SM backgrounds for VLLs

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Science & Technology Facilities Council

UK Research and Innovation

Asymptotic Safety meets Particle Physics & Friends
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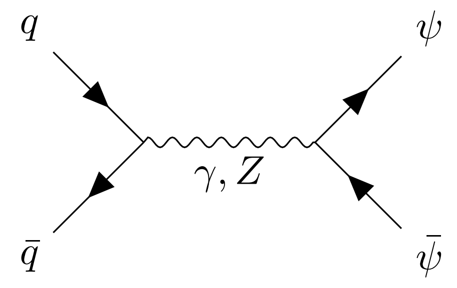
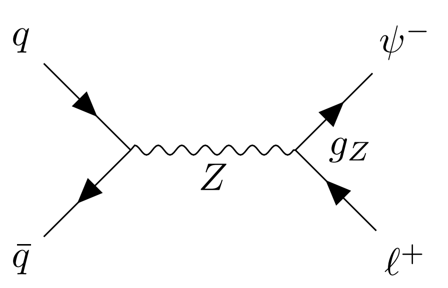




$\psi_i \to S^*_{ij}\,\ell^-_j \to \ell^-_i\,\ell^+_j\,\ell^-_j$

$\psi^0_i \to S_{ji}\,\nu_j \to \ell^-_i\,\ell^+_j\,\nu_j$

....

Signatures for VLL's

Processes

Singlet-model

$pp \to \psi_i\bar{\psi}_i \to \ell^-_i\ell^+_i\ell^+_j\ell^-_j\ell^+_k\ell^-_k \quad \text{for } i,j,k=1,2,3$

$pp \to \psi_i\bar{\psi}_i \to \ell^-_i\ell^+_i q_j\bar{q}_j\ell^+_k\ell^-_k \quad \text{for } i,k=1,2$

$pp \to \psi_i\bar{\psi}_i \to \ell^-_i\ell^+_i\ell^+_j\ell^-_j\nu_k\bar{\nu}_k \quad \text{for } i,j=1,2$

$pp \to \psi_i\bar{\psi}_i \to \nu_i\ell^+_i\ell^+_j\ell^-_j\ell^-_k\bar{\nu}_k \quad \text{for } i,j,k=1,2$

$pp \to \psi_i\bar{\psi}_i \to \ell^-_i\bar{\nu}_i\ell^+_j\ell^-_j\ell^+_k\nu_k \quad \text{for } i,j,k=1,2$

$pp \to \psi_i\ell^+_i \to \ell^-_i\ell^+_j\ell^-_j\ell^+_i \quad \text{for } i,j=1,2$

$pp \to \bar{\psi}_i\ell^-_i \to \ell^+_i\ell^+_j\ell^-_j\ell^-_i \quad \text{for } i,j=1,2$

Doublet-model

$pp \to \psi^0_i\overline{\psi}^0_i \to \nu_j\bar{\nu}_k\ell^+_j\ell^-_i\ell^+_i\ell^-_k \quad \text{for } i,j,k=1,2$

$pp \to \psi^-_i\overline{\psi}^0_i \to \ell^-_i\ell^+_i\bar{\nu}_j\ell^-_j\ell^+_k\ell^-_k \quad \text{for } i,j,k=1,2$

$pp \to \psi^0_i\psi^+_i \to \ell^-_i\ell^+_i\ell^+_j\nu_j\ell^+_k\ell^-_k \quad \text{for } i,j,k=1,2$

$pp \to \psi^-_i\overline{\psi}^0_i \to \ell^-_i\ell^+_i\overline{q}_j q_j\ell^+_k\ell^-_k \quad \text{for } i,k=1,2$

$pp \to \psi^0_i\psi^+_i \to \ell^-_i\ell^+_i\overline{q}_j q_j\ell^+_k\ell^-_k \quad \text{for } i,k=1,2$

Signature	SM background	
6L : 3 OS-SF leptons pairs	ZZZ	Triboson
4L + jets / 4L+MET	ZZ	Diboson
5L +MET	ZZW	Triboson

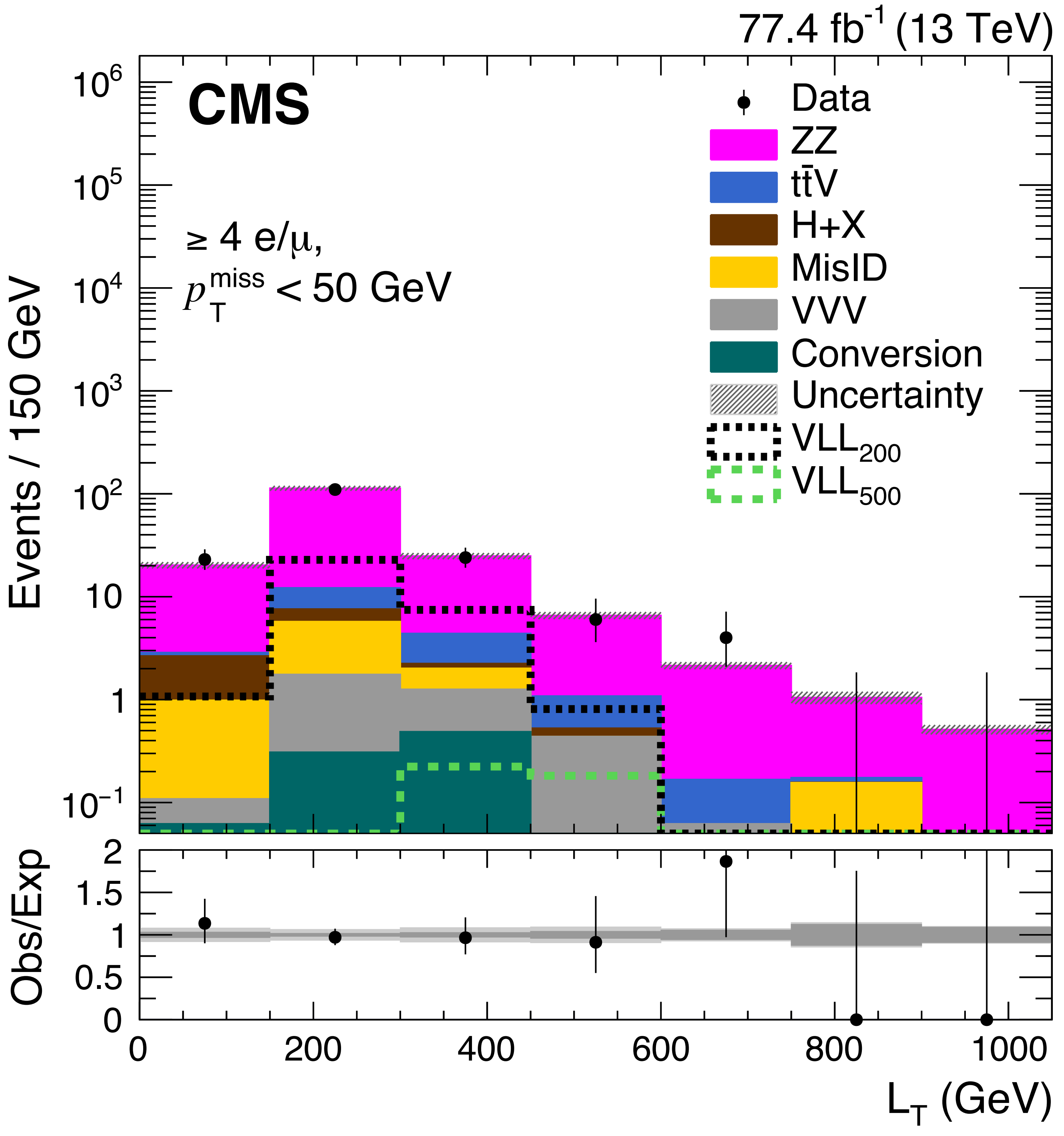
6L/5L very clean. However, small rates!

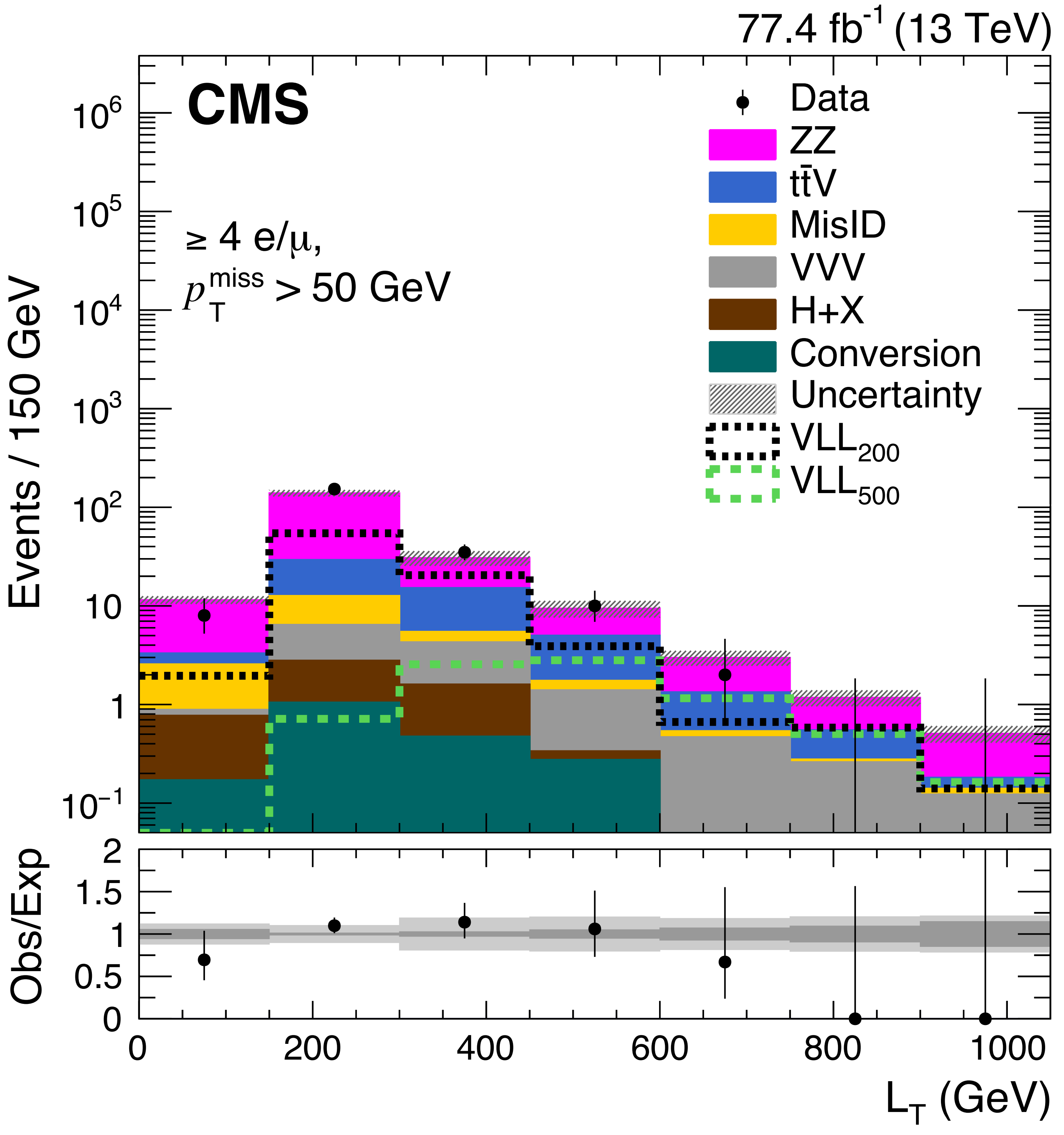
-> Look at 4L/3L signatures

[*Multi-lepton signatures of vector-like leptons with flavor*, Bißmann, Hiller, Hormigos-Feliu, Litim, 20]

Available searches: CMS-EXO-18-005

$N_{leptons}$	p_T^{miss} (GeV)
$\geq 4e/\mu$	<50
	>50
$3e/\mu$	<150
	>150
$2e/\mu$ OS (or SS) + $\geq 1\tau_h$	<150
	>150





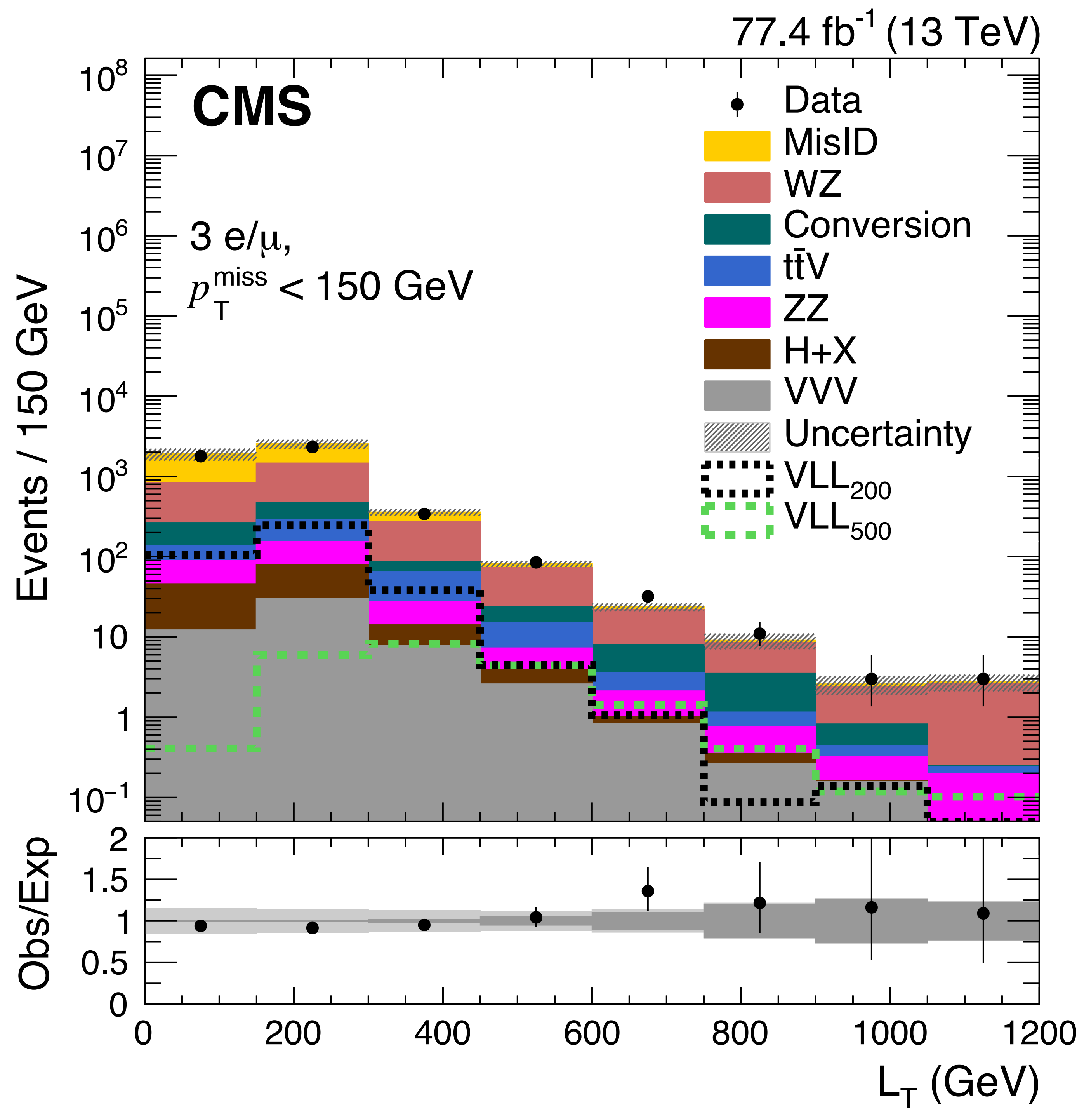
Dominant background — ZZ — ZZ / (ttV)

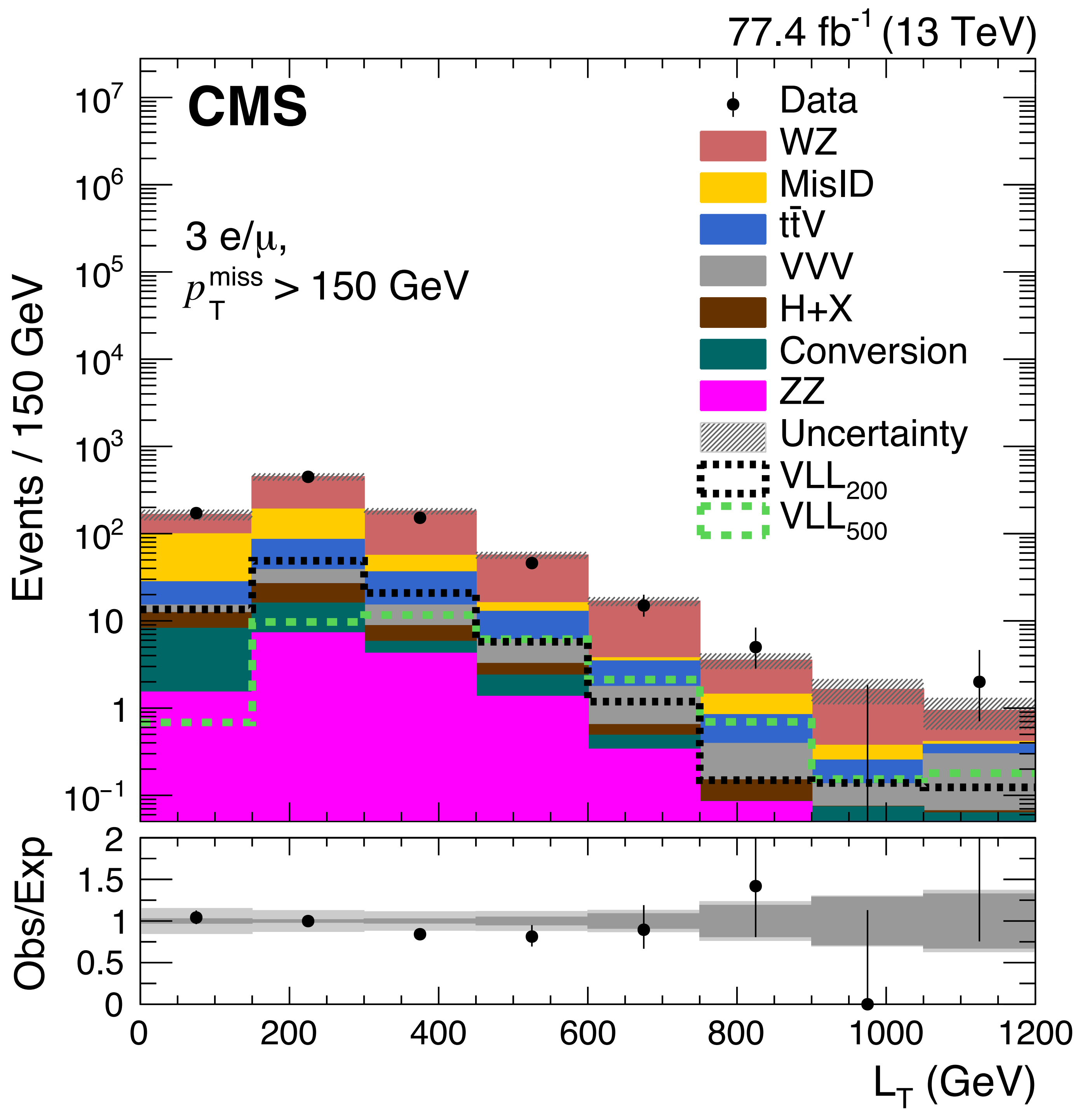
$$L_T = \sum_{i \in \ell} p_{\mathrm{T,i}}$$

also: misID -> Z+jets / ttbar+jets

Available searches: CMS-EXO-18-005

$N_{leptons}$	p_T^{miss} (GeV)
$\geq 4e/\mu$	<50
	>50
$3e/\mu$	<150
	>150
$2e/\mu$ OS (or SS) + $\geq 1\tau_h$	<150
	>150





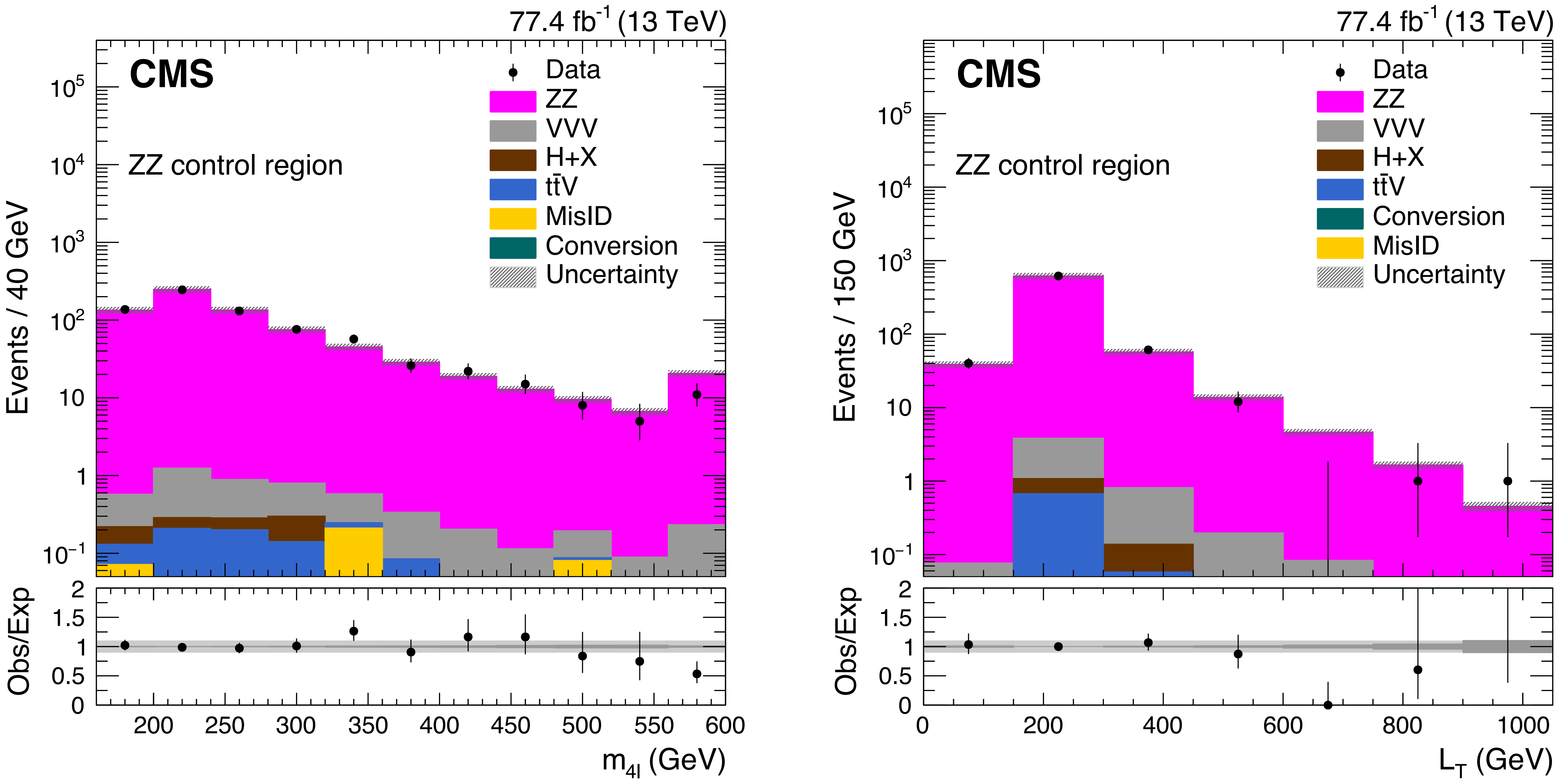
Dominant background WZ WZ

Background determination: VV@NLO+PS & overall normalization from CR

Available searches: CMS-EXO-18-005

$N_{leptons}$	p_T^{miss} (GeV)
$\geq 4e/\mu$	<50
	>50
$3e/\mu$	<150
	>150
$2e/\mu$ OS (or SS) + $\geq 1\tau_h$	<150
	>150

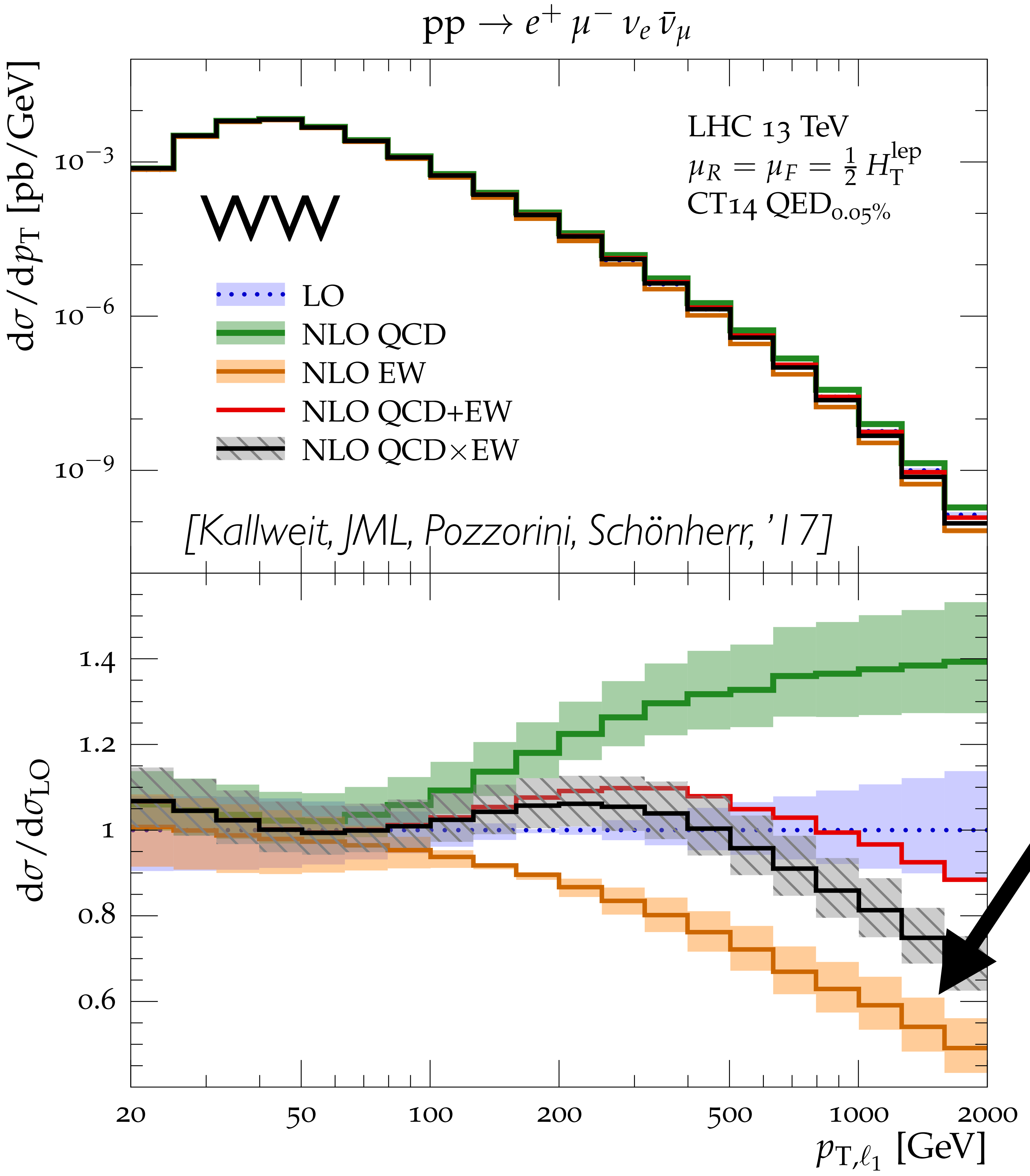
Control region

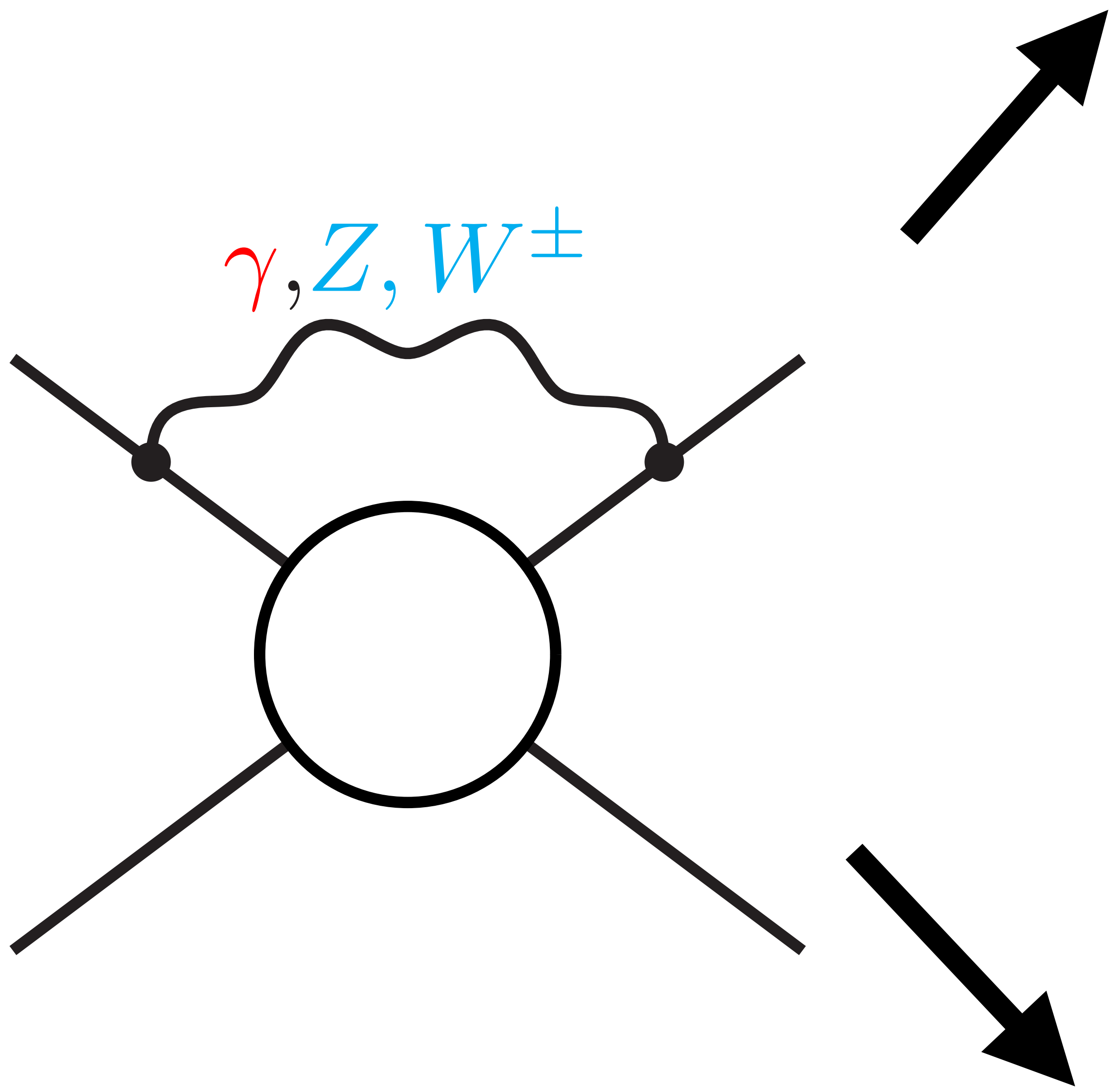


This will not be good enough with HL-LHC data samples!

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]

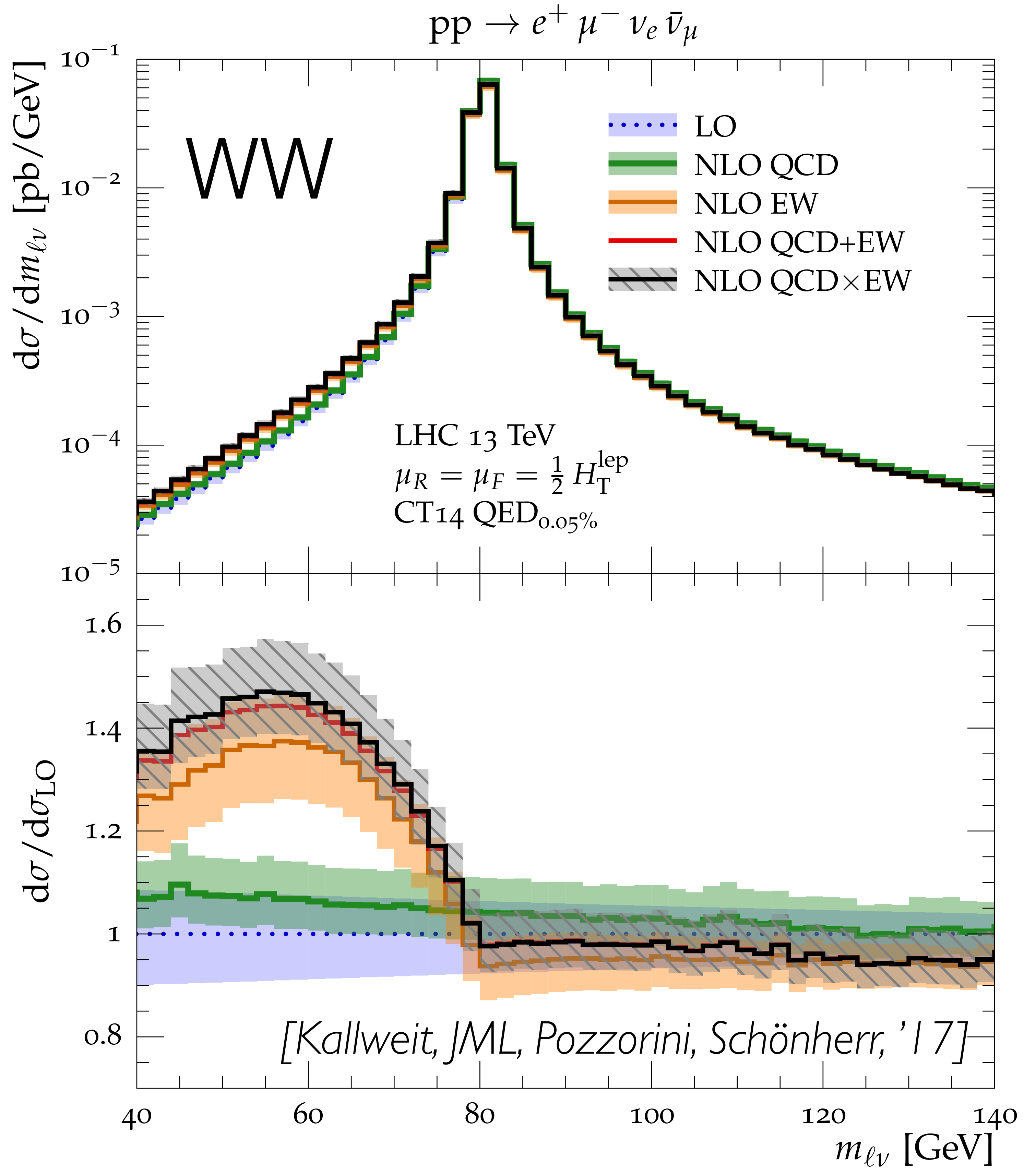
Universality and factorisation: *[Denner, Pozzorini; '01]*

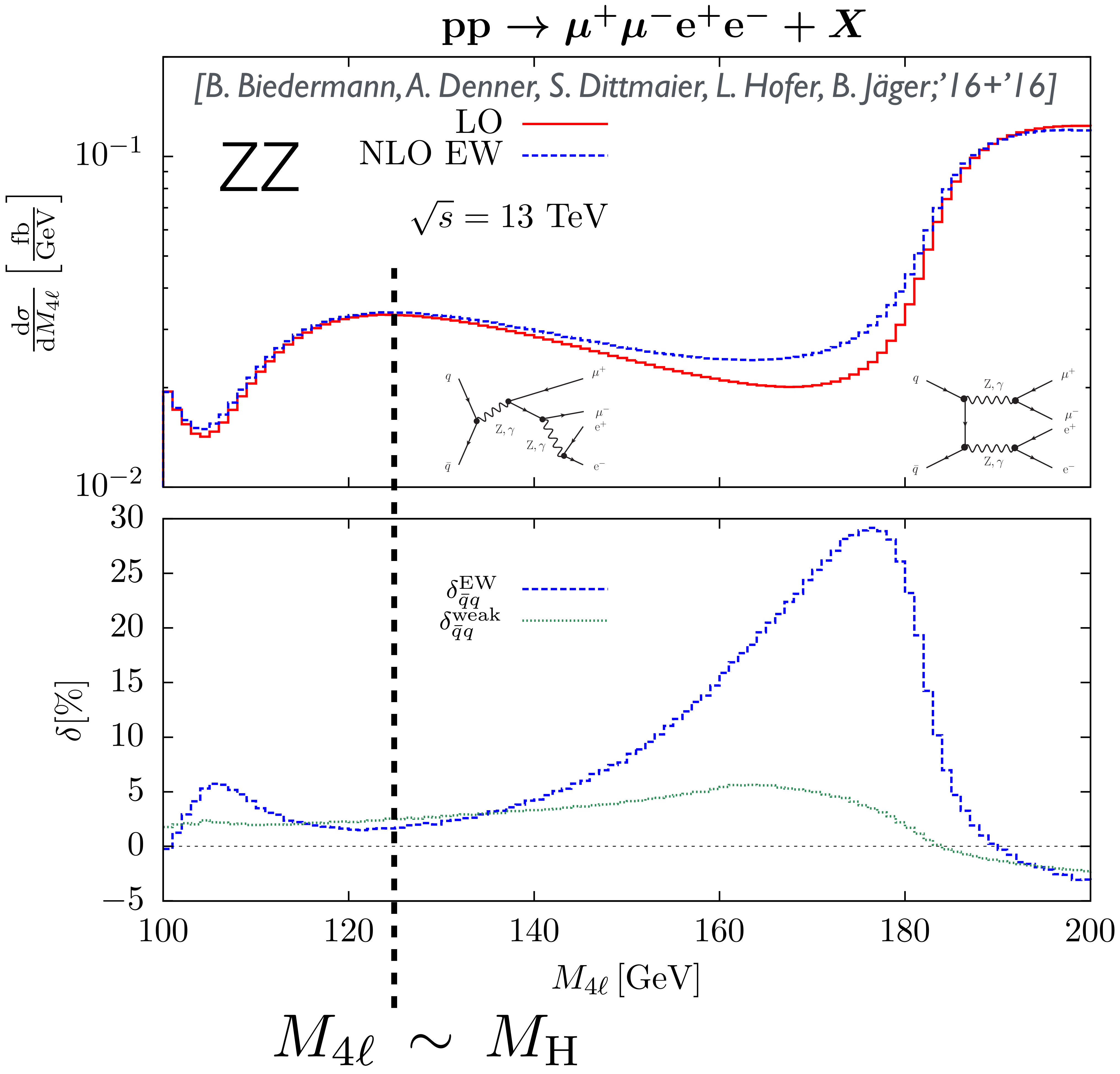
$$\delta\mathcal{M}^{1-\text{loop}}_{\text{LL+NLL}} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^\pm} I^a(k)I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\text{ew}}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

➜ 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 ~ $\alpha \log\left(\frac{m_f^2}{Q^2}\right)$ in sufficiently exclusive observables.





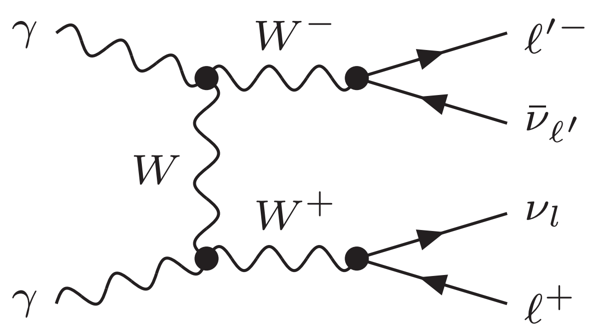
➜ important for radiative tails, Higgs backgrounds etc.

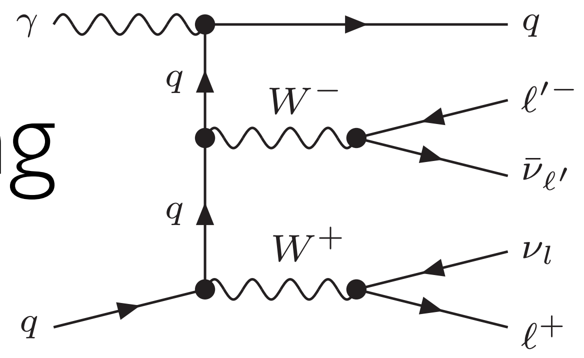
➜typically considered via QED PS (PHOTOS / YFS)

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

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

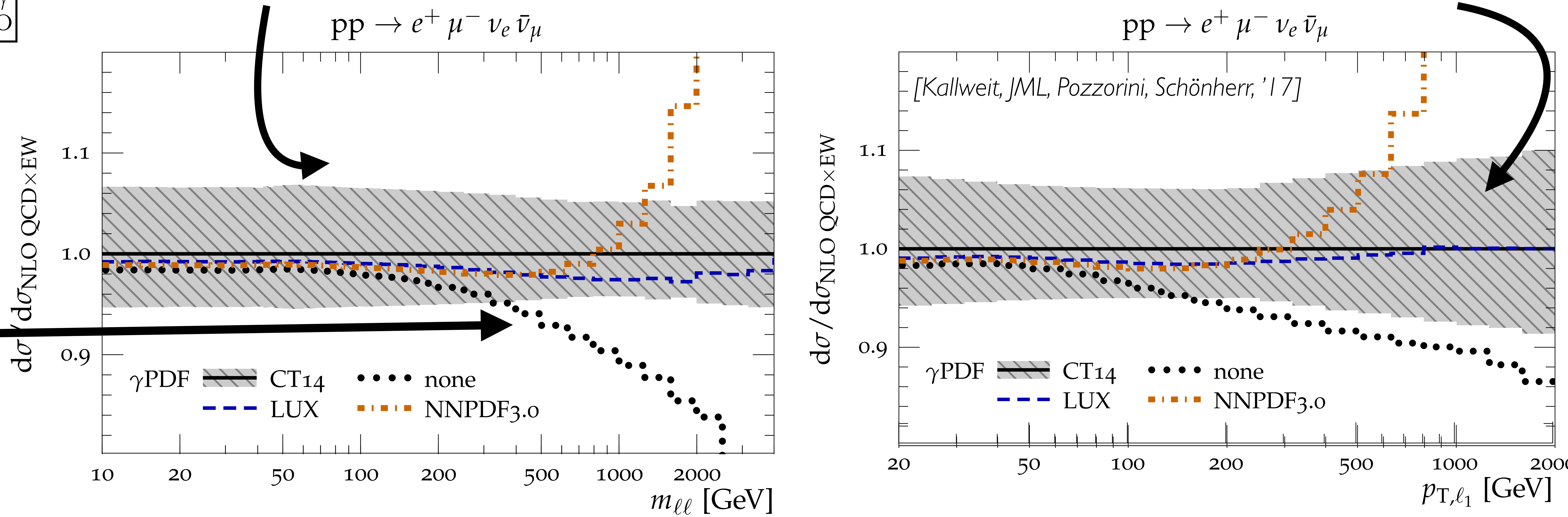
➜ Possible large enhancement due to photon-induced channels in the tails of kinematic distributions,

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 for VV

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

NLO QCD NLO EW

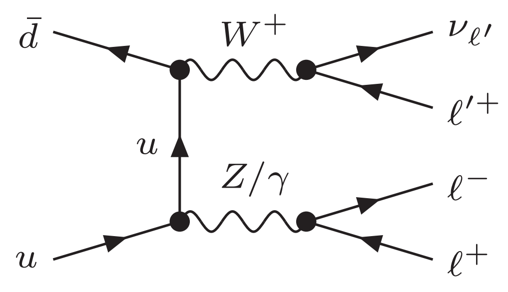
$$+ \alpha_S^2\, d\sigma_{\mathrm{NNLO}} + \alpha_{\mathrm{EW}}^2\, d\sigma_{\mathrm{NNLO\,EW}} \,? + \alpha_S \alpha_{\mathrm{EW}}\, d\sigma_{\mathrm{NNLO\,QCDxEW}} \,?$$

NNLO QCD NNLO EW NNLO QCD-EW

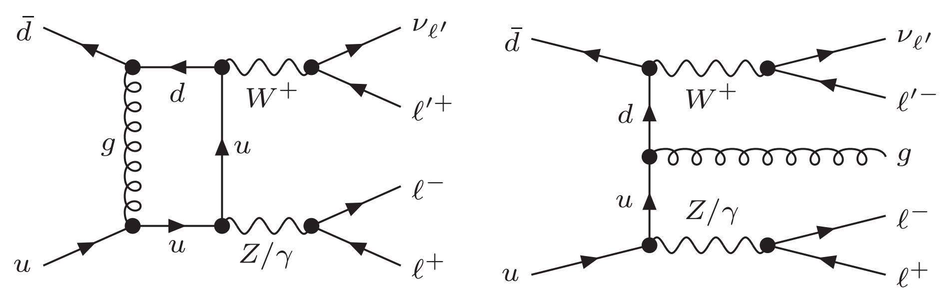
$$+ \alpha_S^3\, d\sigma_{\mathrm{NNLO}} \,? + \ldots$$

N3LO QCD

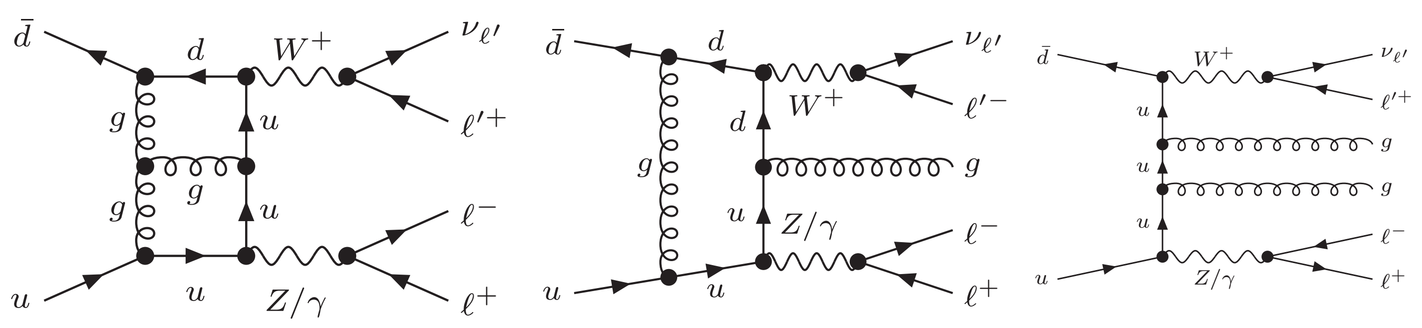
LO



NLO QCD



NNLO QCD



Perturbative expansion for VV

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

NLO QCD NLO EW

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

? ?

NNLO QCD NNLO EW NNLO QCD-EW

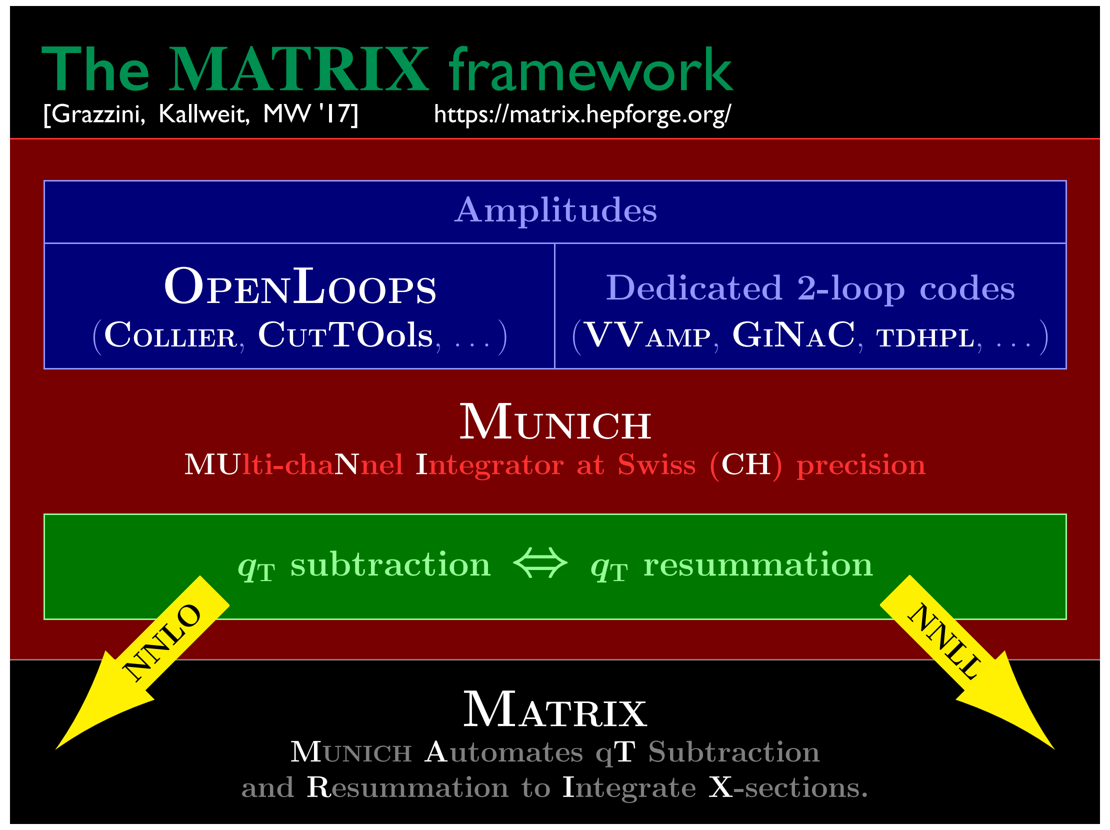
$$+\alpha_S^3\, d\sigma_{\rm NNLO} + \ldots$$

?

N3LO QCD

NNLO QCD

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



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

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 for VV

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

NLO QCD — NLO EW

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

NNLO QCD — NNLO EW — NNLO QCD-EW

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

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

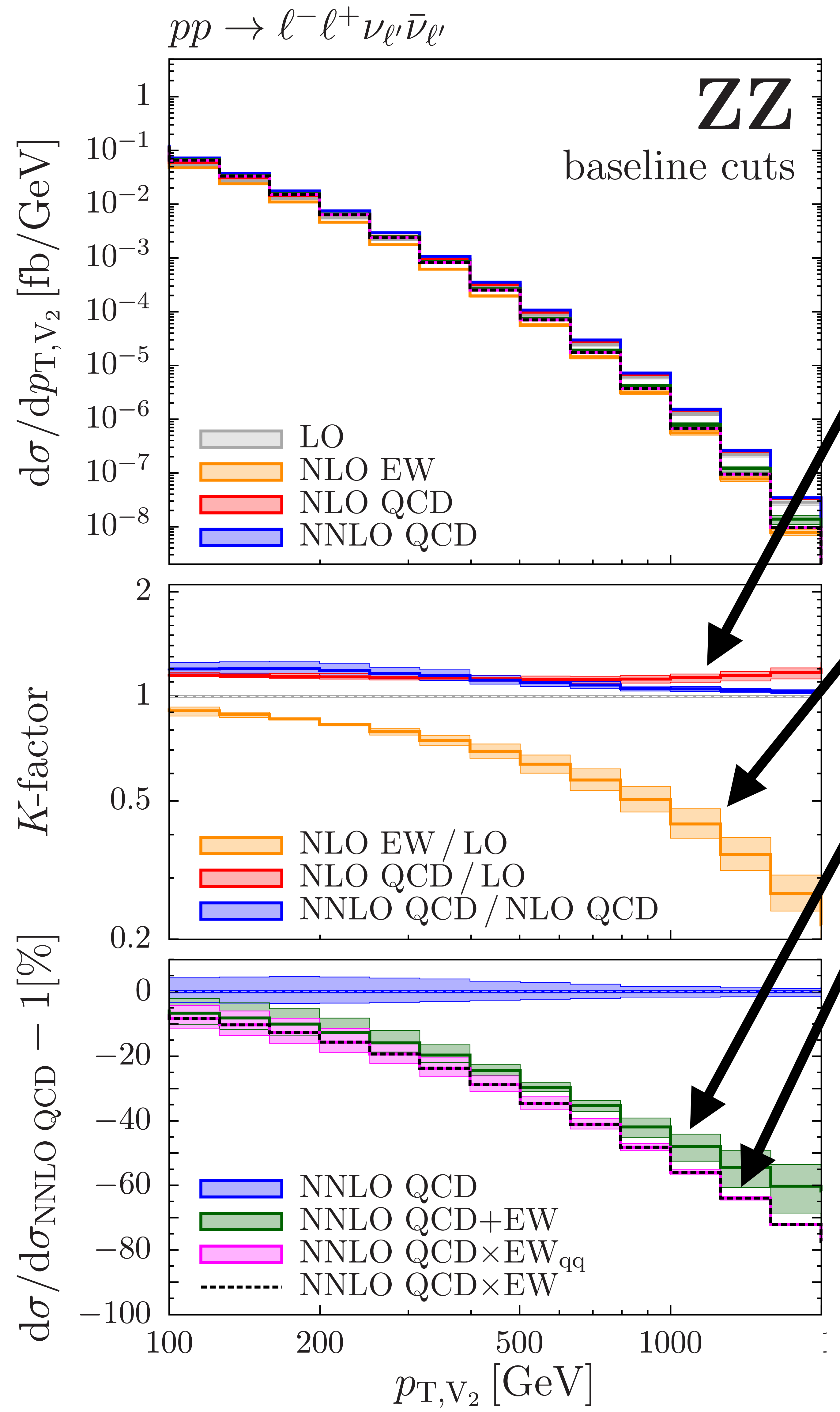
In Matrix+OpenLoops all (massive) diboson processes are now available at **NNLO QCD + NLO EW**

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

(code available upon request)

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

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

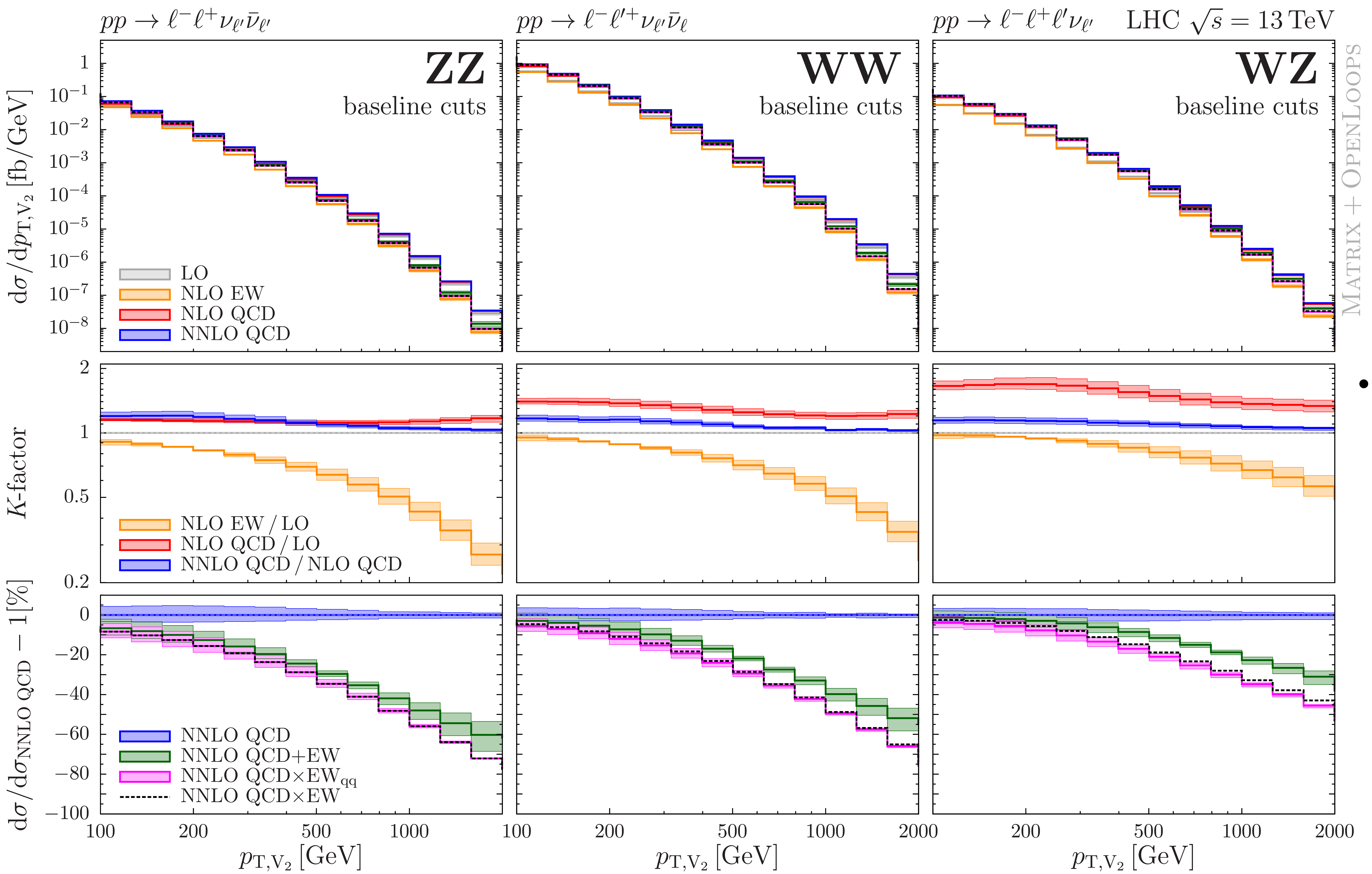
$$d\sigma_{NNLO\,QCD\times EW} = d\sigma_{LO}\left(1+\delta_{QCD}\right)\left(1+\delta_{EW}\right) + d\sigma_{LO}^{gg}$$

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

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

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

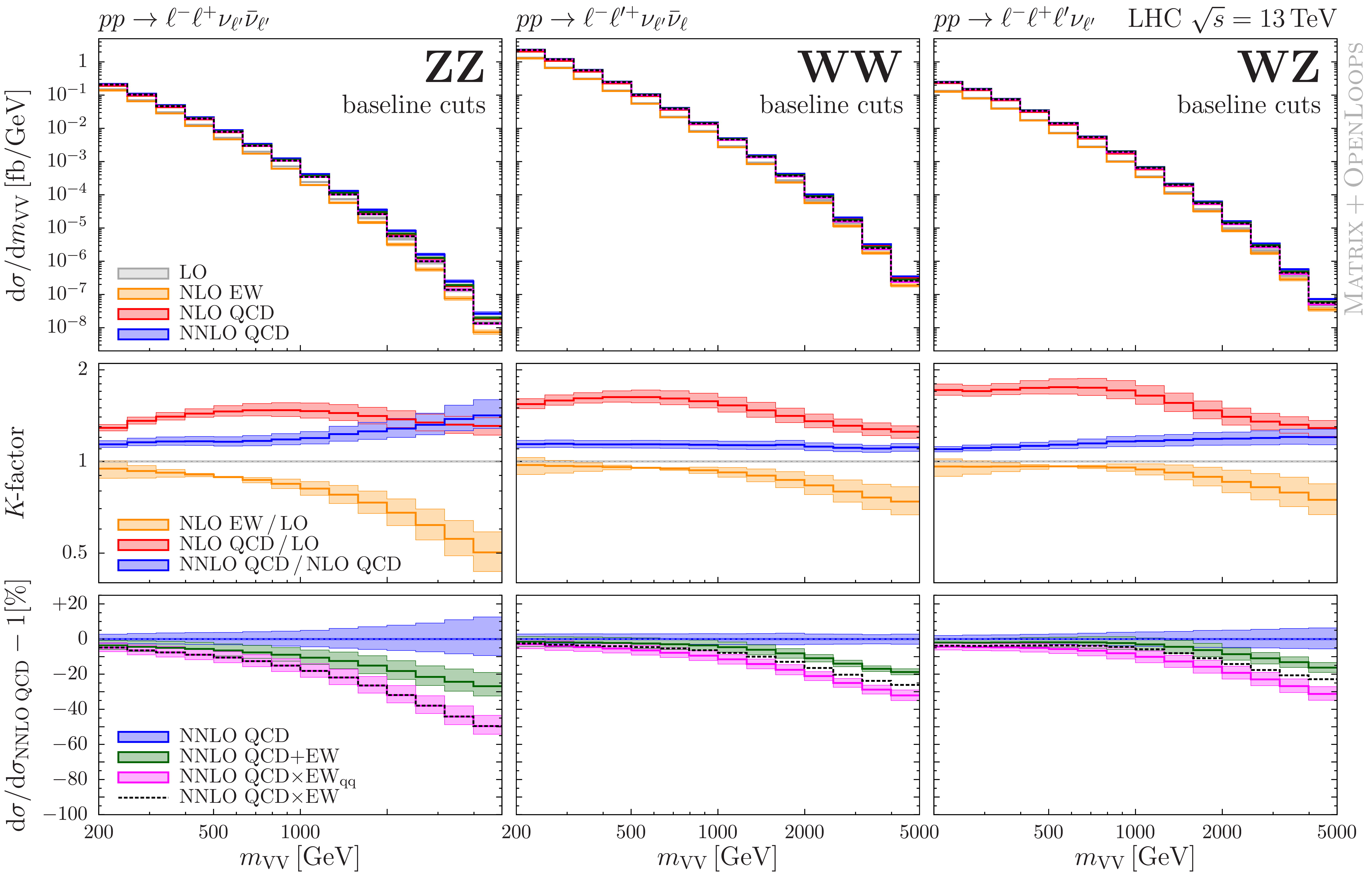
NNLO QCD + NLO EW for dibosons: pTV2



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

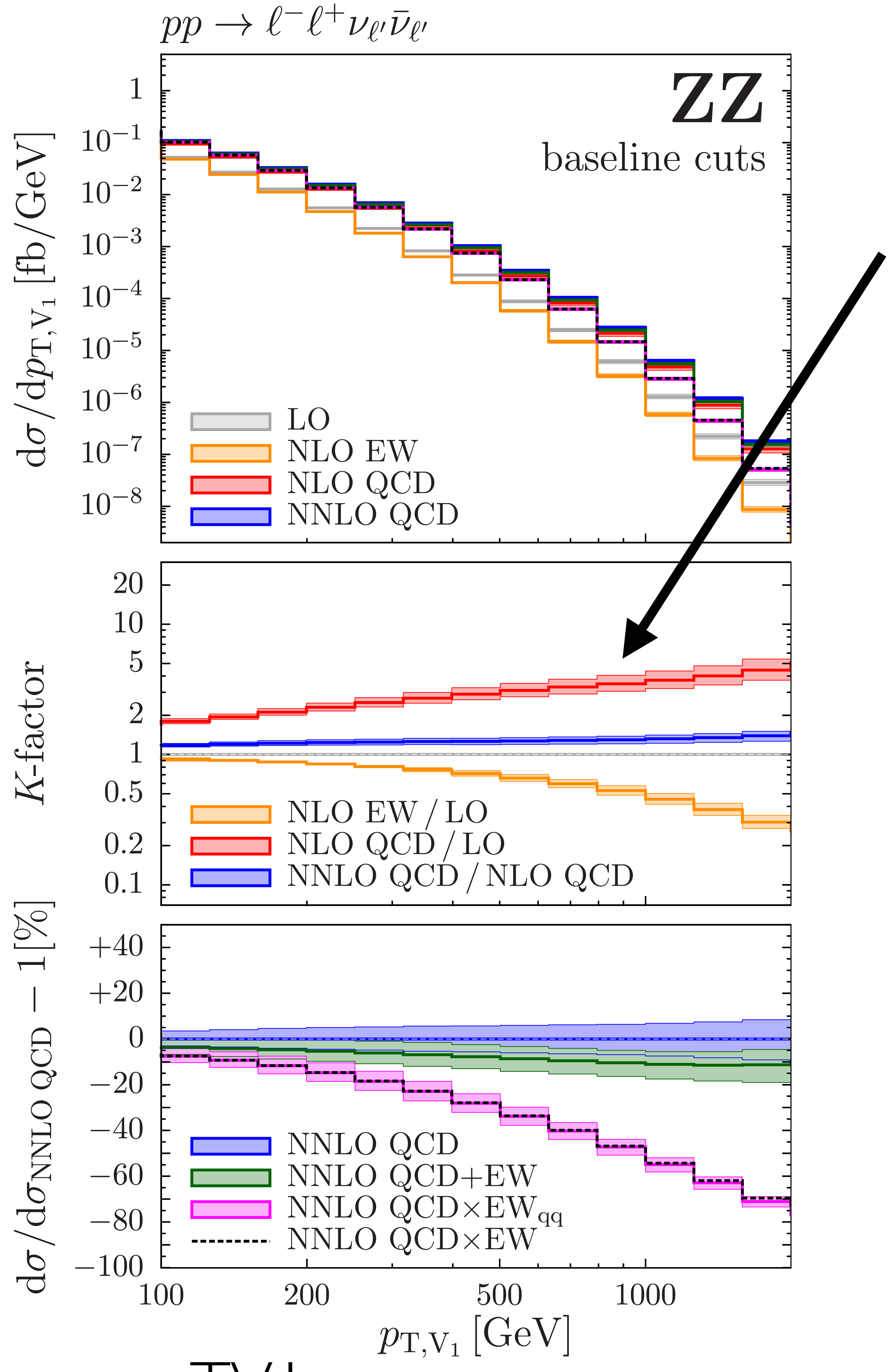
pTV2

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

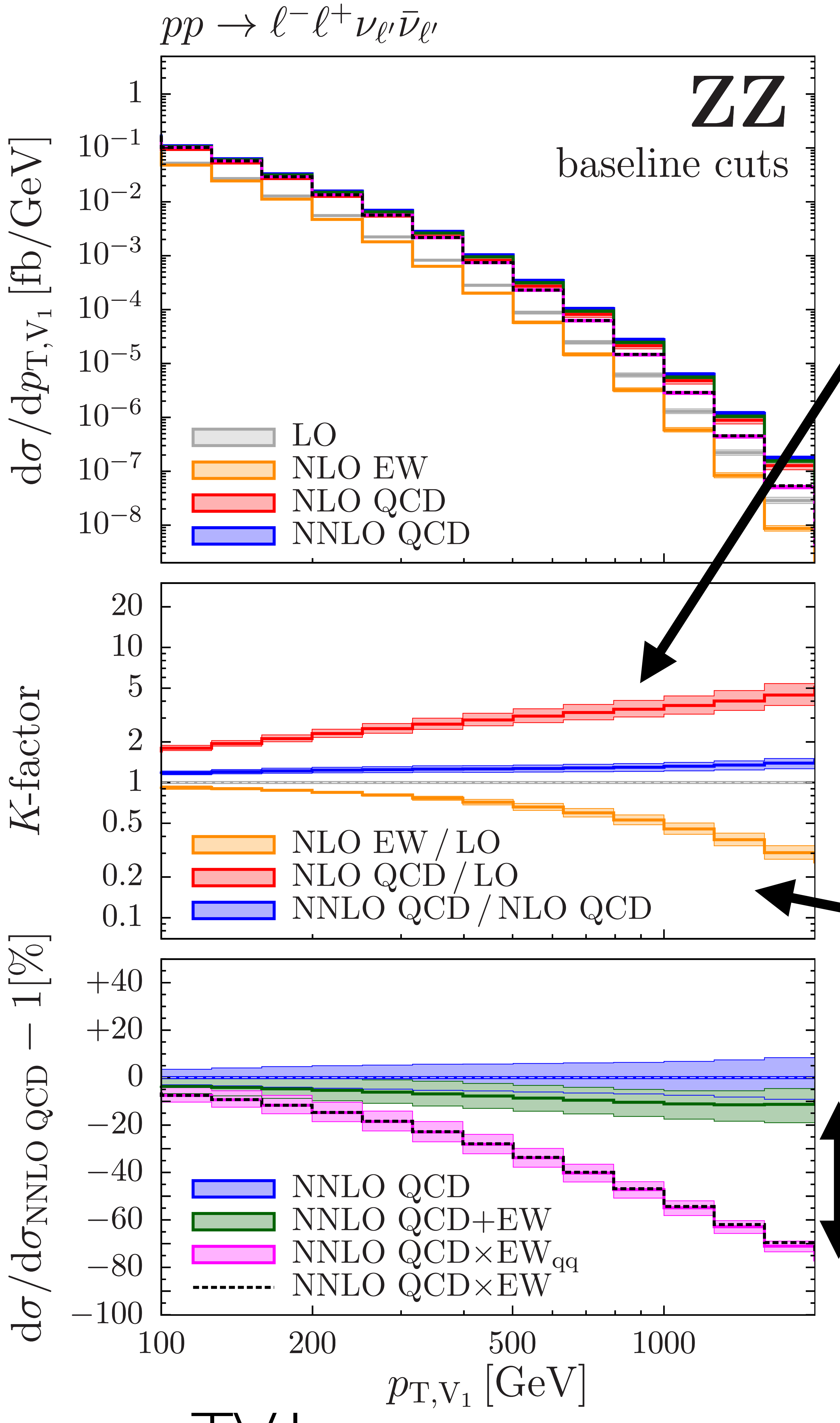
Giant QCD K-factors and EW corrections: pTV1



pTV1

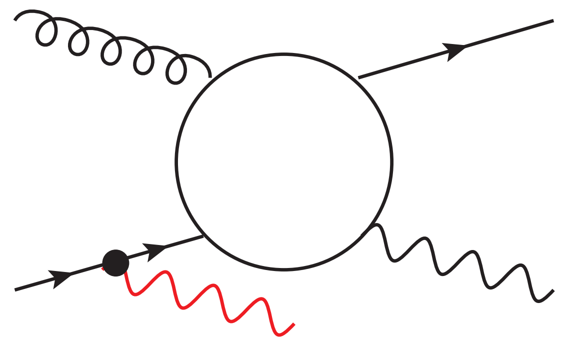
- NLO QCD/LO=2-5! ("giant K-factor")

Giant QCD K-factors and EW corrections: pTV1



pTV1

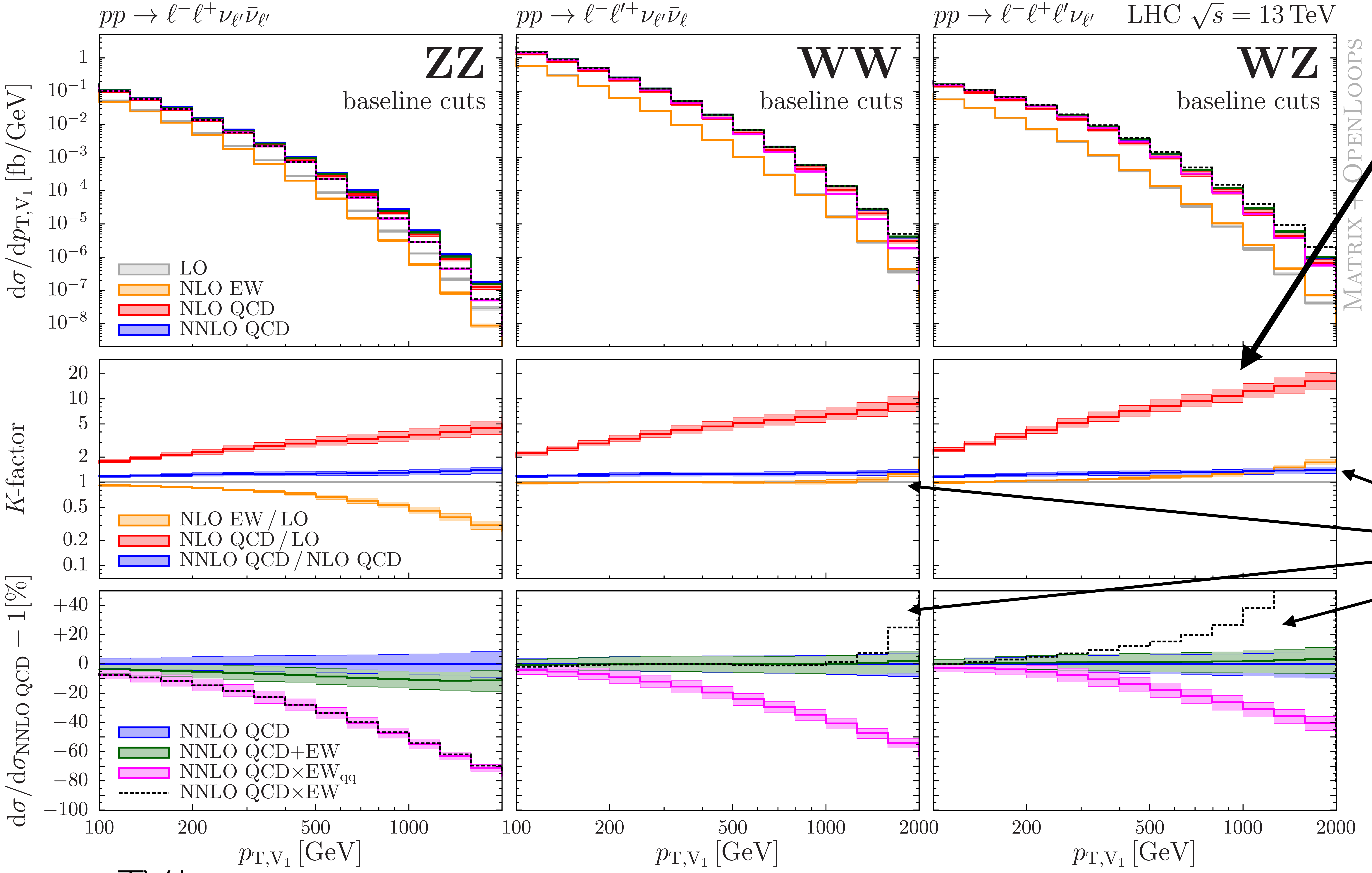
- NLO QCD/LO=2-5! ("giant K-factor")
- at large pTV1: VV phase-space is dominated by V+jet (w/ soft V radiation)



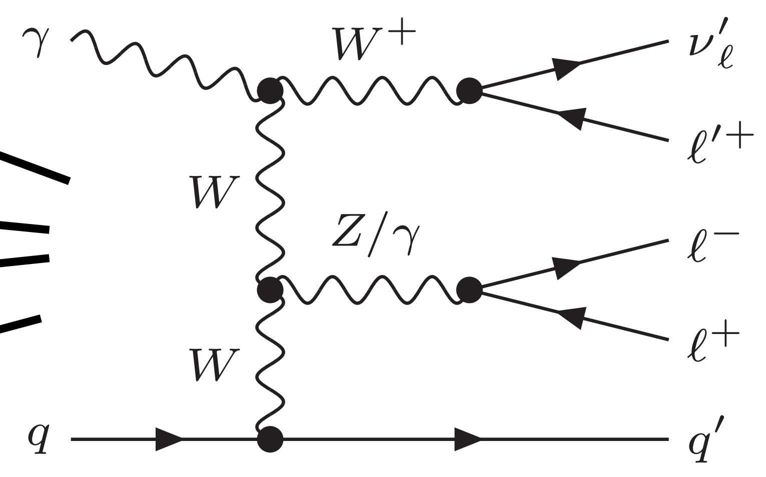
$$\longrightarrow \frac{d\sigma^{V(V)j}}{d\sigma^{LO}_{VV}} \propto \alpha_S \log^2\left(\frac{Q^2}{M_W^2}\right) \simeq 3 \qquad \text{at} \quad Q = 1\,\text{TeV}$$

- NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- NLO EW/LO=-(40-50)%
- Very large difference $\mathrm{d}\sigma_{\mathrm{NNLO\,QCD+EW}}$ 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: **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



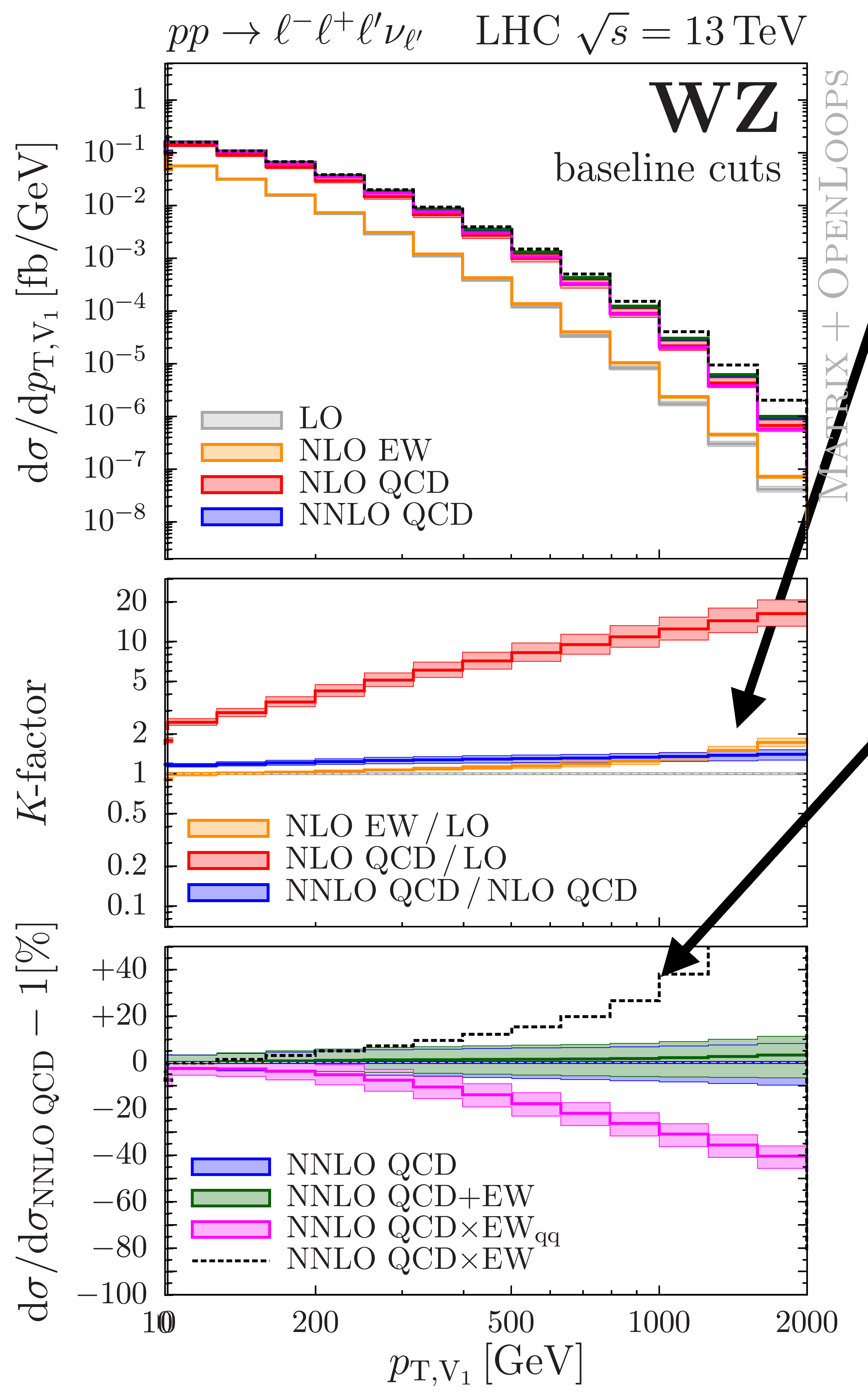
- NLO QCD/LO=5-10!
- Similar giant K-factor mechanism also in gamma-induced:



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

pTV1

Giant QCD K-factors and EW corrections: pTV1



- Giant EW K-factor

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

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

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

- alternative/modified multiplicative ansatz:

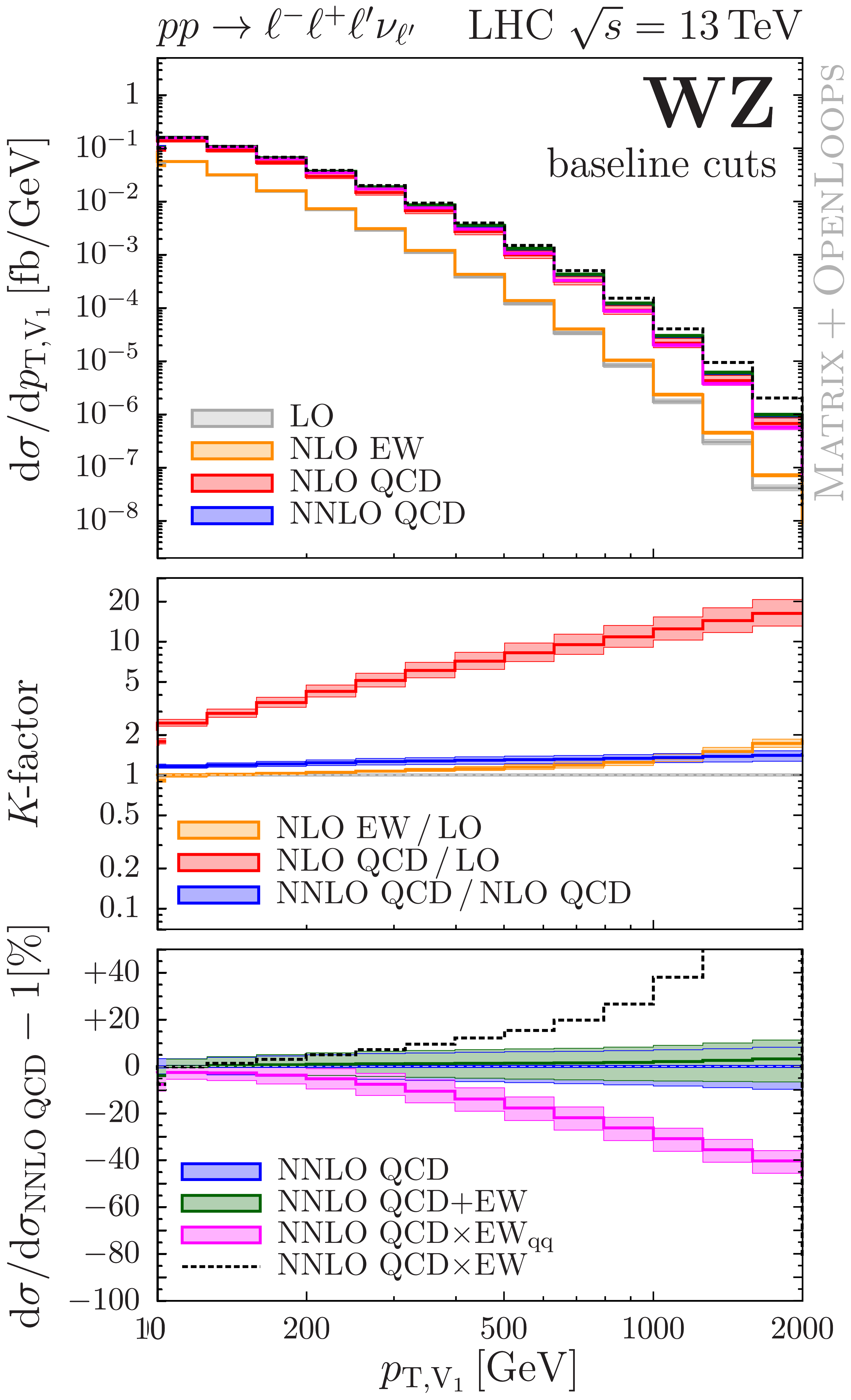
$$d\sigma_{\text{NNLO QCD}\times\text{EW}_{qq}} = d\sigma^{q\bar{q}}_{\text{LO}}\left(1+\delta^{q\bar{q}}_{\text{QCD}}\right)\left(1+\delta^{q\bar{q}}_{\text{EW}}\right) + d\sigma^{\gamma\gamma}_{\text{LO}}\left(1+\delta^{\gamma\gamma/q\gamma}_{\text{EW}}\right) + d\sigma^{gg}_{\text{LO}}$$
$$= d\sigma_{\text{NNLO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

yields behaviour consistent with EW Sudakov logs

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

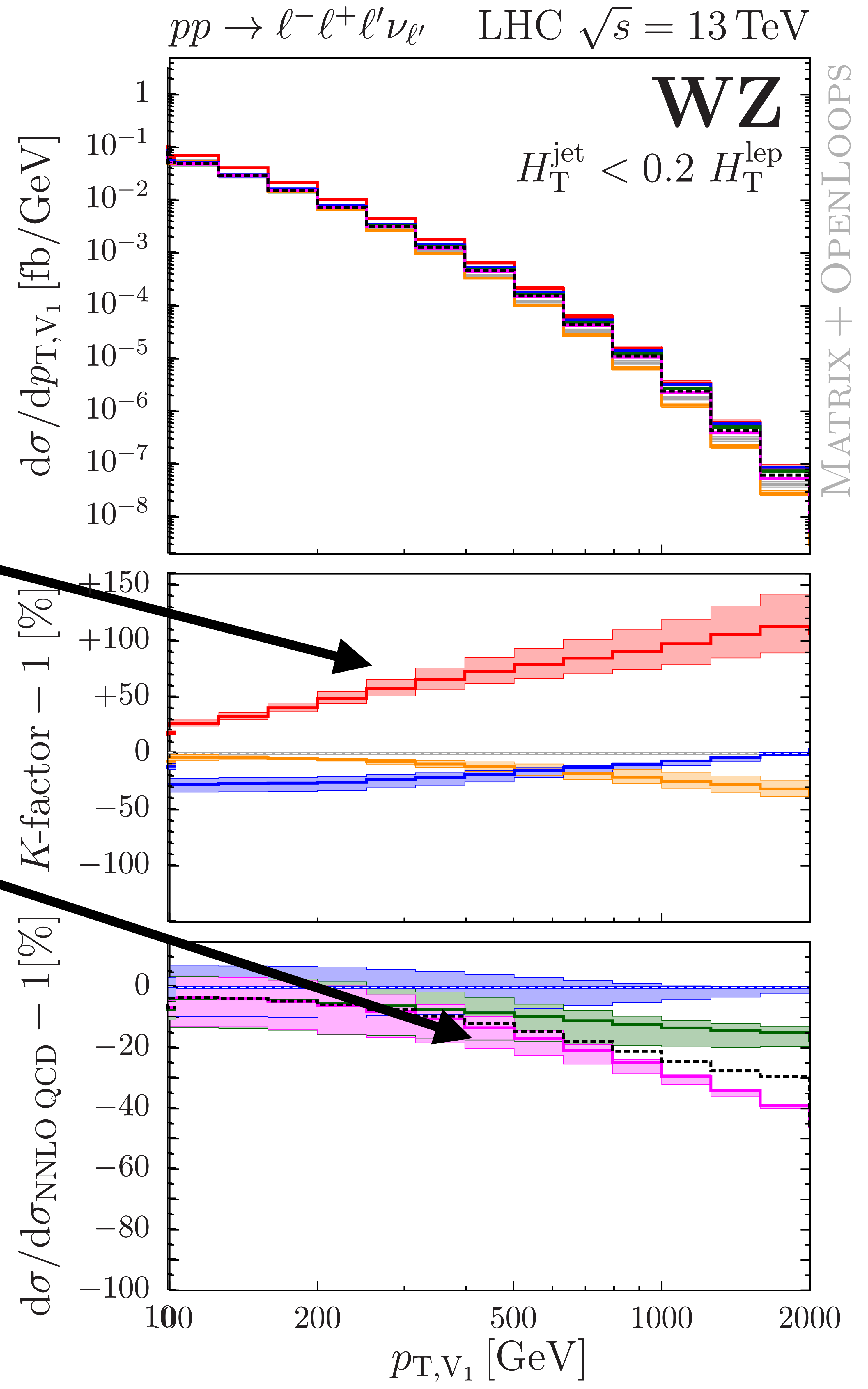
- Caveat: splitting in $q\bar{q}$ and $\gamma\gamma/\gamma q$ channels is ad-hoc/scheme dependent

Giant QCD K-factors and EW corrections: pTV1



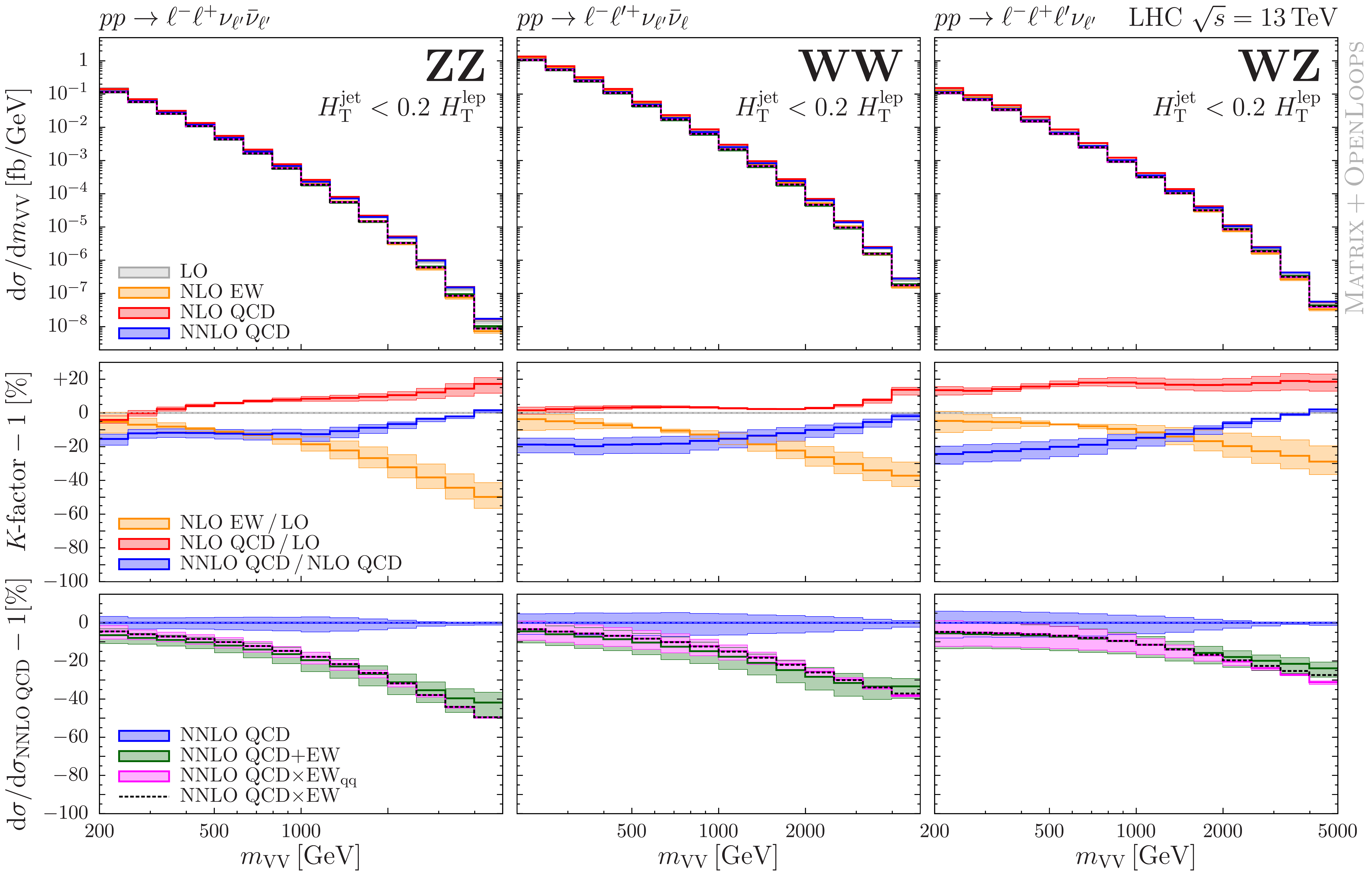
jet veto

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



- 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!

NNLO QCD + NLO EW for dibosons: mVV

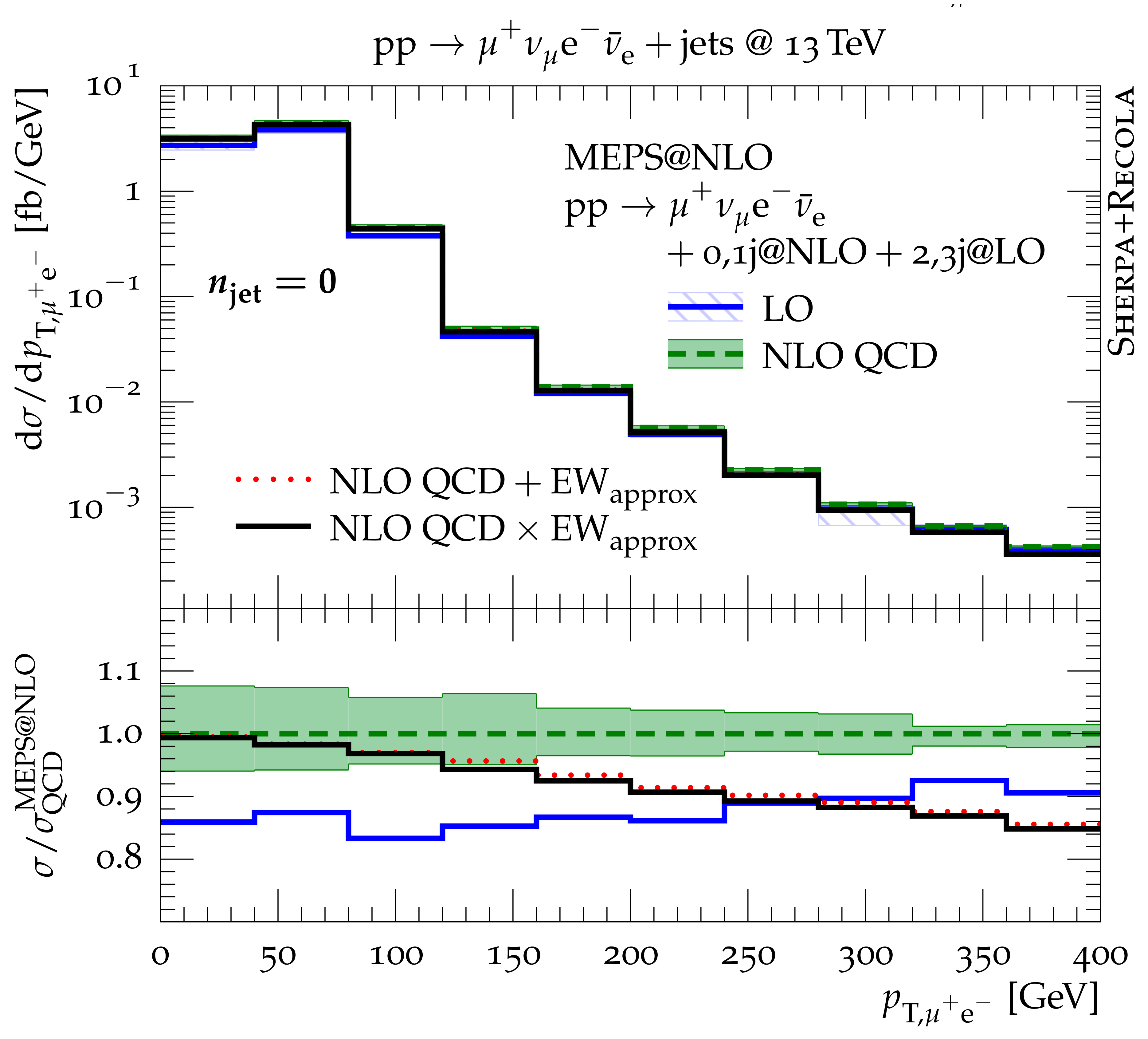


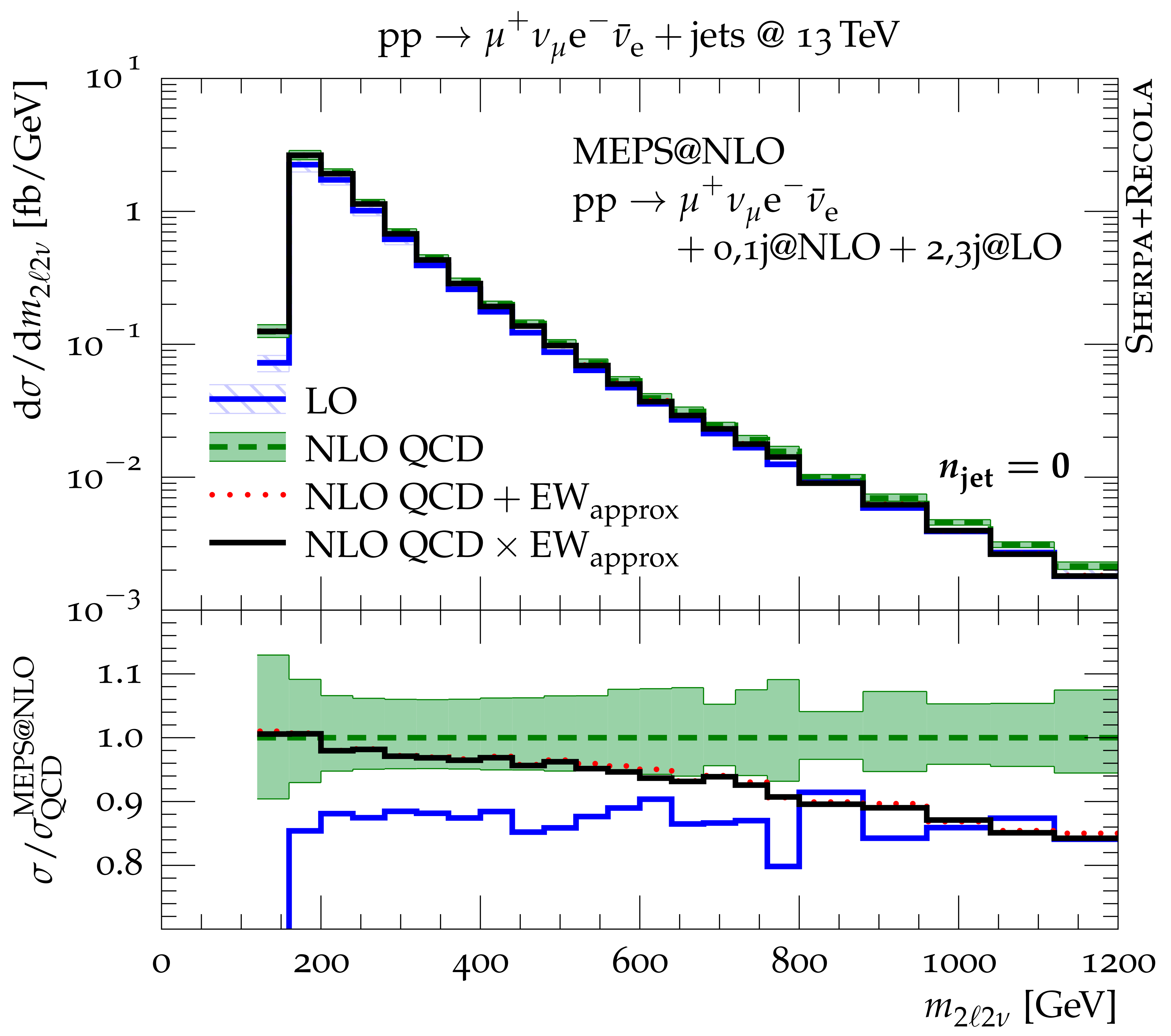
- NLO QCD/LO reduced to 10-20%
- Very small difference between additive and multiplicative QCD-EW combinations

MEPS @ NLO QCD + EW

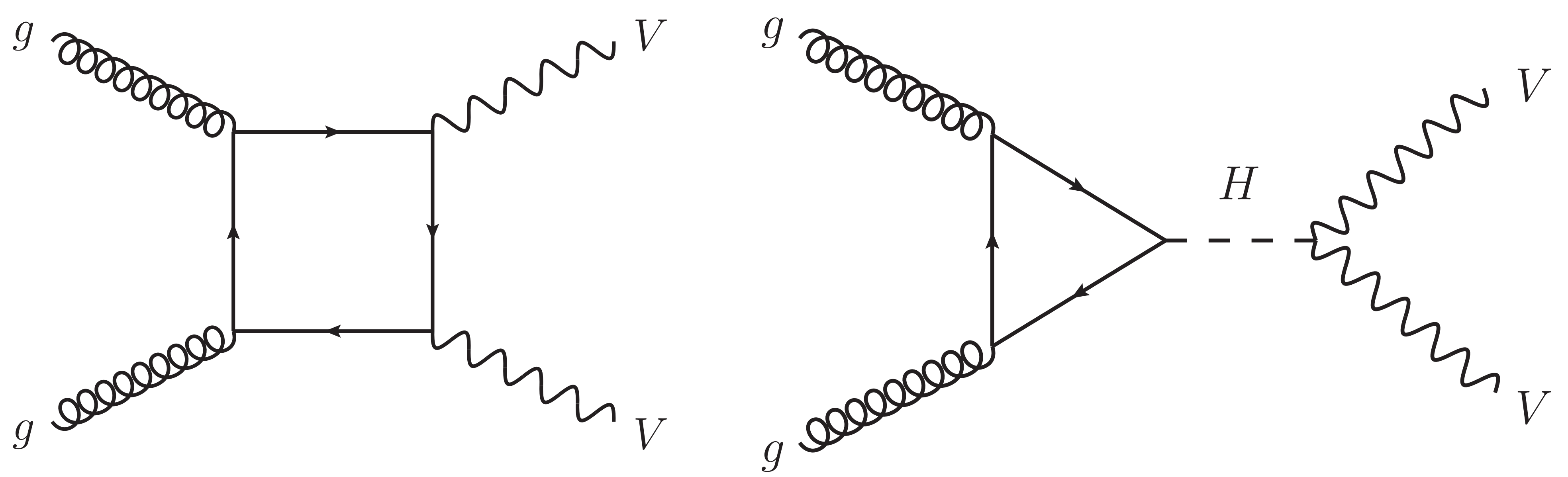
[Bräuer, Denner, Pellen, Schönherr, Schumann; '20]
[Bothmann, Napoletano, Schönherr, Schumann, Villani; '21]

- "Rigorous approximate solution": merge VVj incl. approx. EW corrections with VV with Sherpa's MEPS@NLO

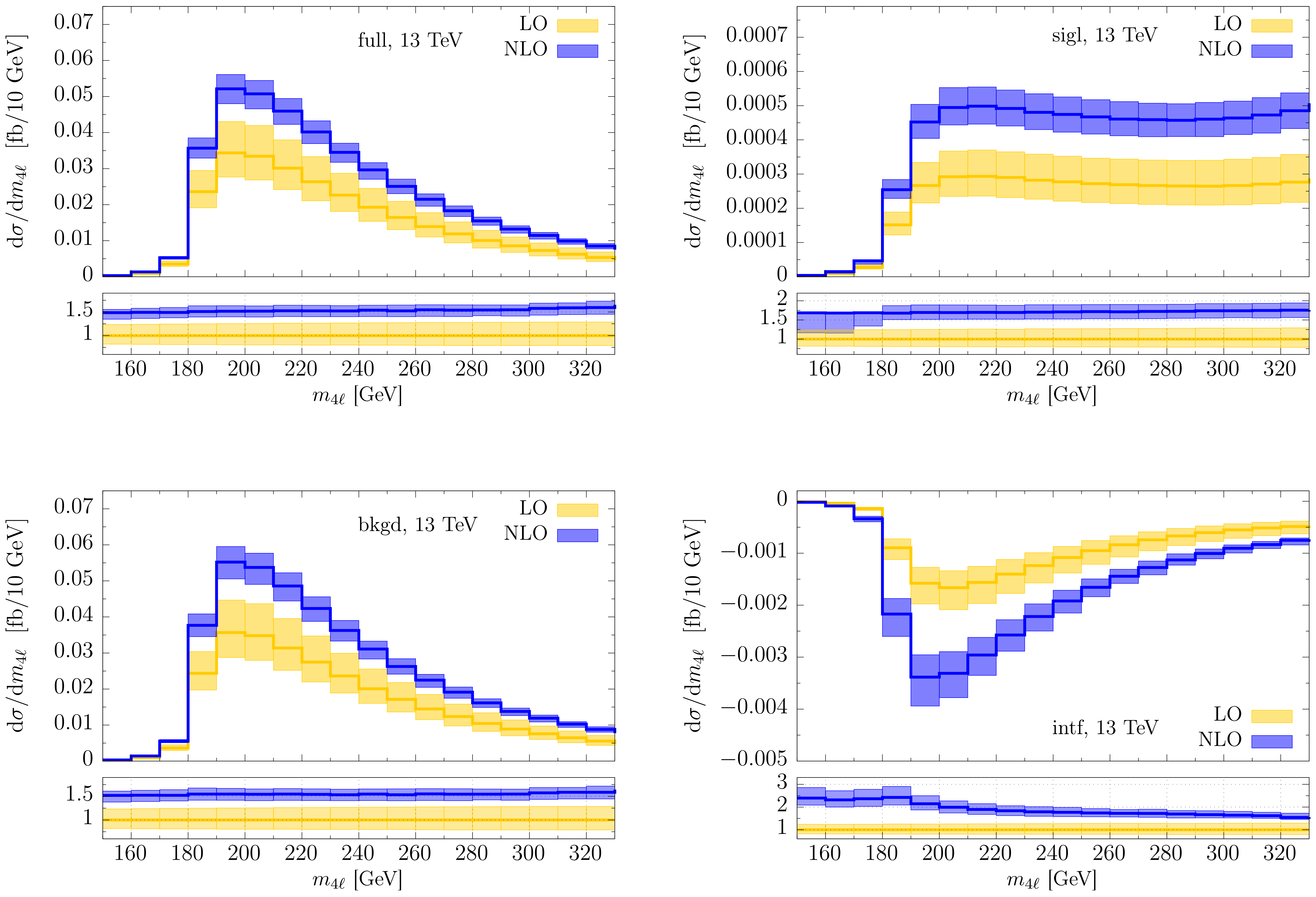




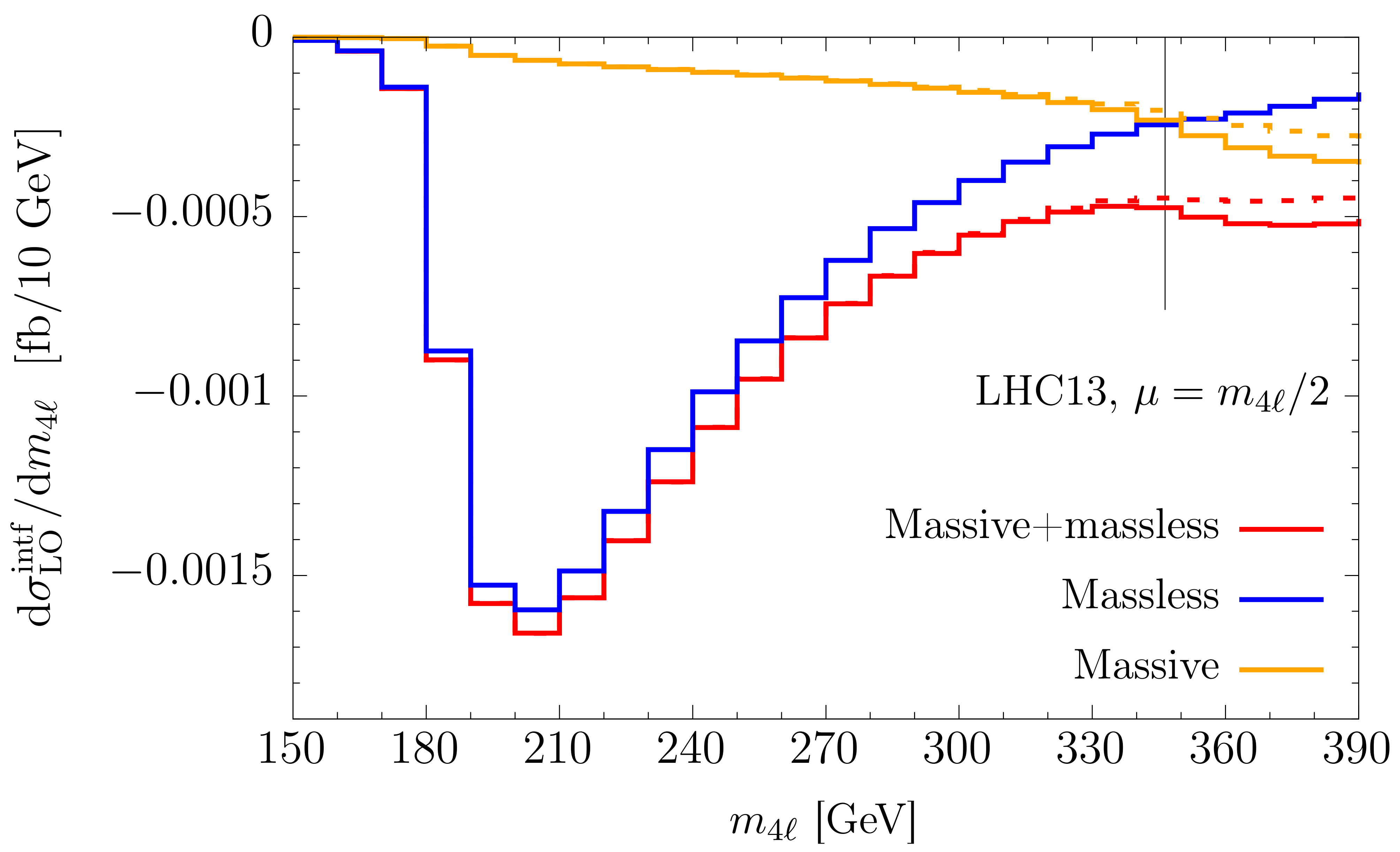
gg-induced WW and ZZ production



- Formally same order as NNLO QCD
- Enhanced due to gg flux
- Interference with H->VV

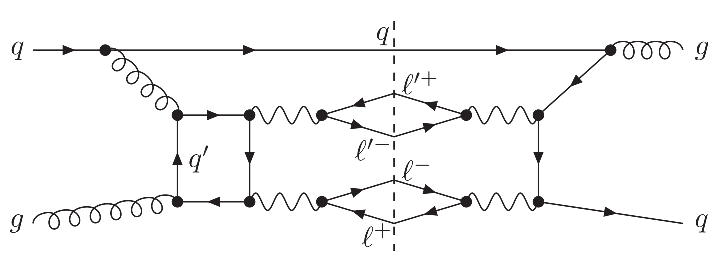


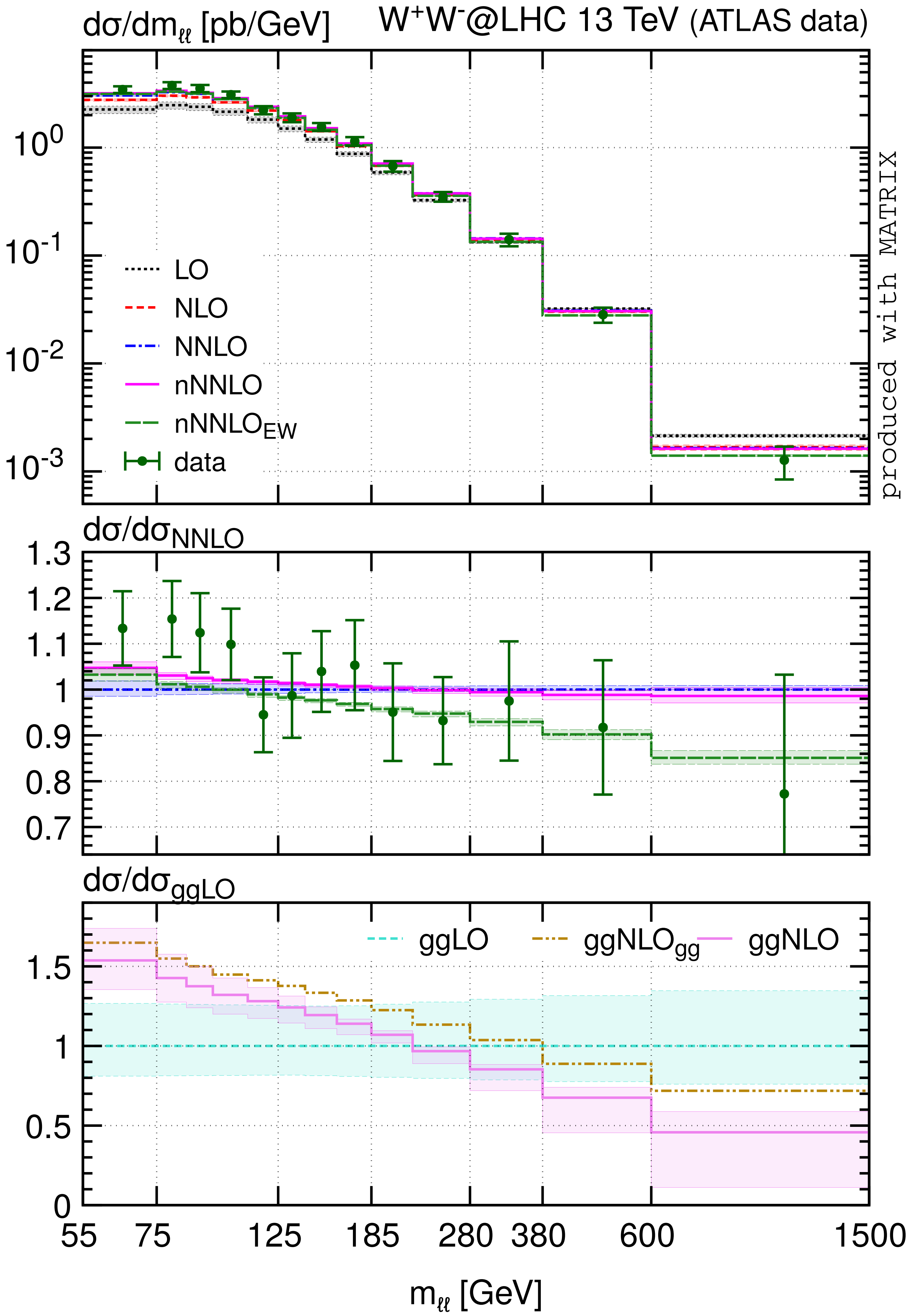
- Sizeable QCD corrections (formally N3LO QCD)
- For m4l < 340 GeV 1/Mt expansion reliable



NLO QCDgg

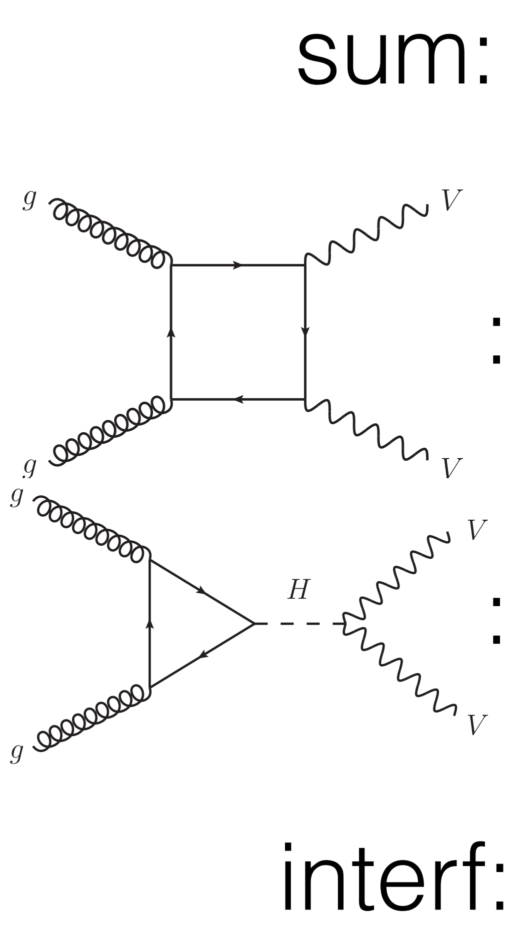
[M. Grazzini, S. Kallweit, J.Y. Yook, M. Wiesemann; WW: '20, ZZ: '21]

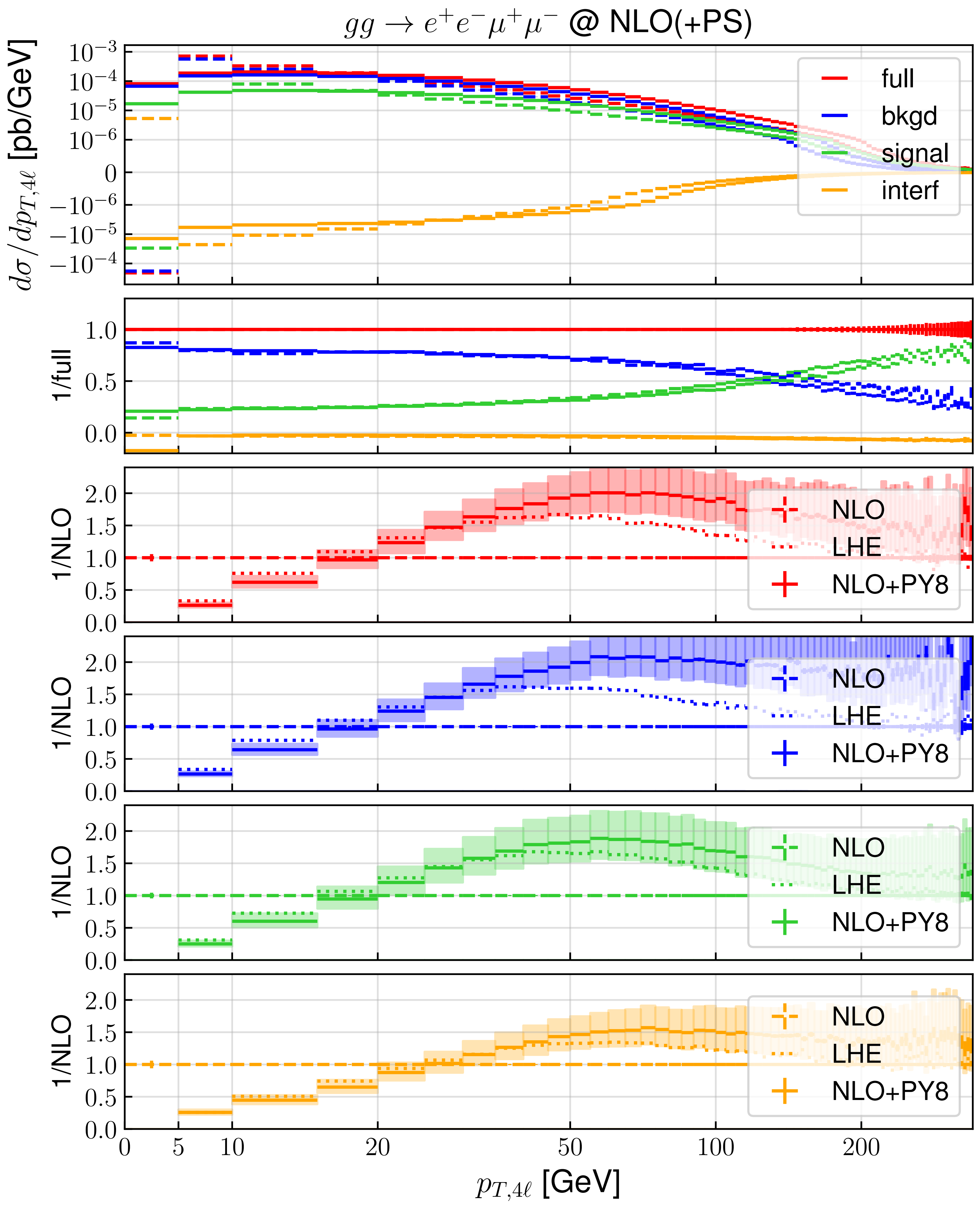




- Very good data agreement with NNLO QCD + NLO QCDgg + NLO EW

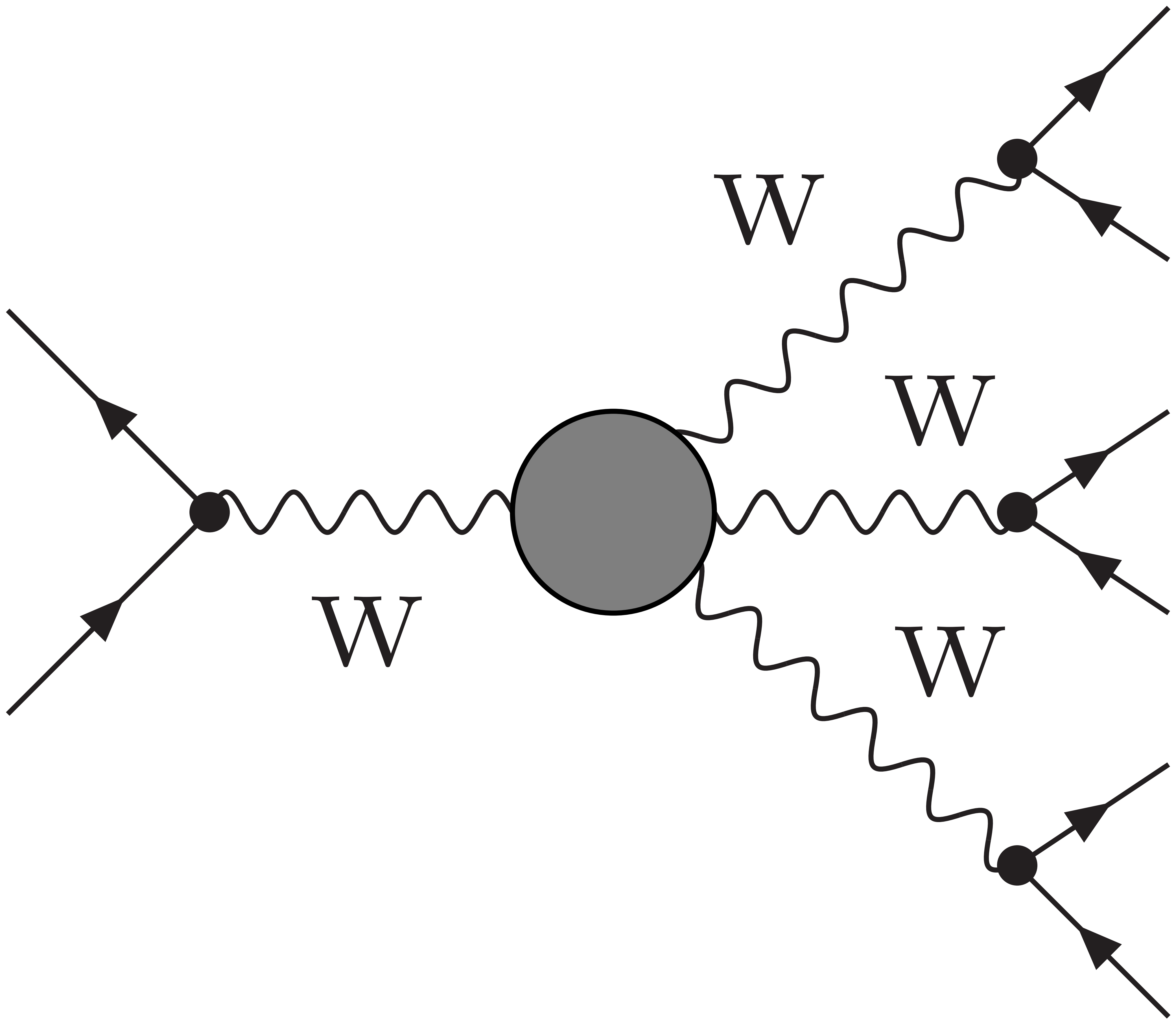
[Alioli, Ferrario Ravasio, JML, Röntsch, '21]





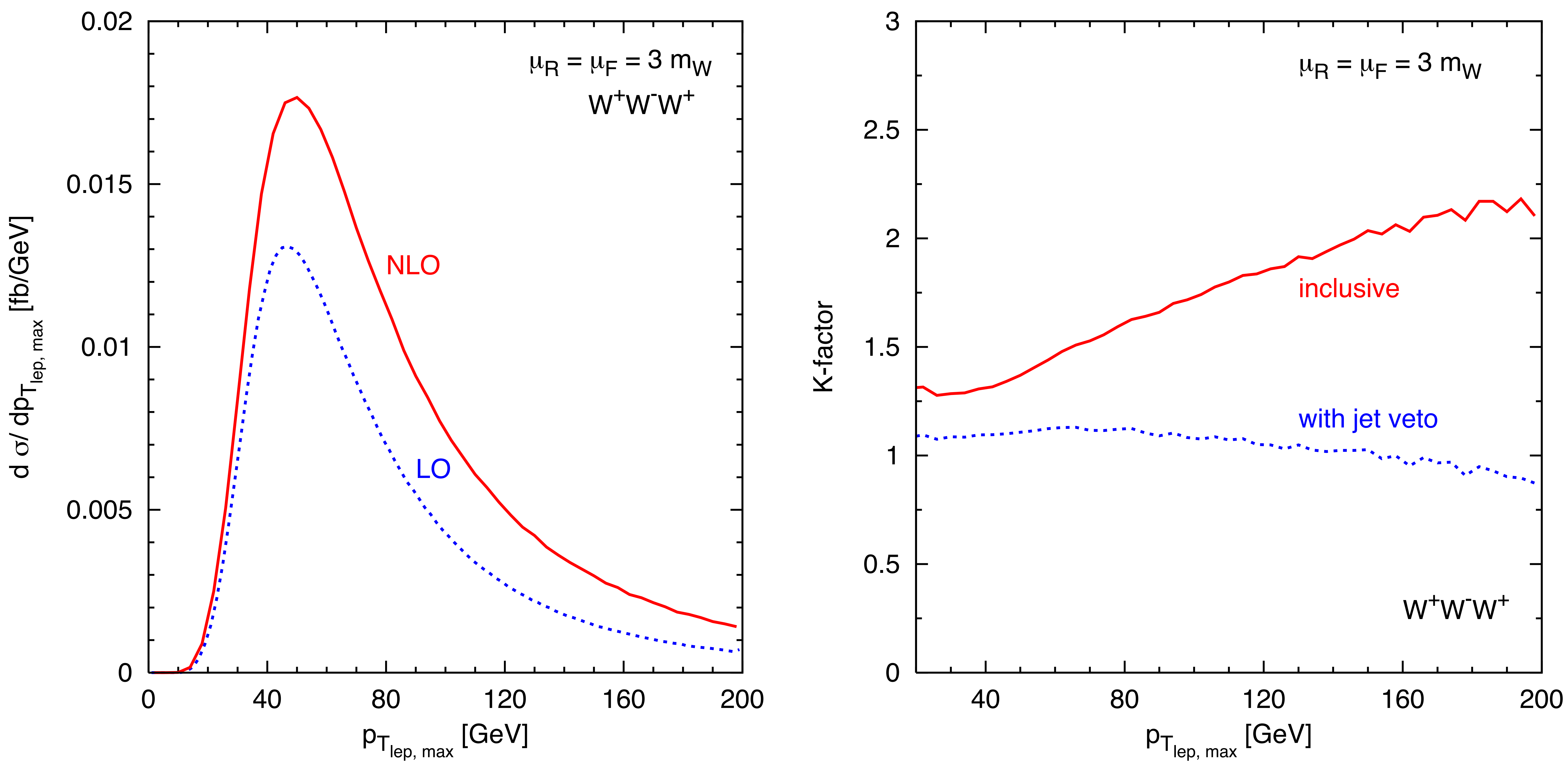
- ggWW/ggZZ @ NLO QCD + PS available! (VV-cont., H→VV & interference)

Tribosons



Triboson production @ NLO QCD

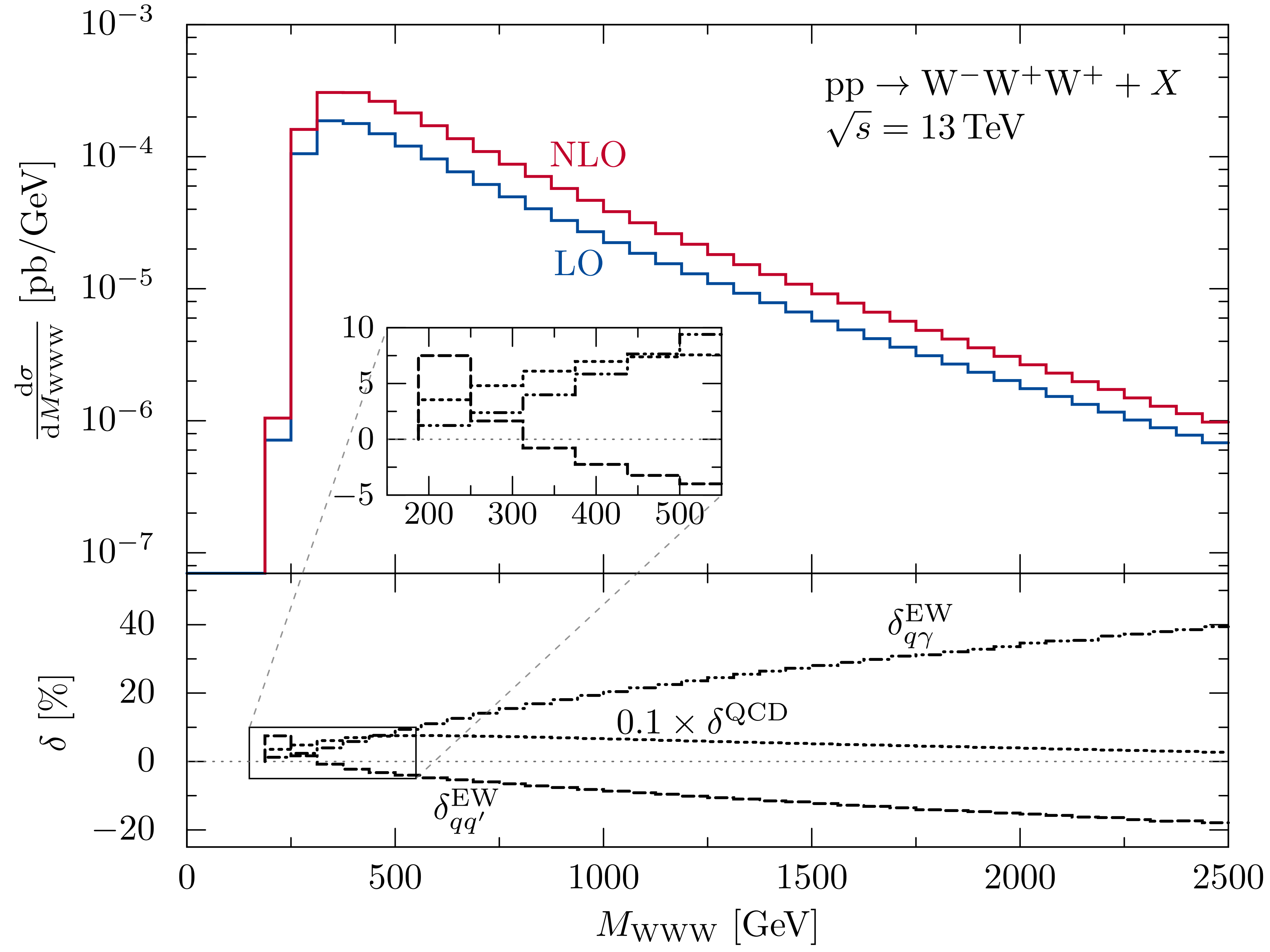
[Campanario et.al., '08]

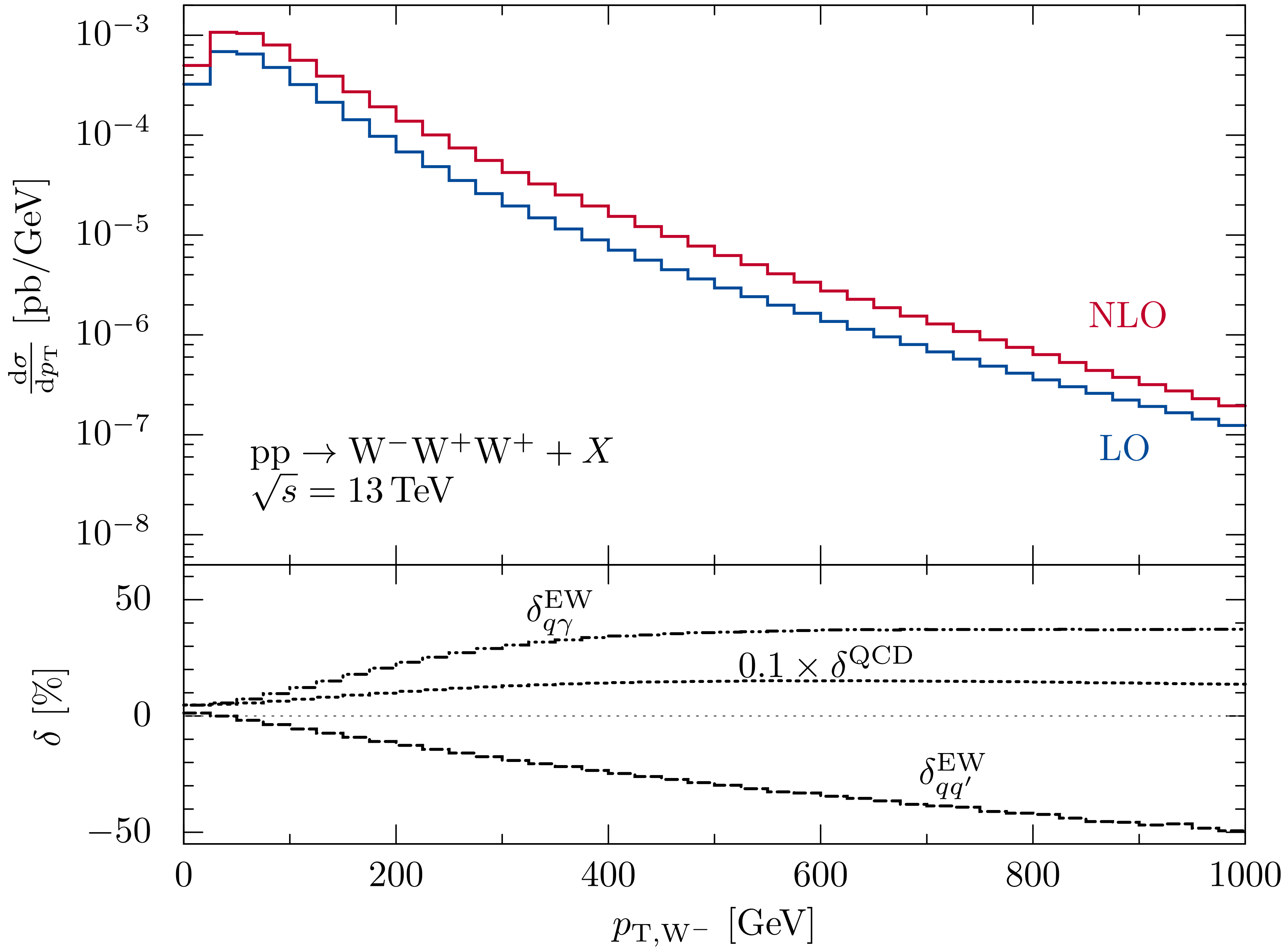


- QCD correction driven by additional jet activity: VV+jet topologies with soft V
  - → 'giant K-factors'
  - → strong observable dependence
  - → NLO mandatory
- jet veto (pT_{cut} = 50 GeV) reduces size and phase space dependence
  - → better: multi-jet merging

WWW @ NLO QCD+EW

Dittmaier, Huss, Knippen arXiv:1705.03722



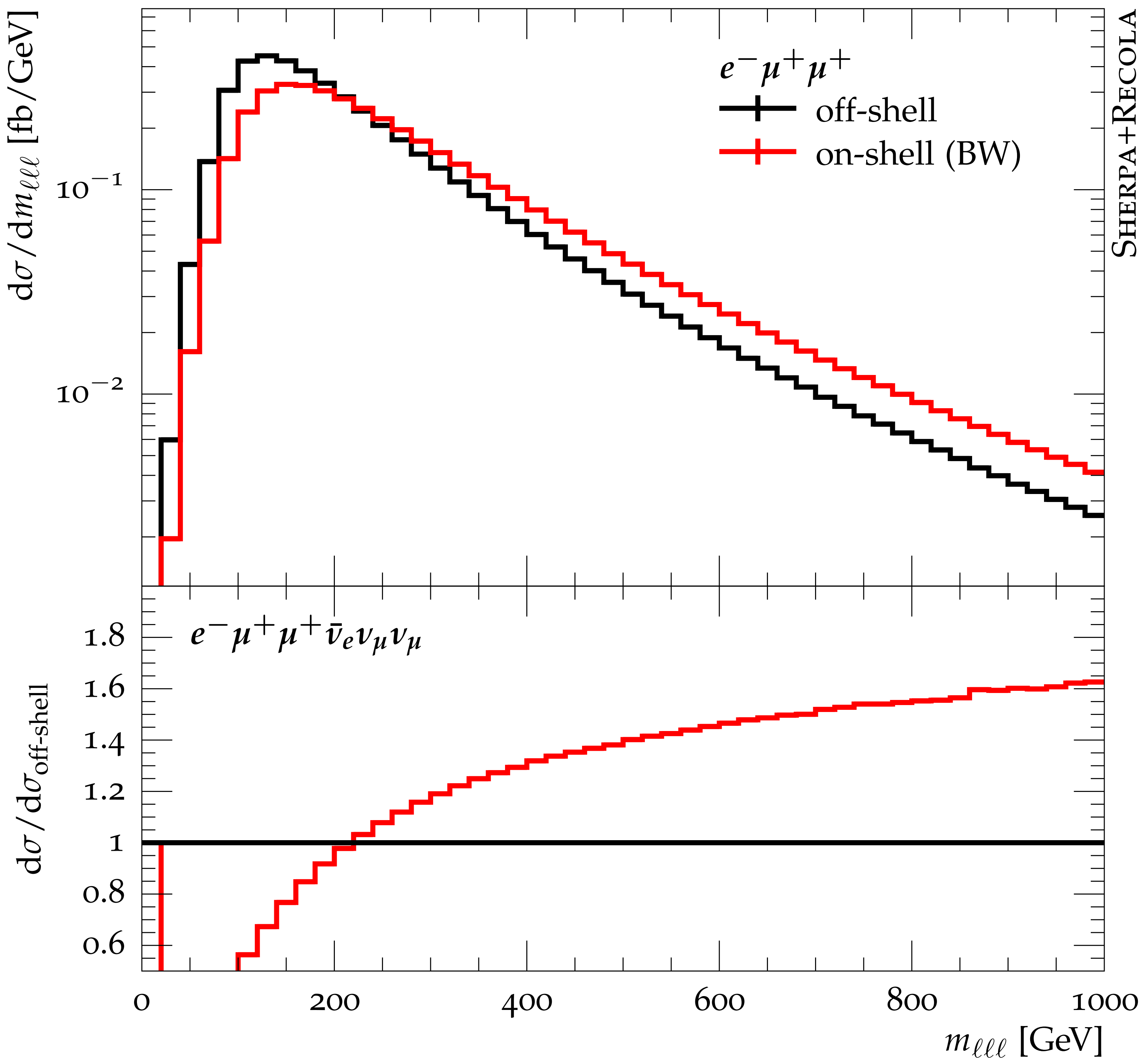


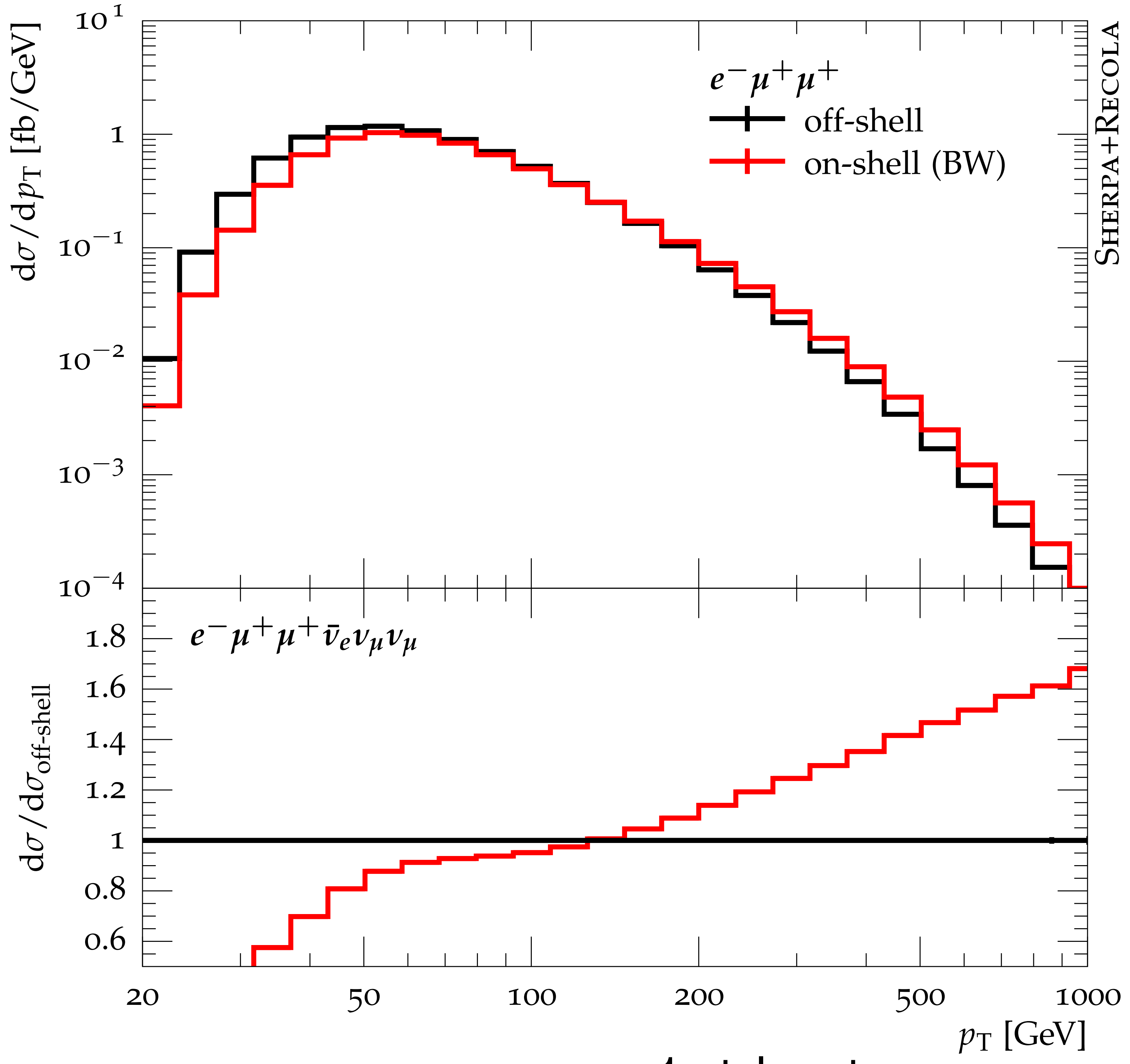
- corrections w/o jet veto
- QCD corrections ≈ 70%, slight observable dependence
- γ-induced EW corrections large and observable dependent
  → large accidental cancellations with EW corrections in $q\bar{q}$-channel

[Slide: M. Schönherr]

Triboson production: on-shell vs. off-shell

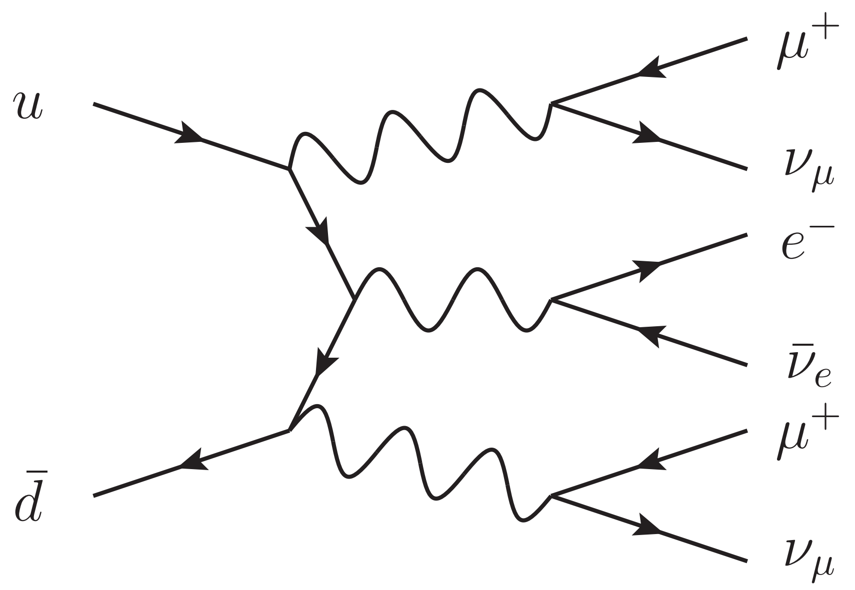
[M. Schönherr, '18]



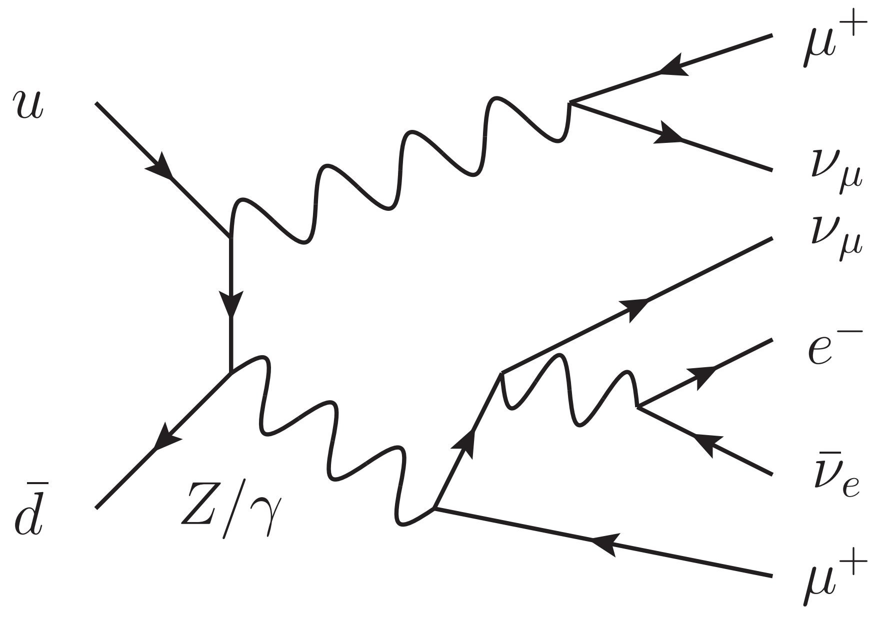


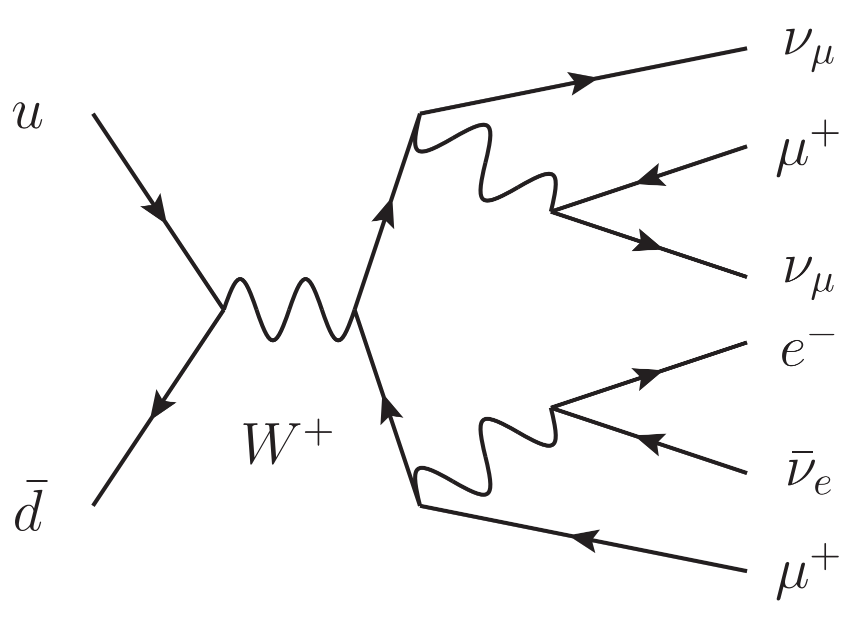
1st lepton

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



vs.





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

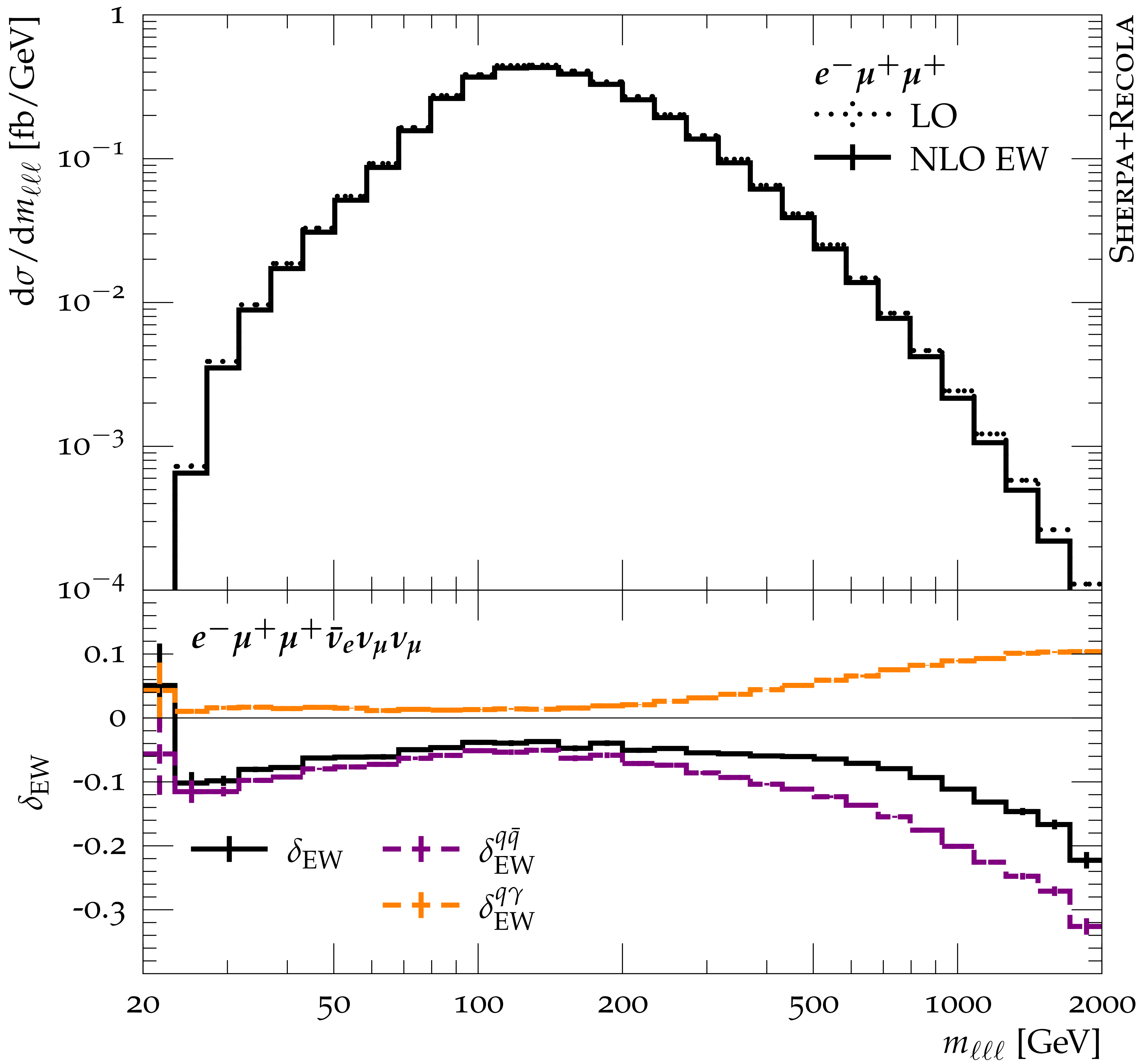
[M. Schönherr, '18]

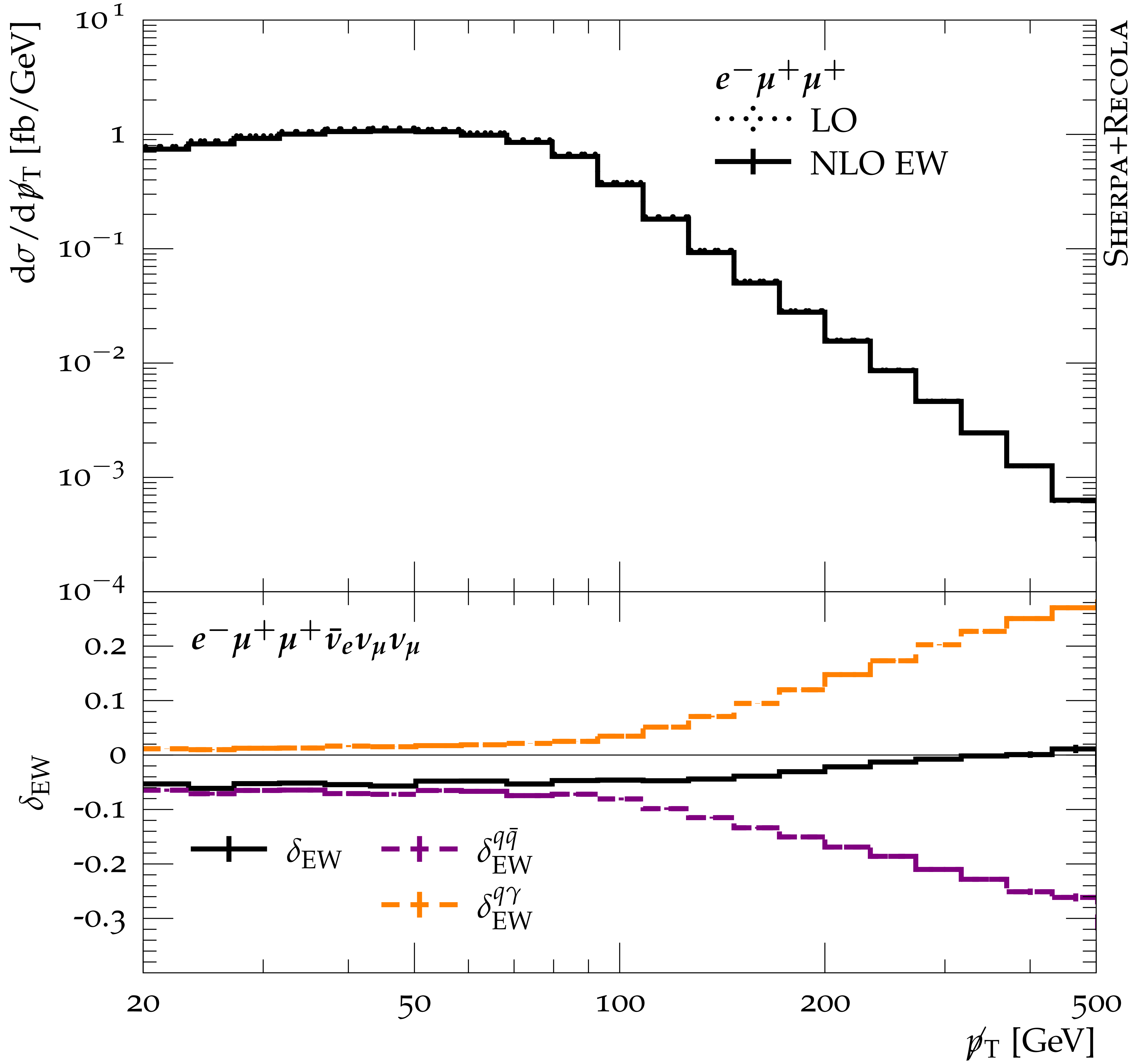
	inclusive			
	LO [fb]	δ_{EW}	$\delta^{\text{EW}}_{q\bar{q}}$	$\delta^{\text{EW}}_{q\gamma/\bar{q}\gamma}$
$\ell^-\ell^+\ell^+$	**0.4209**	**$-2.0\,\%$**	**$-5.2\,\%$**	**$3.2\,\%$**
$e^-e^+e^+$	0.0212	$-3.4\,\%$	$-7.1\,\%$	$3.6\,\%$
$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	0.0206	$-3.4\,\%$	$-7.0\,\%$	$3.6\,\%$
$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	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]





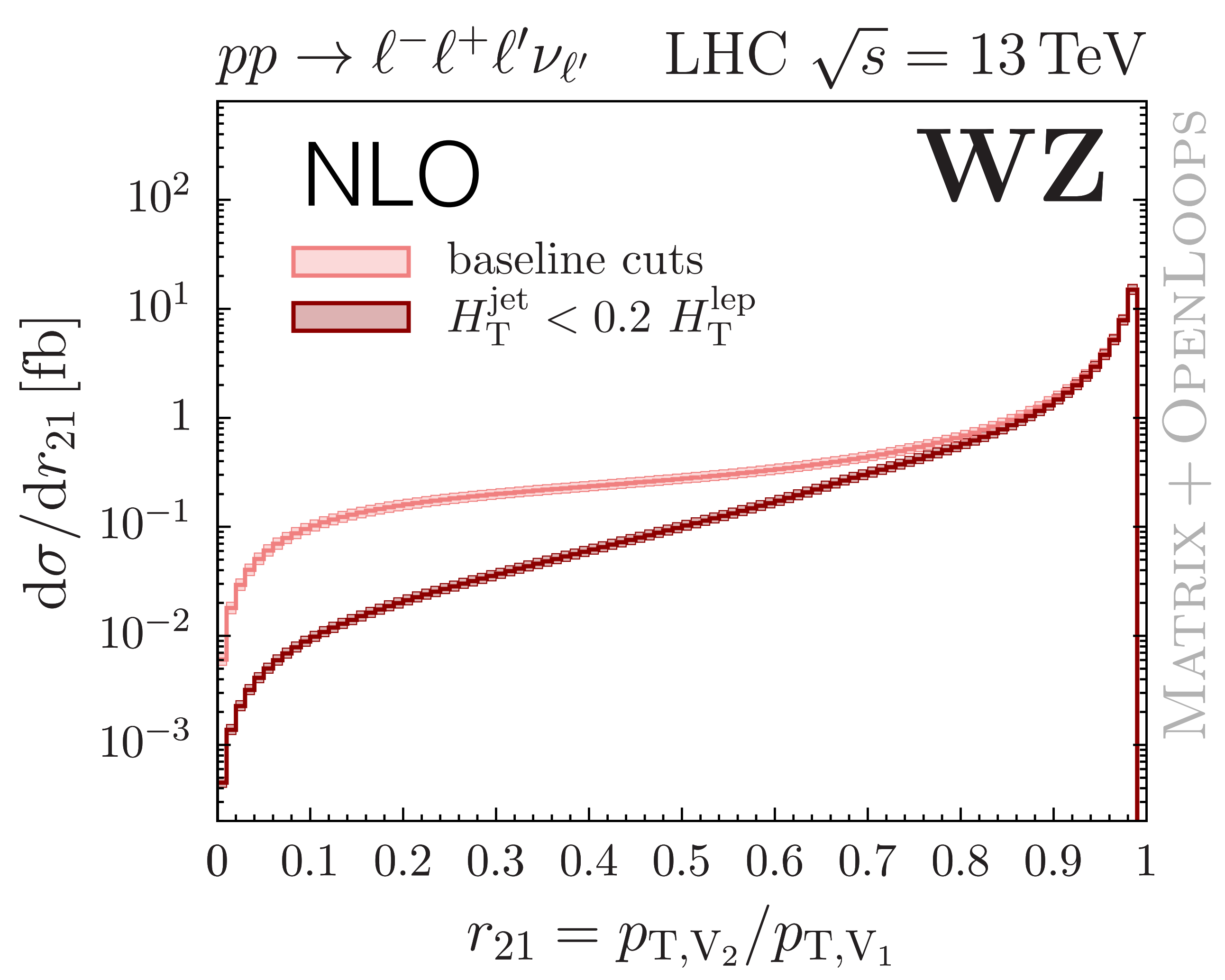
- cancellations of EW corr. in qq and q**γ** channels highly observable dependent

Conclusions

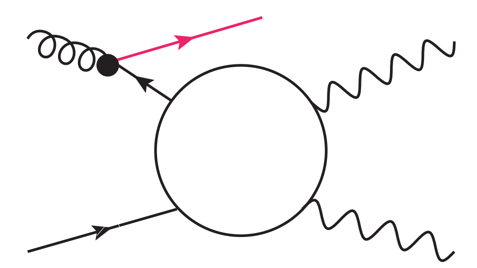
- Multilepton signatures dominated by VV / VVV / ttV SM backgrounds
- Upcoming large data samples will require more careful background estimates
- It will become mandatory to include higher-order QCD & EW
- Stare-of-the-art for VV at fixed-order: NNLO QCD x NLO EW
    - QCD -> giant K-factors, but NNLO often allows to reach few percent precision
    - EW -> large EW Sudakov corrections at large energies: several tens of percent
- Beyond fixed-order for VV:
    - NNLO QCD + PS
    - MEPS @ NLO QCDxEW
    - NLO QCD + EW PS
- Stare-of-the-art for VVV at fixed-order: NLO QCD x NLO EW
    - off-shell calculations mandatory
    - Very large cancellations between EW Sudakov and photon-induced corrections

Backup

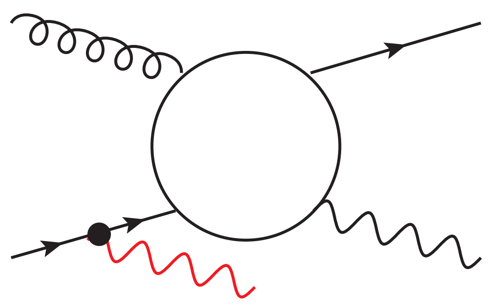
Giant K-factors and effect of jet veto

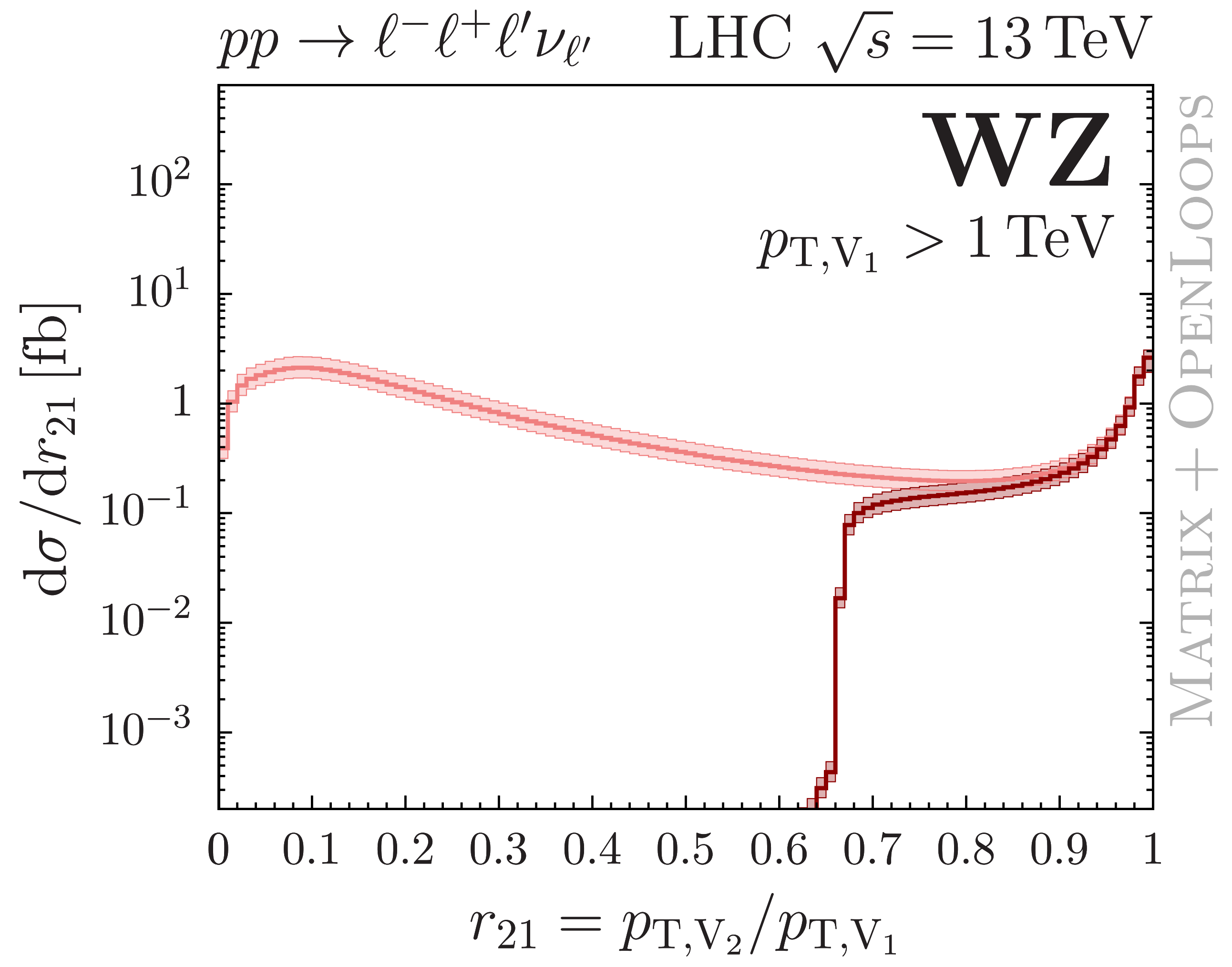


- at r21 → 1: hard-VV topologies



- at r21 → 0: hard-Vj topologies



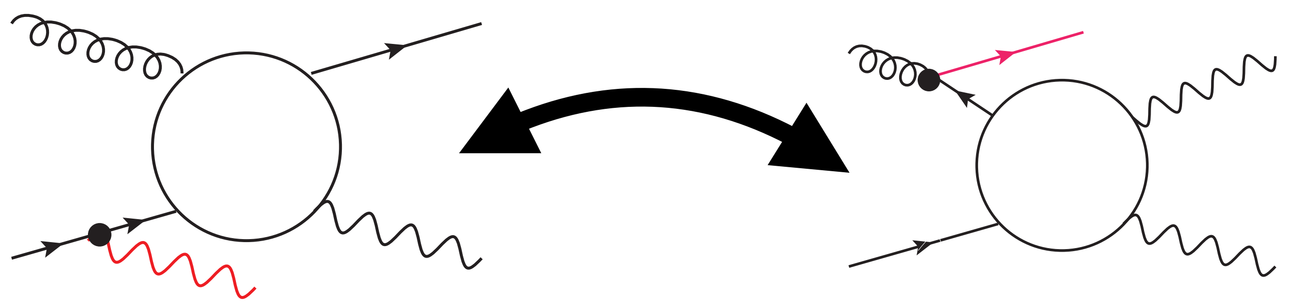


- for pTV1 > 1 TeV: hard-Vj topologies dominate over hard-VV
- Jet veto $H_T^{jet} < \xi_{veto}\, H_T^{lep}$ corresponds to

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

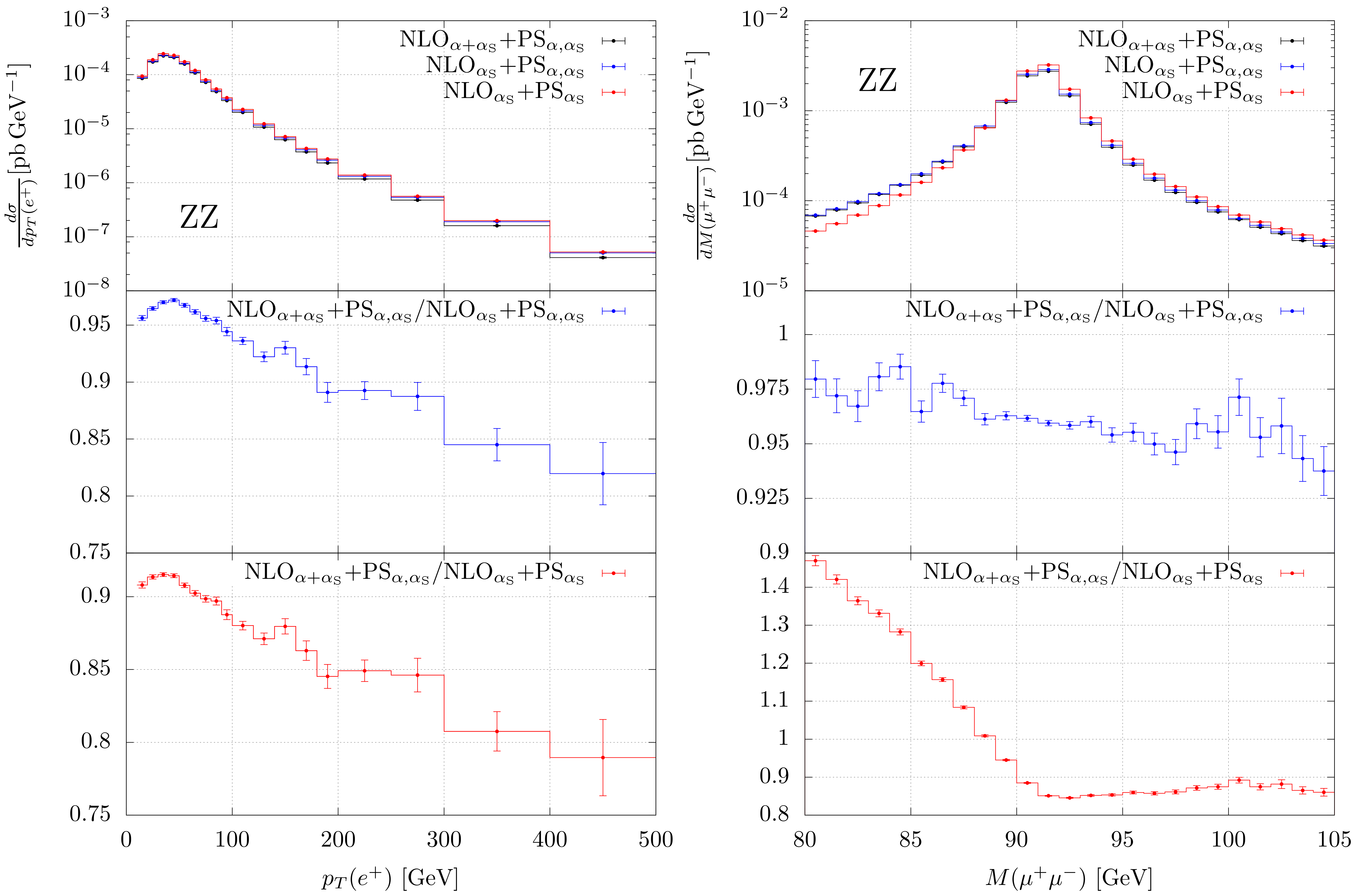
(violated by off-shell topologies)

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



PS MC: NLO QCD + EW PS

[Chiesa, Re, Oleari '20]



Available in POWHEG-BOX-RES
(Resonance aware matching)

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

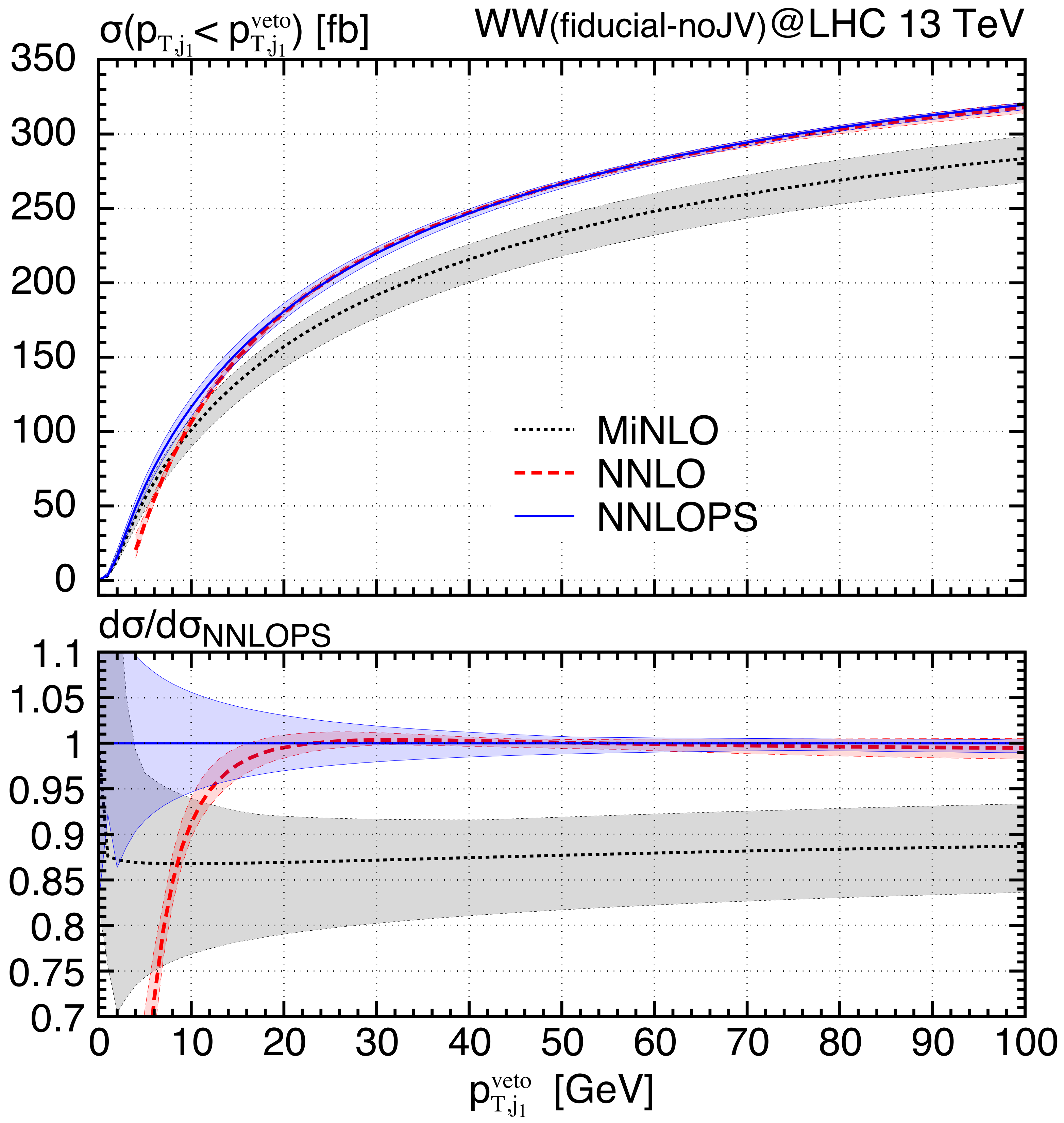
NLO (QCD + EW) PS (QCD + QED)/
NLO QCD PS QCD

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

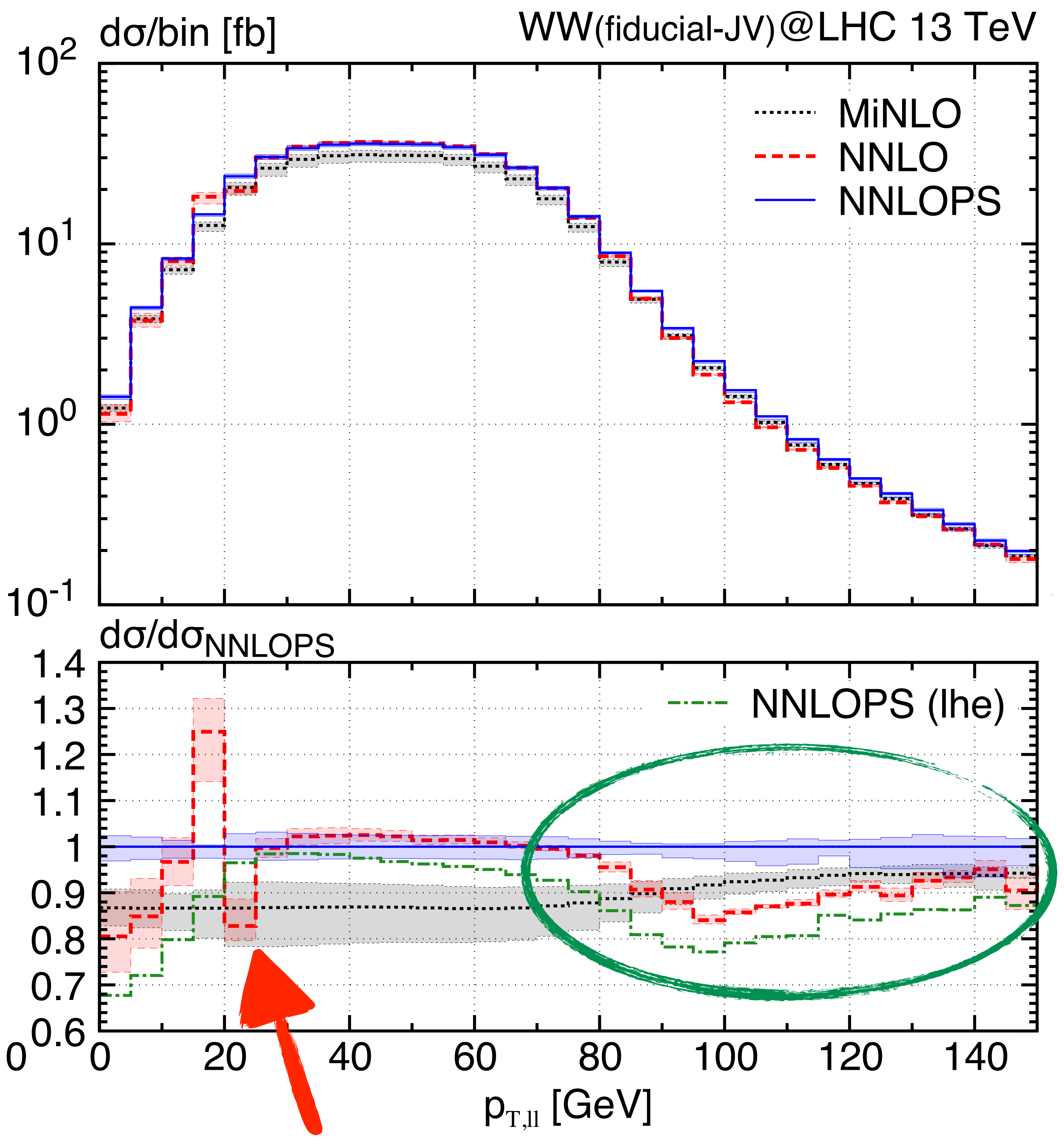
Parton shower Monte Carlos: NNLO QCD +PS via Mi(N)NLOPS

[Re, Wiesemann; Zanderighi '18]

Jet veto



p_T of dilepton system



→ **NNLOPS physical down to $p_T = 0$**

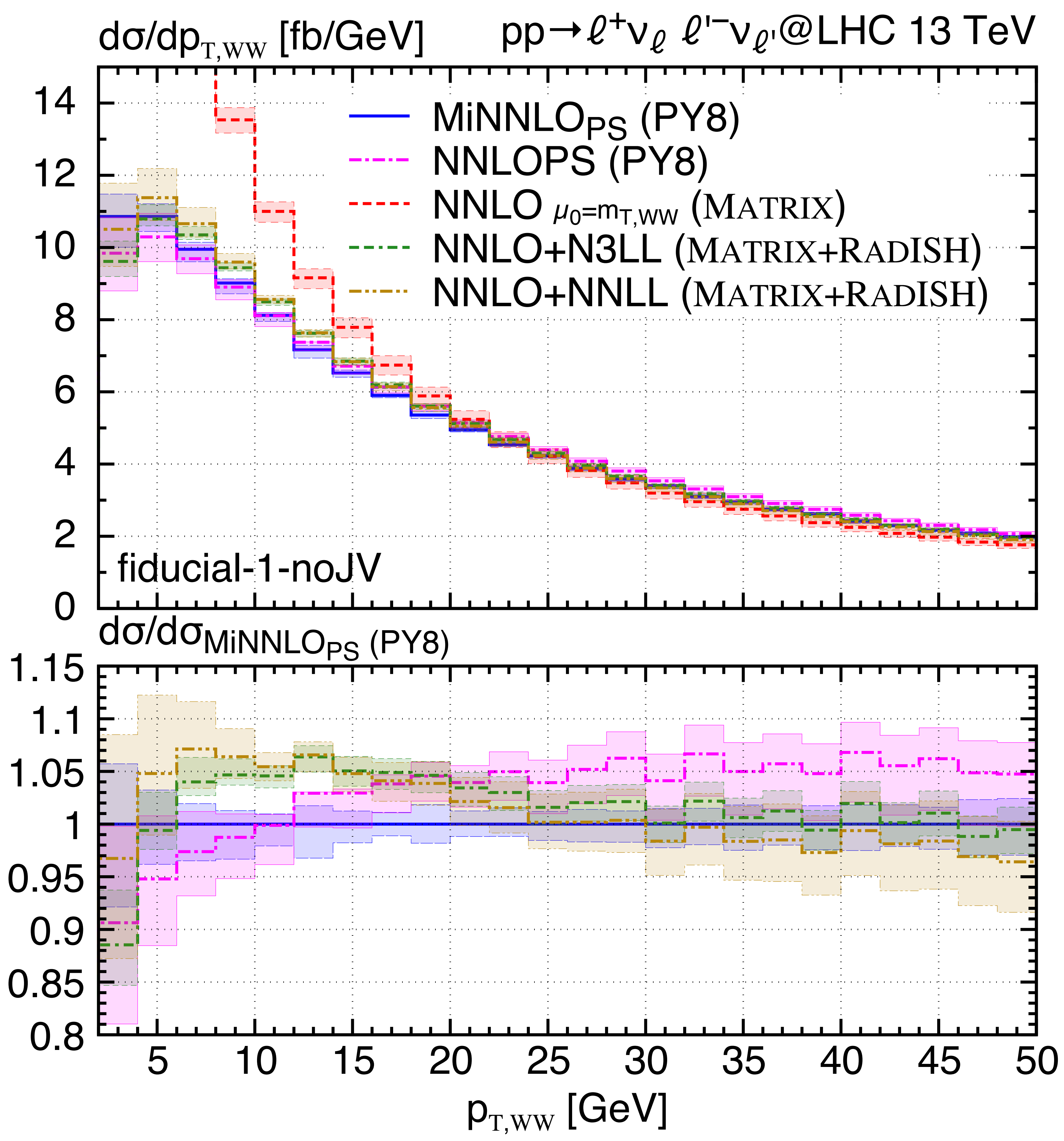
→ **NNLOPS cures perturbative instabilities (p_T^{miss} cut)**

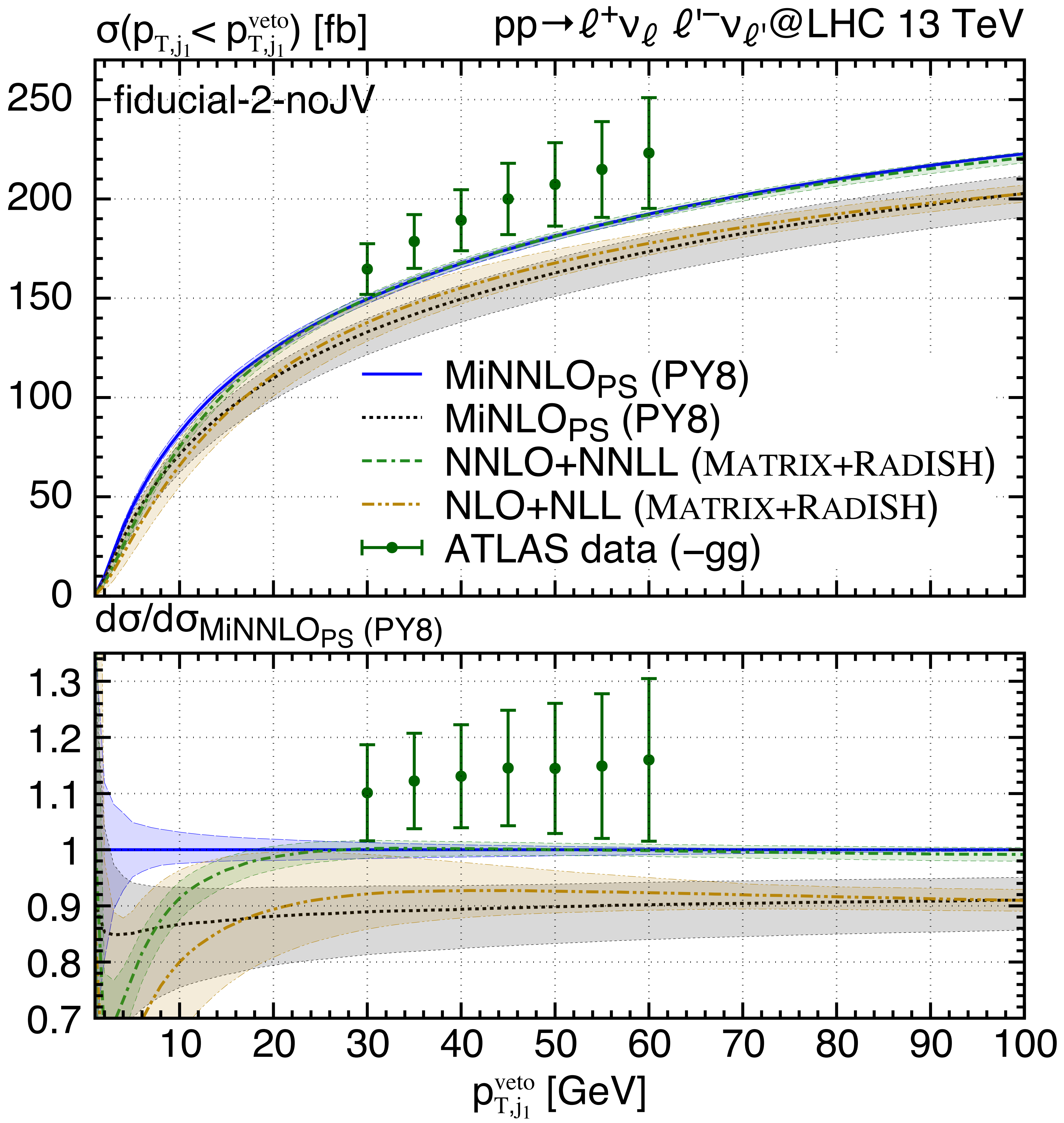
→ **NNLOPS induces additional shape effects**

- Currently only available for WW via MiNLOPS + reweighing
- Full MiNNLOPS work in progress (recent results for Zɣ - 2010.10478)

PS MC: NNLO QCD + PS for VV via MiNNLOPS

[Lombardi, Wiesemann; Zanderighi '21]





- MiNNLOPS physical down to pTVV=0
- Latest implementation does not require computationally expensive reweighting required earlier
- Also available for Zγ: - 2010.10478 *[Lombardi, Wiesemann; Zanderighi '20]*
- Alternative NNLOPS approach available for ZZ in GENEVA *[Alioli, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano '21]*

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]