NLO QCD corrections to the loop-induced ZZ production via gluon-fusion at the LHC

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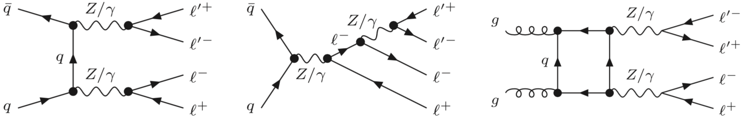
Outline

Vector boson production at the LHC

- Why study vector boson production?
  - The discovery of the Higgs was a milestone in particle physics, but no evidence of New Physics is found and Higgs couplings are found consistent with the Standard Model (SM)
  - Vector boson production is important because it is:
    - $\rightarrow$ Irreducible background to Higgs studies
    - $\rightarrow$ Background to BSM searches
    - $\rightarrow$ Sensitive to anomalous triple gauge couplings (aTGCs)
- Higher order calculations are demanded by improved experimental precision

ZZ production at the LHC

- Born processes:



- The complete four lepton production is considered in the process ZZ$\rightarrow$ 4l, including off-shell and interference effects
- Leading contribution: q$\bar{\text{q}}$ production
- Gluon-fusion production is formally of $\mathcal{O}(\alpha_s^2)$ (NNLO), but it has a large contribution due to the large gluon luminosity

ZZ production at the LHC

- First NLO QCD calculation: J. Ohnemus and J. F. Owens (1991); B. Mele, P. Nason and G. Ridolfi (1991)
- Inclusion of leptonic decays: T. Matsuura and J. J. van der Bij (1991); C. Zecher, T. Matsuura and J. J. van der Bij (1994)
- Inclusion of spin correlations in the decays: J. M. Campbell and R. K. Ellis (1999); L. J. Dixon, Z. Kunszt and A. Signer (1999)
- Gluon-fusion production: D. A. Dicus, C. Kao and W. Repko (1987); E. W. N. Glover and J. J. van der Bij (1989)
- Two-loop amplitudes are also available: F. Caola, J. M. Henn, K. Melnikov, A. V. Smirnov and V. A. Smirnov (2014); T. Gehrmann, A. von Manteuffel and L. Tancredi (2015)
- Inclusive NNLO calculation: F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P.Maierhoefer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi and E.Weihs (2014)
- Differential NNLO calculation: M. Grazzini , S. Kallweit and D. Rathlev (2015); G. Heinrich, S. Jahn, S. P. Jones, M. Kerner, J. Piresa (2018)

Infrared (IR) divergences

- Ultraviolet (UV) divergences are handled by renormalization
- IR divergences arising from soft and collinear particles cancel in IR safe quantities
- Born processes: finite
- NLO: singularities in real and virtual contributions
- NNLO: singularities in double real, real-virtual and double virtual contributions

  $\rightarrow$ A method is required to handle and cancel them

Infrared (IR) divergences

- NLO methods:
  - Dipole subtraction S. Catani and M. Seymour (1996)
  - FKS subtraction S. Frixione, Z. Kunszt and A. Signer (1996)
- NNLO methods:
  - Sector decomposition T. Binoth and G.Heinrich (2000,2004); C. Anastasiou, K. Melnikov and F. Petriello (2004)
  - Antenna subtraction T. Gehrmann, A. Gehrmann-De Ridder and N. Glover (2005)
  - Colourful subtraction G. Somogyi, Z. Trocsanyi and V. Del Luca (2005)
  - q_T subtraction S. Catani and M. Grazzini (2007)
  - N-jettiness method Boughezal, Focke, Liu, Petriello (2015); Gaunt, Stahlhofen, Tackmann and Walsh (2015)
  - Projection-to-Born method M. Cacciari, F. A. Dreyer, A. Karlberg, G. P. Salam, G. Zanderighi (2015)

q_T subtraction S. Catani and M. Grazzini (2007)

- Non-local subtraction
- Consider the following process with hadrons h_1, h_2 and a colourless final state F: $h_1 + h_2 \to F(Q) + X$
  - $\rightarrow$ At LO, $q_T = 0$
  - $\rightarrow$ $d\sigma^{F}_{(N)NLO}|_{q_T \neq 0} = d\sigma^{F\,+\,jets}_{(N)LO}$
- The divergent behaviour of $d\sigma^{F\,+\,jets}_{(N)LO}$ as $q_T \to 0$ is known from transverse momentum resummation G. Bozzi, S. Catani, D. de Florian and M. Grazzini(2005)

q_T subtraction S. Catani and M. Grazzini (2007)

- The subtraction counterterm is defined as:

  $$d\sigma^{CT} = d\sigma^{F}_{LO} \otimes \Sigma^{F}(q_T/Q)\, d^2 q_T$$

  $$\Sigma^{F}(q_T/Q) \to \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F\,(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1}\left(\frac{Q^2}{q_T^2}\right) \text{ as } q_T \to 0$$

  Σ^F is known to NNLO - G. Bozzi, S. Catani, D. de Florian and M. Grazzini (2006)

- Then the $q_T = 0$ contribution can be included to yield:

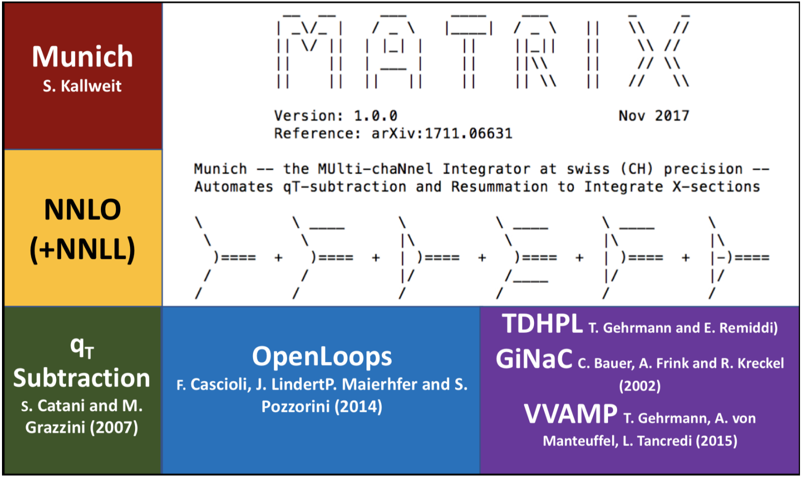
$$d\sigma^{F}_{(N)NLO} = \mathcal{H}_{(N)NLO} \otimes d\sigma^{F}_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO}\right]$$

$$\mathcal{H}^{F} = \left(\frac{\alpha}{\pi}\right)\mathcal{H}^{F(1)} + \left(\frac{\alpha}{\pi}\right)^2 \mathcal{H}^{F(2)} + \cdots$$

- $\mathcal{H}^{F(1)}$ is known generally - G. Bozzi, S. Catani, D. de Florian and M. Grazzini (2005)
- $\mathcal{H}^{F(2)}$ is known for Higgs and vector boson productions - S. Catani and M. Grazzini (2007); S. Catani, L. Cieri, G.Ferrera, D. de Florian, M. Grazzini (2009)
- The general structure of $\mathcal{H}^{F(2)}$ is known for a colour singlet final state in terms of the virtual amplitudes - S. Catani, L. Cieri, D. de Florian, G. Ferrera and M. Grazzini (2013); T. Gehrmann, T. Lubbert and L. Yang (2014)

The MATRIX framework M. Grazzini, S. Kallweit and M. Wiesemann (2017)

- Munich Automates qT subtraction and Resummation to Integrate X–sections (MATRIX) $\to$ Exclusive NNLO calculation



The MATRIX framework M. Grazzini, S. Kallweit and M. Wiesemann (2017)

- $\mathrm{d}\sigma^{\mathrm{F+jets}}_{\mathrm{(N)LO}} - \mathrm{d}\sigma^{\mathrm{CT}}_{\mathrm{(N)LO}}$ is finite as $q_T \to 0$
- Subtraction is non local and the two terms are separately divergent
- A technical cut r_{cut}, $r = q_T/M$ is implemented
- Cross sections evaluated at several different r_{cut} values
- $r_{cut} \to 0$ is extrapolated using a simple quadratic fit

pp $\rightarrow$ ZZ $\rightarrow$ 4l at NNLO

- pp $\rightarrow$ ZZ $\rightarrow$ 4l available in MATRIX at NNLO - S. Kallweit, D. Rathlev, M. Grazzini (2015)
- With ATLAS fiducial cuts at 8 TeV
- NNLO contributions increase the NLO results by $\sim$15%
- Gluon-fusion takes up about 60% of NNLO corrections
- NLO corrections to the gg channel are expected to be quantitatively relevant!

pp → ZZ → $e^+e^-\mu^+\mu^-$ at nNNLO

- Current experimental analyses: NLO_{gg} and $\mathrm{NNLO}_{q\bar{q}}$ are treated as independent contributions
  → Not independent at NNLO
- NLO amplitudes including two-loop amplitudes are available for gg → ZZ (formally N3LO) - F. Caola, J. M. Henn, K. Melnikov, A. V. Smirnov and V. A. Smirnov (2015); A. von Manteuffel and L. Tancredi (2015); F. Caola, K. Melnikov, R. Roentsc and L. Tancredi (2015)
  → NLO calculation for the gg contribution is possible
- NLO calculation performed by F. Caola, K. Melnikov, R. Roentsch, and L. Tancredi (2015): only gg channel included
- MATRIX: combine the NNLO contribution with NLO corrections to the gg channel in a single generator M. Grazzini, S. Kallweit, M. Wiesemann and J. Y. Yook (in progress)
  → Approximate N3LO calculation (nNNLO)

$gg \to ZZ \to e^+e^-\mu^+\mu^-$ at NLO Preliminary

Validation of the MATRIX calculation

- Compare the MATRIX NLO_{gg} results at $\sqrt{s}$ =8 TeV with the results from S. Alioli, F. Caola, and G. Luisoni (2017)
- NNPDF 3.0 NLO PDF for both LO and NLO
- NLO method: dipole subtraction
- Set-up:

  Exclude triangle diagrams, exclude top quark, $m_Z = 91.1876$ GeV, $m_W = 80.3980$ GeV, $\Gamma_Z = 2.4952$ GeV, $\sin\theta_W = 0.2226$, $\alpha^{-1} = 132.3384$
- Kinematic cuts:

  5 GeV $< m_{ll} <$ 180 GeV, 60 GeV $< m_{4l} <$ 360 GeV

Preliminary

	$\mu = m_{4l}/2$		$\mu = m_Z$	
[fb]	LO	NLO	LO	NLO
Alioli et al.	$1.60^{+0.41}_{-0.30}$	$2.98^{+0.51}_{-0.41}$	$1.62^{+0.42}_{-0.31}$	$2.98^{+0.29}_{-0.40}$
MATRIX	$1.6023(4)^{+0.41}_{-0.30}$	$2.987(3)^{+0.51}_{-0.42}$	$1.6188(3)^{+0.42}_{-0.31}$	$2.985(3)^{+0.49}_{-0.40}$

$pp \to ZZ \to e^+e^-\mu^+\mu^-$ at nNNLO Preliminary

- Triangle diagrams and top quark are included
- NNPDF 3.0 at LO, NLO and NNLO
- NLO method: dipole subtraction
- $\mu_R = \mu_F = m_{ZZ}/2$
- ATLAS 13 TeV fiducial cuts:

$$p_{T,\ell} > 7\,\text{GeV}, \quad \text{one electron with } |\eta_e| < 4.9, \quad \text{the others } |\eta_e| < 2.5, \quad |\eta_\mu| < 2.7$$

$$\Delta R_{\ell\ell} > 0.2, \quad \Delta R_{\ell\ell'} > 0.2, \quad 66\,\text{GeV} \le m_{Z^{\text{rec}}_{a/b}} \le 116\,\text{GeV},$$

$$\text{anti-}k_T \text{ jets with } R = 0.4,\ p_{T,j} > 25\,\text{GeV},\ |\eta_j| < 4.5$$

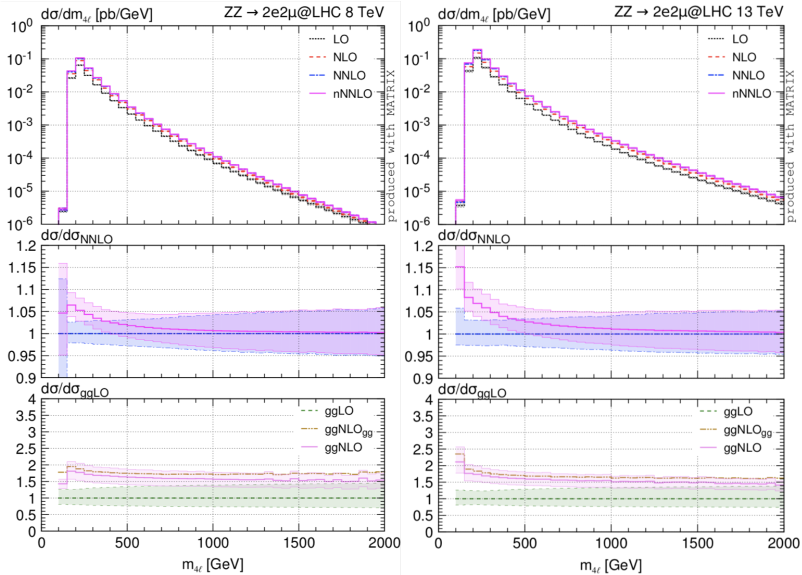
pp $\to$ ZZ $\to e^+e^-\mu^+\mu^-$ at nNNLO Preliminary

Preliminary

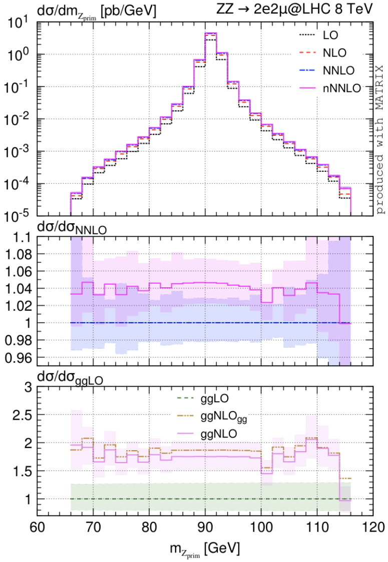
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
	σ [fb]		$\sigma/\sigma_{\rm NLO}$	
LO	$8.188(1)^{+2.4\%}_{-3.2\%}$	$13.93(1)^{+5.5\%}_{-6.4\%}$	0.725	0.703
NLO	$11.30(0)^{+2.5\%}_{-2.0\%}$	$19.80(2)^{+2.5\%}_{-2.1\%}$	1	1
qqNNLO	$12.13(2)^{+1.2\%}_{-1.2\%}$	$21.60(3)^{+1.2\%}_{-1.2\%}$	1.073	1.091
	σ [fb]		$\sigma/\sigma_{\rm ggLO}$	
ggLO	$0.7932(3)^{+28.2\%}_{-20.9\%}$	$2.004(2)^{+23.5\%}_{-17.9\%}$	1	1
ggNLO$_{gg}$	$1.481(2)^{+15.9\%}_{-13.2\%}$	$3.630(8)^{+15.2\%}_{-12.7\%}$	1.867	1.811
ggNLO	$1.387(2)^{+15.4\%}_{-13.6\%}$	$3.426(4)^{+13.9\%}_{-12.0\%}$	1.749	1.710
	σ [fb]		$\sigma/\sigma_{\rm NLO}$	
NNLO	$12.92(2)^{+2.9\%}_{-2.2\%}$	$23.59(2)^{+3.1\%}_{-2.6\%}$	1.143	1.191
nNNLO	$13.51(2)^{+2.7\%}_{-2.3\%}$	$25.02(3)^{+2.9\%}_{-2.7\%}$	1.196	1.264

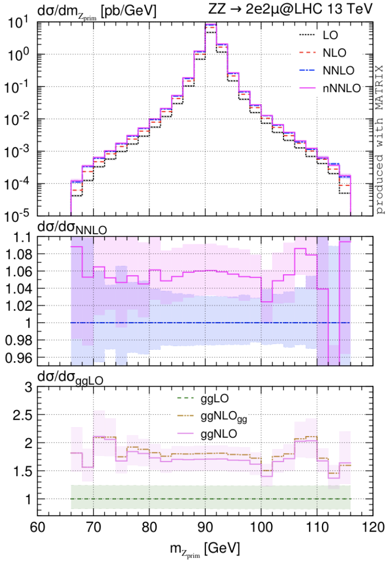
- ggNLO makes up 10% of the total rate at 8 TeV and 14% at 13 TeV
- ggNLO$_{\rm gg}$ increases ggLO contribution by 87% at 8 TeV and 81% at 13 TeV
- Including the qg channel lowers the ggNLO cross section by 6% at both 8 and 13 TeV
- ggNLO increases the NNLO prediction by 4.6% at 8 TeV and 6.1% at 13 TeV

$pp \to ZZ \to e^+e^-\mu^+\mu^-$ at nNNLO Preliminary



$pp \to ZZ \to e^+e^-\mu^+\mu^-$ nNNLO Preliminary





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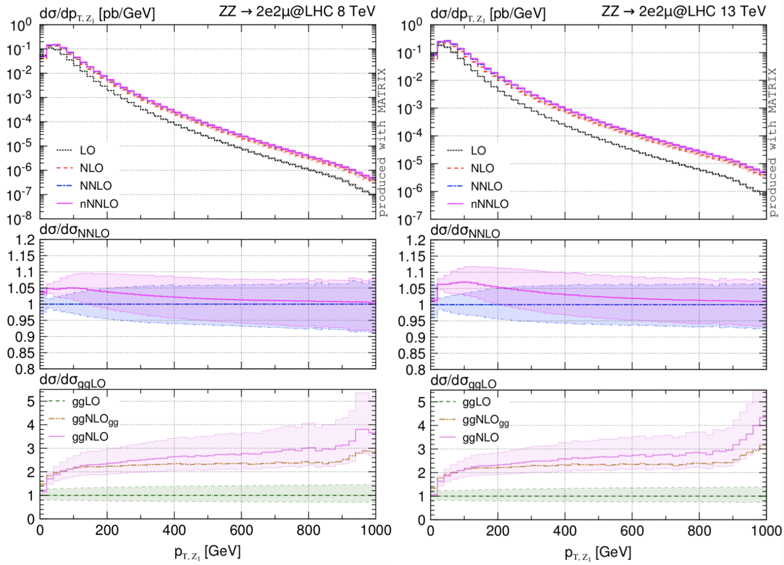
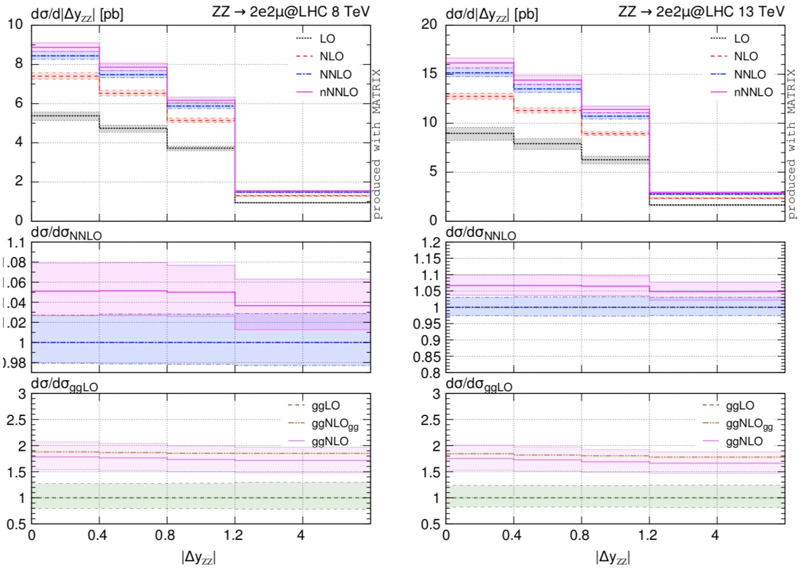
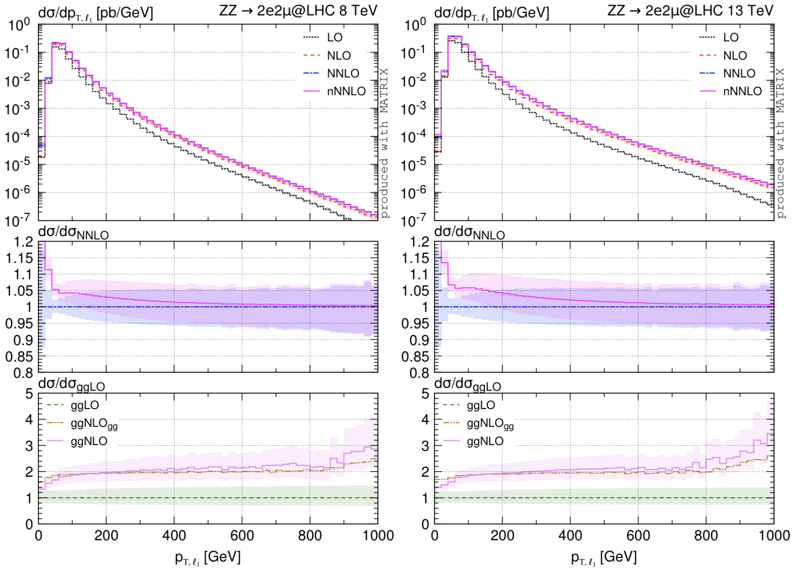


pp $\to$ ZZ $\to e^+e^-\mu^+\mu^-$ at nNNLO Preliminary



pp $\rightarrow$ ZZ $\rightarrow e^+e^-\mu^+\mu^-$ nNNLO Preliminary



Summary and outlook

- The NLOgg contribution to the process pp $\rightarrow$ ZZ $\rightarrow e^+e^-\mu^+\mu^-$ has been implemented within the MATRIX framework
- qg channel contributions were added for the first time
- The nNNLO prediction for the above process was achieved
- Including the NLOgg contribution increases the previous NNLO prediction by 4.6% at 8 TeV and 6.1% at 13 TeV
- Validation of the NLOgg calculation is still to be completed
- The calculation can be extended to other diboson processes

Back-up slides

$gg \to ZZ \to e^+e^-\mu^+\mu^-$ at NLO

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MATRIX	$3.8486(8)^{+0.97}_{-0.70}$	$7.016(7)^{+1.15}_{-0.95}$	$3.9454(8)^{+0.98}_{-0.71}$	$7.068(7)^{+1.11}_{-0.93}$

pp $\to$ ZZ $\to$ 4l at NNLO: comparison with data at 8 TeV

- ATLAS fiducial cuts at 8 TeV:

  66 GeV $\leq m_{ll} \leq$ 116 GeV, $p_{T,l} \geq$ 7 GeV, $|\eta_l| \leq 2.7$, $\Delta R(l,l') > 0.2$

Channel	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NNLO} (fb)	σ_{exp} (fb)
$e^+e^-e^+e^-$	$3.547(1)^{+2.9\%}_{-3.9\%}$	$5.047(1)^{+2.8\%}_{-2.3\%}$	$5.79(2)^{+3.4\%}_{-2.6\%}$	$4.6^{+0.8}_{-0.7}(\mathrm{stat})^{+0.4}_{-0.4}(\mathrm{syst.})^{+0.1}_{-0.1}(\mathrm{lumi.})$
$\mu^+\mu^-\mu^+\mu^-$				$5.0^{+0.6}_{-0.5}(\mathrm{stat})^{+0.2}_{-0.2}(\mathrm{syst.})^{+0.2}_{-0.2}(\mathrm{lumi.})$
$e^+e^-\mu^+\mu^-$	$6.950(1)^{+2.9\%}_{-3.9\%}$	$9.864(2)^{+2.8\%}_{-2.3\%}$	$11.31(2)^{+3.2\%}_{-2.5\%}$	$11.1^{+1.0}_{-0.9}(\mathrm{stat})^{+0.5}_{-0.5}(\mathrm{syst.})^{+0.3}_{-0.3}(\mathrm{lumi.})$

$pp \to ZZ \to e^+e^-\mu^+\mu^-$ nNNLO Preliminary