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

Marius Wiesemann

Universität Zürich[UZH]

High Precision for Hard Processes 6, Buenos Aires (Argentina)

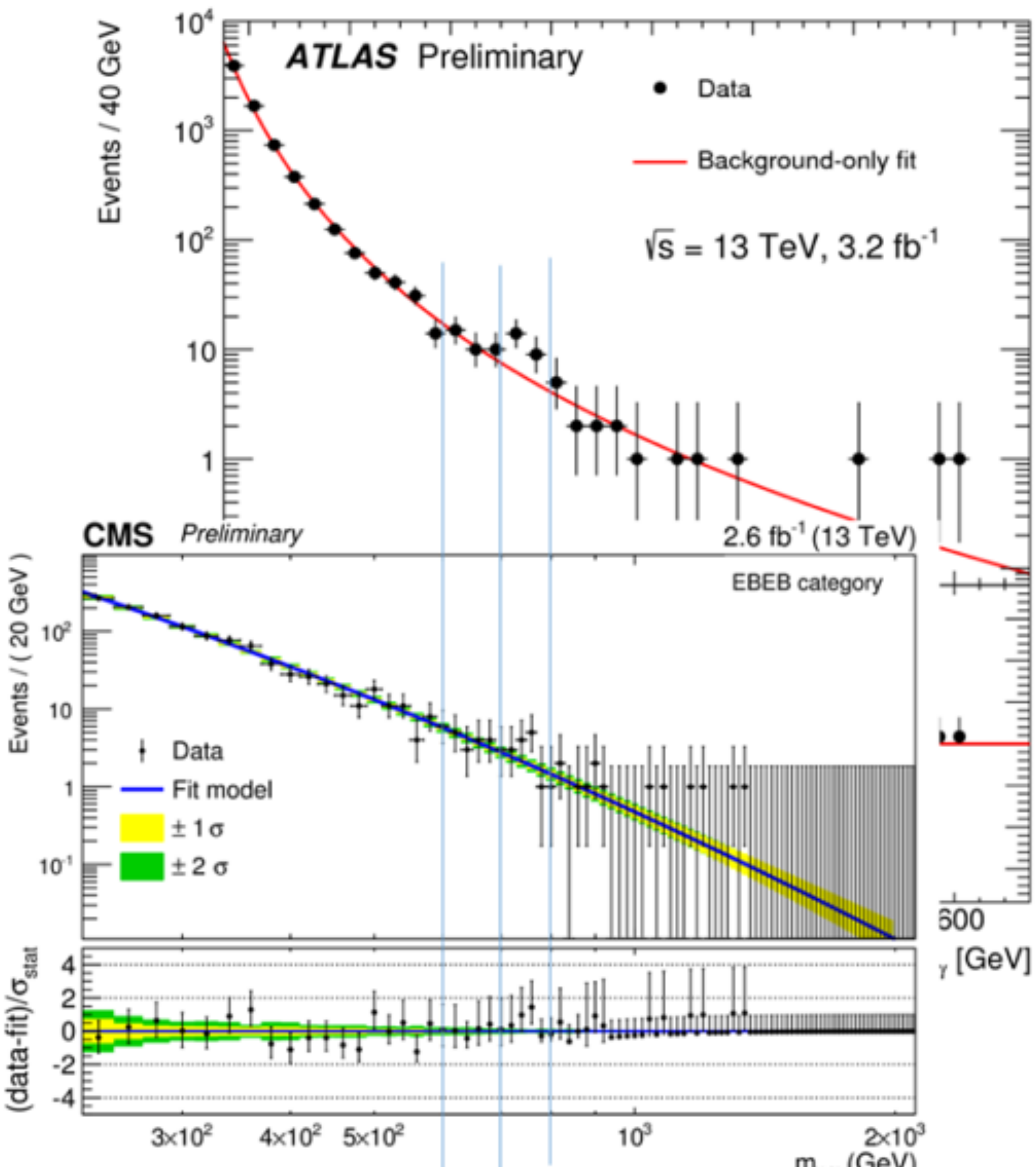
6-9 September, 2016

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

Outline

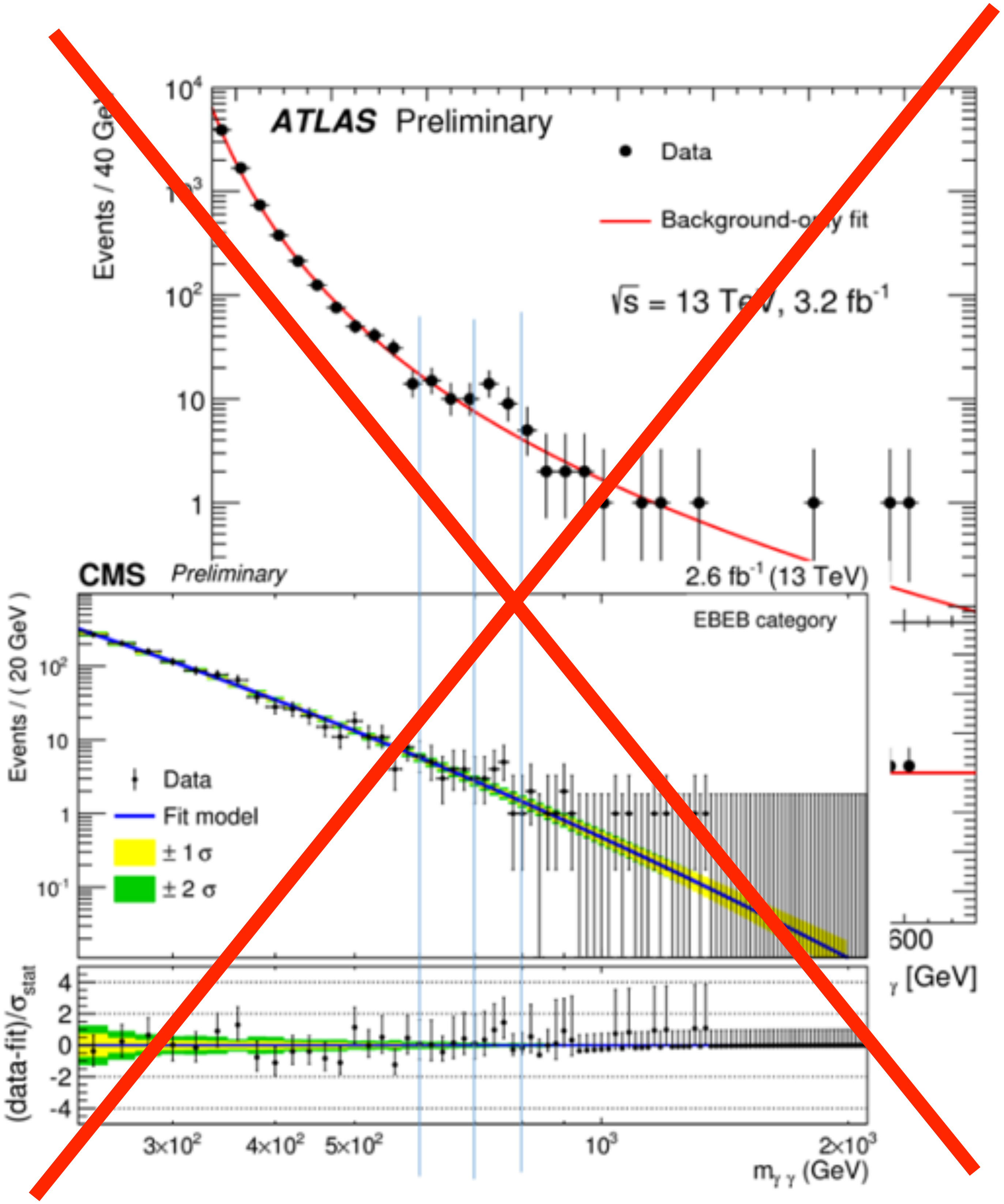
1. Motivation for precision physics
2. NNLO methods
3. p_T subtraction and resummation
4. The MATRIX
5. ZZ and WW at NNLO+NNLL (p_T resummation)
6. NEW: pp→WW→llνν at NNLO (fully differential)
7. NEW: pp→WZ+X at NNLO (inclusive)
8. **VERY VERY NEW+Preliminary:** pp→WZ+X (fully differential)

2015 → 2016



ATLAS Preliminary
Data
Background-only fit
√s = 13 TeV, 3.2 fb-1
Events / 40 GeV
600
[GeV]
CMS Preliminary
2.6 fb-1 (13 TeV)
EBEB category
Data
Fit model
± 1 σ
± 2 σ
Events / (20 GeV)
(data-fit)/σstat
m γ γ (GeV)

2015 → 2016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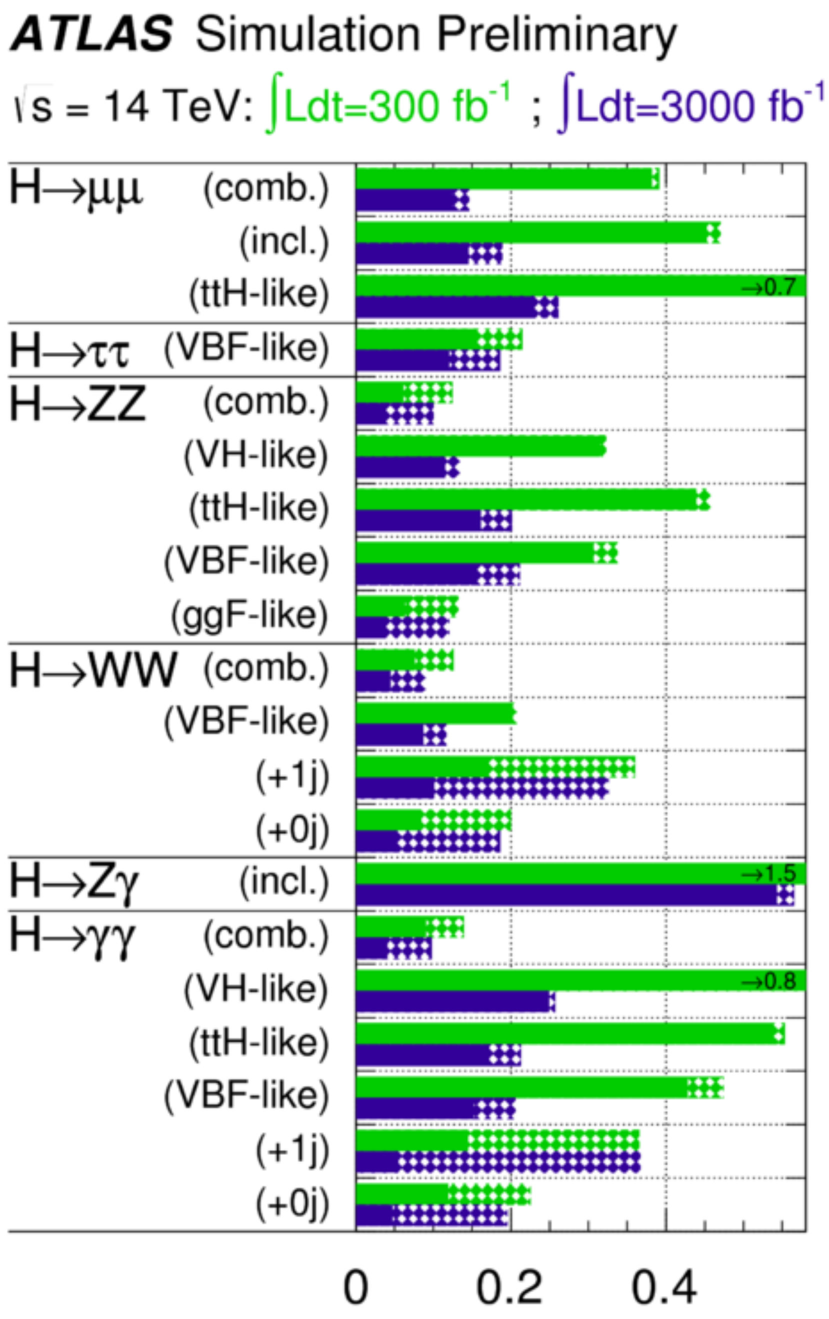
± 1 σ
± 2 σ
(data-fit)/σ_stat
3×10²
4×10²
5×10²
10³
2×10³
m_γγ (GeV)


750-GEV DIPHOTON EXCESS...
AAAND IT'S GONE!
imgflip.com


Diphoton Excess
2015 - 2016
R.I.P.
FutureGravestone.com

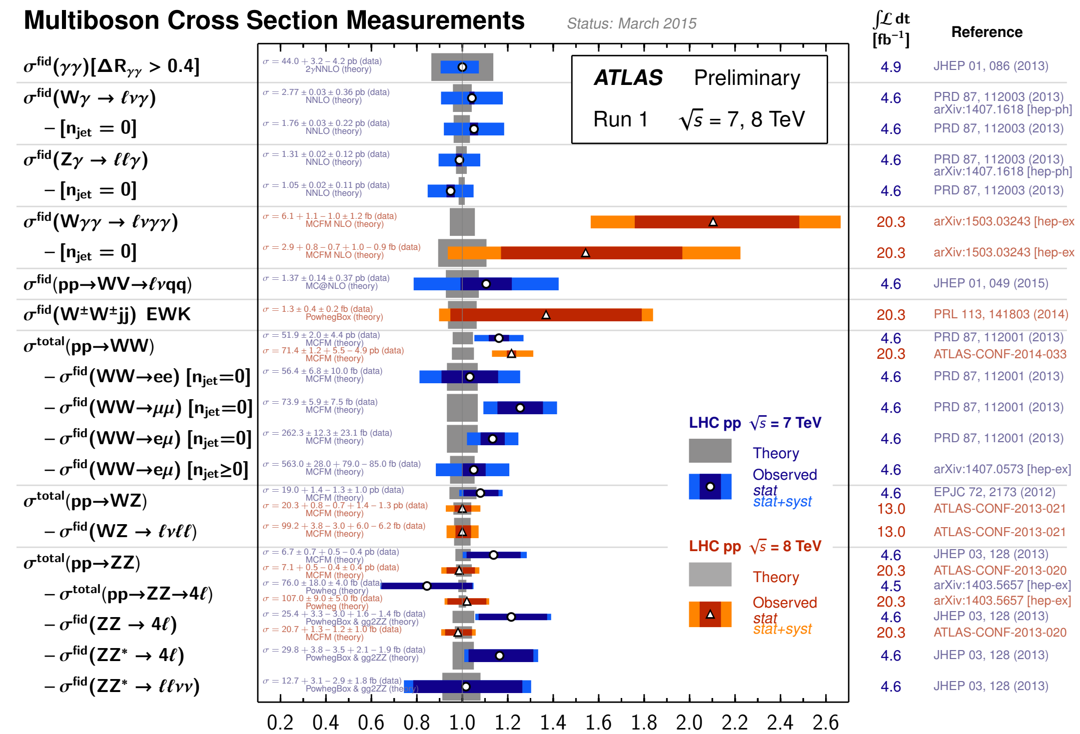
Introduction

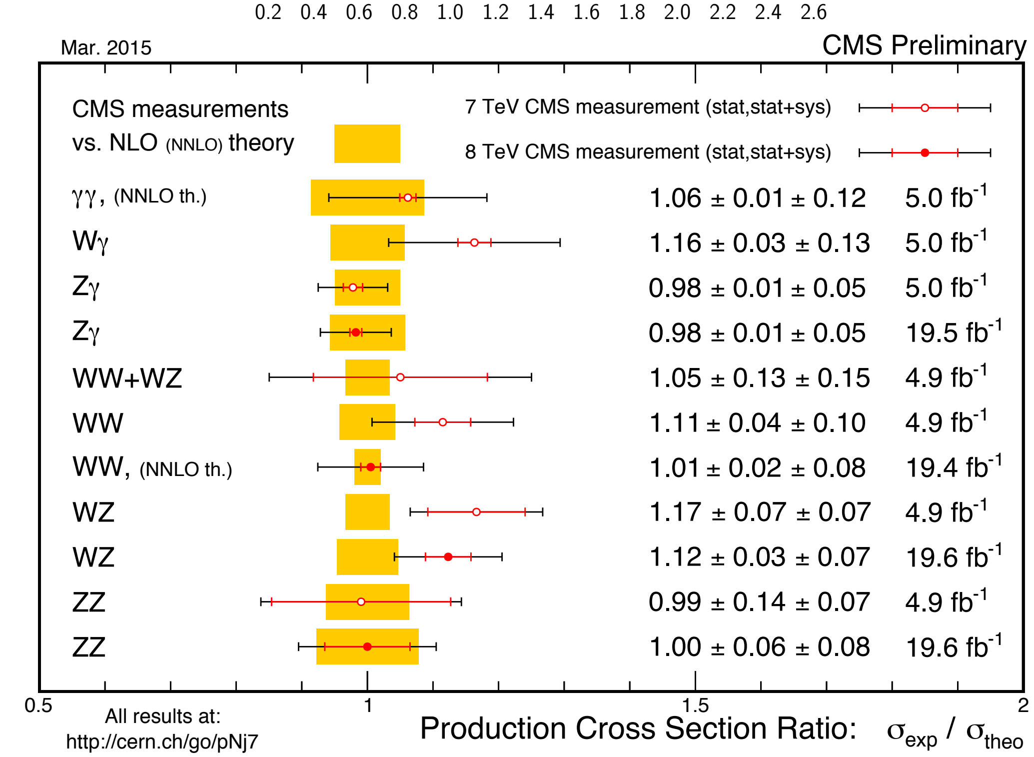
Higgs measurements



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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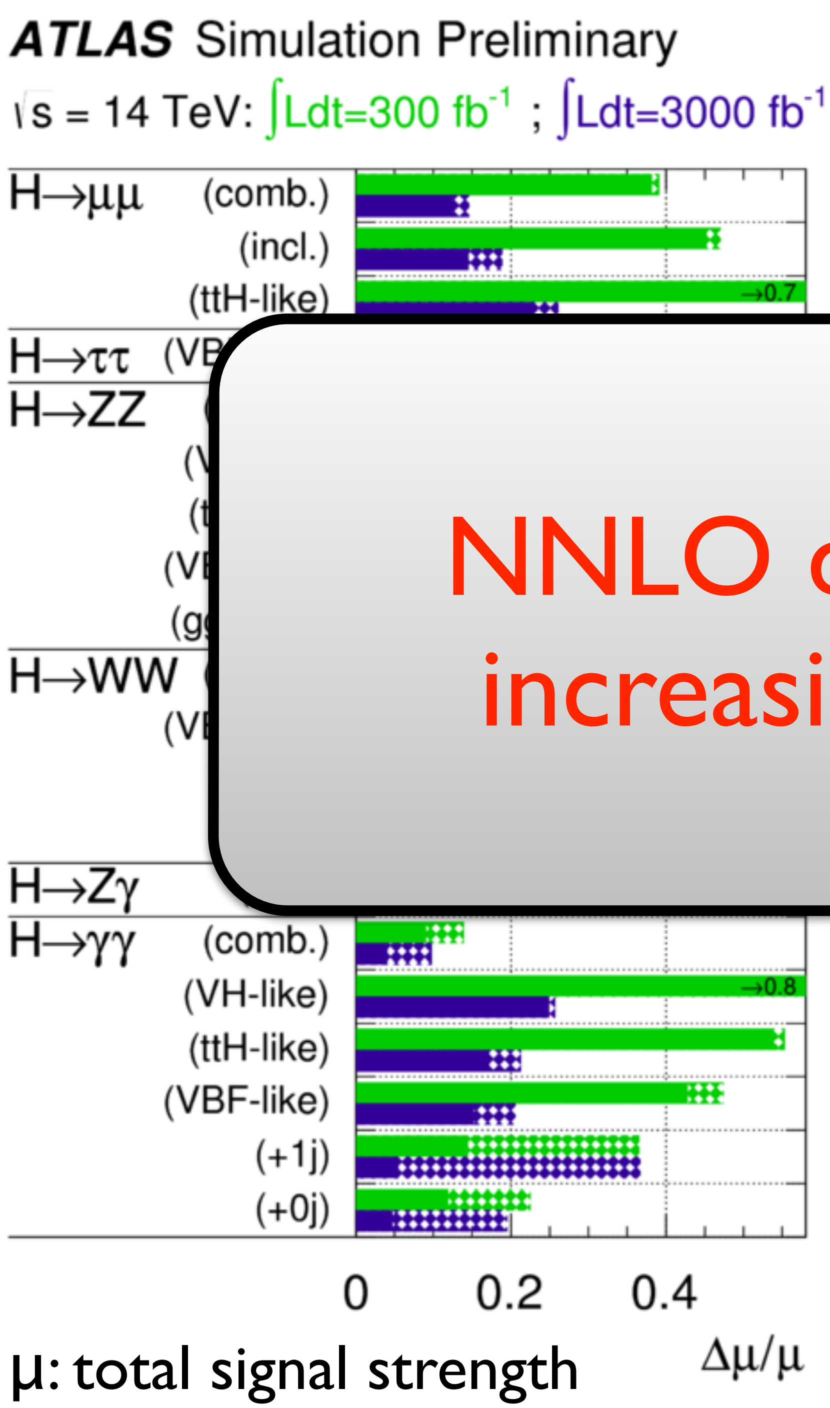
Higgs measurements



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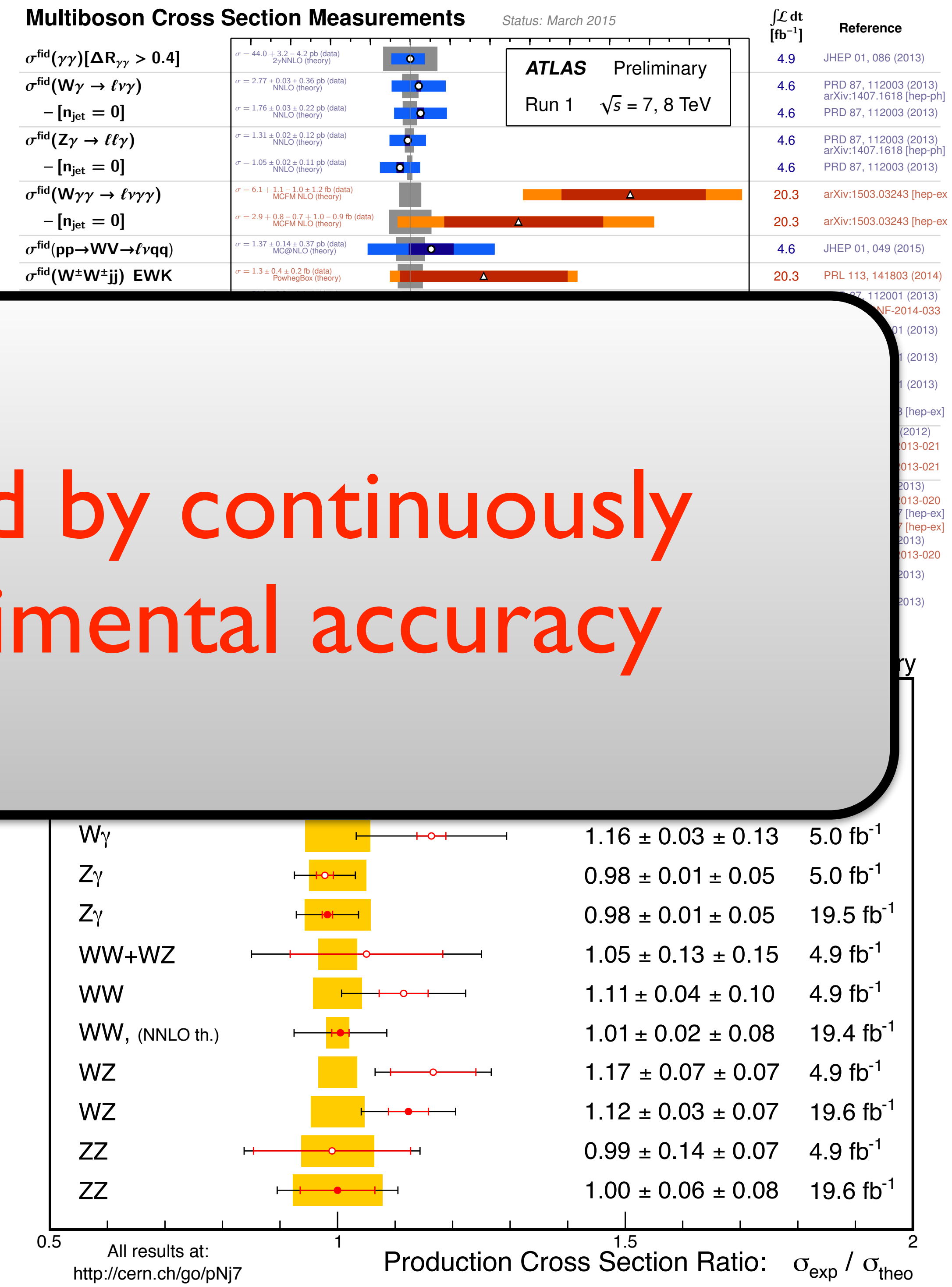

NNLO demanded by continuously increasing experimental accuracy

- 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]
- Colourful subtraction [Somogyi, Trocsanyi, Del Duca '05, '07]

Schemes that start from F+1jet process at NLO

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

NNLO methods

Universität Zürich[UZH]

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+ Two-loop amplitudes required for each process!

NNLO methods

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see talk by Jan Niehues

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

see talk by Hayk Sargsyan

p_T subtraction and resummation

→ *see also talks by J. Mazzitelli and F. Coradeschi*

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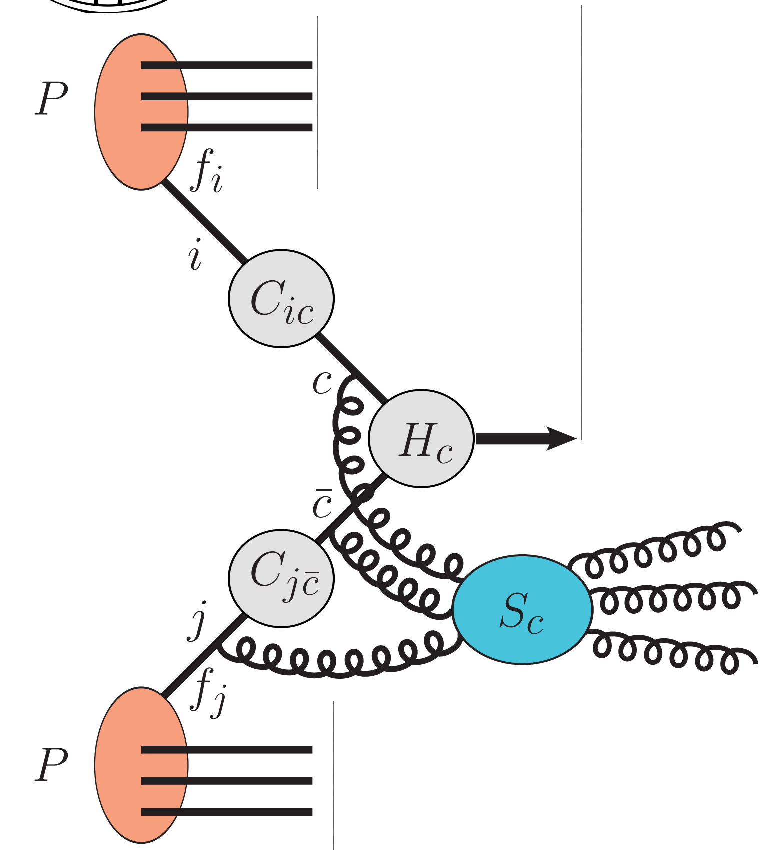
$$\frac{d\sigma^{(\mathrm{res})}}{dp_T^2\, dy\, dM\, d\Omega} \sim \int db\, \frac{b}{2}\, J_0(b\, p_T)\, S(b, A, B)\, \mathcal{H}_{N_1,N_2}\, f_{N_1}\, f_{N_2}$$

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



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

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

unitarity of p_T resummation due to modified logs:

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

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

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

p_T subtraction and resummation

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

practical implementation:

- subtraction not local
- both terms in squared brackets separately divergent
- introduce lower cut-off $r_{\rm cut}$ on dimensionless quantity $r = p_{T,WW}/m_{WW}$
- use very small $r_{\rm cut}$ value and integrate both terms separately down to $r \geq r_{\rm cut}$
- assumption: for $r \leq r_{\rm cut}$ terms cancel (true up to power-suppressed terms)
- to be shown: small residual $r_{\rm cut}$ dependence as $r_{\rm cut} \to 0$
- numerics forbids arbitrarily small $r_{\rm cut}$ values: use fit towards $r_{\rm cut} \to 0$ limit

WW fully differential at NNLO

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

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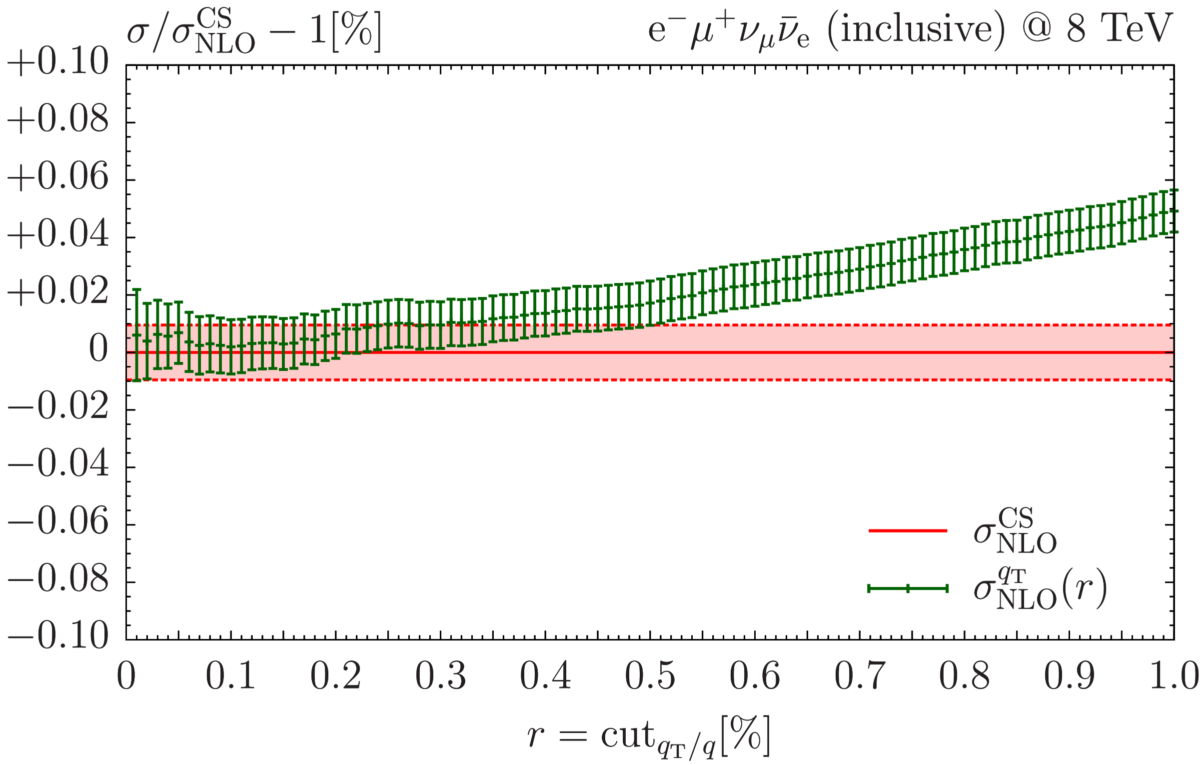
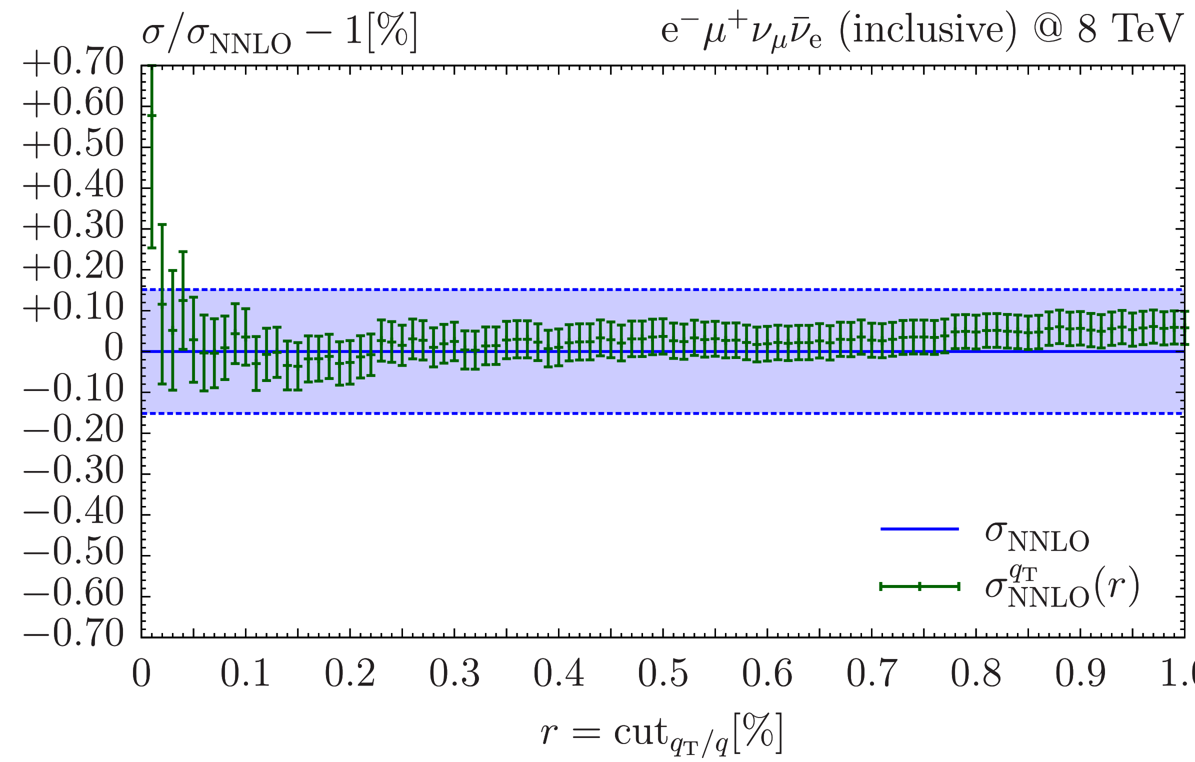
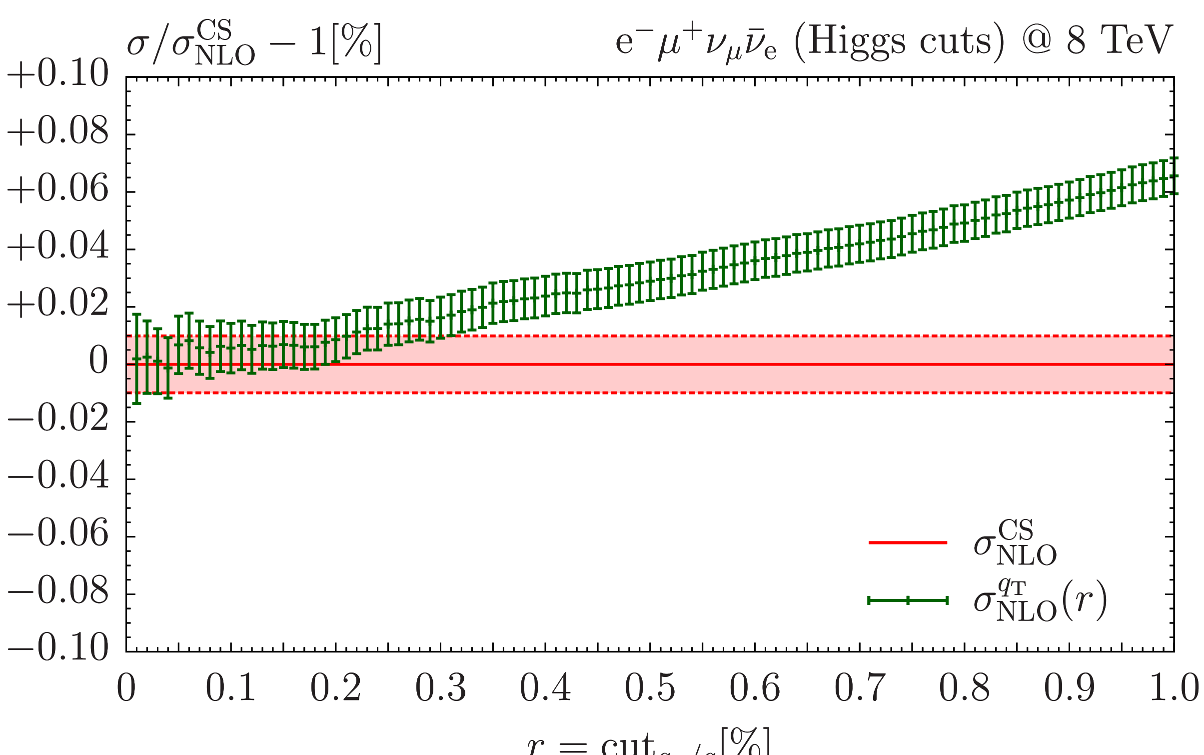
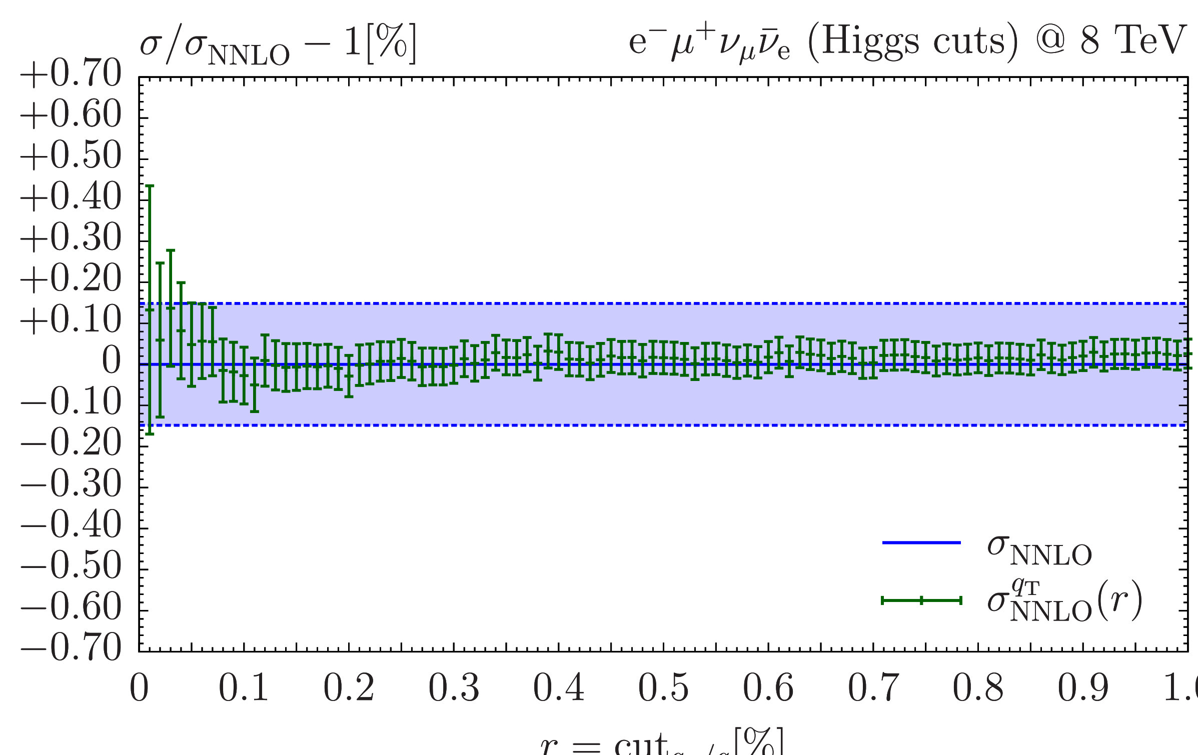
stability of r_{cut} dependence









We implemented...

The MATRIX team

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

The MATRIX team

Dirk "Cypher" Rathlev

Massimiliano "Morpheus" Grazzini

Stefan "Neo" Kallweit

Marius "Trinity" Wiesemann

The MATRIX framework

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

Amplitudes

OpenLoops (Collier, CutTools, ...)	**Dedicated 2-loop codes** (VVamp, GiNaC, TDHPL, ...)

Munich

MUlti-cha**N**nel **I**ntegrator at Swiss (**CH**) precision

q_T subtraction $\Leftrightarrow$ q_T resummation

NNLO

NNLL

Matrix

Munich **A**utomates q**T** Subtraction and **R**esummation to **I**ntegrate **X**-sections.

The MATRIX

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 |

 | M. Grazzini                          (grazzini@physik.uzh.ch) |
 | 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

process	status	comment
$pp \to Z/\gamma^*(\to \ell^+\ell^-)$	✓	validated analytically (+ DYNNLO)
$pp \to W \to \ell\nu$	(✓)	to be validated
$pp \to H$	✓	validated analytically
$pp \to \gamma\gamma$	✓	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
$pp \to HH$	✓	[de Florian et al. '16]

The Status and Plan

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1. 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 [Grazzini, Kallweit, Rathlev, MW '15]

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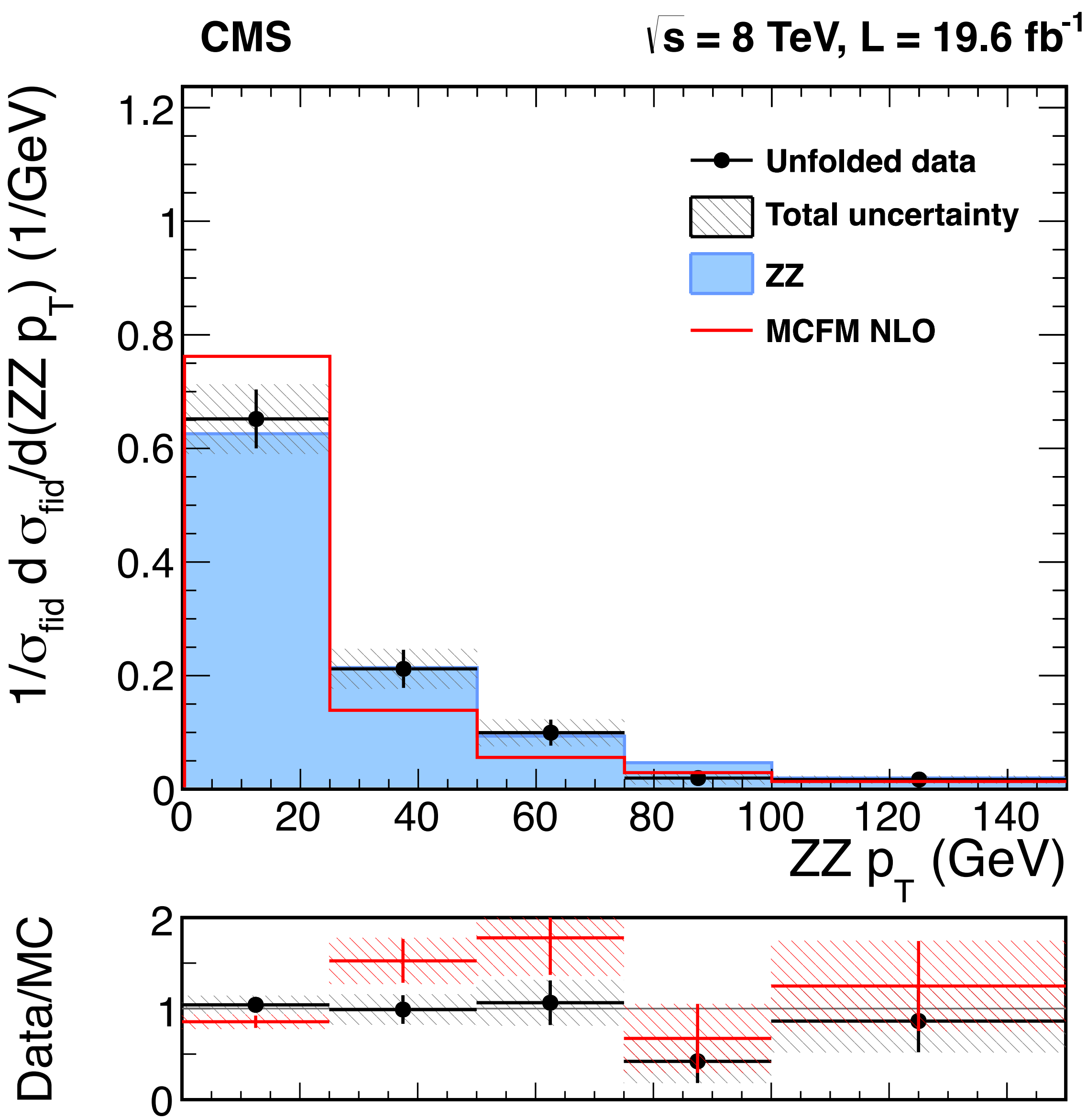
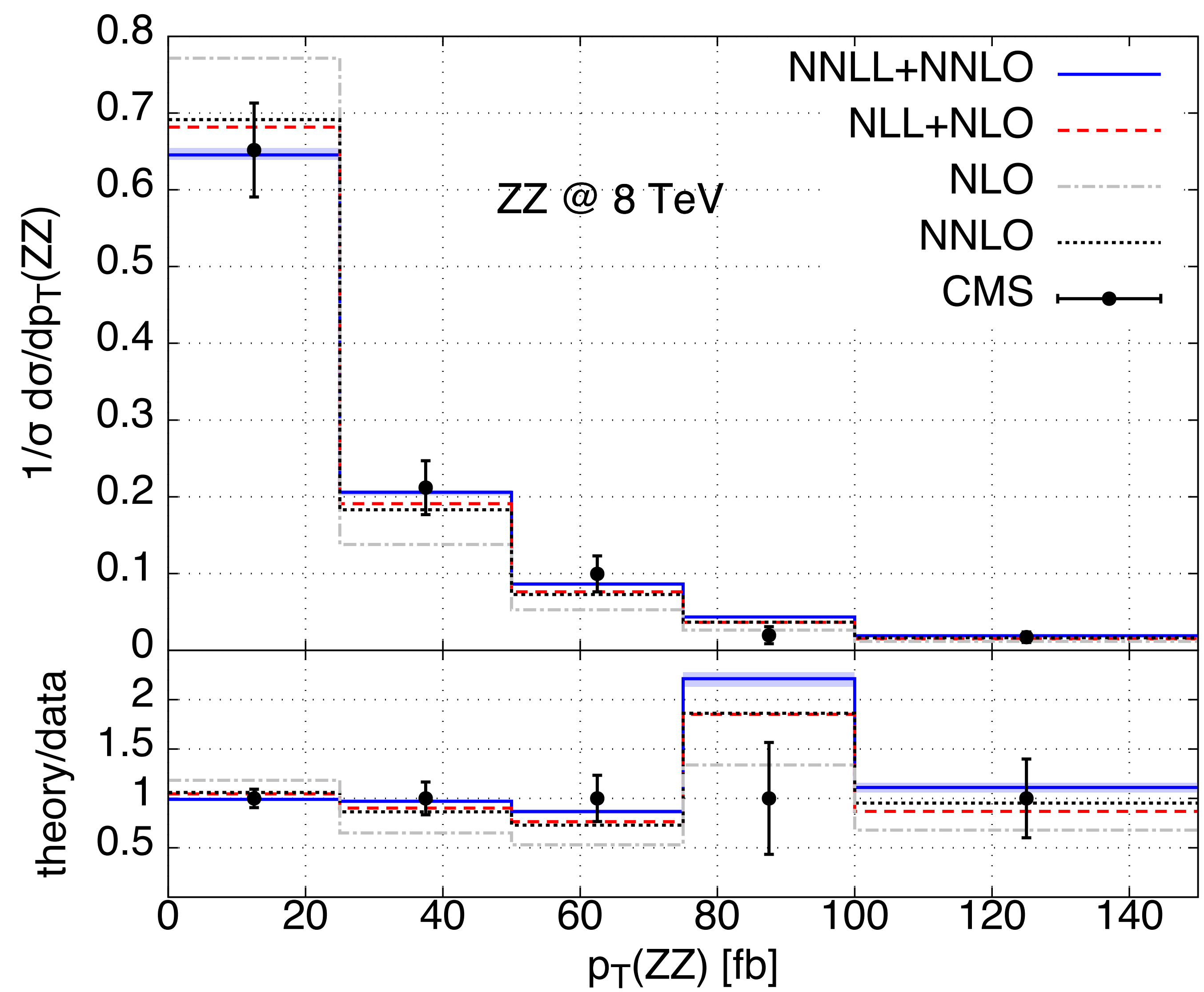
p_T spectrum of ZZ pair: comparison to data

[CMS '15]



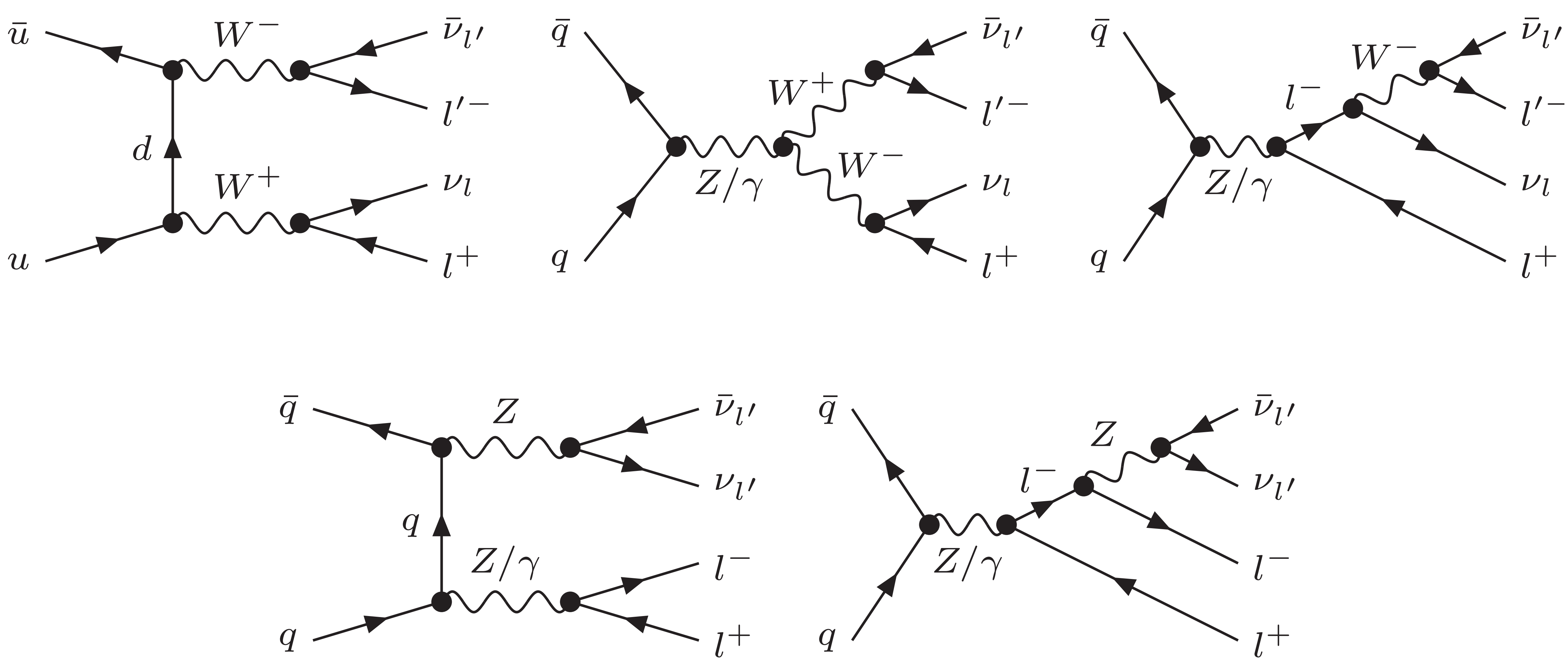
[Grazzini, Kallweit, Rathlev, MW '15]



WW fully differential at NNLO

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

- all **pp→WW→ℓν ℓ'ν'** processes, including:
  - double-resonant W decays
  - single-resonant Z/γ* decays (**pp→Z/γ*→WW*/ℓνW→ℓν ℓ'ν'**)
  - double(single)-resonant **pp→ZZ/Zγ*→ℓνℓν**(**pp→Z/γ*→ℓνℓν**) in equal-flavor channel



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- all **pp→WW→ℓν ℓ'ν'** processes, including:
  - double-resonant W decays
  - single-resonant Z/γ* decays (**pp→Z/γ*→WW*/ℓνW→ℓν ℓ'ν'**)
  - double(single)-resonant **pp→ZZ/Zγ*→ℓνℓν(pp→Z/γ*→ℓνℓν)** in equal-flavor channel
- HERE: different-flavour channel **pp→WW→$e\nu_e\,\mu\nu_\mu$** (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 '16]

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

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NLO	$623.47(6)^{+3.6\%}_{-2.9\%}$	+47%	$1205.11(12)^{+3.9\%}_{-3.1\%}$	+55%
NLO′+gg	$655.83(8)^{+4.3\%}_{-3.3\%}$	+5.2%	$1286.81(13)^{+4.8\%}_{-3.7\%}$	+6.8%
NNLO	$690.4(5)^{+2.2\%}_{-1.9\%}$	+5.3%	$1370.9(11)^{+2.6\%}_{-2.3\%}$	+6.5%

fiducial rates (WW cuts)

	8 TeV	13 TeV
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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 (inclusive)		13 TeV (inclusive)		8 TeV (fiducial)		13 TeV (fiducial)	
LO	$425.41(4)^{+2.8\%}_{-3.6\%}$	+47%	$778.99\ (8)^{+5.7\%}_{-6.7\%}$	+55%	$147.23(2)^{+3.4\%}_{-4.4\%}$	+4%	$233.04(2)^{+6.6\%}_{-7.6\%}$	+1.3%
NLO	$623.47(6)^{+3.6\%}_{-2.9\%}$	+5.2%	$1205.11(12)^{+3.9\%}_{-3.1\%}$	+6.8%	$153.07(2)^{+1.9\%}_{-1.6\%}$	+8.7%	$236.19(2)^{+2.8\%}_{-2.4\%}$	+13%
NLO′+gg	$655.83(8)^{+4.3\%}_{-3.3\%}$	+5.3%	$1286.81(13)^{+4.8\%}_{-3.7\%}$	+6.5%	$166.41(3)^{+1.3\%}_{-1.3\%}$	-1.4%	$267.31(4)^{+1.5\%}_{-2.1\%}$	-2.2%
NNLO	$690.4(5)^{+2.2\%}_{-1.9\%}$		$1370.9(11)^{+2.6\%}_{-2.3\%}$		$164.1\ (1)^{+1.3\%}_{-0.8\%}$		$261.5(2)^{+1.9\%}_{-1.2\%}$	

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]

Universität Zürich UZH

inclusive rates

σ [fb]	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%
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)

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

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

→ acceptances (WW cuts)

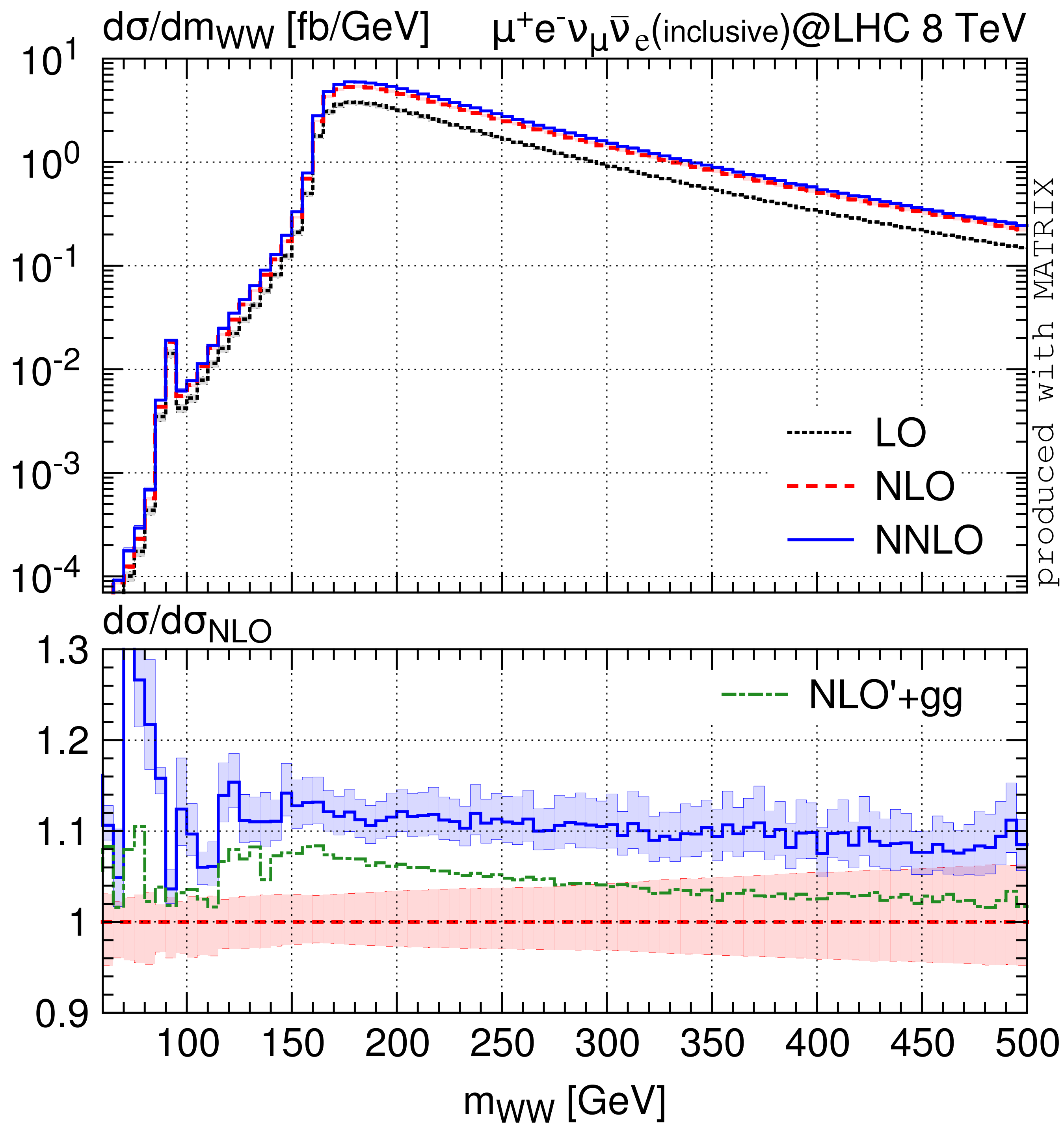
$A = \sigma^{\text{cuts}}/\sigma^{\text{inclusive}}$	8 TeV		13 TeV	
LO	$0.34608(7)^{+0.6\%}_{-0.7\%}$	+29%	$0.29915(6)^{+0.8\%}_{-1.0\%}$	+34%
NLO	$0.24552(5)^{+4.4\%}_{-4.7\%}$	+3.3%	$0.19599(4)^{+4.4\%}_{-4.7\%}$	+6%
NLO′+gg	$0.25374(7)^{+3.5\%}_{-3.7\%}$	-6.3%	$0.20773(5)^{+3.2\%}_{-3.1\%}$	-8.2%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

WW fully differential at NNLO

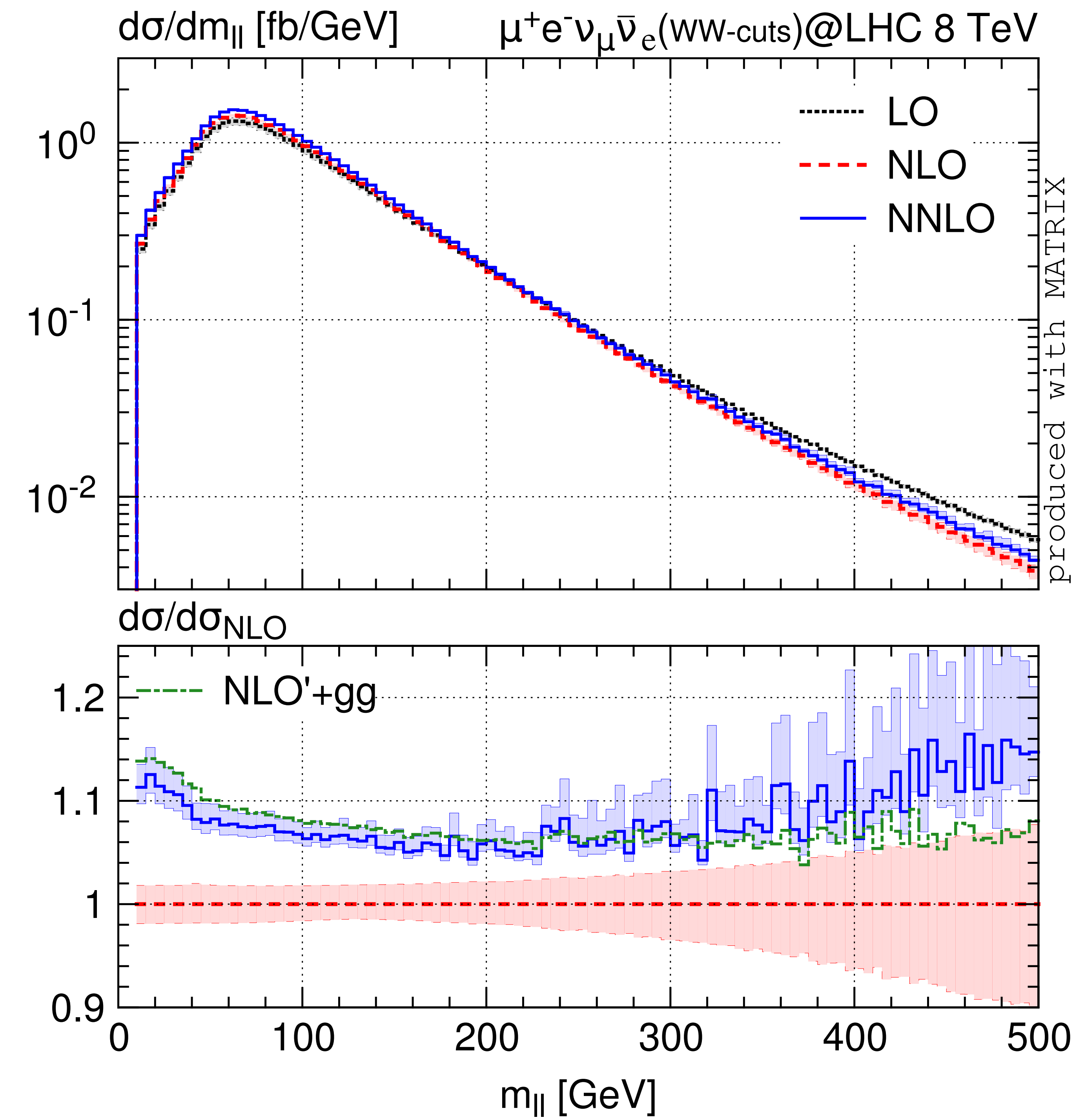
[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

Universität Zürich[UZH]

inclusive: distributions



WW cuts: distributions

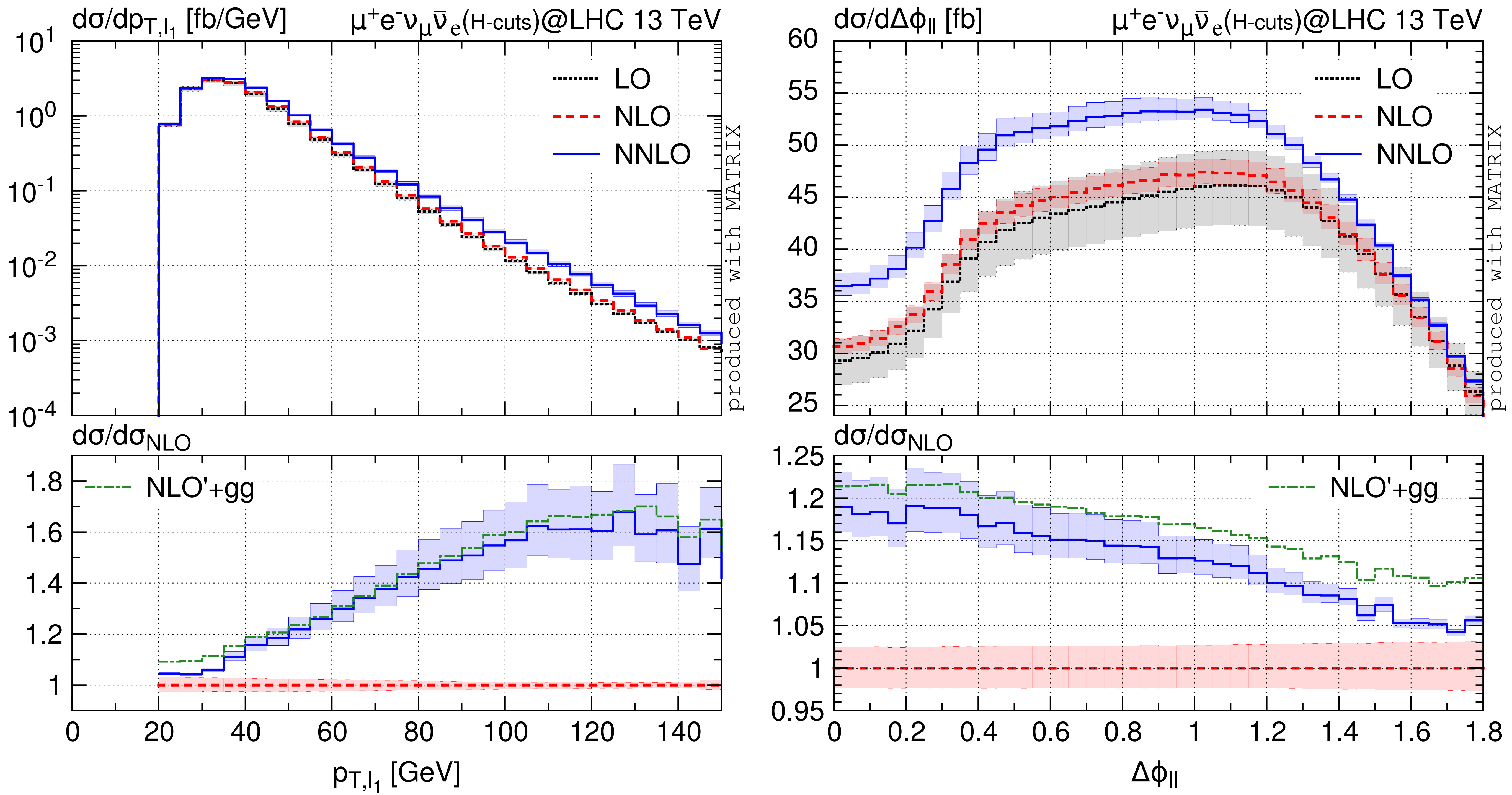


WW fully differential at NNLO

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

Universität Zürich[UZH]

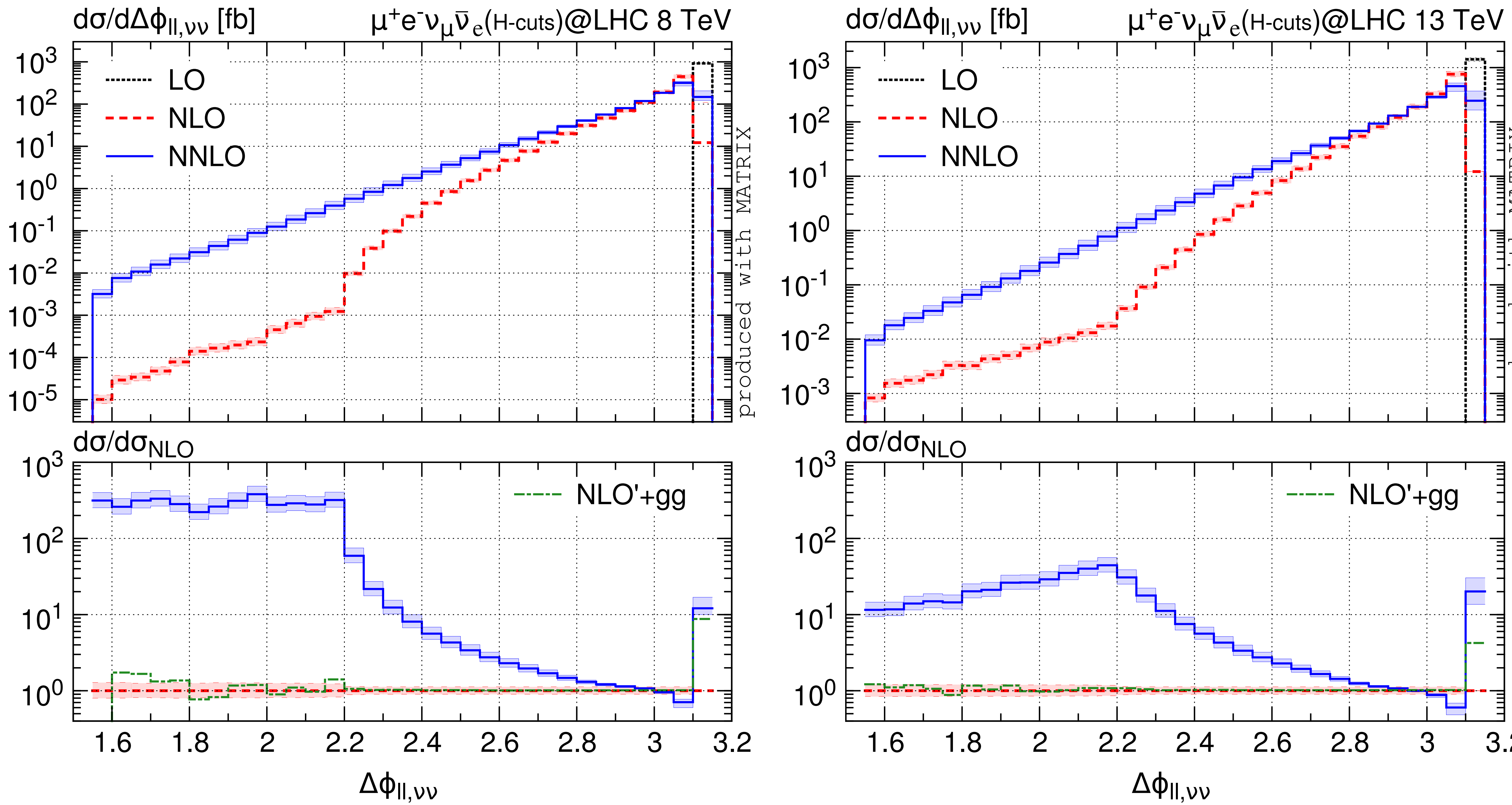
Higgs background cuts: distributions (13 TeV)



WW fully differential at NNLO

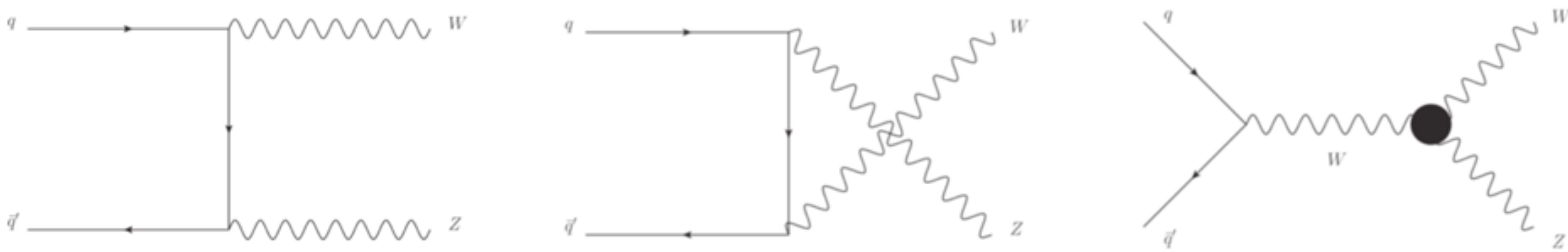
[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

Higgs cuts: distributions (left: 8 TeV, right: 13 TeV)



WZ cross section at NNLO

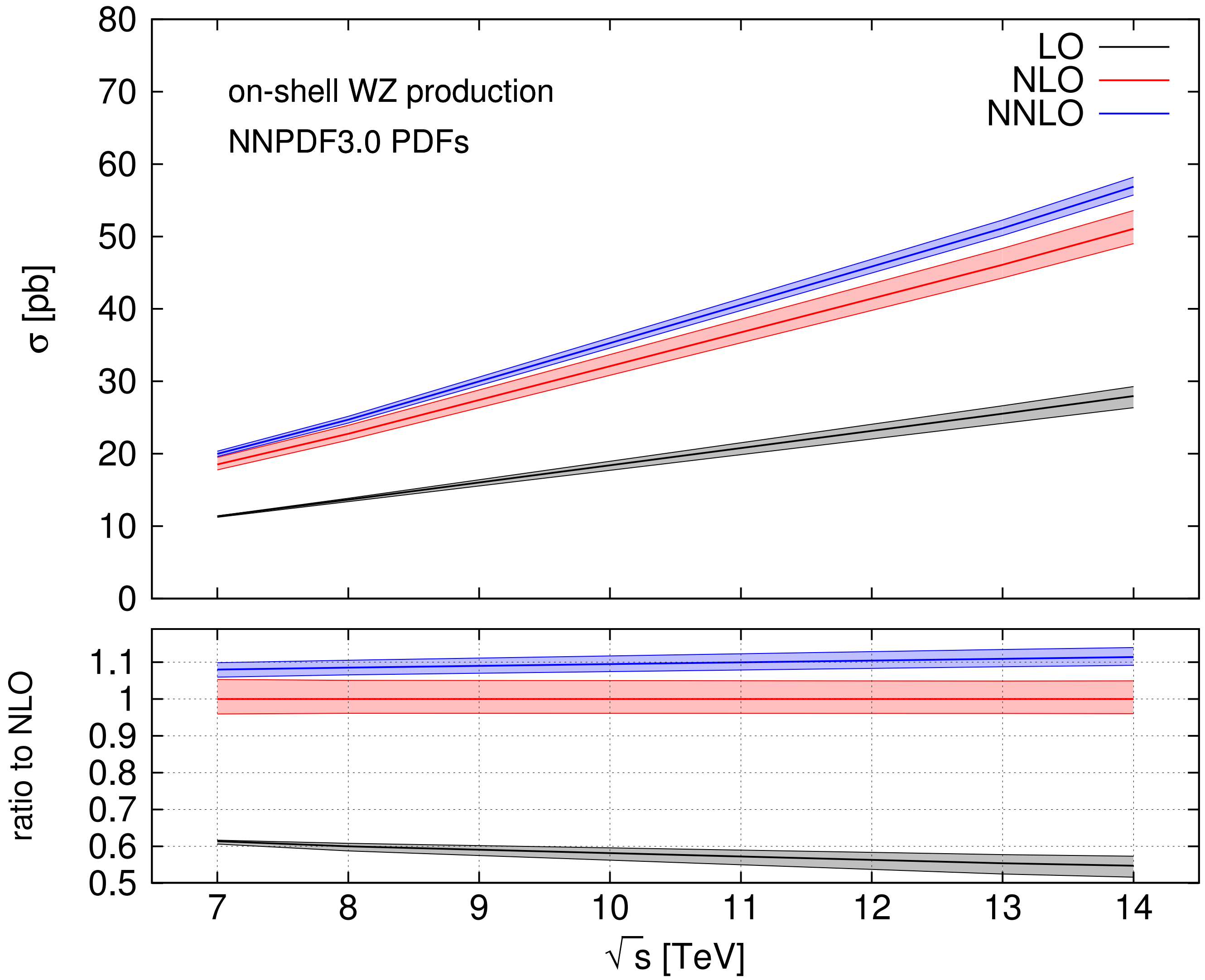
[Grazzini, Kallweit, Rathlev, MW '16]



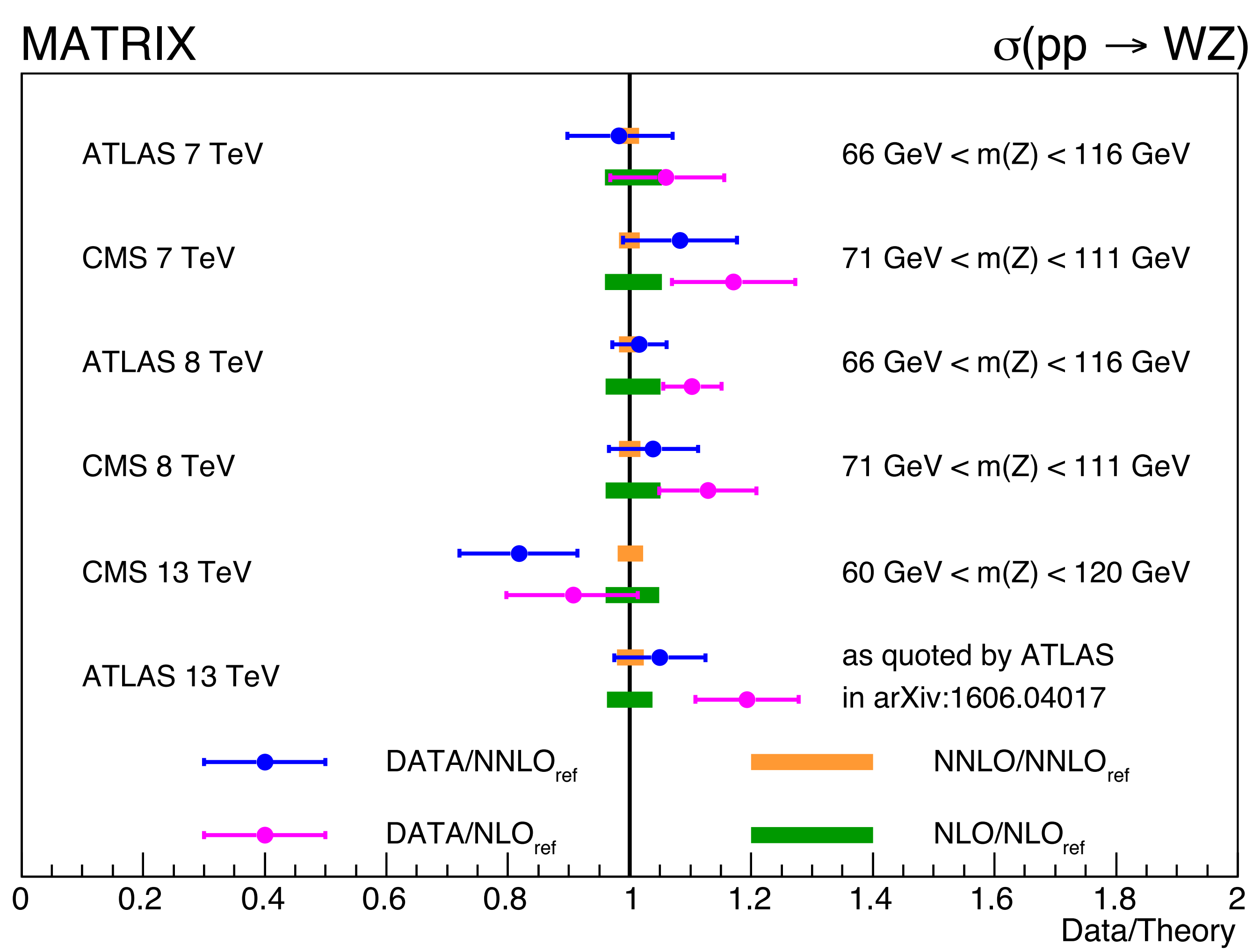
- first computation of NNLO corrections to WZ
- no loop-induced gg component at NNLO
- access to trilinear gauge coupling → relevance for BSM physics
- in principle: same two-loop amplitudes as for off-shell WW [Gehrmann, von Manteuffel, Tancredi '15]
- HERE: only inclusive cross section (minimal cuts 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]



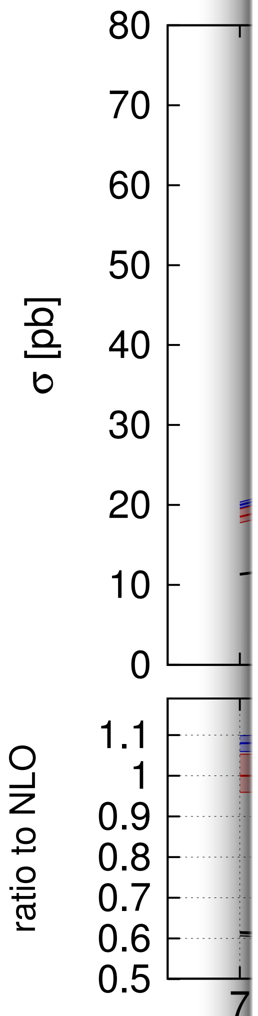
- Huge radiative corrections due to approximate radiation zero [Baur, Han, Ohnemus '94]
- ~63-83% NLO corrections
- ~8-11% NNLO corrections



- 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]

WZ cross section at NNLO

[Graz



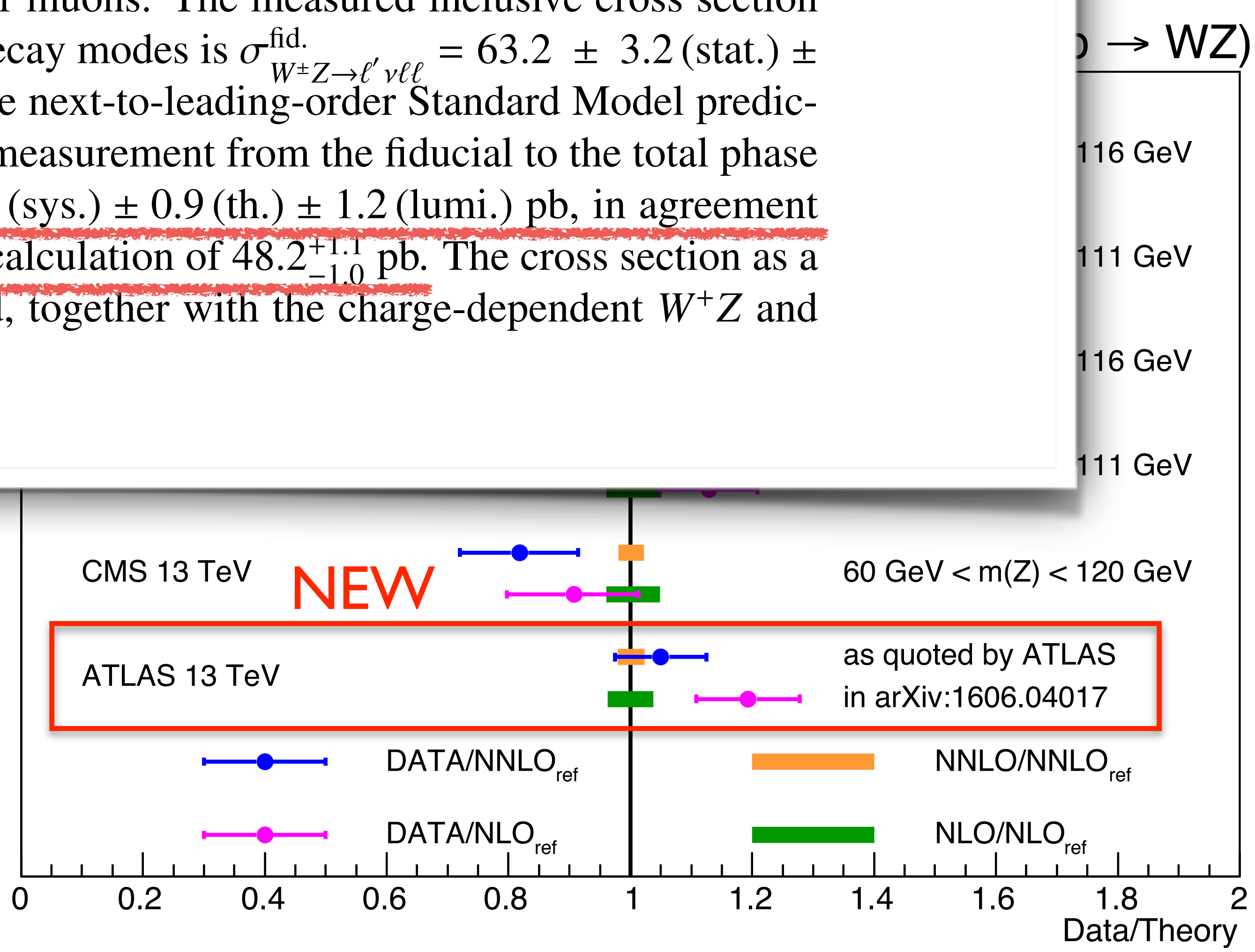
Measurement of the $W^{\pm}Z$ boson pair-production cross section in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector

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 $\sigma^{\text{fid.}}_{W^{\pm}Z\to\ell'\nu\ell\ell} = 63.2 \pm 3.2\,(\text{stat.}) \pm 2.6\,(\text{sys.}) \pm 1.5\,(\text{lumi.})$ fb. In comparison, the next-to-leading-order Standard Model prediction is $53.4^{+3.6}_{-2.8}$ fb. The extrapolation of the measurement from the fiducial to the total phase space yields $\sigma^{\text{tot.}}_{W^{\pm}Z} = 50.6 \pm 2.6\,(\text{stat.}) \pm 2.0\,(\text{sys.}) \pm 0.9\,(\text{th.}) \pm 1.2\,(\text{lumi.})$ pb, in agreement with a recent next-to-next-to-leading-order calculation of $48.2^{+1.1}_{-1.0}$ 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.

o

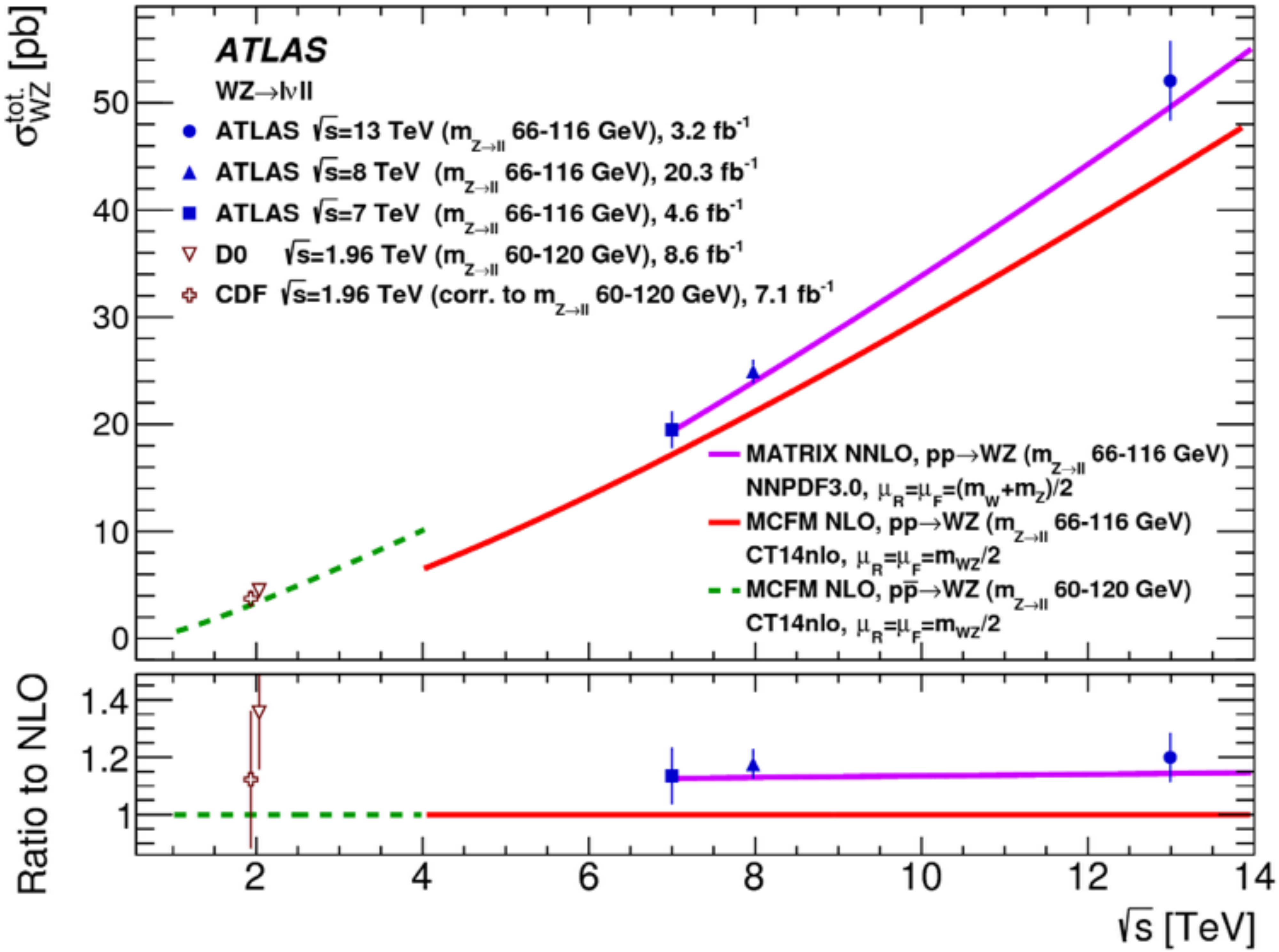


- NNLO corrections nicely improve agreement with data at 7 and 8 TeV
- slightly worse for 13 TeV CMS (large uncertainties)
- NEW: well agreement with [ATLAS '16]

Measured WZ cross section

[ATLAS '16]

→ *see talk by Gustavo Garzon*



WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW]

Universität Zürich[UZH]

VERY VERY PRELIMINARY

- various channels:
  - different-flavor (DF) channels

    $pp \to \mu^+\nu_\mu\, e^+e^-$, $pp \to e^+\nu_e\, \mu^+\mu^-$ (identical for massless fermions)

    $pp \to \mu^-\nu_\mu\, e^+e^-$, $pp \to e^-\nu_e\, \mu^+\mu^-$ (identical for massless fermions)

  - same-flavor (SF) channels

    $pp \to e^+\nu_e\, e^+e^-$, $pp \to \mu^+\nu_\mu\, \mu^+\mu^-$ (identical for massless fermions)

    $pp \to e^-\nu_e\, e^+e^-$, $pp \to \mu^-\nu_\mu\, \mu^+\mu^-$ (identical for massless fermions)

- fiducial phase space (ATLAS 8/13 TeV) for $pp \to l'\nu_{l'}\, ll$ $(l,l' \in \{e,\mu\})$
  - Z/W reconstruction: trivial for DF channels; "resonant shape" [arXiv:1603.02151] for SF

    for all possible combinations of pairs $W=(l',\nu_{l'})$ and $Z=(l^+,l^-)$ compute

$$P = \left|\frac{1}{m^2_{(\ell^+,\ell^-)} - \left(m_Z^{\mathrm{PDG}}\right)^2 + i\,\Gamma_Z^{\mathrm{PDG}}\, m_Z^{\mathrm{PDG}}}\right|^2 \times \left|\frac{1}{m^2_{(\ell',\nu_{\ell'})} - \left(m_W^{\mathrm{PDG}}\right)^2 + i\,\Gamma_W^{\mathrm{PDG}}\, m_W^{\mathrm{PDG}}}\right|^2$$

    and identify W and Z bosons by combination with highest estimator value P

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW]

Universität Zürich[UZH]

VERY VERY PRELIMINARY

- various channels:
  - different-flavor (DF) channels

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  - same-flavor (SF) channels

    $pp \to e^+\nu_e\, e^+e^-$, $pp \to \mu^+\nu_\mu\, \mu^+\mu^-$ (identical for massless fermions)

    $pp \to e^-\nu_e\, e^+e^-$, $pp \to \mu^-\nu_\mu\, \mu^+\mu^-$ (identical for massless fermions)
- fiducial phase space (ATLAS 8/13 TeV) for $pp \to l'\nu_{l'}\, ll$ $(l,l' \in \{e,\mu\})$
  - Z/W reconstruction: trivial for DF channels; "resonant shape" [arXiv:1603.02151] for SF
  - Z and W cuts: $m_Z - 10$ GeV $< m(ll) < m_Z + 10$ GeV,

    $m_T(W) = (2\, p_T(l')\, p_T(\nu_{l'})\, (1-\cos\Delta\Phi(l',\nu_{l'})))^{0.5} > 30$ GeV,
  - lepton cuts: $p_T(l) > 15$ GeV, $p_T(l') > 20$ GeV, $\eta(l)<2.5$, $\eta(l')<2.5$,
  - lepton isolation: $\Delta R(ll)>0.2$, $\Delta R(ll')>0.3$

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW] LHC@8 TeV

Universität Zürich[UZH]

VERY VERY PRELIMINARY

channel	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NNLO} [fb]	σ_{ATLAS} [fb]
$\mu^\pm e^+ e^-$	$18.32(0)^{+2.3\%}_{-3.1\%}$	$32.76(1)^{+5.5\%}_{-4.1\%}$	$35.52(2)^{+1.8\%}_{-1.9\%}$	$36.3 \pm 5.4\%(\text{stat}) \pm 2.6\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$e^\pm \mu^+ \mu^-$	$18.32(0)^{+2.3\%}_{-3.1\%}$	$32.76(1)^{+5.5\%}_{-4.1\%}$	$35.52(2)^{+1.8\%}_{-1.9\%}$	$35.7 \pm 5.3\%(\text{stat}) \pm 3.7\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$e^\pm e^+ e^-$	$18.37(0)^{+2.3\%}_{-3.1\%}$	$32.86(1)^{+5.5\%}_{-4.1\%}$	$35.65(6)^{+1.8\%}_{-1.9\%}$	$38.1 \pm 6.2\%(\text{stat}) \pm 4.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$\mu^\pm \mu^+ \mu^-$	$18.37(0)^{+2.3\%}_{-3.1\%}$	$32.86(1)^{+5.5\%}_{-4.1\%}$	$35.65(6)^{+1.8\%}_{-1.9\%}$	$33.3 \pm 4.7\%(\text{stat}) \pm 2.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
combined	$18.35(0)^{+2.3\%}_{-3.1\%}$	$32.82(1)^{+5.5\%}_{-4.1\%}$	$35.59(4)^{+1.8\%}_{-1.9\%}$	$35.1 \pm 2.7\%(\text{stat}) \pm 2.4\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$\mu^+ e^+ e^-$	$11.59(0)^{+2.2\%}_{-3.0\%}$	$20.41(0)^{+5.3\%}_{-4.0\%}$	$22.10(1)^{+1.8\%}_{-1.9\%}$	$23.9 \pm 6.5\%(\text{stat}) \pm 2.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$e^+ \mu^+ \mu^-$	$11.59(0)^{+2.2\%}_{-3.0\%}$	$20.41(0)^{+5.3\%}_{-4.0\%}$	$22.10(1)^{+1.8\%}_{-1.9\%}$	$19.9 \pm 7.2\%(\text{stat}) \pm 3.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$e^+ e^+ e^-$	$11.62(0)^{+2.2\%}_{-3.0\%}$	$20.48(0)^{+5.3\%}_{-4.0\%}$	$22.18(4)^{+1.8\%}_{-1.9\%}$	$22.6 \pm 8.0\%(\text{stat}) \pm 4.4\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$\mu^+ \mu^+ \mu^-$	$11.62(0)^{+2.2\%}_{-3.0\%}$	$20.48(0)^{+5.3\%}_{-4.0\%}$	$22.18(4)^{+1.8\%}_{-1.9\%}$	$19.8 \pm 6.0\%(\text{stat}) \pm 2.5\%(\text{syst}) \pm 2.2\%(\text{lumi})$
combined	$11.61(0)^{+2.2\%}_{-3.0\%}$	$20.45(0)^{+5.3\%}_{-4.0\%}$	$22.14(3)^{+1.8\%}_{-1.9\%}$	$21.2 \pm 3.4\%(\text{stat}) \pm 2.3\%(\text{syst}) \pm 2.2\%(\text{lumi})$
$\mu^- e^+ e^-$	$6.732(1)^{+2.4\%}_{-3.4\%}$	$12.35(0)^{+5.7\%}_{-4.3\%}$	$13.42(1)^{+1.8\%}_{-1.9\%}$	$12.4 \pm 9.5\%(\text{stat}) \pm 3.1\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$e^- \mu^+ \mu^-$	$6.732(1)^{+2.4\%}_{-3.4\%}$	$12.35(0)^{+5.7\%}_{-4.3\%}$	$13.42(1)^{+1.8\%}_{-1.9\%}$	$15.7 \pm 7.5\%(\text{stat}) \pm 2.8\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$e^- e^+ e^-$	$6.750(1)^{+2.4\%}_{-3.4\%}$	$12.38(0)^{+5.7\%}_{-4.3\%}$	$13.47(2)^{+1.8\%}_{-1.9\%}$	$15.4 \pm 9.8\%(\text{stat}) \pm 5.0\%(\text{syst}) \pm 2.3\%(\text{lumi})$
$\mu^- \mu^+ \mu^-$	$6.750(1)^{+2.4\%}_{-3.4\%}$	$12.38(0)^{+5.7\%}_{-4.3\%}$	$13.47(2)^{+1.8\%}_{-1.9\%}$	$13.4 \pm 7.5\%(\text{stat}) \pm 2.8\%(\text{syst}) \pm 2.3\%(\text{lumi})$
combined	$6.741(1)^{+2.4\%}_{-3.4\%}$	$12.37(0)^{+5.7\%}_{-4.3\%}$	$13.45(2)^{+1.8\%}_{-1.9\%}$	$14.0 \pm 4.3\%(\text{stat}) \pm 2.8\%(\text{syst}) \pm 2.3\%(\text{lumi})$

WZ fully differential at NNLO

[Grazzini, Kallweit, Rathlev, MW] **LHC@13 TeV**

Universität Zürich[UZH]

channel	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]	$\sigma_{\rm ATLAS}$ [fb]
$\mu^\pm e^+ e^-$	$28.83(0)^{+5.5\%}_{-6.5\%}$	$57.68(1)^{+5.4\%}_{-4.4\%}$	$63.92(3)^{+2.2\%}_{-2.0\%}$	$55.1 \pm 11.1\%$(stat) $\pm 5.1\%$(syst) $\pm 2.4\%$(lumi)
$e^\pm \mu^+ \mu^-$	$28.83(0)^{+5.5\%}_{-6.5\%}$	$57.68(1)^{+5.4\%}_{-4.4\%}$	$63.92(3)^{+2.2\%}_{-2.0\%}$	$75.2 \pm 9.5\%$(stat) $\pm 5.3\%$(syst) $\pm 2.3\%$(lumi)
$e^\pm e^+ e^-$	$28.90(0)^{+5.5\%}_{-6.5\%}$	$57.84(1)^{+5.4\%}_{-4.4\%}$	$64.20(10)^{+2.2\%}_{-2.0\%}$	$50.5 \pm 14.2\%$(stat) $\pm 10.6\%$(syst) $\pm 2.4\%$(lumi)
$\mu^\pm \mu^+ \mu^-$	$28.90(0)^{+5.5\%}_{-6.5\%}$	$57.84(1)^{+5.4\%}_{-4.4\%}$	$64.20(10)^{+2.2\%}_{-2.0\%}$	$63.6 \pm 8.9\%$(stat) $\pm 4.1\%$(syst) $\pm 2.3\%$(lumi)
combined	$28.87(0)^{+5.5\%}_{-6.5\%}$	$57.76(1)^{+5.4\%}_{-4.4\%}$	$64.06(7)^{+2.2\%}_{-2.0\%}$	$63.2 \pm 5.2\%$(stat) $\pm 4.1\%$(syst) $\pm 2.4\%$(lumi)
$\mu^+ e^+ e^-$	$17.33(0)^{+5.3\%}_{-6.3\%}$	$34.11(1)^{+5.3\%}_{-4.3\%}$	$37.75(2)^{+2.2\%}_{-2.0\%}$	$32.2 \pm 14.4\%$(stat) $\pm 5.0\%$(syst) $\pm 2.4\%$(lumi)
$e^+ \mu^+ \mu^-$	$17.33(0)^{+5.3\%}_{-6.3\%}$	$34.11(1)^{+5.3\%}_{-4.3\%}$	$37.75(2)^{+2.2\%}_{-2.0\%}$	$45.0 \pm 12.1\%$(stat) $\pm 4.6\%$(syst) $\pm 2.3\%$(lumi)
$e^+ e^+ e^-$	$17.37(0)^{+5.3\%}_{-6.3\%}$	$34.21(1)^{+5.3\%}_{-4.3\%}$	$37.95(6)^{+2.3\%}_{-2.1\%}$	$28.0 \pm 19.2\%$(stat) $\pm 11.2\%$(syst) $\pm 2.4\%$(lumi)
$\mu^+ \mu^+ \mu^-$	$17.37(0)^{+5.3\%}_{-6.3\%}$	$34.21(1)^{+5.3\%}_{-4.3\%}$	$37.95(6)^{+2.3\%}_{-2.1\%}$	$36.5 \pm 11.6\%$(stat) $\pm 4.1\%$(syst) $\pm 2.3\%$(lumi)
combined	$17.35(0)^{+5.3\%}_{-6.3\%}$	$34.16(1)^{+5.3\%}_{-4.3\%}$	$37.85(4)^{+2.3\%}_{-2.1\%}$	$36.7 \pm 6.7\%$(stat) $\pm 3.9\%$(syst) $\pm 2.3\%$(lumi)
$\mu^- e^+ e^-$	$11.50(0)^{+5.7\%}_{-6.8\%}$	$23.57(0)^{+5.5\%}_{-4.5\%}$	$26.17(1)^{+2.3\%}_{-2.1\%}$	$22.9 \pm 17.5\%$(stat) $\pm 5.8\%$(syst) $\pm 2.4\%$(lumi)
$e^- \mu^+ \mu^-$	$11.50(0)^{+5.7\%}_{-6.8\%}$	$23.57(0)^{+5.5\%}_{-4.5\%}$	$26.17(1)^{+2.3\%}_{-2.1\%}$	$30.2 \pm 15.2\%$(stat) $\pm 6.9\%$(syst) $\pm 2.3\%$(lumi)
$e^- e^+ e^-$	$11.53(0)^{+5.7\%}_{-6.8\%}$	$23.63(0)^{+5.5\%}_{-4.5\%}$	$26.25(4)^{+2.3\%}_{-2.1\%}$	$22.5 \pm 21.0\%$(stat) $\pm 10.5\%$(syst) $\pm 2.4\%$(lumi)
$\mu^- \mu^+ \mu^-$	$11.53(0)^{+5.7\%}_{-6.8\%}$	$23.63(0)^{+5.5\%}_{-4.5\%}$	$26.25(4)^{+2.3\%}_{-2.1\%}$	$27.1 \pm 13.7\%$(stat) $\pm 5.0\%$(syst) $\pm 2.4\%$(lumi)
combined	$11.52(0)^{+5.7\%}_{-6.8\%}$	$23.60(0)^{+5.5\%}_{-4.5\%}$	$26.21(3)^{+2.3\%}_{-2.1\%}$	$26.1 \pm 8.1\%$(stat) $\pm 4.7\%$(syst) $\pm 2.4\%$(lumi)

VERY VERY PRELIMINARY

Summary

Universität Zürich[UZH]

- MATRIX: tool for fully-differential NNLO(+NNLL) computations
- CURRENTLY: closed beta SOON: public release
- large list of 2→1, 2→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

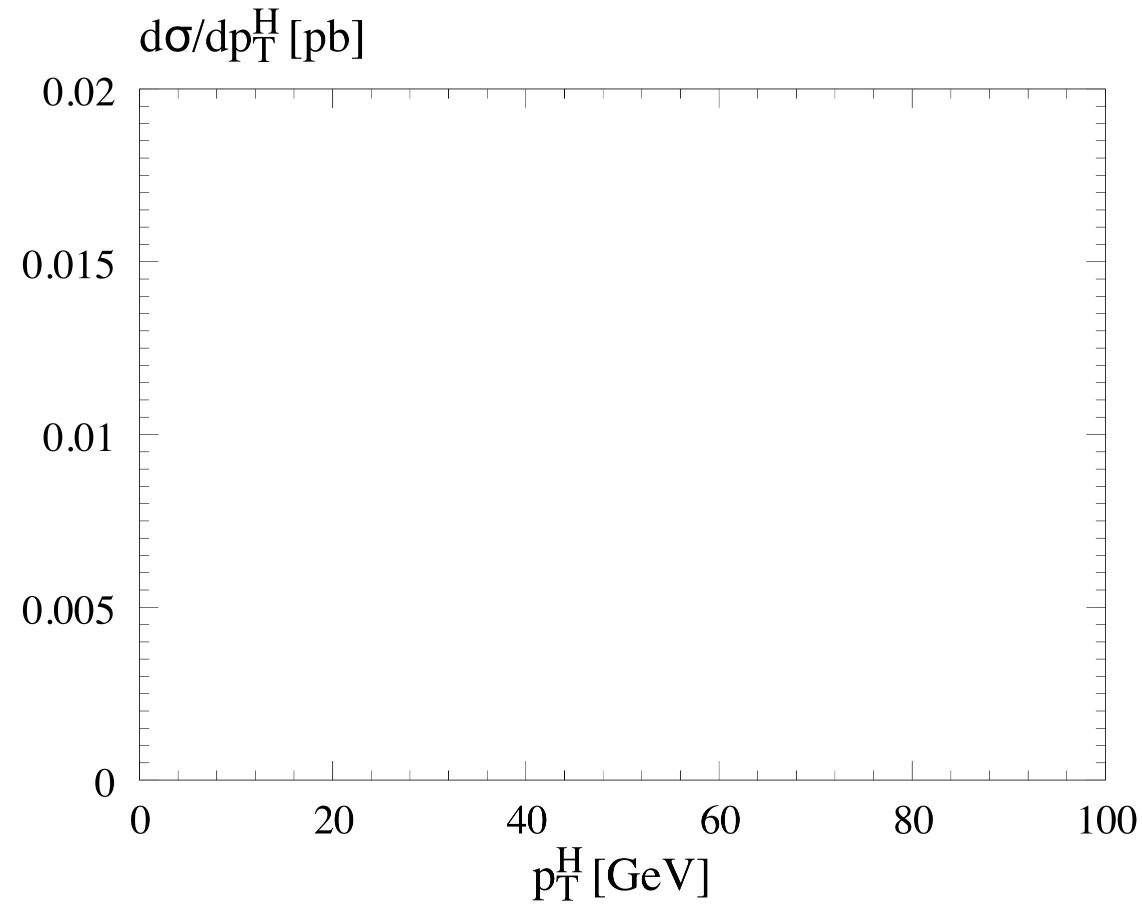
Thank You !

Back Up

matching: FO+resummation

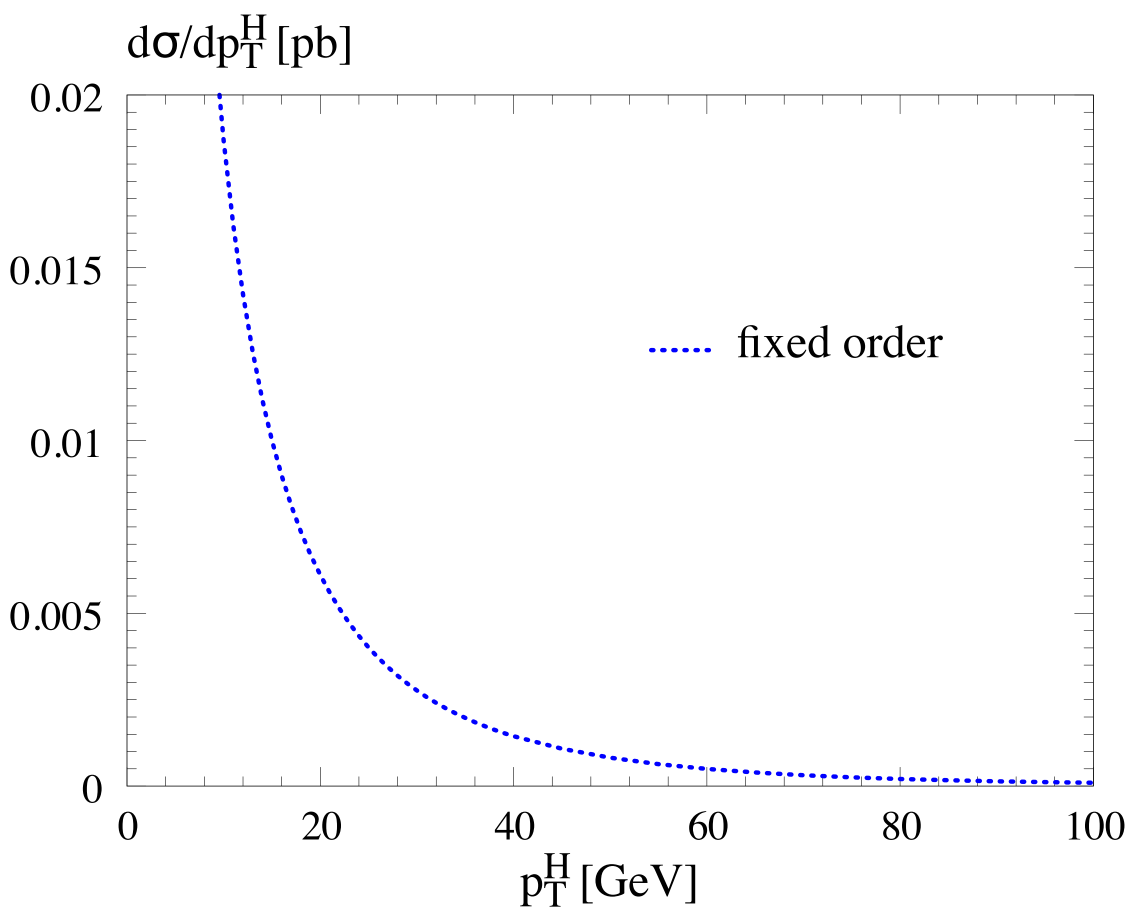
Universität Zürich[UZH]

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



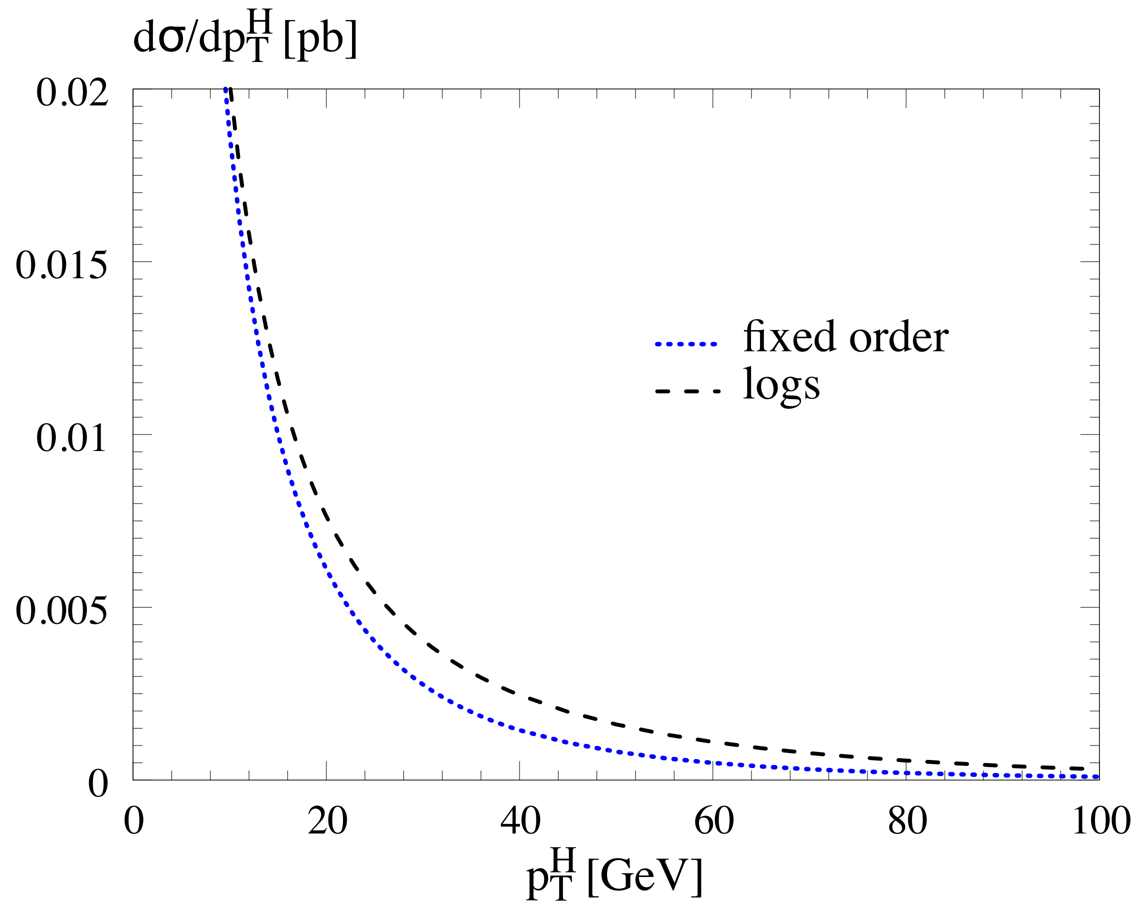
matching: FO+resummation

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



matching: FO+resummation

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



matching: FO+resummation

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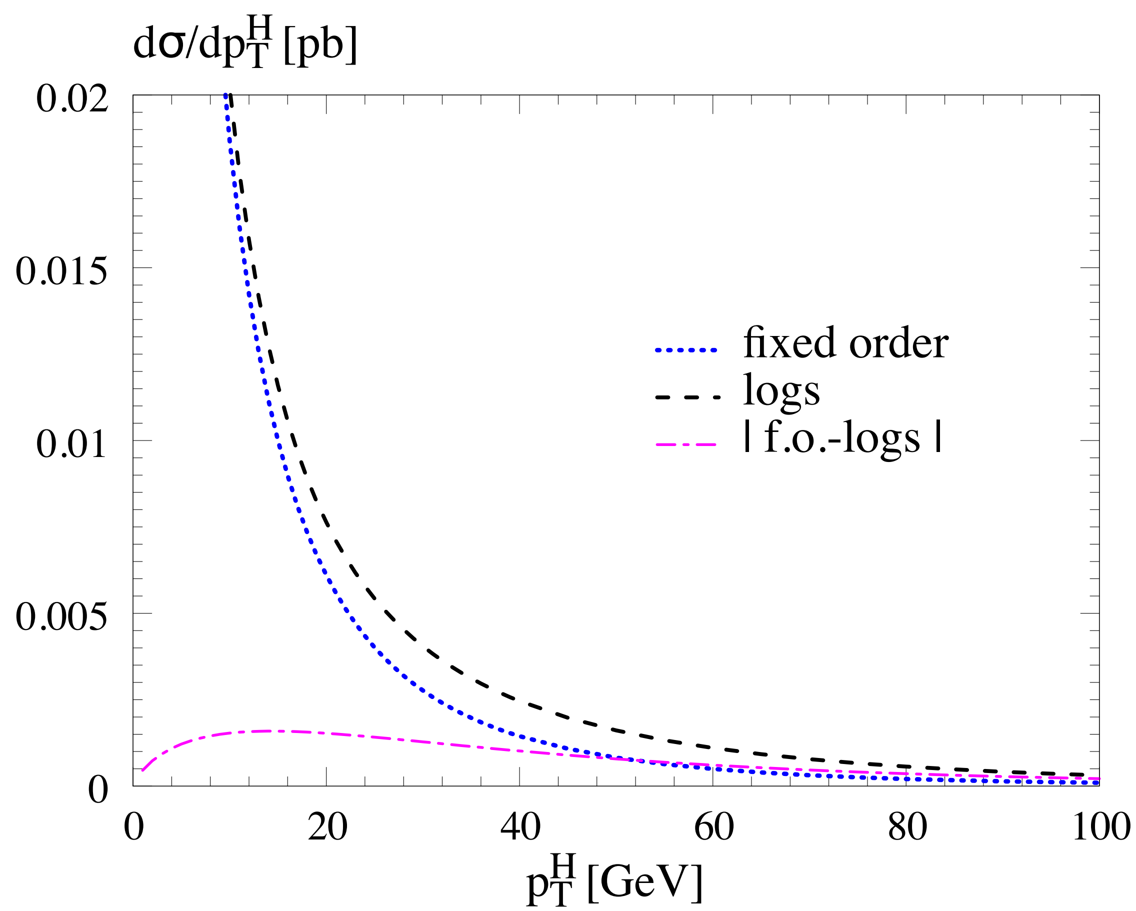
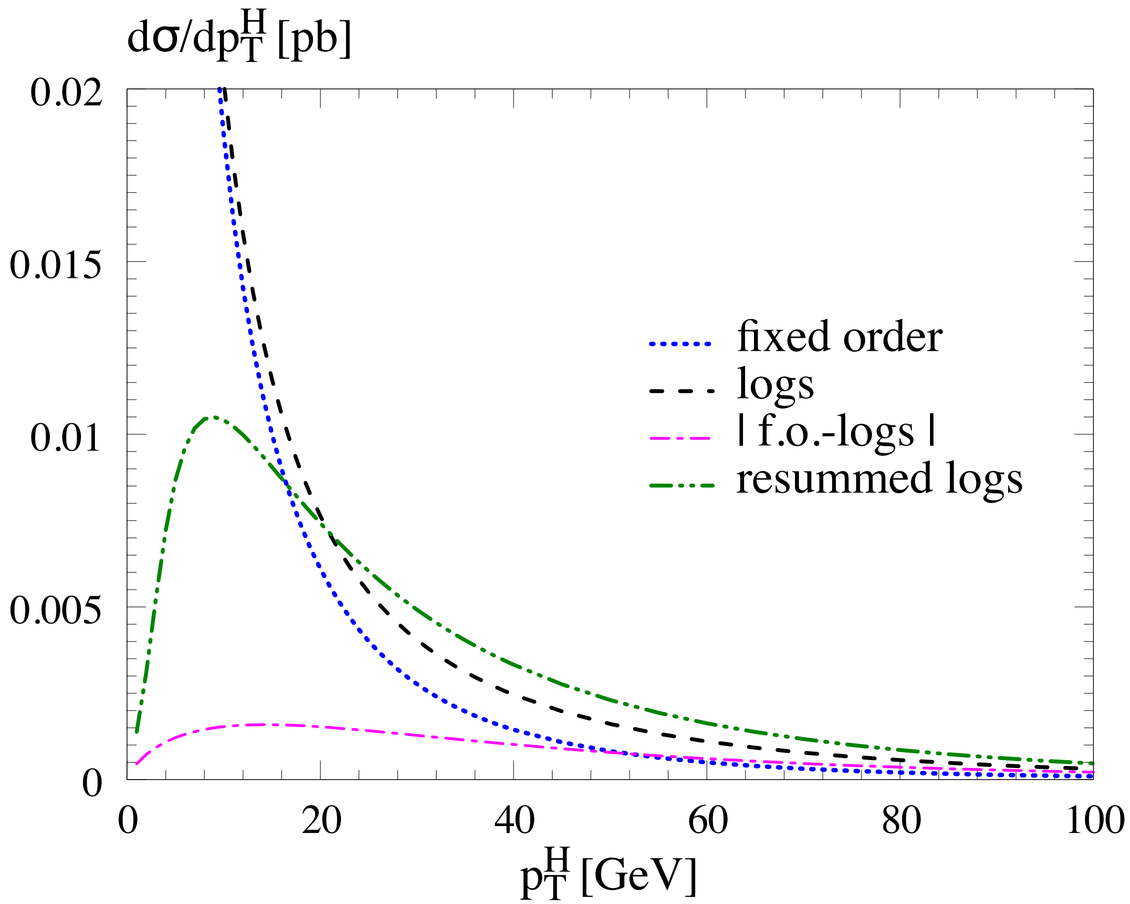
$$\left[\frac{d\sigma}{dp_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{d\sigma}{dp_T^2}\right]_{\text{f.o.}} - \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{f.o.}}$$



matching: FO+resummation

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



matching: FO+resummation

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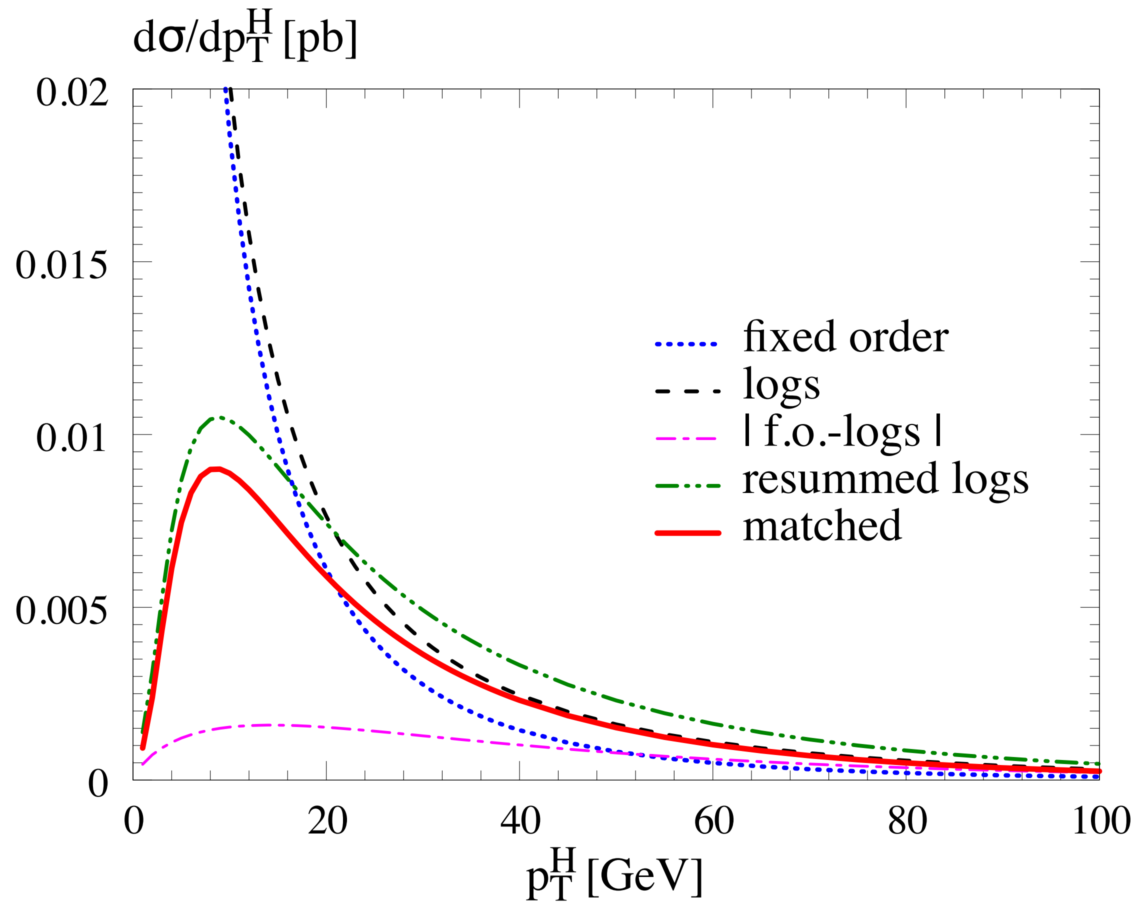
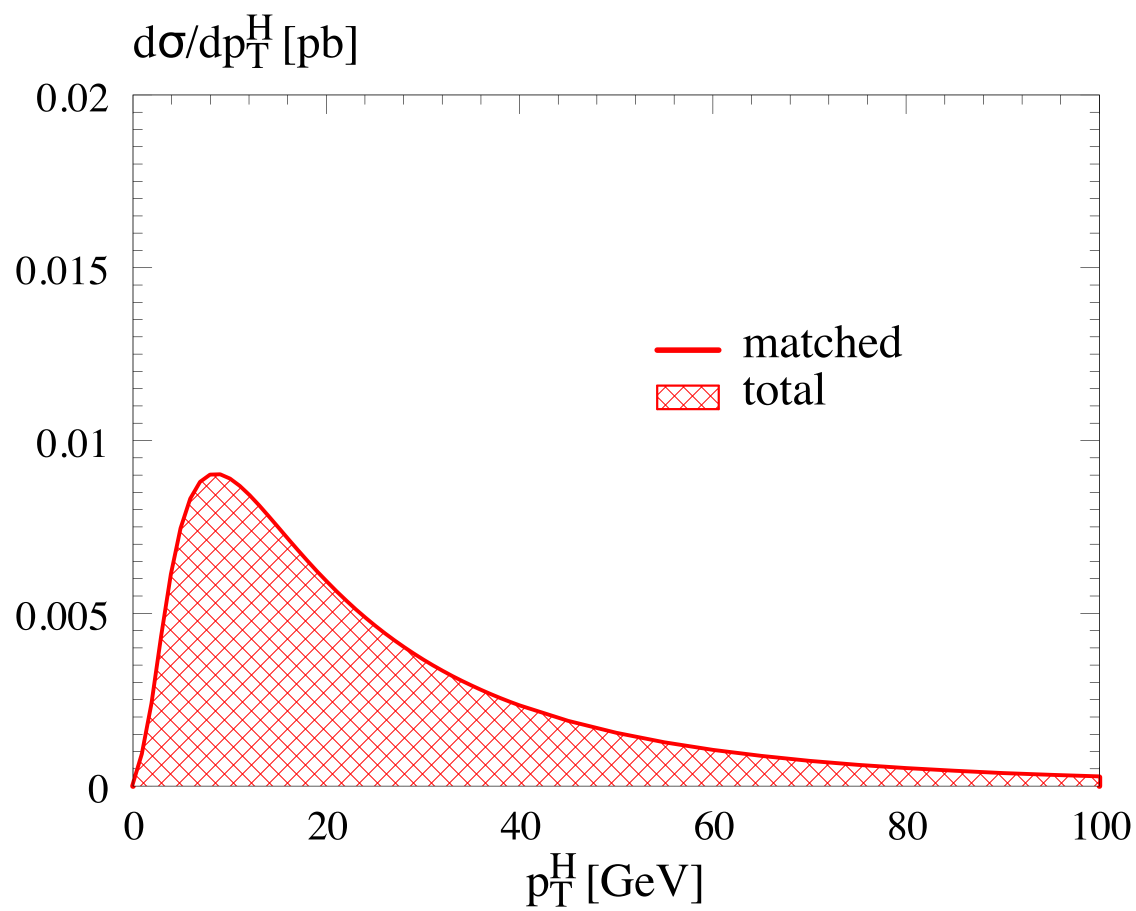
$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} + \left[\frac{\mathrm{d}\sigma^{(\text{res})}}{\mathrm{d}p_T^2}\right]_{\text{l.a.}}$$



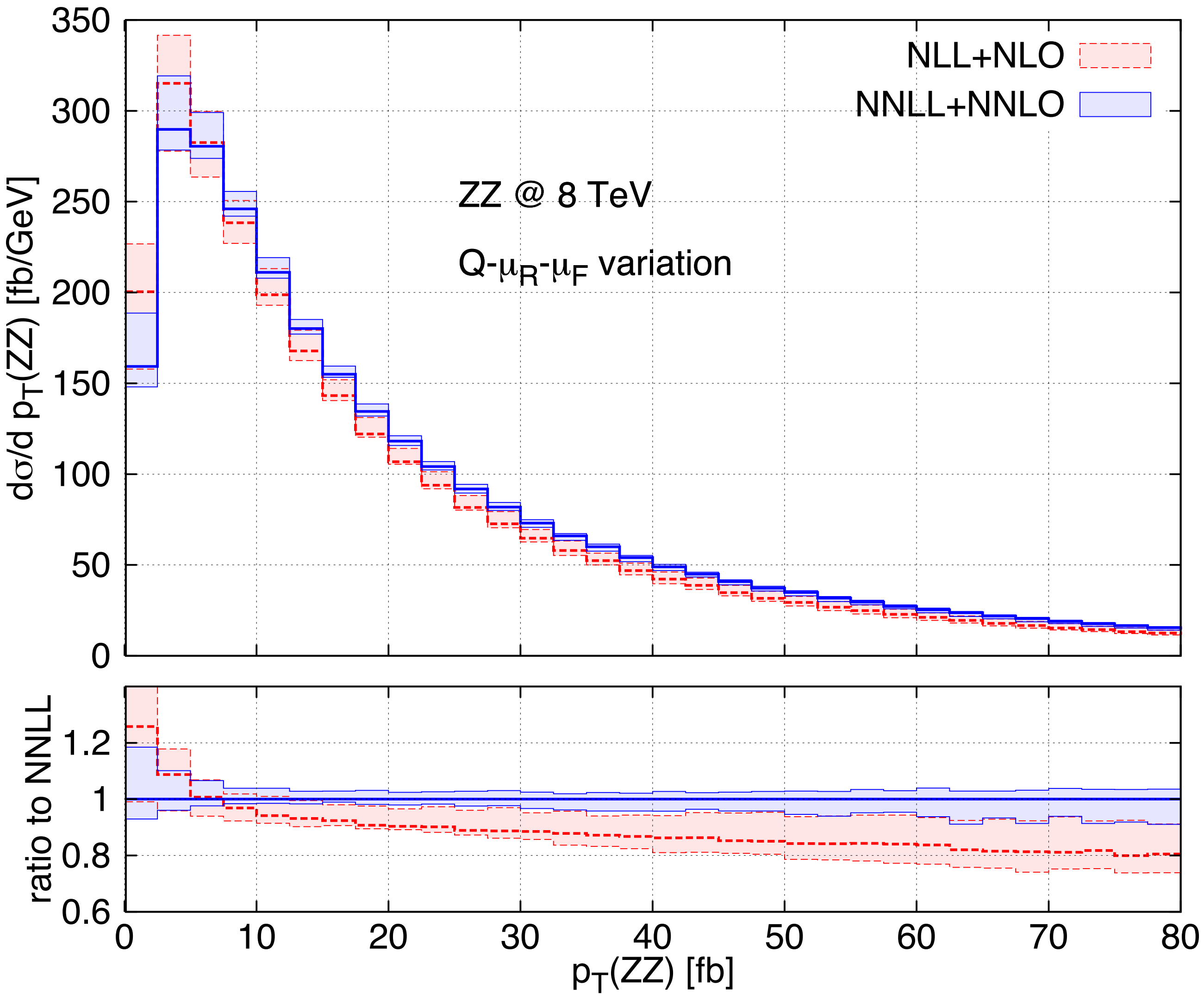
matching: FO+resummation

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

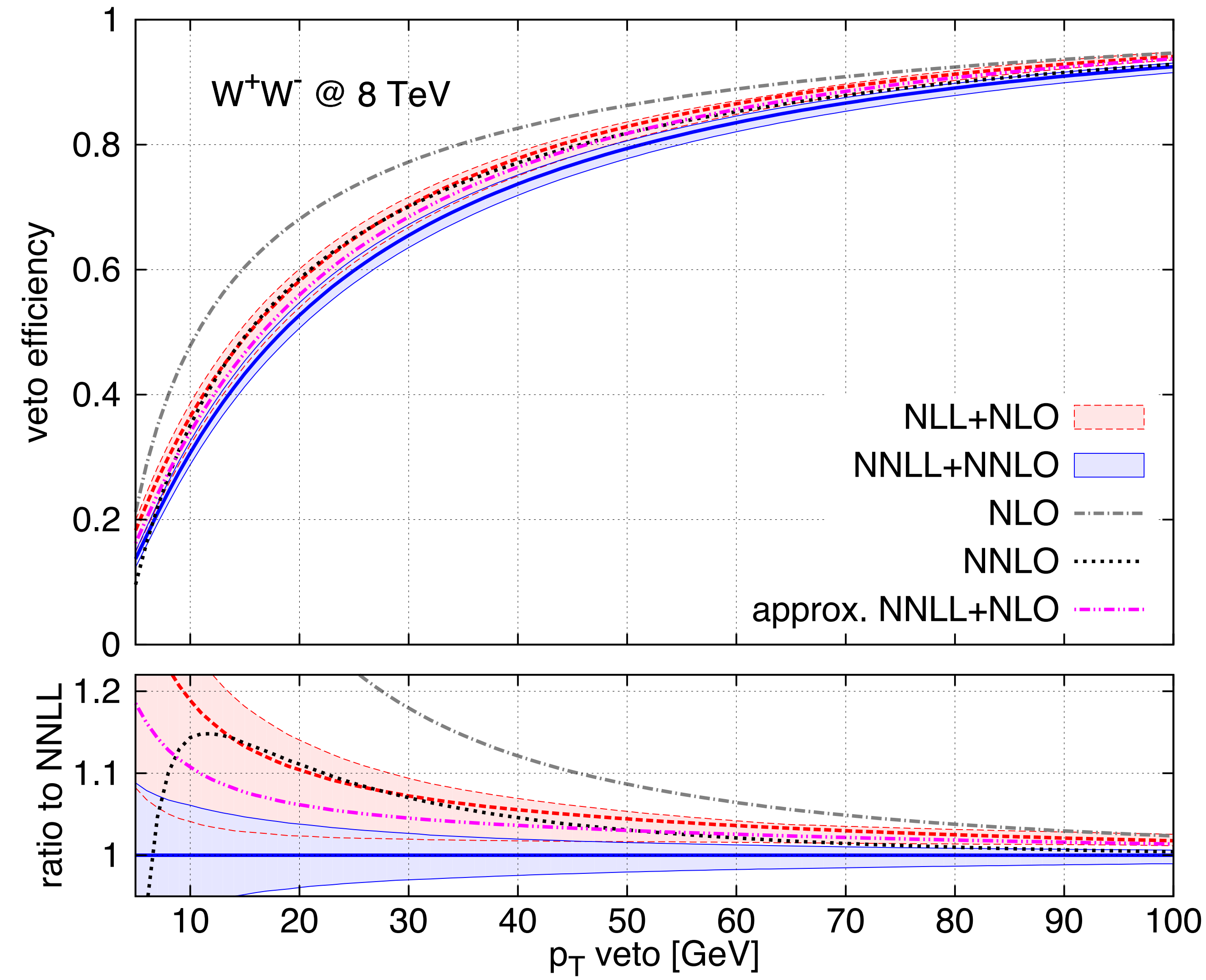


NNLO+NNLL resummation for ZZ and WW [Grazzini, Kallweit, Rathlev, MW '15]

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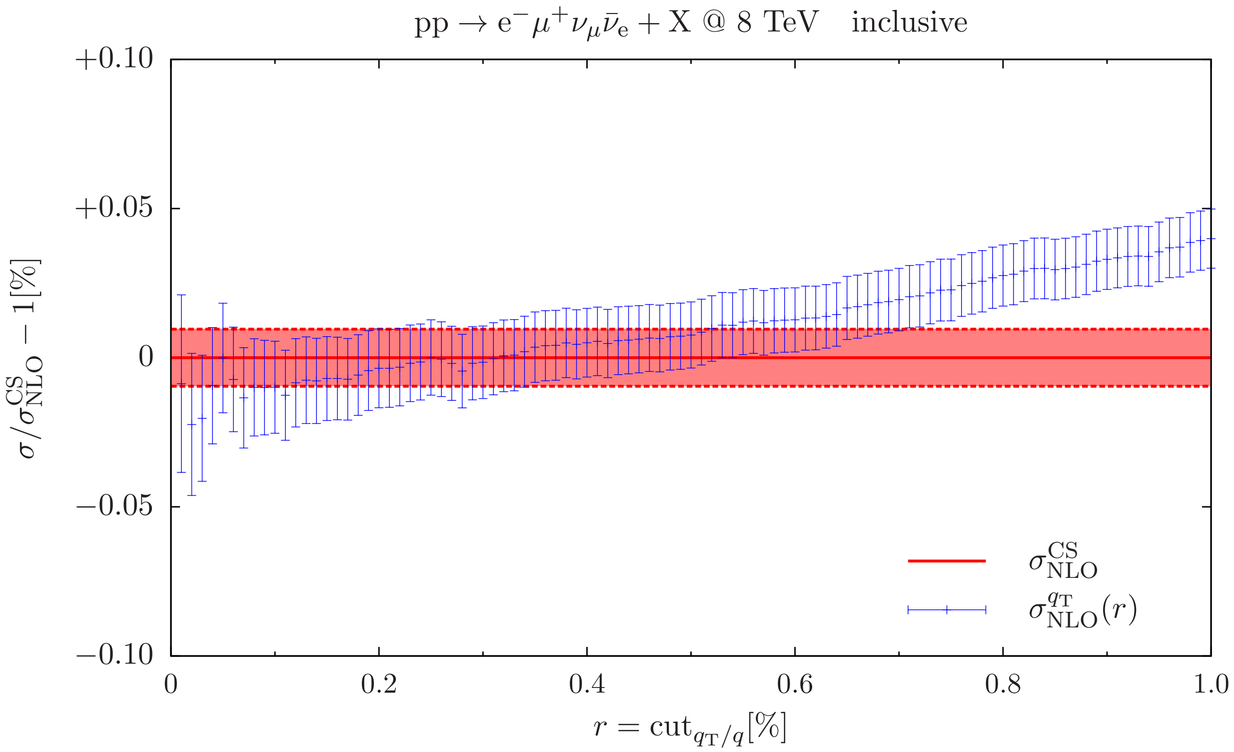
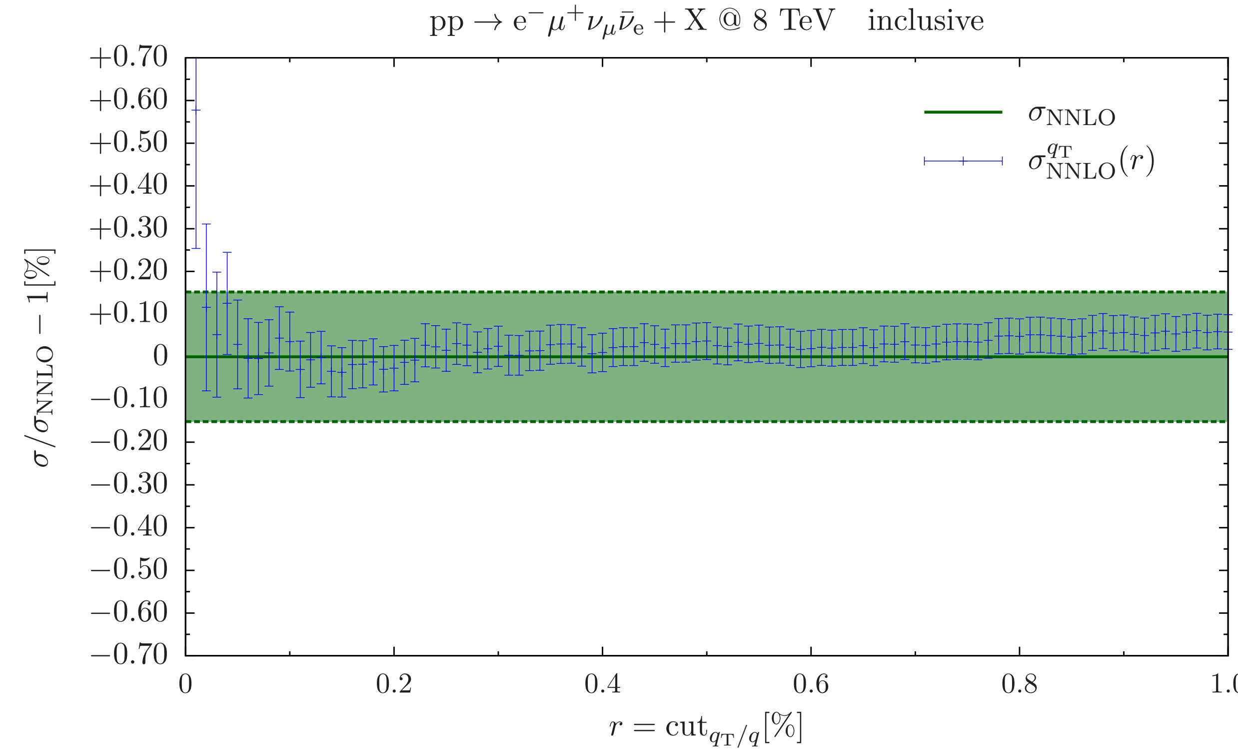
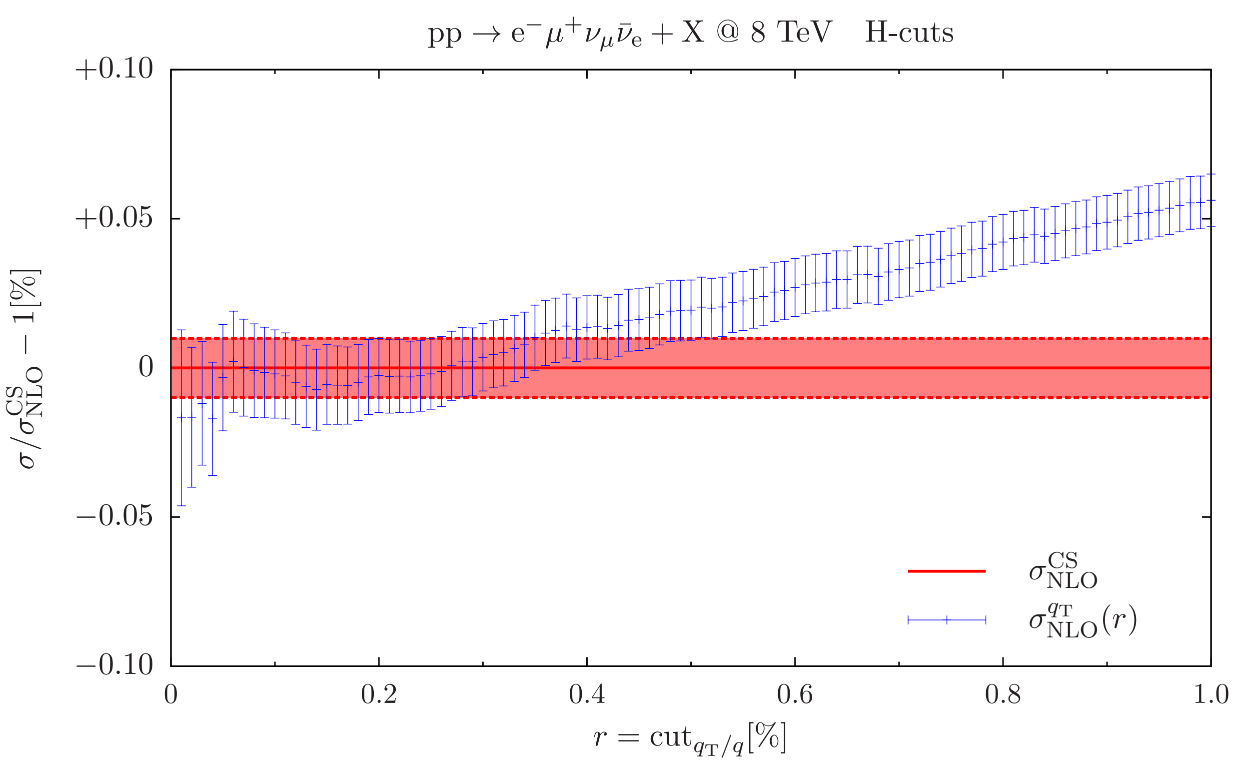
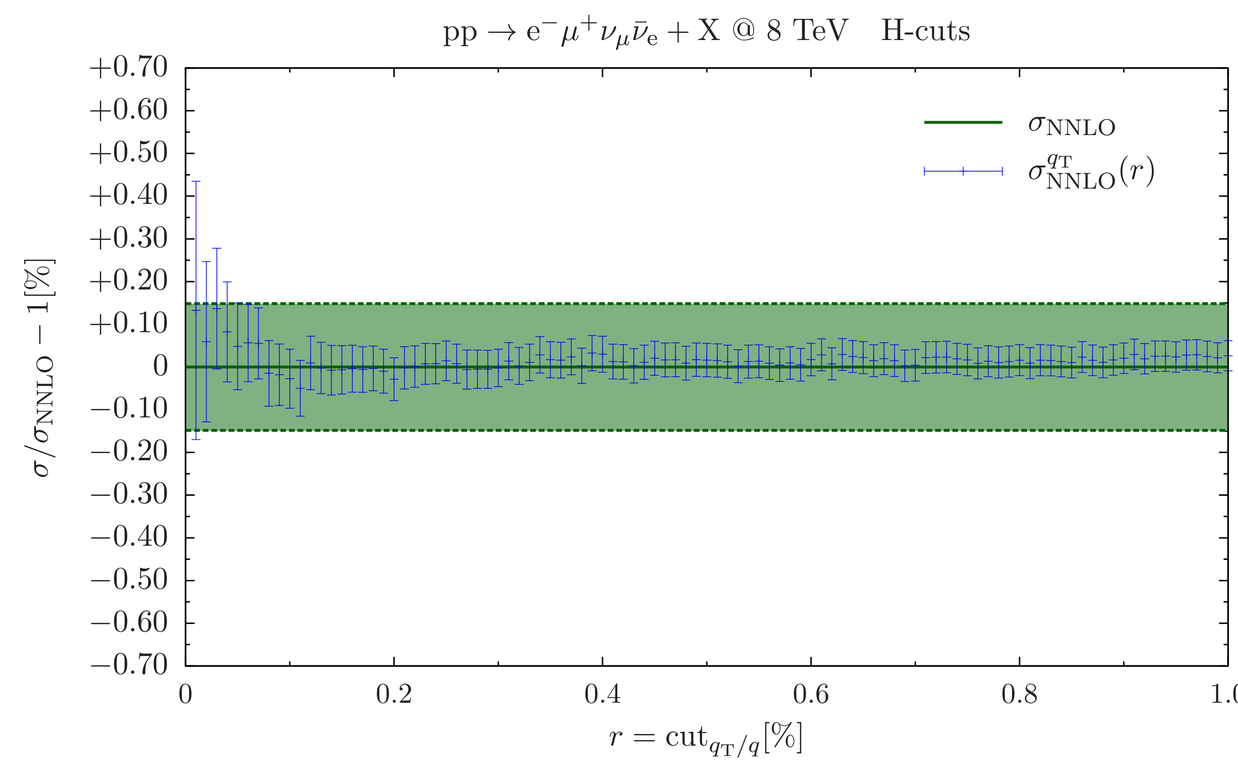
stability of $r_{cut} = p_T/m_{WW}$ dependence







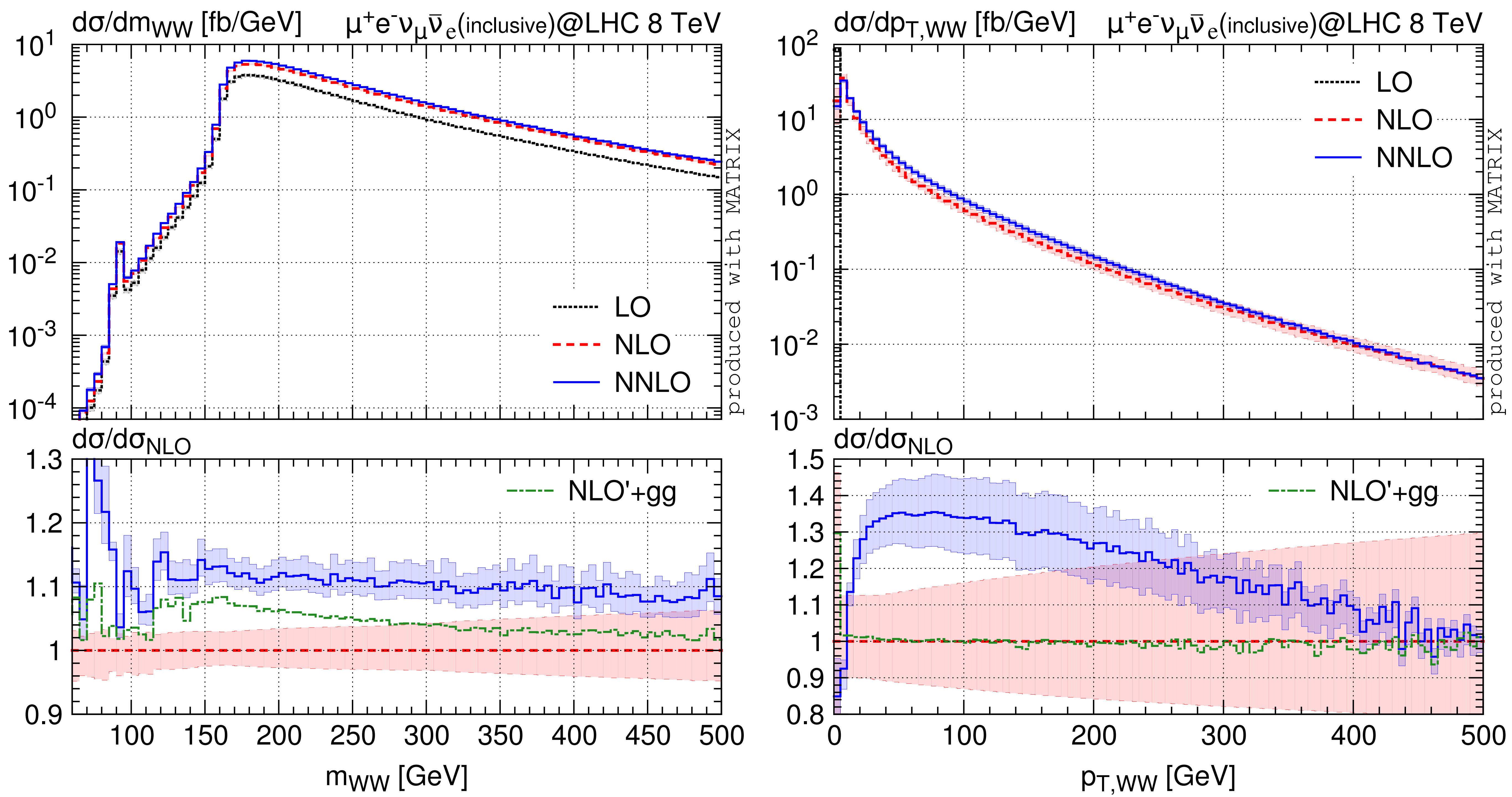


WW fully differential at NNLO

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

Universität Zürich[UZH]

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)