Status of theory predictions for single bosons, diboson, and multiboson

Jonas M. Lindert

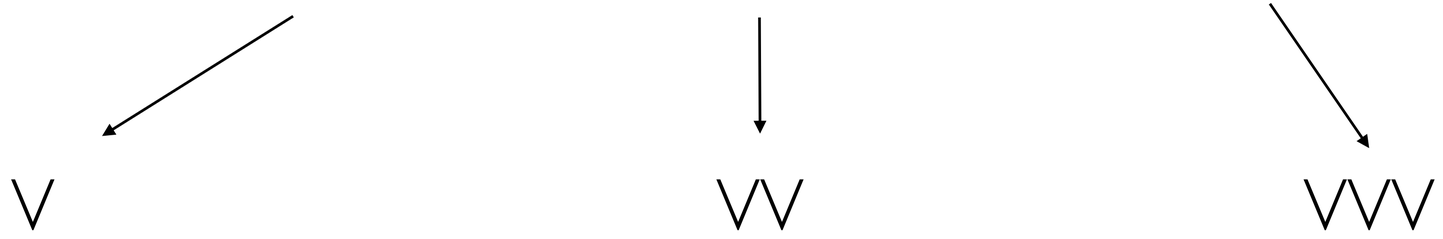
University of Sussex

Science & Technology Facilities Council | UK Research and Innovation

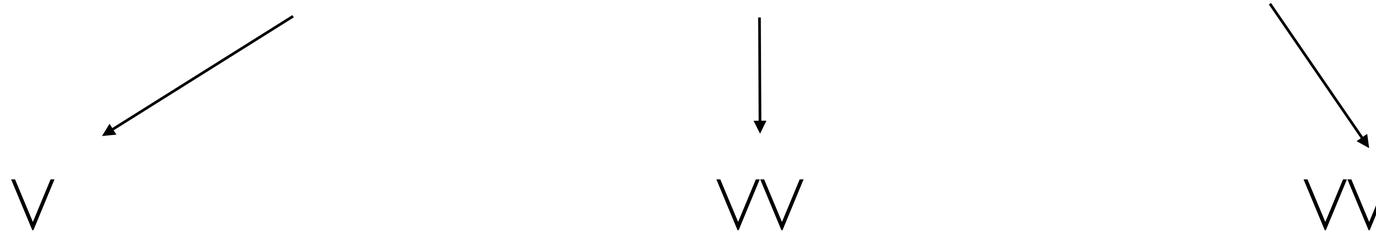
SM@LHC 2021
29. April 2021

Status of theory predictions for single bosons, diboson, and multiboson

Status of theory predictions for single bosons, diboson, and multiboson



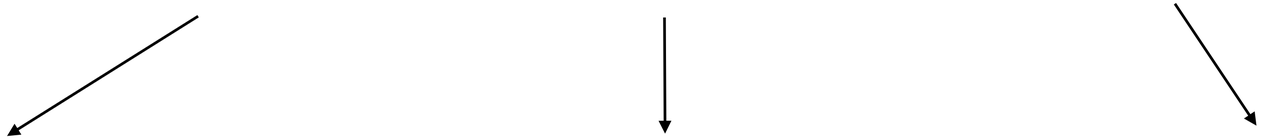
Status of theory predictions for single bosons, diboson, and multiboson



Perturbative expansion for hard scattering process:

$$\begin{aligned}\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{LO}} &+ \alpha_S\,\mathrm{d}\sigma_{\mathrm{NLO}} + \alpha_{\mathrm{EW}}\,\mathrm{d}\sigma_{\mathrm{NLO\,EW}} \\ &+ \alpha_S^2\,\mathrm{d}\sigma_{\mathrm{NNLO}} + \alpha_{\mathrm{EW}}^2\,\mathrm{d}\sigma_{\mathrm{NNLO\,EW}} + \alpha_S\alpha_{\mathrm{EW}}\,\mathrm{d}\sigma_{\mathrm{NNLO\,QCDxEW}} \\ &+ \alpha_S^3\mathrm{d}\sigma_{\mathrm{N3LO}} + \ldots\end{aligned}$$

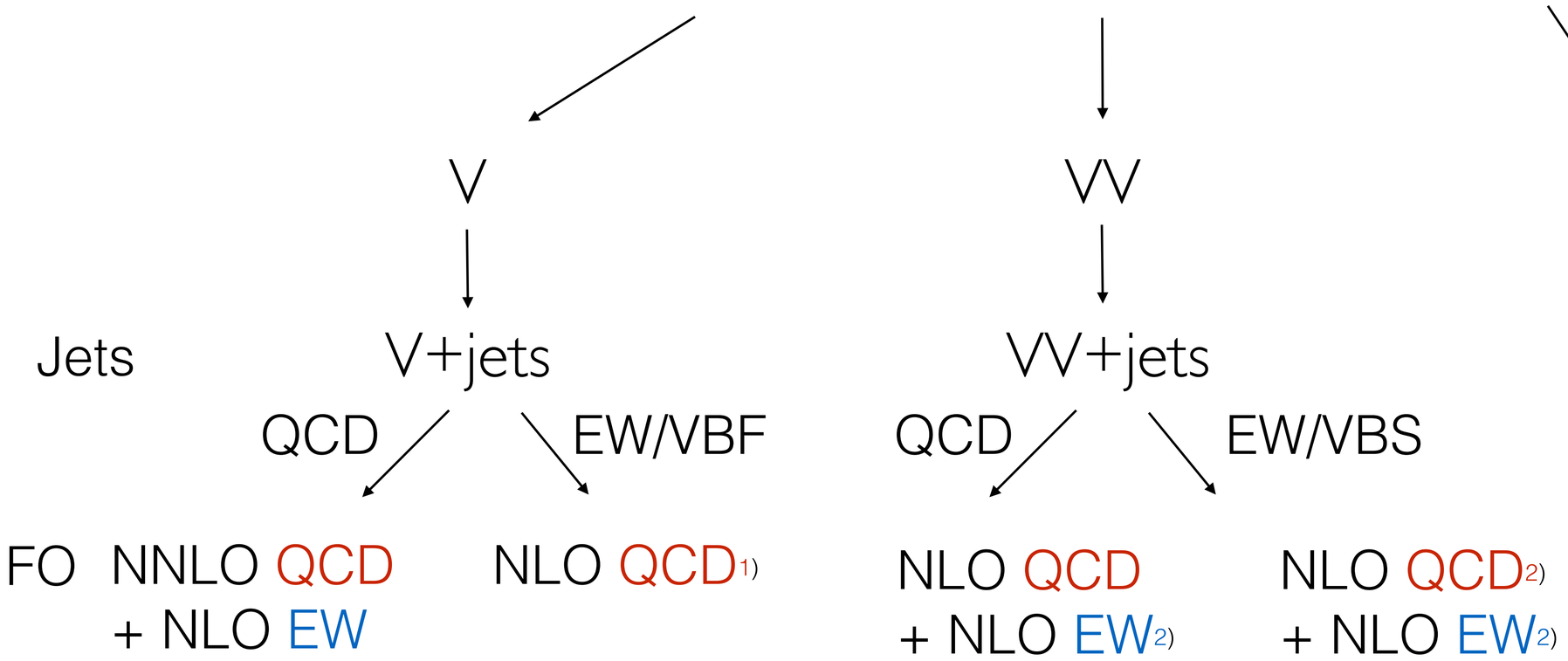
Status of theory predictions for single bosons, diboson, and multiboson



	V	VV	VVV
FO	N3LO QCD + NLO EW + NNLO QCD-EW[1)]	NNLO QCD + NLO EW	NLO QCD + NLO EW
AO	NNLO+N3LL’ NNLO QCD x PS NLO QCD+EW x PS	NNLO+N3LL NNLO QCD x PS[2)] NLO QCD+EW x PS	 NLO QCD x PS
Precision	~1%	~1-10%	~10%

1) approximate, 2) for some VV processes

Status of theory predictions for single bosons, diboson, and multiboson

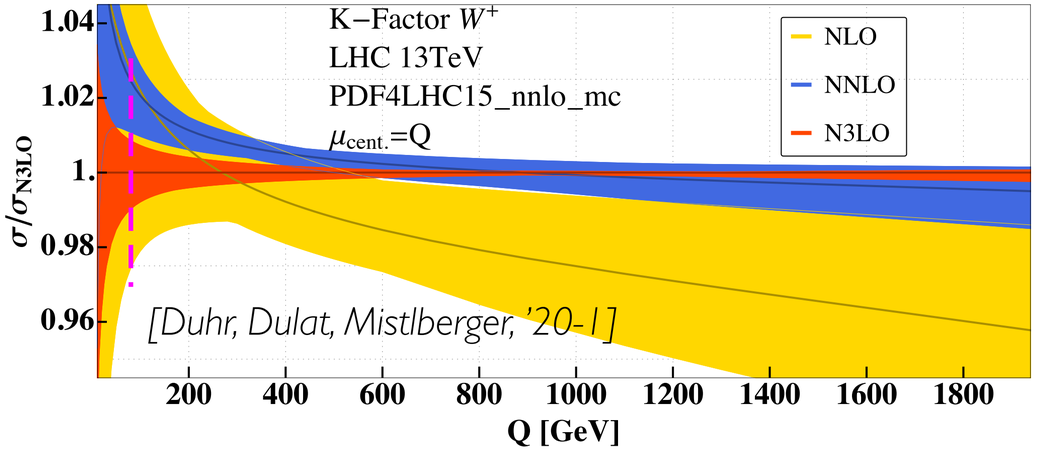


1) in VBF approx, 2) for some VV processes

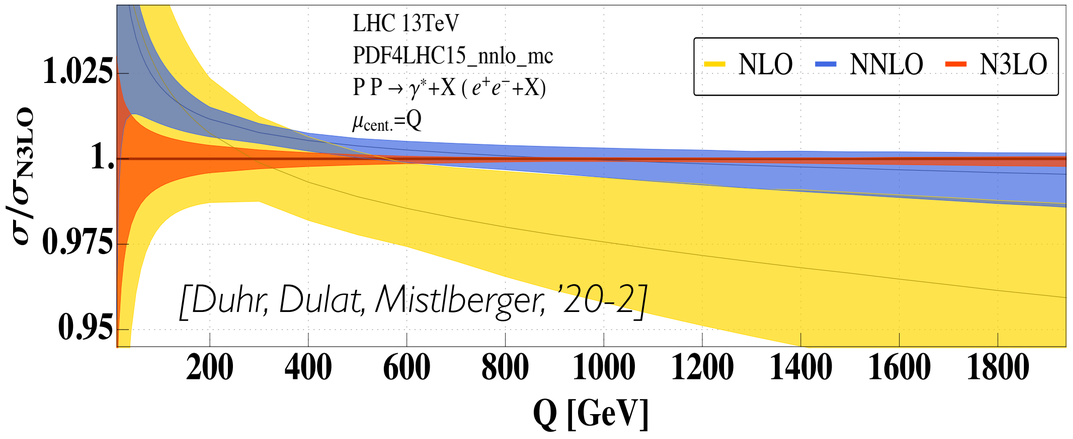
Some recent selected highlights:

Inclusive DY up to N3LO

[See talk by Caola]



W+



γ^*

➡ δN3LO~<1%

➡ Very similar behaviour in CC and NC DY

➡ At large Q scale variations bands are nicely overlapping, i.e. convincing convergence of perturbative series.

➡ However, for Q < 400 GeV NNLO and N3LO do not overlap! (Here: δN3LO~1-2%)

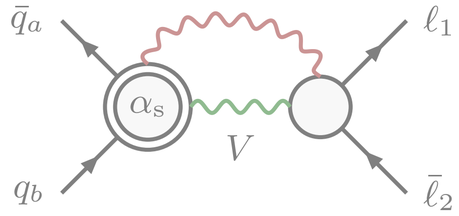
➡ Origin: quite large cancellation of quark and gluon initial state.

➡ Might be compensated by currently missing N3LO PDFs

Note: very precise measurements of high-mass DY can be used to constrain BSM, see Farina et. al. '16 (1609.08157)

Mixed QCD-EW corrections to NC-DY production

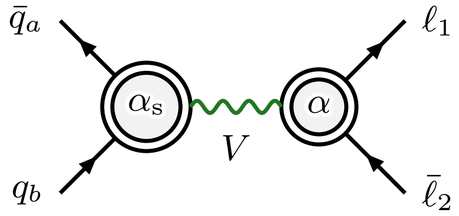
- Complete O(αs α) corrections still beyond current two-loop technology
- For precision in resonant region: expand around M^2



Non-factorizable

[Dittmaier, Huss, Schwinn, '14]

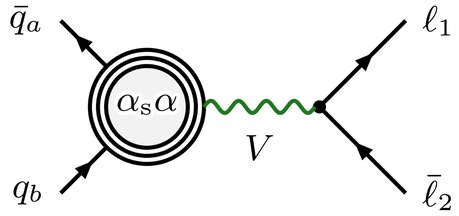
negligible



On-shell production x decay

[Dittmaier, Huss, Schwinn, '15]

expected to be dominant



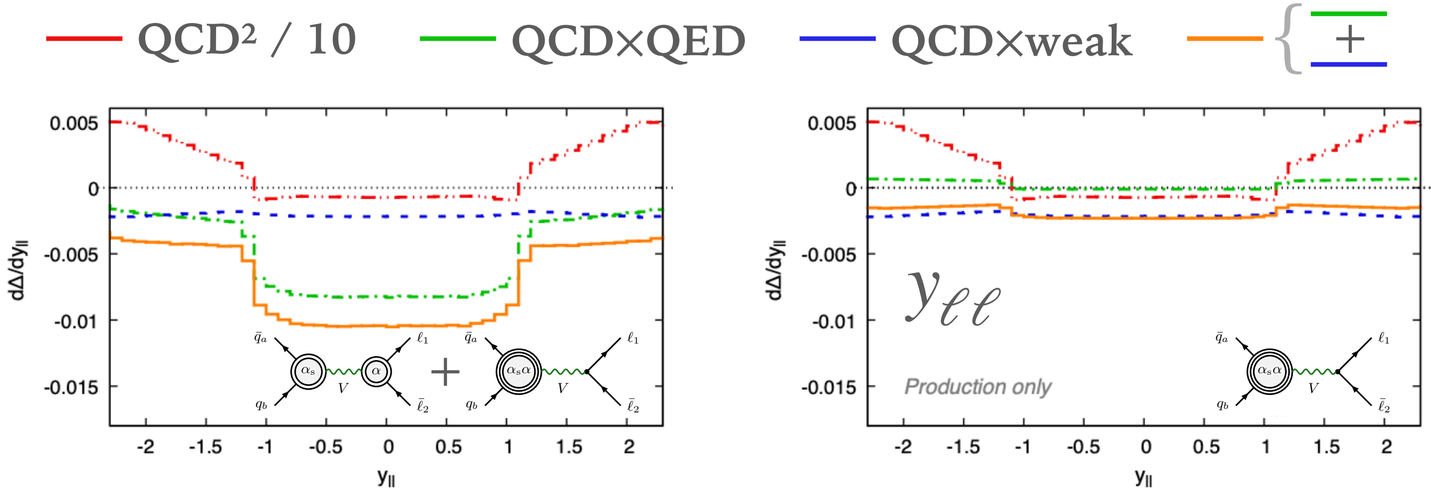
On-shell production

[Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch, '20]

last missing piece

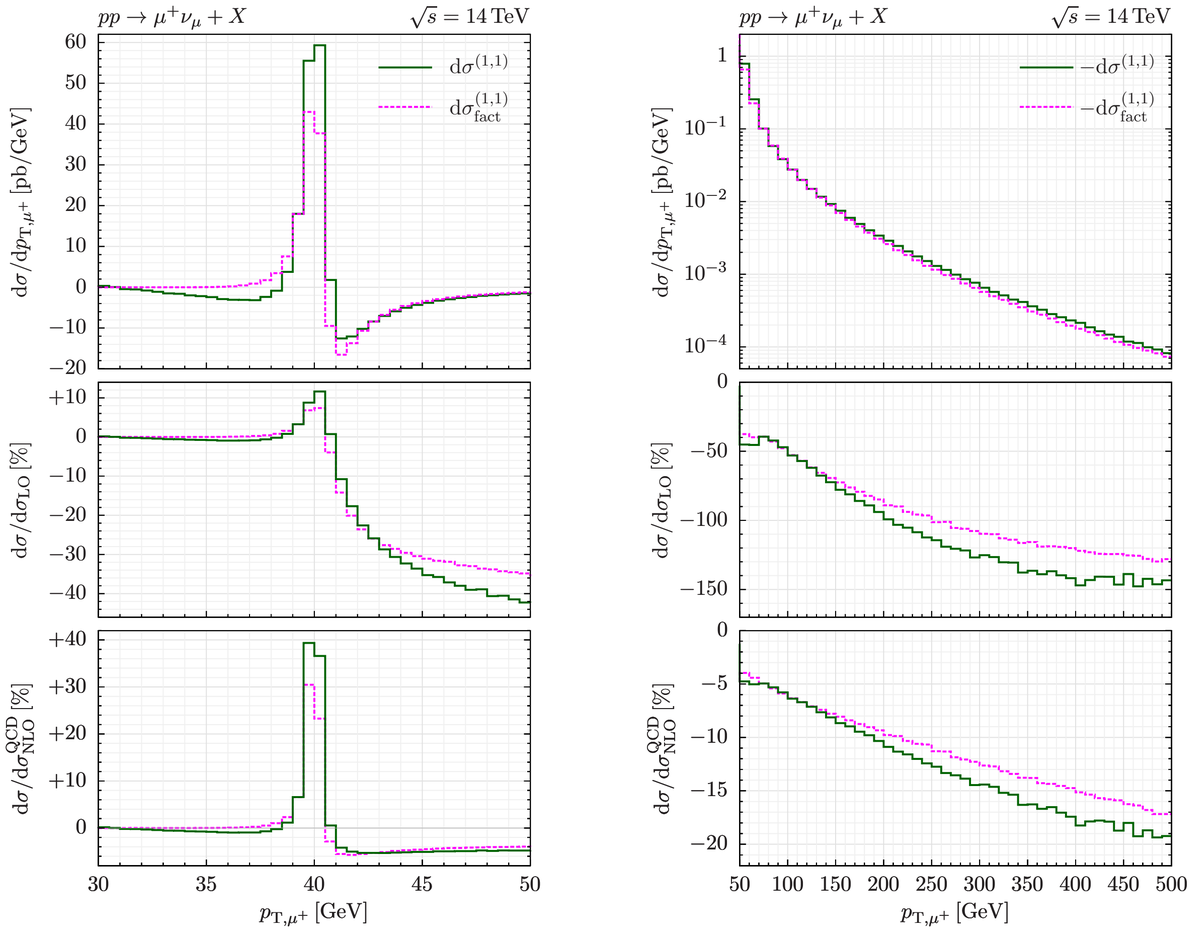
For production only

- QCD×weak dominant over QCD×QED
- net effect: few per-mille



Mixed QCD-EW corrections to CC-DY production

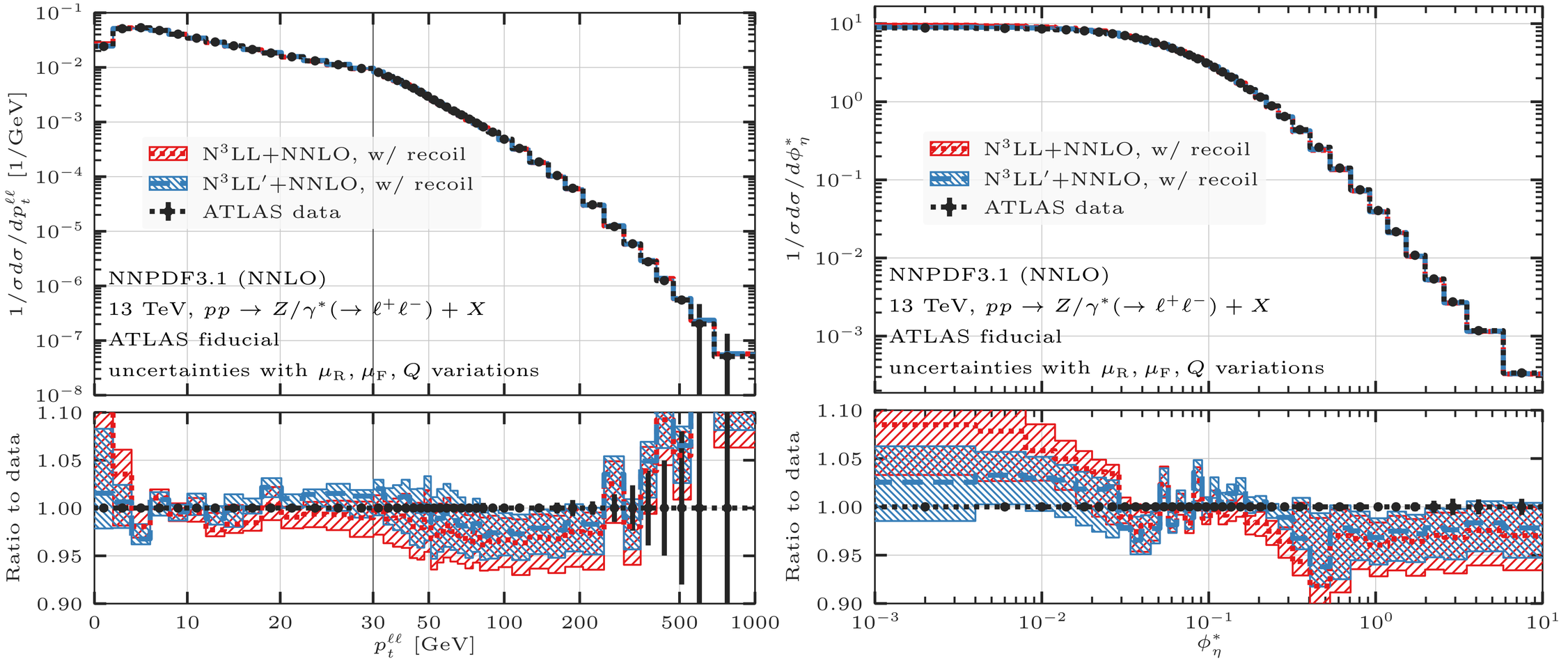
[Buonocore, Grazzini, Kallweit, Savoini, Tramontano, '21]



- Apart from 2-loop virtuals (included in pole approx) everything is exact at $O(\alpha_S\alpha)$
- Comparison against factorised (NLO QCD x NLO EW) ansatz
- Question: comparison against factorizable corrections.

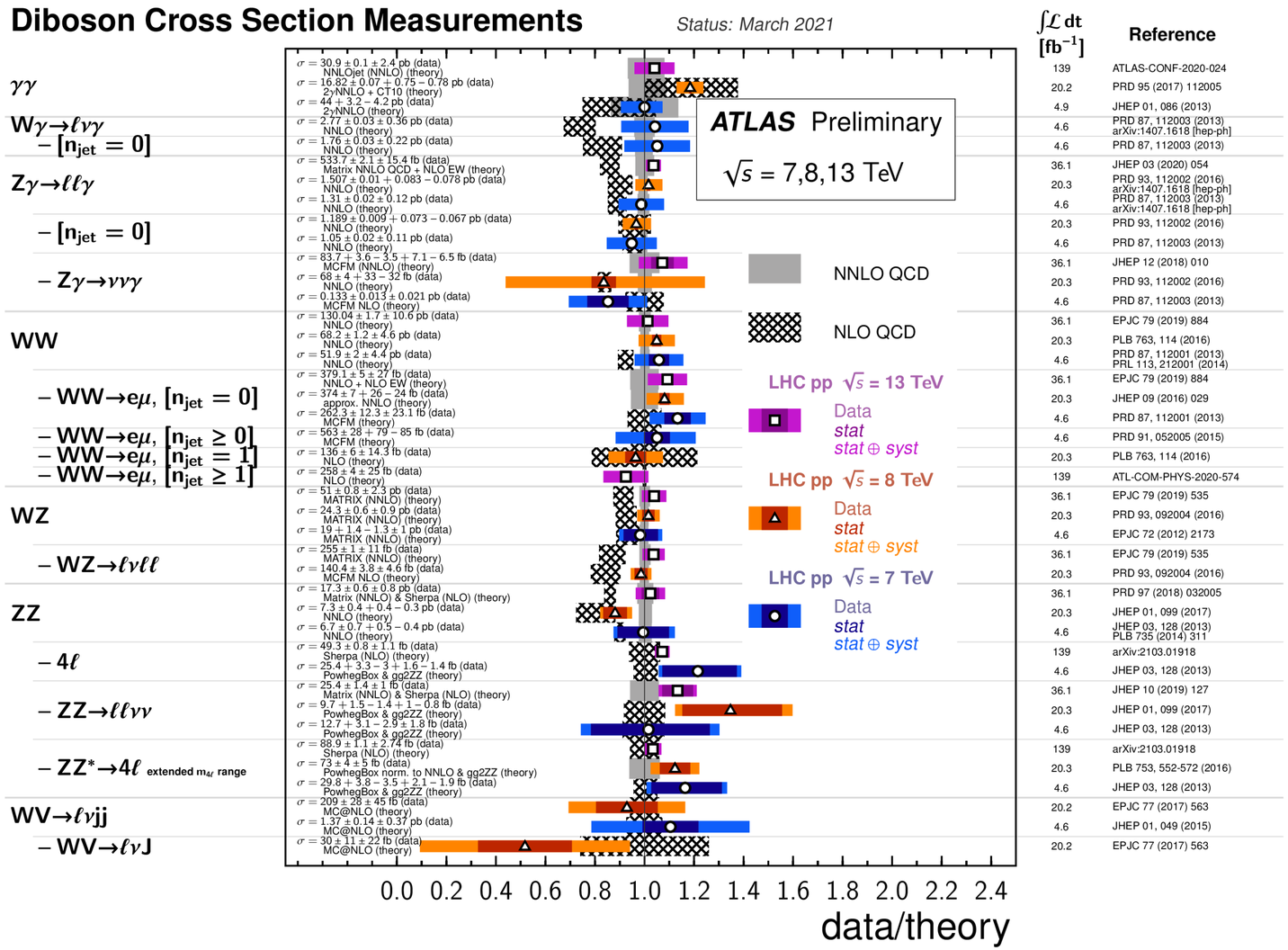
DY at finite pT at NNLO+N3LL'

[E. Re, L. Rottoli, P.Torrielli; 2104.07509]



- O(5%) shift due to ““ (finite α_S^3 contributions)
- remarkable theory with data agreement at the few% level

VV Exp vs. Theory Status



∫L dt [fb⁻¹]	Reference
139	ATLAS-CONF-2020-024
20.2	PRD 95 (2017) 112005
4.9	JHEP 01, 086 (2013)
4.6	PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
4.6	PRD 87, 112003 (2013)
36.1	JHEP 03 (2020) 054
20.3	PRD 93, 112002 (2016) arXiv:1407.1618 [hep-ph]
4.6	PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
20.3	PRD 93, 112002 (2016)
4.6	PRD 87, 112003 (2013)
36.1	JHEP 12 (2018) 010
20.3	PRD 93, 112002 (2016)
4.6	PRD 87, 112003 (2013)
36.1	EPJC 79 (2019) 884
20.3	PLB 763, 114 (2016)
4.6	PRD 87, 112001 (2013) PRL 113, 212001 (2014)
36.1	EPJC 79 (2019) 884
20.3	JHEP 09 (2016) 029
4.6	PRD 87, 112001 (2013)
4.6	PRD 91, 052005 (2015)
20.3	PLB 763, 114 (2016)
139	ATL-COM-PHYS-2020-574
36.1	EPJC 79 (2019) 535
20.3	PRD 93, 092004 (2016)
4.6	EPJC 72 (2012) 2173
36.1	EPJC 79 (2019) 535
20.3	PRD 93, 092004 (2016)
36.1	PRD 97 (2018) 032005
20.3	JHEP 01, 099 (2017)
4.6	JHEP 03, 128 (2013) PLB 735 (2014) 311
139	arXiv:2103.01918
4.6	JHEP 03, 128 (2013)
36.1	JHEP 10 (2019) 127
20.3	JHEP 01, 099 (2017)
4.6	JHEP 03, 128 (2013)
139	arXiv:2103.01918
20.3	PLB 753, 552-572 (2016)
4.6	JHEP 03, 128 (2013)
20.2	EPJC 77 (2017) 563
4.6	JHEP 01, 049 (2015)
20.2	EPJC 77 (2017) 563

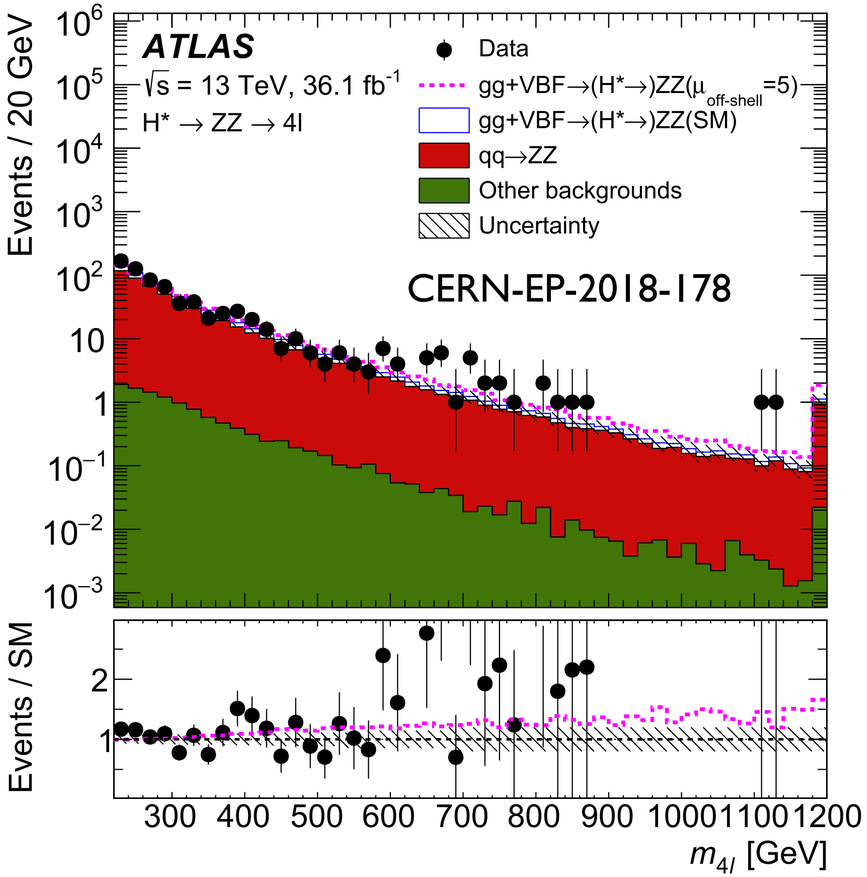
Remarkable agreement of inclusive diboson cross sections with **NNLO QCD**

Allows for stringent SM tests

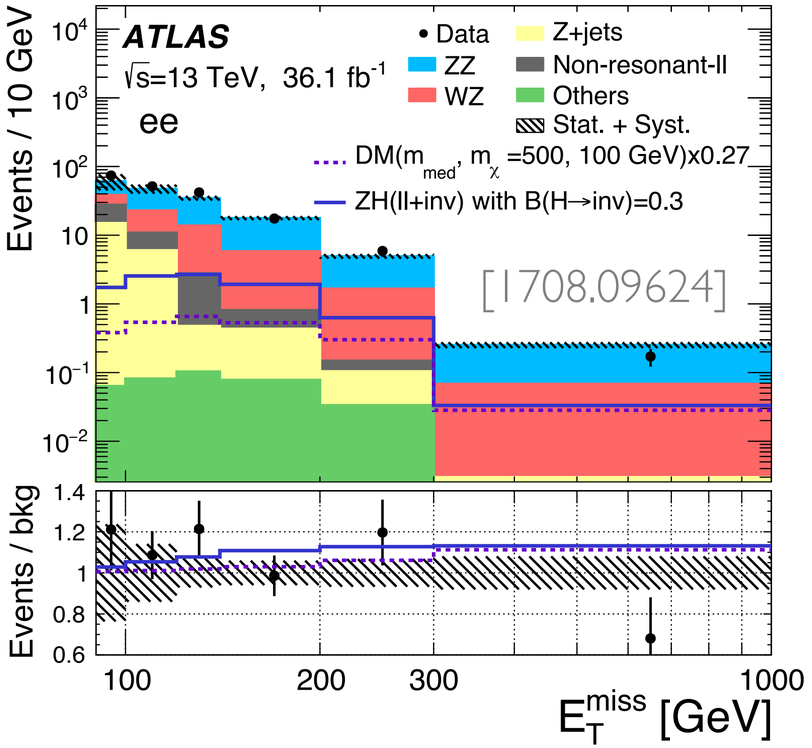
Dibosons important background for Higgs and BSM searches

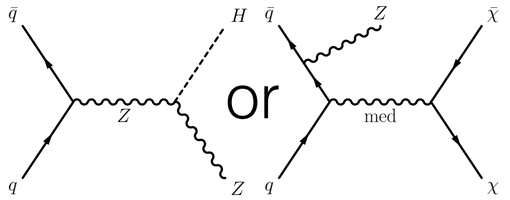
Tails, tails, tails,…. !!!

Off-shell Higgs



Direct searches



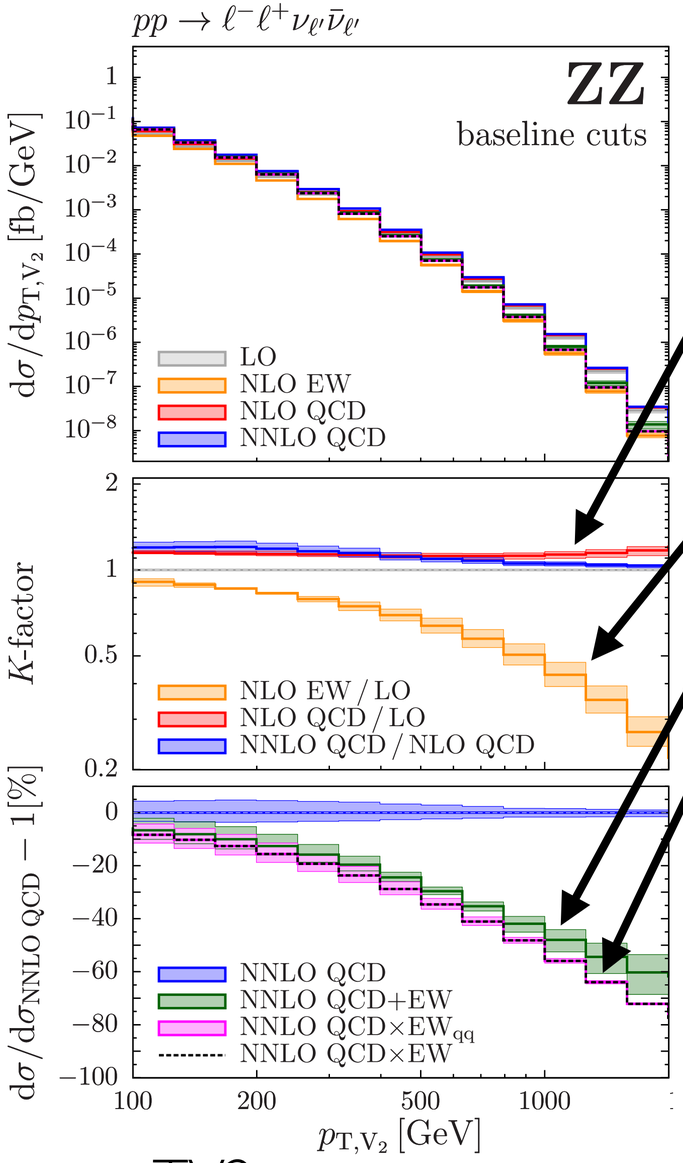


vs. ZZ(vv)

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

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

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

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

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

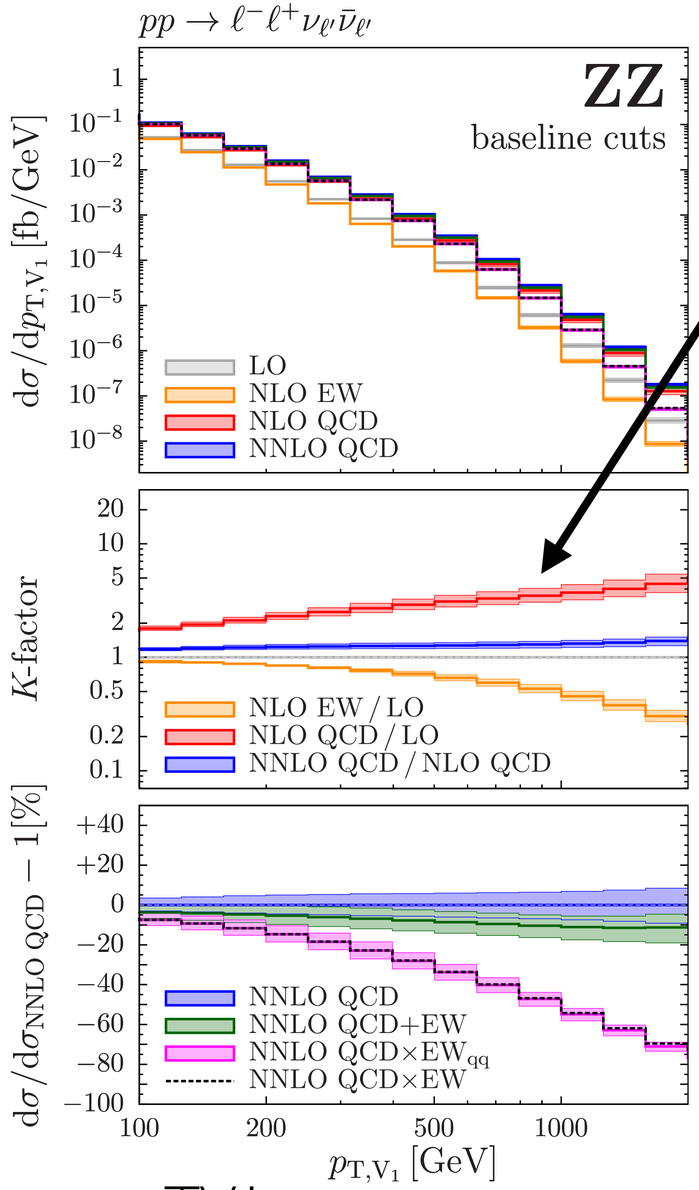
$$= \mathrm{d}\sigma_{\mathrm{NNLO\,QCD+EW}} + \mathrm{d}\sigma_{\mathrm{LO}}\delta_{\mathrm{QCD}}\,\delta_{\mathrm{EW}}$$

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

Giant QCD K-factors and EW corrections: pTV1

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

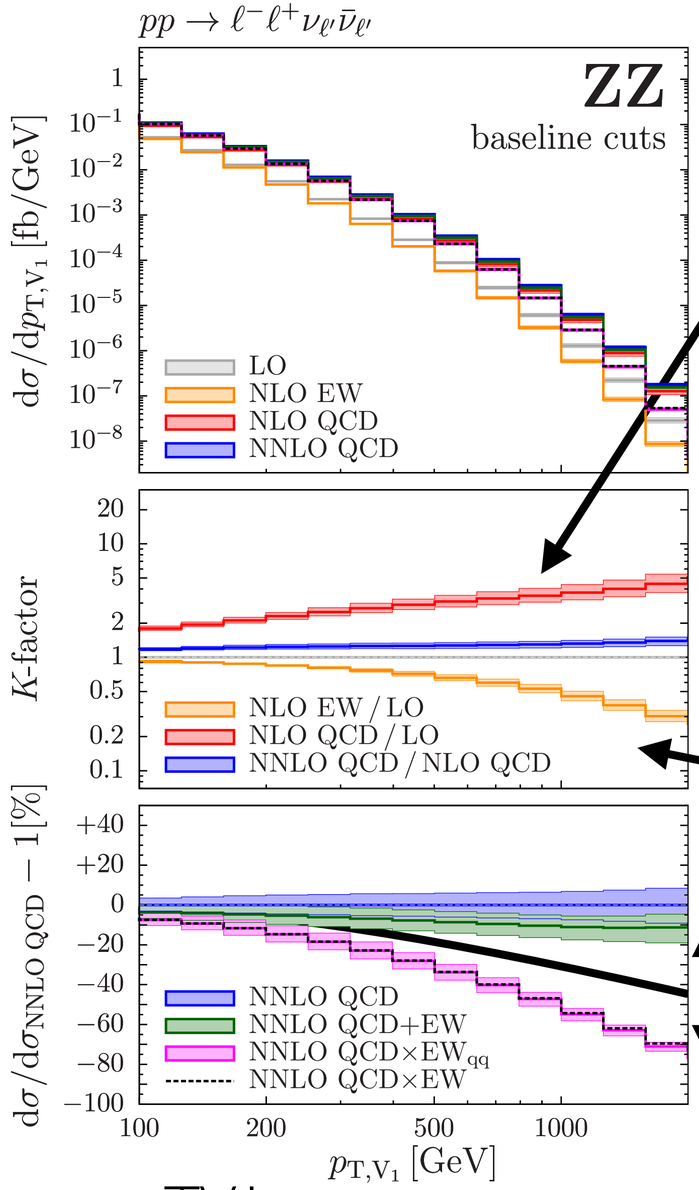


pTV1

- NLO QCD/LO=2-5! (“giant K-factor”)

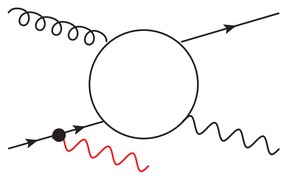
Giant QCD K-factors and EW corrections: pTV1

[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)

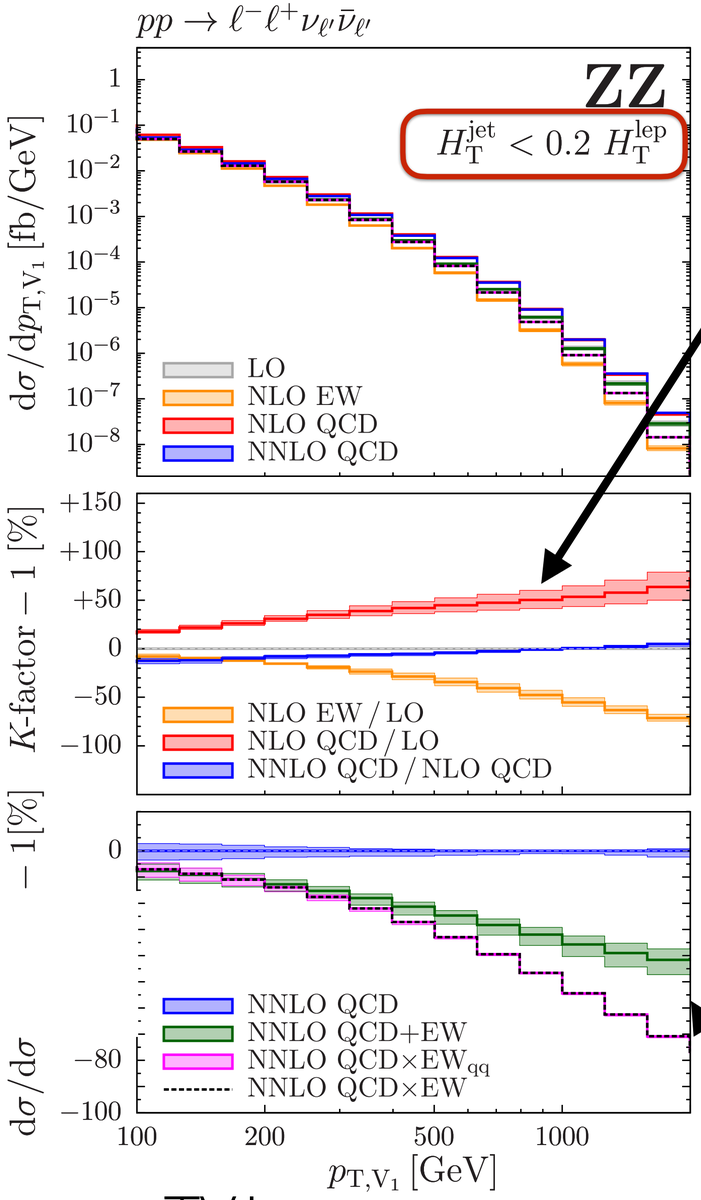


$$\frac{d\sigma^{V(V)j}}{d\sigma^{\mathrm{LO}}_{VV}} \propto \alpha_{\mathrm{S}} \log^2\left(\frac{Q^2}{M_W^2}\right) \simeq 3 \qquad \text{at} \quad Q = 1\,\mathrm{TeV}$$

- 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**
- Rigorous solution: **merge VVj incl. EW corrections with VV** retaining NNLO QCD + EW

Giant QCD K-factors and EW corrections: pTV1

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



pTV1

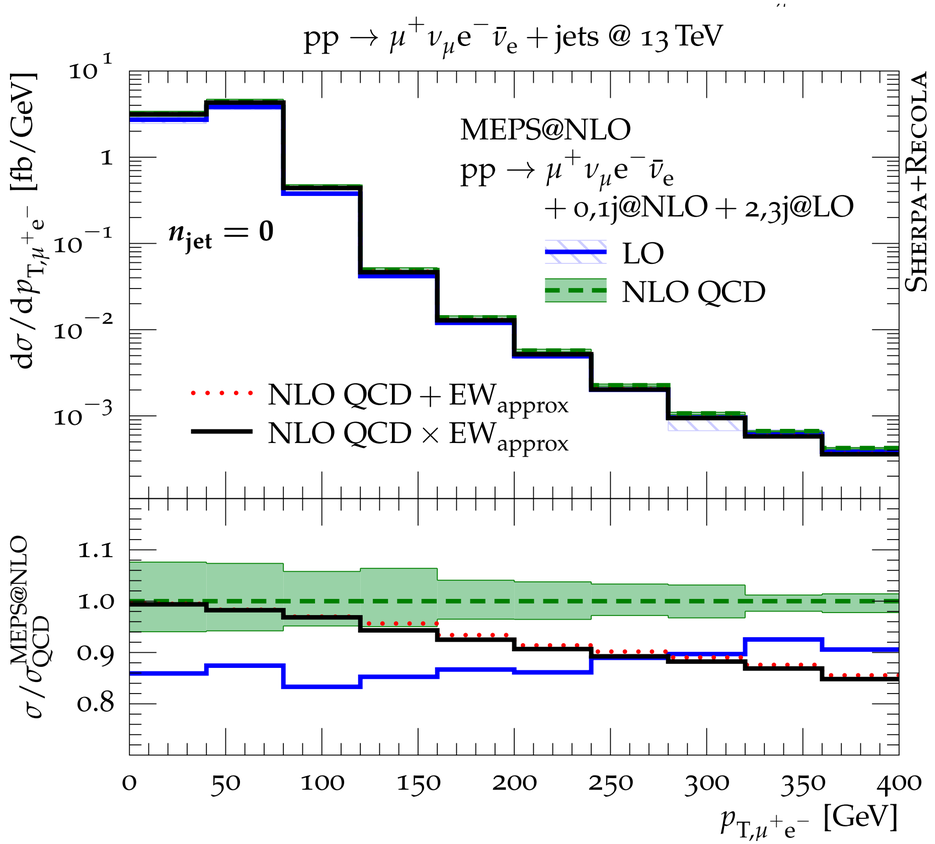
- NLO QCD/LO=~<1.5 (“normal K-factor”)
- very small NNLO / NLO QCD corrections and ~5% NNLO uncert

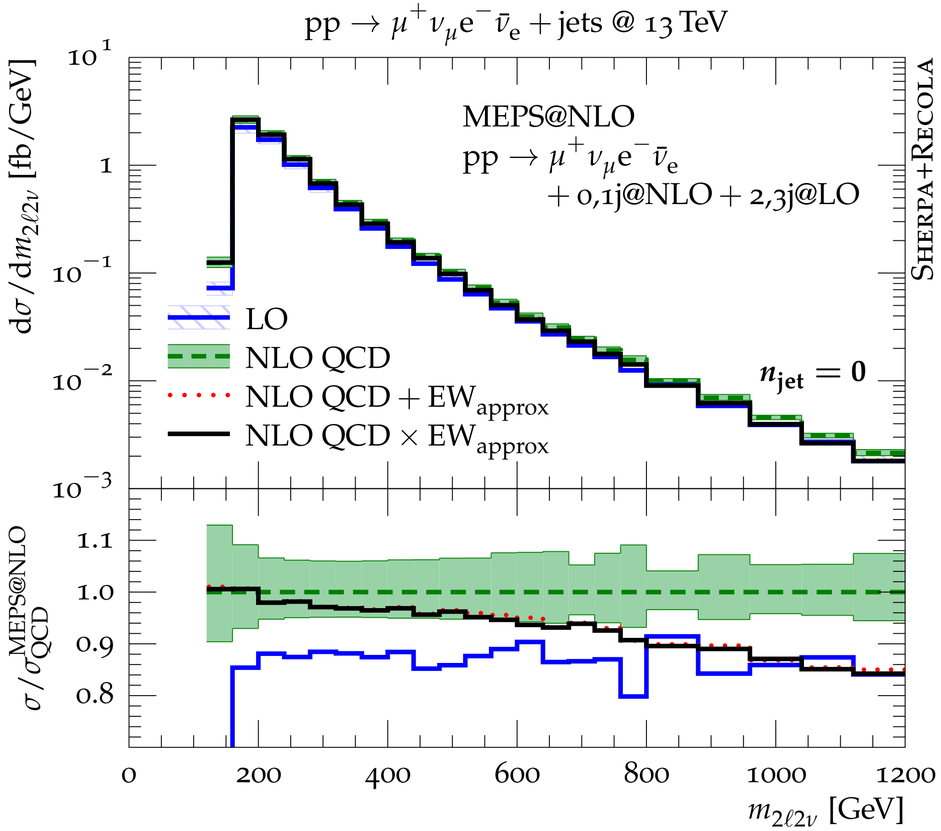
- Problems:
  1. In additive combination dominant Vj topology does not receive any EW corrections
  2. In multiplicative combination EW correction for VV is applied to Vj hard process
- Pragmatic solution I: **take average as nominal and spread as uncertainty**
- **Pragmatic solution II: apply jet veto to constrain Vj toplogoies**
- Rigorous solution: **merge VVj incl. EW corrections with VV** retaining NNLO QCD + EW

MEPS @ NLO QCD + EW

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

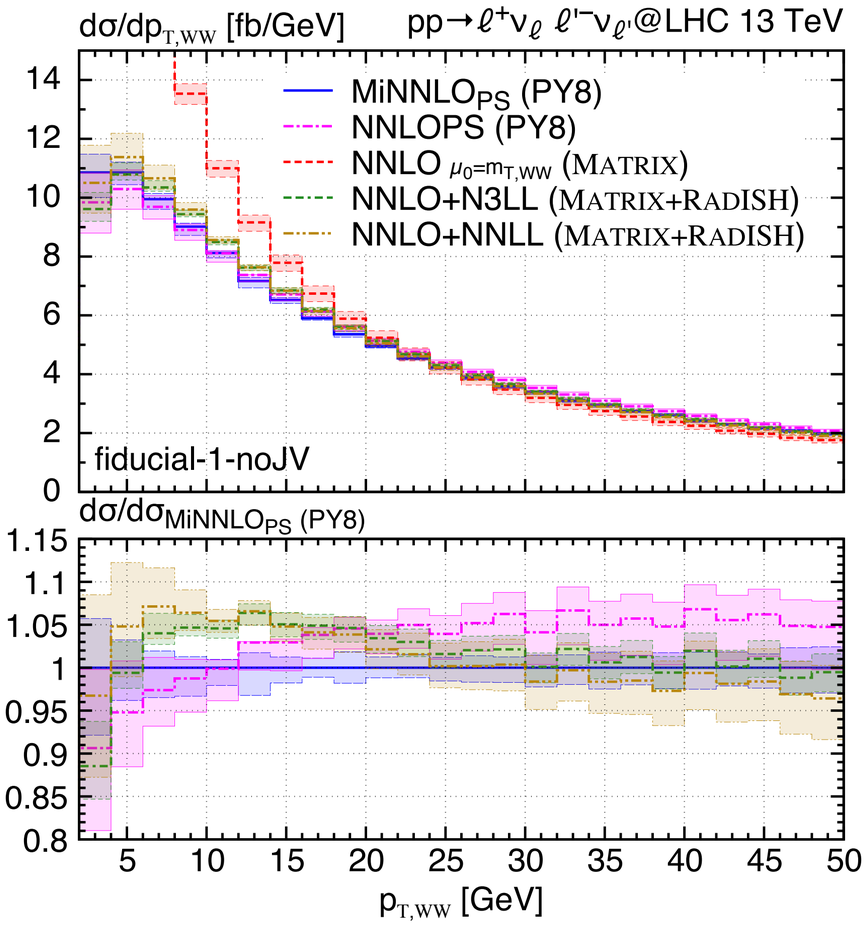
- "Rigorous approximate solution": merge VVj incl. approx. EW corrections with VV with Sherpa's MEPS@NLO

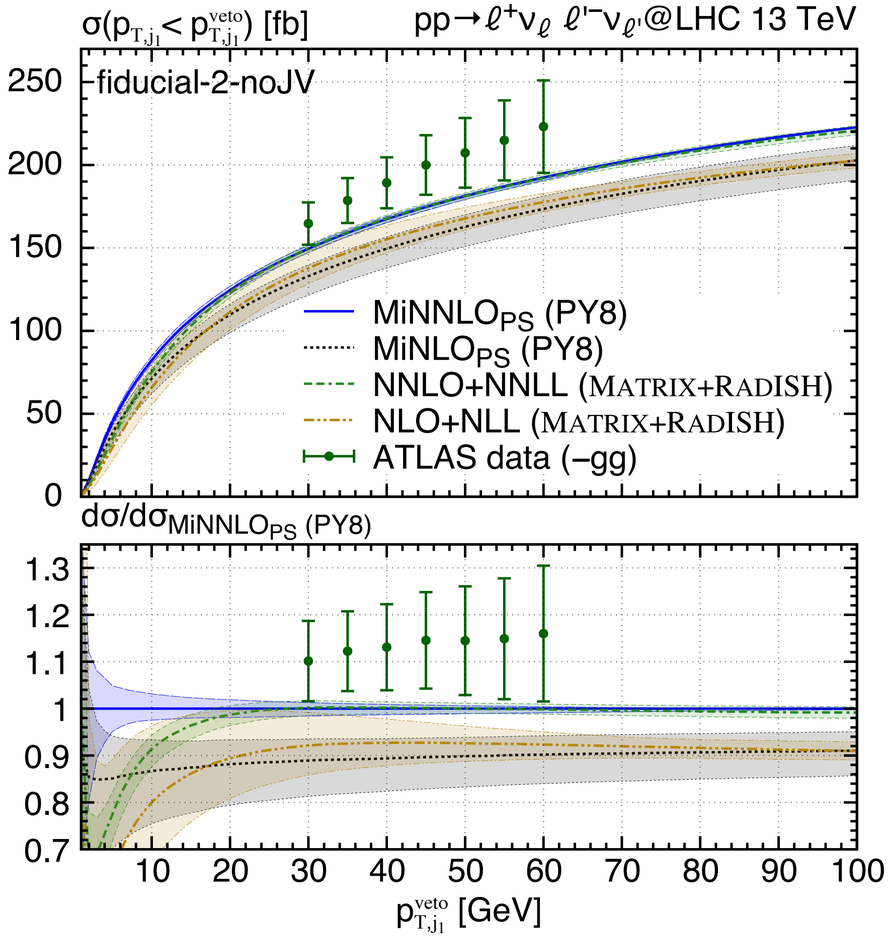




PS MC: NNLO QCD + PS for VV via MiNNLO$_{PS}$

[Lombardi, Wiesemann; Zanderighi '21]

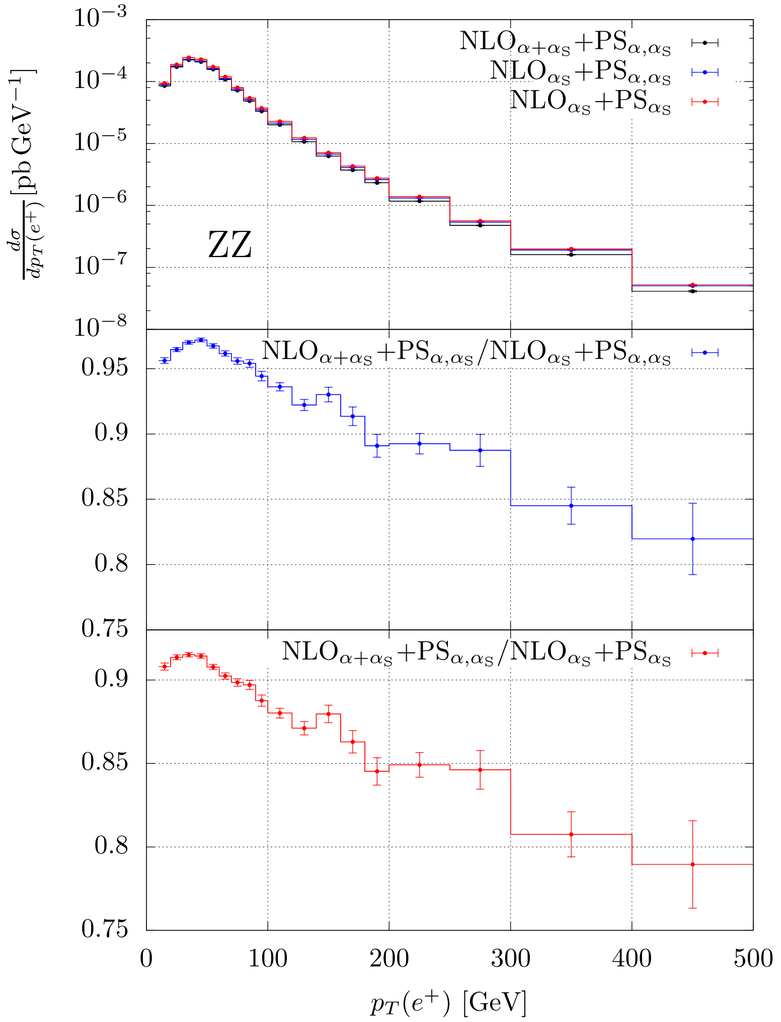


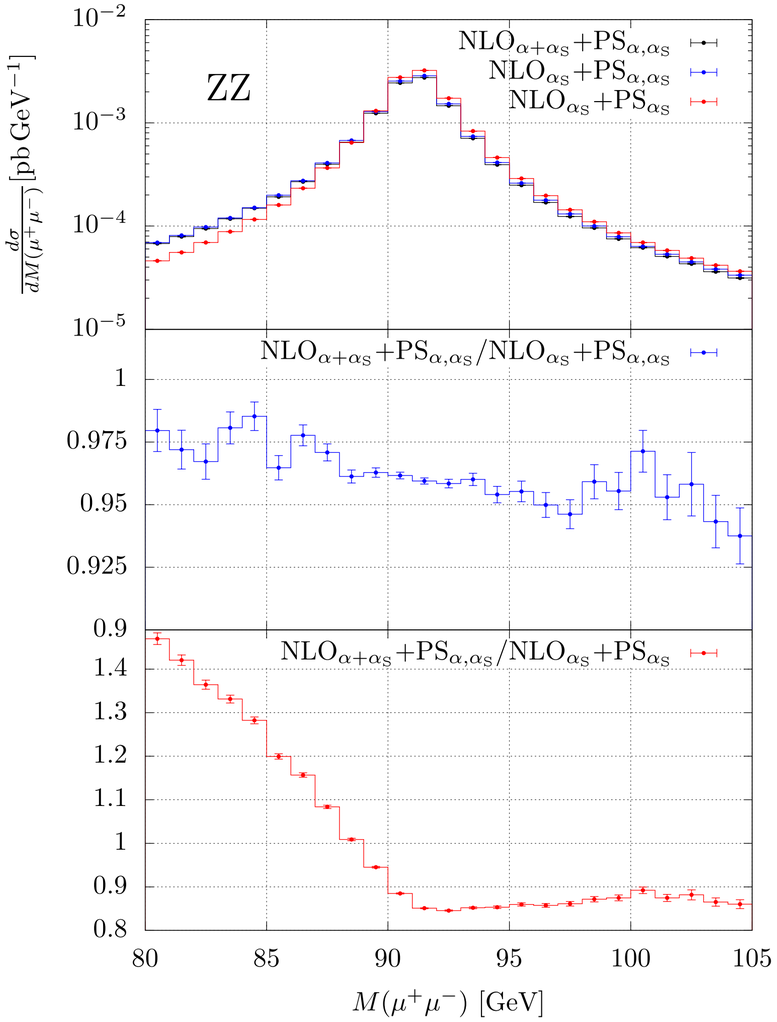


- MiNNLO$_{PS}$ physical down to pTVV=0
- Latest implementation does not require computationally expensive reweighting required earlier
- Also available for Zγ: - 2010.10478 *[Lombardi, Wiesemann; Zanderighi '20]*
- Alternative NNLOPS approach available for ZZ in GENEVA *[Alioli, Broggio, Gavardi, Kallweit,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

PS MC: NLO QCD + EW PS

[Chiesa, Re, Oleari '20]





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

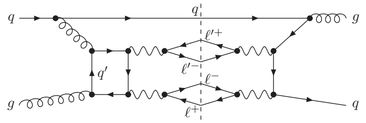
NLO (QCD + EW) PS (QCD + QED)/
NLO QCD PS (QCD + QED)

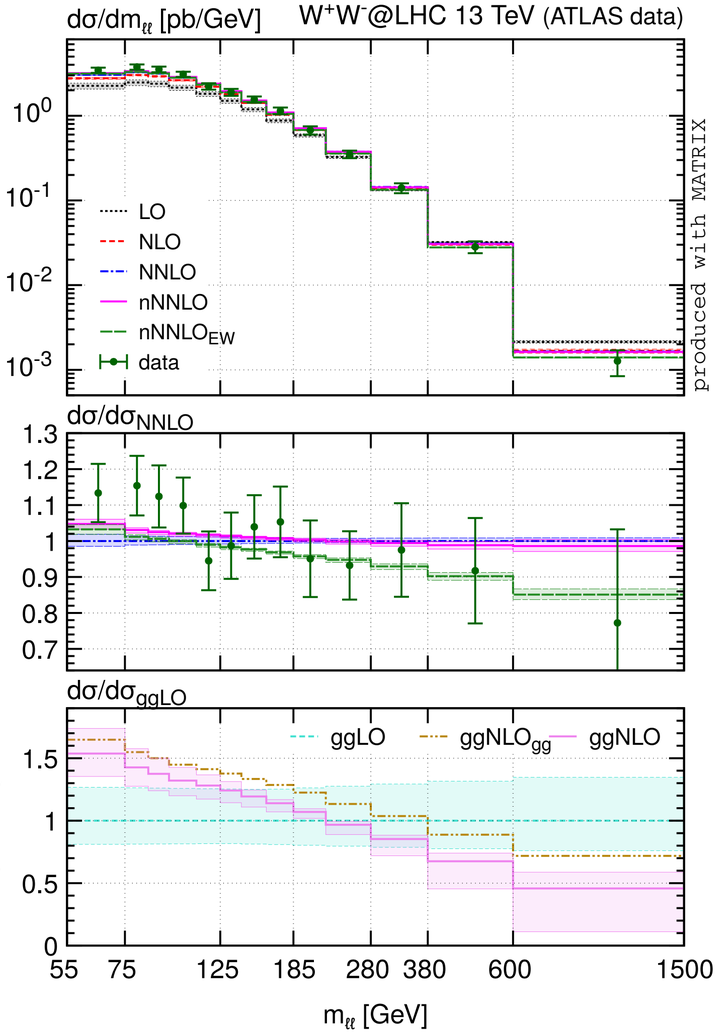
NLO (QCD + EW) PS (QCD + QED)/
NLO QCD PS QCD

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

NLO QCDgg

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

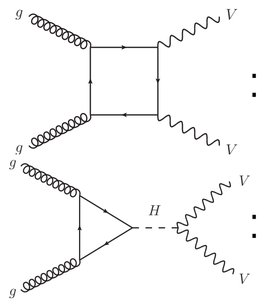




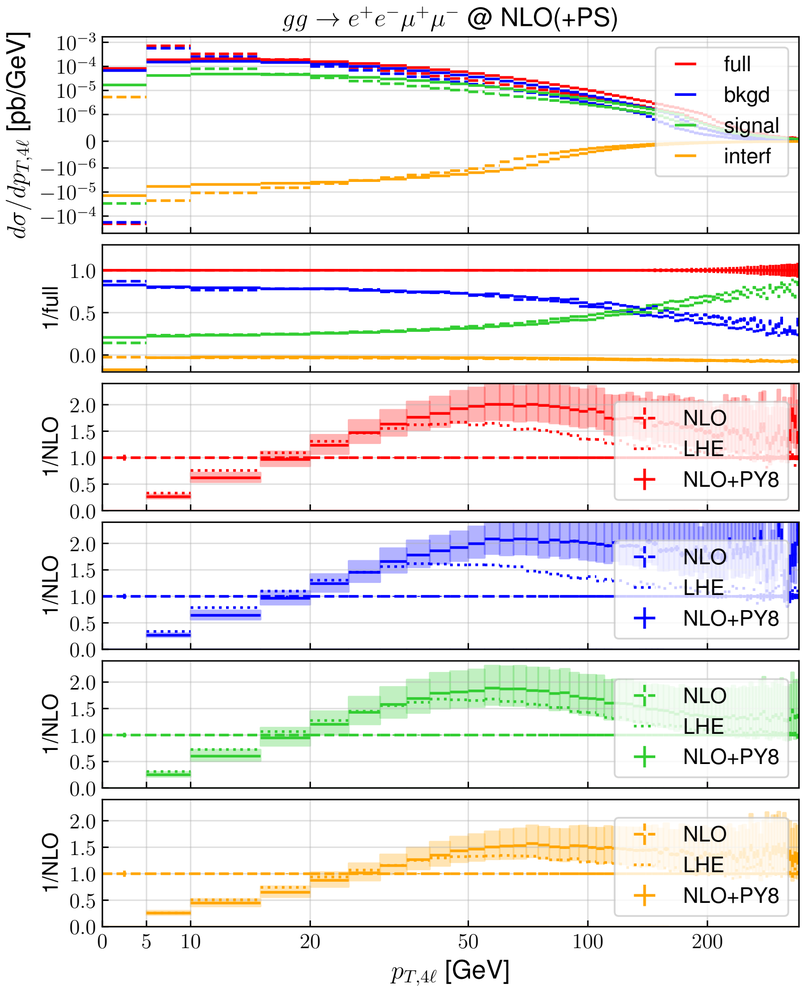
- Very good data agreement with NNLO QCD + NLO QCDgg + NLO EW

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

sum:



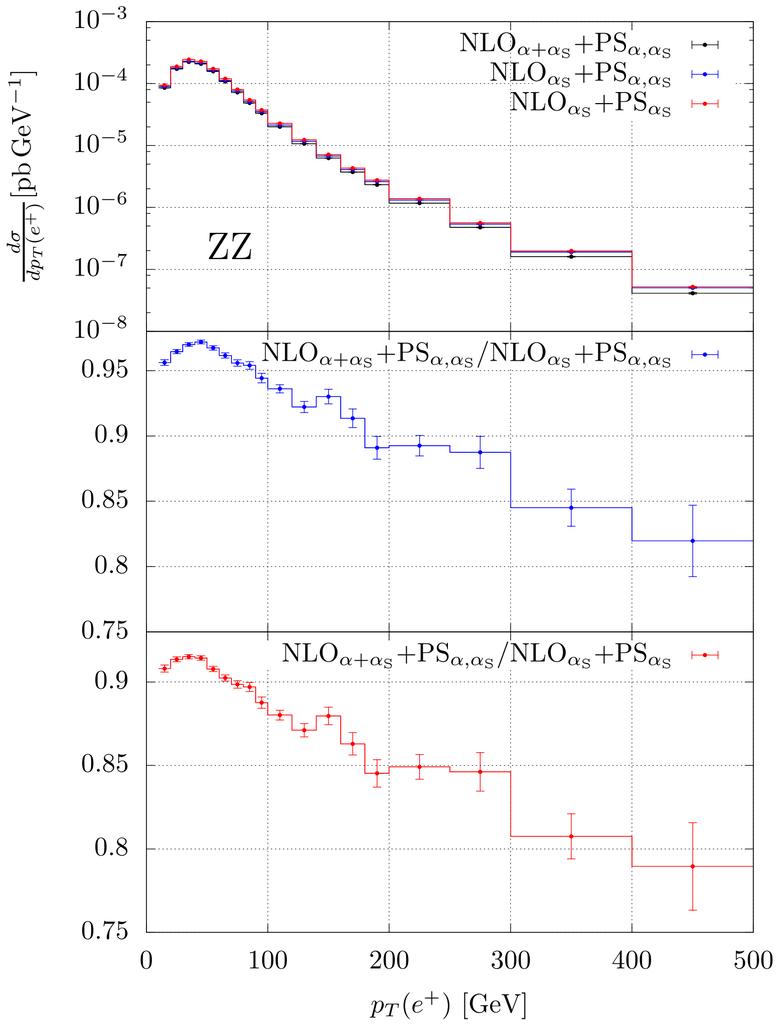
interf:

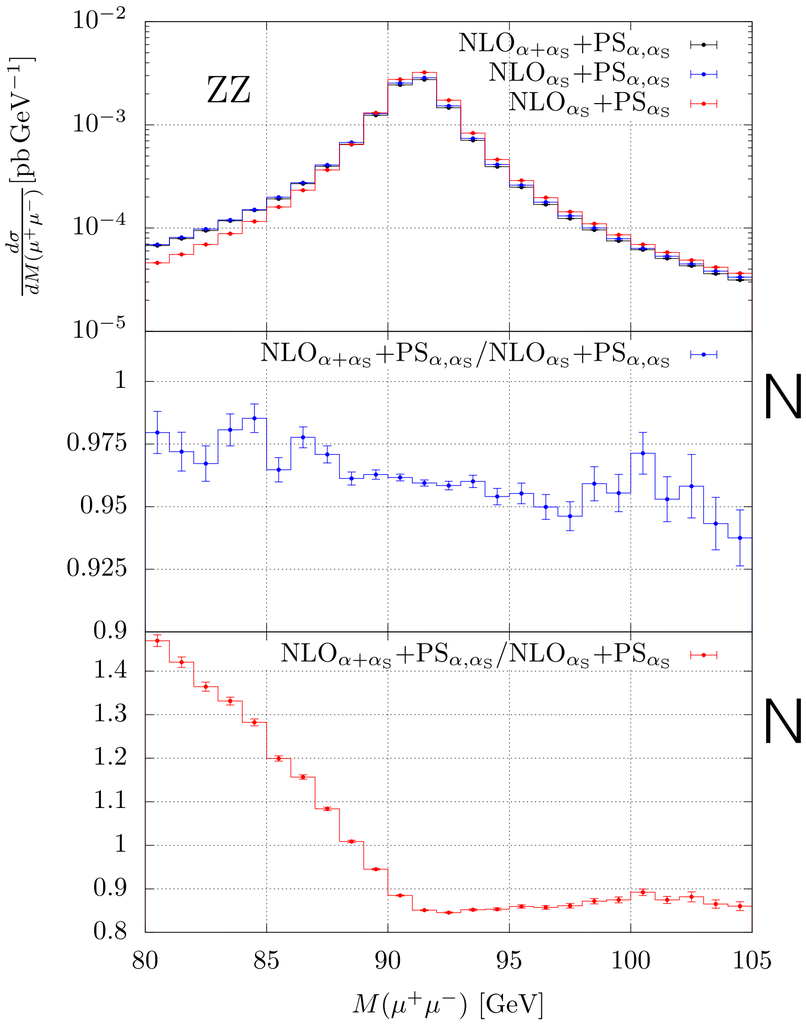


- ggWW/ggZZ @ NLO QCD + PS available! (VV-cont., H→VV & interference)

Parton shower Monte Carlos: NLO QCD + EW PS

[Chiesa, Re, Oleari '20]





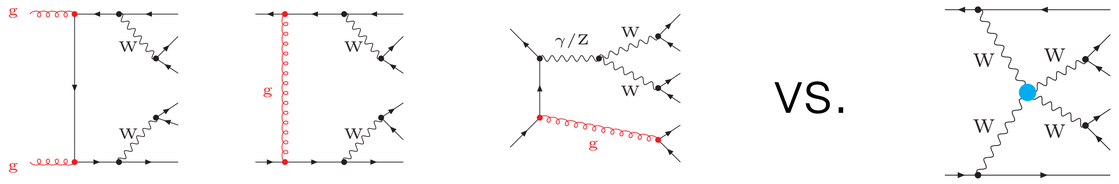
NLO (QCD + EW) PS (QCD + QED)/
NLO QCD PS (QCD + QED)"

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

- Missing: photon-induced channels
- To be investigates: NLO (QCD + EW) PS (QCD + QED) / (NLO QCD PS QCD) x NLO EW

VV+2jets production

Note: severe QCD background to VBS signatures + interference:



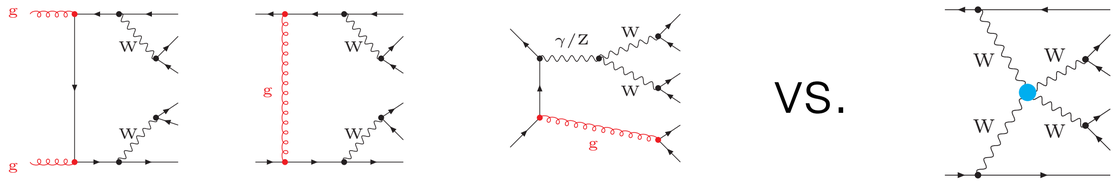
$$\mathrm{d}\sigma = \mathrm{d}\sigma(\alpha_S^2\alpha^4) + \mathrm{d}\sigma(\alpha_S\alpha^5) + \mathrm{d}\sigma(\alpha^6) + \ldots$$

LO

QCD-background interference VBS-signal

VV+2jets production

Note: severe QCD background to VBS signatures + interference:



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

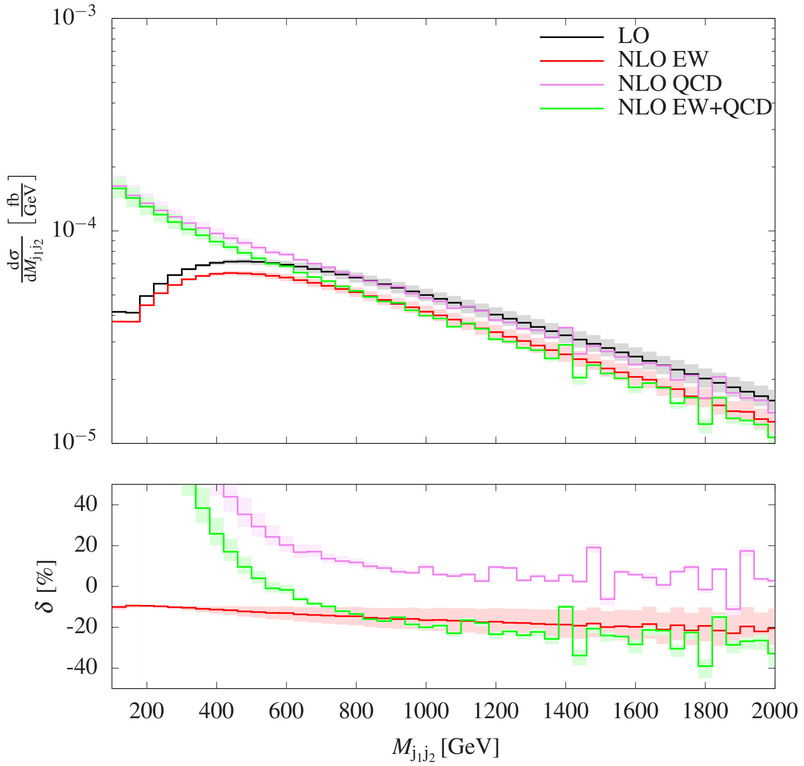
➡ separation formally meaningless at NLO

➡ strictly well defined measurements: fiducial cross sections

EW ZZ+2jets @ NLO QCD + EW

[A. Denner, R. Franken, M. Pellen, T. Schmidt; '20]

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]*



- 2 → 6 particles at NLO EW !

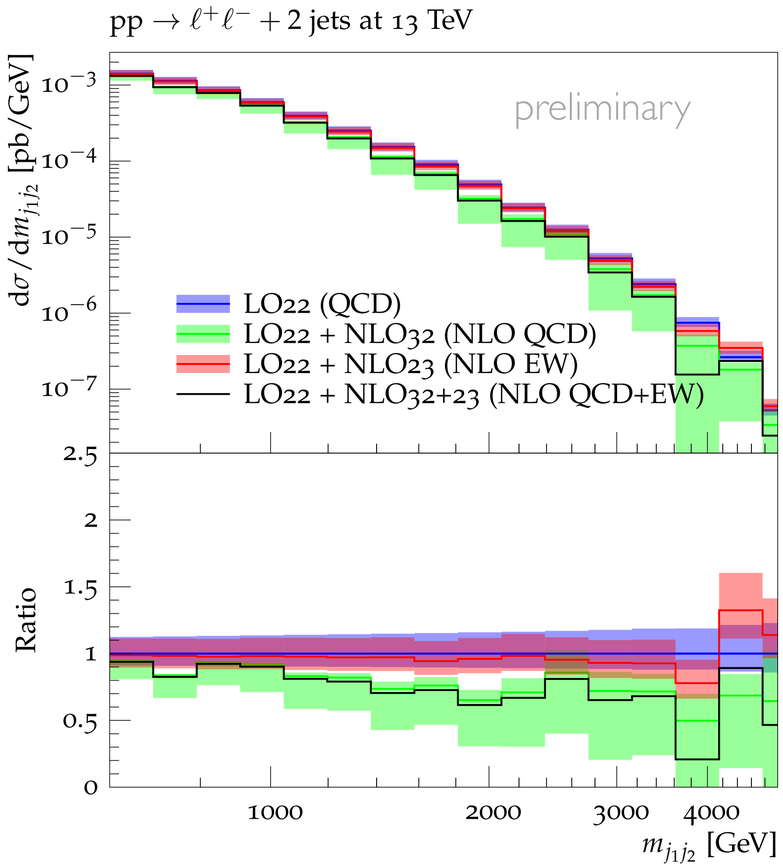
Order	$\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha^7)+\mathcal{O}(\alpha_s\alpha^6)$
$M_{j_1j_2} > 100\,\text{GeV}$			
σ_{NLO}[fb]	0.08211(4)	0.12078(11)	0.10521(11)
δ[%]	−15.9	23.6	7.7
$M_{j_1j_2} > 500\,\text{GeV}$			
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 and EW V+2jets @ NLO QCD + EW

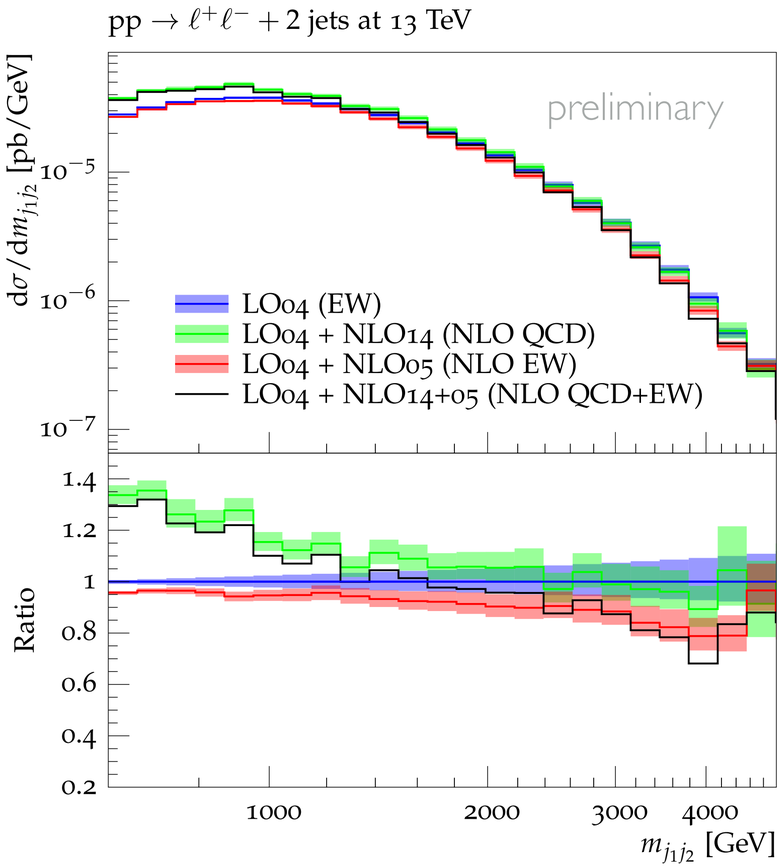
[JML, S. Pozzorini, M. Schönherr,; to appear soon]

QCD-mode



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

EW-mode

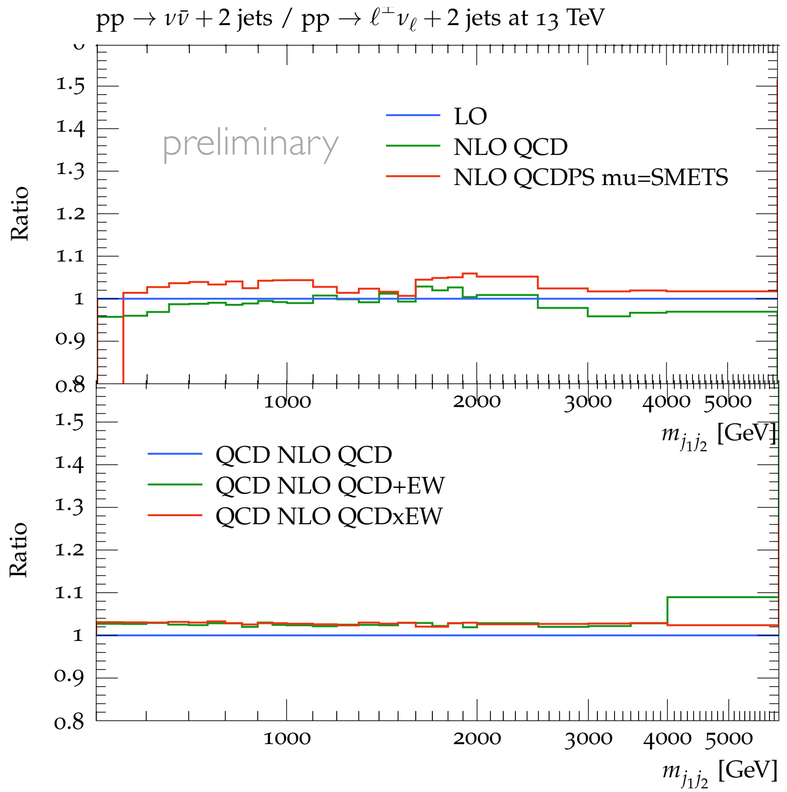


- QCD: very small K-factor at large mjj, uncertainty ~10%
- EW: up to -20% in multi TeV

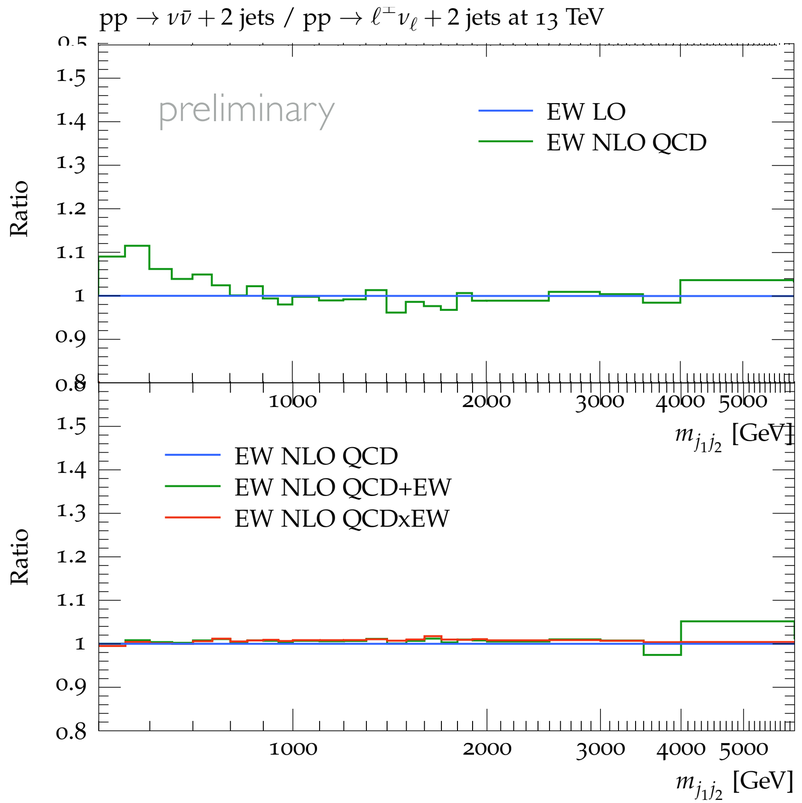
V+2jets ratios @ NLO QCD + EW

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

QCD-mode



EW-mode



- ~few % correction on the ratio doe to QCD corrections
- ~1-2% corrections on the ratio due to EW corrections
- tiny QCD+EW vs. QCDxEW uncertainties on ratio
- comprehensive study of theoretical uncertainties on Zvv/Wen ratio (transfer factor) allow for significant improvements in H→invisible searches

Conclusions

- Many exciting new results for nV(+jets) processes pushing theory precision to the O(1-10%) level

V

- Milestone N3LO results
- DY precision at the 1% level!

VV

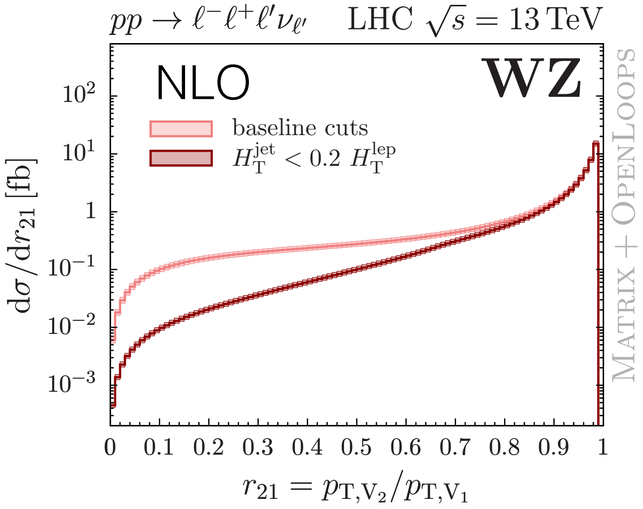
- NNLO QCD + NLO EW available in MATRIX+OpenLoops for all massive VV processes
- NLO (QCD + EW) + PS (QCD + QED) for VV available in POWHEG
- NNLO QCD PS via MiNNLO is becoming available for many VV processes
- NLO QCDgg PS is available

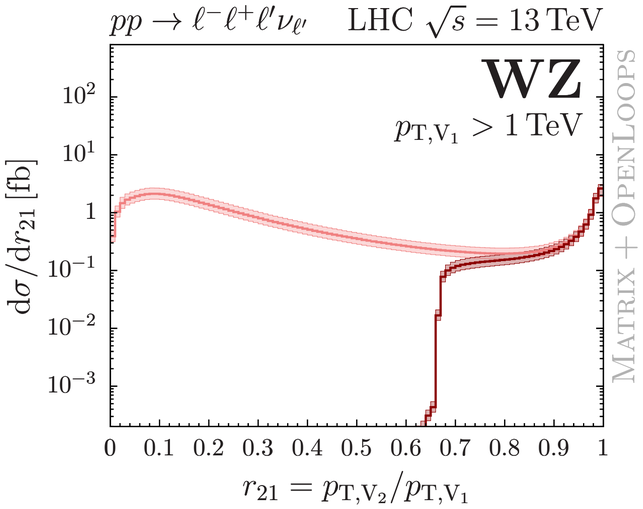
V+jets / VV+jets

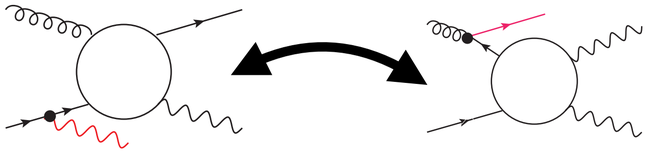
- QCD and EW processes formally overlap at NLO
- EW corrections become dominant in VBF/VBS phase-space
- O(1%) uncertainties in VBF-V ratios

BACKUP

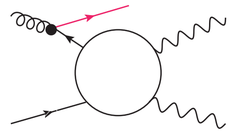
Giant K-factors and effect of jet veto



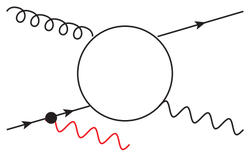




- at r21 → 1: hard-VV topologies



- at r21 → 0: hard-Vj topologies



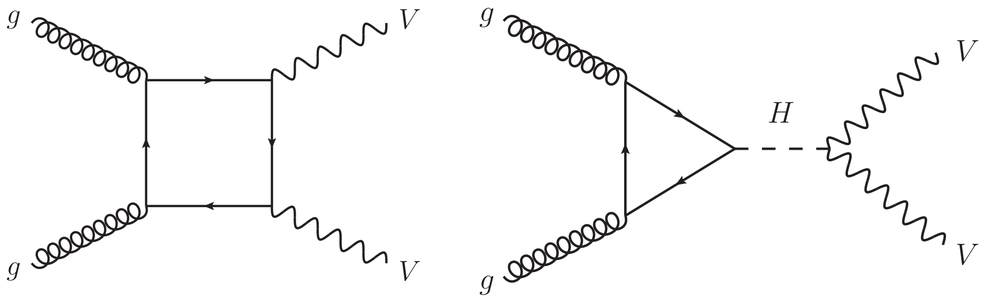
- for pTV1 > 1 TeV: hard-Vj topologies dominate over hard-VV
- Jet veto $H_\text{T}^\text{jet} < \xi_\text{veto}\ H_\text{T}^\text{lep}$ corresponds to

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

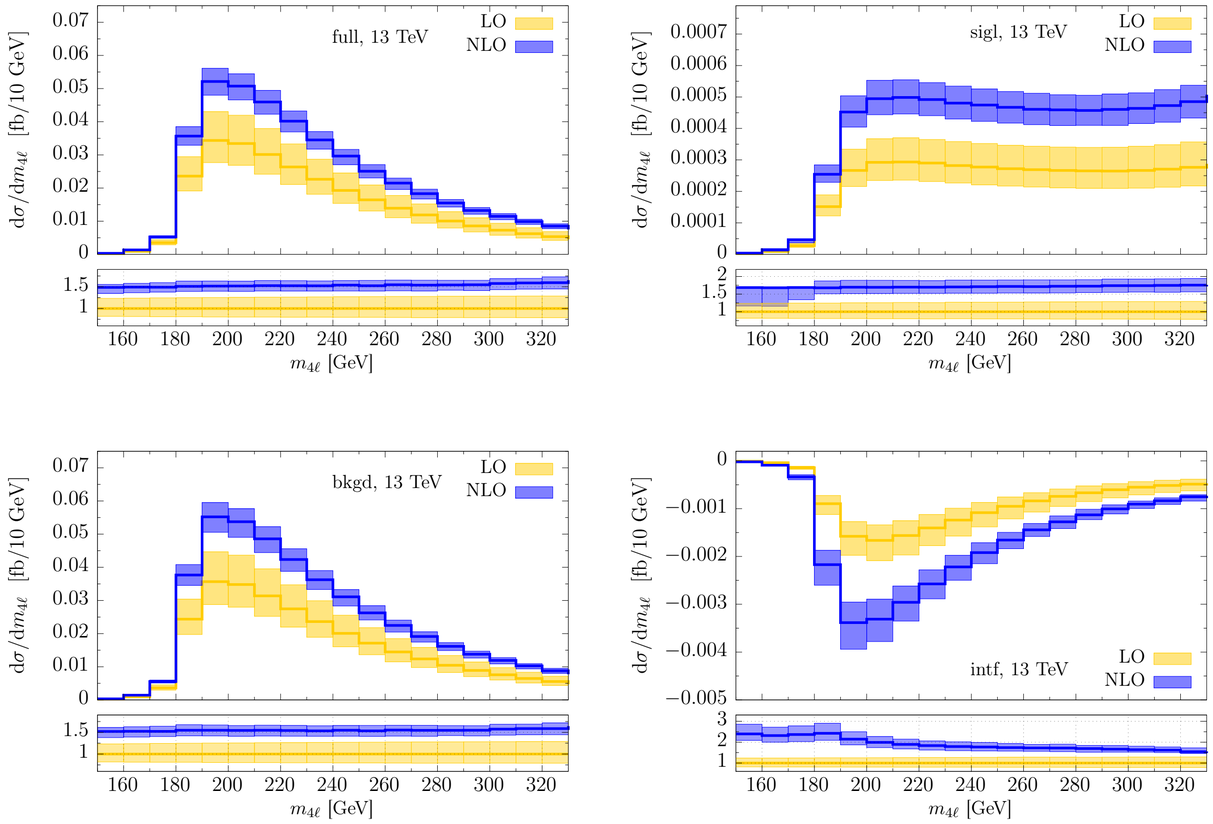
(violated by off-shell topologies)

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

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