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

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in collaboration with S. Actis, L. Hofer, A. Scharf, S. Uccirati

Introduction

- Discovery of Higgs boson 2012: $\Rightarrow$ Standard Model completed
  no direct evidence for physics beyond Standard Model
- tasks for the future:
  - precise investigation of Higgs boson
  - precise study of other Standard Model processes
  - search for physics beyond Standard Model
- decent predictions require higher-order corrections
- automation of NLO corrections performed by many groups, e.g.

  FORMCALC Agrawal, Hahn, Mirabella

  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

  Numerical Integration Becker, Götz, Reuschle, Schwan, Weinzierl

  efforts focus on QCD

Relevance EW NLO corrections at LHC

- Naively: $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \sim \text{few } \%$
- 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. real photonic corrections near resonances
    $\Rightarrow$ radiative tails near resonances
  - 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 EW Standard Model
- important backgrounds for Higgs studies and new physics searches (supersymmetry, . . .)
- testing ground for perturbative calculations and event generators
- NLO QCD corrections exist for $\mathrm{Z}+\leq 4\mathrm{j}$, $\mathrm{W}+\leq 5\mathrm{j}$ Blackhat collaboration

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

- EW 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 EW NLO corrections
- part of Les Houches wish list 2013

Existing results on Z + 2 jets at NLO

- QCD corrections
  - QCD corrections to QCD production — Campbell, Ellis, Rainwater ’02, ’03
  - QCD corrections to EW production — Oleari, Zeppenfeld ’04
- parton-shower matching
  - via POWHEG for QCD production — Re ’12
  - via POWHEG BOX for QCD production — Campbell, Ellis, Nason, Zanderighi ’13
  - via POWHEG BOX for EW production — Jäger, Schneider, Zanderighi ’13; Schissler, Zeppenfeld ’13
- EW corrections
  - EW corrections to gluon channels with stable Z — Actis, Denner, Hofer, Scharf, Uccirati ’12
  - electroweak corrections for $\nu\bar{\nu} + 2$ jets in Sudakov limit — Chiesa et al. ’13

this talk: electroweak corrections for $l^+l^- + 2$ jets

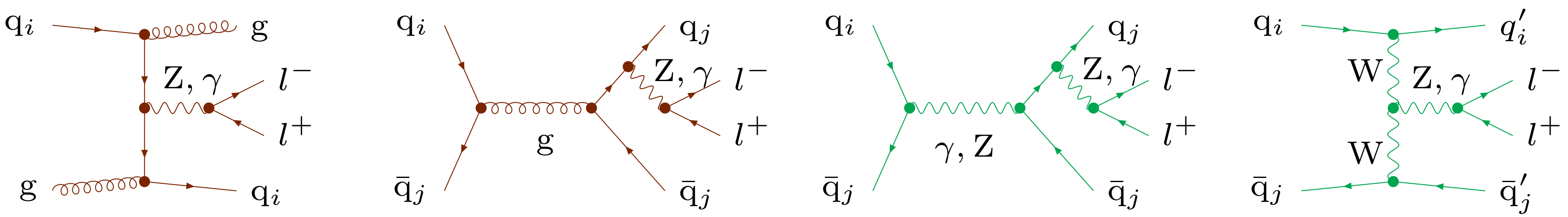
Details of the calculation

Z + 2 jets at LO

Partonic subprocesses + crossings

- gluon: $q\,g \to q\,g\,l^+l^-$: $\sigma \sim \mathcal{O}(\alpha_s^2\alpha^2)$
- four-quark: $q\,\bar{q} \to q\,\bar{q}\,l^+l^-$: $\sigma \sim \mathcal{O}(\alpha_s^2\alpha^2)$, $\mathcal{O}(\alpha_s\alpha^3)$, $\mathcal{O}(\alpha^4)$

Sample diagrams QCD, $\mathcal{O}(g_s^2e^2)$ and EW, $\mathcal{O}(e^4)$ contributions



Contributions ($pp \to l^+l^- + 2j$, $l = e$ or μ or τ, LHC13)

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

Partonic channels: gg, gq, $g\bar{q}$, $q\bar{q}$, qq, $\bar{q}\bar{q}$, $q = u, c, d, s, b$

γq, $\gamma\bar{q}$, γg, $\gamma\gamma$ (γ induced), contribution $< 0.05\%$ for $8/13\,\mathrm{TeV}$

$Z + 2$ jets: channels at LO/NLO

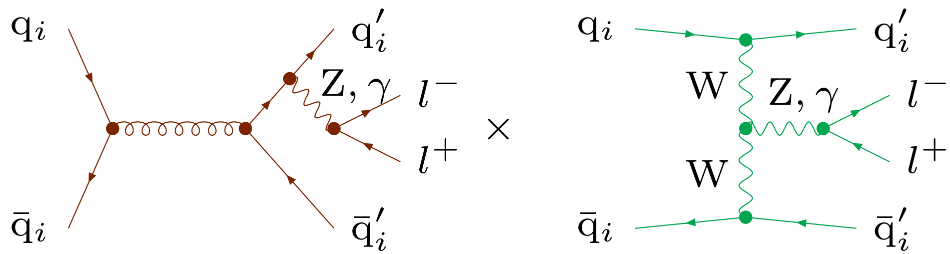
6 basic channels for $\mathrm{pp} \to \mathrm{jj}l^+l^-$

	$\mathrm{ug} \to \mathrm{ug}l^+l^-$	$\mathrm{us} \to \mathrm{us}l^+l^-$	$\mathrm{us} \to \mathrm{dc}l^+l^-$	
	$\mathrm{dg} \to \mathrm{dg}l^+l^-$	$\mathrm{uc} \to \mathrm{uc}l^+l^-$		
		$\mathrm{ds} \to \mathrm{ds}l^+l^-$		
# 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

- combination of basic channels, e.g. $\mathrm{ud} \to \mathrm{ud}l^+l^-$ or $\mathrm{uu} \to \mathrm{uu}l^+l^-$
- crossing of quarks, gluons and photons

$\mathcal{O}(\alpha_s \alpha^3)$ contributions result only from interferences between different kinematic channels



Z + 2 jets at NLO

Tower of contributions to σ:

- $\mathcal{O}(\alpha_s^3\alpha^2)$: QCD corrections to QCD diagrams — Campbell, Ellis, Rainwater '02, '03
- $\mathcal{O}(\alpha_s^2\alpha^3)$: — this work
  - 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
  - EW corrections EW–QCD to interferences
- $\mathcal{O}(\alpha^5)$: EW corrections to EW diagrams

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

in preparation: complete $\mathcal{O}(\alpha_s^2\alpha^3)$ corrections (including leptonic Z decay)
Denner, Hofer, Scharf, Uccirati

General setup

- G_μ scheme for electromagnetic coupling:

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

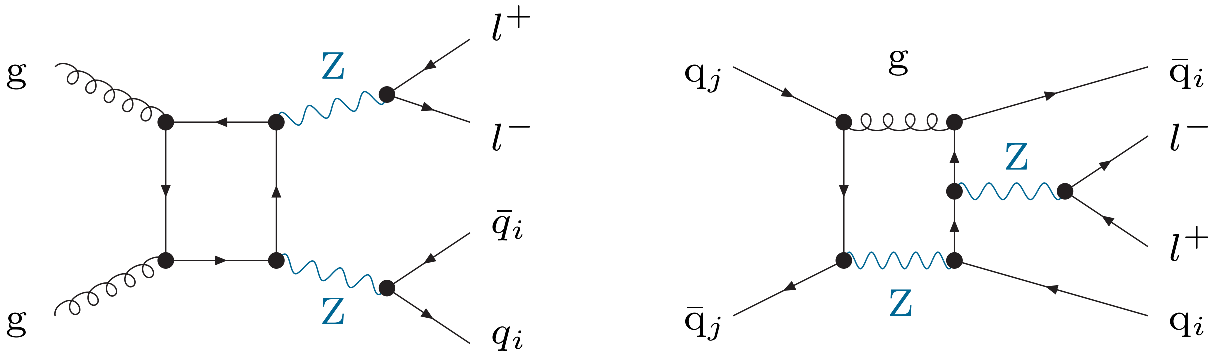
$\Rightarrow$ absorbs running of α to EW scale and some universal corrections $\propto m_{\mathrm{t}}^2$

- complex-mass scheme for Z-boson resonances

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

complex pole: $\mu_{\mathrm{Z}}^2 = M_{\mathrm{Z}}^2 - \mathrm{i} M_{\mathrm{Z}} \Gamma_{\mathrm{Z}}, \quad \mu_{\mathrm{W}}^2 = M_{\mathrm{W}}^2 - \mathrm{i} M_{\mathrm{W}} \Gamma_{\mathrm{W}}$

$\Rightarrow$ complex EW mixing angle: $\cos\theta_{\mathrm{w}} = \mu_{\mathrm{W}}/\mu_{\mathrm{Z}}$

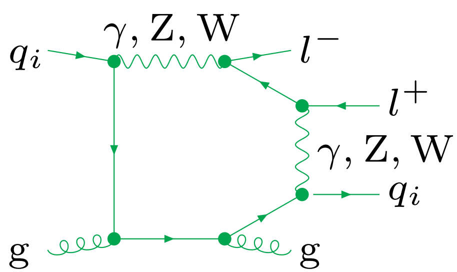


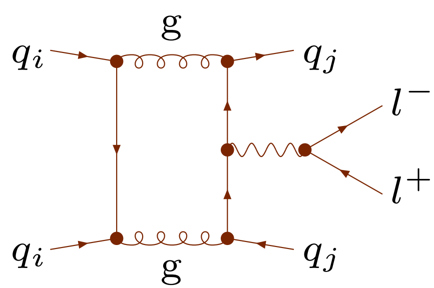
- massless light fermions
- 't Hooft–Feynman gauge

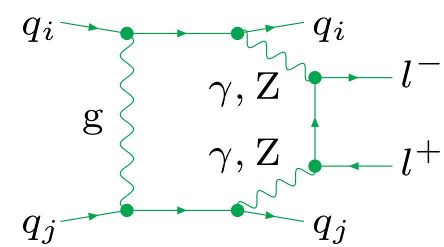
Virtual electroweak corrections

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

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





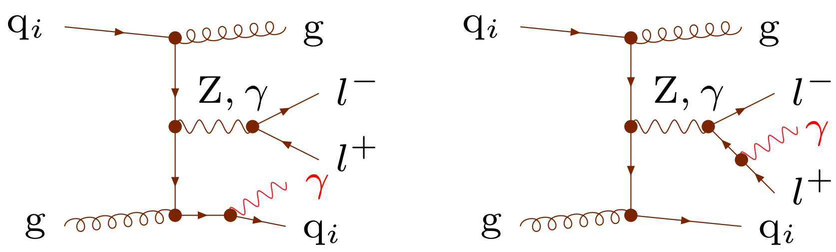


- most complicated topology: hexagon of rank 4
- finite top-quark-mass effects:
  - fully included in closed fermion loops
  - contributions with external bottom quarks neglected at NLO
    ($\mathrm{bg} \to \mathrm{bgZ}$, $\mathrm{b\bar{b}} \to \mathrm{ggZ}$, $\mathrm{gg} \to \mathrm{b\bar{b}Z}$, LO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

Real EW NLO corrections to gluonic processes

real photon emission from LO QCD contributions:

$\mathrm{qg} \to \mathrm{qg} l^+ l^- \gamma$: $\delta\sigma \sim \mathcal{O}(\alpha_s^2 \alpha^3)$



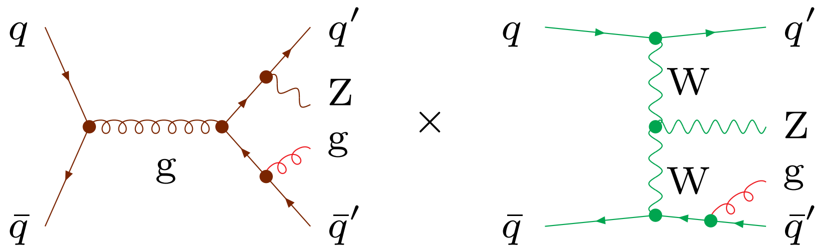
soft and collinear singularities

- Catani–Seymour dipole subtraction — Catani, Seymour '96; Nagy, Trocsanyi '99; Campbell, Ellis, Tramontano '04
- initial-state collinear singularities cancelled by $\overline{\mathrm{MS}}$ redefinition of PDFs
- recombination of collinear parton–photon pairs
  extension of jet algorithm to photons
  $\Rightarrow$ cancellation of singularities from collinear photon emission from quarks
- (soft-gluon) IR divergences in $l^+l^-\mathrm{jj}\gamma$ related to virtual QCD corrections to $l^+l^-\mathrm{j}\gamma$ (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

Real EW NLO corrections to four-quark processes

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

- real photon emission from LO QCD contributions
  $\mathrm{qq} \to \mathrm{qq}l^+l^-\gamma$
- real gluon emission in QCD–EW interferences
  $\mathrm{qq} \to \mathrm{qq}l^+l^-\mathrm{g}$



  only for channels with identical quarks ($q = q'$) or isospin partners q, q'
- crossing of gluon $\Rightarrow$ new partonic channels $\mathrm{gq} \to \mathrm{qq\bar{q}}l^+l^-$ (IR-finite)

soft and collinear singularities

- same treatment as for gluonic contributions
- no IR singularities from soft gluons
  $\hookrightarrow$ no cut on z_γ and fragmentation function necessary
  we use same recombination procedure as in gluonic case
  $\Rightarrow$ equal treatment of all channels

Implementation and checks

Setup for calculation

- (tree-level and one-loop) matrix elements with RECOLA
  (Recursive computation of one-loop amplitudes) ⇒ talk by Sandro Uccirati
- tensor integrals with COLLIER
  (Complex one-loop library in extended regularizations)
  ⇒ talk by Lars Hofer
- 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

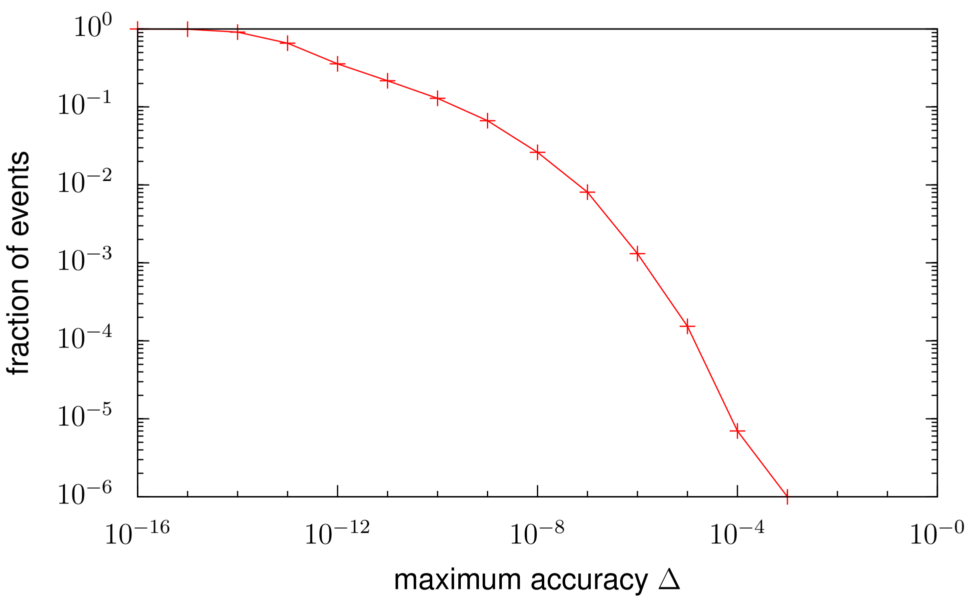
checks in progress

Numerical accuracy

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

Process class	virtual [fb]	$\lvert R/P - 1 \rvert [\%]$	real [fb]	$\lvert R/P - 1 \rvert [\%]$
$q\mathrm{g} \to q\mathrm{gZ}$, $\bar{q}\mathrm{g} \to \bar{q}\mathrm{gZ}$	-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 contributions for 10^6 events:



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

Results

Setup for phenomenological analysis

- PDFs: MSTW2008LO Martin et al. '09
- scales: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = M_{\mathrm{Z}}$
- jet clustering: anti-k_{T} algorithm with $\Delta R = 0.4$, also for photons
  Cacciari, Salam, Soyez '08
- basic cuts: motivated by ATLAS '13

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

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

- VBF cuts: basic cuts without cut on $M_{l^+l^-}$

$$\text{plus} \quad M_{\mathrm{jj}} > 600\ \mathrm{GeV}, \quad |y_{\mathrm{j}_1} - y_{\mathrm{j}_2}| > 4, \quad y_{\mathrm{j}_1} \cdot y_{\mathrm{j}_2} < 0$$
$$\min(y_{\mathrm{j}_1}, y_{\mathrm{j}_2}) < y_l < \max(y_{\mathrm{j}_1}, y_{\mathrm{j}_2})$$

Results for LHC at 13 TeV

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

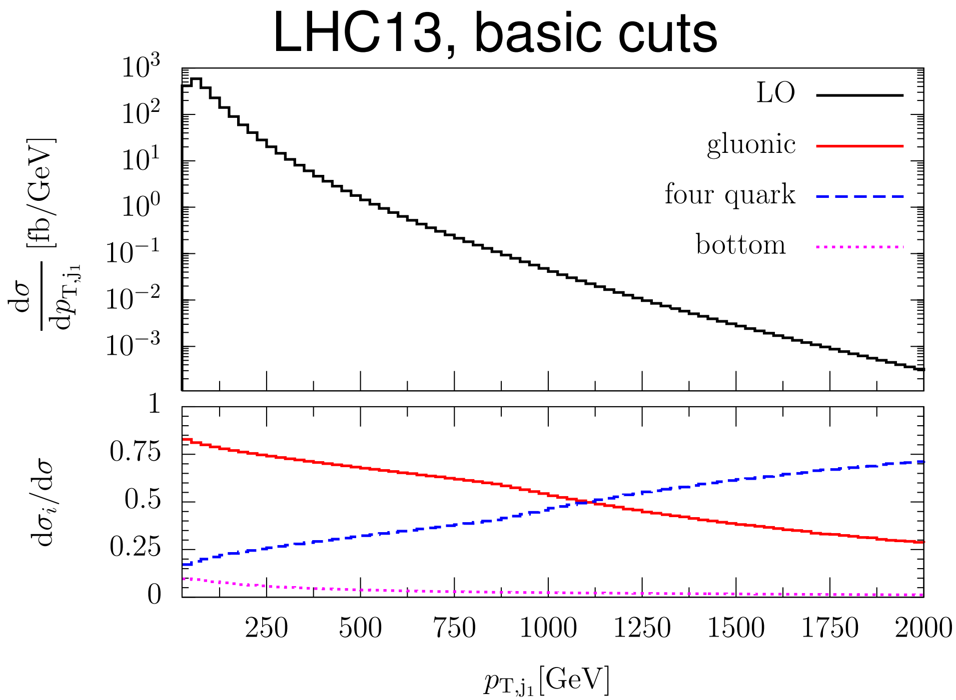
LHC13, basic cuts

PRELIMINARY

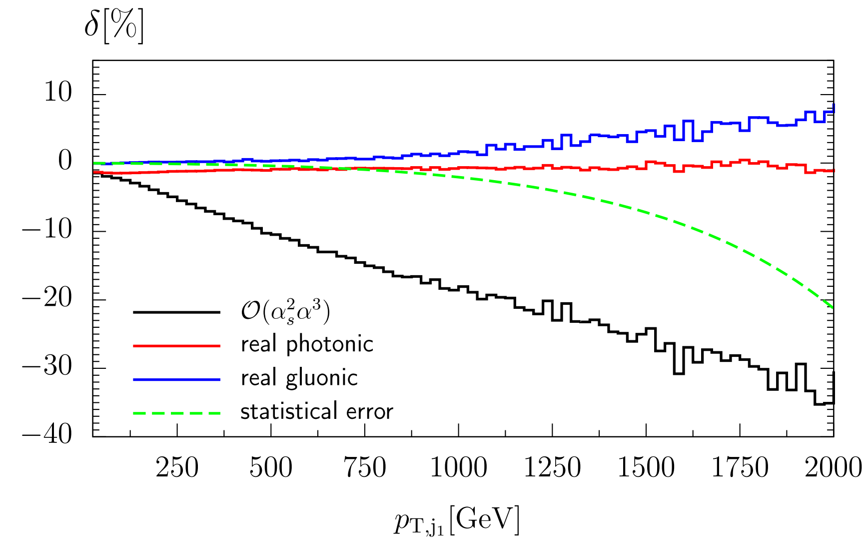
process class	σ^{LO} [fb]	$\sigma^{\mathrm{LO}}/\sigma^{\mathrm{LO}}_{\mathrm{tot}}$ [%]	$\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$ [fb]	$\frac{\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{\sigma^{\mathrm{LO}}} - 1$ [%]
$qg \to qgl^-l^+$ $\bar{q}g \to \bar{q}gl^-l^+$	34584(8)	67.5	33751(9)	-2.41
$q\bar{q} \to ggl^-l^+$	2713(1)	5.3	2626(1)	-3.21
$gg \to q\bar{q}l^-l^+$	3612(1)	7.1	3556(1)	-1.55
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		

qg channels dominate

LHC13: Distribution in p_T of leading jet



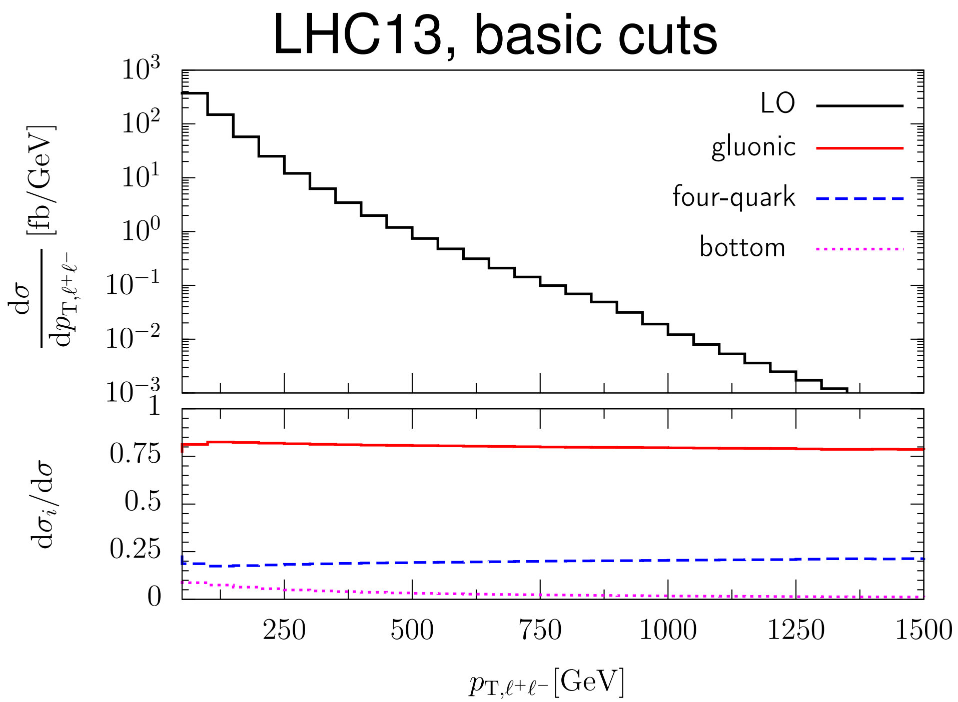
PRELIMINARY

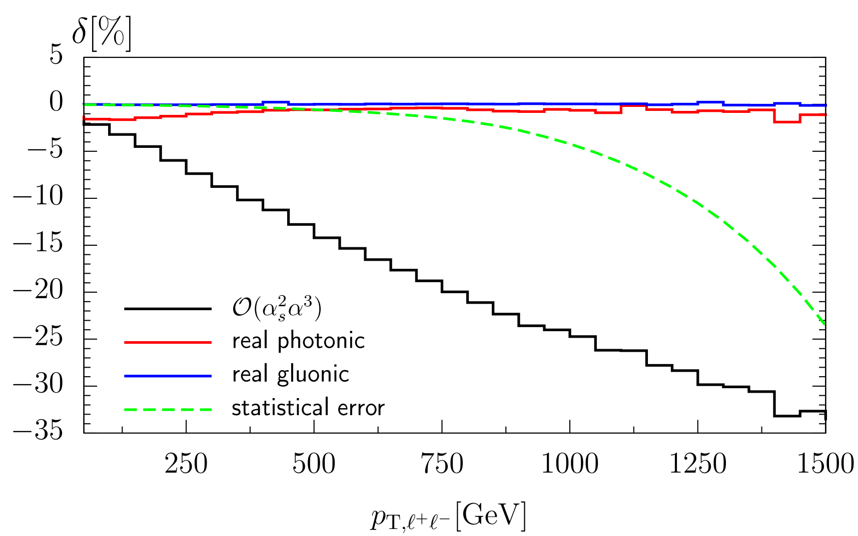


statistical error based on $300\,\mathrm{fb}^{-1}$

- 4-quark channels dominate for high p_T (compare dijet production)
- bottom contributions below $5–10\%$
- EW corrections sizeable for large p_T
  dominated by virtual corrections (Sudakov logarithms)
- subtracted real photonic corrections small
  subtracted real gluonic corrections small for $p_{\mathrm{T},\mathrm{j}_1} \lesssim 1\,\mathrm{TeV}$
  8% for $p_{\mathrm{T},\mathrm{j}_1} = 2\,\mathrm{TeV}$

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

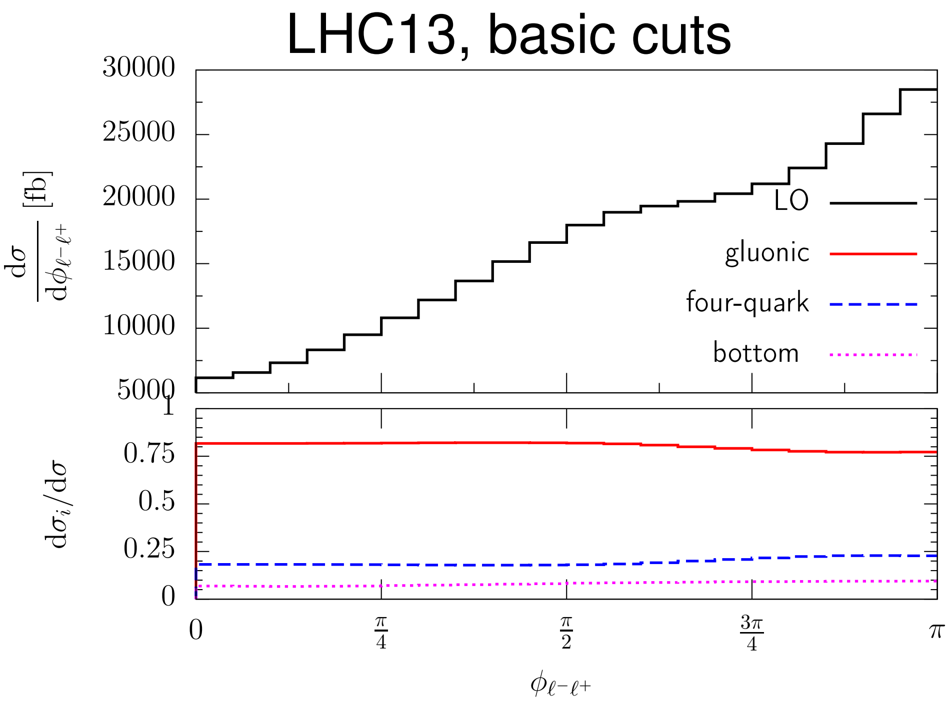


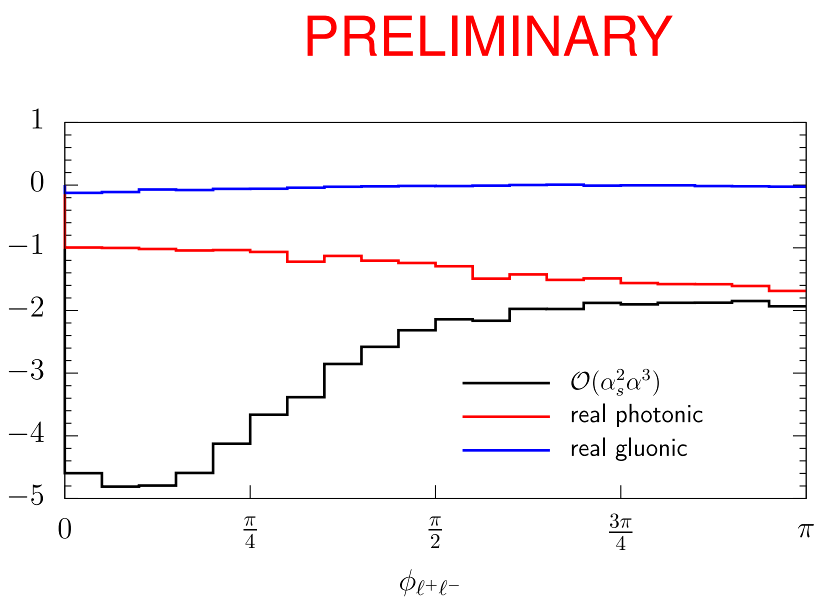


statistical error based on $300\,\mathrm{fb}^{-1}$

- gluon channels dominate for all $p_{\mathrm{T},ll}$ (different kinematic configuration)
- 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 ($\lesssim 2\%$)

LHC13: Distribution in azimuthal angle ϕ_{ll}





- distribution peaked in backward direction
- bottom contributions below 10%
- virtual EW corrections distort distribution by 3%

Results for LHC at 13 TeV in VBF setup

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

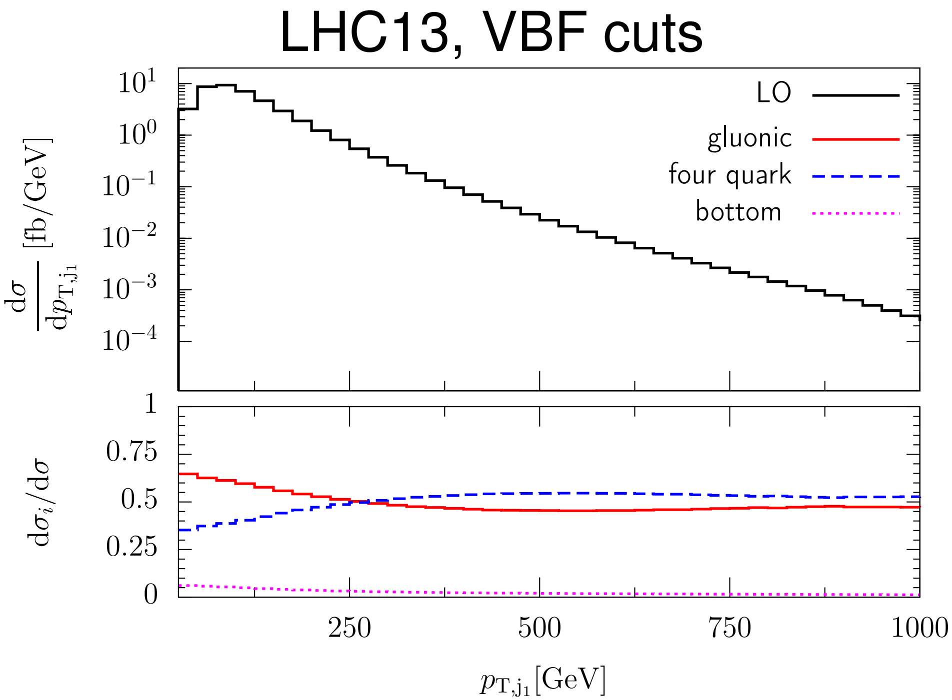
LHC 13, VBF cuts

VERY PRELIMINARY

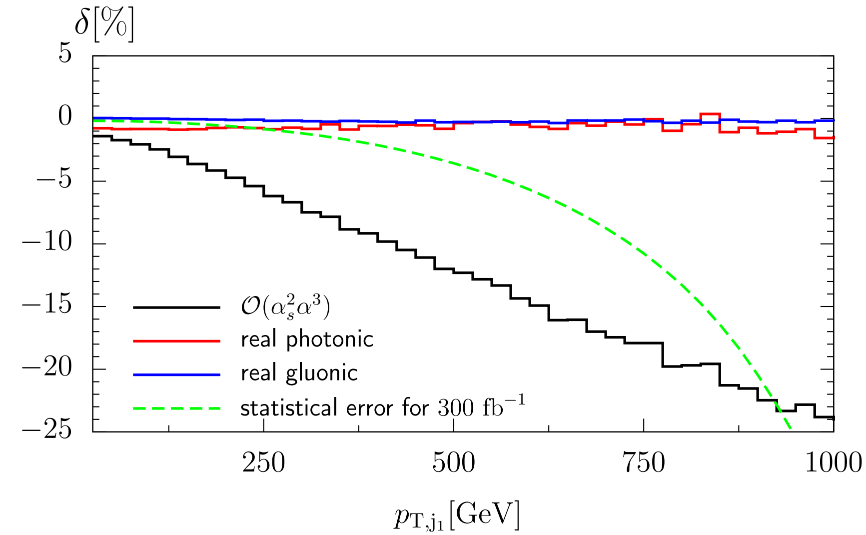
process class	σ^{LO} [fb]	$\sigma^{\mathrm{LO}}/\sigma^{\mathrm{LO}}_{\mathrm{tot}}$ [%]	$\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$ [fb]	$\frac{\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{\sigma^{\mathrm{LO}}} - 1$ [%]
$qg \to qgl^-l^+$ $\bar{q}g \to \bar{q}gl^-l^+$	540.9(3)	52.0	524.1(4)	-3.1
$q\bar{q} \to ggl^-l^+$	22.35(1)	2.2	21.14(2)	-5.4
$gg \to q\bar{q}l^-l^+$	54.53(4)	5.2	54.01(4)	-1.0
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
bottom quarks	51.82(2)	5.0		

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

LHC13: Distribution in p_T of leading jet



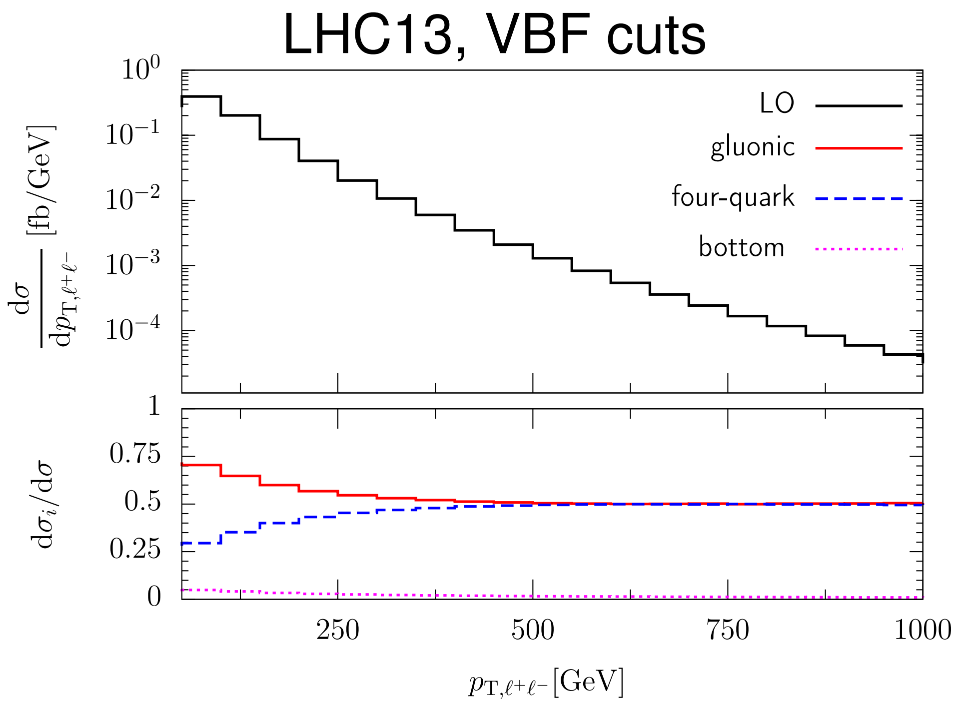
VERY PRELIMINARY

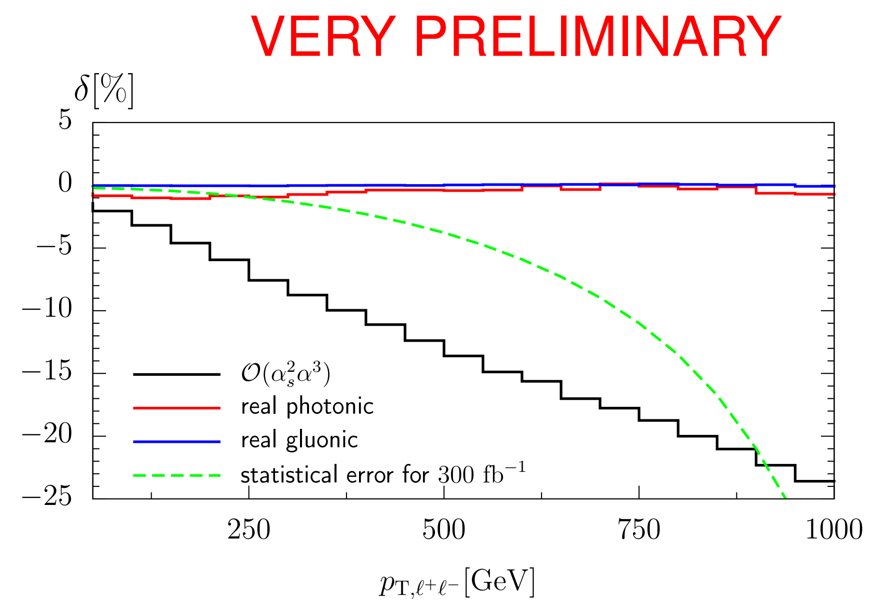


statistical error based on $300\,fb^{-1}$

- 4-quark and gluon channels comparable for high p_T
- bottom contributions below $\sim 5\%$
- EW corrections for large p_T larger as for basic cuts
  dominated by virtual corrections (Sudakov logarithms)
- subtracted real photonic corrections small
  subtracted real gluonic corrections tiny

LHC13: Distribution in p_T of l^+l^-

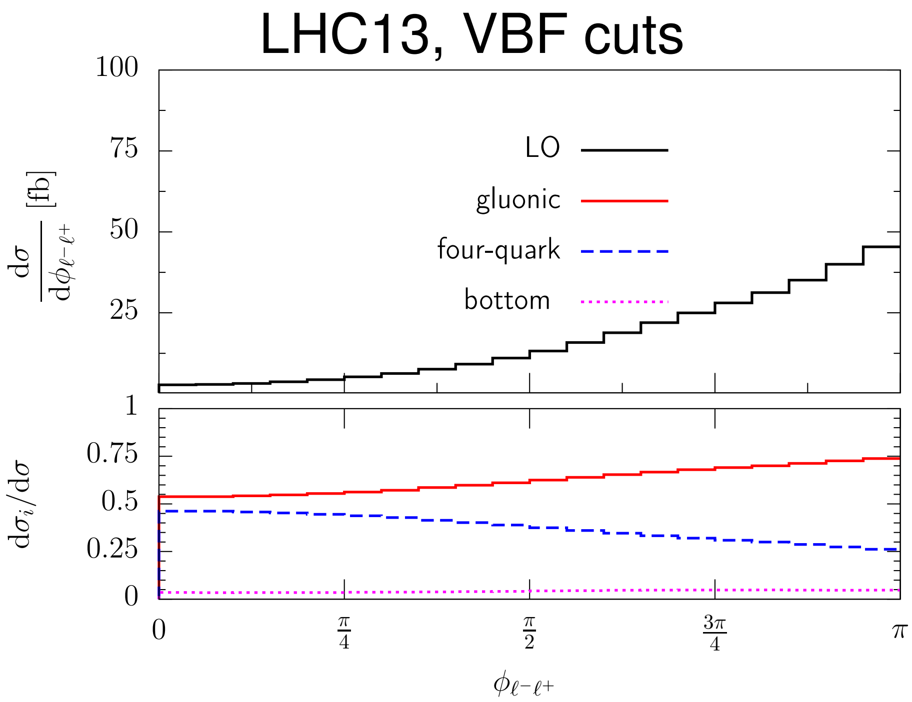


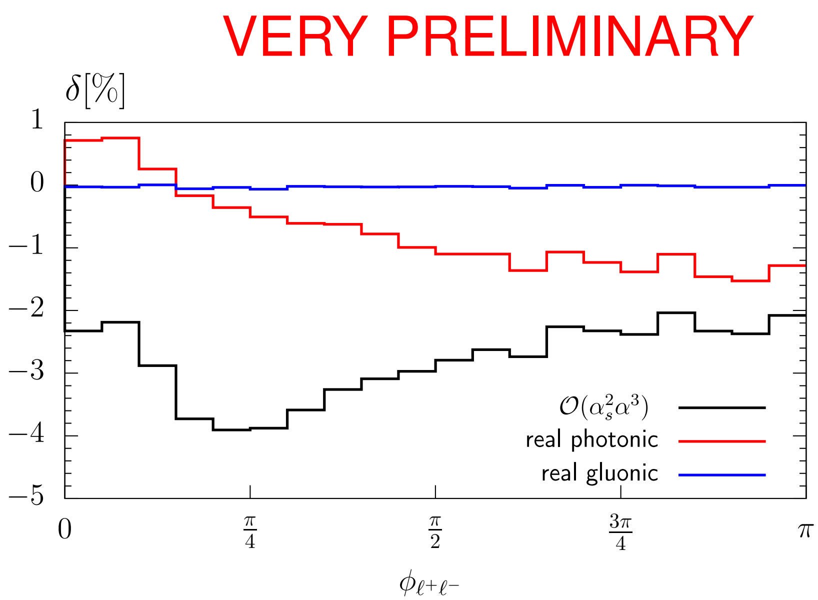


statistical error based on $300\,\mathrm{fb}^{-1}$

- gluon channels dominate for all $p_{T,ll}$
- bottom contributions below $\sim 5\%$
- EW corrections for large $p_{T,ll}$ similar as for $p_{T,j}$
  dominated by virtual corrections (Sudakov logarithms)
- subtracted real corrections small ($\lesssim 2\%$)

LHC13: Distribution in azimuthal angle ϕ_{ll}





- distribution peaked in backward direction
- bottom contributions below 5%
- virtual EW corrections distort distribution by 2%
- real EW corrections distort distribution by 3%

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 electroweak 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 ($\sim -2.5\%$)
  - corrections of several ten per cent in high-energy tails of distributions from virtual Sudakov logarithms
  - real (photonic) corrections small
  - angular distributions distorted by few per cent

Backup

LO results for LHC at 13 TeV

LHC13, basic cuts

PRELIMINARY

process class	σ [fb]	$\sigma/\sigma_{\mathrm{tot}}$ [%]	$\sigma_{\alpha_s^2\alpha^2}/\sigma$ [%]	$\sigma_{\alpha_s\alpha^3}/\sigma$ [%]	σ_{α^4}/σ [%]
$uu \to uul^-l^+$, $dd \to ddl^-l^+$ $\bar{u}\bar{u} \to \bar{u}\bar{u}l^-l^+$, $\bar{d}\bar{d} \to \bar{d}\bar{d}l^-l^+$	1315.1(3)	2.6	97.4	2.0	0.5
$u\bar{u} \to u'\bar{u}'l^-l^+$, $d\bar{d} \to d'\bar{d}'l^-l^+$, $u\bar{u}' \to u\bar{u}'l^-l^+$, $d\bar{d}' \to d\bar{d}'l^-l^+$	2463.7(5)	4.8	98.3	−1.3	2.9
$u\bar{u} \to d\bar{d}l^-l^+$, $d\bar{d} \to u\bar{u}l^-l^+$, $u\bar{u}' \to d\bar{d}'l^-l^+$, $d\bar{d}' \to u\bar{u}'l^-l^+$	438.82(7)	0.9	76.6	−9.0	32.3
$ud \to u'd'l^-l^+$, $\bar{u}\bar{d} \to \bar{u}'\bar{d}'l^-l^+$, $ud \to udl^-l^+$, $\bar{u}\bar{d} \to \bar{u}\bar{d}l^-l^+$ $uu' \to uu'l^-l^+$, $\bar{u}\bar{u}' \to \bar{u}\bar{u}', l^-l^+$ $dd' \to dd'l^-l^+$, $\bar{d}\bar{d}' \to \bar{d}\bar{d}', l^-l^+$	3856.8(7)	7.5	92.9	2.8	4.3
$u\bar{d} \to u'\bar{d}'l^-l^+$, $\bar{u}d \to \bar{u}'d'l^-l^+$, $u\bar{d} \to u\bar{d}l^-l^+$, $\bar{u}d \to \bar{u}dl^-l^+$	2224.9(4)	4.3	95.9	−1.1	5.2
gluonic	40910(8)	79.9	100	—	—
four-quark	10299(1)	20.1	94.7	0.4	4.8
sum	51209(8)	100	98.9	< 0.1	1.0

$u \neq u'$, $d \neq d'$

LO results for LHC at 13 TeV

LHC13, VBF cuts

PRELIMINARY

process class	σ [fb]	$\sigma/\sigma_{\mathrm{tot}}$ [%]	$\sigma_{\alpha_s^2\alpha^2}/\sigma$ [%]	$\sigma_{\alpha_s\alpha^3}/\sigma$ [%]	σ_{α^4}/σ [%]
$uu \to uul^-l^+$, $dd \to ddl^-l^+$, $\bar{u}\bar{u} \to \bar{u}\bar{u}l^-l^+$, $\bar{d}\bar{d} \to \bar{d}\bar{d}l^-l^+$	86.22(5)	8.3	97.0	0.1	2.8
$u\bar{u} \to u'\bar{u}'l^-l^+$, $d\bar{d} \to d'\bar{d}'l^-l^+$, $u\bar{u}' \to u\bar{u}'l^-l^+$, $d\bar{d}' \to d\bar{d}'l^-l^+$	65.98(3)	6.3	98.2	-0.1	2.0
$u\bar{u} \to d\bar{d}l^-l^+$, $d\bar{d} \to u\bar{u}l^-l^+$, $u\bar{u}' \to d\bar{d}'l^-l^+$, $d\bar{d}' \to u\bar{u}'l^-l^+$	21.198(7)	2.0	1.9	-4.6	102.7
$ud \to u'd'l^-l^+$, $\bar{u}\bar{d} \to \bar{u}'\bar{d}'l^-l^+$, $ud \to udl^-l^+$, $\bar{u}\bar{d} \to \bar{u}\bar{d}l^-l^+$, $uu' \to uu'l^-l^+$, $\bar{u}\bar{u}' \to \bar{u}\bar{u}',l^-l^+$, $dd' \to dd'l^-l^+$, $\bar{d}\bar{d}' \to \bar{d}\bar{d}',l^-l^+$	180.61(8)	17.3	74.0	1.1	24.9
$u\bar{d} \to u'\bar{d}'l^-l^+$, $\bar{u}d \to \bar{u}'d'l^-l^+$, $u\bar{d} \to u\bar{d}l^-l^+$, $\bar{u}d \to \bar{u}dl^-l^+$	67.73(3)	6.5	99.0	-0.1	1.1
gluonic	617.8(4)	59.4	100	—	—
four-quark	421.7(1)	40.6	82.9	0.2	16.9
sum	1039.6(4)	100	93.1	0.01	6.9

$u \neq u'$, $d \neq d'$

Results for LHC at 8 TeV

Composition of LO cross section

PRELIMINARY

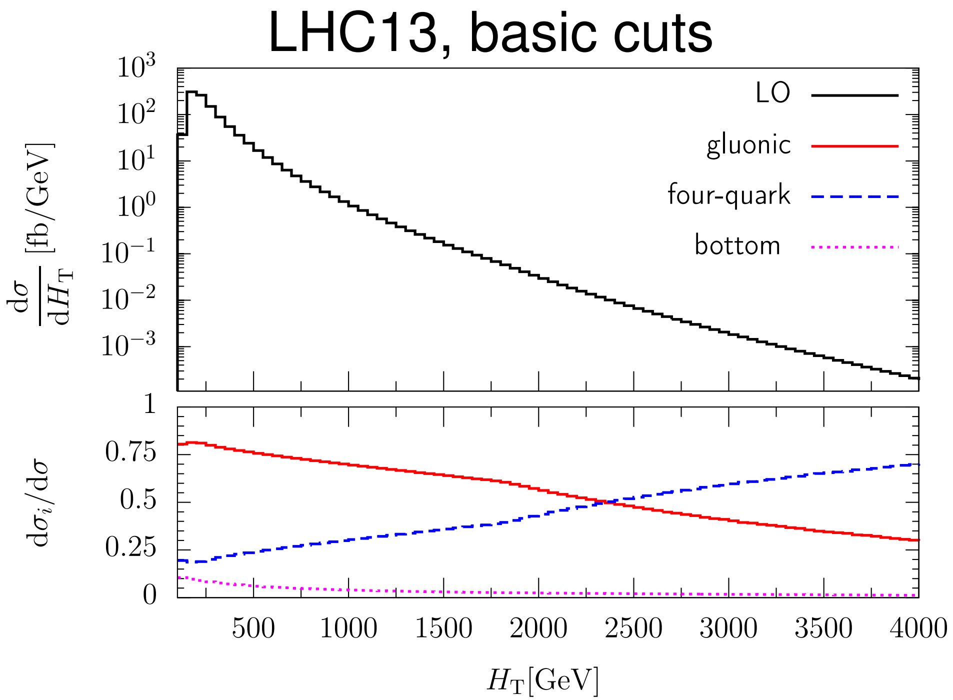
process class	σ [fb]	$\sigma/\sigma_{\rm tot}$ [%]	$\sigma_{\alpha_s^2\alpha^2}/\sigma$ [%]	$\sigma_{\alpha_s\alpha^3}/\sigma$ [%]	σ_{α^4}/σ [%]
gluonic	17949(4)	77.3	100	—	—
four-quark	5270.0(5)	22.7	94.6	0.6	4.8
sum	23218(4)	100	98.8	0.1	1.1

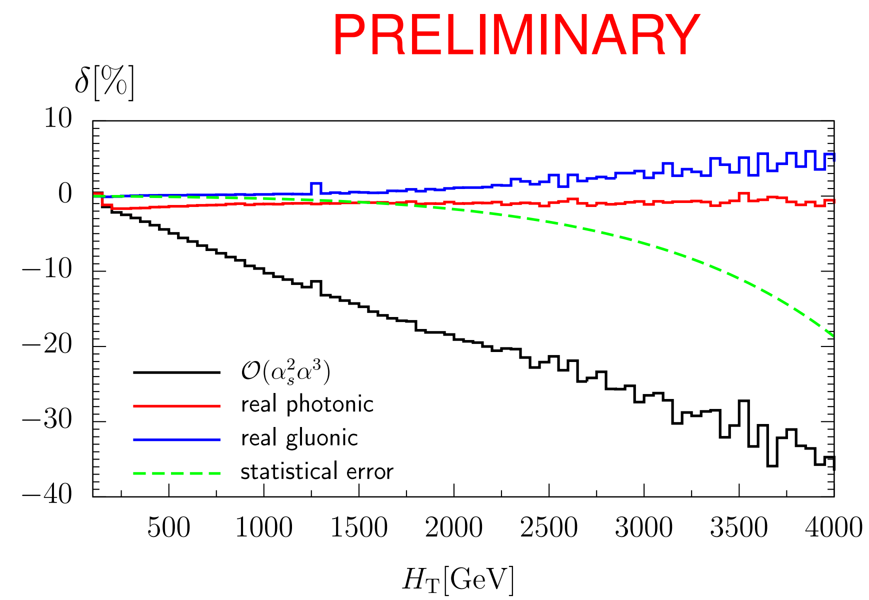
EW corrections small for total cross section: $\sim -2.3\%$
similar for all channels

PRELIMINARY

process class	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm LO}/\sigma^{\rm LO}_{\rm tot}$ [%]	$\sigma^{\rm NLO}_{\rm EW}$ [fb]	$\frac{\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm LO}} - 1$ [%]
gluonic	17949(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

LHC13: Distribution in total transverse energy H_{T}





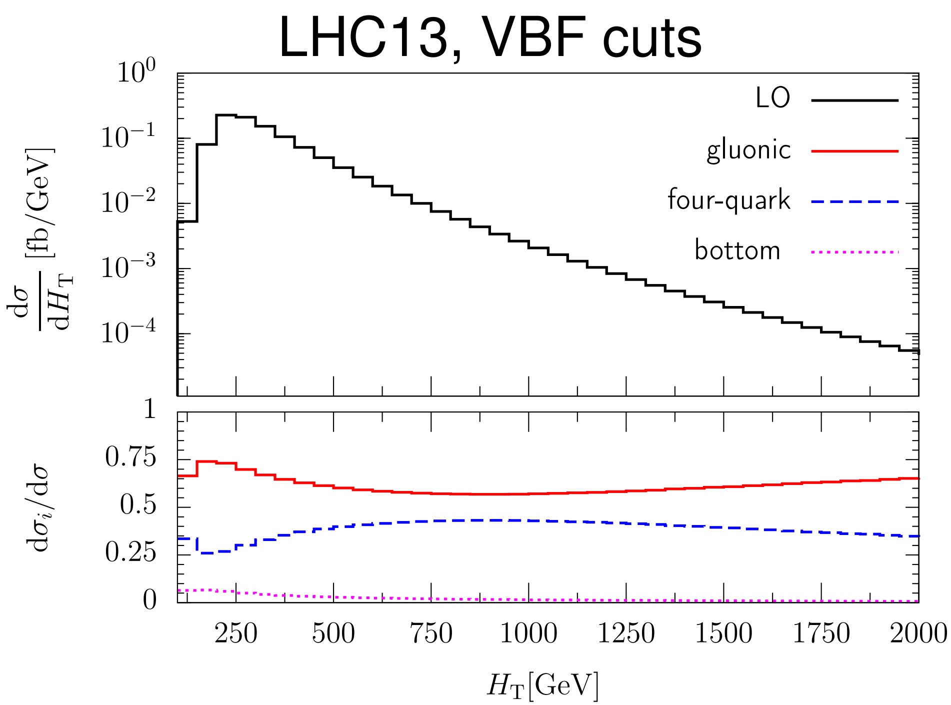
statistical error based on $300\,\mathrm{fb}^{-1}$

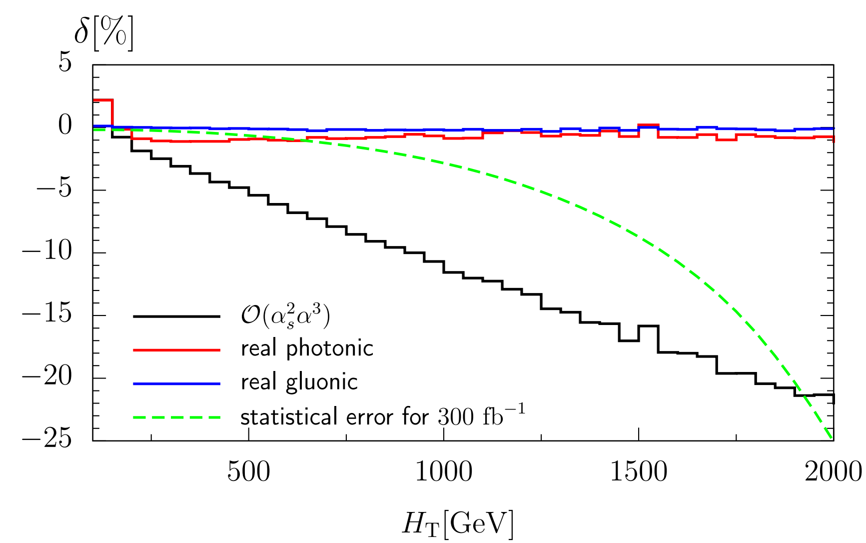
similar behaviour as for distribution in p_{T} of leading jet

$$(H_{\mathrm{T}} = p_{\mathrm{T},j_1} + p_{\mathrm{T},j_2} + p_{\mathrm{T},\ell^-} + p_{\mathrm{T},\ell^+})$$

- 4-quark channels dominate for high H_{T}
- bottom contributions below $5\!-\!10\%$
- EW corrections sizeable for large p_{T}, dominated by virtual corrections
- subtracted real corrections small for $p_{\mathrm{T,j_1}} \lesssim 2\,\mathrm{TeV}$, $\sim 5\%$ for $p_{\mathrm{T,j_1}} = 4\,\mathrm{TeV}$

LHC13: Distribution in total transverse energy H_T





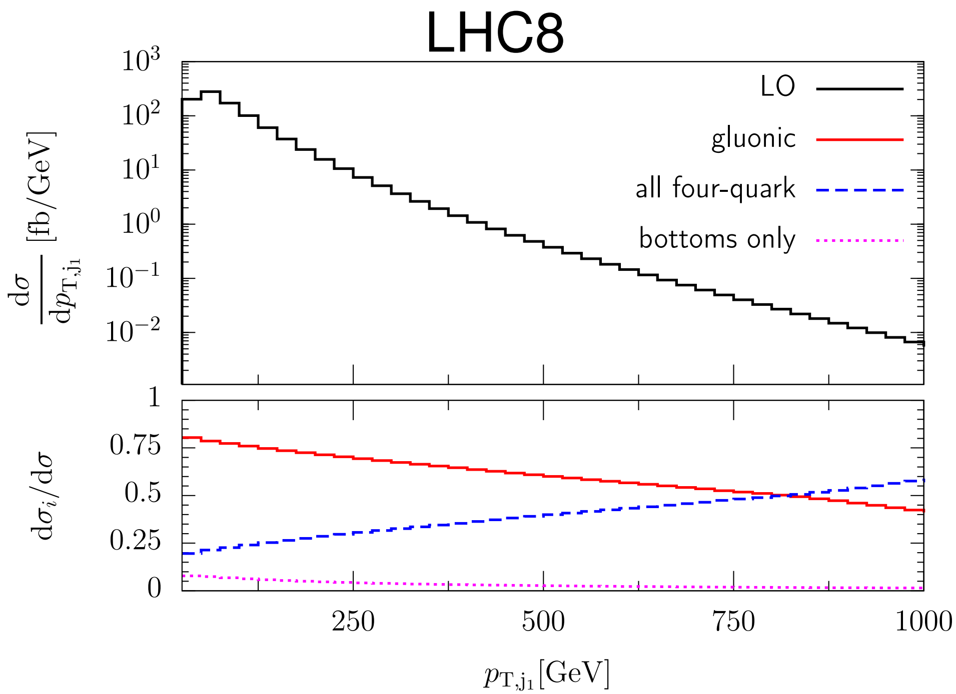
statistical error based on $300\,\mathrm{fb}^{-1}$

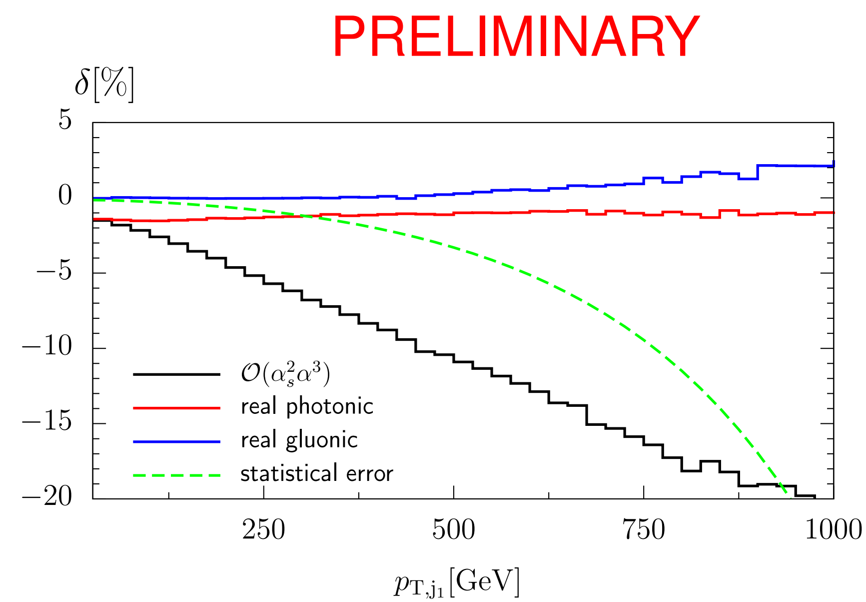
similar behaviour as for distribution in p_T of leading jet

$$(H_\mathrm{T} = p_{\mathrm{T},j_1} + p_{\mathrm{T},j_2} + p_{\mathrm{T},\ell^-} + p_{\mathrm{T},\ell^+})$$

- gluon channels dominate for all H_T
- bottom contributions below $\sim 5\%$
- EW corrections sizeable for large p_T, dominated by virtual corrections
- subtracted real corrections small ($\lesssim 2\%$)

LHC8: Distribution in p_{T} of leading jet

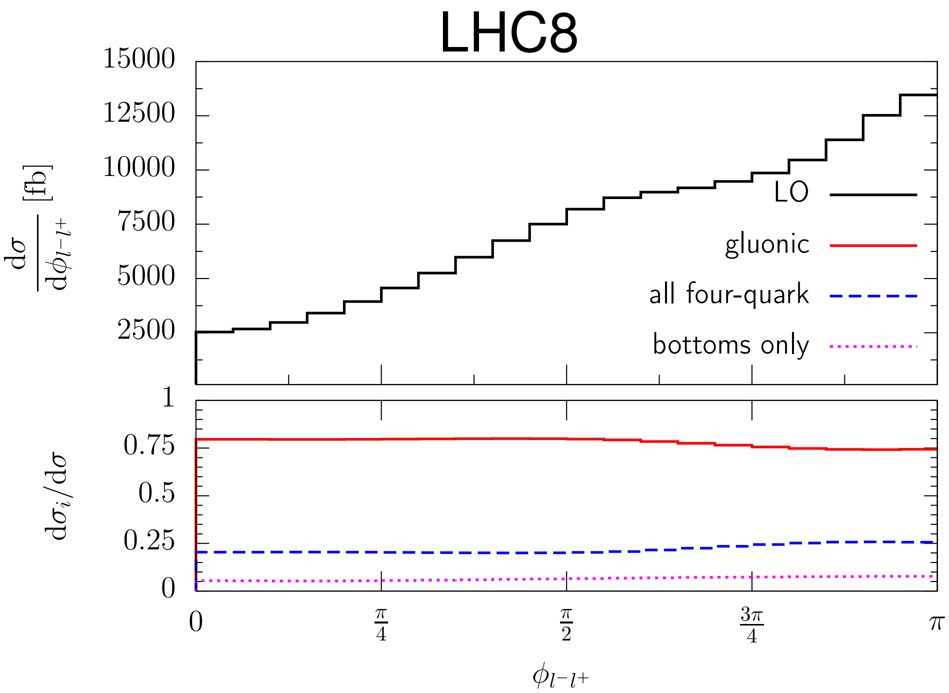


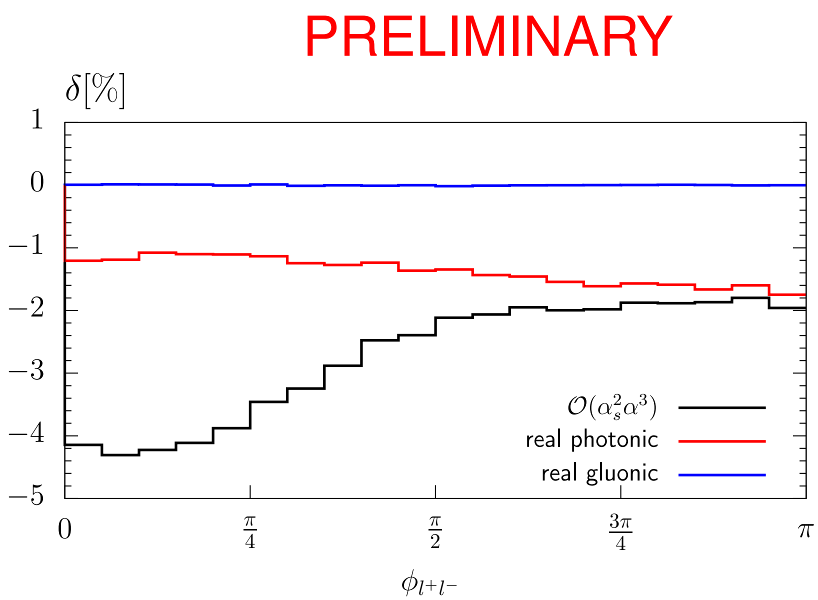


statistical error based on $20\,\mathrm{fb}^{-1}$

- 4-quark channels dominate for high p_{T}
- bottom contributions below $5{-}10\%$
- EW corrections sizeable for large p_{T}
  dominated by virtual corrections (Sudakov logarithms)
- subtracted real corrections small ($\lesssim 2\%$)

LHC8: Distribution in azimuthal angle ϕ_{ll}



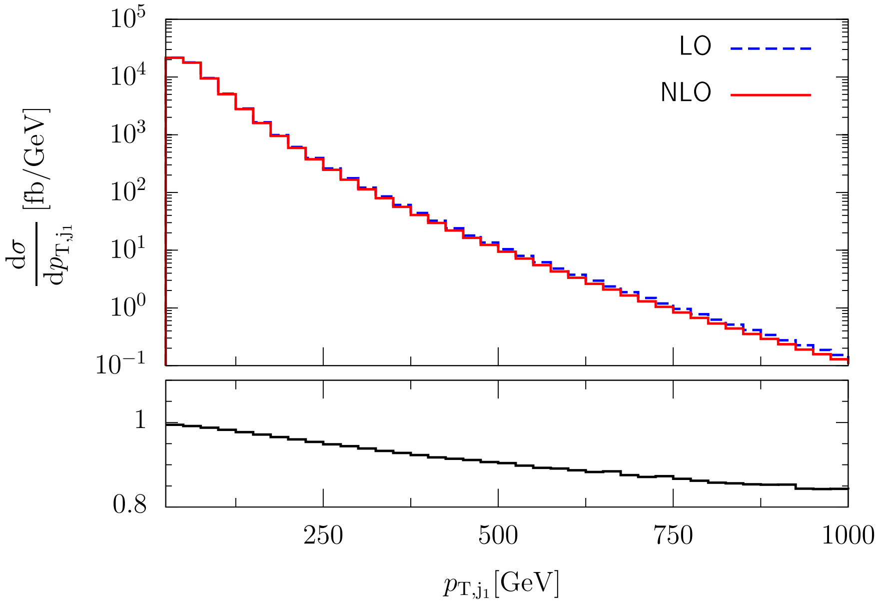


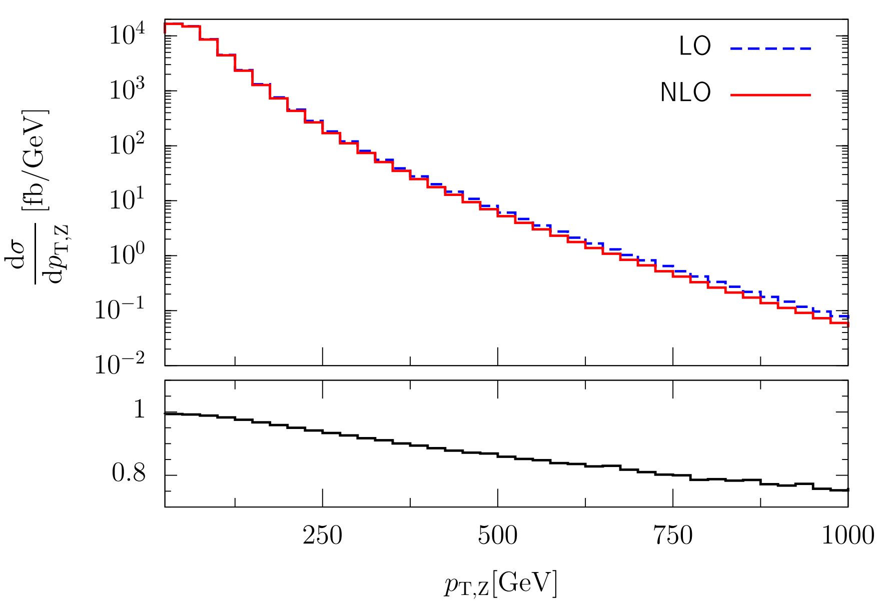
- distribution peaked in backward direction
- bottom contributions below 10%
- EW corrections distort distribution by 2%

Results for LHC at 8 TeV (on-shell Z)

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 $z_\gamma < 0.7$