

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

Marius Wiesemann



Universität
Zürich^{UZH}

QCD@LHC 2016, Zürich (Switzerland)

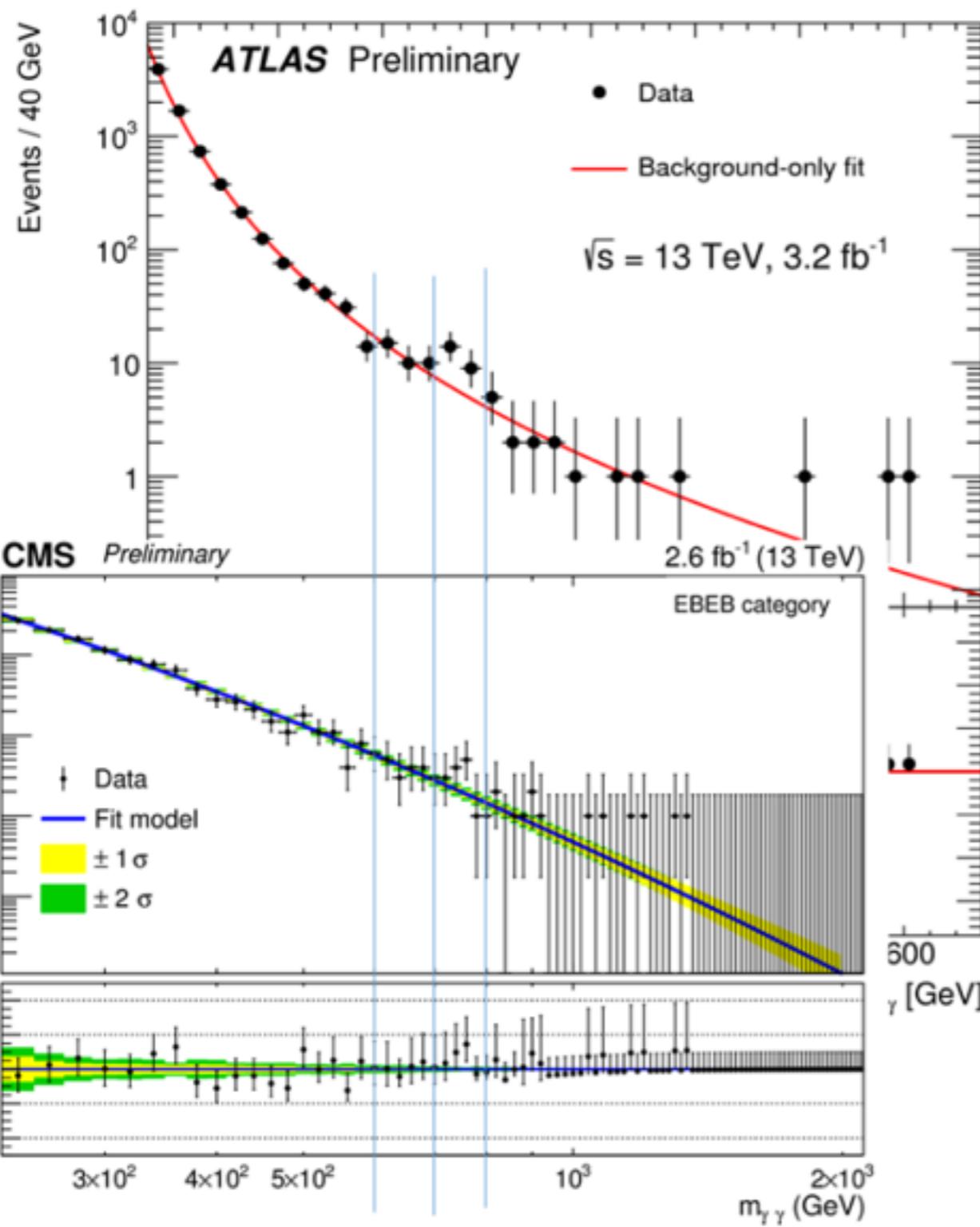
22-26 August, 2016

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

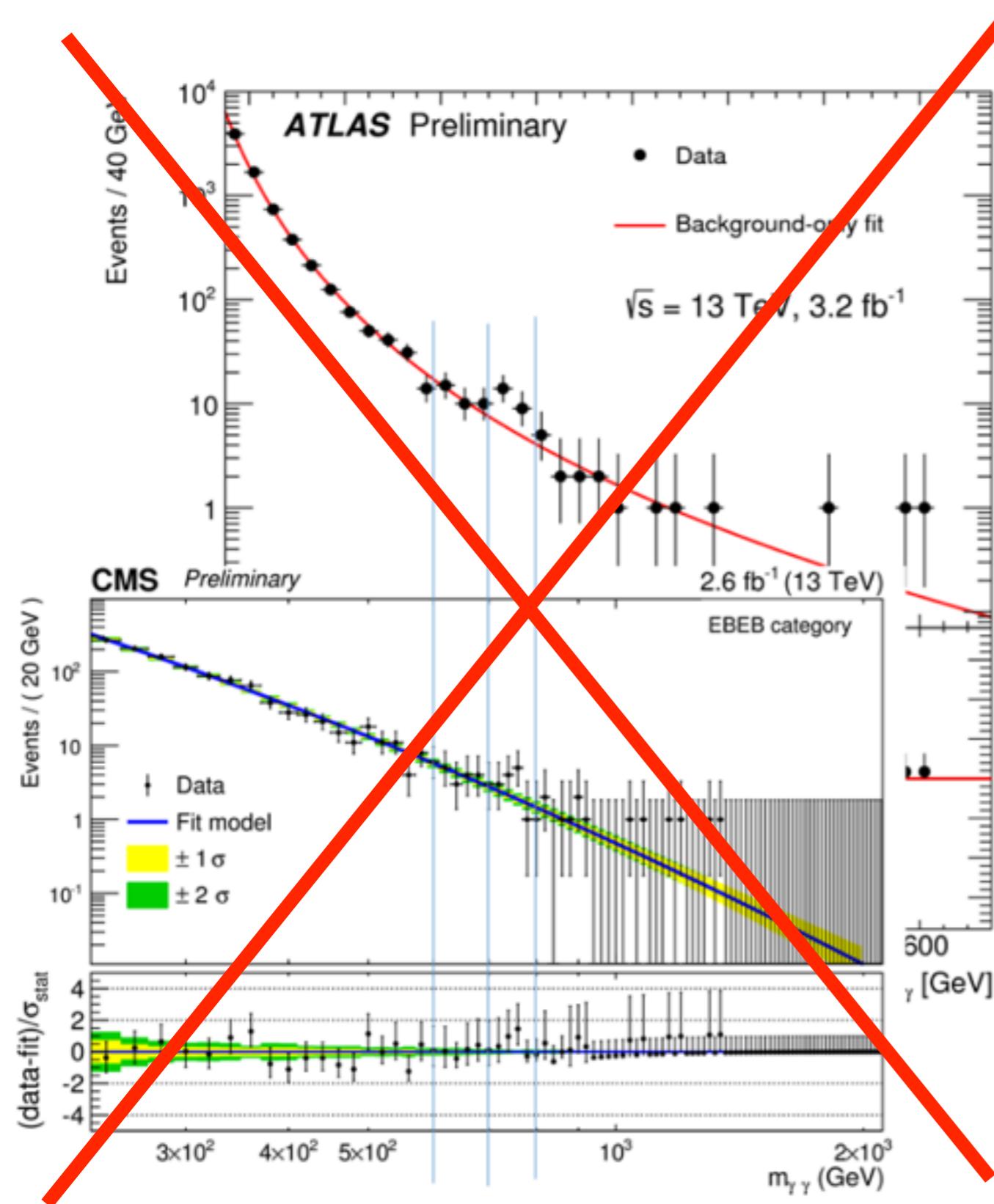
2015



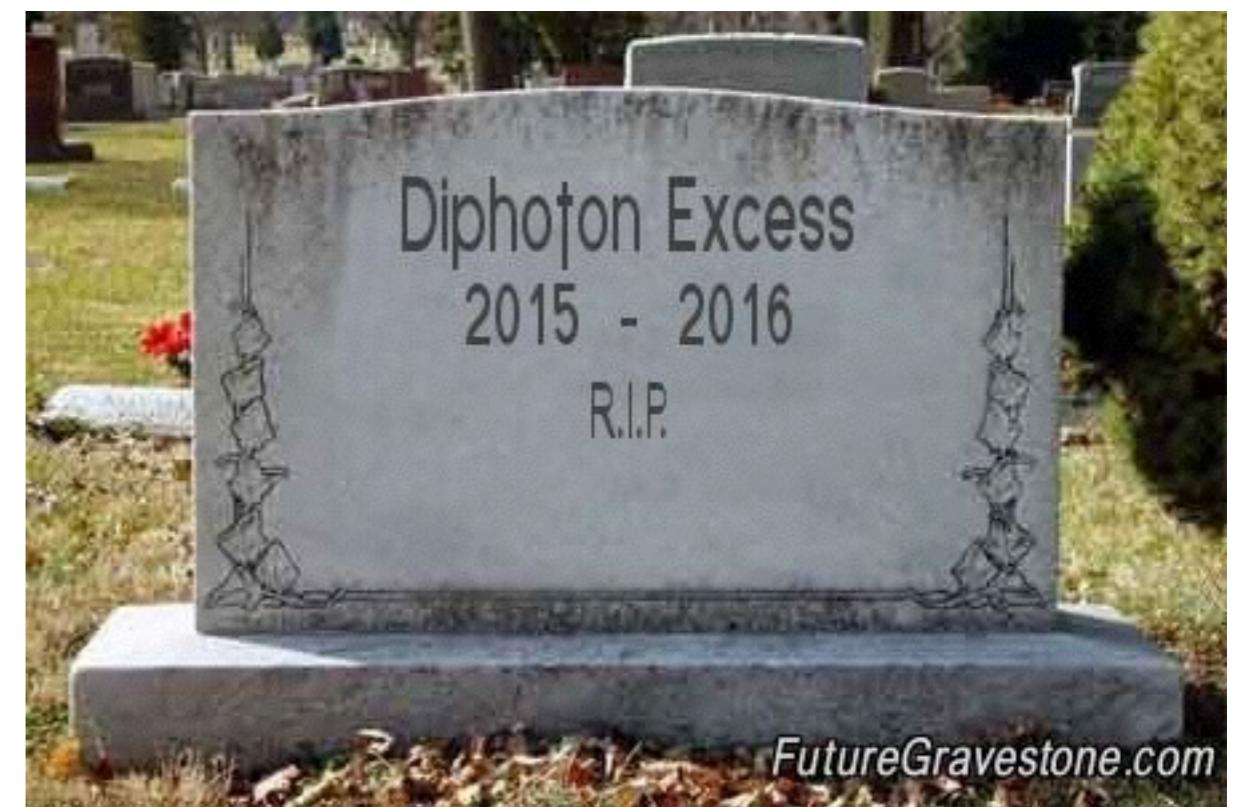
2016



2015



2016

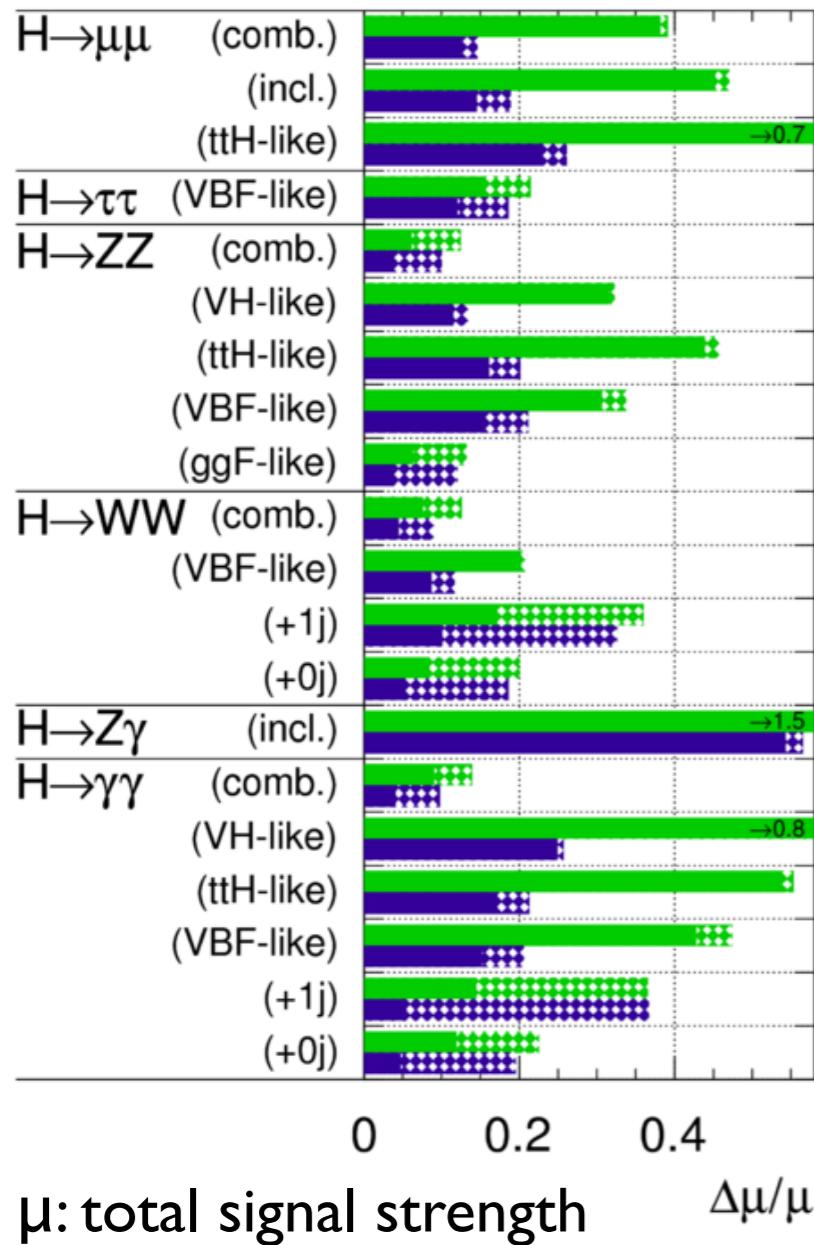


Introduction

Higgs measurements

ATLAS Simulation Preliminary

$\sqrt{s} = 14 \text{ TeV}$: $\int L dt = 300 \text{ fb}^{-1}$; $\int L dt = 3000 \text{ fb}^{-1}$



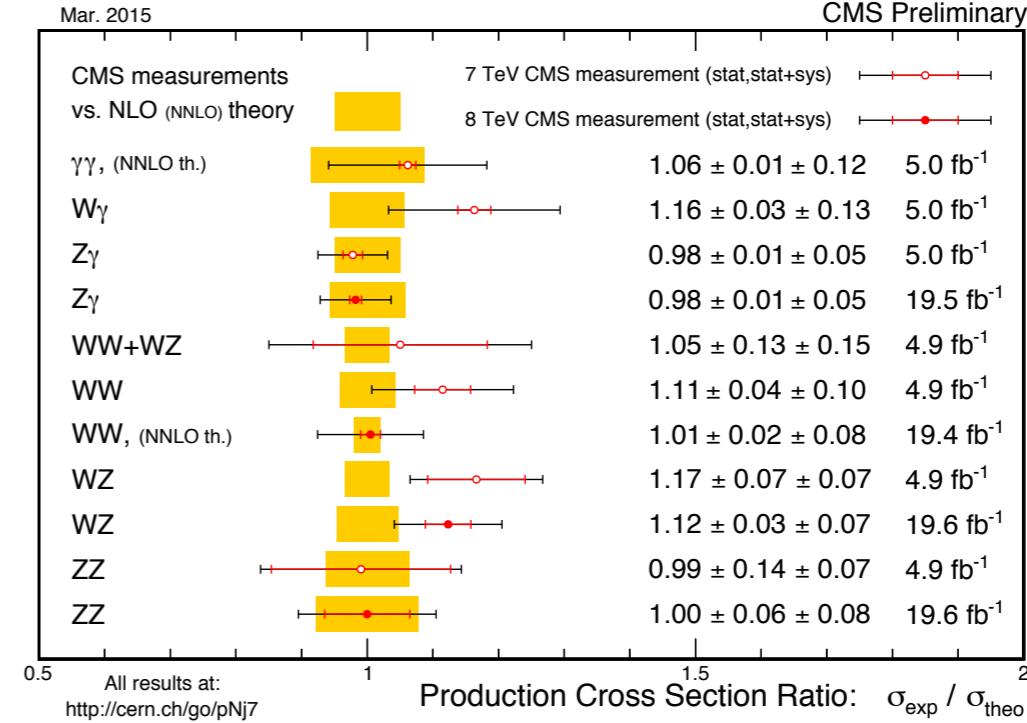
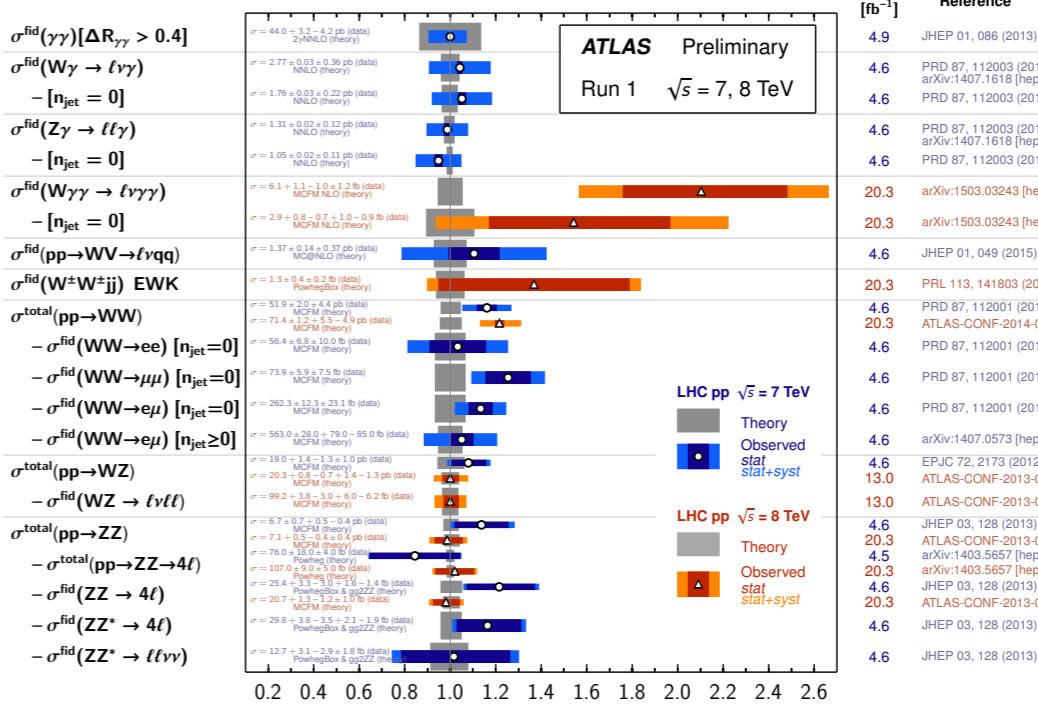
All vector-boson pair processes are on the Les Houches NNLO wishlist 2013



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vector-boson pair measurements

Multiboson Cross Section Measurements

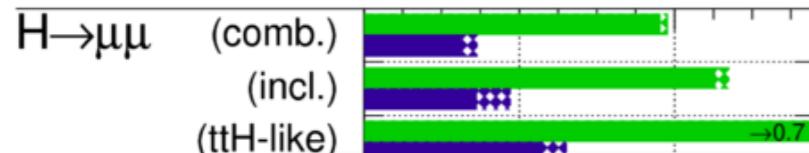


Introduction

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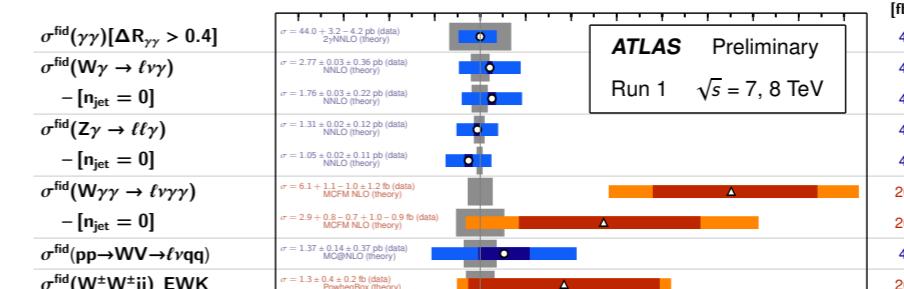


μ : total signal strength $\Delta\mu/\mu$

vector-boson pair measurements

Multiboson Cross Section Measurements

Status: March 2015

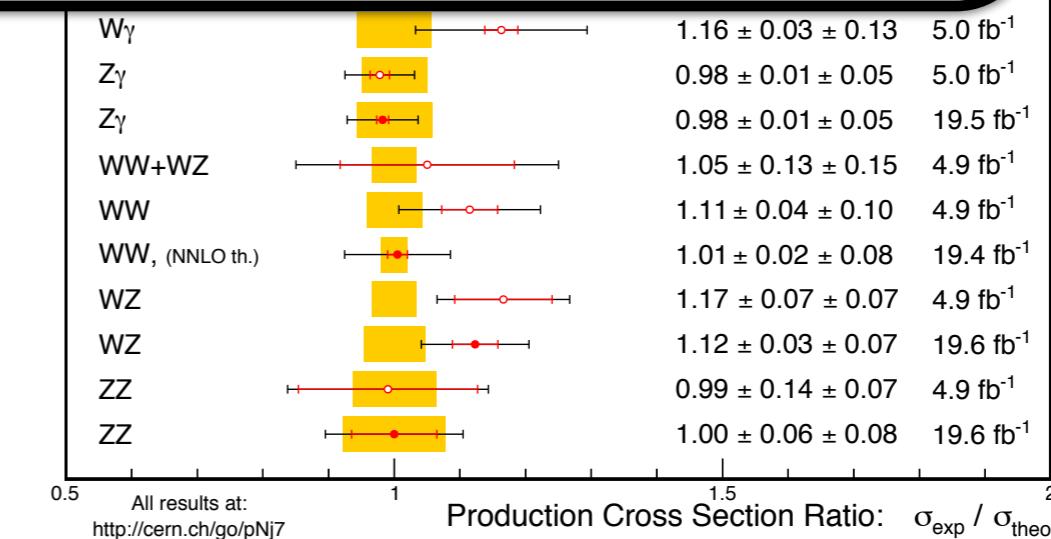


$\int L dt$ [fb $^{-1}$]

Reference

ATLAS Preliminary
Run 1 $\sqrt{s} = 7, 8 \text{ TeV}$

NNLO demanded by continuously increasing experimental accuracy



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



p_T subtraction and resummation



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

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

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

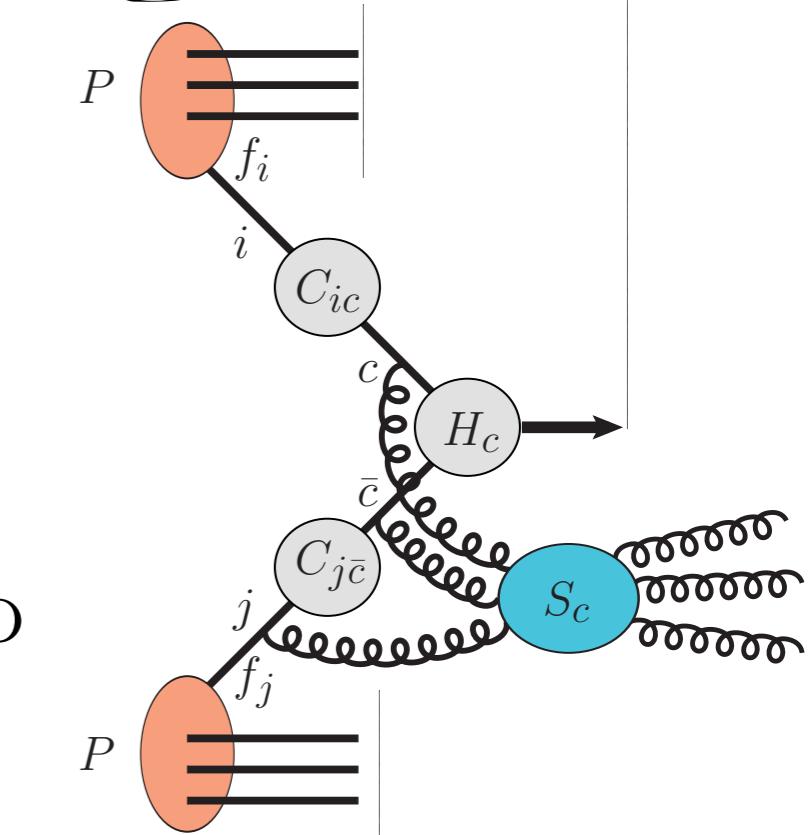
$$d\sigma^{F+1\text{jet}} \xrightarrow{p_T \ll Q} \left[d\sigma^{(\text{res})} \right]_{\text{f.o.}} \equiv \Sigma(p_T/Q) \otimes d\sigma_{\text{LO}}$$

unitarity of p_T resummation due to modified logs:

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

→ **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 q_T Subtraction
and Resummation to Integrate X-sections.

The MATRIX



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

-----+
| MATRIX: A fully-differential NNLO(NNLL) process library
|   V   |   \   |   \   |   \   |   \   |   \   |   \   |
|   V   |   \   |   \   |   \   |   \   |   \   |   \   |
|   V   |   \   |   \   |   \   |   \   |   \   |   \   |
|   V   |   \   |   \   |   \   |   \   |   \   |   \   |
|   V   |   \   |   \   |   \   |   \   |   \   |   \   |
|   V   |   \   |   \   |   \   |   \   |   \   |   \   |
|-----+
| 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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|   \   |   \   |   \   |   \   |   \   |   \   |   \   |
|-----+
| M. Grazzini          (grazzini@physik.uzh.ch)
| S. Kallweit          (kallweit@uni-mainz.de)
| D. Rathlev           (rathlev@physik.uzh.ch)
| M. Wiesemann         (marlusw@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
ppxne02    >> 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
ppeeexex84 >> p p --> e^- e^- e^+ e^+                         >> ZZ & Z gamma & gamma gamma with decay
ppemexmx84 >> p p --> e^- mu^- e^+ mu^+                         >> ZZ & Z gamma & gamma gamma with decay
ppxnea03   >> p p --> e^+ v_e^- gamma                         >> W+ gamma with decay
ppenexa03   >> p p --> e^- v_e^+ gamma                         >> W- gamma with decay
ppemxnmx84 >> p p --> e^- mu^+ v_mu^- v_e^+                         >> W W production with decay
ppemexnmx84 >> p p --> e^- mu^- e^+ v_mu^+                         >> W-Z production with decay
ppeexmnm84 >> p p --> e^- e^+ mu^+ v_mu^-                         >> W-Z production with decay
|-----+>
<<MATRIX-MAKE>> pph21
<<MATRIX-MAKE>> Starting compilation...
```

The Status

| process | status | comment |
|---|--------|--|
| $pp \rightarrow Z/\gamma^*(\rightarrow \ell^+ \ell^-)$ | ✓ | validated analytically (+ DYNNLO) |
| $pp \rightarrow W \rightarrow \ell v$ | (✓) | to be validated |
| $pp \rightarrow H$ | ✓ | validated analytically |
| $pp \rightarrow \gamma\gamma$ | ✓ | validated with 2 γ NNLO |
| $pp \rightarrow Z\gamma \rightarrow \ell^+ \ell^- \gamma$ | ✓ | [Grazzini, Kallweit, Rathlev, Torre '13] |
| $pp \rightarrow W\gamma \rightarrow \ell v \gamma$ | ✓ | [Grazzini, Kallweit, Rathlev '15] |
| $pp \rightarrow ZZ$ | ✓ | [Cascioli et al. '14] |
| $pp \rightarrow ZZ \rightarrow 4\ell$ | ✓ | [Grazzini, Kallweit, Rathlev '15] |
| $pp \rightarrow WW$ | ✓ | [Gehrmann et al. '14] |
| $pp \rightarrow WW \rightarrow \ell v \ell' v'$ | ✓ | NEW HERE: fully differential |
| $pp \rightarrow WZ$ | ✓ | NEW HERE: inclusive cross section |
| $pp \rightarrow HH$ | ✓ | [de Florian et al. '16] |

The Status and Plan



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I. Closed beta has started!

- **PROCESSES:** all processes of previous slide
- **ACCURACY:** NNLO QCD
- **CURRENTLY SUPPORTED:**
 - local running
 - cluster running: LSF (lxplus), SLURM, condor; under validation: PBS
 - easy to add new schedulers → **which other cluster are required?**
- **WHO:** already used by selected experimentalists from ATLAS and CMS

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

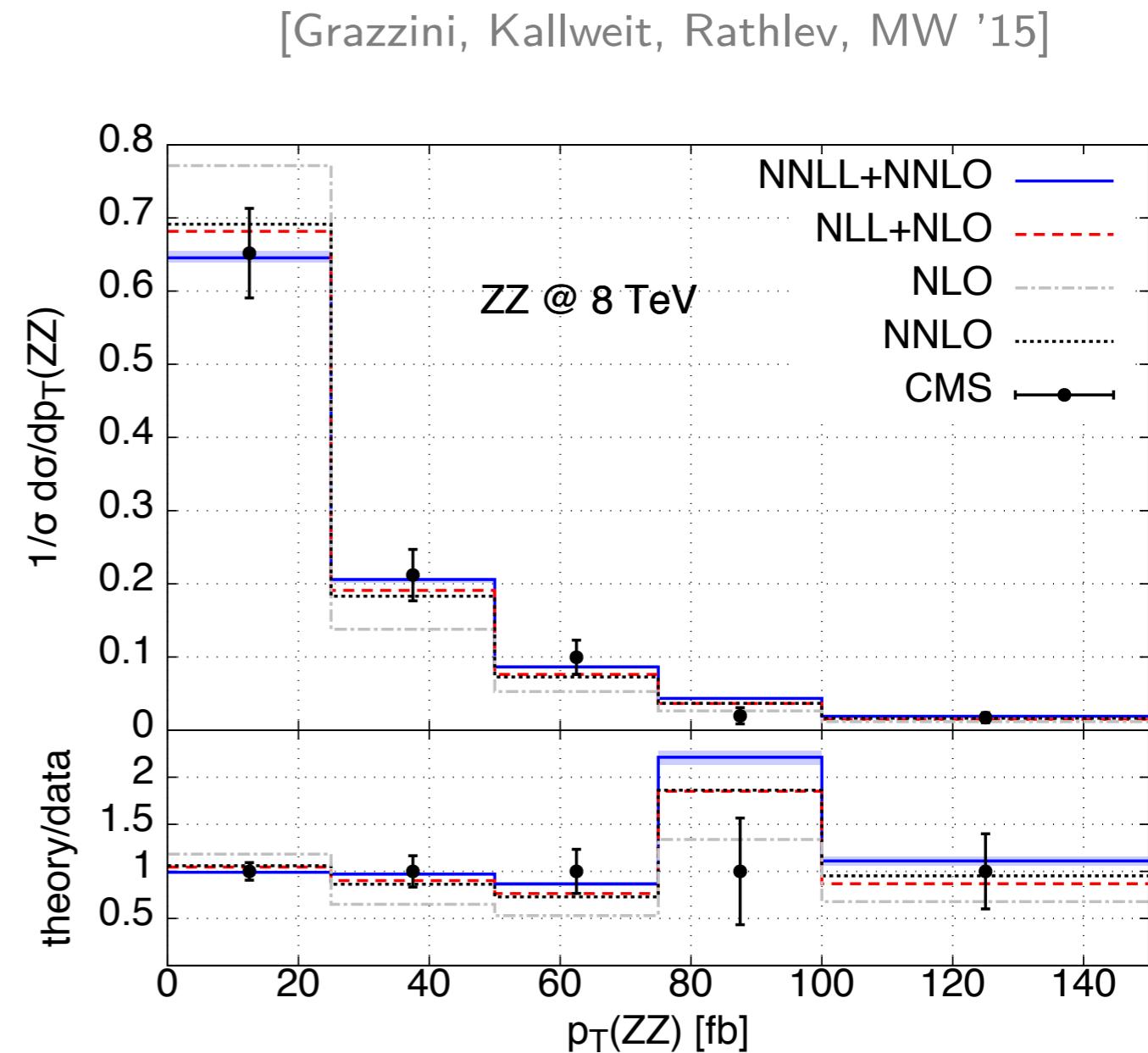
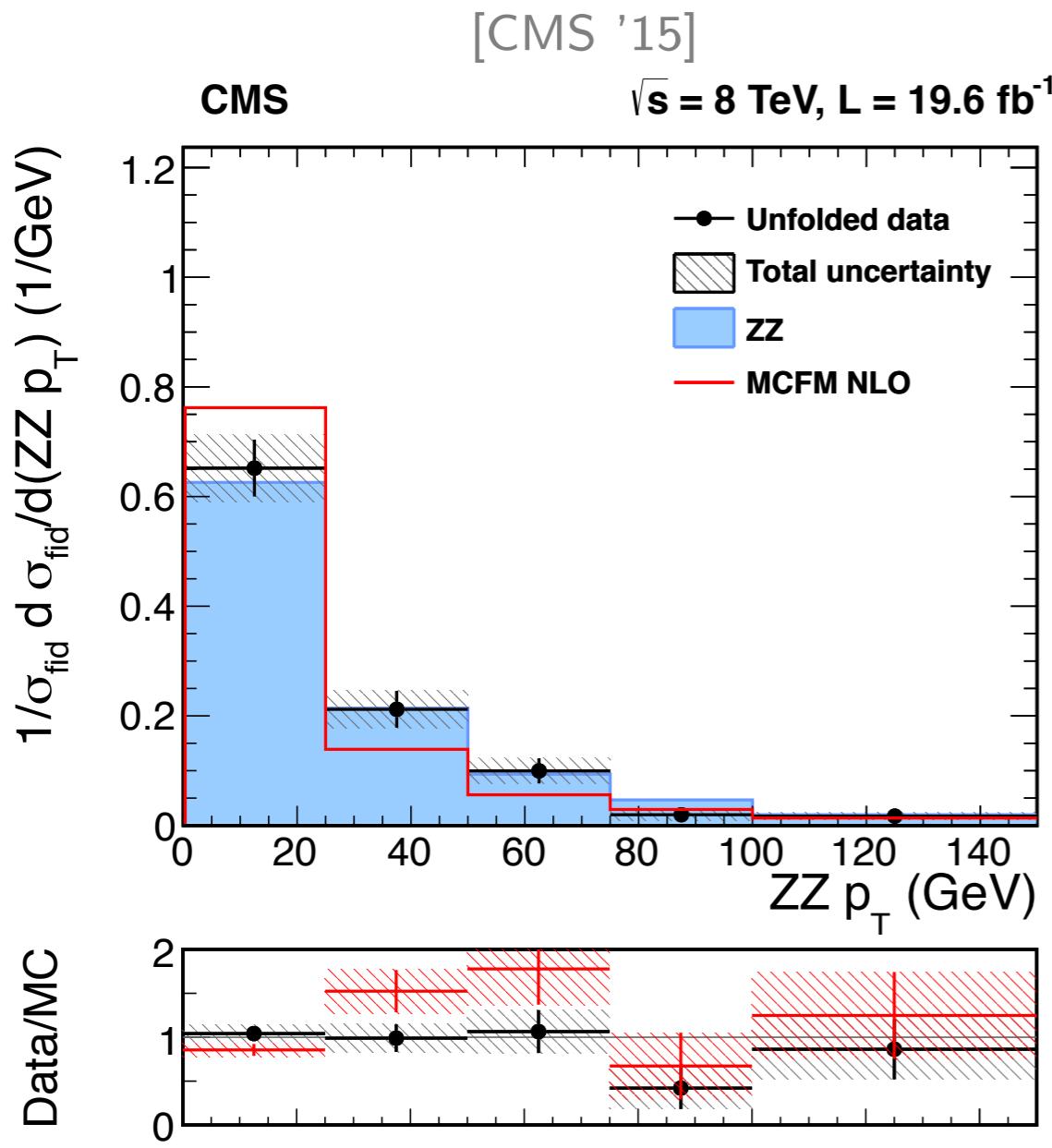
NNLO+NNLL resummation for ZZ and WW



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[Grazzini, Kallweit, Rathlev, MW '15]

p_T spectrum of ZZ pair: comparison to data



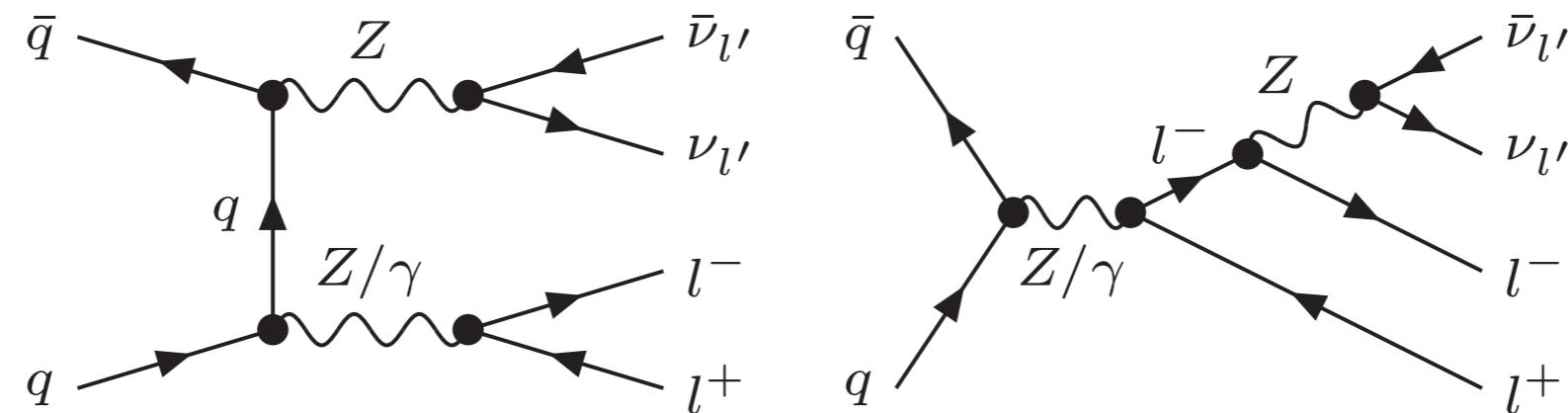
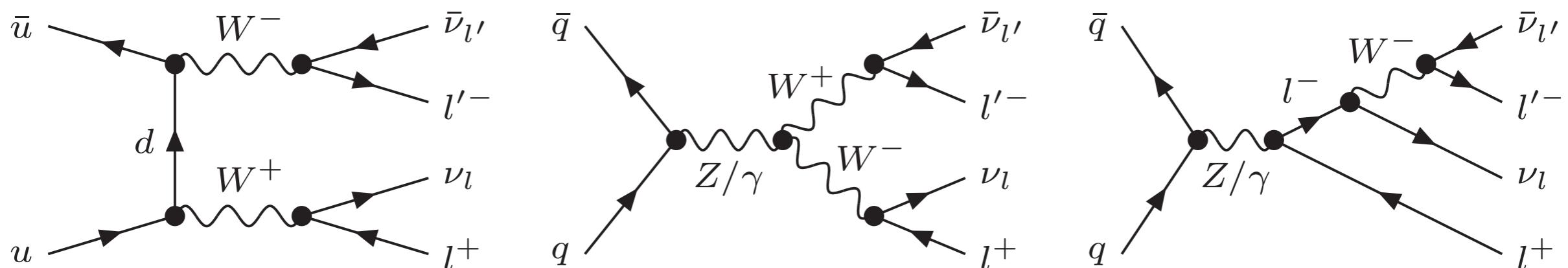
WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]



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



WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]



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- all $p\bar{p} \rightarrow WW \rightarrow l\nu l'\nu'$ processes, including:
 - double-resonant W decays
 - single-resonant Z/ γ^* decays ($p\bar{p} \rightarrow Z/\gamma^* \rightarrow WW^*/l\nu W \rightarrow l\nu l'\nu'$)
 - double(single)-resonant $p\bar{p} \rightarrow ZZ/Z\gamma^* \rightarrow l\nu l\nu$ ($p\bar{p} \rightarrow Z/\gamma^* \rightarrow l\nu l\nu$) in equal-flavor channel
- **HERE:** different-flavour channel $p\bar{p} \rightarrow WW \rightarrow e\nu_e \mu\nu_\mu$ (for simplicity):
 - inclusive
 - WW signal cuts:

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

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

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

-
- Higgs background cuts:

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

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

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

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

WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]



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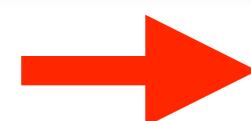
inclusive rates

| 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%} |
| 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 '16]



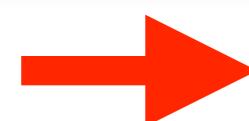
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inclusive rates

fiducial rates (WW cuts)

| σ [fb] | 8 TeV | 13 TeV | 8 TeV | 13 TeV |
|---------------|--------------------------------|--------|----------------------------------|--------|
| 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% |
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NLO'+gg = NLO+gg **BOTH** with NNLO PDFs



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WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]



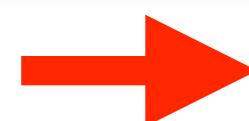
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inclusive rates

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



acceptances (WW cuts)

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|--|---------------------------------|---------------------------------|
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| NLO | 0.24552(5) $^{+4.4\%}_{-4.7\%}$ | 0.19599(4) $^{+4.4\%}_{-4.7\%}$ |
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WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]



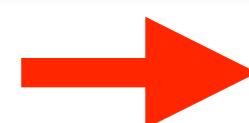
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inclusive rates

fiducial rates (WW cuts)

| σ [fb] | 8 TeV | 13 TeV | 8 TeV | 13 TeV |
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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) $^{+4.3\%}_{-3.3\%}$ | | 1286.81(13) $^{+4.8\%}_{-3.7\%}$ | |
| NNLO | 690.4(5) $^{+2.2\%}_{-1.9\%}$ | +5.3% | 1370.9(11) $^{+2.6\%}_{-2.3\%}$ | +6.5% |

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% |
| NLO | 0.24552(5) $^{+4.4\%}_{-4.7\%}$ | +3.3% |
| NLO'+gg | 0.25374(7) $^{+3.5\%}_{-3.7\%}$ | -6.3% |
| NNLO | 0.2378(4) $^{+1.3\%}_{-0.9\%}$ | +34% |
| | | +6% |
| | | -8.2% |

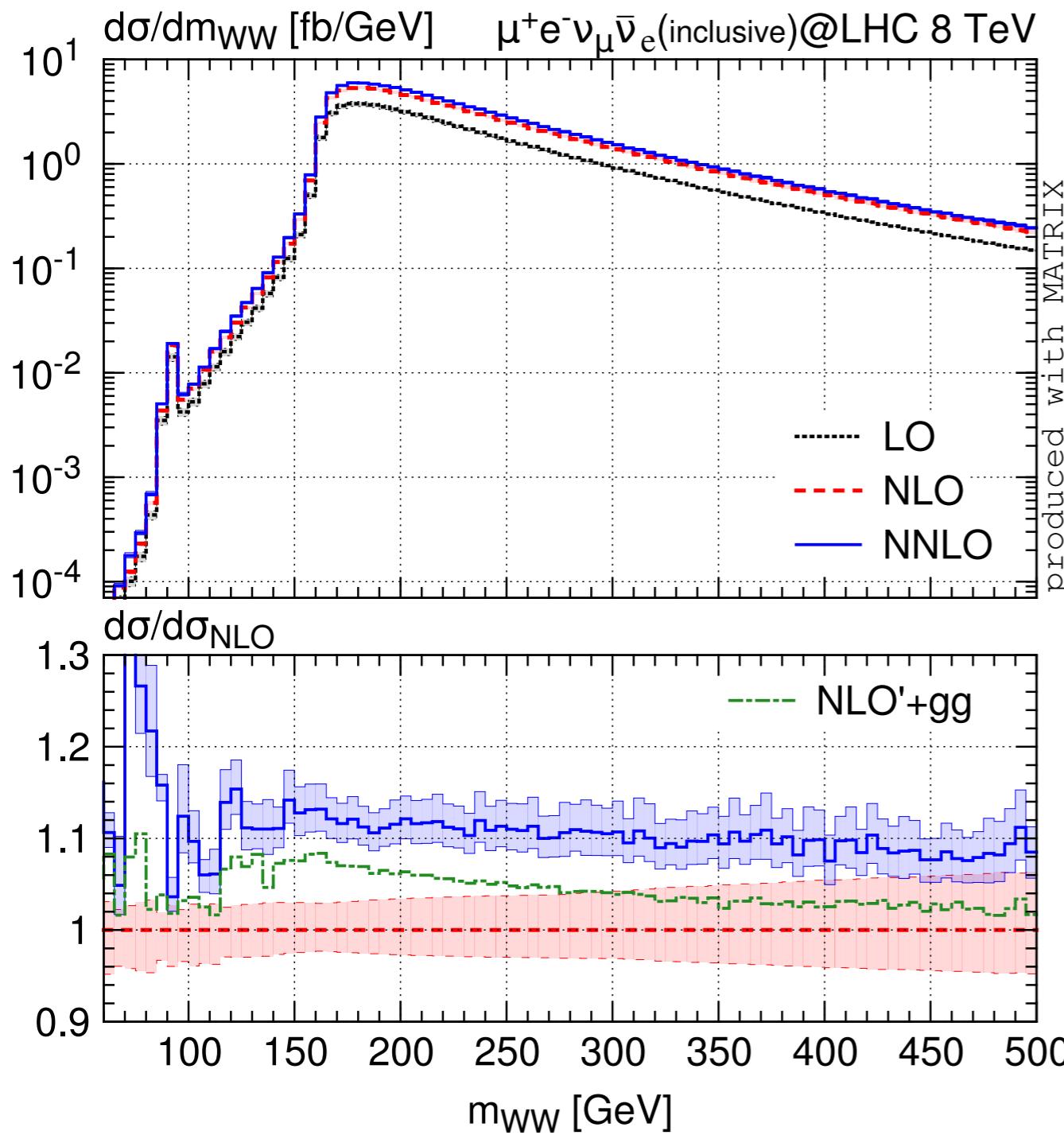
WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

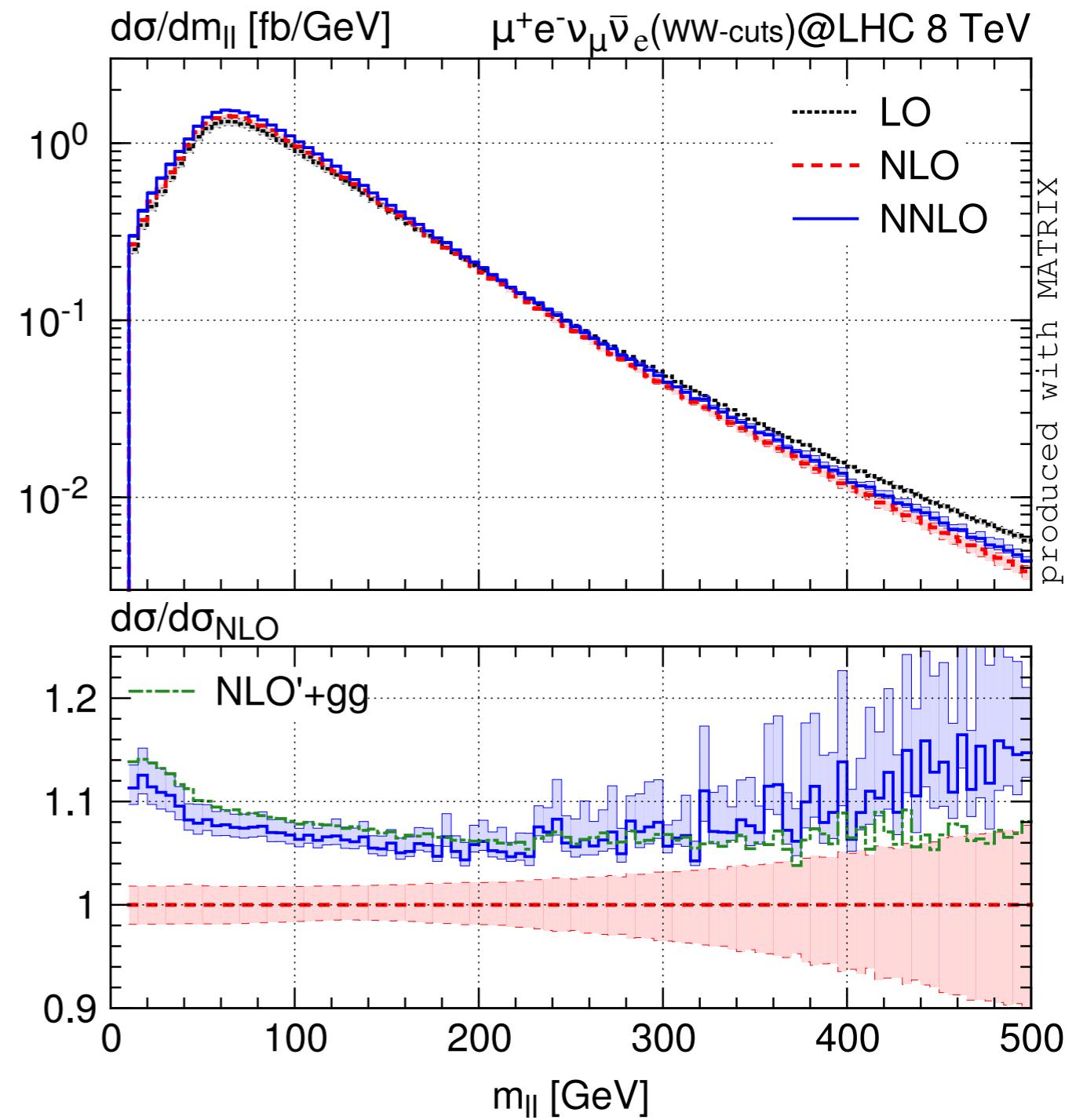


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inclusive: distributions



WW cuts: distributions



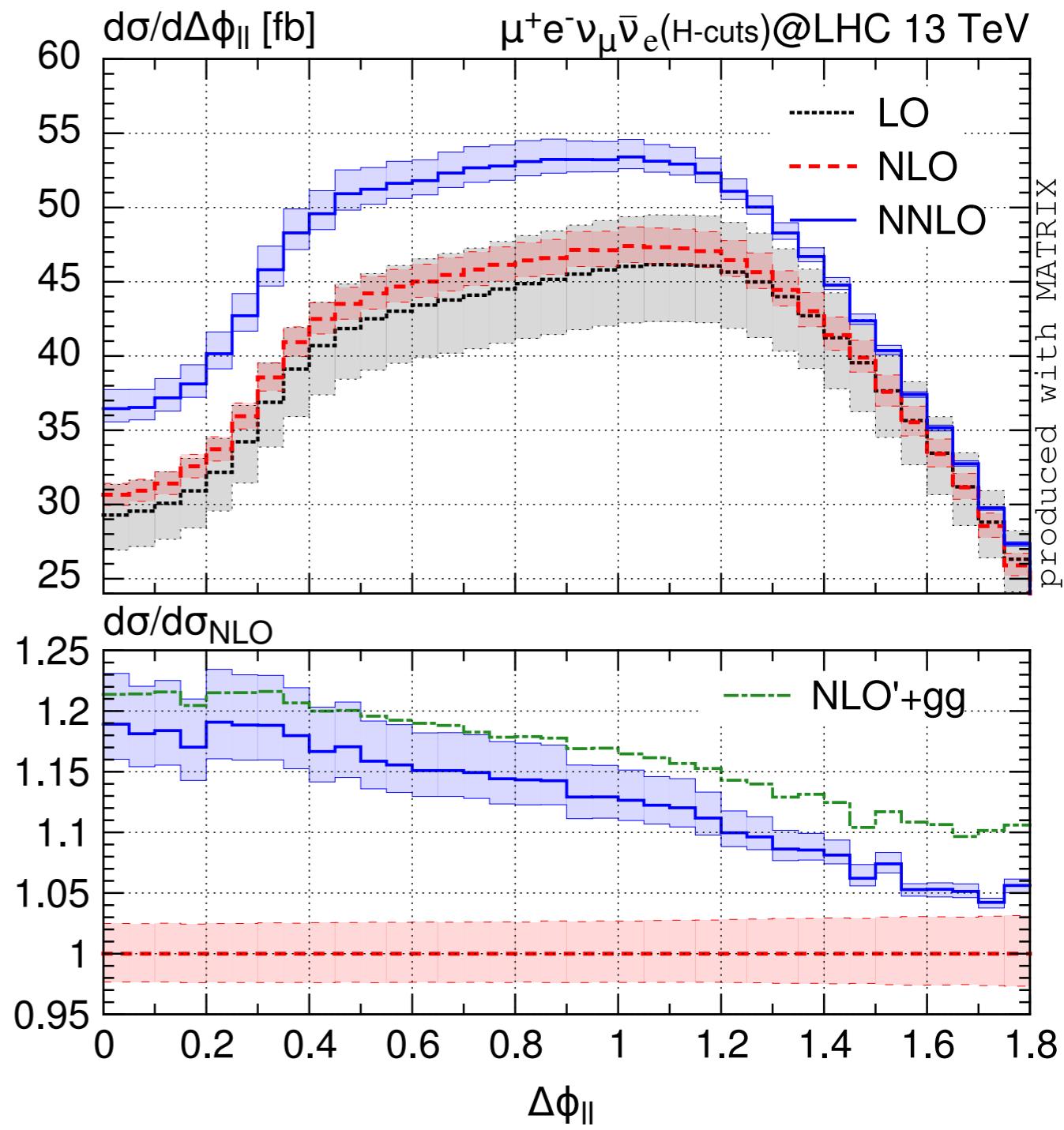
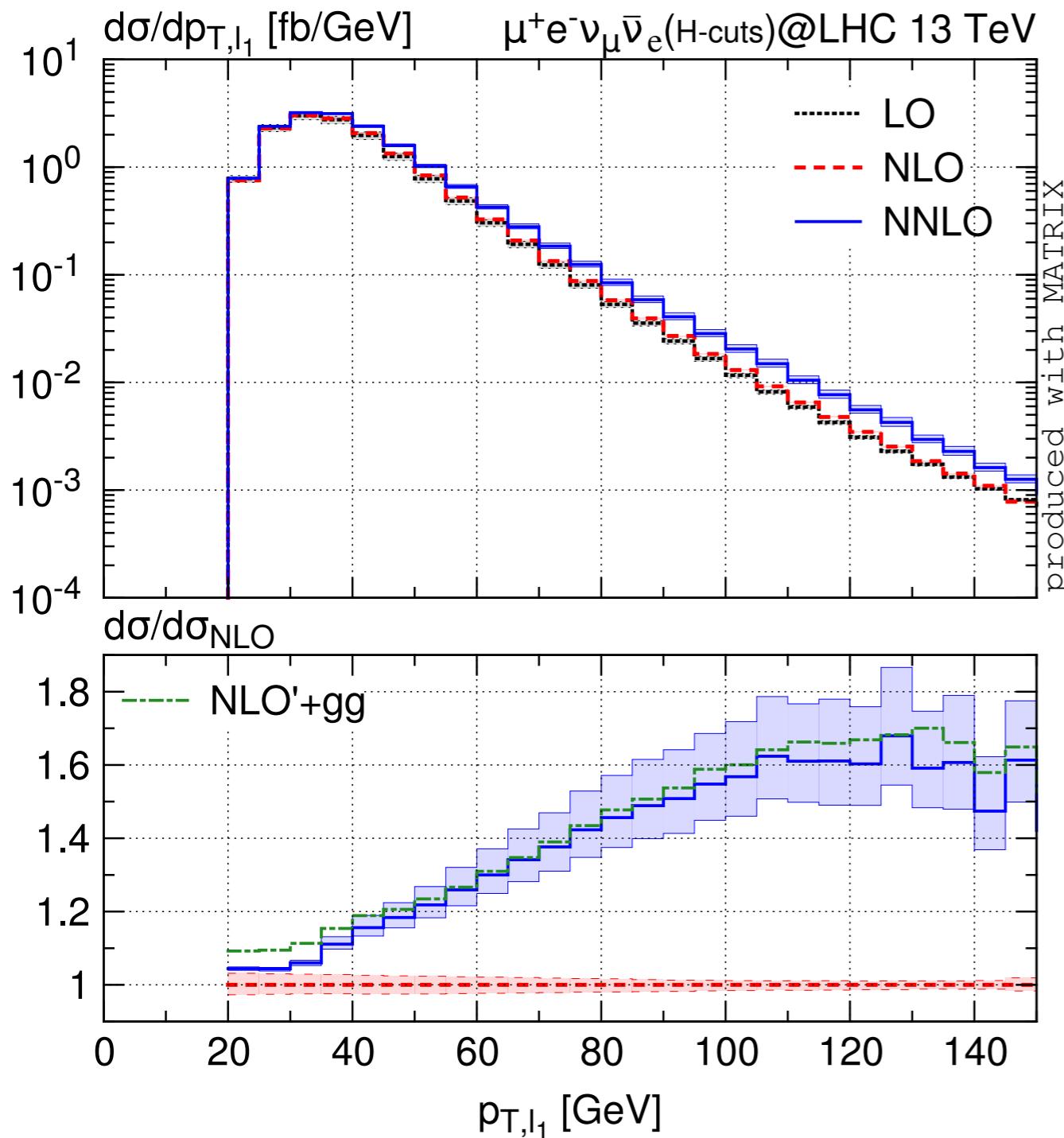
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Higgs background cuts: distributions (13 TeV)

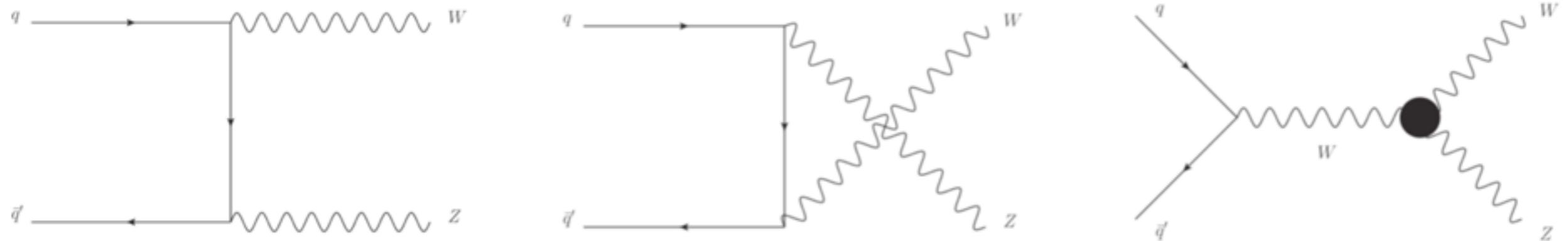


WZ cross section at NNLO

[Grazzini, Kallweit, Rathlev, MW '16]



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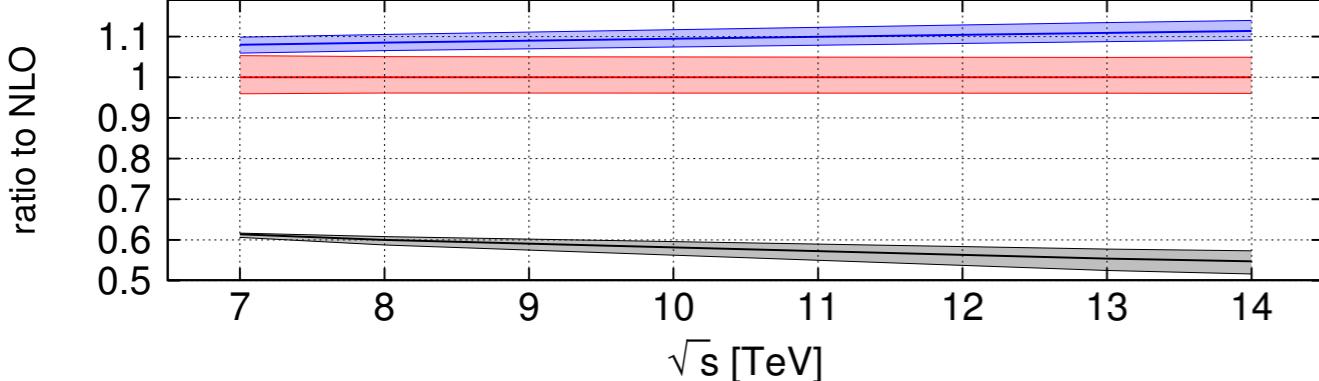
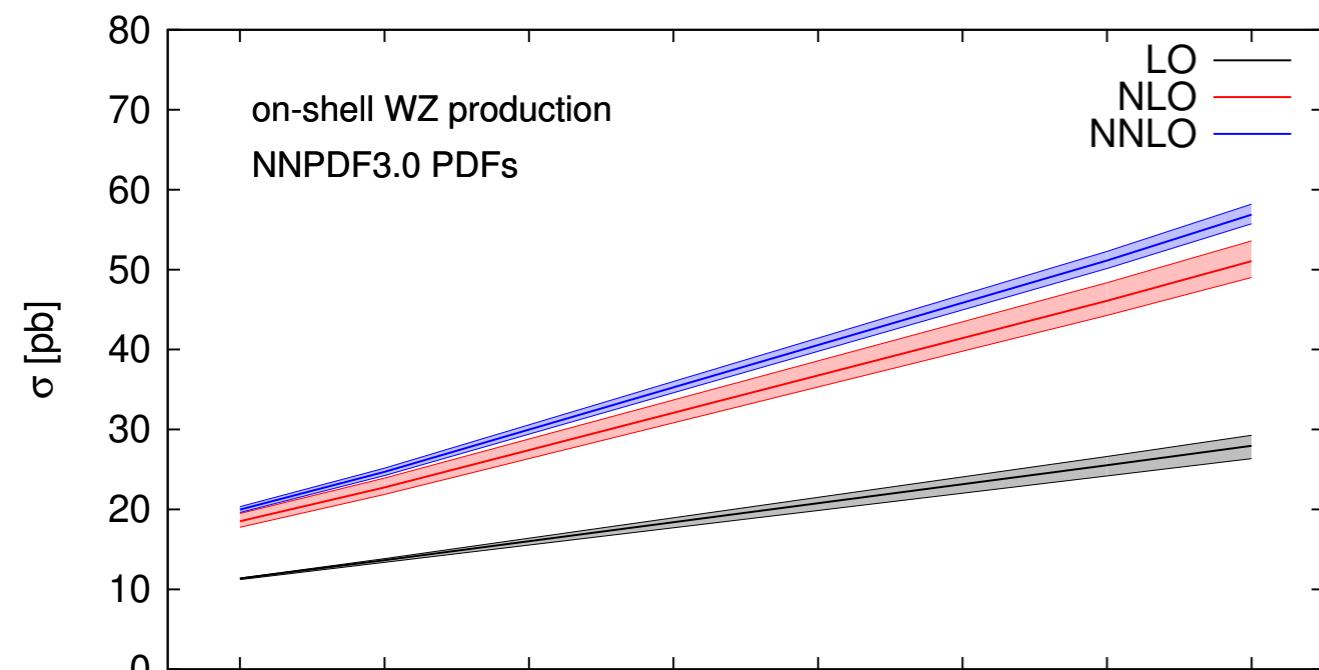
- first computation of NNLO corrections to WZ
- no loop-induced gg component at NNLO
- access to trilinear gauge coupling → relevance for BSM physics
- in principle: same two-loop amplitudes as for off-shell WW
[Gehrmann, von Manteuffel, Tancredi '15]
- **HERE:** only inclusive cross section (minimal cuts on reconstructed Z mass)
- **BUT:** computation in principle ready for off-shell WZ with decays
(amplitudes with different-mass vector bosons already in on-shell case)

WZ cross section at NNLO

[Grazzini, Kallweit, Rathlev, MW '16]

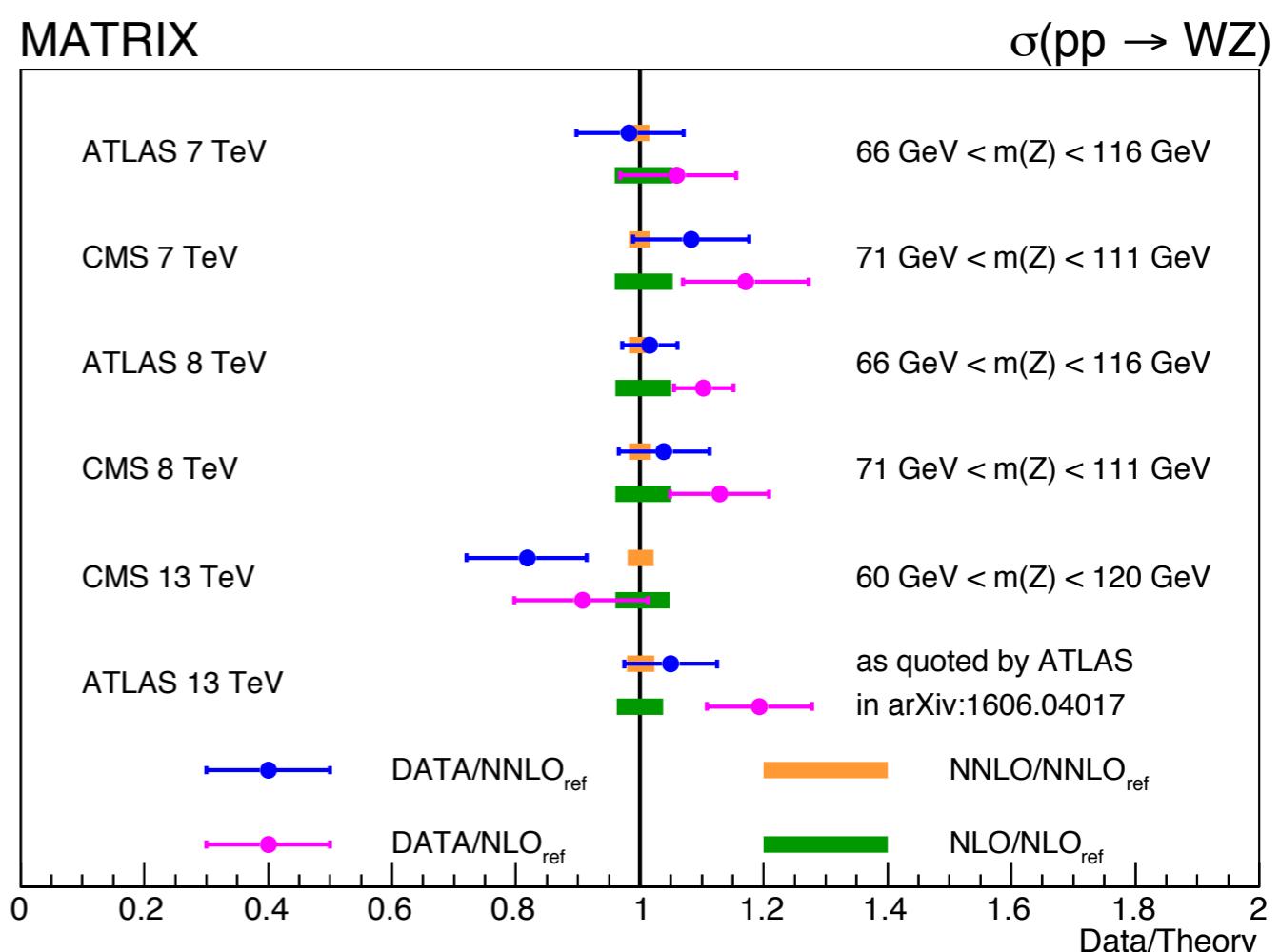


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- Huge radiative corrections due to approximate radiation zero
[Baur, Han, Ohnemus '94]
- ~63-83% NLO corrections
- ~8-11% NNLO corrections
- NNLO corrections nicely improve agreement with data at 7 and 8 TeV
- slightly worse for 13 TeV CMS (large uncertainties)
- NEW: well agreement with [ATLAS '16]

MATRIX



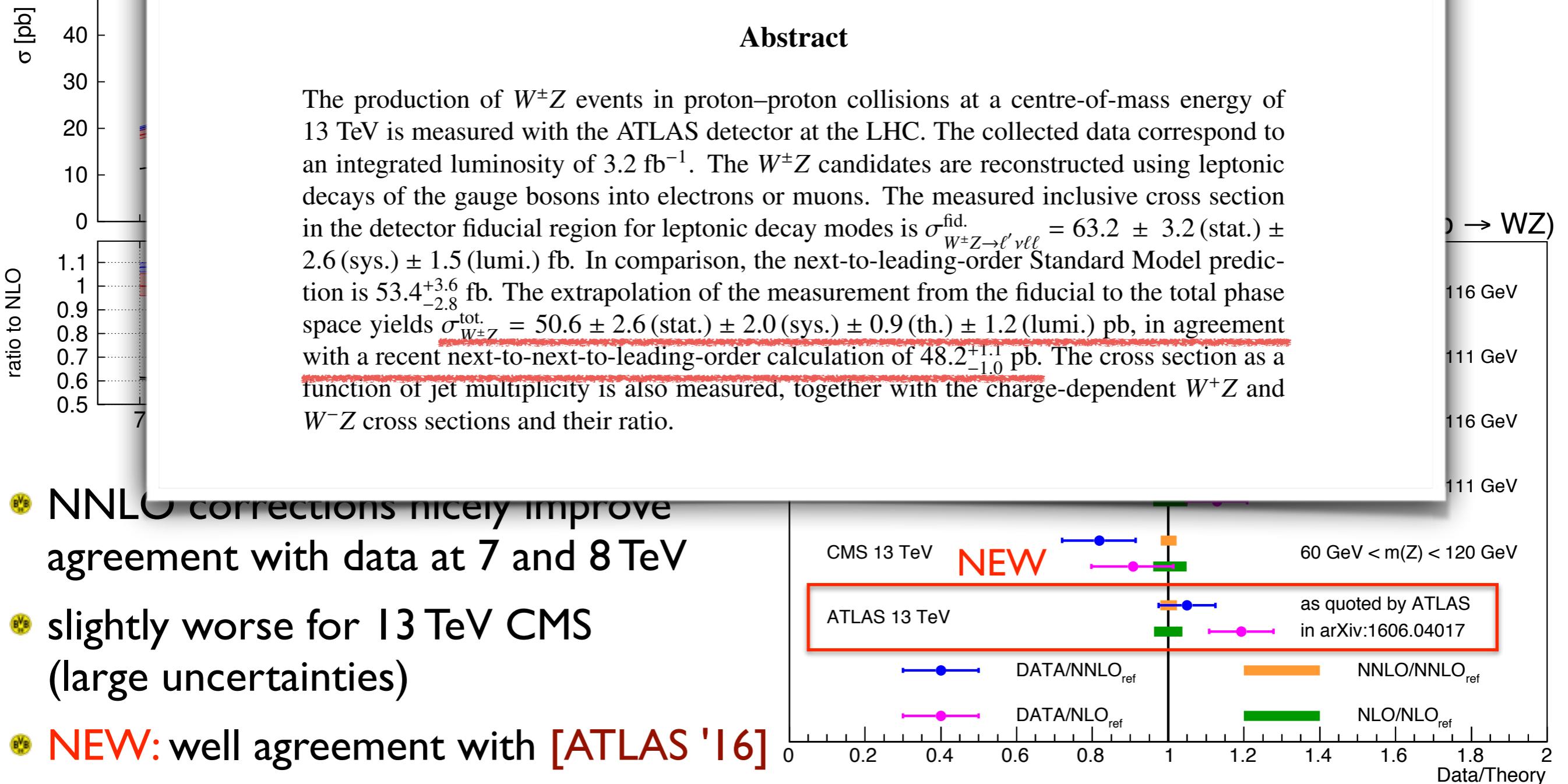
[Graz]

Measurement of the $W^\pm Z$ boson pair-production cross section in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

The ATLAS Collaboration

Abstract

The production of $W^\pm Z$ events in proton–proton collisions at a centre-of-mass energy of 13 TeV is measured with the ATLAS detector at the LHC. The collected data correspond to an integrated luminosity of 3.2 fb^{-1} . The $W^\pm Z$ candidates are reconstructed using leptonic decays of the gauge bosons into electrons or muons. The measured inclusive cross section in the detector fiducial region for leptonic decay modes is $\sigma_{W^\pm Z \rightarrow \ell' \nu \ell}^{\text{fid.}} = 63.2 \pm 3.2 \text{ (stat.)} \pm 2.6 \text{ (sys.)} \pm 1.5 \text{ (lumi.) fb}$. In comparison, the next-to-leading-order Standard Model prediction is $53.4^{+3.6}_{-2.8} \text{ fb}$. The extrapolation of the measurement from the fiducial to the total phase space yields $\sigma_{W^\pm Z}^{\text{tot.}} = 50.6 \pm 2.6 \text{ (stat.)} \pm 2.0 \text{ (sys.)} \pm 0.9 \text{ (th.)} \pm 1.2 \text{ (lumi.) pb}$, in agreement with a recent next-to-next-to-leading-order calculation of $48.2^{+1.1}_{-1.0} \text{ pb}$. The cross section as a function of jet multiplicity is also measured, together with the charge-dependent W^+Z and W^-Z cross sections and their ratio.



- NNLO corrections nicely improve agreement with data at 7 and 8 TeV

- slightly worse for 13 TeV CMS (large uncertainties)

- NEW: well agreement with [ATLAS '16]



Summary

- **MATRIX:** tool for fully-differential NNLO(+NNLL) computations
- **CURRENTLY:** closed beta **SOON:** public release
- large list of $2 \rightarrow 1, 2 \rightarrow 2$ Higgs and vector-boson processes
- p_T resummation automated in same framework (first application: WW, ZZ)
- NNLO corrections for all vector-boson pair processes **COMPLETED**
- WW: important NNLO corrections on acceptances and shapes
- WZ: large radiative corrections (radiation zero) → **agreement with data improved at NNLO**

Outlook

- 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
"Cypher"
Rathlev

Massimiliano
"Morpheus"
Grazzini

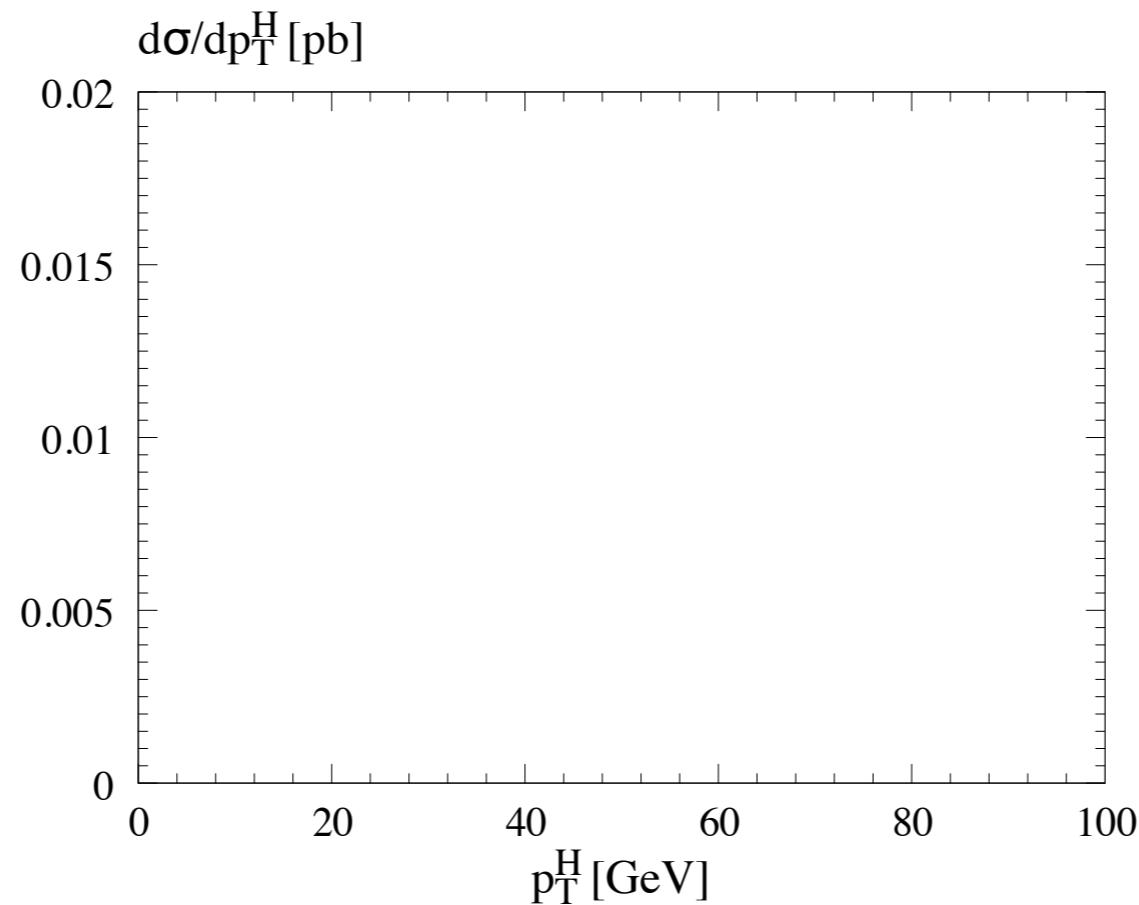
Stefan
"Neo"
Kallweit

Marius
"Trinity"
Wiesemann

matching: FO+resummation



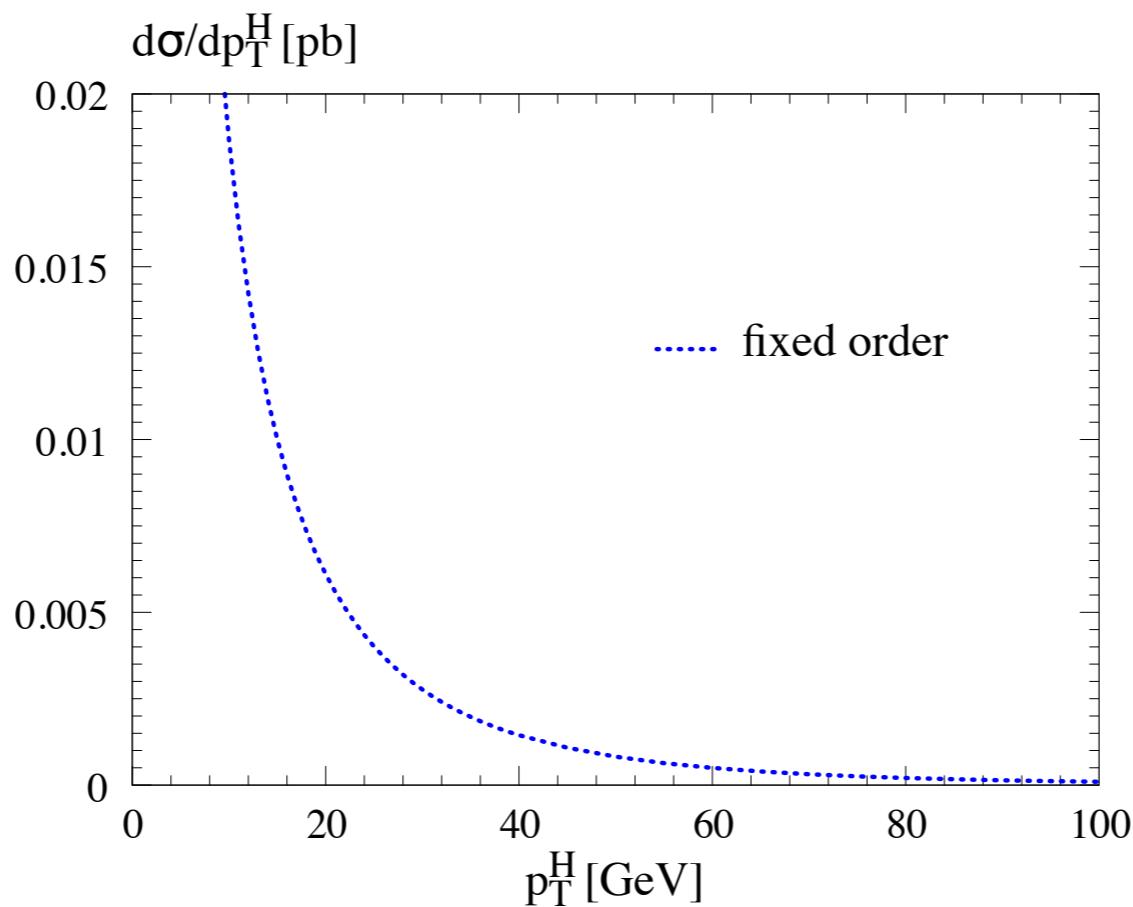
$$\left[\frac{d\sigma}{dp_T^2} \right]_{\text{f.o.}+\text{l.a.}} =$$



matching: FO+resummation



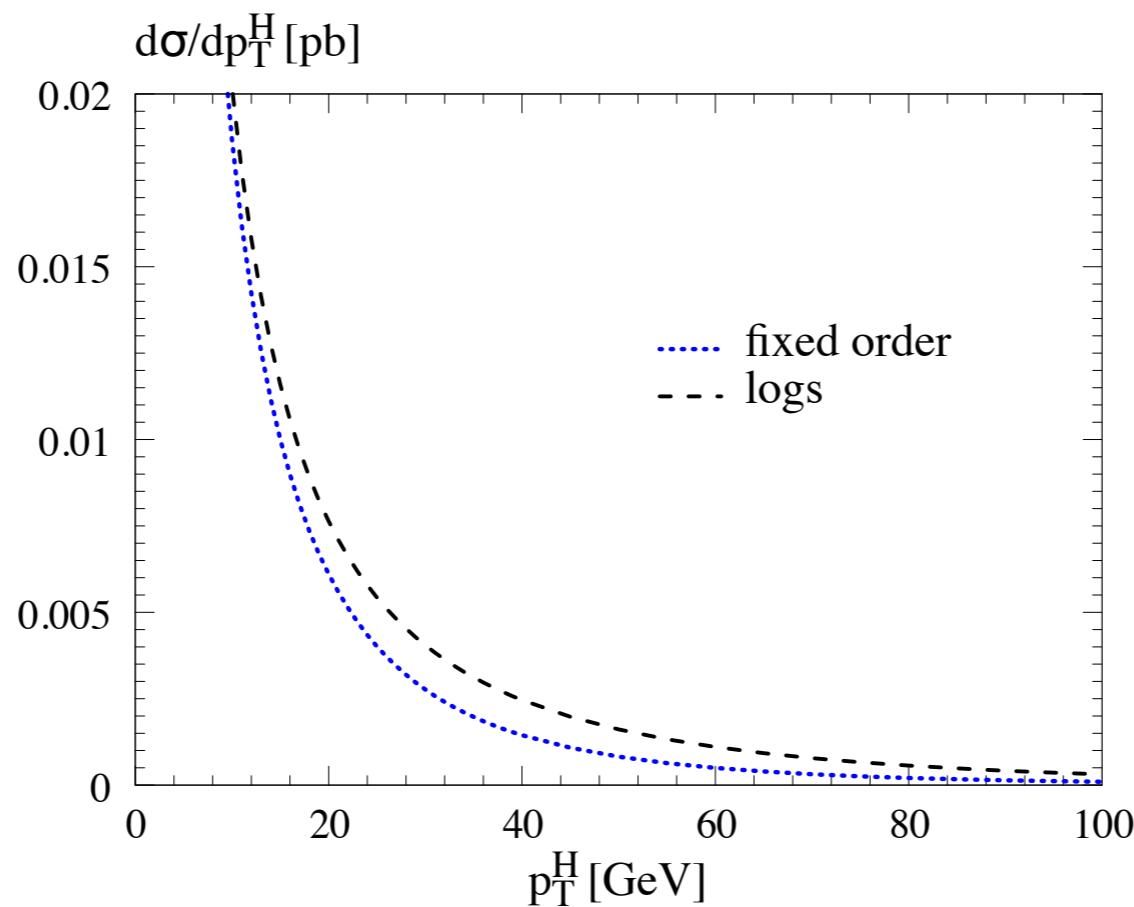
$$\left[\frac{d\sigma}{dp_T^2} \right]_{\text{f.o.}+\text{l.a.}} = \left[\frac{d\sigma}{dp_T^2} \right]_{\text{f.o.}}$$



matching: FO+resummation



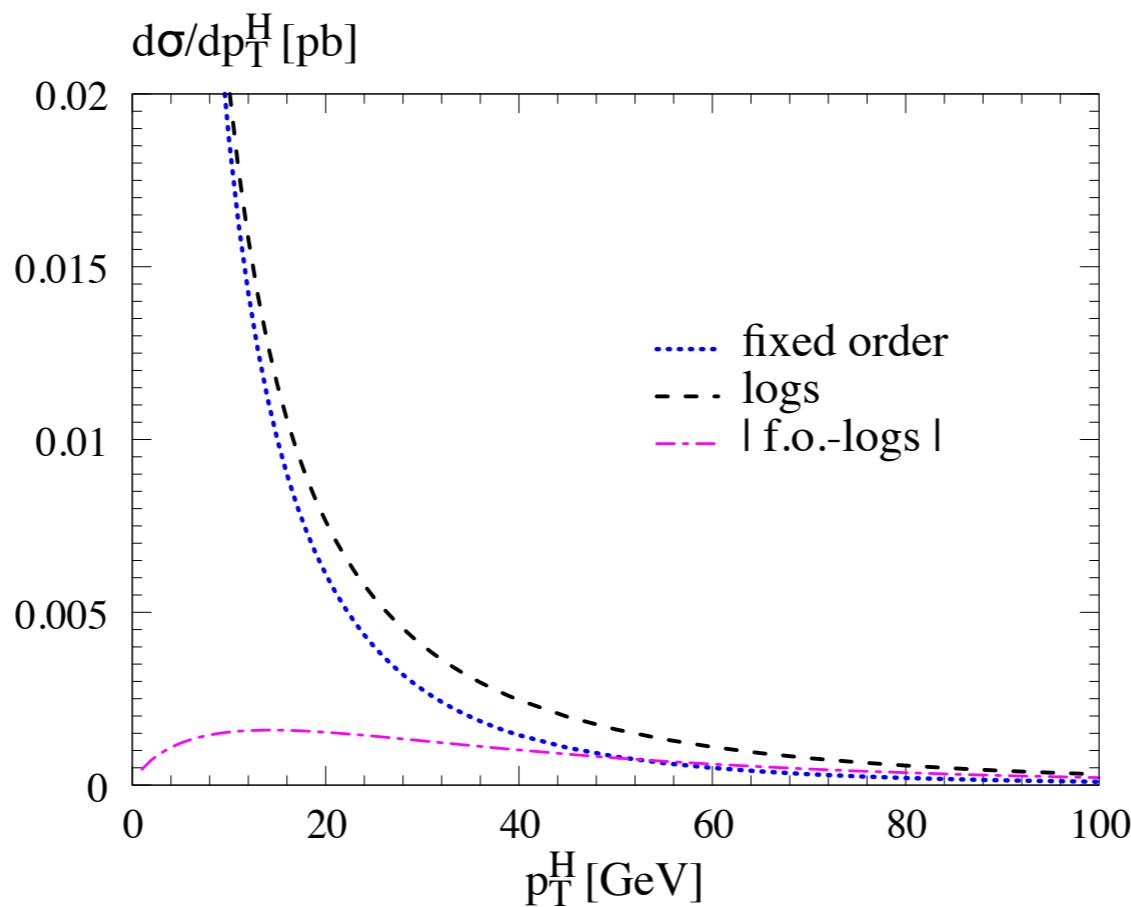
$$\left[\frac{d\sigma}{dp_T^2} \right]_{\text{f.o.} + \text{l.a.}} = \left[\frac{d\sigma}{dp_T^2} \right]_{\text{f.o.}} - \left[\frac{d\sigma^{(\text{res})}}{dp_T^2} \right]_{\text{f.o.}}$$



matching: FO+resummation



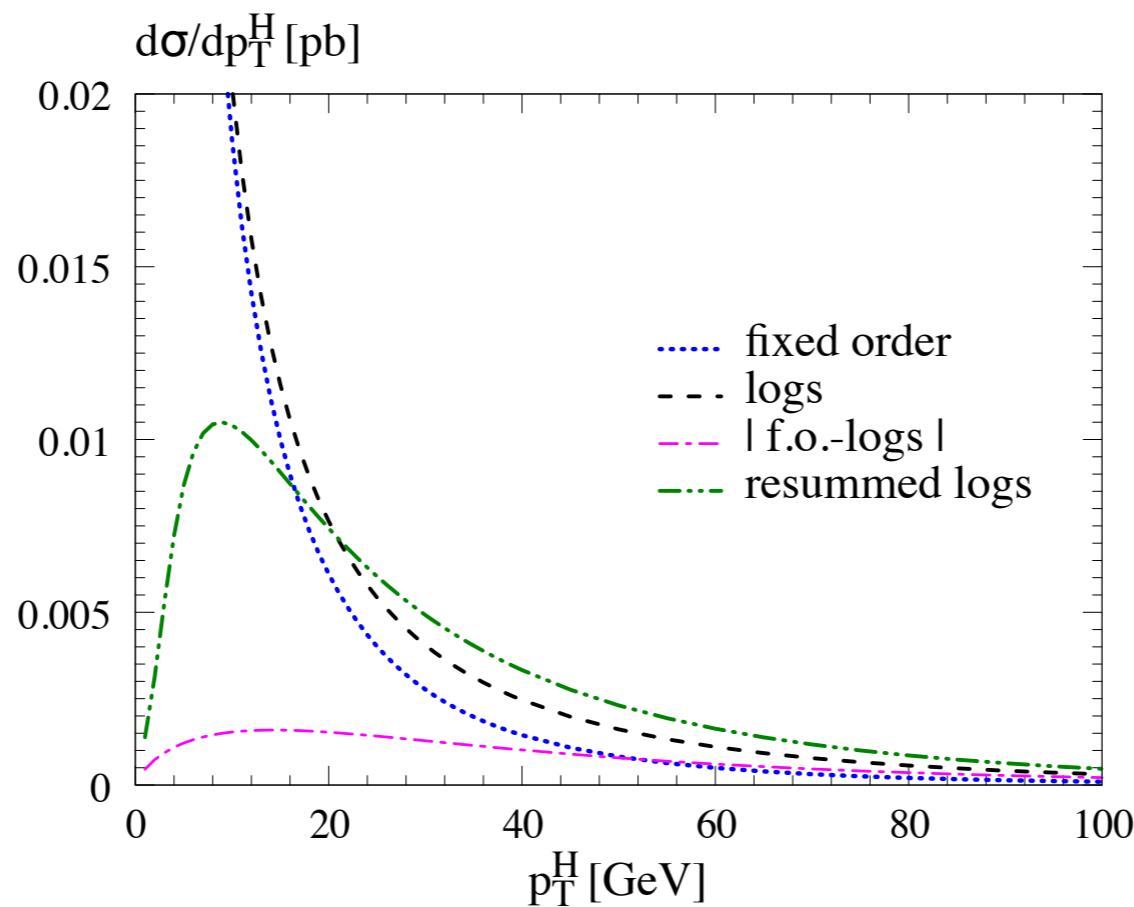
$$\left[\frac{d\sigma}{dp_T^2} \right]_{f.o.+l.a.} = \left[\frac{d\sigma}{dp_T^2} \right]_{f.o.} - \left[\frac{d\sigma^{(res)}}{dp_T^2} \right]_{f.o.}$$



matching: FO+resummation



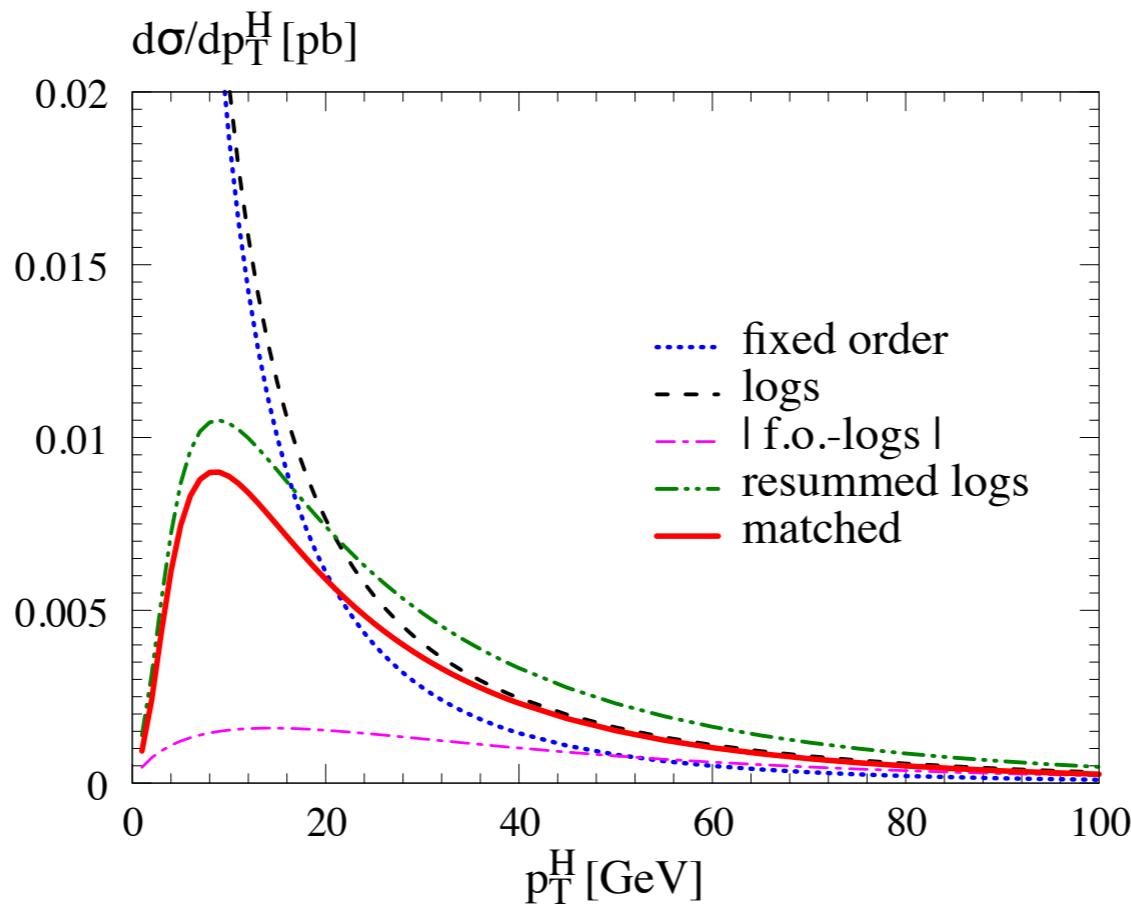
$$\left[\frac{d\sigma}{dp_T^2} \right]_{\text{f.o.}+\text{l.a.}} = \left[\frac{d\sigma}{dp_T^2} \right]_{\text{f.o.}} - \left[\frac{d\sigma^{(\text{res})}}{dp_T^2} \right]_{\text{f.o.}} + \left[\frac{d\sigma^{(\text{res})}}{dp_T^2} \right]_{\text{l.a.}}$$



matching: FO+resummation



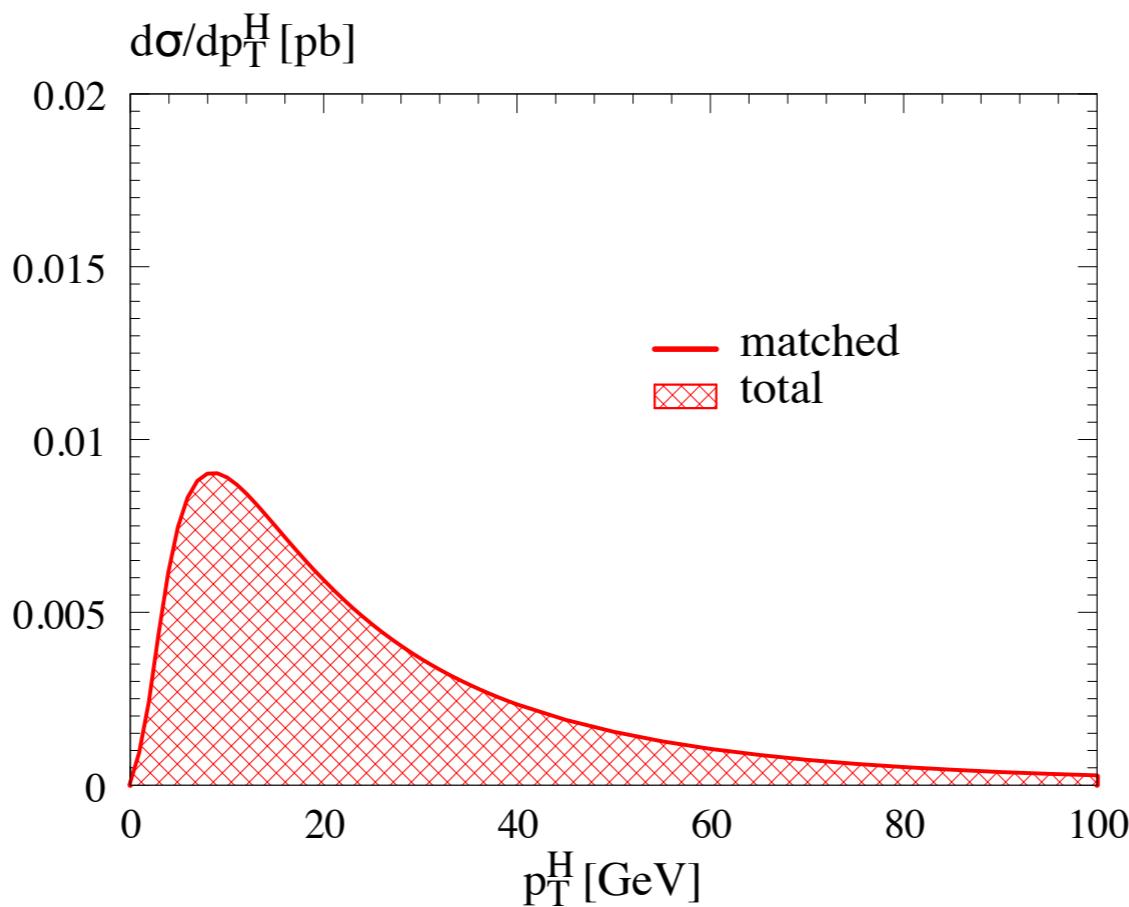
$$\left[\frac{d\sigma}{dp_T^2} \right]_{\text{f.o.}+\text{l.a.}} = \left[\frac{d\sigma}{dp_T^2} \right]_{\text{f.o.}} - \left[\frac{d\sigma^{(\text{res})}}{dp_T^2} \right]_{\text{f.o.}} + \left[\frac{d\sigma^{(\text{res})}}{dp_T^2} \right]_{\text{l.a.}}$$



matching: FO+resummation



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



NNLO+NNLL resummation

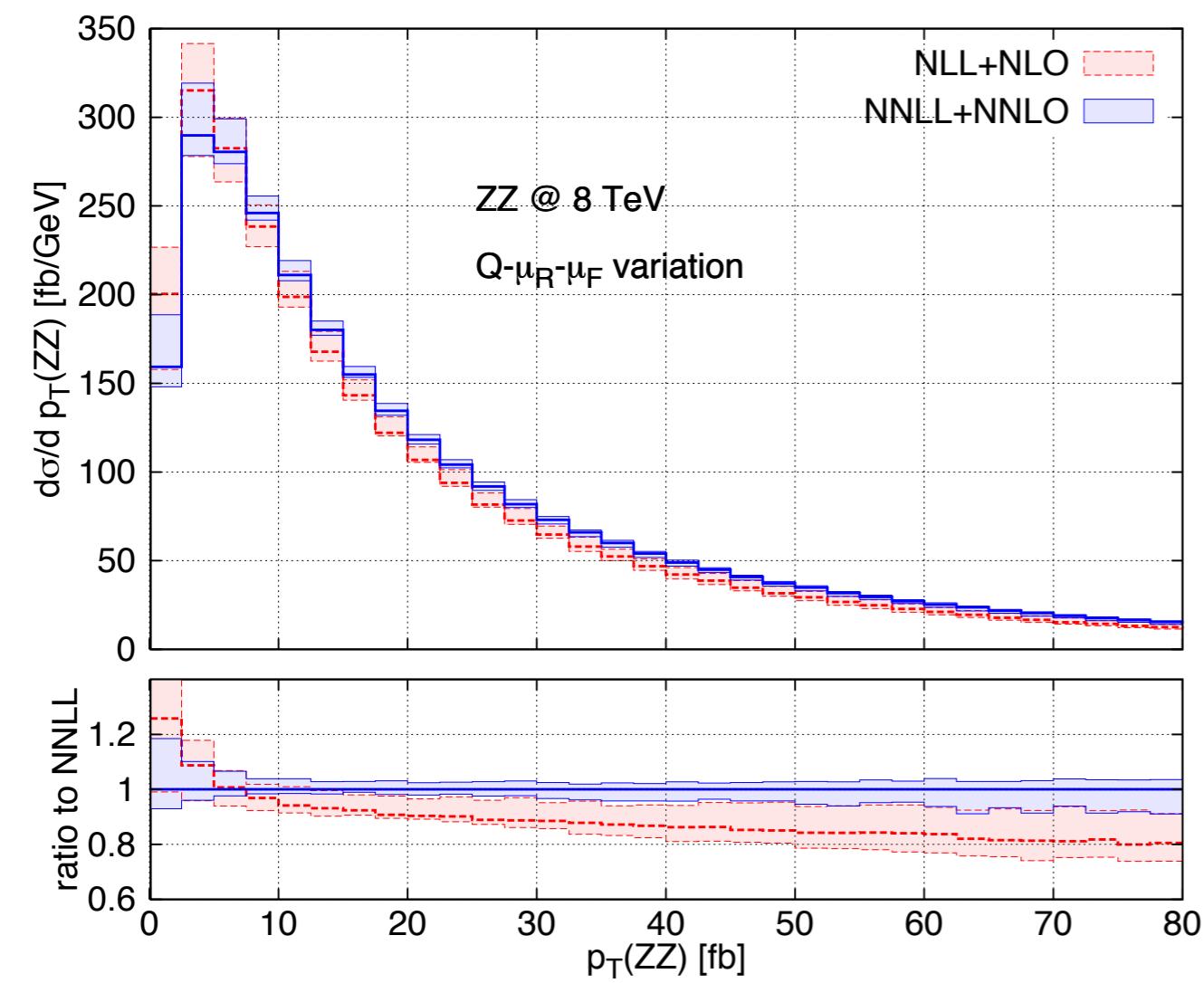
for ZZ and WW

[Grazzini, Kallweit, Rathlev, MW '15]

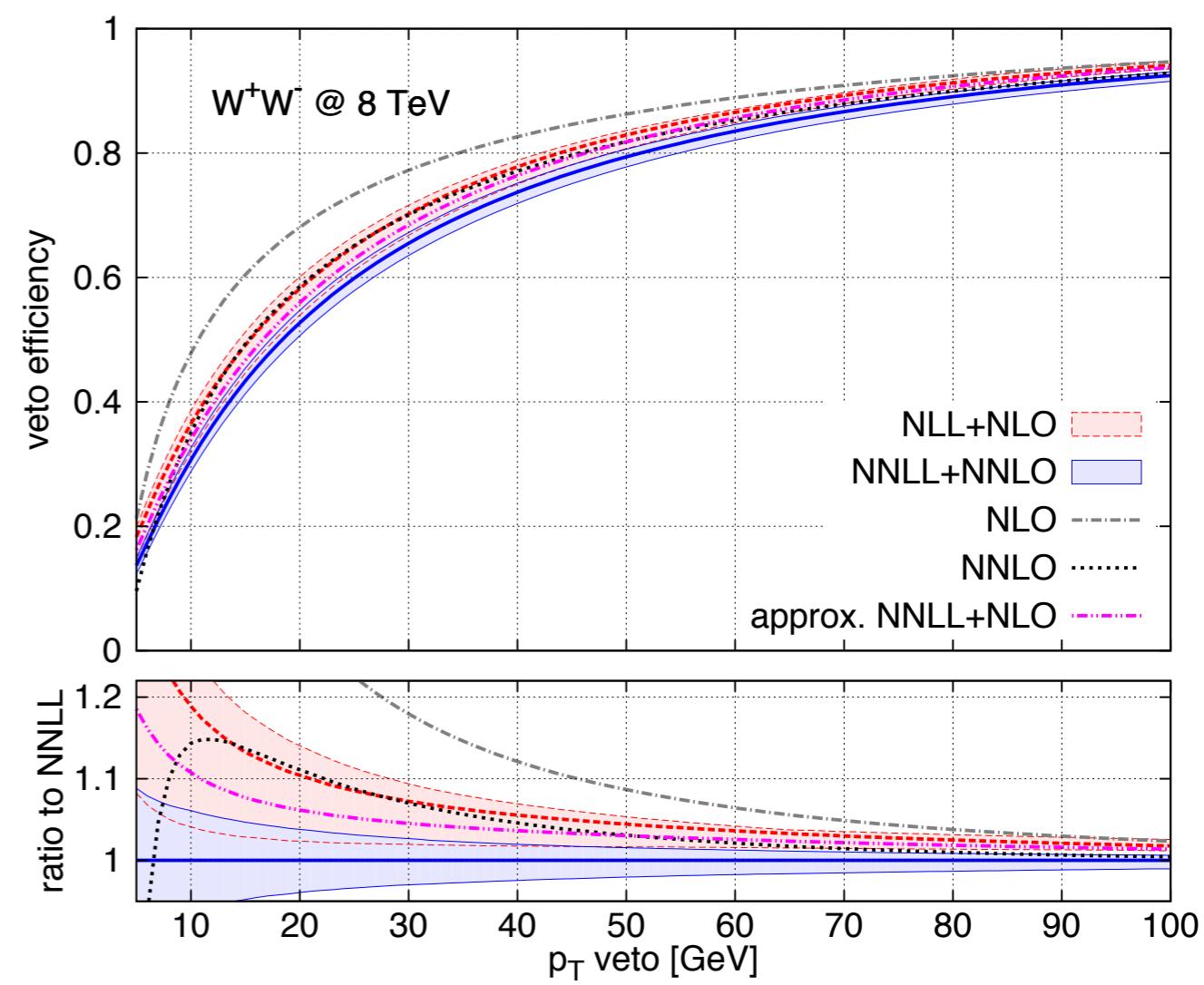


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p_T spectrum of ZZ pair

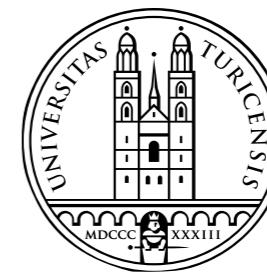


p_T veto WW cross section



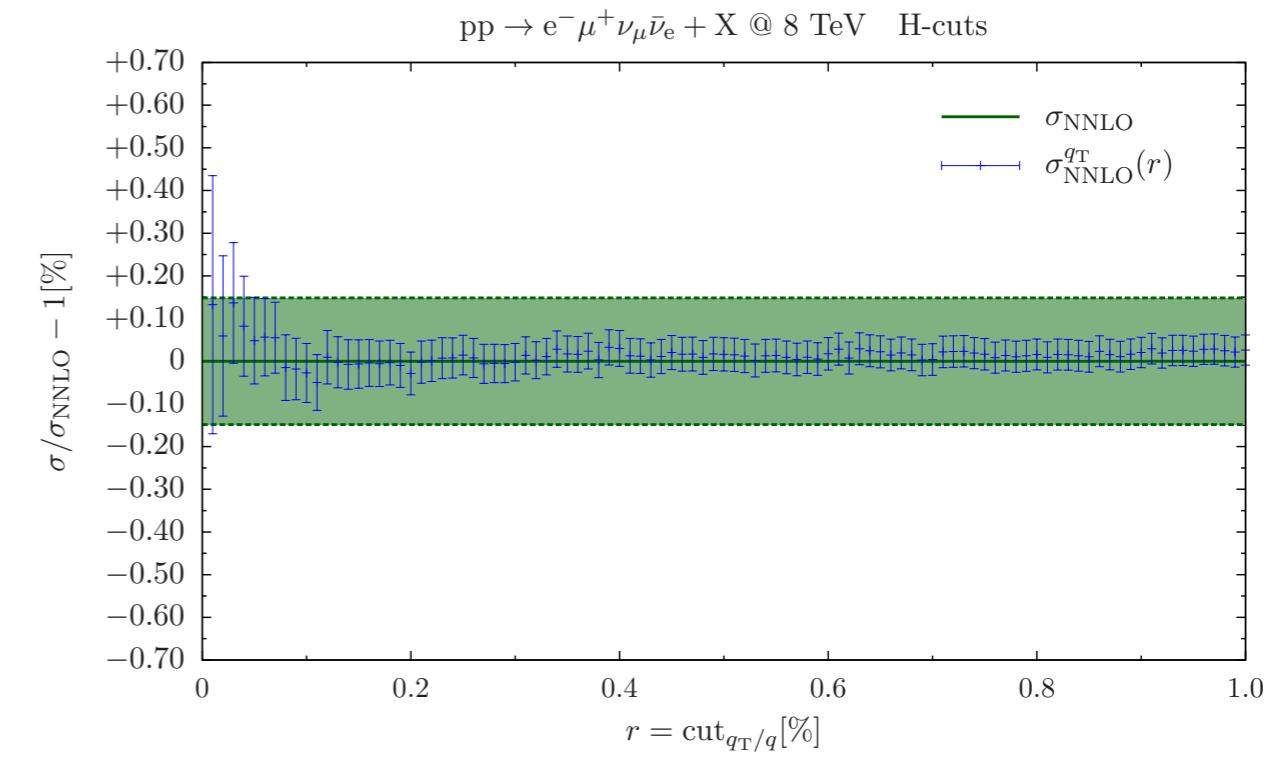
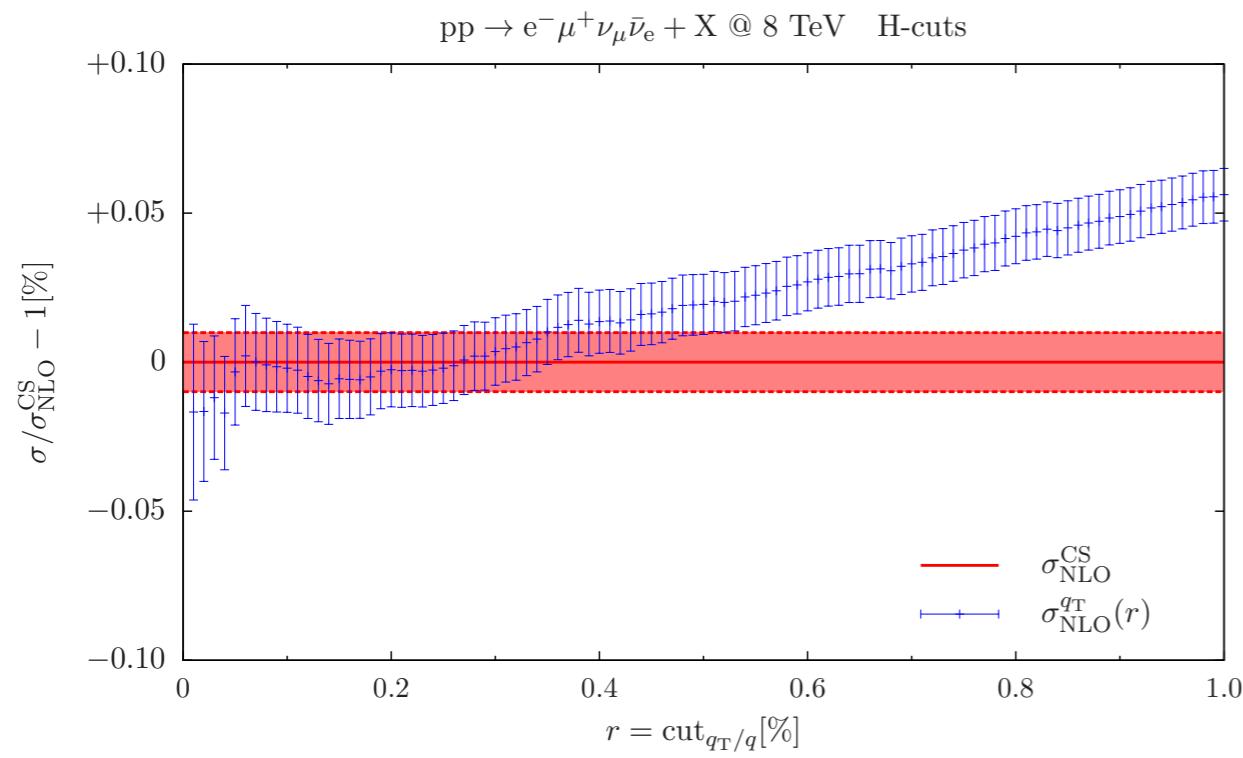
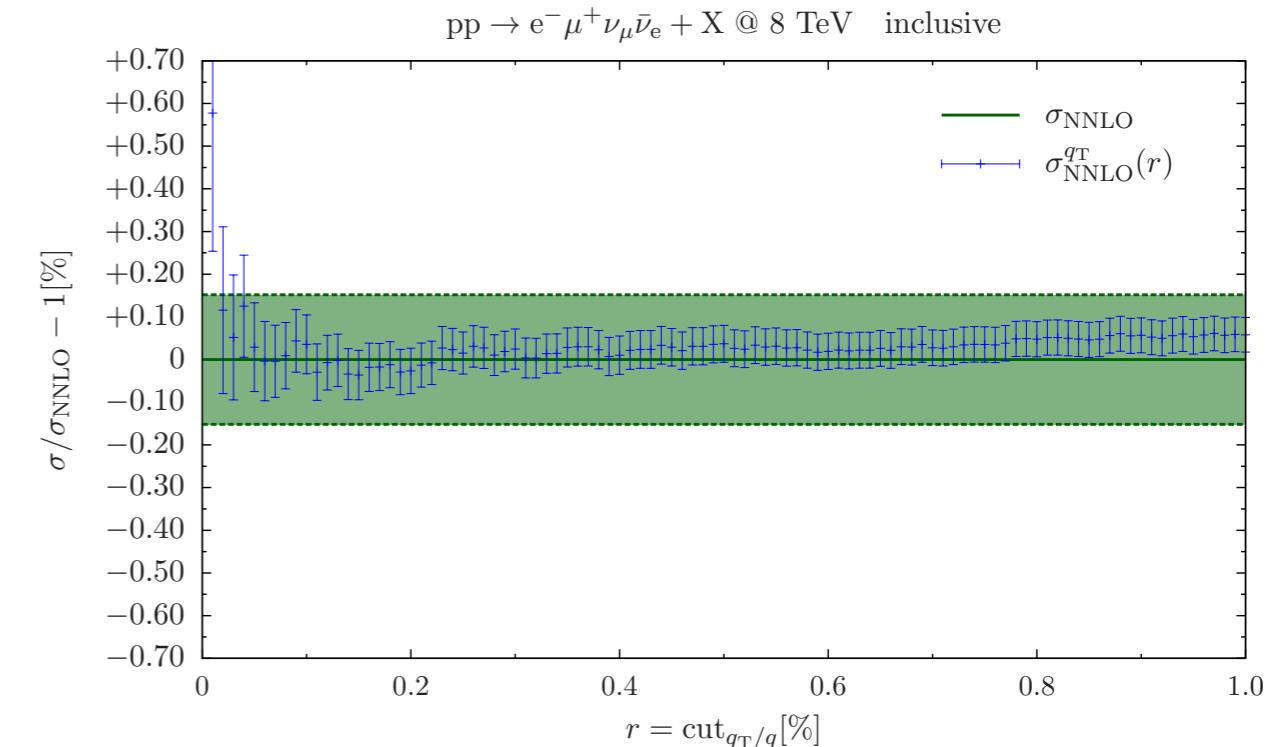
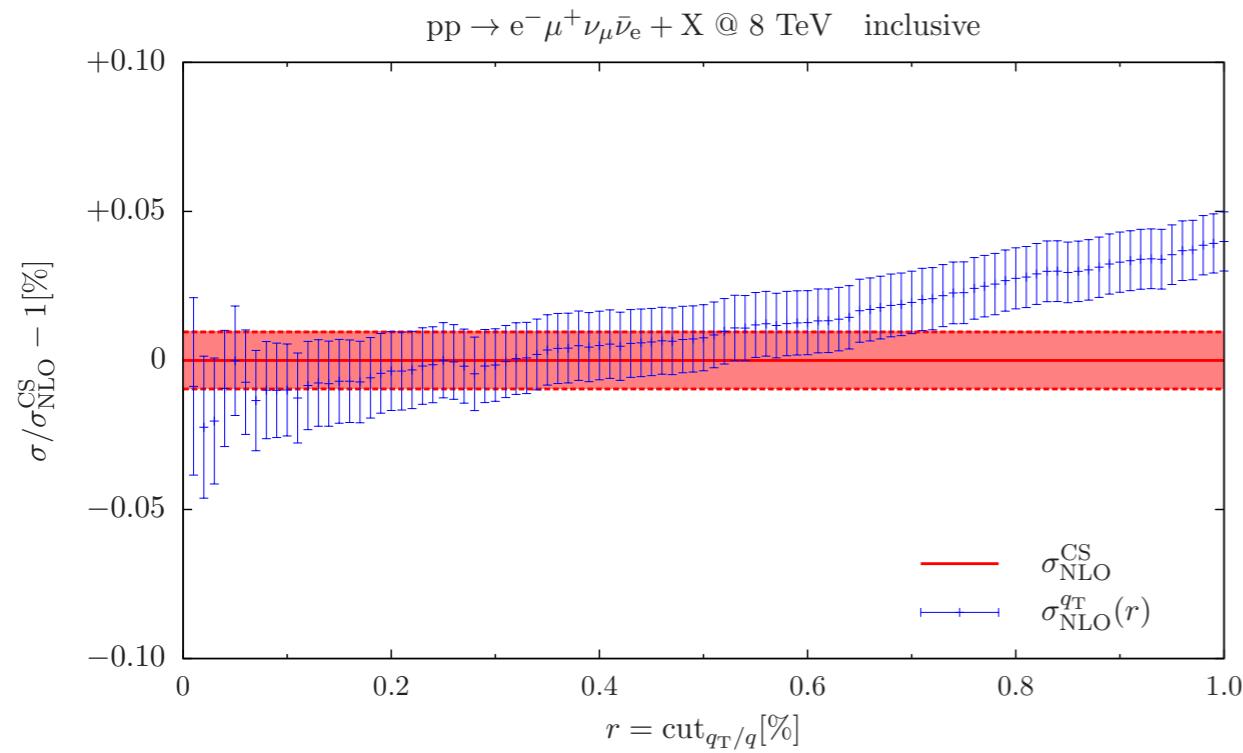
WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]



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stability of $r_{\text{cut}} = p_T/m_{WW}$ dependence



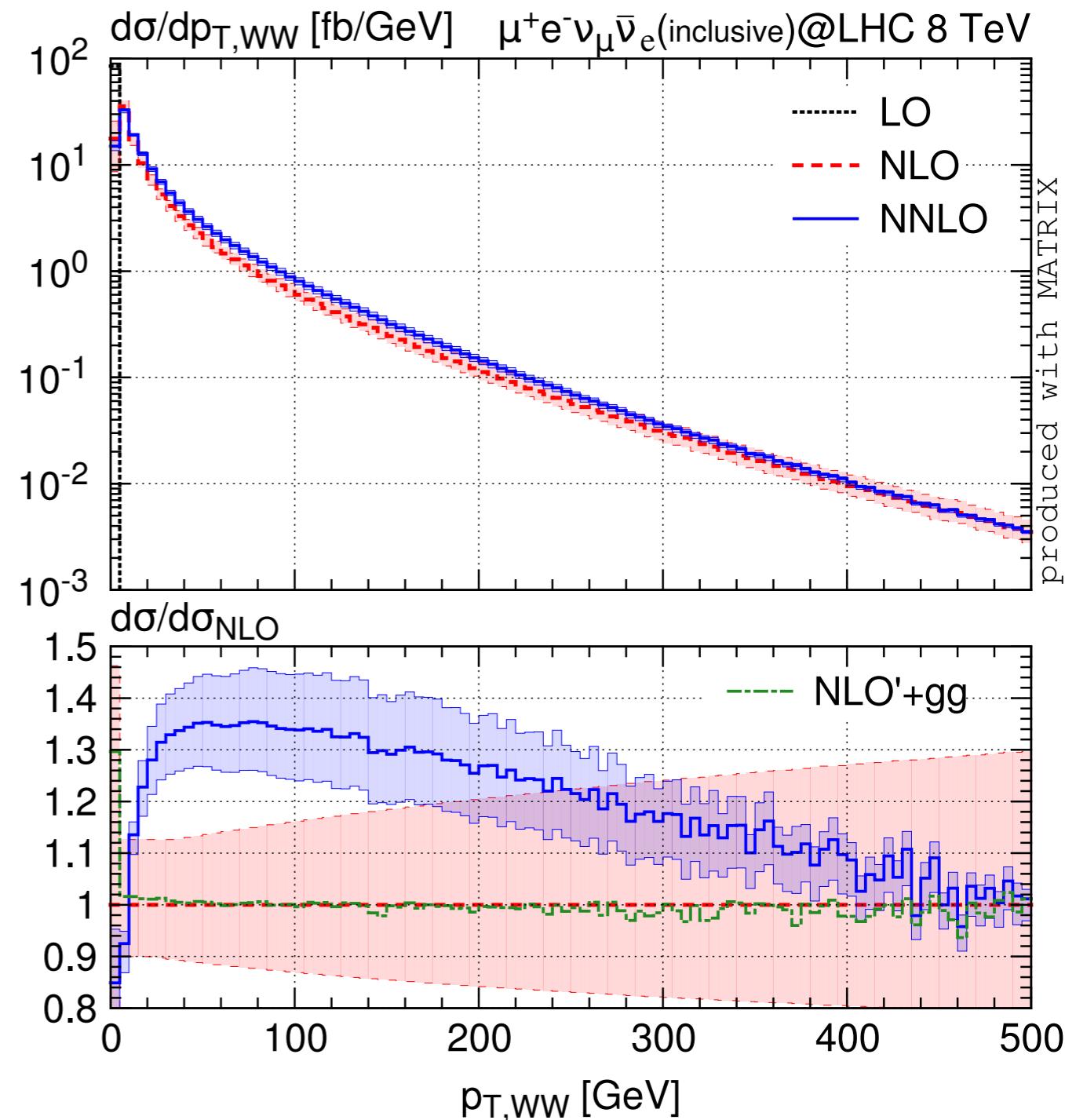
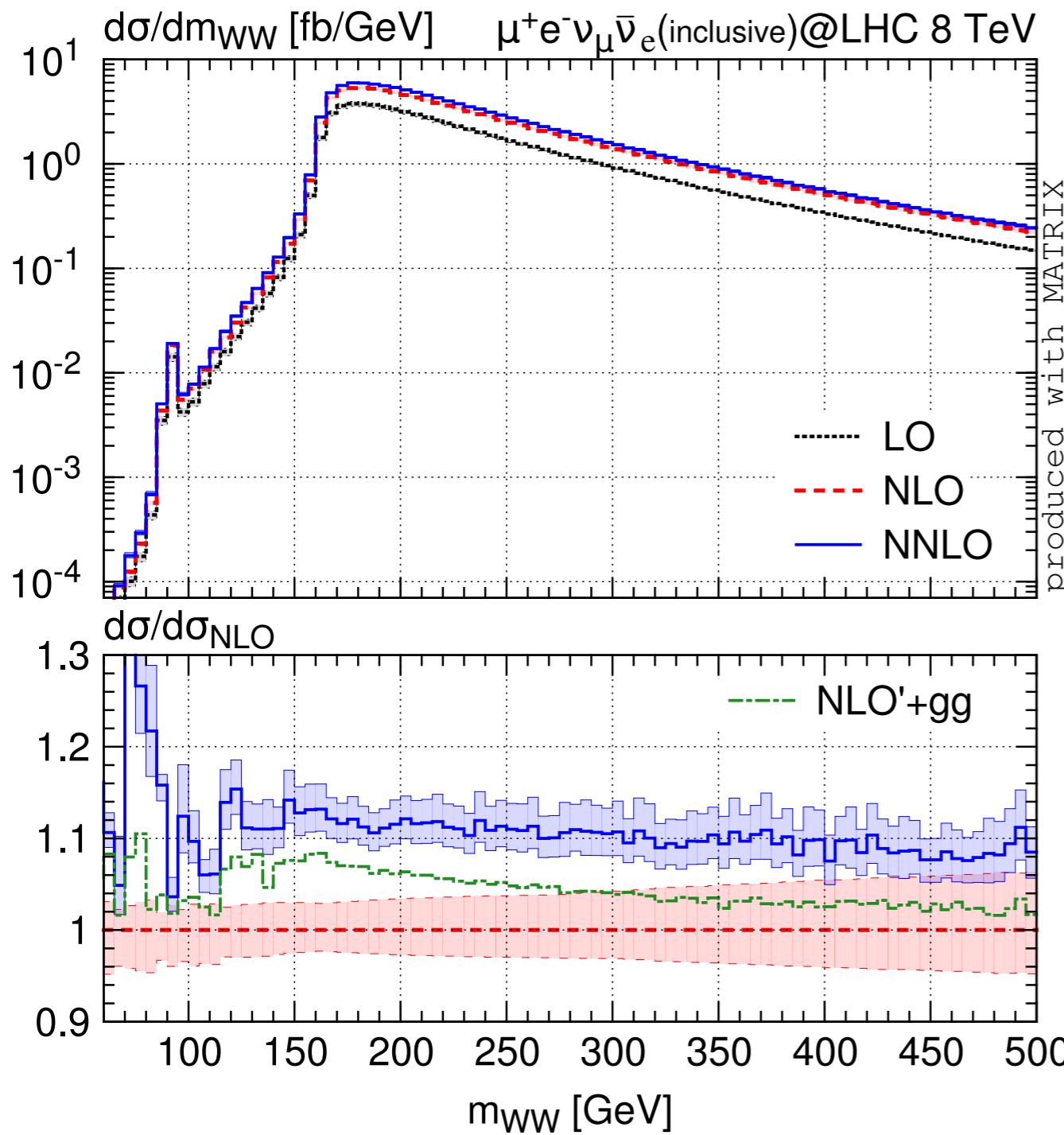
WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]



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inclusive: distributions (8 TeV)



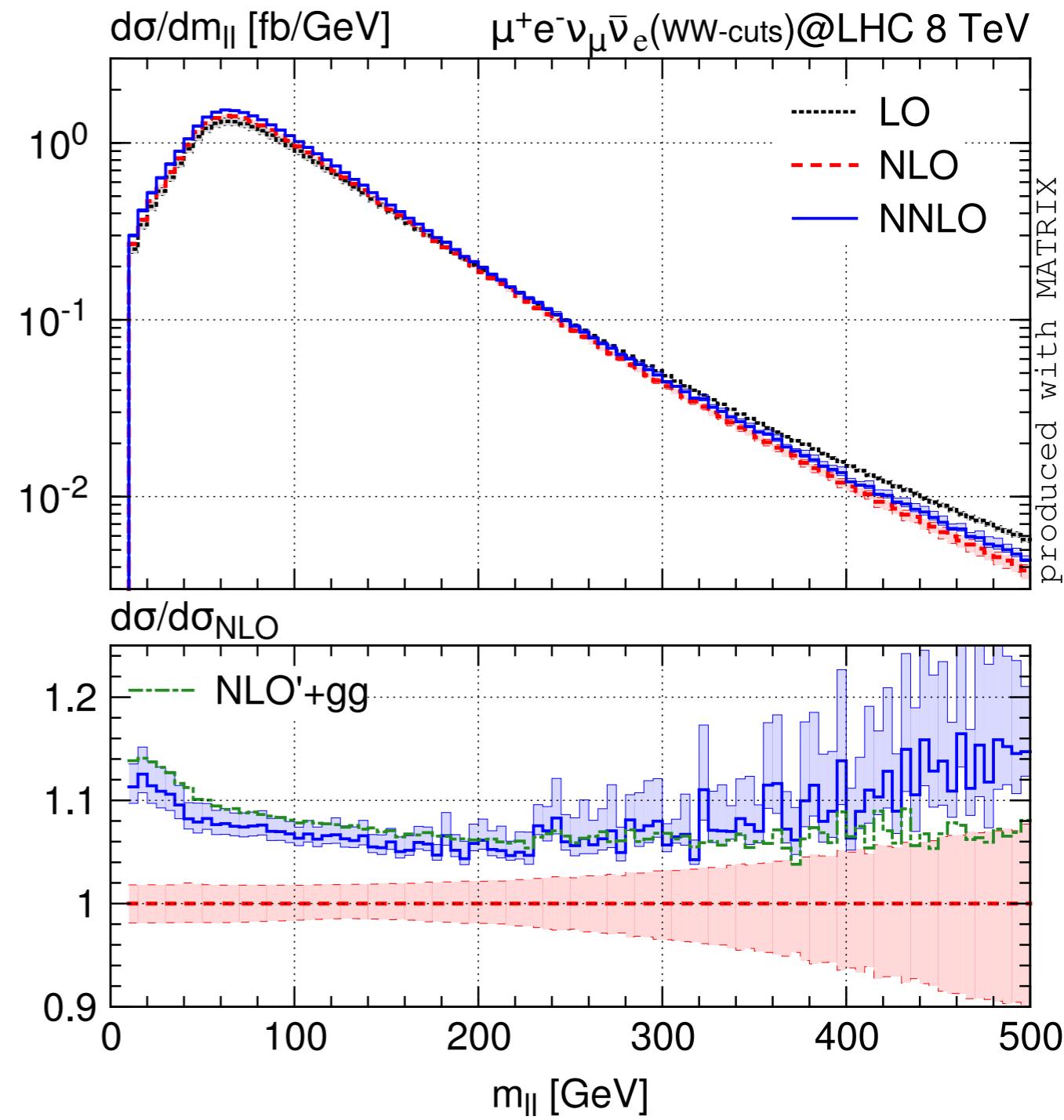
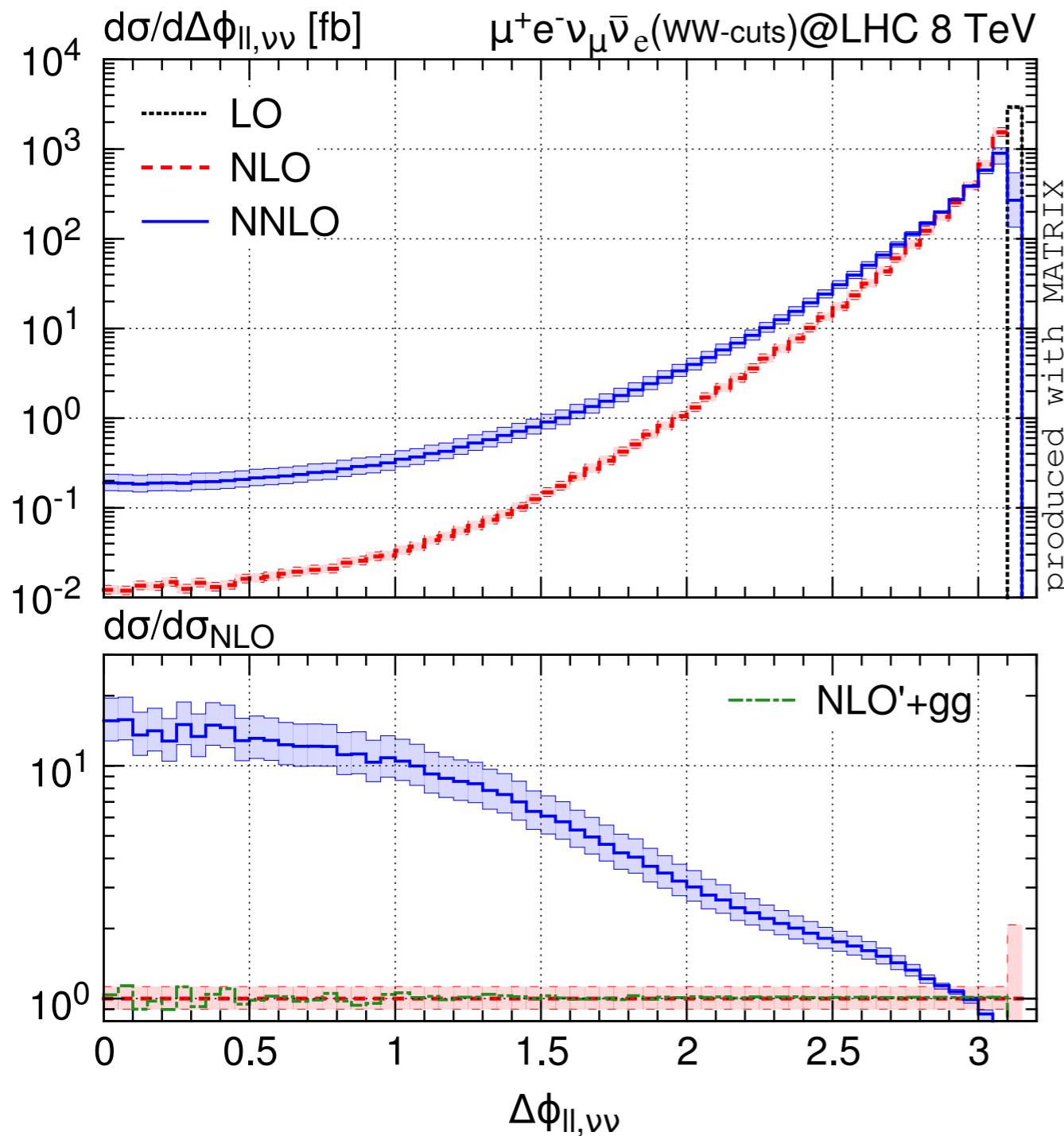
WW fully differential at NNLO

[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

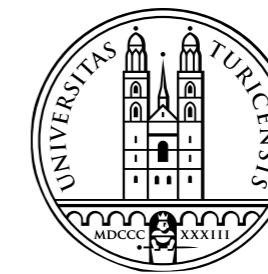


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WW signal cuts: distributions (8 TeV)



Measured WZ cross section



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