Multibosons: Theory overview

Jonas M. Lindert

University of Sussex

Science & Technology Facilities Council | UK Research and Innovation

LHC EW WG General Meeting
16. Feb 2022

Multibosons

VV VVV

VBF-V VBS-VV

Multibosons

VV $\xrightarrow{\text{background}}$ VVV

VV $\searrow$ background $\rightarrow$ VBS-VV

VBF-V $\xrightarrow{\text{background}}$ VBS-VV

Multibosons

V+jet

VV →(background)→ VVV

VV →(background)→ VBS-VV

V+jet →(background)→ VBF-V

VBF-V →(background)→ VBS-VV

VBF-V ⟷(forward-jet dynamics)⟷ VBS-VV
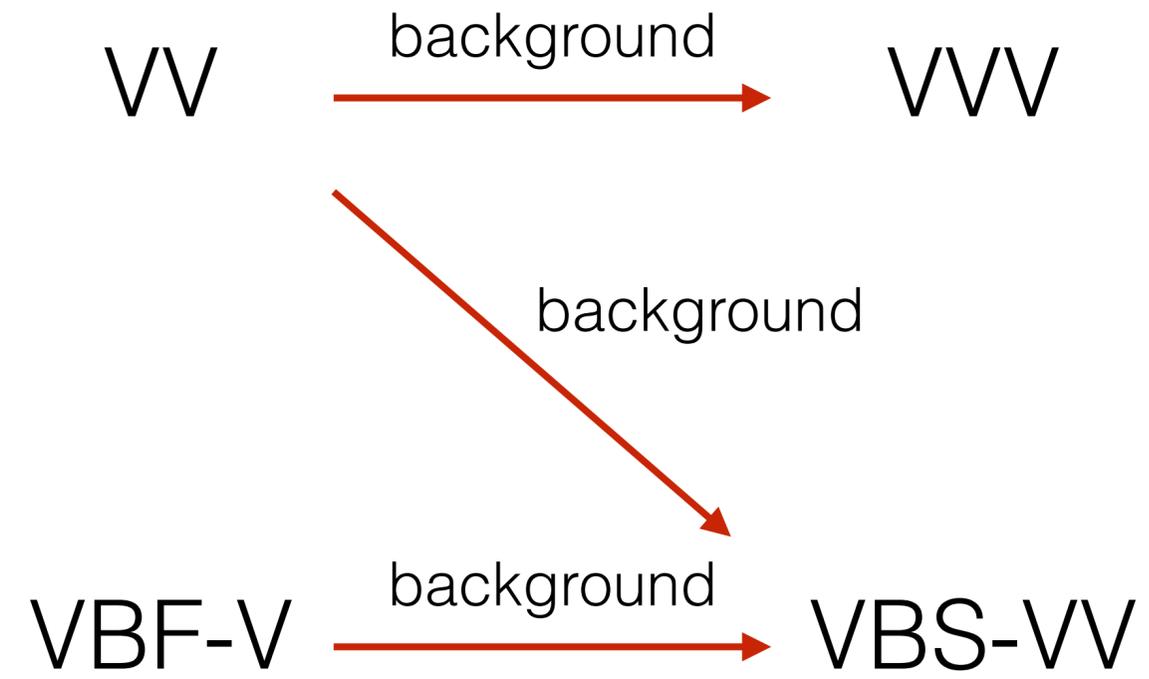
Multibosons

Multibosons

V+jet

VV

VVV

multi-lepton dynamics, giant QCD K-factors

background

background

background

VBF-V

VBS-VV

background

forward-jet dynamics

aTGC

aQGC
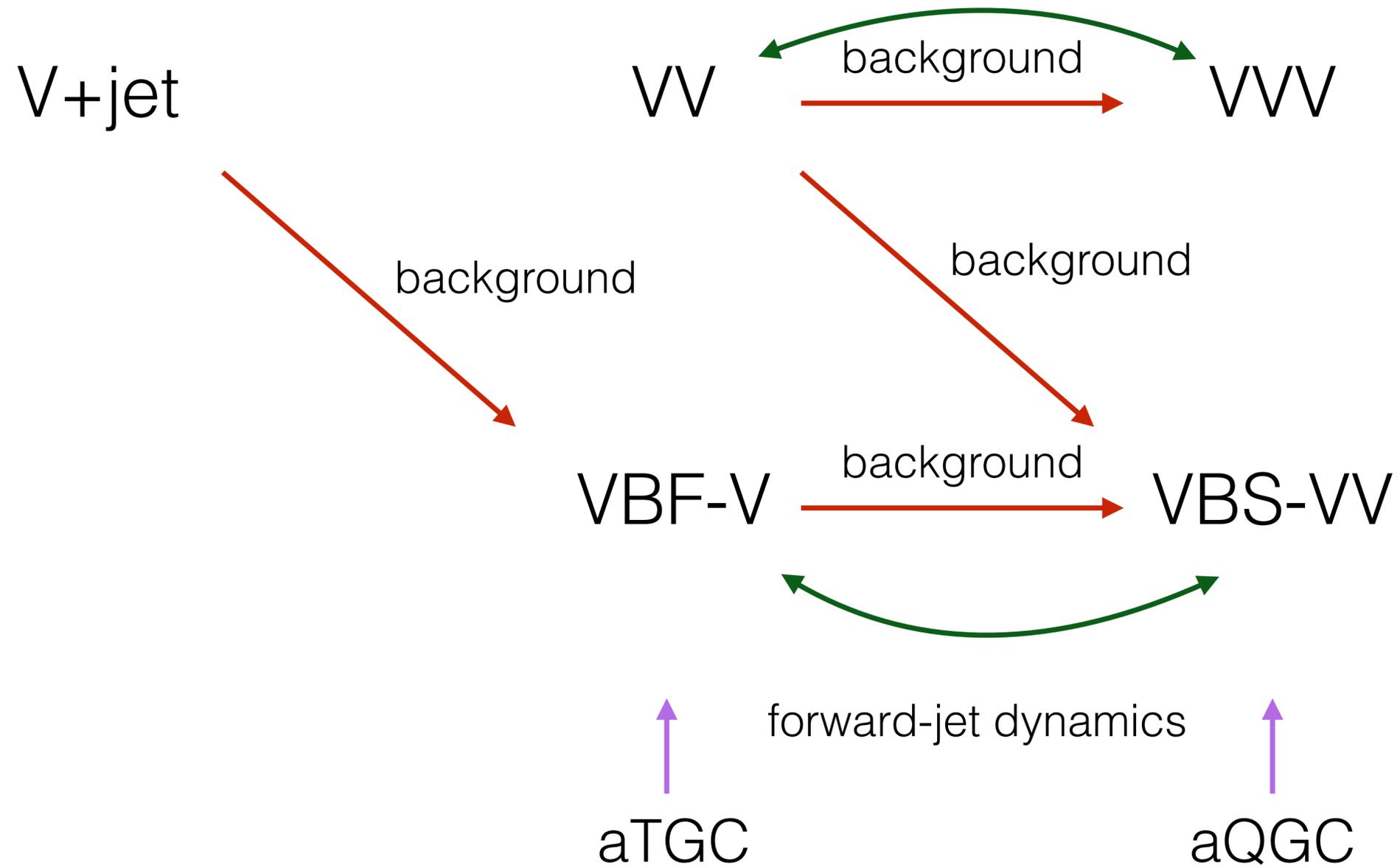
Multibosons: theory state-of-the art fixed-order

V+jets

NLO QCD+NLO EW

VV

NNLO QCD+NLO EW

VVV

NLO QCD+NLO EW

VBF-V

NLO QCD*+LO EW

VBS-VV

NLO QCD+NLO EW / NLO QCD*+LO EW

*: VBF approximation

Multibosons: theory state-of-the art

V+jets

NLO QCD+NLO EW

NLOPS QCD

Talk by Wiesemann

Talk by Pelliccioli: polarised multiboson

VV

NNLO QCD+NLO EW

NNLOPS QCD

NLOPS QCD + EW

VVV

NLO QCD+NLO EW

NLOPS QCD

VBF-V

NLO QCD*+LO EW

NLOPS* QCD

VBS-VV

NLO QCD+NLO EW / NLO QCD*+LO EW

NLOPS* QCD

NLOPS EW

*: VBF approximation

Perturbative expansion: VV, VVV

(single perturbative order at LO)

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

NLO QCD   NLO EW

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

NNLO QCD   NNLO EW   NNLO QCD-EW

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

N3LO QCD

Perturbative expansion: VV, VVV

(single perturbative order at LO)

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

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

scale variation at NNLO

scheme variation, e.g. Gmu vs. a(mZ)
+
in case of EW Sudakov
dominance: exponentiation

NLO QCD + EW
vs.
NLO QCD x EW

NNLO QCD + NLO EW for dibosons: pTV2

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

$pp \to \ell^- \ell^+ \nu_{\ell'} \bar{\nu}_{\ell'}$

ZZ baseline cuts

- LO
- NLO EW
- NLO QCD
- NNLO QCD

- NLO EW / LO
- NLO QCD / LO
- NNLO QCD / NLO QCD

- NNLO QCD
- NNLO QCD+EW
- NNLO QCD×EW$_{qq}$
- NNLO QCD×EW

pTV2

NNLO QCD + NLO EW in Matrix+OpenLoops

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
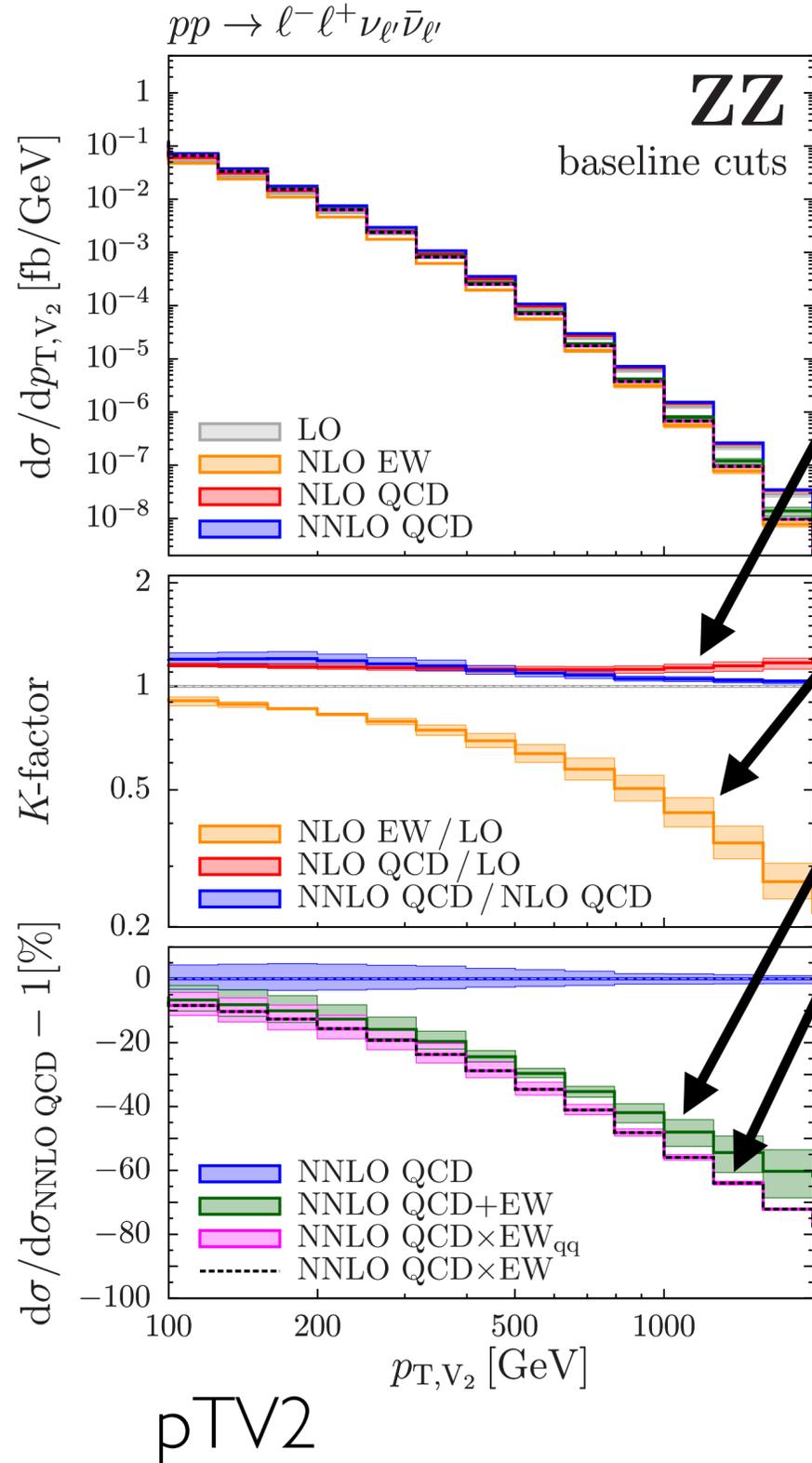
- moderate QCD corrections
  - ▶ NNLO/NLO QCD very small at large pTV2
  - ▶ NNLO QCD uncertainty: few percent

- NLO EW/LO=-(50-60)% @ 1 TeV

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

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

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

- difference very conservative upper bound on $\mathcal{O}(\alpha_S\alpha)$

- multiplicative/factorised combination clearly superior (EW Sudakov logs × soft QCD)

- dominant uncertainty at large pTV2: $\mathcal{O}(\alpha^2) \sim \alpha_{\text{w}}^2 \log^4(Q^2/M_W^2)$

  Estimate: $\boxed{\dfrac{1}{2}\delta_{\text{EW}}^2}$

NNLO QCD + NLO EW for dibosons: pTV2
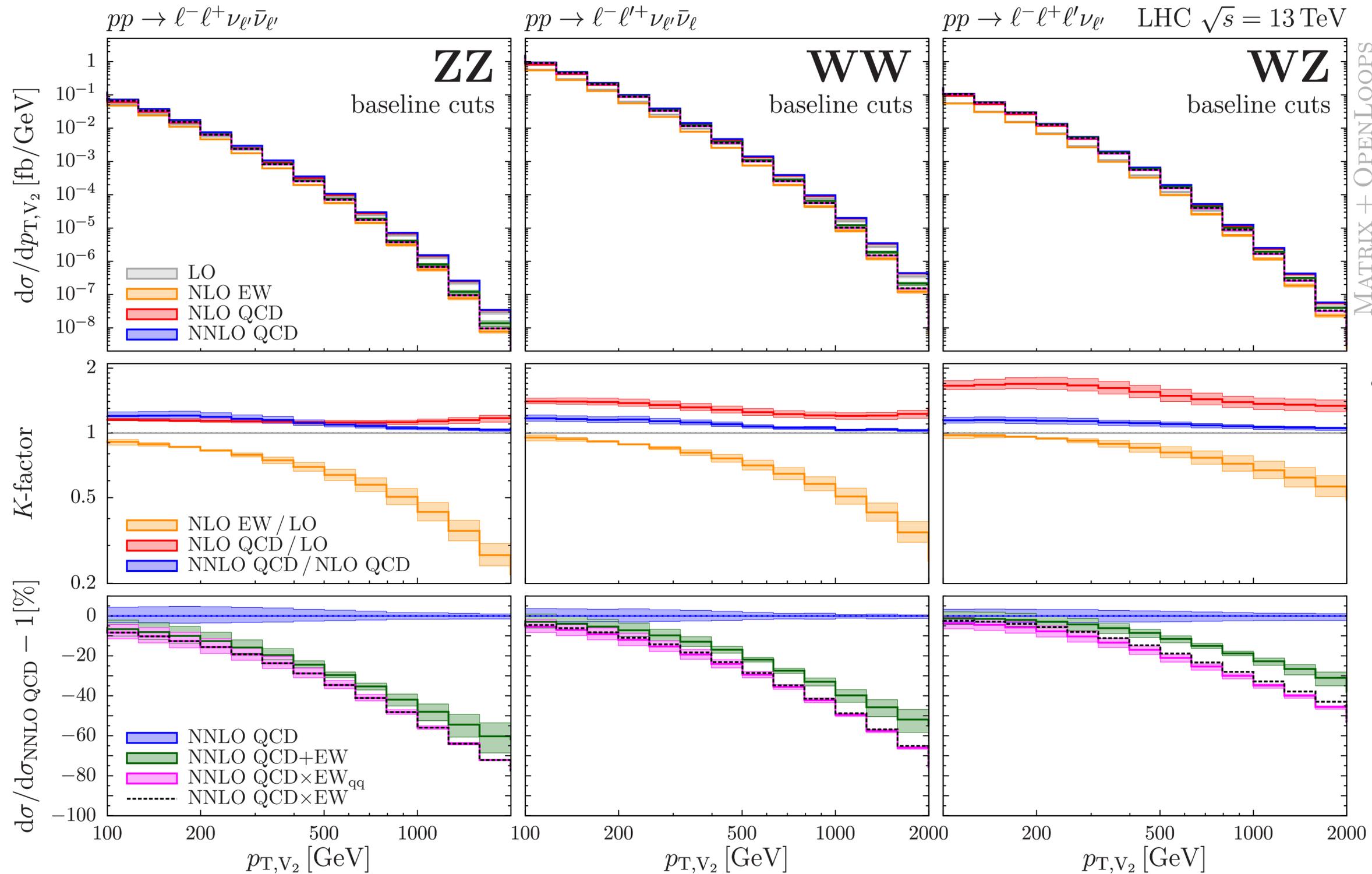
- consistent picture amongst all processes

- Largest QCD corrections in WZ (radiation zero at LO)

- Largest EW corrections in ZZ

pTV2

Giant QCD K-factors and EW corrections: pTV1

$pp \to \ell^- \ell^+ \nu_{\ell'} \bar{\nu}_{\ell'}$

ZZ
baseline cuts

LO
NLO EW
NLO QCD
NNLO QCD

NLO EW / LO
NLO QCD / LO
NNLO QCD / NLO QCD

NNLO QCD
NNLO QCD+EW
NNLO QCD×EW$_{qq}$
NNLO QCD×EW

p_{T,V_1} [GeV]

pTV1

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

- at large pTV1: VV phase-space is dominated by V+jet (w/ soft V radiation)
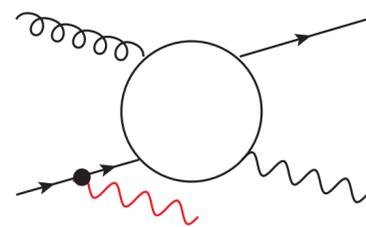
$$\left(\frac{d\sigma^{V(V)j}}{d\sigma^{LO}_{VV}} \right) \propto \alpha_S \log^2\left(\frac{Q^2}{M_W^2}\right) \simeq 3 \qquad \text{at} \quad Q = 1\,\text{TeV}$$

- NNLO / NLO QCD moderate and NNLO uncert. 5-10%

- NLO EW/LO=-(40-50)%

- Very large difference $d\sigma_{\text{NNLO QCD+EW}}$ vs. $d\sigma_{\text{NNLO QCD×EW}}$

- 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 I**: take average as nominal and spread as uncertainty

- Pragmatic solution II: **apply jet veto to constrain Vj toplogoies**

13

MEPS @ NLO QCD + EW: WW(+jet)

[Bräuer, Denner, Pellen, Schönherr, Schumann; '20]

- More rigorous solution: merge VVj incl. approx. EW corrections with VV with full QCD + EWvirt

- However, not NNLO QCD accurate

FO

FO

$pp \to \mu^+ \nu_\mu e^- \bar{\nu}_e + X$ @ 13 TeV

WW

$n_{jet} = 0$

Legend:
- LO
- NLO QCD
- NLO QCD+EW
- NLO QCD×EW
- NLO QCD×EW$_{approx}$

SHERPA+RECOLA

$pp \to \mu^+ \nu_\mu e^- \bar{\nu}_e + jet + X$ @ 13 TeV

WW+jet

$n_{jet} = 1$

MEPS @ NLO QCD + EW: WW(+jet)

[Bräuer, Denner, Pellen, Schönherr, Schumann; '20]

- More rigorous solution: merge VVj incl. approx. EW corrections with VV with Sherpa's MEPS@NLO QCD + EWvirt
- However, not NNLO QCD accurate
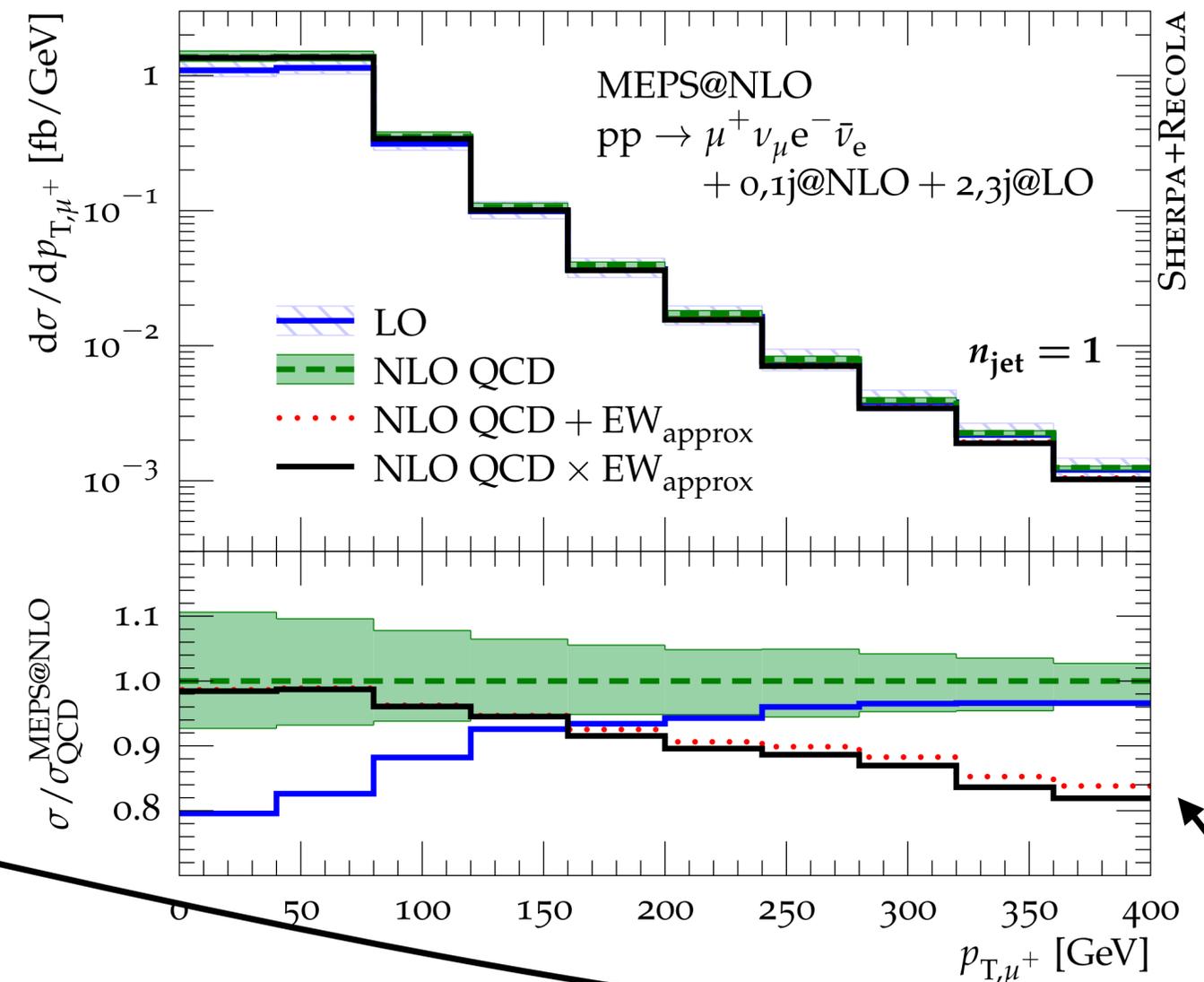
FO

MEPS@NLO QCD + EWvirt

MEPS @ NLO QCD + EW: ZZ(+jet)

[Bothmann, Napoletano, Schönherr, Schumann, Villani, 21]

$pp \to e^+ e^- \mu^+ \mu^-$, $\sqrt{s} = 13\,\mathrm{TeV}$

$d\sigma / dm_{2e2\mu}$ [fb/GeV]

NLO EW
LO
LO + EW_{virt} + YFS
LO + EW_{sud} + YFS
LO + $EW_{\mathrm{sud}}^{\mathrm{exp}}$ + YFS
NLO EW + NLL $EW_{\mathrm{sud}}^{\mathrm{exp}}$

$\sigma / \sigma_{\mathrm{NLO\ EW}}$

$m_{2e2\mu}$ [GeV]

SHERPA+OPENLOOPS/RECOLA

$pp \to e^+ e^- \mu^+ \mu^-$, $\sqrt{s} = 13\,\mathrm{TeV}$

NLO EW
LO
LO + EW_{virt} + YFS
LO + EW_{sud} + YFS
NLO EW + $EW_{\mathrm{sud}}^{\mathrm{exp}}$ + YFS
LO + NLL $EW_{\mathrm{sud}}^{\mathrm{exp}}$
LO + EW_{virt} + YFS
LO + EW_{sud} + YFS
LO + $EW_{\mathrm{sud}}^{\mathrm{exp}}$ + YFS
NLO EW + NLL $EW_{\mathrm{sud}}^{\mathrm{exp}}$

$\sigma / \sigma_{\mathrm{NLO\ EW}}$

$p_{T,2e}$ [GeV]

SHERPA+OPENLOOPS/RECOLA

$pp \to e^+ e^- \mu^+ \mu^-$, $\sqrt{s} = 13\,\mathrm{TeV}$

- scheme variation: Gmu vs. a(mZ)
- EWsud based on [Bothmann,Napoletano, '20]: process-independent implementation of Sudakov logs, see also [Pagani, Zaro '21]

16

MEPS @ NLO QCD + EW: ZZ(+jet)

[Bothmann, Napoletano, Schönherr, Schumann, Villani, '21]

$pp \to e^+e^-\mu^+\mu^-$, $\sqrt{s} = 13$ TeV

$\mathrm{d}\sigma/\mathrm{d}m_{2e2\mu}$ [fb/GeV]

- NLO EW
- LO
- $\mathrm{LO} + \mathrm{EW}_{\mathrm{virt}} + \mathrm{YFS}$
- $\mathrm{LO} + \mathrm{EW}_{\mathrm{sud}} + \mathrm{YFS}$
- $\mathrm{LO} + \mathrm{EW}_{\mathrm{sud}}^{\mathrm{exp}} + \mathrm{YFS}$
- $\mathrm{NLO\ EW} + \mathrm{NLL\ EW}_{\mathrm{sud}}^{\mathrm{exp}}$

$\sigma/\sigma_{\mathrm{NLO\ EW}}$

$m_{2e2\mu}$ [GeV]

SHERPA+OpenLoops/Recola

$\sigma/\sigma_{\mathrm{NLO\ EW}}$

$m_{2e2\mu}$ [GeV]

$pp \to e^+e^-\mu^+\mu^-$, $\sqrt{s} = 13$ TeV

$\mathrm{d}\sigma/\mathrm{d}\Delta R_{2\ell}$ [fb]

- NLO EW
- LO
- $\mathrm{LO} + \mathrm{EW}_{\mathrm{virt}} + \mathrm{YFS}$
- $\mathrm{LO} + \mathrm{EW}_{\mathrm{sud}} + \mathrm{YFS}$
- $\mathrm{NLO\ EW} + \mathrm{EW}_{\mathrm{sud}}^{\mathrm{exp}} + \mathrm{YFS}$
- $\mathrm{LO} + \mathrm{NLL\ EW}_{\mathrm{sud}}^{\mathrm{exp}}$
- $\mathrm{LO} + \mathrm{EW}_{\mathrm{virt}} + \mathrm{YFS}$
- $\mathrm{LO} + \mathrm{EW}_{\mathrm{sud}} + \mathrm{YFS}$
- $\mathrm{LO} + \mathrm{EW}_{\mathrm{sud}}^{\mathrm{exp}} + \mathrm{YFS}$
- $\mathrm{NLO\ EW} + \mathrm{NLL\ EW}^{\mathrm{exp}}$

$\sigma/\sigma_{\mathrm{NLO\ EW}}$

$\Delta R_{2\ell}$

$p_{\mathrm{T},2e}$ [GeV]

SHERPA+OpenLoops/Recola

- scheme variation: Gmu vs. a(mZ)
- EWsud based on [Bothmann, Napoletano, '20]: process-independent implementation of Sudakov logs, see also [Pagani, Zaro '21]

$pp \to e^+e^-\mu^+\mu^-$, $\sqrt{s} = 13$ TeV

$\mathrm{d}\sigma/\mathrm{d}y_{e^-}$ [fb]

$\sigma/\sigma_{\mathrm{NLO\ EW}}$

17
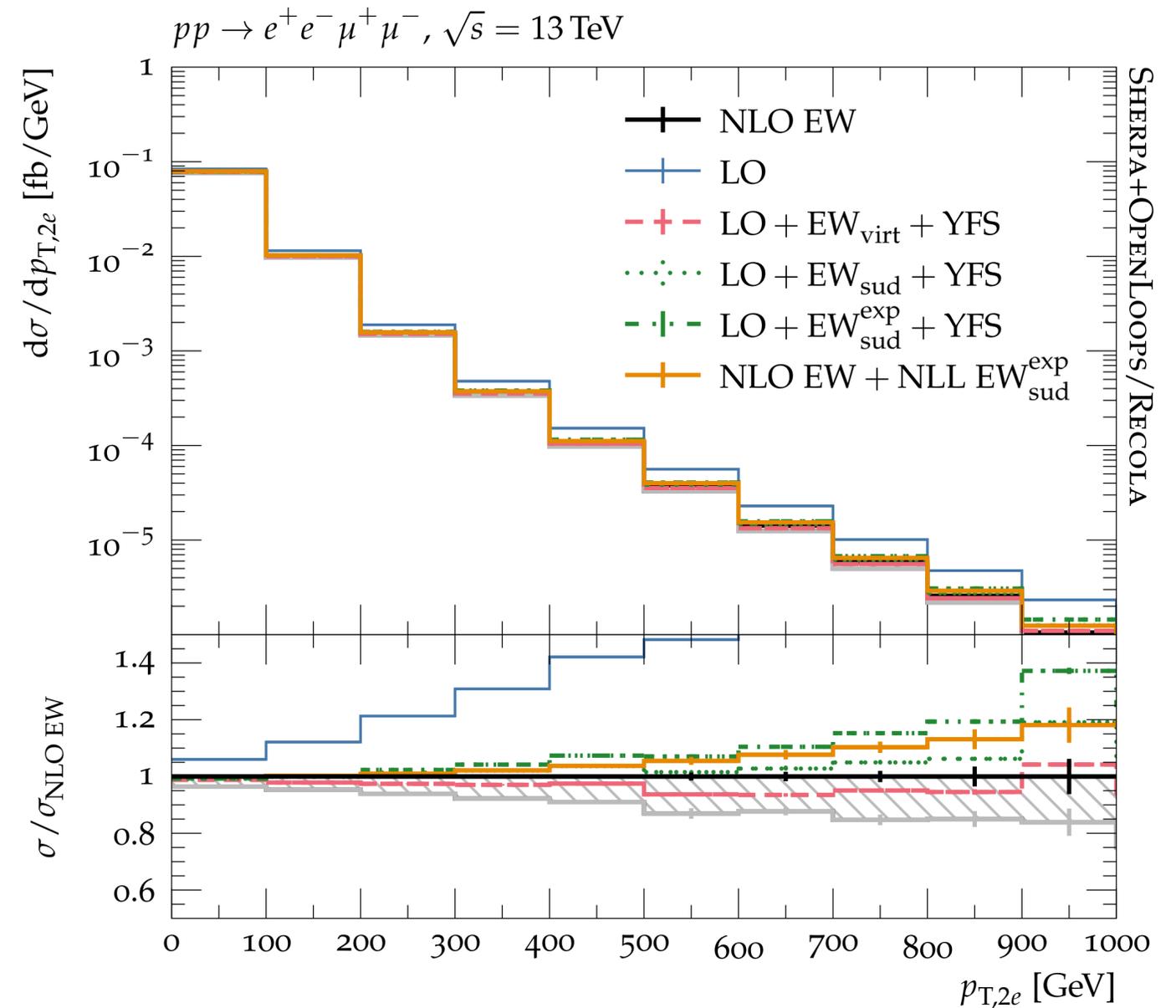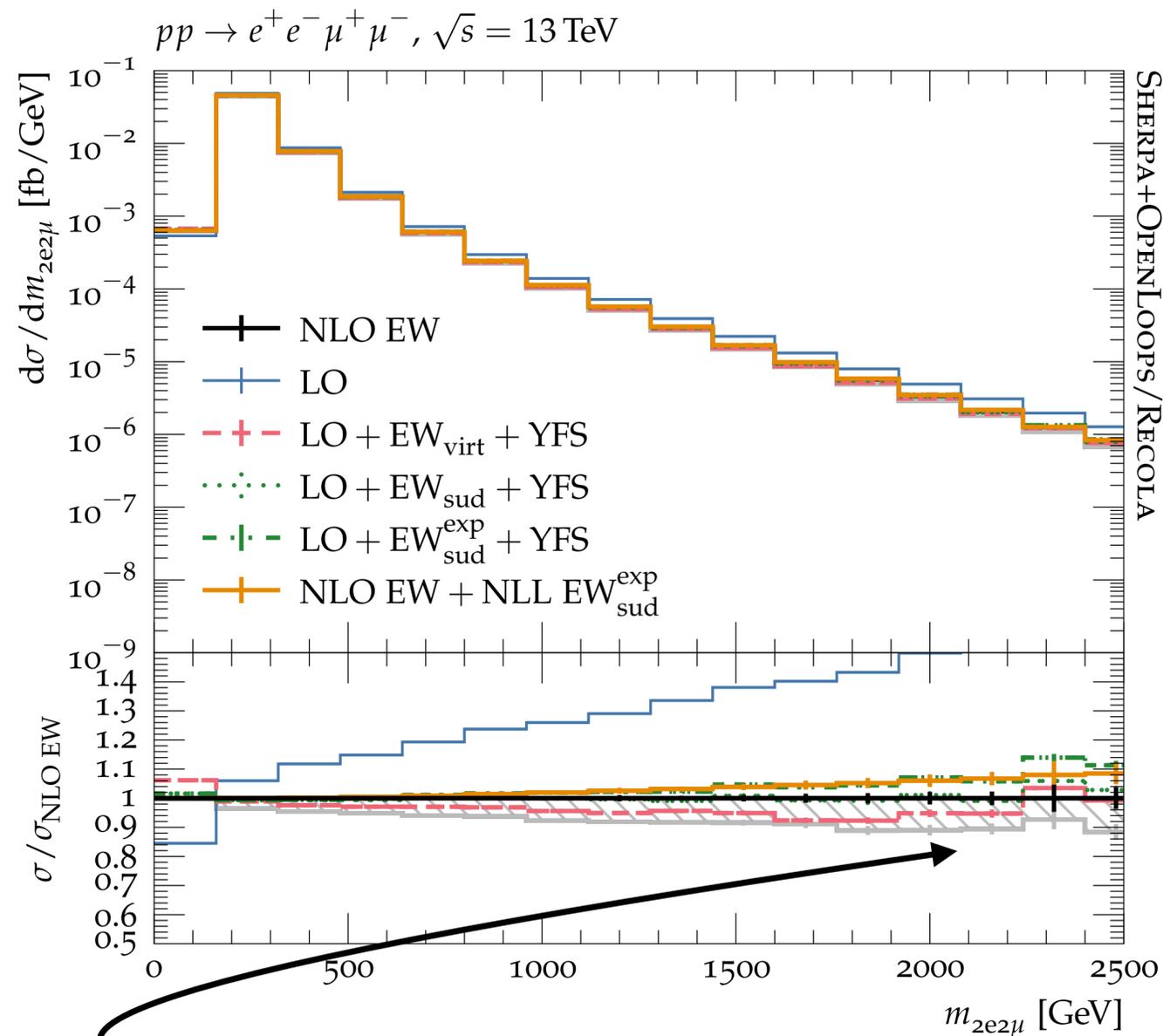
MEPS @ NLO QCD + EW: ZZ(+Jet)

[Bothmann, Napoletano, Schönherr, Schumann, Villani; '21]

gg-induced WW and ZZ production
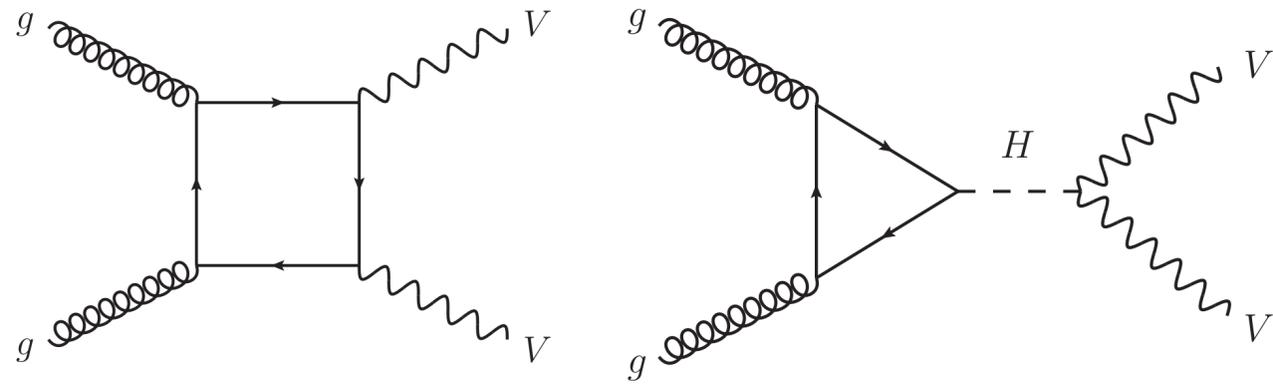
- Formally same order as NNLO QCD
- Enhanced due to gg flux
- Interference with H->VV

- Sizeable QCD corrections (formally N3LO QCD)
- For m4l < 340 GeV 1/Mt expansion reliable
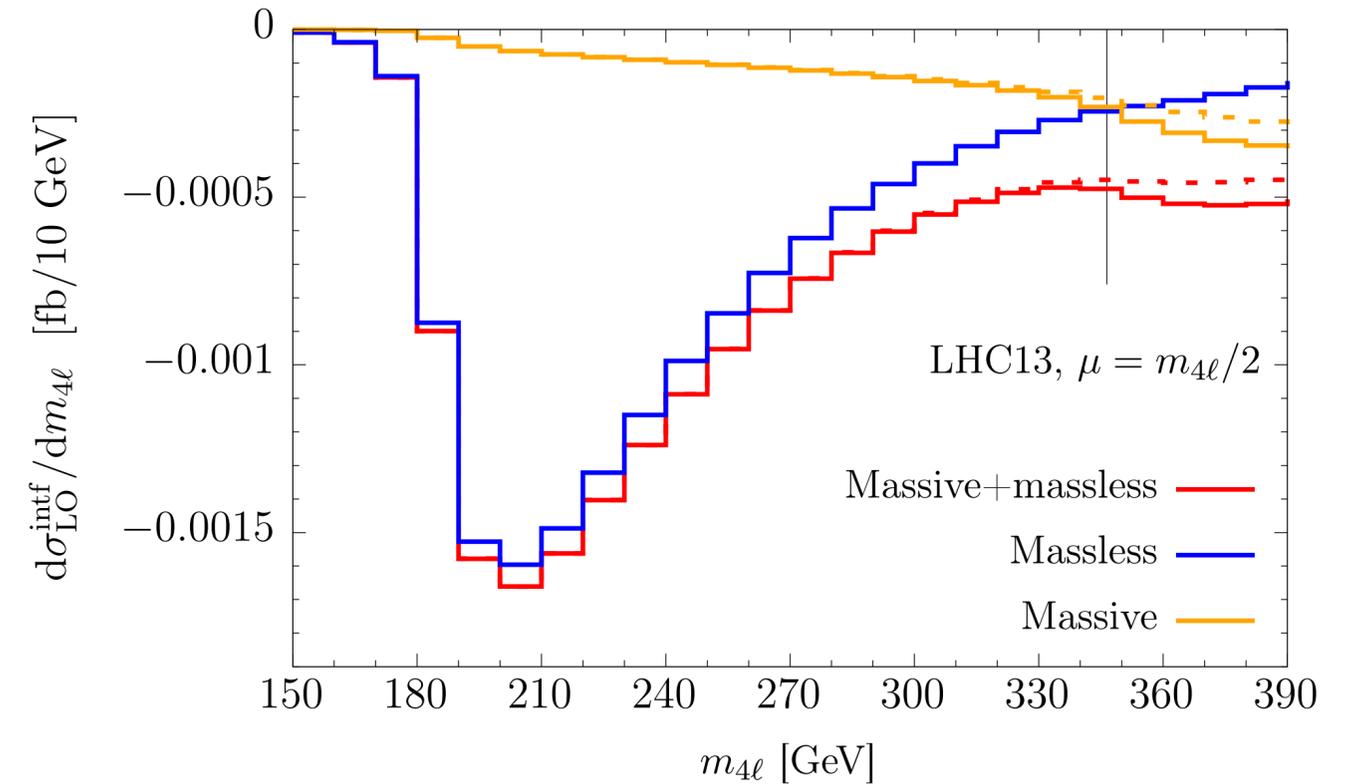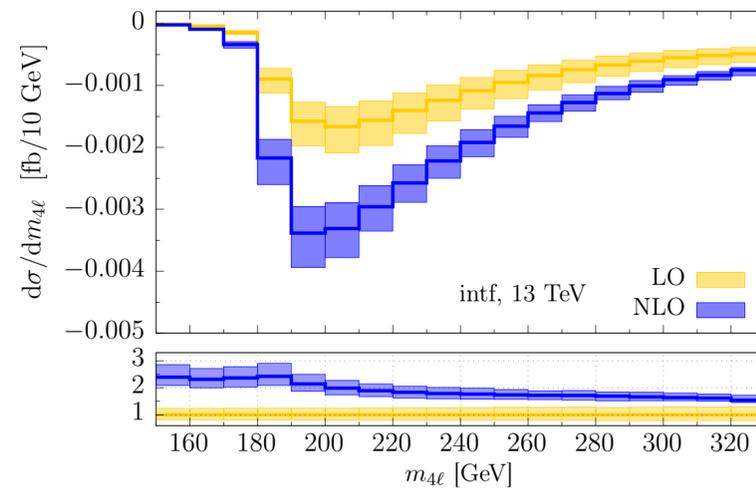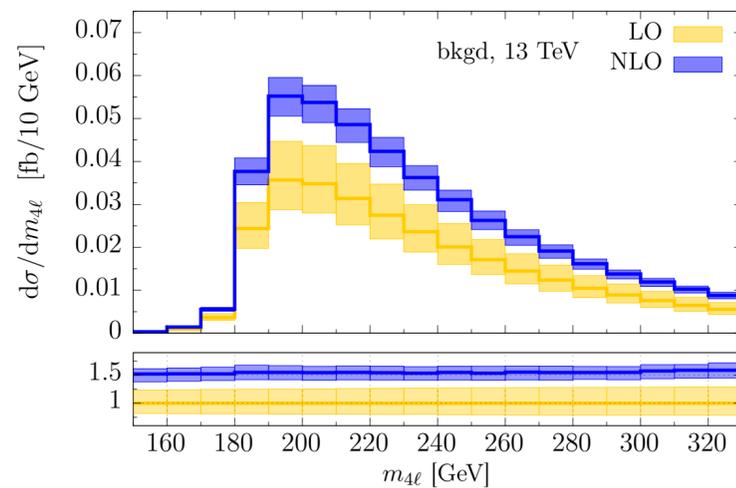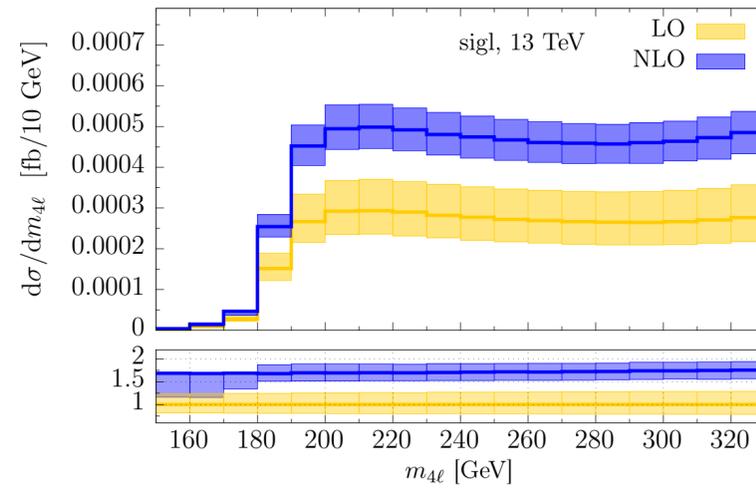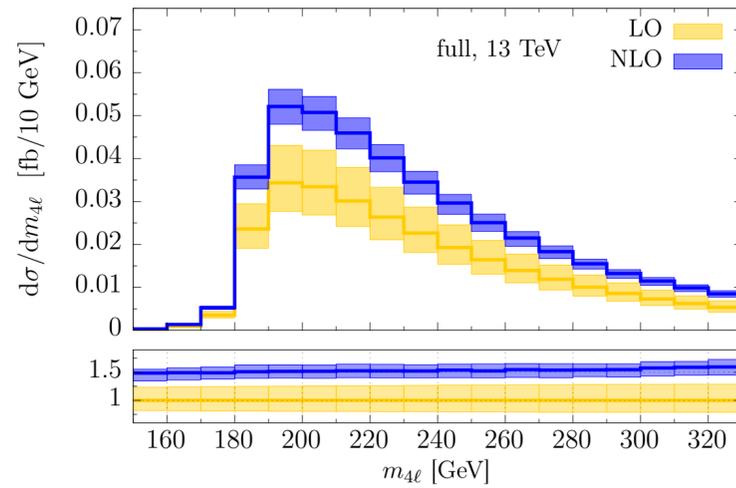
NLO+PS for gg → VV/H→4l

[Alioli, Ferrario Ravasio, JML, Röntsch, '21]

gg → VV→4l

gg → H→4l

sum:

interference:

$gg \to e^+e^-\mu^+\mu^-$ @ NLO(+PS)
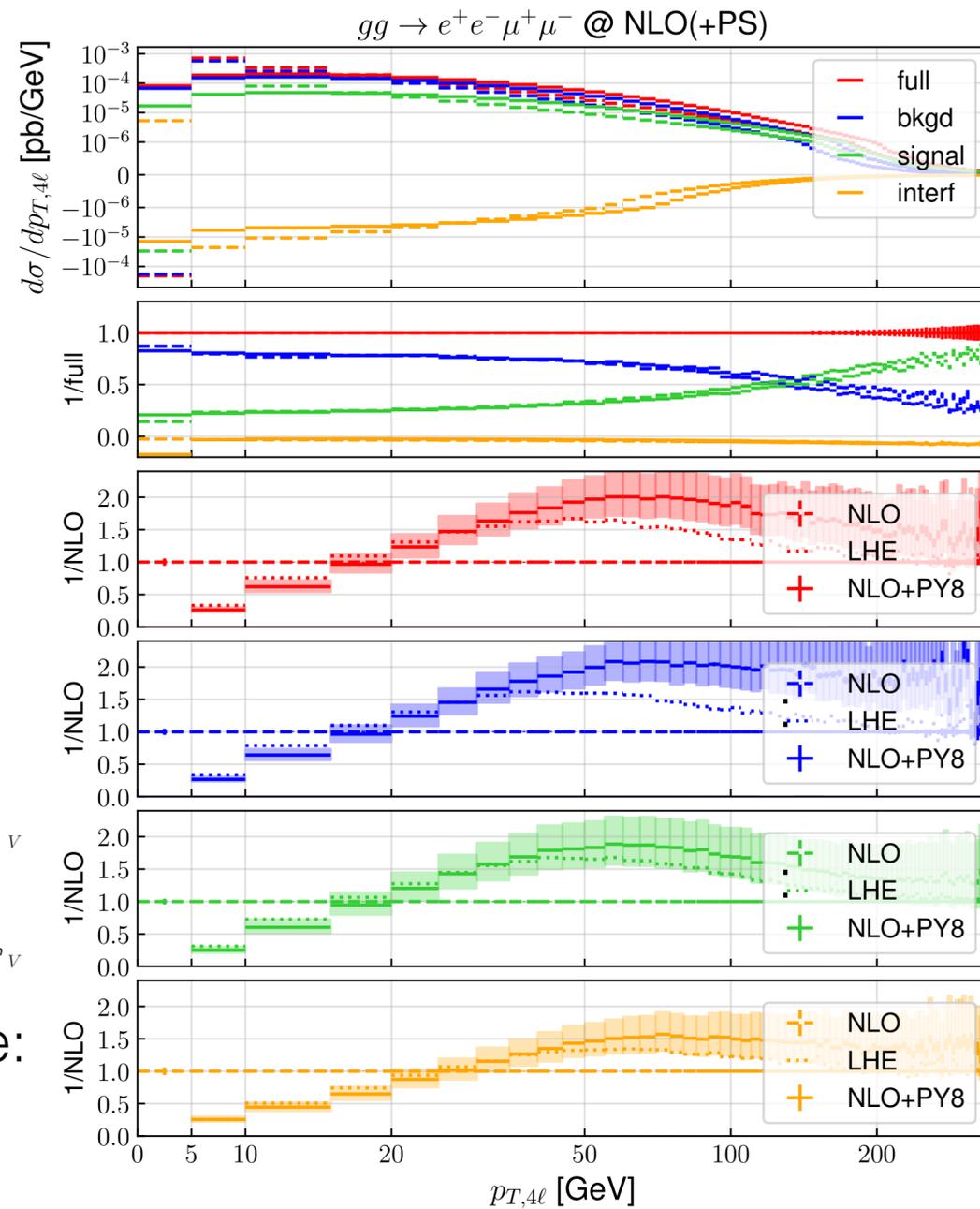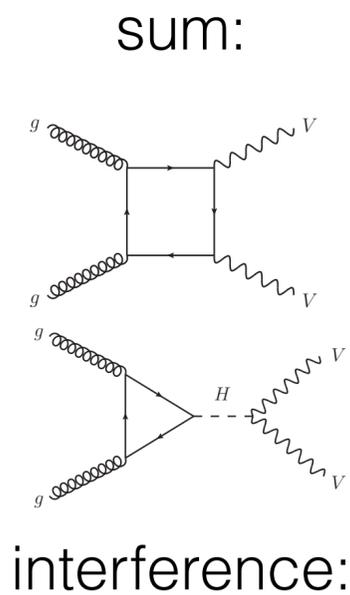
- ggWW/ggZZ @ NLO QCD + PS available!
- crucial for off-shell Higgs measurements

Parton shower Monte Carlos: NLO QCD + EW PS

[Chiesa, Re, Oleari '20]
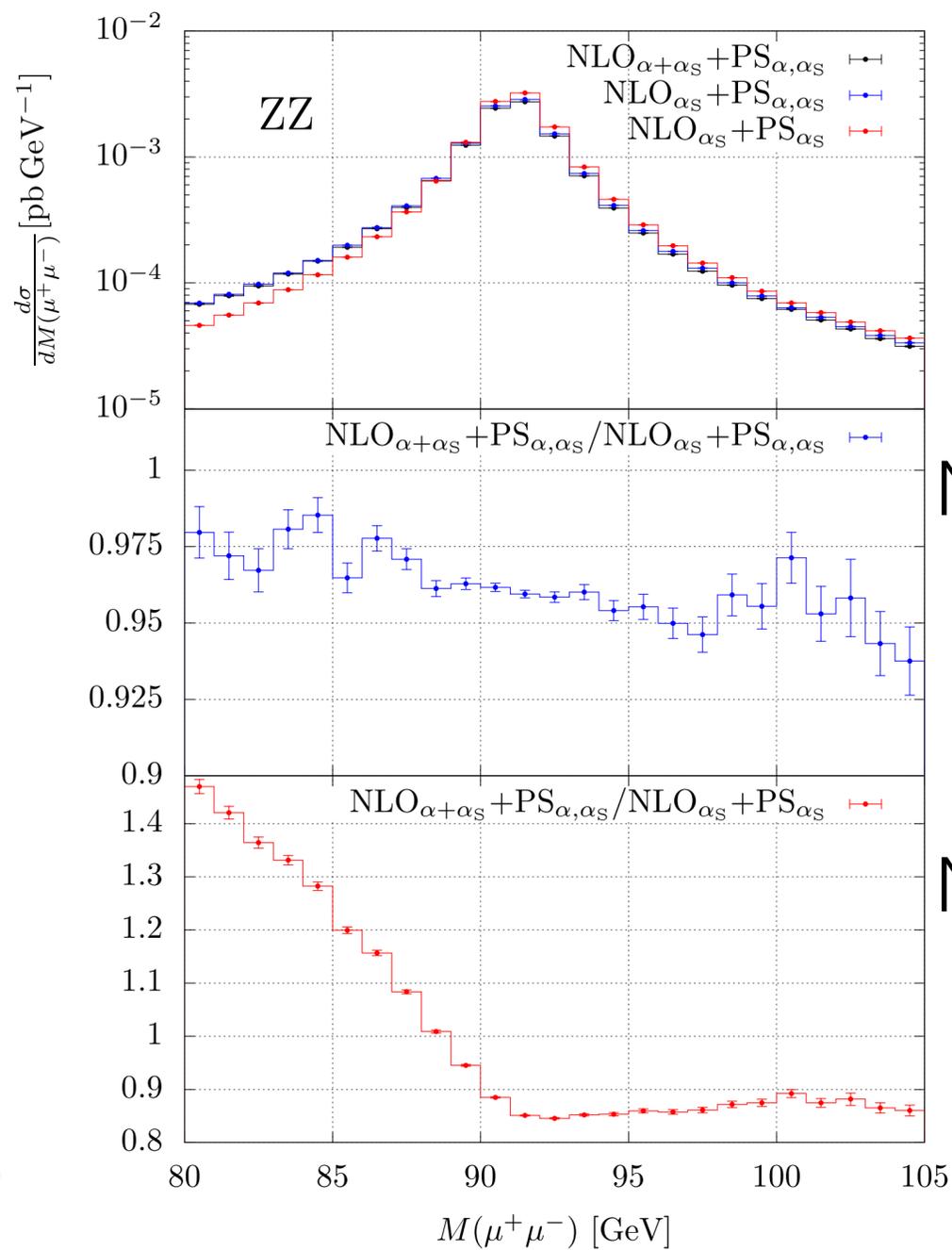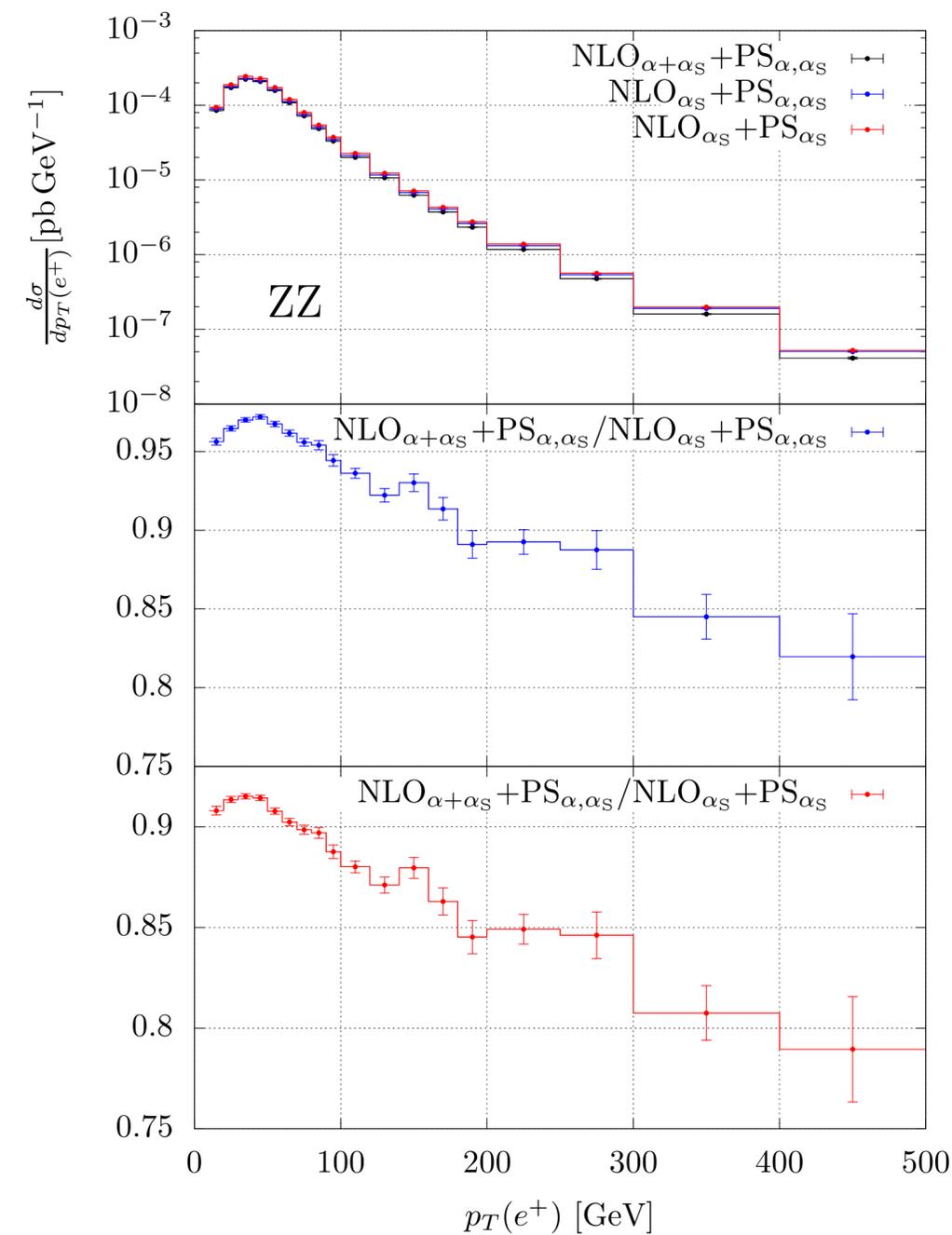
NLO (QCD + EW) PS (QCD + QED)/
NLO QCD PS (QCD + QED)"

NLO (QCD + EW) PS (QCD + QED)/
NLO QCD PS QCD"

- Missing: photon-induced channels
- Question: NLO (QCD + EW) PS (QCD + QED) / (NLO QCD PS QCD) × NLO EW

[Slide thanks to M. Schönherr]

NLO QCD corrections trivial, known for on-shell and o -shell processes.

NLO EW on-shell corrections calculated by Hefei group '14-'17,
WWW also by Dittmaier, Huss, Knippen '17.

NLO EW off-shell corrections more involved, up to $2 \to 6$ complexity
(like VBS, just with more and competing resonances)

- $pp \to \gamma\gamma\gamma \,/\, \gamma\gamma\ell\nu \,/\, \gamma\gamma\ell\ell$ Greiner, Schönherr '17

- $pp \to 3\ell 3\nu$ ($\ell = e^\pm, \mu^\pm$, 0/1/2 SFOS channels,   Schönherr '18
  incl. *WWW* and *WZZ* topologies)

  $pp \to e^\mp \nu_e \, \mu^\pm \nu_\mu \, \tau^\pm \nu_\tau$ (*WWW* only)   Dittmaier, Knippen, Schwan '19

- $pp \to \gamma 2\ell 2\nu$ ($\ell = e^\pm, \mu^\pm$, 0,1 SFOS channels,   Ju, Lindert, Schönherr tbp
  incl. γWW and γZZ topologies)

Generically, large contribution from photon-induced processes.

Triboson production @ NLO QCD
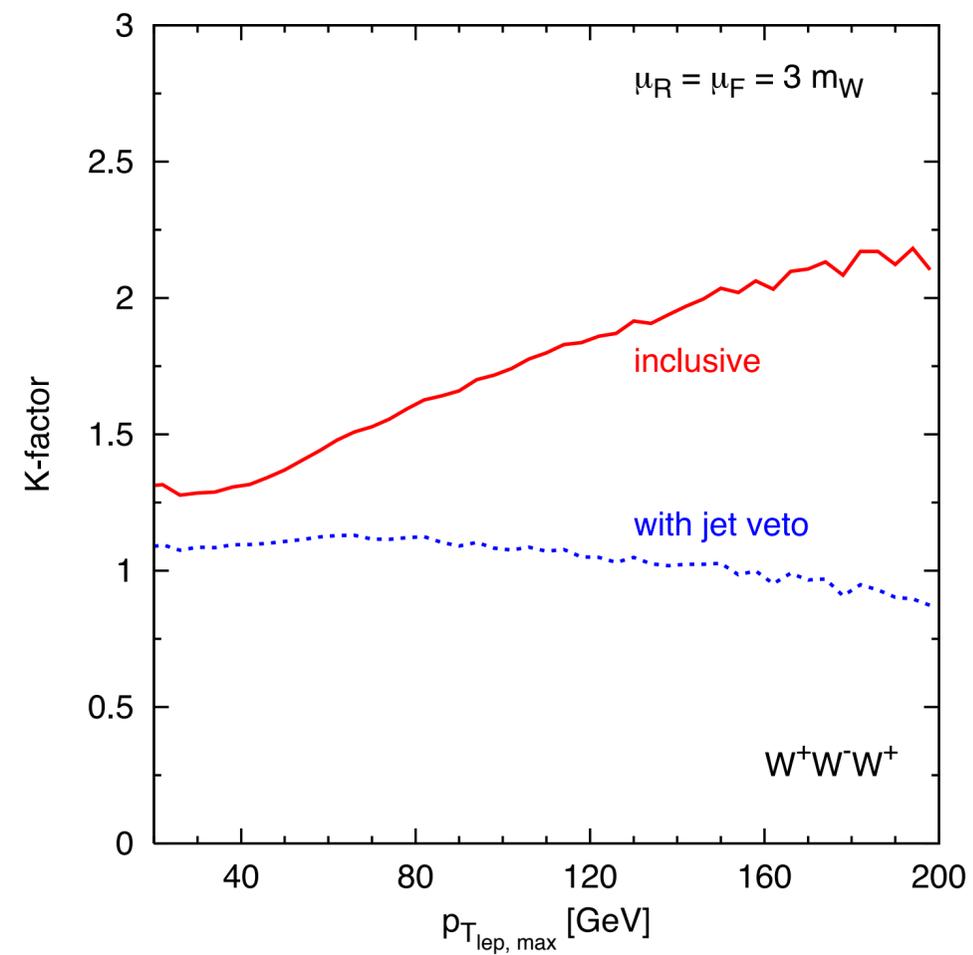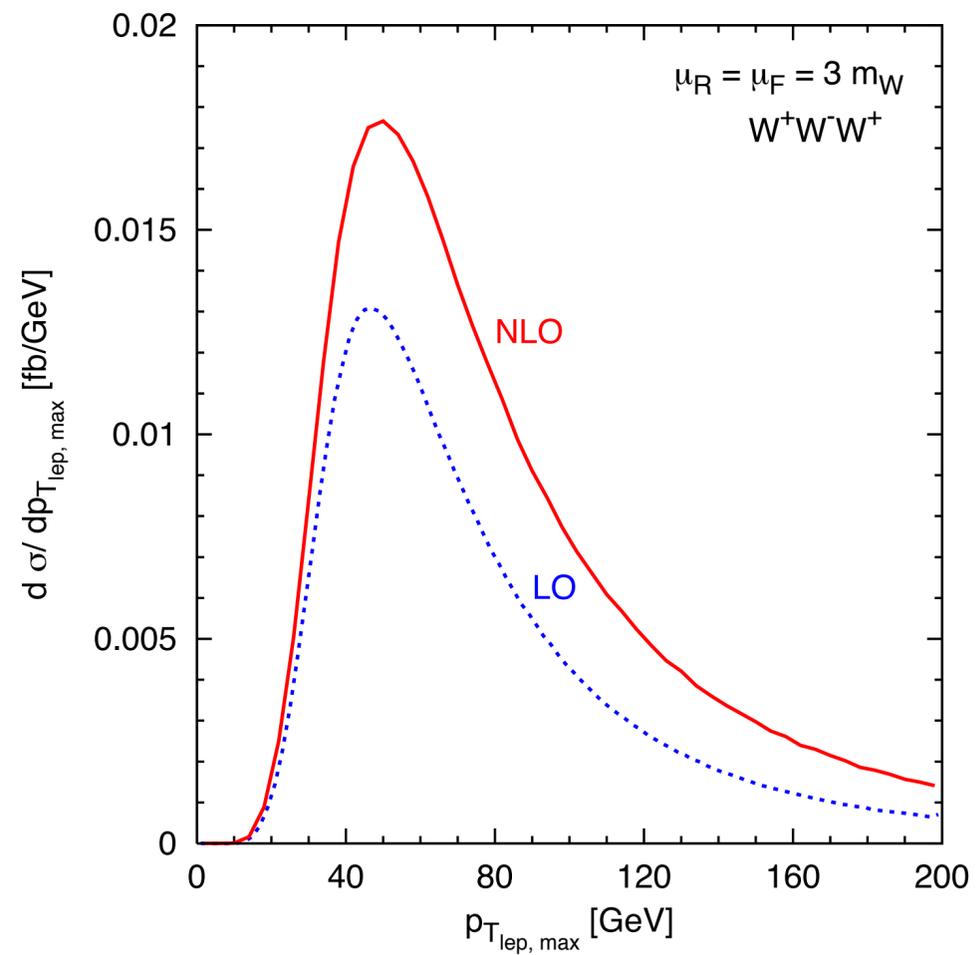
- QCD correction driven by additional jet activity: VV+jet topologies with soft V

  → 'giant K-factors'

  → strong observable dependence

  → NLO mandatory

- jet veto (pT$_{cut}$ = 50 GeV) reduces size and phase space dependence

  → better: multi-jet merging

$e^- \mu^+ \mu^+$
off-shell
on-shell (BW)

SHERPA+RECOLA

$e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$

$e^- \mu^+ \mu^+$
off-shell
on-shell (BW)

SHERPA+RECOLA

$e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$

1st lepton
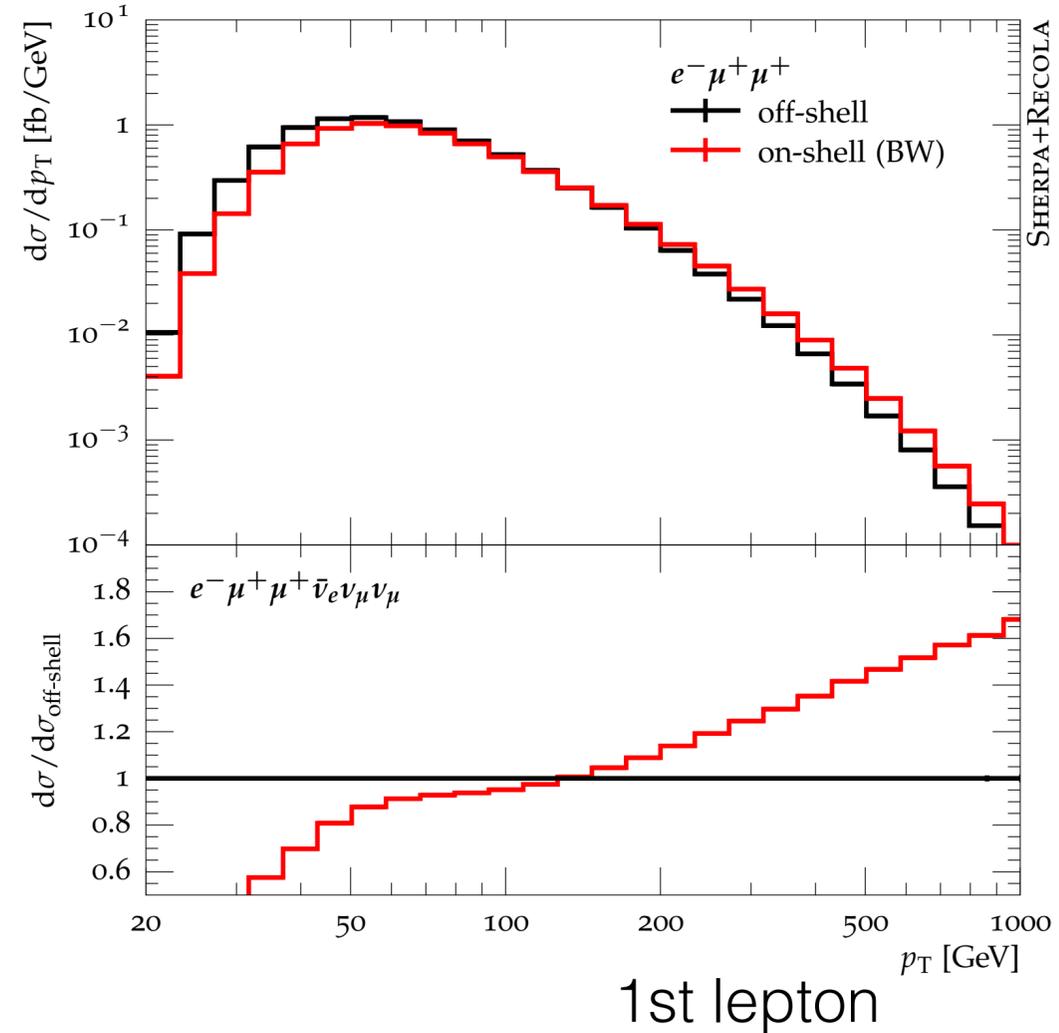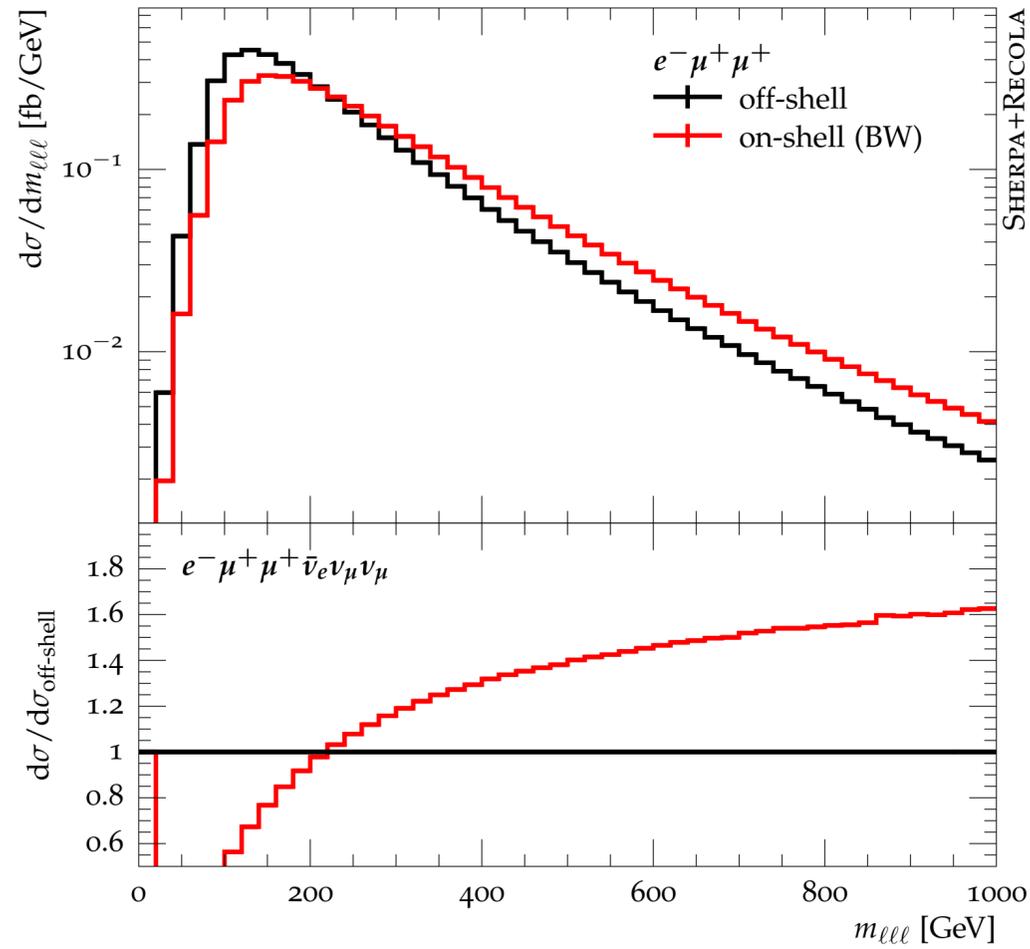
- at large mlll and pT$_{ll}$ large interference with other resonance structures

vs.
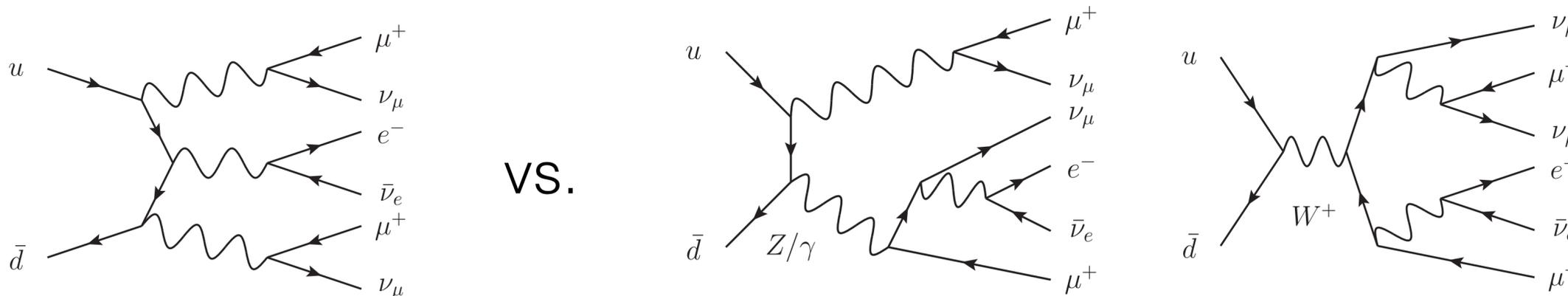
Off-shell VVV production @ NLO EW
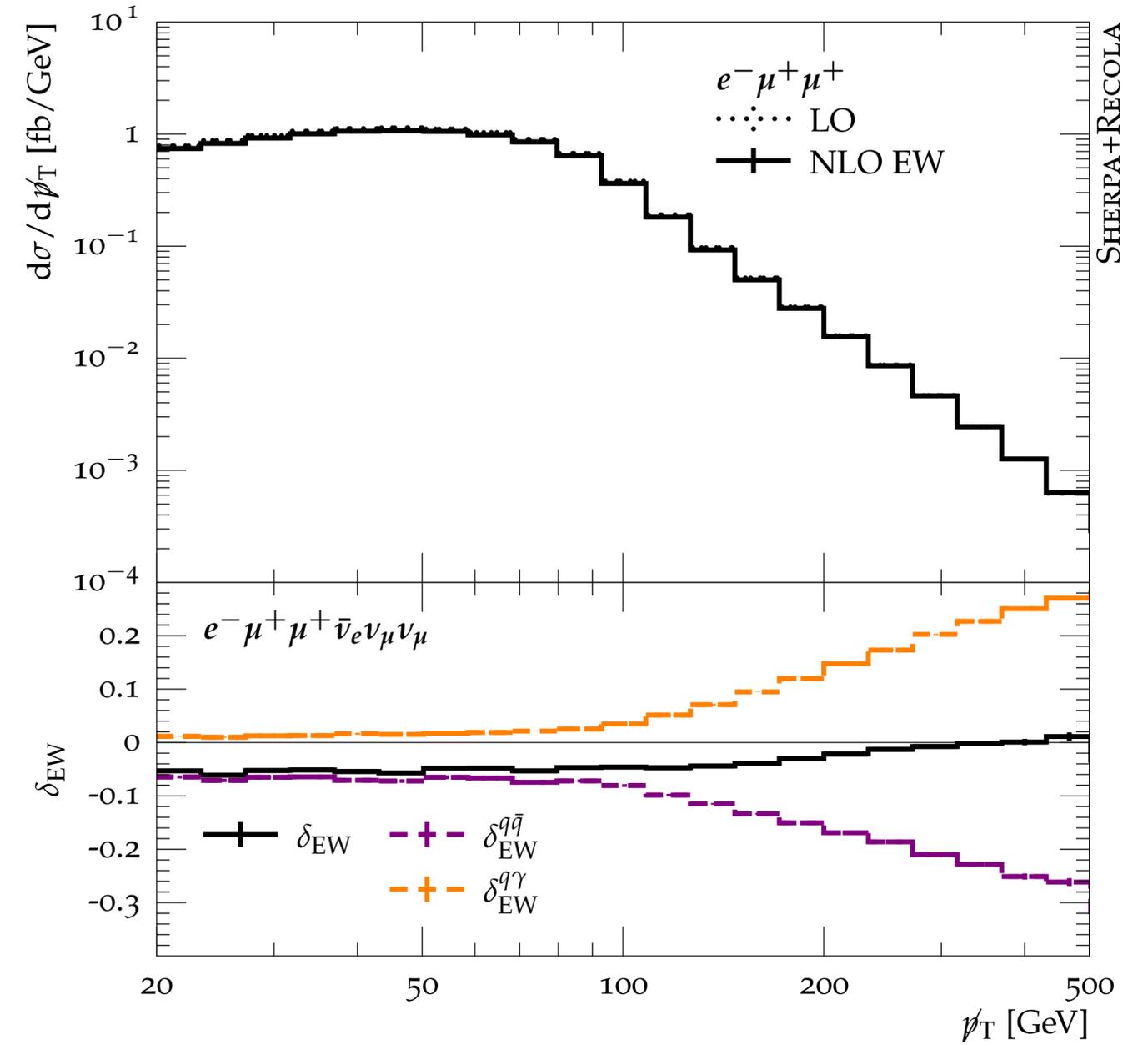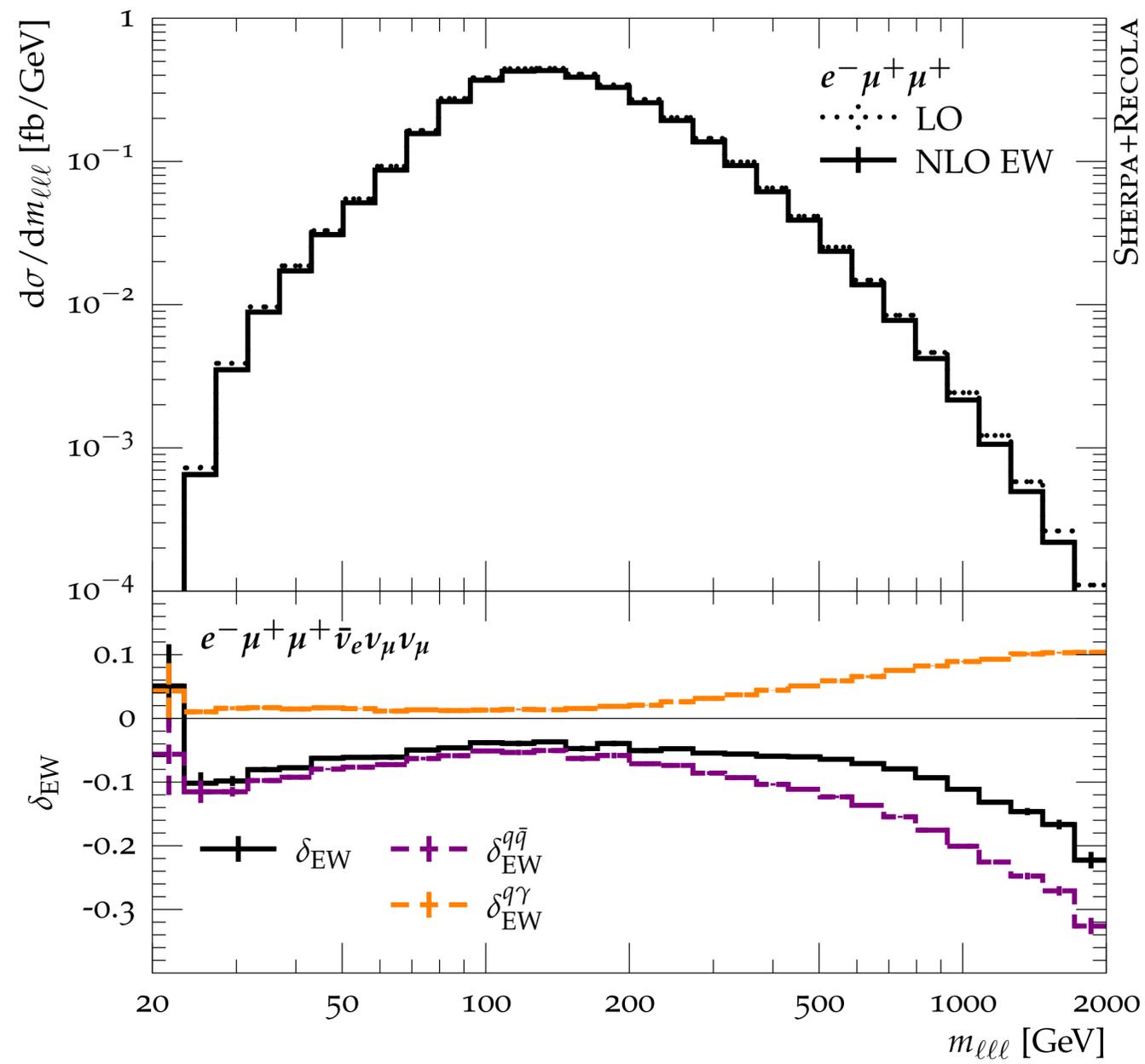
- Very large cancellations of EW corr. in qq and qγ channels / highly observable dependent

Interplay of WWW and Wh[→ WW∗]

[Slide thanks to M. Schönherr]

- due to interference, *Wh* cannot be treated as independent background, but is part of the signal

→ should not be subtracted
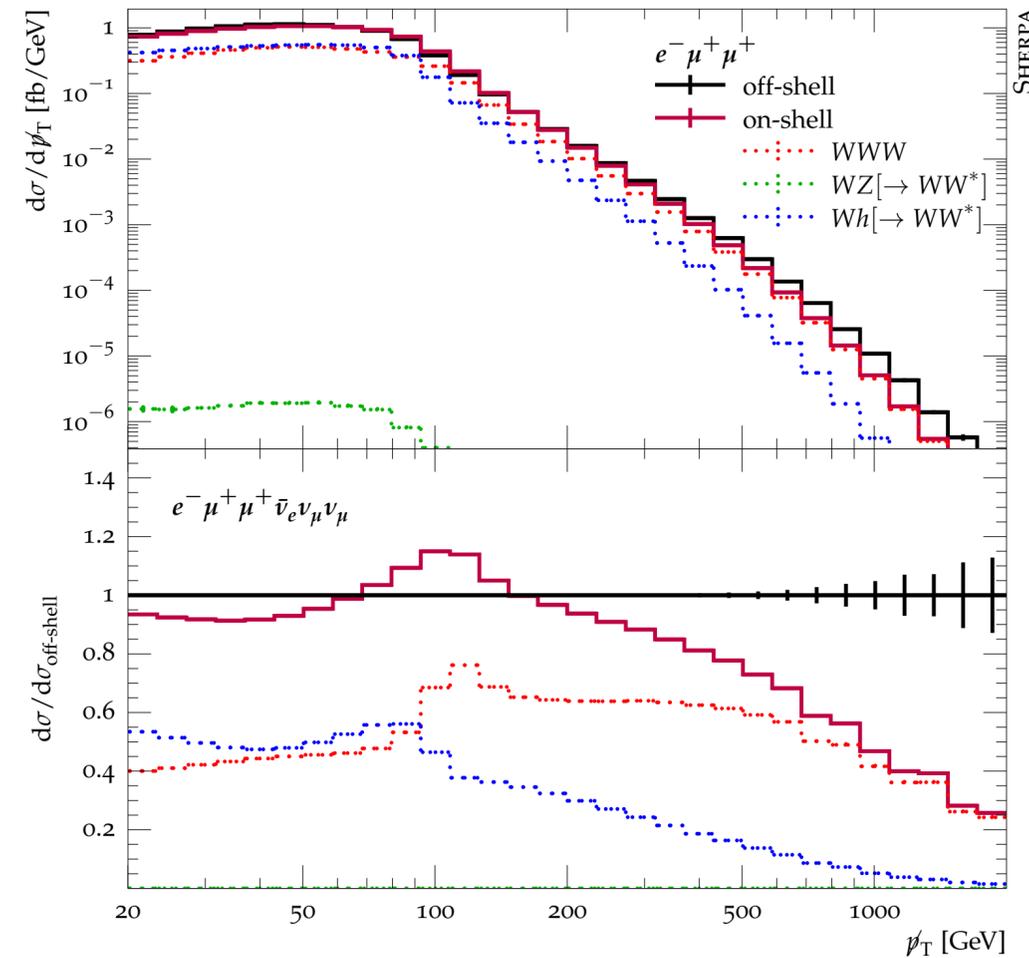
⇒ **measure signature (e.g. 3ℓ + MET) in fiducial volume**
→ for limits on, e.g., AGCs: define fiducial region that has large *WWW* component, still measure signature, interferences can be as important as sought-after signal

Perturbative expansion: VBF-V, VBS-VV

Example: WW+2jets

vs.

$$\mathrm{d}\sigma = \mathrm{d}\sigma(\alpha_S^2\alpha^4) + \mathrm{d}\sigma(\alpha_S\alpha^5) + \mathrm{d}\sigma(\alpha^6) + \dots$$

LO
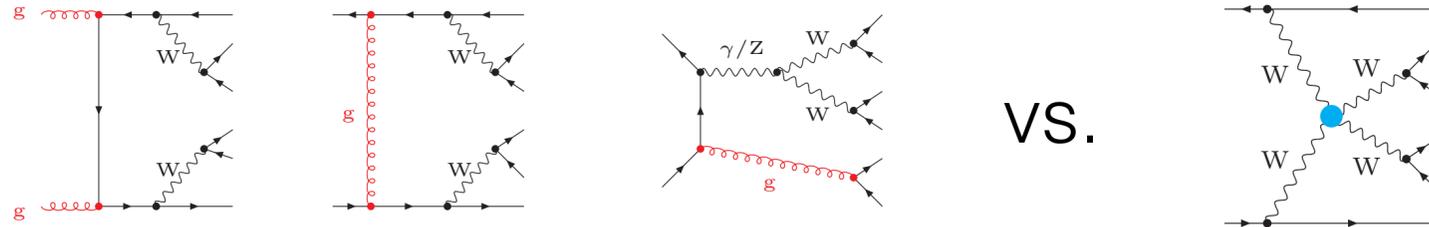
QCD-background   interference   VBS-signal

Perturbative expansion: VBF-V, VBS-VV

Example: WW+2jets

vs.

$$\mathrm{d}\sigma = \mathrm{d}\sigma(\alpha_S^2 \alpha^4) + \mathrm{d}\sigma(\alpha_S \alpha^5) + \mathrm{d}\sigma(\alpha^6) + \ldots$$

LO
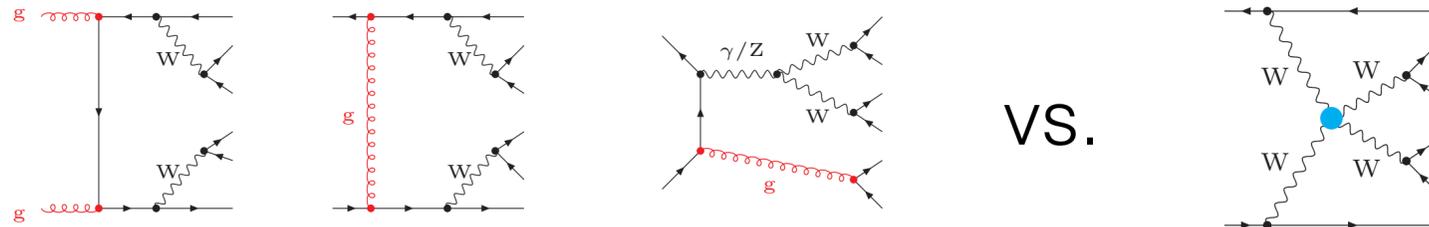
QCD-background   interference   VBS-signal

$\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha)$

$$\cdots + \mathrm{d}\sigma(\alpha_S^3 \alpha^4) + \mathrm{d}\sigma(\alpha_S^2 \alpha^5) + \mathrm{d}\sigma(\alpha_S \alpha^6) + \sigma(\alpha^7)$$

NLO

"NLO QCD"   "NLO EW"   "NLO QCD"   "NLO EW"

➡ separation formally meaningless at NLO
➡ strictly well defined measurements: fiducial cross sections

# QCD & EW ZZ+2jets @ NLO QCD + EW

long-term program for VBS@NLO

- QCD and EW **ss-WWjj** at NLO QCD+EW: *[Biedermann, Denner, Pellen '16+'17]*
- EW **WZjj** at NLO QCD+EW: *[Denner, Dittmaier, Maierhöfer, Pellen, Schwan, '19]*
- QCD and EW **ZZjj** at NLO QCD+EW: *[Denner, Franken, Pellen, Schmidt, '20+'21]*

## EW ZZ+2jets @ NLO QCD + EW

[Denner, Franken, Pellen, Schmidt, '20]
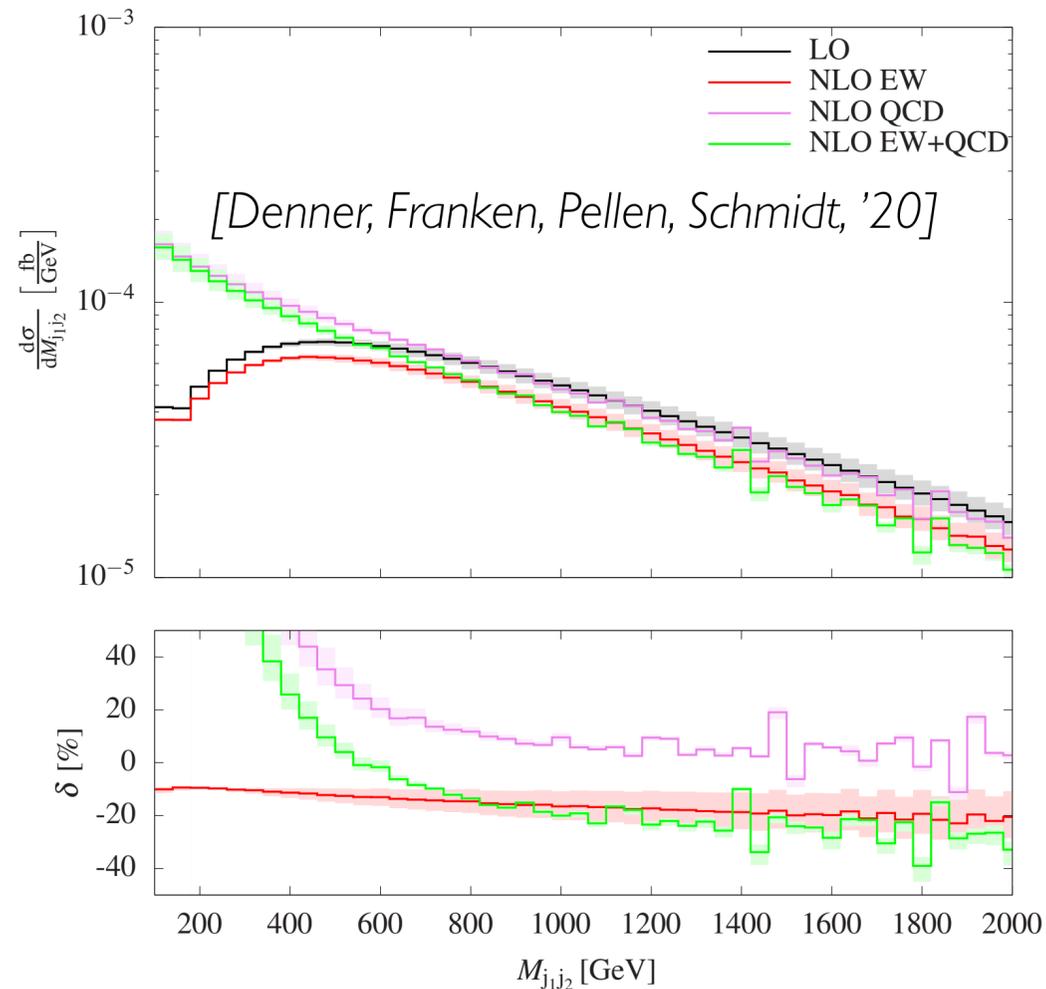
- 2 → 6 particles at NLO EW+QCD

Order	$\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha^7) + \mathcal{O}(\alpha_s\alpha^6)$
$M_{j_1j_2} > 100$ GeV			
$\sigma_{\mathrm{NLO}}[\mathrm{fb}]$	0.08211(4)	0.12078(11)	0.10521(11)
$\delta[\%]$	$-15.$	23.6	7.7
$M_{j_1j_2} > 500$ GeV			
$\sigma_{\mathrm{NLO}}[\mathrm{fb}]$	0.06069(4)	0.07375(25)	0.06077(25)
$\delta[\%]$	-17.6	0.	-17.5

- In the VBS phase-space EW mode receives:
  ▸ very small QCD corrections (percent level)
  ▸ O(20%) EW corrections

QCD & EW ZZ+2jets @ NLO QCD + EW

[Denner, Franken, Pellen, Schmidt; '21]

ZZ+2jets

ZZ+2jets
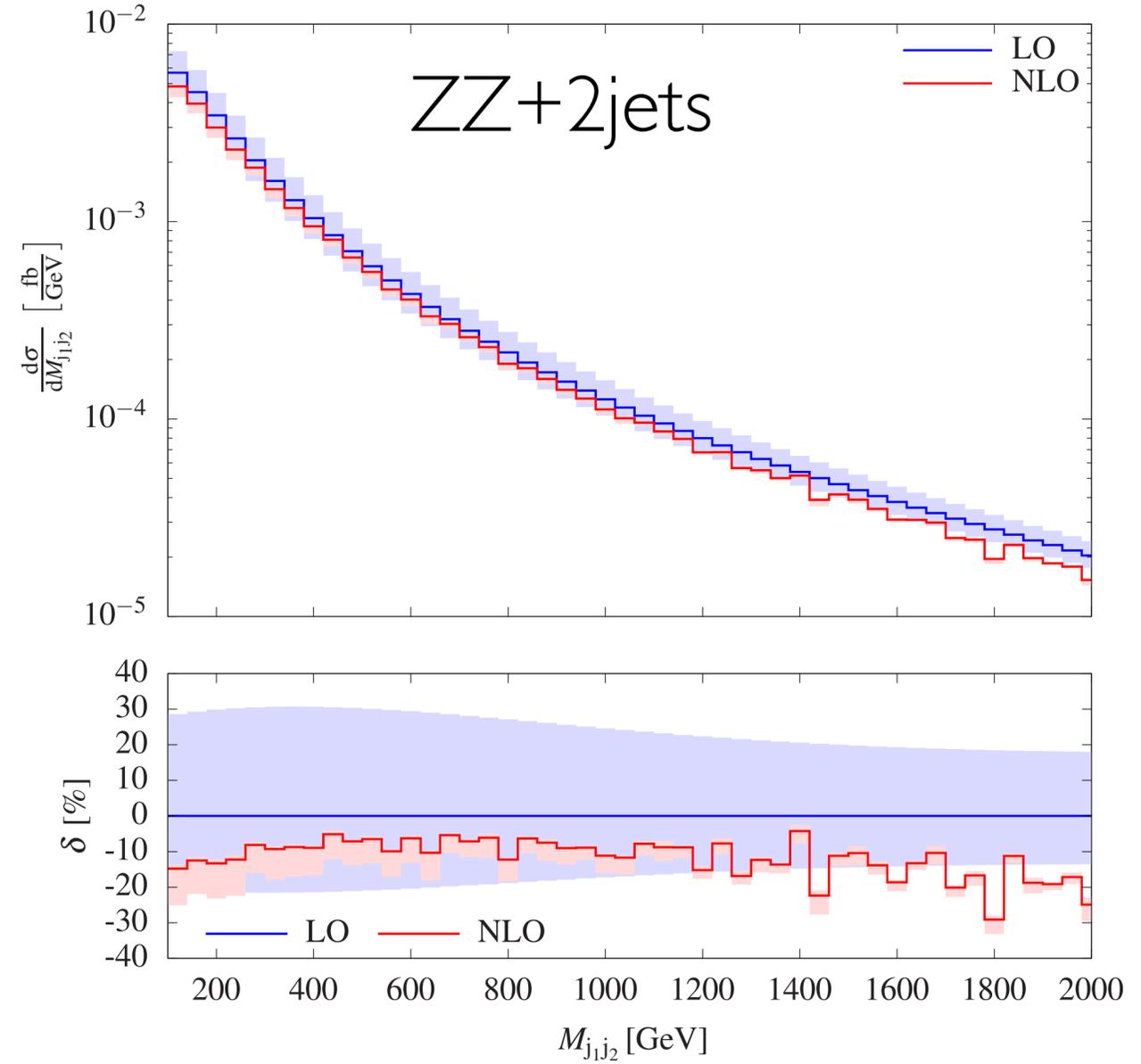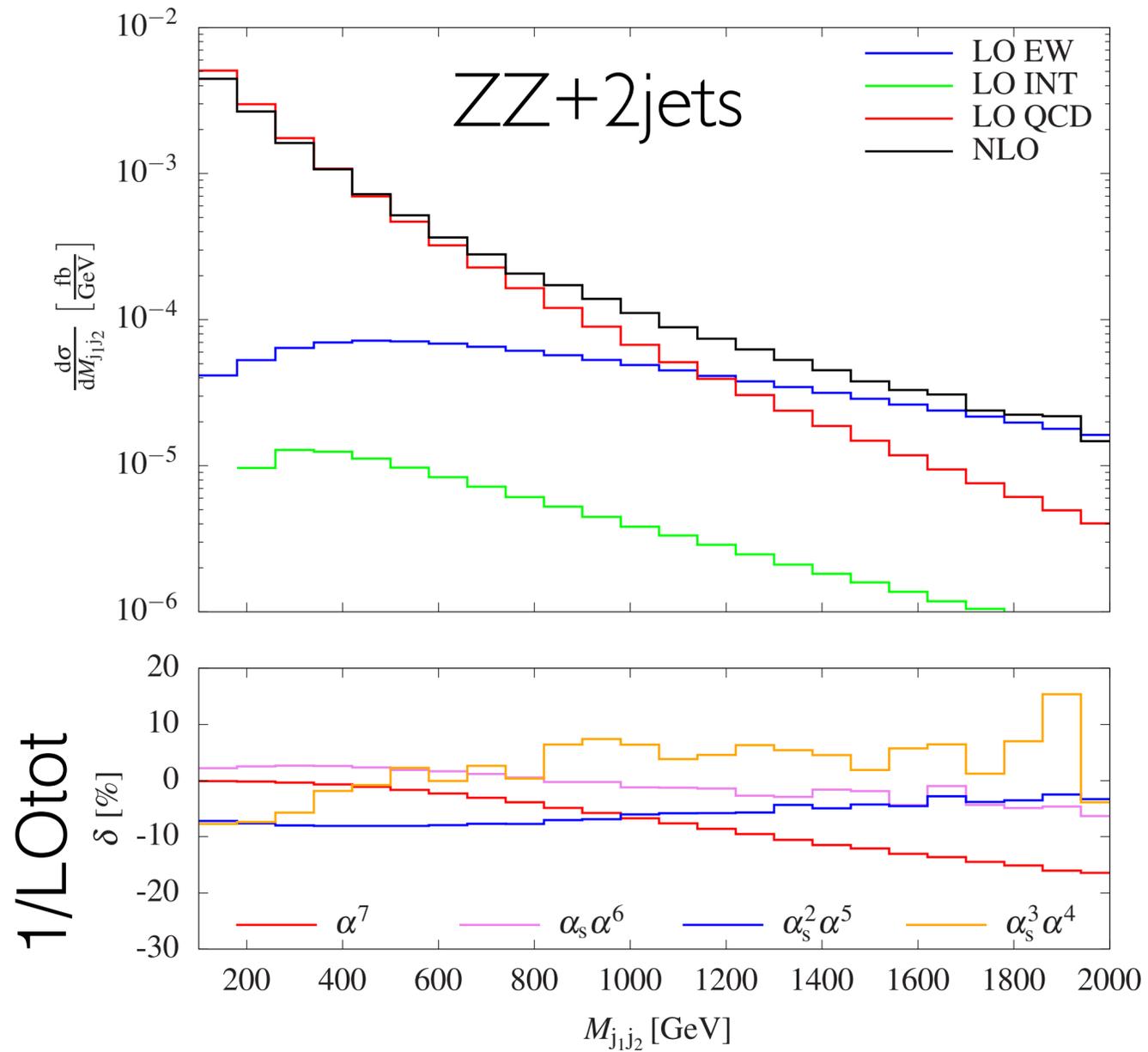
QCD and EW V+2jets @ NLO QCD + EW

[JML, S. Pozzorini, M. Schönherr; to appear]

QCD-mode

EW-mode

$pp \rightarrow \ell^{\pm} \nu_{\ell} + 2$ jets at 13 TeV

$pp \rightarrow \nu_{\ell} \bar{\nu}_{\ell} + 2$ jets at 13 TeV

$pp \rightarrow \ell^{\pm} \nu_{\ell} + 2$ jets at 13 TeV

W+2jets

QCD-mode legend:
- QCD NLO QCD
- QCD LO
- QCD NLO QCDxEW
- QCD NLO QCD+EW
- EW NLO QCD
- EW LO
- EW NLO QCDxEW
- EW NLO QCD+EW

EW-mode legend:
- EW NLO QCD
- EW LO
- EW NLO QCDxEW
- EW NLO QCD+EW
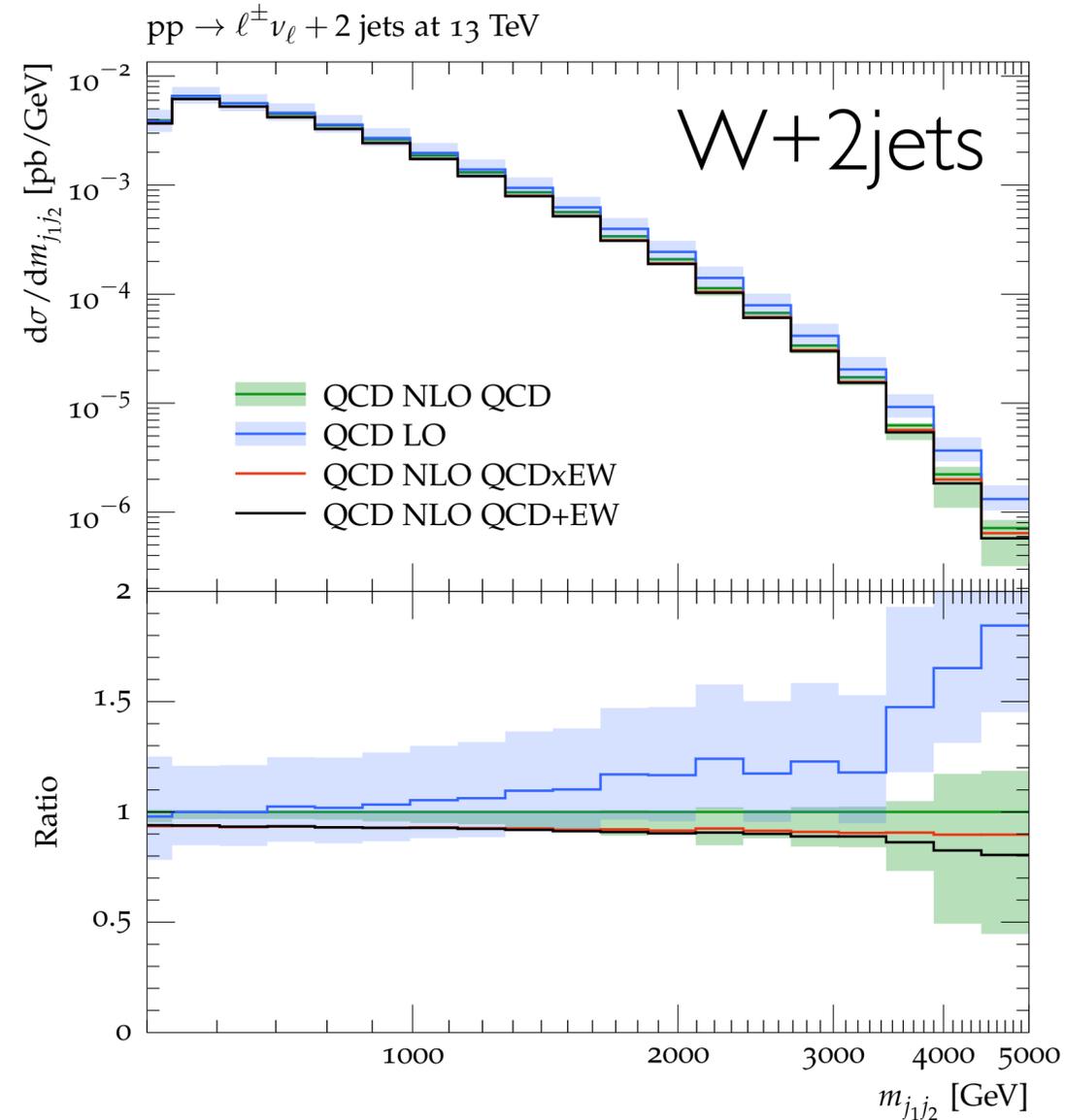
- **QCD**: negative K-factor (increasing for large mjj), uncertainty ~20-25%
- **EW**: up to -10% in multi TeV
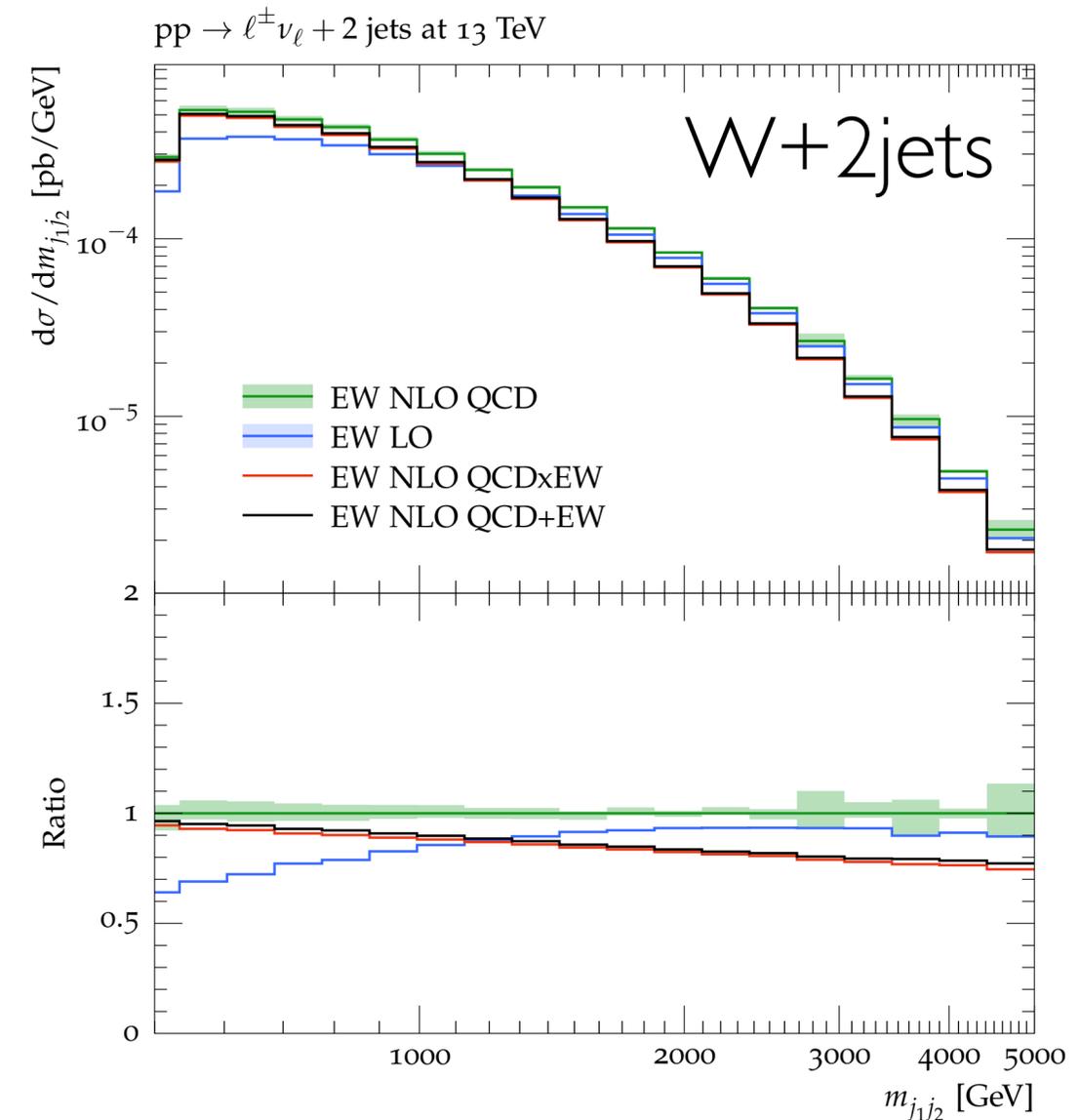
- **QCD**: very small K-factor at large mjj, uncertainty ~10% (no VBF approximation)
- **EW**: up to -20% in multi TeV

Conclusions

Incredible progress in theory predictions for multibosons

VV
- NNLO QCD + NLO EW available in MATRIX+OpenLoops for all (massive) diboson processes
- MEPS @ NLO (QCD + EWapprox) available in Sherpa
- NLO (QCD + EW) + PS (QCD + QED) available in POWHEG
- NLO QCDgg PS soon available in POWHEG
- NNLO QCD PS via MiNNLO available

VBS-VV / VBF-V
- QCD and EW processes formally overlap at NLO
- NLO EW to EW mode often dominant correction
- full NLO precision is becoming widely available

VVV
- on-shell production poor approximation of full off-shell production
- large accidental and observable dependent cancellation
  between EW Sudakov corrections and photon-induced at NLO EW

BACKUP

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
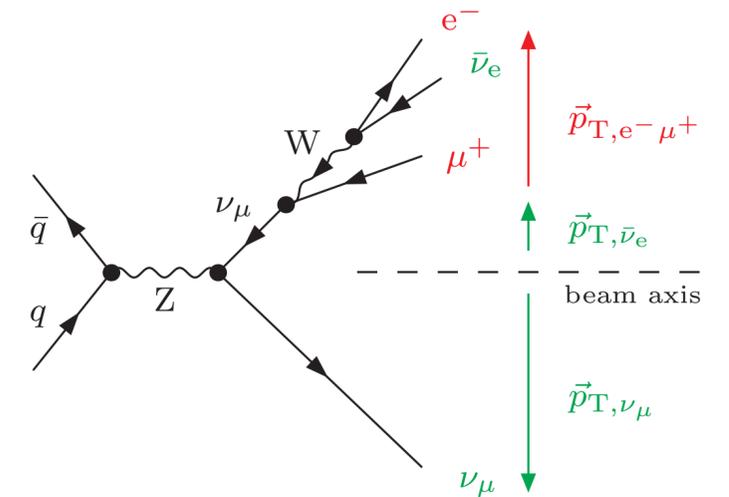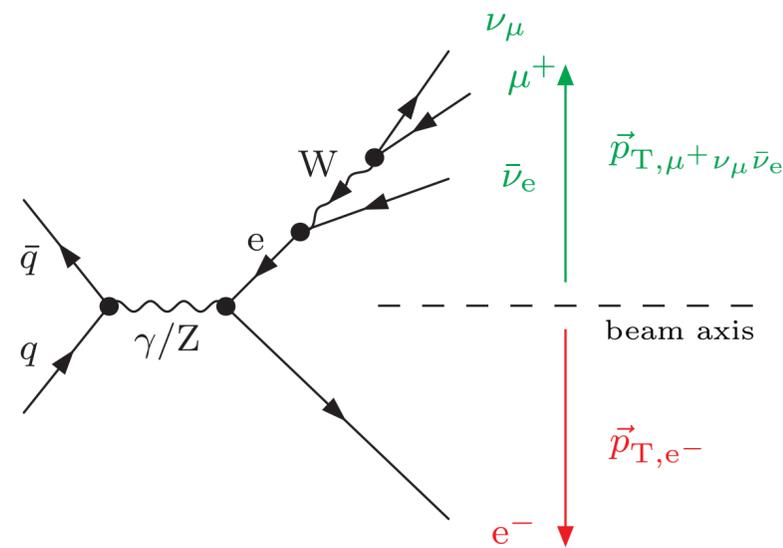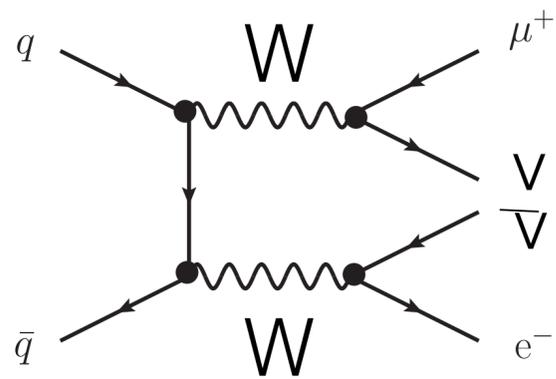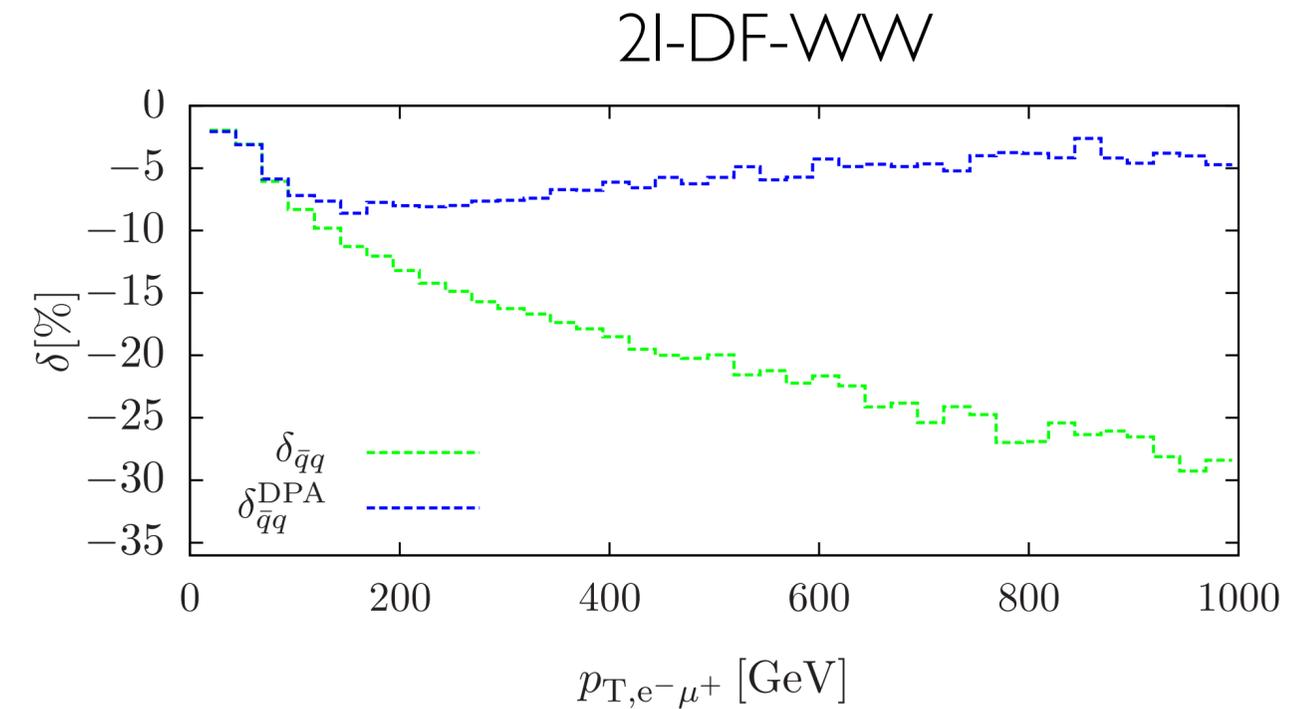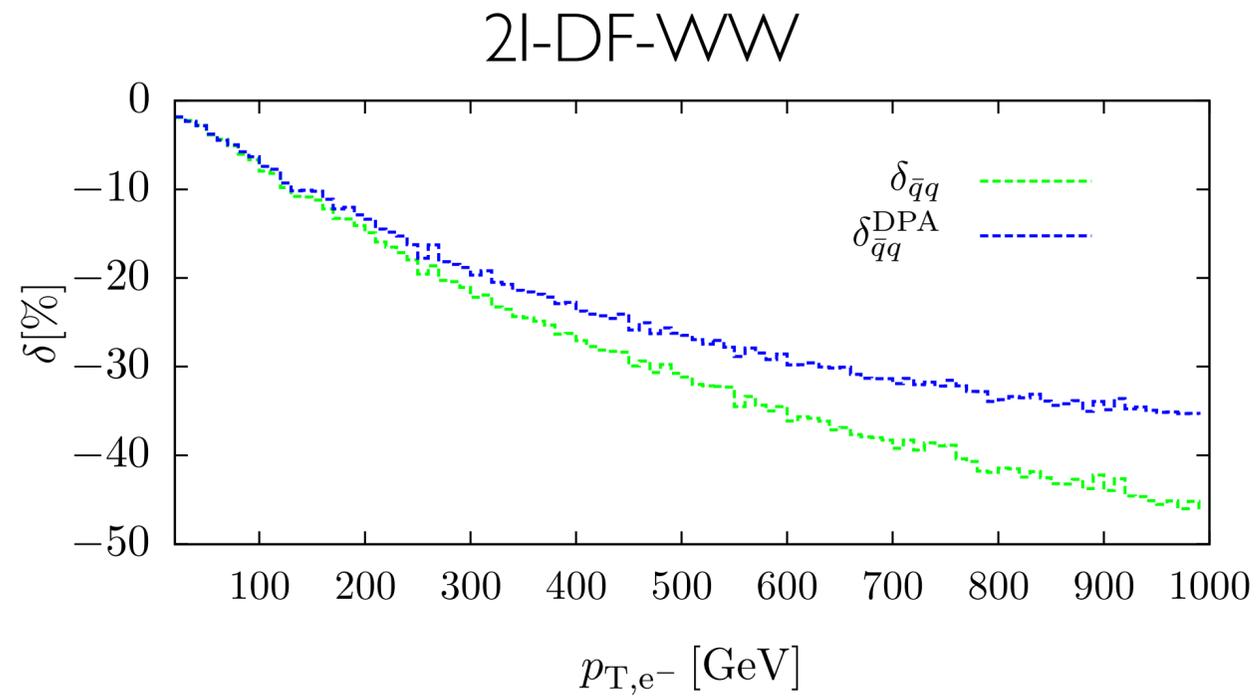
➡ sizeable differences in fully off-shell vs. double-pole approximation in tails
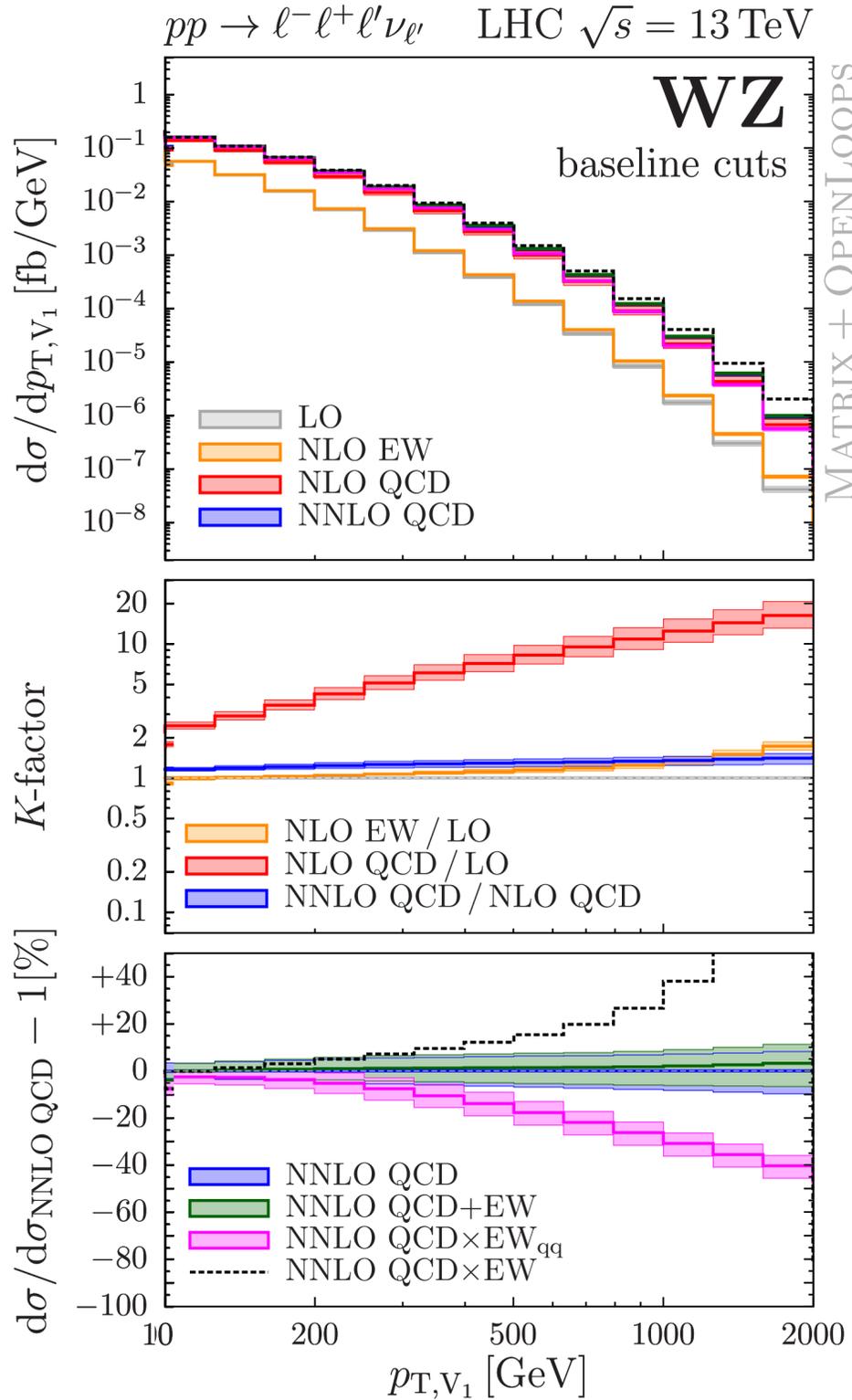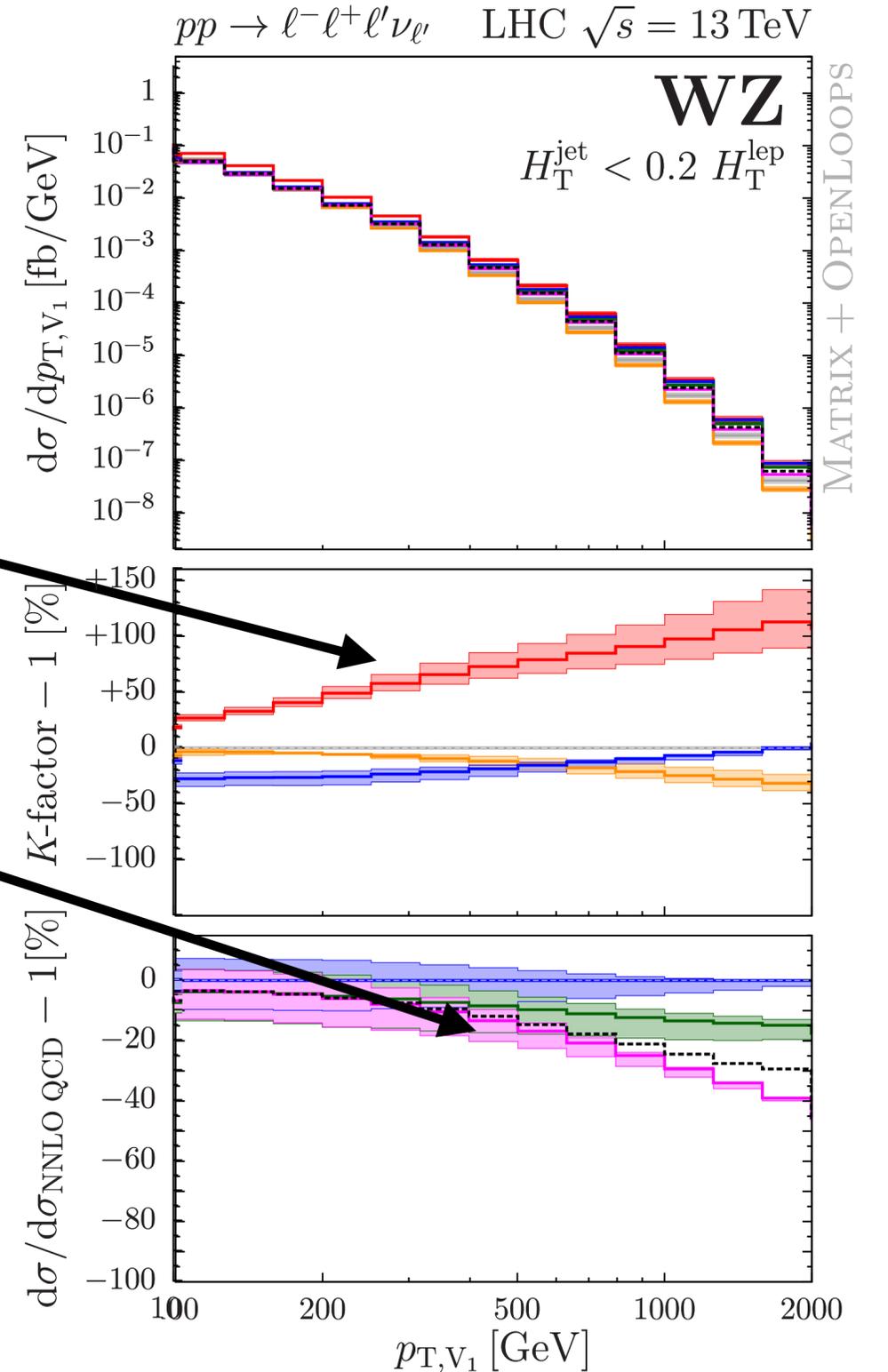
- NLO QCD/LO=~<1.5
  ("normal K-factor")

- 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!