A few comments on EW schemes in VV

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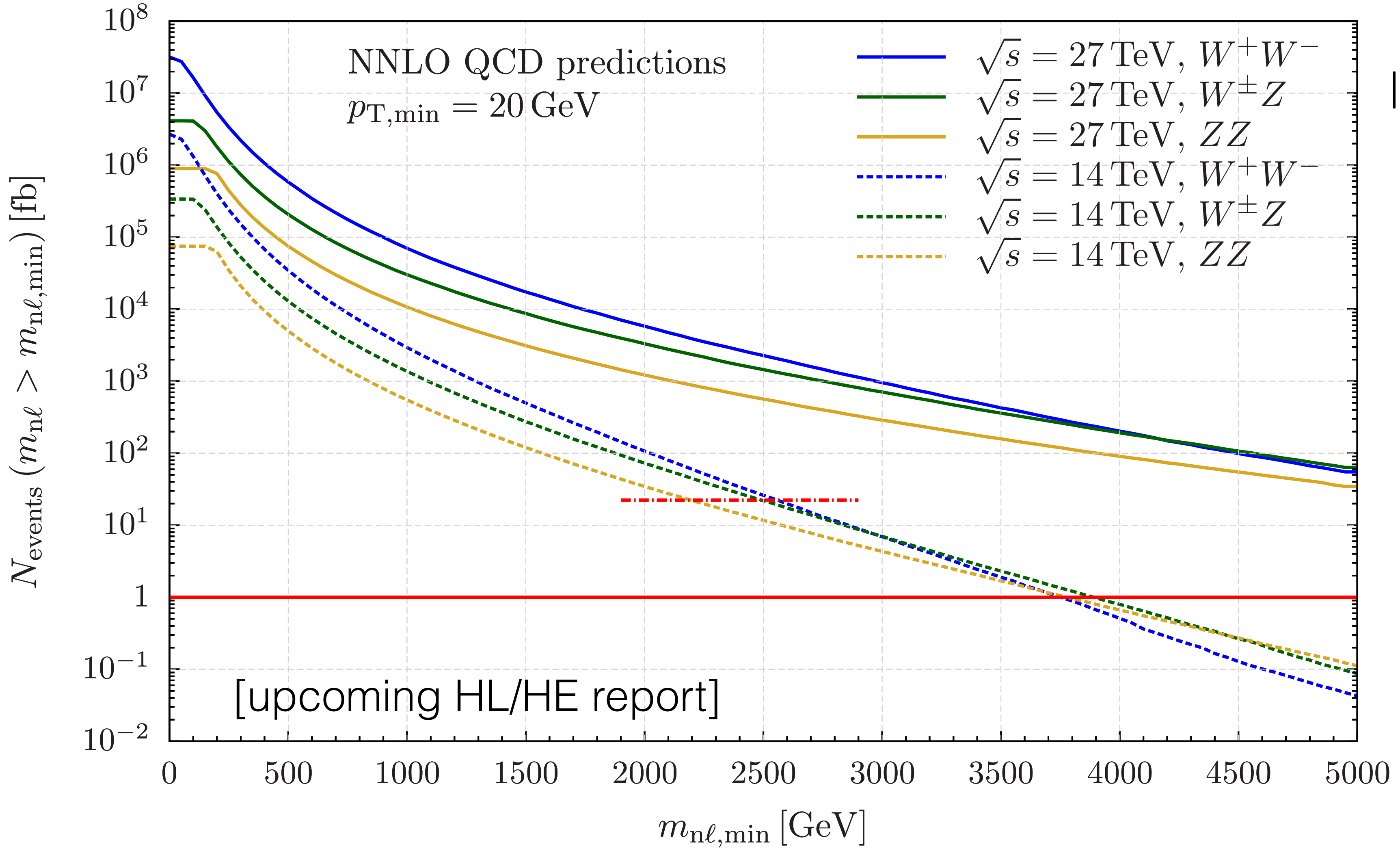
General remarks

- precision in VV by far not at the same level as DY. However:



15ab^{-1} @ 27 TeV

3ab^{-1} @ 14 TeV

- current reach (150fb^{-1}) ~ 1% statistical precision up to about 500 GeV
- reach for HL-LHC ~ 1% statistical precision up to about 1 TeV

EW schemes

- consistent EW input schemes: mZ,mW +

LO
- α(0)
- α(mZ)
- Gμ $\alpha_{G_\mu} = \sqrt{2} G_\mu M_{\rm W}^2 (1 - M_{\rm W}^2/M_{\rm Z}^2)/\pi$

} $\sin\theta_W^2 = 1 - m_W^2/m_Z^2$

- consistent EW renormalisation schemes:

NLO
- α(0) free of mass singularities for external photons
- α(mZ) relevant for high-energetic virtual photon exchange
- Gμ absorbs universal corrections into LO→ NLO EW/LO reduced

$$\delta Z_e\big|_{\alpha(0)} \to \delta Z_e\big|_{\alpha_{G_\mu}} = \delta Z_e\big|_{\alpha(0)} - \frac{\Delta r}{2}$$

→mixed scheme: $\sigma_{\rm LO} \;=\; \alpha(G_\mu)^n \alpha(0)^{n_\gamma} A_{\rm LO}$ for n_γ resolved photons

$$\sigma_{\rm NLO} = \sigma_{\rm LO}\,(1 + \delta_{\rm EW}) \qquad \delta_{\rm EW}^{\rm mix} \;=\; \delta_{\rm EW}^{\alpha(0)} + n\Delta r + \ldots \;=\; \mathcal{O}(\alpha)$$

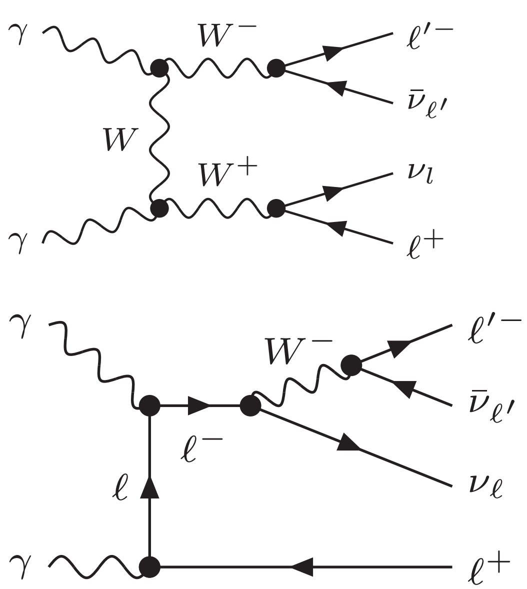
α_{G_μ} or $\alpha(0)$

→consistent schemes required at LO and NLO EW
(in particular for reweighting of Monte Carlo samples)

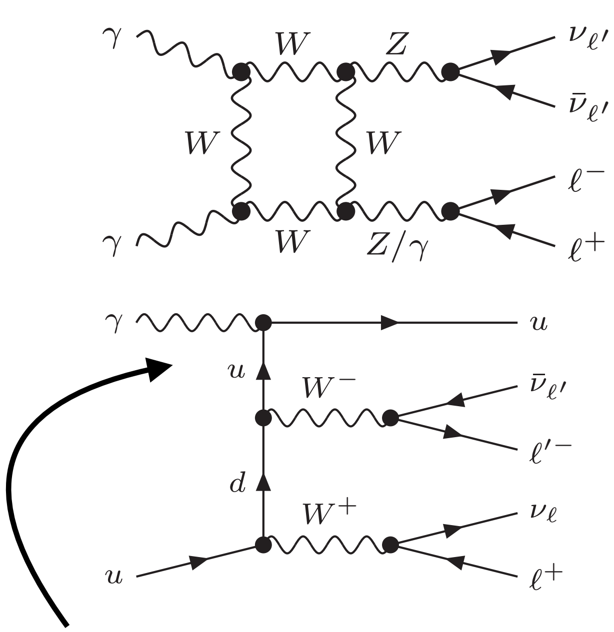
γ-induced contributions

- in particular in WW there are sizeable **γ**-induced contributions

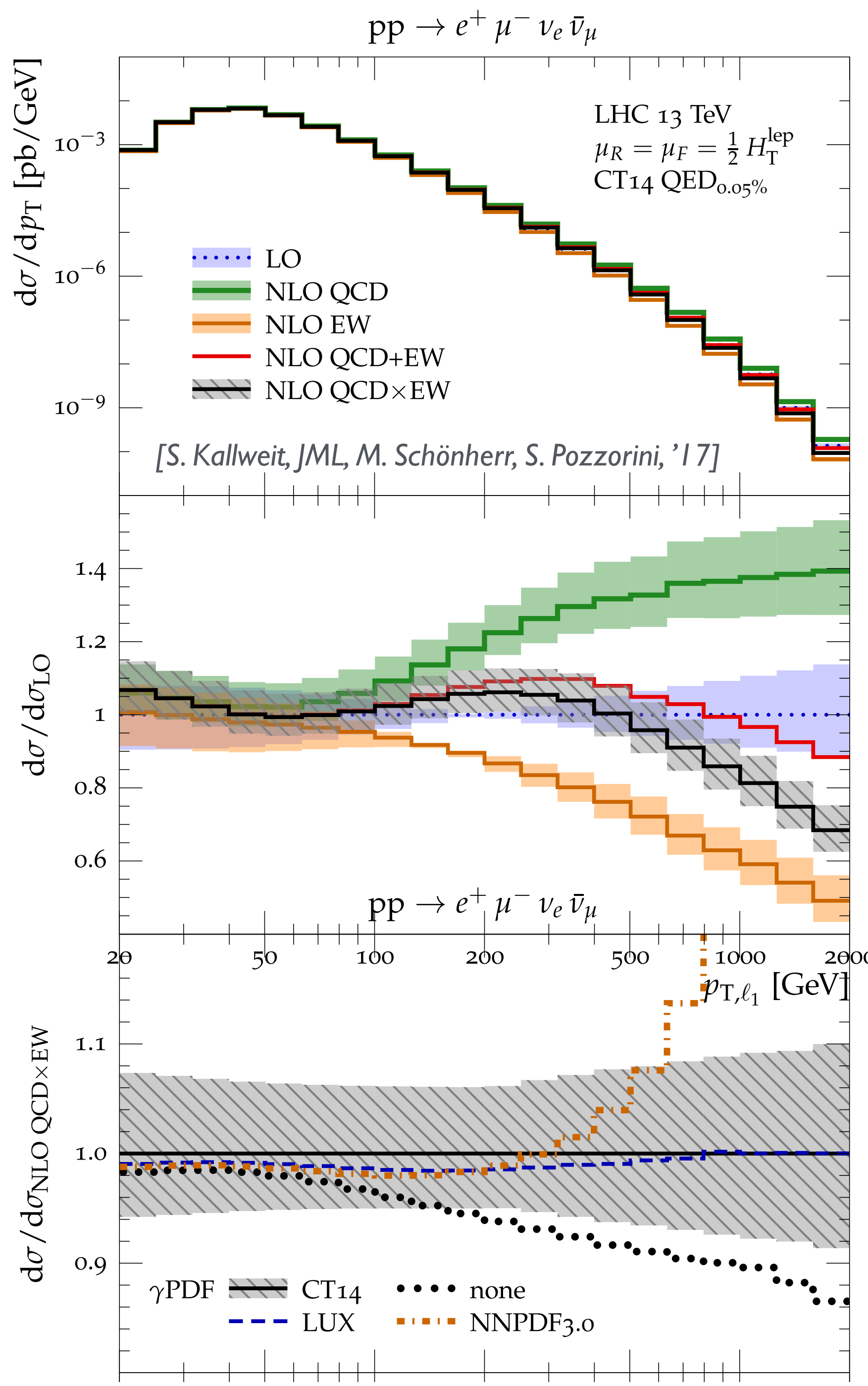
LO



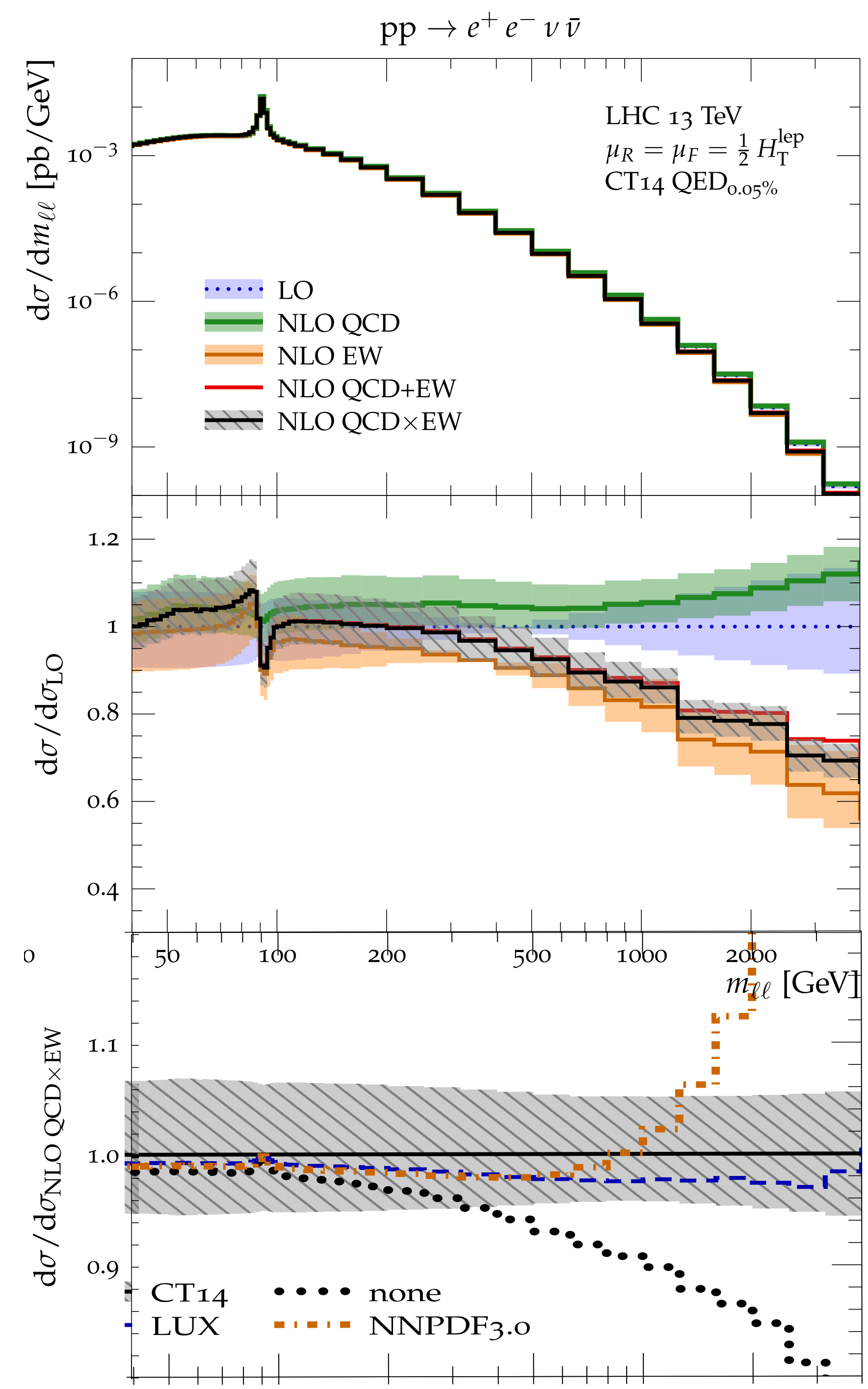
NLO



impact strongly jet-veto dependent. Here: $H_T^{\text{jet}} < 0.2\, H_T^{\text{lep}}$



pTl1



mll

- sizeable impact of **γ**PDF: **10% at 1 TeV pTl1 / mll**
- CT14qed and LUXqed agree at ~2% level

EW schemes for γ-induced

[S. Kallweit, JML, M. Schönherr, S. Pozzorini, '17]

- external photon in hard process → α(0) ?
- PDF renormalisation at O(α) yields for each initial state photon: $\delta Z_{\gamma,\mathrm{PDF}} = \frac{\alpha}{2\pi}\gamma_\gamma\left[\frac{C_\epsilon}{\epsilon} + \ln\left(\frac{\mu_\mathrm{D}^2}{\mu_\mathrm{F}^2}\right)\right]$
- This collinear singularity has to be cancelled by renormalisation of photon wave function and EM coupling: $\delta Z_{\gamma,\mathrm{virt}} = \frac{\delta\alpha}{\alpha} + \delta Z_{AA}$

in α(0)-scheme: $\delta Z_{\gamma,\mathrm{virt}}\Big|_{\mathrm{OS,light}} = \left[\frac{\delta\alpha(0)}{\alpha(0)} + \delta Z_{AA}\right]_{\mathrm{light}} = 0$

no fermion mass singularities in on-shell scheme!

in α(mZ)-scheme: $\delta Z_{\gamma,\mathrm{virt}}\Big|_{M_Z,\mathrm{light}} = -\left(\Pi^{\gamma\gamma}_{\mathrm{light}}(0) - \Pi^{\gamma\gamma}_{\mathrm{light}}(M_Z^2)\right)$

$$= \frac{\alpha}{2\pi}\gamma_\gamma\left[\frac{C_\epsilon}{\epsilon} + \ln\left(\frac{\mu_\mathrm{D}^2}{M_Z^2}\right) + \frac{5}{3}\right] - \frac{\alpha}{3\pi}\sum_{f\in F_\mathrm{m}} N_{\mathrm{C},f}\, Q_f^2\left[\ln\left(\frac{m_f^2}{M_Z^2}\right) + \frac{5}{3}\right]$$

from dispersion relations

→ $\delta Z_{\gamma,\mathrm{virt}}\Big|_{M_Z,\mathrm{light}} + \delta Z_{\gamma,\mathrm{PDF}}$ free from manifest 1/ε singularities

→ couplings of initial-state photons and unresolved final-state photons should be parametrised in terms of α(mZ) or any other short-distance scheme, e.g. Gμ / $\overline{\mathrm{MS}}$

[see also: Harland-Lang et.al., 1605.04935]

Validation

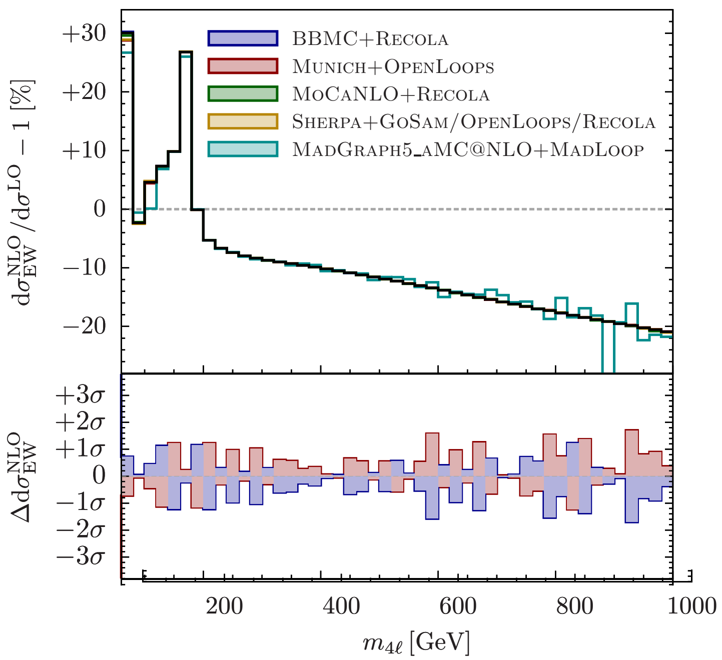
- There are subtle differences in implementation of these schemes in particular in the context of CMS (complex mass scheme).
  →Have been studied for ZZ in the context of [LH17, 1803.07977]

$u\bar{u} \to e^+e^-\mu^+\mu^-$

a) PSP 1	$B/10^{-15}$	$V_{\text{finite}}/10^{-16}$	$V_1/10^{-17}$	$V_2/10^{-17}$
MadLoop	5.26592465401088	6.60297993618509	2.63915540074976	−3.09566543908773
Recola	5.26592465401090	6.60088670209820	2.63915540075328	−3.09566543908732
OpenLoops	5.26592465401100	6.60088670210145	2.63915540078563	−3.09566543905505
GoSam	5.26592465401086	6.60088670209788	2.63915540076095	−3.09566543909091
NLOX	5.26592465401084	6.60088670211436	2.63915540076702	−3.09566543908783

$\gamma\gamma \to e^+e^-\mu^+\mu^-$

c) PSP 1	$B/10^{-13}$	$V_{\text{finite}}/10^{-14}$	$V_1/10^{-15}$	$V_2/10^{-15}$
MadLoop	4.63762790127829	6.79330655006349	4.07216839247769	−2.23061748556626
Recola	4.63762790127830	6.79163662486900	4.07216839245629	−2.23061748556050
OpenLoops	4.63762790127838	6.79163662486753	4.07216839246097	−2.23061748560388
GoSam	4.63762790127830	6.79163662486761	4.07216839247955	−2.23061748556541



→very convincing agreement between automated tools

Conclusions

- scheme of choice: Gμ or α(mZ) for hard processes and initial state photons combined with
  α(0) for resolved final state photons

- This is the default scheme implemented for NLO EW in
  Sherpa+OpenLoops, MATRIX+OpenLoops, Sherpa+Recola, MoCaNLO+Recola

- Questions/Comments:
  - Best scheme for WZ polarizations?
  - EW scheme uncertainties at NLO have not been studied in VV. Necessary?

- See also: "Dictionary for electroweak corrections" by S. Dittmaier in [LH2013,1405.1067]