Electroweak corrections to $\mathrm{Z}+2$ jets production at the LHC

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- Motivation
- COLLIER: a Fortran library for tensor integrals
- Electroweak corrections to $\mathrm{pp} \to \mathrm{Z}+2$ jets
- Conclusion

Introduction

- Discovery of Higgs boson: spectacular success of Standard Model
- tasks for the future:
  - precise investigation of Higgs boson
  - precise study of other Standard Model processes
  - search for physics beyond Standard Model
- QCD corrections are indispensable for decent predictions
- automation of NLO QCD corrections performed by many groups, e.g.

  BLACKHAT Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maître

  NJET Badger, Biedermann, Uwer, Yundin

  HELACNLO Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau, Worek

  AMC@NLO Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau

  GOSAM Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano

  OPENLOOPS Cascioli, Maierhöfer, Pozzorini

Relevance EW NLO corrections at LHC

- generically: $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \sim \text{few}\ \%$
- Electroweak (EW) corrections can be enhanced
  - high energy scales, $E \gg M_W \Rightarrow$ Sudakov logarithms $\ln^2\left(\frac{E^2}{M_W^2}\right)$

    $\Rightarrow$ corrections of several 10% for $E \sim 1\,\text{TeV}$

    tails of distributions

    M. Ciafaloni, P. Ciafaloni, Comelli; Beccaria, Renard, Verzegnassi; Beenakker, Werthenbach; Denner, Pozzorini; Melles; Fadin, Lipatov, Martin; Hori, Kawamura, Kodaira; Jantzen, Kühn, Penin, Smirnov; Chiu, Fuhrer, Golf, Kelley, Manohar, ...
  - kinematic effects, e.g. photonic corrections near resonances

    $\Rightarrow$ radiative tails
  - Higgs production in vector-boson fusion:

    EW and QCD corrections have same order of magnitude ($\sim 5\%$)

    Ciccolini, Denner, Dittmaier '07
- Les Houches wishlist 2013:

  NNLO QCD and NLO EW for various processes desired

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

Vector-boson + jets production

- important for tests of QCD and Standard Model
- important backgrounds for Higgs and new physics searches (Higgs, supersymmetry, ...)
- NLO QCD corrections exist for $\mathrm{Z} + 4\mathrm{j}$, $\mathrm{W} + 5\mathrm{j}$ Blackhat

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

- electroweak corrections available Denner, Dittmaier, Kasprzik, Mück '09, '11, '12

$\mathrm{Z} + 2$ jets production

- background to Higgs production in vector-boson fusion
  $\Rightarrow$ study of systematics for $\mathrm{H} + \mathrm{jj}$ final state
- nontrivial study case for (automatized) calculation of electroweak NLO corrections
- part of Les Houches wish list 2013
- electroweak corrections for $\nu\bar{\nu} + 2$ jets in Sudakov limit Chiesa et al. '13

COLLIER

a Fortran library for tensor integrals

Calculation of LO and NLO matrix elements

General form of one-loop amplitudes (free of unphysical singularities)

$$\delta\mathcal{M} = \sum_j \sum_{R_j} c^{(j,R_j,N_j)}_{\mu_1\cdots\mu_{R_j}} T^{\mu_1\cdots\mu_{R_j}}_{(j,R_j,N_j)} = \sum_j d^{(j,N_j)} T_{(j,0,N_j)}$$

tensor integrals

$$T^{\mu_1\cdots\mu_{R_j}}_{(j,R_j,N_j)} = \frac{(2\pi\mu)^{4-D}}{\mathrm{i}\pi^2}\int \mathrm{d}^D q \, \frac{q^{\mu_1}\cdots q^{\mu_{R_j}}}{D_{j,0}\cdots D_{j,N_j-1}}, \qquad D_{j,a} = (q+p_{j,a})^2 - m^2_{j,a}$$

$c^{(j,R_j,N_j)}_{\mu_1\cdots\mu_{R_j}}$ free of, $d^{(j,N_j)}$ involve unphysical singularities

proposal of van Hameren '09:
calculate $c^{(j,R_j,N_j)}_{\mu_1\cdots\mu_{R_j}}$ numerically in a recursive way

implemented for full Standard Model in RECOLA $\Rightarrow$ talk by Sandro Uccirati
(Recursive calculation of one-loop amplitudes)

evaluation of tensor integrals by COLLIER — Denner, Dittmaier, Hofer, in preparation
(Complex one loop library in extended regularizations)

Reduction of N-point tensor integrals

Different methods used depending on number N of propagators

- $N = 1, 2$: explicit analytical expressions (no reduction, numerically stable)
- $N = 3, 4$: exploit Lorentz covariance
  different methods used depending on kinematics
  - standard Passarino–Veltman (PV) reduction — Passarino, Veltman '79
  - stable expansions in exceptional phase-space regions (small Gram determinants)

    Denner, Dittmaier '05 (see also R.K.Ellis et al. '05; Binoth et al. '05; Ferroglia et al. '02)
- $N \geq 5$: exploit 4-dimensionality of space-time
  direct reduction of $T^{N,R}$ to $T^{N-1,R-1}$ (free of inverse Gram determinants)
  Melrose '65; Denner, Dittmaier '02,'05; Binoth et al. '05; Diakonidis et al. '08,'09

$\Rightarrow$ fast and stable numerical reduction algorithm

Basic scalar integrals A_0, B_0, C_0, D_0 from explicit analytical expressions
't Hooft, Veltman '79; Beenakker, Denner '90; Denner, Nierste, Scharf '91; Ellis, Zanderighi '08;
Denner, Dittmaier '11

Reduction of 3-point and 4-point integrals

Passarino–Veltman reduction

covariant decomposition of tensor integrals:

$$T^{N,\mu_1\cdots\mu_R} = \sum_{i_1,\ldots,i_k} T^{N,R}_{\underbrace{0\cdots0}_{R-k}i_1\cdots i_k}\{\underbrace{g\cdots g}_{(R-k)/2}\,p_{i_1}\cdots p_{i_k}\}^{\mu_1\cdots\mu_R} \sim \int \mathrm{d}^D q\,\frac{q^{\mu_1}\cdots q^{\mu_{R_j}}}{D_{j,0}\cdots D_{j,N_j-1}}$$

contract tensor integral with external momenta p_i^μ and metric tensor $g^{\mu\nu}$ and use

$$\begin{aligned} 2p_i^\mu q_\mu &= -f_i + D_i - D_0, \qquad f_i = p_i^2 - m_i^2 + m_0^2 \\ g^{\mu\nu} q_\mu q_\mu &= m_0^2 + D_0 \end{aligned}$$

cancel denominators and insert covariant decomposition

$\Rightarrow$ recursive solution for tensor coefficients:

$$\Delta\, T^{N,R} = \left[T^{N,R-1}, T^{N,R-2}, T^{N-1}\right]$$

reduction to lower-rank and lower-point integrals

Gram determinant: $\Delta = \det(Z)$ with $Z_{ij} = 2p_ip_j, \quad Z^{-1} = \tilde{Z}/\Delta$

Reduction of 3-point and 4-point integrals (cont.)

$$2(D+R-N-1)\underbrace{T^N_{00i_3\ldots i_R}}_{\text{rank } R} = 2m_0^2\underbrace{T^N_{i_3\ldots i_R}}_{\text{rank } R-2} + \sum_{n=1}^{N-1} f_n \underbrace{T^N_{ni_3\ldots i_R}}_{\text{rank } R-1} + (T^{N-1}\text{ terms})$$

$$\underbrace{\Delta\, T^N_{i_1\ldots i_R}}_{\substack{\text{rank } R\\ i_1\neq 0}} = \sum_{n=1}^{N-1}\tilde{Z}_{i_1 n}\Big[-f_n\underbrace{T^N_{i_2\ldots i_R}}_{\text{rank } R-1} -2\sum_{r=2}^{R}\delta_{ni_r}\underbrace{T^N_{00i_2\ldots\hat{i}_r\ldots i_R}}_{\text{rank } R} + (T^{N-1}\text{ terms})\Big]$$

$\hookrightarrow$ recursive calculation of $T^N_{i_1\ldots i_R}$ from scalar integral T^N_0 and $T^{N-1}_{i_2\ldots i_R}$:

$T^N_0 =$ basis integral $\quad\rightarrow\quad T^N_{i_1} \quad\rightarrow\quad T^N_{i_1i_2} \quad\rightarrow\quad T^N_{i_1i_2i_3} \quad\rightarrow\quad \ldots$

- explicit D requires expansion of $T^N_{00\ldots}$ around $D=4$
  - UV-poles produce finite polynomial terms (rational terms) $[\mathcal{O}(D-4)/(D-4)]$ easily obtained from recursion relations (no Δ^{-1} since $T^N_{i_1\ldots i_R}$ finite for $i_j\neq 0$)
  - $T^N_{00\ldots}$ do not involve IR poles, reduction valid for any IR regularization
- appearance of inverse Gram determinant Δ
  $\Rightarrow$ potential instabilities for $\Delta\rightarrow 0$ in exceptional points

Small Gram determinants

PV: $\Delta T^{N,R} = \left[T^{N,R-1}, T^{N,R-2}, T^{N-1}\right]$

small Gram determinant: $\Delta \to 0$

- finite $T^{N,R}$ as sum of $1/\Delta$-singular terms
  - spurious singularities cancel to give $\mathcal{O}(\Delta)/\Delta$-result
  - numerical determination of $T^{N,R}$ becomes unstable

- $T^{N,R-1}, T^{N,R-2}, T^{N-1}$ become linearly dependent

$\Rightarrow$ scalar integrals D_0, C_0, B_0, A_0 become linearly dependent

$\Rightarrow$ $\mathcal{O}(\Delta)/\Delta$-instabilities intrinsic to all methods relying on the full set of basis integrals D_0, C_0, B_0, A_0

- solution: choose appropriate set of base functions depending on phase-space point

Expansion in Gram determinant

$$\Delta\, T^{N,R+1} = \left[T^{N,R}, T^{N,R-1}, T^{N-1}\right] \qquad (1)$$

- exploit linear dependence of $T^{N,R}, T^{N,R-1}, T^{N-1}$ for $\Delta = 0$ to determine $T^{N,R}$ up to terms of $\mathcal{O}(\Delta)$
- calculate $T^{N,R+1}$ from $\Delta\, T^{N,R+2} = \left[T^{N,R+1}, T^{N,R}, T^{N-1}\right]$ in the same way
- use $T^{N,R+1}$ in (1) to compute $\mathcal{O}(\Delta)$ in $T^{N,R}$
- higher orders in Δ iteratively:
  $\mathcal{O}(\Delta^k)$ of $T^{N,R}$ requires lower-point T^{N-1} up to rank $R+k$
- basis of scalar integrals effectively reduced
  (e.g. D_0 expressed by C_0's)

Expansion breaks down in certain regions of phase space
$\Rightarrow$ alternative expansions

Features of COLLIER

- implementation of tensor integrals for (in principle) arbitrary number of external momenta N
  (tested in physical processes up to $N = 6$)
- various expansion methods for exceptional phase-space points
  (to arbitrary order in expansion parameter)
- mass- and dimensional regularization supported for IR singularities
- complex masses supported (unstable particles)
- cache-system to avoid recalculation of identical integrals
- output: coefficients $T^N_{0\cdots 0 i_1 \cdots i_k}$ or tensors $T^{N,\mu_1\cdots\mu_R}$
- two independent implementations $\Rightarrow$ checks during run possible
- COLLIER contains complete set of one-loop scalar integrals
- used in RECOLA and OPENLOOPS Cascioli, Maierhöfer, Pozzorini

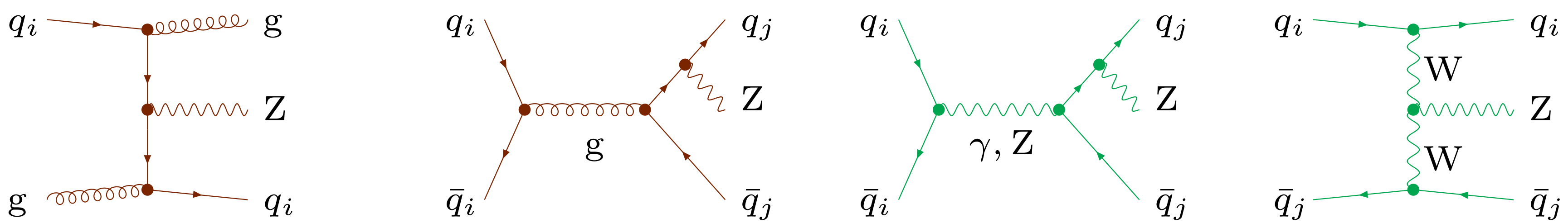
$\mathrm{pp} \to \mathrm{Z} + 2$ jets production

Z + 2 jets at LO

Partonic subprocesses + crossings

- gluon: $q\,g \to q\,g\,Z$: $\sigma \sim \mathcal{O}(\alpha_s^2\alpha)$
- four-quark: $q\,\bar{q} \to q\,\bar{q}\,Z$: $\sigma \sim \mathcal{O}(\alpha_s^2\alpha),\ \mathcal{O}(\alpha_s\alpha^2),\ \mathcal{O}(\alpha^3)$

Sample diagrams QCD, $\mathcal{O}(g_s^2 e)$ and EW, $\mathcal{O}(e^3)$ contributions



Contributions $(\mathrm{pp} \to \mathrm{Z} + 2\mathrm{j})$

Process class	σ^{LO} [pb]	$\sigma^{\mathrm{LO}}/\sigma^{\mathrm{LO}}_{\mathrm{tot}}$ [%]
gluon	1540.4(2)	80.02
four-quark	384.41(4)	19.98
sum	1924.8(2)	100.00

Partonic channels: $\mathrm{gg, gq, g\bar{q}, q\bar{q}, qq, \bar{q}\bar{q}}$, $\mathrm{q = u, c, d, s, b}$
$\gamma\mathrm{q}$, $\gamma\bar{\mathrm{q}}$ (photon induced), contribution $< 0.04\%$ for $8/13\,\mathrm{TeV}$

$\mathrm{Z} + 2$ jets: channels at LO/NLO

Basic channels for $\mathrm{pp} \to \mathrm{Zjj}$

	$\mathrm{ug} \to \mathrm{ugZ}$	$\mathrm{us} \to \mathrm{usZ}$	$\mathrm{us} \to \mathrm{dcZ}$	
	gluon	4-q NC	4-q CC	
# LO diagrams	8	$4 + 8$	5	$\mathcal{O}(g_s^2 e), \mathcal{O}(e^3)$
# real photon diagrams	30	$20 + 40$	35	$\mathcal{O}(g_s^2 e^2), \mathcal{O}(e^4)$
# real gluon diagrams	50	$24 + 40$	24	$\mathcal{O}(g_s^3 e), \mathcal{O}(g_s e^3)$

basic channels for $\mathrm{pp} \to \mathrm{jj}l^+l^-$

	$\mathrm{ug} \to \mathrm{ug}l^+l^-$	$\mathrm{us} \to \mathrm{us}l^+l^-$	$\mathrm{us} \to \mathrm{dc}l^+l^-$	
# LO diagrams	16	$8 + 24$	11	$\mathcal{O}(g_s^2 e^2), \mathcal{O}(e^4)$
# real photon diagrams	92	$56 + 168$	94	$\mathcal{O}(g_s^2 e^3), \mathcal{O}(e^5)$
# real gluon diagrams	100	$48 + 112$	52	$\mathcal{O}(g_s^3 e^2), \mathcal{O}(g_s e^4)$

all channels can be constructed via

- replacement of quark pairs by different flavour, e.g. $\mathrm{u} \to \mathrm{d}$
- combination of basic channels, e.g. $\mathrm{ud} \to \mathrm{udZ}$ or $\mathrm{uu} \to \mathrm{uuZ}$
- crossing of quarks, gluons and photons

$Z + 2$ jets at NLO

Tower of contributions to σ: (additional α for Z decay)

- $\mathcal{O}(\alpha_s^3\alpha)$: QCD corrections to QCD diagrams — Campbell, Ellis, Rainwater '02, '03
- $\mathcal{O}(\alpha_s^2\alpha^2)$: — this work
  - EW corrections to QCD diagrams
  - QCD corrections to EW–QCD interferences
- $\mathcal{O}(\alpha_s\alpha^3)$:
  - EW corrections EW–QCD to interferences
  - QCD corrections to EW diagrams — Oleari, Zeppenfeld '04
- $\mathcal{O}(\alpha^4)$: EW corrections to EW diagrams

first step: EW corrections to gluon channels with stable Z (dominant contributions) — Actis, Denner, Hofer, Scharf, Uccirati '12

preliminary: complete $\mathcal{O}(\alpha_s^2\alpha^2)$ corrections including leptonic Z decay

General setup

- G_μ scheme for electromagnetic coupling:

$$\alpha_{G_\mu} = \frac{\sqrt{2}G_\mu M_\mathrm{W}^2}{\pi}\left(1 - \frac{M_\mathrm{W}^2}{M_\mathrm{Z}^2}\right)$$

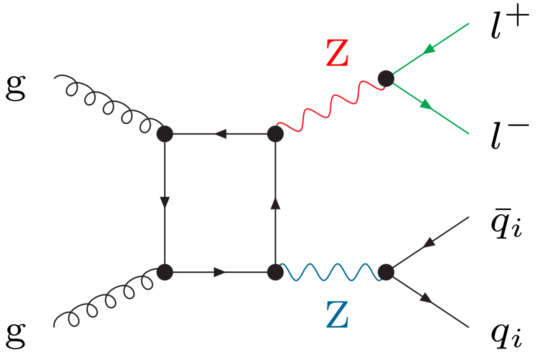
$\Rightarrow$ absorbs running of α to EW scale and some universal m_t^2 corrections

- 't Hooft–Feynman gauge
- complex-mass scheme for Z-boson resonances

Denner, Dittmaier, Roth, Wackeroth, Wieders '99, '05

complex pole: $\mu_\mathrm{Z}^2 = M_\mathrm{Z}^2 - \mathrm{i}M_\mathrm{Z}\Gamma_\mathrm{Z}$
$\Rightarrow$ complex EW mixing angle

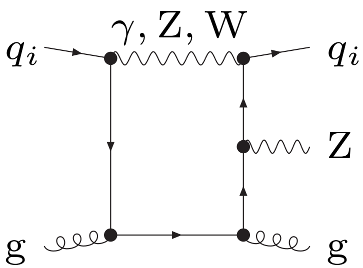
external Z boson treated as stable:
$p^2 = M_\mathrm{Z}^2$
(not relevant for off-shell calculation)

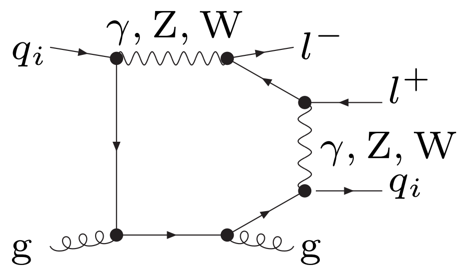


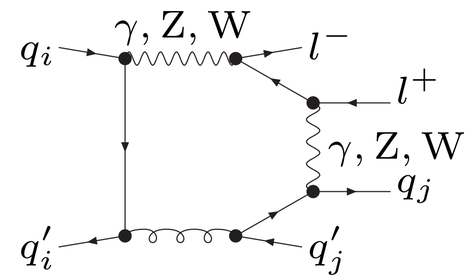
Virtual electroweak corrections

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

	$\mathrm{ug}\to\mathrm{ugZ}$	$\mathrm{ug}\to\mathrm{ug}l^+l^-$	$\mathrm{us}\to\mathrm{us}l^+l^-$	$\mathrm{us}\to\mathrm{dc}l^+l^-$
order	$\mathcal{O}(g_s^2e^3)$	$\mathcal{O}(g_s^2e^4)$	$\mathcal{O}(g_s^4e^2)+\mathcal{O}(g_s^2e^4)$	$\mathcal{O}(g_s^2e^4)$
loop diagrams	~ 300	~ 1200	$\sim 150+800$	~ 120
hexagons	0	18	$0+32$	4
pentagons	20	85	$8+50$	24





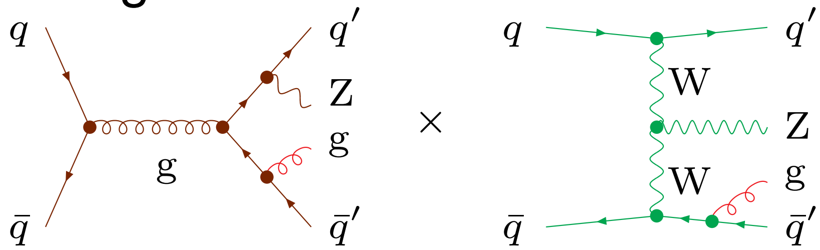


- most complicated topology: pentagon of rank 4 for on-shell Z
  hexagon of rank 4 if Z decay included
- finite top-quark-mass effects:
  - fully included in closed fermion loops
  - neglected in contributions with external bottom quarks
    ($\mathrm{bg}\to\mathrm{bgZ}$, $\mathrm{b\bar{b}}\to\mathrm{ggZ}$, $\mathrm{gg}\to\mathrm{b\bar{b}Z}$, LO contributions at per-cent level)

Real EW NLO corrections

contributions to σ in $\mathcal{O}(\alpha_s^2\alpha^2)$ ($\mathcal{O}(\alpha_s^2\alpha^3)$ including Z decay)

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



soft and collinear singularities

- Catani–Seymour dipole subtraction Catani, Seymour '96
- initial-state collinear singularities cancelled by $\overline{\mathrm{MS}}$ redefinition of PDFs
- recombination of collinear parton-photon pairs
  $\Rightarrow$ cancellation of singularities from collinear photon emission from quarks
- (soft-gluon) IR divergences in $\mathrm{Zjj}\gamma$ related to virtual QCD corrections to $\mathrm{Zj}\gamma$ (soft gluon recombined with hard photon):
  eliminated via cut on photon energy fraction z_γ in jet and
  photon fragmentation function contribution
  compare Denner, Dittmaier, Gehrmann, Kurz '10, Denner, Dittmaier, Kasprzik, Mück '09

Implementation and checks

Setup for calculation with recursive method

- (tree-level and one-loop) matrix elements with RECOLA
- tensor integrals with COLLIER
- phase-space integration with in-house multi-channel Monte Carlo

Check with independent calculation based on conventional methods
(setup used for calculation of EW corrections to $\mathrm{Z}+\mathrm{j}$, $\mathrm{W}+\mathrm{j}$
Denner, Dittmaier, Kasprzik, Mück '09, '11, '12)

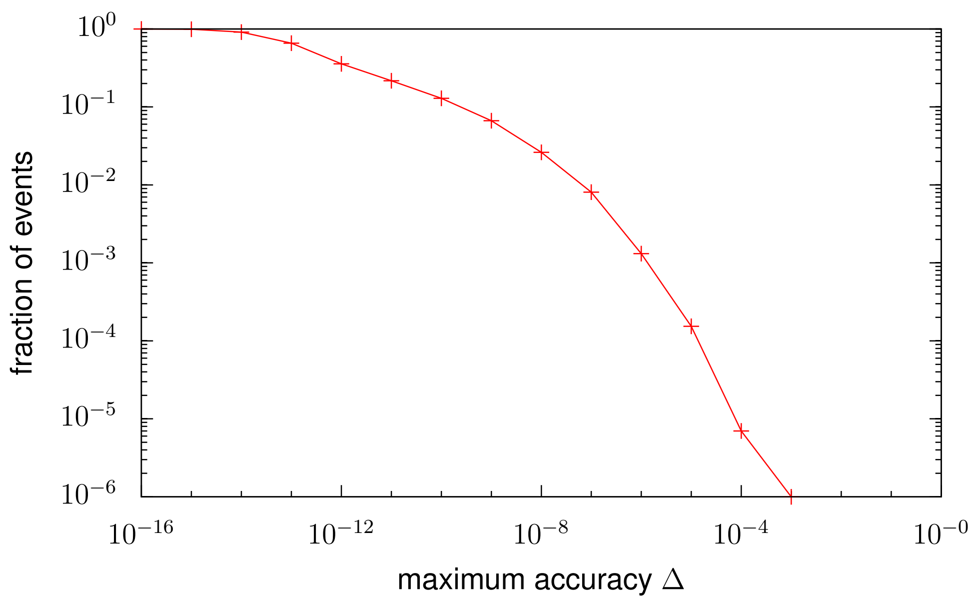
- matrix elements with FEYNARTS/FORMCALC/POLE Hahn et al. '99, '01; Meier '06
- tensor integrals with COLLIER (second independent implementation)
- phase-space integration with LUSIFER Dittmaier, Roth '02

Numerical accuracy

comparison of results by RECOLA and POLE: $(\mathrm{pp} \to \mathrm{Zjj})$
($5 \times 10^6/10^8$ and $5 \times 10^5/10^7$ virtual/real events)

Process class	virtual [fb]	$\vert\mathrm{R}/\mathrm{P}-1\vert[\%]$	real [fb]	$\vert\mathrm{R}/\mathrm{P}-1\vert[\%]$
$q\mathrm{g} \to q\mathrm{gZ}$, $\bar{q}\mathrm{g} \to \bar{q}\mathrm{gZ}$	-14463 ± 10 -14499 ± 27	0.3 ± 0.2	-825 ± 9 -841 ± 22	2 ± 3
$q\bar{q} \to \mathrm{ggZ}$	-1395 ± 2 -1406 ± 7	0.8 ± 0.5	118 ± 1 118 ± 1	0.01 ± 1
$\mathrm{gg} \to q\bar{q}\mathrm{Z}$	-1024 ± 2 -1018 ± 3	0.5 ± 0.4	-186 ± 1 -187 ± 1	0.7 ± 0.9

comparison of virtual squared matrix element 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 8 TeV

EW corrections small for total cross section: $\sim -2.3\%$
similar for all channels

PRELIMINARY

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	17948(4)	77.3	17534(4)	-2.31
four-quark	5270.0(5)	22.7	5139.4(7)	-2.48
sum	23218(4)	100	22674(4)	-2.34

Setup

Jet clustering: anti-k_{T} algorithm with $\Delta R = 0.4$

cuts:

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

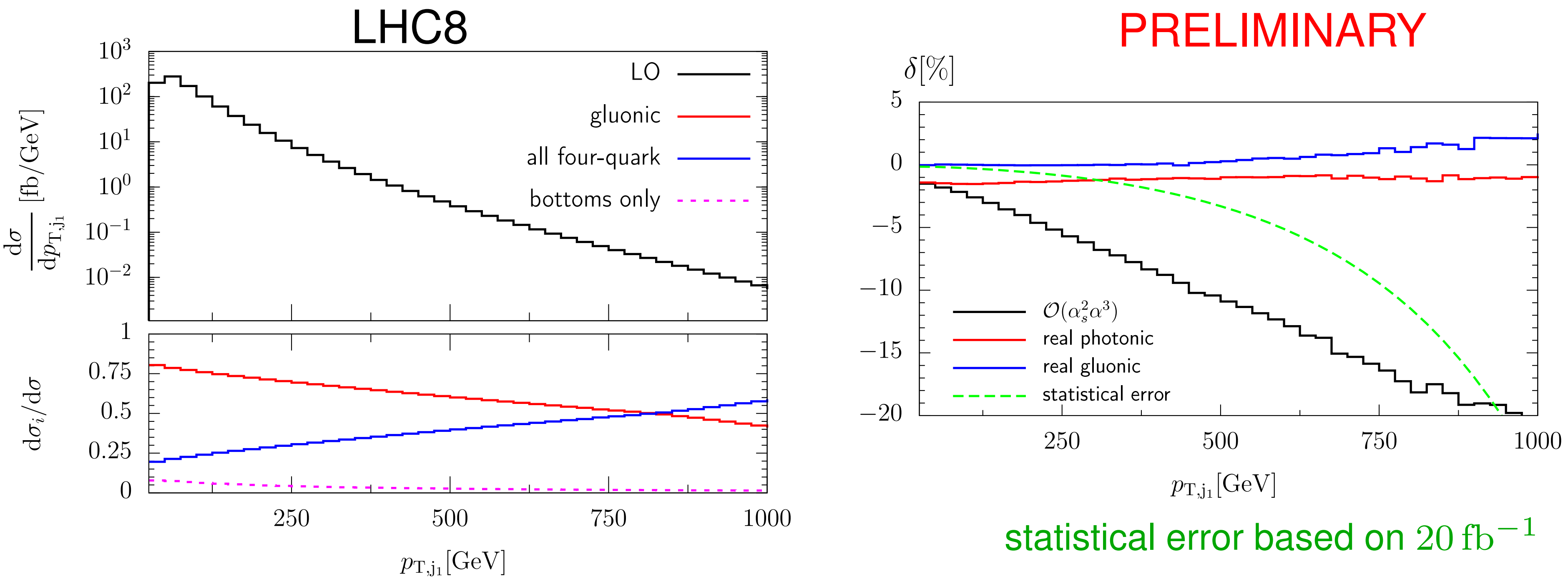
$$P_{\mathrm{T},\tau} > 20\ \mathrm{GeV}, \quad |\eta_\tau| < 2.5$$

$$\Delta R_{\tau^+\tau^-} > 0.2, \quad 66\ \mathrm{GeV} < M_{\tau^+,\tau^-} < 116\ \mathrm{GeV}$$

$$\Delta R_{j\tau^-} > 0.5, \quad \Delta R_{j\tau^+} > 0.5$$

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

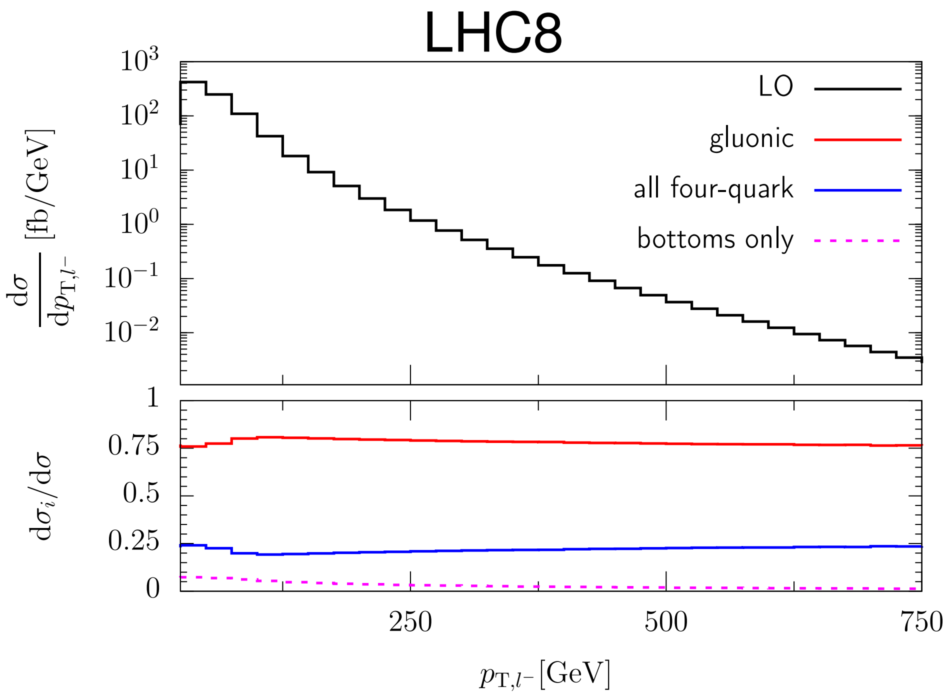
LHC8: Distribution in p_T of leading jet

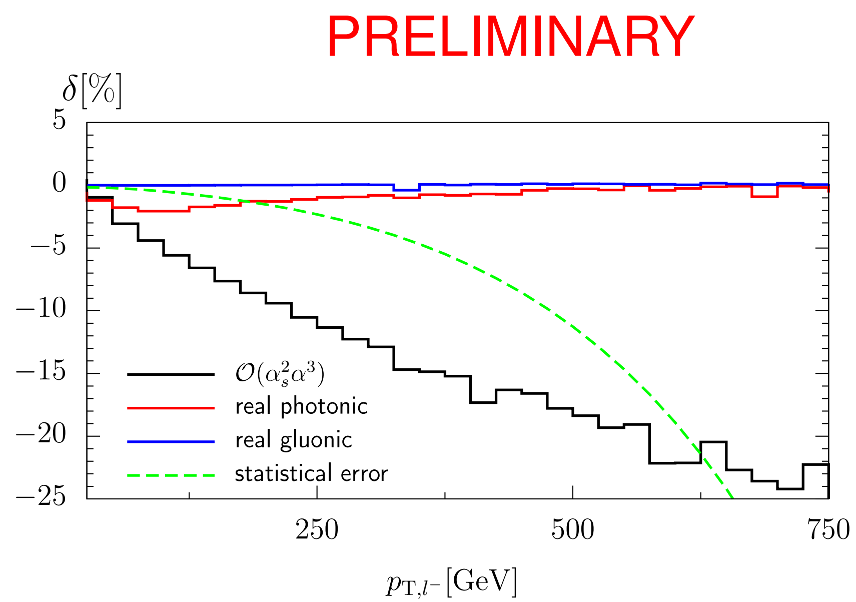


statistical error based on $20\,\mathrm{fb}^{-1}$

- 4-quark channels dominate for high p_T
- bottom contributions below 5%
- EW corrections sizeable for large p_T, dominated by virtual corrections (Sudakov logarithms)
- subtracted real corrections small ($\lesssim 2\%$)

LHC8: Distribution in p_T of l^-

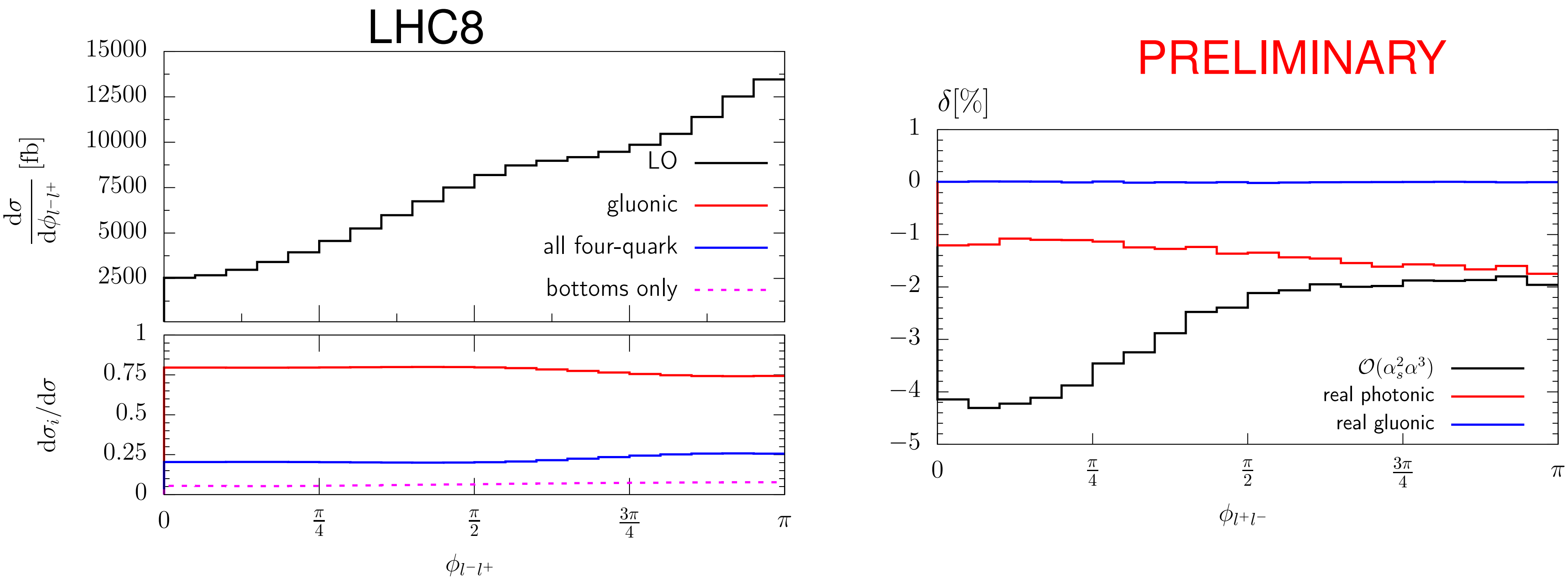




statistical error based on $20\,\mathrm{fb}^{-1}$

- gluon channels dominate for all $p_{\mathrm{T},l}$
- bottom contributions below 5%
- EW corrections -25% for $p_{\mathrm{T},l^-} = 750\,\mathrm{GeV}$
  dominated by virtual corrections (Sudakov logarithms)
- subtracted real corrections small ($\lesssim 2\%$)

LHC8: Distribution in azimuthal angle ϕ_{ll}



- distribution peaked in backward direction
- bottom contributions below 5%
- EW corrections distort distribution by 2%

Conclusions

- Electroweak corrections relevant for many LHC processes
- general tools for their calculation:
  - COLLIER: fast and numerically stable calculation of one-loop tensor integrals
  - RECOLA: recursive generator for tree-level and one-loop amplitudes in the full Standard Model (including EW corrections)

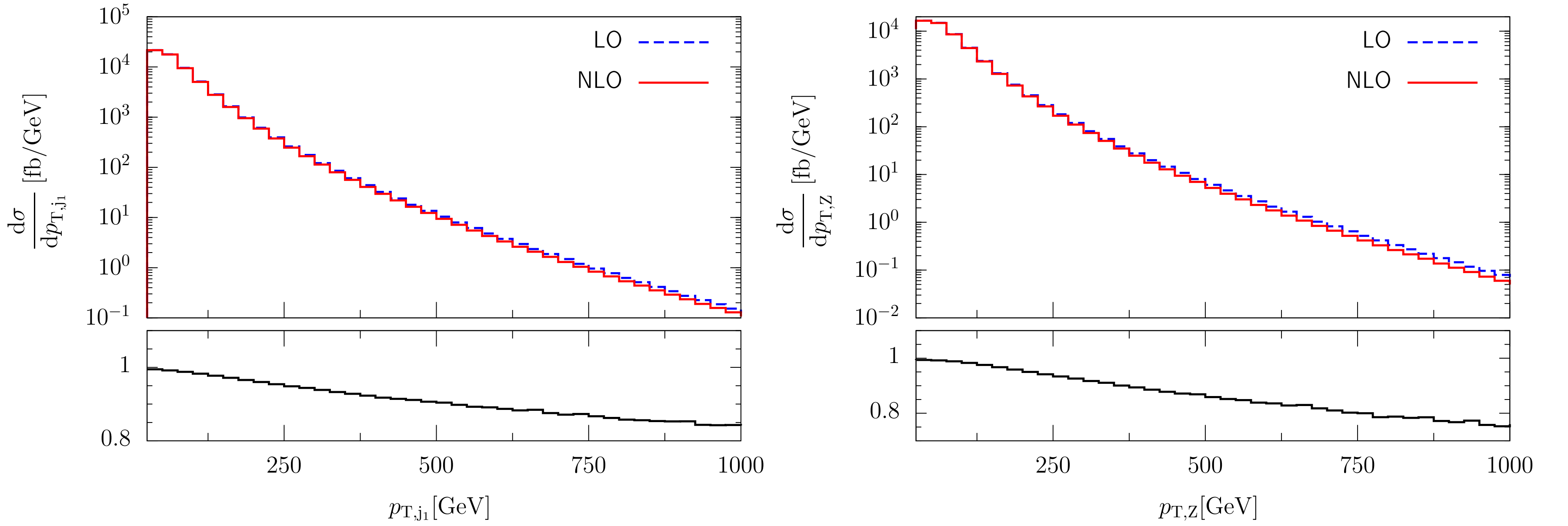
- Electroweak corrections to $\mathrm{pp} \to l^+l^- +$ 2 jets
  - $\mathcal{O}(\alpha^3\alpha_\mathrm{s}^2)$ corrections calculated
    (EW corrections to LO QCD diagrams,
    QCD corrections to LO EW-QCD interferences)
  - corrections to total cross section at per-cent level
  - corrections of several ten per cent in high-energy tails of distributions from virtual Sudakov logarithms
  - real (photonic) corrections typically small

Backup

Results for LHC at 8 TeV

On-shell Z boson:

- EW corrections small on total cross section: -1.2%
  similar for all gluon channels
- can be sizable in distributions where large energy scales are relevant (Sudakov logarithms)



recombination: photons and jets are recombined if $R_{\gamma j} < 0.4$
cuts: two hard jets with $p_{T,jet} > 25\,\mathrm{GeV}$, $|y_{jet}| < 4.5$
photon energy fraction in jet $z_\gamma < 0.7$