

# Differential WW production in NNLO QCD

Stefan Kallweit

based on work with: T. Gehrmann<sup>a</sup>, M. Grazzini<sup>ab</sup>, P. Maierhöfer<sup>a</sup>, A. v. Manteuffel<sup>a</sup>, S. Pozzorini<sup>ab</sup>,  
D. Rathlev<sup>ab</sup>, L. Tancredi<sup>a</sup>, M. Wiesemann<sup>b</sup>

<sup>b</sup> [JHEP 1608 \(2016\) 140 \[arXiv:1605.02716 \[hep-ph\]\]](#)

<sup>a</sup> [Phys.Rev.Lett. 113 \(2014\) 21, 212001 \[arXiv:1408.5243 \[hep-ph\]\]](#)

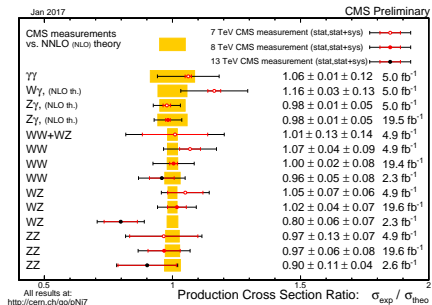
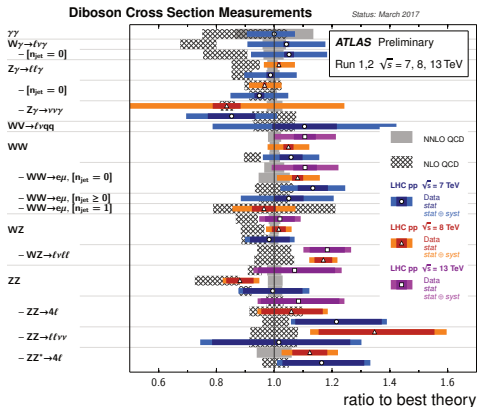


Rencontres de Moriond LII: QCD and High Energy Interactions  
La Thuile, March 25–April 1, 2017

# Outline

- 1 Motivation for NNLO QCD accuracy in  $VV$  production
- 2 Calculation of NNLO QCD cross sections in the `MATRIX` framework
- 3 Numerical `MATRIX` results for  $pp (\rightarrow W^+W^-) \rightarrow 2\ell 2\nu + X$ 
  - Results for inclusive  $WW$  production at 13 TeV
  - Results for  $WW$  signal cuts in  $2\ell 2\nu$  channel at 13 TeV
- 4 Corrections to  $WW$  production beyond NNLO QCD
- 5 Conclusions & Outlook

# Data-theory comparison for VV cross sections — status winter 2017



[CMS collaboration, January 2017]

[ATLAS collaboration, March 2017]

## VV production (with leptonic decays) at NNLO QCD is important:

- Standard Model test → trilinear gauge-boson couplings
- Background for Higgs analyses and BSM searches

↔ Inclusion of NNLO QCD corrections improves agreement with Standard Model.

# The MATRIX framework for automated NNLO+NNLL calculations

[Grazzini, SK, Rathlev, Wiesemann]

## Amplitudes

**OPENLOOPS**  
(COLLIER, CUTTOOLS, ...)

Dedicated 2-loop codes  
(VVAMP, GiNAC, TDHPL, ...)

## MUNICH

MULTI-chaNNel Integrator at Swiss (CH) precision

$q_T$  subtraction  $\Leftrightarrow$   $q_T$  resummation

NNLO

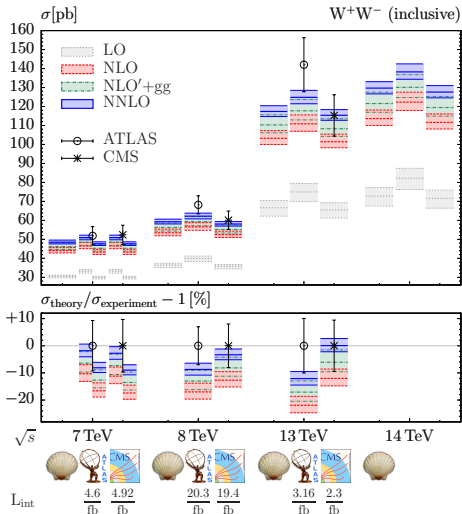
NNLL

## MATRIX

MUNICH Automates  $q_T$  subtraction  
and Resummation to Integrate X-sections.

# Inclusive WW cross sections for relevant LHC energies

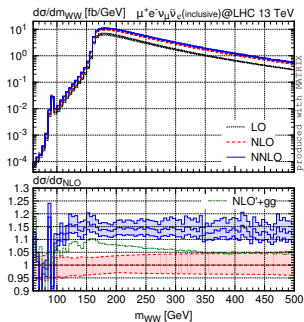
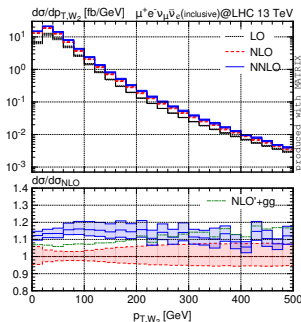
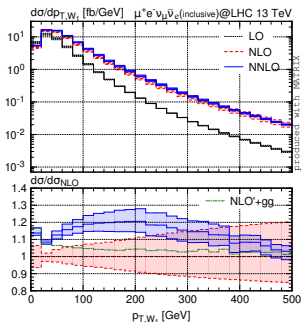
[ATLAS collaboration (2012 – 2017), CMS collaboration (2012 – 2016)]



● **MATRIX** results with NNPDF3.0 PDF sets.

- **on-shell** (left):  $m_{\ell\nu} = m_W$
- **ATLAS** (center): 8, 13, 14 TeV:  $H \rightarrow WW^*$  **included**
- **CMS** (right): 8, 13, 14 TeV:  $H \rightarrow WW^*$  **not included**
- **ATLAS** and **CMS**: 7 TeV: Predictions shown **with** (left) and **without** (right)  $H \rightarrow WW^*$
- **NLO/LO** ranges from **44% to 56%** (7 TeV to 14 TeV).
- **NNLO/NLO** ranges from **10% to 14%** (7 TeV to 14 TeV).
- **NNLO** scale variation  $\approx \pm 3\%$ .  

$$\left( \begin{array}{l} M_W/2 \leq \mu_R, \mu_F \leq 2M_W \\ 1/2 \leq \mu_R/\mu_F \leq 2 \end{array} \right)$$
- **Loop-induced gg channel** makes for **about 35%** of **NNLO** effect.

Inclusive distributions for reconstructed  $W$ 's:  $p_{T,W_1}$ ,  $p_{T,W_2}$ ,  $m_{WW}$ 

$p_{T,W_1}$  and  $p_{T,W_2}$ :

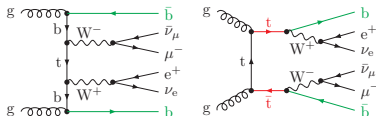
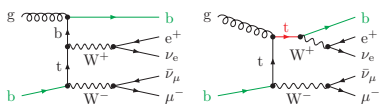
- Giant NLO  $K$ -factor in  $p_{T,W_1}$ , but not in  $p_{T,W_2}$  (jet-recoil topologies).
- NLO and NNLO scale-variation bands typically do not overlap.
  - ↪ New channels open up at NNLO (loop-induced  $gg$  channel, but also e.g.  $q\bar{q}$ ).
- NLO' +  $gg$  provides only about 35% of the NNLO corrections.
  - ↪ No sufficient approximation of full NNLO result (both normalization and shape).

$m_{WW}$ :

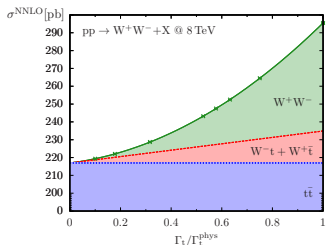
- Threshold behaviour at  $2 m_W$ .
- $Z \rightarrow 2\ell 2\nu$  peak well resolved.

# Definition of top-contamination free WW cross section

- Straightforward in 4FNS (massive b's  $\rightarrow WWb\bar{b}$  finite and can be split off)
- Non-trivial in 5FNS (massless b's  $\rightarrow WW$  and  $WWb\bar{b}$  connected by IR structure)
  - Single-top production enters at NLO.
  - Top-pair production enters at NNLO.



$\hookrightarrow$  Huge “higher-order corrections” result from top-resonance contamination in 5FNS (cross-section enhancement of 30%/400% at NLO/NNLO for  $\sqrt{s} = 8$  TeV).



- $\Gamma_t$ -dependence of NNLO cross section can be used to isolate the different processes:
 
$$\sigma_{WW} \propto 1, \quad \sigma_{tW} \propto 1/\Gamma_t, \quad \sigma_{t\bar{t}} \propto 1/\Gamma_t^2.$$
- Parabolic fit of  $(\Gamma_t/\Gamma_t^{\text{phys}})^2$ -rescaled NNLO cross section delivers  $\sigma_{WW}$ ,  $\sigma_{tW}$ ,  $\sigma_{t\bar{t}}$ .

$\hookrightarrow \approx 1\text{-}2\%$  agreement between 4FNS and 5FNS.

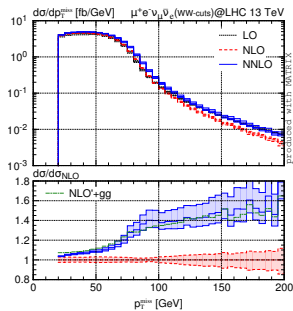
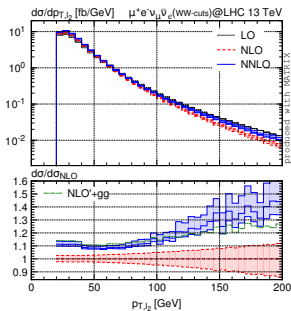
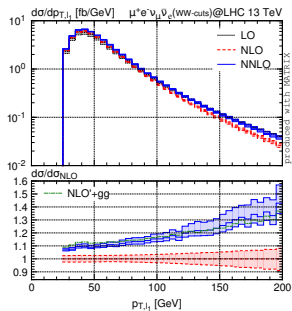
# Fiducial off-shell cross sections for $pp (\rightarrow W^+W^-) \rightarrow 2\ell 2\nu + X$

## Setup motivated by the ATLAS analysis @ 8 TeV [ATLAS collaboration (2014 & 2016)]

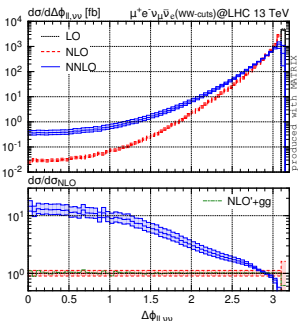
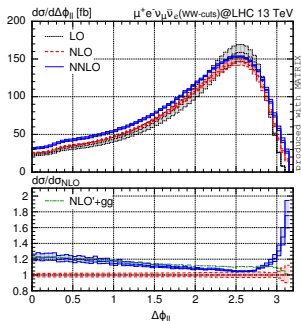
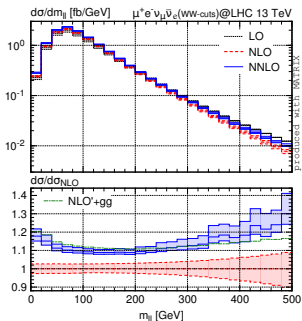
$\sqrt{s}$	$\sigma_{\text{fiducial}}(W^+W^- \text{-cuts}) [\text{fb}]$		$\sigma/\sigma_{\text{NLO}} - 1$	
	8 TeV	13 TeV	8 TeV	13 TeV
LO	147.23 (2) $^{+3.4\%}_{-4.4\%}$	233.04(2) $^{+6.6\%}_{-7.6\%}$	-3.8%	- 1.3%
NLO	153.07 (2) $^{+1.9\%}_{-1.6\%}$	236.19(2) $^{+2.8\%}_{-2.4\%}$	0	0
NLO'	156.71 (3) $^{+1.8\%}_{-1.4\%}$	243.82(4) $^{+2.6\%}_{-2.2\%}$	+2.4%	+ 3.2%
NLO'+ <i>gg</i>	166.41 (3) $^{+1.3\%}_{-1.3\%}$	267.31(4) $^{+1.5\%}_{-2.1\%}$	+8.7%	+13.2%
NNLO	164.16(13) $^{+1.3\%}_{-0.8\%}$	261.5(2) $^{+1.9\%}_{-1.2\%}$	+7.2%	+10.7%

- Results refer to only **one different-flavour channel**:  $pp \rightarrow e^- \mu^+ \nu_\mu \bar{\nu}_e + X$
- Event selection imposes a **jet veto**.
  - $\hookrightarrow$  Usual scale variation underestimates missing higher-order corrections.
- **NLO corrections** amount to about **+4% (+1%) wrt. LO** result at **8 (13) TeV**.
- **NNLO corrections** amount to about **+7% (+10%) wrt. NLO** result at **8 (13) TeV**.
- **The positive impact of the NNLO corrections is entirely due to the loop-induced *gg* contribution**, which is about **+6% (+10%) wrt. NLO** result at **8 (13) TeV**.
  - $\hookrightarrow \mathcal{O}(\alpha_s^2)$  corrections to  $q\bar{q}$  are negative and amount to roughly **-2% (-3%)**.



Distributions with WW signal cuts:  $p_{T,l_1}$ ,  $p_{T,l_2}$ ,  $p_{T,miss}$ 

- The loop-induced  $gg$  contribution dominates the NNLO corrections.  
 $\hookrightarrow$  NLO and NNLO scale-variation bands typically do not overlap.  
 ( $gg$  channel not covered by scale-variation uncertainties from  $q\bar{q}$  channel)
- By and large NLO' +  $gg$  approximates the full NNLO prediction very well (in particular for observables without strong kinematical constraints).
- However, shape distortions of up to about 10% result from genuine NNLO corrections (compared to NLO' +  $gg$  approximation).

Di-lepton distributions with WW signal cuts:  $m_{ll}$ ,  $\Delta\phi_{ll}$ ,  $\Delta\phi_{ll,\nu\nu}$ 

$m_{ll}$  and  $\Delta\phi_{ll}$  ( $\ll \pi$ ):

- The loop-induced  $gg$  contribution dominates the NNLO corrections.
  - $\hookrightarrow$  NLO and NNLO scale-variation bands typically do not overlap.
- Shape distortions of up to about 10% result from genuine NNLO corrections.

$\Delta\phi_{ll}$  ( $\lesssim \pi$ ) and  $\Delta\phi_{ll,\nu\nu}$ :

- Phase-space regions that imply the presence of QCD radiation:
  - Huge NNLO corrections
  - Loop-induced  $gg$  contribution cannot approximate the shapes of full NNLO corrections.

# Corrections to WW production beyond NNLO QCD

## NLO QCD corrections to $gg \rightarrow W^+W^-$ (gg-channel, massless 2-loop amplitudes)

[Caola, Melnikov, Rötsch, Tancredi (2015)]

(based on amplitudes from [Caola, Henn, Melnikov, Smirnov, Smirnov (2015); von Manteuffel, Tancredi (2015)])

- The LO gg-fusion cross section is increased by  $\mathcal{O}(24\% - 80\%)$  for  $M_W/2 < \mu_R = \mu_F < 2M_W$  at  $\sqrt{s} = 8$  TeV (slightly smaller at  $\sqrt{s} = 13$  TeV).
  - ↔ Corresponds to increase of full NLO QCD prediction by about **+2%** at  $\sqrt{s} = 8$  and 13 TeV (covered by the NNLO QCD scale-uncertainty estimate)
- In the ATLAS fiducial region, NLO QCD corrections to gg shrink to about **+20%**.
- **NLO QCD to  $gg \rightarrow W^+W^-$  including interference effects with off-shell Higgs.** [Caola, Dowling, Melnikov, Rötsch, Tancredi (2016)]

## NLO EW corrections to off-shell $W^+W^-$ production

[Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder (2016)]

- Corrections of about **-4% (-3%)** wrt. the inclusive (fiducial ATLAS) cross section at LO for both  $\sqrt{s} = 8, 13$  TeV.
  - ↔ Larger (typically tens of per cent) corrections at high transverse momenta.
- Contribution from  $\gamma\gamma$ -induced process of about **+1%** wrt. both the inclusive and the fiducial ATLAS cross section at LO for both  $\sqrt{s} = 8$  and 13 TeV.

# Conclusions & Outlook

**MATRIX** – an automated framework to perform fully differential NNLO (+NNLL) QCD computations for colourless final-state production – introduced, which is based on

- the **MUNICH** Monte Carlo integrator,
- the  **$q_T$  subtraction** (+resummation) method,
- **OPENLOOPS** and dedicated 2-loop amplitudes from **VVAMP**.

## NNLO QCD predictions for

$pp (\rightarrow W^+W^-) \rightarrow 2\ell 2\nu + X$

- **inclusive:** NNLO/NLO: **10% to 14%** (7 TeV to 14 TeV) ( $\approx 35%$  from gg).
- **different situation with jet-veto:** *gg* dominates, *q $\bar{q}$*  slightly negative.

## Future developments in MATRIX

- combination with NLO EW corrections
- NLO QCD corrections to gg channel
- **first public release . . .**

MATRIX: A fully-differential NNLO(+NNLL) process library

Version: 1.0.0.release\_candidate Mar 2017

Munich -- the MULTI-channel Integrator at swiss (CH) precision --  
Automates  $q_T$ -subtraction and Resummation to Integrate X-sections

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MATRIX is based on a number of different computations and tools from various people and groups. Please acknowledge their efforts by citing the list of references which is created with every run.

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 \* arXiv:1607.02611, 1612.04164, 1612.04164 [hep-ph]  
 \* Phys.Rev.Lett. 117 (2016) 21, 212002 [hep-th:1604.03649]



Recontres de Moriond LII: QCD and High Energy Interactions  
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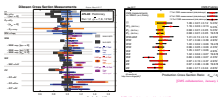
01

Outline

- 1 Motivation for NNLO QCD accuracy in VV production
- 2 Calculation of NNLO QCD cross sections in the Matrix framework
- 3 Numerical 3 cross-section results for  $pp(\rightarrow W^+W^-) \rightarrow 2e2\mu + X$ 
  - Results for inclusive WW production at 13 TeV
  - Results for WW signal cross in 2D channel at 13 TeV
- 4 Corrections to WW production beyond NNLO QCD
- 5 Conclusions & Outlook

02

Data-theory comparison for VV cross sections — status winter 2017

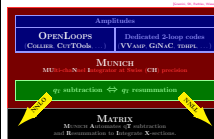


VV production (with leptonic decay) at NNLO QCD is important:
 

- Standard Model test → influence gauge-boson couplings
- Background for Higgs analyses and BSM searches
- Inclusion of NNLO QCD corrections improves agreement with Standard Model

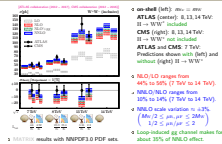
03

The MATRIX framework for automated NNLO-MNLL calculations



04

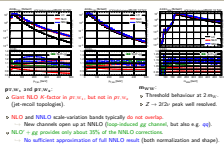
Inclusive WW cross sections for relevant LHC energies



1 MATRIX results with NNPDF3.0 PDF sets

05

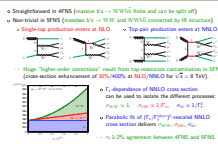
Inclusive distributions for reconstructed  $W$ 's:  $p_{T,W}, p_{T,W^*}, \theta_{W^*}$



2 No sufficient approximation of full NNLO result (both normalization and shape)

06

Definition of top-pomeration-free WW cross section



3  $\sim 1\%$  agreement between 4FN5 and FN5

07

Fiducial off-shell cross sections for  $pp(\rightarrow W^+W^-) \rightarrow 2e2\mu + X$

Setup motivated by the ATLAS analysis 8+8 TeV

$\sqrt{s}$	7 TeV	8 TeV	13 TeV	$\delta$ (in)	$\delta$ (out)
LO	147.23 (2.1%)	218.04(2.7%)	448.1 (1.8%)	-4.8%	-1.8%
NLO	164.01 (10.7%)	248.92(11.2%)	471 (1.2%)	0	0
NLO*	166.16 (11.6%)	249.03(11.2%)	470.6 (1.2%)	+0.4%	+0.3%
NNLO	168.41 (11.5%)	249.31(11.2%)	470.7 (1.2%)	+0.7%	+0.3%
NNLO	168.60(11.2%)	249.30(11.2%)	470.7 (1.2%)	+0.7%	+0.3%

4 Results refer to only one different flavour channel:  $gg \rightarrow u^*d^*s^*u^* + X$

5 Event selection involves 3 jet cuts

6 Dual scale variation underestimates missing higher-order corrections

7 NNLO corrections amount to about +4% (+1%) w/o LO result at 8 (13) TeV

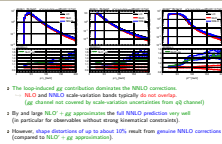
8 NNLO correction amount to about +7% (+10%) w/o. NNLO result at 8 (13) TeV

9 The positive impact of the NNLO correction is mainly due to the loop-induced  $gg$  contribution, which is about +6% (+10%) w/o. NNLO result at 8 (13) TeV

10  $q\bar{q}$  corrections to  $q\bar{q}$  are negative and amount to roughly -2% (-3%)

08

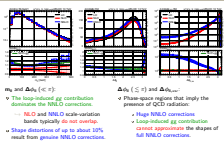
Distributions with WW signal cuts:  $p_{T,W}, p_{T,W^*}, p_{T,W^*}$



3 However, shape distortions of up to about 10% result from genuine NNLO corrections (compared to NLO\*  $\rightarrow$   $gg$  approximation)

09

Di-lepton distributions with WW signal cuts:  $\theta_{W^*}, \Delta\theta_{W^*}, \Delta\theta_{W^*}$



4 Shape distortions of up to about 10% result from genuine NNLO corrections

10

Corrections to WW production beyond NNLO QCD

4 NNLO QCD corrections to  $gg \rightarrow W^+W^-$  (gg-channel, excludes 2-loop amplitudes) (based on amplitudes from [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100])

5 The LO  $gg$  fusion cross section is increased by  $\mathcal{O}(30\% - 100\%)$  for  $M_H/2 < p_{T,W} < p_{T,W^*} < 2M_H$  at  $\sqrt{s} = 8$  TeV (highly sensitive at  $\sqrt{s} = 13$  TeV)

6 Corresponds to increase of full NNLO QCD prediction by about +2% at  $\sqrt{s} = 8$  and 13 TeV (powered by the NNLO QCD scale-uncertainty estimate)

7 In the ATLAS fiducial region, NNLO QCD corrections to  $gg$  amount to about +10%

8 NNLO QCD  $\rightarrow$   $gg \rightarrow W^+W^-$  including interference effects with off-shell Higgs

9 NNLO EW corrections to off-shell  $W^+W^-$  production (from [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100])

10 Corrections of about -4% (-3%) w/o the inclusive (fiducial ATLAS) cross section at LO for both  $\sqrt{s} = 8, 13$  TeV

11 Larger (typical) sets of per cent) corrections at high transverse momenta

12 Contribution from  $\gamma$ -induced processes of about +3% w/o. both the inclusive and the fiducial ATLAS cross section at LO for both  $\sqrt{s} = 8$  and 13 TeV

11

Conclusions & Outlook

MATRIX — an automated framework to perform fully differential NNLO (N<sup>3</sup>LQCD) computations for colourless final-state production — introduced, which is based on:
 

- the MUNICH Monte Carlo integrator,
- the  $gg$  subtraction ( $\rightarrow$  resummed) method,
- OPENLOOPS and dedicated 2-loop amplitudes from VVAMP.

NNLO QCD predictions for  $pp(\rightarrow W^+W^-) \rightarrow 2e2\mu + X$ :
 

- inclusive: NNLO/LO: 10% to 14% (7 TeV to 14 TeV) (vs 50% from 50)
- different observables with jet veto
- $gg$  distortions,  $q\bar{q}$  slightly negative

Future developments in MATRIX
 

- combination with NLO EW corrections
- NNLO QCD corrections of  $gg$  channel
- first public release ...

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### Idea of the $q_T$ subtraction method for (N)NLO cross sections

Consider the production of a **colorless final state**  $F$  via  $q\bar{q} \rightarrow F$  or  $gg \rightarrow F$ :

$$d\sigma^{(F)} = \frac{d\sigma^{\text{NLO}}}{d\sigma^{\text{LO}}} = d\sigma^{\text{NLO}}.$$

where  $q_T$  refers to the **transverse momentum of the colorless system**  $F$ . [\(from: arXiv:1008.4074\)](#)

$d\sigma^{\text{NLO}} = \Sigma(q_T/Q) \otimes d\sigma^{\text{LO}}$ , where  $Q$  is the invariant mass of the colorless system  $F$ .

• Add the  $q_T < Q$  part with the **hard-vertex coefficient**  $N_H$ , which is derived from the 1-loop amplitude or (NN)LO, and also compensate for the subtraction of  $\Sigma$ .

• **Full result for (N)NLO cross section**

$$d\sigma^{\text{NNLO}} = N_H^{\text{NNLO}} \otimes d\sigma^{\text{LO}} + [d\sigma^{\text{NNLO}} - \Sigma^{\text{NNLO}} \otimes d\sigma^{\text{LO}}]_{q_T > Q}$$

B01

### Ingredients of the $q_T$ subtraction method

$d\sigma^{\text{NNLO}} = N_H^{\text{NNLO}} \otimes d\sigma^{\text{LO}} + [d\sigma^{\text{NNLO}} - \Sigma^{\text{NNLO}} \otimes d\sigma^{\text{LO}}]_{q_T > Q}$

• The **hard-vertex coefficient**  $N_H$

$$N_H = 1 + \left(\frac{\alpha_s}{4\pi}\right)^2 N_H^{(2)} + \left(\frac{\alpha_s}{4\pi}\right)^3 N_H^{(3)} + \dots$$

It is known up to 2-loop order by means of a **process-independent extraction procedure**, starting from the all-order virtual amplitude of the specific process.

• The **counterterm**  $\Sigma(Q)$

$$\Sigma(Q) = \left(\frac{\alpha_s}{4\pi}\right)^2 \Sigma^{(2)}(Q) + \left(\frac{\alpha_s}{4\pi}\right)^3 \Sigma^{(3)}(Q) + \dots$$

It is **universal** (differs for  $q\bar{q} \rightarrow F$  and  $gg \rightarrow F$ , tri-loop process dependent), and the coefficients are known (up to 2-loop order). [\(from: arXiv:1008.4074\)](#)

• The **real-emission contribution**  $d\sigma^{\text{NNLO}}$  can be treated by any local NLO subtraction technique, e.g. by conventional dipole subtraction. [\(from: arXiv:1008.4074\)](#)

B02

### Numerical realization of the calculation

Realized within the fully automated NLO (QCD+EW) Monte Carlo framework **MUNICH (M11+M12)@prog** prepared at Swiss (QCD) center:

- Applicable for arbitrary Standard Model processes (including partonic bookkeeping)
- Phase-space integration by highly efficient multi-channel Monte Carlo techniques
- Additional MC channels based on dipole kinematics constructed in runtime.
- **OpenLoops** interface, automated implementation of dipole subtraction, etc.
- **OpenLoops** calculation for different scale choices and variations.

Extension to automated ( $q_T$  subtraction) NNLO QCD framework [\(from: arXiv:1608.03462\)](#)

- Process-independent construction of  $q_T < Q$  dependent counterterms  $\Sigma^{(2,3)}$
- Process-independent extraction procedure for hard coefficients  $N_H^{(2,3)}$
- Importance sampling performed on top of multi-channel approach
- Improved efficiency and reliability in particular for low  $q_{T, \text{min}}$  values.
- Simultaneous evaluation of observables for different values of the regulator  $q_{T, \text{min}} \rightarrow 0$
- allows for monitoring of  $q_{T, \text{min}}^2$  and for extrapolation  $q_{T, \text{min}}^2 \rightarrow 0$

B03

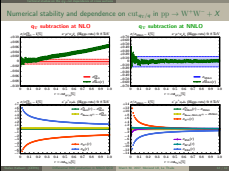
### External ingredients: amplitudes applied in the calculation

- 1-loop amplitudes with **OpenLoops** [\(from: arXiv:1008.4074\)](#) **OpenLoops** [\(from: arXiv:1008.4074\)](#) **OpenLoops** [\(from: arXiv:1008.4074\)](#)
- All tree and [square] one-loop amplitudes (including colour helicity correlations)
- Fully automated compact and fast numerical code for any SM process (QCD+EW)
- Tensor reduction by means of the **Colorless Library** [\(from: arXiv:1008.4074\)](#)
- Numerically stable **Deuser-Strohmaier reduction method** [\(from: arXiv:1008.4074\)](#)
- Scalar integrals with complex masses [\(from: arXiv:1008.4074\)](#)
- Tensor system based on **quad-precision CvtTorus** [\(from: arXiv:1008.4074\)](#)
- Scalar integrals from **QuadGoo** [\(from: arXiv:1008.4074\)](#)

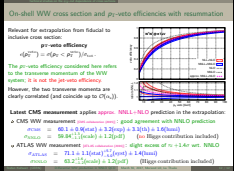
2-loop amplitudes from analytic results

- 2-Loop-Vet the amplitudes from **arXiv:1008.4074**, [\(from: arXiv:1008.4074\)](#)
- Vet helicity amplitudes from **arXiv:1008.4074**, using **TRISLEN** [\(from: arXiv:1008.4074\)](#)
- On-shell TV amplitudes from private code [\(from: arXiv:1008.4074\)](#), using **GNiACT** [\(from: arXiv:1008.4074\)](#)
- Applied in **arXiv:1008.4074**, [\(from: arXiv:1008.4074\)](#), [\(from: arXiv:1008.4074\)](#)
- Off-shell helicity TV amplitudes from **VVctor** [\(from: arXiv:1008.4074\)](#)
- using **GNiACT** [\(from: arXiv:1008.4074\)](#) **GNiACT** [\(from: arXiv:1008.4074\)](#)
- (independent calculation by [\(from: arXiv:1008.4074\)](#), [\(from: arXiv:1008.4074\)](#))

B04



B05

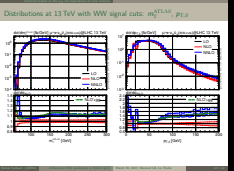


B06

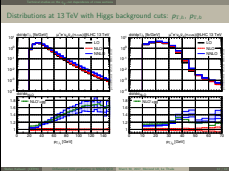
### Definition of WW signal/Higgs background cuts

cut variable	WW cuts	Higgs cuts
$p_{T,1}$	> 20 GeV	> 20 GeV
$p_{T,2}$	> 20 GeV	> 30 GeV
$ \eta $	< 2.4	< 2.4
$ \Delta\eta $	< 2.47 and $\Delta E \in [1.37, 1.52]$	< 2.47 and $\Delta E \in [1.37, 1.52]$
isolation cuts		
$p_{T, \text{miss}}$	> 30 GeV	> 30 GeV
$p_{T, \text{jet}}$	> 15 GeV	> 30 GeV
$R_{\text{jet}}$	> 15 GeV	> 10 GeV
$\Delta R_{\text{jet}}$	> 0.1	> 0.1
$\Delta R_{\text{jet,miss}}$	---	< 1.8
$\Delta R_{\text{jet,miss}}$	---	< 1/2
self-41 jets with $R_{\text{jet}} \leq 0.4$ , $p_{T, \text{jet}} > 20 \text{ GeV}$ , $ \eta  \leq 4.5$		
	0	0

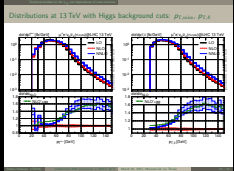
B07



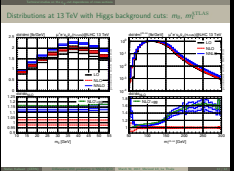
B08



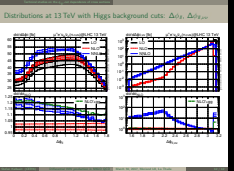
B09



B10



B11



B12

# Idea of the $q_T$ subtraction method for (N)NLO cross sections

Consider the production of a **colourless final state F** via  $q\bar{q} \rightarrow F$  or  $gg \rightarrow F$ :

$$d\sigma_F^{(N)NLO} \Big|_{q_T \neq 0} = d\sigma_{F+jet}^{(N)LO},$$

where  $q_T$  refers to the **transverse momentum of the colourless system F**. [Catani, Grazzini (2007)]

$d\sigma_F^{(N)NLO} \Big|_{q_T \neq 0}$  is **singular for  $q_T \rightarrow 0$** , but the **limiting behaviour is known from transverse-momentum resummation**. [Bozzi, Catani, de Florian, Grazzini (2006)]

- Define a **universal counterterm  $\Sigma$**  with the **complementary  $q_T \rightarrow 0$  behaviour**,  
 $d\sigma^{CT} = \Sigma(q_T/Q) \otimes d\sigma^{LO}$ , where  $Q$  is the invariant mass of the colourless system F.
- Add the  **$q_T = 0$  piece** with the **hard-virtual coefficient  $\mathcal{H}_F$** , which is derived from the 1-(2-)loop amplitudes at (N)NLO, and also compensates for the subtraction of  $\Sigma$ .

↪ **Full result for (N)NLO cross section**

$$d\sigma_F^{(N)NLO} = \mathcal{H}_F^{(N)NLO} \otimes d\sigma^{LO} + \left[ d\sigma_{F+jet}^{(N)LO} - \Sigma^{(N)NLO} \otimes d\sigma^{LO} \right]_{\text{cut}_{q_T} \rightarrow 0}$$

# Ingredients of the $q_T$ subtraction method

$$d\sigma_{\mathbf{F}}^{(N)\text{NLO}} = \mathcal{H}_{\mathbf{F}}^{(N)\text{NLO}} \otimes d\sigma^{\text{LO}} + \left[ d\sigma_{\mathbf{F}+\text{jet}}^{(N)\text{LO}} - \Sigma^{(N)\text{NLO}} \otimes d\sigma^{\text{LO}} \right]_{\text{cut}_{q_T} \rightarrow 0}$$

- The **hard-virtual coefficient**  $\mathcal{H}_{\mathbf{F}}$ ,

$$\mathcal{H}_{\mathbf{F}} = \underbrace{1}_{\text{tree-level amplitude}} + \underbrace{\left(\frac{\alpha_S}{\pi}\right) \mathcal{H}^{\mathbf{F}(1)}}_{\text{contains (finite) 1-loop amplitude}} + \underbrace{\left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{\mathbf{F}(2)}}_{\text{contains (finite) 2-loop amplitude}} + \dots,$$

is **known up to 2-loop order** by means of a **process-independent extraction procedure**, starting from the all-order virtual amplitude of the specific process.

[Catani, Cieri, de Florian, Ferrera, Grazzini (2013)]

- The **counterterm**  $\Sigma(q_T/Q)$ ,

$$\Sigma(q_T/Q) = \left(\frac{\alpha_S}{\pi}\right) \Sigma^{(1)}(q_T/Q) + \left(\frac{\alpha_S}{\pi}\right)^2 \Sigma^{(2)}(q_T/Q) + \dots,$$

is **universal** (differs for  $q\bar{q} \rightarrow \mathbf{F}$  and  $g\bar{g} \rightarrow \mathbf{F}$ , trivial process dependence),

and the **coefficients** are **known (up to 2-loop order)**. [Bozzi, Catani, de Florian, Grazzini (2006)]

- The **real-emission contribution**  $d\sigma_{\mathbf{F}+\text{jet}}^{\text{NLO}}$  can be treated by any local **NLO subtraction technique**, e.g. by conventional dipole subtraction. [Catani, Seymour (1993)]



## Numerical realization of the calculation

### Realized within the fully automated NLO (QCD+EW) Monte Carlo framework MUNICH (MUlti-chaNnel Integrator at Swiss (CH) precision) [SK]

- Applicable for arbitrary Standard Model processes (including partonic bookkeeping).
- Phase-space integration by highly efficient multi-channel Monte Carlo techniques  
 ↪ Additional MC channels based on dipole kinematics constructed at runtime.
- OPENLOOPS interface, automatized implementation of dipole subtraction, etc.
- Simultaneous calculation for different scale choices and variations.

### Extension to automated ( $q_T$ subtraction) NNLO QCD framework [Grazzini, SK, Rathlev]

- Process-independent construction of  $\text{cut}_{q_T/q}$ -dependent counterterms  $\Sigma^{(1,2)}$ .
- Process-independent extraction procedure for hard coefficients  $\mathcal{H}^{(1,2)}$ .
- Importance sampling performed on top of multi-channel approach  
 ↪ improved efficiency and reliability in particular for low  $\text{cut}_{q_T/q}$  values.
- Simultaneous evaluation of observables for different values of the regulator  $\text{cut}_{q_T/q}$   
 ↪ allows for monitoring of  $\text{cut}_{q_T/q}$  and for extrapolation  $\text{cut}_{q_T/q} \rightarrow 0$ .

# External ingredients: amplitudes applied in the calculation

## 1-loop amplitudes with OPENLOOPS

[Cascioli, Maierhöfer, Pozzorini (2011); Cascioli, Lindert, Maierhöfer, Pozzorini (2014)]

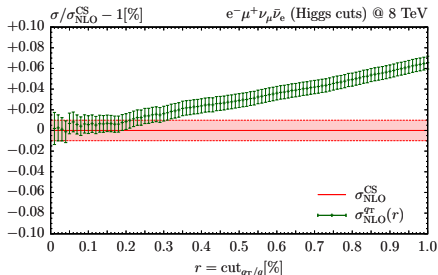
- All tree and (squared) one-loop amplitudes (including colour/helicity correlations)
- Fully automated compact and fast numerical code for any SM process (QCD+EW)
- Tensor reduction by means of the COLLIER library [Denner, Dittmaier, Hofer (2014)]
  - Numerically stable Denner–Dittmaier reduction methods [Denner, Dittmaier (2002 & 2005)]
  - Scalar integrals with complex masses [Denner, Dittmaier (2010)]
- Rescue system based on quad-precision CUTTOOLS [Ossola, Papadopoulos, Pittau (2008)]
  - Scalar integrals from ONELOOP [van Hameren, Papadopoulos, Pittau (2009); van Hameren (2010)]

## 2-loop amplitudes from analytic results

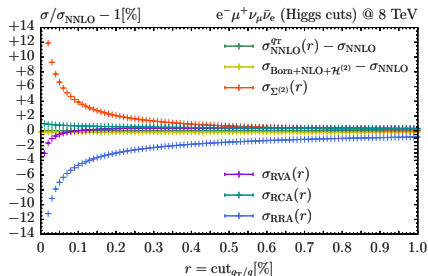
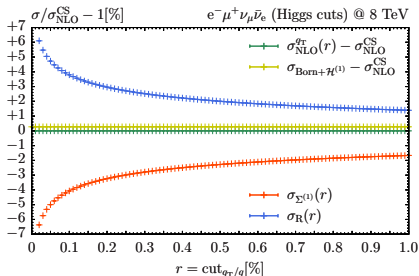
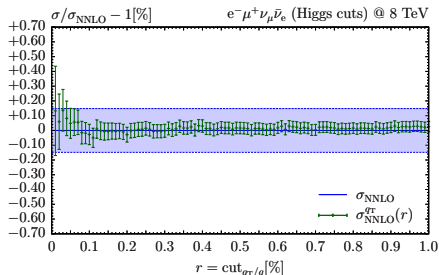
- Drell–Yan-like amplitudes from [Matsuura, van der Marck, van Neerven (1989)]
- $V\gamma$  helicity amplitudes from [Gehrmann, Tancredi (2011)], using TDHPL [Gehrmann, Remiddi (2001)]
- On-shell VV amplitudes from private code [von Manteuffel, Tancredi (2014)], using GINAC (applied in [Cascioli et al. (2014); Gehrmann et al. (2014); Grazzini, SK, Rathlev, Wiesemann (2015)])
- Off-shell helicity  $VV'$  amplitudes from VVAMP [Gehrmann, von Manteuffel, Tancredi (2015)], using GINAC [Bauer, Frink, Kreckel (2002); Vollinga, Weinzierl (2005)] (independent calculation by [Caola, Henn, Melnikov, Smirnov, Smirnov (2014)])

# Numerical stability and dependence on cut $q_{T/q}$ in $pp \rightarrow W^+W^- + X$

## $q_T$ subtraction at NLO



## $q_T$ subtraction at NNLO



# On-shell WW cross section and $p_T$ -veto efficiencies with resummation

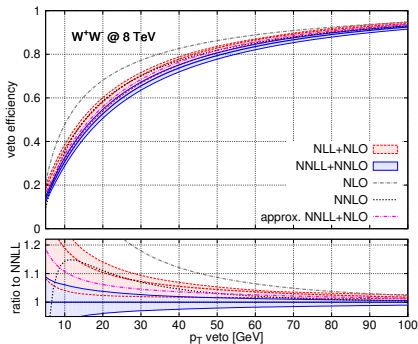
Relevant for extrapolation from fiducial to inclusive cross section:

**$p_T$ -veto efficiency**

$$\epsilon(p_T^{\text{veto}}) = \sigma(p_T < p_T^{\text{veto}}) / \sigma_{\text{tot}}.$$

The  $p_T$ -veto efficiency considered here refers to the transverse momentum of the WW system; it is not the jet-veto efficiency.

However, the two transverse momenta are clearly correlated (and coincide up to  $\mathcal{O}(\alpha_s)$ ).



**Latest CMS measurement** applies **approx. NNLL+NLO** prediction in the extrapolation:

- CMS WW measurement [CMS collaboration (2015)]: **good agreement with NNLO prediction**

$$\sigma_{\text{CMS}} = 60.1 \pm 0.9(\text{stat}) \pm 3.2(\text{exp}) \pm 3.1(\text{th}) \pm 1.6(\text{lumi})$$

$$\sigma_{\text{NNLO}} = 59.84_{-1.1}^{+1.3}(\text{scale}) \pm 1.2(\text{pdf}) \quad (\text{no Higgs contribution included})$$

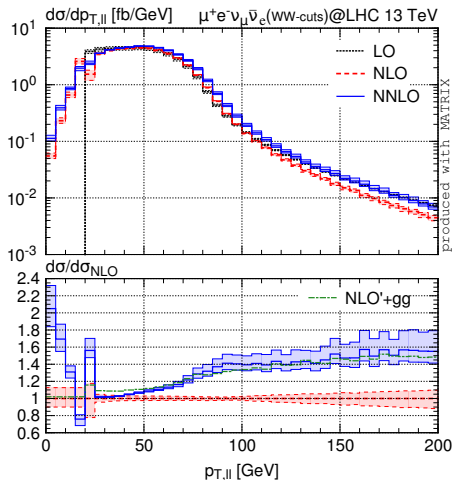
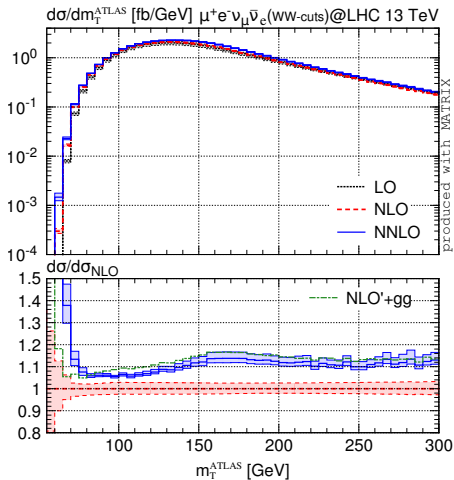
- ATLAS WW measurement [ATLAS collaboration (2016)]: **slight excess of  $\approx +1.4\sigma$  wrt. NNLO**

$$\sigma_{\text{ATLAS}} = 71.1 \pm 1.1(\text{stat})_{-5.0}^{+5.7}(\text{syst}) \pm 1.4(\text{lumi})$$

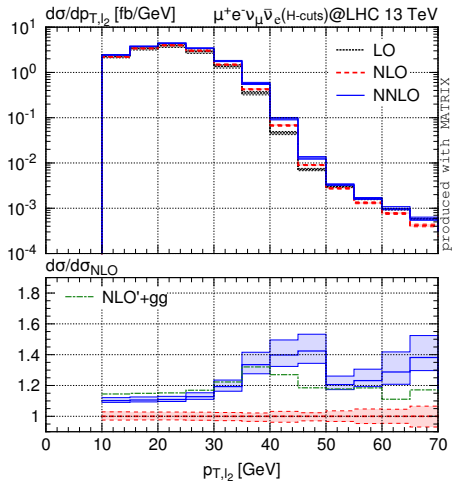
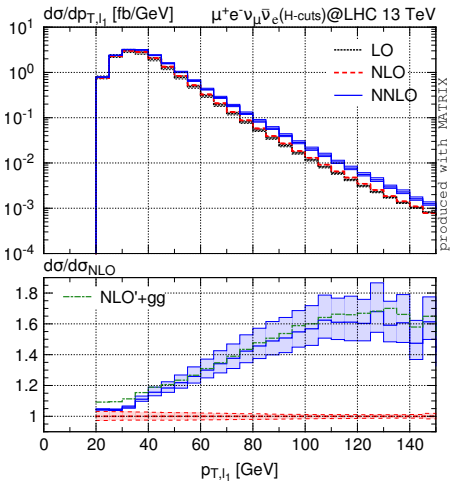
$$\sigma_{\text{NNLO}} = 63.2_{-1.2}^{+1.6}(\text{scale}) \pm 1.2(\text{pdf}) \quad (\text{Higgs contribution included})$$

## Definition of WW signal/Higgs background cuts

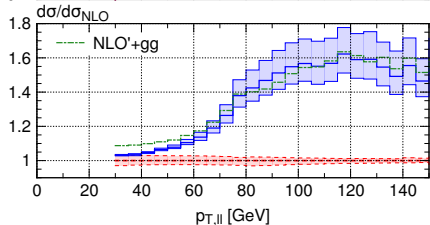
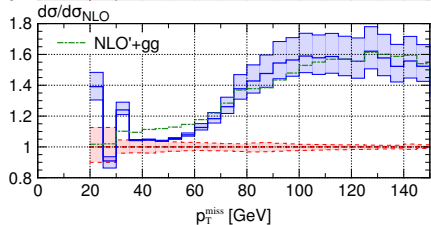
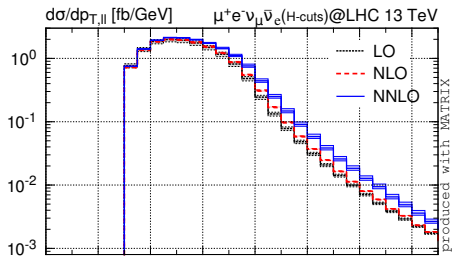
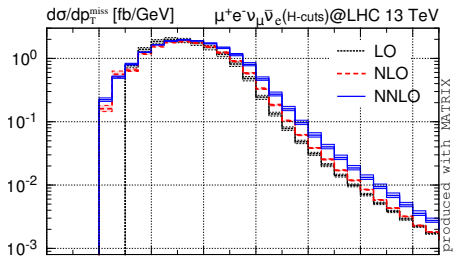
cut variable	WW cuts	Higgs cuts
lepton definition		
$p_{T,\ell_1}$	$> 25 \text{ GeV}$	$> 22 \text{ GeV}$
$p_{T,\ell_2}$	$> 20 \text{ GeV}$	$> 10 \text{ GeV}$
$ y_\mu $	$< 2.4$	$< 2.4$
$ y_e $	$< 2.47$ and $\notin [1.37; 1.52]$	$< 2.47$ and $\notin [1.37; 1.52]$
leptonic cuts		
$p_{T,\text{miss}}$	$> 20 \text{ GeV}$	$> 20 \text{ GeV}$
$p_{T,\text{miss}}^{\text{rel}}$	$> 15 \text{ GeV}$	—
$p_{T,\ell\ell}$	—	$> 30 \text{ GeV}$
$m_{\ell\ell}$	$> 10 \text{ GeV}$	$\in [10 \text{ GeV}; 55 \text{ GeV}]$
$\Delta R_{\ell\ell}$	$> 0.1$	—
$\Delta\phi_{\ell\ell}$	—	$< 1.8$
$\Delta\phi_{\ell\ell,\nu\nu}$	—	$> \pi/2$
anti- $k_T$ jets with $R = 0.4$ , $p_{T,j} > 25 \text{ GeV}$ , $ y_j  < 4.5$		
$N_{\text{jets}}$	0	0

Distributions at 13 TeV with WW signal cuts:  $m_T^{\text{ATLAS}}$ ,  $p_{T,\parallel}$ 


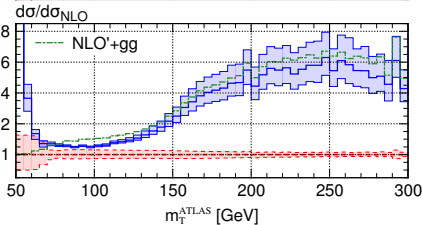
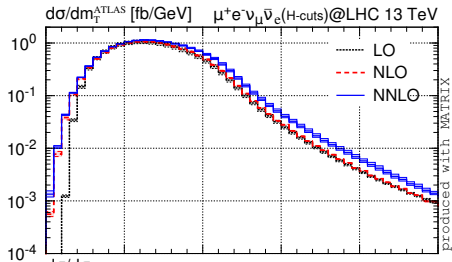
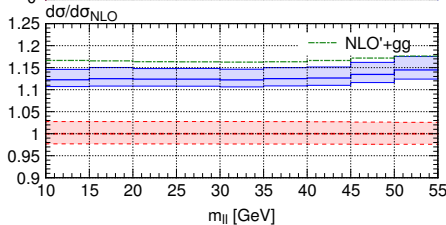
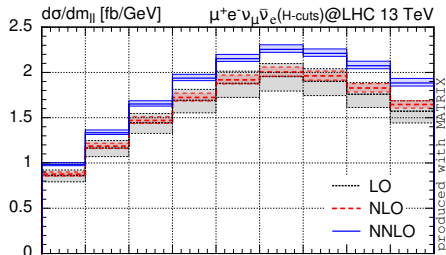
# Distributions at 13 TeV with Higgs background cuts: $p_{T,l_1}$ , $p_{T,l_2}$



# Distributions at 13 TeV with Higgs background cuts: $p_{T,miss}$ , $p_{T,||}$





Distributions at 13 TeV with Higgs background cuts:  $m_{ll}$ ,  $m_T^{\text{ATLAS}}$ 


Distributions at 13 TeV with Higgs background cuts:  $\Delta\phi_{ll}$ ,  $\Delta\phi_{ll,\nu\nu}$ 
