Higher-order corrections to differential WW production

Marius Wiesemann

CERN

LHC EWK WG multiboson discussion, CERN (Switzerland)

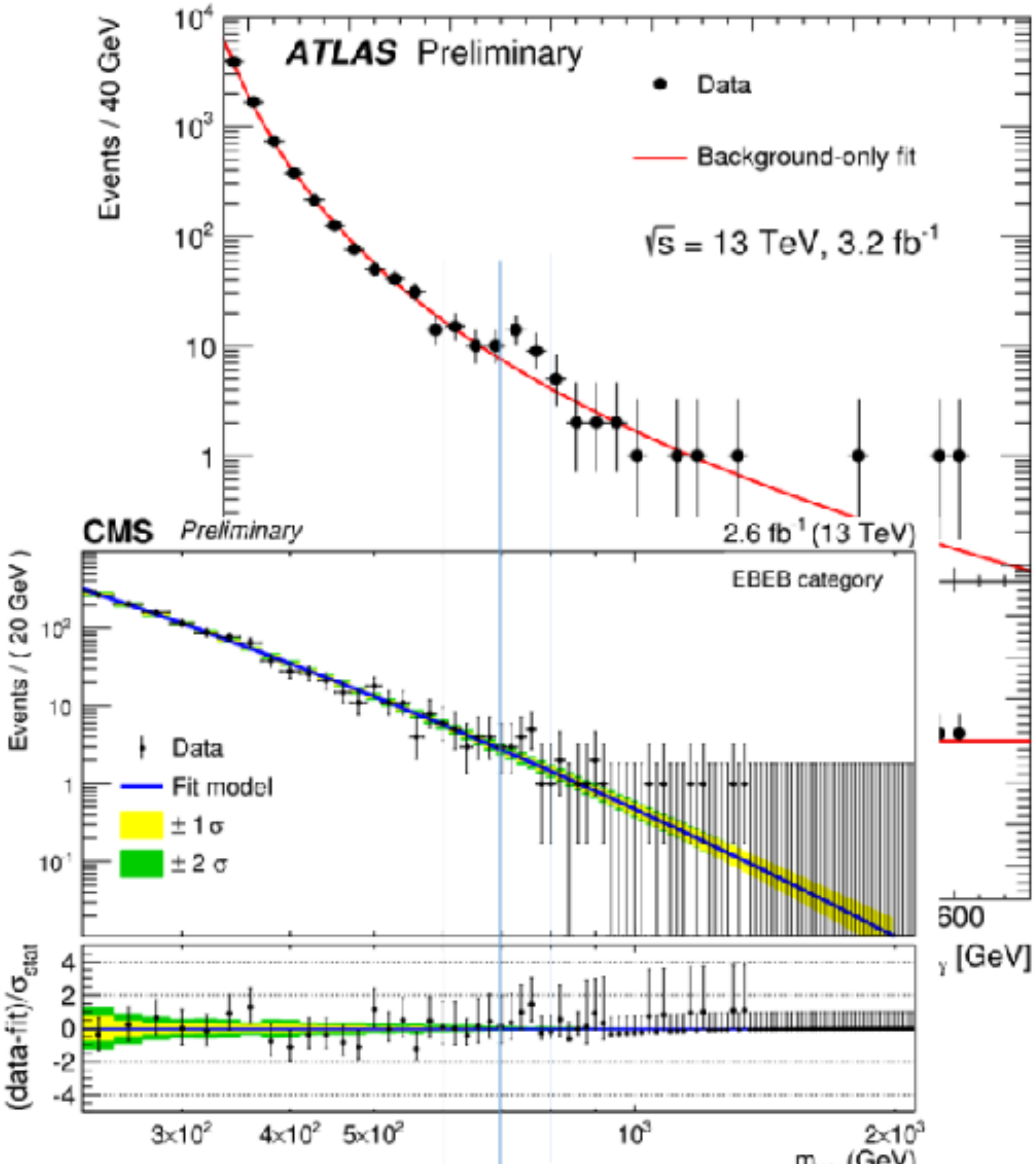
13. February, 2017

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

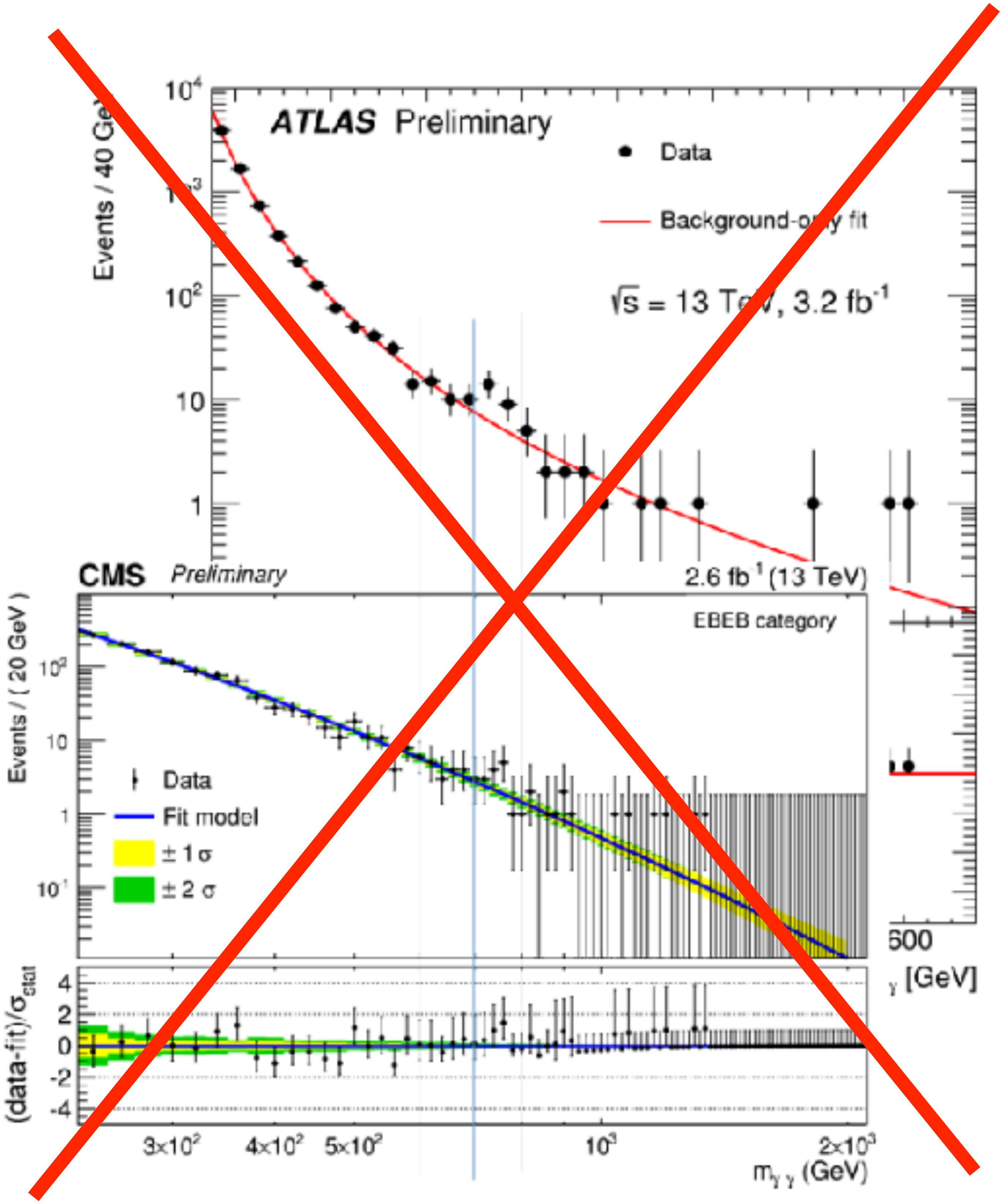
Outline

1. Motivation and introduction to precision computations
2. The MATRIX
3. Theoretical status of WW production
4. WW at NNLO+NNLL (p_T resummation)
5. pp→WW→llνν at NNLO (fully differential)
6. Inclusion of the Higgs contribution

2015 → 2016


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

2015 → 2016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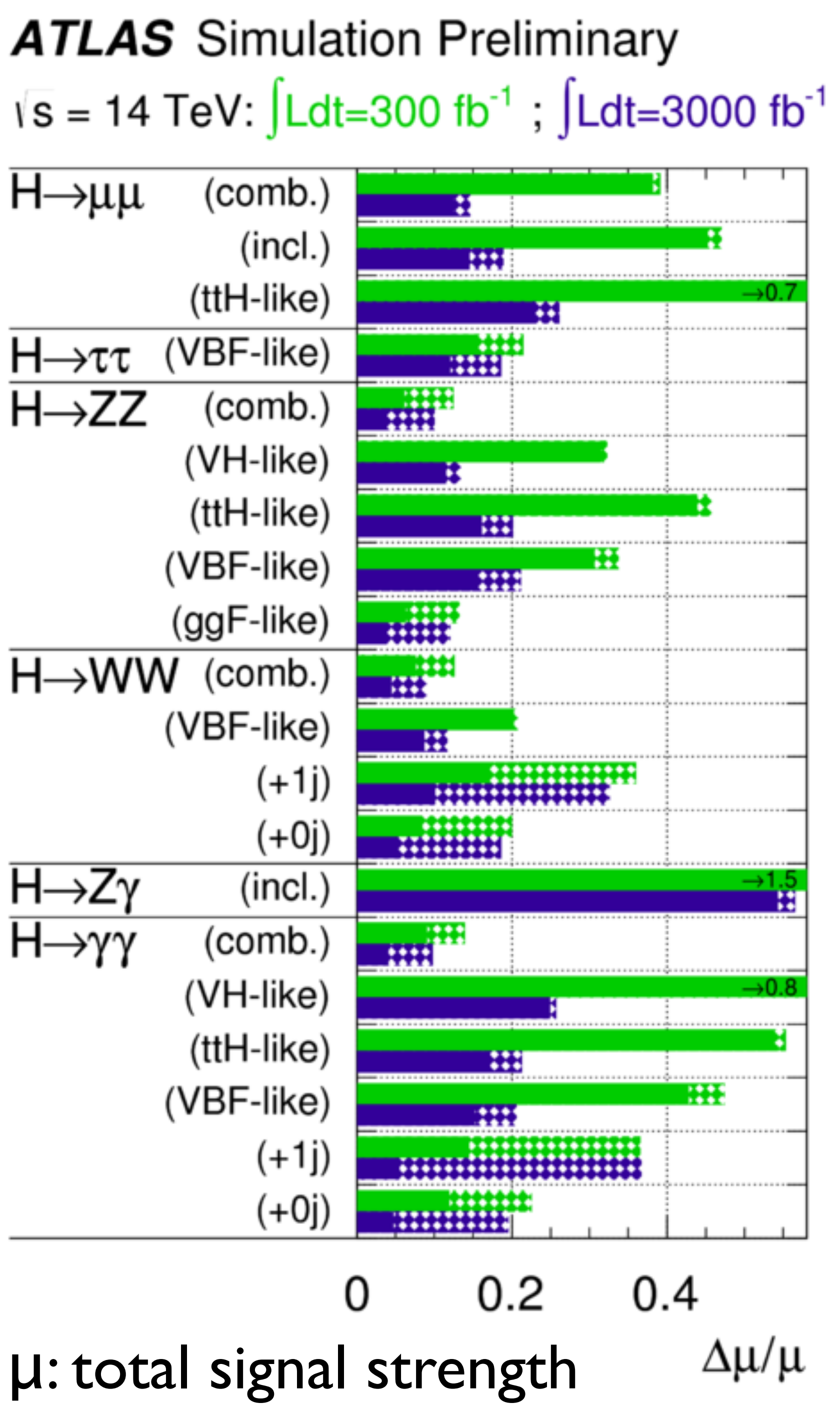
± 2 σ
Events / (20 GeV)
(data-fit)/σ$_{stat}$
$m_{\gamma\gamma}$ (GeV)
[GeV]


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

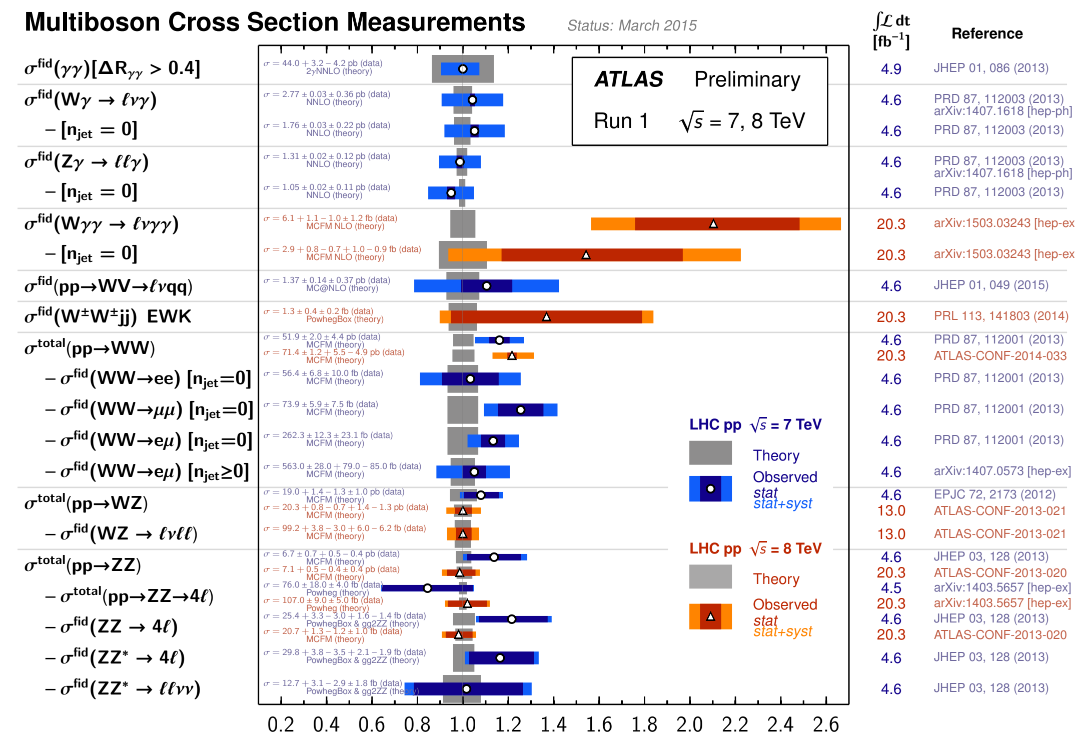

Diphoton Excess
2015 - 2016
R.I.P.
FutureGravestone.com

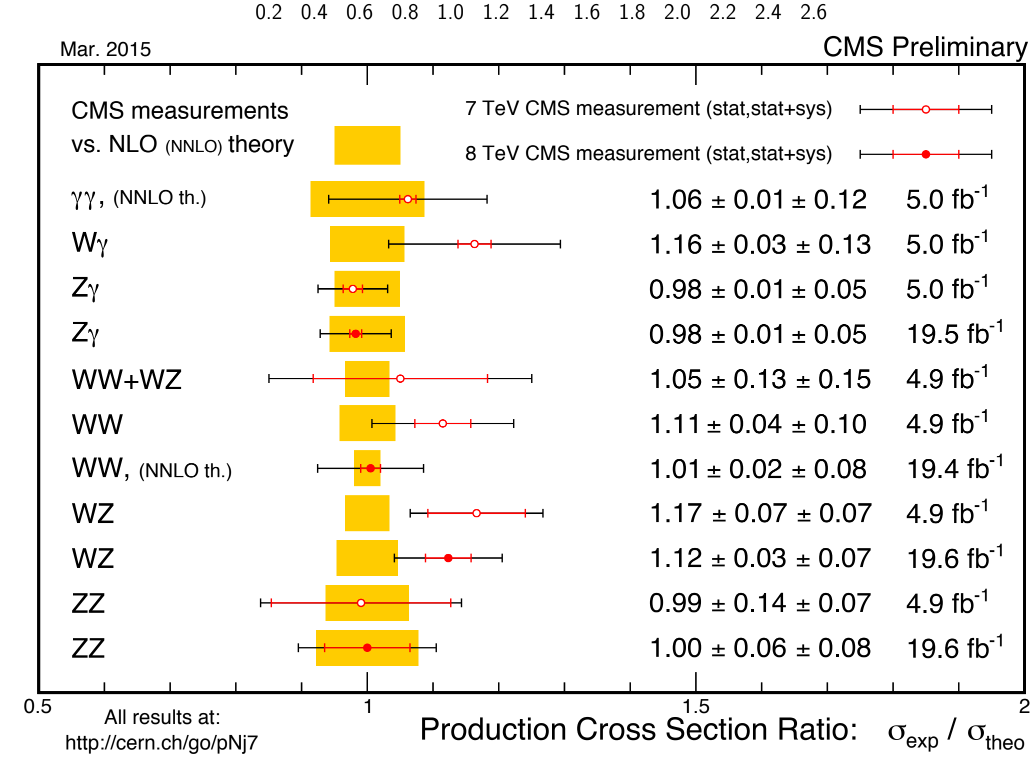
Introduction

Higgs



vector-boson pairs

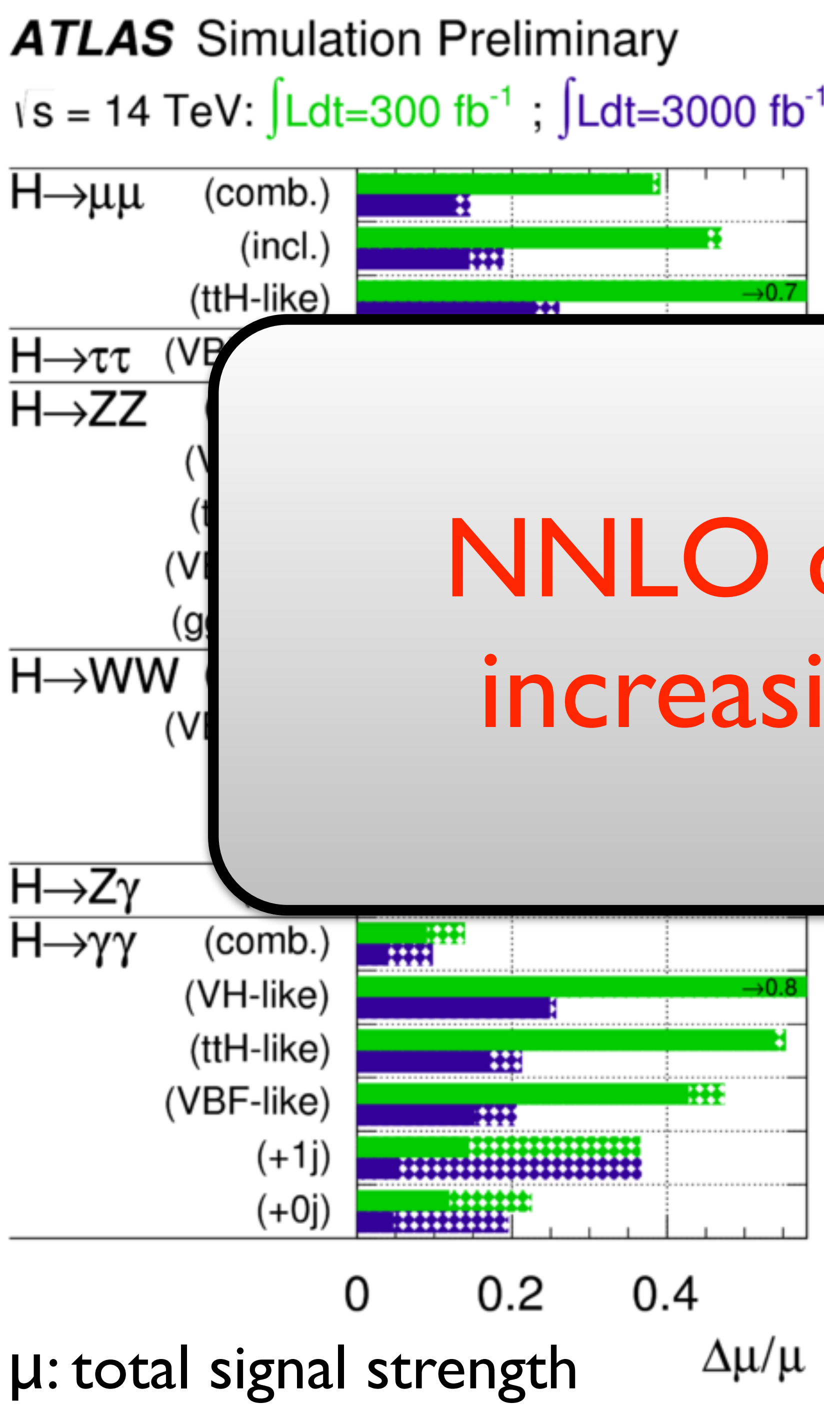




- All vector-boson pair processes are on the Les Houches NNLO wishlist 2013

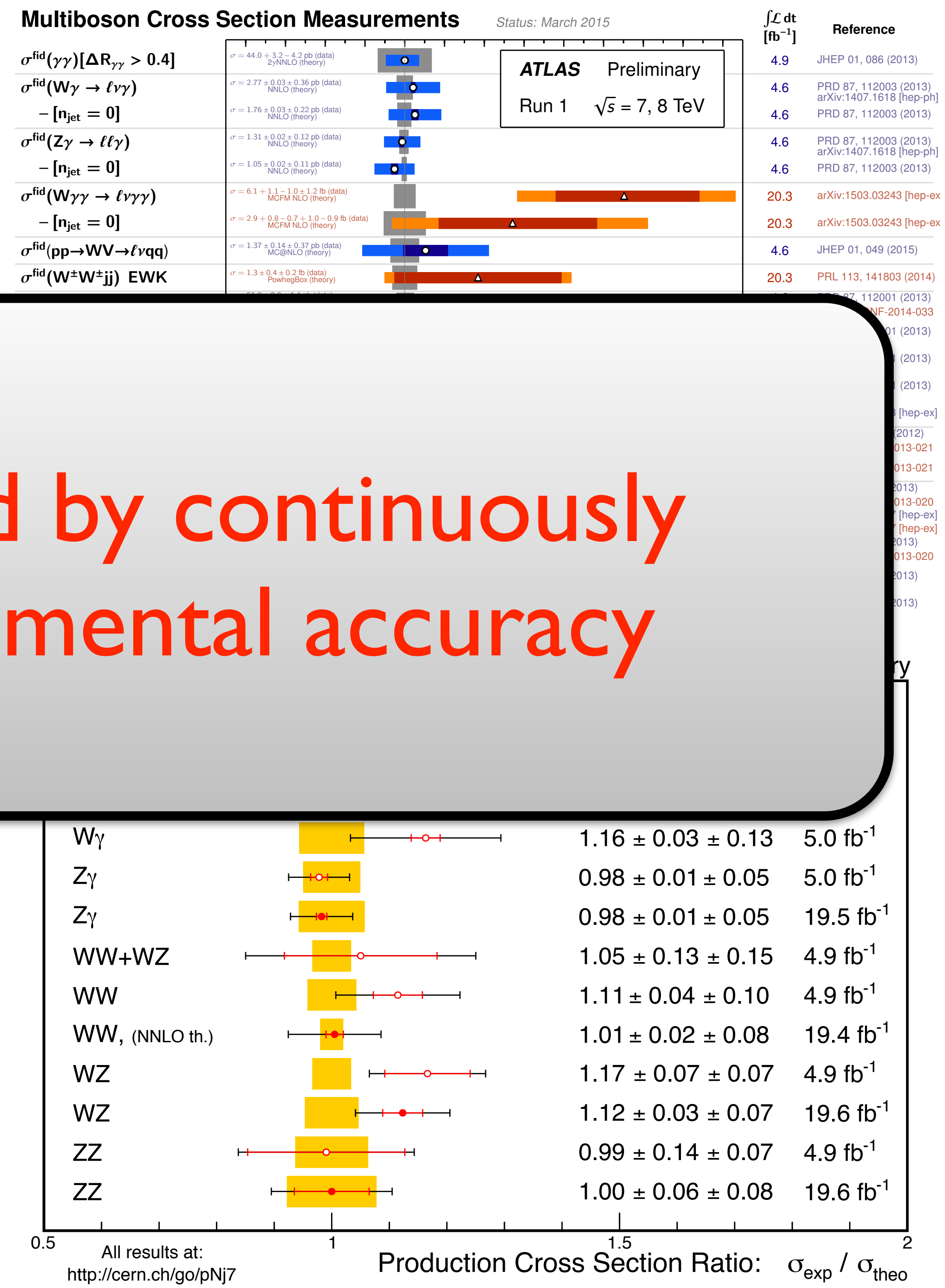
Introduction

Higgs



μ: total signal strength

vector-boson pairs



NNLO demanded by continuously increasing experimental accuracy

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

NNLO methods

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

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✚ Two-loop amplitudes required for each process!

p_T subtraction master formula:

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

[Catani, Grazzini '07]

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[Catani, Grazzini '07]

subtraction terms known from resummation:

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

Resummation formula:

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

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

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[Catani, Grazzini '07]

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NNLO accuracy consequence of unitarity:

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

Resummation formula:

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

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

p_T subtraction master formula:

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

[Catani, Grazzini '07]

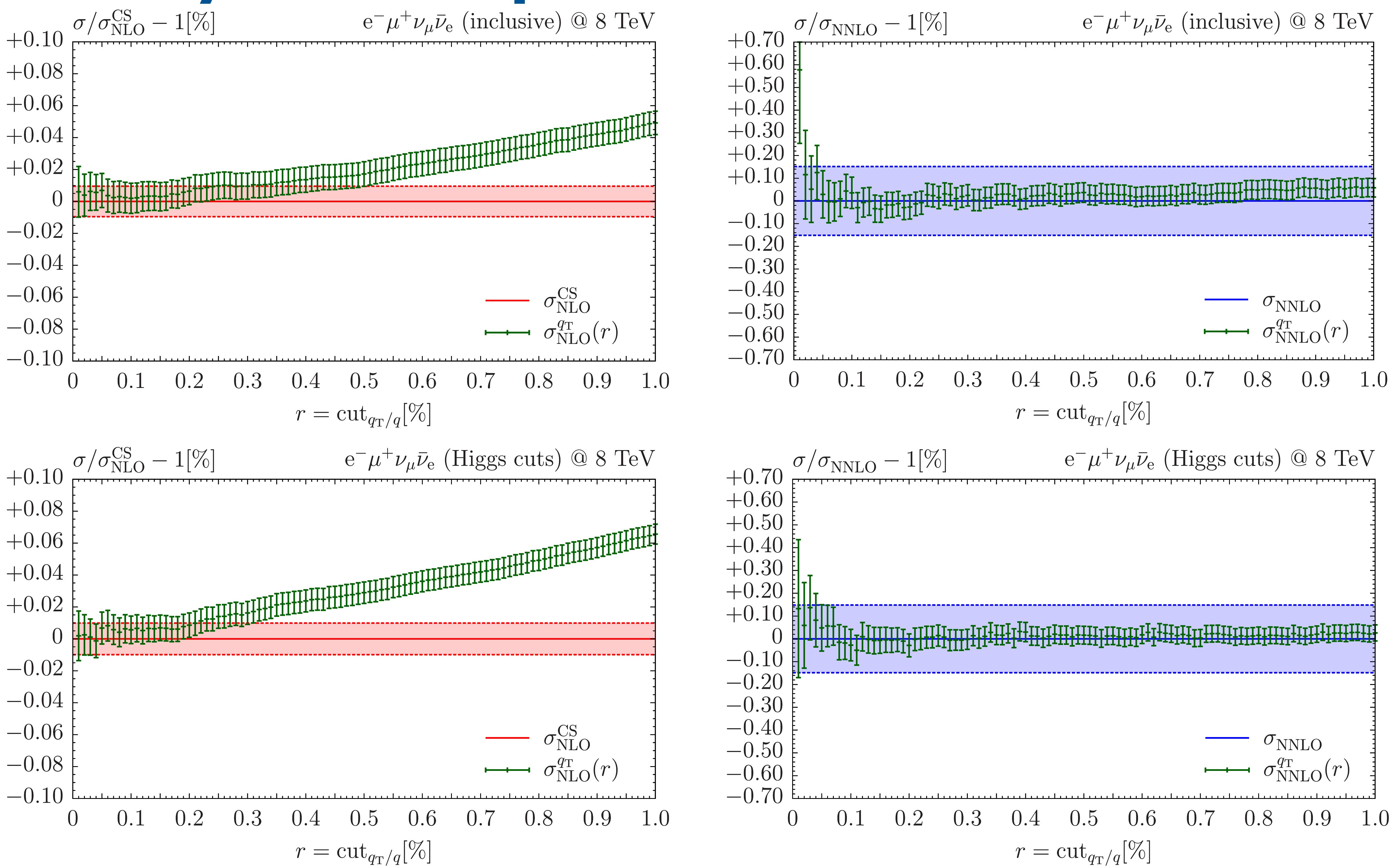
practical implementation:

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

WW fully differential at NNLO

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

stability of r_{cut} dependence



We implemented...

The MATRIX framework

[Grazzini, Kallweit, Rathlev, MW] (+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

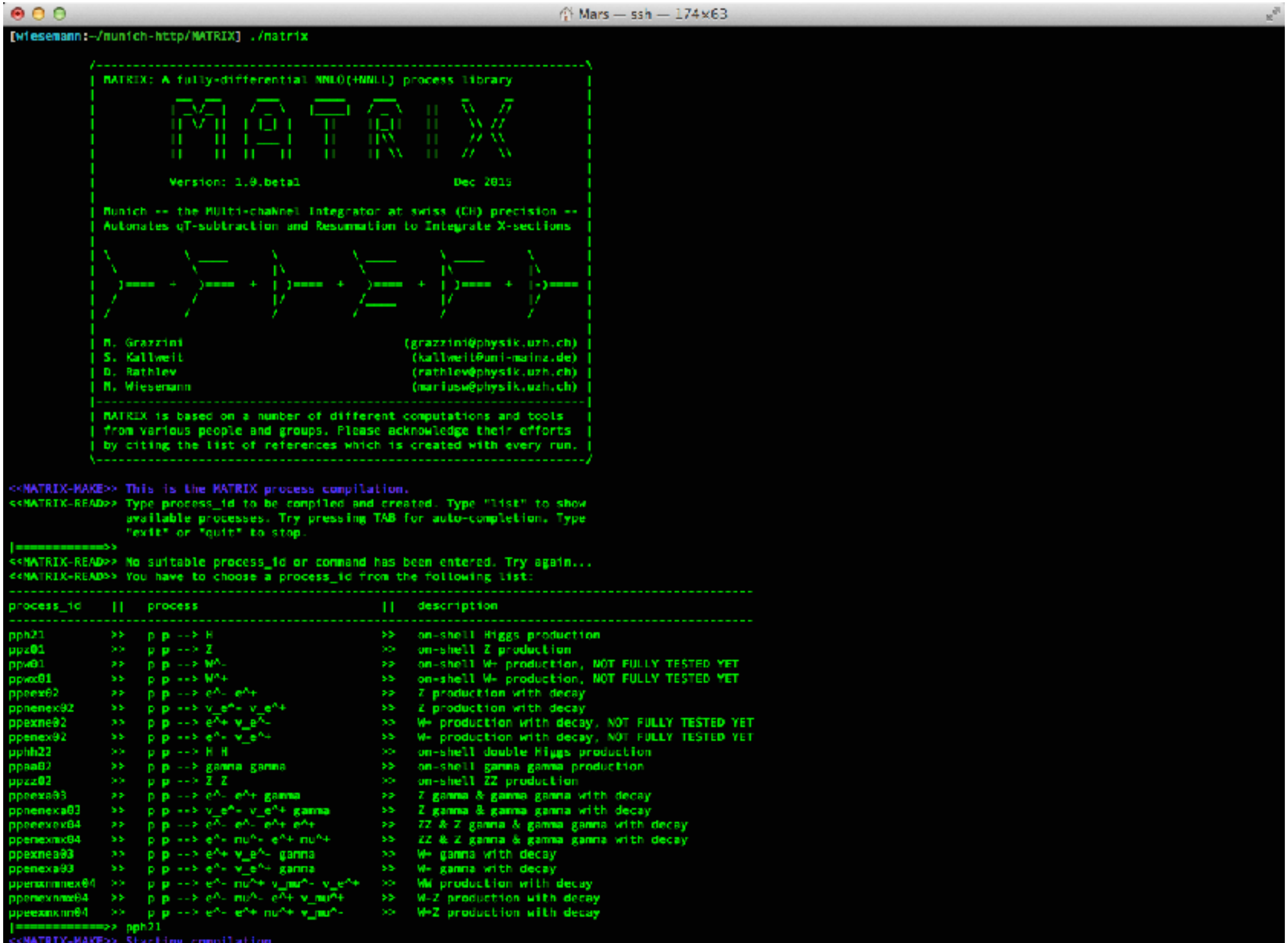
NNLO

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	statu	comment
$pp \to Z/\gamma^*(\to \ell^+\ell^-)$	✓	**validated analytically + DYNNLO**
$pp \to W \to \ell\nu$	(✓)	**to be validated (with CKM)**
$pp \to H$	✓	**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]
$pp \to WW \to \ell\nu$	✓	**HERE: fully differential**
$pp \to WZ$	✓	[Grazzini, Kallweit, Rathlev, MW '16]
$pp \to HH$	✓	[de Florian et al. '16]

WW production

Theoretical status of WW production

fixed-order:

- NNLO corrections to inclusive [Gehrmann, Grazzini, Kallweit, P. Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi '14]
  and differential cross sections [Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]
- NLO corrections to gg channel
  [Caola, Melnikov, Röntsch, Tancredi '15]
- NLO EW corrections
  [Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder '16]

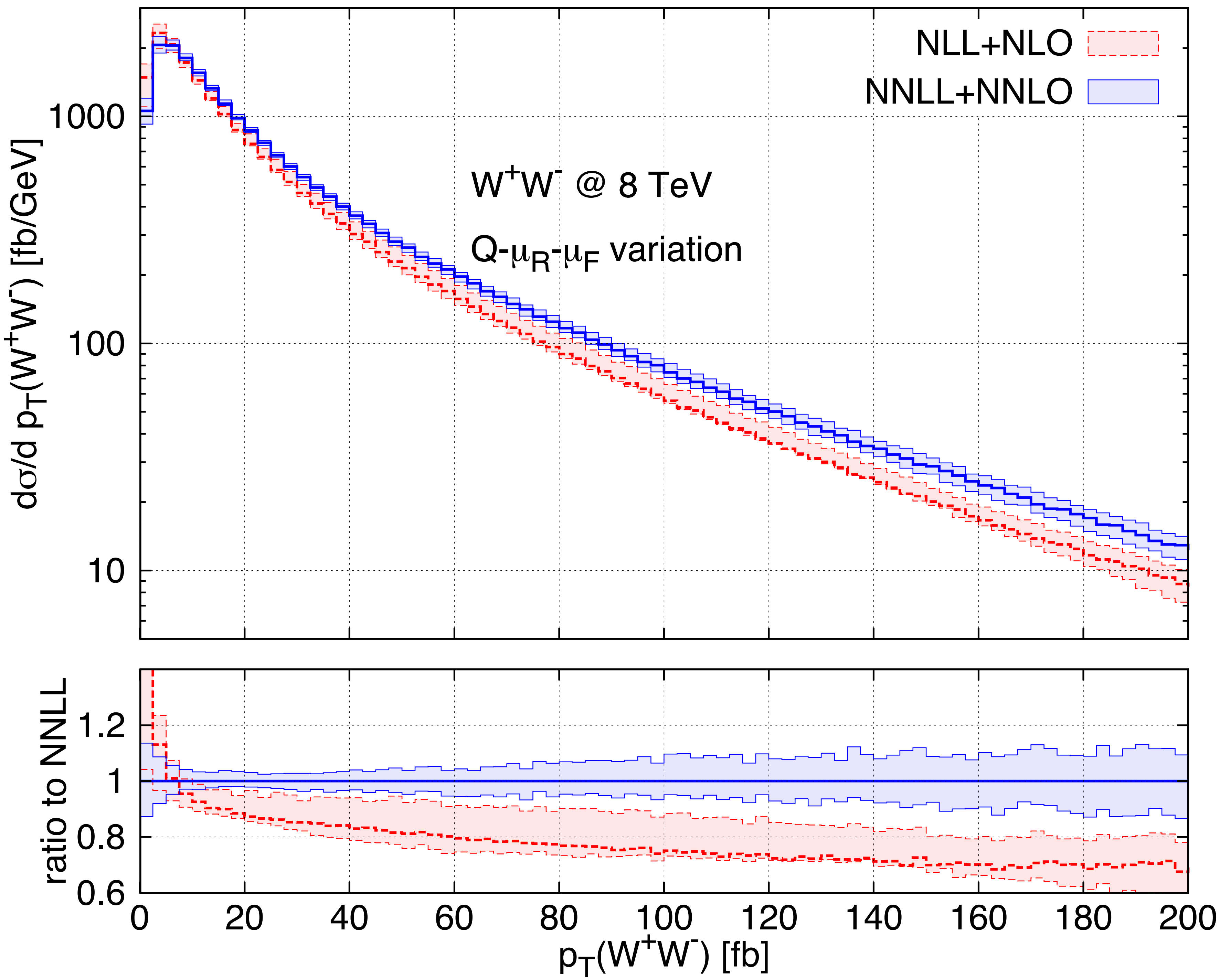
resummation:

- NNLO+NNLL pT resummation of WW pair
  [Grazzini, Kallweit, Rathlev, MW '15]
- **recently:** NNLO+NNLL jet-veto resummation
  [Dawson, Jaiswal, Li, Ramani, Zeng '16]

WW p_T resummation at NNLO+NNLL

[Grazzini, Kallweit, Rathlev, MW '15]

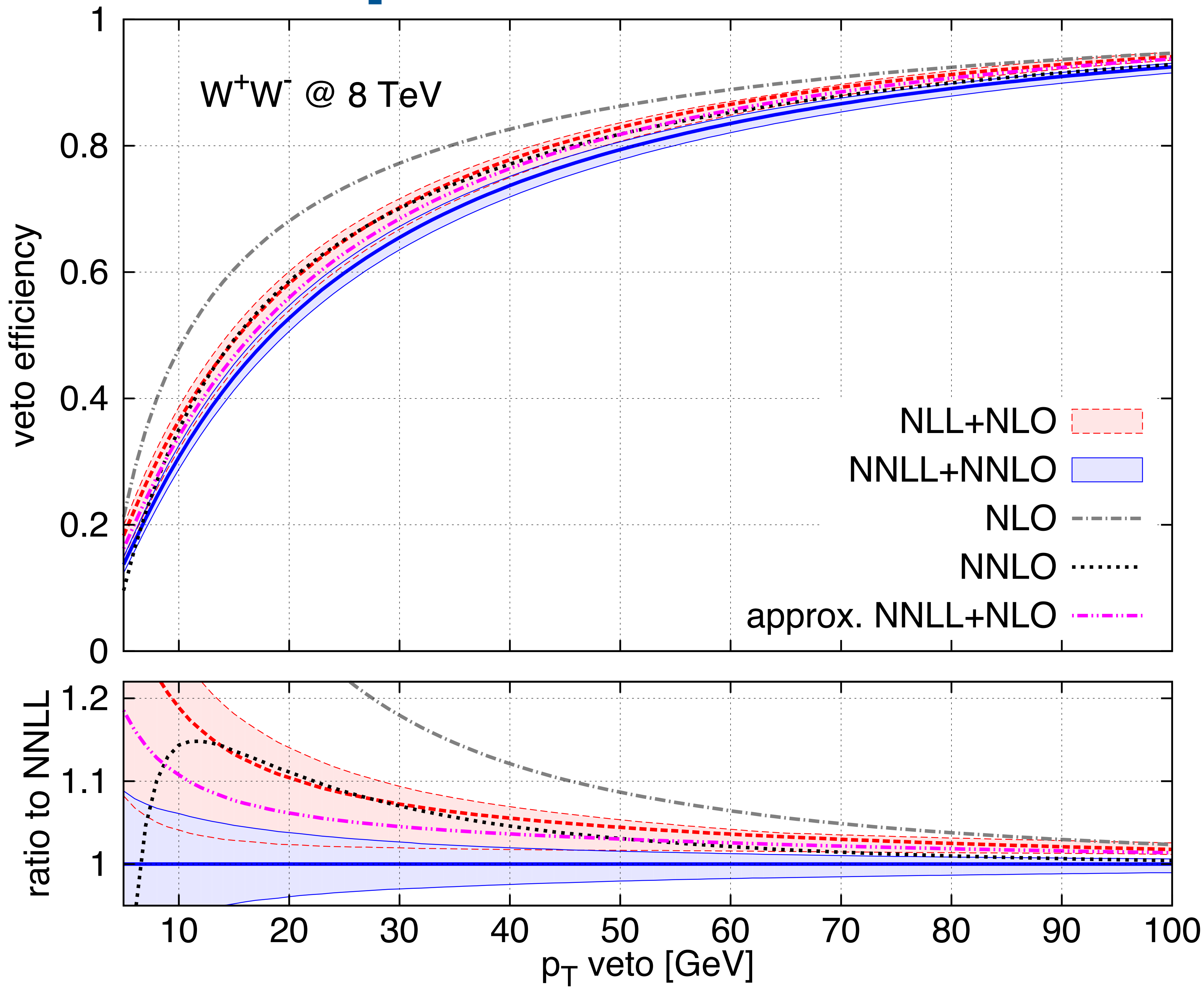
WW p_T spectrum



WW p_T resummation at NNLO+NNLL

[Grazzini, Kallweit, Rathlev, MW '15]

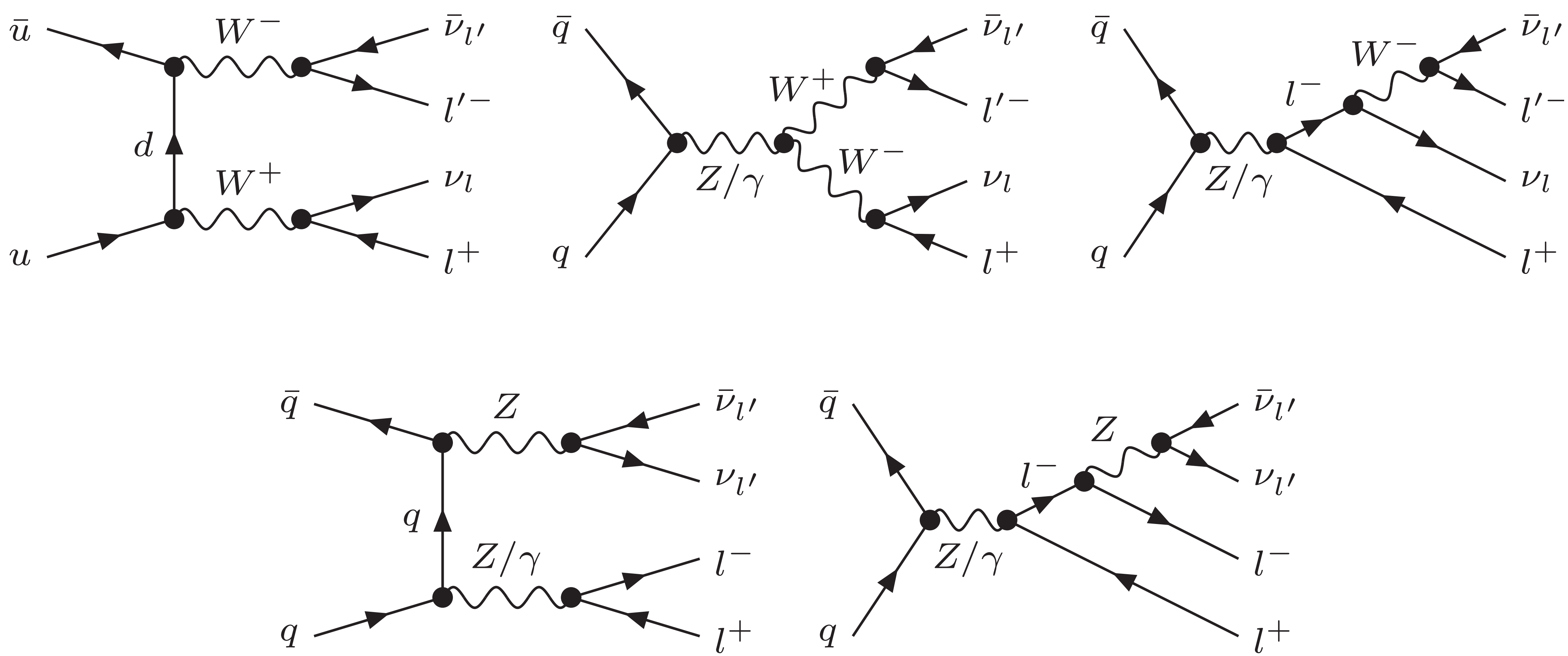
WW p_T veto cross section



WW fully differential at NNLO

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

- 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 SF chan



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 SF chan
- HERE: different-flavour channel **pp→WW→eν_e μν_μ** (for simplicity):

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

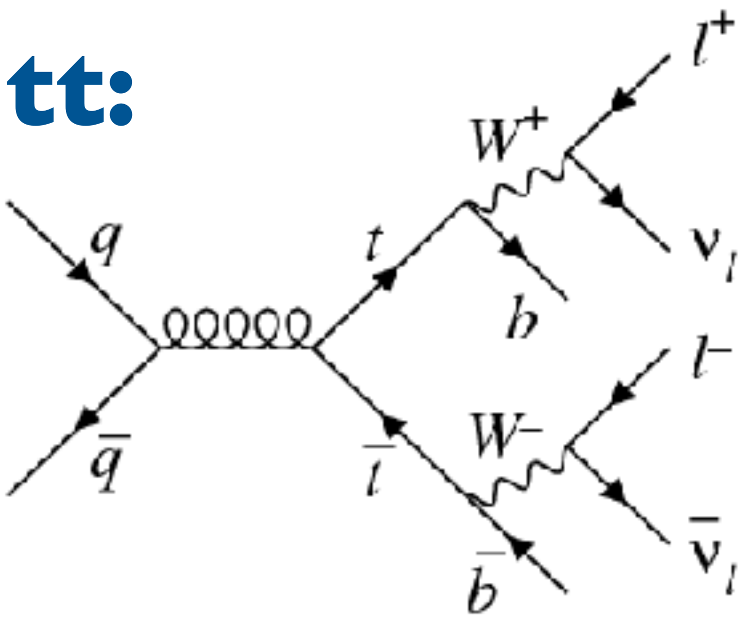
lepton cuts $(p_{T,l_1} > 22\,\text{GeV},\ p_{T,l_2} > 10\,\text{GeV},\ |y_\mu| < 2.4,\ |y_e| < 1.37 \text{ or } 1.52 < |y_e| < 2.47)$

WW fully differential at NNLO

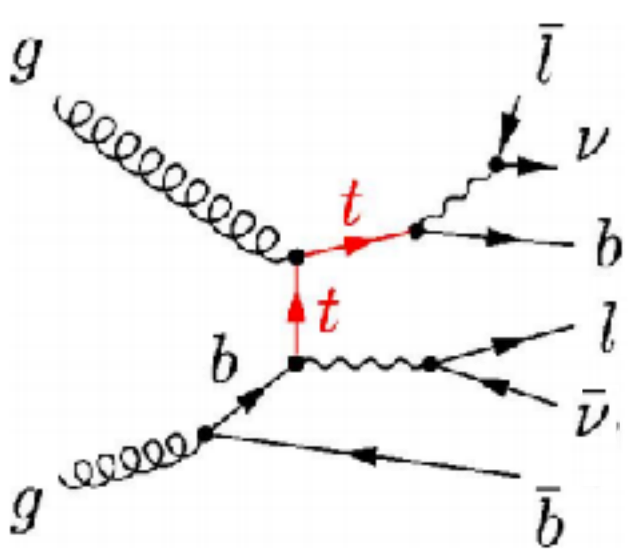
[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]

top-quark contamination

tt:



Wt:



how to avoid tt/Wt contributions in computation:

four-flavour scheme (4FS)

- diagrams with final-state b-quarks finite subgroup (b massive)
- remove top-quark contamination by dropping such diagrams
- default choice in our computation

five-flavour scheme (5FS)

- b-quark contributions not finite (b massless, clustered in jets)
- use resonance structure with respect to top-quark width:

$$\sigma = A \cdot \frac{1}{\Gamma_t^2} + B \cdot \frac{1}{\Gamma_t} + C$$

- fit coefficients for different Γ_t → C: top-subtracted c.s.
- used as cross check (agreement for fiducial rates ~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	$0.25374(7)^{+3.5\%}_{-3.7\%}$	$0.20773(5)^{+3.2\%}_{-3.1\%}$
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WW fully differential at NNLO

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

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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%
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WW fully differential at NNLO

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

inclusive rates

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		+5.2%		+6.8%
NLO′+gg	$655.83(8)^{+4.3\%}_{-3.3\%}$		$1286.81(13)^{+4.8\%}_{-3.7\%}$	
		+5.3%		+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	
LO	$147.23(2)^{+3.4\%}_{-4.4\%}$		$233.04(2)^{+6.6\%}_{-7.6\%}$	
		+4%		+1.3%
NLO	$153.07(2)^{+1.9\%}_{-1.6\%}$		$236.19(2)^{+2.8\%}_{-2.4\%}$	
		+8.7%		+13%
NLO′+gg	$166.41(3)^{+1.3\%}_{-1.3\%}$		$267.31(4)^{+1.5\%}_{-2.1\%}$	
		-1.4%		-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	$0.34608(7)^{+0.6\%}_{-0.7\%}$	$0.29915(6)^{+0.8\%}_{-1.0\%}$
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]

inclusive rates

σ [fb]	8 TeV		13 TeV	
LO	$425.41(4)^{+2.8\%}_{-3.6\%}$		$778.99\ (8)^{+5.7\%}_{-6.7\%}$	
NLO	$623.47(6)^{+3.6\%}_{-2.9\%}$	+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	
LO	$147.23(2)^{+3.4\%}_{-4.4\%}$		$233.04(2)^{+6.6\%}_{-7.6\%}$	
NLO	$153.07(2)^{+1.9\%}_{-1.6\%}$	+4%	$236.19(2)^{+2.8\%}_{-2.4\%}$	+1.3%
NLO′+gg	$166.41(3)^{+1.3\%}_{-1.3\%}$	+8.7%	$267.31(4)^{+1.5\%}_{-2.1\%}$	+13%
NNLO	$164.1\ (1)^{+1.3\%}_{-0.8\%}$	-1.4%	$261.5(2)^{+1.9\%}_{-1.2\%}$	-2.2%

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	$0.24552(5)^{+4.4\%}_{-4.7\%}$	+29%	$0.19599(4)^{+4.4\%}_{-4.7\%}$	+34%
NLO′+gg	$0.25374(7)^{+3.5\%}_{-3.7\%}$	+3.3%	$0.20773(5)^{+3.2\%}_{-3.1\%}$	+6%
NNLO	$0.2378(4)^{+1.3\%}_{-0.9\%}$	-6.3%	$0.1907(3)^{+1.2\%}_{-0.9\%}$	-8.2%

WW fully differential at NNLO

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

fiducial rates (Higgs cuts)

	$\sigma_{\rm fiducial}$(H−cuts) [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′	$49.318(7)\,^{+1.7\%}_{-1.6\%}$	$75.578(11)\,^{+2.5\%}_{-2.2\%}$	$+\ 2.7\%$	$+\ 3.4\%$
NLO′+gg	$53.496(8)\,^{+2.0\%}_{-1.5\%}$	$85.231(12)\,^{+2.5\%}_{-2.5\%}$	$+11.3\%$	$+16.6\%$
NNLO	$52.30(4)\,^{+1.6\%}_{-1.0\%}$	$82.32(12)\,^{+2.4\%}_{-2.6\%}$	$+\ 8.9\%$	$+12.6\%$

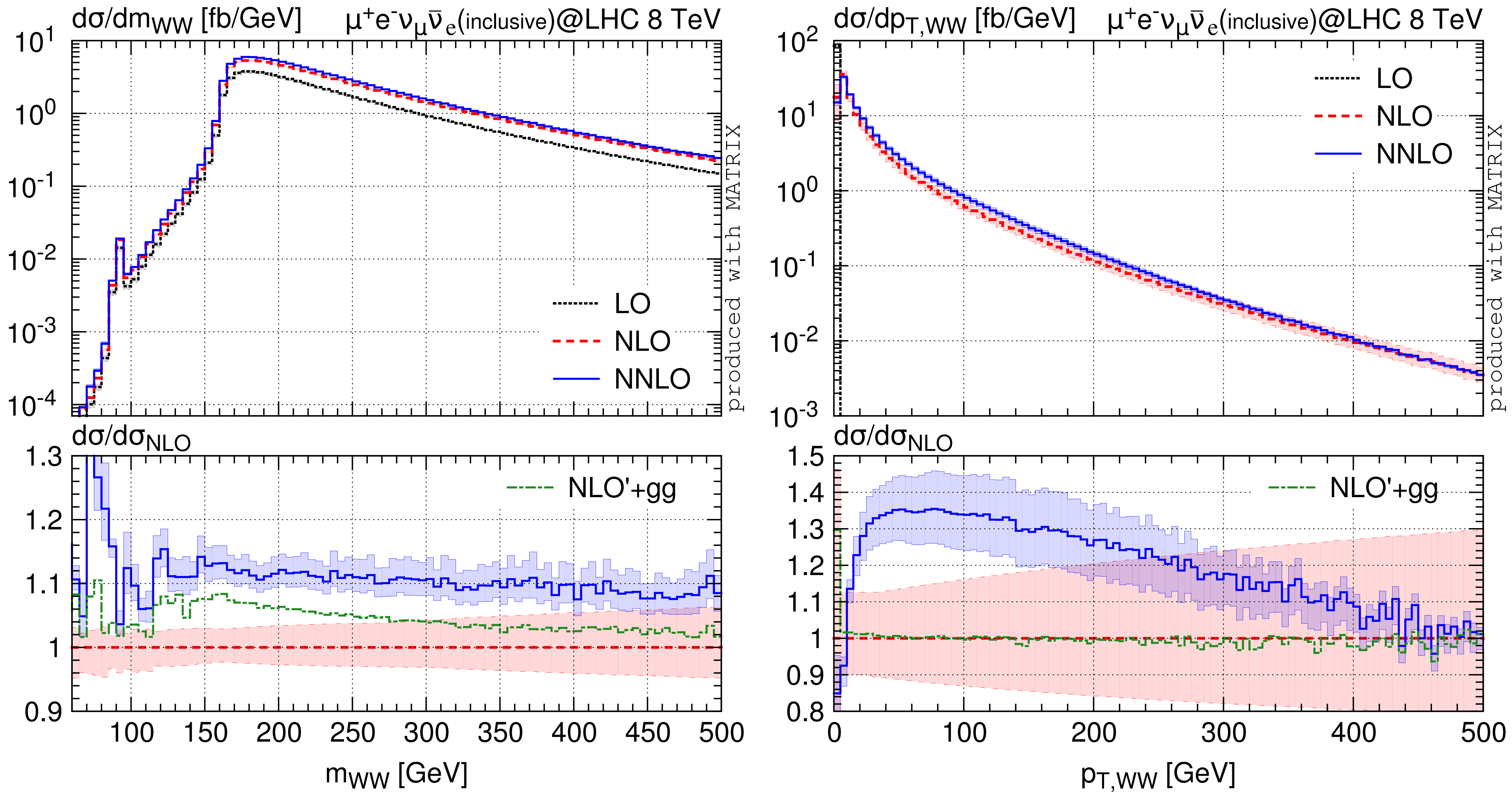
acceptances (Higgs cuts)

	$\epsilon = \sigma_{\rm fiducial}$(H−cuts)$/\sigma_{\rm inclusive}$		$\epsilon/\epsilon_{\rm NLO} - 1$	
$\sqrt{s}$	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 '16]

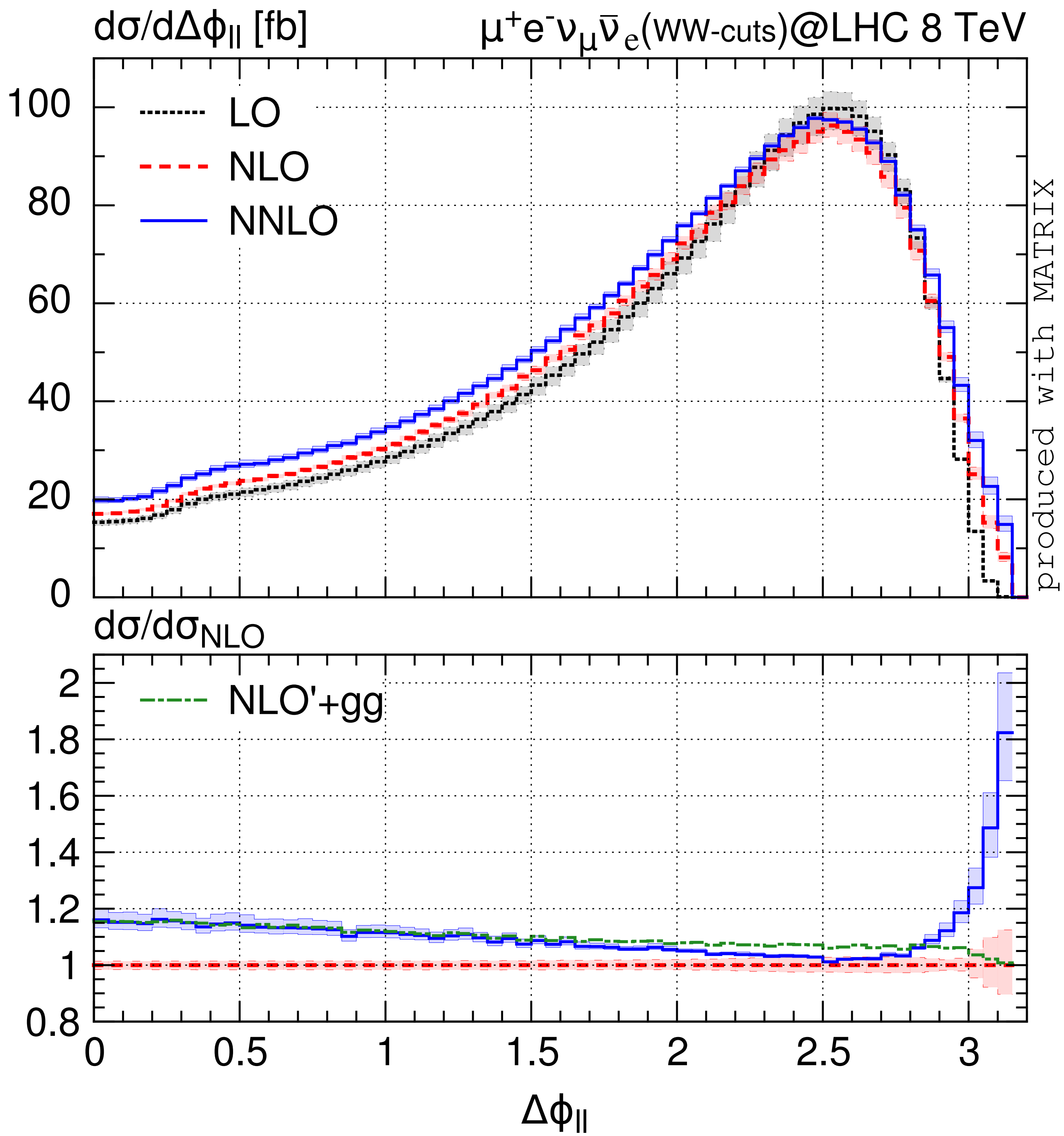
inclusive (8 TeV)

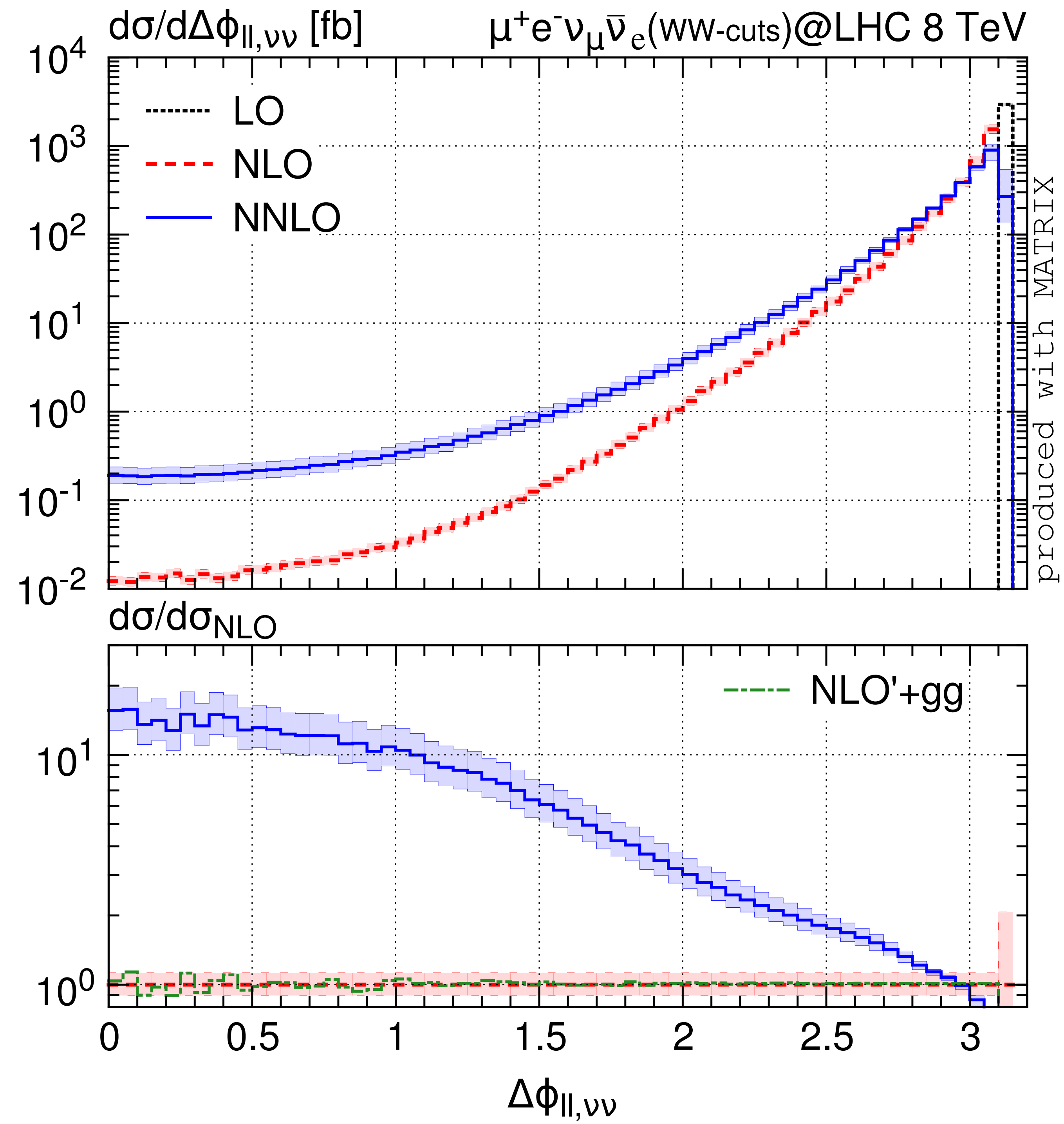


WW fully differential at NNLO

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

WW signal cuts (8 TeV)

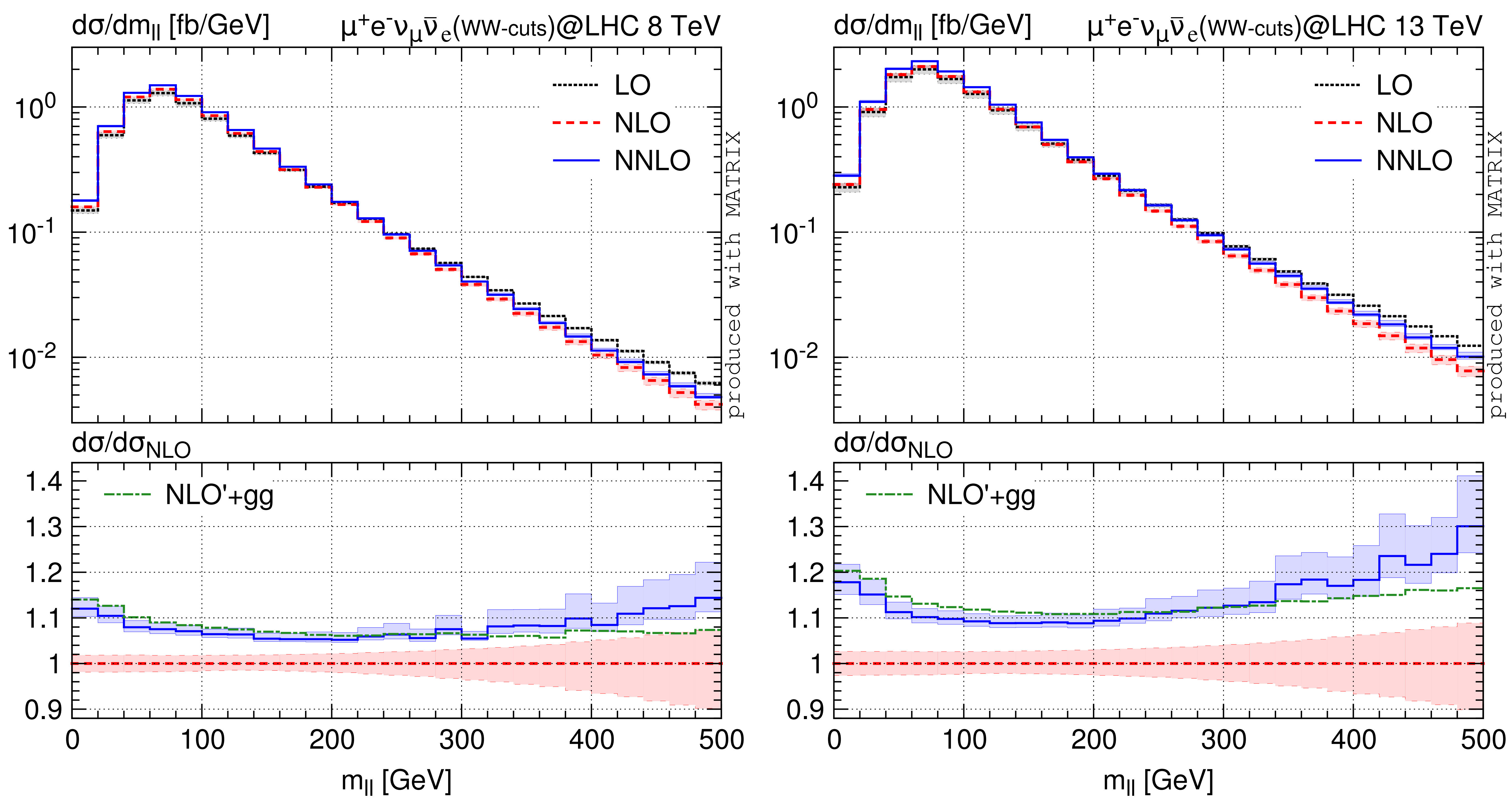




WW fully differential at NNLO

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

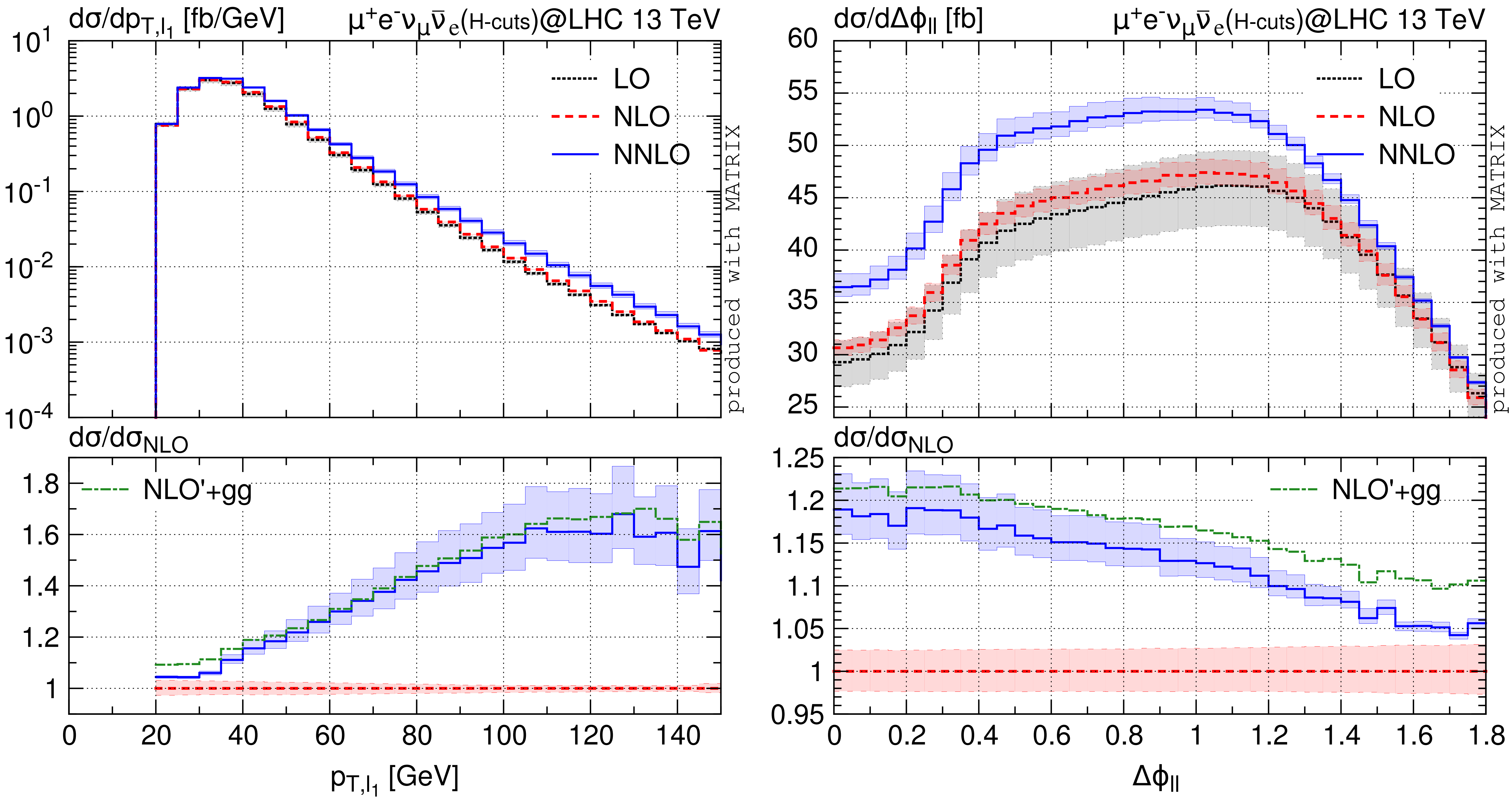
WW signal cuts (left: 8 TeV, right: 13 TeV)



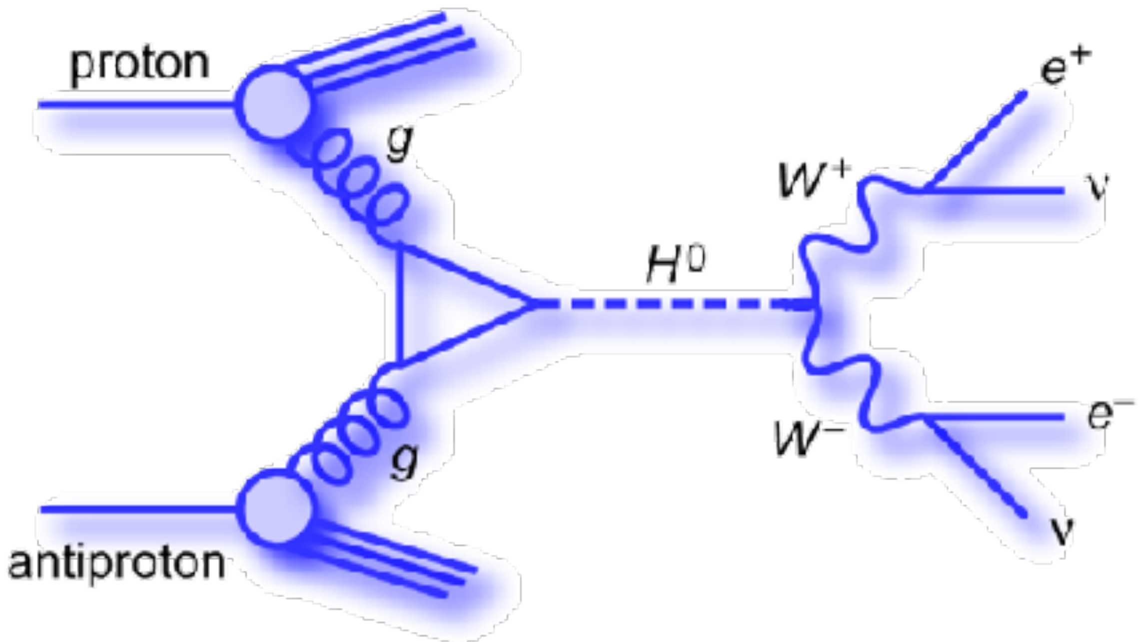
WW fully differential at NNLO

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

Higgs background cuts (13 TeV)



Including the Higgs in WW predictions



Current state-of-the-art approach:

- Our computation (setting finite m_H) allows to consistently include the Higgs at $O(\alpha_S^2)$
- Higher-order corrections to the squared $H \to WW(\to l l \nu\nu)$ amplitude with several tools:
  - e.g.: HNNLO [Catani, Grazzini '07; Grazzini '08; Grazzini, Sargsyan '13]

→ compute $O(\alpha_S^3)$ and $O(\alpha_S^4)$ contributions (including quark-mass effects) and incoherently add it full $O(\alpha_S^2)$ computation

- **Missing:** interference effects between WW and $H \to WW$ at $O(\alpha_S^3)$ (doable but not available)

Summary

<u>WW transverse-momentum spectrum resummed at NNLO+NNLL</u>

- differential in the born-level phase-space (eg, in the rapidity of the WW pair)
- **evident:** importance of both perturbative and logarithmic corrections

<u>WW fully-differential cross section computed at NNLO</u>

- full process: $pp \to ll\nu\nu$
- **includes:** all topologies (with W, Z,γ, H), off-shell effects and spin correlations

  ➜ realistic computation of WW cross section in the fiducial volume
- large NNLO corrections to acceptance of the fiducial cross section
- important NNLO effects on shapes of distributions

Outlook

- **soon:** public version of MATRIX (a fully-differential NNLO(+NNLL) library)
- NLO QCD corrections to loop-induced gg channel
- NLO EW effects

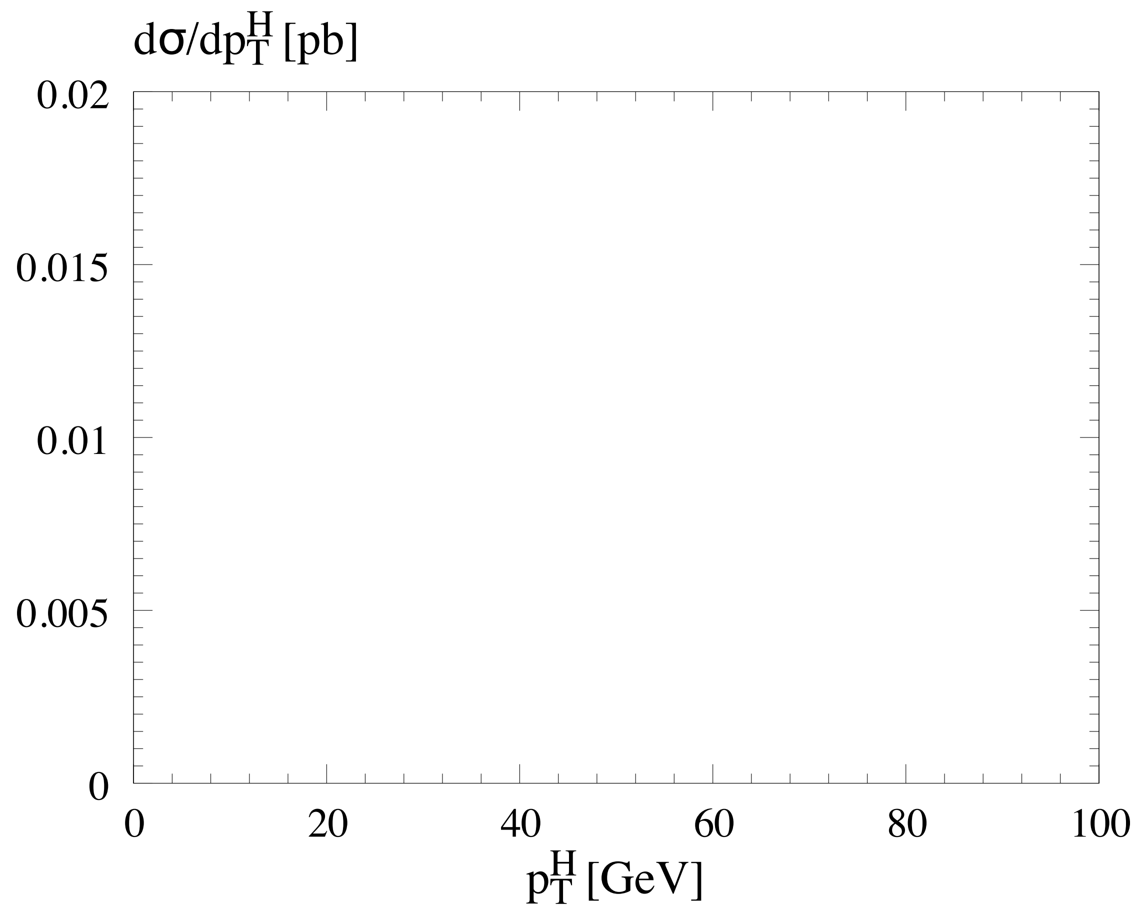

FREE YOUR MIND.
THE MATRIX

Thank You !

Back Up

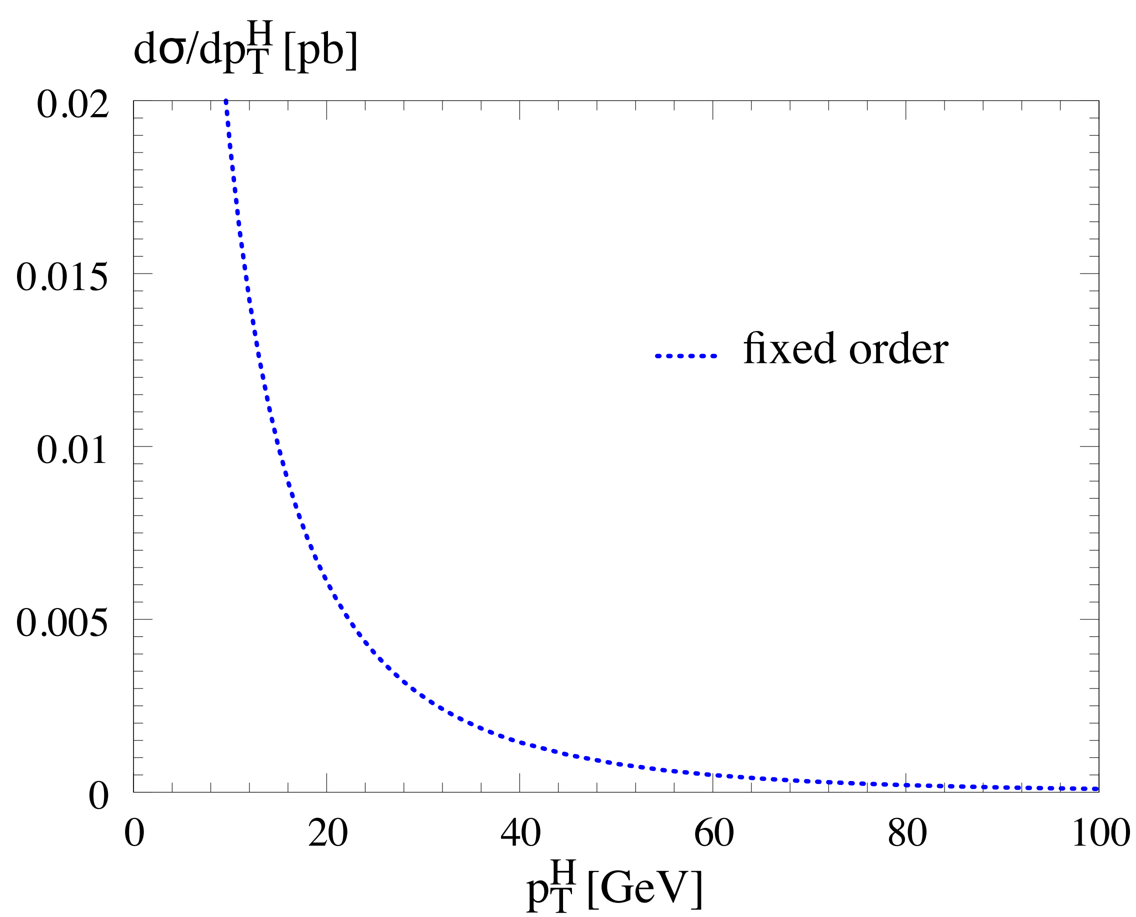
matching: FO+resummation

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



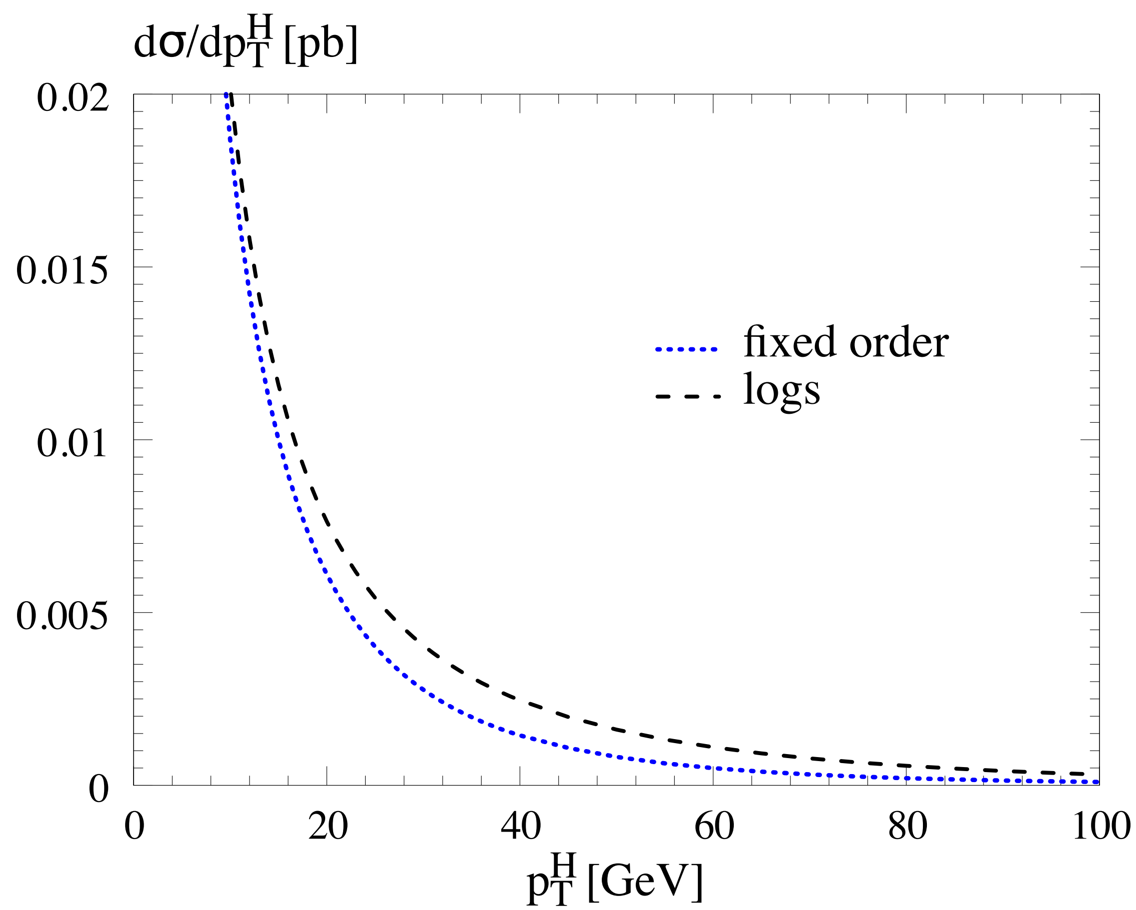
matching: FO+resummation

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



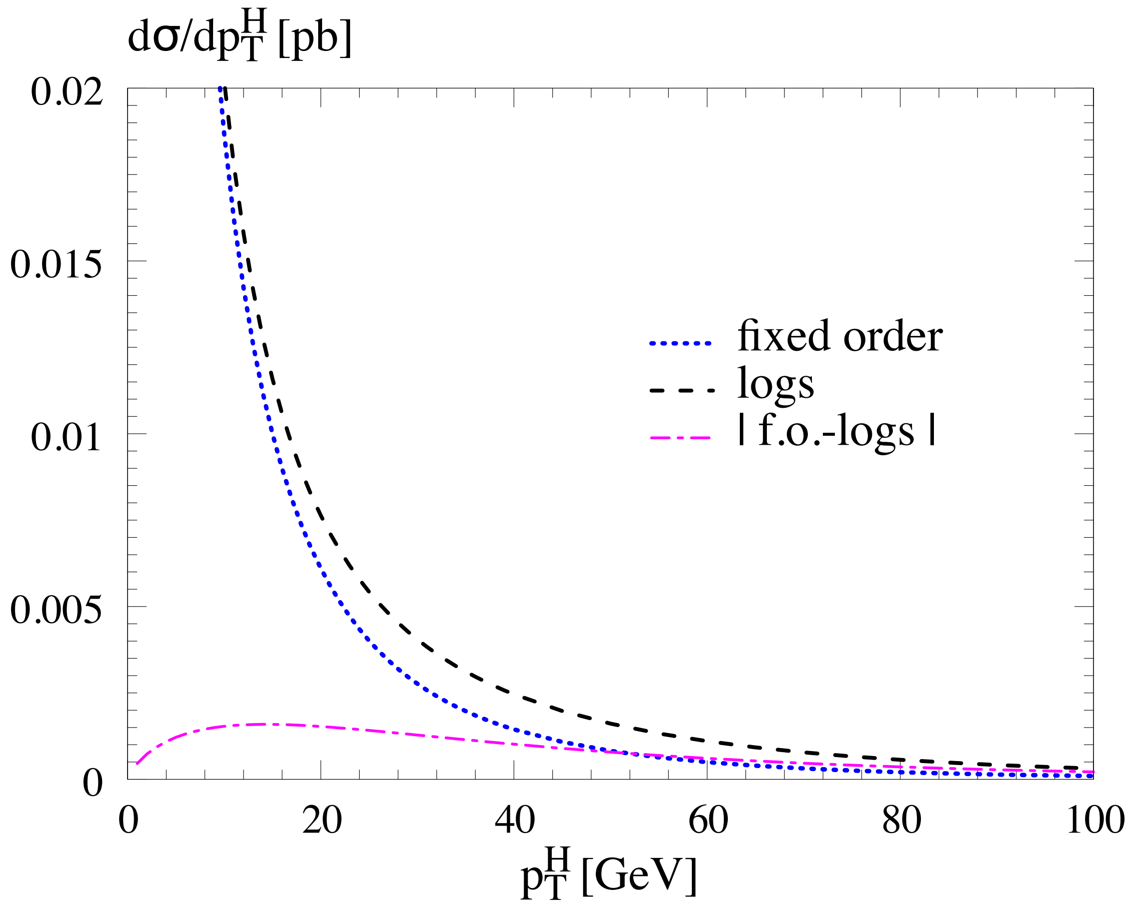
matching: FO+resummation

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



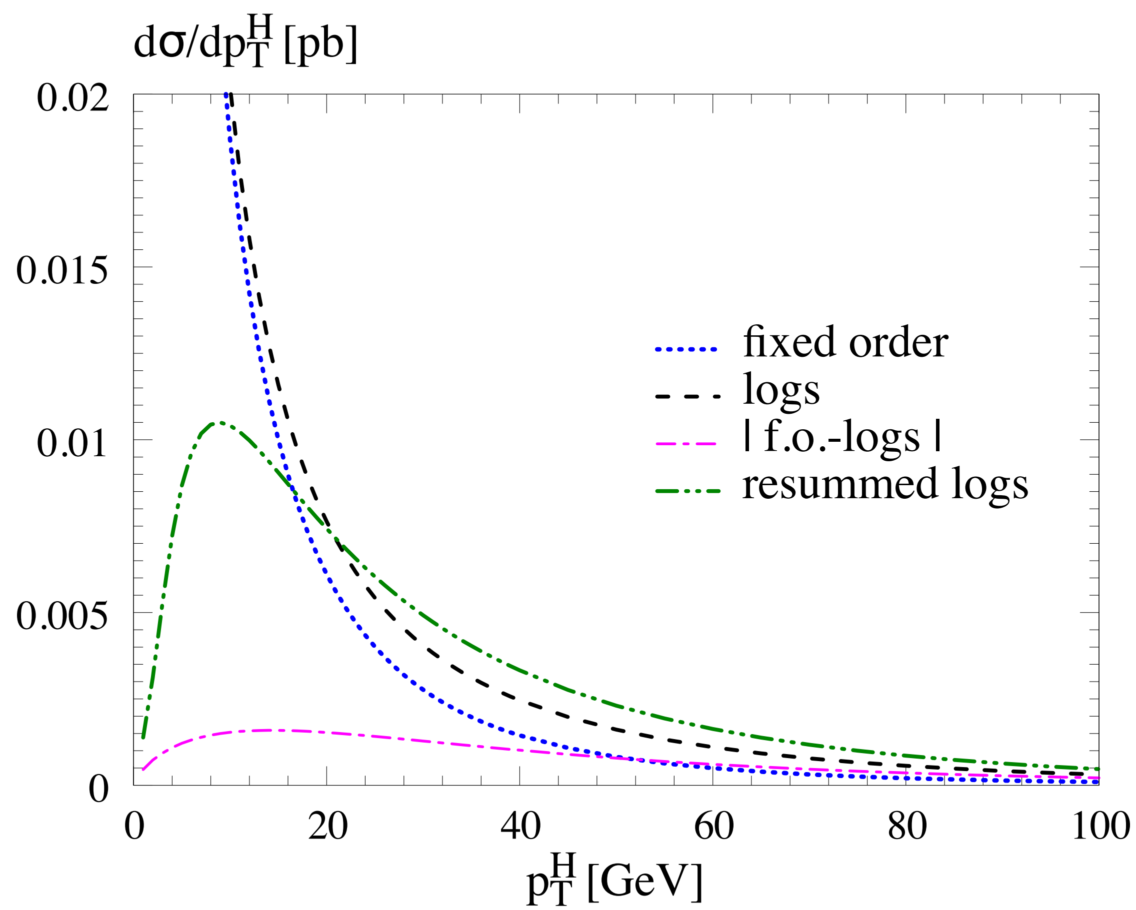
matching: FO+resummation

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



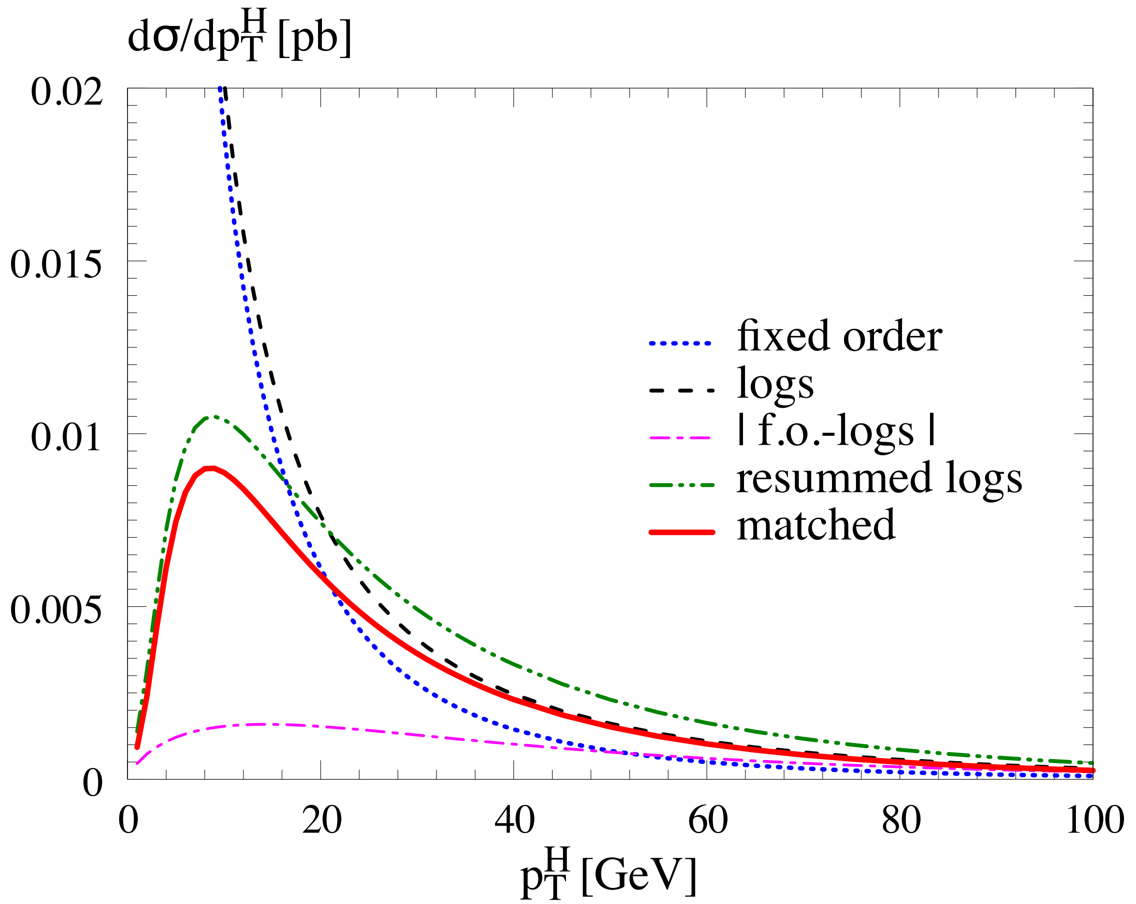
matching: FO+resummation

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



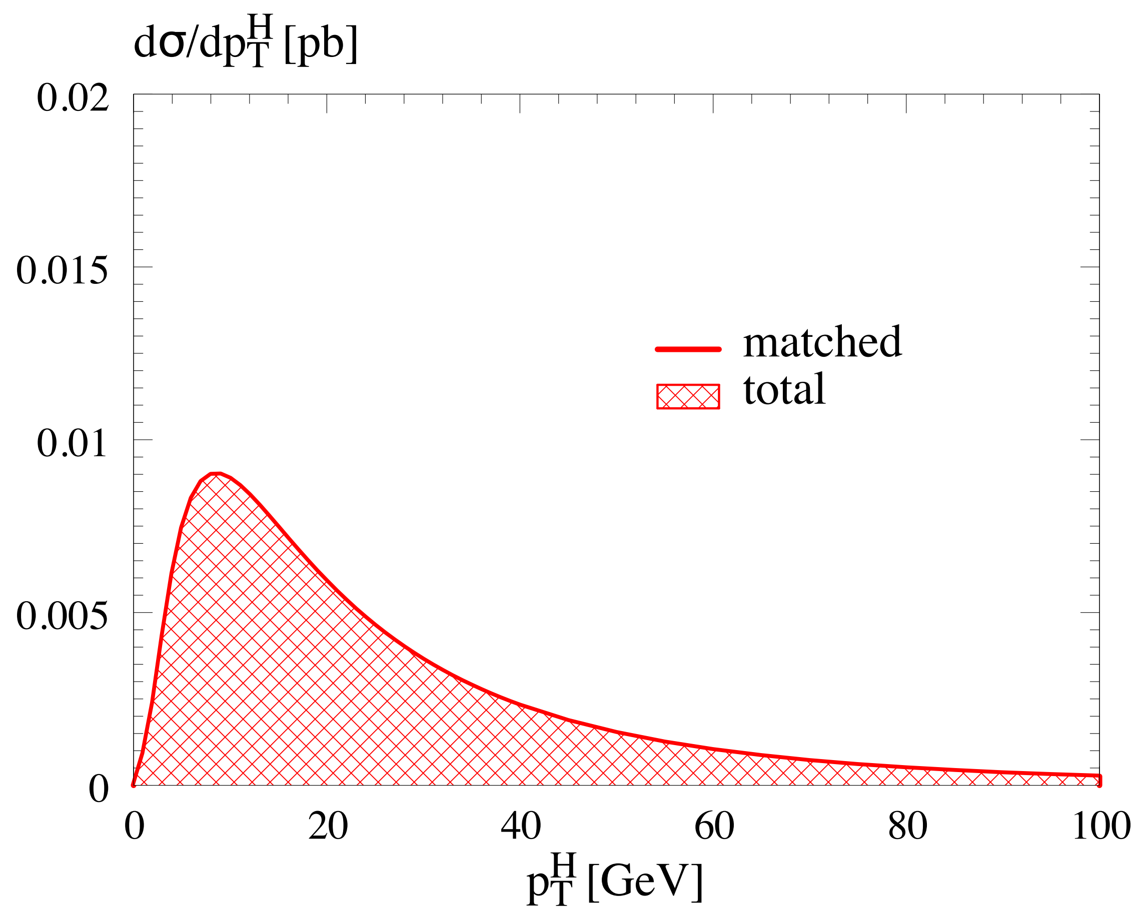
matching: FO+resummation

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



matching: FO+resummation

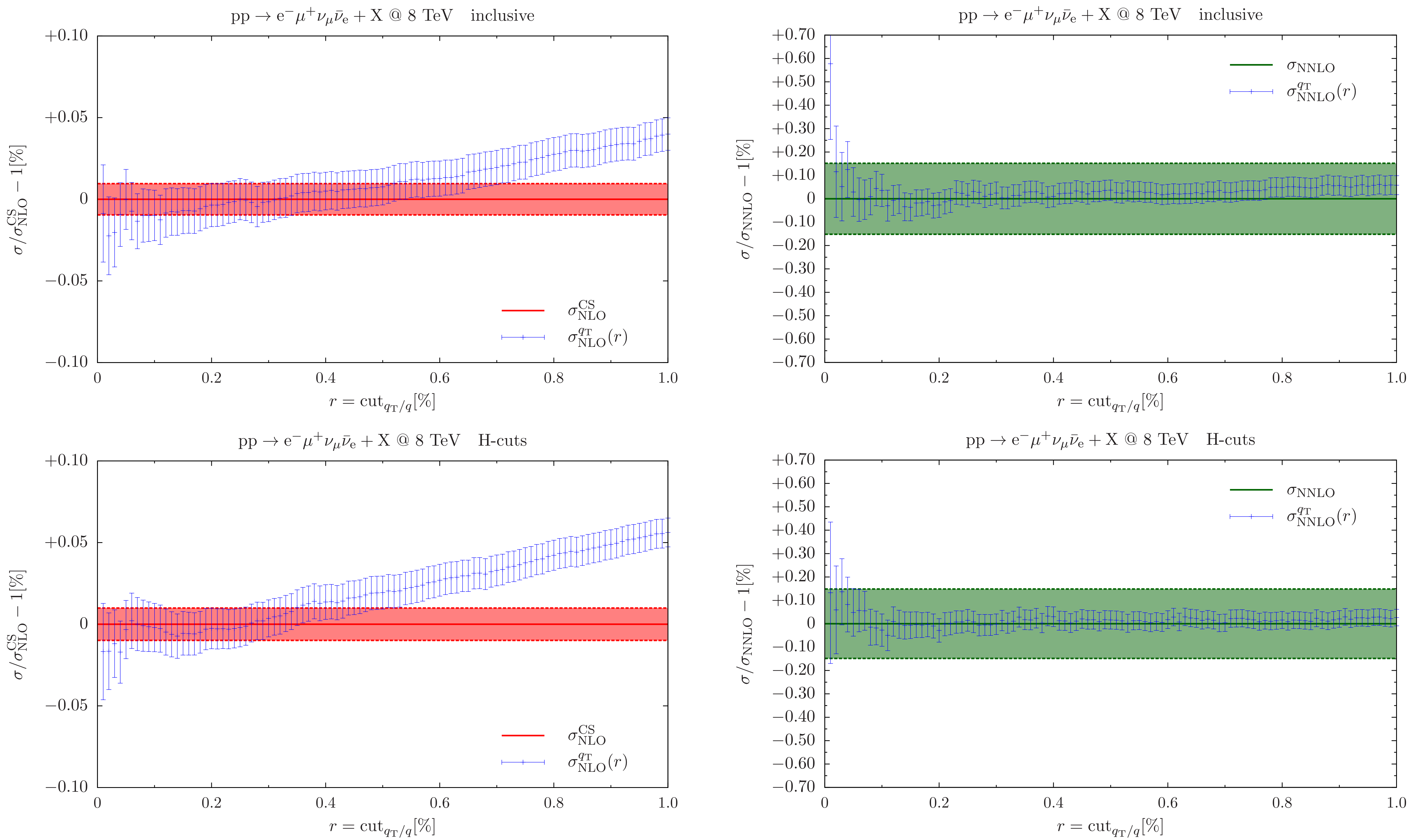
$$\int \mathrm{d}p_T^2 \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\mathrm{f.o.+l.a.}} \equiv \left[\sigma^{(\mathrm{tot})}\right]_{\mathrm{f.o.}} .$$



WW fully differential at NNLO

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

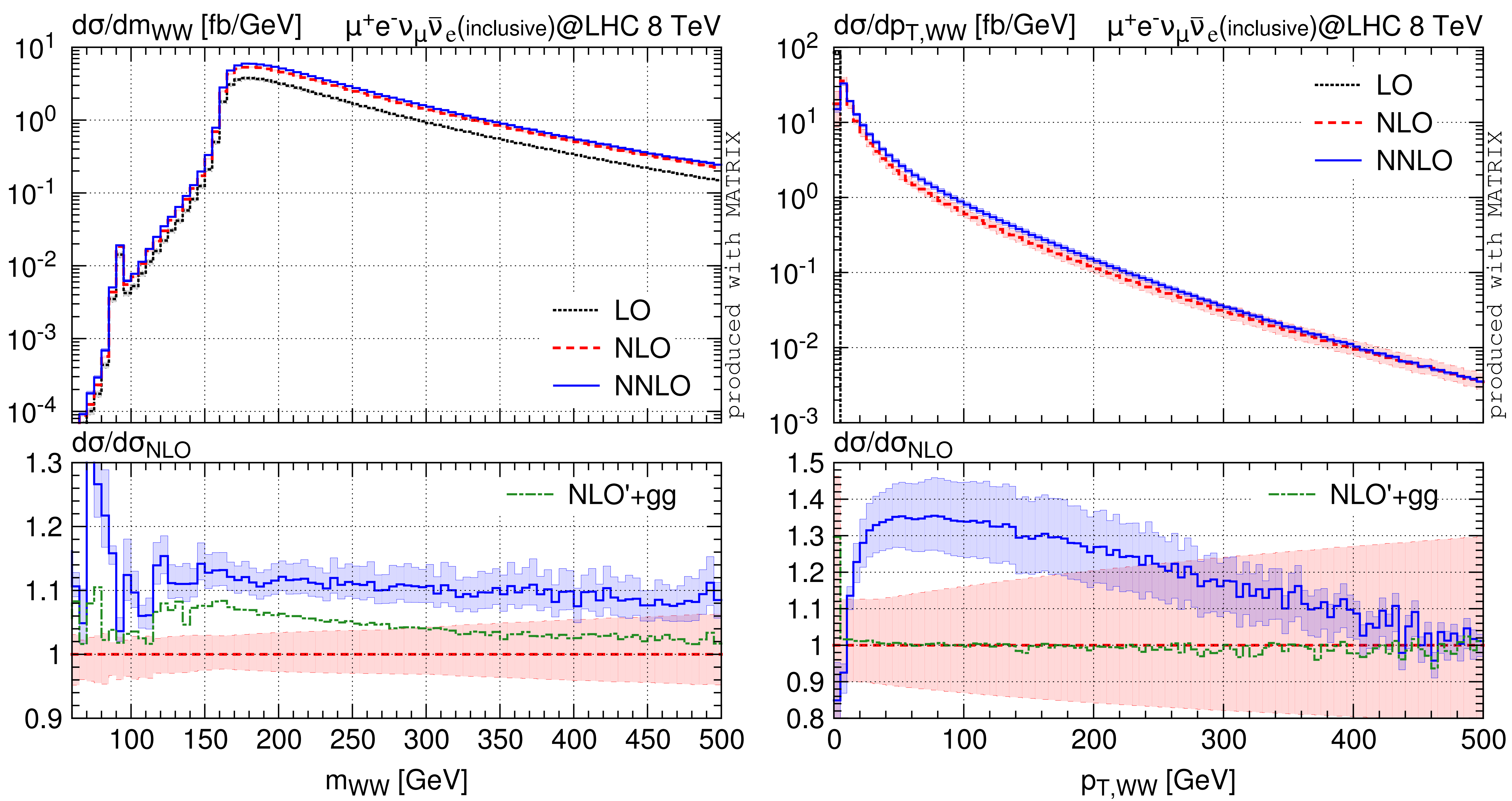
stability of r_{cut}= p_T/m_{WW} dependence



WW fully differential at NNLO

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

inclusive: distributions (8 TeV)



WW fully differential at NNLO

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

WW signal cuts: distributions (8 TeV)