# gg → VV at NLO

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# Diboson production

**Why study pp → VV ?**

- Background to Higgs in H → VV decay channel
- Interference effects with Higgs in high mass tail

  (see talk by N. Kauer)

- Probe of trilinear EW gauge couplings
- Discovery potential for new physics

  (750 GeV diphoton excess)

- Test of pQCD in collider environment
- …

# Gluon fusion contribution

- pp → VV known to NNLO

  (Catani, Cieri, de Florian, Ferrera, Grazzini '11; Grazzini, Kallweit, Rathlev, Torre '14; Cascioli *et al* '14; Gehrmann *et al* '14; Grazzini, Kallweit, Rathlev '15 )

- Includes loop-induced (LO) **gluon fusion contribution gg** (for $\gamma\gamma$ , $Z\gamma$, ZZ, WW)

- Enhanced by large gluon flux – expected to be significant
  - **Important** for $\gamma\gamma$, NLO corrections to gg known (Bern, Dixon, Schmidt, '02)
  - **Negligible** for $Z\gamma$ (Grazzini, Kallweit, Rathlev, '15)

# Gluon fusion contribution

Focus on ZZ and WW production:

- ZZ: (Cascioli *et. al*., hep-ph/1405.2219)
  - 60% of NNLO corrections
  - 8 TeV: 0.55 fb / 8.284 fb at NNLO
- WW: (Gehrmann *et. al.*, hep-ph/1408.5243)
  - 35% of NNLO corrections
  - 8 TeV: 1.7 fb / 59.84fb at NNLO
- **Strongly cut-dependent**

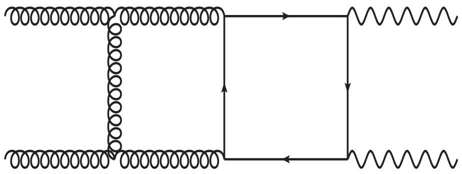
(Binoth, Ciccolini, Kauer, Krämer, '05)

# Corrections to gluon fusion

- NLO corrections to $gg \to VV$ contribute to VV production at NNNLO.
- Reasons to compute them:
  - Analogy with Higgs production (gluon fusion to light, colorless particle) → expect large radiative corrections to $gg \to VV$ (seen in $\gamma\gamma$)
  - $gg \to VV$ provides large contribution to residual scale uncertainty at NNLO
  - Leading corrections to interference effects in far off-shell regime

# Massless and massive corrections

Require two-loop amplitudes for gg → VV



- Available for massless internal lines

  (Caola, Henn, Melnikov, Smirnov, Smirnov, hep-ph/1503.08759; von Manteuffel, Tancredi, hep-ph/1503.08835)

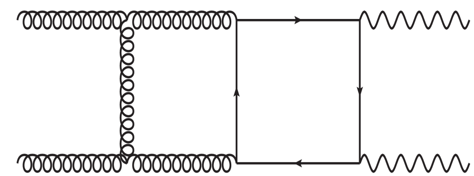
- Not available for massive internal lines – cannot fully include third generation
- ZZ: include massless loops with 5 flavors* – effect ~1%
- WW: neglect third generation** – effect ~ 10%
- **Massive loops become important in high mass region!**

*: neglecting vector-axial triangle diagrams, suppressed by top mass

**: except in SR real radiation amplitudes

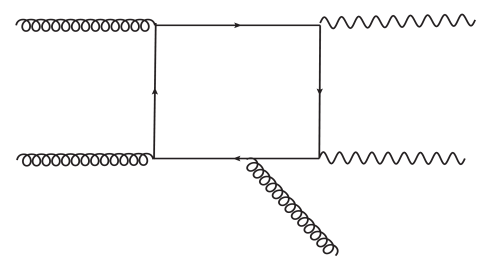
# Outline of calculation

- **Two-loop** amplitudes for $gg \rightarrow VV$



- **One-loop** amplitudes for $gg \rightarrow VV+g$

  (analytic+numerical unitarity methods)



- **Single** soft/collinear singularities

  (FKS, $q_T$ subtraction)

# Results: gg → ZZ

- Z bosons generated with BW about $m_Z$
- Include leptonic decays $ZZ \to e^+e^-\mu^+\mu^-$
- Use NNPDF3.0 and $\mu_0 = 2m_Z$ (scale variation: $\mu = \mu_0/2$ and $\mu = 2\mu_0$)

- At $\sqrt{s} = 8$ TeV

$$\sigma_{gg,\mathrm{LO}} = 0.97^{+0.3}_{-0.2}\ \mathrm{fb} \qquad \sigma_{gg,\mathrm{NLO}} = 1.8^{+0.2}_{-0.2}\ \mathrm{fb}$$

Increase by k-factor 1.85 (1.6 – 2.1 across scale range)

- At $\sqrt{s} = 13$ TeV

$$\sigma_{gg,\mathrm{LO}} = 2.8^{+0.7}_{-0.6}\ \mathrm{fb} \qquad \sigma_{gg,\mathrm{NLO}} = 4.7^{+0.4}_{-0.4}\ \mathrm{fb}$$

Increase by k-factor 1.67 (1.4 – 1.9 across scale range)

# Impact on pp → ZZ at NNLO

- gg contribution to pp → ZZ at NNLO increased by 80% at 8 TeV and 70% at 13 TeV
- This increases the NNLO corrections from 12% → 18% at 8 TeV and 16% → 23% at 13 TeV

$$\sigma_{\mathrm{NLO}} = 7.369^{+2.8\%}_{-2.3\%}\ \mathrm{pb}$$

$$\sigma_{\mathrm{NNLO}} = 8.284^{+3.0\%}_{-2.3\%}\ \mathrm{pb}$$

$$\sigma_{\mathrm{NNLO+gg,NLO}} = 8.7\ \mathrm{pb}$$

(Cascioli *et. al*., hep-ph/1405.2219)

undecayed ZZ

- Beyond expected ~3% scale variation in NNLO results.

# Results: gg → WW

- W bosons generated on-shell
- Include leptonic decays $W^+W^- \to \nu_e e^+ \mu^- \bar{\nu}_\mu$
- Use NNPDF3.0 and $\mu_0 = m_W$ (scale variation: $\mu = \mu_0/2$ and $\mu = 2\mu_0$)
- At $\sqrt{s} = 8$ TeV

$$\sigma_{gg,LO} = 20.9^{+6.8}_{-4.8}\ \text{fb} \qquad \sigma_{gg,NLO} = 32.2^{+2.3}_{-3.1}\ \text{fb}$$

Increase by k-factor 1.54 (1.24 – 1.8 across scale range)

- At $\sqrt{s} = 13$ TeV

$$\sigma_{gg,LO} = 56.5^{+15.4}_{-11.5}\ \text{fb} \qquad \sigma_{gg,NLO} = 79.5^{+4.2}_{-5.9}\ \text{fb}$$

Increase by k-factor 1.4 (1.2 – 1.6 across scale range)

# Impact on pp → WW at NNLO

- Looking at 8 TeV cross sections (Gehrmann *et. al.*, hep-ph/1408.5243, undecayed WW):

$$\sigma_{\mathrm{NLO}} = 54.77^{+3.7\%}_{-2.9\%}\ \mathrm{pb} \qquad \sigma_{\mathrm{NNLO}} = 59.84^{+2.2\%}_{-1.9\%}\ \mathrm{pb}$$

  - Include *BR(W → lν)* = 0.108

$$\sigma_{\mathrm{NLO}} = 638.84\ \mathrm{fb} \qquad \sigma_{\mathrm{NNLO}} = 697.97\ \mathrm{fb}$$

- 35% of NNLO corrections from gg $\Rightarrow \sigma_{\mathrm{gg}} \simeq 20\ \mathrm{fb}$
- Increased to 32.2 fb by NLO corrections
- Increases NNLO corrections by ~2%

$$\sigma_{\mathrm{NNLO+gg,NLO}} \simeq 710\ \mathrm{fb}$$

- Within scale uncertainty bands of NNLO results

# Fiducial cross sections

- ~2 – 2.5σ discrepancy between Run I measurement of WW cross section & (NLO + gg) theory
- Resolved by resummation effects & NNLO calculation

  (Gehrmann *et. al.* '14; Monni, Zanderighi '15; Meade, Ramani, Zeng '15; Jaiswal, Okui '15; Jaiswal, Meade, Ramani '15)

- Compare theory & experiment in fiducial regions

# Fiducial regions

- ee, μμ, eμ+μe decay channels
- W boson off-shell
- Fiducial regions defined by ATLAS cuts as implemented by Monni and Zanderighi, hep-ph/1410.4745.

| 8 TeV fiducial region |
|---|
| $p_t > 25(20)$ GeV for the leading (subleading) lepton and charged leptons separated by $\Delta R > 0.1$ |
| muon pseudorapidity $\lvert y \rvert < 2.4$ and electron pseudorapidity $\lvert y \rvert < 1.37$ or $1.52 < \lvert y \rvert < 2.47$ |
| no jets (anti-$k_t$ [10], $R = 0.4$) with $p_t > 25$ GeV and $\lvert y \rvert < 4.5$, separated from the electron by $\Delta R > 0.3$ |
| $m_{ll'} > 15, 15, 10$ GeV and $\lvert m_{ll'} - m_Z \rvert > 15, 15, 0$ GeV for $ee$, $\mu\mu$, and $e\mu$, respectively |
| $p_{t,\mathrm{Rel}}^{\nu+\bar{\nu}} > 45, 45, 15$ GeV and $p_t^{\nu+\bar{\nu}} > 45, 45, 20$ GeV for $ee$, $\mu\mu$, and $e\mu$, respectively |

# Fiducial cross sections

| | $\sigma_{\mu\mu,8\text{ TeV}}$ | $\sigma_{ee,8\text{ TeV}}$ | $\sigma_{e\mu,8\text{ TeV}}$ |
|---|---|---|---|
| $\sigma_{gg,\text{LO}}$ [fb] | $5.94^{+1.89}_{-1.35}$ | $5.40^{+1.71}_{-1.23}$ | $9.79^{+3.13}_{-2.24}$ |
| $\sigma_{gg,\text{NLO}}$ [fb] | $7.01^{-0.36}_{-0.17}$ | $6.40^{-0.32}_{-0.16}$ | $11.78^{-0.46}_{-0.34}$ |

Significantly smaller k-factor ~ 1.18 – 1.20 due to jet veto

Combining with qq (NLO) + H → WW (NLO) + gg massive loop (LO):

$$\sigma^{q\bar{q}+H+gg,\text{NLO}}_{\mu\mu,ee,e\mu+\mu e} = (72.0^{+1.3}_{-2.1},\ 66.3^{+1.2}_{-1.7},\ 337.3^{+6.3}_{-4.5})\ \text{fb}.$$

Comparing with ATLAS measurement:

$$\sigma_{\mu\mu,ee,e\mu+\mu e} = (74.4^{+8.1}_{-7.1},\ 68.5^{+9.0}_{-8.0},\ 377.8^{+28.4}_{-25.6}),$$

- Perfect agreement for ee,μμ
- Agreement at 1.5 sigma for eμ+μe
- Full NNLO corrections: ~ 4fb for ee,μμ, ~20 fb for eμ+μe

# Parton showering

Lesson from this:

Extrapolating fiducial measurement to total cross section is tricky.

Motivates matching of NLO corrections to gluon-initiated processes to parton showers.

At present, gg only at LO+PS, merging 0+1 jet, (Cascioli *et. al.* '13)

- Have amplitudes
- **No new conceptual developments needed** – usual matching with one radiated parton
- **Technical difficulties:**
  - Loop-induced so no tree-level process for phase space generation
  - Amplitudes more complicated than normal NLO process
  - …

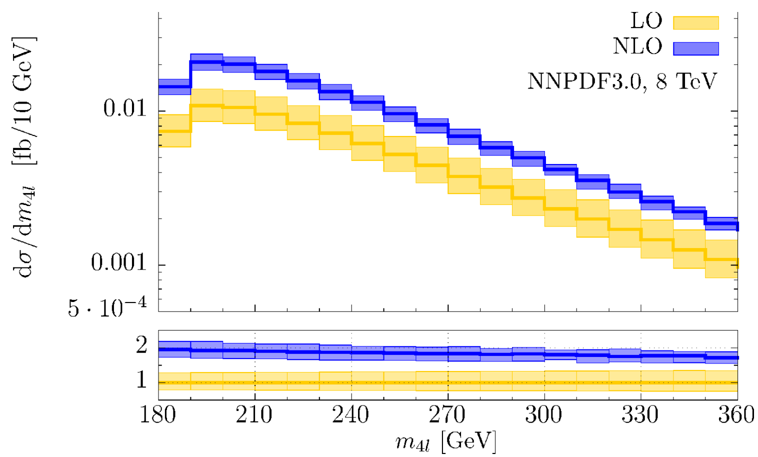
# Conclusions

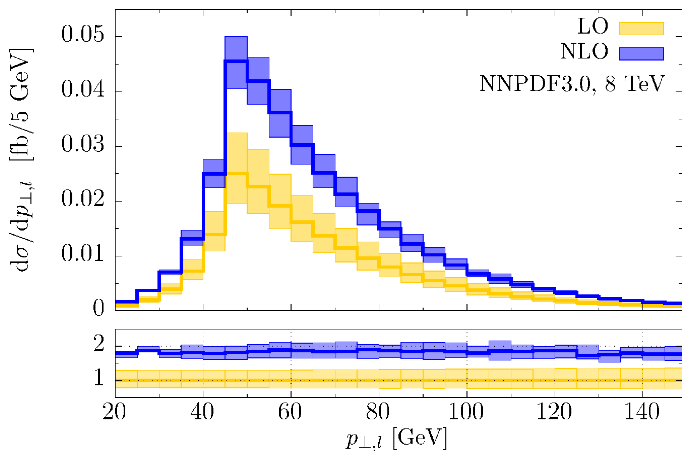
- NLO corrections to gg → ZZ, WW calculated (massless loops only)
- Increase gg contribution by ~1.6 at 8 TeV and ~1.4 at 13 TeV (for $\mu = m_V$)
- Increase NNLO pp → ZZ cross sections by ~4% and pp → WW cross sections by ~2%
- Smaller k-factor for WW in ATLAS fiducial region
- **Desirable to have matching to PS**

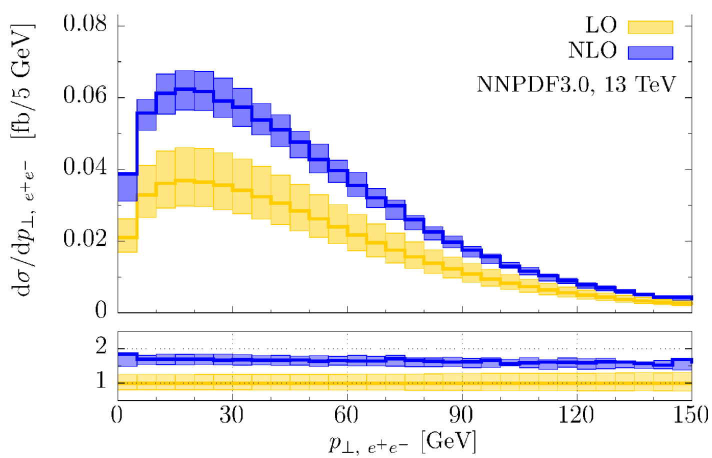
THANK YOU!

# BACKUP SLIDES

# Kinematic distributions for gg → ZZ

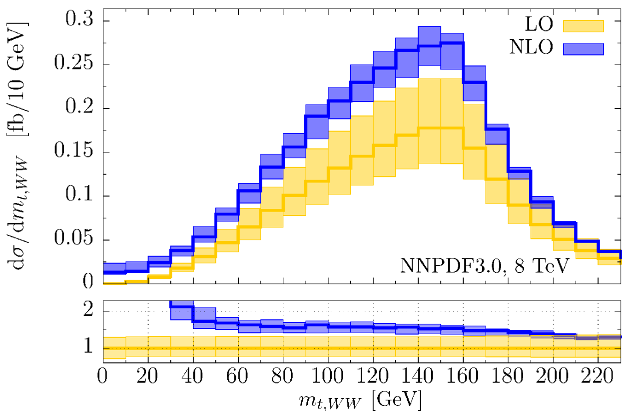


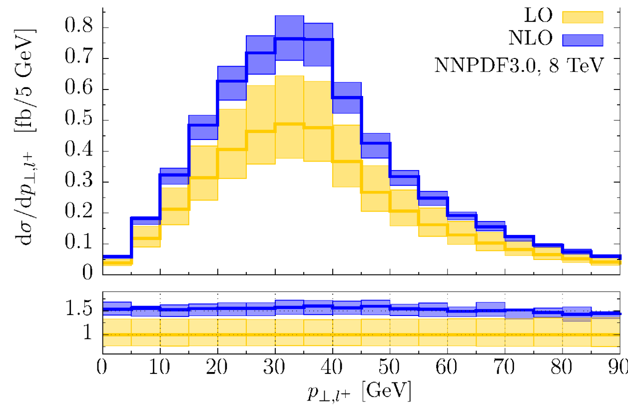



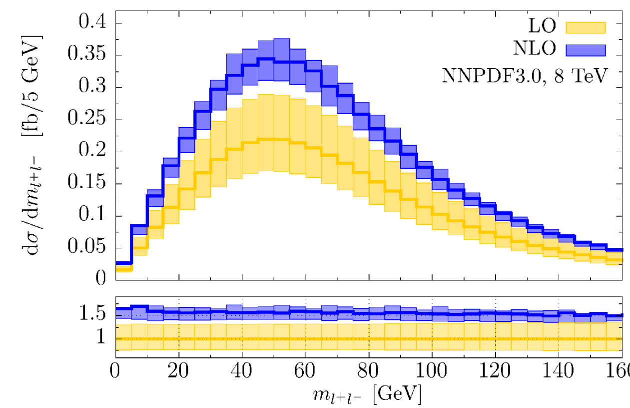



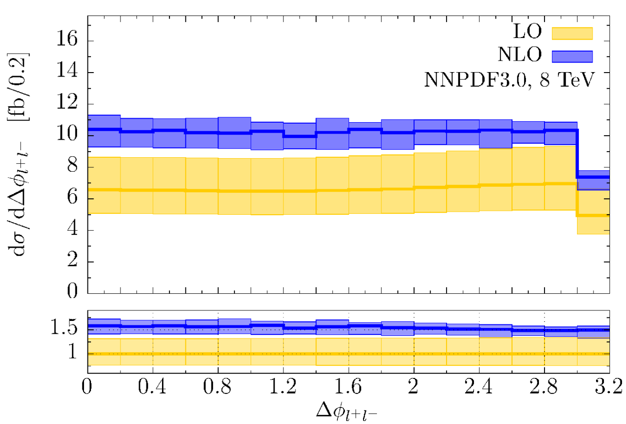

- Corrections become smaller at large $m_{4l}$ and $p_{T,l+l-}$
- Corrections flat for $p_{T,l}$

# Kinematic distributions for gg → WW




- $\Delta\phi_{ll}$ uniform
- Low $m_{T,WW}$ – collinear leptons not possible at LO, possible with additional jet (same effect in $q\bar{q}$)
- Uniform corrections otherwise