NLO electroweak corrections in $V+$ jets

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FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

Introduction

Electroweak correction come in two variants: virtual corrections and real emission correction.

Most observables driven by either

- virtual corrections, often studied in the context of vector boson or jet production at large $p_\perp$ (EW-Sudakov suppression)

  $\rightarrow$ **NLO EW calculation**

- real photon emission/bremsstrahlung, very important for most lepton observables, less important for quarks as drowned in QCD bremsstrahlung

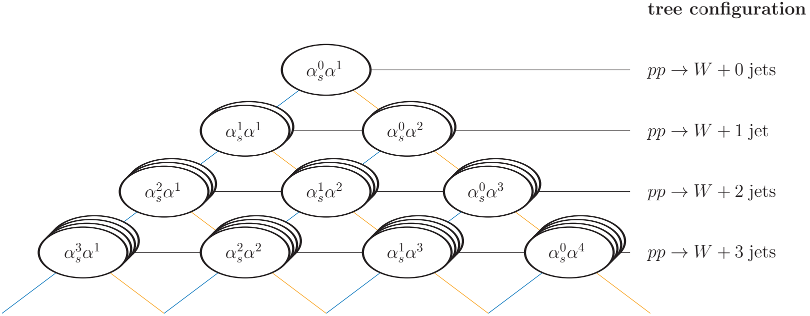
  $\rightarrow$ **NLO EW matched to resummation**

- real weak boson emissions, constitutes separately finite process, depending on decay channel and analysis different signature

  $\rightarrow$ **add as separate LO process**

Resummation of genuine weak corr. important if scale $\gg m_V$ present

Consistent setup: counting orders and defining signatures



— NLO QCD: $\alpha_s^1 = 1$ parton, only MEs from squared diagrams

— NLO EW: $\alpha^1 = 1$ photon or 1 parton

also MEs from interfering [illegible] diagrams, resonances

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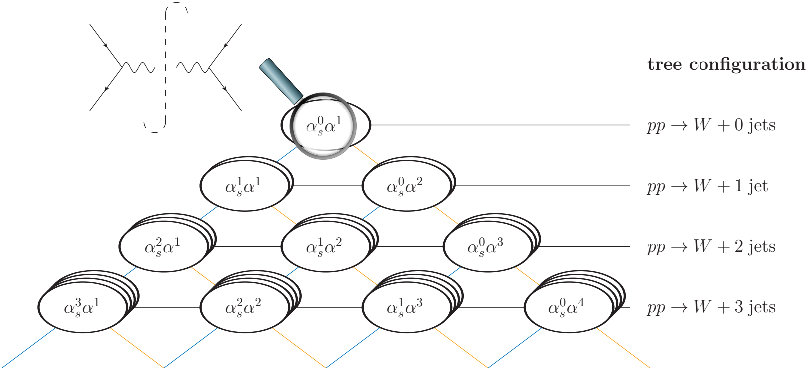

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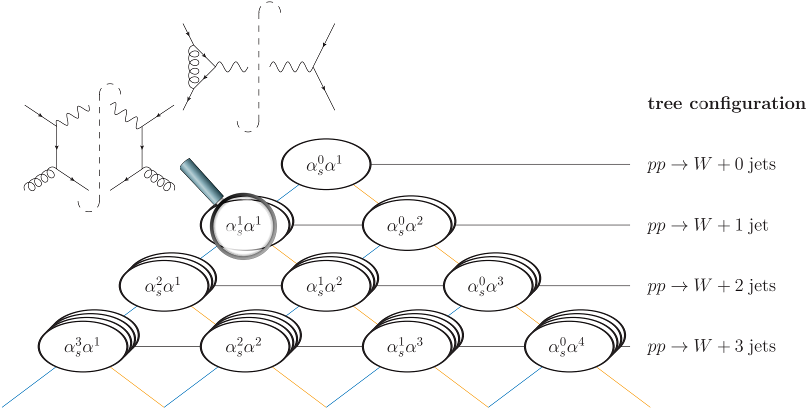

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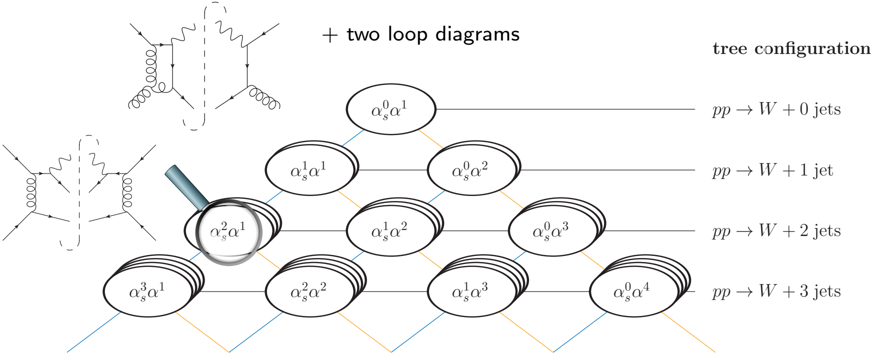

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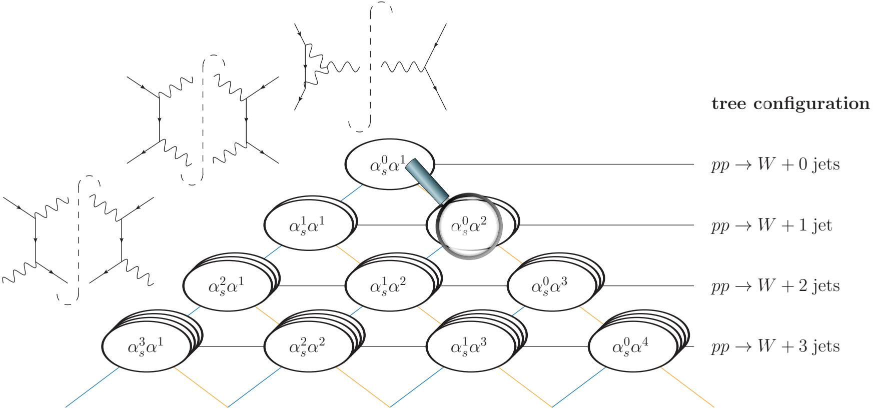

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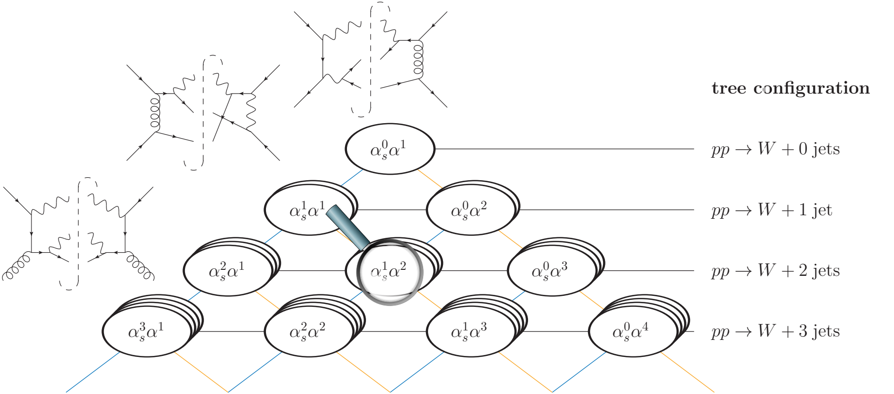

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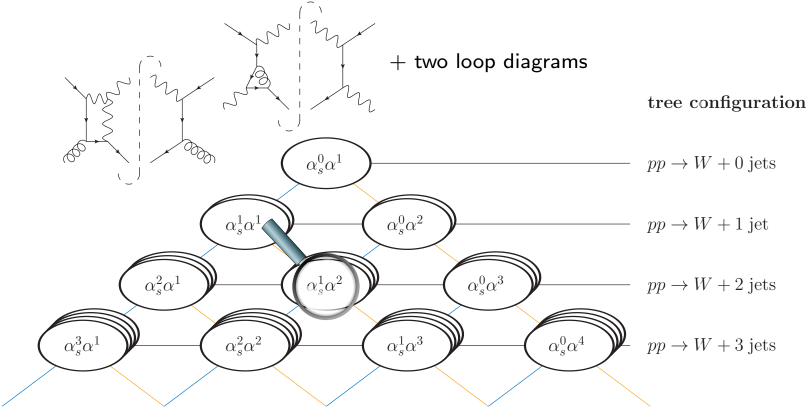

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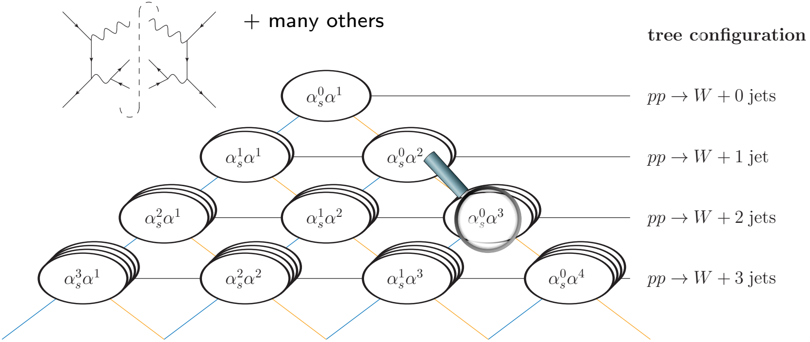

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Next-to-leading order electroweak corrections

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2015)012, JHEP04(2016)021

- fixed-order next-to-leading order electroweak corrections

$$d\sigma^{\text{NLO}} = \int d\Phi_B \left[\mathrm{B}(\Phi_B) + \mathrm{V}_{\text{EW}}(\Phi_B) + \mathrm{I}_{\text{QED}}(\Phi_B)\right] + \int d\Phi_R \left[\mathrm{R}_{\text{EW}}(\Phi_R) - \mathrm{S}_{\text{QED}}(\Phi_R)\right]$$

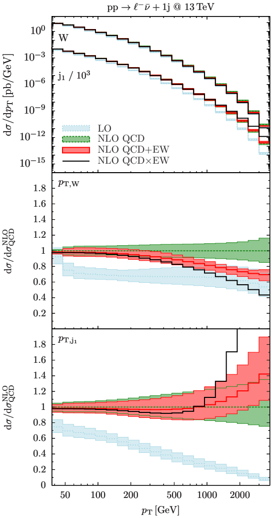
- automated implementation, independent cross checks:
  - OpenLoops for virtual corrections cross checked against independent private generator
  - Munich for phase space integration (MEs from OpenLoops), Sherpa for Born, real em., subtraction and phase space int.

Next-to-leading order electroweak corrections

- combine QCD and EW corrections as:
  QCD+EW: $\sigma_{\text{NLO QCD+EW}} = \sigma_{\text{LO}}\,(1+\delta_{\text{QCD}}+\delta_{\text{EW}})$
  QCD×EW: $\sigma_{\text{NLO QCD}\times\text{EW}} = \sigma_{\text{LO}}\,(1+\delta_{\text{QCD}})\,(1+\delta_{\text{EW}})$
  $\Rightarrow$ use difference as indication of potential size of $\mathcal{O}(\alpha_s\alpha)$ corrs.
- already studied a range of processes:
  - $pp \to V + 0,1,2(,3)$ jets
    Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2015)012, JHEP04(2016)021
  - $pp \to t\bar{t}h$
    LH'15 arXiv:1605.04692
  - $pp \to Zj/pp \to \gamma j$ ratio
    Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1505.05704
    LH'15 arXiv:1605.04692
  - $pp \to Vh$
    FCC report, to appear
- dedicated comparisons in LH'15 against Recola ($Z+2j$) and MadGraph (tth) showed agreement

$pp \to Wj$ @ 13 TeV

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021



- NLO QCD to $p_{\mathrm{T}}^{j_1}$ dominated by hard dijet topologies
  $\to$ LO, no EW corr.

  Rubin, Salam, Sapeta JHEP09(2010)084

  $\to$ need merging
- remove dijet configs through $\Delta\phi_{j_1 j_2} < \frac{3}{4}\pi$
  $\to$ EW Sudakov recovered

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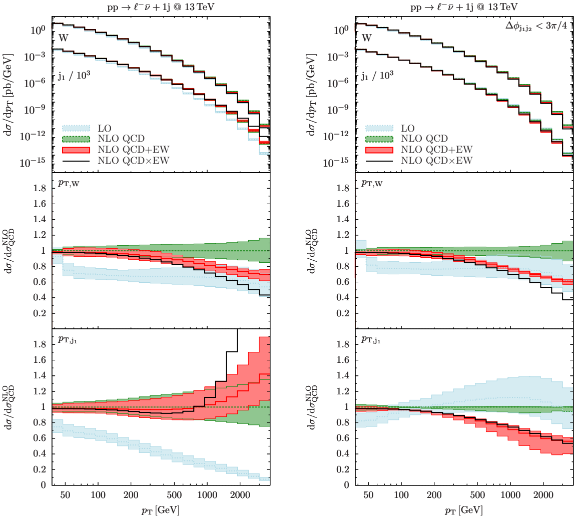

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$pp \to Wj\,/\,Wjj\,/\,Wjjj$ @ 13 TeV

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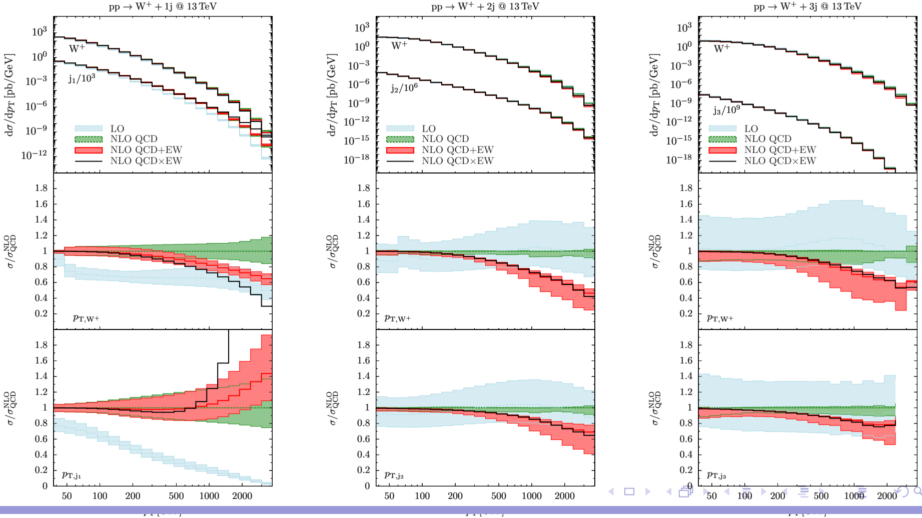
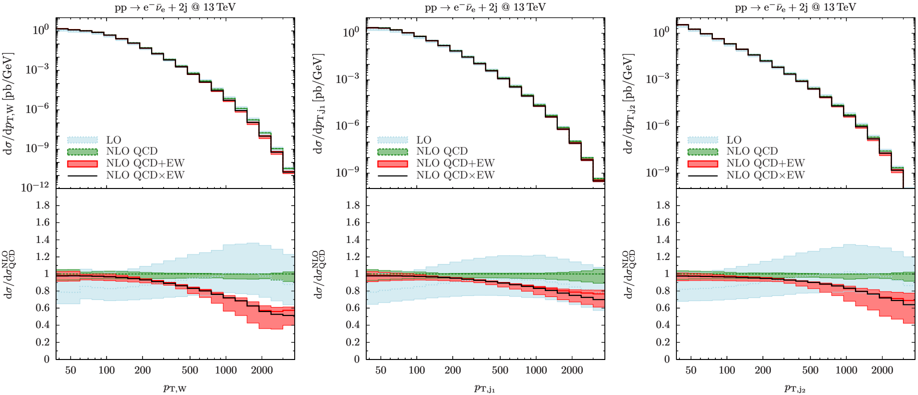


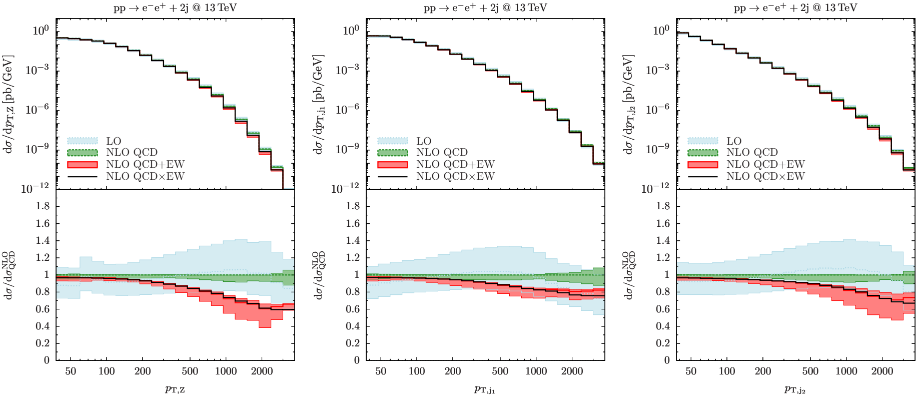
$pp \to Wjj$ @ 13 TeV

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021



$pp \to Zjj$ @ 13 TeV

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021



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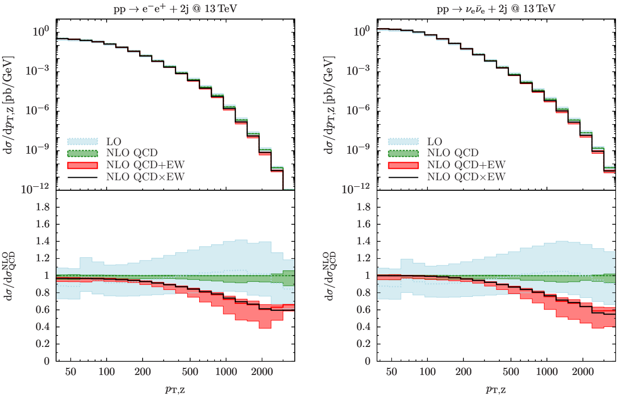
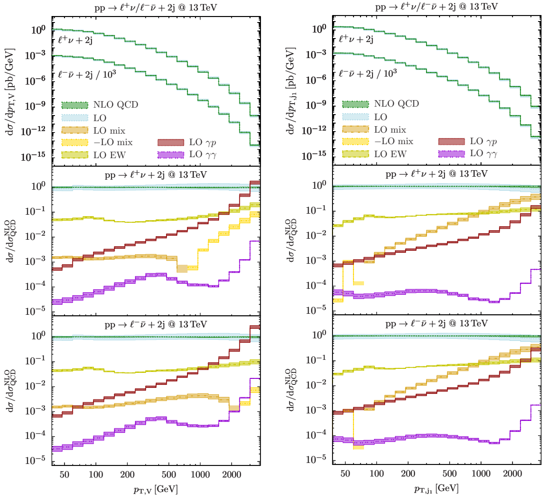


→ EW corrections independent of the decay mode

$pp \to Wjj$ @ 13 TeV – subleading Born contributions

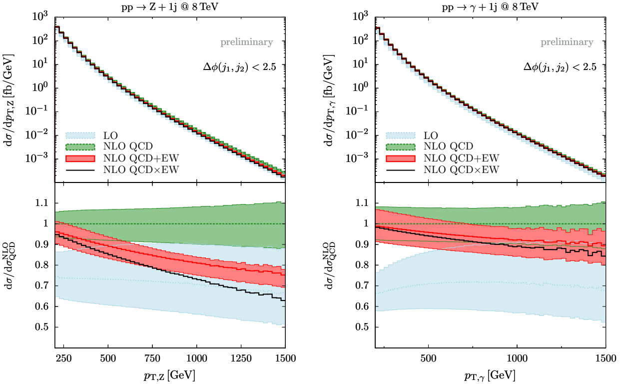
Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021



- LO dominated by gq IS
- either $4q$ procs (LO mix) or photon initiated
  $\rightarrow$ can be important in TeV range (large x)
- $4q$ interferences of diagrams of different $\mathcal{O}(g_s^n e^m)$
  $\rightarrow$ not pos. definite
- γPDF has $\mathcal{O}(1)$ unc.
  $\rightarrow$ high-$p_\perp$ data can be used as constraint

Z/γ ratio @ 8 TeV

Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1505.05704



→ EW corrections different for Z and γ

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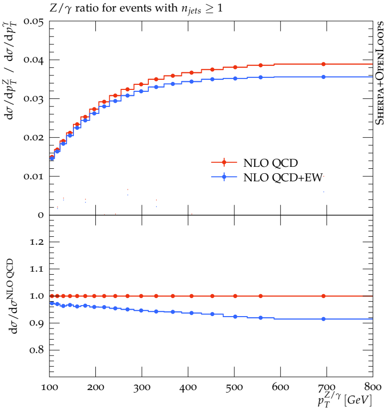

Kallweit, Lindert, Pozzorini, MS for LH'15

- use this ratio to get handle on $p_\perp^Z$ in $Z \to \nu\bar{\nu}$ for NP searches
- test how well data is described in $Z \to \ell\ell$

⇒ NLO EW improves data description

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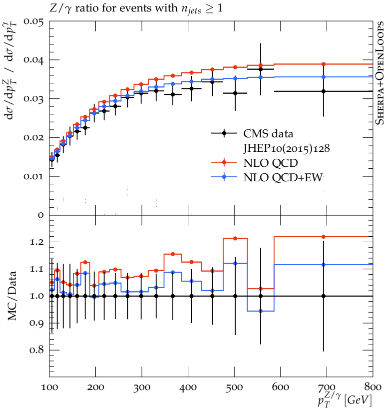

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Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)
- modify MC@NLO $\overline{\mathrm{B}}$-function to include NLO EW virtual corrections and integrated approx. real corrections

$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_n(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging
  $\rightarrow$ validated at fixed order, found to be reliable,
  diff. $\lesssim 5\%$ for observables not driven by real radiation

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exact virtual contribution ($\mathrm{V}_{n,\mathrm{EW}}$)

approximate integrated real contribution ($\mathrm{I}_{n,\mathrm{EW}}$)

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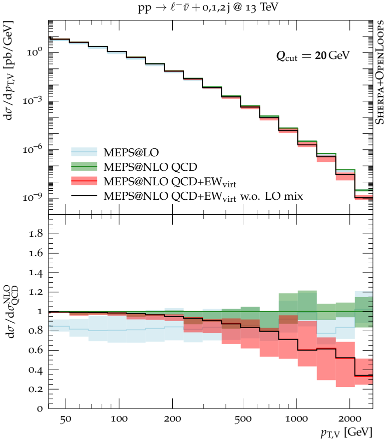
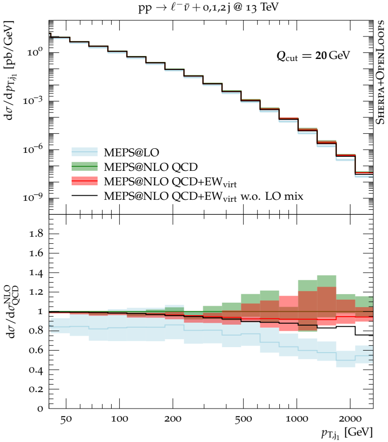
Results: $pp \to \ell^- \bar{\nu} + \text{jets}$

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021





$\Rightarrow$ particle level events including dominant EW corrections

Conclusions

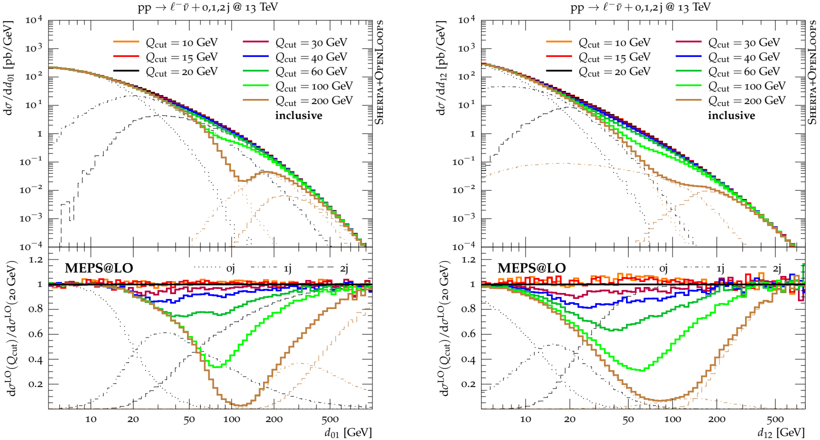
- electroweak effects are important at LHC at 13 TeV and beyond
- become large whenever the intrinsic scale is large compared to the electroeweak scale (e.g. high-$p_\perp$)
- NLO EW automated in SHERPA/MUNICH+OPENLOOPS framework
  $\rightarrow$ programs will become public soon
- suitable approximation can be integrated in existing NLO QCD multijet merging methods
  $\rightarrow$ can be directly incorporated in particle level event generation
  $\rightarrow$ will be available in next SHERPA release

Thank you for your attention!

Backup

Merging systematics: $pp \to \ell^- \bar{\nu} + \text{jets}$

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021



$\Rightarrow$ dead zones in incl. obs. if Q_{cut} too high

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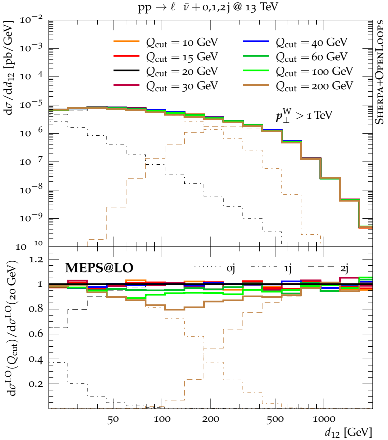

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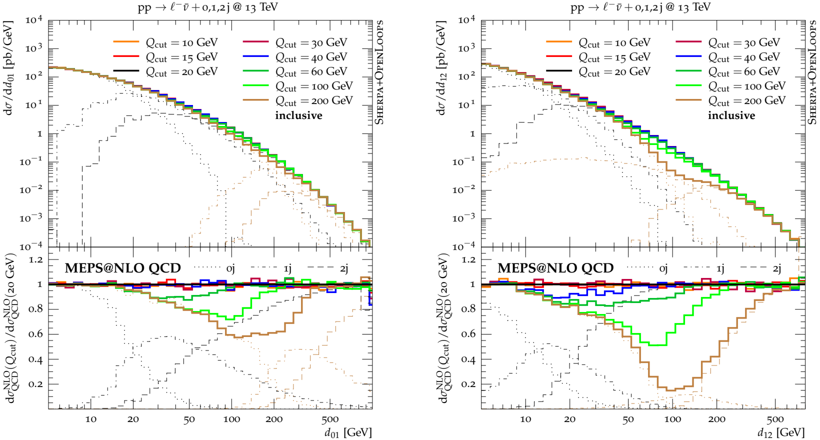

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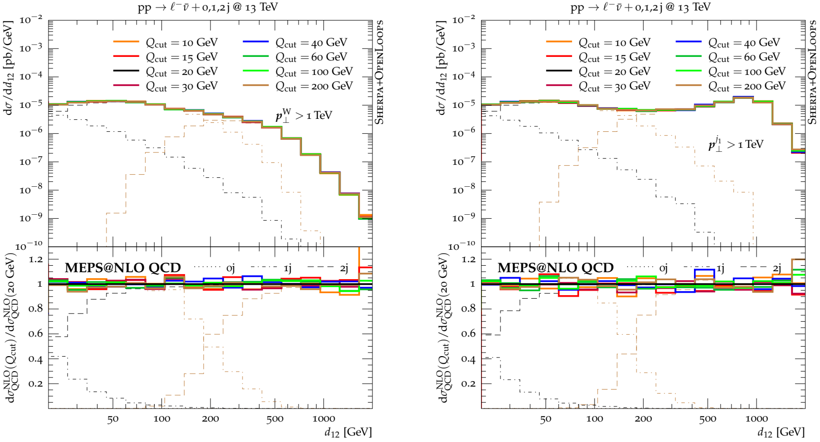

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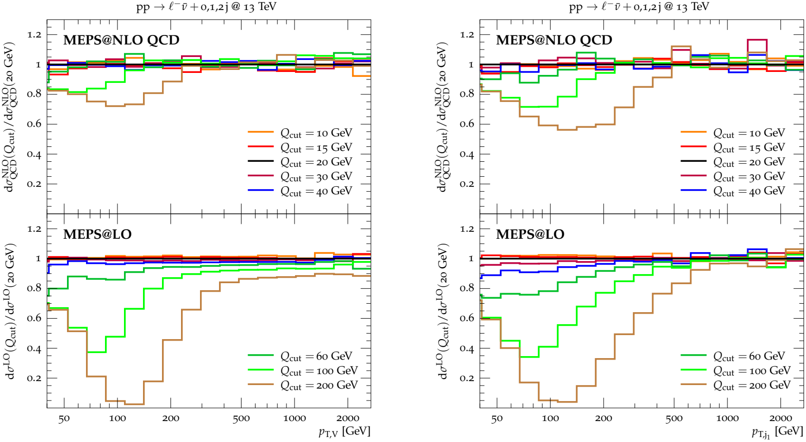

$\Rightarrow$ TeV region stable ($\lesssim 5\%$), $Q_{cut} = 20\,\text{GeV}$ suitable for whole range