Diboson/(triboson) production: QCD and EW corrections

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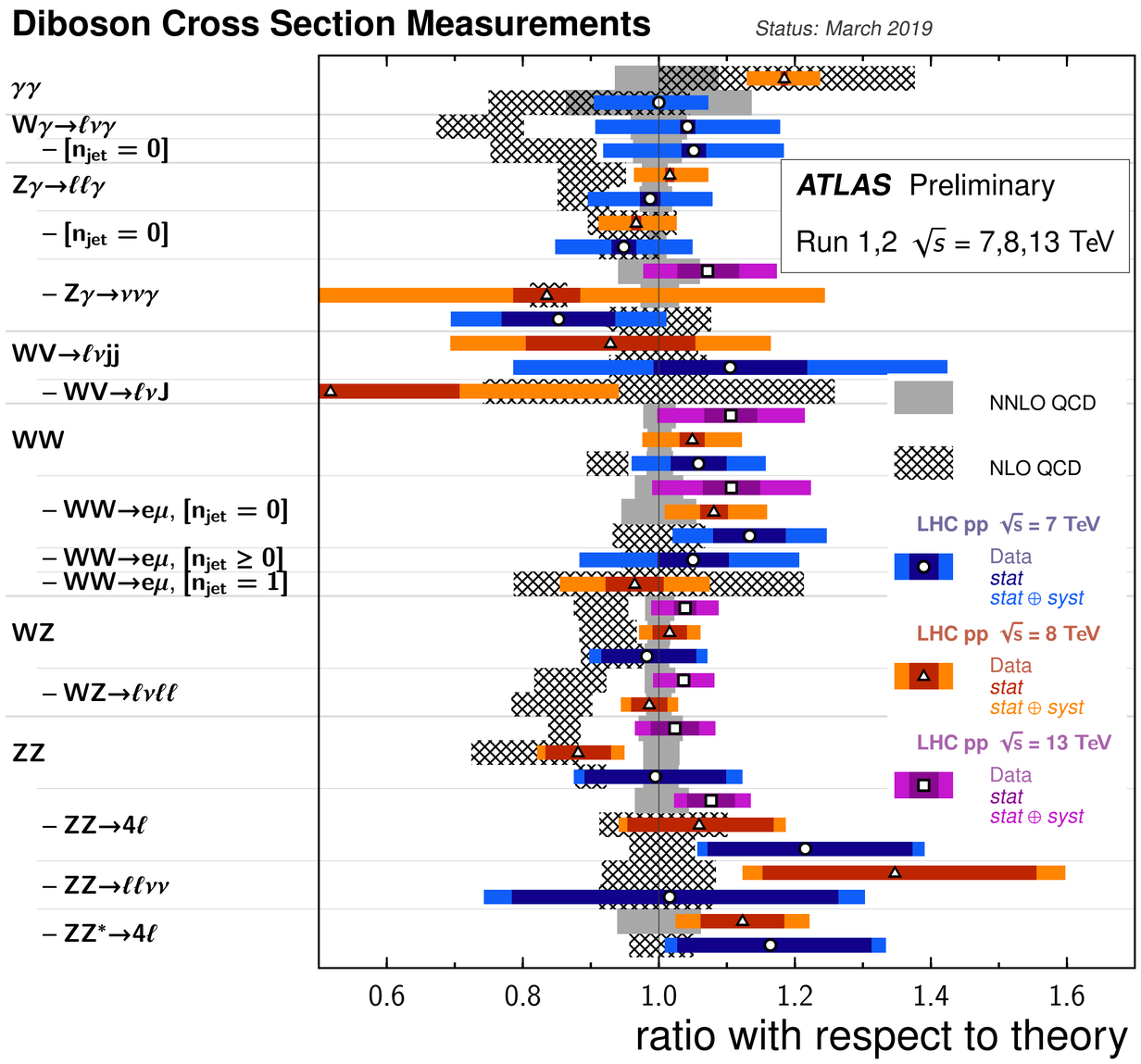
Science & Technology Facilities Council

UK Research and Innovation

Ultimate Precision at Hadron Colliders
Higgs and High Energy Probes
Orsay, 3. December 2019

Status



Remarkable agreement of inclusive diboson cross sections with **NNLO QCD**

Allows for stringent SM tests

Dibosons important background for Higgs and BSM searches

Perturbative expansion

$$d\sigma = d\sigma_{\rm LO} + \alpha_S\, d\sigma_{\rm NLO}$$

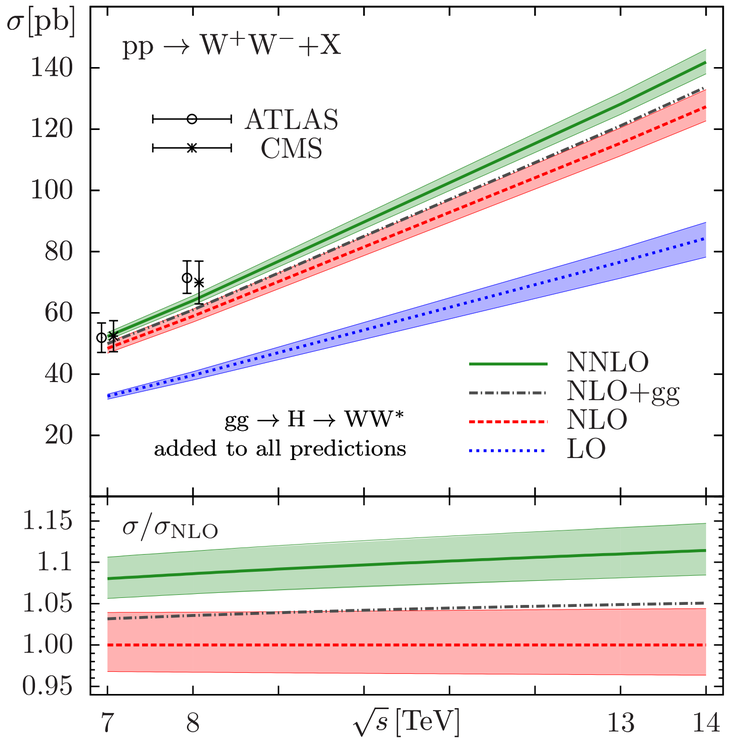
NLO QCD O(100%)

$$+\alpha_S^2\, d\sigma_{\rm NNLO}$$

NNLO QCD O(10%)

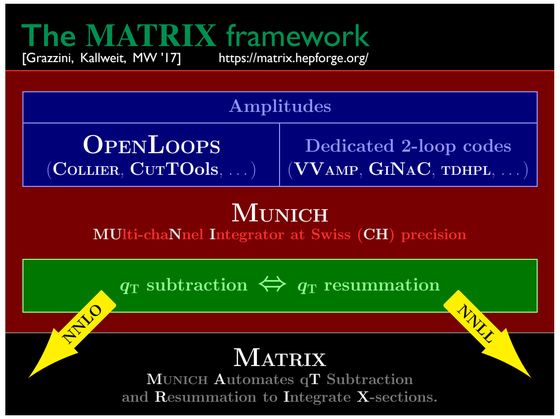
$$+\alpha_S^3\, d\sigma_{\rm NNLO} + \ldots$$

N3LO QCD O(1%)



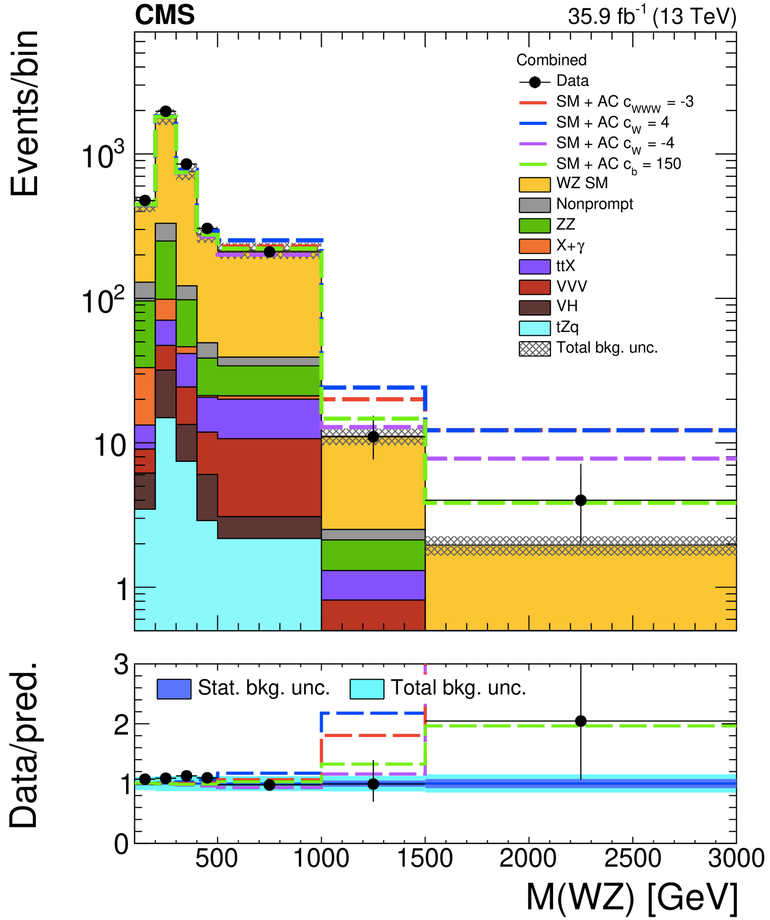
NNLO QCD

In MATRIX *[Grazzini, Kallweit, Wiesemann '17]* all on-shell & off-shell diboson processes pp->VV' are available

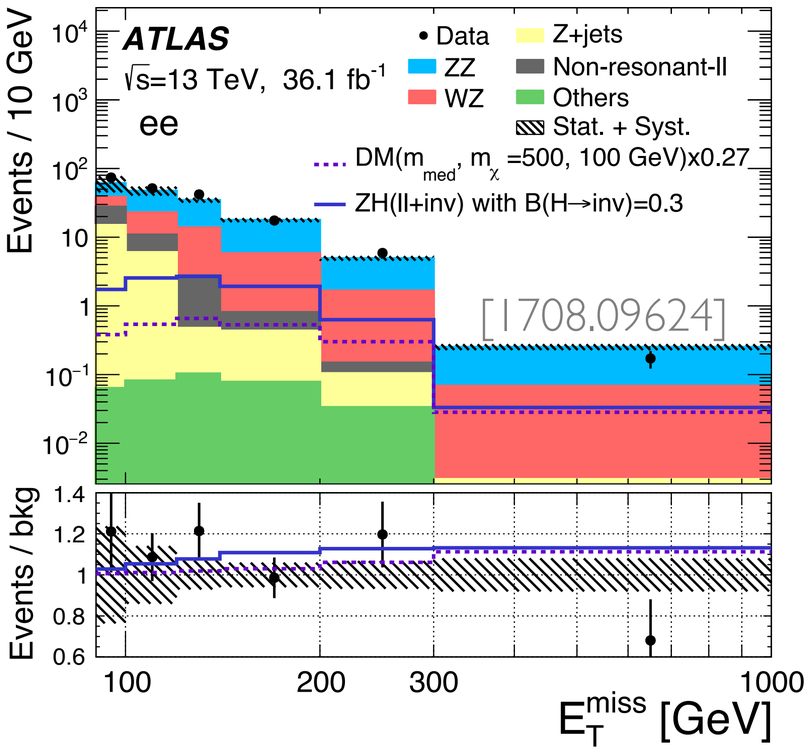


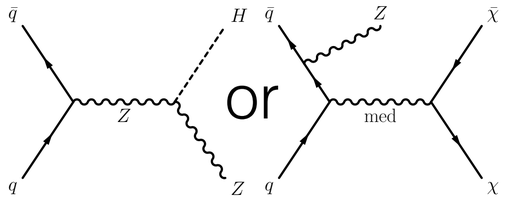
Tails, tails, tails,. . . . !!!

Indirect probes



Direct probes



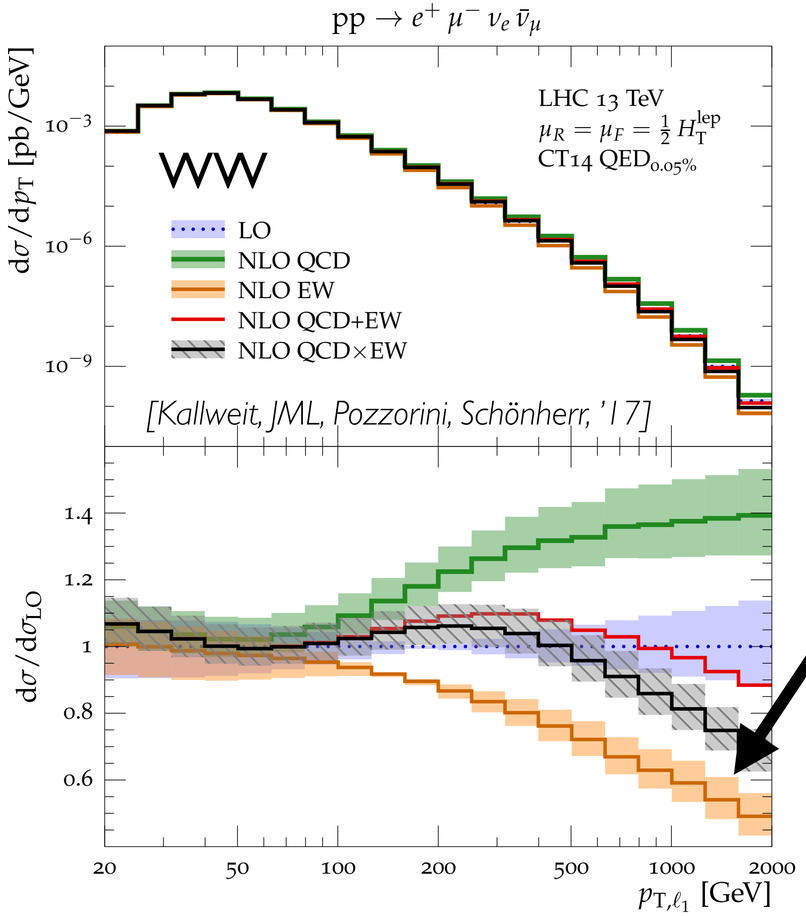


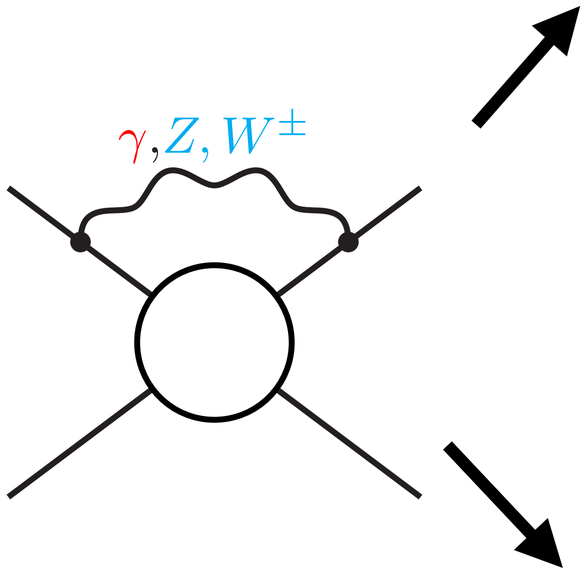
vs. ZZ(vv)

→Theory precision is key to harness full potential of LHC data!

Relevance of EW higher-order corrections: Sudakov logs in the tails

I. Possible large (negative) enhancement due to soft/collinear **logs** from virtual EW gauge bosons:





[Ciafaloni, Comelli,'98;
Lipatov, Fadin, Martin, Melles, '99;
Kuehen, Penin, Smirnov, '99;
Denner, Pozzorini, '00]

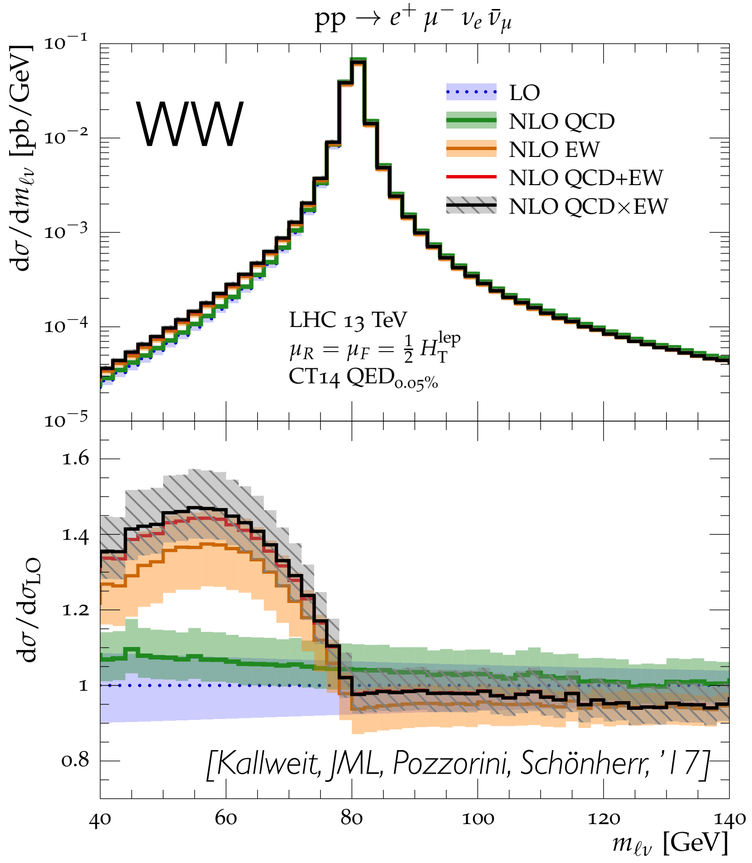
Universality and factorisation: *[Denner, Pozzorini; '01]*

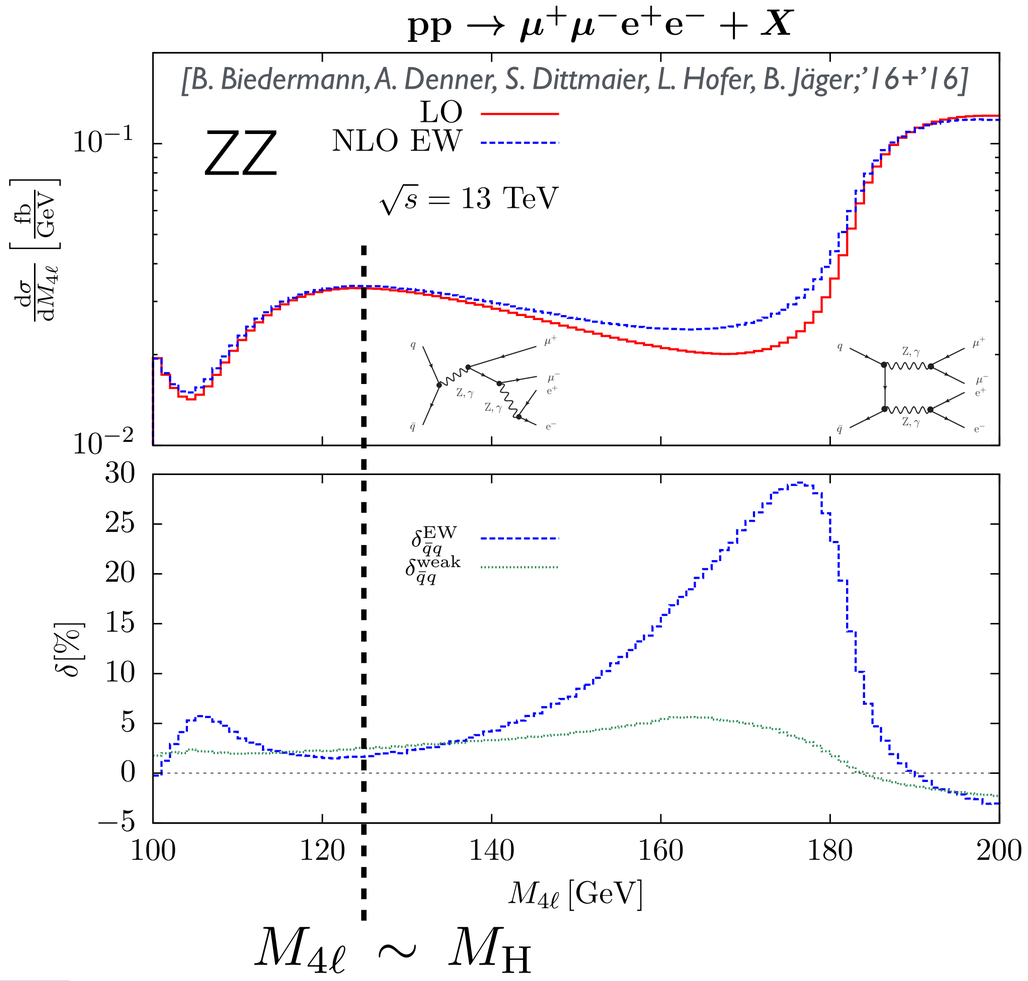
$$\delta\mathcal{M}^{1-\text{loop}}_{\text{LL+NLL}} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^\pm} I^a(k)I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\text{ew}}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

➜ **overall large (negative) effect in the tails of distributions: p_T, m_{inv}, H_T, … (relevant for BSM searches!)**

Relevance of EW higher-order corrections: collinear QED radiation

II. Possible large enhancement due to soft/collinear **logs** from photon radiation $\sim \alpha \log\left(\frac{m_f^2}{Q^2}\right)$ in sufficiently exclusive observables.





$M_{4\ell} \sim M_{\mathrm{H}}$

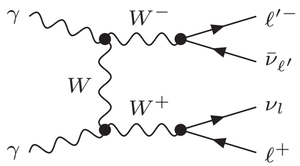
➜ important for radiative tails, Higgs backgrounds etc.

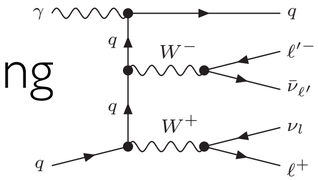
➜typically considered via QED PS (PHOTOS / YFS)

Relevance of EW higher-order corrections: photon-induced channels

III. QED factorisation and thus photon luminosities needed to absorb IS photon singularities.

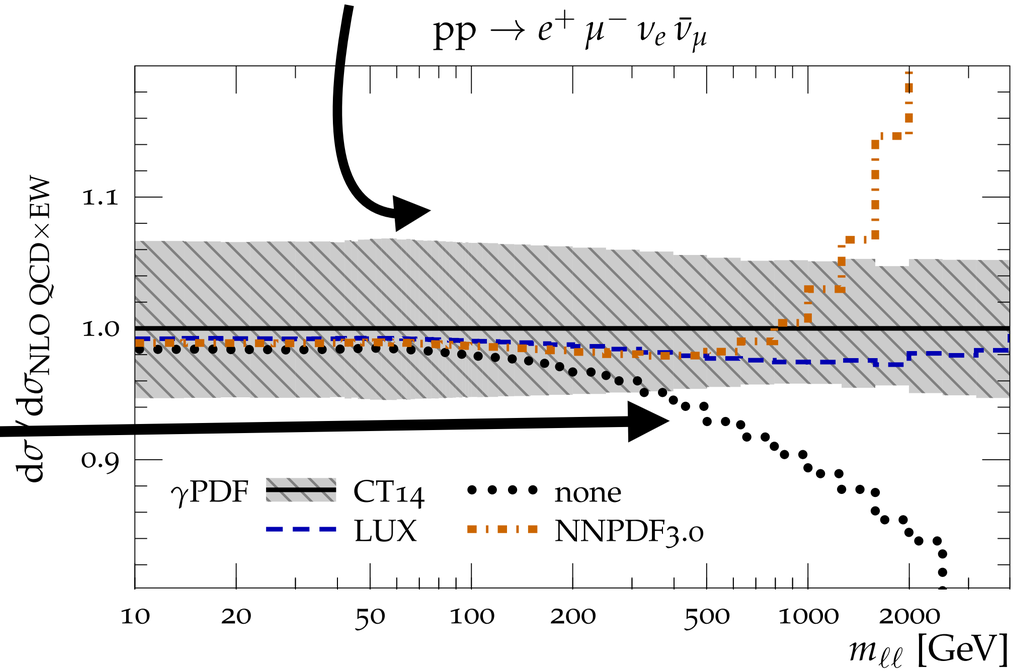
➜ Possible large enhancement due to photon-induced channels in the tails of kinematic distributions,

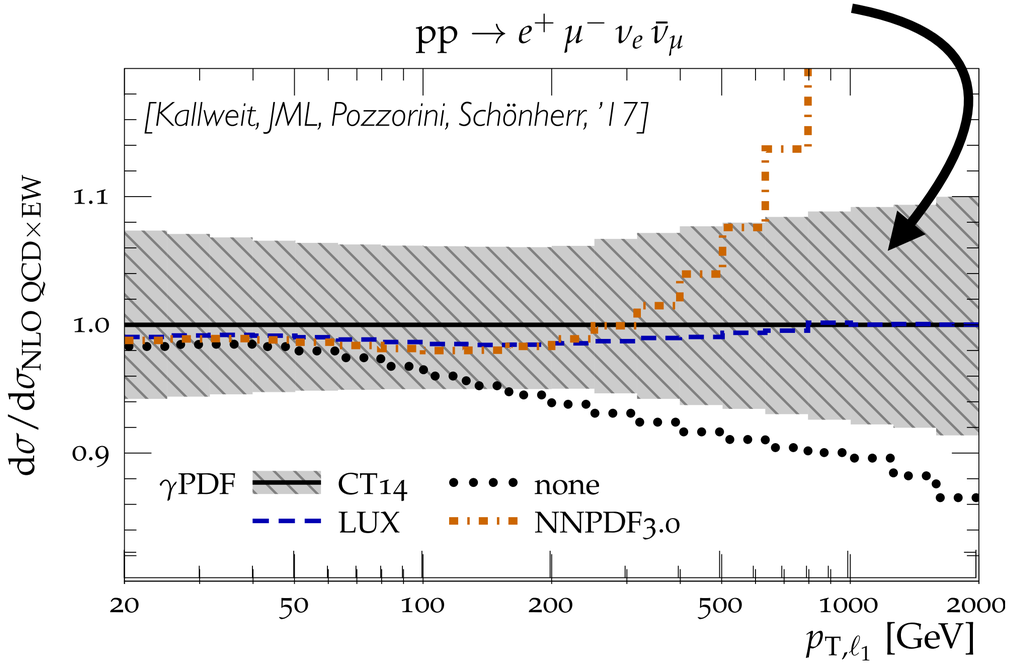
in particular in WW: 

(t-channel enhancement), but also in Bremsstrahlung 

$$\mathrm{d}\sigma_{\mathrm{LO}} = \mathrm{d}\sigma_{\mathrm{LO}}^{q\bar{q}} + \mathrm{d}\sigma_{\mathrm{LO}}^{\gamma\gamma}$$

no γ





➜ large differences between different photon descriptions. Now settled: LUXqed superior

➜ O(10%) contributions from photon-induced channels

Perturbative expansion

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{LO}} + \alpha_S\, \mathrm{d}\sigma_{\mathrm{NLO}} + \alpha_{\mathrm{EW}}\, \mathrm{d}\sigma_{\mathrm{NLO\,EW}}$$

NLO QCD NLO EW

$$+\alpha_S^2\, \mathrm{d}\sigma_{\mathrm{NNLO}} + \alpha_{\mathrm{EW}}^2\, \mathrm{d}\sigma_{\mathrm{NNLO\,EW}} + \alpha_S \alpha_{\mathrm{EW}}\, \mathrm{d}\sigma_{\mathrm{NNLO\,QCDxEW}}$$

NNLO QCD NNLO EW NNLO QCD-EW

$$+\alpha_S^3\, \mathrm{d}\sigma_{\mathrm{NNLO}} + \ldots$$

N3LO QCD

NLO EW

- 4l-DF-ZZ — Biedermann, Denner, Dittmaier, Hofer, Jäger; '16, '16
- 2l-DF-WW — Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder; '16
- 2l-SF-ZZ & 2l-SF-ZZWW & 2l-DF-WW — Kallweit, JML, Pozzorini, Schönherr, '17
- 3l-DF-WZ & 3l-DF-WZ — Biedermann, Denner, Hofer, '17

Perturbative expansion

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{LO}} + \alpha_S\, \mathrm{d}\sigma_{\mathrm{NLO}} + \alpha_{\mathrm{EW}}\, \mathrm{d}\sigma_{\mathrm{NLO\,EW}}$$

NLO QCD NLO EW

$$+\alpha_S^2\, \mathrm{d}\sigma_{\mathrm{NNLO}} + \alpha_{\mathrm{EW}}^2\, \mathrm{d}\sigma_{\mathrm{NNLO\,EW}} + \alpha_S \alpha_{\mathrm{EW}}\, \mathrm{d}\sigma_{\mathrm{NNLO\,QCDxEW}}$$

NNLO QCD NNLO EW NNLO QCD-EW

$$+\alpha_S^3\, \mathrm{d}\sigma_{\mathrm{NNLO}} + \ldots$$

N3LO QCD

NNLO QCD + NLO EW

4l-SF-ZZ	$pp \to \ell^+\ell^-\ell^+\ell^-$	ZZ
4l-DF-ZZ	$pp \to \ell^+\ell^-\ell'^+\ell'^-$	ZZ
3l-SF-WZ	$pp \to \ell^+\ell^-\ell\nu_\ell$	WZ
3l-DF-WZ	$pp \to \ell^+\ell^-\ell'\nu_{\ell'}$	WZ
2l-SF-ZZ	$pp \to \ell^+\ell^-\nu_{\ell'}\bar{\nu}_{\ell'}$	ZZ
2l-SF-ZZWW	$pp \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell$	ZZ,WW
2l-DF-WW	$pp \to \ell^+\ell'^-\nu_\ell\bar{\nu}_{\ell'}$	WW

In Matrix+OpenLoops all (massive) diboson processes are now available at **NNLO QCD + NLO EW**

[M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; 1912.00068]

(code soon to be public)

Perturbative expansion

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{LO}} + \alpha_S\, \mathrm{d}\sigma_{\mathrm{NLO}} + \alpha_{\mathrm{EW}}\, \mathrm{d}\sigma_{\mathrm{NLO\,EW}}$$

NLO QCD NLO EW

$$+\alpha_S^2\, \mathrm{d}\sigma_{\mathrm{NNLO}} + \alpha_{\mathrm{EW}}^2\, \mathrm{d}\sigma_{\mathrm{NNLO\,EW}} + \alpha_S \alpha_{\mathrm{EW}}\, \mathrm{d}\sigma_{\mathrm{NNLO\,QCDxEW}}$$

? ?

NNLO QCD NNLO EW NNLO QCD-EW

$$+\alpha_S^3\, \mathrm{d}\sigma_{\mathrm{NNLO}} + \ldots$$

N3LO QCD

NNLO QCD + NLO EW

4l-SF-ZZ	$pp \to \ell^+\ell^-\ell^+\ell^-$	ZZ
4l-DF-ZZ	$pp \to \ell^+\ell^-\ell'^+\ell'^-$	ZZ
3l-SF-WZ	$pp \to \ell^+\ell^-\ell\nu_\ell$	WZ
3l-DF-WZ	$pp \to \ell^+\ell^-\ell'\nu_{\ell'}$	WZ
2l-SF-ZZ	$pp \to \ell^+\ell^-\nu_{\ell'}\bar{\nu}_{\ell'}$	ZZ
2l-SF-ZZWW	$pp \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell$	ZZ,WW
2l-DF-WW	$pp \to \ell^+\ell'^-\nu_\ell\bar{\nu}_{\ell'}$	WW

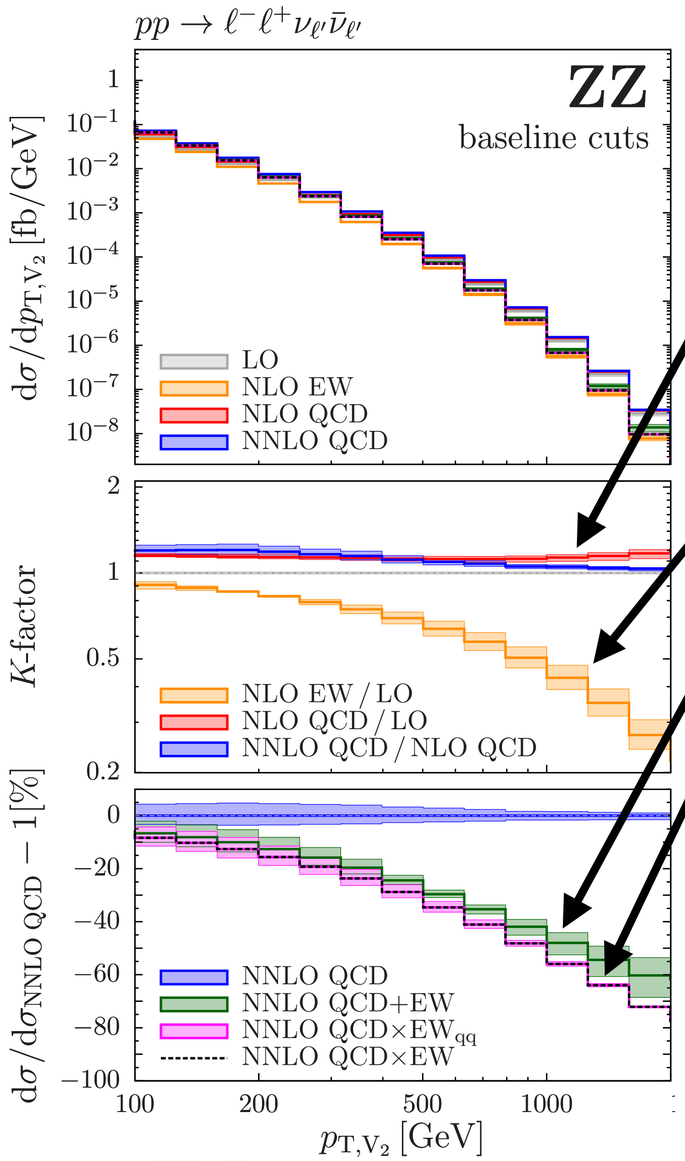
In Matrix+OpenLoops all (massive) diboson processes are now available at **NNLO QCD + NLO EW**

[M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; 1912.00068]

(code soon to be public)

NNLO QCD + NLO EW for dibosons: pTV2

[M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; 1912.00068]



pTV2

- moderate QCD corrections
  - NNLO/NLO QCD very small at large pTV2
  - NNLO QCD uncertainty: few percent
- NLO EW/LO=-(50-60)% @ 1 TeV

$$d\sigma_{\text{NNLO QCD+EW}} = d\sigma_{\text{LO}}\left(1+\delta_{\text{QCD}}+\delta_{\text{EW}}\right) + d\sigma^{gg}_{\text{LO}}$$

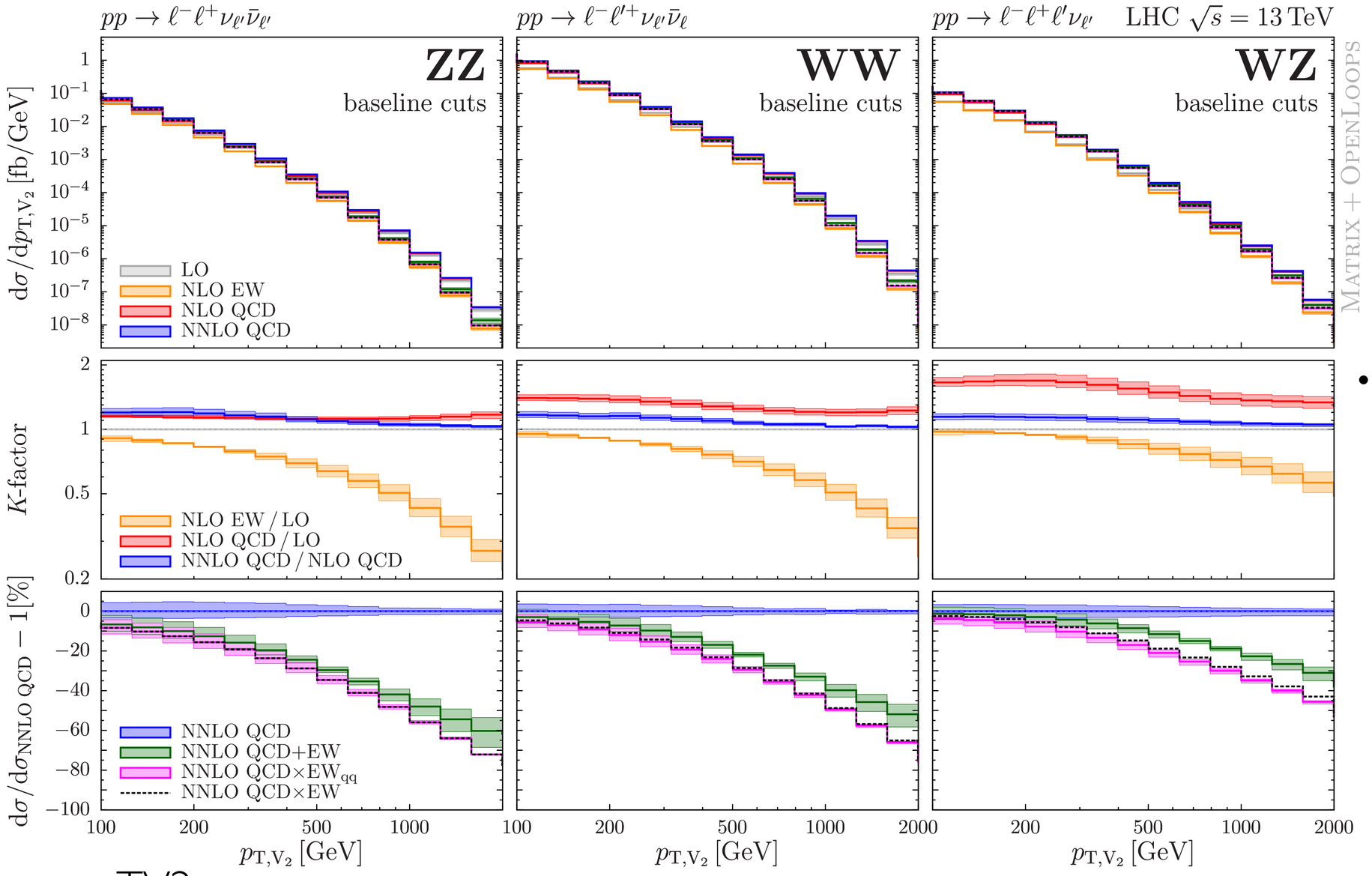
$$d\sigma_{\text{NNLO QCD}\times\text{EW}} = d\sigma_{\text{LO}}\left(1+\delta_{\text{QCD}}\right)\left(1+\delta_{\text{EW}}\right) + d\sigma^{gg}_{\text{LO}}$$

$$= d\sigma_{\text{NNLO QCD+EW}} + d\sigma_{\text{LO}}\delta_{\text{QCD}}\,\delta_{\text{EW}}$$

- difference very conservative upper bound on $\mathcal{O}(\alpha_S\alpha)$
- multiplicative/factorised combination clearly superior (EW Sudakov logs x soft QCD)
- dominant uncertainty at large pTV2: $\mathcal{O}(\alpha^2) \sim \alpha_{\text{w}}^2 \log^4(Q^2/M_W^2)$

Estimate: $\boxed{\frac{1}{2}\delta^2_{\text{EW}}}$

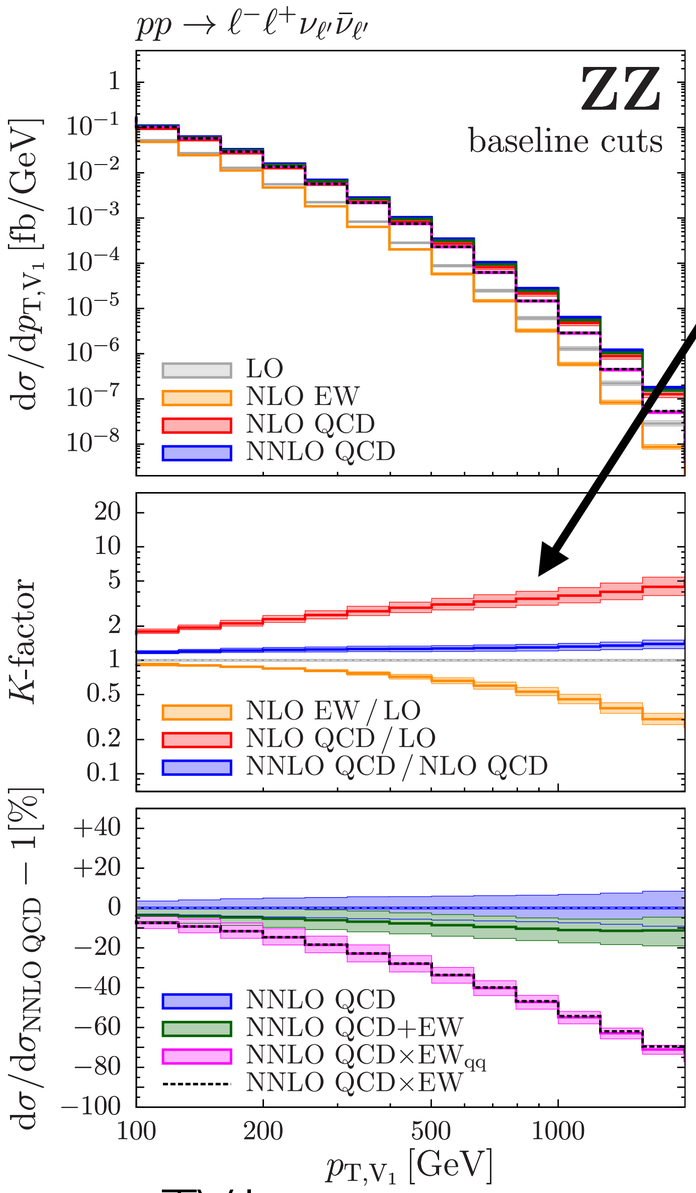
NNLO QCD + NLO EW for dibosons: pTV2



- consistent picture amongst all processes
- Largest QCD corrections in WZ (radiation zero at LO)
- Largest EW corrections in ZZ

pTV2

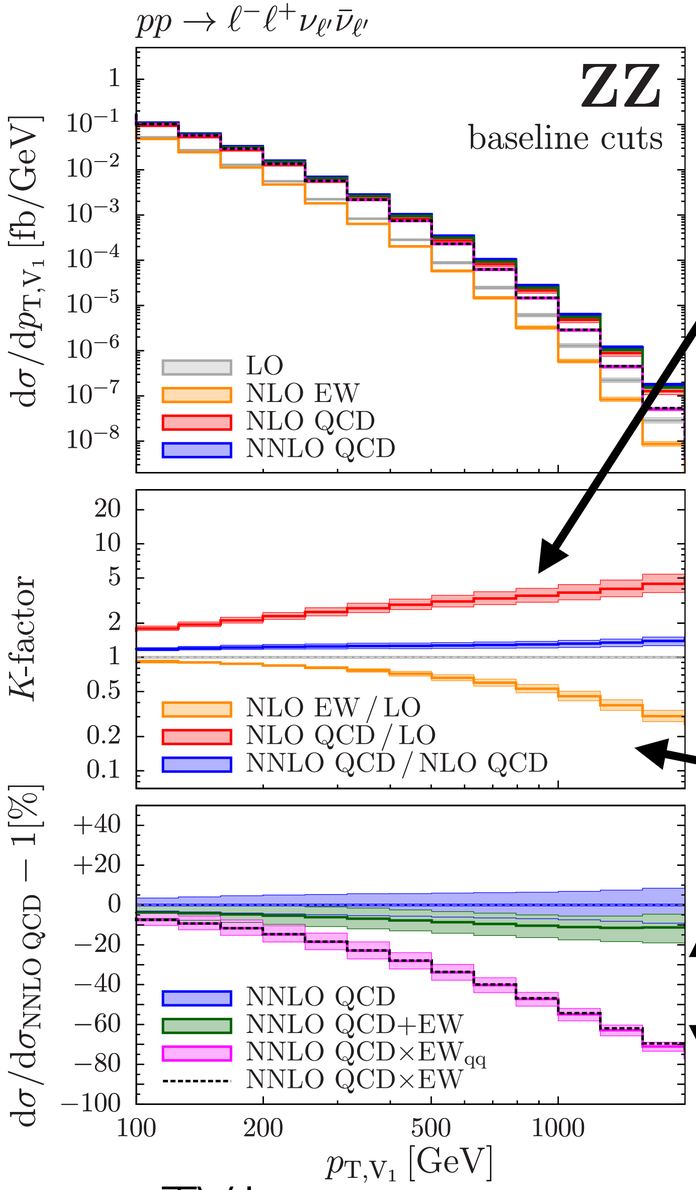
Giant QCD K-factors and EW corrections: pTV1



pTV1

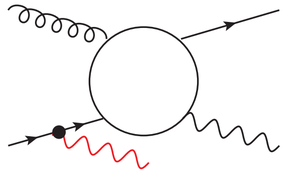
- NLO QCD/LO=2-5! ("giant K-factor")

Giant QCD K-factors and EW corrections: pTV1



pTV1

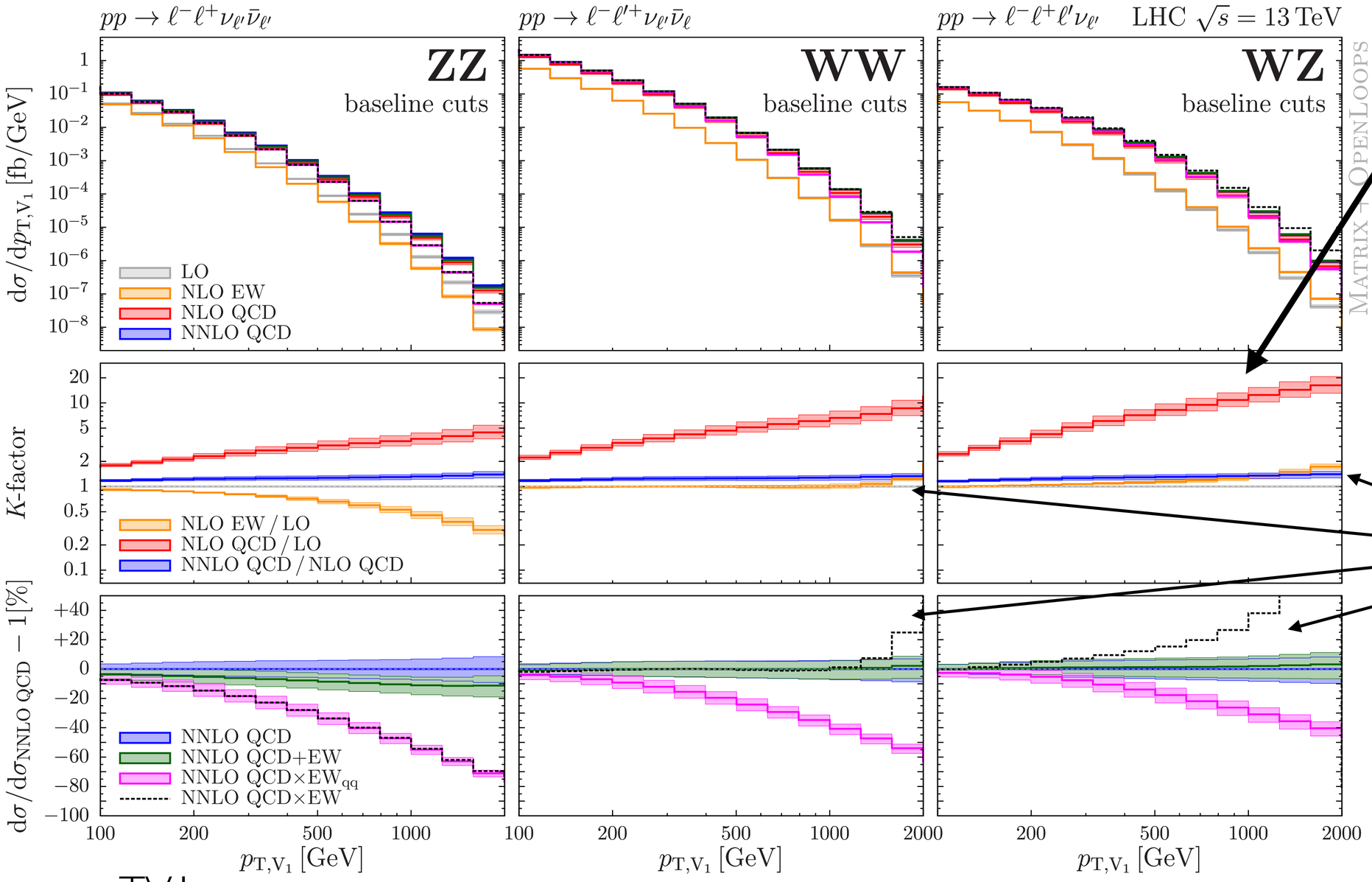
- NLO QCD/LO=2-5! ("giant K-factor")
- at large pTV1: VV phase-space is dominated by V+jet (w/ soft V radiation)



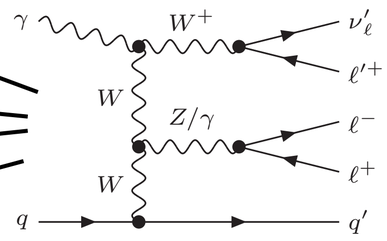
$$\frac{d\sigma^{V(V)j}}{d\sigma^{\rm LO}_{VV}} \propto \alpha_S \log^2\left(\frac{Q^2}{M_W^2}\right) \simeq 3 \qquad \text{at} \quad Q = 1\,\text{TeV}$$

- NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- NLO EW/LO=-(40-50)%
- Very large difference $d\sigma_{\rm NNLO\ QCD+EW}$ vs. $d\sigma_{\rm NNLO\ QCD\times EW}$
- Problems:
  1. In additive combination dominant Vj topology does not receive any EW corrections
  2. In multiplicative combination EW correction for VV is applied to Vj hard process
- Pragmatic solution: take average as nominal and spread as uncertainty
- Rigorous solution: merge VVj incl. EW corrections with VV retaining NNLO QCD + EW

Giant QCD K-factors and EW corrections: pTV1



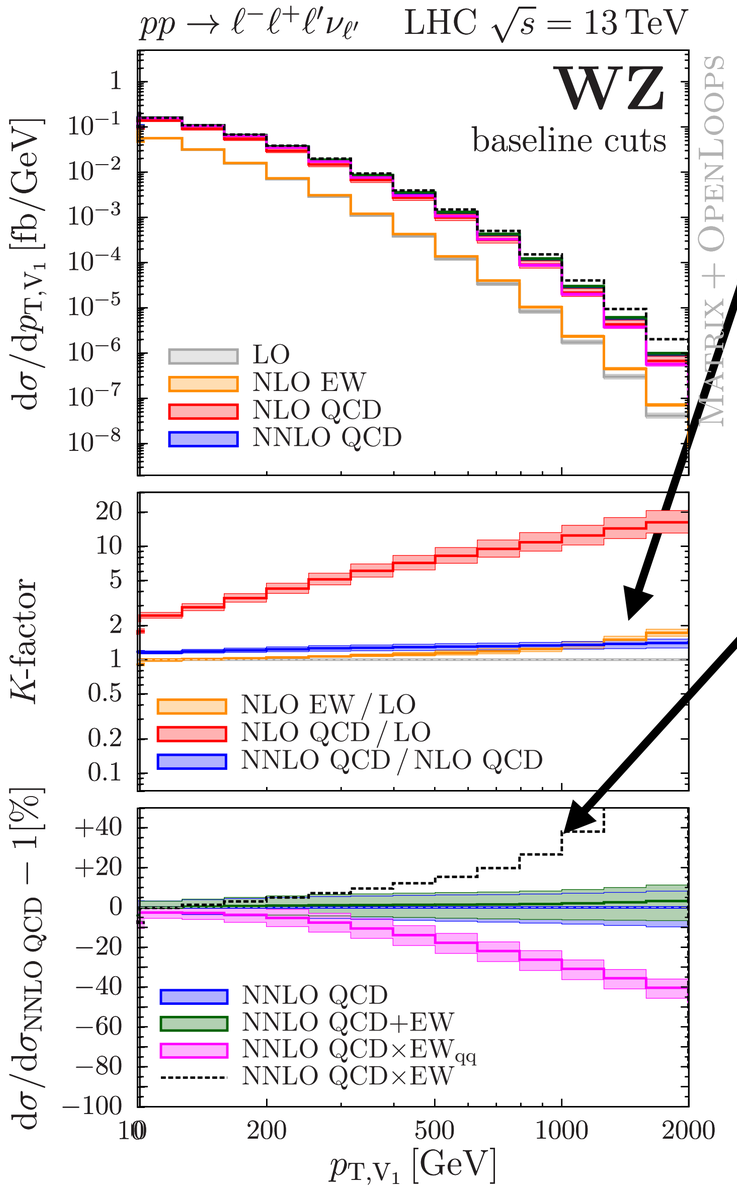
- NLO QCD/LO=5-10!
- Similar giant K-factor mechanism also in gamma-induced:



$$\sim \alpha \log^2\left(\frac{Q^2}{M_W^2}\right)$$

pTV1

Giant QCD K-factors and EW corrections: pTV1



- Giant EW K-factor

- $$d\sigma_{\mathrm{NNLO\,QCD\times EW}} = \left[d\sigma^{q\bar{q}}_{\mathrm{LO}}\left(1+\delta^{q\bar{q}}_{\mathrm{QCD}}\right) + d\sigma^{\gamma\gamma}_{\mathrm{LO}}\right](1+\delta_{\mathrm{EW}}) + d\sigma^{gg}_{\mathrm{LO}}$$

  with $$\delta_{\mathrm{EW}} = \frac{\delta^{q\bar{q}}_{\mathrm{EW}} d\sigma^{q\bar{q}}_{\mathrm{LO}} + \delta^{\gamma\gamma/\gamma q}_{\mathrm{EW}} d\sigma^{\gamma\gamma}_{\mathrm{LO}}}{d\sigma^{q\bar{q}}_{\mathrm{LO}} + d\sigma^{\gamma\gamma}_{\mathrm{LO}}}$$ averaged EW corr. factor

yields pathological behaviour when δ_{EW} is dominated by giant EW K-factors

- alternative/modified multiplicative ansatz:

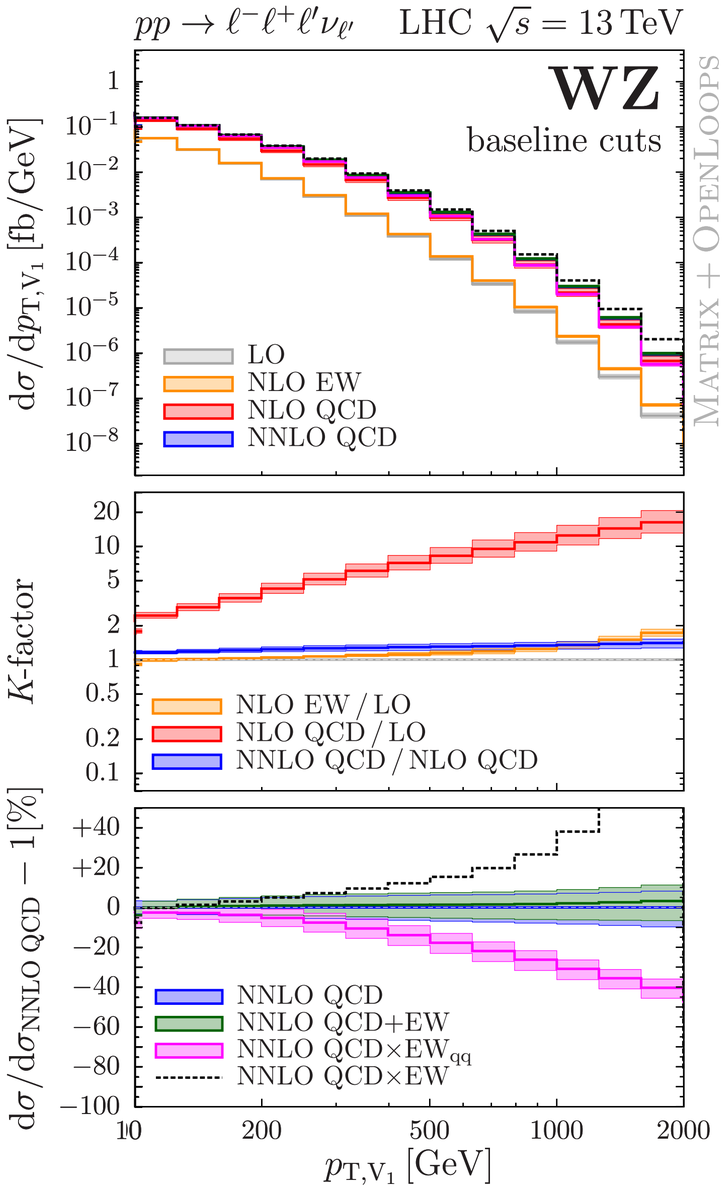
$$d\sigma_{\mathrm{NNLO\,QCD\times EW_{qq}}} = d\sigma^{q\bar{q}}_{\mathrm{LO}}\left(1+\delta^{q\bar{q}}_{\mathrm{QCD}}\right)\left(1+\delta^{q\bar{q}}_{\mathrm{EW}}\right) + d\sigma^{\gamma\gamma}_{\mathrm{LO}}\left(1+\delta^{\gamma\gamma/q\gamma}_{\mathrm{EW}}\right) + d\sigma^{gg}_{\mathrm{LO}}$$
$$= d\sigma_{\mathrm{NNLO\,QCD+EW}} + d\sigma_{\mathrm{LO}}\delta_{\mathrm{QCD}}\,\delta^{q\bar{q}}_{\mathrm{EW}}$$

yields behaviour consistent with EW Sudakov logs

- Thus: discard $d\sigma_{\mathrm{NNLO\,QCD\times EW}}$

- Caveat: splitting in $q\bar{q}$ and $\gamma\gamma/\gamma q$ channels is ad-hoc/scheme dependent

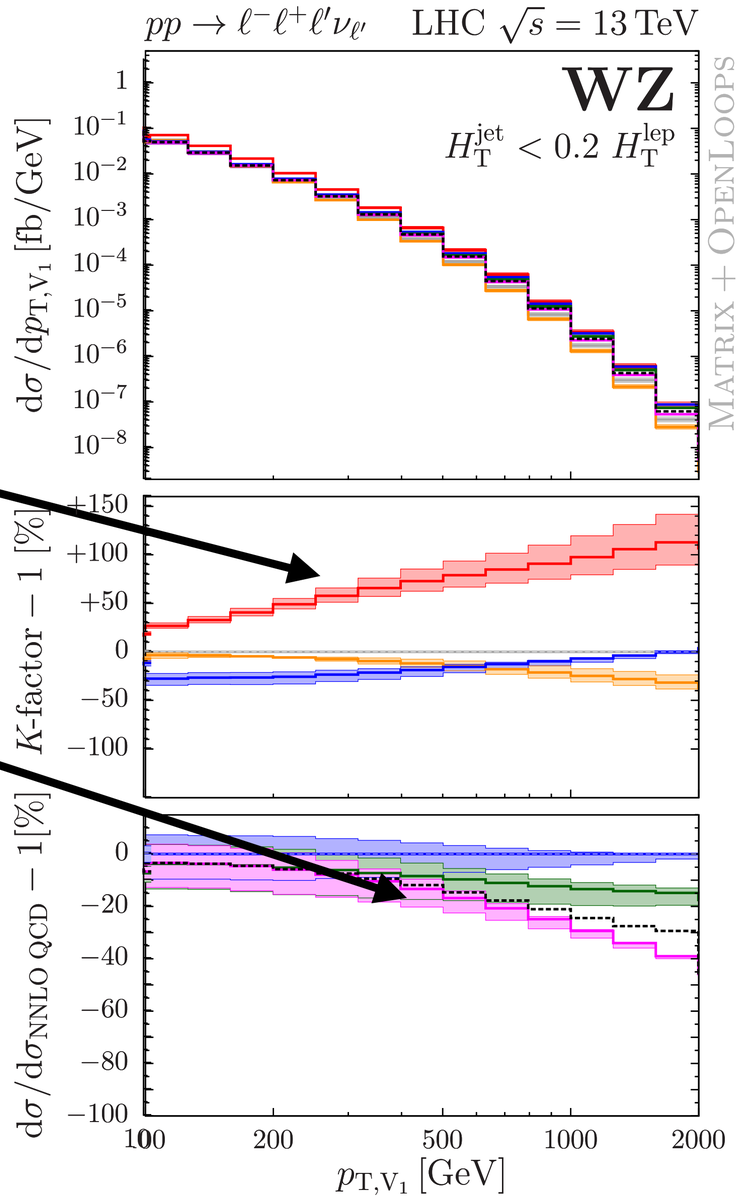
Giant QCD K-factors and EW corrections: pTV1



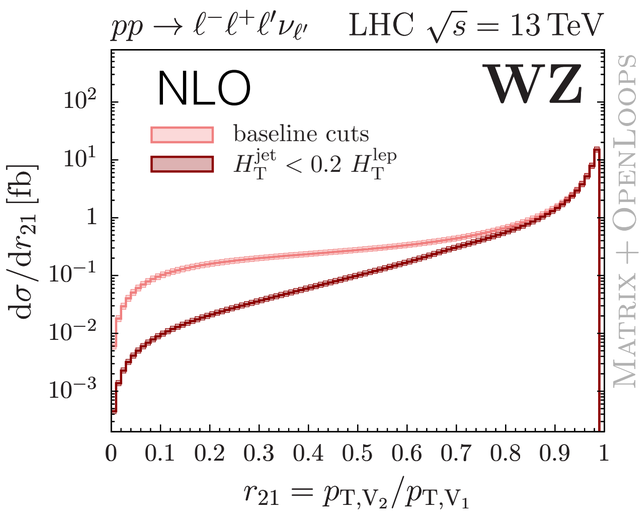
jet veto

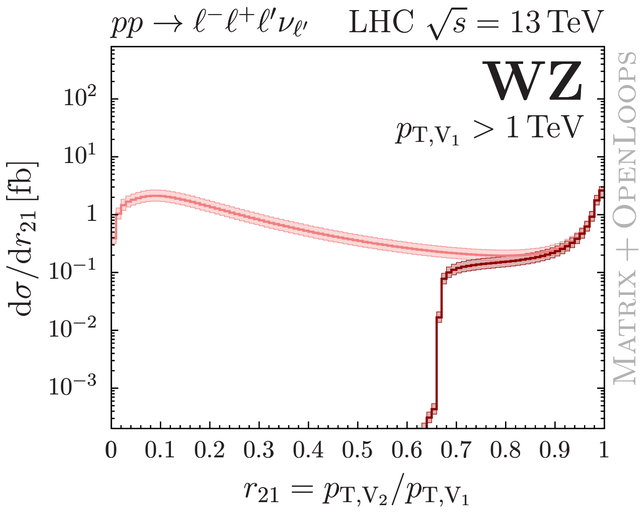
$$H_T^{jet} < 0.2\, H_T^{lep}$$

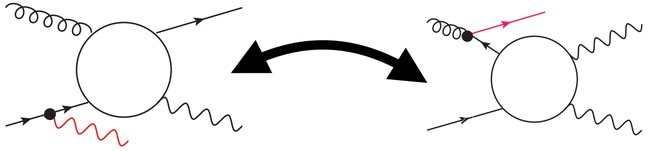
- NLO QCD/LO=~<1.5 ("normal K-factor")
- small differences between the two multiplicative combinations
  ➡check!
- consistent results for all processes
- In case we are now really dominated by VV topologies: multiplicative dominations should be seen as superior
  ➡check!



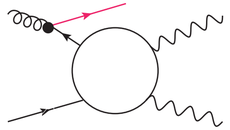
Giant K-factors and effect of jet veto



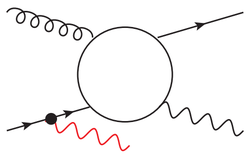




- at r21 → 1: hard-VV topologies



- at r21 → 0: hard-Vj topologies



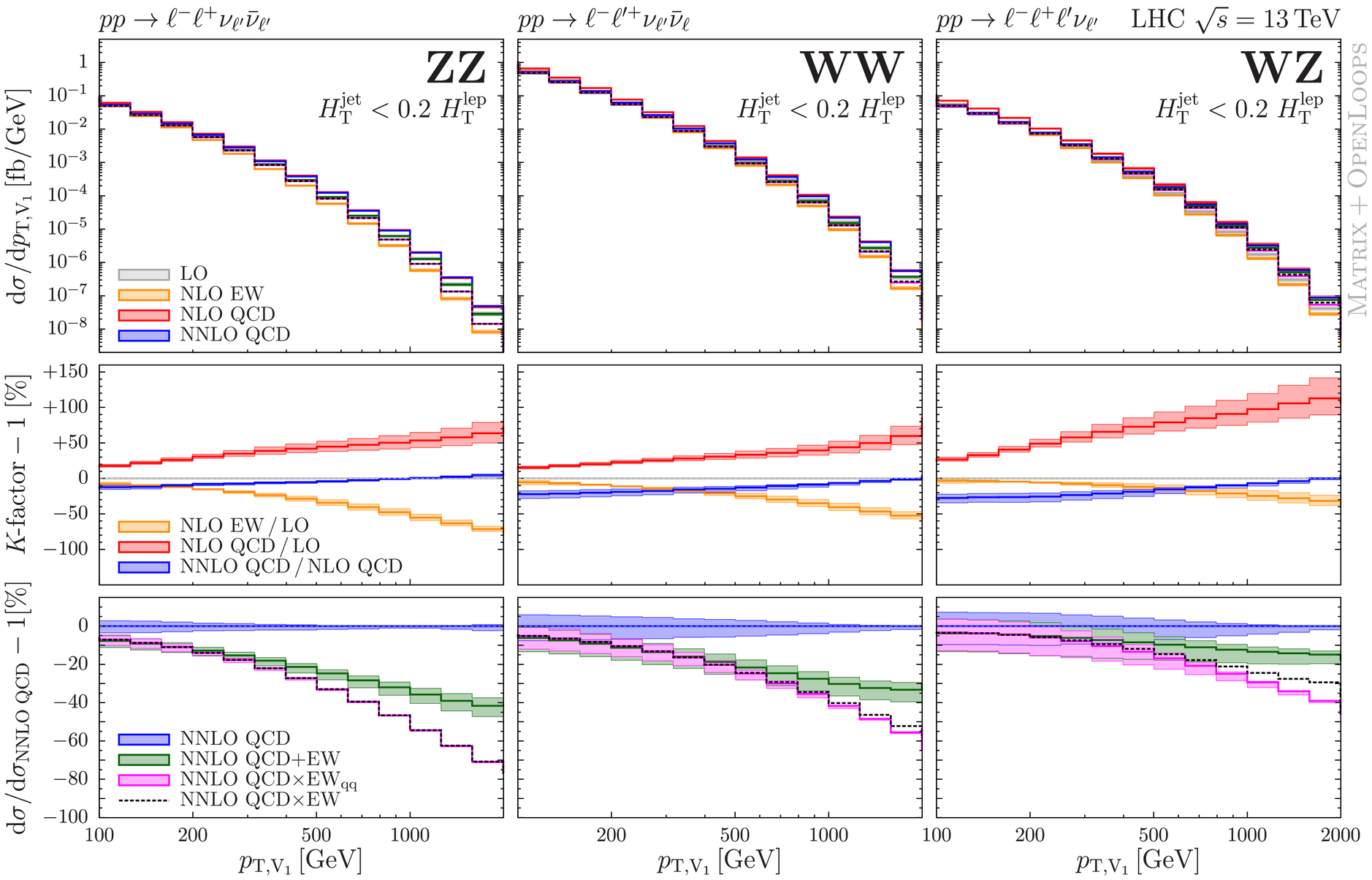
- for pTV1 > 1 TeV: hard-Vj topologies dominate over hard-VV
- Jet veto $H_T^{jet} < \xi_{veto}\ H_T^{lep}$ corresponds to

$$p_{T,V_2} \geq \frac{1-\xi_{veto}}{1+\xi_{veto}}\, p_{T,V_1} = \frac{2}{3}\, p_{T,V_1} \qquad \text{for} \quad \xi_{veto} = 0.2$$

(violated by off-shell topologies)

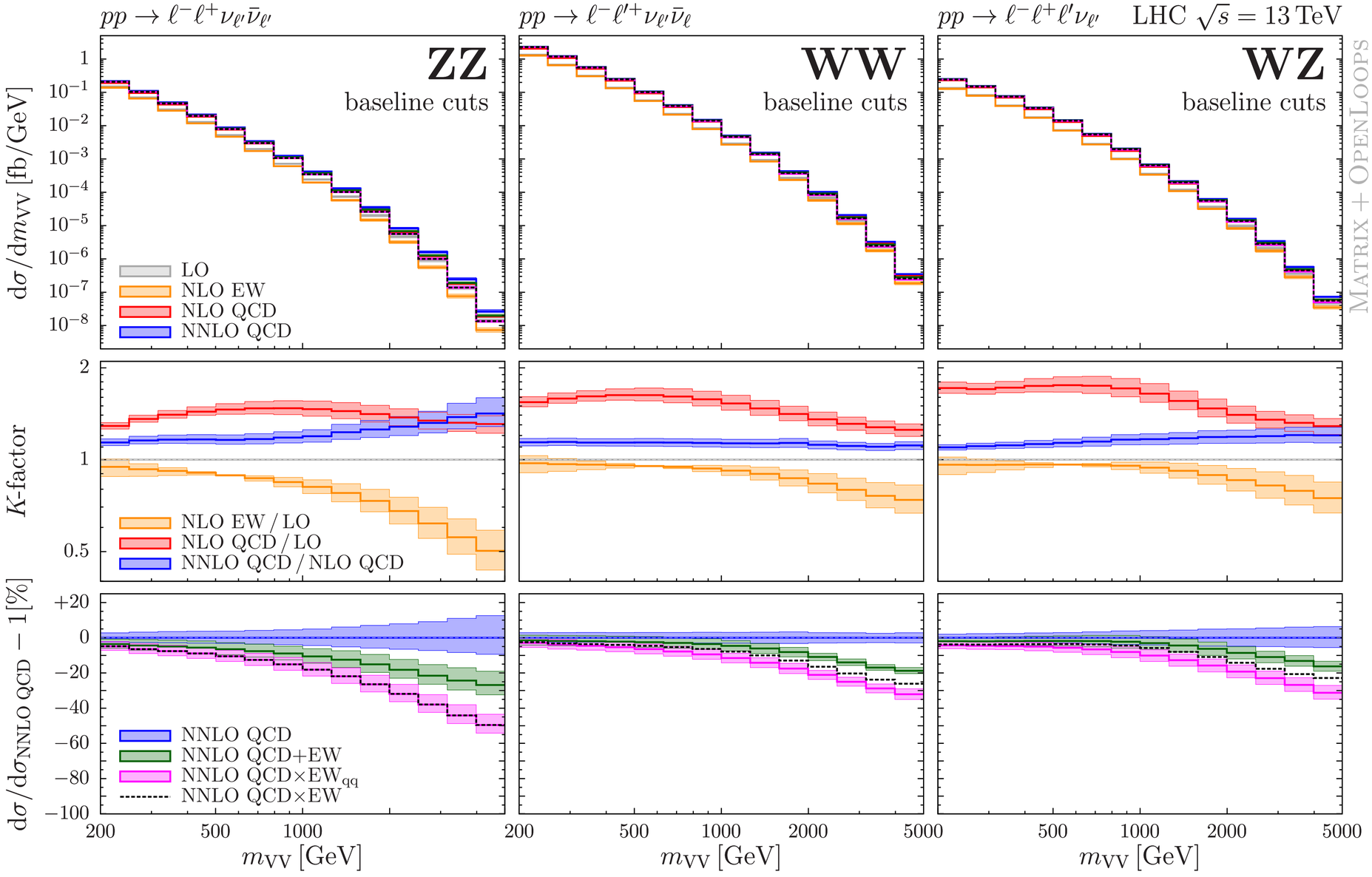
- Jet veto results in phase-space dominated by hard-VV

Giant QCD K-factors and EW corrections: pTV1



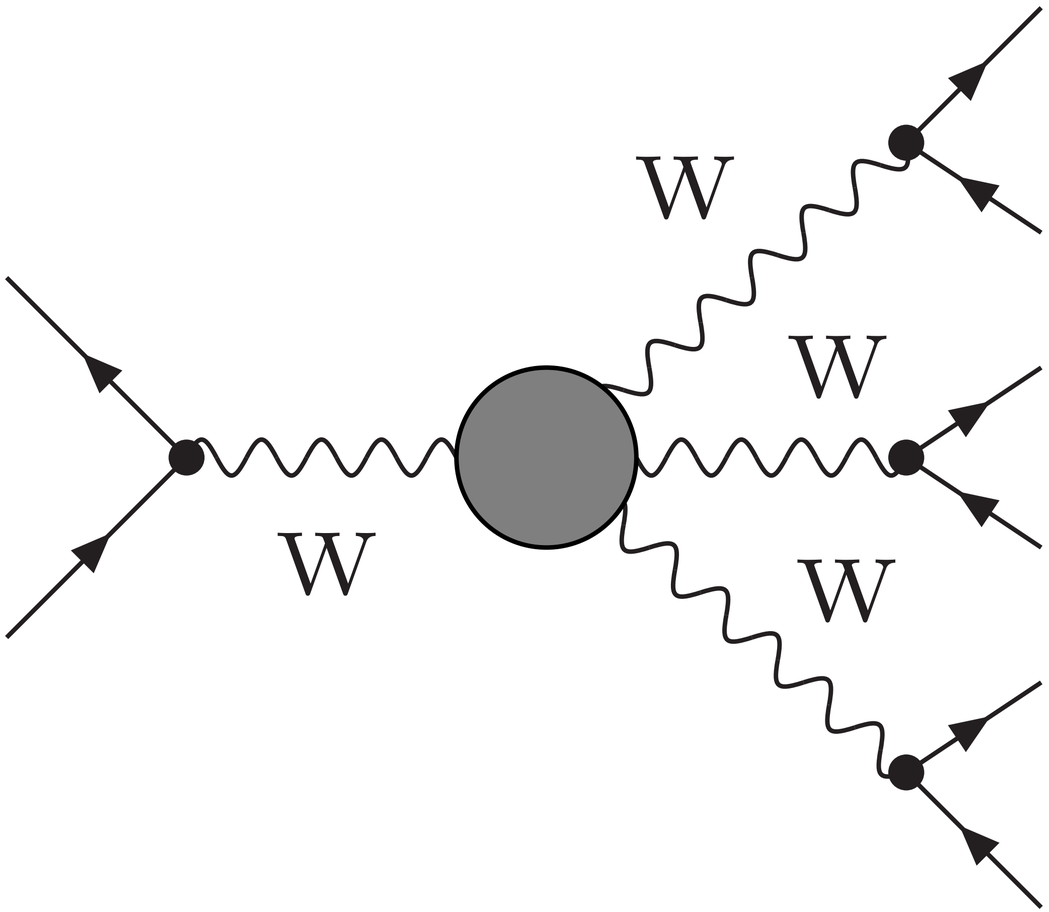
- consistent picture amongst all processes
- multiplicative combinations should be seen as superior

NNLO QCD + NLO EW for dibosons: mVV



- NLO QCD/LO = 30-70%
- NNLO QCD/NLO = 10-20%
- NLO EW = -30/-20/-20% at 2 TeV
- multiplicative combinations should be seen as superior

Tribosons



Triboson production calculations

NLO QCD

- on-shell fixed-order — Binoth et.al. arXiv:0804.0350
  off-shell fixed-order — Campanario et.al. arXiv:0809.0790
  $\rightarrow$ available in aut. tools (MG5_aMC, SHERPA+OPENLOOPS/RECOLA)
- on-shell matched to parton showers in SHERPA,
  multijet merged $WWW + 0, 1j$ — Höche et.al. arXiv:1403.7516
- off-shell matched to parton showers should be available in automated tools (MG5_aMC, SHERPA+OPENLOOPS/RECOLA)

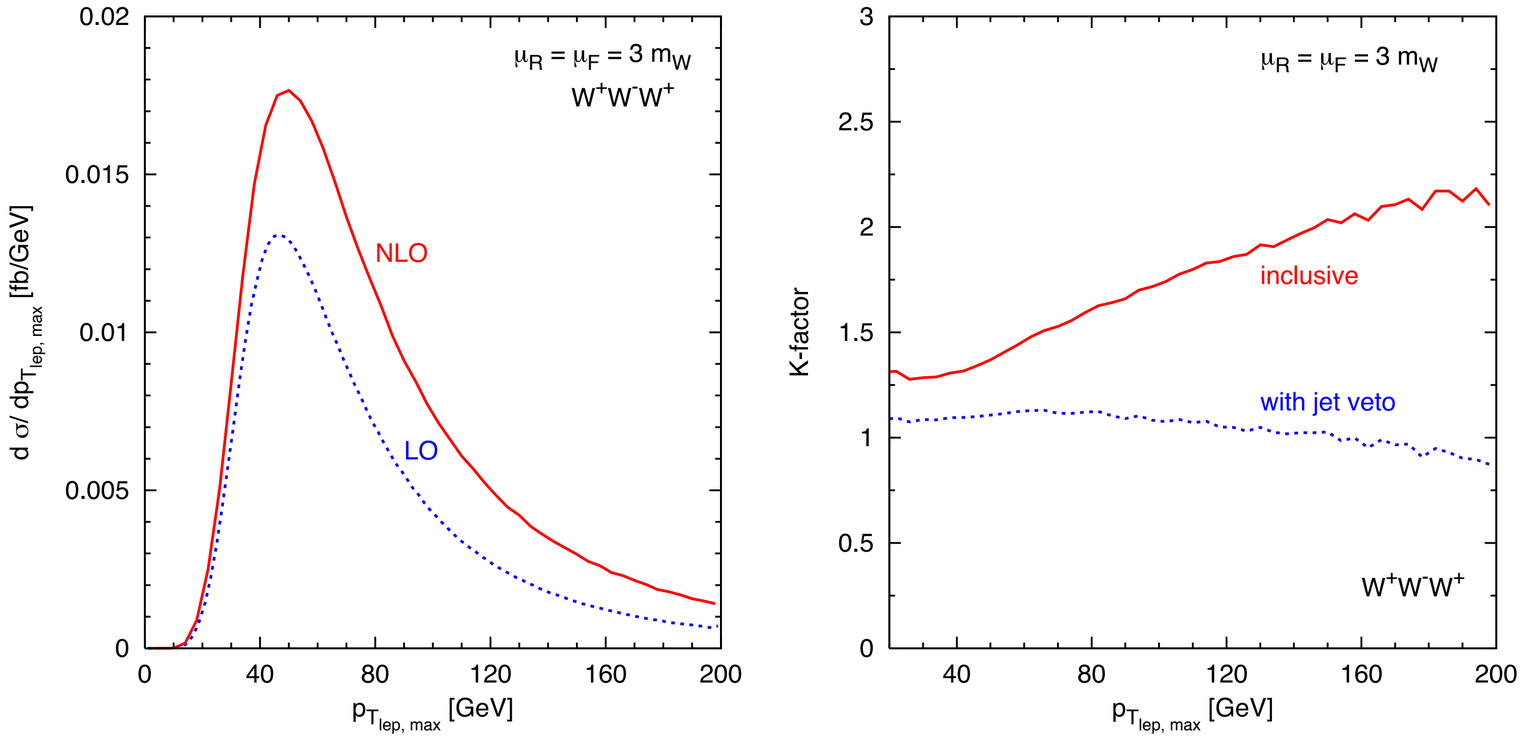
NLO EW

- on-shell known for some time — Yong-Bai et.al. arXiv:1605.00554
  Dittmaier, Huss, Knippen arXiv:1705.03722
- off-shell recently computed — MS arXiv:1806.00307
- no matching to parton showers available yet

[Slide: M. Schönherr]

Triboson production @ NLO QCD

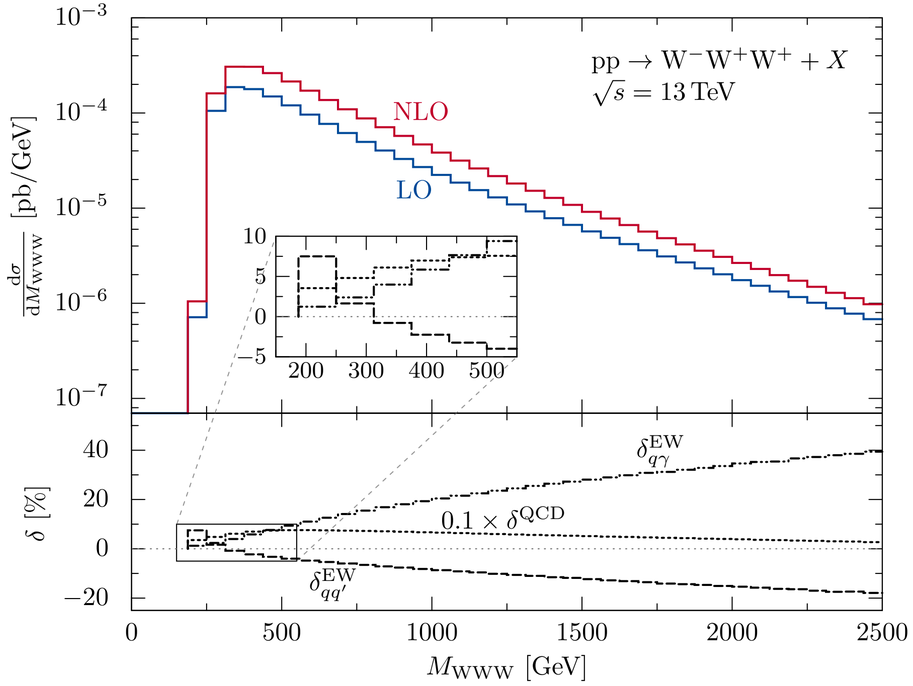
[Campanario et.al., '08]

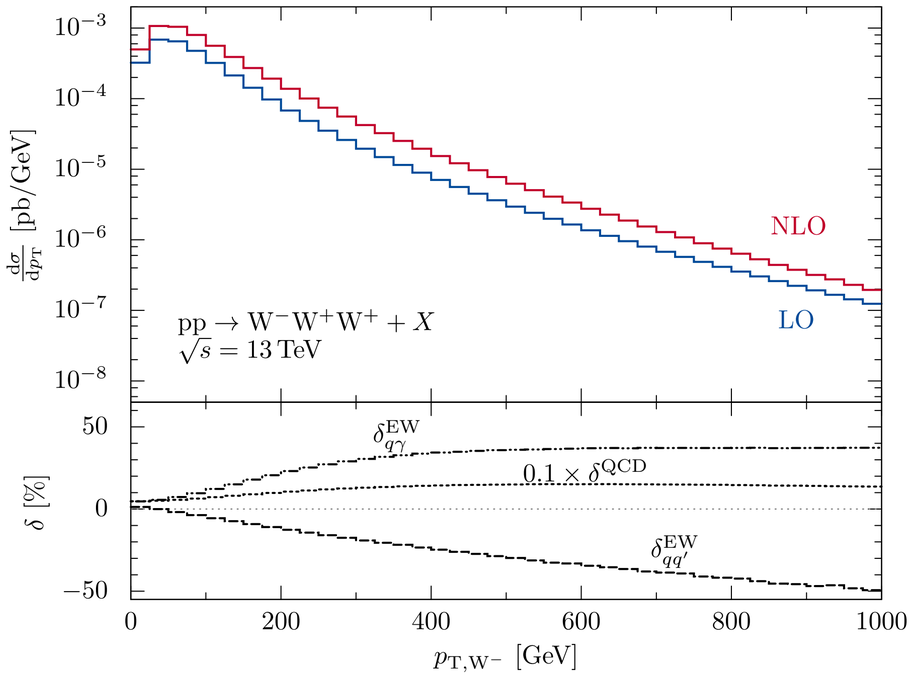


- QCD correction driven by additional jet activity: VV+jet topologies with soft V
  - → 'giant K-factors'
  - → strong observable dependence
  - → NLO mandatory
- jet veto (pT_{cut} = 50 GeV) reduces size and phase space dependence
  - → better: multi-jet merging

WWW @ NLO QCD+EW

Dittmaier, Huss, Knippen arXiv:1705.03722



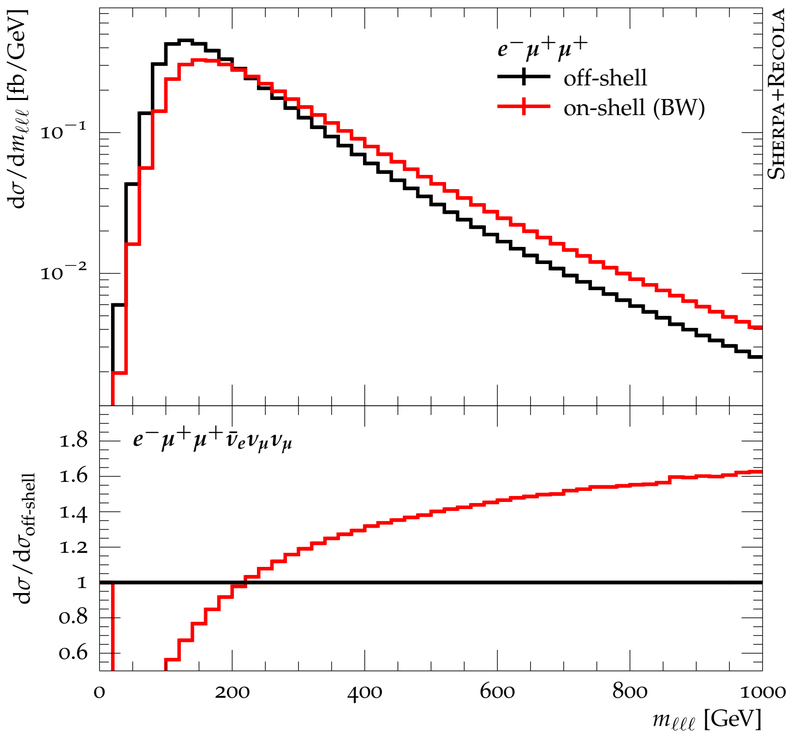


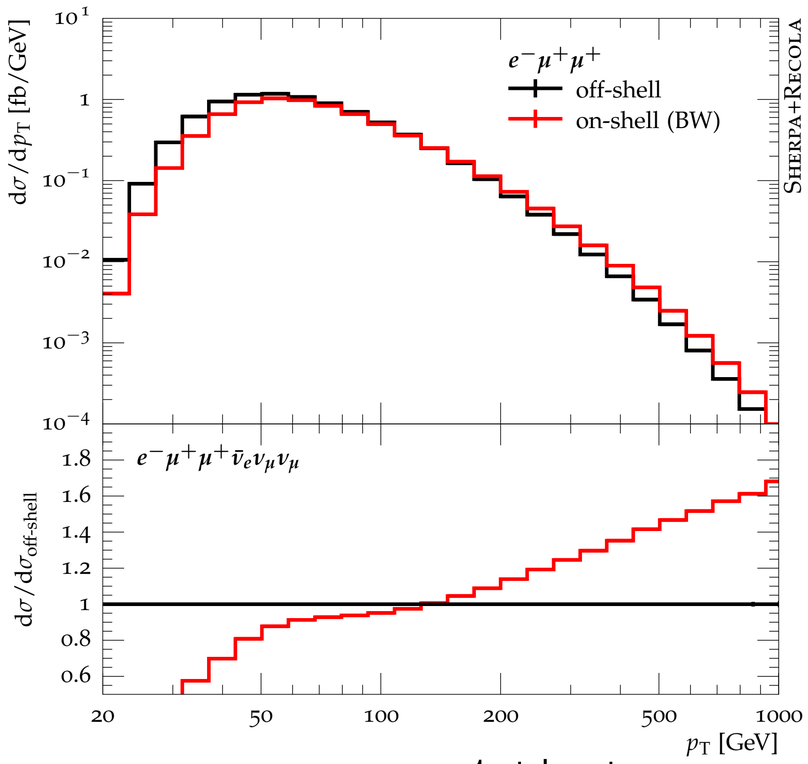
- corrections w/o jet veto
- QCD corrections $\approx$ 70%, slight observable dependence
- γ-induced EW corrections large and observable dependent
  $\to$ large accidental cancellations with EW corrections in $q\bar{q}$-channel

[Slide: M. Schönherr]

Triboson production: on-shell vs. off-shell

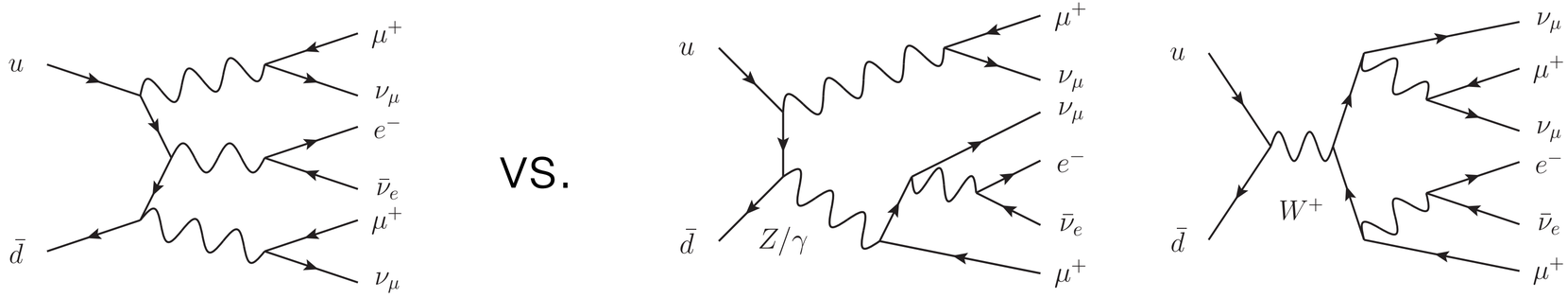
[M. Schönherr, '18]





1st lepton

- at large mlll and pT_{ll} large interference with other resonance structures



Off-shell VVV(3l+MET) production @ NLO EW

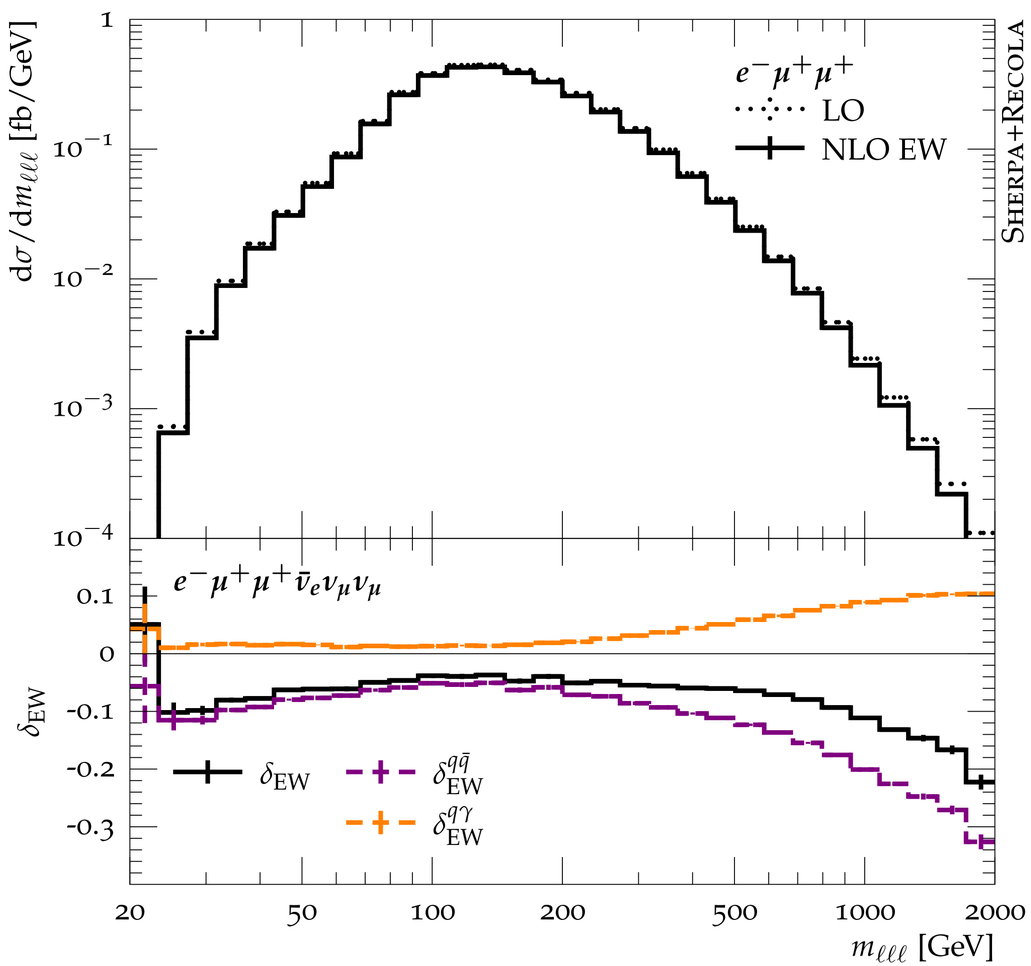
[M. Schönherr, '18]

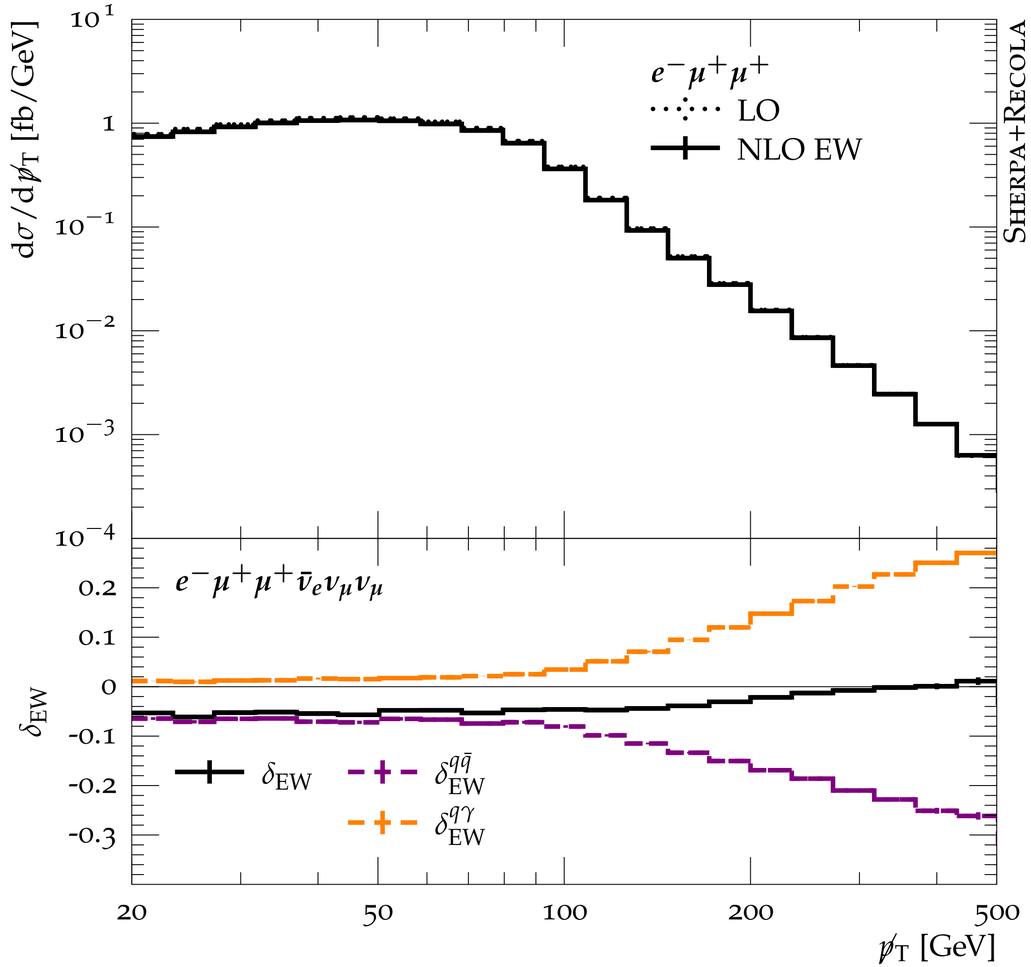
	inclusive			
	LO [fb]	δ_{EW}	$\delta^{\mathrm{EW}}_{q\bar{q}}$	$\delta^{\mathrm{EW}}_{q\gamma/\bar{q}\gamma}$
$\ell^-\ell^+\ell^+$	**0.4209**	**−2.0 %**	**−5.2 %**	**3.2 %**
$e^-e^+e^+$	0.0212	−3.4 %	−7.1 %	3.6 %
$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	0.0206	−3.4 %	−7.0 %	3.6 %
$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	0.0006	−5.4 %	−9.5 %	4.1 %
$e^-e^+\mu^+$	0.0938	−1.4 %	−5.4 %	4.1 %
$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	0.0924	−1.4 %	−5.4 %	4.1 %
$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	0.0007	−2.9 %	−6.1 %	3.2 %
$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	0.0007	−2.7 %	−6.2 %	3.5 %
$e^-\mu^+\mu^+$	0.0955	−2.2 %	−4.6 %	2.4 %
$e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu$	0.0955	−2.2 %	−4.6 %	2.4 %

- large accidental and cut dependent cancellations of Sudadov-type neg. EW corrections and γ-induced pos. contribs w/ extra jet activity
- *WWW* channels receive smaller corrections than pure *WZZ* channels

Off-shell VVV production @ NLO EW

[M. Schönherr, '18]





- cancellations of EW corr. in qq and qγ channels highly observable dependent

Conclusions

- NNLO QCD + NLO EW available in **MATRIX+OpenLoops** for all (massive) diboson processes (soon public in MATRIX v2)

- QCD uncertainties at NNLO often reach 1-10% percent level.
- EW corrections enhanced at high energies reaching several tens of percent.
- In observables subject to 'giant K-factors': large $\mathcal{O}(\alpha_S \alpha)$ uncertainties
- Can be avoided via jet-veto.

- Open issues:
  - When measuring diboson processes at large pTV1/MET/mVV would it be beneficial to always consider a jet veto? Increased sensitivity to aTGCs?
  - How to obtain reliable inclusive predictions? In particular relevant for background simulations.
    - ➡ MEPS@NLO multi-jet merging including EW corrections (see V+jets, 1511.08692)
    - ➡ how to retain NNLO QCD precision?
  - Rigorous estimate of remaining $\mathcal{O}(\alpha_S \alpha)$
  - How to improve on $\mathcal{O}(\alpha^2)$?

BACKUP

NNLO QCD corrections vor VV

All VV processes known through NNLO QCD:

→ inclusive/on-shell Z,W & differential/off-shell Z,W (leptonic)

γγ - inclusive and differential [Catani, Cieri, de Florian, Ferrera, Grazzini '12], [Campbell, Ellis, Li, Williams '16], [Grazzini, Kallweit, MW '17]

Zγ - inclusive/on-shell and differential/off-shell
[Grazzini, Kallweit, Rathlev, Torre '13], [Grazzini, Kallweit, Rathlev '15]; see also: [Campbell et al. '17]

Wγ - inclusive/on-shell and differential/off-shell
[Grazzini, Kallweit, Rathlev, Torre '13], [Grazzini, Kallweit, Rathlev '15]

ZZ - inclusive/on-shell [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14]; see also: [Heinrich et al. '17]
- differential/off-shell [Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]

WW - inclusive/on-shell [Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, et al. '14]
- differential/off-shell [Grazzini, Kallweit, Pozzorini, Rathlev, MW '15]

WZ - inclusive/on-shell [Grazzini, Kallweit, Rathlev, MW '16]
- differential/off-shell [Grazzini, Kallweit, Rathlev, MW '17]

Combination of NNLO QCD and NLO EW

- In Matrix+OpenLoops all (massive) diboson processes are available at NNLO QCD + NLO EW (parton-level) *[M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; very soon]*

4l-SF-ZZ	$pp \to \ell^+\ell^-\ell^+\ell^-$	(ZZ)
4l-DF-ZZ	$pp \to \ell^+\ell^-\ell'^+\ell'^-$	(ZZ)
2l-SF-ZZ	$pp \to \ell^+\ell^-\nu_{\ell'}\bar{\nu}_{\ell'}$	(ZZ)
2l-SF-ZZWW	$pp \to \ell^+\ell^-\nu_{\ell}\bar{\nu}_{\ell}$	(ZZ/WW)
2l-DF-WW	$pp \to \ell^+\ell'^-\nu_{\ell}\bar{\nu}_{\ell'}$	(WW)
3l-SF-WZ	$pp \to \ell^+\ell^-\ell\nu_{\ell}$	(WZ)
3l-DF-WZ	$pp \to \ell^+\ell^-\ell'\nu_{\ell'}$	(WZ)

(soon to be made public)

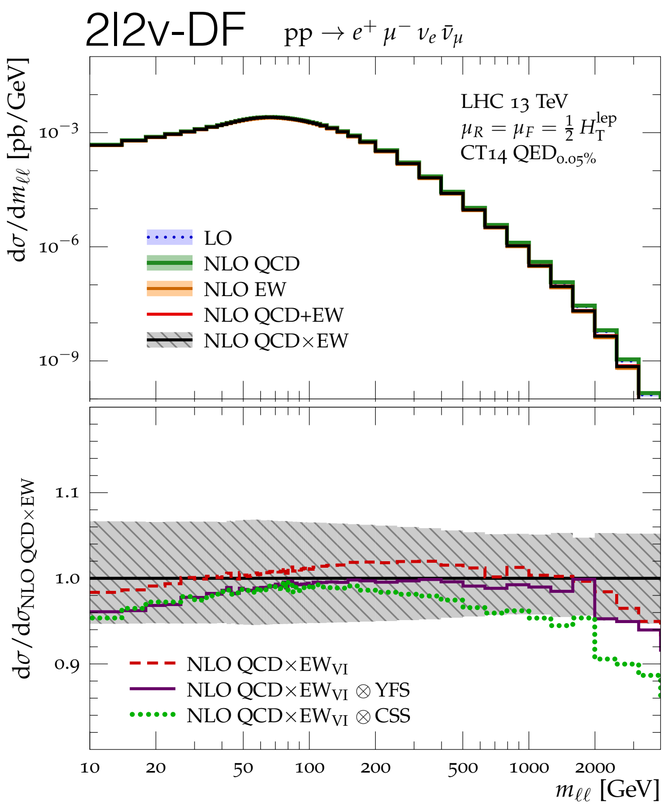
- Combination of QCD and EW

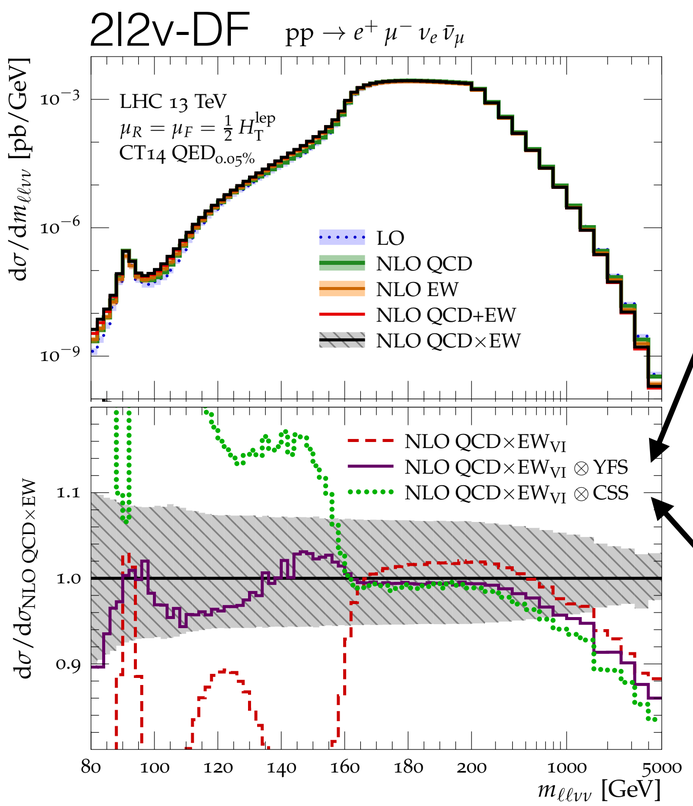
additive: $$\mathbf{d\sigma^{(N)NLO}_{QCD+EW}} = \mathbf{d\sigma^{LO}}(1 + \boldsymbol{\delta}^{\mathbf{(N)NLO}}_{\mathbf{QCD}} + \boldsymbol{\delta}_{\mathbf{EW}}) + \mathbf{d\sigma^{ggLO}}$$

multiplicative: $$\mathbf{d\sigma^{(N)NLO}_{QCD\times EW}} = \mathbf{d\sigma^{LO}}(1 + \boldsymbol{\delta}^{\mathbf{(N)NLO}}_{\mathbf{QCD}})(1 + \boldsymbol{\delta}_{\mathbf{EW}}) + \mathbf{d\sigma^{ggLO}}$$

Diboson production at NLO QCD+EW: Collinear QED radiation

[Kallweit, JML, Pozzorini, Schönherr; '17]





YFS (Multi-Photon-Resummation) **preserves resonance structure** → EW effects agree at the few percent level.

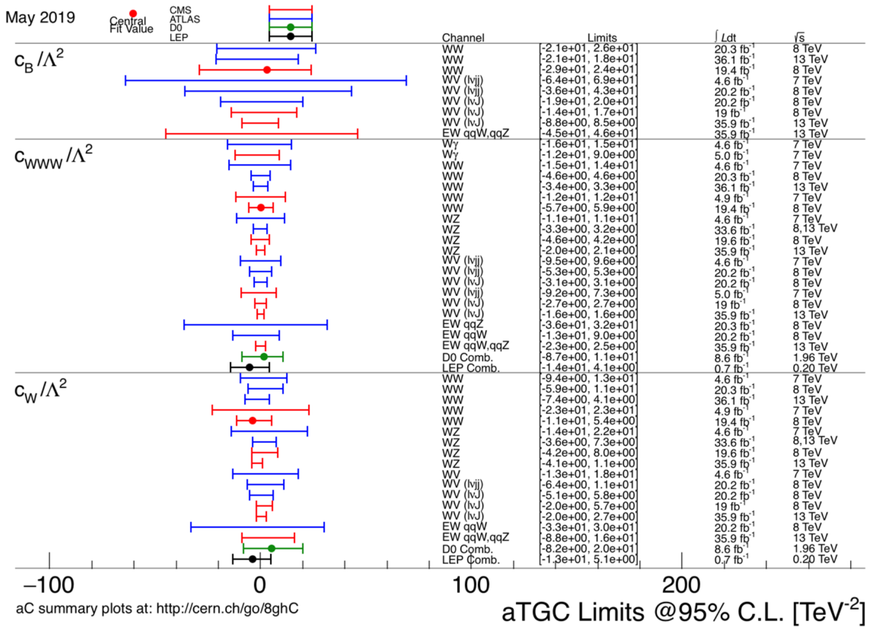
Source of differences:
- Multi-poton effects in YFS
- Resonance-assignment in YFS

CSS (Catani-Seymour-Shower) unaware of resonance structure → QED effects largely overestimated

- **Fully consistent PS matching at NLO EW under development**
- Naive NLO EW+PS matching available in Sherpa+OpenLoops (applicable at particle level)
  - ➡CSS dipole shower (not resonaonce aware) ⇒ significant mismodelling
  - ➡YFS resummation **(resonaonce aware)** ⇒ valid approximation

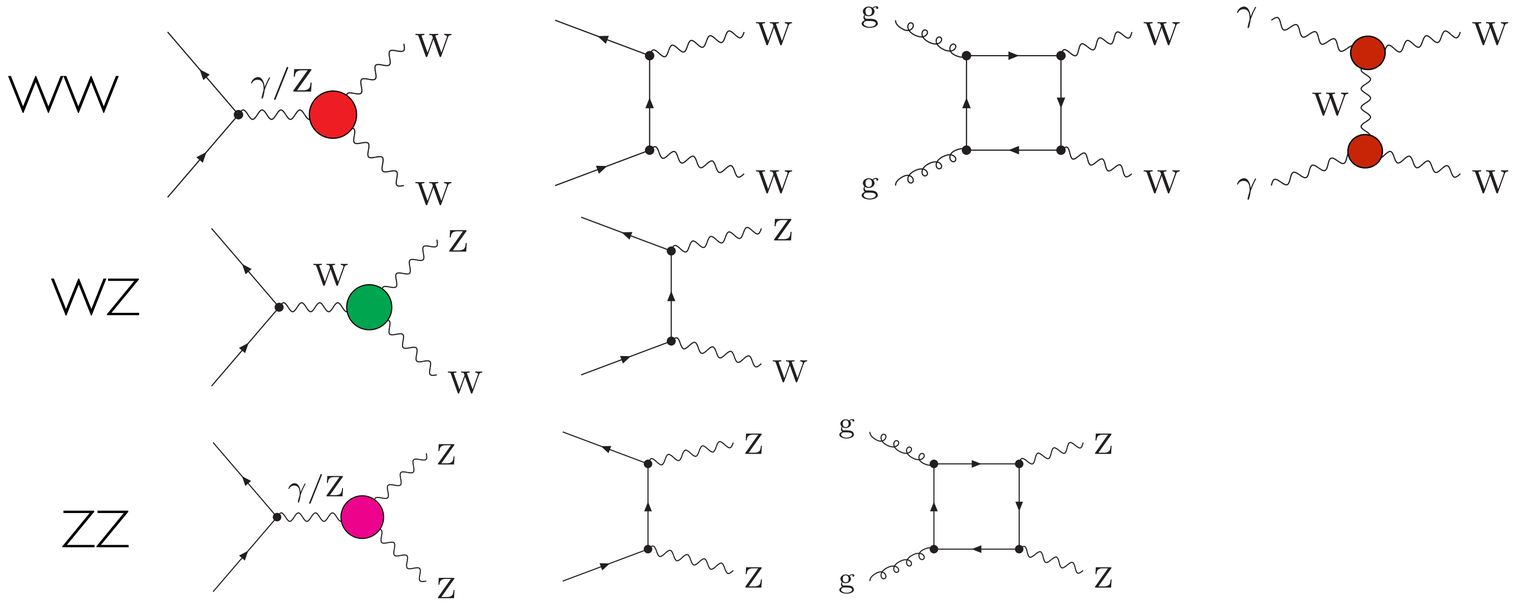
Stress-testing aTGCs

From: VV + VBF-V



$$\mathcal{O}_W = D_\mu h^\dagger W^{\mu\nu} D_\nu h$$
$$\mathcal{O}_B = D_\mu h^\dagger B^{\mu\nu} D_\nu h$$
$$\mathcal{O}_{WWW} = \mathrm{Tr}\left(W_{\mu\nu} W^{\nu\rho} W_\rho^\mu\right)$$

Complementarity in WW / WZ / ZZ production



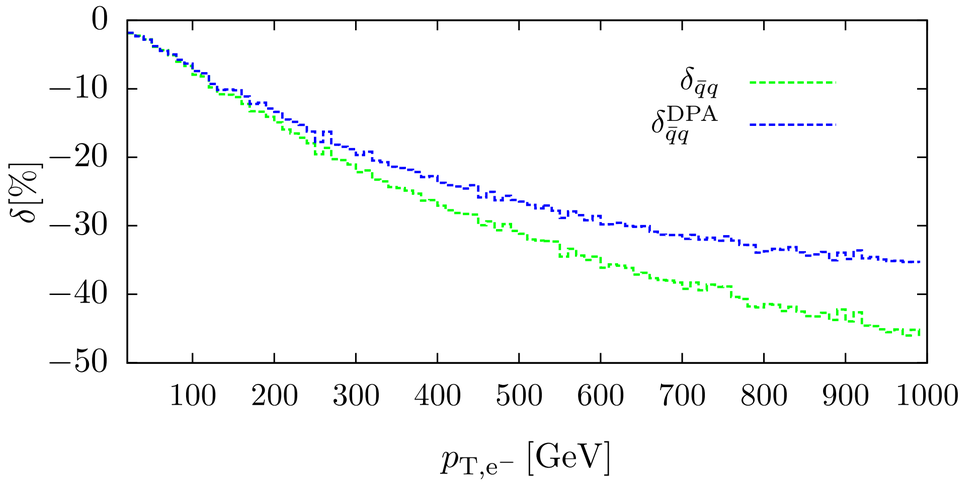
Sensitivity to different aTGCs:

- overlay of γWW/ZWW in WW
- only ZWW inWZ
- γZZ/ZZZ in ZZ

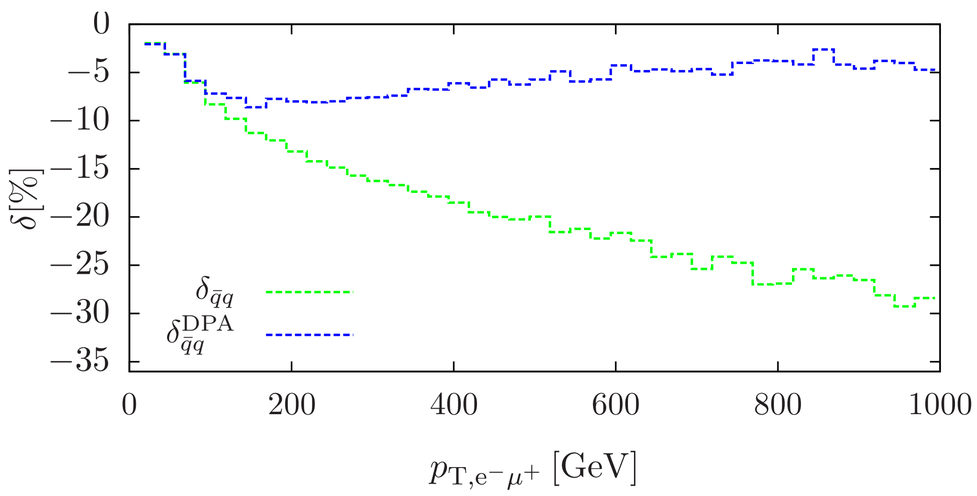
The need for off-shell calculations

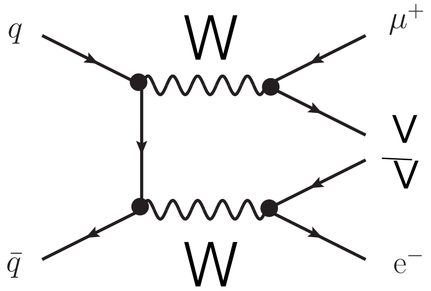
[Biedermann, M. Billoni, A. Denner, S. Dittmaier, L. Hofer, B. Jäger, L. Salfelder ;'16]

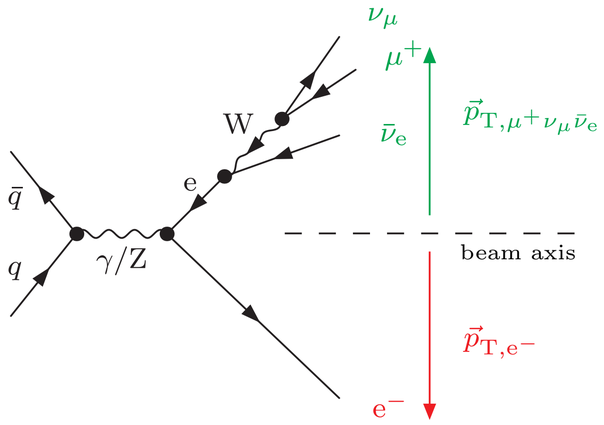
2l-DF-WW

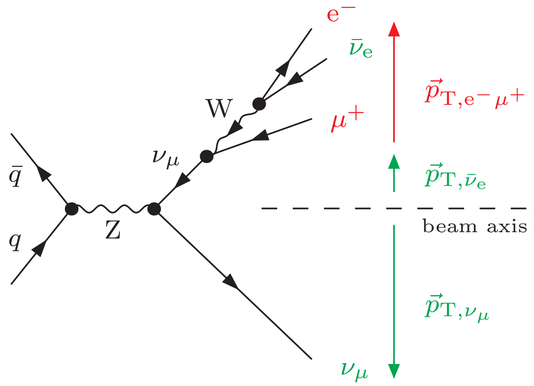


2l-DF-WW





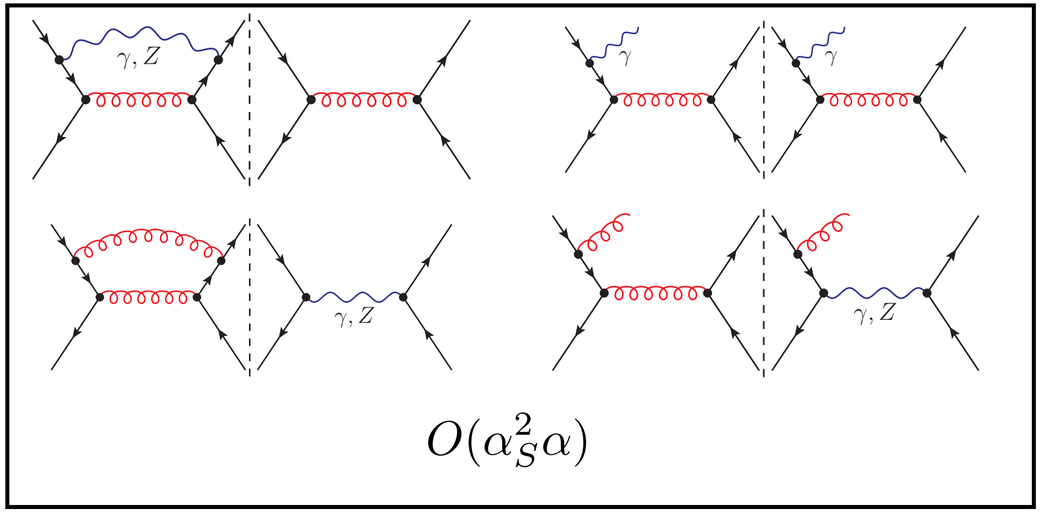




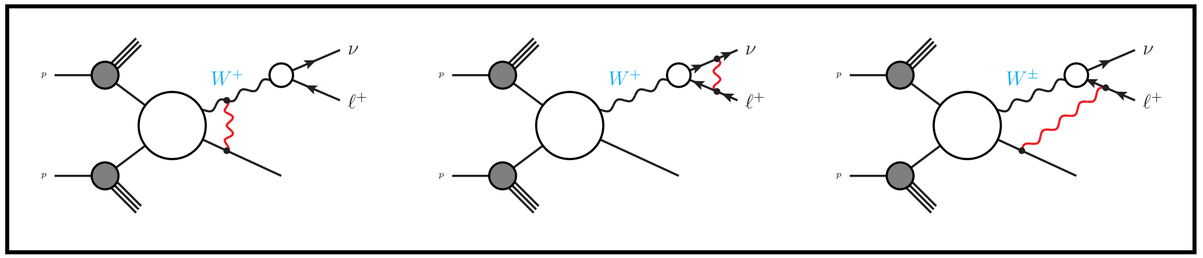
➡ sizeable differences in fully off-shell vs. double-pole approximation in tails

Nontrivial features in NLO QCD → NLO EW

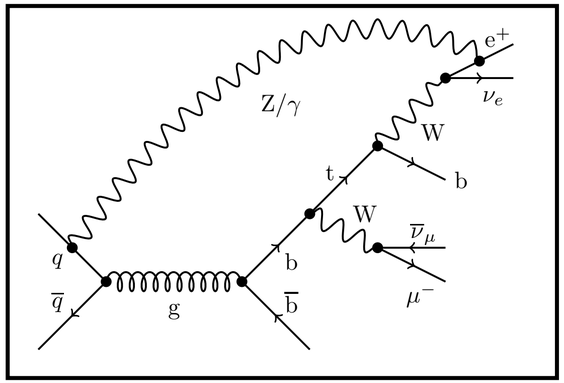
1. **QCD-EW interplay**



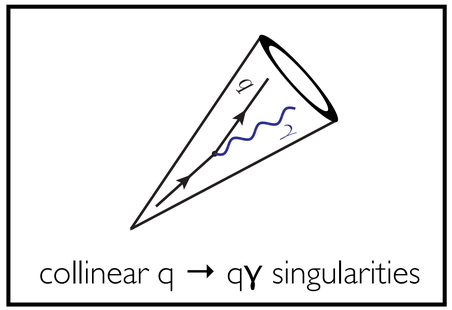
2. At NLO EW corrections in production, decay and non-factorizable contributions for V decays
   → **complex-mass-scheme**



3. **virtual EW corrections** more involved than QCD (many internal masses)



4. photon contributions in jets and proton
   → **photon-jet separation, γPDF**



collinear q → qγ singularities

Automation of fixed-order NLO EW well advanced:
MadGraph_aMC@NLO, Sherpa+OpenLoops/Recola, MUNICH+OpenLoops, …

Validation between tools

- 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]

individual phase-space points:

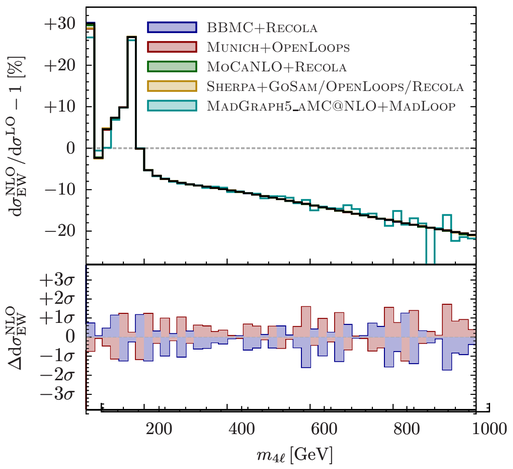
$$u\bar{u} \to e^+e^-\mu^+\mu^-$$

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

inclusive cross sections:

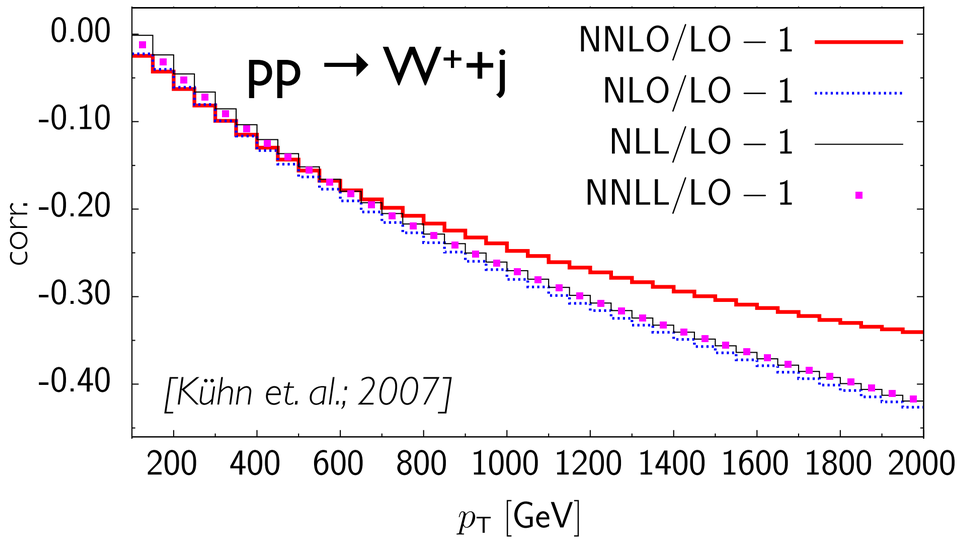


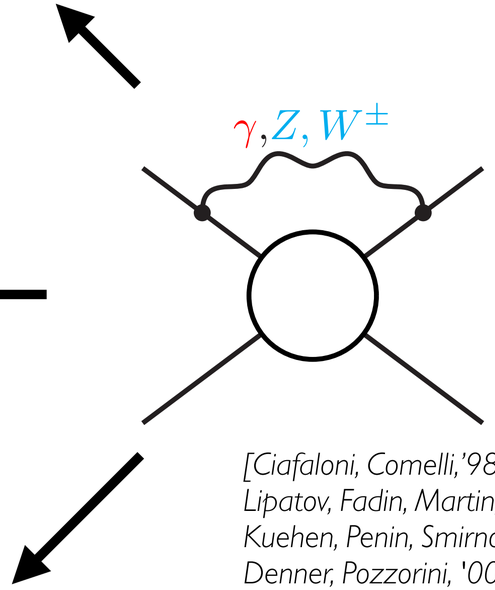
→very convincing agreement between automated tools

Relevance of EW higher-order corrections I

Numerically $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \Rightarrow$ **NLO EW ~ NNLO QCD**

Possible large (negative) enhancement due to soft/collinear **logs** from virtual EW gauge bosons:





[Ciafaloni, Comelli,'98; Lipatov, Fadin, Martin, Melles, '99; Kuehen, Penin, Smirnov, '99; Denner, Pozzorini, '00]

Universality and factorisation: *[Denner, Pozzorini; '01]*

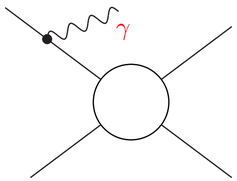
$$\delta\mathcal{M}^{1-\text{loop}}_{\text{LL+NLL}} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^\pm} I^a(k)I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\text{ew}}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

➜ **overall large effect in the tails of distributions: p_T, m_{inv}, H_T,…**

Relevance of EW higher-order corrections II

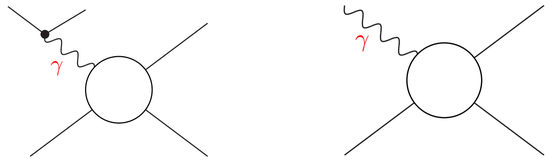
Real photon radiation

- soft/coll. photon unresolved
- needed to cancel QED singularities



Photon initial states

- QED factorisation needed to absorb IS photon singularities
- possible strong enhancement, e.g. for VV



Real W,Z,h radiation (HBR)

- partial cancellation with virtual Sudakov logs (KLN theorem not applicable)
  (strongly dependent on experimental selection)
- free from singularities $\Longrightarrow$ separate processes
- themselves receive large virtual EW corrections
  & inclusion requires care (double-counting issues)