NLO+PS $gg \to ZZ \to e^+e^-\mu^+\mu^-$ production with POWHEG

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15th MCnet Meeting

CERN
6 April 2017

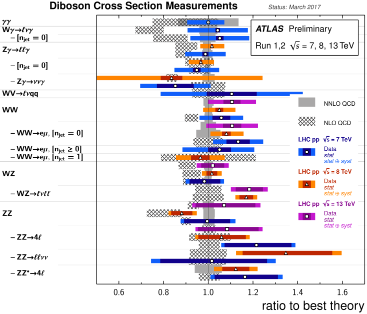
SA, G. Luisoni, F. Caola, R. Röntsch
Phys.Rev. D95 (2017) arXiv:1609.09719

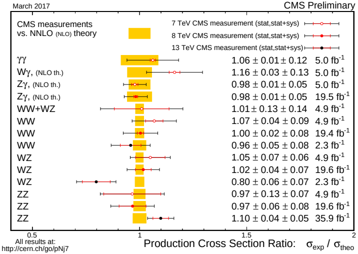
Vector boson pair production at the LHC

Important process at the LHC:

- Background to $H \to VV$
- Interference effects with Higgs production at high-mass
- Probe of trilinear gauge couplings and discovery potential for BSM physics via aTGC.
- All diboson xsecs known to NNLO.

  Catani et al '11, Grazzini et al. '14 '15 '16 '17, Cascioli et al. '15, Gehrmann et al. '15, Campbell et al '16
- Experimental errors at 10-15% become sensitive to NNLO corrections. Test of pQCD in collider environment.





Vector boson pair production via gluon fusion

- All VV process start with quarks-only initial states at LO $q\bar{q}^{(\prime)} \to VV$
- Gluon-induced contributions $gg \to VV$ start to appear at N^2LO for $ZZ, WW, Z\gamma, \gamma\gamma$ production
- Enhancement due to large gluon flux can make them not negligible:

ZZ: 9% total, 60 % NNLO corrections Cascioli et al. '14

WW: 5% total, 35 % NNLO corrections Gehrmann et al. '14

$Z\gamma, \gamma\gamma$: less important Grazzini et al. '15 ($\gamma\gamma$ known at NLO) Bern et al. '02

- Gluon induced terms have LO scale variations. Can produce the bulk of the total NNLO scale variations.

This motivates the calculation of the QCD NLO corrections to $gg \to VV$

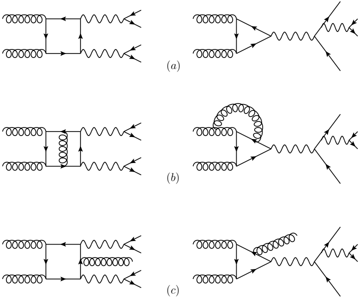
- Formally they are N^3LO corrections to VV production.
- Inclusion brings results outside NNLO scale variation band.
- Only a subset of full N^3LO corrections, other channels might have considerable impact.

NLO correction to $gg \to ZZ$

- Recently NLO calculations for ZZ and WW were presented

  Caola,Röntsh,Tancredi,Dowling,Melnikov [hep-ph/1509.06734, hep-ph/1511.0861, hep-ph/1605.04610]

- In-house analytic Born and real matrix elements, particular care in soft/collinear limits needed.
- Quad precision re-evaluation. Usage of new QCDloop. Hard cutoff at $p_T^{ZZ} = 0.5$ GeV, check effect on total xsec.
- Single PS points also validated against OpenLoops and GoSam.
- 2-loop amplitudes with massless internal lines in https://vvamp.hepforge.org/
- vvamp uses quad precision. Cross-checks done with arbitrary precision.



NLO correction to $gg \to ZZ$

Approximations used :

Massless quarks

- Do not consistently include third generation (only massless $b-$quarks). 2-loop with internal masses not available.
- Neglect triangle diagrams to all orders to avoid spoiled anomaly cancellation (due to missing t-quarks)
- Mass effects become very relevant above top-threshold or when high-p_T radiation resolves inner loops details ($p_T > m_t$)
- Avoiding these regions, at LO the effect is roughly 1 % of total xsec.

Large gluon PDF

- Initial state quarks neglect throughout.
- Small effect on inclusive quantities.
- Quark effects become relevant at high-p_T

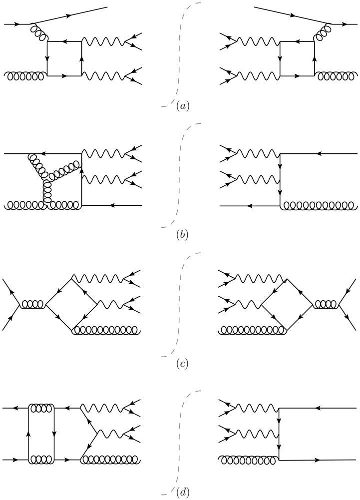
NLO correction to $gg \to ZZ$

- Quark-initiated loop-squared contributions (a) and (c) are known and separately gauge invariant.

Not including loop-squared

- Different use-case compared to merged LO samples Cascioli et al. 1309.0500
- Don't see any reason why there could not be large cancellations
- Incomplete compensation of fact. scale logs, parametrically suppressed by g/q PDF ratio. Can be used to give an indication of the rough size of the missing channels.
- Severely limits applicability of calculation to low p_T region (same region where massless quark approx was valid)

- Contributions (b) and (d) are well beyond current technology.



Implementation in the POWHEG-BOX

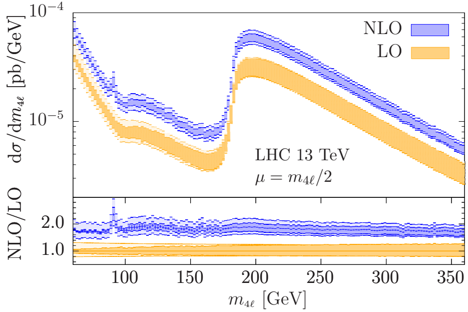
- Consider process as signal, neglecting all Higgs interference effects
- Focus on $gg \to (Z \to e^+e^-)(Z \to \mu^+\mu^-)$ to avoid identical fermion interference.
- Extends previous results to single-resonant region.
- Approximations used strongly constrain phase-space of sensible predictions.

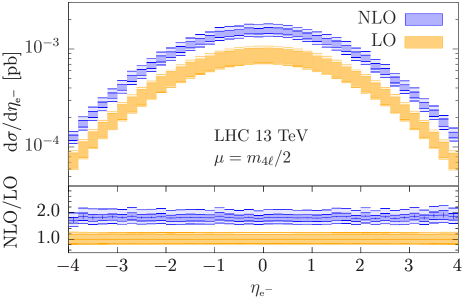
$$5\ \text{GeV} < m_{\ell\ell} < 180\ \text{GeV},$$
$$60\ \text{GeV} < m_{4\ell} < 360\ \text{GeV}.$$

[fb]	$\mu = m_{4\ell}/2$		$\mu = m_Z$	
CME	LO	NLO	LO	NLO
8 TeV	$1.60^{+0.41}_{-0.30}$	$2.98^{+0.51}_{-0.41}$	$1.62^{+0.42}_{-0.31}$	$2.98^{+0.29}_{-0.40}$
13 TeV	$3.85^{+0.97}_{-0.70}$	$6.98^{+1.14}_{-0.94}$	$3.94^{+0.98}_{-0.71}$	$7.22^{+1.04}_{-1.04}$

- Validated perfect agreement with previous results when excluding single resonant and use correlated scale variations.
- Default scale choice for remaining results is $m_{4\ell}/2$

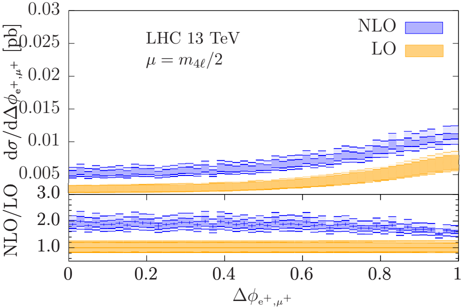
Fixed-order results

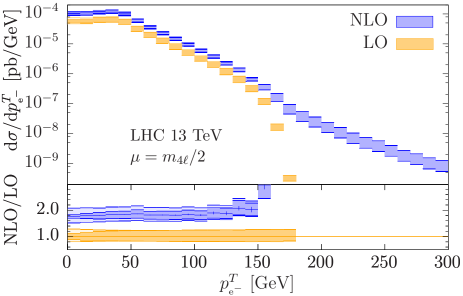




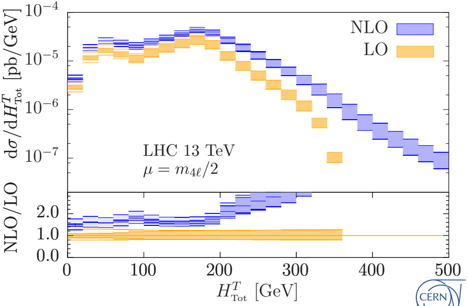
- Mostly flat, but large 100% K-factors.
- Inner darker band correlated scale variations, outer light band 7-points variations
- Single resonant region only appears at NLO

Fixed-order results

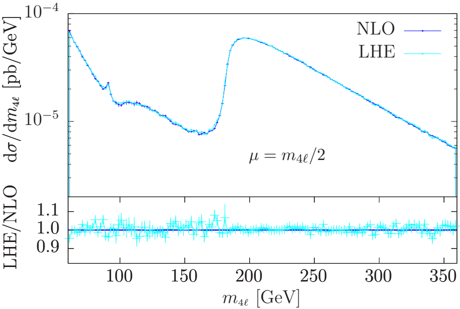


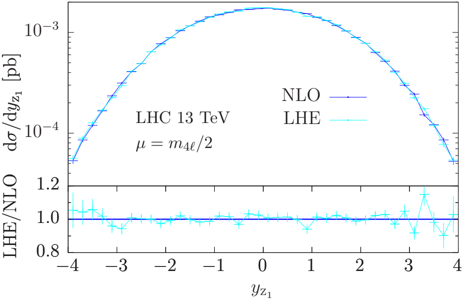


- Mostly flat, but large 100% K-factors
- Inner darker band correlated scale variations, outer light band 7-points variations
- Real radiation allows to evade kinematics bounds, huge corrections.

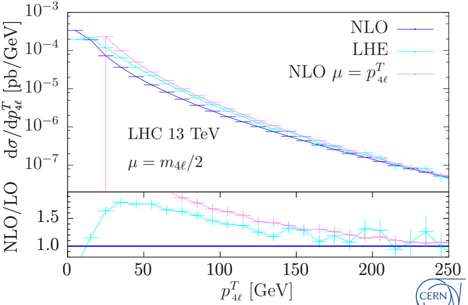


Validation of LHE-level events

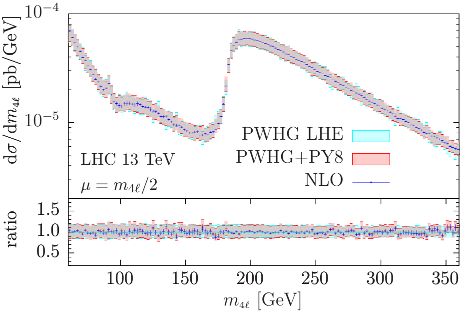


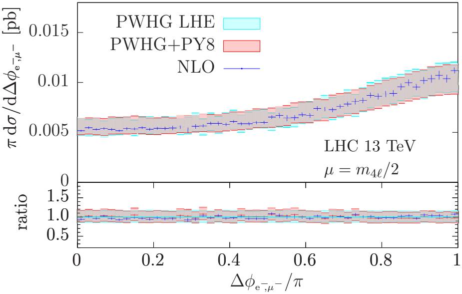


- Unphysical predictions, just checks correctness of implementation
- `hdamp` set to 100 GeV to avoid large enhancement of tail due to large K-factor
- At high-p_T one recovers real-matrix element once the same scale choice is used.



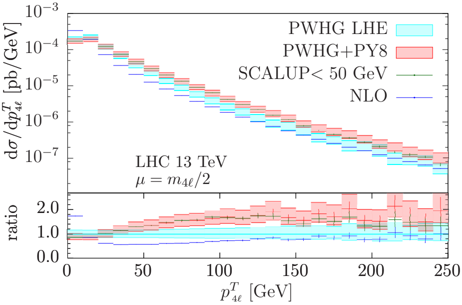
Showered results

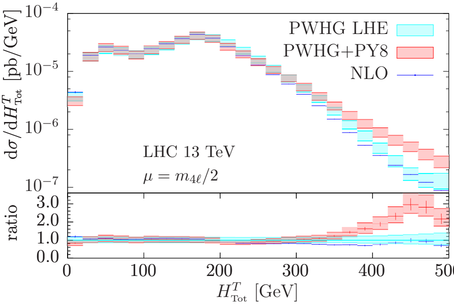




- Shower allowed to generate quarks in ISR. Unitary preserves cross-section.
- Excellent agreement for observables inclusive over extra radiation, as expected

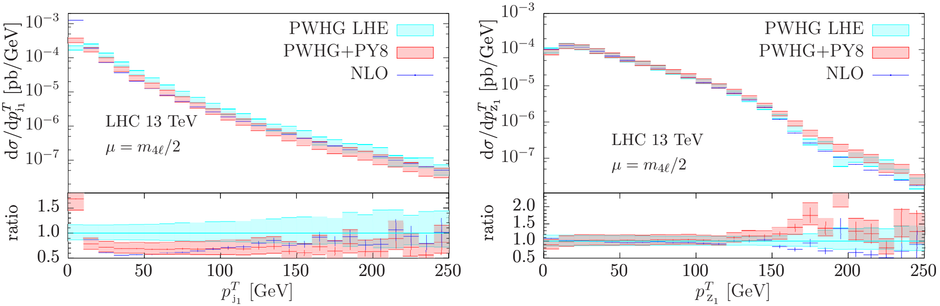
Showered results





- Much more marked differences for exclusive quantities.
- Shower effect on $p_T^Z Z$ can be ascribed to recoil from all emitted particles. Slight unbalance can give large effects.
- Still roughly compatible inside large LO bands.
- Same feature present in H_T, even more marked because of scalar sum.
- Limiting the starting scale of the shower the effect is reduced.

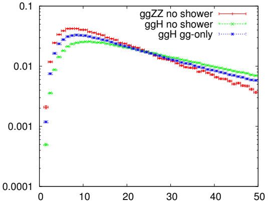
Showered results

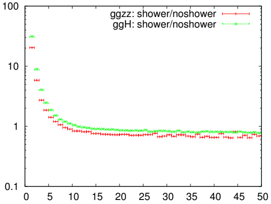


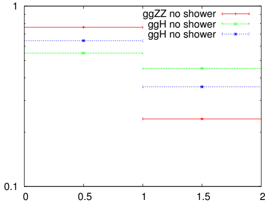
- Hardest jet p_T less affected. Shower emission unbalance less likely to affect significantly the hardest radiation.
- Z-boson momentum not much affect by the shower, until crosses kinematic threshold.

Effects of missing quark-initiated contributions

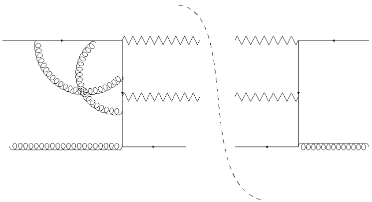
- Lack of quark-initiated contributions leads to noticeable different Sudakov and radiation activities
- Similar effect present in $gg \to H$ when quarks switched off







- Clearly quarks should be included in Sudakov to get a physical description.
- Difference within LL uncertainty.
- Missing NLL contributions not known, NLL could not be claimed even after including loop-squared.
- Many other example where adding 'some NLL' resulted in better predictions.



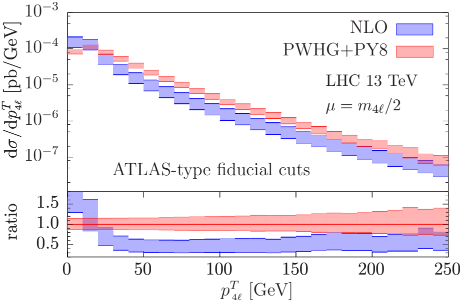
ATLAS fiducial cuts

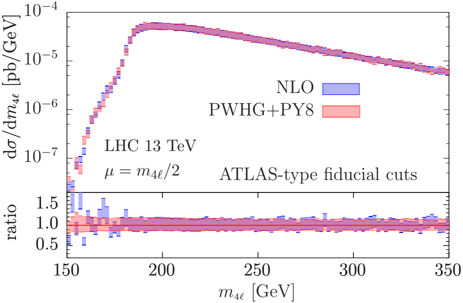
- fiducial cuts:

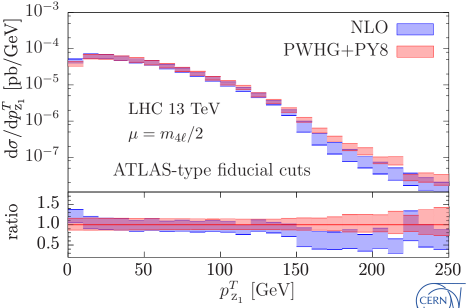
$$
\begin{aligned}
80\ \text{GeV} < m_{4\ell} < 350\ \text{GeV},\\
66\ \text{GeV} < m_{\ell\ell} < 160\ \text{GeV},\\
\Delta R_{\ell\ell} > 0.2,\\
p_\ell^T > 7\ \text{GeV},\\
|\eta_\ell| > 2.7.
\end{aligned}
$$

- cross section:

$$\sigma^{\text{fid.}} = 4.57^{+0.71}_{-0.59}\ \text{fb}.$$







Summary and Outlook

- Implemented $gg \to ZZ \to e^+e^-\mu^+\mu^-$ at NLO+PS in POWHEG-BOX V2.
- Shower effects found to be small for inclusive quantities.
- More marked differences for exclusive quantities, like p_T^{ZZ} and H_T
- Gluon-only approximation reasonably good to describe inclusive quantities
- However, it leads to noticeable differences in Sudakov peak and radiation activity.
- Not clear (to me) if including quark-initiated loop-squared contribution is the solution. Is LL the best we can get anyway ?

Outlook:

- Extend the framework to $gg \to 4\ell$, including identical lepton interferences.
- Add Higgs mediated channels and interference effects
- Investigate inclusion of loop-squared quark-initiated contributions.

Thank you for your attention!