MATRIX:

A fully-differential NNLO process library (+NNLL)

Marius Wiesemann

Universität Zürich[UZH]

Loops and Legs, Leipzig (Germany)

24-29 April, 2016

in collaboration with M. Grazzini, S. Kallweit, S. Pozzorini and D. Rathlev

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Outline

1. Higgs and vector-boson production at the LHC
2. NNLO methods
3. p_T subtraction and resummation
4. The MATRIX
5. ZZ and WW at NNLO+NNLL (p_T resummation)
6. NEW: pp→WW→llνν at NNLO (fully differential)
7. NEW: pp→WZ+X at NNLO (inclusive)

Introduction

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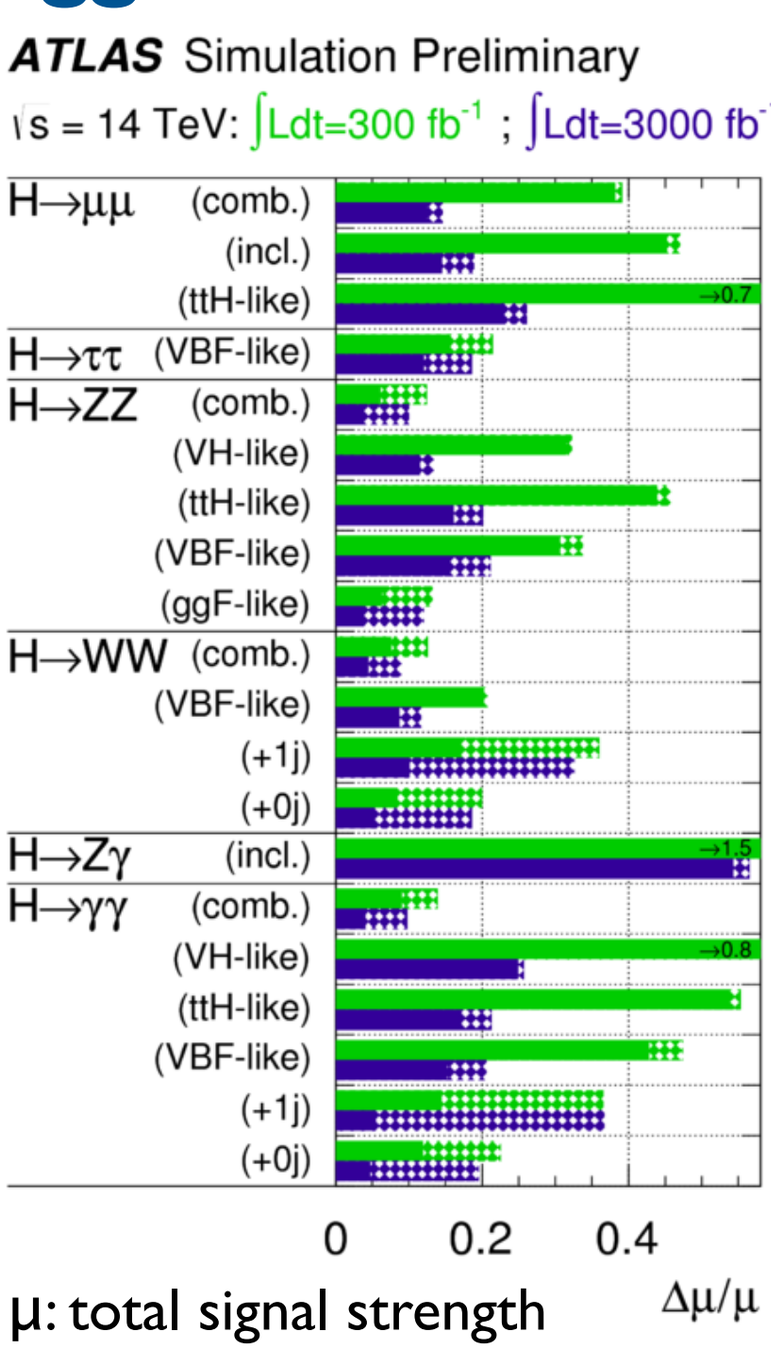
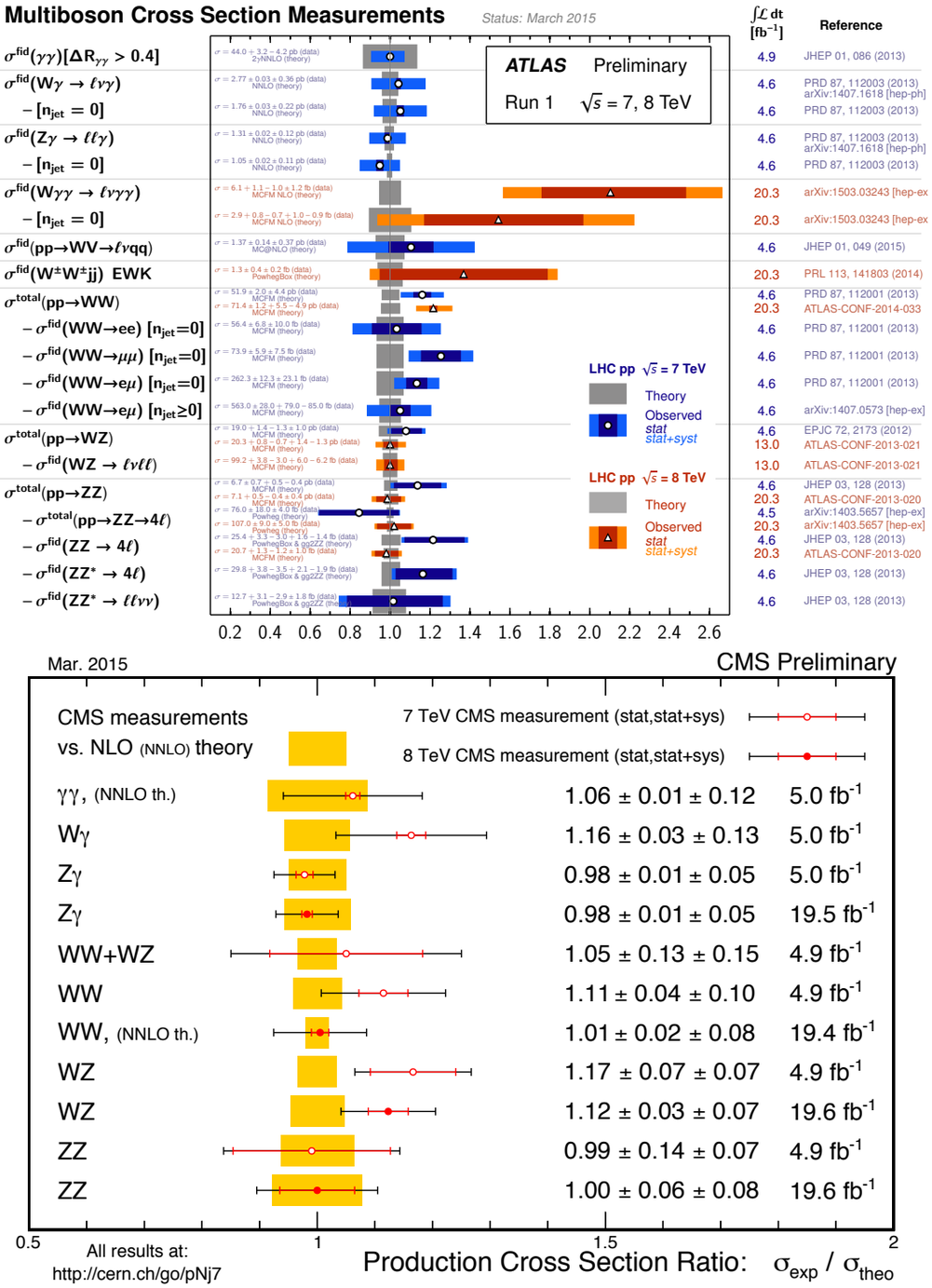
Higgs measurements



μ: total signal strength

vector-boson pair measurements



- All vector-boson pair processes are on the Les Houches NNLO wishlist 2013

Introduction

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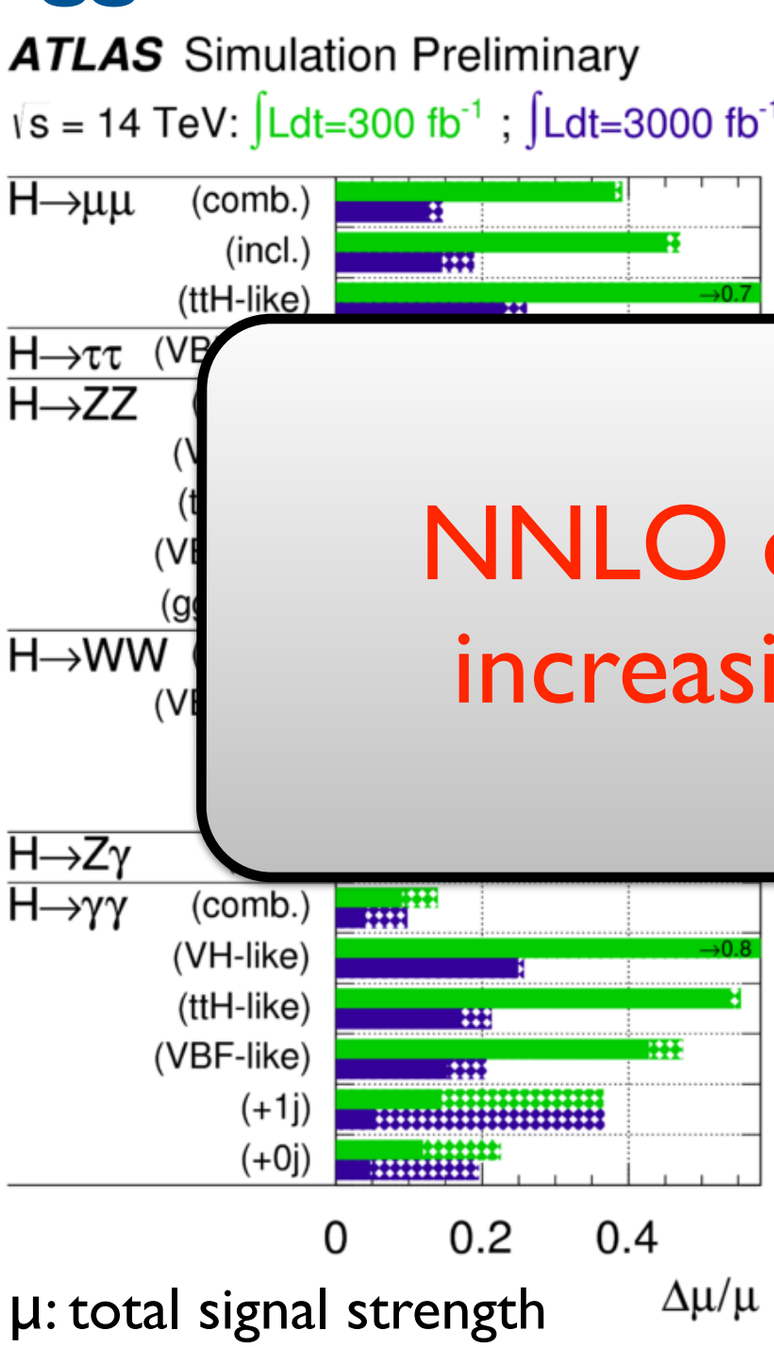
Higgs measurements



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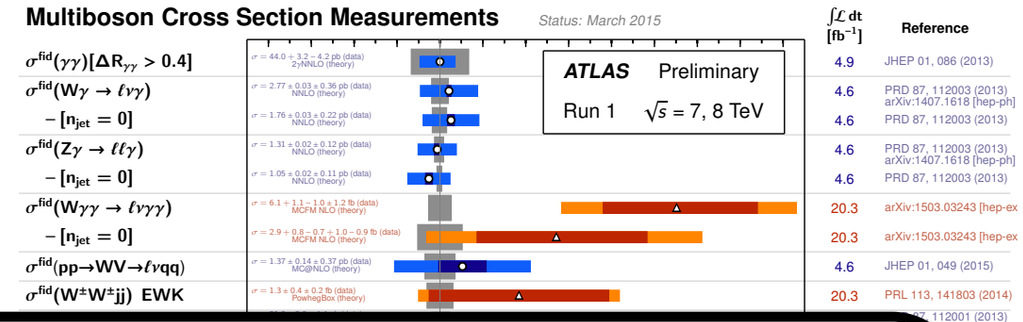

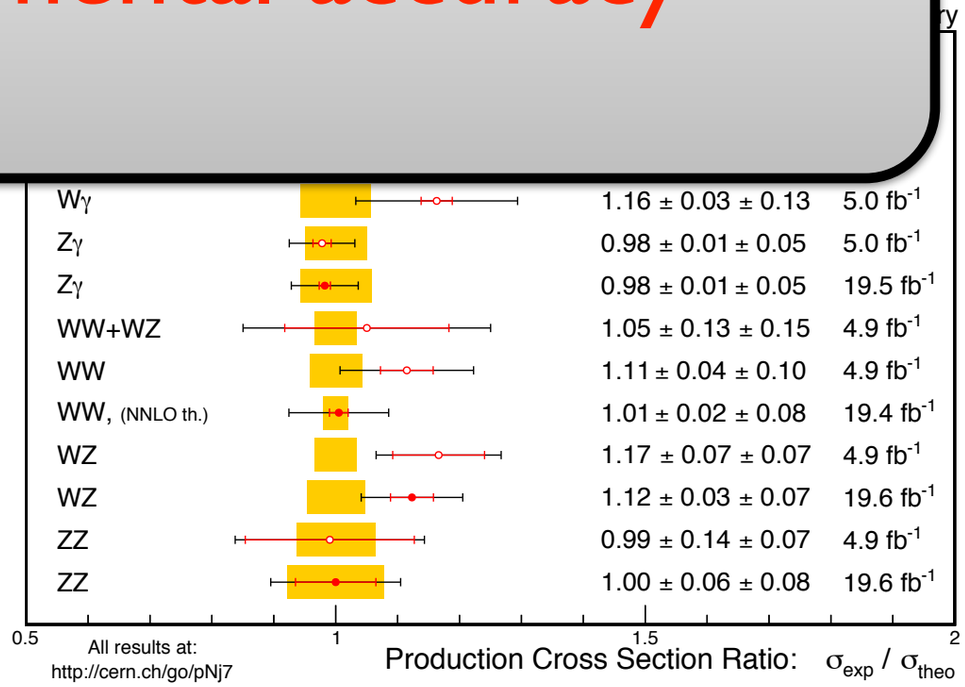

NNLO demanded by continuously increasing experimental accuracy

- All vector-boson pair processes are on the Les Houches NNLO wishlist 2013

NNLO methods

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Schemes with local cancellation of singularities

- Sector decomposition [Binoth, Heinrich '00 '04] [Anastasio, Melnikov, Petriello '04]
- Antenna subtraction [Gehrmann-de Ridder, Gehrmann, Glover '05]
- STRIPPER (FKS+sec.dec.) [Czakon '10, '11]
- FKS + sector decomposition [Boughezal, Melnikov, Petriello '11]
- Colourful subtraction [Somogyi, Trocsanyi, Del Duca '05, '07]

Schemes that start from X+1jet process at NLO

- p_T subtraction [Catani, Grazzini '07]
- N-jettiness subtraction [Tackmann et al. '15]
- (Born projection method) [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]

NNLO methods

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Two-loop amplitudes required for each process!

NNLO methods

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	local	not restricted	automated	applications
Antenna	✓	✓	✗	e^+e^-→2/3jet, pp→H+jets, pp→Z+jets
STRIPPER / FKS+sec.dec	✓	✓	✗	pp→t t-bar, singletop, pp→H+jets
Colourful	✓	only e^+e^- / decays	✗	H→b b-bar
p_T subtraction	✗	only colorless (+massive quarks)	✓	pp→H, pp→Z/W, pp→γγ, pp→ZZ, pp→Z/Wγ, pp→WW, ...
N-jettiness subtraction	✗	no massive quarks	✗	pp→H+jets, pp→Z/W+jets, pp→VH, pp→γγ, more to come...

p_T subtraction and resummation

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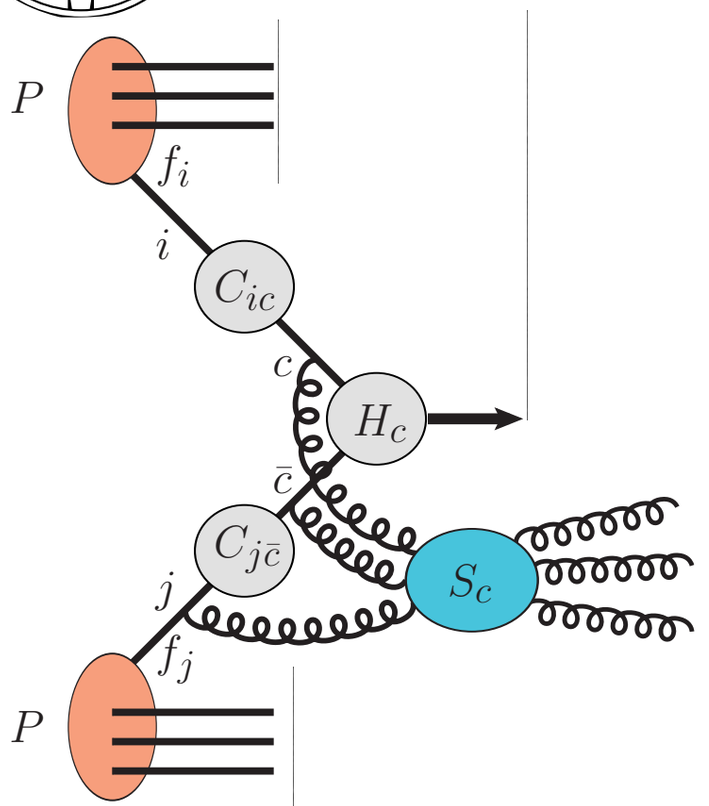
$$\frac{d\sigma^{(\text{res})}}{dp_T^2\, dy\, dM\, d\Omega} \sim \int db\, \frac{b}{2}\, J_0(b\, p_T)\, S(b, A, B)\, \mathcal{H}_{N_1,N_2}\, f_{N_1}\, f_{N_2}$$

[Collins, Soper, Sterman '85], [Bozzi, Catani, de Florian, Grazzini '06]



singular structure of F+1jet process (F -- colorless):

$$d\sigma^{F+1\text{jet}} \xrightarrow{p_T \ll Q} \left[d\sigma^{(\text{res})}\right]_{\text{f.o.}} \equiv \Sigma(p_T/Q) \otimes d\sigma_{\text{LO}}$$

unitarity of p_T resummation due to modified logs:

$$\int dp_T^2\, \frac{d\sigma^{(\text{res})}}{dp_T^2\, dy\, dM\, d\Omega} = \mathcal{H} \otimes d\sigma_{\text{LO}} \quad \left(\ln(Q^2b^2/b_0^2) \to \ln(Q^2b^2/b_0^2 + 1)\right)$$

→ **p_T subtraction master formula:** [Catani, Grazzini '07]

$$d\sigma_{\text{NNLO}} = \left[d\sigma_{\text{NLO}}^{F+1\text{jet}} - \Sigma_{\text{NNLO}} \otimes d\sigma_{\text{LO}}\right] + \mathcal{H}_{\text{NNLO}} \otimes d\sigma_{\text{LO}}$$

We implemented...

The MATRIX framework

[Grazzini, Kallweit, Rathlev, MW] (+Hanga, Sargsyan)

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 qT Subtraction and Resummation to Integrate X-sections.

The MATRIX framework

[Grazzini, Kallweit, Rathlev, MW] (+Hanga, Sargsyan)

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Fully differential NNLO(+NNLL) for colorless particle production

NNLO part applies:

- Fully-automated NLO computation through MUNICH [Kallweit]
- Fully-automated p_T subtraction [Catani, Grazzini '07]
- Fully-automated tree and one-loop amplitudes through OpenLoops [Cascioli, Maierhöfer, Pozzorini '11]
- REQUIRED: two-loop amplitude (e.g. for VV and V*V*) [Gehrmann, von Manteuffel, Tancredi '15]

NNLL part applies:

- Fully-automated p_T resummation (qq and gg initiated)
- Based on HRES implementation (gg initiated) [de Florian, Ferrera, Grazzini, Tommasini '12]

The MATRIX

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Mars — ssh — 174×63

```
[wiesemann:~/munich-http/MATRIX] ./matrix

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

          Version: 1.0.beta1                    Dec 2015

 Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision --
 Automates qT-subtraction and Resummation to Integrate X-sections

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 S. Kallweit                             (kallweit@uni-mainz.de)
 D. Rathlev                              (rathlev@physik.uzh.ch)
 M. Wiesemann                            (mariusw@physik.uzh.ch)

 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.

<<MATRIX-MAKE>> This is the MATRIX process compilation.
<<MATRIX-READ>> Type process_id to be compiled and created. Type "list" to show
                available processes. Try pressing TAB for auto-completion. Type
                "exit" or "quit" to stop.
|=============>>
<<MATRIX-READ>> No suitable process_id or command has been entered. Try again...
<<MATRIX-READ>> You have to choose a process_id from the following list:
--------------------------------------------------------------------------------------------------------
process_id    ||   process                          ||   description
--------------------------------------------------------------------------------------------------------
pph21         >>   p p --> H                        >>   on-shell Higgs production
ppz01         >>   p p --> Z                        >>   on-shell Z production
ppw01         >>   p p --> W^-                      >>   on-shell W+ production, NOT FULLY TESTED YET
ppwx01        >>   p p --> W^+                      >>   on-shell W- production, NOT FULLY TESTED YET
ppeex02       >>   p p --> e^- e^+                  >>   Z production with decay
ppnenex02     >>   p p --> v_e^- v_e^+              >>   Z production with decay
ppexne02      >>   p p --> e^+ v_e^-                >>   W+ production with decay, NOT FULLY TESTED YET
ppenex02      >>   p p --> e^- v_e^+                >>   W- production with decay, NOT FULLY TESTED YET
pphh22        >>   p p --> H H                      >>   on-shell double Higgs production
ppaa02        >>   p p --> gamma gamma              >>   on-shell gamma gamma production
ppzz02        >>   p p --> Z Z                      >>   on-shell ZZ production
ppeexa03      >>   p p --> e^- e^+ gamma            >>   Z gamma & gamma gamma with decay
ppnenexa03    >>   p p --> v_e^- v_e^+ gamma        >>   Z gamma & gamma gamma with decay
ppeeexex04    >>   p p --> e^- e^- e^+ e^+          >>   ZZ & Z gamma & gamma gamma with decay
ppemexmx04    >>   p p --> e^- mu^- e^+ mu^+        >>   ZZ & Z gamma & gamma gamma with decay
ppexnea03     >>   p p --> e^+ v_e^- gamma          >>   W+ gamma with decay
ppenexa03     >>   p p --> e^- v_e^+ gamma          >>   W- gamma with decay
ppemxnmnex04  >>   p p --> e^- mu^+ v_mu^- v_e^+    >>   WW production with decay
ppemexnmx04   >>   p p --> e^- mu^- e^+ v_mu^+      >>   W-Z production with decay
ppeexmxnm04   >>   p p --> e^- e^+ mu^+ v_mu^-      >>   W+Z production with decay
|=============>> pph21
<<MATRIX-MAKE>> Starting compilation...
```

The Status

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process	status	comment
$pp \to Z/\gamma^*(\to \ell^+\ell^-)$	✓	validated analytically (+ DYNNLO)
$pp \to W \to \ell\nu$	(✓)	to be validated
$pp \to H$	(✓)	under validation
$pp \to \gamma\gamma$	✓	validated with 2γNNLO
$pp \to Z\gamma \to \ell^+\ell^-\gamma$	✓	[Grazzini, Kallweit, Rathlev, Torre '13]
$pp \to W\gamma \to \ell\nu\gamma$	✓	[Grazzini, Kallweit, Rathlev '15]
$pp \to ZZ$	✓	[Cascioli et al. '14]
$pp \to ZZ \to 4\ell$	✓	[Grazzini, Kallweit, Rathlev '15]
$pp \to WW$	✓	[Gehrmann et al. '14]
$pp \to WW \to \ell\nu\,\ell'\nu'$	✓	**NEW HERE:** fully differential
$pp \to WZ$	✓	**NEW HERE:** inclusive cross section

The Plan

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1. Closed beta
   - TIME FRAME: within next 1-2 month
   - PROCESSES: all processes of previous slide
   - ACCURACY: NNLO QCD
   - CURRENTLY SUPPORTED:
     - local running
     - SLURM cluster
     - which other cluster are needed?
2. Public release
   - TIME FRAME: within this year
   - further cluster support
3. Plans beyond first release
   - enable NNLO+NNLL p_T resummation
   - add NLO EW effects to certain processes

NNLO+NNLL resummation for ZZ and WW

[Grazzini, Kallweit, Rathlev, MW '15]

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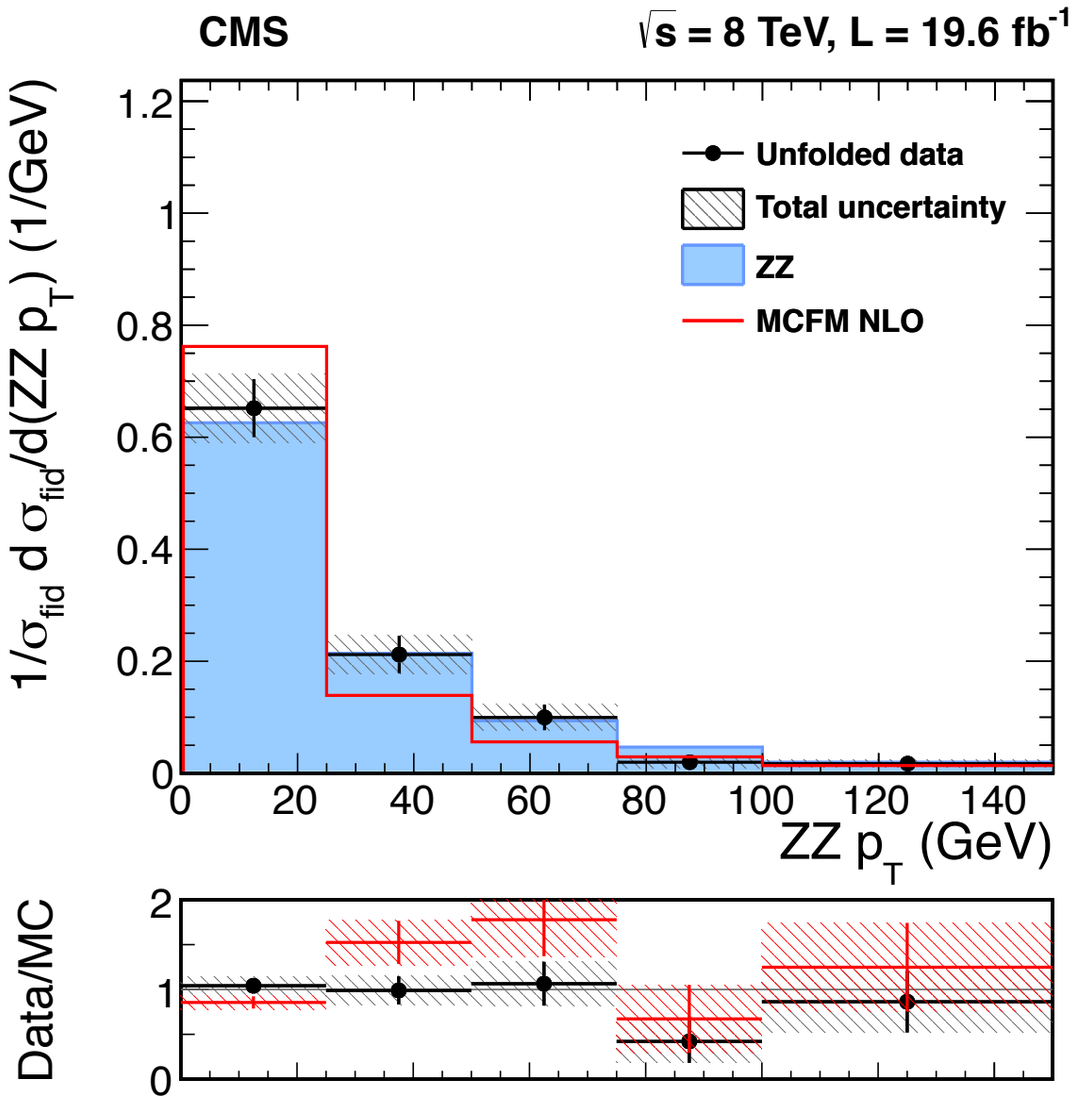
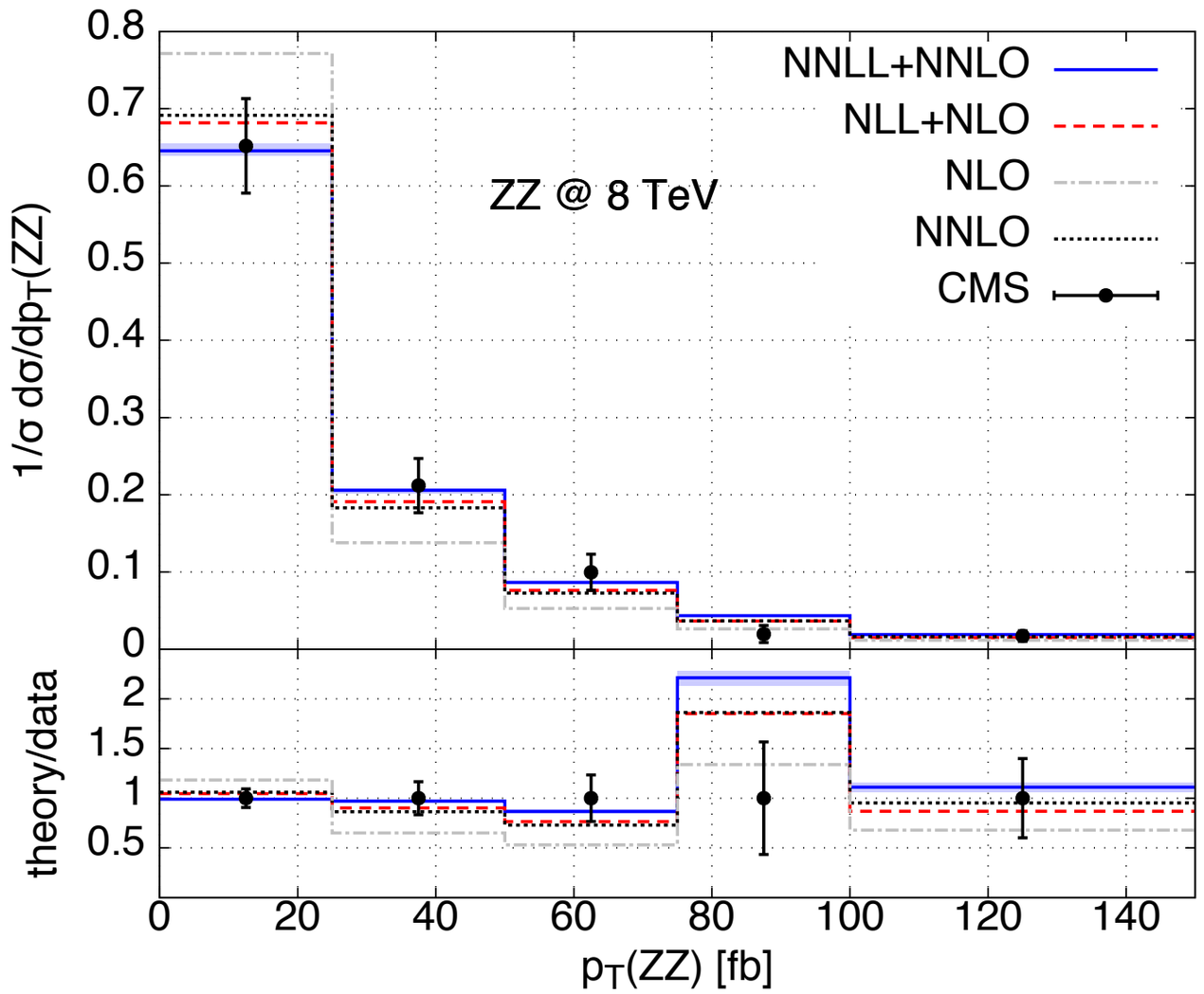
p_T spectrum of ZZ pair: comparison to data

[CMS '15]



[Grazzini, Kallweit, Rathlev, MW '15]



WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW to appear]

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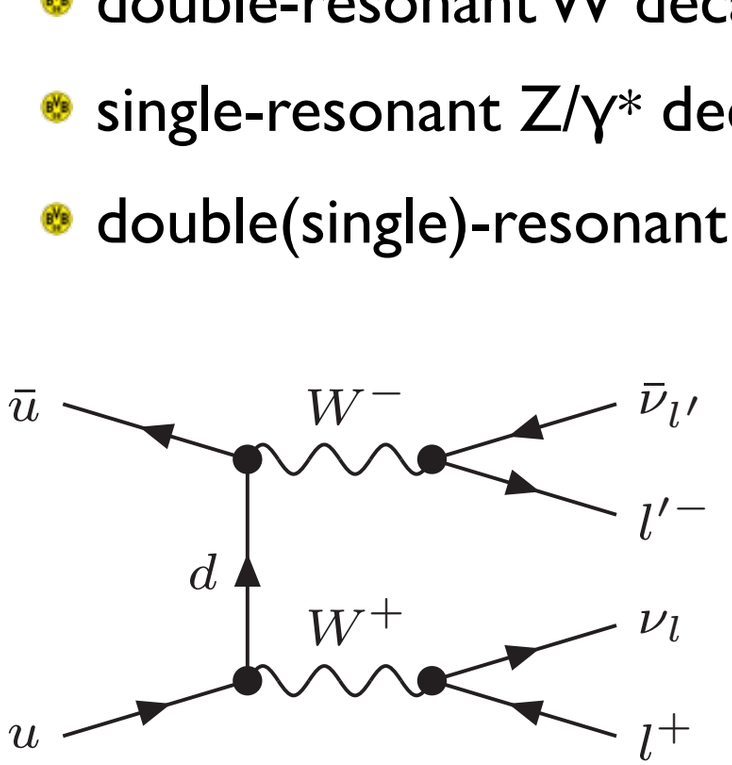
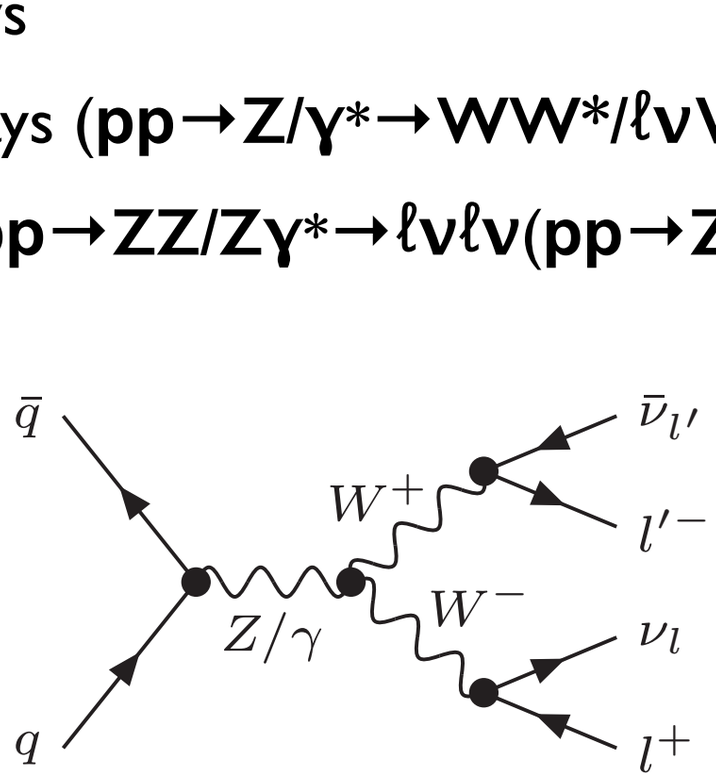
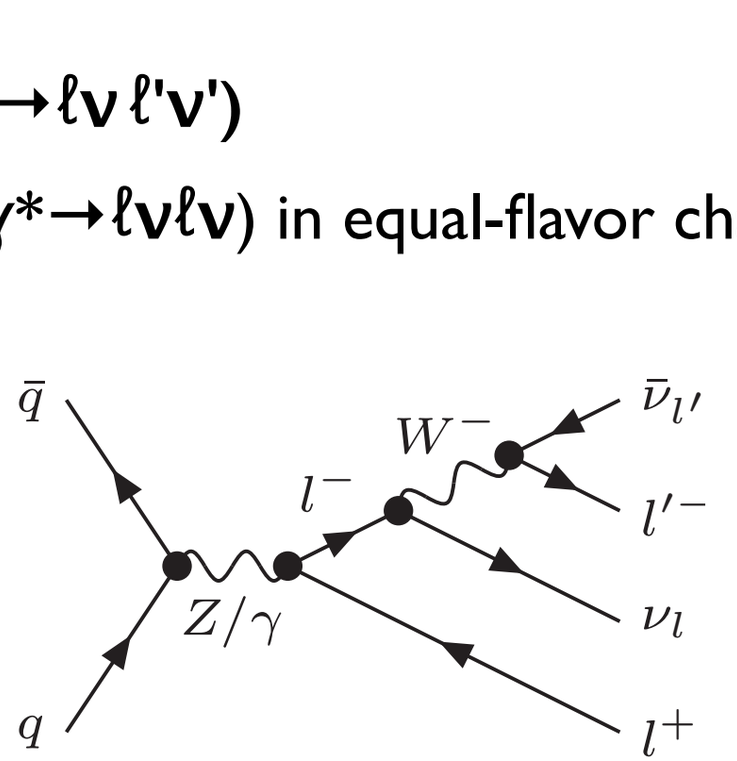
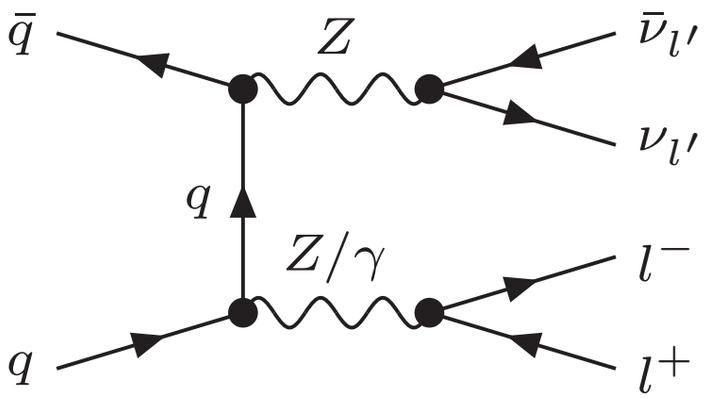
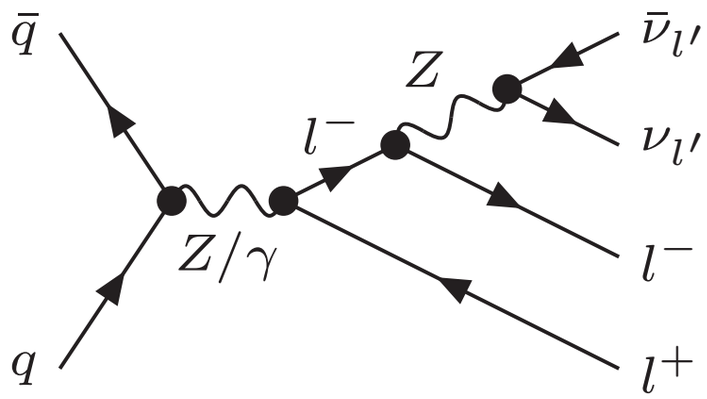
- all $pp \to WW \to \ell\nu\,\ell'\nu'$ processes, including:
  - double-resonant W decays
  - single-resonant Z/γ* decays ($pp \to Z/\gamma^* \to WW^*/\ell\nu W \to \ell\nu\,\ell'\nu'$)
  - double(single)-resonant $pp \to ZZ/Z\gamma^* \to \ell\nu\ell\nu$($pp \to Z/\gamma^* \to \ell\nu\ell\nu$) in equal-flavor channel











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  - double(single)-resonant $pp \to ZZ/Z\gamma^* \to \ell\nu\ell\nu$($pp \to Z/\gamma^* \to \ell\nu\ell\nu$) in equal-flavor channel
- HERE: different-flavour channel $pp \to WW \to e\nu_e\,\mu\nu_\mu$ (for simplicity):
- inclusive

- **WW signal cuts:**

$m_{ll} > 10\,\text{GeV}, \quad \Delta R_{ll} > 0.1, \quad p_T^{\text{miss}} > 15\ \text{GeV}, \quad p_T^{\text{miss, rel}} > 20\,\text{GeV}$

jet veto $(\text{anti-}k_T,\ R = 0.4,\ p_{T,j} > 25\,\text{GeV},\ |y_j| < 4.5)$

lepton cuts $(p_{T,l_1} > 25\,\text{GeV},\ p_{T,l_2} > 20\,\text{GeV},\ |y_\mu| < 2.4,\ |y_e| < 1.37 \text{ or } 1.52 < |y_e| < 2.47)$

- **Higgs background cuts:**

$10\,\text{GeV} < m_{ll} < 55\,\text{GeV}, \quad p_{T,ll} > 30\ \text{GeV}, \quad \Delta\phi_{ll} < 1.8, \quad \Delta\phi_{ll,\nu\nu} > \pi/2, \quad p_T^{\text{miss}} > 20\ \text{GeV}$

jet veto $(\text{anti-}k_T,\ R = 0.4,\ p_{T,j} > 25\,\text{GeV},\ |y_j| < 4.5)$

lepton cuts $(p_{T,l_1} > 22\,\text{GeV},\ p_{T,l_2} > 10\,\text{GeV},\ |y_\mu| < 2.4,\ |y_e| < 1.37 \text{ or } 1.52 < |y_e| < 2.47)$

- avoid top contamination: 4FS with all bottom final states removed.
  (checked against top-subtracted 5FS predicion for all fiducial rates up to ~1%)

WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW to appear]

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inclusive rates

σ [fb]	8 TeV	13 TeV
LO	$425.41(4)\,^{+2.8\%}_{-3.6\%}$	$778.99\ (8)\,^{+5.7\%}_{-6.7\%}$
NLO	$623.47(6)\,^{+3.6\%}_{-2.9\%}$	$1205.11(12)\,^{+3.9\%}_{-3.1\%}$
NLO′+gg	$655.83(8)\,^{+4.3\%}_{-3.3\%}$	$1286.81(13)\,^{+4.8\%}_{-3.7\%}$
NNLO	$690.4(5)\,^{+2.2\%}_{-1.9\%}$	$1370.9(11)\,^{+2.6\%}_{-2.3\%}$

fiducial rates (WW cuts)

8 TeV	13 TeV
$147.23(2)\,^{+3.4\%}_{-4.4\%}$	$233.04(2)\,^{+6.6\%}_{-7.6\%}$
$153.07(2)\,^{+1.9\%}_{-1.6\%}$	$236.19(2)\,^{+2.8\%}_{-2.4\%}$
$166.41(3)\,^{+1.3\%}_{-1.3\%}$	$267.31(4)\,^{+1.5\%}_{-2.1\%}$
$164.1\ (1)\,^{+1.3\%}_{-0.8\%}$	$261.5(2)\,^{+1.9\%}_{-1.2\%}$

NLO'+gg = NLO+gg BOTH with NNLO PDFs

→ **acceptances (WW cuts)**

$A = \sigma^{\text{cuts}}/\sigma^{\text{inclusive}}$	8 TeV	13 TeV
LO	$0.34608(7)^{+0.6\%}_{-0.7\%}$	$0.29915(6)^{+0.8\%}_{-1.0\%}$
NLO	$0.24552(5)^{+4.4\%}_{-4.7\%}$	$0.19599(4)^{+4.4\%}_{-4.7\%}$
NLO′+gg	$0.25374(7)^{+3.5\%}_{-3.7\%}$	$0.20773(5)^{+3.2\%}_{-3.1\%}$
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[Grazzini, Kallweit, Pozzorini, Rathlev, MW to appear]

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$166.41(3)^{+1.3\%}_{-1.3\%}$	-1.4%	$267.31(4)^{+1.5\%}_{-2.1\%}$	-2.2%
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LO	$425.41(4)^{+2.8\%}_{-3.6\%}$	+47%	$778.99\ (8)^{+5.7\%}_{-6.7\%}$	+55%
NLO	$623.47(6)^{+3.6\%}_{-2.9\%}$	+5.2%	$1205.11(12)^{+3.9\%}_{-3.1\%}$	+6.8%
NLO′+gg	$655.83(8)^{+4.3\%}_{-3.3\%}$	+5.3%	$1286.81(13)^{+4.8\%}_{-3.7\%}$	+6.5%
NNLO	$690.4(5)\ ^{+2.2\%}_{-1.9\%}$		$1370.9(11)\ ^{+2.6\%}_{-2.3\%}$	

fiducial rates (WW cuts)

8 TeV		13 TeV	
$147.23(2)^{+3.4\%}_{-4.4\%}$	+4%	$233.04(2)^{+6.6\%}_{-7.6\%}$	+1.3%
$153.07(2)^{+1.9\%}_{-1.6\%}$	+8.7%	$236.19(2)^{+2.8\%}_{-2.4\%}$	+13%
$166.41(3)^{+1.3\%}_{-1.3\%}$	-1.4%	$267.31(4)^{+1.5\%}_{-2.1\%}$	-2.2%
$164.1\ (1)^{+1.3\%}_{-0.8\%}$		$261.5(2)\ ^{+1.9\%}_{-1.2\%}$	

NLO'+gg = NLO+gg BOTH with NNLO PDFs

→ acceptances (WW cuts)

$A = \sigma^{\text{cuts}}/\sigma^{\text{inclusive}}$	8 TeV		13 TeV	
LO	$0.34608(7)^{+0.6\%}_{-0.7\%}$	+29%	$0.29915(6)^{+0.8\%}_{-1.0\%}$	+34%
NLO	$0.24552(5)^{+4.4\%}_{-4.7\%}$	+3.3%	$0.19599(4)^{+4.4\%}_{-4.7\%}$	+6%
NLO′+gg	$0.25374(7)^{+3.5\%}_{-3.7\%}$	-6.3%	$0.20773(5)^{+3.2\%}_{-3.1\%}$	-8.2%
NNLO	$0.2378(4)\ ^{+1.3\%}_{-0.9\%}$		$0.1907(3)\ ^{+1.2\%}_{-0.9\%}$	

WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW to appear]

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fiducial rates (Higgs cuts)

	σ [fb]		$\sigma/\sigma_{\rm NLO} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$45.923(4)\,^{+4.0\%}_{-5.0\%}$	$71.164\ (7)\,^{+7.2\%}_{-8.2\%}$	$-\ 4.4\%$	$-\ 2.6\%$
NLO	$48.045(5)\,^{+1.9\%}_{-1.7\%}$	$73.085\ (6)\,^{+2.7\%}_{-2.4\%}$	0	0
NLO'+gg	$53.496(8)\,^{+2.0\%}_{-1.5\%}$	$85.231(12)\,^{+2.5\%}_{-2.5\%}$	$+11.3\%$	$+16.6\%$
NNLO	$52.30(4)\ \,^{+1.6\%}_{-1.0\%}$	$82.32(12)\ \,^{+2.4\%}_{-2.6\%}$	$+\ 8.9\%$	$+12.6\%$

acceptances (Higgs cuts)

	$A = \sigma^{\rm H-cuts}/\sigma^{\rm inclusive}$ [fb]		$A/A_{\rm NLO} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$0.10795\ (2)^{+1.2\%}_{-1.4\%}$	$0.09135\ (2)^{+1.5\%}_{-1.7\%}$	$+40.1\%$	$+50.6\%$
NLO	$0.07706\ (2)^{+4.3\%}_{-4.6\%}$	$0.06065\ (1)^{+4.3\%}_{-4.5\%}$	0	0
NLO'+gg	$0.08157\ (2)^{+3.1\%}_{-3.1\%}$	$0.06623\ (2)^{+2.7\%}_{-2.5\%}$	$+\ 5.9\%$	$+\ 9.2\%$
NNLO	$0.07575(11)^{+1.2\%}_{-0.8\%}$	$0.06005(14)^{+1.1\%}_{-0.9\%}$	$-\ 1.7\%$	$-\ 1.0\%$

WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW to appear]

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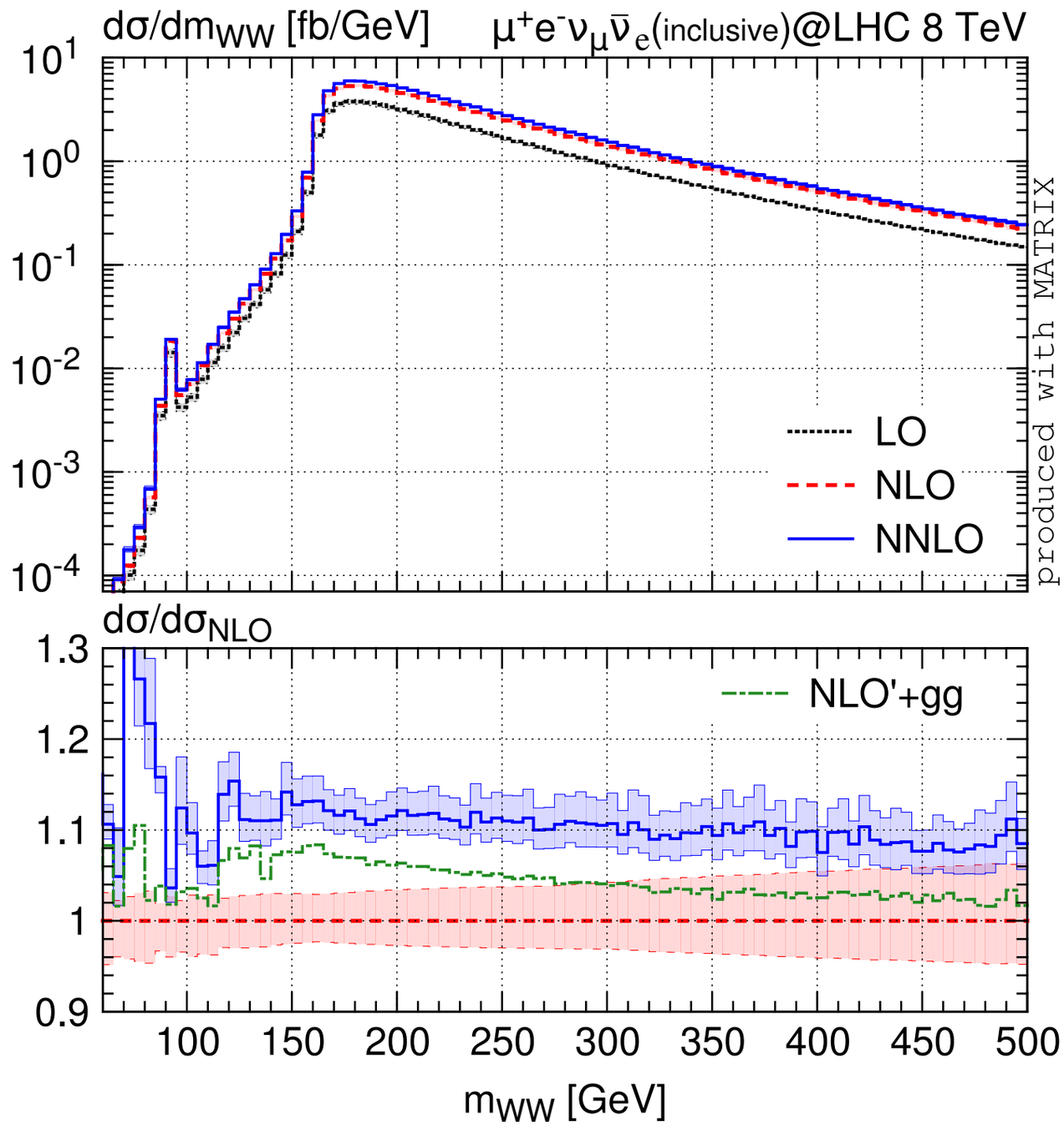
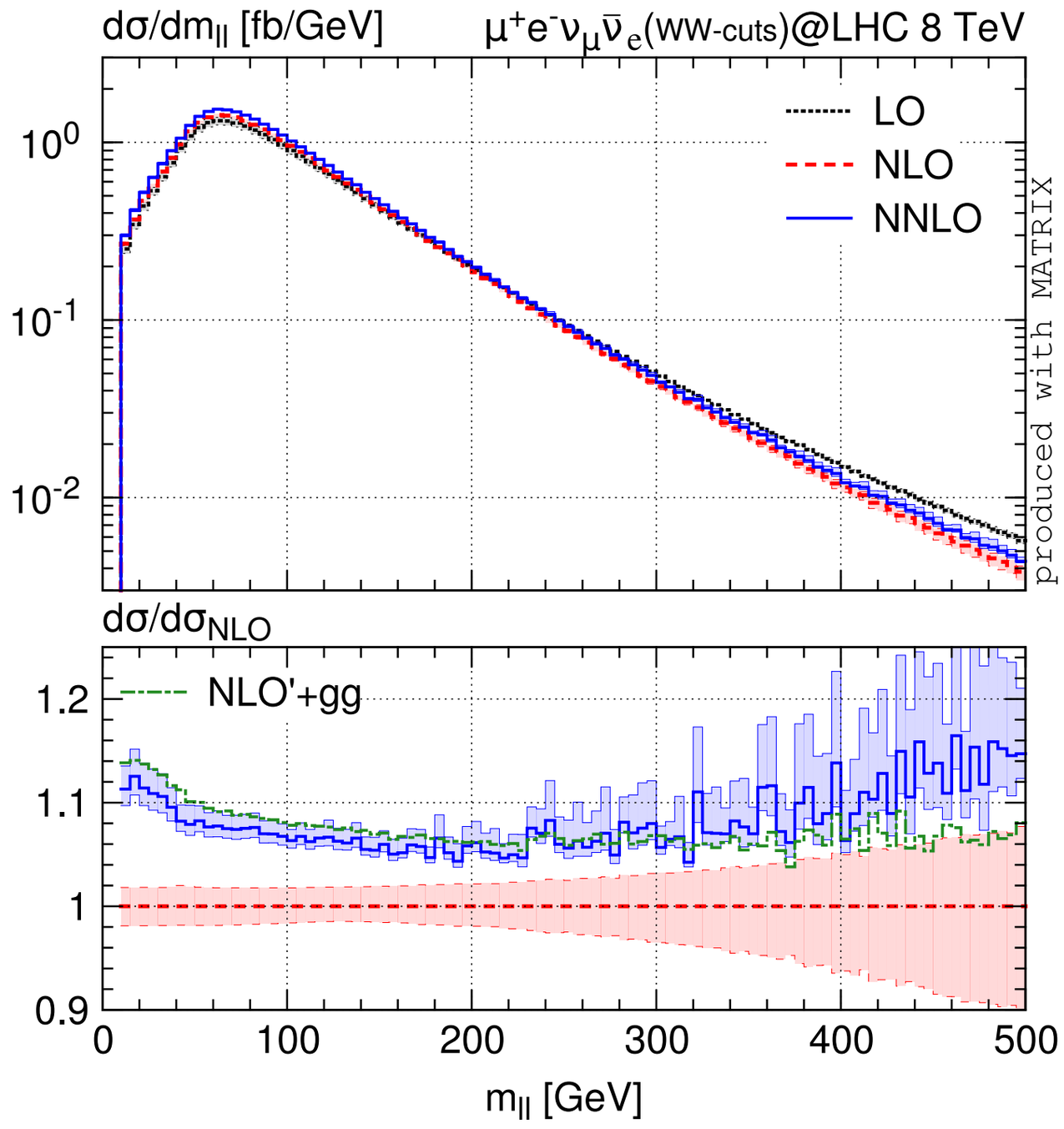
inclusive: distributions



WW cuts: distributions



WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW to appear]

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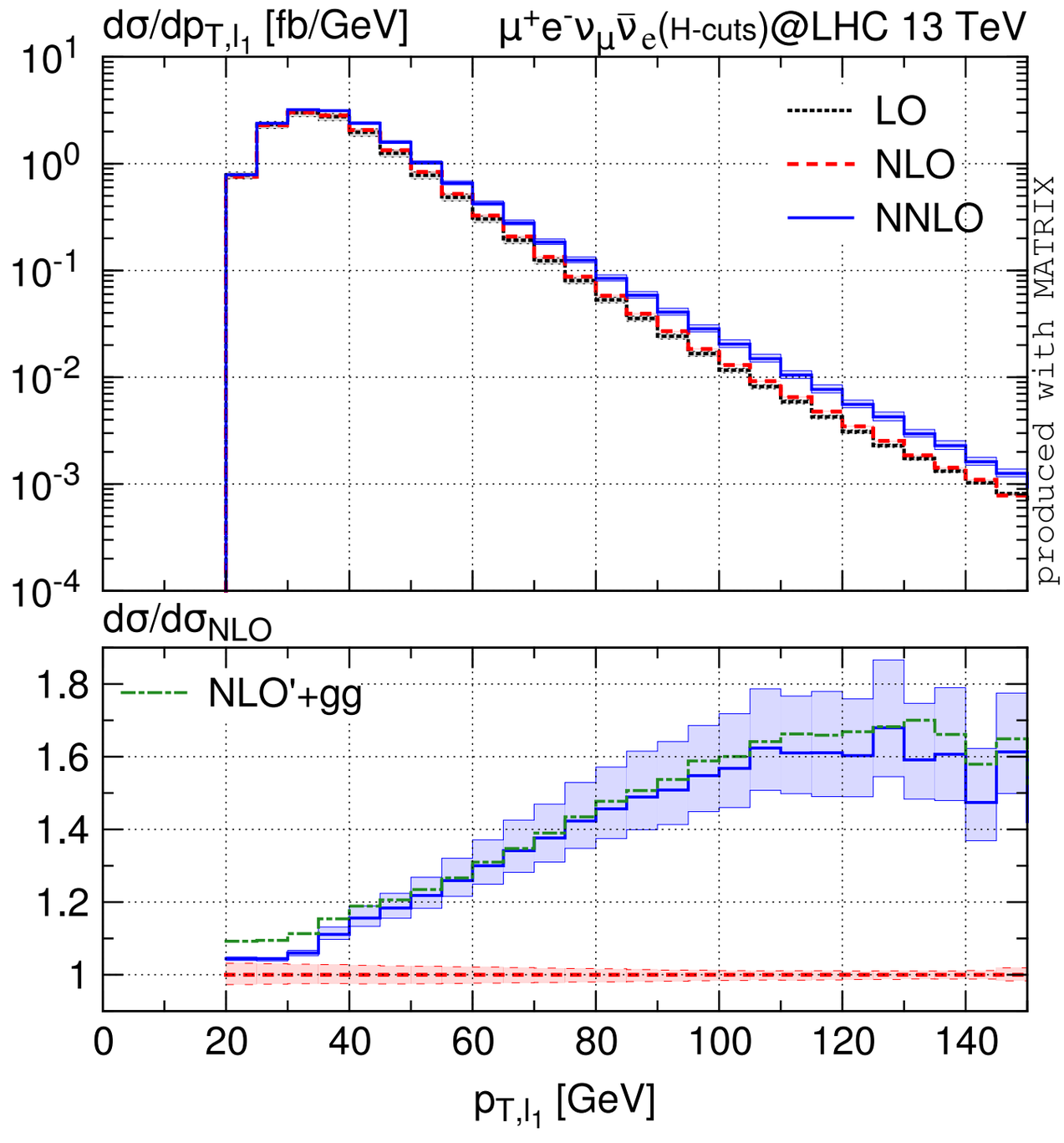
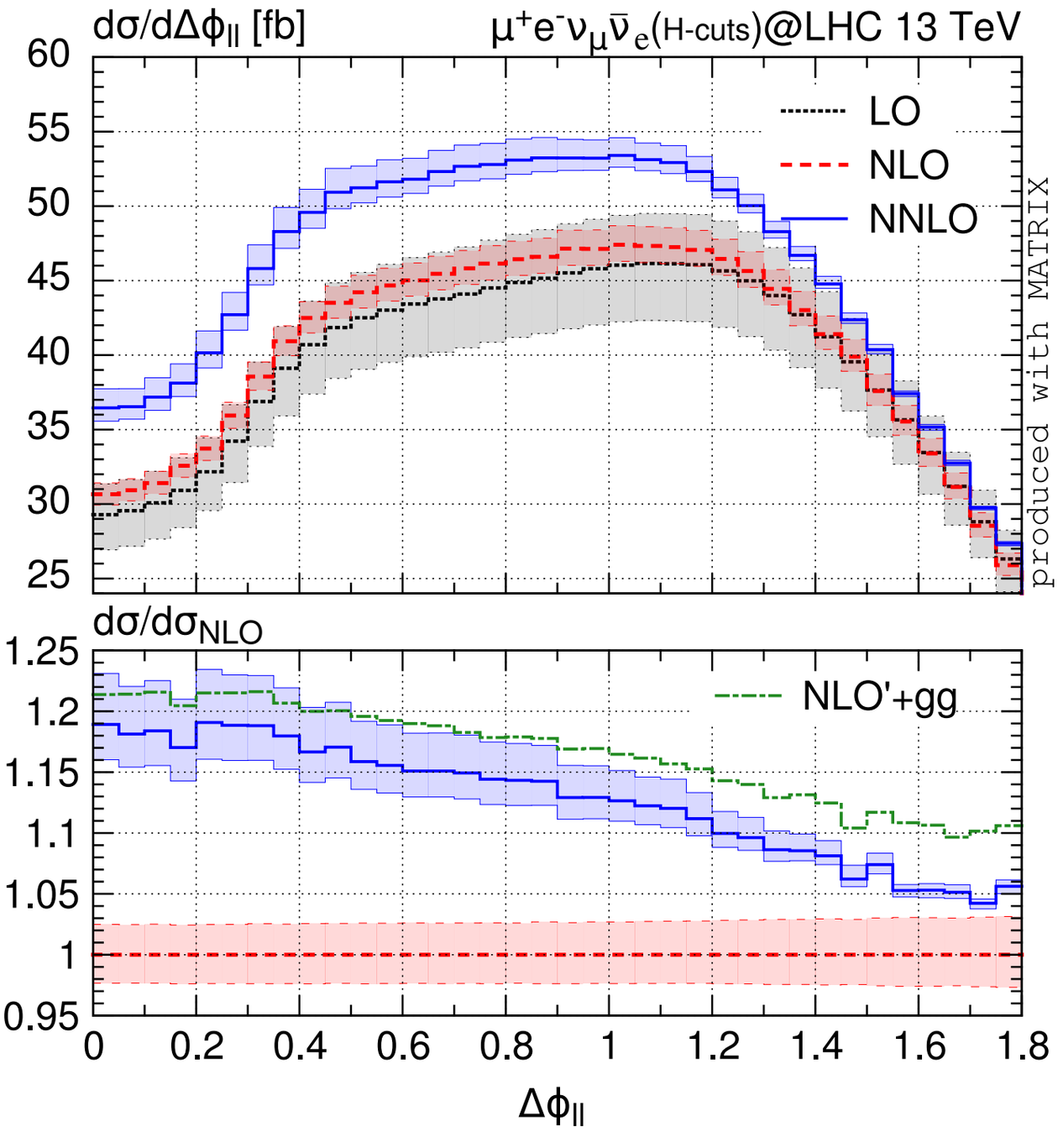
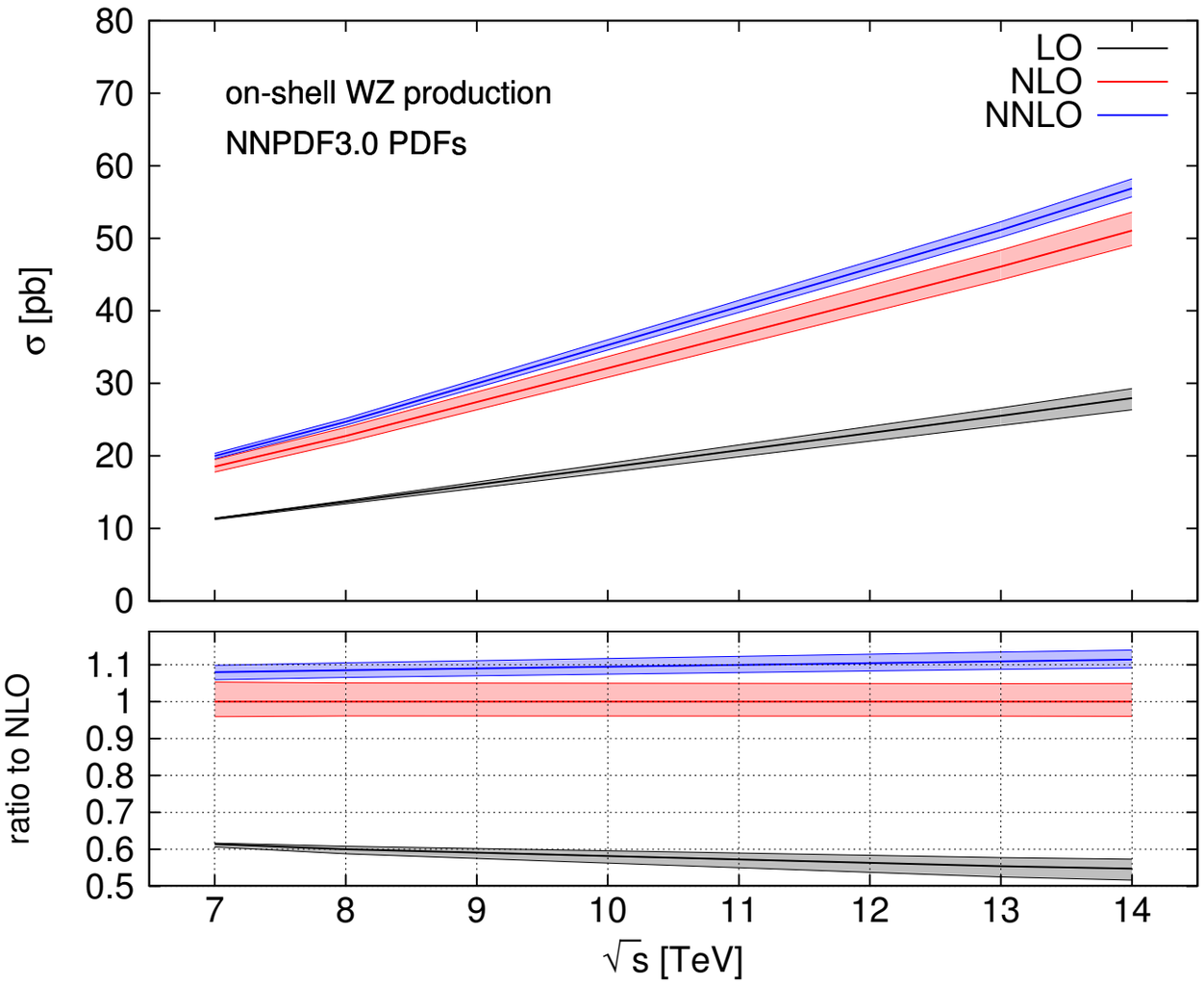
Higgs background cuts: distributions (13 TeV)





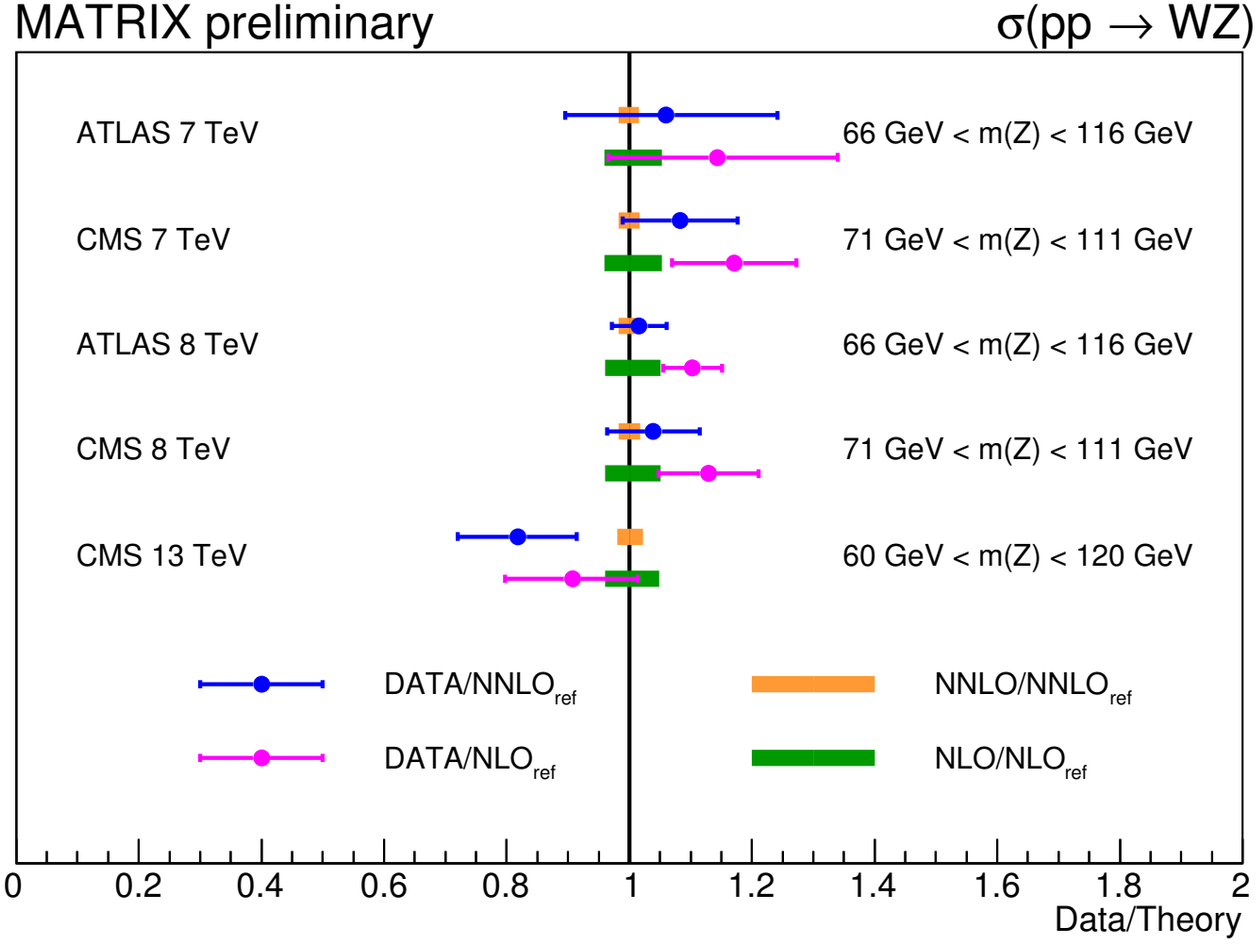
WZ cross section at NNLO

[Grazzini, Kallweit, Rathlev, MW to appear]



- Huge radiative corrections due to approximate radiation zero [Baur, Han, Ohnemus '94]
- ~63-83% NLO corrections
- ~8-11% NNLO corrections

- NNLO corrections nicely improve agreement with data at 7 and 8 TeV
- slightly worse for 13 TeV CMS, but still large uncertainties



Summary

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MATRIX:

- tool for fully-differential NNLO(+NNLL) computations
- SOON: closed beta
- large list of 2→1, 2→2 Higgs and vector-boson processes
- including various fully-differential EW decays

p_T resummation automated in same framework (first application: WW, ZZ)

NNLO corrections for all vector-boson pair processes COMPLETED:

- WZ with large radiative corrections due to approximate radiation zero
- WW fully-differential NNLO cross section
- NLO'+gg good approximation of NNLO, when jet veto applied
- BUT: significant NNLO corrections on fiducial acceptances
- AND: additional shape effects by genuine NNLO corrections

Outlook

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- public release within this year
- NNLL p_T resummation for all available NNLO processes
- fully-differential NNLO cross section for WZ production
- NLO QCD corrections to loop-induced gg channel of diboson processes
- NLO EW effects for dedicated processes
- LONG TERM: heavy-quark pair production at NNLO

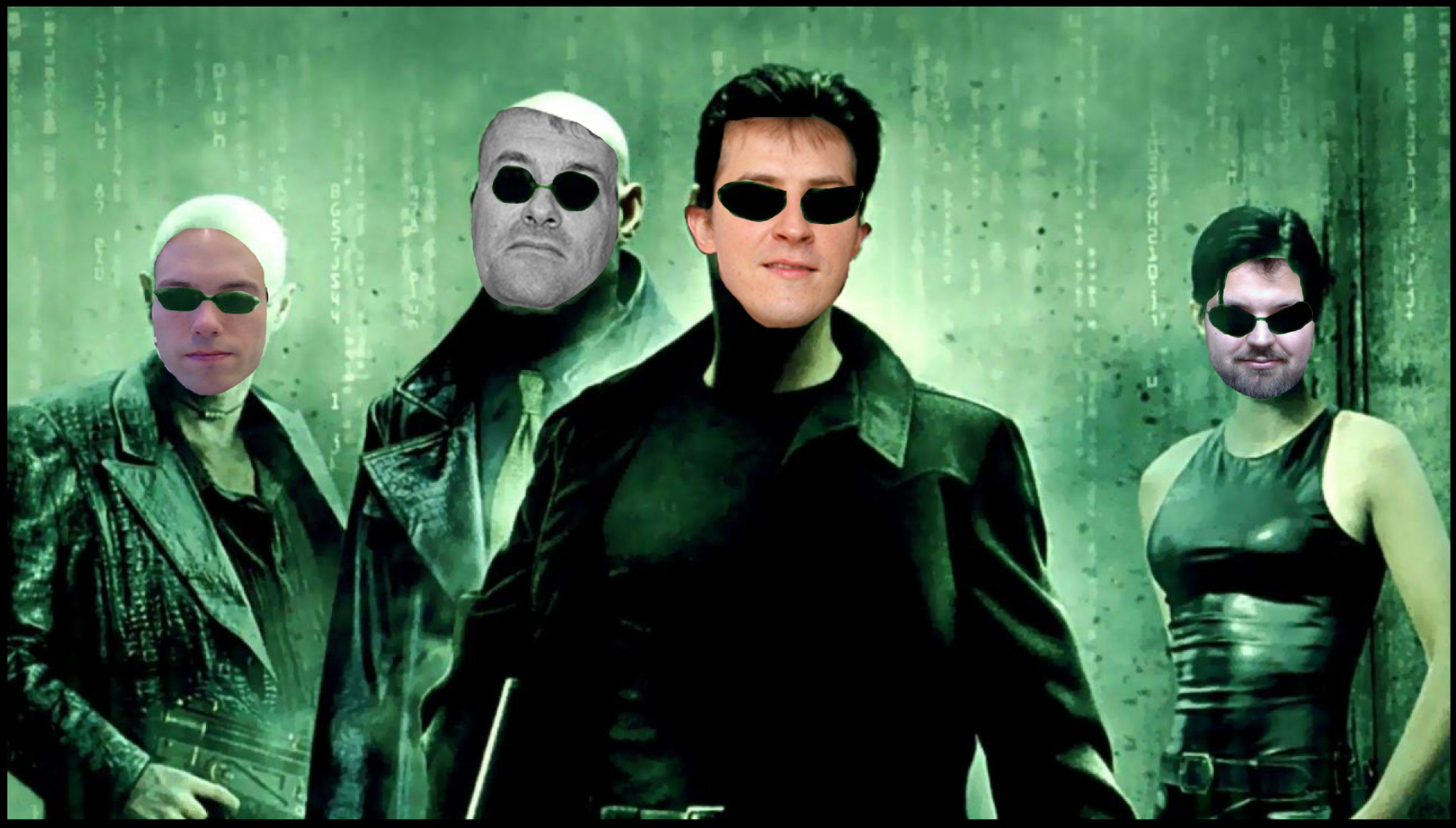
FREE YOUR MIND.

THE MATRIX

Thank You !

Back Up

The MATRIX team



Dirk	Massimiliano	Stefan	Marius
"Cypher"	"Morpheus"	"Neo"	"Trinity"
Rathlev	Grazzini	Kallweit	Wiesemann

matching: FO+resummation

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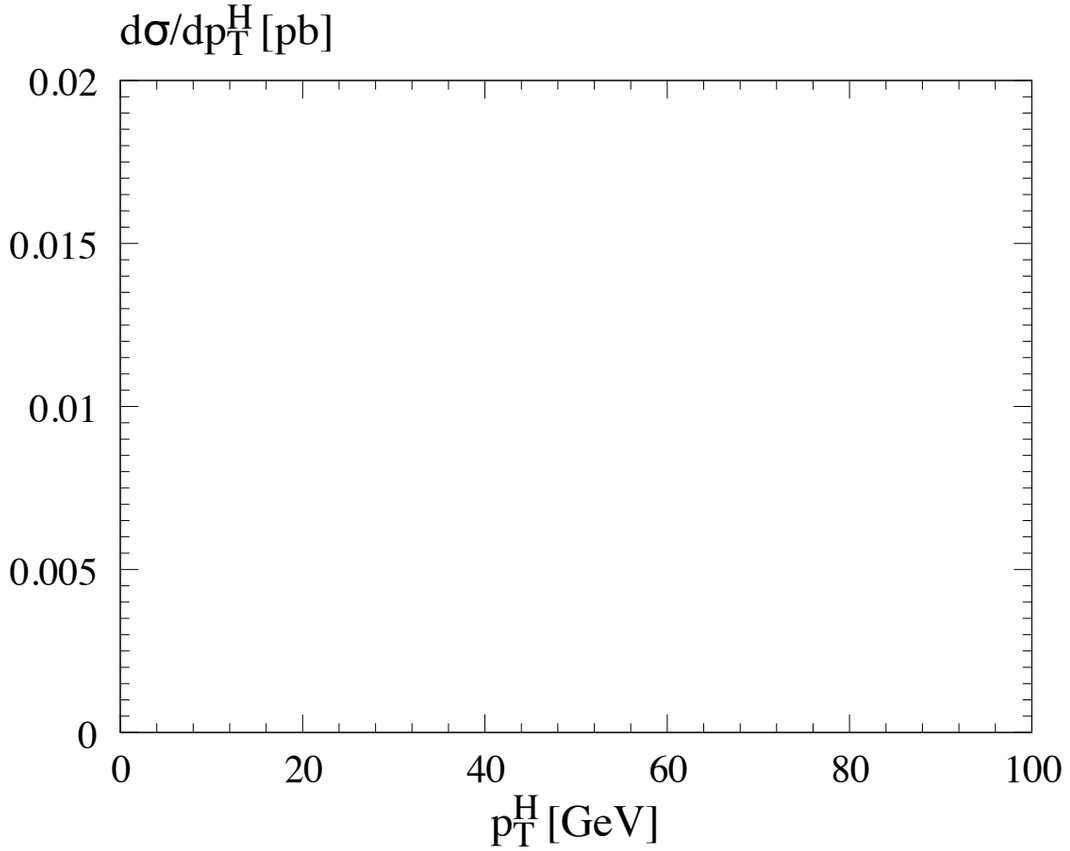
$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} =$$



matching: FO+resummation

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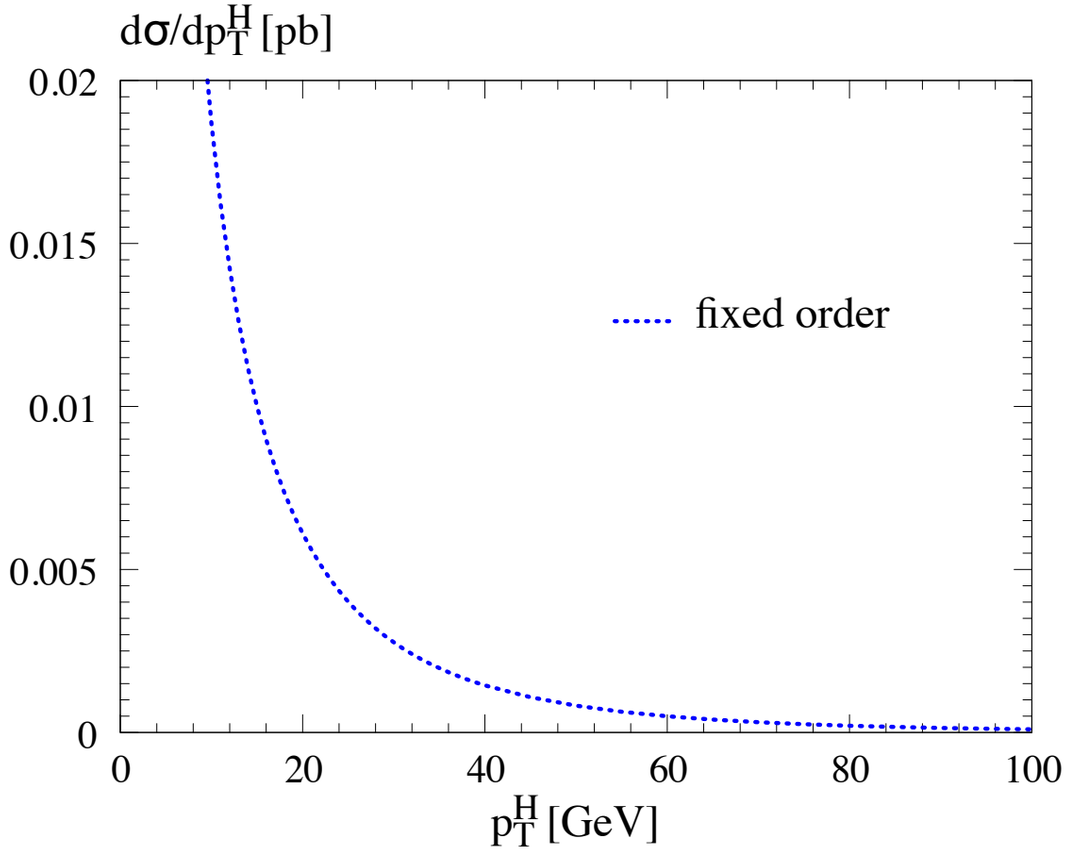
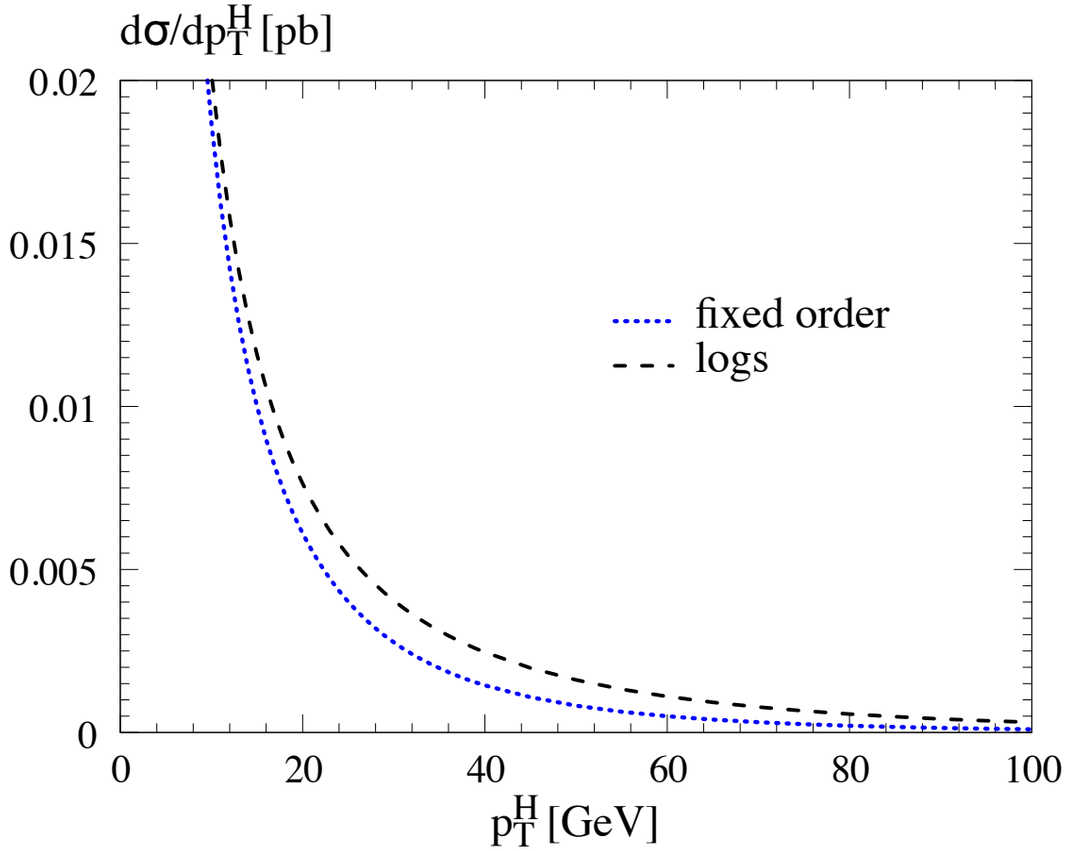
$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}}$$



matching: FO+resummation

Universität Zürich[UZH]

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{f.o.}}$$



matching: FO+resummation

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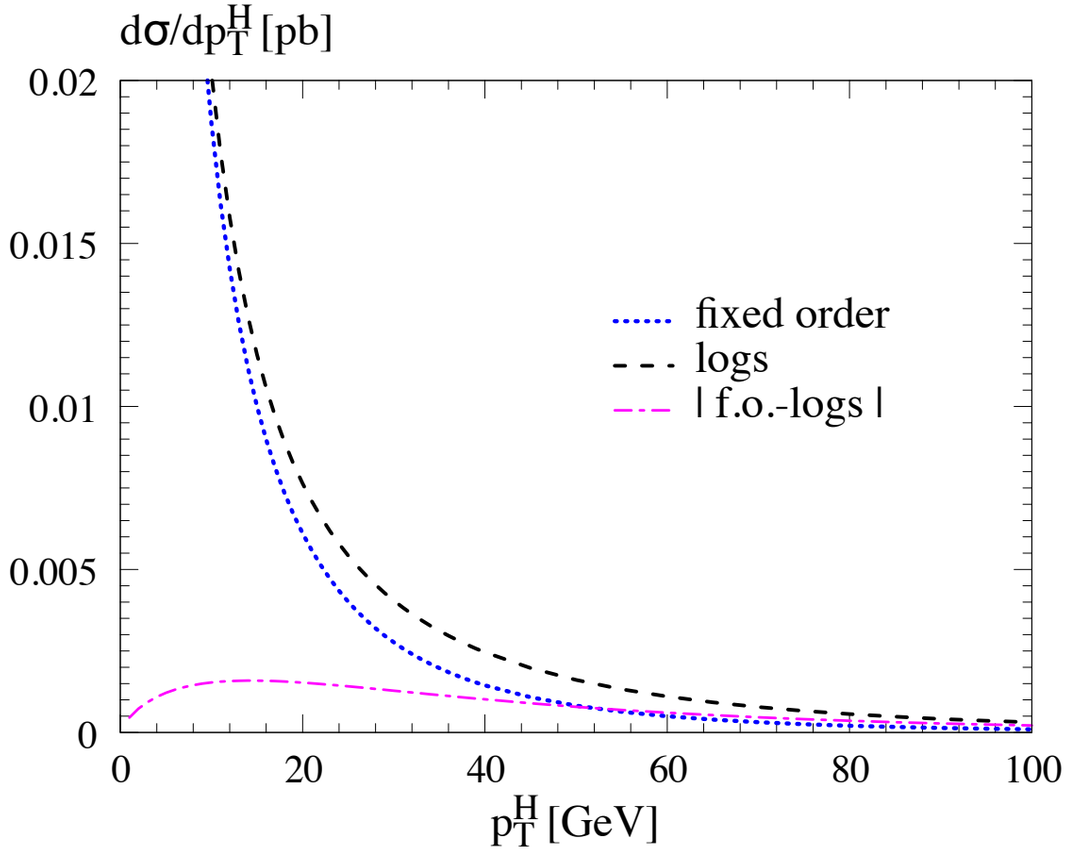
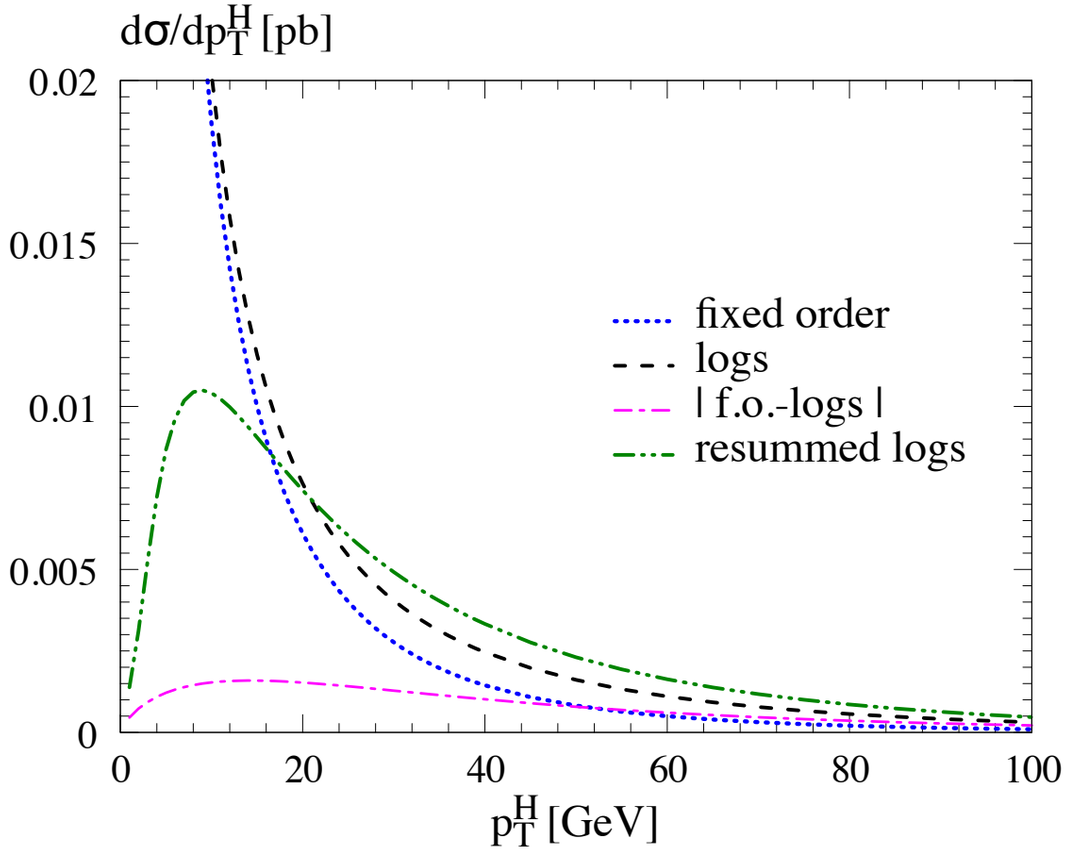
$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{f.o.}}$$



matching: FO+resummation

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} + \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{l.a.}}$$



matching: FO+resummation

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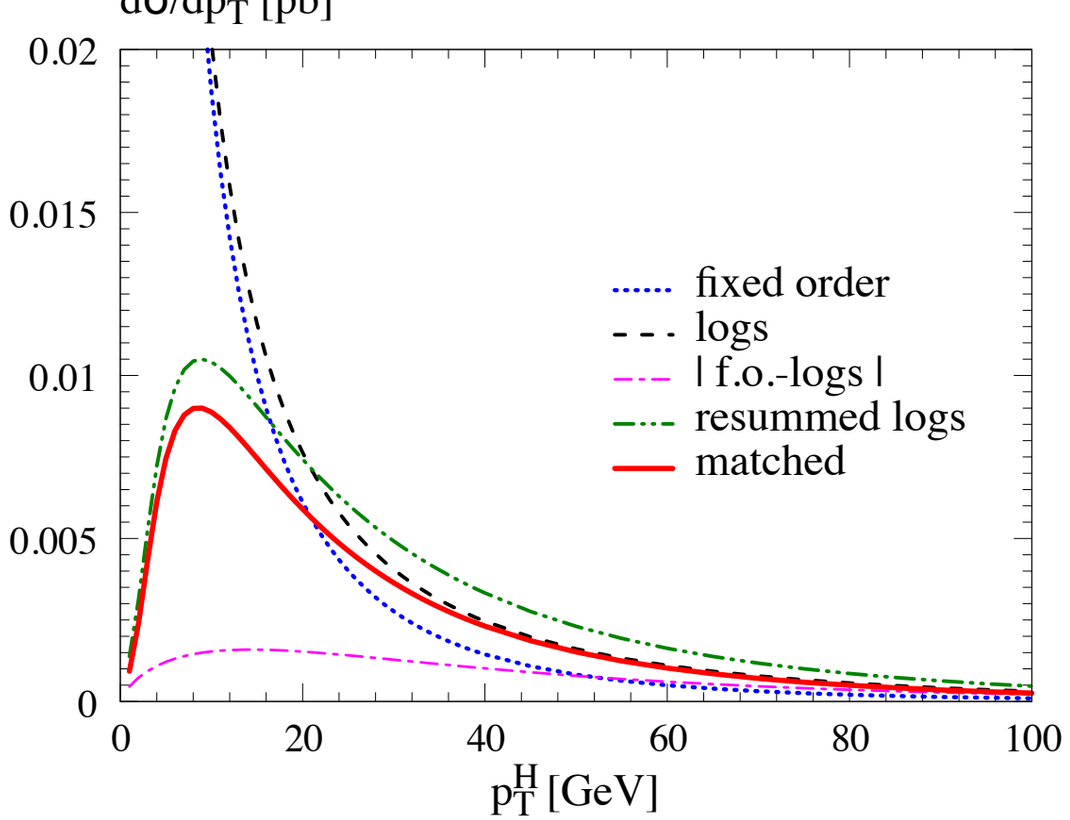
$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} + \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{l.a.}}$$



matching: FO+resummation

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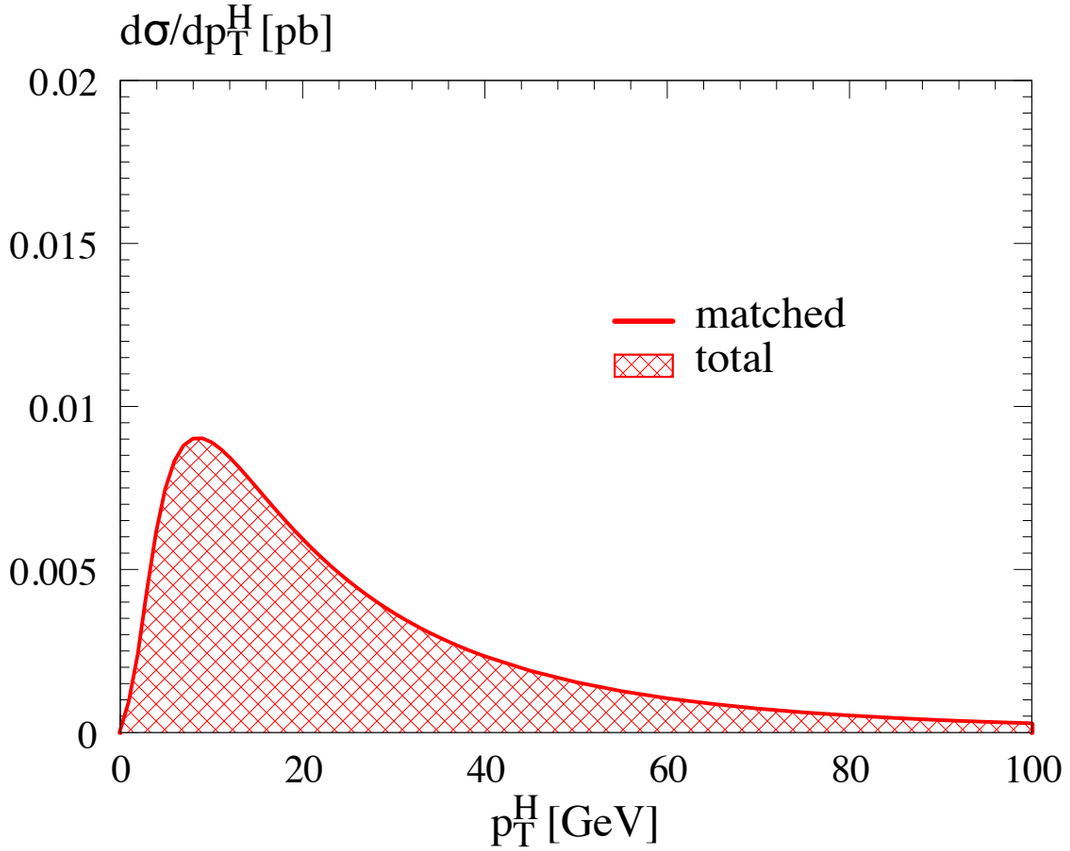
$$\int \mathrm{d}p_T^2 \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} \equiv \left[\sigma^{(\text{tot})}\right]_{\text{f.o.}} .$$



NNLO+NNLL resummation for ZZ and WW

[Grazzini, Kallweit, Rathlev, MW '15]

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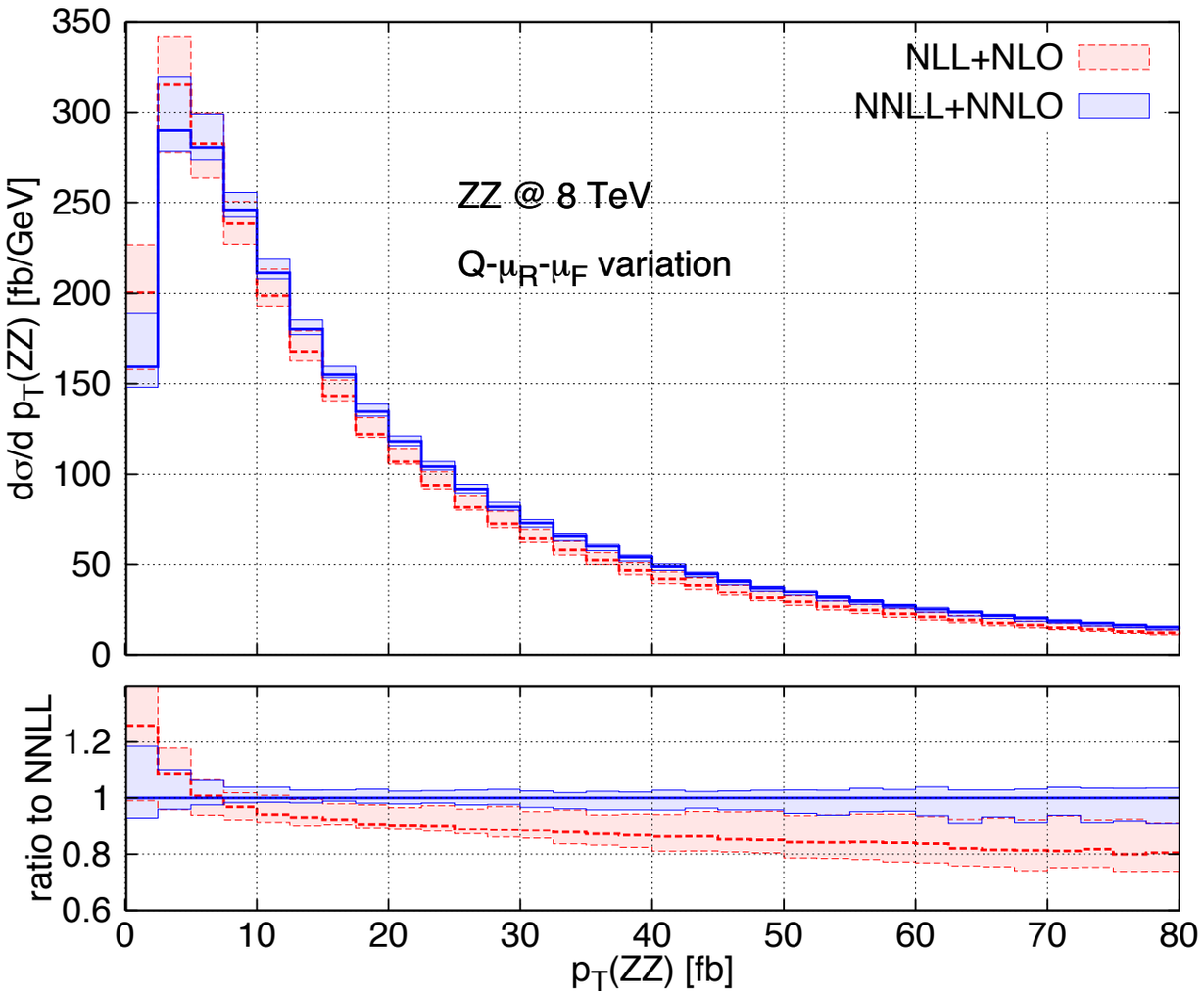
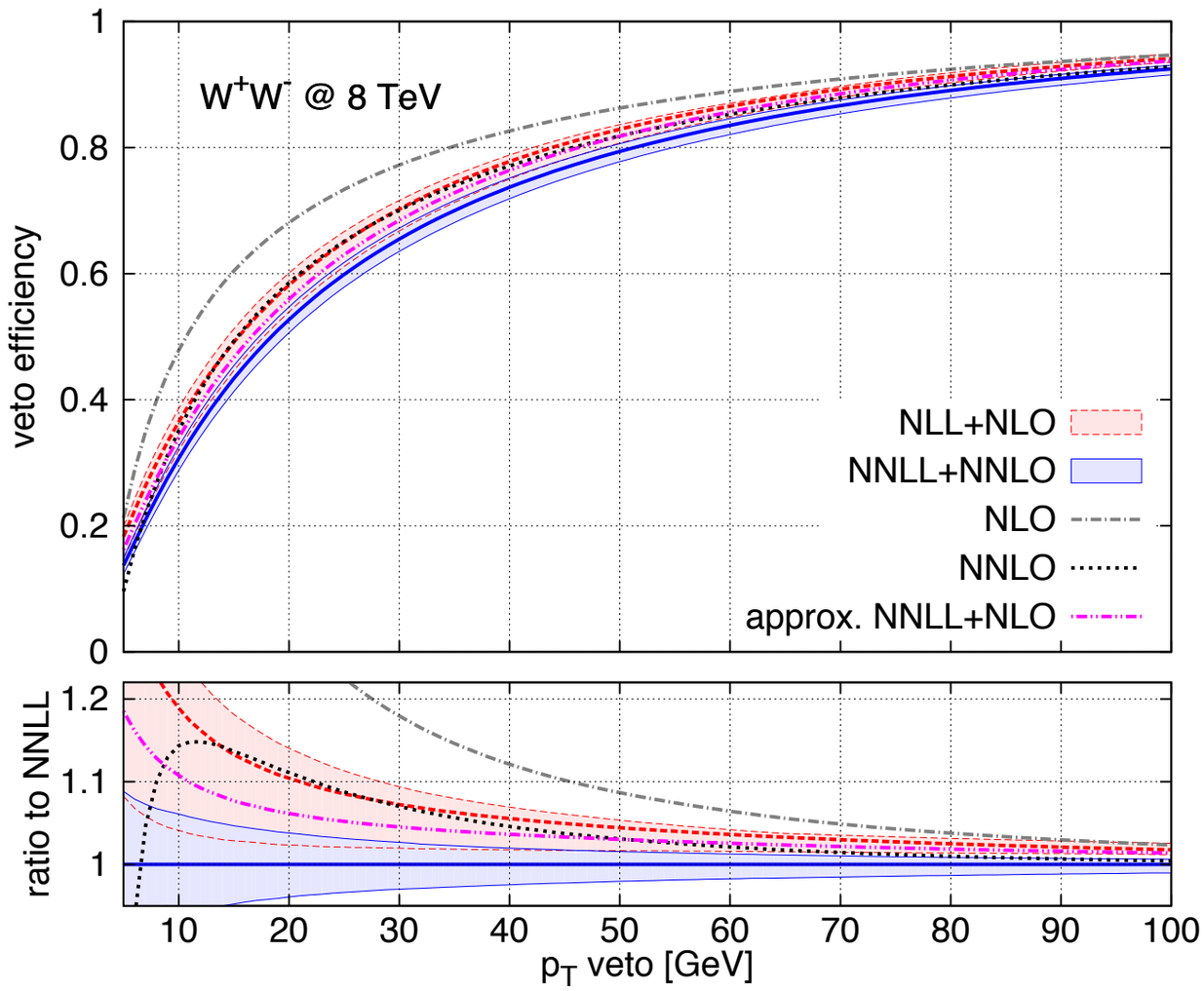
p_T spectrum of ZZ pair



p_T veto WW cross section



WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW to appear]

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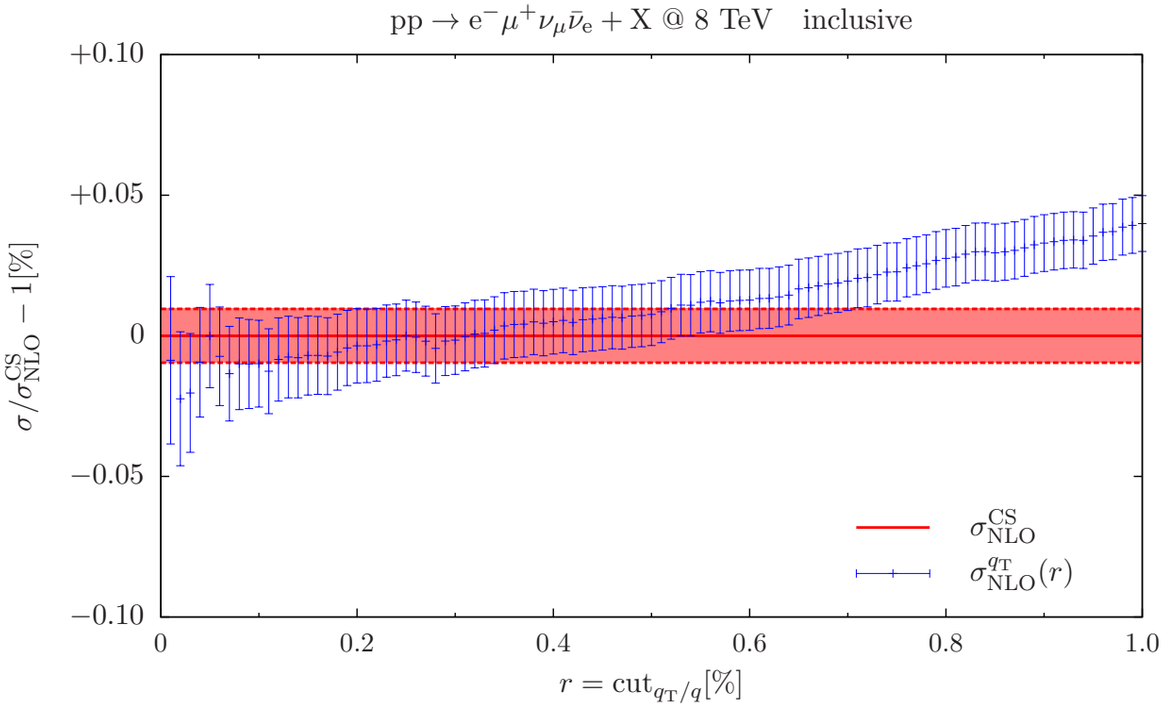
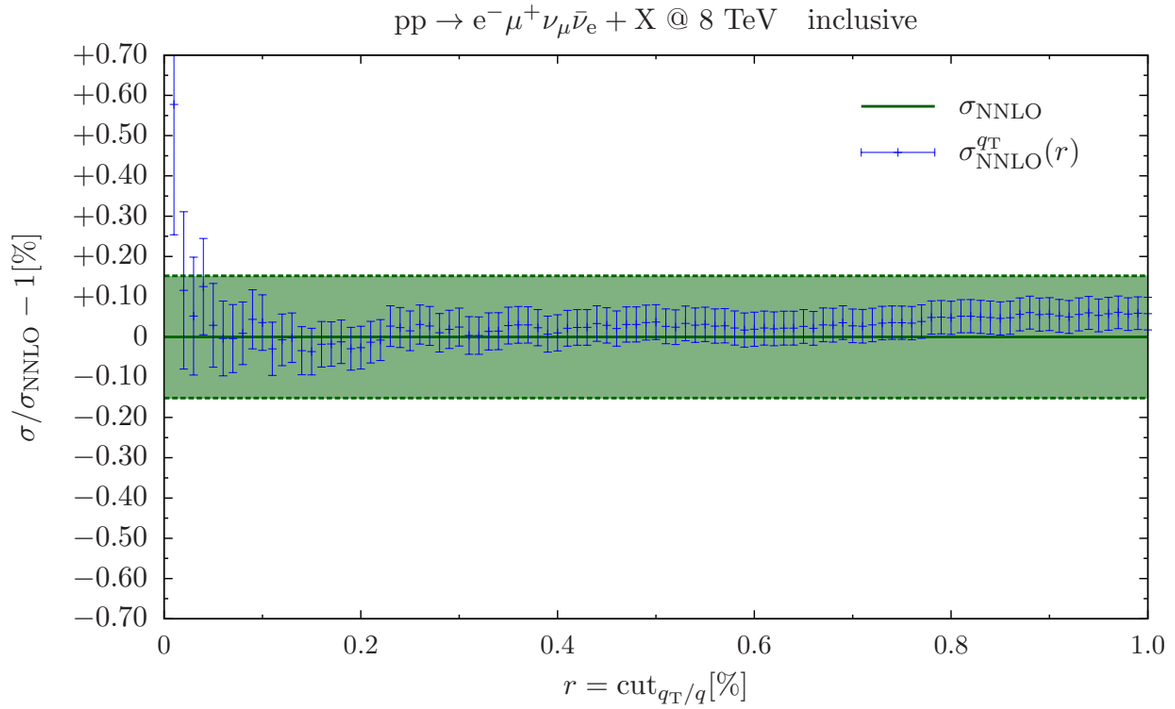
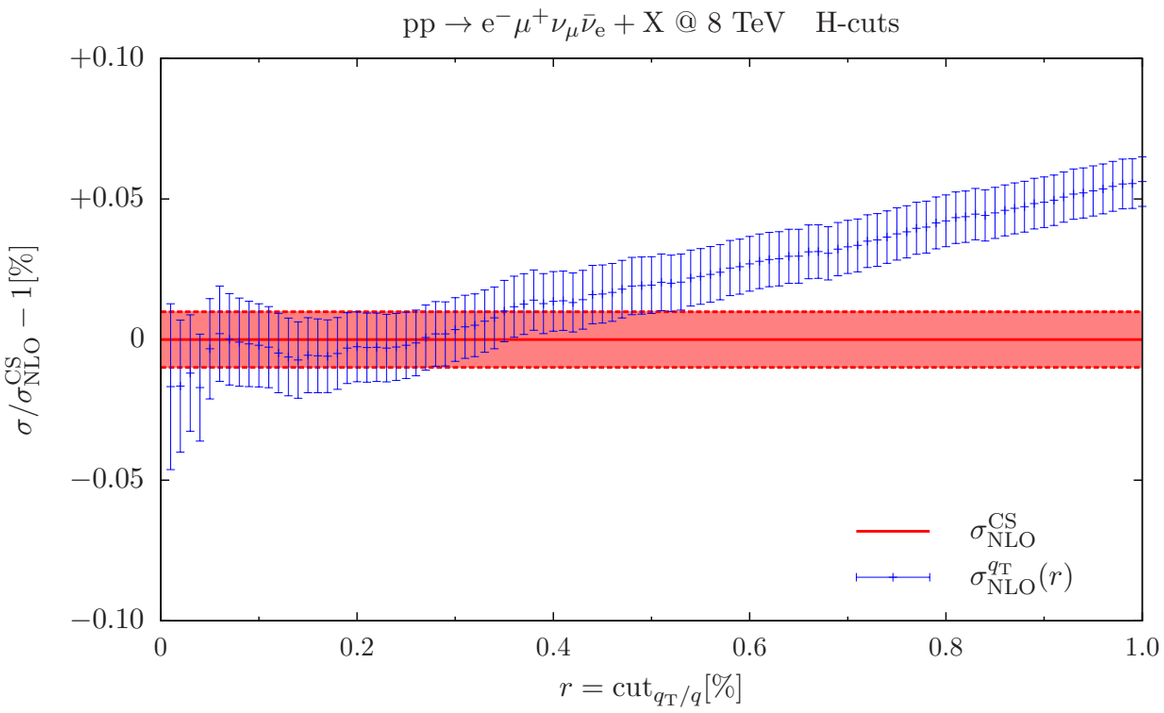
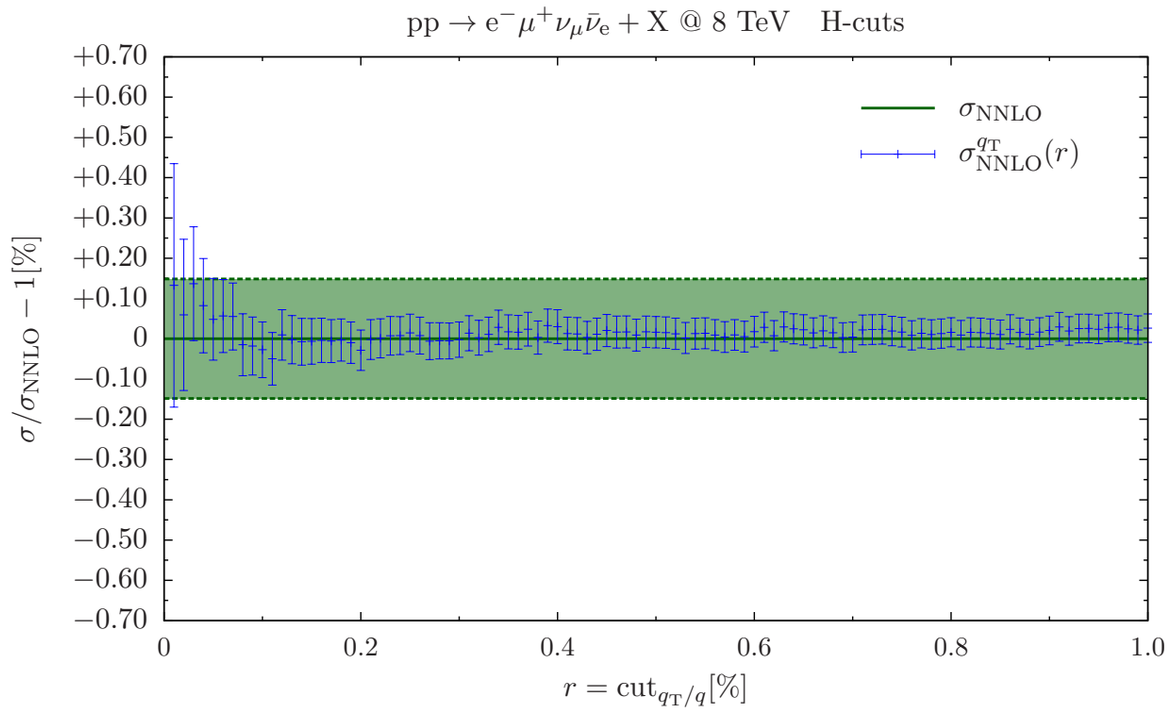
stability of r_{cut}= p_T/mww dependence









WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW to appear]

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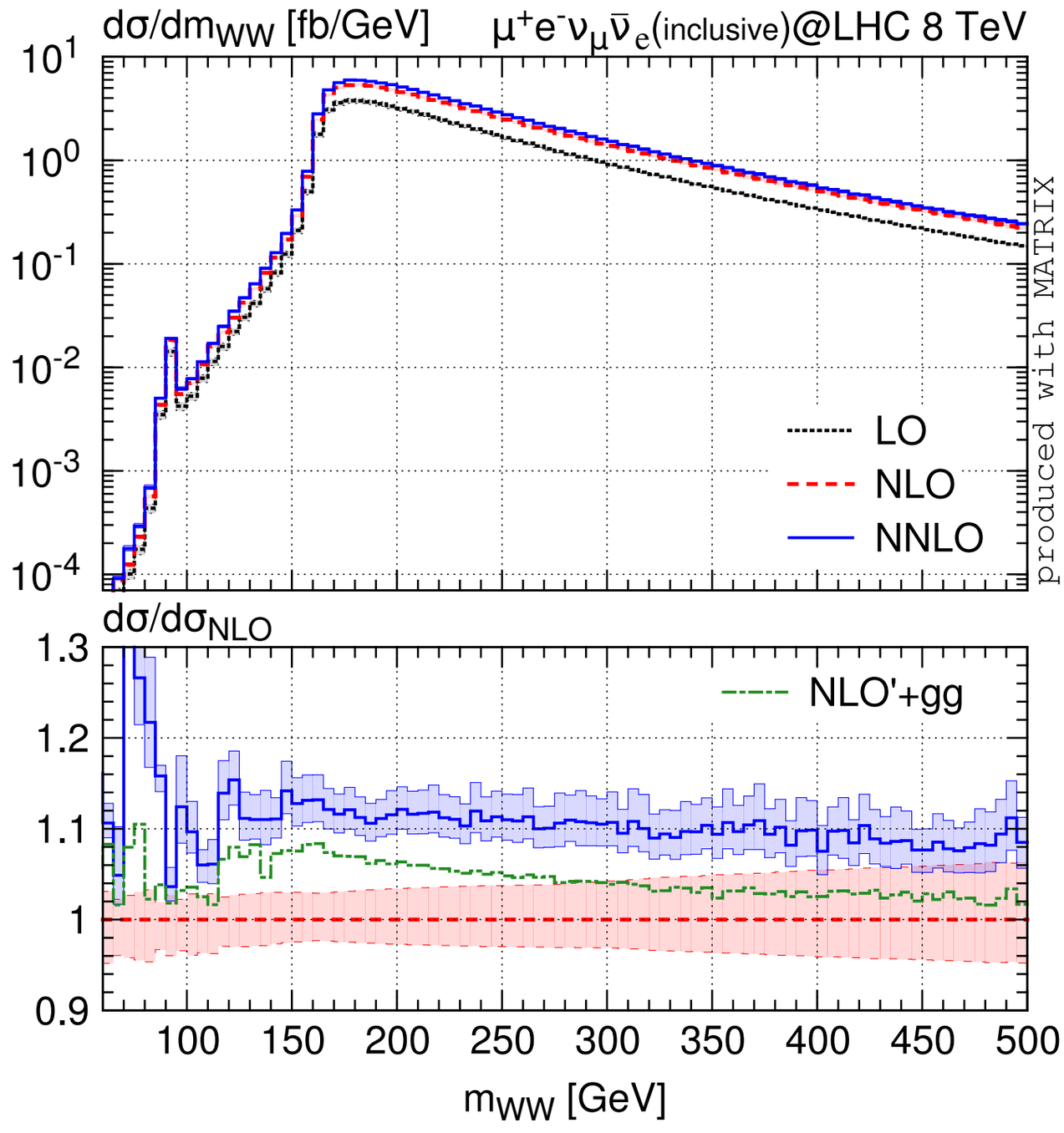
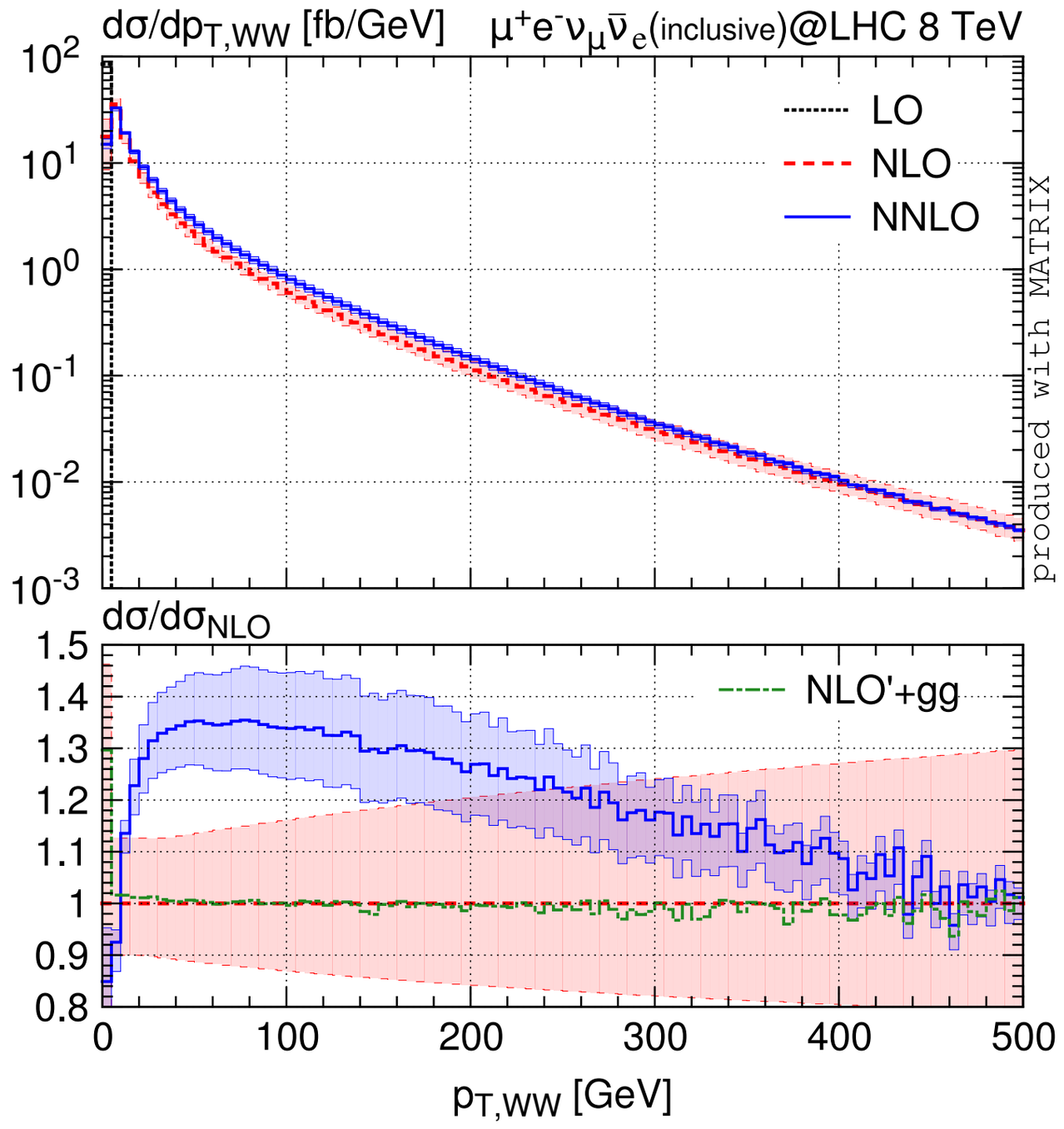
inclusive: distributions (8 TeV)





WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW to appear]

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WW signal cuts: distributions (8 TeV)