Electroweak corrections

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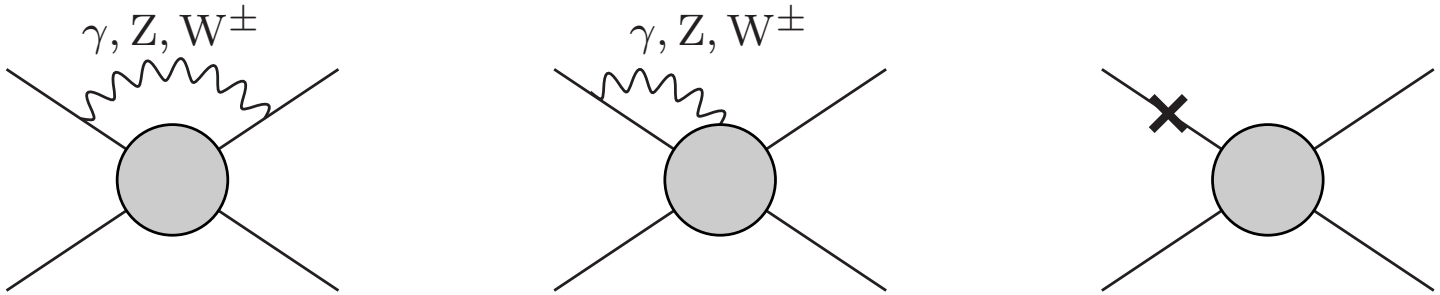
Features of EW corrections

Sudakow logarithms:

Exchange of virtual EW bosons with external legs:



At high energies $Q^2 \gg M_{\mathrm{W}}^2$, large soft/collinear $\ln \frac{Q^2}{M_{\mathrm{W}}^2}$ are generated

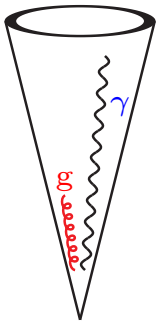
$$\frac{\sigma_{NLO}}{\sigma_{LO}} - 1 = \underbrace{c_2 \frac{\alpha}{4\pi s_W^2} \ln^2 \frac{Q^2}{M_{\mathrm{W}}^2}}_{\sim \textbf{-25\%} \text{ at 1 TeV}} + \underbrace{c_1 \frac{\alpha}{4\pi s_W^2} \ln \frac{Q^2}{M_{\mathrm{W}}^2}}_{\sim +15\% \text{ at 1 TeV}} + c_0$$

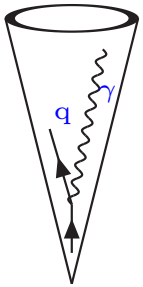
Q^2 can be p_T, $\not{E}_T$, M_{inv}, ...

- Photon exchange compensated by real photon emission
- Z and W exchange usually not compensated by real emission

Photon emission: Fermion-photon recombination

- Collinear electrons and photons usually recombined $\rightsquigarrow$ collinear-safe (CS)
- Collinear muons and photons not recombined $\rightsquigarrow$ non-collinear-safe (NCS)
  $\alpha \ln(m_\mu/Q)$ terms survive
- Parton-photon recombination in processes with jets
  - Democratic clustering
  - Hard-photon jets (containing soft gluon) are QCD IR unsafe
    $\rightsquigarrow$ Cut hard-photon jets
  - Hard-photons collinear to quarks also cutted
    $\rightsquigarrow$ QED IR unsafe
  - Rigorous approach: fragmentation functions
    [Denner, Hofer, Scharf, U. '14]
  - Approximate approach: treate $q\gamma$ with tiny $\Delta R_{q\gamma}$ as quarks
    [Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '14]

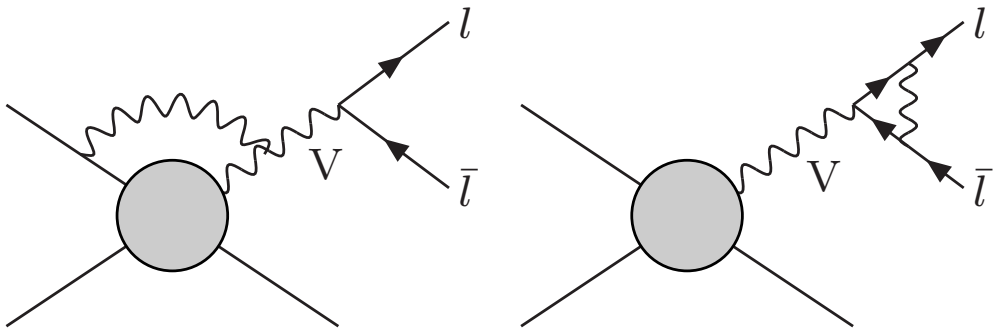




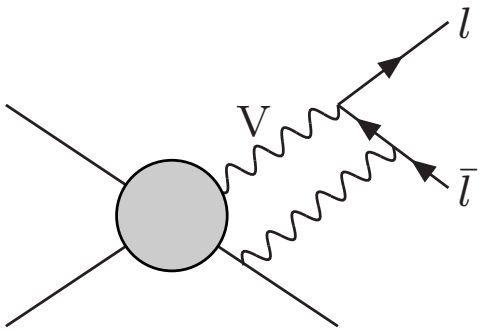
Decays of the vector boson:

Non trivial treatment of the V-decays at NLO EW

Factorizable contributions



Non-factorizable contributions



- Pole approximation:

  Production $\times$ decay with on-shell V, except in V propagator

  - It describes the Sudakov effects
  - Typical approximation error: $1-3\%$

- Exact computation:
  - Complex mass scheme to properly take care of unstable vector bosons.

EW (and QCD) Tools at NLO

Libraries for one-loop Integrals:

FF	Oldenborgh
LoopTools	Hahn, Perez-Victoria
QCDLoop	Ellis, Zanderighi
CutTools	Ossola, Papadopoulos, Pittau
OneLOop	van Hameren
Samurai	Mastrolia, Ossola, Reiter, Tramontano
PJFry	Fleischer, Riemann
Golem95C	Cullen, Guillet, Heinrich, Kleinschmidt, Pilon,Reiter, Rodgers
Collier	Denner, Dittmaier, Hofer

Matrix-element generators:

Feynarts/FormCalc	Agrawal, Hahn, Mirabella
BlackHat	Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maître
Helac-1loop	van Hameren, Papadopoulos, Pittau
NGluon	Badger, Biedermann, Uwer
MadLoop	Frederix, Frixione, Garzelli, Hirschi, Maltoni, Pittau
GoSam	Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano
OpenLoops	Cascioli, Maierhöfer, Pozzorini
Recola	Actis, Denner, Hofer, Lang, Scharf, U.

Parton-level Monte Carlo event generators:

MCFM	Campbell, Ellis
ALPGEN	Mangano, Moretti, Piccinini, Pittau, Polosa
VBFNLO	Arnold, Bähr, Bozzi, Campanario, Englert, Figy, Greiner, Hackstein, Hankele, Jäger, Klämke, Kubocz, Oleari, Plätzer, Prestel, Worek, Zeppenfeld
MADGRAPH5_AMC@NLO	Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torielli, Zaro
MUNICH	Kallweit

Matching programs:

MC@NLO	Frixione, Webber
POWHEG-BOX	Alioli, Nason, Oleari, Re

General-purpose Monte Carlo event generators:

PYTHIA8	Edén, Friberg, Lönnblad, Miu, Mrenna, Norrbin, Sjöstrand, Skands
HERWIG	Bahr, Gieseke, Gigg, Grellscheid, Hamilton, Latunde-Dada, Plätzer, Richardson, Seymour, Sherstnev, Tully, Webber
SHERPA	Gleisberg, Höche, Krauss, Schälicke, Schönherr, Schumann, Siegert, Winter

Latest developments in EW NLO Tools:

- Computations of LHC processes at EW NLO:

FEYNARTS/FORMCALC + LOOPTOOLS	$pp \to VV + \text{jet}$
	$pp \to VVV$
RECOLA + COLLIER	$pp \to l\bar{l}, \nu\bar{\nu} + 2\ \text{jets}$
	$pp \to l\bar{l}\, l'\bar{l}' + X$
OPENLOOPS + COLLIER + MUNICH,SHERPA	$pp \to W + \leq 3\ \text{jets}$
	$pp \to l\bar{l}, \nu\bar{\nu}, l\bar{\nu}, \bar{l}\nu + \leq 2\ \text{jets}$
MADGRAPH5_AMC@NLO + MADLOOP + CUTTOOLS	$pp \to t\bar{t}\, H$
	$pp \to t\bar{t}\, V$
GOSAM	$pp \to W + 2\ \text{jets}$

- COLLIER is now public on https://collier.hepforge.org
- RECOLA (+COLLIER) is now public on https://recola.hepforge.org

Performances of RECOLA + COLLIER

- RAM needed: less than 2 Gbyte also for complicated processes
- **CPU time** (processor Intel(R) Core(TM) i5-2450M CPU @ 2.50GHz):

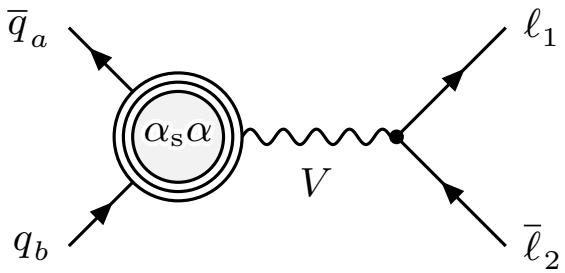
NLO	Process	Generation RECOLA	Computation 1 PS point RECOLA + COLLIER
QCD	$u\,\bar{d} \to l^+\nu_l\,g\,g$	1.6 s	1.6 ms + 3.2 ms
	$u\,\bar{d} \to l^+\nu_l\,g\,g\,g$	12 s	49 ms + 61 ms
	$u\,\bar{u} \to l^+\nu_l\,l'^-\bar{\nu}_{l'}\,g\,g$	29 s	26 ms + 48 ms
QCD + EW	$u\,\bar{u} \to l^+l^-\,g\,g$	2.8 s	28 ms + 17 ms
	$u\,\bar{u} \to l^+l^-\,u\,\bar{u}$	4.1 s	38 ms + 70 ms
	$u\,\bar{u} \to l^+l^-\,t\bar{t}$	3.6 s	47 ms + 36 ms
	$u\,\bar{u} \to l^+l^-\,u\,\bar{u}\,g$	32 s	713 ms + 565 ms

Drell-Yan

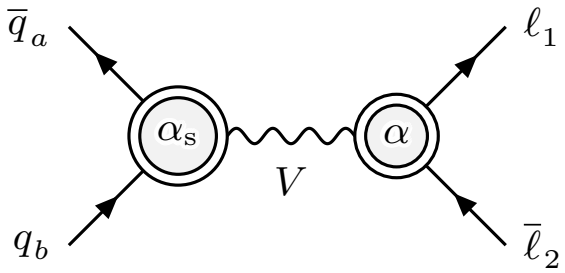
$\mathrm{pp} \to \mathrm{V}$:

- NNLO QCD + PS corrections to $\mathrm{pp} \to l^+l^-, l^+\nu, l^-\bar{\nu}$
  [Karlberg, Re, Zanderighi '14]
- NNLO QCD + NNLL' + PS corrections to $\mathrm{pp} \to l^+l^-$
  [Alioli, Bauer, Berggren, Tackmann, Walsh '15]
- NLO EW corrections + h.o. QED effects to $\mathrm{pp} \to l^+\nu, l^-\bar{\nu}$
  [Carloni Calame, Montagna, Nicrosini, Treccani '03]
  [Brensing, Dittmaier, Krämer, Mück '07]
- NLO EW corrections + h.o. QED effects to $\mathrm{pp} \to l^+l^-$ [Dittmaier, Huber '09]
- NLO EW + QCD + PS corrections to $\mathrm{pp} \to l^+\nu, l^-\bar{\nu}$
  [Bernaciak, Wackeroth '12]
- NLO EW + QCD + PS corrections to $\mathrm{pp} \to l^+l^-$
  [Barzè, Montagna, Nason, Nicrosini, Piccinini, Vicini '13]
- Dominant mixed NNLO QCD-EW corrections to $\mathrm{pp} \to l^+l^-, l^+\nu, l^-\bar{\nu}$
  [Dittmaier, Huss, Schwinn '14,'15]

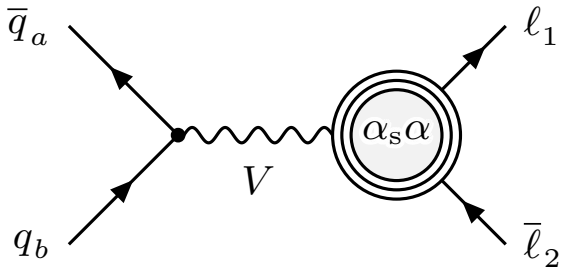
Enhanced contributions in pole approximation:



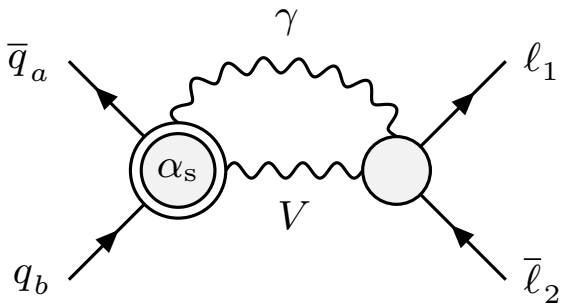
- Partially computed
- Would need $\mathcal{O}(\alpha_s\alpha)$ PDFs, not available yet
- Expected much smaller than QCD corrections



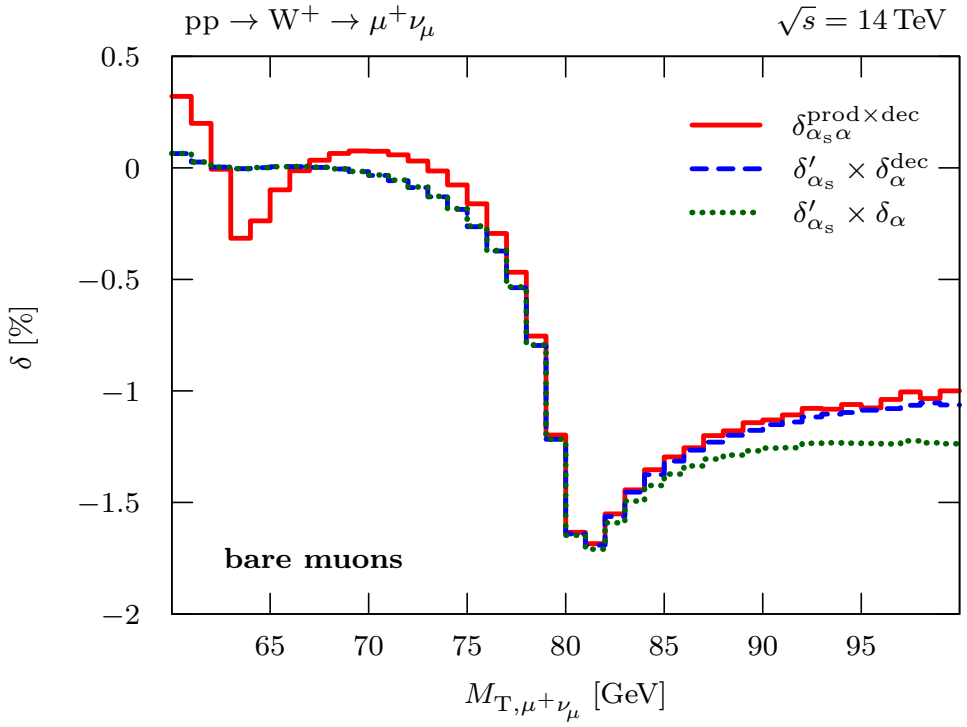
- Dominant contribution

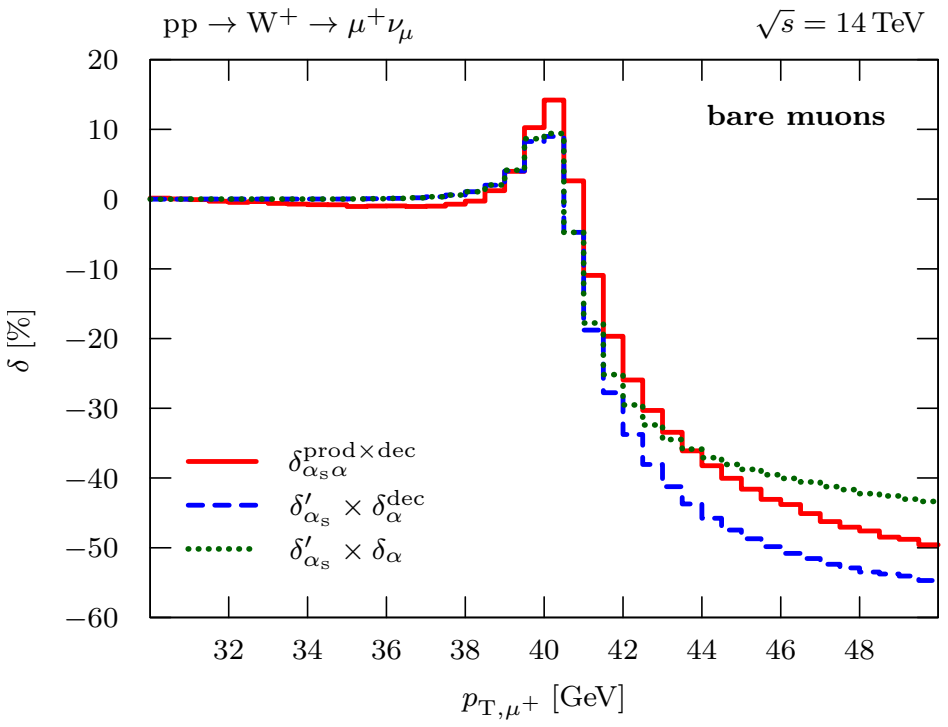


- Arise from $\mathcal{O}(\alpha_s\alpha)$ counterterms of the lepton-V vertex
- Negligible



- Carefully studied in [1403.3216]
- Turn out to be negligible (below 0.1%)

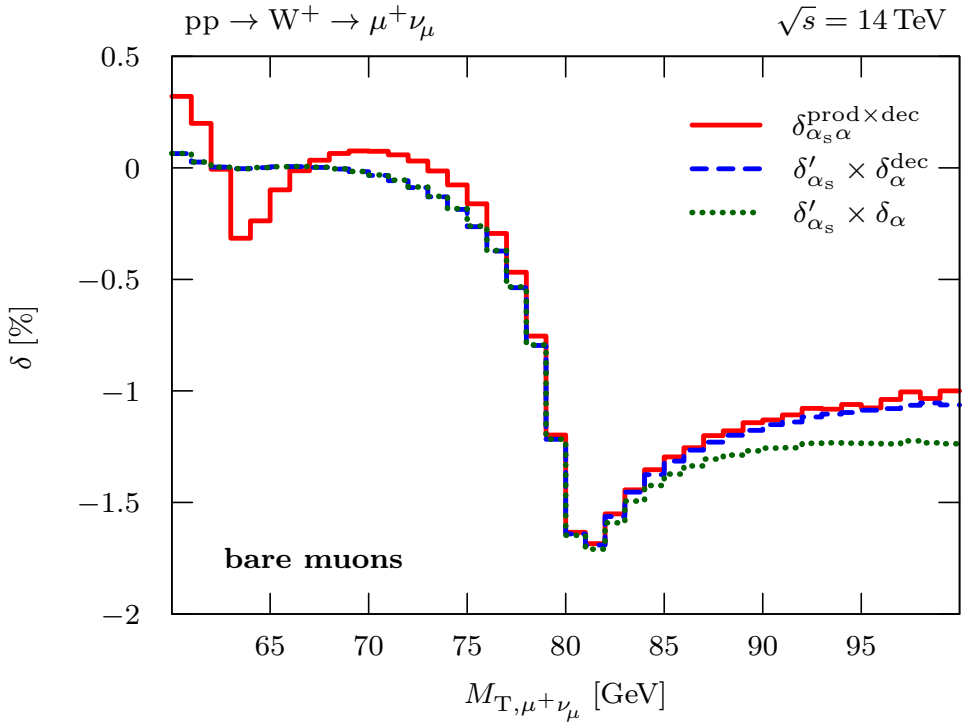


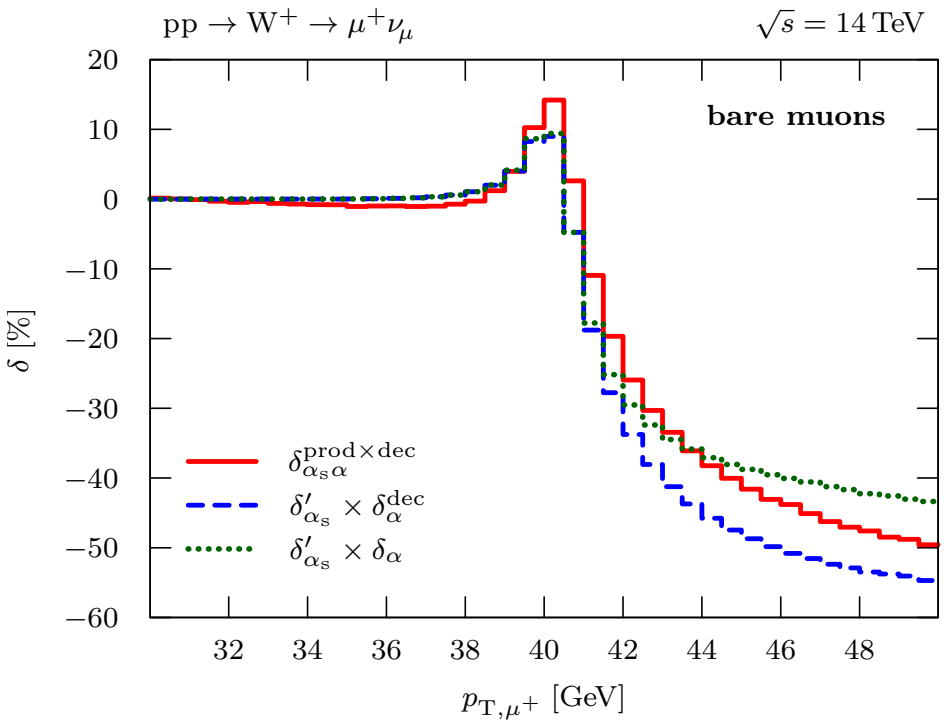


- Small corrections in the $M_{\mathrm{T},\mu^+\nu_\mu}$ distribution
- Large corrections in the p_{T,μ^+} distribution for $p_{\mathrm{T},\mu^+} \geq M_{\mathrm{W}}/2$

$\delta'_{\alpha_s} \times \delta_\alpha$ represents the naive QCD$\times$EW approximation

- It works well for the $M_{\mathrm{T},\mu^+\nu_\mu}$ distribution
- It fails for the p_{T,μ^+} distribution for $p_{\mathrm{T},\mu^+} \geq M_{\mathrm{W}}/2$





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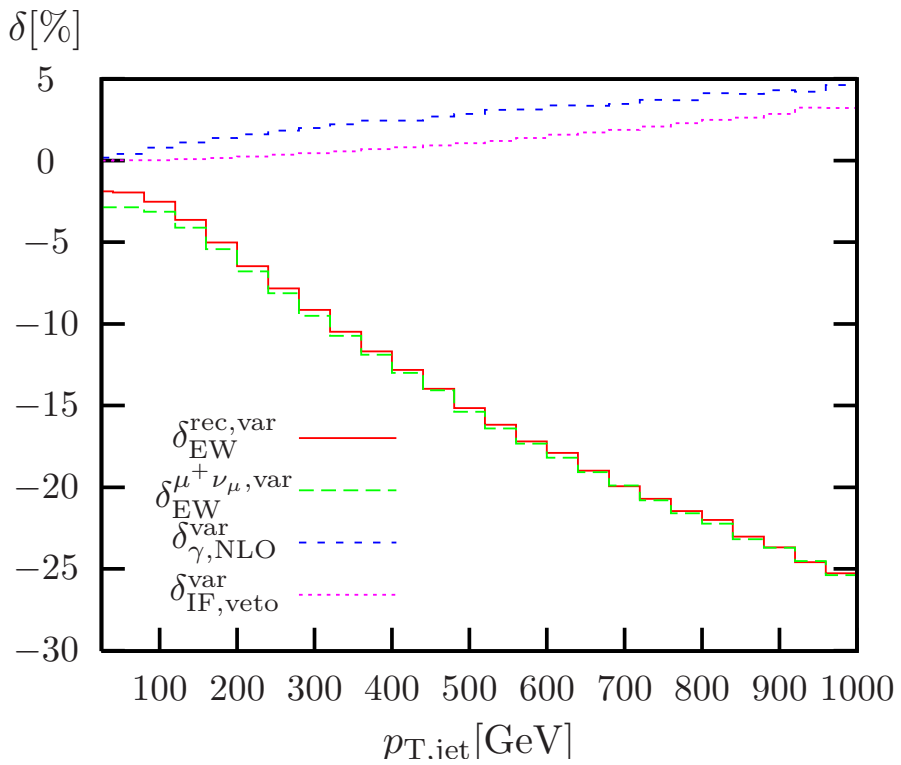
$$\Delta M_{\mathrm{W}}^{\mu} \sim -14\,\mathrm{MeV}$$
$$\Delta M_{\mathrm{W}}^{e} \sim -4\,\mathrm{MeV}$$

$\mathrm{pp} \to \mathrm{V} + \mathrm{jets}$

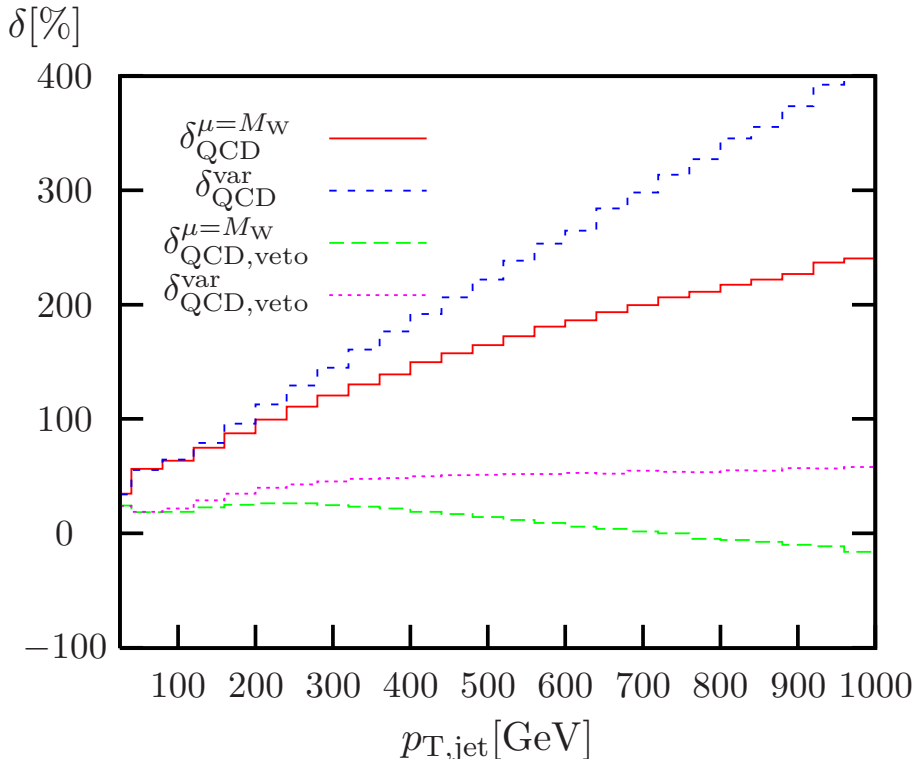
$\mathrm{pp} \to \mathrm{V} + 1\ \mathrm{jet}$:

- QCD corrections [Giele, Glover, Kosower '93]
- EW corrections [Denner, Dittmaier, Kasprzik, Mück '09, '11, '12]

$$p_{\mathrm{T,l}} > 25\ \mathrm{GeV} \qquad \not{E}_{\mathrm{T}} > 25\ \mathrm{GeV} \qquad |\eta_{j,l}| < 2.5 \qquad \Delta R_{jl} > 0.5$$



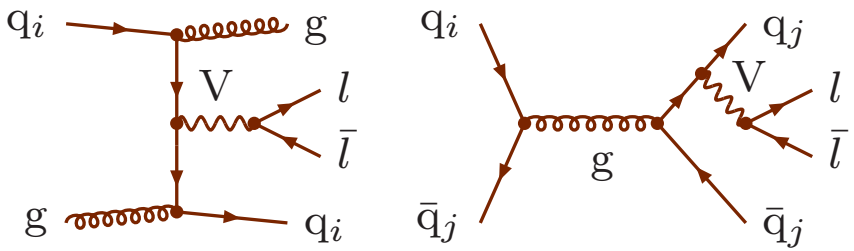
Typical large negative EW corrections



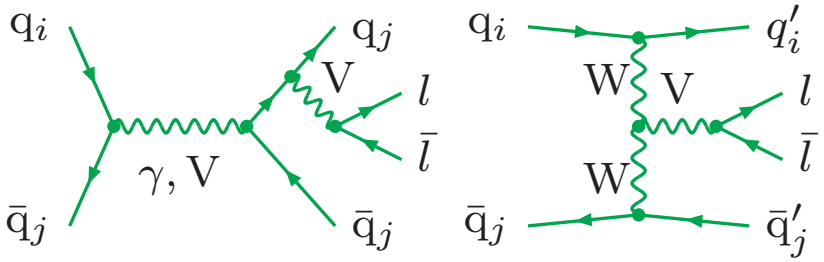
Huge QCD corrections in the TeV region

$\mathrm{pp} \to V + 2$ jets at LO:

QCD LO $\mathcal{O}(g_s^2 e^2)$



EW LO $\mathcal{O}(e^4)$



$\mathrm{pp} \to V + 2$ jets at NLO:

$\mathcal{O}(\alpha_s^3 \alpha^2)$: QCD corrections to QCD diagrams [Campbell, Ellis, Rainwater '02, '03]

$\mathcal{O}(\alpha_s^2 \alpha^3)$: EW corrections to QCD diagrams

QCD corrections to EW-QCD interferences

[Denner, Hofer, Scharf, U. '14; Kallweit, Lindert, Maierhöfer, Pozzorini, Schönerr '14,'15]

$\mathcal{O}(\alpha_s \alpha^4)$: QCD corrections to EW diagrams [Oleari, Zeppenfeld '04]

EW corrections to EW-QCD interferences

$\mathcal{O}(\alpha^5)$: EW corrections to EW diagrams

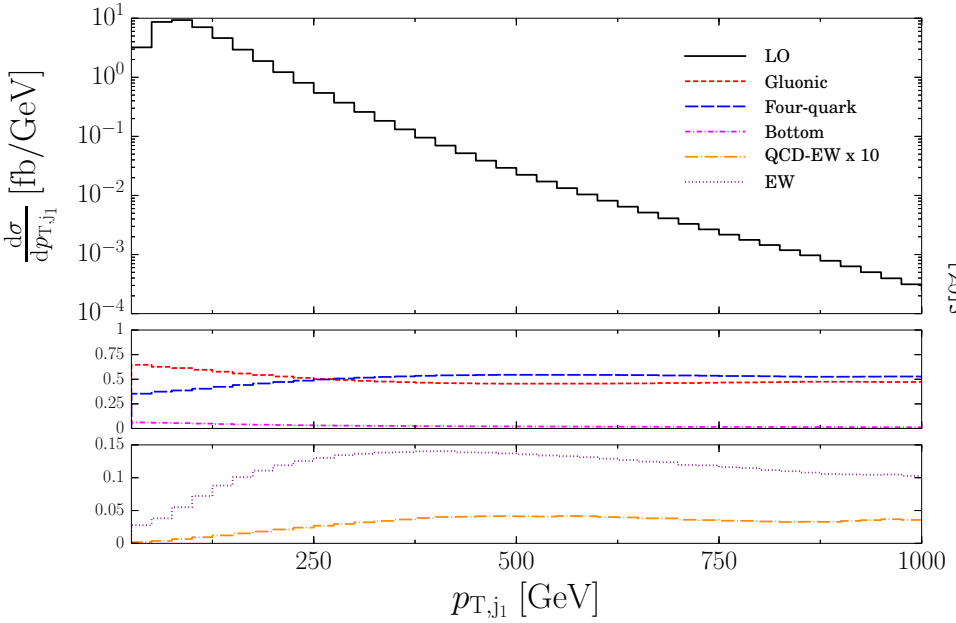
Electroweak corrections for $\mathrm{pp} \to l^+l^-\,jj$ - VBF cuts

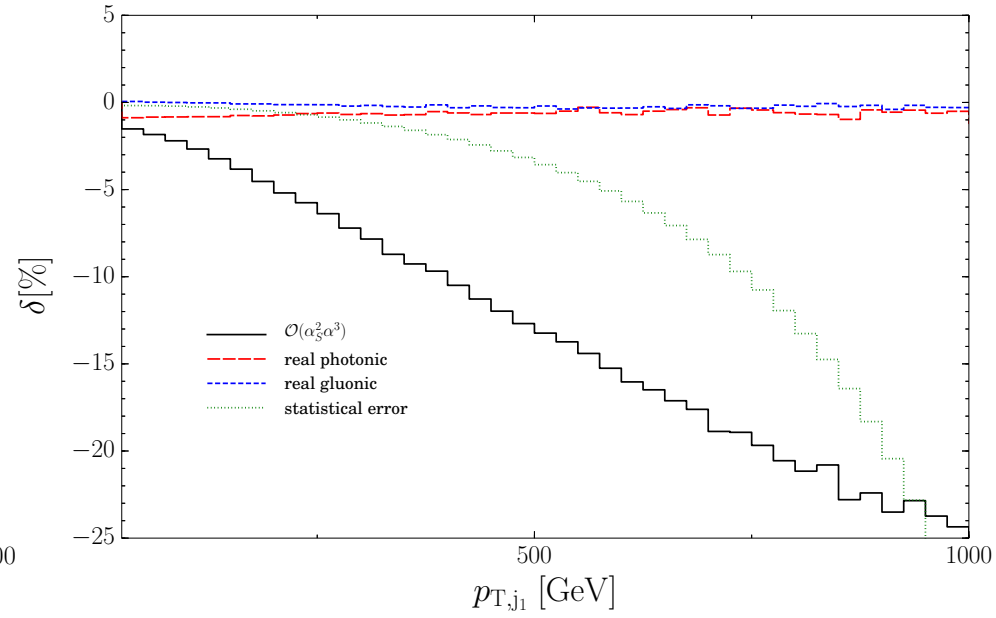
$$p_{\mathrm{T,j}} > 30\ \mathrm{GeV} \qquad |\eta_j| < 4.5 \qquad p_{\mathrm{T,l}} > 20\ \mathrm{GeV} \qquad |\eta_l| < 2.5$$

$$\Delta R_{jl^-} > 0.5 \qquad \Delta R_{jl^+} > 0.5 \qquad \Delta R_{l^+l^-} > 0.2$$

$$|y_{\mathrm{j}_1} - y_{\mathrm{j}_2}| > 4 \qquad y_{\mathrm{j}_1} \cdot y_{\mathrm{j}_2} < 0 \qquad \min(y_{\mathrm{j}_1}, y_{\mathrm{j}_2}) < y_l < \max(y_{\mathrm{j}_1}, y_{\mathrm{j}_2})$$

$$M_{\mathrm{jj}} > 600\ \mathrm{GeV} \qquad \text{photon energy fraction in jet } z_\gamma < 0.7$$





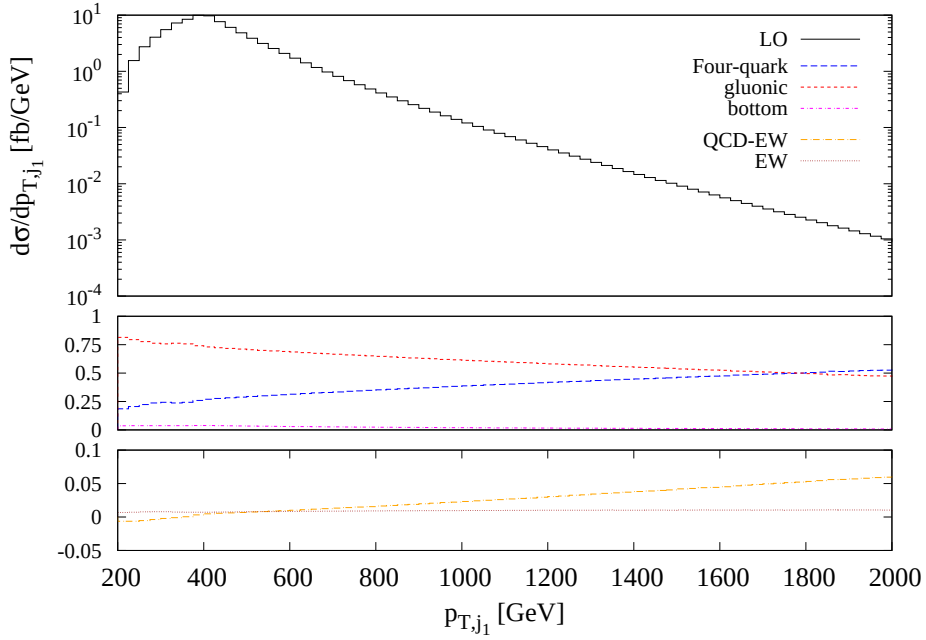
- Cross section reduced by factor 50 w.r.t. basic cuts
- EW Sudakov effects more sizeble than for basic cuts

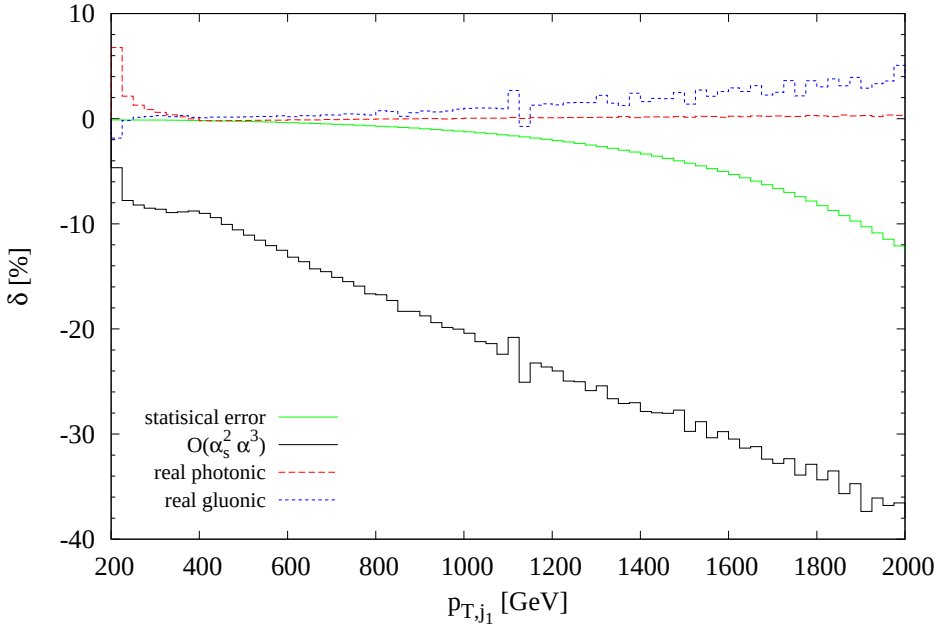
Electroweak corrections for $\mathrm{pp} \to \nu\bar{\nu}\, jj$ - ATLAS [1405.7875] cuts

$$p_{\mathrm{T,j1}} > 130\ \mathrm{GeV} \qquad p_{\mathrm{T,j2}} > 60\ \mathrm{GeV} \qquad |\eta_j| < 4.5$$

$$H_{\mathrm{T}} > 800\ \mathrm{GeV} \qquad \frac{\not{E}_{\mathrm{T}}}{\sqrt{H_{\mathrm{T}}}} > 8\ \sqrt{\mathrm{GeV}} \qquad \Delta\phi_{\not{E}_{\mathrm{T}} j} > 0.4$$

photon energy fraction in jet $z_\gamma < 0.7$





- Cross section reduced by factor 250 w.r.t. basic cuts
- EW corrections for total cross section around -10%

Fixed order computations for $pp \to V+ \geq 3$ jets

- QCD corrections to $pp \to W+ \leq 5j$

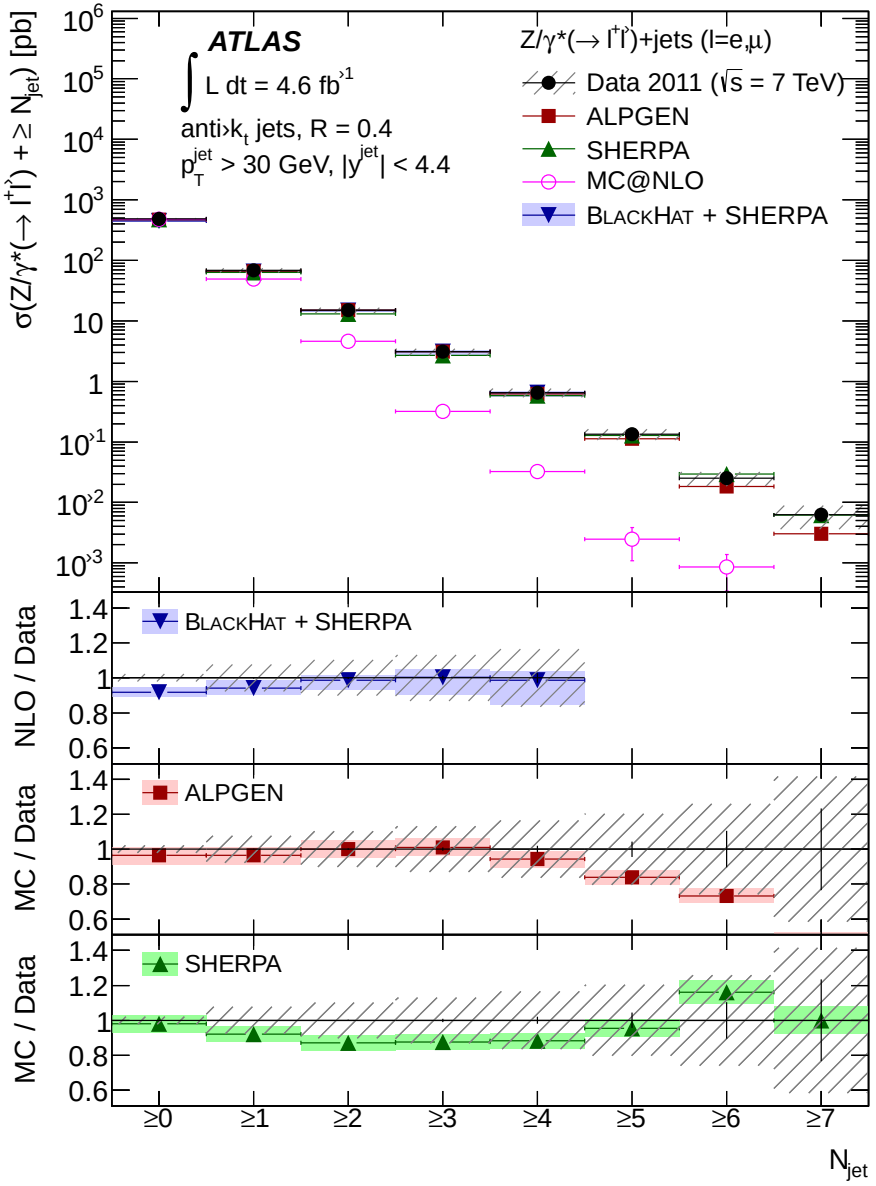
  [Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, Ozeren '13]

- QCD corrections for $pp \to Z+ \leq 4j$

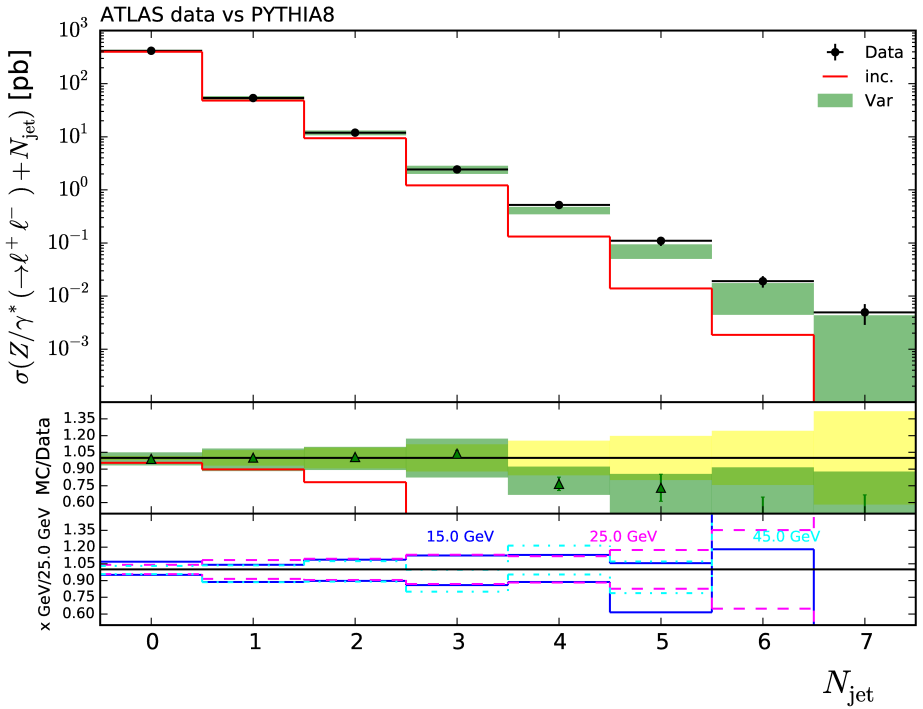
  [Ita, Bern, Dixon, Febres Cordero, Kosower, Maitre '11]

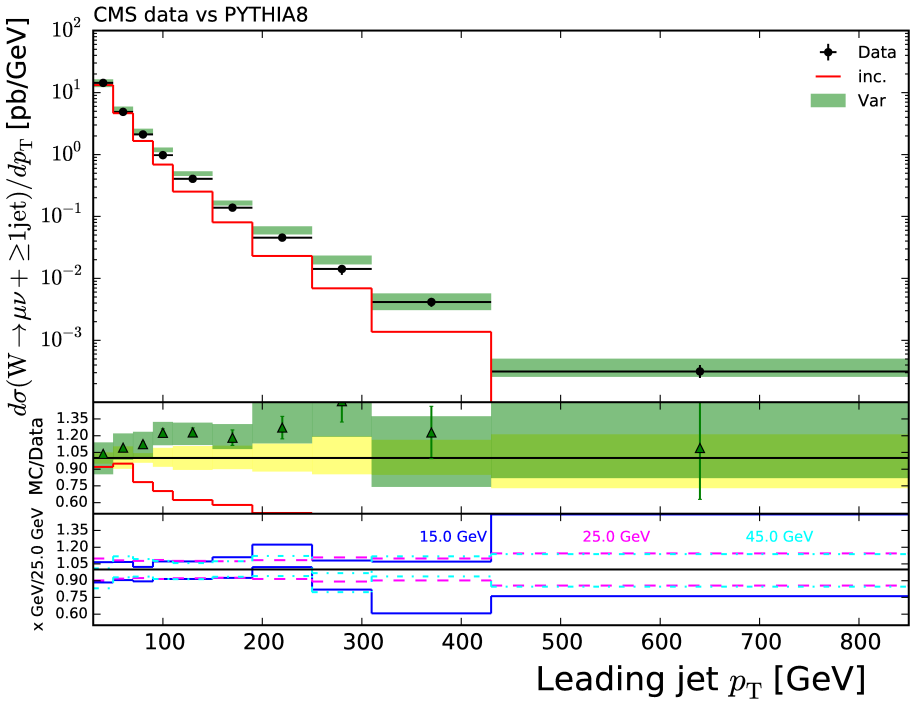
- QCD + EW corrections for $pp \to W+ \leq 3j$

  [Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '14]



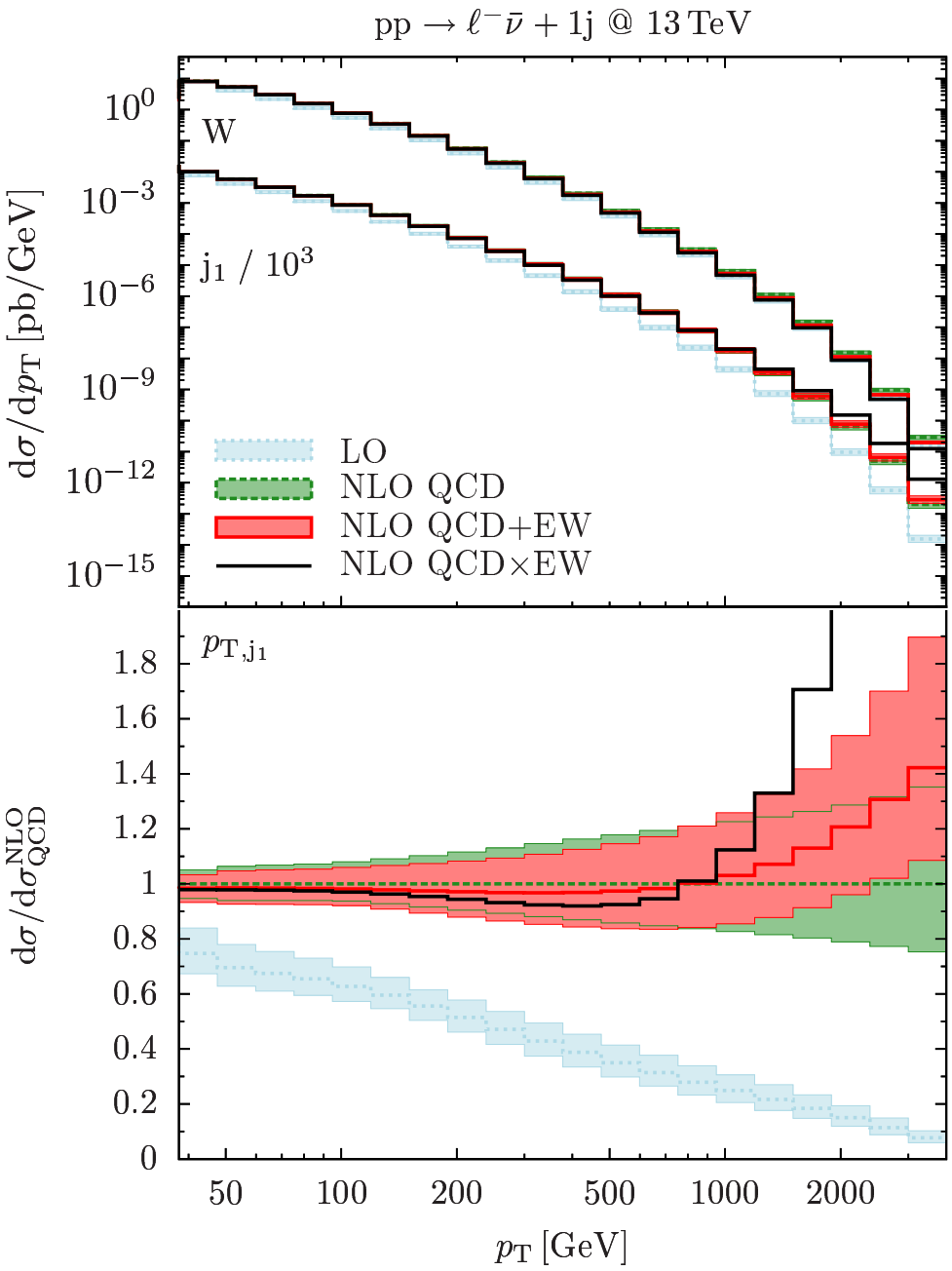
PS matching and merging for $\mathrm{pp} \to \mathrm{V}+ \leq 2\mathrm{j}$ at NLO QCD





Frederix, Frixione, Papaefstathiou, Prestel, Torielli '15

- Merging using NLO matrix elements up to 2 jets (LO up to 3 jets)
- Very good agreement with data also at high jet multiplicities
- Merging for $\mathrm{pp} \to \mathrm{V}+ \leq 3\mathrm{j}$ really needed?

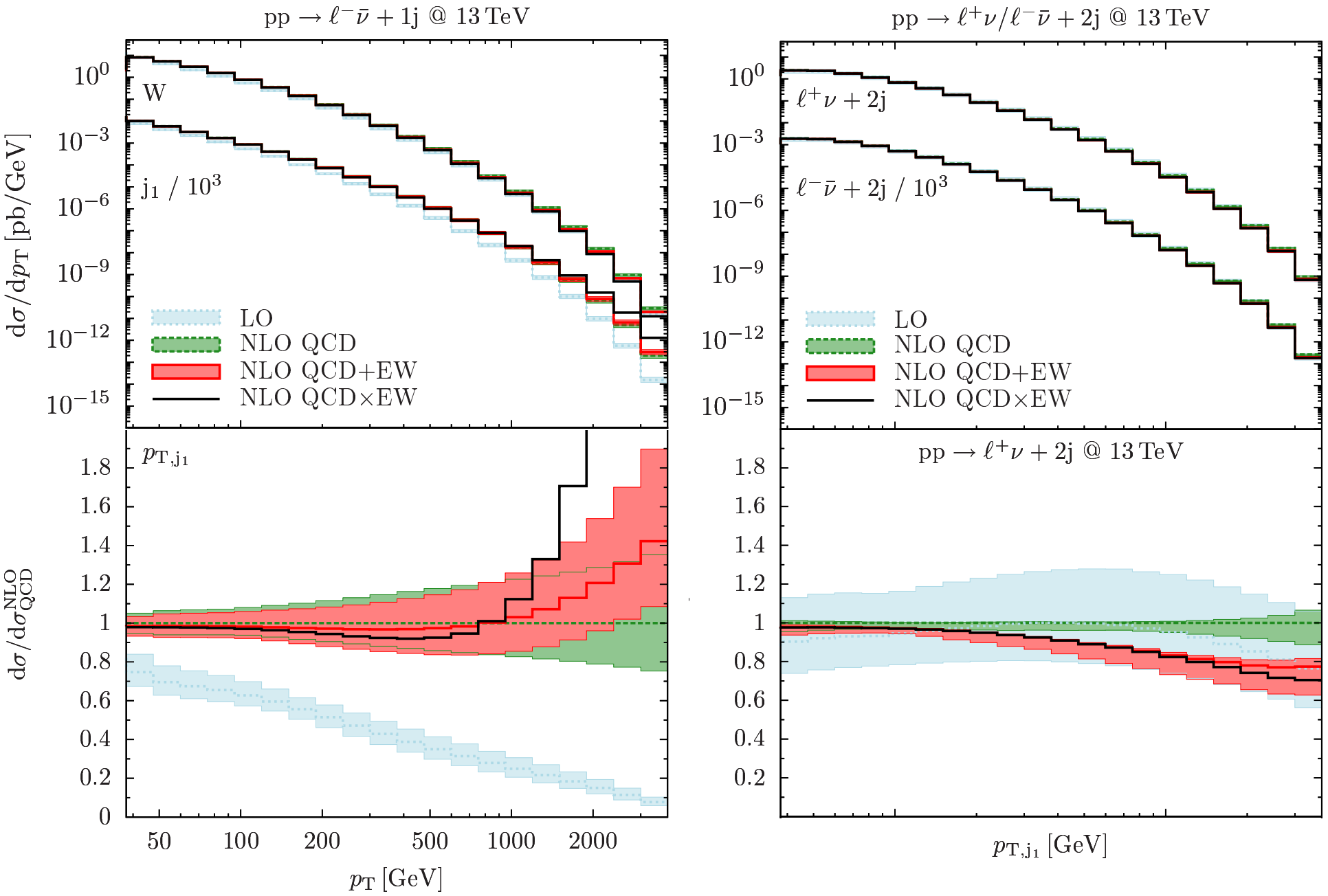


Combining QCD and EW corrections

$$pp \to V + 1 \text{ jet}$$

- Huge QCD corrections in the TeV region
- Typical negative EW corrections overwhelmed

Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '15


pp → ℓ⁻ν̄ + 1j @ 13 TeV
W
j1 / 10^3
LO
NLO QCD
NLO QCD+EW
NLO QCD×EW
dσ/dpT [pb/GeV]
pT,j1
dσ/dσ^NLO_QCD
pT [GeV]
pp → ℓ⁺ν/ℓ⁻ν̄ + 2j @ 13 TeV
ℓ⁺ν + 2j
ℓ⁻ν̄ + 2j / 10^3
pp → ℓ⁺ν + 2j @ 13 TeV
pT,j1 [GeV]

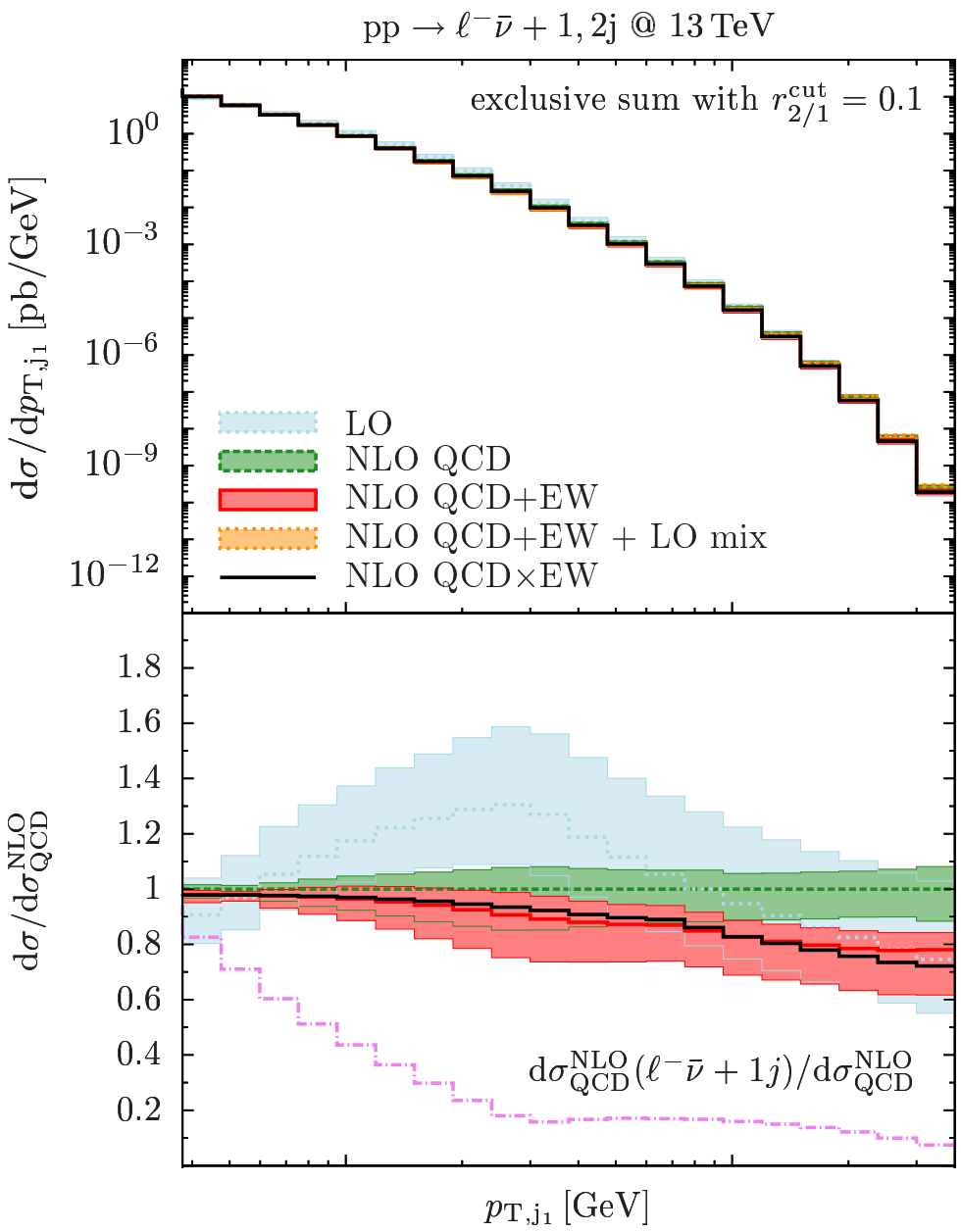
Merging 1, 2j via exclusive sums

$$r_{2/1} = \frac{p_{\mathrm{T}j_2}}{p_{\mathrm{T}j_1}}$$

Phase-space populated by:

$$\mathrm{V}+1\mathrm{j} \quad \text{for} \quad r_{2/1} < r_{2/1}^{\mathrm{cut}}$$
$$\mathrm{V}+2\mathrm{j} \quad \text{for} \quad r_{2/1} > r_{2/1}^{\mathrm{cut}}$$

- QCD corrections stabilized
- Typical negative EW corrections



PS matching and merging $pp \to V+ \leq 2j$ at NLO QCD + EW

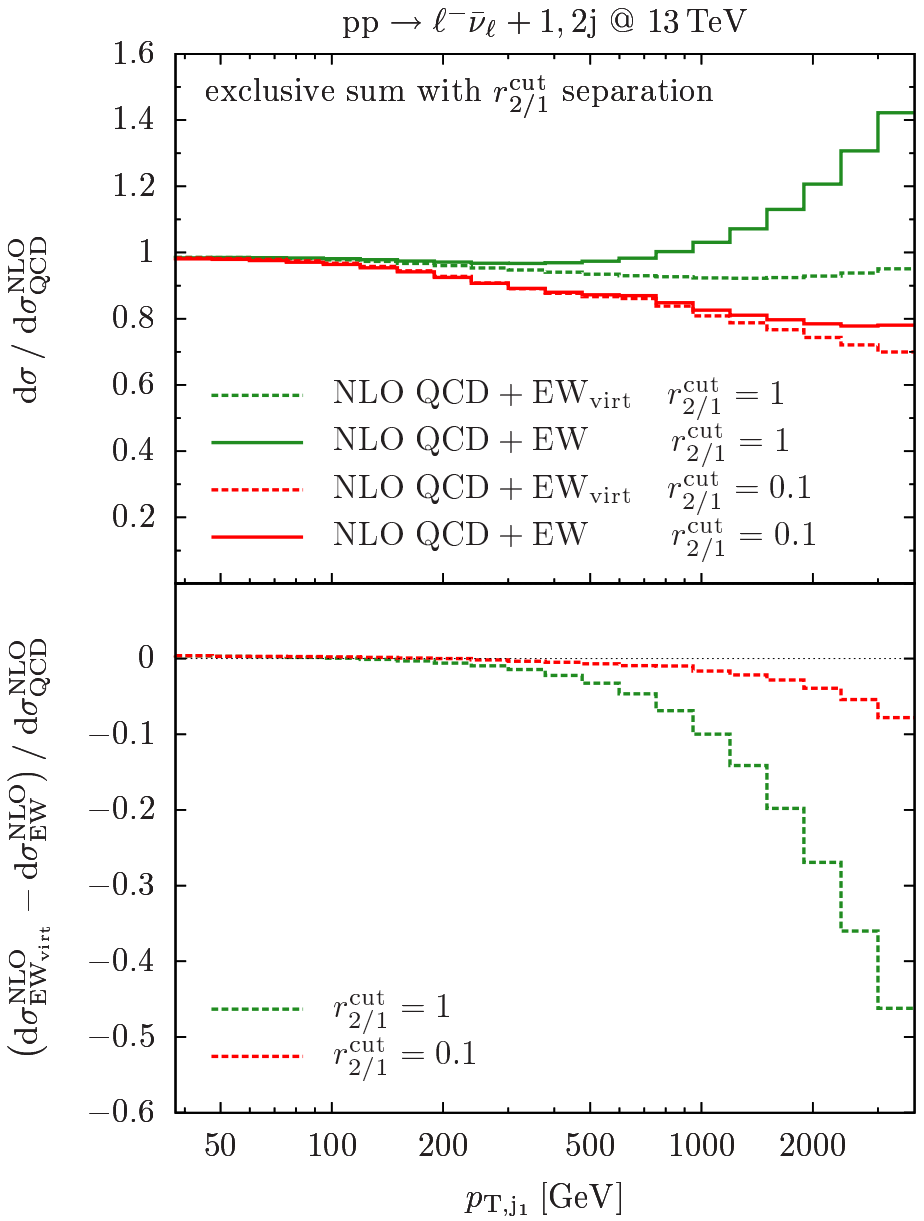
EW_{virt} = EW virtual correction +

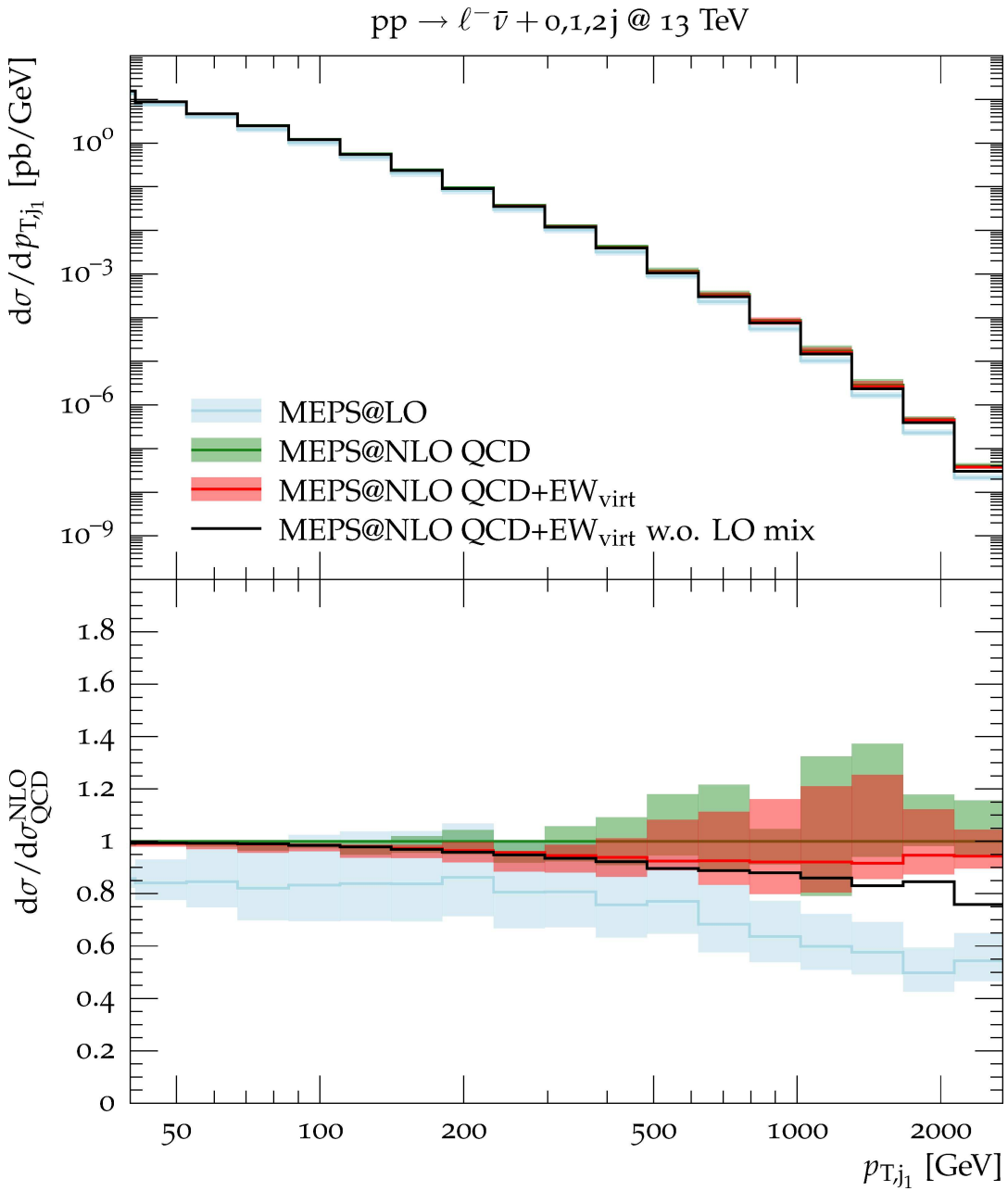
Integrated dipoles

$\rightsquigarrow$ i.e. soft/collinear emission treated inclusively

- Describes well $pp \to V+1,2\,\text{jets}$ at NLO QCD+EW
- EW Sudakov effect reproduced

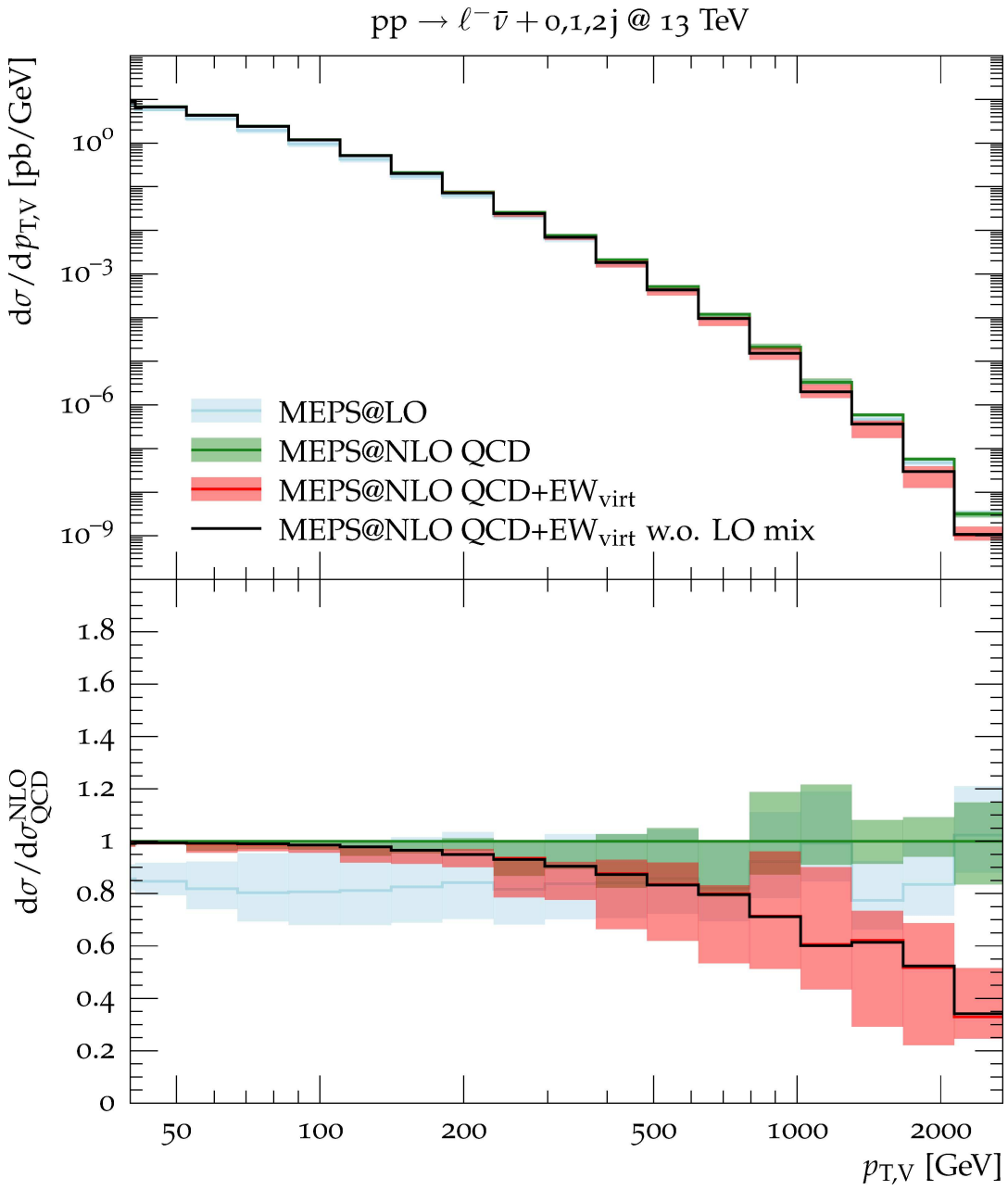
Insert EW corrections in the MEPS@NLO framework using EW_{virt}





Distribution in p_T of the hardest jet

- No enhanced QCD behaviour at high p_T
- Small EW Sudakov effects (canceled by LO mix)



Distribution in p_{T} of the Vector boson

- No enhanced behaviour at high p_T
- Large EW Sudakov effects
- Quantitatively consistent with factorized QCD$\times$EW prescription

$\mathrm{pp} \to t\bar{t} + \mathrm{H}, \mathrm{V}$

$\mathrm{pp} \to t\bar{t} + \mathrm{H}$:

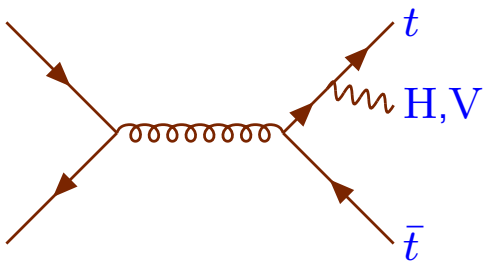
- QCD corrections (on-shell t, $\bar{t}$ and H) matched with parton shower
  [Frederix, Frixione, Hirschi, Maltoni, Pittau '11]
  [Gaezelli, Kardos, Papadopoulos, Trócsányi '11]
  [Hartanto, Jäger, Reina, Wackeroth '15]
- QCD corrections to $\mathrm{pp} \to t\bar{t}\,b\bar{b}$ (on-shell t, $\bar{t}$) matched with parton shower
  [Bredenstein, Denner, Dittmaier, Pozzorini '09]
  [Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09]
  [Kardos, Trócsányi '13]
  [Cascioli, Maierhfer, Moretti, Pozzorini, Siegert '13]
- QCD and EW corrections (on-shell t, $\bar{t}$ and H)
  [Frixione, Hirschi, Pagani, Shao, Zaro '14]
  [Yu, Wen-Gan, Ren-You, Chong, Lei '14]
- QCD corrections to $\mathrm{pp} \to e^+\nu_e b\,\mu^-\bar{\nu}_\mu\bar{b}\,\mathrm{H}$ [Denner, Feger '15]

$\mathrm{pp} \to t\bar{t} + \mathrm{V}$:

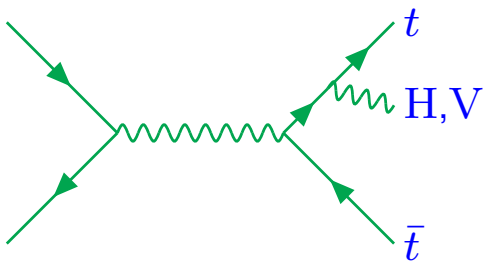
- QCD and EW corrections (on-shell t, $\bar{t}$ and V)
  [Frixione, Hirschi, Pagani, Shao, Zaro '15]

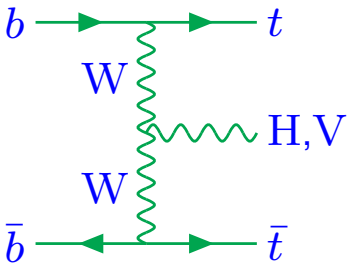
$\mathrm{pp} \to t\bar{t} + \mathrm{H, V}$ at LO:

QCD LO $\mathcal{O}(g_s^2 e)$



EW LO $\mathcal{O}(e^3)$





Tiny QCD-EW interference at LO $\rightsquigarrow$ $|\text{QCD LO}|^2$ dominates at LO

$\mathrm{pp} \to t\bar{t} + \mathrm{H, V}$ at NLO:

$\mathcal{O}(\alpha_s^3 \alpha)$: QCD corrections to QCD diagrams — NLO QCD

$\mathcal{O}(\alpha_s^2 \alpha^2)$: EW corrections to QCD diagrams
QCD corrections to EW-QCD interferences — NLO EW

...

		$\sigma_{\mathrm{LO}}(\mathrm{pb})$	$\delta_{\mathrm{QCD}}[\%]$	$\delta_{\mathrm{EW}}[\%]$	$\delta_{\mathrm{HBR}}[\%]$
$t\bar{t}H$	13 TeV	$3.617 \cdot 10^{-1}$	$29.7^{+6.8}_{-11.1} \pm 2.8$	-1.4 ± 0.0	0.89
	13 TeV*	$1.338 \cdot 10^{-2}$	$24.2^{+4.8}_{-10.6} \pm 4.5$	-8.5 ± 0.2	1.87
	100 TeV	23.57	$40.8^{+9.3}_{-9.1} \pm 1.0$	-2.7 ± 0.0	0.91
$t\bar{t}Z$	13 TeV	$5.282 \cdot 10^{-1}$	$45.9^{+13.2}_{-15.5} \pm 2.9$	-4.1 ± 0.1	0.96
	13 TeV*	$1.955 \cdot 10^{-2}$	$40.2^{+11.1}_{-15.0} \pm 4.7$	-11.5 ± 0.3	2.13
	100 TeV	37.69	$50.4^{+11.4}_{-10.9} \pm 1.1$	-5.4 ± 0.0	0.85
$t\bar{t}W^+$	13 TeV	$2.496 \cdot 10^{-1}$	$50.1^{+14.2}_{-13.5} \pm 2.4$	-8.0 ± 0.2	3.88
	13 TeV*	$7.749 \cdot 10^{-3}$	$59.7^{+18.9}_{-17.7} \pm 3.1$	-20.0 ± 0.5	7.41
	100 TeV	3.908	$156.4^{+38.3}_{-35.0} \pm 2.4$	-9.6 ± 0.1	21.52
$t\bar{t}W^-$	13 TeV	$1.265 \cdot 10^{-1}$	$51.5^{+14.8}_{-13.8} \pm 2.8$	-7.0 ± 0.2	6.50
	13 TeV*	$3.186 \cdot 10^{-3}$	$66.3^{+21.7}_{-19.6} \pm 3.9$	-19.1 ± 0.6	15.01
	100 TeV	2.833	$153.6^{+37.7}_{-34.9} \pm 2.2$	-8.8 ± 0.1	28.91

* = $p_T(t, \bar{t}, H, V) > 200\,\mathrm{GeV}$

- Large EW corrections at high p_{T}, but inside QCD scale uncertainties
- Effect of Heavy Boson Radiation (HBR) not negligible for $t\bar{t}W$

$pp \to VV$

$\mathrm{pp} \to \mathrm{Z}\gamma, \mathrm{W}\gamma$:

- NLO + PS QCD corrections to $\mathrm{pp} \to l^+\nu\gamma, l^-\bar{\nu}\gamma$
  [Barzè, Chiesa, Montagna, Nason, Nicrosini, Piccinini, Prosperi '14]
- NNLO QCD corrections to $\mathrm{pp} \to l^+l^-\gamma, \nu\bar{\nu}\gamma, l^+\nu\gamma, l^-\bar{\nu}\gamma$
  [Grazzini, Kallweit, Rathlev '15]
- NLO EW corrections to $\mathrm{pp} \to l^+\nu\gamma$
  [Denner, Dittmaier, Hecht, Pasold '14]
- NLO EW corrections to $\mathrm{pp} \to l^+l^-\gamma, \nu\bar{\nu}\gamma$
  [Denner, Dittmaier, Hecht, Pasold '15]

$$\sigma^{\rm NLO} = \sigma^{\rm LO}\,(1+\delta_{\rm QCD})\,(1+\delta_{{\rm EW},q\bar{q}}+\delta_{{\rm EW},q\gamma})$$

Basic cuts:

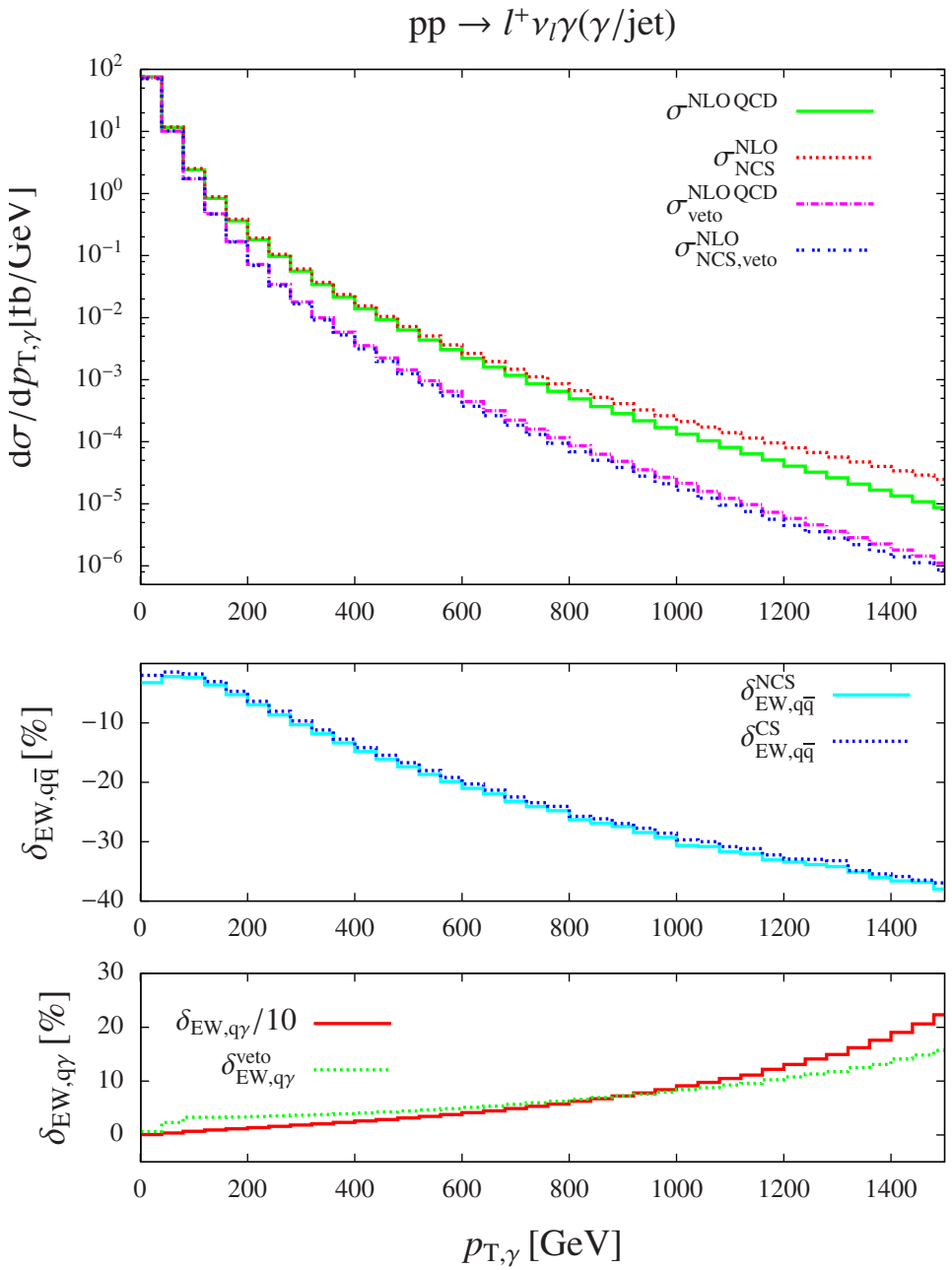
$$p_{{\rm T},\gamma} > 15\,{\rm GeV} \qquad |\eta_\gamma| < 2.5$$

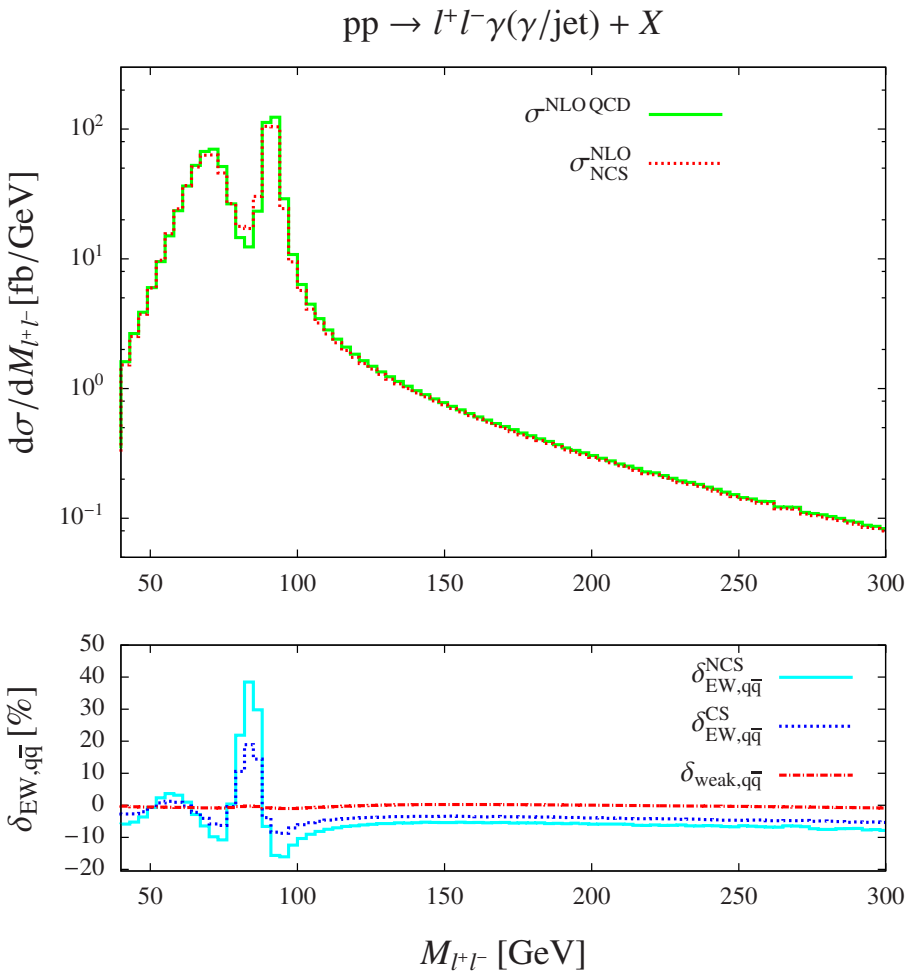
$$p_{{\rm T,l}} > 25\,{\rm GeV} \qquad |\eta_l| < 2.5$$

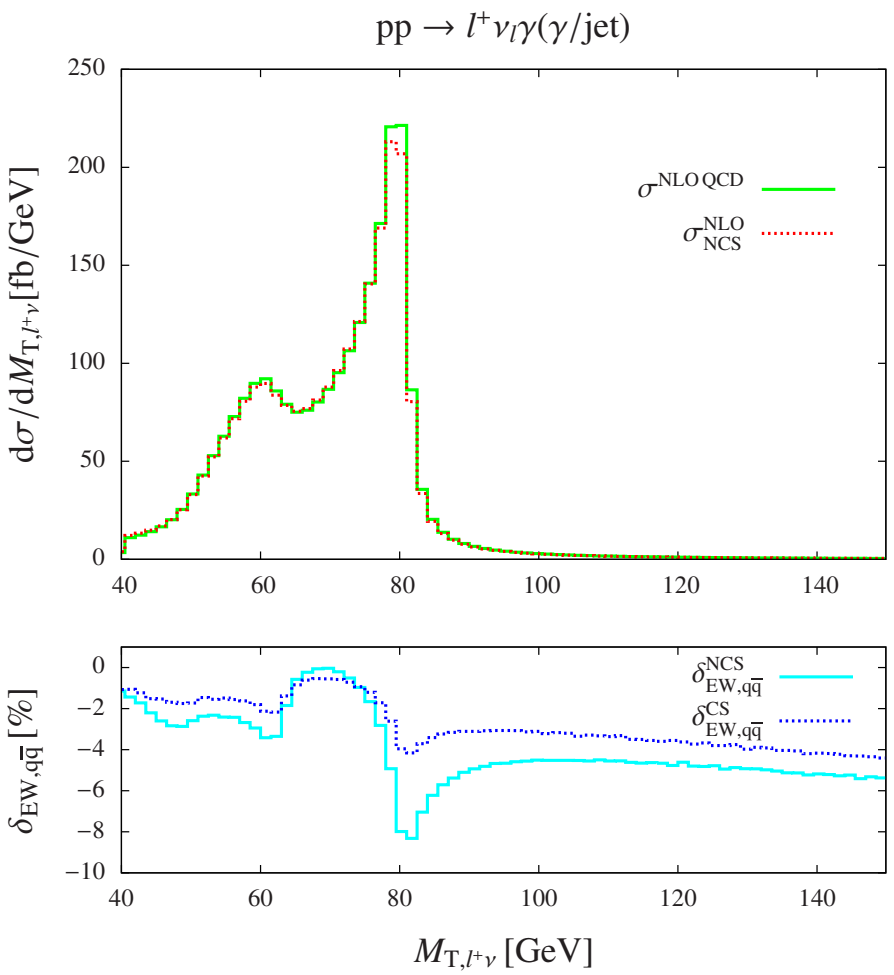
$$\Delta R_{l\gamma} > 0.7 \qquad M_{ll}, M_{\bar{l}\nu} > 40\,{\rm GeV}$$

Photon energy fraction in jet $z_\gamma > 0.9$

- Large EW corrections at high $p_{\rm T}$
- $\delta_{{\rm EW},q\gamma}$ huge at high $p_{\rm T}$
- $\delta_{{\rm EW},q\gamma}$ plagued by large uncertainties in photon PDF



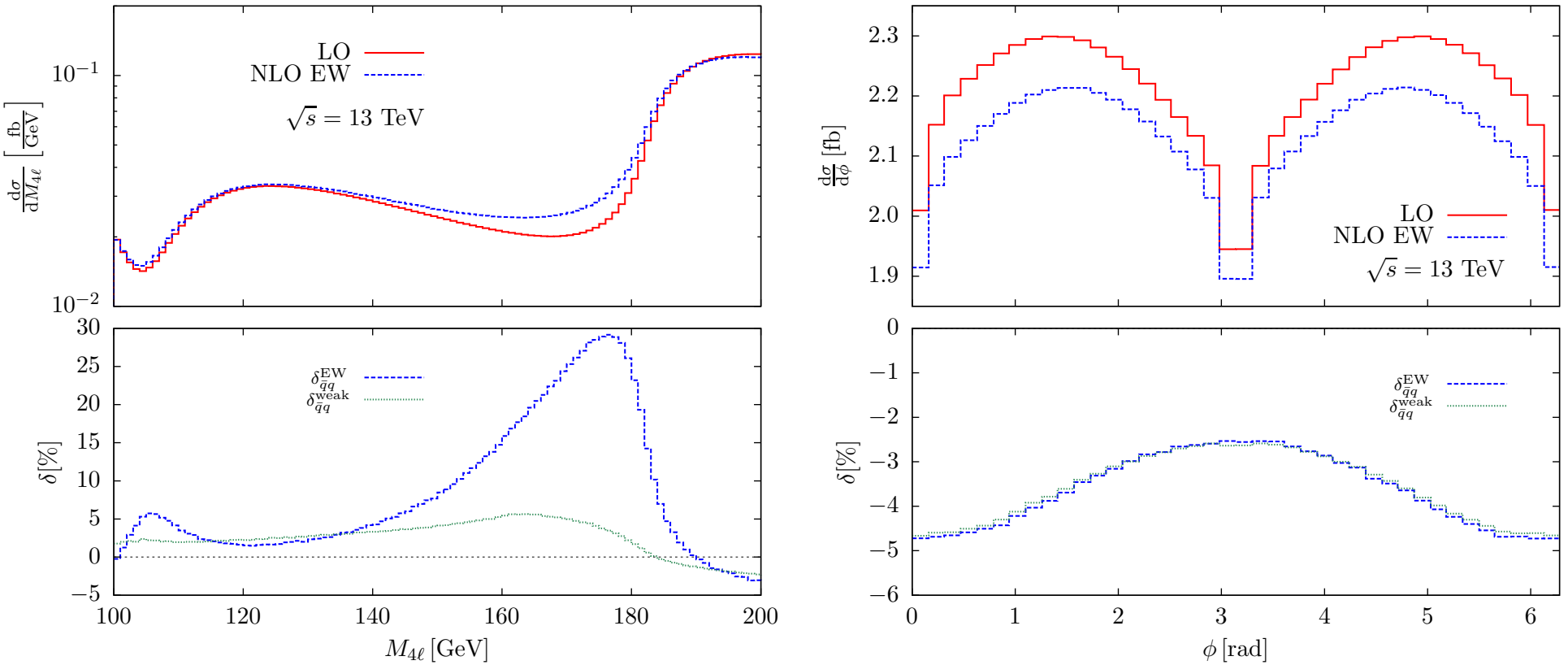




- Large photonic corrections (well described by parton shower) in $M_{l^+l^-}$ distribution
- EW corrections of some percent in $M_{l^+\nu}$ distribution

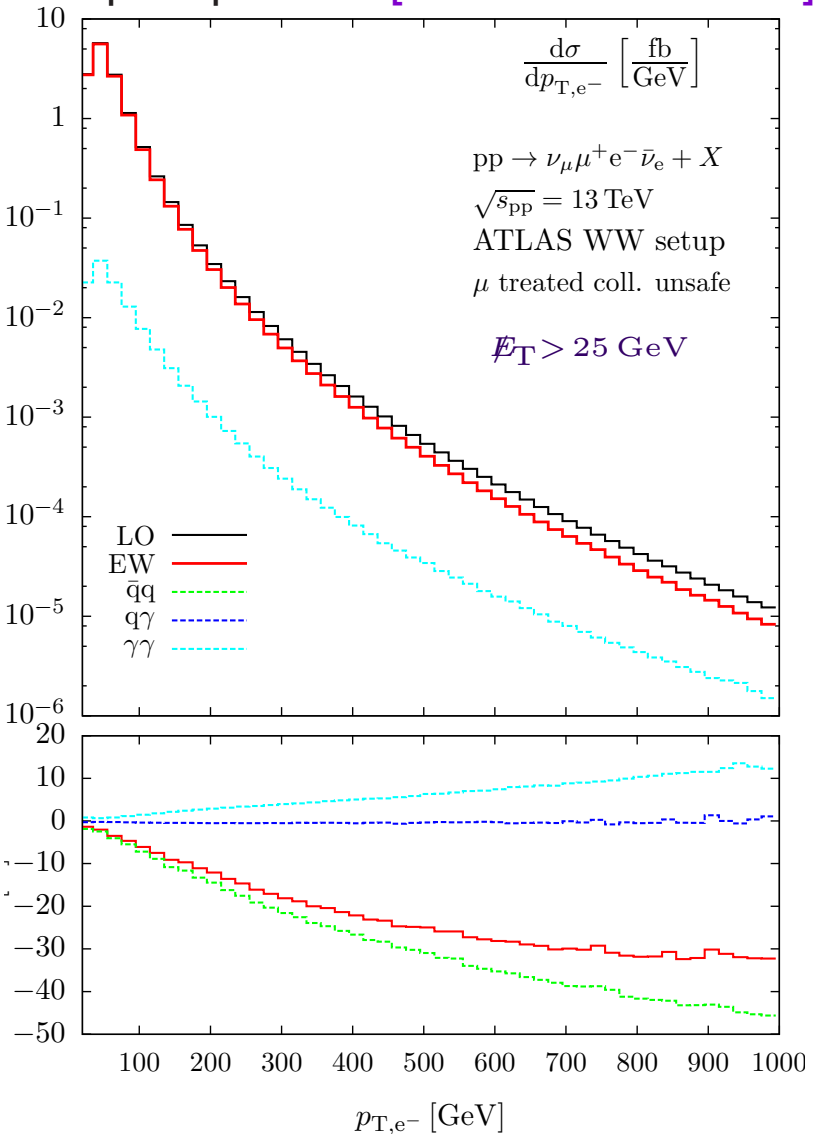
$\mathrm{pp} \to \mathrm{WW}, \mathrm{WZ}, \mathrm{ZZ}$:

- NLO + PS QCD corrections [Melia, Nason, Rontsch, Zanderighi '11] [Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli '11] [Nason, Zanderighi '13]
- NNLO QCD corrections to $\mathrm{pp} \to l^{(\prime)+} l^{(\prime)-} l^+ l^-$ [Grazzini, Kallweit, Rathlev '15]
- NNLO QCD corrections to $\mathrm{pp} \to l^{(\prime)+} \nu_{l^{(\prime)}} l^+ l^-, l^{(\prime)-} \bar{\nu}_{l^{(\prime)}} l^+ l^-$ [Grazzini, Kallweit, Rathlev, Wiesemann '16]
- NNLO QCD corrections to $\mathrm{pp} \to \mu^+ \nu_\mu \, e^- \bar{\nu}_e$ [Grazzini, Kallweit, Pozzorini, Rathlev, Wiesemann '16]
- NLO EW corrections to $\mathrm{pp} \to \mu^+ \mu^- e^+ e^-, \mu^+ \nu_\mu \, e^- \bar{\nu}_e$ [Biedermann, Denner, Dittmaier, Hofer, Jäger '16]



- Large photonic corrections (can be well described by parton shower)
- Weak corrections change sign (from -3% to $+6\%$)
  - ⇝ can not be described by a global rescaling
- Percent EW corrections in ϕ distribution
  (ϕ is the angle between the two Z decay planes)

Setup inspired to [ATLAS 1210.2979]



$p_{T,l} > 20\,GeV$

$p_{T,l}^{lead.} > 25\,GeV$

$|\eta_l| < 2.5$

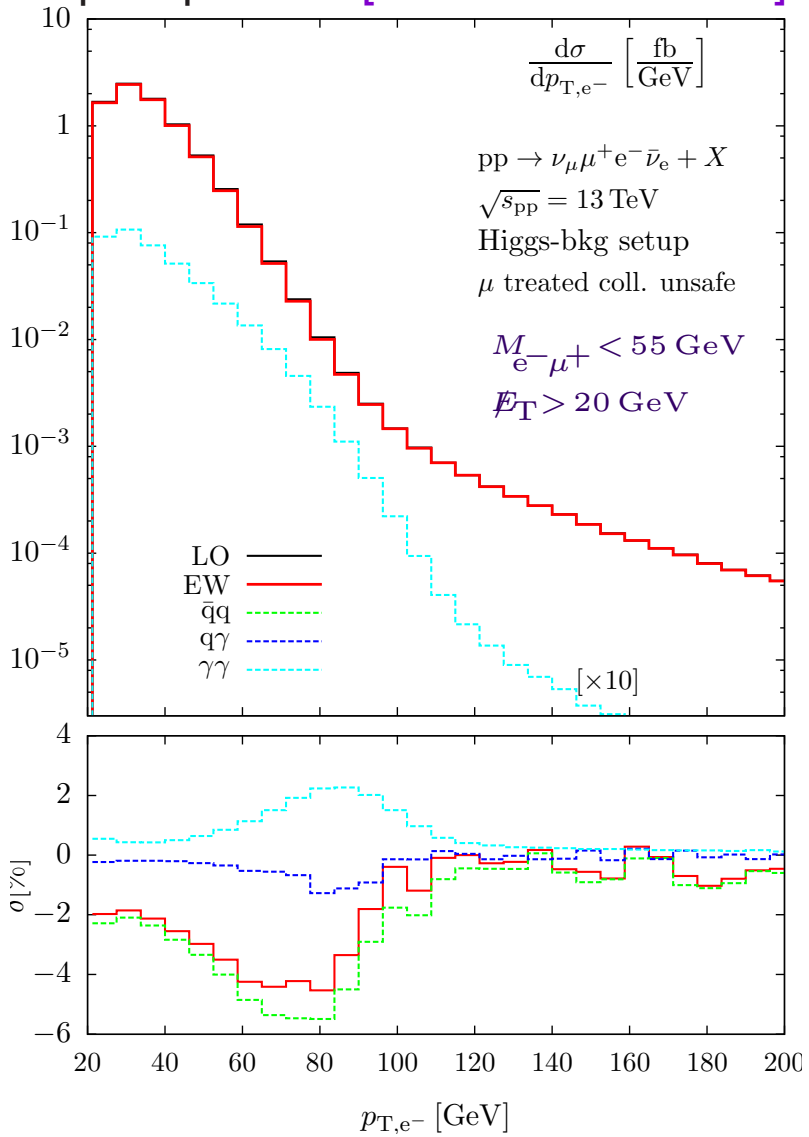
$\Delta R_{e^-\mu^+} > 0.1$

$M_{e^-\mu^+} > 10\,GeV$

$\Delta R_{jet,l} > 0.4$

$p_{T,jet} < 25\,GeV$

Setup inspired to [ATLAS 1412.2641]



EW corrections $\sim -20\%$ at $p_{T,e^-} \sim 400\,GeV$

EW corrections significant only for $p_{T,e^-} < 100\,GeV$

Conclusions

- Large negative EW corrections at TeV scale in all fixed order computations
- Efficient automatization for elementary EW and QCD processes at NLO
- First implementations of EW NLO in general-purpose MC generators
- Attempts to combine EW corrections with QCD in the merging procedure

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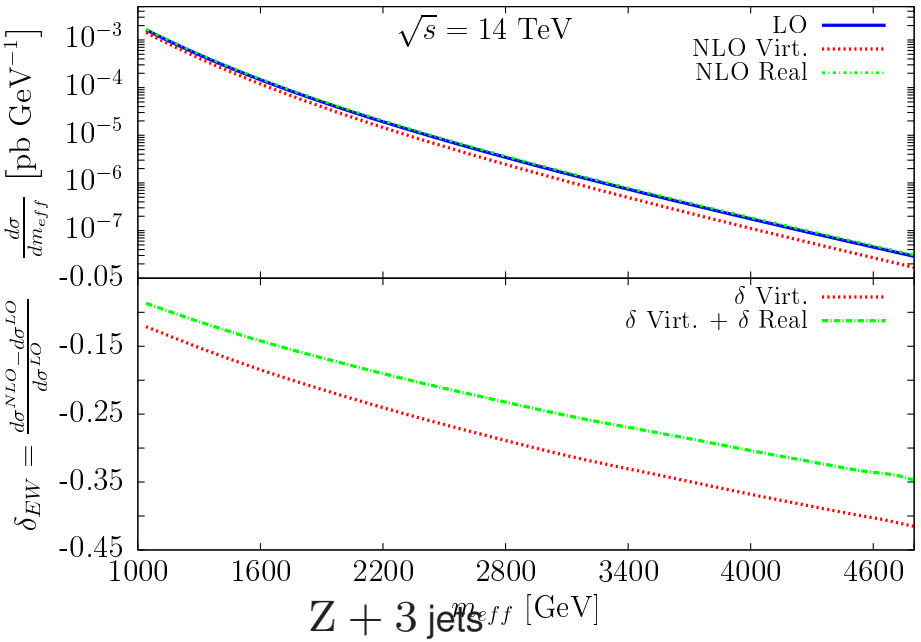
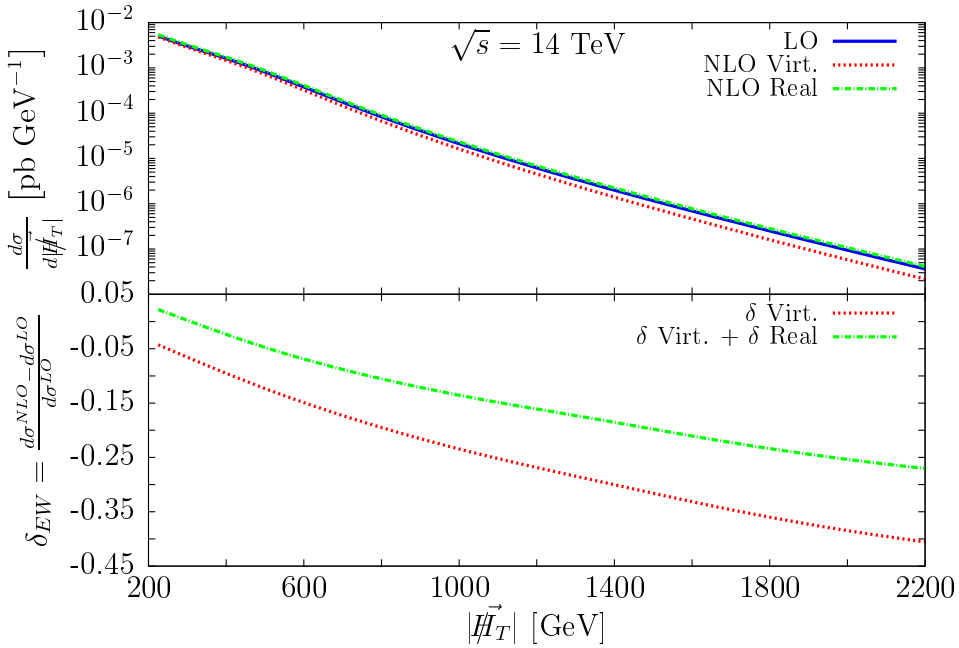
Back-up slides

Electroweak corrections for $pp \to \nu\bar{\nu} + 2, 3$ jets in Sudakov limit

[Chiesa, Montagna, Barzè, Moretti, Nicrosini, Piccinini, Tramontano '13]





- Virtual Sudakov LL+NLL effects implemented in ALPGEN in a process indipendent way
- Large negative corrections in the TeV region
- Study of real emission of Vector Bosons with the same signature, which partially cancels the virtual Sudakov effects.

Basic cuts: motivated by [ATLAS '13]

$$p_{\mathrm{T,j}} > 30\ \mathrm{GeV} \qquad |\eta_j| < 4.5 \qquad p_{\mathrm{T,l}} > 20\ \mathrm{GeV} \qquad |\eta_l| < 2.5$$

$$\Delta R_{jl} > 0.5 \qquad \Delta R_{l^+l^-} > 0.2 \qquad 66\ \mathrm{GeV} < M_{l^+l^-} < 116\ \mathrm{GeV}$$

photon energy fraction in jet $z_\gamma < 0.7$

LHC - 13 TeV - Basic cuts - Total cross section

process class	σ^{LO} [fb]	$\sigma^{\mathrm{LO}}/\sigma^{\mathrm{LO}}_{\mathrm{tot}}$ [%]	$\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$ [fb]	$\frac{\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{\sigma^{\mathrm{LO}}} - 1$ [%]
gluonic	40910(8)	79.9	39932(9)	- 2.39
four-quark	10299(1)	20.1	10033(1)	- 2.58
sum	51209(8)	100	49965(9)	- 2.43
bottom quarks	4376(3)	8.54		

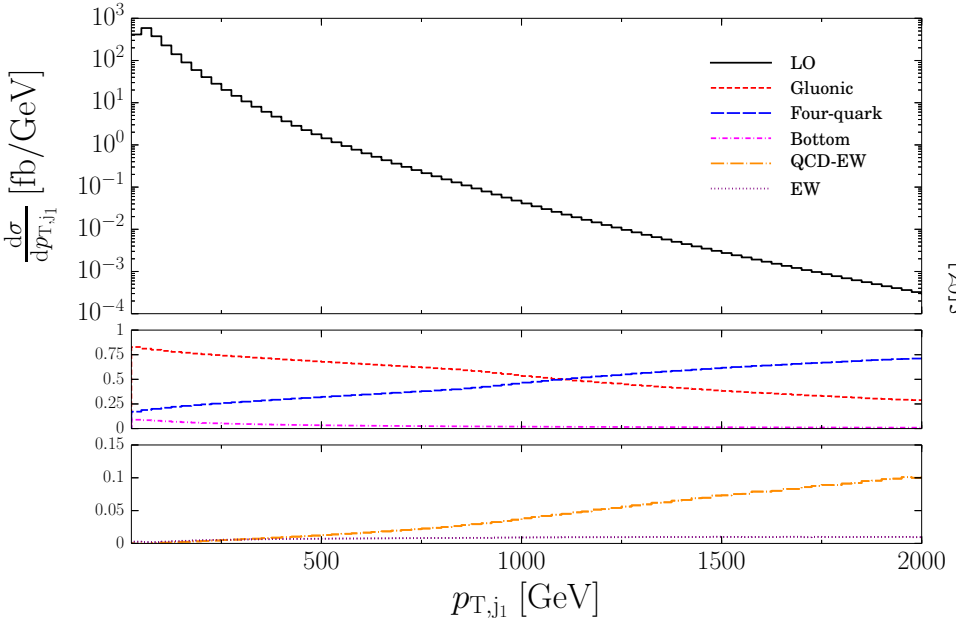
- $q\,g \to q\,g\,l^-\,l^+$ channels dominate
- Small EW corrections for total cross section

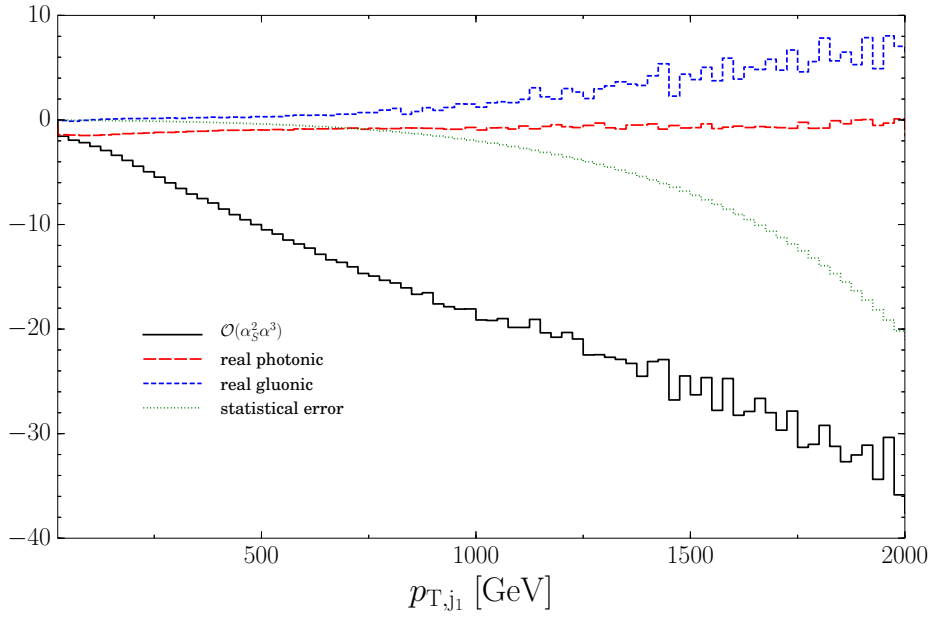
Electroweak corrections for $\mathrm{pp} \to l^+ l^- j j$ - Basic cuts

$$p_{\mathrm{T,j}} > 30\ \mathrm{GeV} \qquad |\eta_j| < 4.5 \qquad p_{\mathrm{T,l}} > 20\ \mathrm{GeV} \qquad |\eta_l| < 2.5$$

$$\Delta R_{jl} > 0.5 \qquad \Delta R_{l^+l^-} > 0.2 \qquad 66\ \mathrm{GeV} < M_{l^+l^-} < 116\ \mathrm{GeV}$$

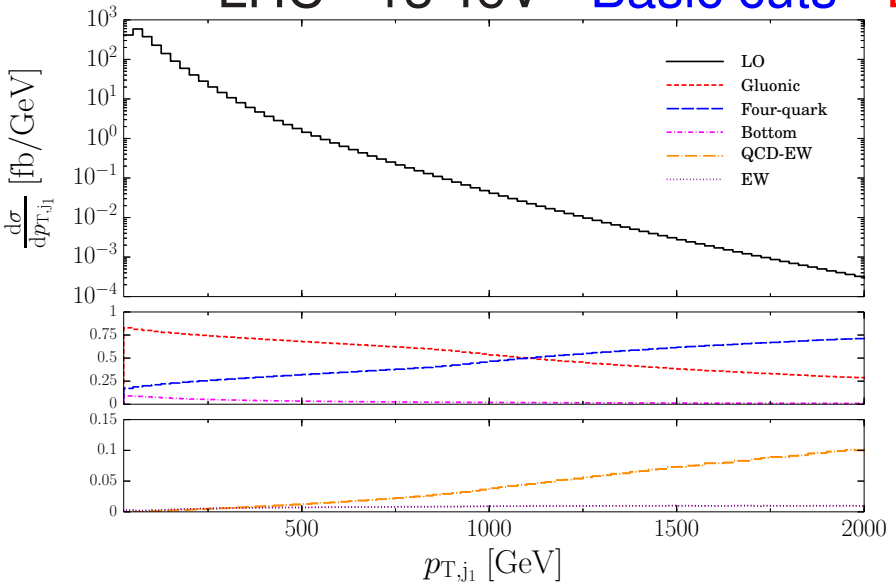
photon energy fraction in jet $z_\gamma < 0.7$

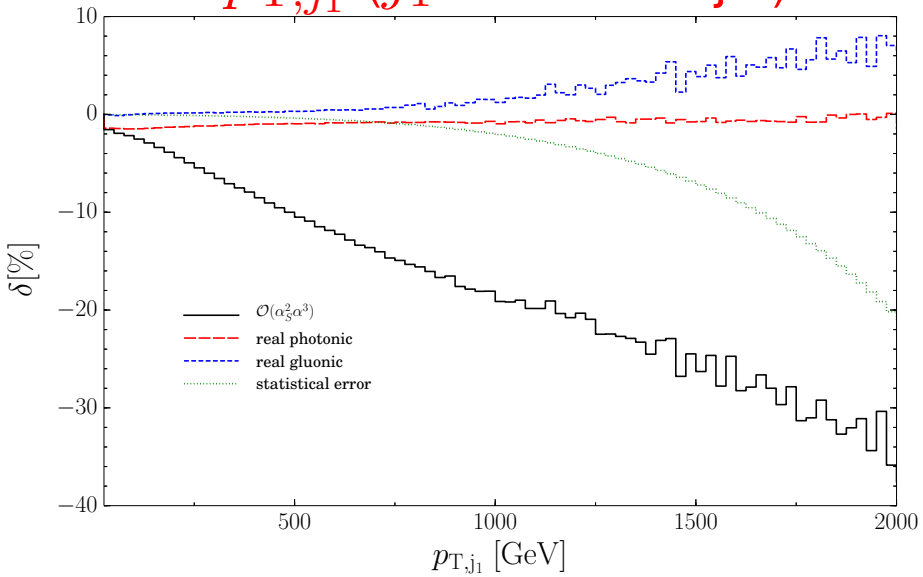




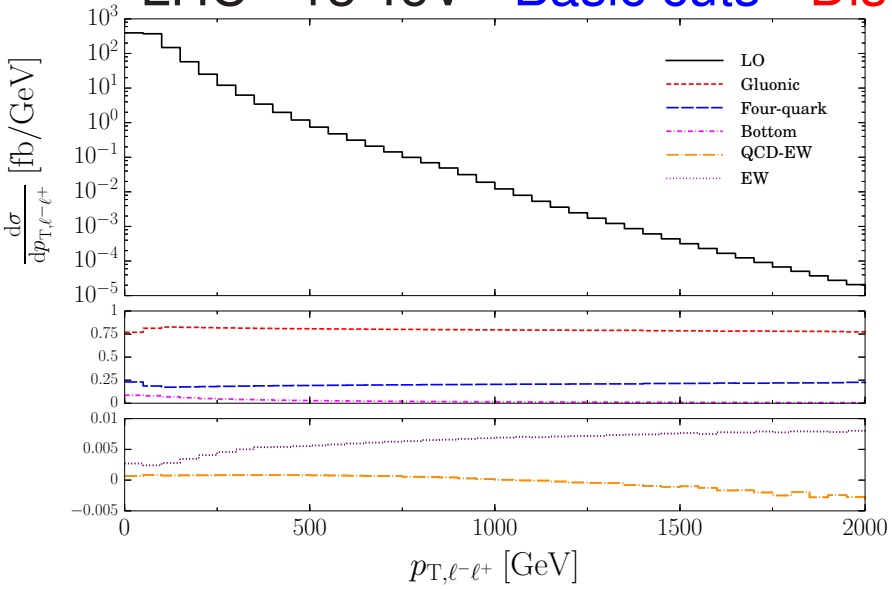
- EW Sudakov effects at high p_{T}
- Small corrections from real + dipoles

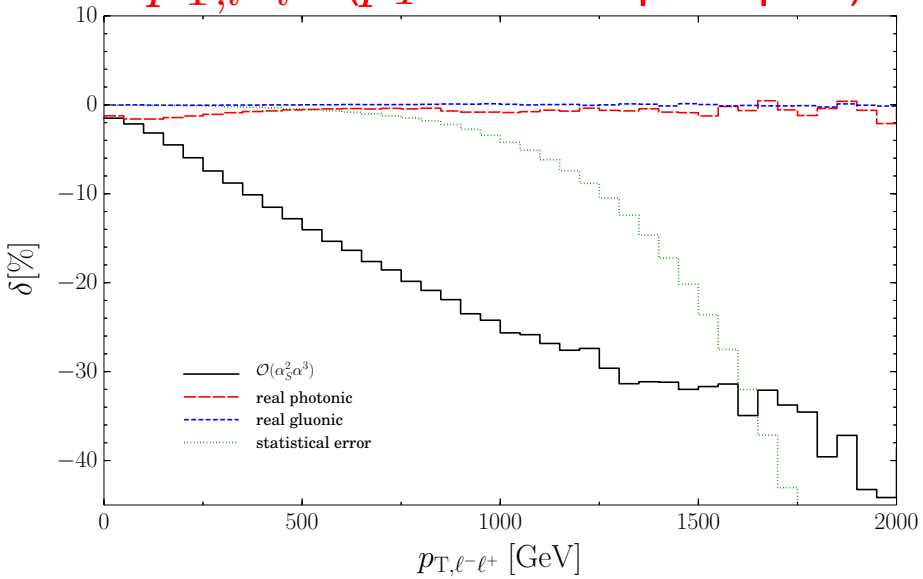
LHC - 13 TeV - Basic cuts - Distribution in p_{T,j_1} (j_1 = hardest jet)





LHC - 13 TeV - Basic cuts - Distribution in p_{T,l^-l^+} (p_T of the lepton pair)





Vector boson fusion (VBF) cuts:

$$p_{\mathrm{T,j}} > 30\ \mathrm{GeV} \qquad |\eta_j| < 4.5 \qquad p_{\mathrm{T,l}} > 20\ \mathrm{GeV} \qquad |\eta_l| < 2.5$$

$$\Delta R_{jl^-} > 0.5 \qquad \Delta R_{jl^+} > 0.5 \qquad \Delta R_{l^+l^-} > 0.2$$

$$|y_{\mathrm{j}_1} - y_{\mathrm{j}_2}| > 4 \qquad y_{\mathrm{j}_1} \cdot y_{\mathrm{j}_2} < 0 \qquad \min(y_{\mathrm{j}_1}, y_{\mathrm{j}_2}) < y_l < \max(y_{\mathrm{j}_1}, y_{\mathrm{j}_2})$$

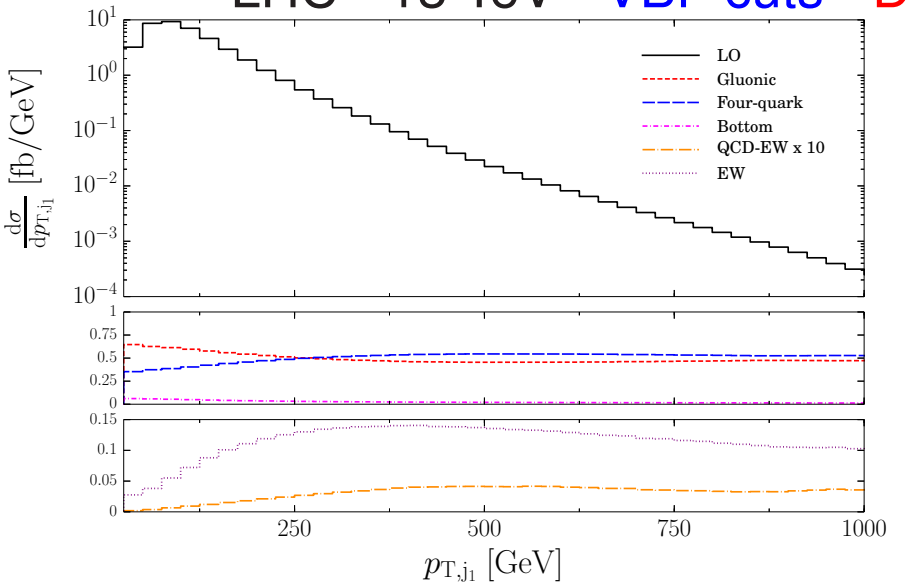
$$M_{\mathrm{jj}} > 600\ \mathrm{GeV} \qquad \text{photon energy fraction in jet } z_\gamma < 0.7$$

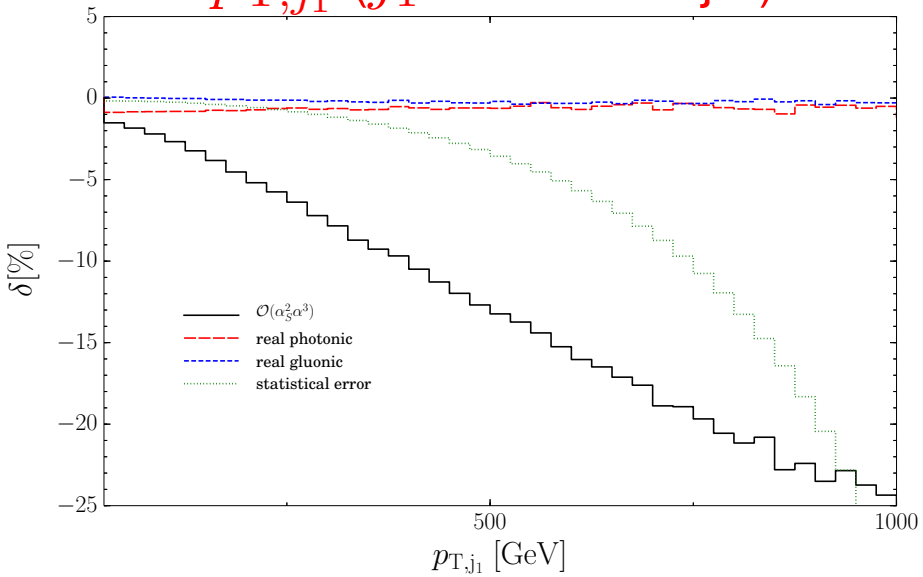
LHC - 13 TeV - VBF cuts - Total cross section

process class	σ^{LO} [fb]	$\sigma^{\mathrm{LO}}/\sigma^{\mathrm{LO}}_{\mathrm{tot}}$ [%]	$\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$ [fb]	$\frac{\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{\sigma^{\mathrm{LO}}} - 1$ [%]
gluonic	617.8(4)	59.4	599.2(3)	- 3.01
four-quark	421.7(1)	40.6	410.2(1)	- 2.73
sum	1039.6(4)	100	1009.3(3)	- 2.91

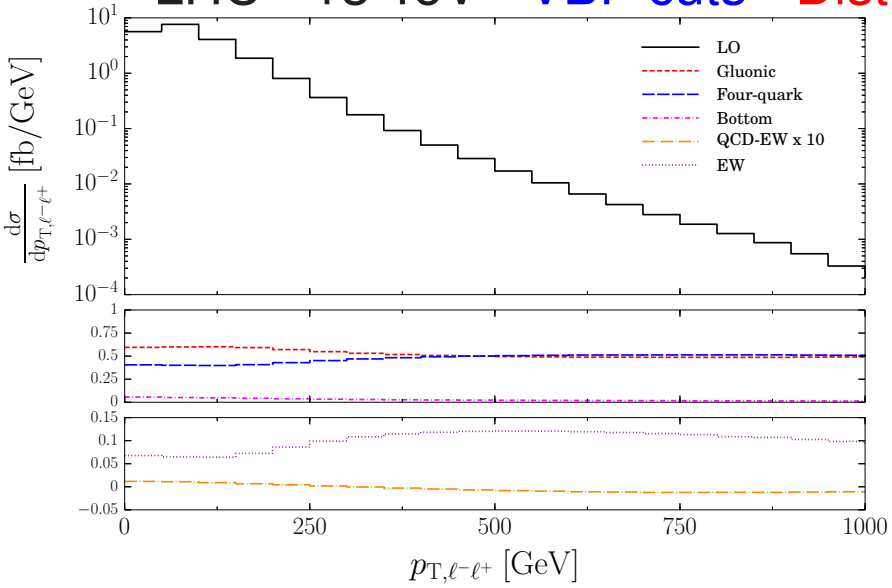
- Cross section reduced by factor 50 w.r.t. basic cuts
- $q\,g \to q\,g\,l^-\,l^+$ channels still dominate, but four-quark channel enhanced
- Still small EW corrections for total cross section

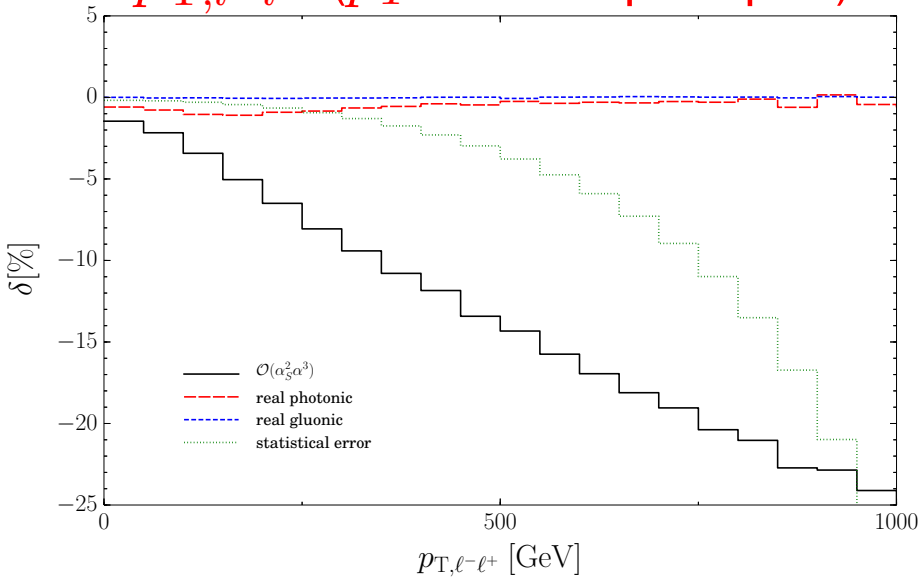
LHC - 13 TeV - VBF cuts - Distribution in p_{T,j_1} (j_1 = hardest jet)





LHC - 13 TeV - VBF cuts - Distribution in p_{T,l^-l^+} (p_T of the lepton pair)





Basic cuts:

$$p_{\mathrm{T,j}} > 30\ \mathrm{GeV} \qquad |\eta_j| < 4.5$$

$$\not{E}_{\mathrm{T}} > 25\ \mathrm{GeV}$$

photon energy fraction in jet $z_\gamma < 0.7$

LHC - 13 TeV - Basic cuts - Total cross section

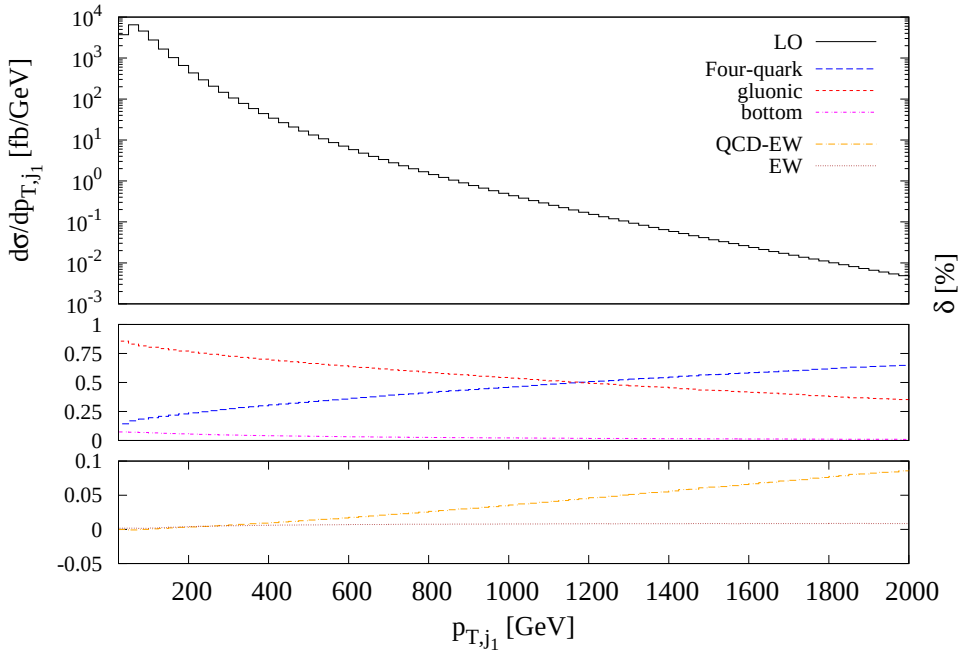
process class	σ^{LO} [pb]	$\sigma^{\mathrm{LO}}/\sigma^{\mathrm{LO}}_{\mathrm{tot}}$ [%]	$\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$ [pb]	$\frac{\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{\sigma^{\mathrm{LO}}} - 1$ [%]
gluonic	456.94(11)	81.5	454.34(11)	- 0.57
four-quark	103.66(01)	18.5	102.40(02)	- 1.22
sum	560.60(11)	100	556.74(11)	- 0.69
bottom quarks	37.699(6)	6.72		

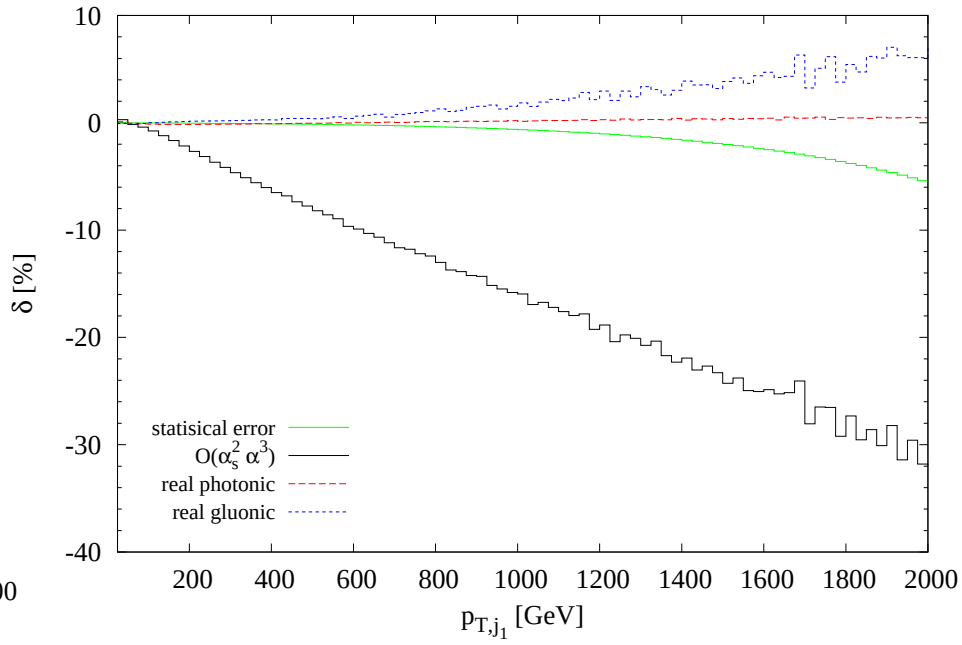
- One order of magnitude larger than for $\mathrm{pp} \to l^+\,l^-\,j\,j$
- $q\,g \to q\,g\,\nu\,\bar{\nu}$ channels dominate
- Negligible EW corrections for total cross section

Electroweak corrections for $\mathrm{pp} \to \nu\bar{\nu}\,jj$ - Basic cuts

$$p_{\mathrm{T,j}} > 30\ \mathrm{GeV} \qquad |\eta_j| < 4.5 \qquad \not{E}_{\mathrm{T}} > 25\ \mathrm{GeV}$$

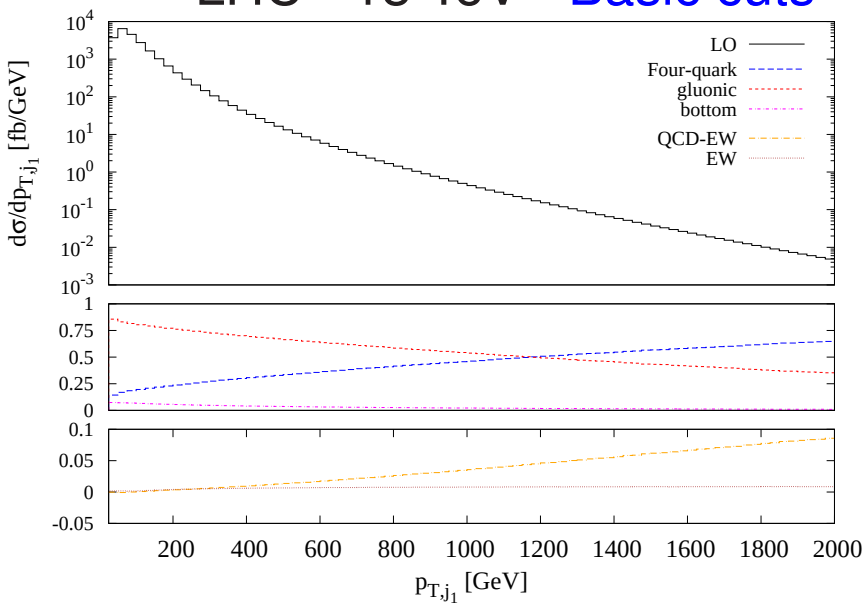
photon energy fraction in jet $z_\gamma < 0.7$

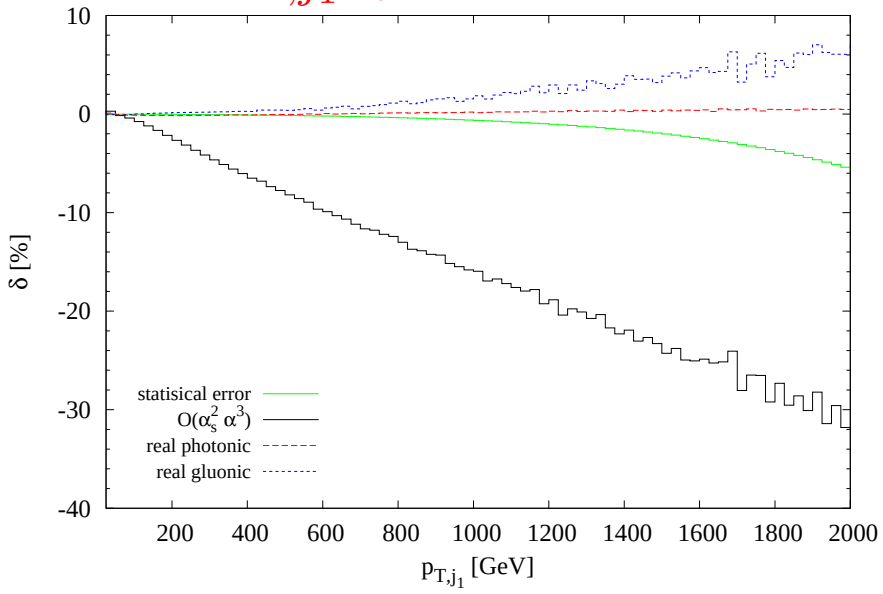




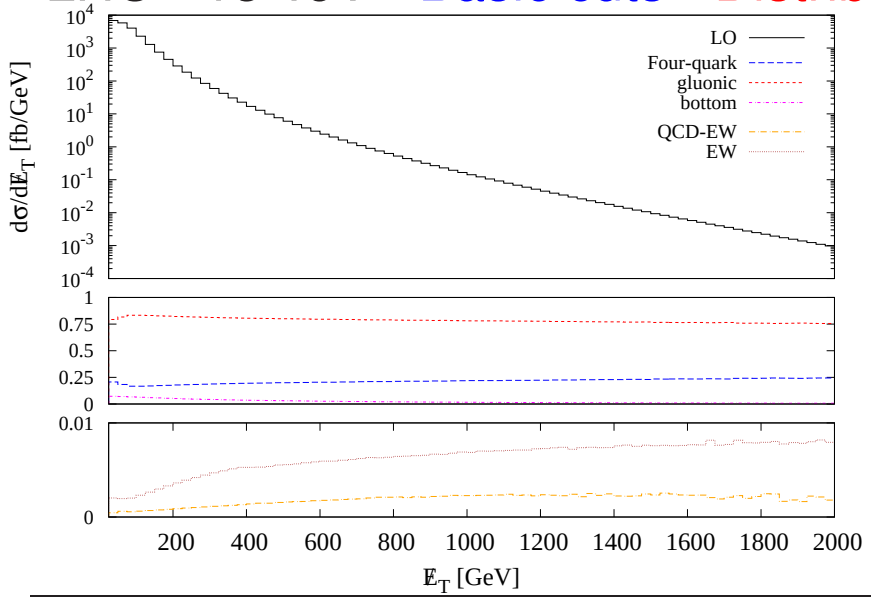
- Cross section one order of magnitude larger than for $\mathrm{pp} \to l^+\,l^-\,j\,j$

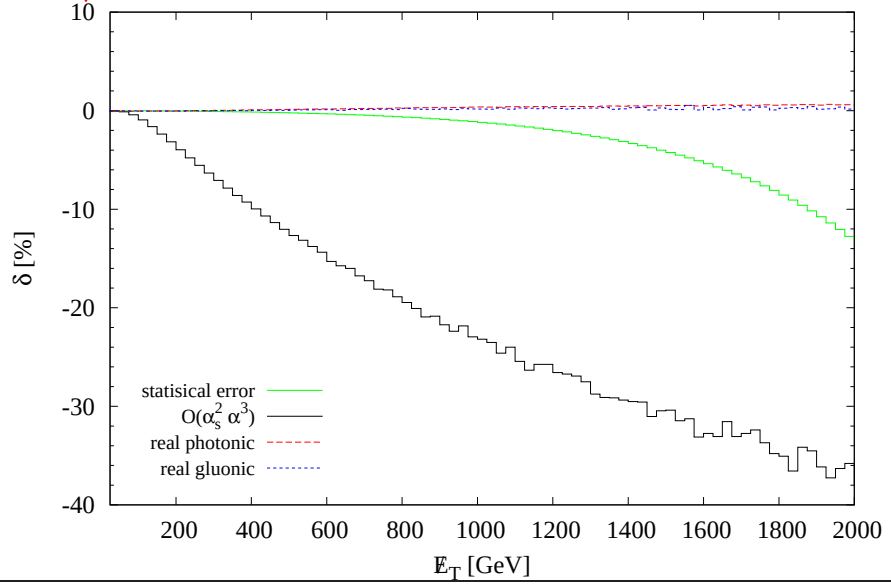
LHC - 13 TeV - Basic cuts - Distribution in p_{T,j_1} (j_1 = hardest jet)





LHC - 13 TeV - Basic cuts - Distribution in $\not{E}_T$ (missing transverse momentum)





ATLAS cuts:

$$p_{\mathrm{T,j_1}} > 130\ \mathrm{GeV} \qquad p_{\mathrm{T,j_2}} > 60\ \mathrm{GeV} \qquad |\eta_j| < 4.5$$

$$H_{\mathrm{T}} > 800\ \mathrm{GeV} \qquad \frac{\not{E}_{\mathrm{T}}}{\sqrt{H_{\mathrm{T}}}} > 8\ \sqrt{\mathrm{GeV}}$$

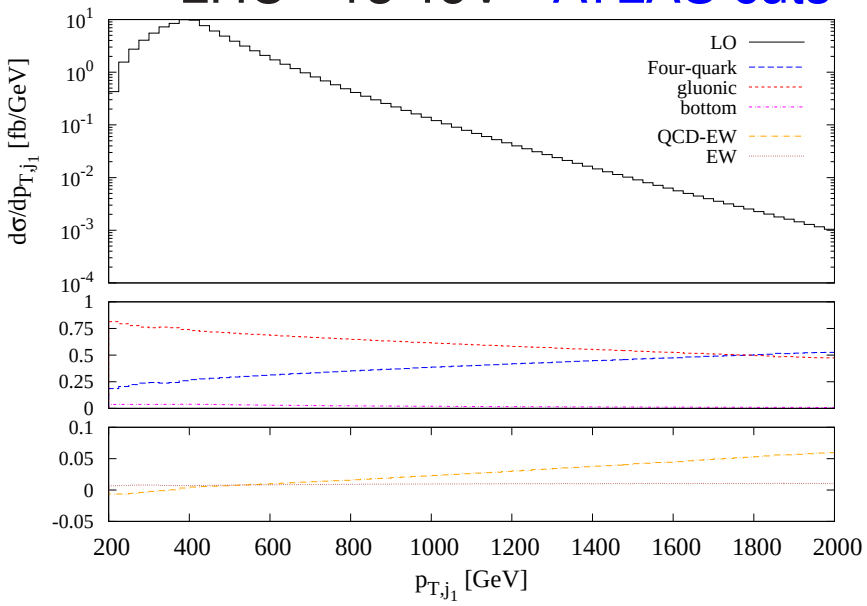
$$\Delta\phi_{\not{E}_{\mathrm{T}} j} > 0.4 \qquad \text{photon energy fraction in jet } z_\gamma < 0.7$$

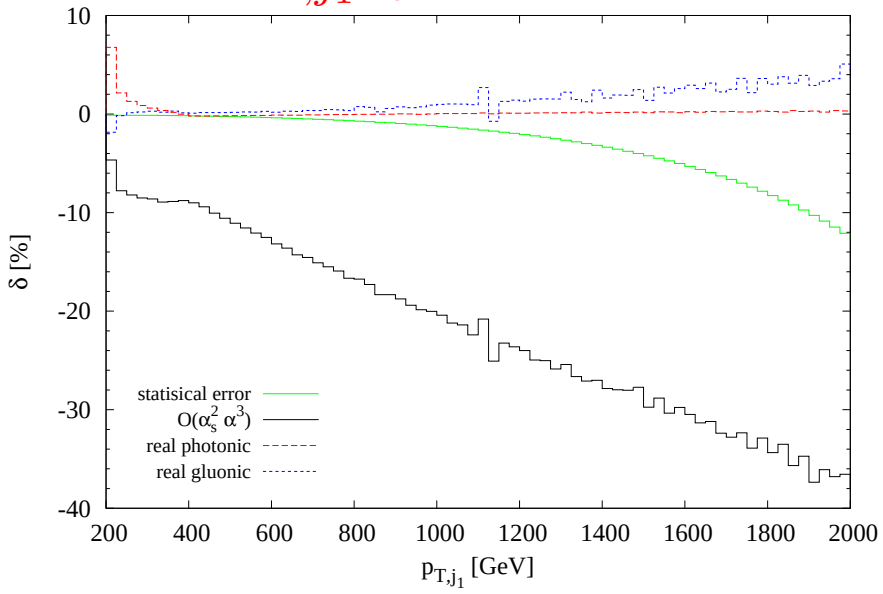
LHC - 13 TeV - ATLAS cuts - Total cross section

process class	σ^{LO} [fb]	$\sigma^{\mathrm{LO}}/\sigma^{\mathrm{LO}}_{\mathrm{tot}}$ [%]	$\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$ [fb]	$\frac{\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{\sigma^{\mathrm{LO}}} - 1$ [%]
gluonic	1649.47(39)	72.7	1479.47(42)	- 10.31
four-quark	618.50(07)	27.3	557.83(16)	- 9.81
sum	2267.97(39)	100	2037.29(45)	- 10.17
bottom quarks	79.69(01)	3.51		

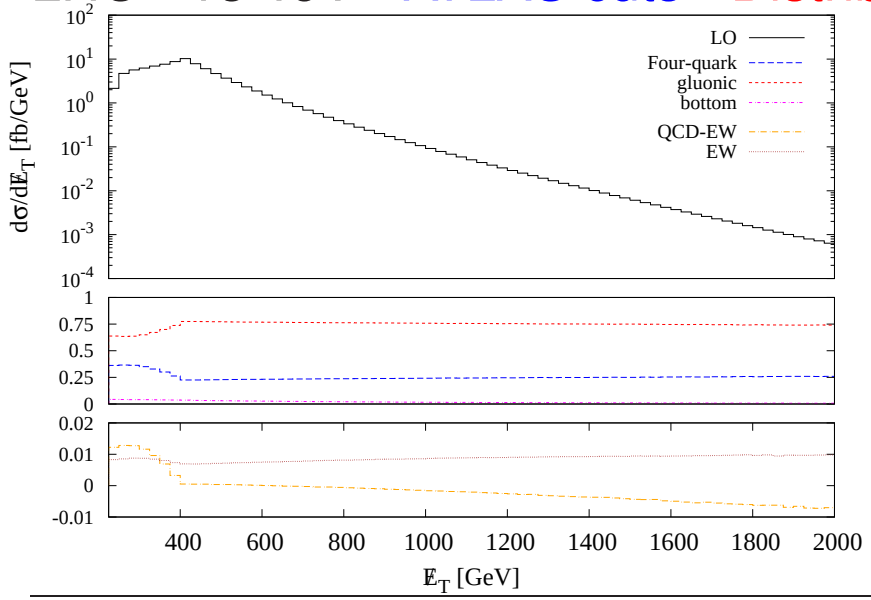
- Cross section reduced by factor 250 w.r.t. basic cuts
- $q\,g \to q\,g\,\nu\,\bar{\nu}$ channels still dominate
- EW corrections for total cross section around -10%

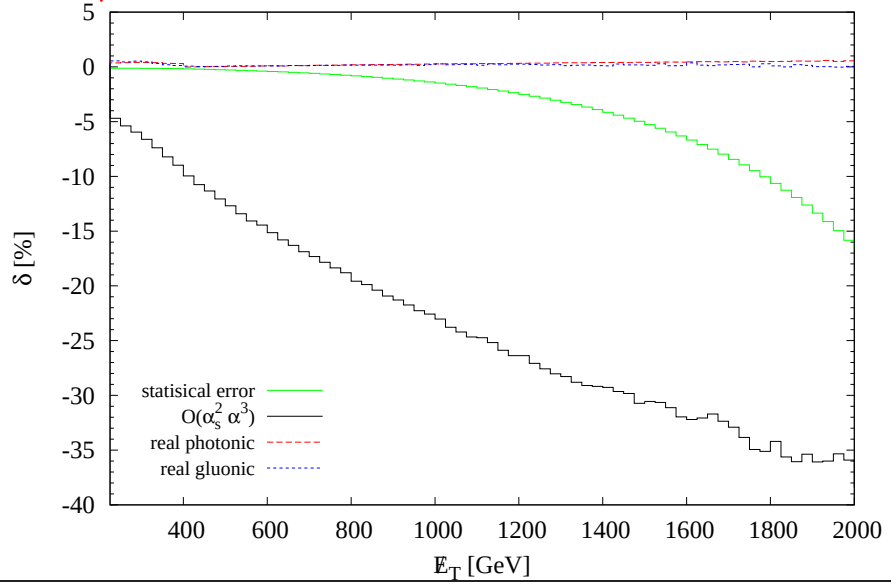
LHC - 13 TeV - ATLAS cuts - Distribution in p_{T,j_1} (j_1 = hardest jet)



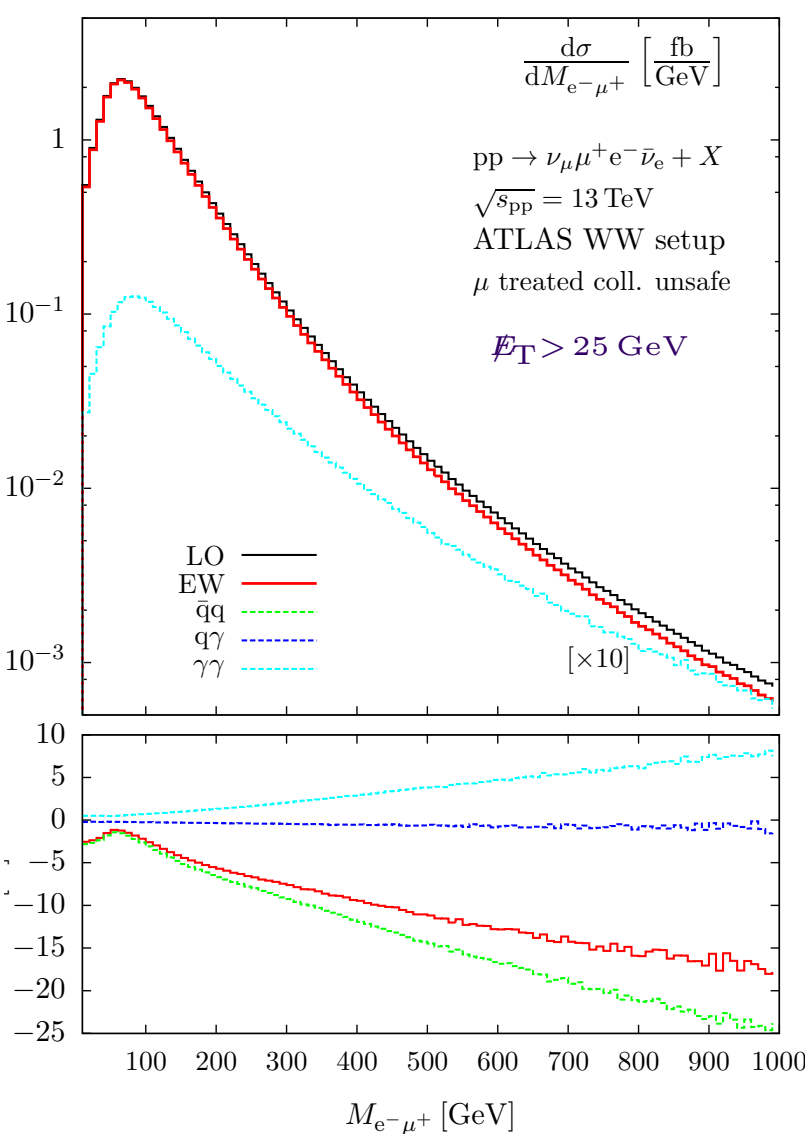


LHC - 13 TeV - ATLAS cuts - Distribution in $\not{E}_T$ (missing transverse momentum)





$pp \to \nu \bar{\nu} j j$



$p_{T,l} > 20\,GeV$

$p_{T,l}^{lead.} > 25\,GeV$

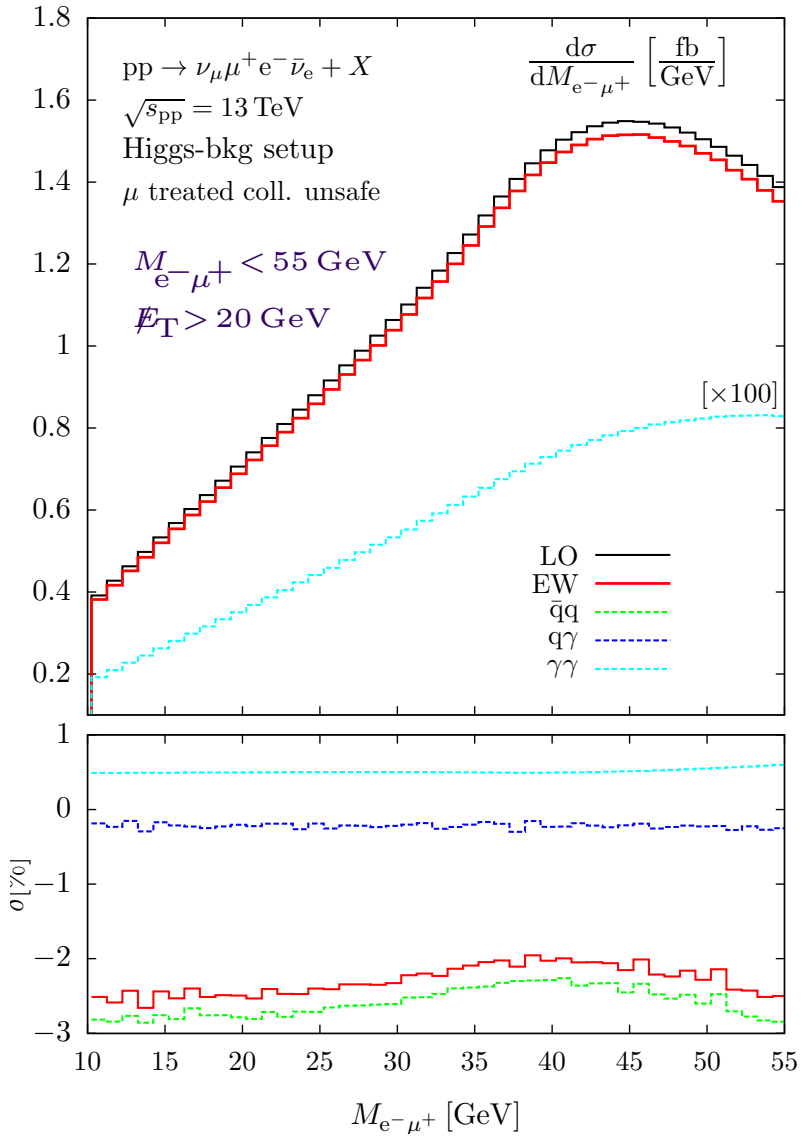
$|\eta_l| < 2.5$

$\Delta R_{e^-\mu^+} > 0.1$

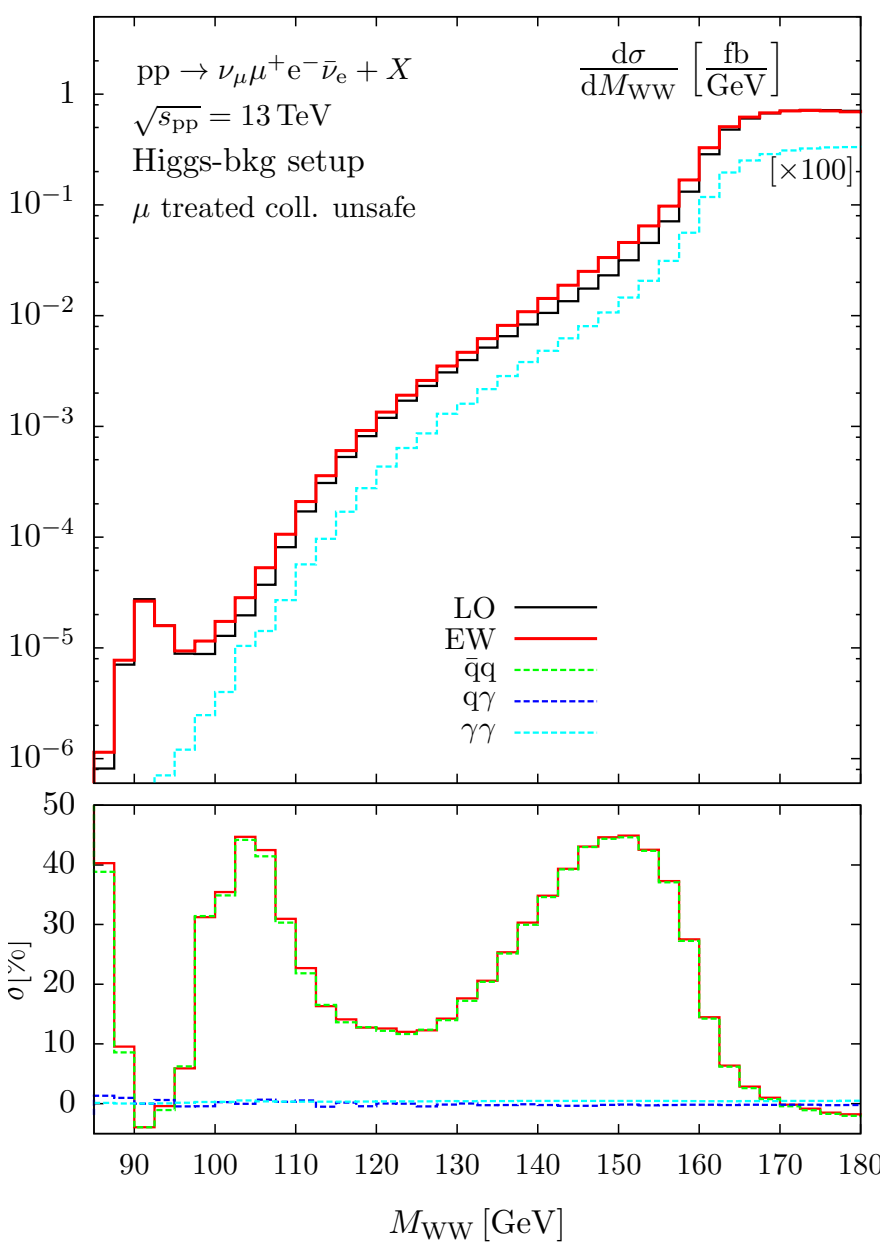
$M_{e^-\mu^+} > 10\,GeV$

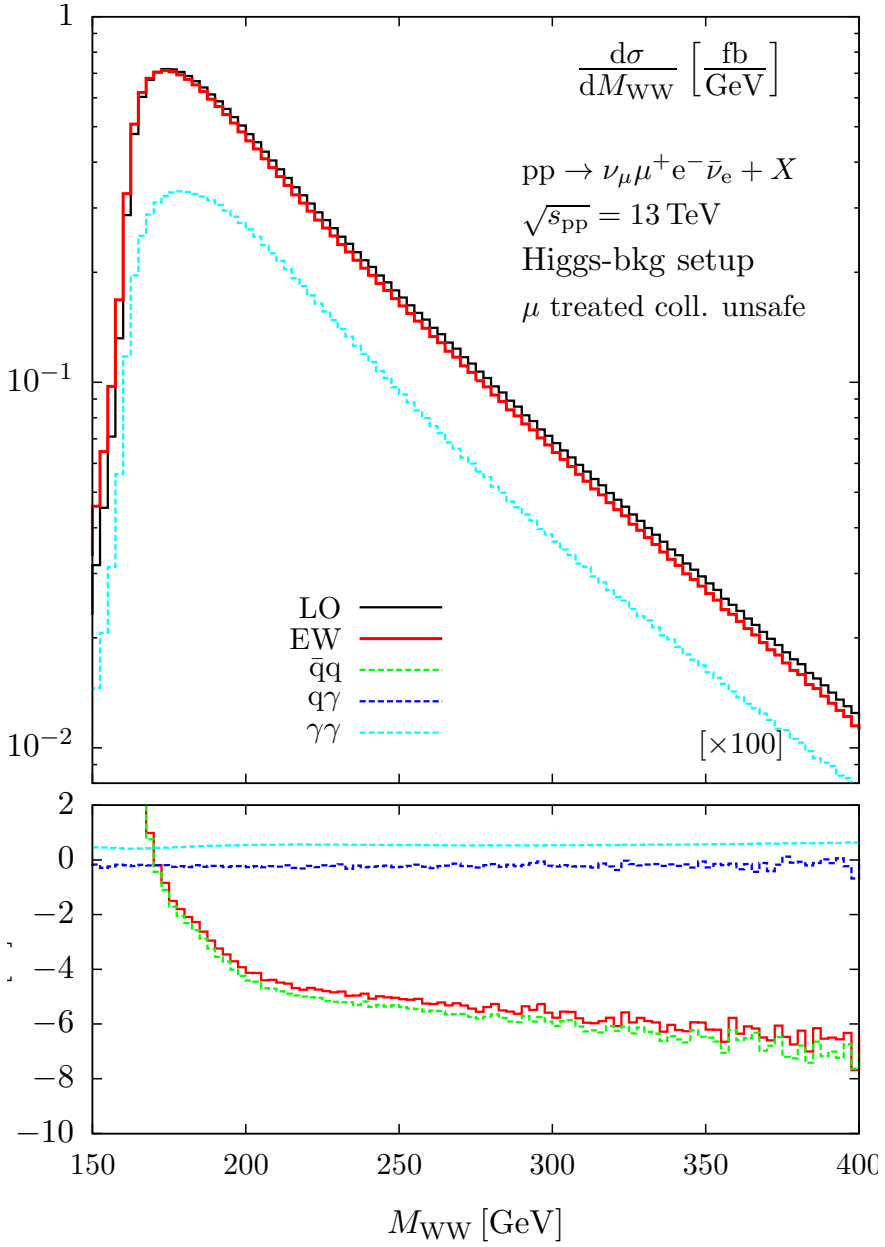
$\Delta R_{jet,l} > 0.4$

$p_{T,jet} < 25\,GeV$



- EW corrections around -15% at $M_{e^-\mu^+} \sim 1\mathrm{TeV}$
- Uniform EW corrections ($\sim -2.5\%$) in the Higgs background setup


$pp \to \nu_\mu \mu^+ e^- \bar{\nu}_e + X$
$\sqrt{s_{pp}} = 13\,\text{TeV}$
Higgs-bkg setup
μ treated coll. unsafe
$\frac{d\sigma}{dM_{WW}}\left[\frac{fb}{GeV}\right]$
[×100]
LO
EW
$\bar{q}q$
$q\gamma$
$\gamma\gamma$
δ [%]
M_{WW} [GeV]


$\frac{d\sigma}{dM_{WW}}\left[\frac{fb}{GeV}\right]$
$pp \to \nu_\mu \mu^+ e^- \bar{\nu}_e + X$
$\sqrt{s_{pp}} = 13\,\text{TeV}$
Higgs-bkg setup
μ treated coll. unsafe
LO
EW
$\bar{q}q$
$q\gamma$
$\gamma\gamma$
[×100]
M_{WW} [GeV]