Vector-Boson Scattering at the LHC – recent theory developments

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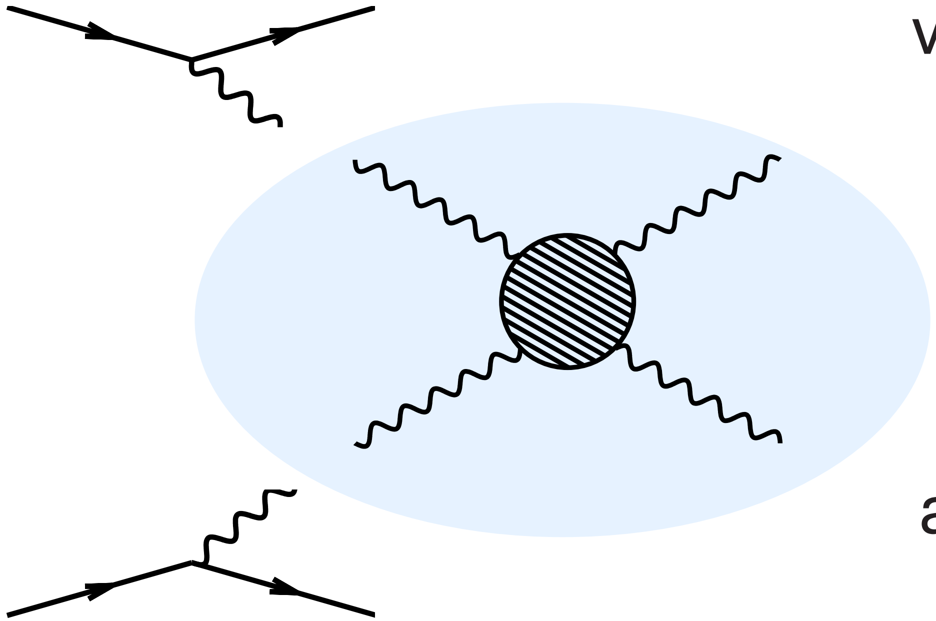
outline

- definition of the VBS signature
- precision calculations for VBS processes
- matching to parton showers
- tools
- polarization observables

vector boson scattering: $VV \to VV$

weak boson and Higgs sector intimately linked

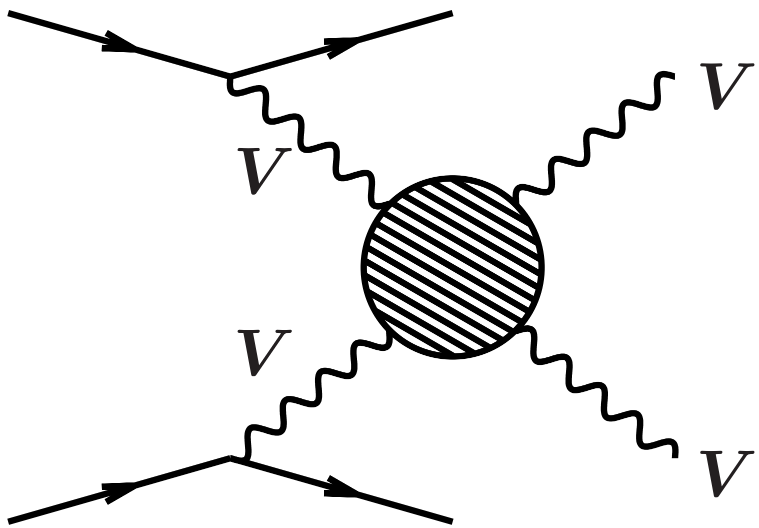
electroweak symmetry breaking: Higgs mechanism gives masses to $W^{\pm}, Z$ ($\to$ longitudinal modes)



vector-boson scattering processes are extremely sensitive to new interactions in the gauge boson sector

☞ search for new resonances, anomalous (quartic) gauge-boson couplings, ...

vector boson scattering at colliders: $pp \to VV$+2 jets



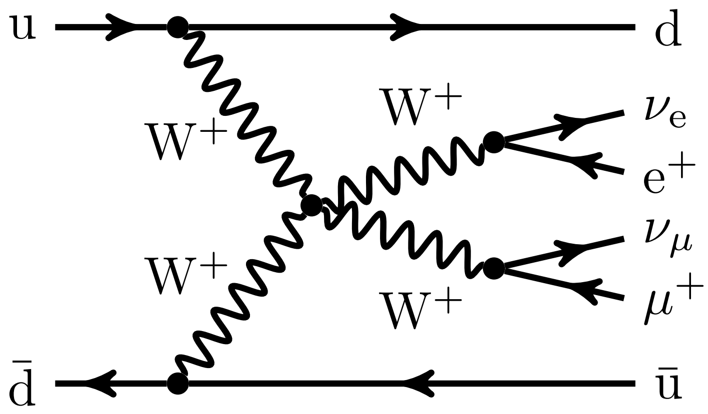
make use of unique VBS topology:

- ✦ jets in forward regions of detector,
- ✦ decay products of weak bosons at central rapidities

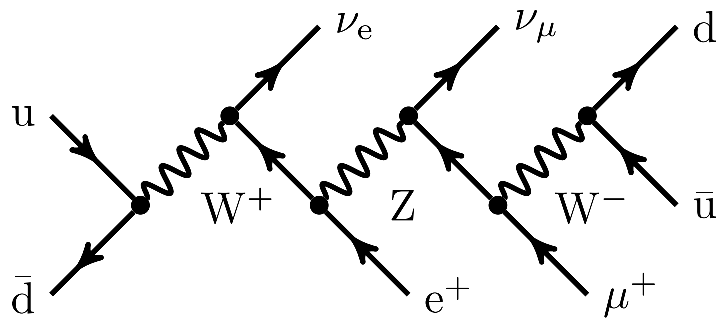
experiment: don't observe gauge bosons of the $VVjj$ final state, but their (hadronic or) leptonic decay products

☞ need predictions for final state with 4 leptons and 2 jets

the W^+W^+ channel: $pp \to \mu^+\nu_\mu e^+\nu_e jj$ at $\mathcal{O}(\alpha^6)$



t-channel



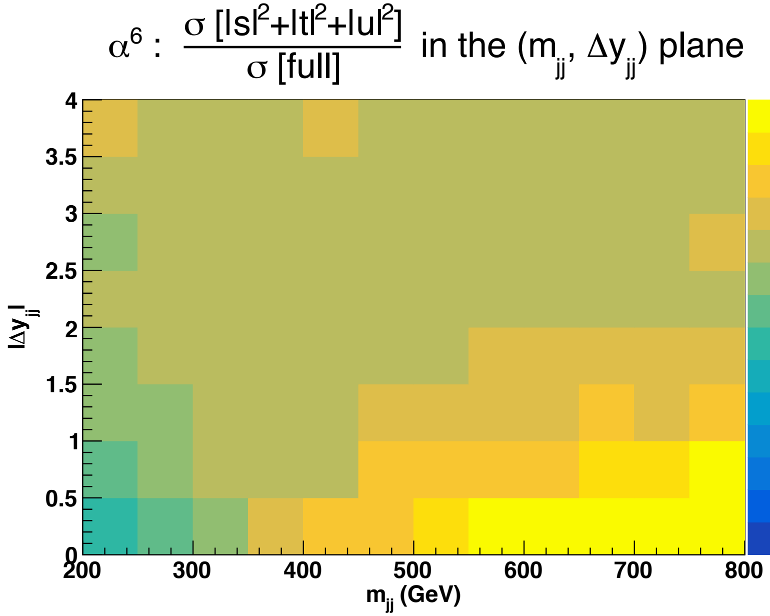
s-channel

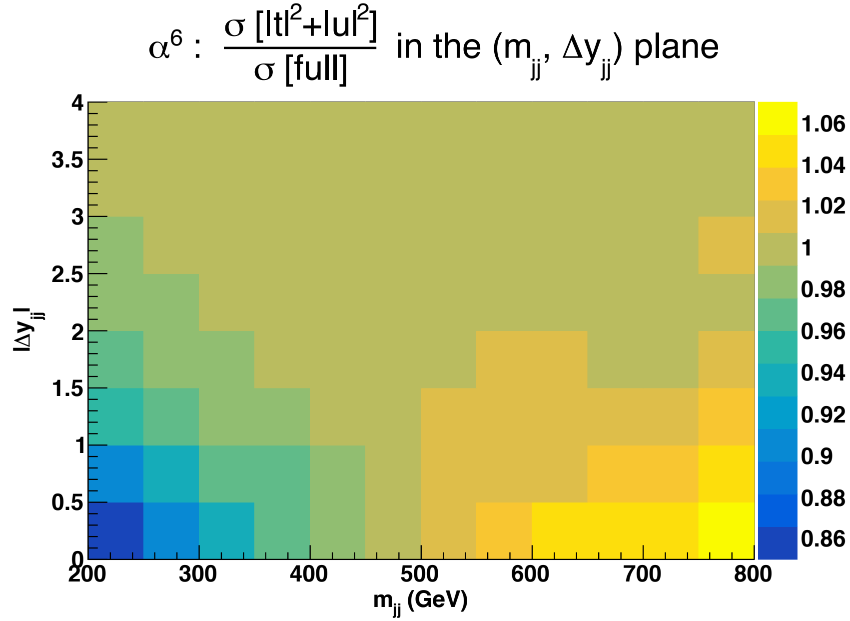
dominant in VBS fiducial region

small when VBS cuts are applied

impact of VBS approximation

"VBS approximation": only t- and u-channel contributions, no s-channel, no $u \cdot t$ interference





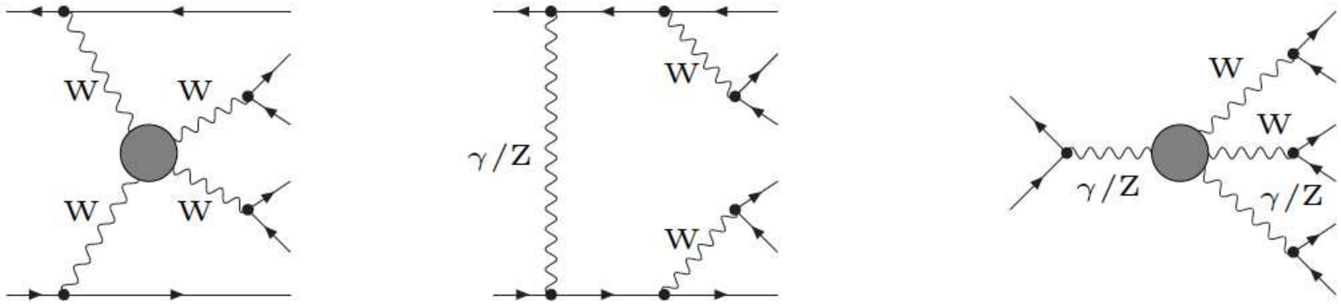
Ballestrero et al. (2018)

typical VBS search region ($m_{jj} > 500$ GeV, $|\Delta y_{jj}| > 2.5$):

VBS approximation works well (better than 5%)

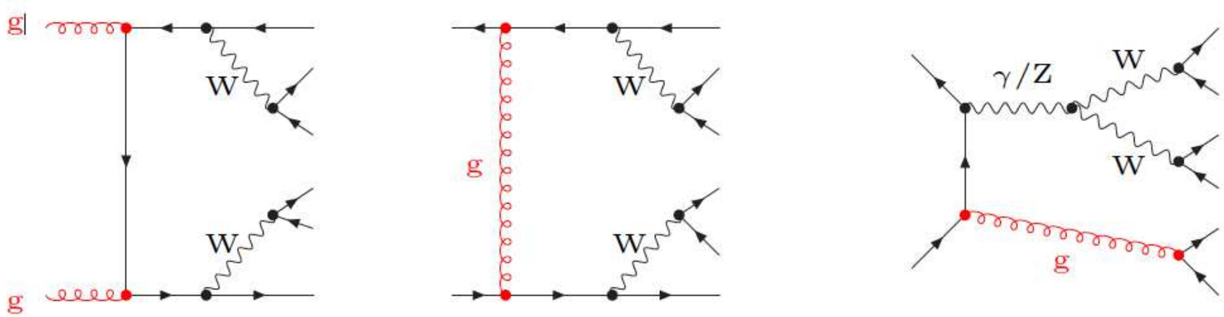
the various contributions to the VVjj final state

EW channels:



$$|\mathcal{M}_{\mathrm{EW}}|^2 \propto \alpha^6$$

QCD channels:



$$|\mathcal{M}_{\mathrm{QCD}}|^2 \propto \alpha_s^2 \alpha^4$$

interference between QCD and EW channels:

possible, but suppressed

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fixed-order calculations: state of the art

- NLO-QCD corrections to 4 lepton+2 jet final state at $\mathcal{O}(\alpha^6\alpha_s)$, using the VBS approximation:

  Bozzi, Oleari, Zeppenfeld, B. J. (2006-2009) $\longrightarrow$ `VBFNLO`

  Denner, Hosekova, Kallweit (2012)

- NLO-QCD corrections to 4 lepton+2 jet final state at $\mathcal{O}(\alpha^4\alpha_s^3)$: (QCD-induced production = irreducible background to VBS signal)

  Melia, Melnikov, Röntsch, Zanderighi (2010-2011)

  Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano (2012)

  Campanario, Kerner, Ninh, Zeppenfeld (2013-14) $\longrightarrow$ `VBFNLO`

- NLO-QCD and EW corrections to 4 lepton+2 jet final state:

  Biedermann, Dittmaier, Denner, Maierhöfer, Pellen, Schwan (2016-19)

  Denner, Franken, Pellen, Schmidt (2020-22)

EW corrections: why worry?

- LHC-2 was operating at 13 TeV

  $\rightarrow$ energy range sensitive to EW effects;
  EW corrections can reach some 10%

- integrated LHC luminosity will reach several 100 fb^{-1}

  $\rightarrow$ many measurements at few-percent level
  (= typical size of EW corrections)

- planned high-precision measurements:

  EW parameters, (anomalous) couplings,. . .
  EW corrections are crucial ingredient

large electroweak corrections in VBS

origin of large EW corrections to $W^+W^+ \to W^+W^+$:

double and single Sudakov logarithms of the form

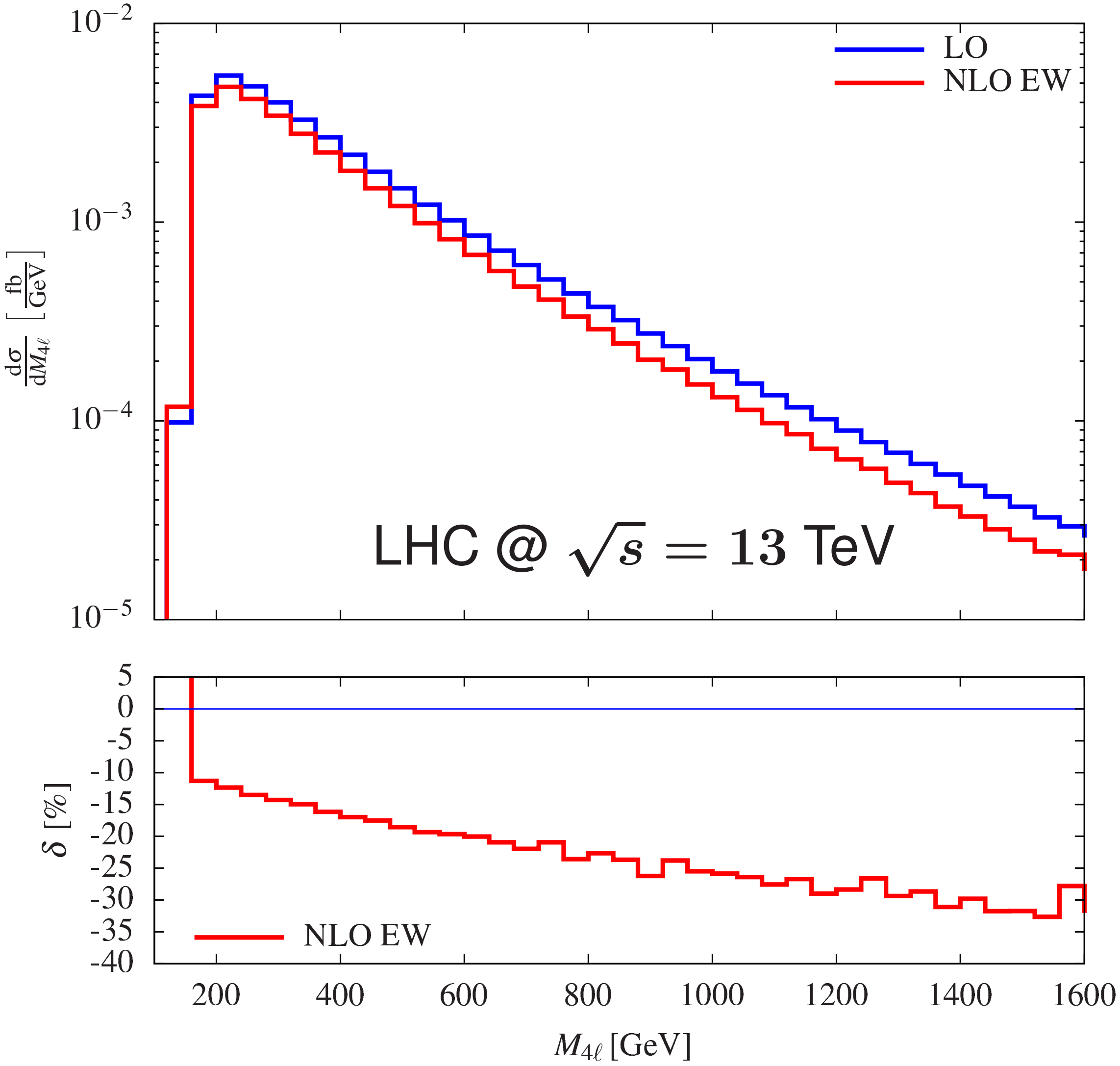
$$\sigma_{\rm LL} = \sigma_{\rm LO}\left[1 \quad -\frac{\alpha}{4\pi}\frac{8}{\sin^2\theta_W}\log^2\left(\frac{Q^2}{M_W^2}\right) \right.$$
$$\left. +\frac{\alpha}{4\pi}\frac{19}{3\sin^2\theta_W}\log\left(\frac{Q^2}{M_W^2}\right)\right],$$

...with scale Q characteristic for VBS $\leftrightarrow m_{4\ell}$

at LHC-13: $\langle m_{4\ell}\rangle$ of order 390 GeV

[Biedermann, Denner, Pellen (2016)]

$pp \to W^+W^+jj$: electroweak corrections



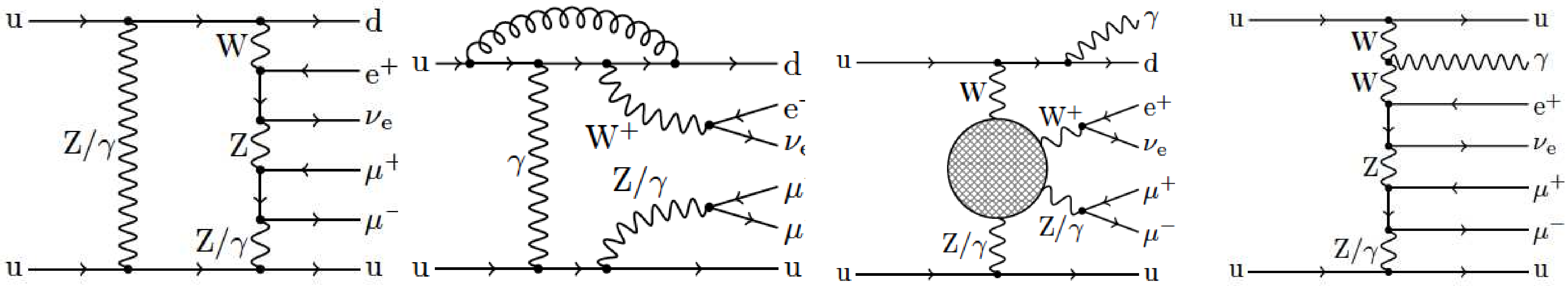
first calculation of NLO-EW corrections to same-sign VBS in fully leptonic decay mode

$$pp \to \mu^+\nu_\mu e^+\nu_e jj$$

dominant EW corrections of about -16% on fiducial xsec and even more ($\sim$ -30%) in tails of distributions

[Biedermann, Denner, Pellen (2016)]

$pp \to WZjj$: strong and EW corrections



systematic expansion in strong and electroweak couplings

☞ NLO corrections: $\mathcal{O}(\alpha_s\alpha^6)$ and $\mathcal{O}(\alpha^7)$;

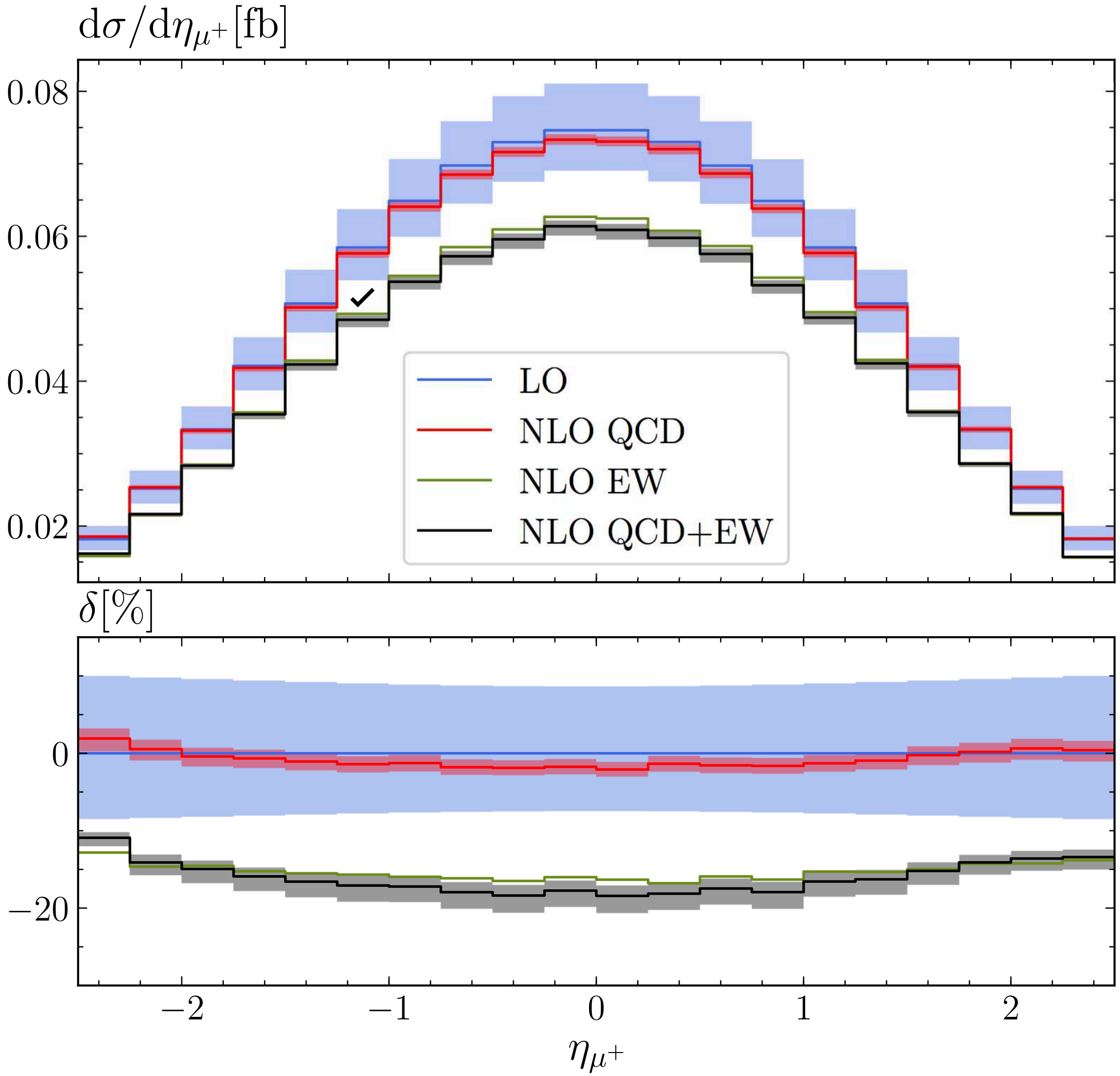
including loop diagrams and real photon or parton emission

very large number of diagrams: computed with the help of automated amplitude generators (`OpenLoops` and `Recola`)

[Denner, Dittmaier, Maierhöfer, Pellen, Schwan (2019)]

$pp \to WZjj$: strong and EW corrections

[Denner, Dittmaier, Maierhöfer, Pellen, Schwan (2019)]

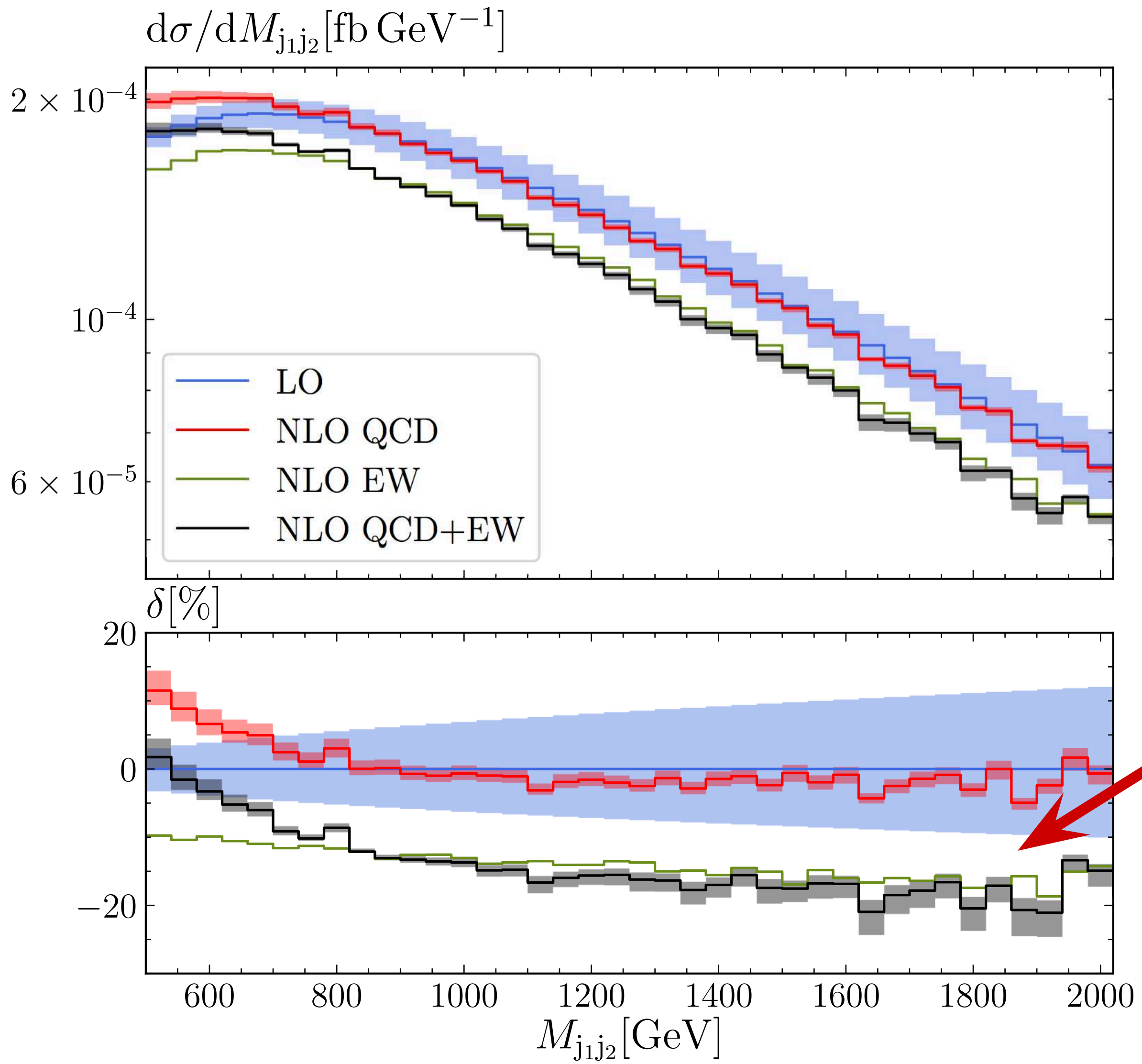


EW corrections larger than QCD corrections, shift xsec by $\sim$ -16%

(compare size of QCD scale uncertainty
$\updownarrow$
width of band)

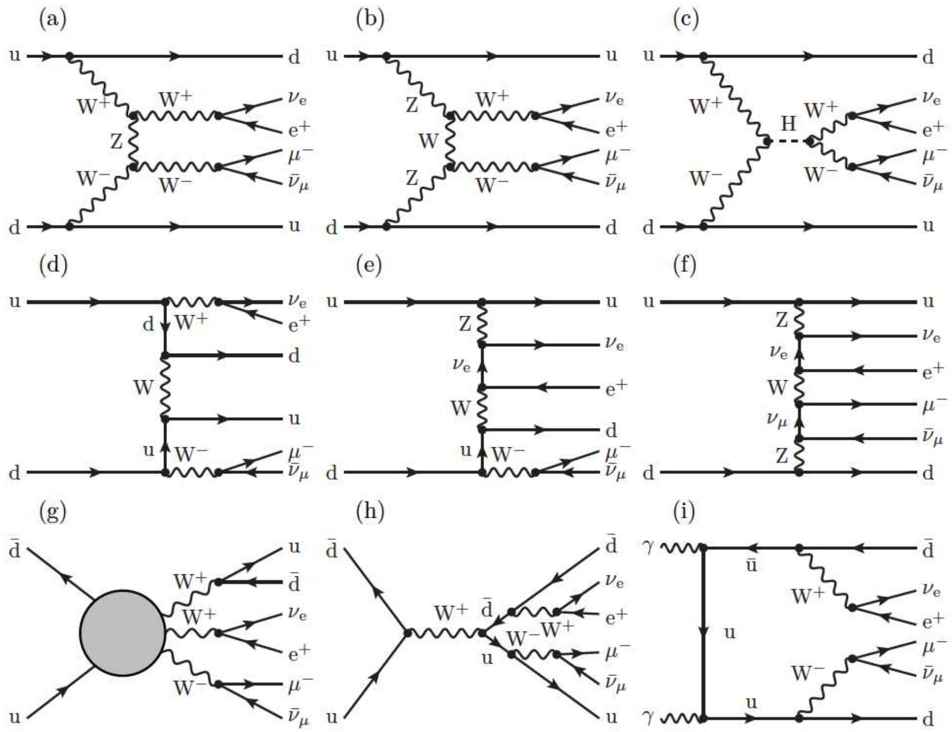
$pp \to WZjj$: strong and EW corrections

[Denner, Dittmaier, Maierhöfer, Pellen, Schwan (2019)]



typical Sudakov behavior of EW corrections in high-energy tails

$pp \to W^+W^-jj$



different topologies and production modes

Denner, Franken, Schmidt, Schwan (02/2022)

impact of various contributions depends on selection cuts:

VBS scenario

versus

Higgs search scenario

$pp \to W^+W^-jj$: impact of contributions at LO

Denner et al. (2022)

order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	$\mathcal{O}(\alpha_s^4\alpha^4)$	sum
VBS setup					
$\sigma_{\mathrm{LO}}[(\mathrm{fb})]$	2.6988	0.06491	6.9115	0.1952	9.8704
fraction [%]	27.3	0.7	70.0	2.0	100
Higgs setup					
$\sigma_{\mathrm{LO}}[(\mathrm{fb})]$	1.5322	0.008996	1.6923	0.1057	3.3392
fraction [%]	45.9	0.3	50.7	3.2	100

$pp \to VVjj$: size of NLO EW corrections

Denner et al. (2022)

process	W^+W^+	W^+Z	ZZ	W^+W^- (VBS setup)	W^+W^- (Higgs setup)
$\sigma_{\mathrm{LO}}^{\alpha^6}$ [fb]	1.4178	0.25511	0.097683	2.6988	1.5322
δ^{EW} [%]	-15.3	-16.0	-15.9	-11.4	-6.7

size of EW corrections depends on channel and cuts

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parton shower matching: dedicated implementations

- matching to parton showers for EW production mode:

  Jäger, Karlberg, Scheller, Zanderighi (2011-18) $\longrightarrow$ `POWHEG-BOX`

  Rauch, Plätzer (2016) $\longrightarrow$ `HERWIG`

- matching to parton showers for QCD production mode:

  Melia, Nason, Röntsch, Zanderighi (2011) $\longrightarrow$ `POWHEG-BOX`

- matching to EW showers:

  Chiesa, Denner, Lang, Pellen (2019) $\longrightarrow$ `POWHEG-BOX`

parton shower matching: multi-purpose tools

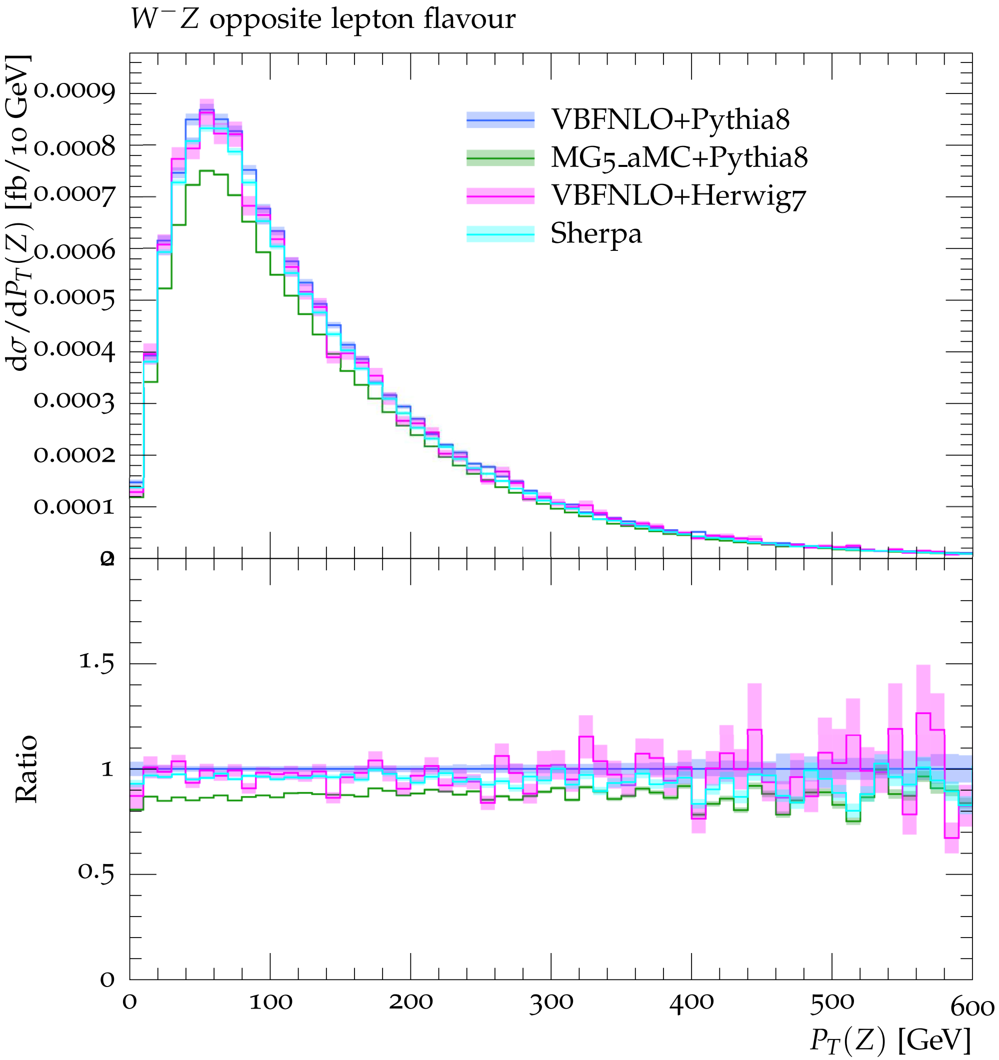
- `Madgraph5aMC@NLO`:

  can in principle do NLO-QCD, but is typically used by experiments at LO with factorized on-shell decays of V bosons

- Sherpa:

  LO for $VVjj$, but can provide merged samples with up to two extra jets

$pp \to WZjj$ matched to parton showers at LO

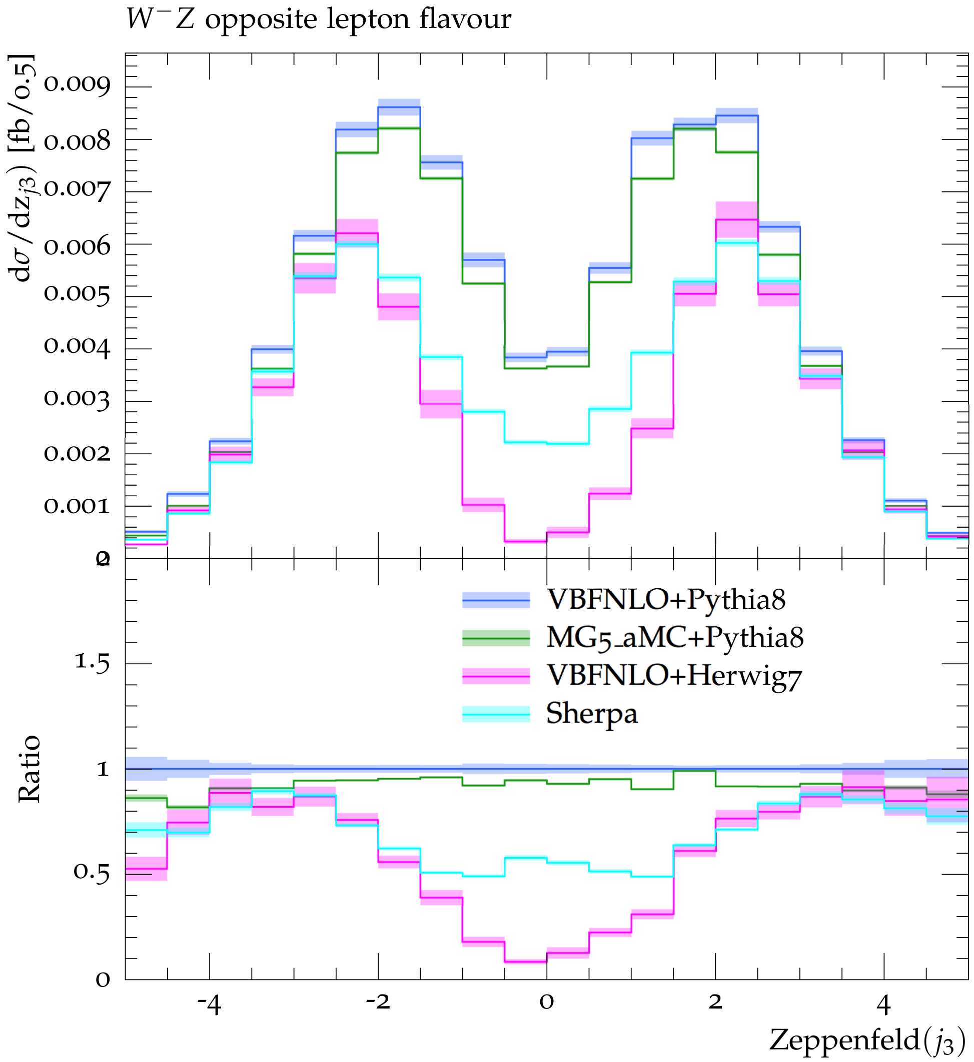


[Les Houches (2018)]

systematic comparison of existing tools matched to parton showers at LO:

- significant discrepancies even for distributions of particles already present at Born level

$pp \to WZjj$ matched to parton showers at LO



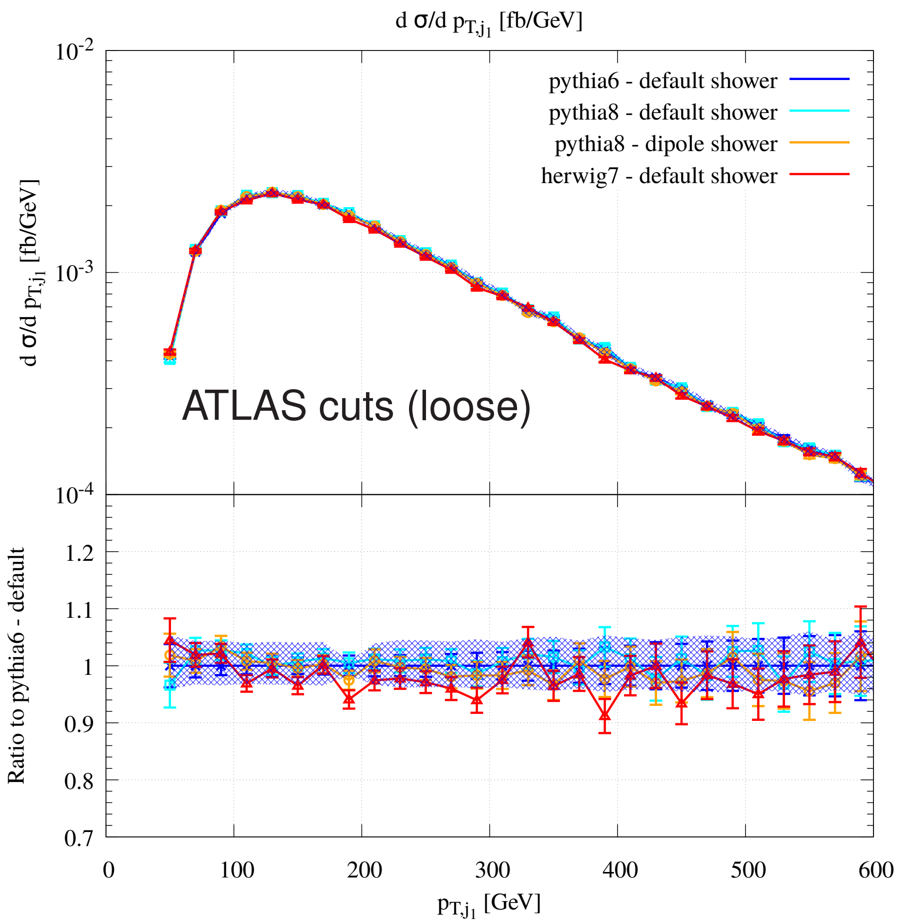
[Les Houches (2018)]

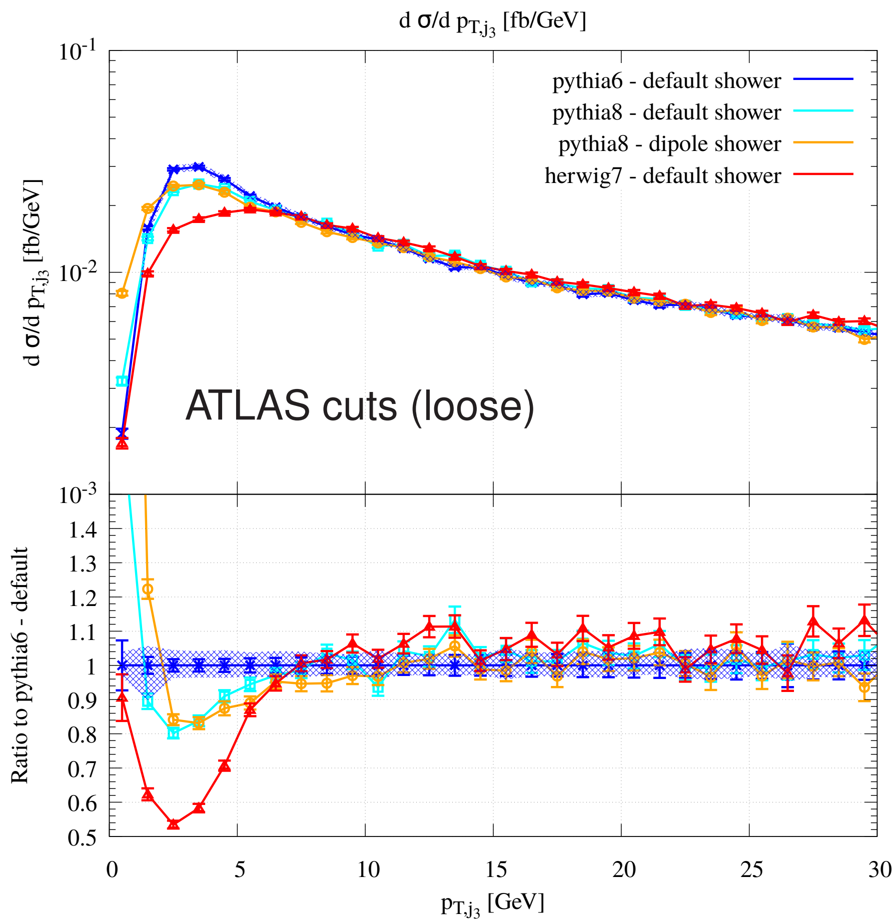
systematic comparison of existing tools matched to parton showers at LO:

- significant discrepancies even for distributions of particles already present at Born level
- up to 100% differences in distributions of 3rd jet, like

$$z = \frac{y_{j3} - \frac{y_{j1}+y_{j2}}{2}}{|y_{j1}-y_{j2}|}$$

$pp \to WZjj$ matched to parton showers at NLO-QCD

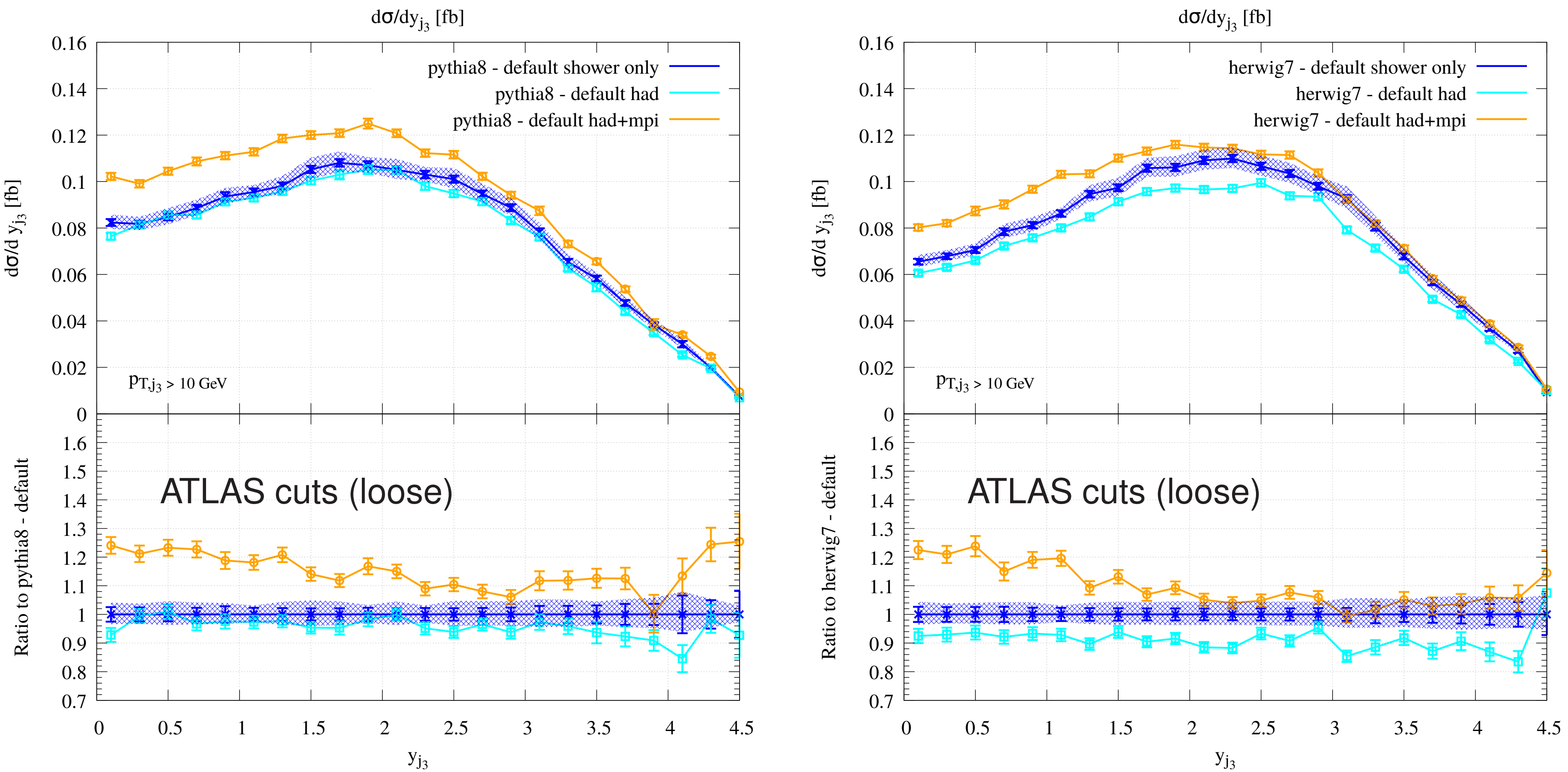




[B.J., Karlberg, Scheller (2018)]

parton-shower settings have little impact on tagging jets;
larger differences for non-tagging jets

$pp \to WZjj$ matched to parton showers at NLO-QCD

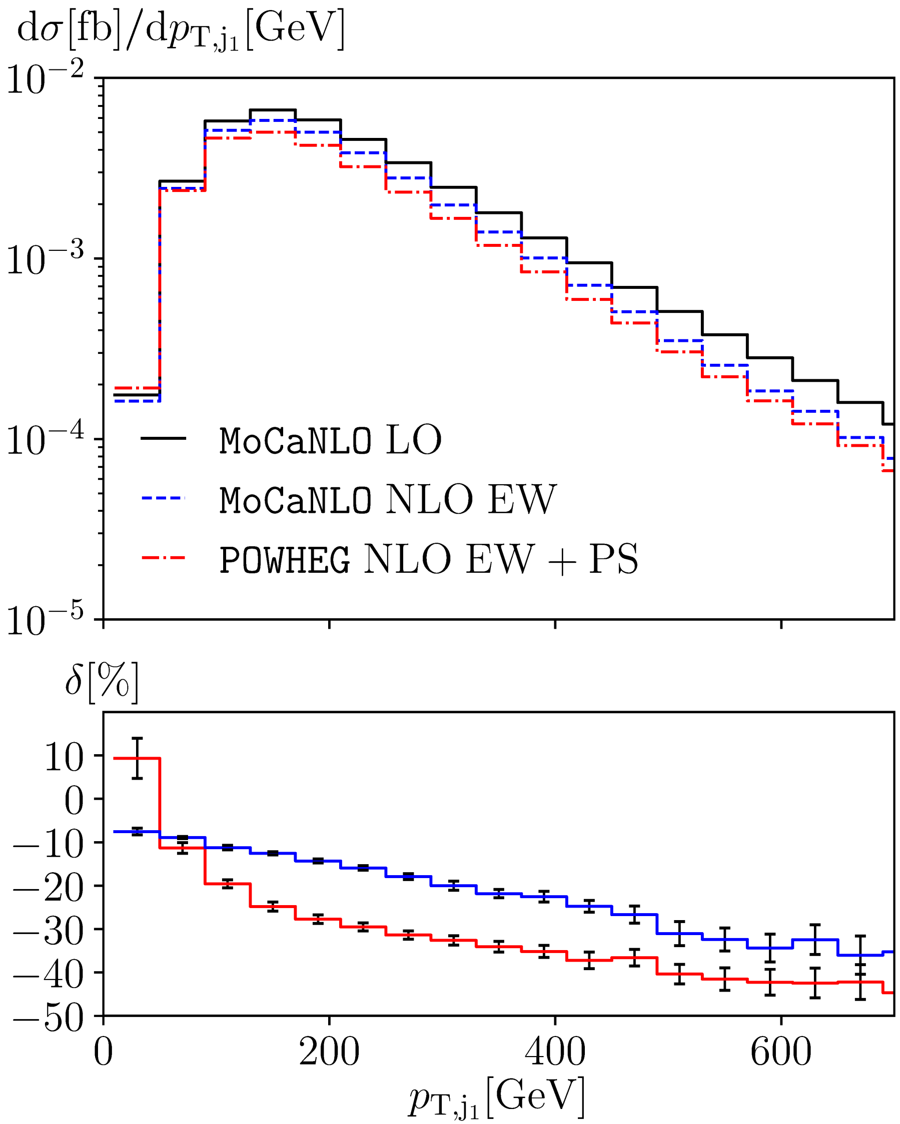


[B.J., Karlberg, Scheller (2018)]

parton-shower settings modify rapidity distribution of 3rd jet

$pp \to W^+W^+jj$ at NLO-EW matched to a QED shower

[Chiesa, Denner, Lang, Pellen (2019)]



matching of NLO EW calculation to QED shower:

- ✦ typical Sudakov suppression in tails because of EW corrections
- ✦ extra shower radiation: additional decrease

✔ implementation available in the POWHEG-BOX

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LO comparison for $pp \to W^+W^+jj$

VBS-typical cuts:

$$p_{T,\ell} > 20 \text{ GeV}, |y_\ell| < 2.5, \Delta R_{\ell\ell} > 0.3$$
$$p_{T,miss} > 40 \text{ GeV},$$
$$p_{T,j} > 30 \text{ GeV}, \quad |y_j| < 4.5, \Delta R_{j\ell} > 0.3$$
$$m_{jj} > 500 \text{ GeV}, |\Delta y_{jj}| > 2.5$$

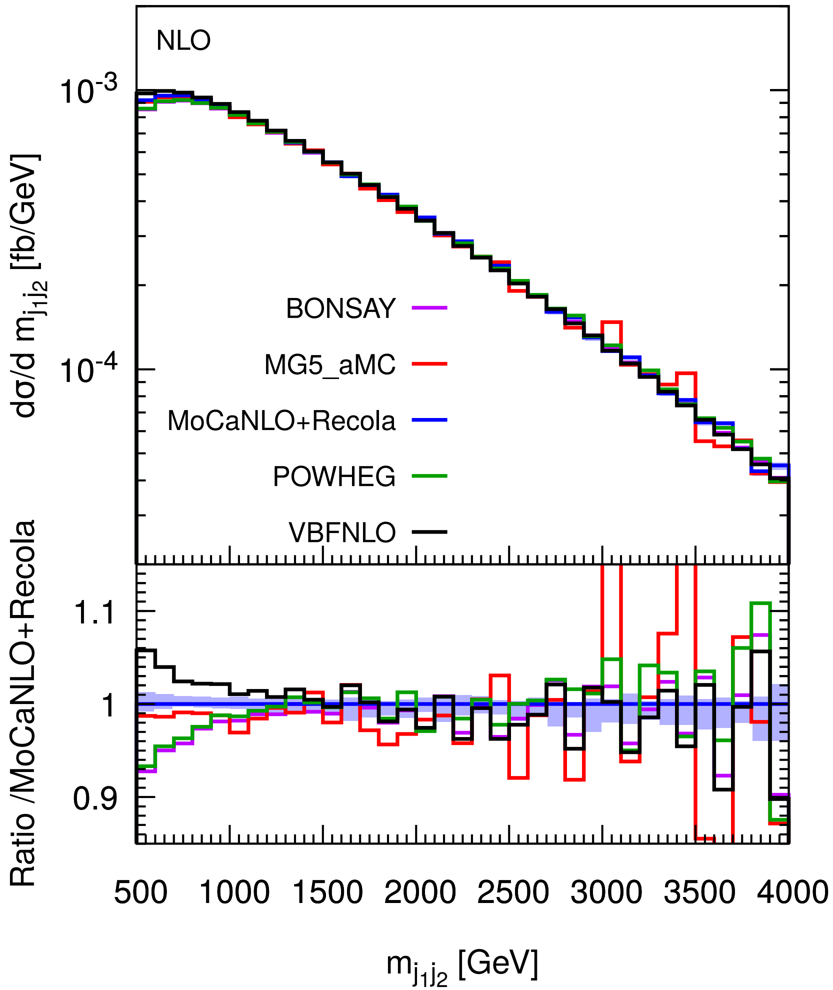
tuned comparison of existing tools performed in context of VBS-COST action

[Ballestrero et al. (2018)]

Code	σ [fb]
BONSAY	1.43636 ± 0.00002
POWHEG-BOX	1.44092 ± 0.00009
VBFNLO	1.43796 ± 0.00005
PHANTOM	1.4374 ± 0.0006
WHIZARD	1.4381 ± 0.0002
MG5_AMC	1.4304 ± 0.0007
MOCANLO+RECOLA	1.43476 ± 0.00009

NLO-QCD comparison for $pp \to W^+W^+jj$

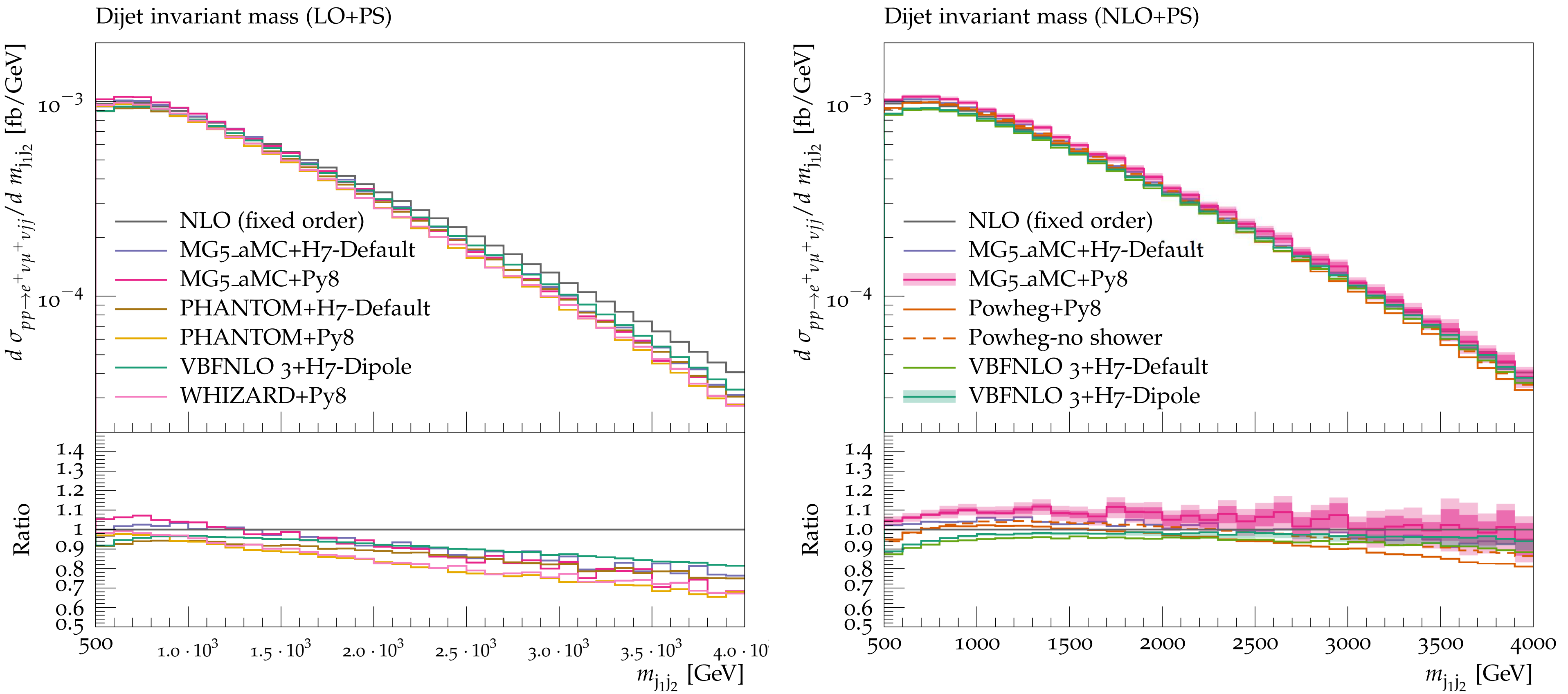
Ballestrero et al. (2018)



good agreement at NLO-QCD

Code	σ [fb]
BONSAY	1.35039 ± 0.00006
POWHEG-BOX	1.3605 ± 0.0007
VBFNLO	1.3916 ± 0.0001
MG5_AMC	1.363 ± 0.004
MOCANLO+RECOLA	1.378 ± 0.001

parton-shower comparison for $pp \to W^+W^+jj$



Ballestrero et al. (2018)

differences between various simulations reduced when going from LO+PS to NLO+PS

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polarization effects in VV scattering

recall: longitudinal gauge boson modes $\boldsymbol{W_L^\pm}$, $\boldsymbol{Z_L}$
intimately linked to Higgs mechanism

↓

can we isolate longitudinal polarization modes of the gauge bosons in VBS processes?

major obstacle: experimentally accessible process is
$pp \to 4$ fermions $+ 2$ jets, not $\boldsymbol{VV \to VV}$!

✘ initial state: collider does not provide polarized gauge bosons

✘ final state contains contributions from non-resonant diagrams

polarized VV scattering: Monte-Carlo tools

tools featuring (approximate) methods to treat spin correlations and off-shell effects for processes involving weak bosons:

✦ MG5_aMC@NLO:

- polarized on-shell V bosons (up to NLO+PS) in SM and several BSM models;
- spin-correlated decays in NWA (with MadSpin or via decay chain)

✦ WHIZARD:

polarized on shell V bosons (NWA, cascade decay), within SM or SMEFT

✦ PHANTOM:

generation of polarized V bosons in $2 \rightarrow 6$ processes, including all spin correlations and off-shell effects at LO in SM, Higgsless and Singlet Extension

✦ WZDECAY:

generator-independent package for decaying polarized V bosons in NWA

take-home message

impressive number of experimental results on VBS . . .

. . . but also status of theoretical work is very advanced:

✦ theorists provide precision calculations and tools:

NLO QCD, NLO EW, NLO QCD+EW,

matching to parton showers, . . .

✦ new line of investigation: polarization effects in VBS processes

tools are on the market which allow for

simulations at high degree of accuracy

☞ they can only unfold their potential if used

...for your attention