Electroweak corrections to $Z + 2$ jets production at the LHC

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in collaboration with
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$\mathrm{Z}+2$ jets production at the LHC

Vector-boson + jets production

- important for tests of QCD and SM
- backgrounds for Higgs studies and new physics searches

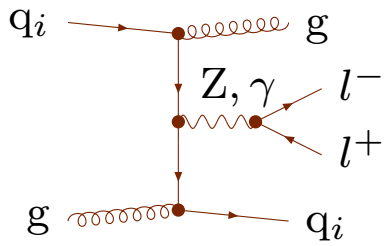
$\mathrm{Z}+2$ jets production

- for $Z \to \tau^+\tau^-$:
  background to Higgs production in vector-boson fusion
- in the case of b-jets:
  background to asociated HZ production with $\mathrm{H} \to \mathrm{b\bar{b}}$
- nontrivial study case for (automatized) calculation of electroweak NLO corrections
- part of Les Houches wish list 2013

Z + 2 jets at LO

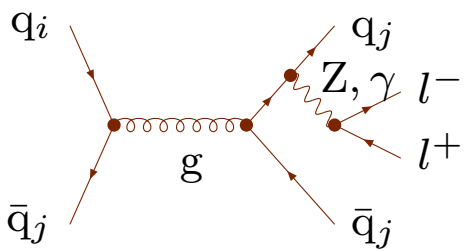
gluon channels:

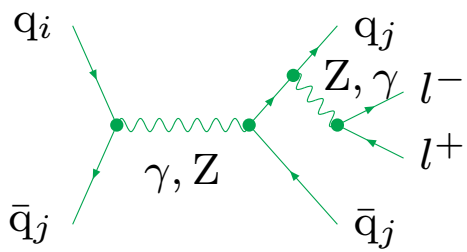
e.g. $q\,g \to q\,g\,l^+\,l^-$ $\quad \sigma \sim \mathcal{O}(\alpha_s^2\alpha)$

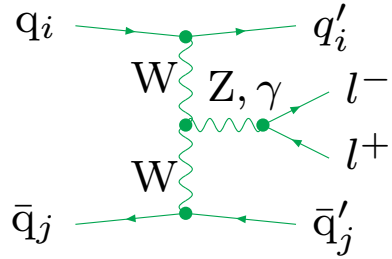


four-quark channels:

e.g. $q\,\bar{q} \to q\,\bar{q}\,l^+\,l^-$ $\quad \sigma \sim \mathcal{O}(\alpha_s^2\alpha),\ \mathcal{O}(\alpha_s\alpha^2),\ \mathcal{O}(\alpha^3)$







LHC 13 TeV	σ^{LO} [pb]	$\sigma^{\mathrm{LO}}/\sigma^{\mathrm{LO}}_{\mathrm{tot}}$ [%]
gluon	40.9	79.9
four-quark	10.3	20.1
sum	51.2	100.00

γ induced contributions $< 0.05\%$ for $8/13\,\mathrm{TeV}$

Z + 2 jets at NLO

Tower of contributions:

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

  $+$ parton shower matching via POWHEG-BOX [Re'12]
  [Campbell,Ellis,Nason,Zanderighi'13]

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

- $\mathcal{O}(\alpha_s\alpha^4)$:
  - QCD corrections to EW diagrams [Oleari, Zeppenfeld '04]
    $+$ parton shower matching via POWHEG-BOX
    [Jäger,Schneider,Zanderighi'13; Schissler,Zeppenfeld'13]
  - EW corrections to EW QCD interferences

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

EW corrections to Z + jets production

$\mathrm{Z} + \mathrm{j}$, $\mathrm{W} + \mathrm{j}$ production

- electroweak corrections available [Denner,Dittmaier,Kasprzik,Mück]

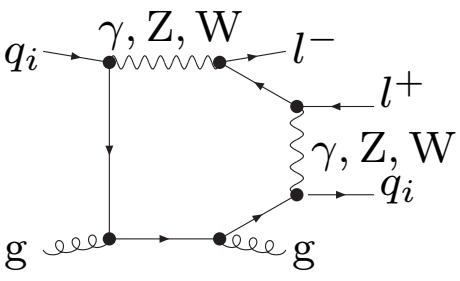
$\mathrm{Z} + 2$ jets production

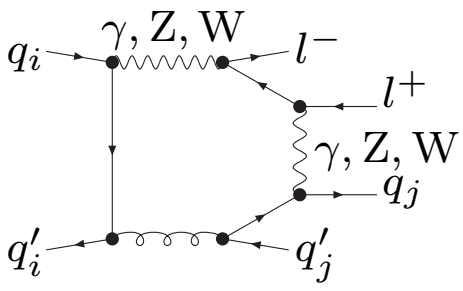
- electroweak corrections for $\nu\bar{\nu} + 2$ jets in Sudakov limit [Chiesa et al. '13]
- EW corrections to gluonic channels with stable Z (=dominant channels) [Actis,Denner,LH,Scharf,Uccirati '12]
- preliminary: complete $\mathcal{O}(\alpha_s^2\alpha^3)$ for full $l^+l^-\mathrm{jj}$ final state

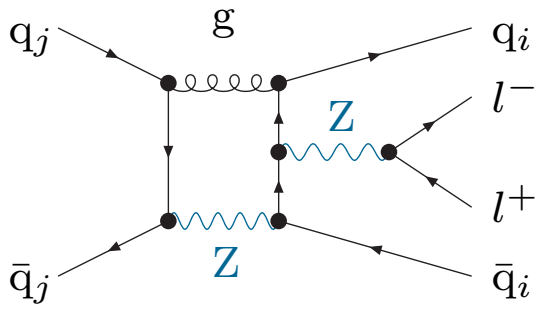
Virtual electroweak corrections

of loop diagrams contributing to σ in $\mathcal{O}(\alpha_s^2\alpha^3)$

	$ug \to ugl^+l^-$	$us \to usl^+l^-$	$us \to dcl^+l^-$
order	$\mathcal{O}(\alpha_s\alpha^2)$	$\mathcal{O}(\alpha_s^2\alpha) + \mathcal{O}(\alpha_s\alpha^2)$	$\mathcal{O}(\alpha_s\alpha^2)$
loop diagrams	~ 1200	$\sim 150 + 800$	~ 120
hexagons	18	$0 + 32$	4
pentagons	85	$8 + 50$	24







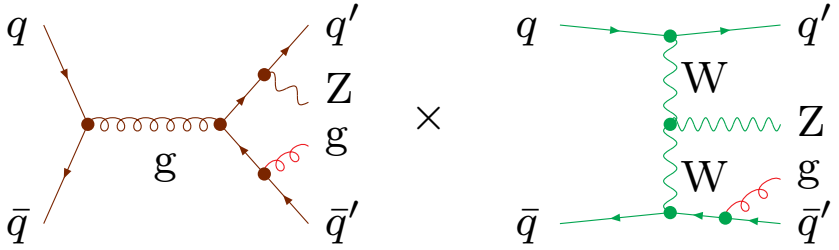
- most complicated topology: hexagon of rank 4
- complex-mass scheme for Z-boson resonances

  [Denner,Dittmaier,Roth,Wackeroth,Wieders]

  complex pole: $\mu_Z^2 = M_Z^2 - iM_Z\Gamma_Z$

Real electroweak corrections

- real photon emission from LO QCD contributions
- real gluon emission in QCD–EW interferences



- IR divergences: dipole subtraction [Catani,Seymour]
- recombination of collinear parton-photon pairs

Real electroweak corrections

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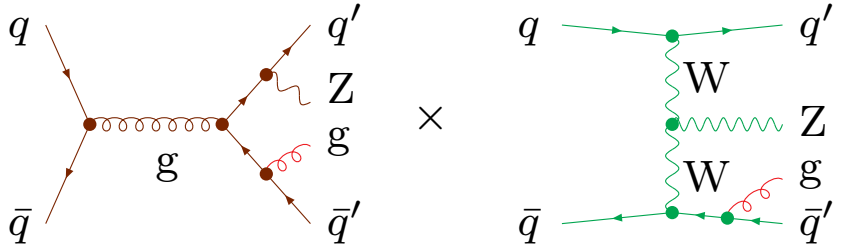


- IR divergences: dipole subtraction [Catani,Seymour]
- recombination of collinear parton-photon pairs
- Zjj at NLO EW $\mathrm{Zj\gamma}$ at NLO QCD

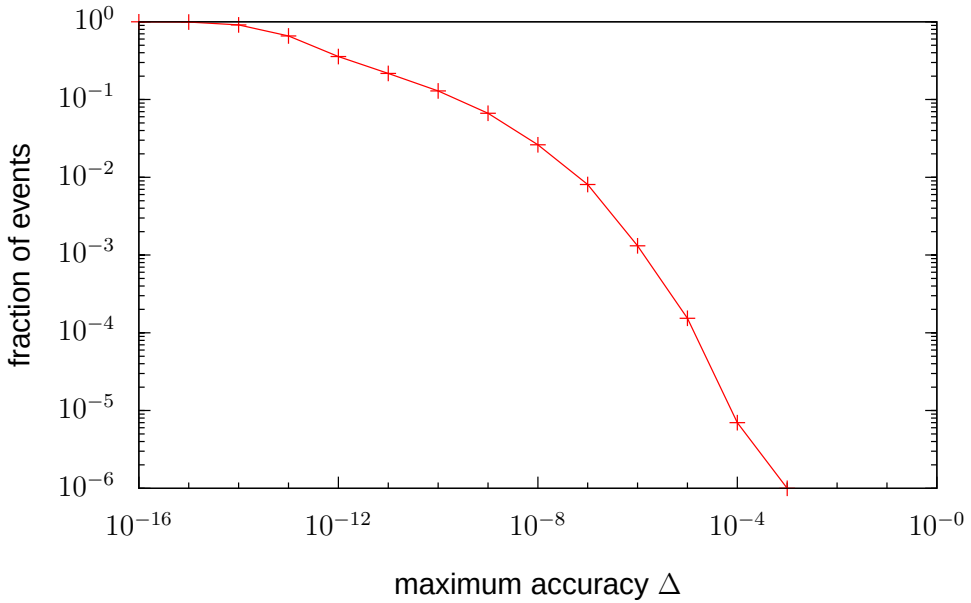
  real corrections: $\mathrm{Zjj\gamma}$

  - separation via cut on photon-energy fraction z_γ within jet $\longrightarrow$ not IR-safe
  - left-over divergences $\longrightarrow$ photon fragmentation function

Implementation

- flexible parton-level Monte-Carlo using
  - RECOLA [Actis,Denner,LH,Scharf,Uccirati]
    for generation of SM amplitudes (incl. EW corrections)
  - COLLIER [Denner,Dittmaier,LH]
    for fast and stable evaluation of tensor integrals
- cross-checks with FEYNARTS/FORMCALC/POLE [Hahn et al.; Meier]

comparison of virtual squared matrix for $\mathrm{ug} \to \mathrm{ugZ}$ for 10^6 events:



- typical agreement:
  $10^{-11} - 10^{-14}$
- less than 0.02% of points with agreement worse than 10^{-5}

Results for LHC at 13 TeV

Setup 1: Basic cuts (motivated by [Atlas'13])

Jet clustering: anti-k_{T} algorithm with $\Delta R = 0.4$
photon energy fraction in jet $z_\gamma < 0.7$

cuts:

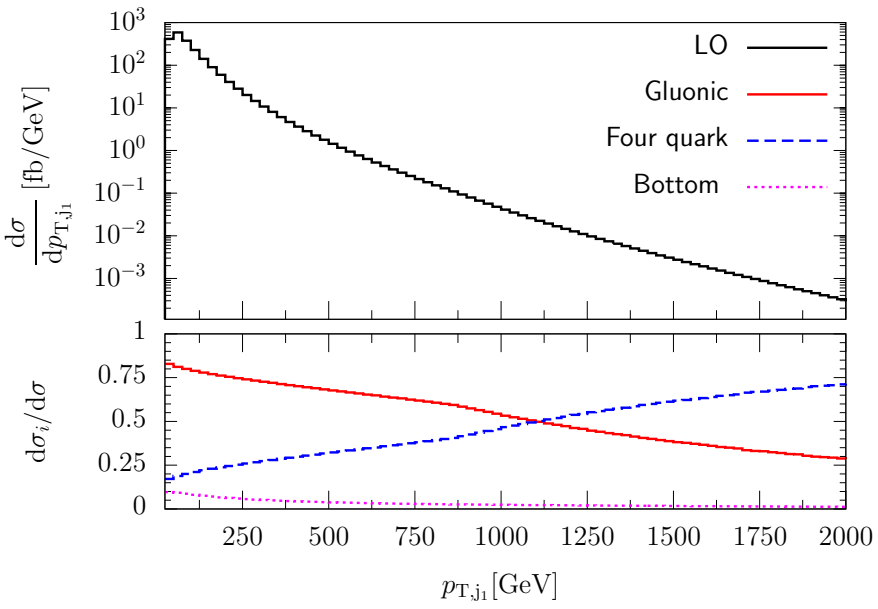
$$p_{\mathrm{T,j}} > 30\ \mathrm{GeV}, \quad |\eta_j| < 4.5$$
$$P_{\mathrm{T},l} > 20\ \mathrm{GeV}, \quad |\eta_l| < 2.5$$
$$\Delta R_{l^+l^-} > 0.2, \quad \Delta R_{jl^-} > 0.5, \quad \Delta R_{jl^+} > 0.5$$
$$66\ \mathrm{GeV} < M_{l^+l^-} < 116\ \mathrm{GeV}$$

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

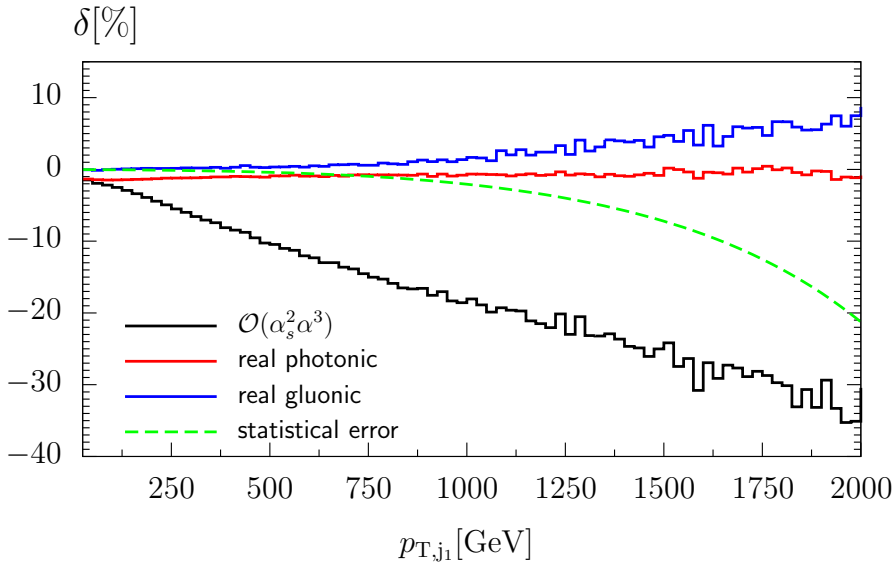
EW corrections small for total cross section: $\sim -2.4\%$
similar for all channels

LHC13: Distribution in p_{T} of leading jet

LHC13, basic cuts



PRELIMINARY

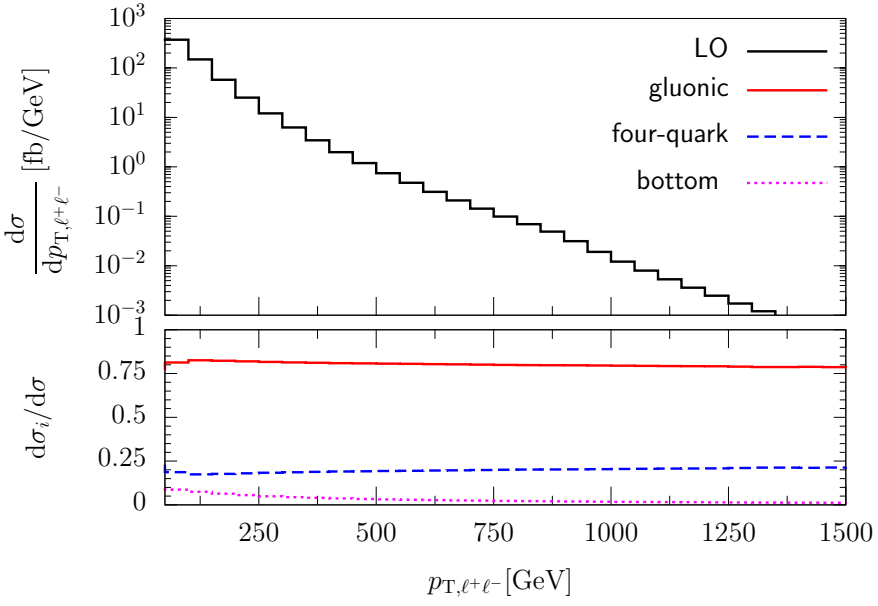


statistical error based on $300\,\mathrm{fb}^{-1}$

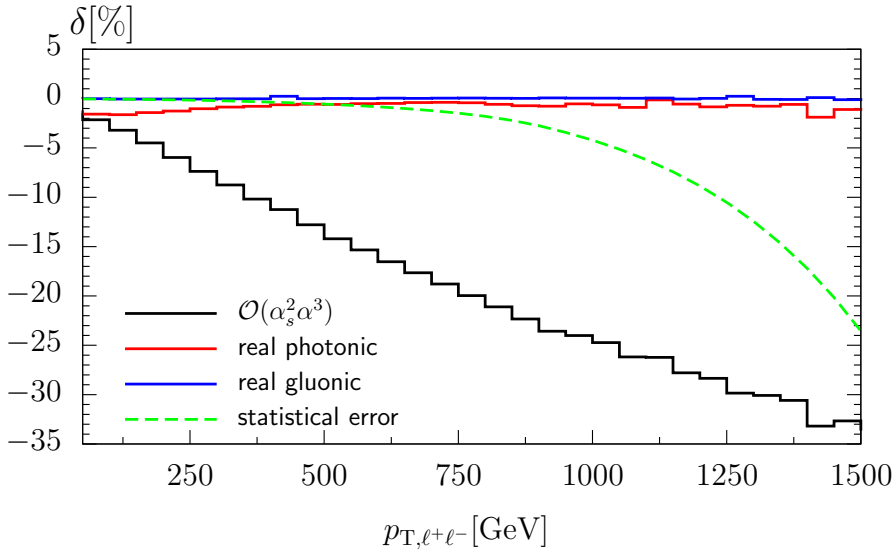
- 4-quark channels dominate for high p_{T}
- bottom contributions below $5-10\%$
- EW corrections sizable for high p_{T}: $-(20\text{ to }30)\%$ for $p_{\mathrm{T}} \gtrsim 1\,\mathrm{TeV}$ dominated by virtual corrections (Sudakov logarithms)

LHC13: Distribution in p_{T} of l^+l^-

LHC13, basic cuts



PRELIMINARY



statistical error based on $300\,\mathrm{fb}^{-1}$

- gluon channels dominate for all $p_{\mathrm{T},ll}$
- bottom contributions below $5-10\%$
- EW corrections -25% for $p_{\mathrm{T},ll}=1\,\mathrm{TeV}$
  dominated by virtual corrections (Sudakov logarithms)
  subtracted real corrections small ($\lesssim 2\%$)

Results for VBF cuts at LHC13

Setup 2: VBF cuts

cuts:

$$p_{\mathrm{T,j}} > 30\ \mathrm{GeV}, \quad |\eta_j| < 4.5$$
$$P_{\mathrm{T},\tau} > 20\ \mathrm{GeV}, \quad |\eta_\tau| < 2.5$$
$$\Delta R_{\tau^+\tau^-} > 0.2, \quad \Delta R_{j\tau^-} > 0.5, \quad \Delta R_{j\tau^+} > 0.5$$
$$M_{\mathrm{jj}} > 600\ \mathrm{GeV}, \quad |y_{\mathrm{j}_1} - y_{\mathrm{j}_2}| > 4, \quad y_{\mathrm{j}_1} \cdot y_{\mathrm{j}_2} < 0$$
$$\min(y_{\mathrm{j}_1}, y_{\mathrm{j}_2}) < y_l < \max(y_{\mathrm{j}_1}, y_{\mathrm{j}_2})$$

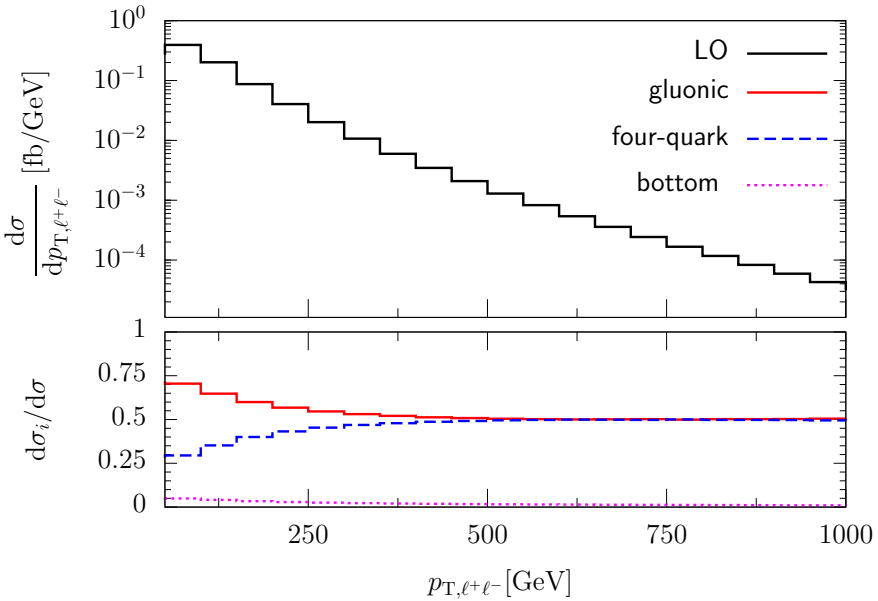
cross section reduced by factor 50
four-quark channels enhanced, but gluonic channels still dominate

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(4)	-3.0
four-quark	421.7(1)	40.6	412.4(1)	-2.2
sum	1039.6(4)	100	1011.7(4)	-2.7

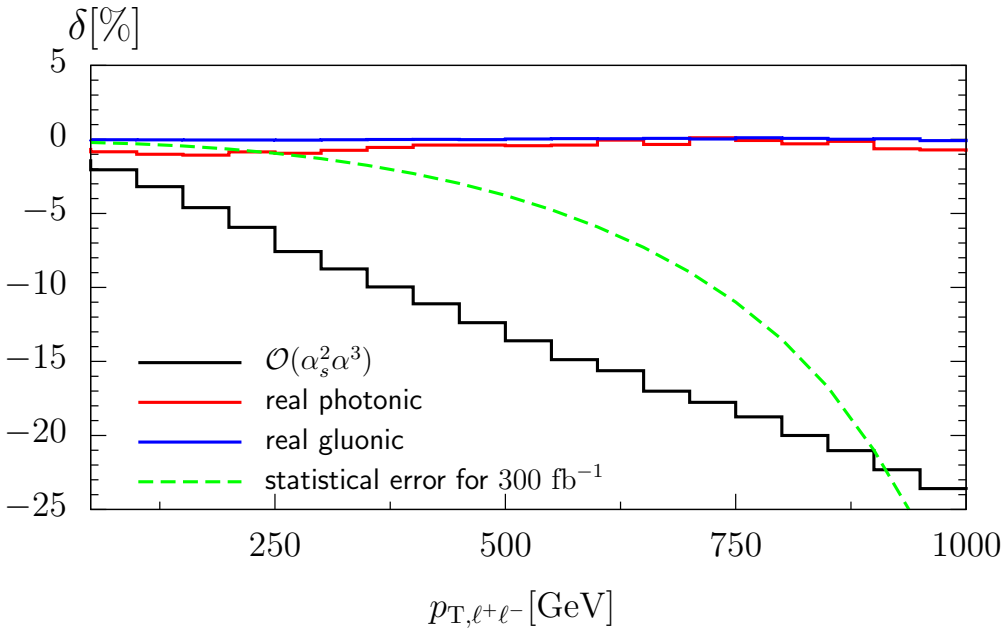
EW corrections small for total cross section: $\sim -2.7\%$
variation over channels increased: $\sim -1\%$ to -6%

LHC13 VBF: Distribution in p_{T} of l^+l^-

LHC13, VBF cuts



PRELIMINARY



statistical error based on $300\,\mathrm{fb}^{-1}$

- gluon and four-quark channels comparable for all $p_{\mathrm{T},ll}$
- bottom contributions below 5%
- EW corrections similar in size as for basic cuts

Conclusions

- Electroweak corrections to $\mathrm{pp} \to l^+l^- +$ 2 jets calculated
- general tools used for calculation:
  - RECOLA: recursive generator for tree-level and one-loop amplitudes in the full Standard Model (including EW corrections)
  - COLLIER: fast and numerically stable calculation of one-loop tensor integrals
- corrections implemented in flexible parton-level Monte-Carlo
- Studies of a setup with basic acceptance cuts and a setup with VBF cuts
  - corrections to total cross section at per-cent level
  - corrections of several ten per cent in high-energy tails of distributions from virtual Sudakov logarithms