ fb	$+55.2\%$	$+15.0\%$
$pp \to e^-\bar{\nu}_e\gamma$ (`ppenexa03`)	$726.1(1)^{+11\%}_{-12\%}$ fb	$1850(1)^{+6.6\%}_{-5.3\%}$ fb	—	$2286(1)^{+4.0\%}_{-3.7\%}$ fb	$2256(15)^{+3.7\%}_{-3.5\%}$ fb	$+155\%$	$+22.0\%$
$pp \to e^+\nu_e\gamma$ (`ppexnea03`)	$861.7(1)^{+10\%}_{-11\%}$ fb	$2187(1)^{+6.6\%}_{-5.3\%}$ fb	—	$2707(3)^{+4.1\%}_{-3.8\%}$ fb	$2671(35)^{+3.8\%}_{-3.6\%}$ fb	$+154\%$	$+22.1\%$
$pp \to ZZ$ (`ppzz02`)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1.361(1)^{+25\%}_{-19\%}$ pb (52.9%)	$16.68(1)^{+3.2\%}_{-2.6\%}$ pb	$16.67(1)^{+3.2\%}_{-2.6\%}$ pb	$+43.3\%$	$+18.2\%$
$pp \to W^+W^-$ (`ppwxw02`)	$66.64(1)^{+5.7\%}_{-6.7\%}$ pb	$103.2(0)^{+3.9\%}_{-3.1\%}$ pb	$4.091(3)^{+27\%}_{-19\%}$ pb (29.5%)	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$+54.9\%$	$+13.4\%$
$pp \to e^-\mu^-e^+\mu^+$ (`ppemexmx04`)	$11.34(0)^{+6.3\%}_{-7.3\%}$ fb	$16.87(0)^{+3.0\%}_{-2.5\%}$ fb	$1.971(1)^{+25\%}_{-18\%}$ fb (57.6%)	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	$+48.8\%$	$+20.3\%$
$pp \to e^-e^-e^+e^+$ (`ppeeexex04`)	$5.781(1)^{+6.3\%}_{-7.4\%}$ fb	$8.623(3)^{+3.1\%}_{-2.5\%}$ fb	$0.9941(4)^{+25\%}_{-18\%}$ fb (56.9%)	$10.37(1)^{+3.5\%}_{-3.0\%}$ fb	$10.37(1)^{+3.5\%}_{-3.0\%}$ fb	$+49.2\%$	$+20.2\%$
$pp \to e^-e^+\nu_\mu\bar{\nu}_\mu$ (`ppeexnmnmx04`)	$22.34(0)^{+5.3\%}_{-6.4\%}$ fb	$33.90(1)^{+3.3\%}_{-2.7\%}$ fb	$3.212(1)^{+25\%}_{-19\%}$ fb (49.6%)	$40.39(2)^{+3.5\%}_{-2.8\%}$ fb	$40.38(2)^{+3.5\%}_{-2.8\%}$ fb	$+51.7\%$	$+19.1\%$
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (`ppemxnmnex04`)	$232.9(0)^{+6.6\%}_{-7.6\%}$ fb	$236.1(1)^{+2.8\%}_{-2.4\%}$ fb	$26.93(1)^{+27\%}_{-19\%}$ fb (94.3%)	$264.7(1)^{+2.2\%}_{-1.4\%}$ fb	$264.6(2)^{+2.2\%}_{-1.4\%}$ fb	$+1.34\%$	$+12.1\%$
$pp \to e^-e^+\nu_e\bar{\nu}_e$ (`ppeexnenex04`)	$115.0(0)^{+6.3\%}_{-7.3\%}$ fb	$203.4(1)^{+4.7\%}_{-3.8\%}$ fb	$12.62(1)^{+26\%}_{-19\%}$ fb (33.8%)	$240.8(1)^{+3.4\%}_{-3.0\%}$ fb	$240.7(1)^{+3.4\%}_{-3.0\%}$ fb	$+76.9\%$	$+18.4\%$
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (`ppemexnmx04`)	$11.50(0)^{+5.7\%}_{-6.8\%}$ fb	$23.55(1)^{+5.5\%}_{-4.5\%}$ fb	—	$26.17(1)^{+2.2\%}_{-2.1\%}$ fb	$26.17(2)^{+2.2\%}_{-2.1\%}$ fb	$+105\%$	$+11.1\%$
$pp \to e^-e^-e^+\bar{\nu}_e$ (`ppeeexnex04`)	$11.53(0)^{+5.7\%}_{-6.8\%}$ fb	$23.63(1)^{+5.5\%}_{-4.5\%}$ fb	—	$26.27(1)^{+2.3\%}_{-2.1\%}$ fb	$26.25(2)^{+2.3\%}_{-2.1\%}$ fb	$+105\%$	$+11.1\%$
$pp \to e^-e^+\mu^+\nu_\mu$ (`ppeexmxnm04`)	$17.33(0)^{+5.3\%}_{-6.3\%}$ fb	$34.14(1)^{+5.3\%}_{-4.3\%}$ fb	—	$37.74(2)^{+2.2\%}_{-2.0\%}$ fb	$37.74(4)^{+2.2\%}_{-2.0\%}$ fb	$+97.0\%$	$+10.6\%$
$pp \to e^-e^+e^+\nu_e$ (`ppeexexne04`)	$17.37(0)^{+5.3\%}_{-6.3\%}$ fb	$34.21(2)^{+5.3\%}_{-4.3\%}$ fb	—	$37.85(2)^{+2.3\%}_{-2.0\%}$ fb	$37.84(3)^{+2.3\%}_{-2.0\%}$ fb	$+96.9\%$	$+10.6\%$

process (`${process_id}`)	LO runtime (relative uncertainty)	NLO runtime (relative uncertainty)	NNLO runtime (relative uncertainty)	NNLO runtime estimate for 10^{-3} uncertainty
$pp \to H$ (pph21)	0 d 0 h 2 m ($1.5 \cdot 10^{-4}$)	0 d 0 h 12 m ($2.7 \cdot 10^{-4}$)	35 d 23 h 23 m ($7.2 \cdot 10^{-4}$)	19 CPU days
$pp \to Z$ (ppz01)	0 d 0 h 10 m ($8.2 \cdot 10^{-5}$)	0 d 0 h 16 m ($2.6 \cdot 10^{-4}$)	53 d 15 h 31 m ($4.6 \cdot 10^{-4}$)	11 CPU days
$pp \to W^-$ (ppw01)	0 d 0 h 7 m ($8.1 \cdot 10^{-5}$)	0 d 0 h 22 m ($2.6 \cdot 10^{-4}$)	50 d 17 h 29 m ($4.4 \cdot 10^{-4}$)	10 CPU days
$pp \to W^+$ (ppwx01)	0 d 0 h 14 m ($8.1 \cdot 10^{-5}$)	0 d 0 h 24 m ($2.6 \cdot 10^{-4}$)	47 d 7 h 46 m ($4.9 \cdot 10^{-4}$)	11 CPU days
$pp \to e^-e^+$ (ppeex02)	0 d 0 h 48 m ($1.0 \cdot 10^{-4}$)	0 d 2 h 24 m ($2.8 \cdot 10^{-4}$)	173 d 20 h 36 m ($3.6 \cdot 10^{-4}$)	22 CPU days
$pp \to \nu_e\bar{\nu}_e$ (ppnenex02)	0 d 1 h 31 m ($8.2 \cdot 10^{-5}$)	0 d 1 h 0 m ($2.5 \cdot 10^{-4}$)	89 d 18 h 17 m ($4.5 \cdot 10^{-4}$)	18 CPU days
$pp \to e^-\bar{\nu}_e$ (ppenex02)	0 d 1 h 46 m ($8.7 \cdot 10^{-5}$)	0 d 5 h 21 m ($2.2 \cdot 10^{-4}$)	114 d 2 h 18 m ($4.3 \cdot 10^{-4}$)	21 CPU days
$pp \to e^+\nu_e$ (ppexne02)	0 d 1 h 56 m ($8.5 \cdot 10^{-5}$)	0 d 3 h 43 m ($2.6 \cdot 10^{-4}$)	114 d 6 h 18 m ($4.6 \cdot 10^{-4}$)	24 CPU days
$pp \to \gamma\gamma$ (ppaa02)	0 d 1 h 13 m ($9.8 \cdot 10^{-5}$)	0 d 4 h 11 m ($2.8 \cdot 10^{-4}$)	27 d 17 h 7 m ($4.6 \cdot 10^{-4}$)	6 CPU days
$pp \to e^-e^+\gamma$ (ppeexa03)	0 d 17 h 55 m ($9.2 \cdot 10^{-5}$)	1 d 19 h 48 m ($2.8 \cdot 10^{-4}$)	1276 d 12 h 47 m ($3.6 \cdot 10^{-4}$)	167 CPU days
$pp \to \nu_e\bar{\nu}_e\gamma$ (ppnenexa03)	0 d 2 h 50 m ($8.7 \cdot 10^{-5}$)	0 d 8 h 59 m ($2.5 \cdot 10^{-4}$)	75 d 9 h 6 m ($4.7 \cdot 10^{-4}$)	17 CPU days
$pp \to e^-\bar{\nu}_e\gamma$ (ppenexa03)	0 d 22 h 18 m ($1.0 \cdot 10^{-4}$)	3 d 16 h 59 m ($3.2 \cdot 10^{-4}$)	1484 d 16 h 50 m ($4.0 \cdot 10^{-4}$)	232 CPU days
$pp \to e^+\nu_e\gamma$ (ppexnea03)	1 d 7 h 8 m ($9.6 \cdot 10^{-5}$)	6 d 8 h 7 m ($3.0 \cdot 10^{-4}$)	428 d 7 h 1 m ($1.0 \cdot 10^{-3}$)	443 CPU days
$pp \to ZZ$ (ppzz02)	0 d 1 h 44 m ($8.2 \cdot 10^{-5}$)	0 d 1 h 6 m ($2.4 \cdot 10^{-4}$)	132 d 19 h 37 m ($4.4 \cdot 10^{-4}$)	25 CPU days
$pp \to W^+W^-$ (ppwxw02)	0 d 1 h 23 m ($8.2 \cdot 10^{-5}$)	0 d 0 h 48 m ($2.5 \cdot 10^{-4}$)	69 d 20 h 49 m ($4.3 \cdot 10^{-4}$)	13 CPU days
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	0 d 5 h 43 m ($8.2 \cdot 10^{-5}$)	0 d 4 h 32 m ($2.7 \cdot 10^{-4}$)	219 d 16 h 33 m ($4.5 \cdot 10^{-4}$)	45 CPU days
$pp \to e^-e^-e^+e^+$ (ppeeexex04)	0 d 11 h 34 m ($9.0 \cdot 10^{-5}$)	0 d 12 h 8 m ($3.4 \cdot 10^{-4}$)	742 d 13 h 37 m ($5.1 \cdot 10^{-4}$)	193 CPU days
$pp \to e^-e^+\nu_\mu\bar{\nu}_\mu$ (ppeexnmnmx04)	0 d 6 h 33 m ($9.4 \cdot 10^{-5}$)	0 d 6 h 36 m ($2.7 \cdot 10^{-4}$)	158 d 13 h 40 m ($4.4 \cdot 10^{-4}$)	31 CPU days
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	0 d 13 h 33 m ($9.2 \cdot 10^{-5}$)	1 d 22 h 9 m ($2.7 \cdot 10^{-4}$)	521 d 2 h 20 m ($4.8 \cdot 10^{-4}$)	119 CPU days
$pp \to e^-e^+\nu_e\bar{\nu}_e$ (ppeexnenex04)	0 d 23 h 36 m ($8.2 \cdot 10^{-5}$)	0 d 17 h 46 m ($4.8 \cdot 10^{-4}$)	270 d 6 h 59 m ($4.4 \cdot 10^{-4}$)	52 CPU days
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	0 d 5 h 18 m ($1.0 \cdot 10^{-4}$)	0 d 5 h 15 m ($2.9 \cdot 10^{-4}$)	104 d 16 h 46 m ($4.3 \cdot 10^{-4}$)	19 CPU days
$pp \to e^-e^-e^+\bar{\nu}_e$ (ppeeexnex04)	0 d 14 h 19 m ($8.3 \cdot 10^{-5}$)	0 d 14 h 56 m ($2.7 \cdot 10^{-4}$)	179 d 14 h 6 m ($4.7 \cdot 10^{-4}$)	39 CPU days
$pp \to e^-e^+\mu^+\nu_\mu$ (ppeexmxnm04)	0 d 10 h 32 m ($8.1 \cdot 10^{-5}$)	0 d 8 h 18 m ($2.6 \cdot 10^{-4}$)	104 d 17 h 58 m ($4.5 \cdot 10^{-4}$)	21 CPU days
$pp \to e^-e^+e^+\nu_e$ (ppeexexne04)	0 d 9 h 19 m ($1.0 \cdot 10^{-4}$)	0 d 13 h 11 m ($4.6 \cdot 10^{-4}$)	167 d 6 h 49 m ($5.1 \cdot 10^{-4}$)	44 CPU days