Precision Monte Carlos for multi-boson processes

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Science & Technology Facilities Council | UK Research and Innovation

Workshop on…. measurements and reinterpretations…
at the LHC
U Sussex
15th June 2022

Multibosons

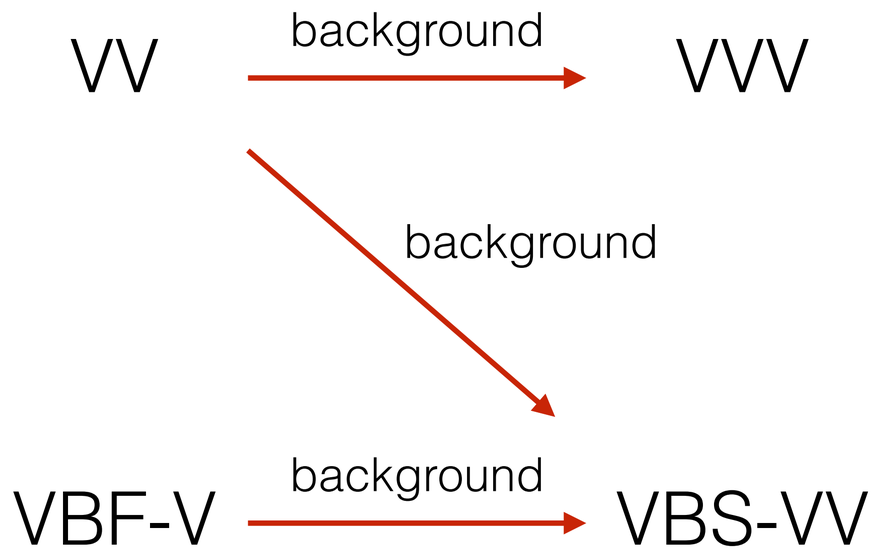
VV

VVV

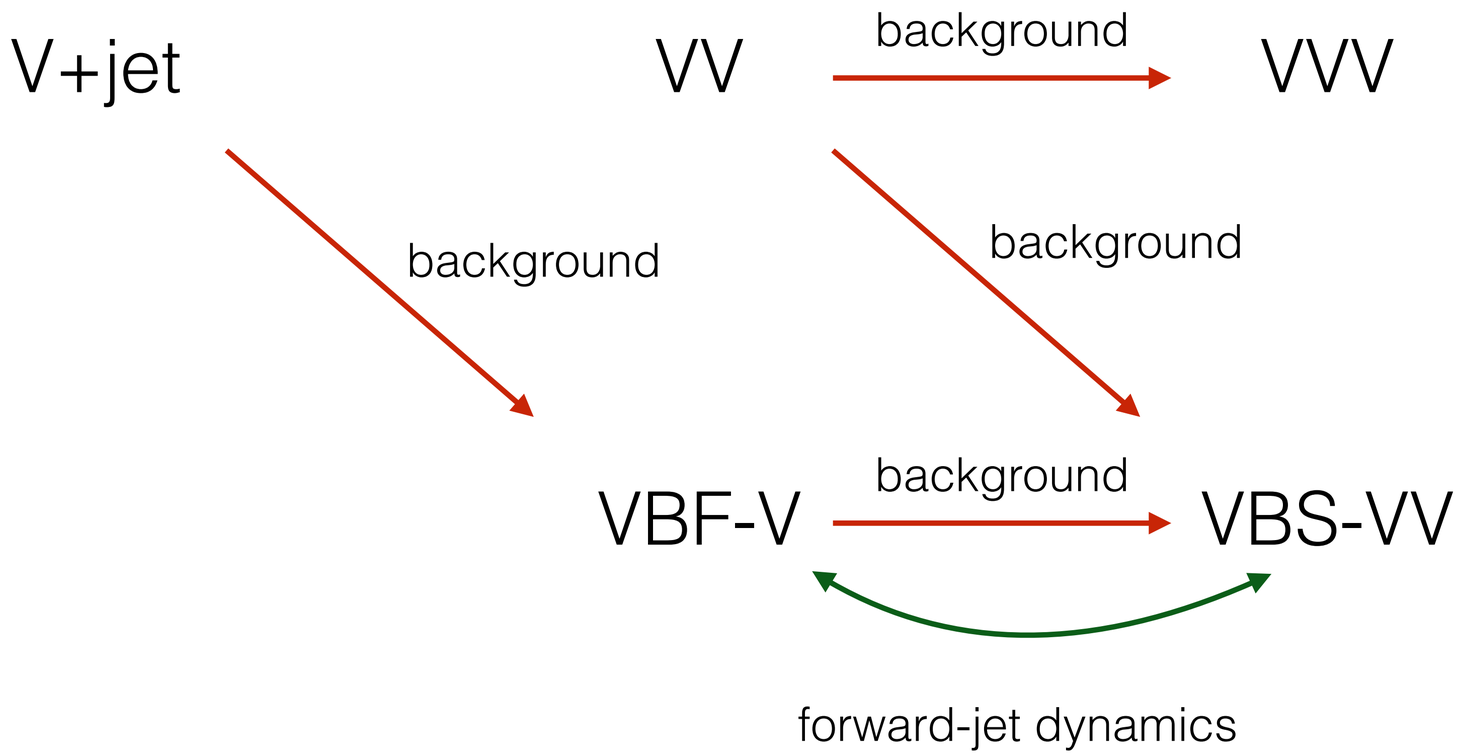
VBF-V

VBS-VV

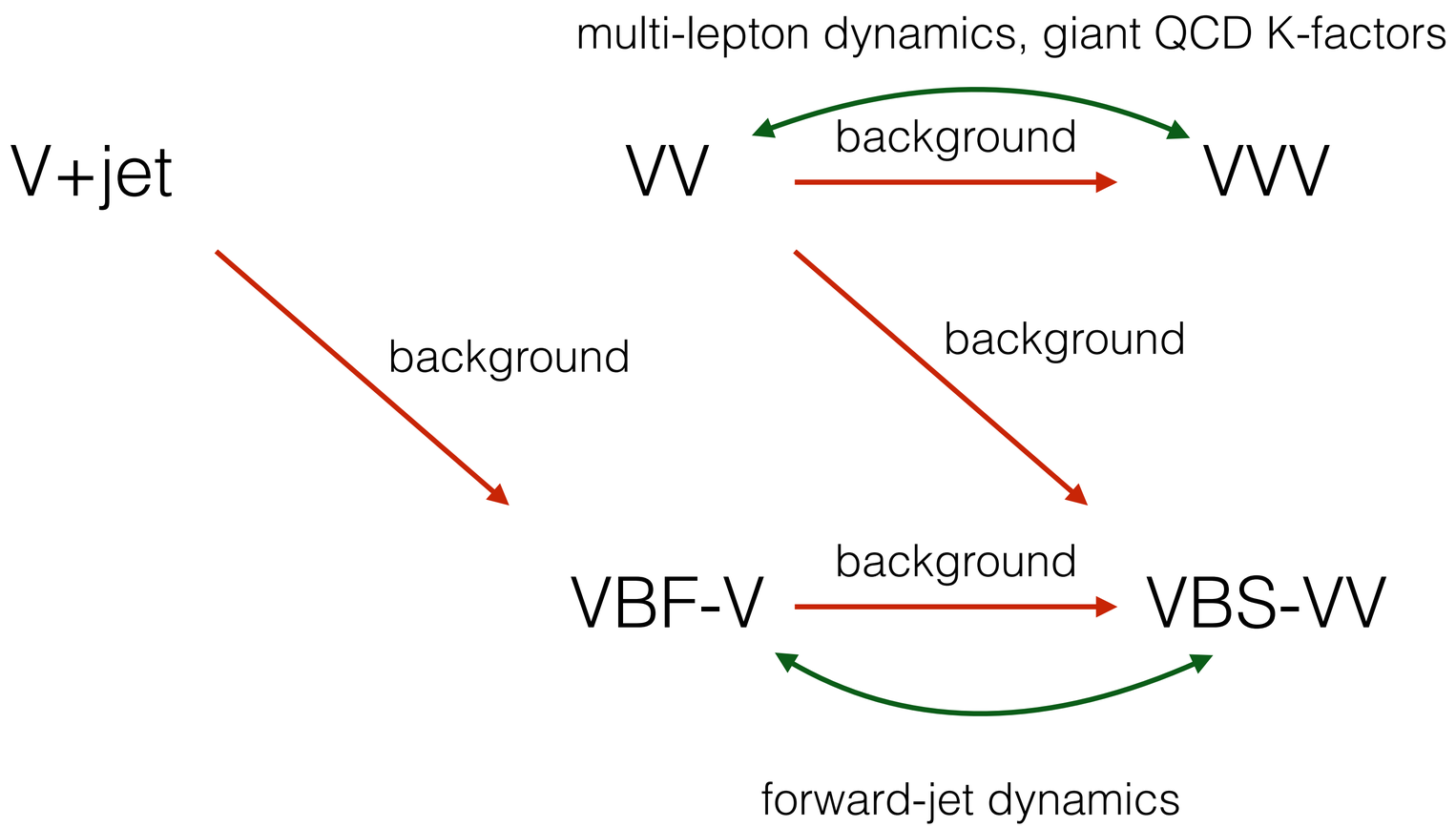
Multibosons



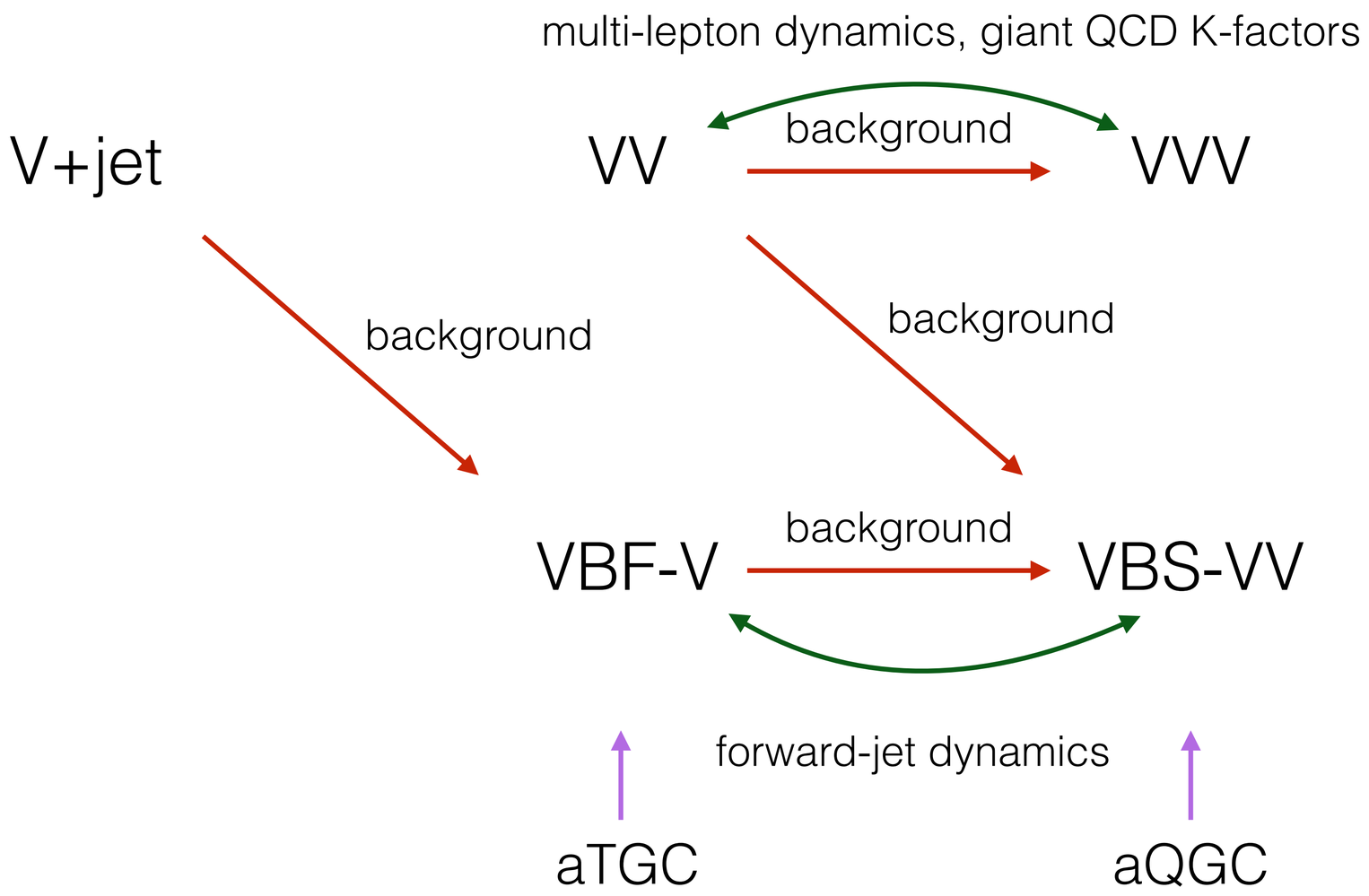
Multibosons



Multibosons



Multibosons



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

fixed-order

V+jets

NLO QCD+NLO EW

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NNLO QCD+NLO EW

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NLO QCD+NLO EW

VBF-V

NLO QCD+NLO EW

[JML, Pozzorini, Schönherr, 2204.07652]

VBS-VV

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

*: VBF approximation

Multibosons: theory state-of-the art

Monte Carlo

V+jets

NLOPS QCD (0,1,2j) x
NLO EWvirt

VV

NLOPS QCD (0,1) x
NLO EWvirt

NNLOPS QCD

NLOPS EW

VVV

NLOPS QCD

VBF-V

NLOPS* QCD

VBS-VV

NLOPS* QCD

NLOPS EW

NLOPS QCD (nj) =
- FxFx in aMC@NLO
- MEPS@NLO in Sherpa

*: VBF approximation

Multibosons: theory state-of-the art

Monte Carlo

V+jets

NLOPS QCD (0,1,2j) x
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NLOPS EW

VVV

NLOPS QCD

VBF-V

NLOPS* QCD

VBS-VV

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

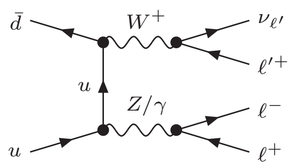
$$+\alpha_S^2\,\mathrm{d}\sigma_{\mathrm{NNLO}} + \alpha_{\mathrm{EW}}^2\,\mathrm{d}\sigma_{\mathrm{NNLO\,EW}}\,? + \alpha_S\alpha_{\mathrm{EW}}\,\mathrm{d}\sigma_{\mathrm{NNLO\,QCDxEW}}\,?$$

NNLO QCD — NNLO EW — NNLO QCD-EW

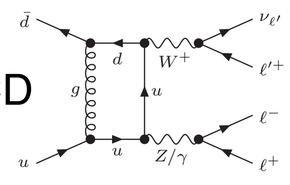
$$+\alpha_S^3\,\mathrm{d}\sigma_{\mathrm{NNLO}}\,? + \ldots$$

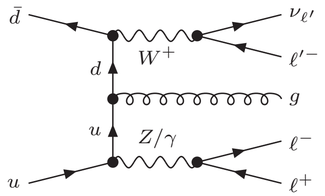
N3LO QCD

LO

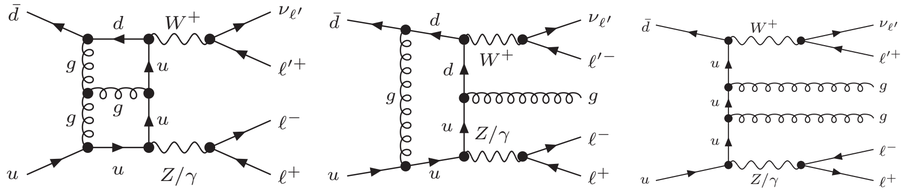


NLO QCD





NNLO 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

Perturbative expansion for VV

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

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

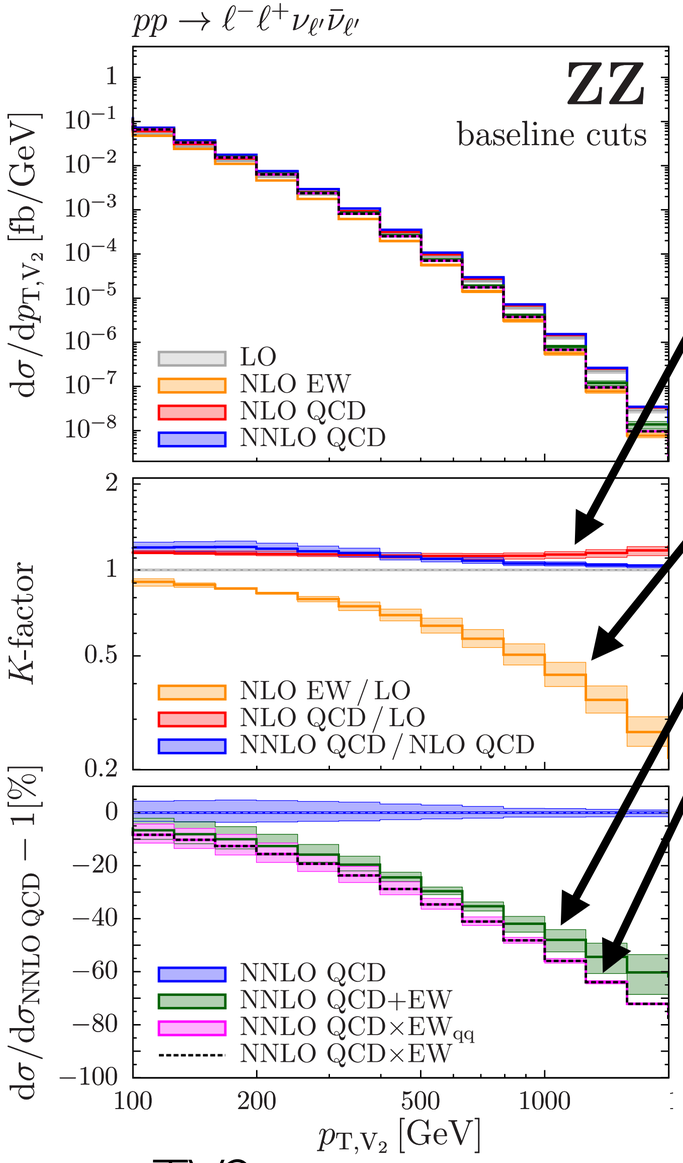
4l-SF-ZZ	$pp \to \ell^+\ell^-\ell^+\ell^-$	ZZ
4l-DF-ZZ	$pp \to \ell^+\ell^-\ell'^+\ell'^-$	ZZ
3l-SF-WZ	$pp \to \ell^+\ell^-\ell\nu_\ell$	WZ
3l-DF-WZ	$pp \to \ell^+\ell^-\ell'\nu_{\ell'}$	WZ
2l-SF-ZZ	$pp \to \ell^+\ell^-\nu_{\ell'}\bar{\nu}_{\ell'}$	ZZ
2l-SF-ZZWW	$pp \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell$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

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

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

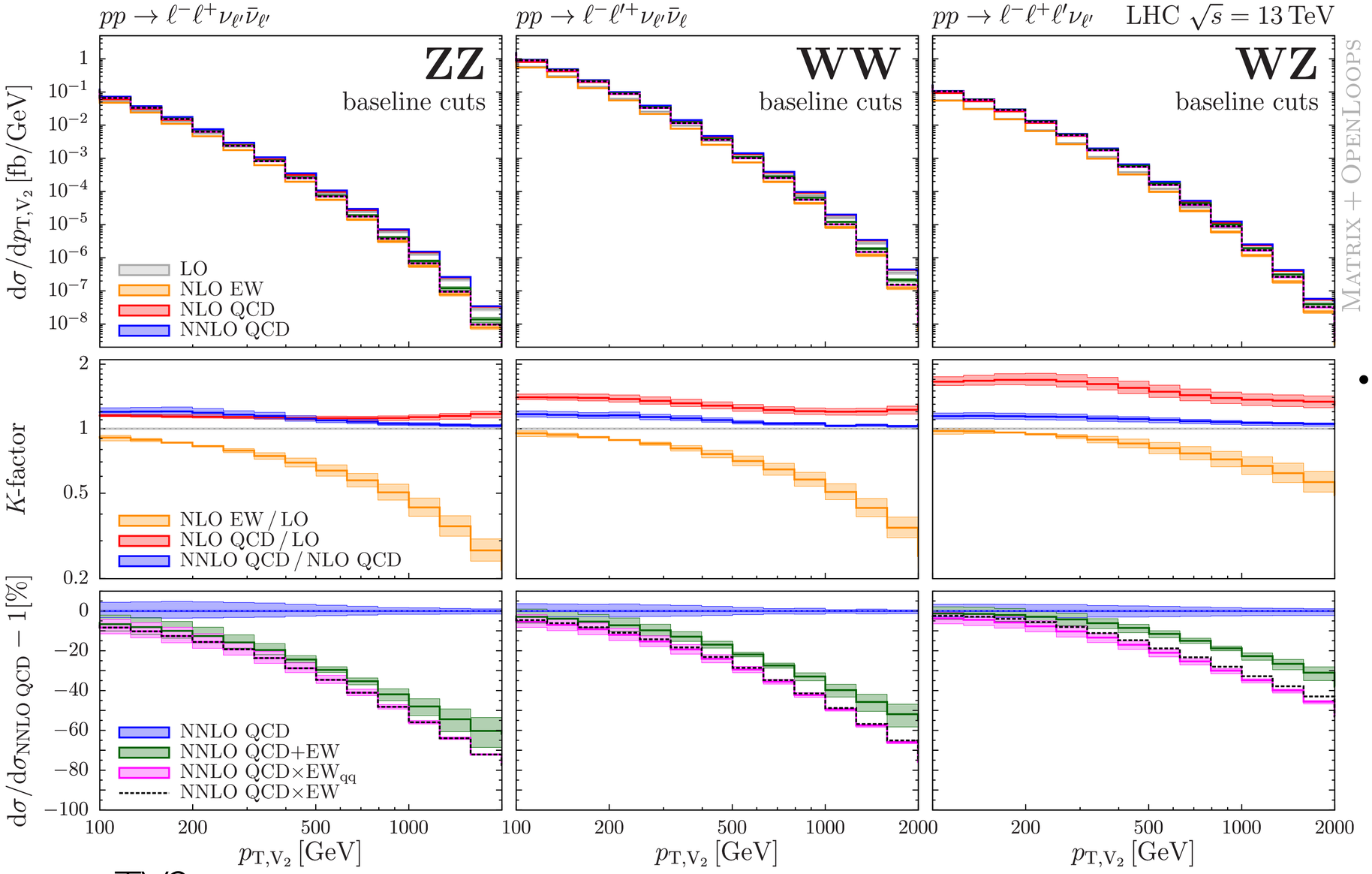
$$\mathrm{d}\sigma_{\mathrm{NNLO\,QCD\times EW}} = \mathrm{d}\sigma_{\mathrm{LO}}\left(1+\delta_{\mathrm{QCD}}\right)\left(1+\delta_{\mathrm{EW}}\right)+\mathrm{d}\sigma^{gg}_{\mathrm{LO}}$$

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

- 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: $\mathcal{O}(\alpha^2) \sim \alpha_{\mathrm{w}}^2 \log^4(Q^2/M_W^2)$

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

NNLO QCD + NLO EW for dibosons: pTV2

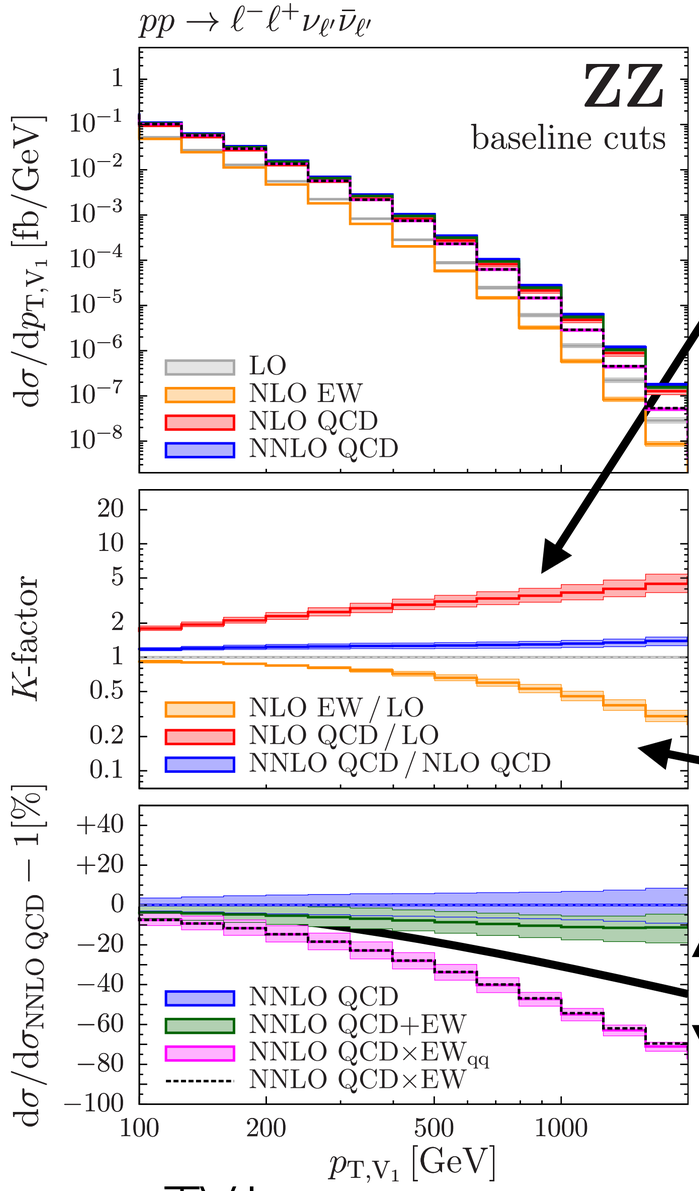


pTV2

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

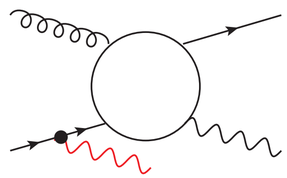
Giant QCD K-factors and EW corrections: pTV1

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



pTV1

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



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

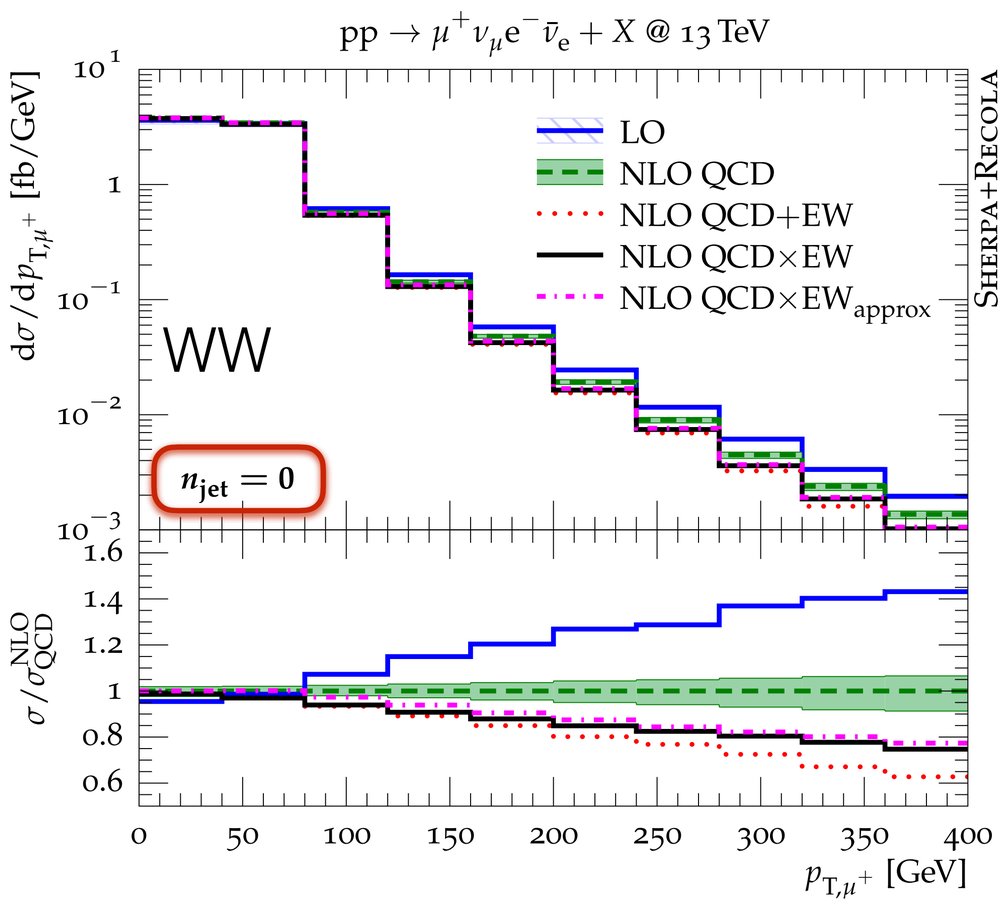
- NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- NLO EW/LO=-(40-50)%
- Very large difference $\mathrm{d}\sigma_{\mathrm{NNLO\,QCD+EW}}$ vs. $\mathrm{d}\sigma_{\mathrm{NNLO\,QCD\times EW}}$
- Problems:
  1. In additive combination dominant Vj topology does not receive any EW corrections
  2. In multiplicative combination EW correction for VV is applied to Vj hard process
- **Pragmatic solution I: take average as nominal and spread as uncertainty**
- Pragmatic solution II: **apply jet veto to constrain Vj toplogoies**

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



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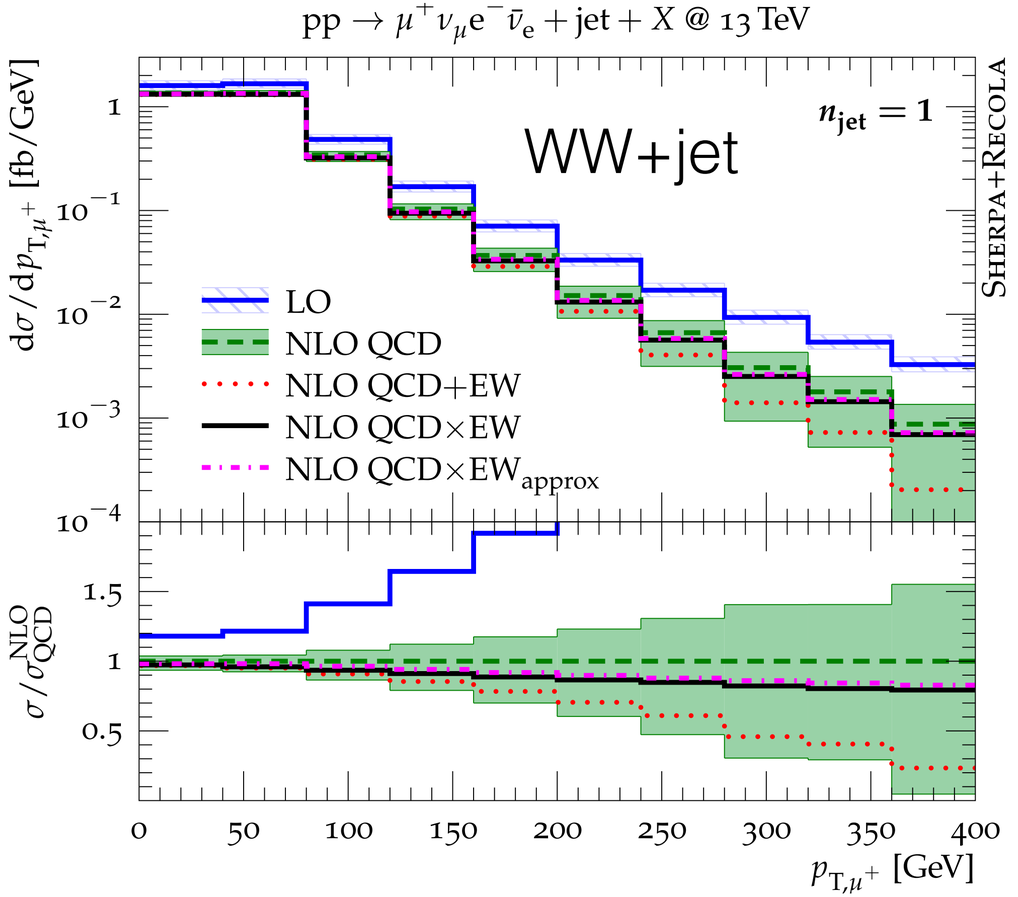

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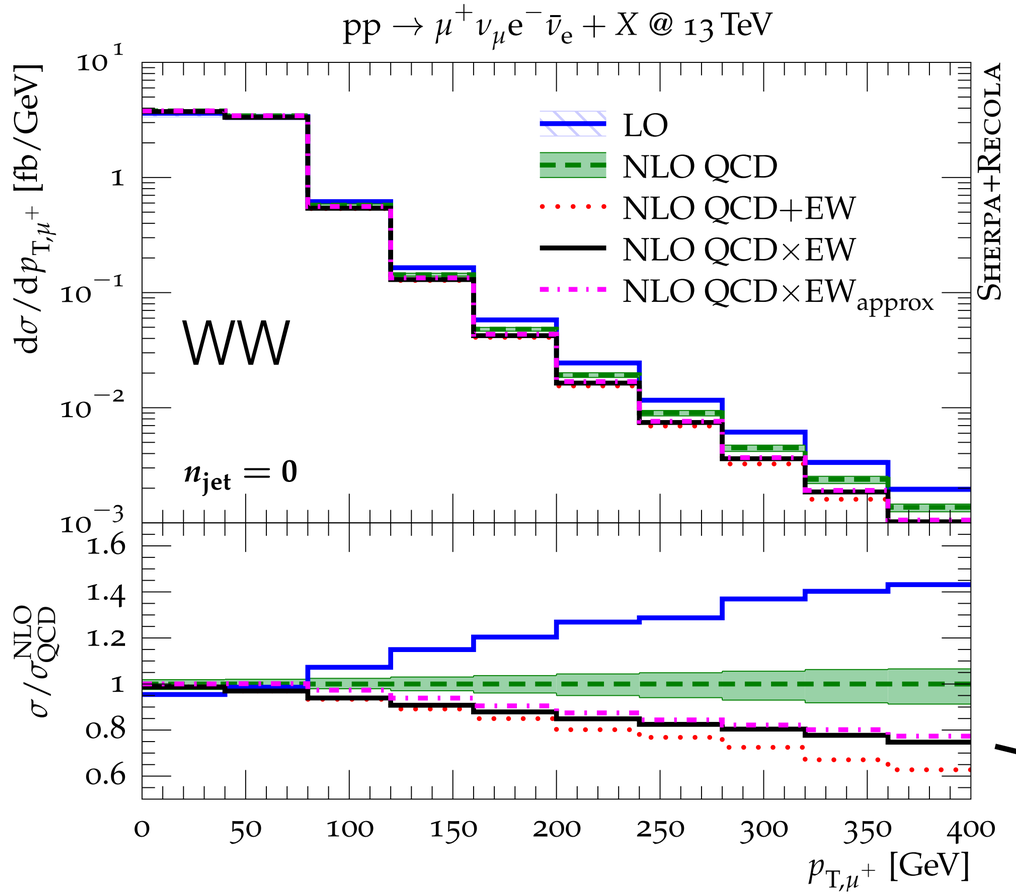
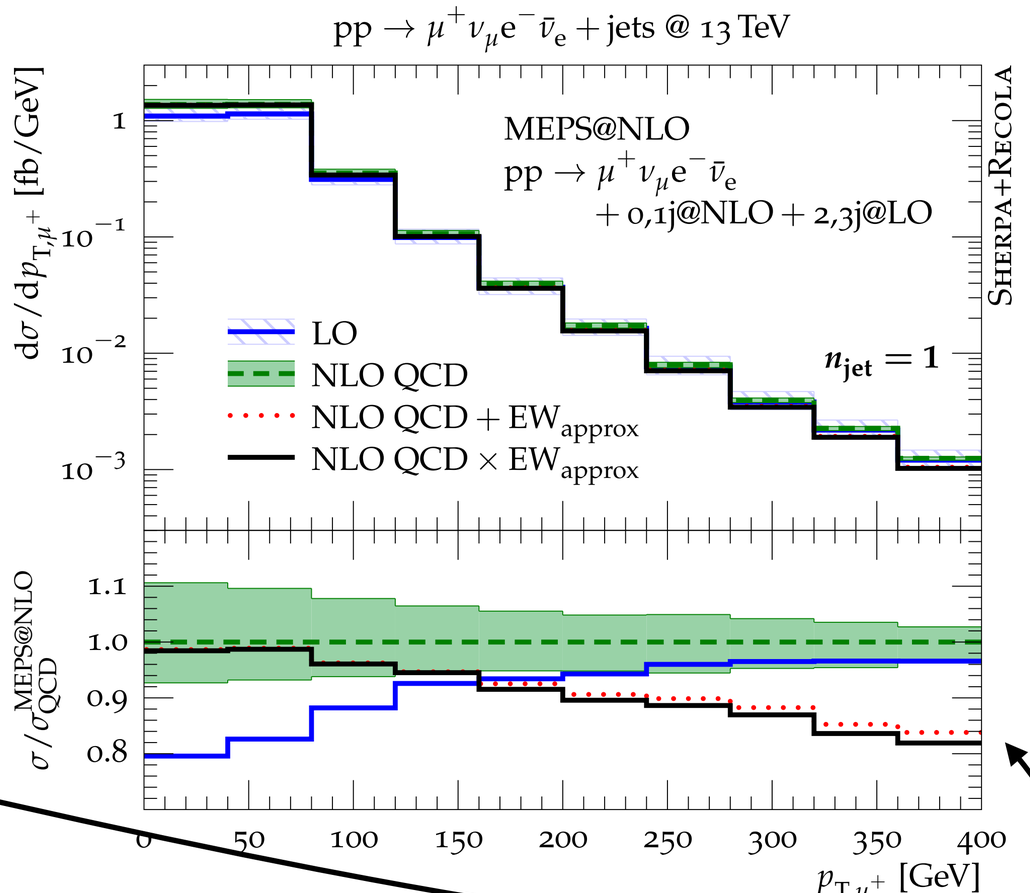


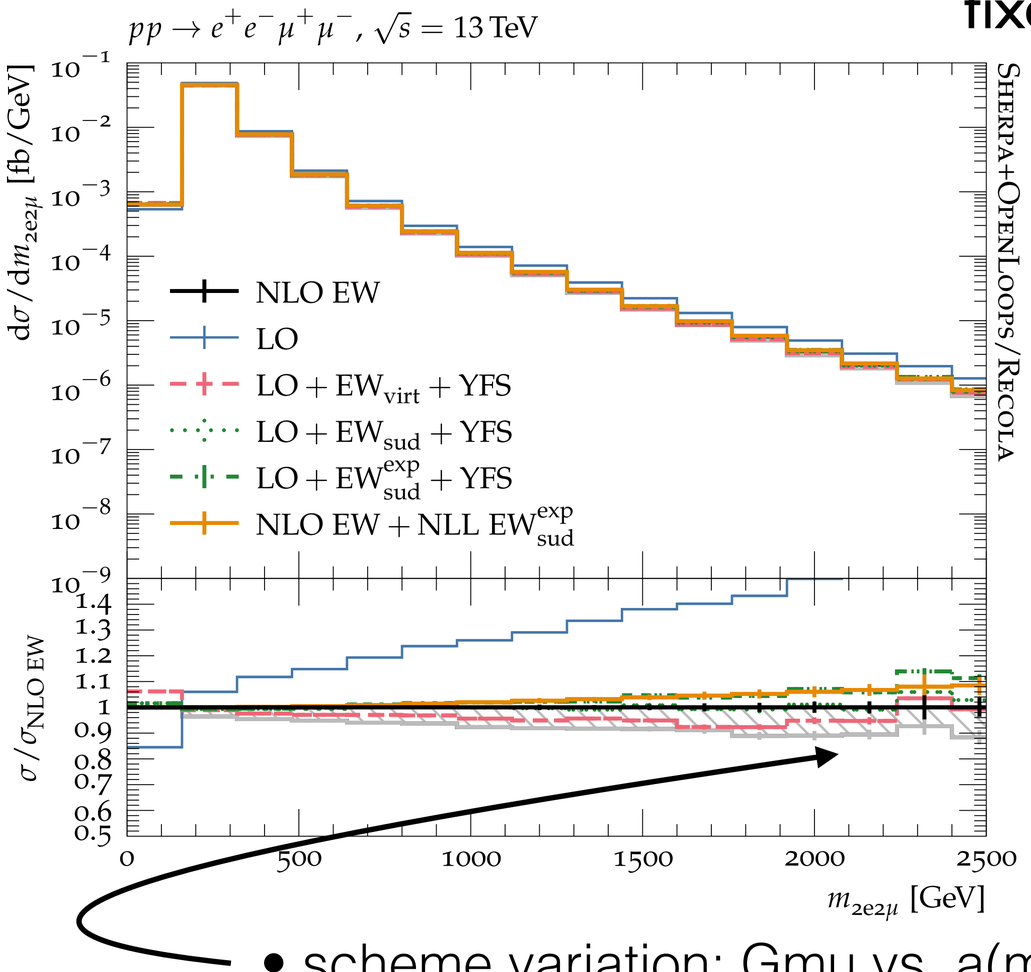
MEPS@NLO QCD + EWvirt

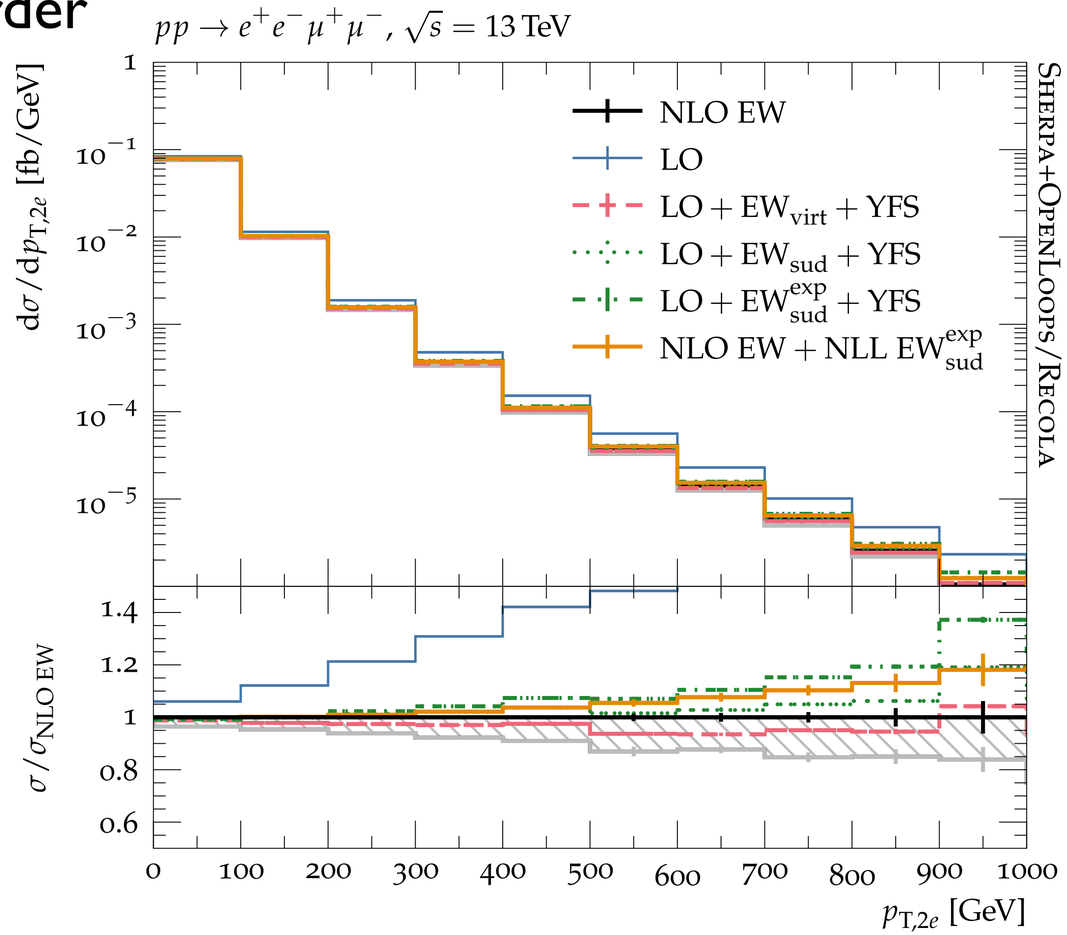


MEPS @ NLO QCD + EW: ZZ(+jet)

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

fixed-order

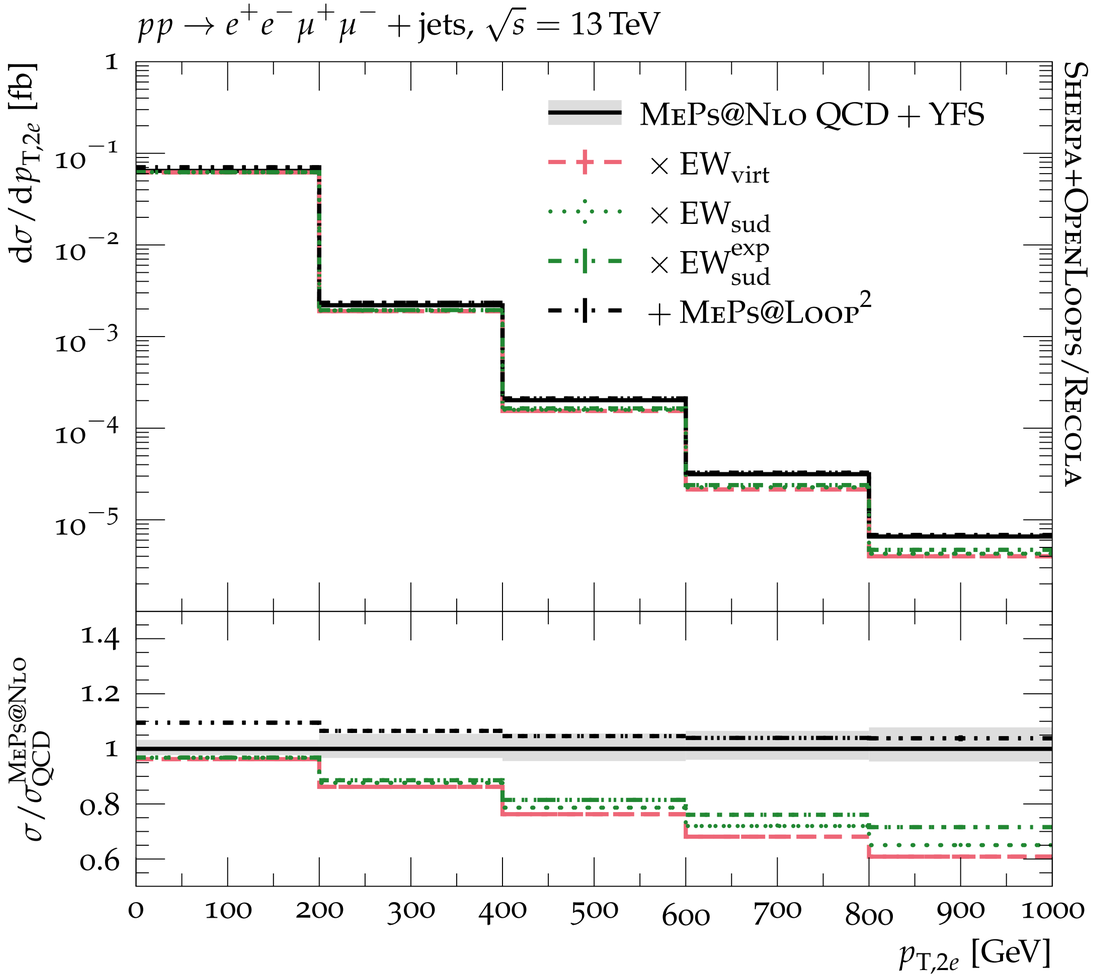


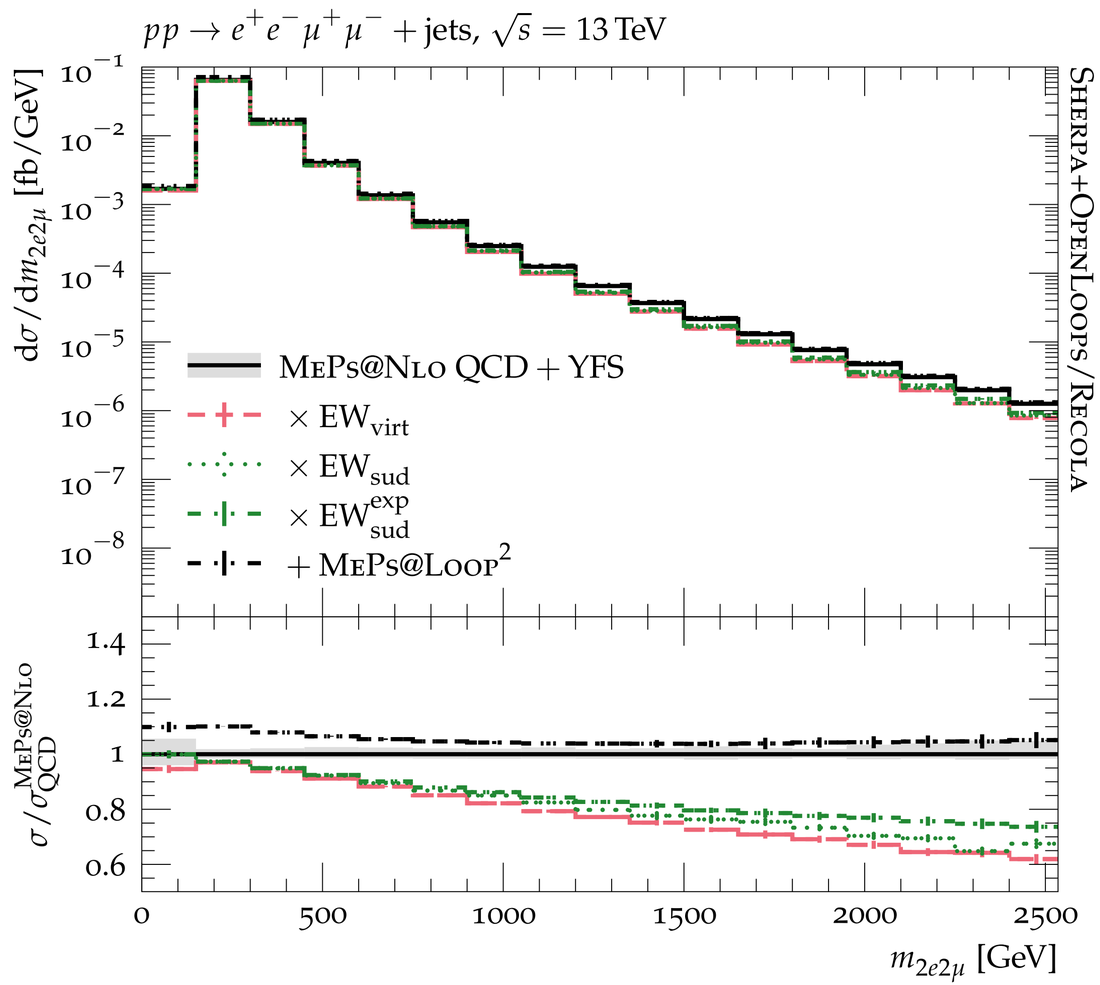


- scheme variation: Gmu vs. a(mZ)
- EWsud based on *[Bothmann,Napoletano, '20]*: process-independent implementation of Sudakov logs, see also *[Pagani, Zaro '21]*

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

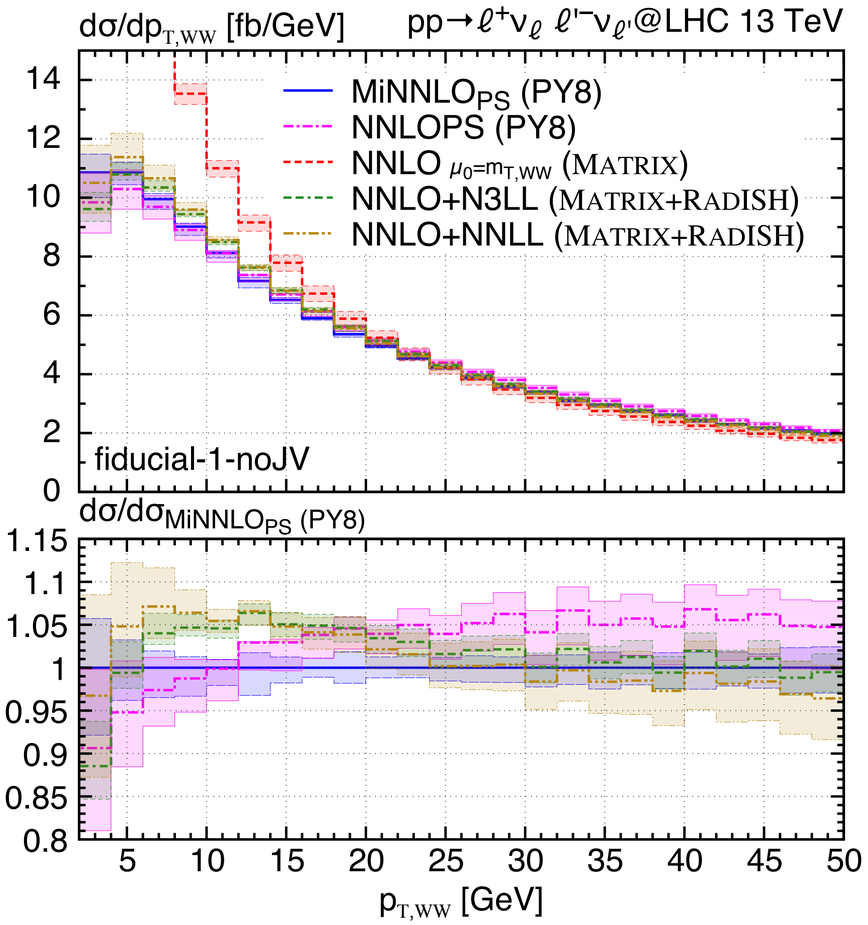
[Bothmann, Napoletano, Schönherr, Schumann, Villani; '21]

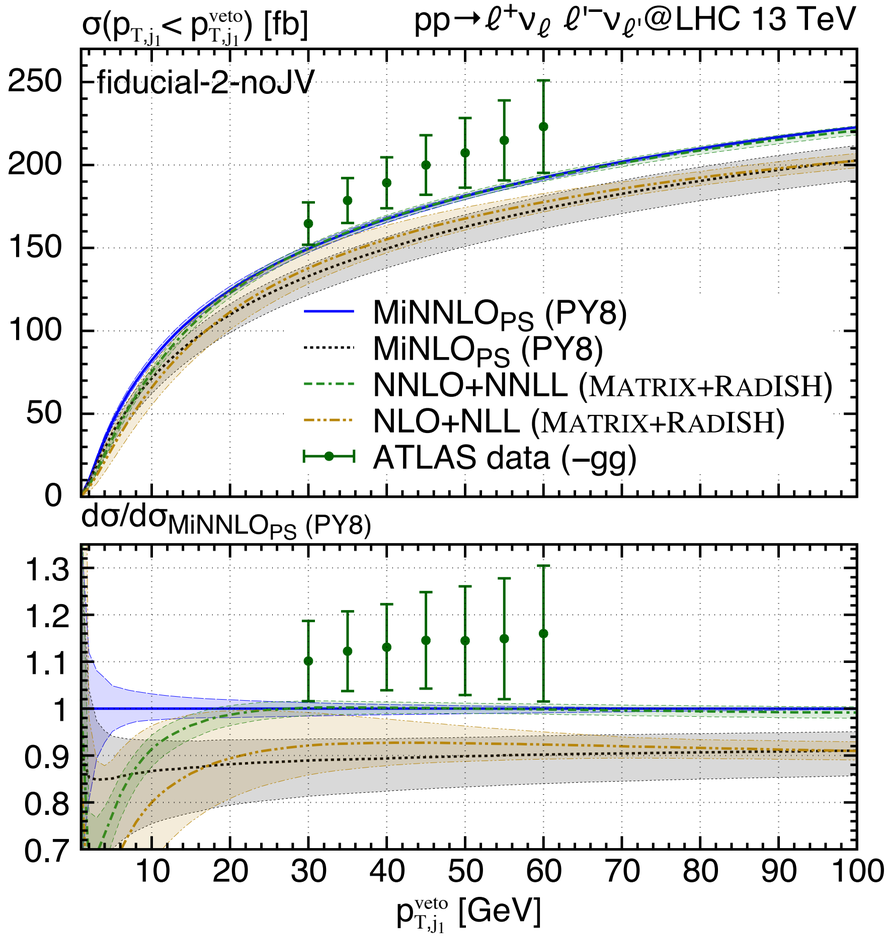




PS MC: NNLO QCD + PS for WW via MiNNLO$_{PS}$

[Lombardi, Wiesemann; Zanderighi '21]

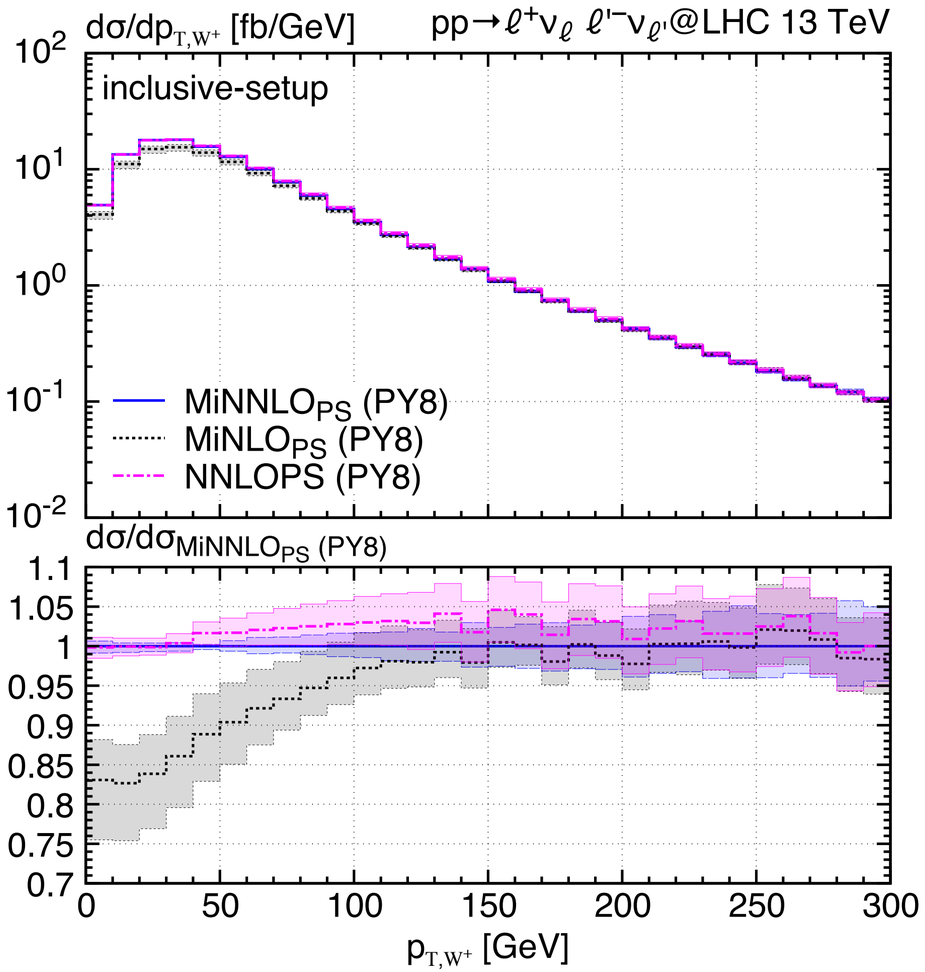


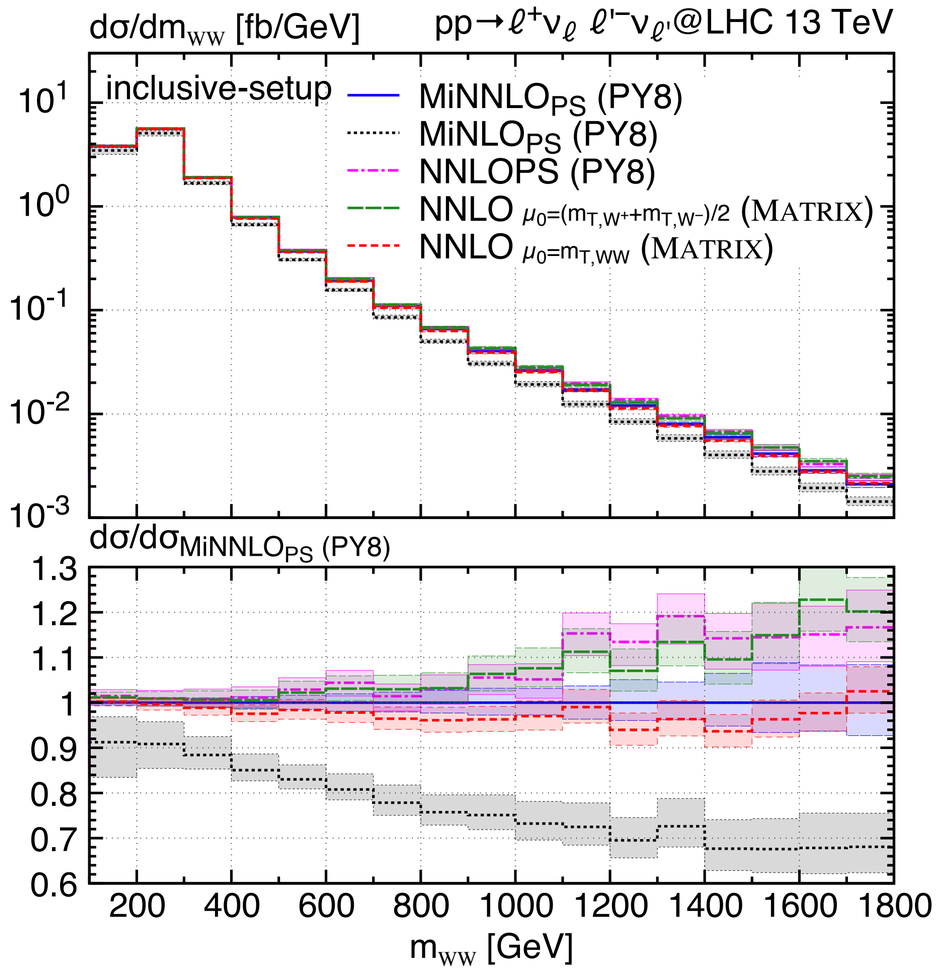


- MiNNLO$_{PS}$ physical down to pTVV=0
- Latest implementation does not require computationally expensive reweighting required earlier

PS MC: NNLO QCD + PS for WW via MiNNLO$_{PS}$

[Lombardi, Wiesemann; Zanderighi '21]

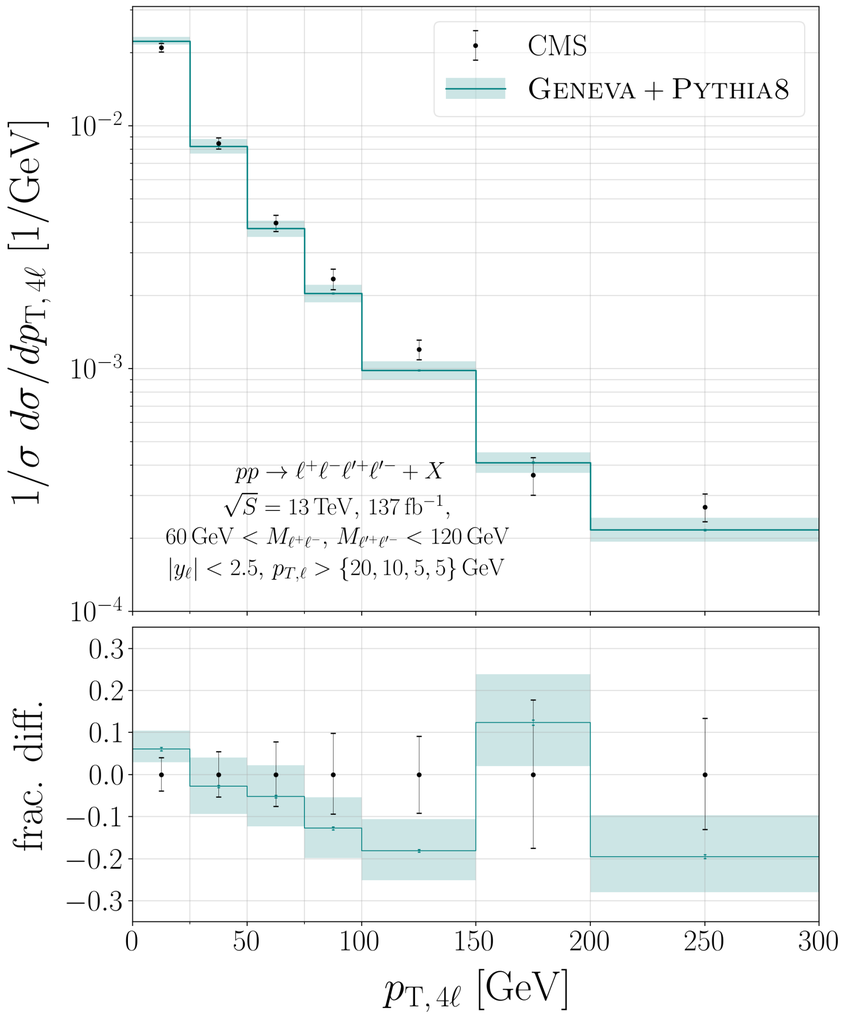




PS MC: NNLO QCD + PS for ZZ via MiNNLO$_{PS}$

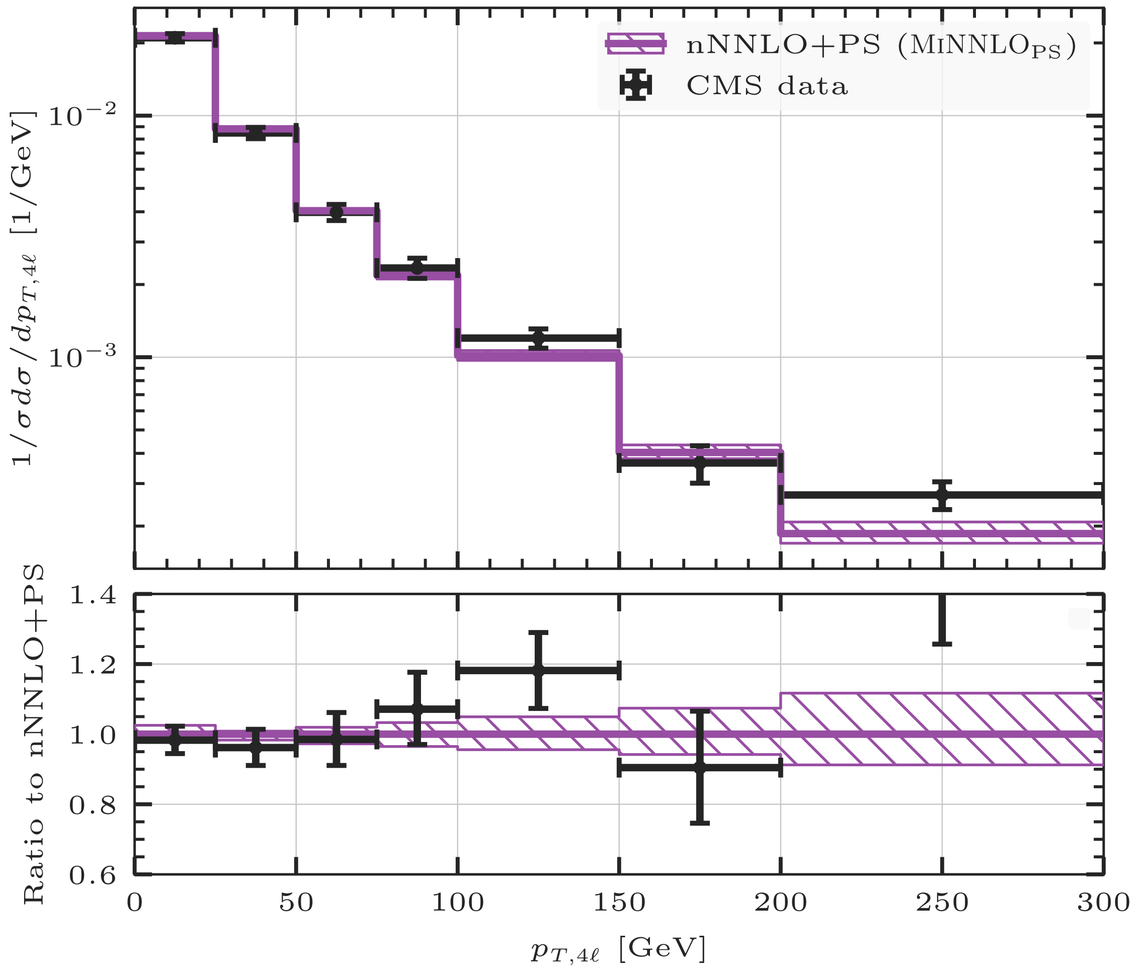
Geneva: NNLO+PS

[Alioli, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, '21]



MiNNLO$_{PS}$: nNNLO+PS

[Buonocore, Koole, Lombardi, Rottoli, Wiesemann, Zanderighi, '21]



PS MC: NNLO QCD + PS for ZZ via MiNNLO$_{PS}$

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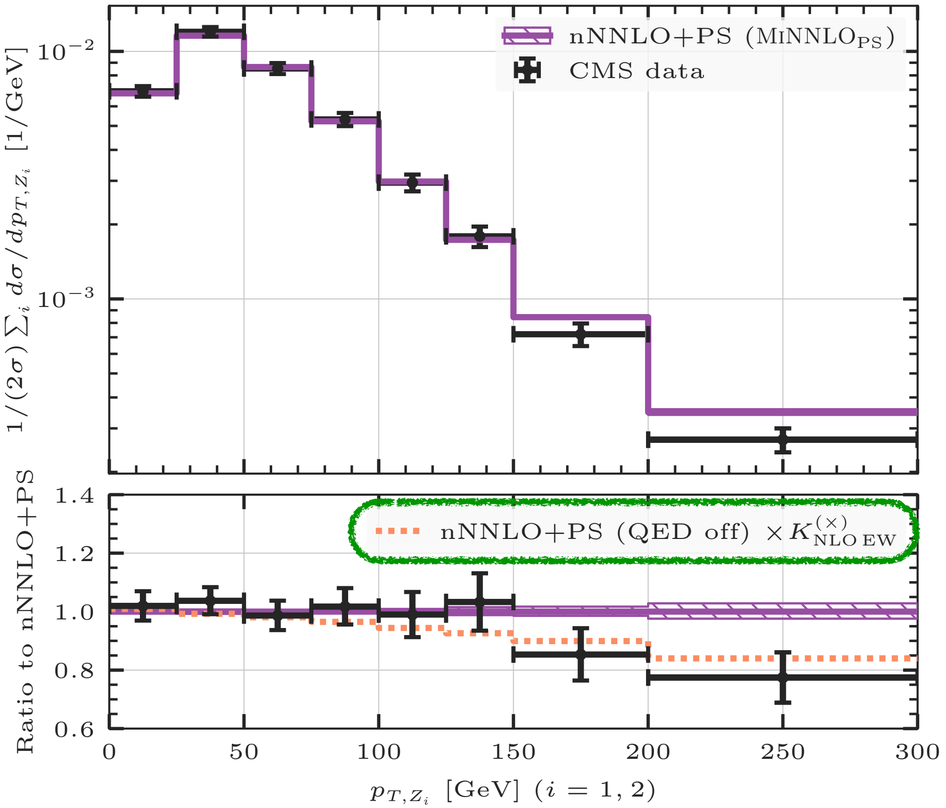
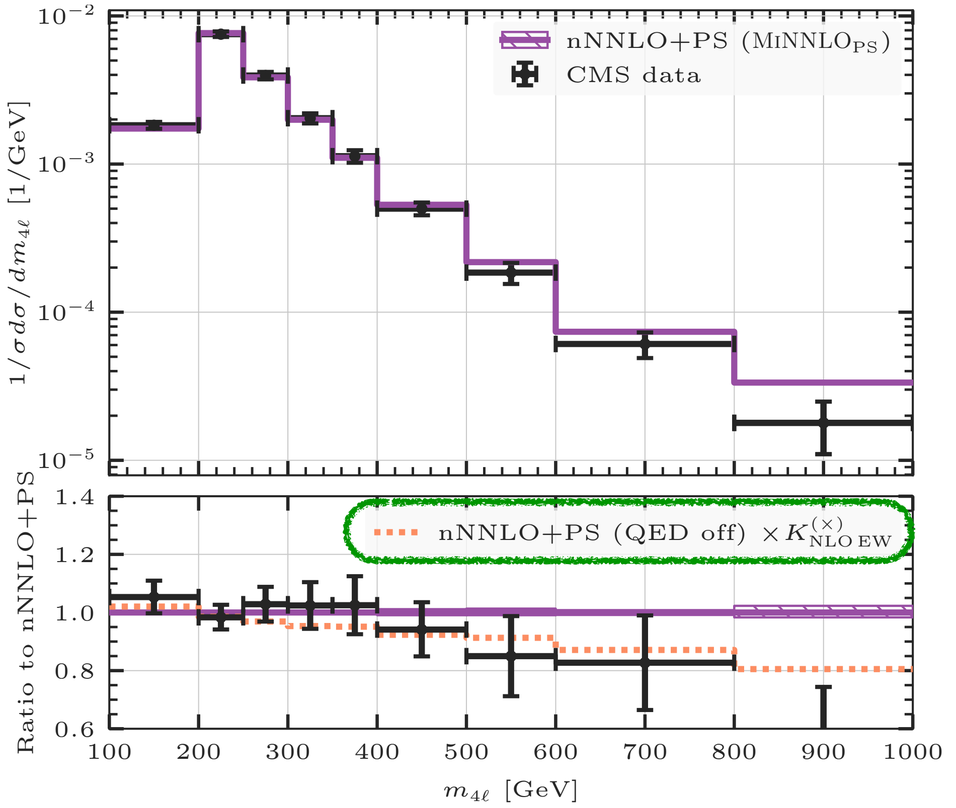
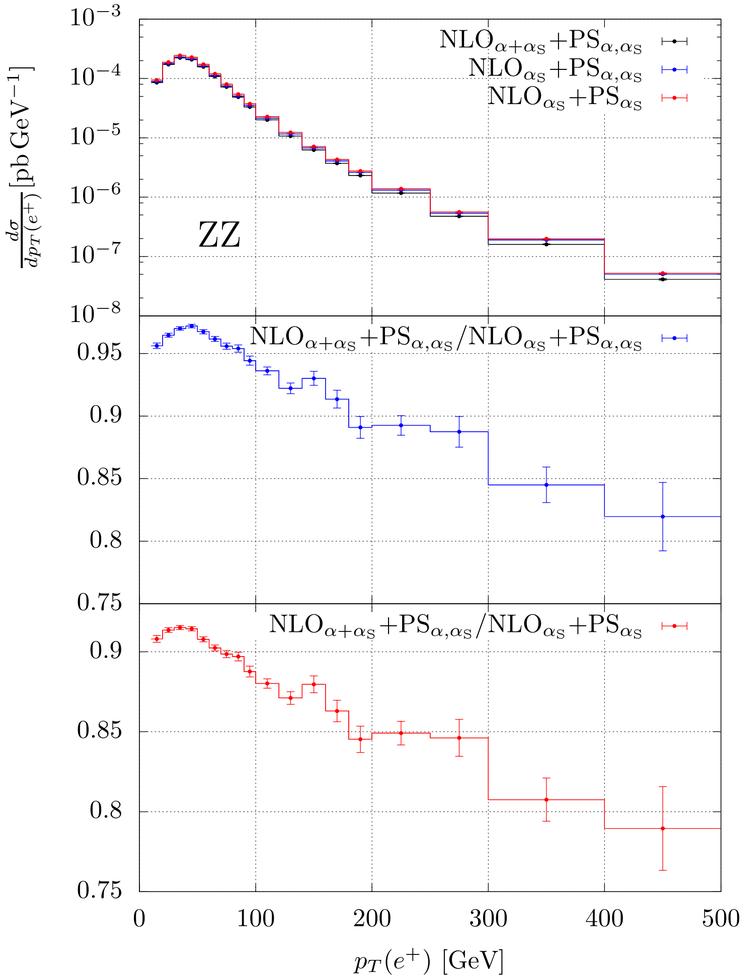


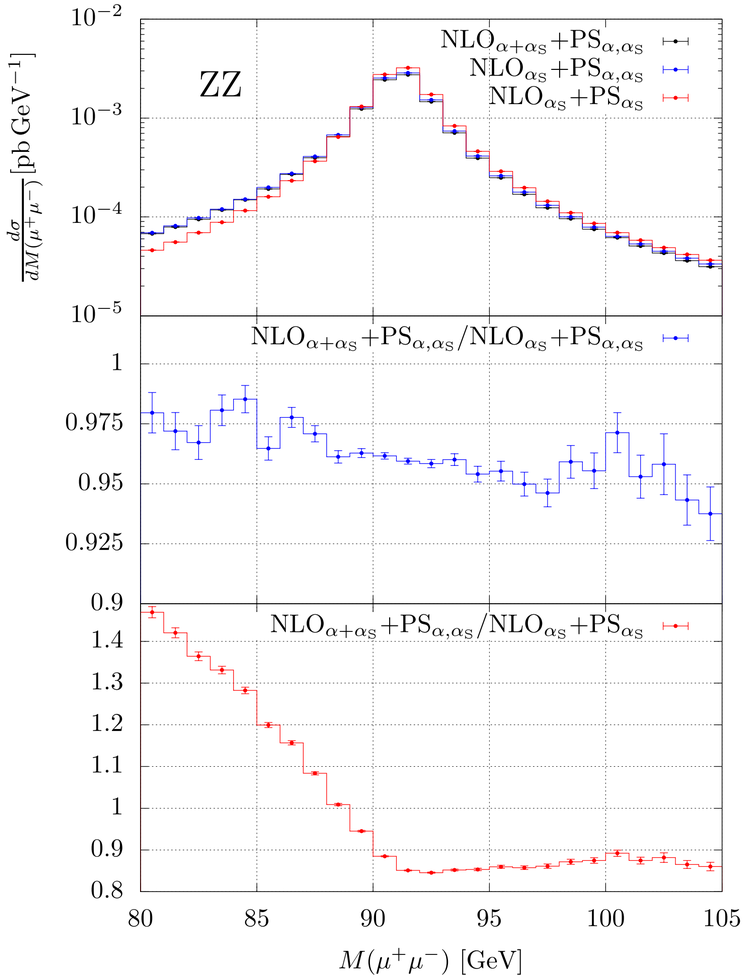


- nNNLO+PS predictions in good agreement with CMS results [arXiv:2009.01186]
- inclusion of EW corrections (through fixed-order NLO K-factor) required to describe tails of distributions

PS MC: NLO QCD + NLO EW PS

[Chiesa, Re, Oleari '20]





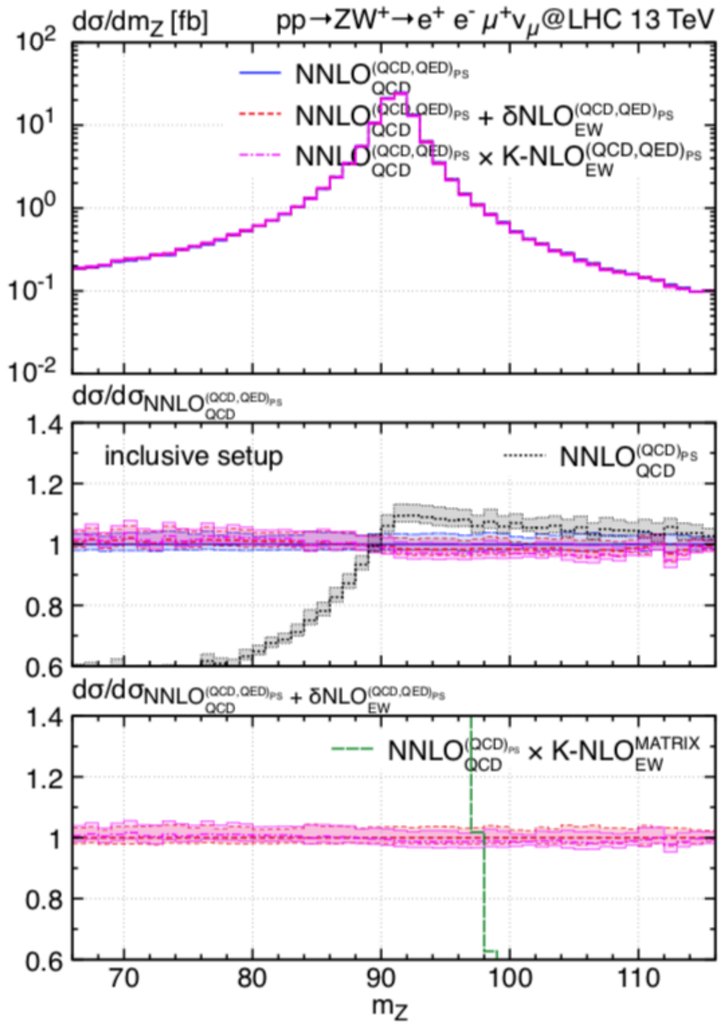
NLO (QCD + EW) PS (QCD + QED)/
NLO QCD PS (QCD + QED)

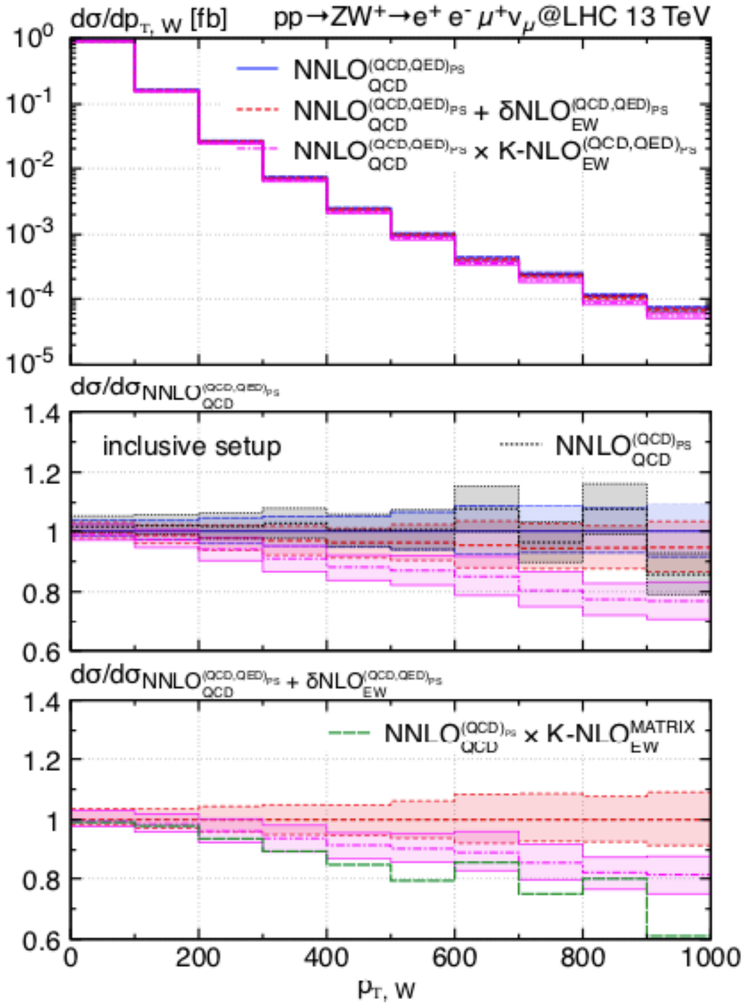
NLO (QCD + EW) PS (QCD + QED)/
NLO QCD PS QCD

- Note: resonance-aware NLO EW matching required (POWHEG-BOX-RES *[Ježo, Nason, '15]*)
- Missing: photon-induced channels
- Question: NLO (QCD + EW) PS (QCD + QED) / (NLO QCD PS QCD) x NLO EW

PS MC: NNLO QCD x NLO EW PS for WZ

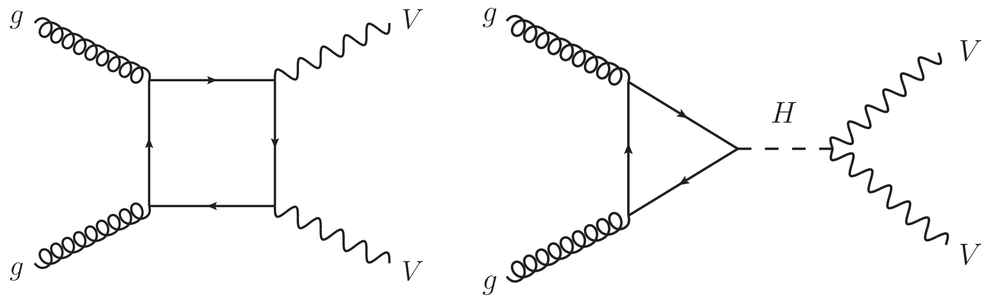
[JML, Lombardi, Wiesemann, Zanderighi, Zanoli, to appear]



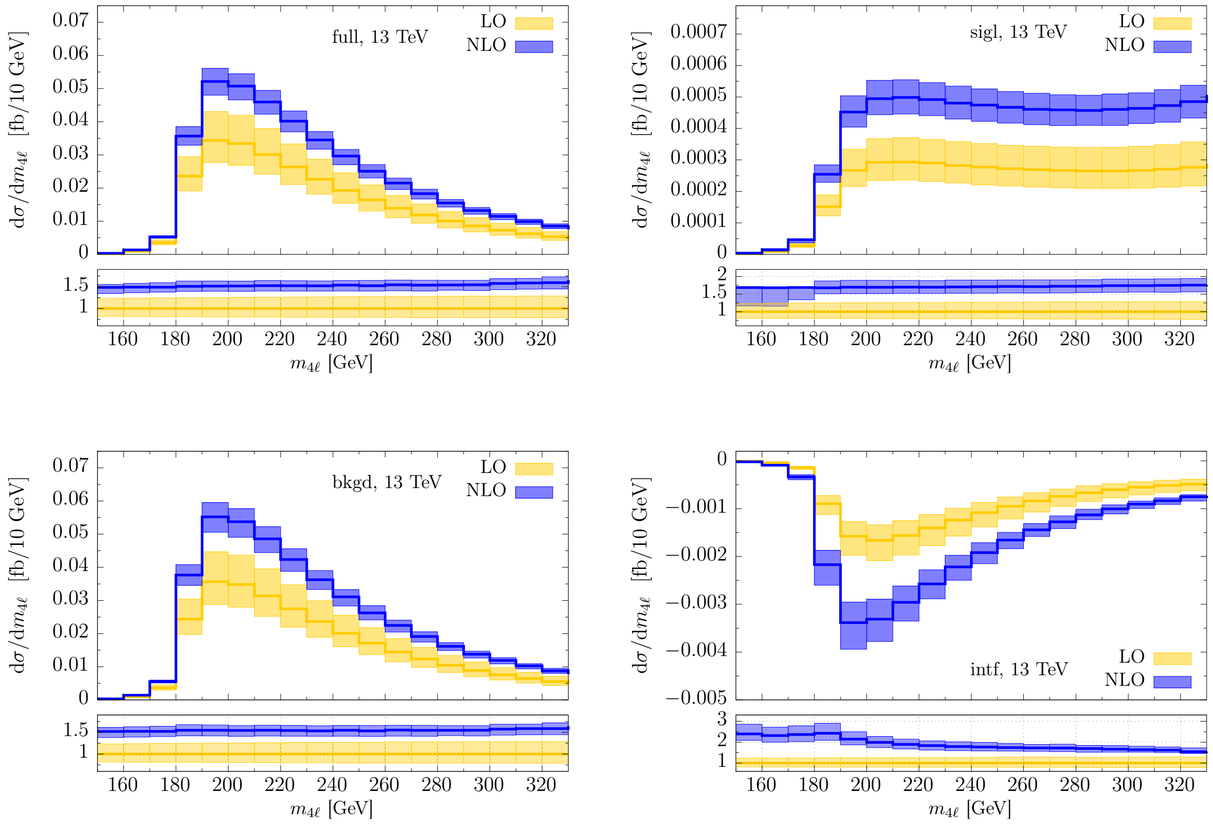


- NNLOPS QCD x NLOPS EW combination via reweighing (NLOPS EW resonance-aware)
- Next: combination at generator level

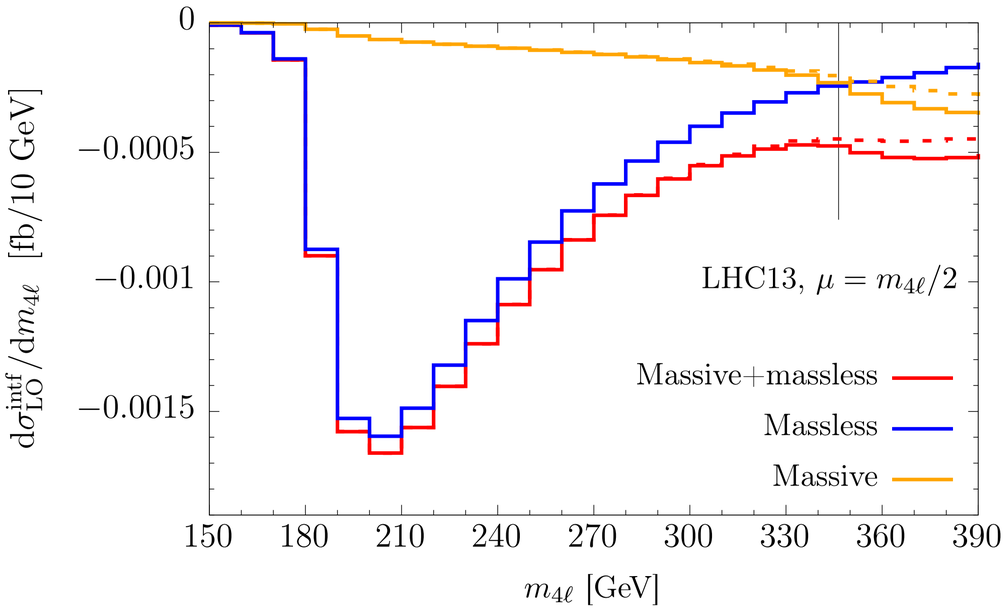
gg-induced WW and ZZ production



- 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



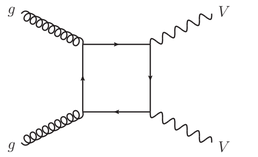
NLO+PS for gg → VV/H→4l

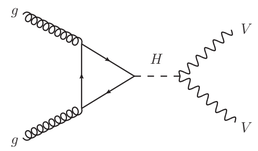
[Alioli, Ferrario Ravasio, JML, Röntsch, '21]

gg → VV→4l

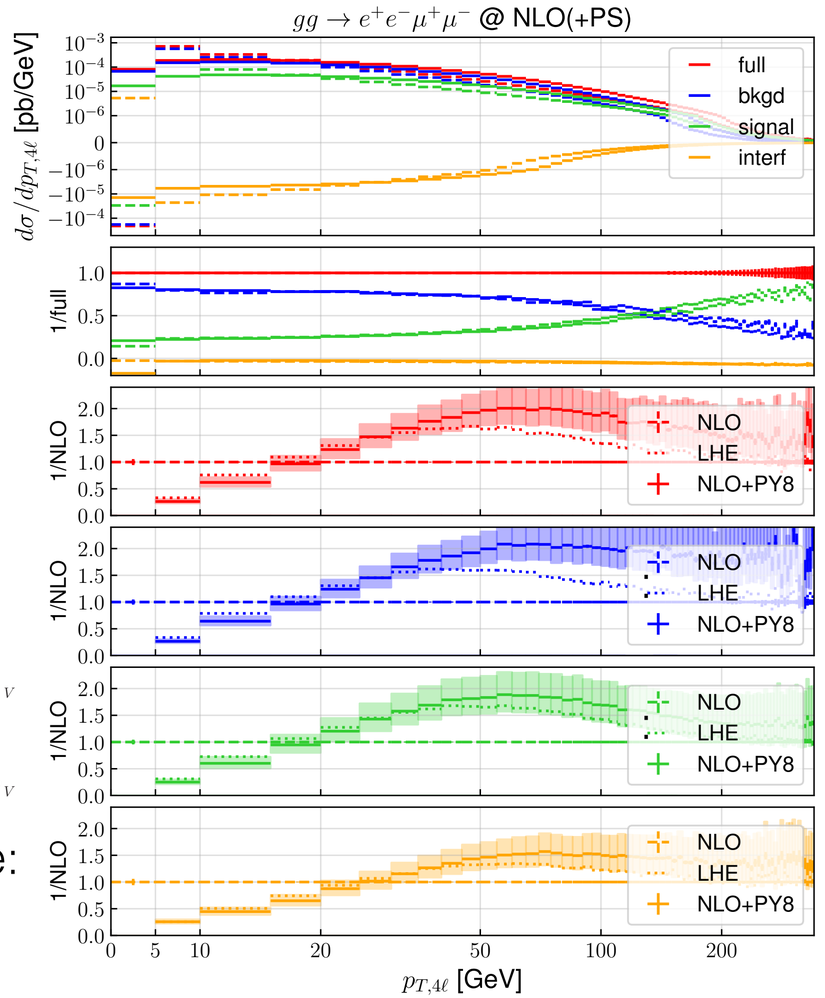
gg → H→4l

sum:





interference:



- ggWW/ggZZ @ NLO QCD + PS available!
- crucial for off-shell Higgs measurements

Conclusions

- There is no clear scale/signature for new physics effects:
  Let's explore the unknown leaving no stone unturned!
- Precision is key for SM (QCD/EW/Higgs) measurements,
  SM parameter determination, as well as for BSM searches.

Incredible progress in theory predictions for multibosons

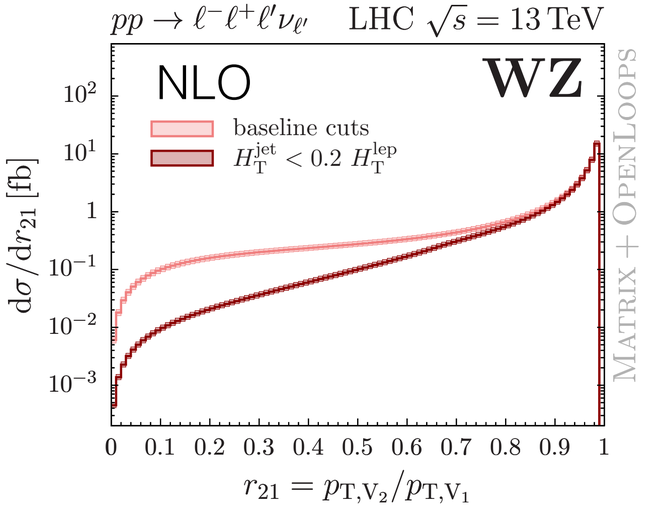
VV:

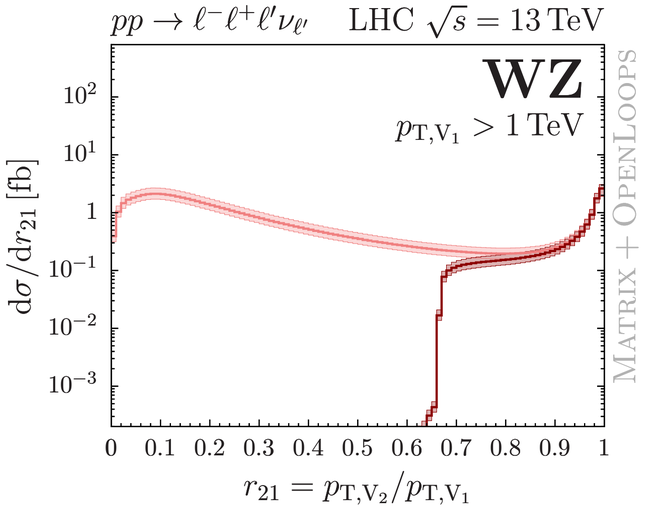
- NNLO QCD + NLO EW available in MATRIX+OpenLoops
- MEPS @ NLO (QCD + EWapprox) available in Sherpa
- NLO (QCD + EW) + PS (QCD + QED) available in POWHEG
- NLO QCDgg PS available in POWHEG
- NNLO QCD PS via MiNNLO available (combined with NLOPS EW)

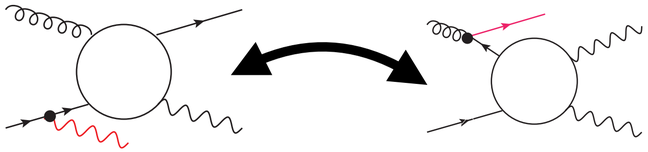
Remaining theory uncertainties: mixed QCD-EW, NNLO EW

Backup

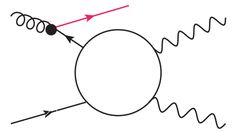
Giant K-factors and effect of jet veto



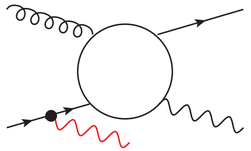




- at r21 → 1: hard-VV topologies



- at r21 → 0: hard-Vj topologies



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

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

(violated by off-shell topologies)

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

Theory status for Triboson

[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)

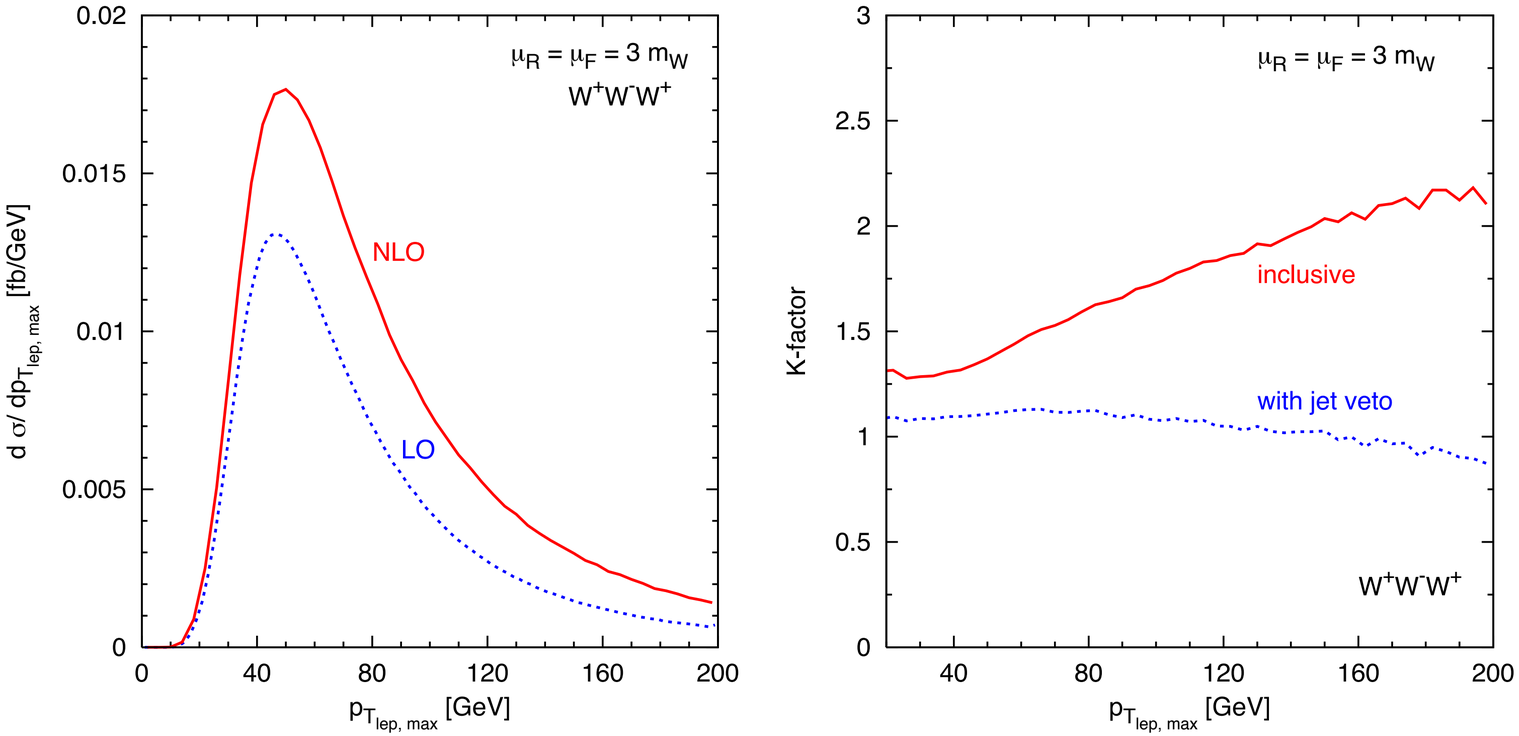
- $pp \to \gamma\gamma\gamma \,/\, \gamma\gamma\ell\nu \,/\, \gamma\gamma\ell\ell$ Greiner, Schönherr '17
- $pp \to 3\ell 3\nu$ ($\ell = e^{\pm}, \mu^{\pm}$, 0/ 1/ 2 SFOS channels, Schönherr '18
  incl. *WWW* and *WZZ* topologies)

  $pp \to e^{\mp}\nu_e\, \mu^{\pm}\nu_\mu\, \tau^{\pm}\nu_\tau$ (*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

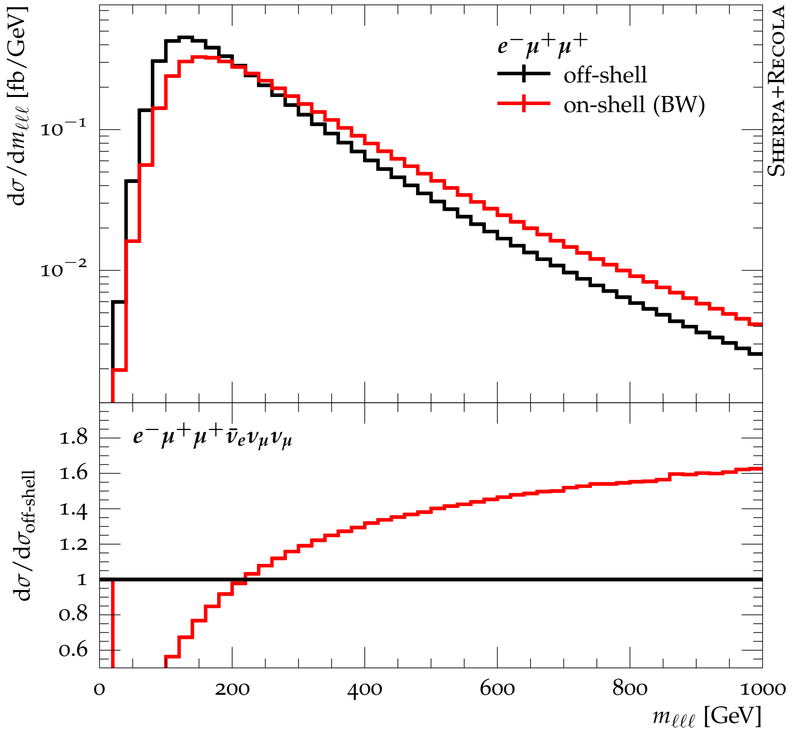
[Campanario et.al., '08]

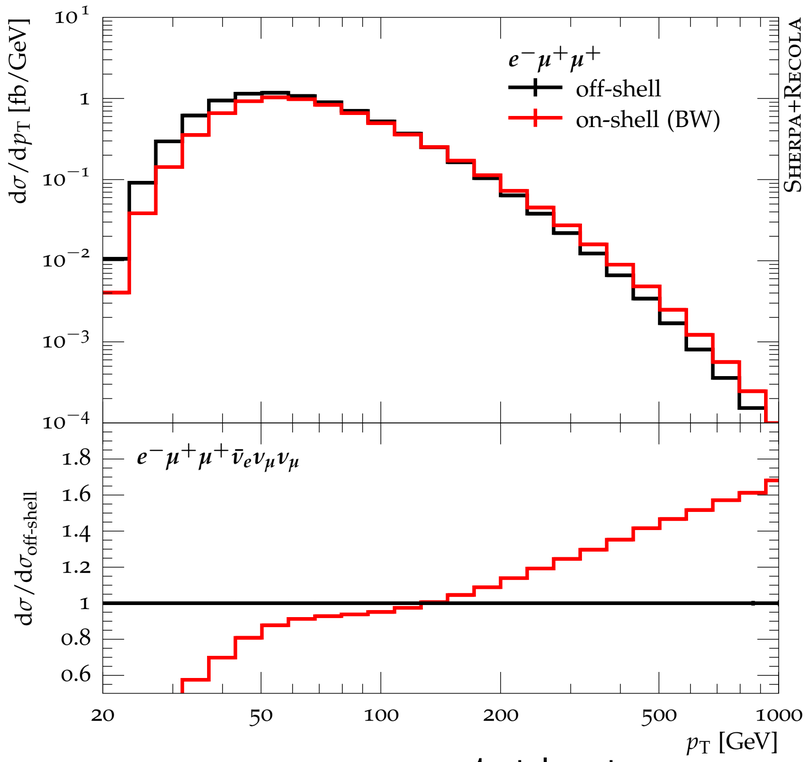


- QCD correction driven by additional jet activity: VV+jet topologies with soft V
  - → 'giant K-factors'
  - → strong observable dependence
  - → NLO mandatory
- jet veto (pT_{cut} = 50 GeV) reduces size and phase space dependence
  - → better: multi-jet merging

Triboson production: on-shell vs. off-shell

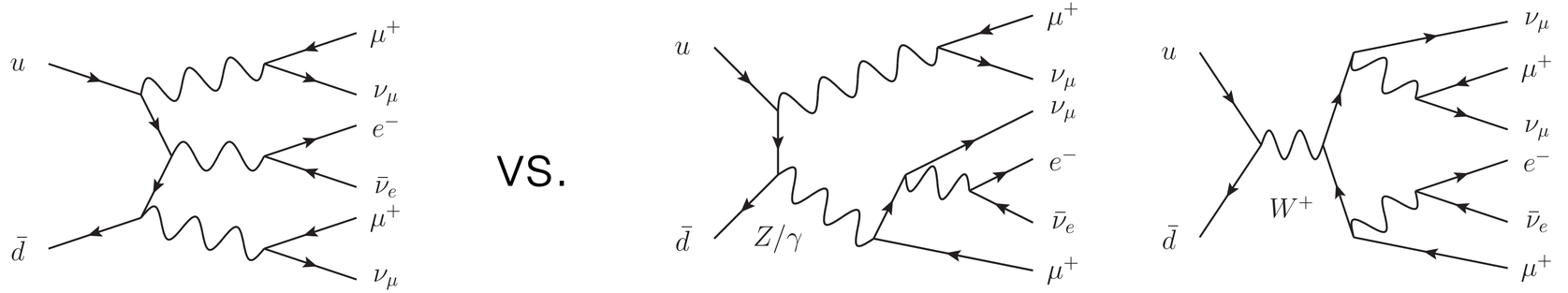
[M. Schönherr, 1806.00307]





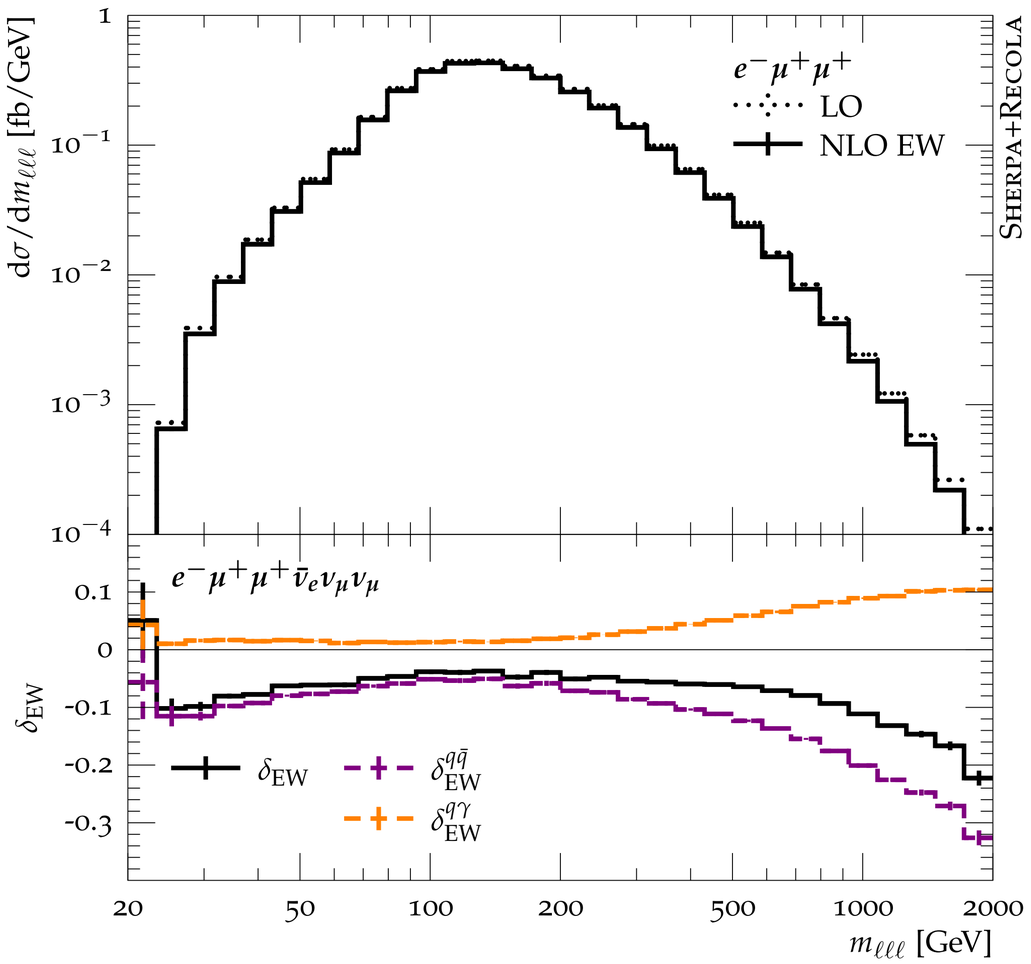
1st lepton

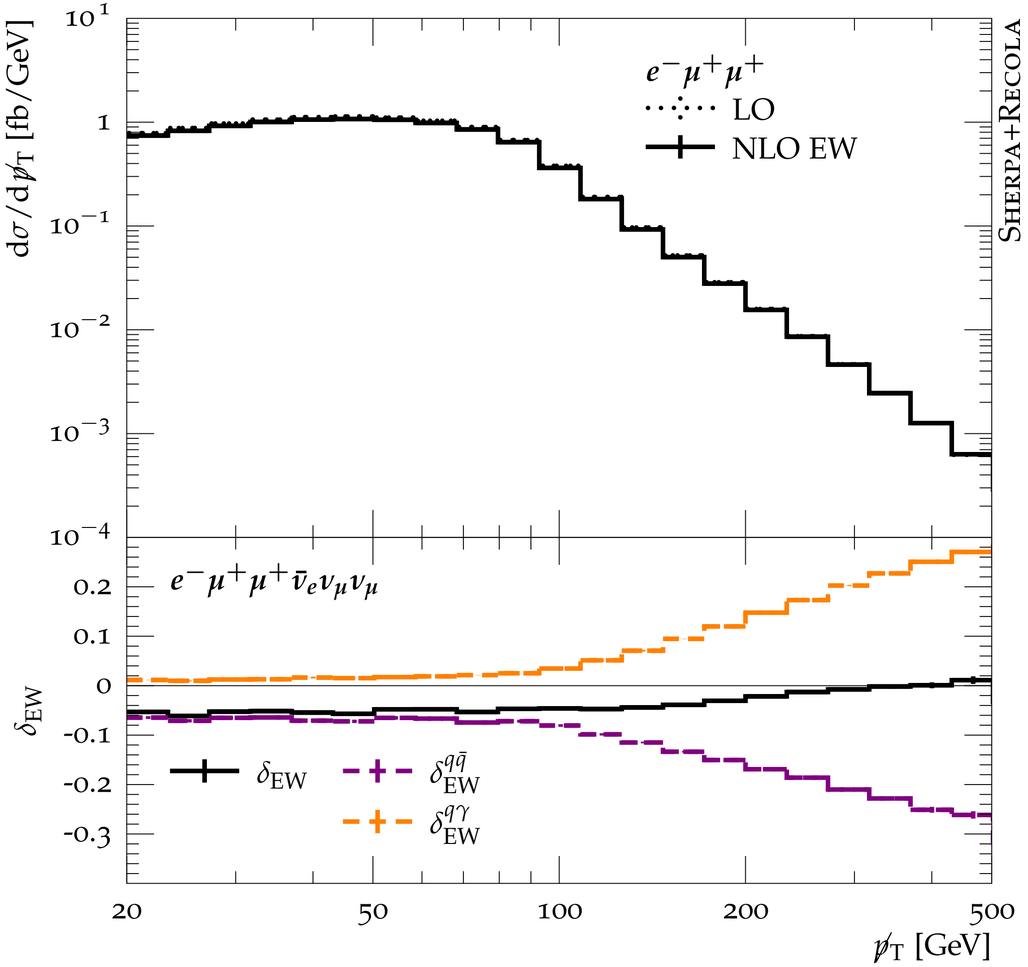
- at large mlll and pT_{ll} large interference with other resonance structures



Off-shell VVV production @ NLO EW

[M. Schönherr, 1806.00307]





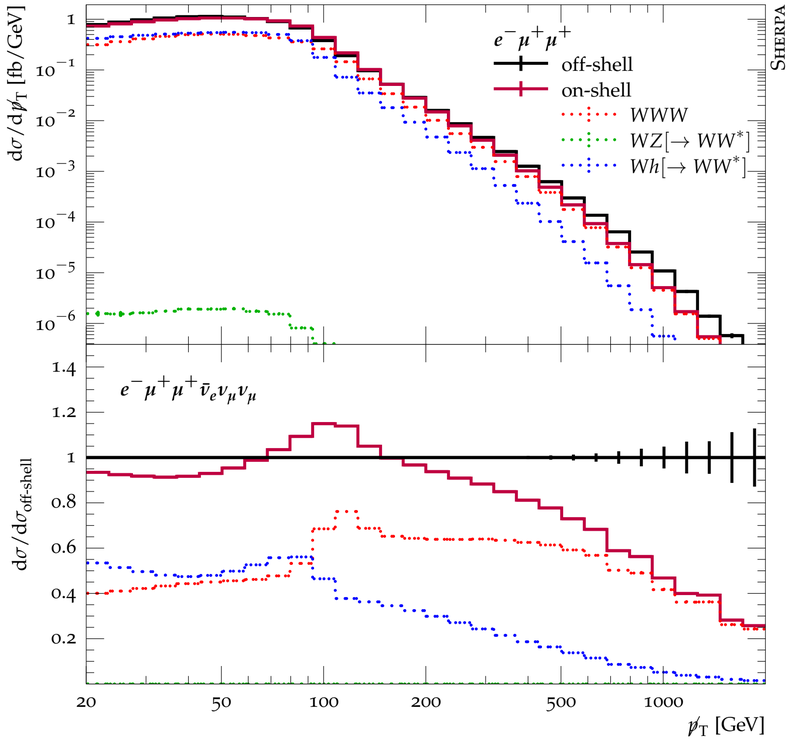
- Very large cancellations of EW corr. in qq and q**γ** channels / highly observable dependent

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

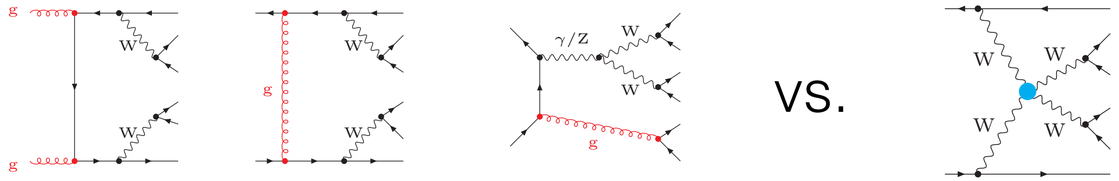


⇒ measure signature (e.g. 3ℓ + MET) in fiducial volume

→ 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



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

LO

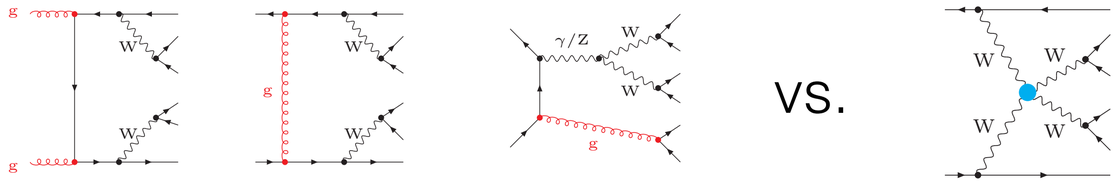
QCD-background

interference

VBS-signal

Perturbative expansion: VBF-V, VBS-VV

Example: WW+2jets



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

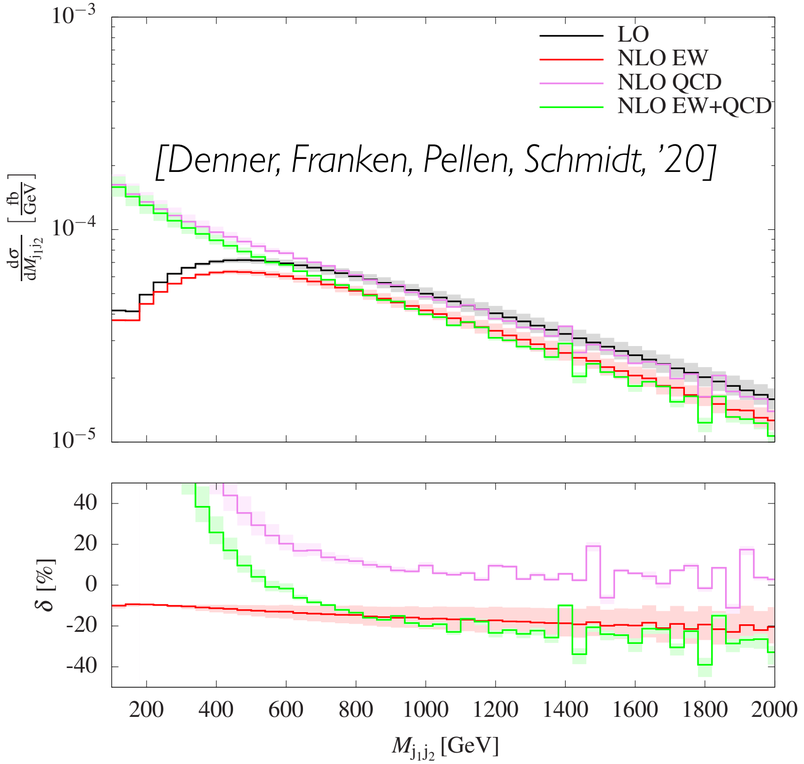
➡ separation formally meaningless at NLO
➡ strictly well defined measurements: fiducial cross sections

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



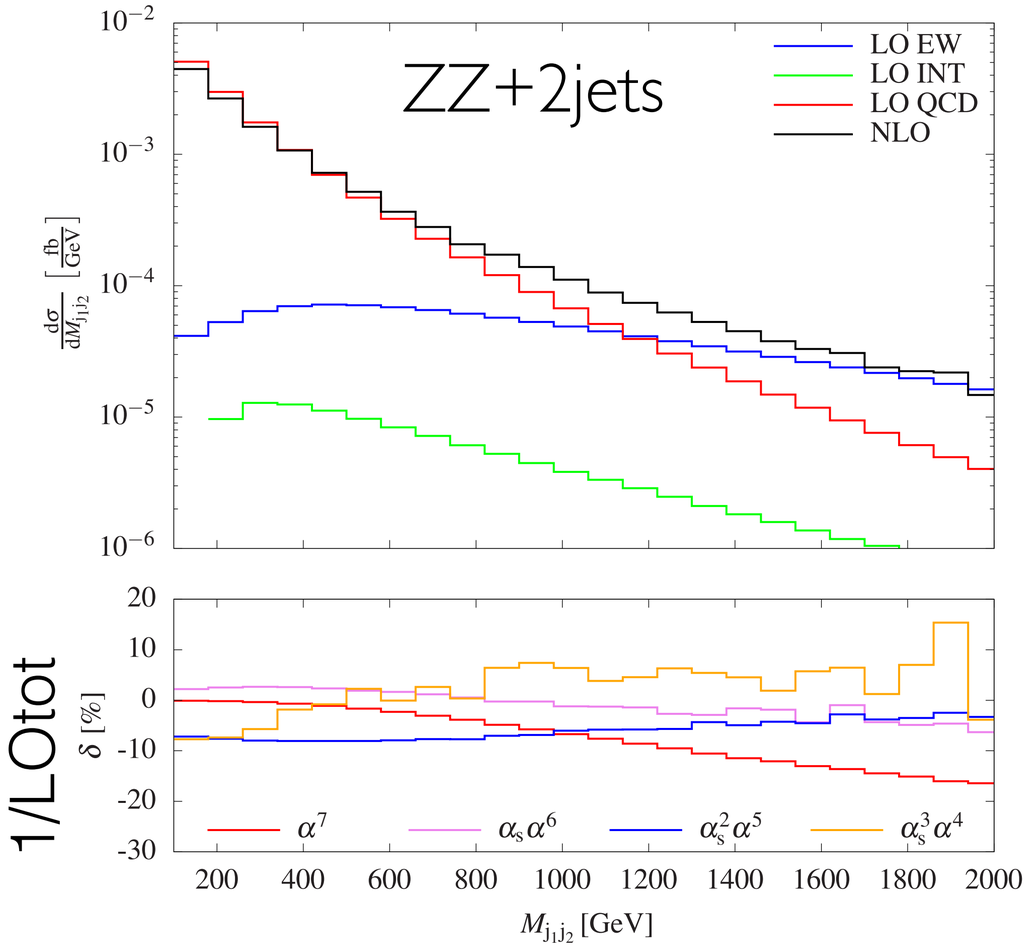
- 2 → 6 particles at NLO EW !

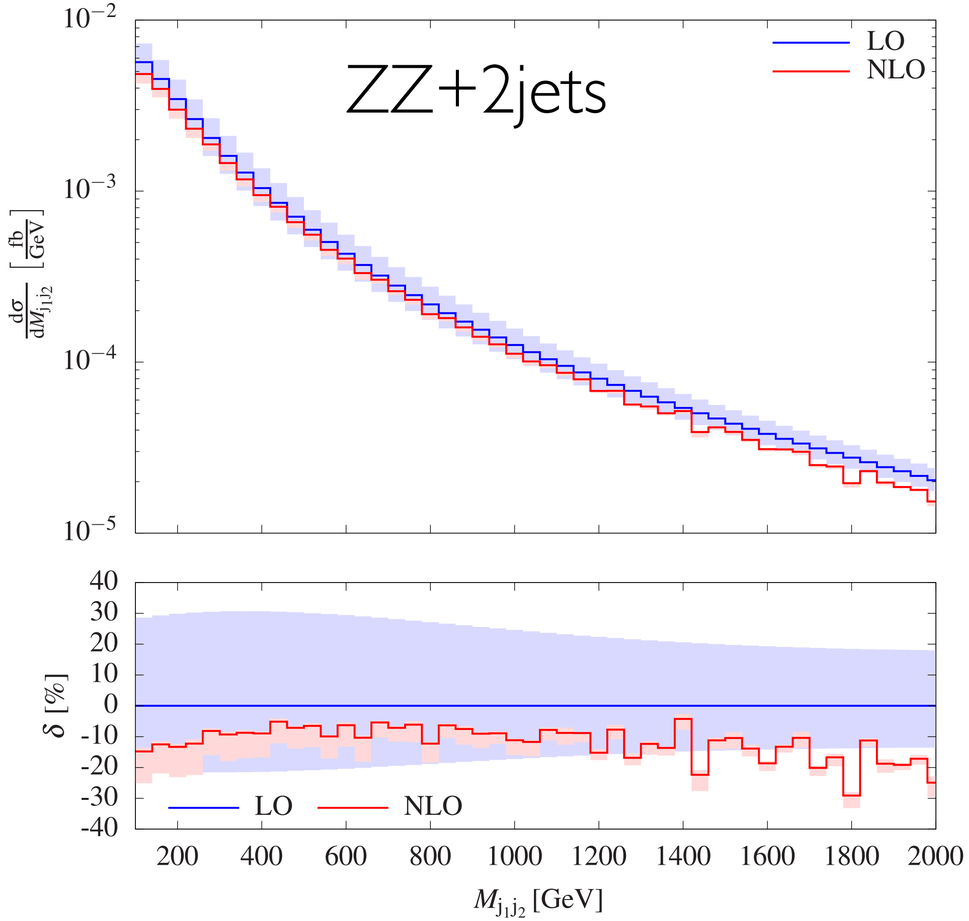
Order	$\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha^7)+\mathcal{O}(\alpha_s\alpha^6)$
$M_{j_1j_2} > 100\,\text{GeV}$			
σ_{NLO}[fb]	0.08211(4)	0.12078(11)	0.10521(11)
δ[%]	−15.9	23.6	7.7
$M_{j_1j_2} > 500\,\text{GeV}$			
σ_{NLO}[fb]	0.06069(4)	0.07375(25)	0.06077(25)
δ[%]	−17.6	0.1	−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]

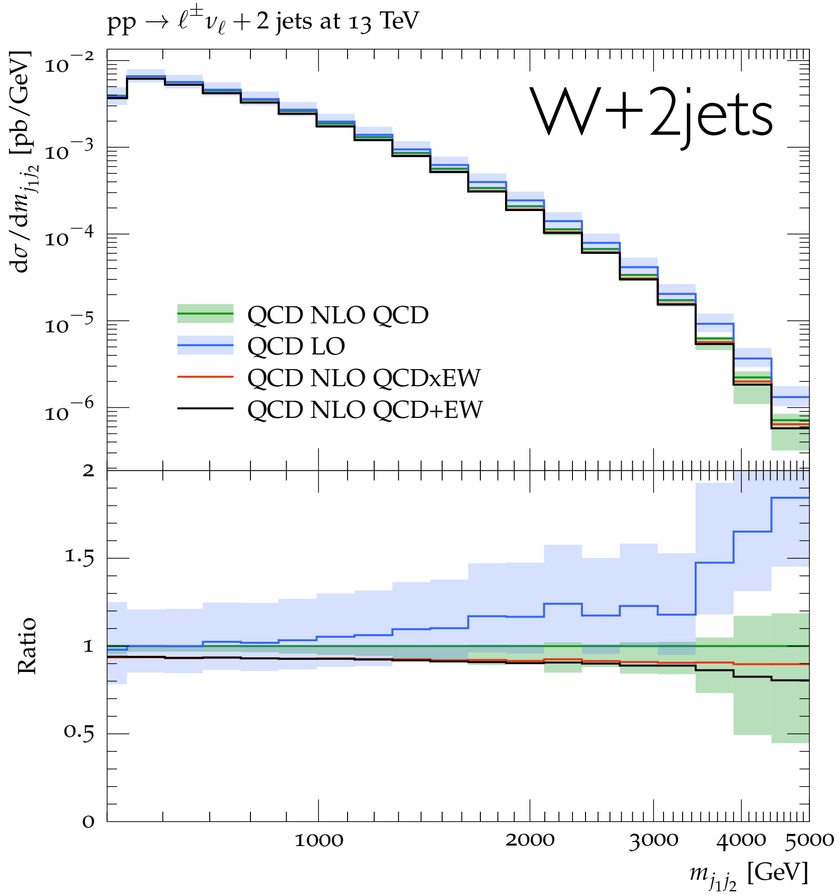




QCD and EW V+2jets @ NLO QCD + EW

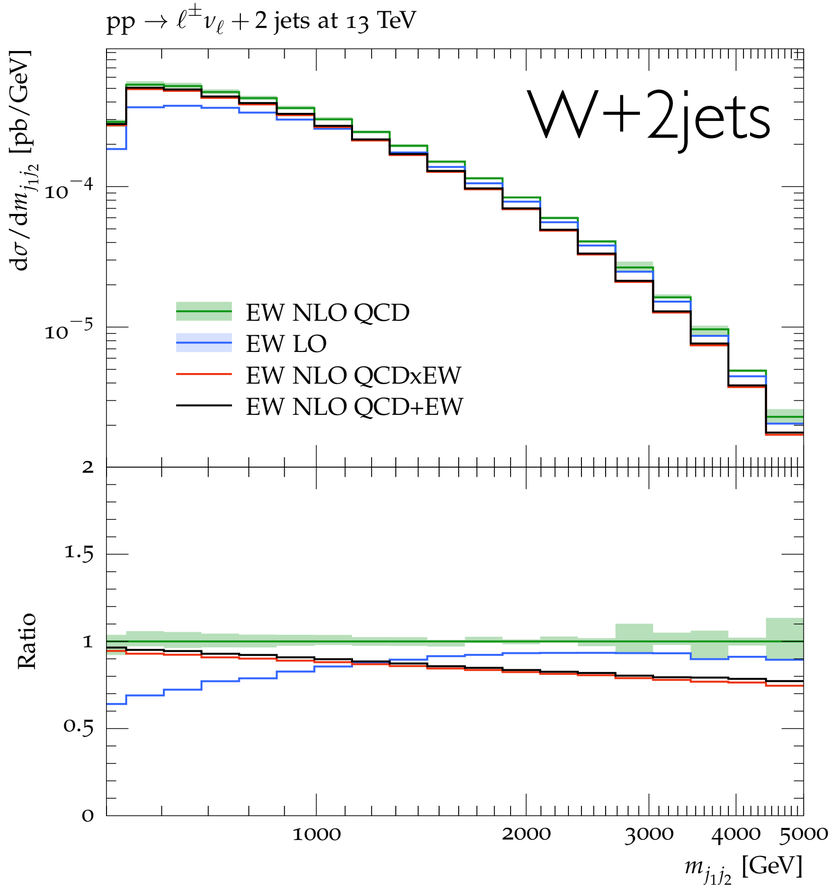
[JML, S. Pozzorini, M. Schönherr; to appear]

QCD-mode



- QCD: negative K-factor (increasing for large mjj), uncertainty ~20-25%
- EW: up to -10% in multi TeV

EW-mode



- QCD: very small K-factor at large mjj, uncertainty ~10% (no VBF approximation)
- EW: up to -20% in multi TeV