Standard Model

Ansgar Denner, Würzburg

44. Herbstschule für Hochenergiephysik, Maria Laach
04. - 14. September 2012

- Lecture 1: Formulation of the Standard Model
- Lecture 2: Precision tests of the Standard Model
- Lecture 3: NLO Calculations for the LHC
- Lecture 4: Higgs physics at the LHC

NLO calculations for the LHC

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- Physics at the LHC
- Relevance of NLO (QCD) corrections
- Calculation of NLO corrections
- Relevance of Electroweak Radiative Corrections
- Example processes

Physics at the LHC

Standard Model (SM) physics at the LHC

Some important SM measurements and relevant processes:

- improved measurement of W-boson mass M_{W}
  main process: $\mathrm{pp} \to \mathrm{W} \to \mathrm{l}\nu_l + X$
- improved measurement of effective weak mixing angle $\sin^2\theta_{\mathrm{eff}}$
  main process: $\mathrm{pp} \to \mathrm{Z} \to \mathrm{ll} + X$
- improved measurement of non-Abelian gauge couplings
  main processes:
  - $\mathrm{pp} \to \mathrm{W}\gamma, \mathrm{Z}\gamma + X$
  - $\mathrm{pp} \to \mathrm{WW}, \mathrm{WZ}, \mathrm{ZZ} + X$
- improved measurement of top-quark mass
  main process $\mathrm{pp} \to \mathrm{tt} + X$
- search for the Higgs boson and measurement of its properties
  different production and decay processes

New Physics at LHC

New physics may reveal itself by

- spectacular new signatures that are easily distinguishable from the Standard Model
  example: new resonance in $\mu^+\mu^-$ like a Z'
  so far nothing of this sort found
- less spectacular signatures with Standard Model background
  (e.g. excess)
  example: missing energy in production of supersymmetric particles
  $\Rightarrow$ need SM prediction
- (small) deviations from Standard Model predictions
  examples: anomalous couplings,
  contributions of heavy degrees of freedom via loop processes
  $\Rightarrow$ need precise SM prediction

In the absence of striking new signatures,
to distinguish new physics from SM effects
precise predictions of SM processes are necessary!

Relevance of NLO (QCD) corrections

Importance of NLO calculations for LHC

QCD corrections: substantial part of predictions

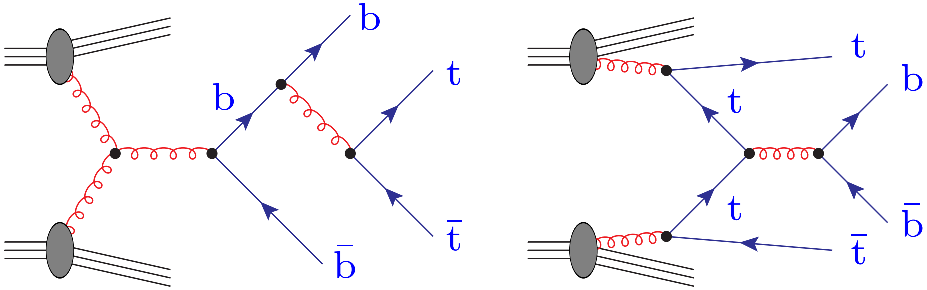
- LO predictions depend on $\alpha_\mathrm{s} = \alpha_\mathrm{s}(\mu)$, scale μ free parameter
  $\Rightarrow$ large scale uncertainty (up to factor 2)
  $\Rightarrow$ often no quantitative prediction possible
  μ dependence due to missing higher orders
- NLO predictions: reduced scale uncertainty
  first real prediction
  $\Rightarrow$ needed for all scattering processes at the LHC
  $\mathcal{O}(\alpha_\mathrm{s}) \times \log(\ldots) \sim 10\% - 100\%, \qquad \alpha_\mathrm{s}(M_\mathrm{Z}) \approx 0.12$
- NNLO predictions: scale uncertainty further reduced
  first real uncertainty estimate
  $\Rightarrow$ needed for light-candle processes like
  single W/Z production, $\mathrm{t\bar{t}}$ production
  $\mathcal{O}(\alpha_\mathrm{s}^2) \times \log^2(\ldots) \sim \text{few}\% - 20\%$

$\hookrightarrow$ NLO (NNLO) corrections important for reliable predictions

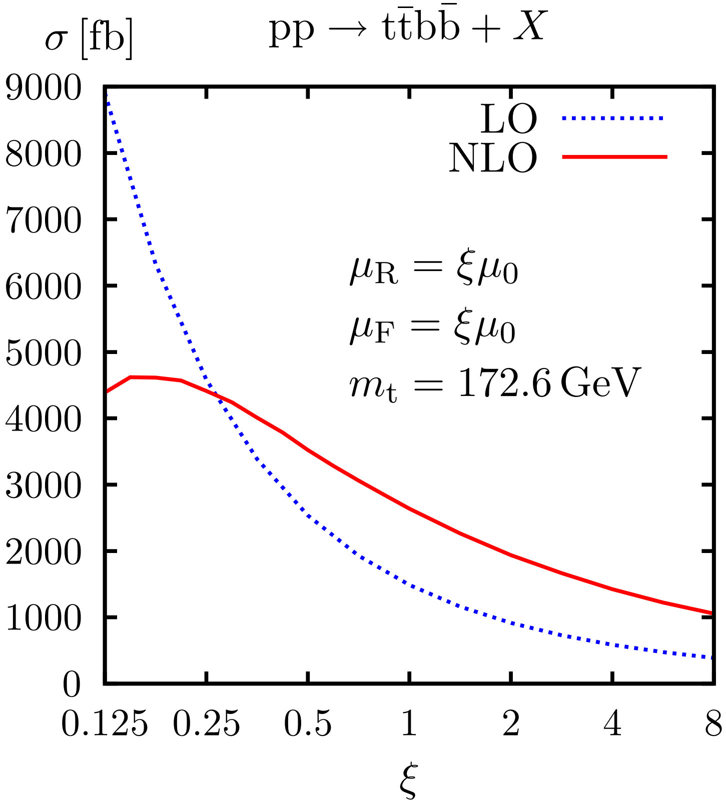
Example: scale dependence for $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$

Background process to

$\mathrm{pp} \to \mathrm{t\bar{t}H} + X \to \mathrm{t\bar{t}b\bar{b}} + X$



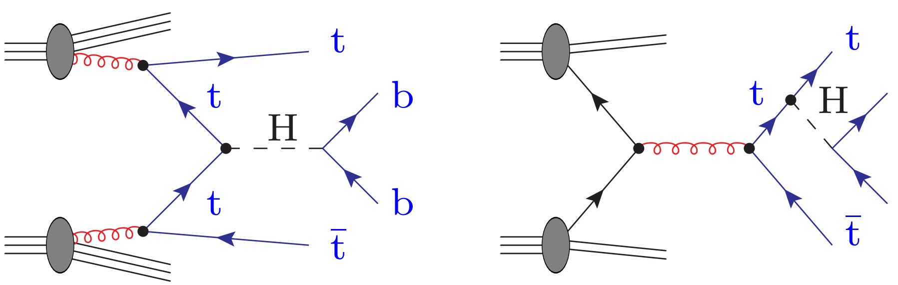
Bredenstein, Denner, Dittmaier, Pozzorini '10



LO $\propto \alpha_S(\mu_R)^4 \Rightarrow$ large scale uncertainty

μ_F	$m_t/8$	$m_t/4$	$m_t/2$	m_t	$2m_t$	$4m_t$	$8m_t$
$\alpha(\mu_F)$	0.151	0.133	0.119	0.108	0.098	0.091	0.084
$\frac{\alpha(\mu_F)}{\alpha(m_t)}$	1.40	1.24	1.11	1.00	0.91	0.84	0.78
$\left(\frac{\alpha(\mu_F)}{\alpha(m_t)}\right)^4$	3.88	2.34	1.49	1.00	0.70	0.50	0.37

original (ATLAS) scale choice based on $\mathrm{t\bar{t}H}$

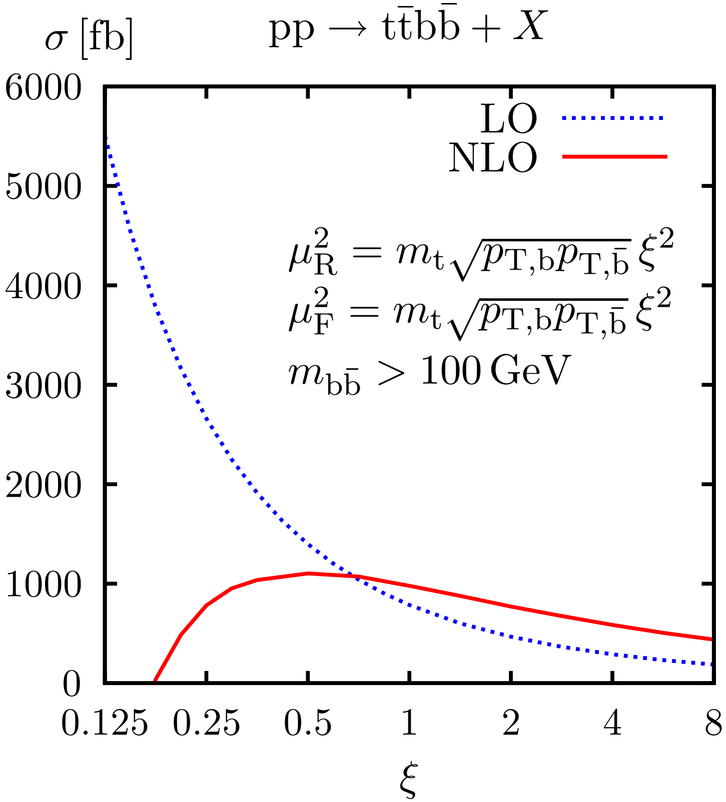


$$\mu_0 = E_{\mathrm{thr}}/2 = m_t + m_{\mathrm{b\bar{b}}}/2$$

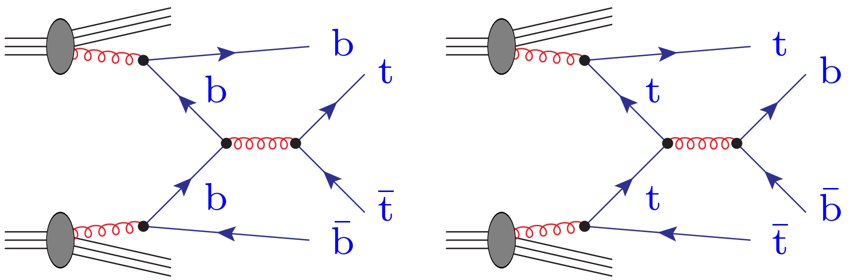
$\Rightarrow$ large K factor (1.8) and scale dependence (34%)

Example: scale dependence for $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$

Bredenstein, Denner, Dittmaier, Pozzorini '10



QCD dynamics of $\mathrm{t\bar{t}H}$ and $\mathrm{t\bar{t}b\bar{b}}$ different



various different channels for $\mathrm{t\bar{t}b\bar{b}}$

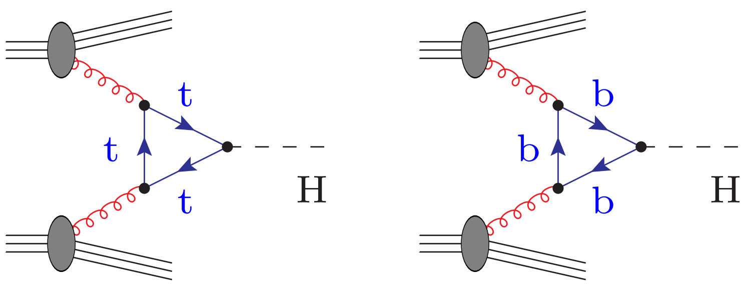
good central scale

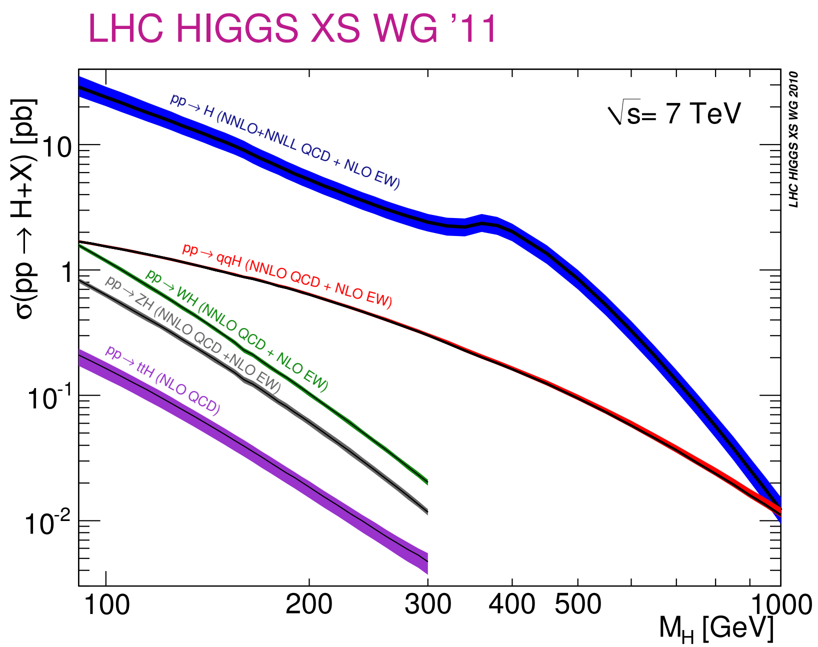
$$\mu_0^2 = m_\mathrm{t}\sqrt{p_{\mathrm{T,b}}p_{\mathrm{T,\bar{b}}}}$$

one α_s at scale m_t
one α_s at scale of p_T of b quarks

- small correction and uncertainty: $K = 1.24 \pm 21\%$
- central scale close to a maximum

Example: Higgs production in gluon-gluon fusion





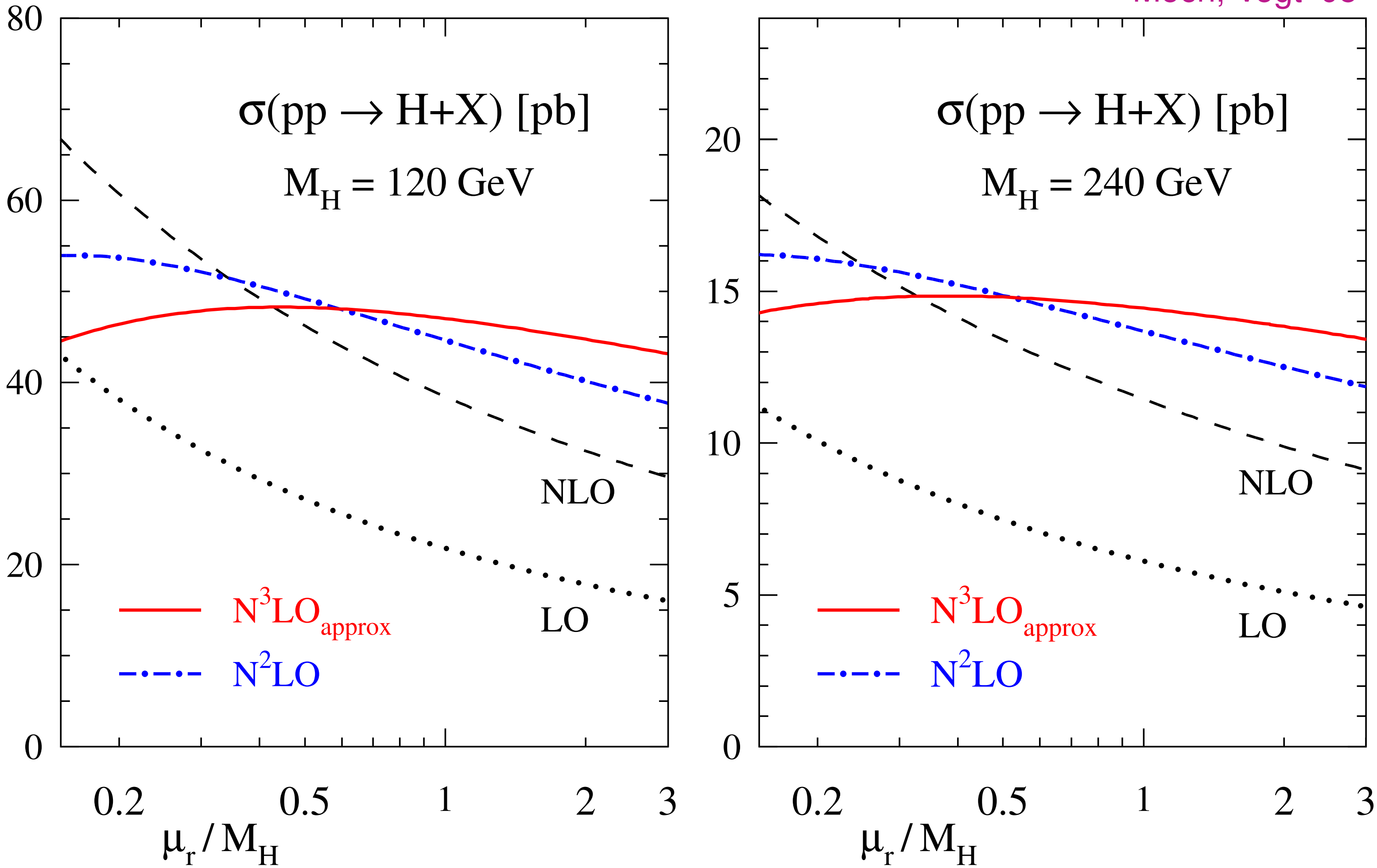
- most important production channel at LHC
- $\sigma_{\mathrm{LO}} \propto \alpha_{\mathrm{s}}^2$
  strong dependence on factorization and renormalization scales (100%)
  $\Rightarrow$ higher-order corrections very important
- complete NLO: $80{-}100\%$
  virtual contribution $\pi\alpha_{\mathrm{s}} \sim 35\%$ $[\pi^2(\alpha_{\mathrm{s}}/\pi)]$
  real contribution $\sim 50\%$

  Graudenz, Spira, Zerwas '93
  Djouadi, Graudenz, Spira, Zerwas '95
- NNLO: $\sim 25\%$

  Harlander, Kilgore '01, '02; Catani, de Florian, Grazzini '01
  Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03, '04
  Ahrens, Becher, Neubert, Yang '08

QCD scale dependence for gg $\to$ H

Moch, Vogt '05



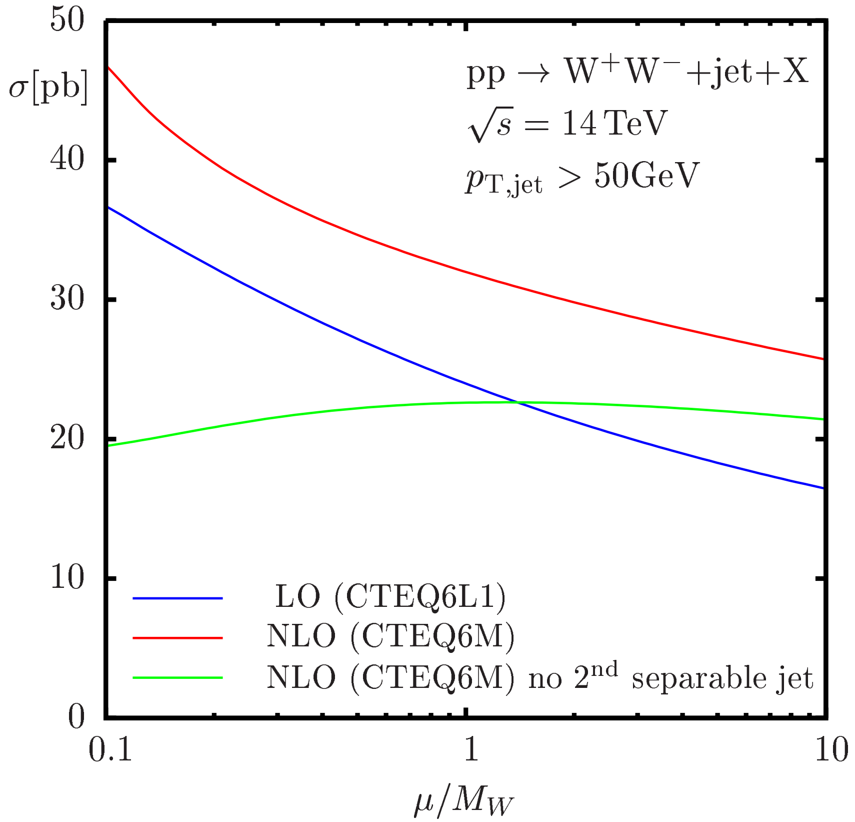
Reduction of renormalization scale dependence with increasing orders!

$\Rightarrow$ residual scale uncertainty $\lesssim 5$–10%

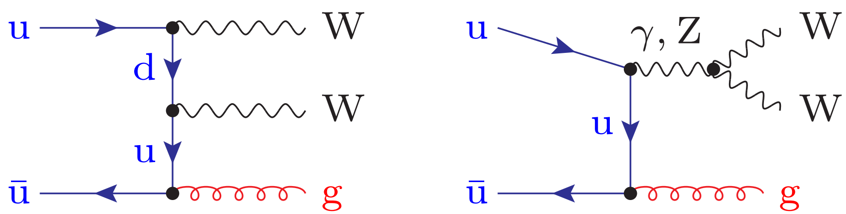
Example: scale dependence for $\mathrm{pp} \to \mathrm{WWj} + X$

Appearance of new channels:

Dittmaier, Kallweit, Uwer '07

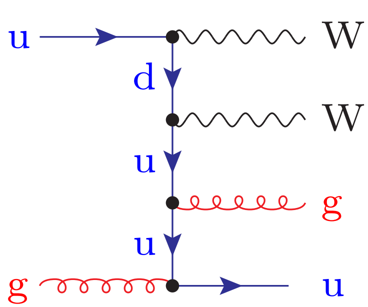


- $\sigma_{\mathrm{LO}} \propto \alpha_{\mathrm{s}}$

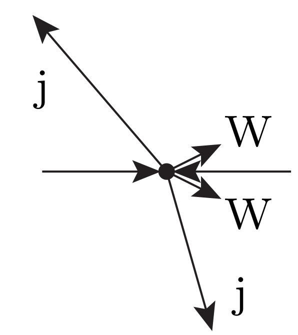


- scale dependence stabilises at NLO for genuine $\mathrm{WW} + \mathrm{j}$ production
- significant scale dependence is introduced by $\mathrm{WW} + 2\,\mathrm{j}$ (difference between green and red curves)

new diagrams



new configuration



Importance of multiparticle processes at the LHC

Most signal processes involve few final-state particles:

- $2 \to 2 \qquad \mathrm{pp} \to \mathrm{ll}, \mathrm{W}\gamma, \mathrm{WW}, \mathrm{tt}, \ldots + X$
- $2 \to 3 \qquad \mathrm{pp} \to \mathrm{Hjj}, \mathrm{WW}\gamma, \ldots + X$

However,

- heavy particles (W, Z, t, $\ldots$) decay into jets, leptons, photons
  $\mathrm{pp} \to \mathrm{WW} \to \mathrm{ll}\nu_l\nu_l + X$, $\mathrm{pp} \to \mathrm{tt} \to \mathrm{be}\nu_\mathrm{e}\bar{\mathrm{b}}\mu\nu_\mu + X$
- irreducible backgrounds involve genuine multiparticle final states
  $\mathrm{pp} \to \mathrm{ll}\nu_l\nu_l + X$, $\mathrm{pp} \to \mathrm{be}\nu_\mathrm{e}\bar{\mathrm{b}}\mu\nu_\mu + X$
  (backgrounds often not fully accessible to measurements)
- large fraction of final states contains additional jets
  $\mathrm{pp} \to \mathrm{WWj} + X$, $\mathrm{pp} \to \mathrm{WWjj} + X, \ldots$

$\Rightarrow$ Need reliable predictions for multiparticle processes!

Existing NLO calculations for the LHC

NLO calculations

- $2 \to 2$ trivial (textbook)
- $2 \to 3$ standard (many groups)
- $2 \to 4$ state of the art (several groups)

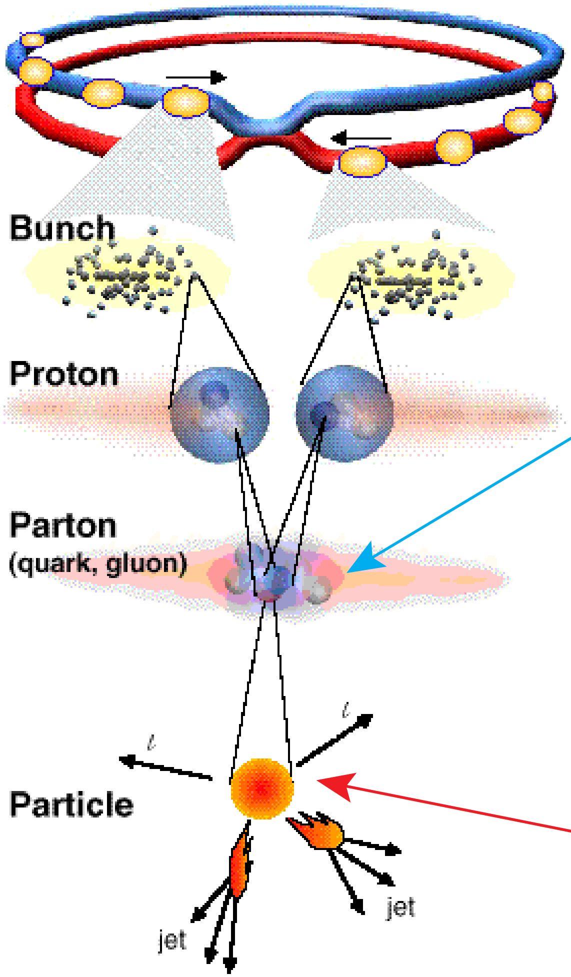
$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$	Bredenstein, Denner, Dittmaier, Pozzorini '09, Bevilacqua et al. '09
$\mathrm{pp} \to \mathrm{t\bar{t}}jj$	Bevilacqua, Czakon, Papadopoulos, Worek '10
$\mathrm{pp} \to \mathrm{W^+W^-b\bar{b}}$	Denner, Dittmaier, Kallweit, Pozzorini '10; Bevilacqua et al. '10
$\mathrm{pp} \to \mathrm{W^+W^\pm}jj$	Melia, Melnikov, Rontsch, Zanderighi '10, '11; Greiner et al. '12
$\mathrm{pp} \to \mathrm{W}jjj$	Berger et al. '09; R.K.Ellis et al. '09
$\mathrm{pp} \to \mathrm{Z}jjj$	Berger et al. '10
$\mathrm{pp} \to \mathrm{b\bar{b}b\bar{b}}$	Binoth et al. '09
$\mathrm{pp} \to jjjj$	Bern et al. '11

- $2 \to 5$ only very few (one group)

$\mathrm{pp} \to \mathrm{W}jjjj$	Berger et al. '10
$\mathrm{pp} \to \mathrm{Z}jjjj$	Berger et al. '11

Calculation of NLO corrections

Hadronic cross sections



parton content of the proton:

valence quarks uud,

sea quarks $\mathrm{u}, \mathrm{d}, \mathrm{c}, \mathrm{s}, (+\mathrm{b},)$ + antiquarks

gluons g (+ photons γ)

"parton distribution functions" (PDFs) $f_{i/\mathrm{p}}(x, \mu_\mathrm{F})$

probability for parton i to have fraction x

of momentum p at "factorization scale" μ_F

= non-perturbative input (from experiment)

process independent

hard interaction of partons

$\hookrightarrow$ perturbative QFT applicable,

model for hard interaction

(except QCD/QED) only enters here

$$\sigma_{\mathrm{pp}\to F+X}(p_1, p_2) = \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \sum_{a,b} f_{a/\mathrm{p}}(x_a, \mu)\, f_{b/\mathrm{p}}(x_b, \mu_\mathrm{F})\, \hat{\sigma}_{ab\to F}(x_a p_1, x_b p_2, \mu_\mathrm{F})$$

LO partonic cross section

LO partonic cross section for a $2 \to n$ process can be written as

$$\mathrm{d}\sigma_{\mathrm{LO}} = \frac{1}{2s} \int \mathrm{d}\Phi_n |\mathcal{M}_{\mathrm{LO}}|^2$$

$$\int \mathrm{d}\Phi_n = (2\pi)^4 \delta^{(4)} \left(P - \sum_{i=1}^{n} q_i \right) \prod_{i=1}^{n} \frac{\mathrm{d}^3 q_i}{(2\pi)^3 2E_i}$$ n-particle phase space

$\mathcal{M}_{\mathrm{LO}}$: LO matrix element (contains model for hard interaction)

$s = P^2 = (\hat{p}_1 + \hat{p}_2)^2$ square of centre-of-mass energy of hard process ($\hat{p}_i = x_i p_i$)

Integration over phase space by Monte Carlo methods $\Rightarrow$

- any distribution can be determined simultaneously
- Monte Carlo events can be unweighted

Many codes exist at LO:

- MADGRAPH Alwall, Herquet, Maltoni, Mattelaer, Stelzer
- WHIZARD Kilian, Ohl, Reuter
- SHEPRA Höche, Krauss, Schuhmann, Siegert, Winter
- HELAC Papadopoulos, Worek
- ...many more

Calculation of leading-order matrix elements

- Feynman diagrams: double factorial complexity $[2n!! = 2n(2n-2)(2n-4)...2]$

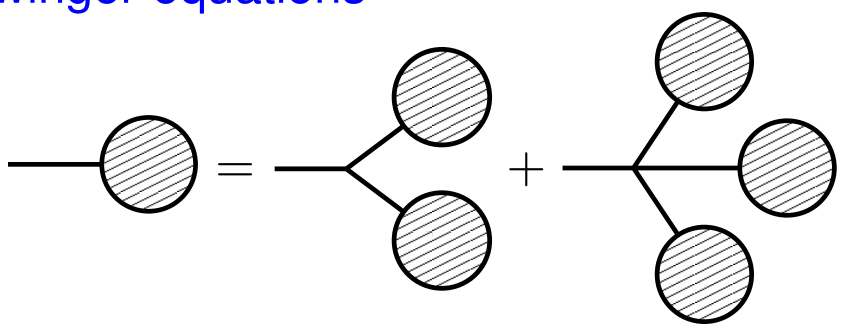
  # diagrams for pure gluon (scalar) processes

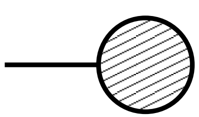
external gluons	4	5	6	7	8	9	...	n
# diags w/ only 3-g vertices	3	15	105	945	10395	135135		$(2n-5)!!$
# diags w/ 3-g and 4-g vert.	4	25	220	2485	34300	559405		

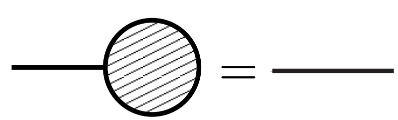
- recursion-relation technique: polynomial complexity of rank 4: $\mathcal{O}(n^4)$

  Berends, Giele '88; Kleiss, Kuijf '89, Caravaglios, Moretti '95, Draggiotis, Kleiss, Papadopoulos '98

  based on Dyson–Schwinger equations



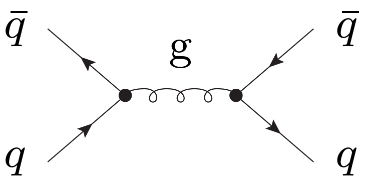
 : off-shell current with arbitrary number of on-shell lines
sub-amplitude with one off-shell and arbitrary many on-shell lines

starting point of iteration:  wave function (polarization vector)

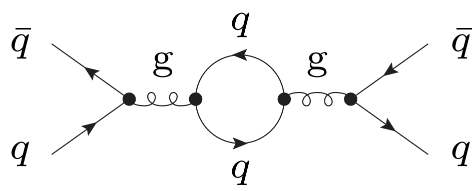
IR singularities in NLO corrections

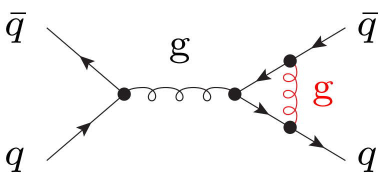
NLO corrections consist of Feynman diagrams of higher order to the same process:

tree diagrams



loop diagrams



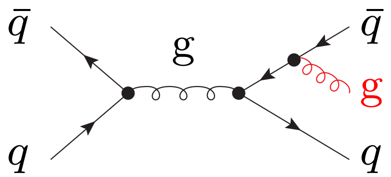


loop diagrams contain infrared singularities

from internal gluons soft or collinear to quarks

Process with an additional gluon has to be added to cancel IR singularities

(soft or collinear photons cannot be separated experimentally!)



Square of bremsstrahlung matrix element of the same order as interference between LO diagrams and loop diagrams!

Some collinear singularities from the initial state do not cancel but can be absorbed by a renormalization of the PDFs $\Rightarrow$ collinear counter term

Structure of NLO computation

NLO partonic cross section can be written as

Structure of NLO computation

NLO partonic cross section can be written as in subtraction method

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \int \mathrm{d}\Phi_n \left[|\mathcal{M}_{\mathrm{LO}}|^2 + 2\,\mathrm{Re}\{\mathcal{M}^*_{\mathrm{LO}}\mathcal{M}_{\mathrm{NLO,V}}\} + C + \int \mathrm{d}\Phi_1 \sum_j S_j \right]$$
$$+ \int \mathrm{d}\Phi_{n+1} \left[|\mathcal{M}_{\mathrm{NLO,R}}|^2 - \sum_j S_j \right]$$

$\int \mathrm{d}\Phi_{n(+1)}$: n or $n+1$ particle phase space

$\mathcal{M}_{\mathrm{LO}}, \mathcal{M}_{\mathrm{NLO,V}}, \mathcal{M}_{\mathrm{NLO,R}}$: matrix elements for LO, virtual and real NLO

C collinear counter term from renormalization of PDFs

$\sum S_j$: subtraction terms for real corrections

$\int \mathrm{d}\Phi_1 \sum S_j$: (analytically) integrated subtraction terms

subtraction terms cancel but render individual integrals finite $\Rightarrow$ stable numerical integration

$\mathcal{M}_{\mathrm{NLO,R}}$: tree-level matrix elements
subtraction terms S_j: colour-weighted tree-level matrix elements
virtual corrections $\mathrm{Re}\{\mathcal{M}^*_{\mathrm{LO}}\mathcal{M}_{\mathrm{NLO,V}}\}$ (loop diagrams): require new methods

Methods for virtual corrections

Until ∼2005: Virtual corrections were the bottleneck of NLO calculations.

- Feynman diagrams: worse than factorial complexity
- relied on process-specific algebraic calculations, no full automation

NLO revolution: Ossola, Papadopoulos, Pittau '07, Bern, Dixon, Kosower, Britto, Cachazo, Feng, Ellis, Giele, Melnikov, . . .

- unitarity-cut technique: polynomial complexity of rank 9: $\mathcal{O}(n^9)$
  Giele, Zanderighi '08
- automation immediately performed by different groups

recursion relation technique for NLO:

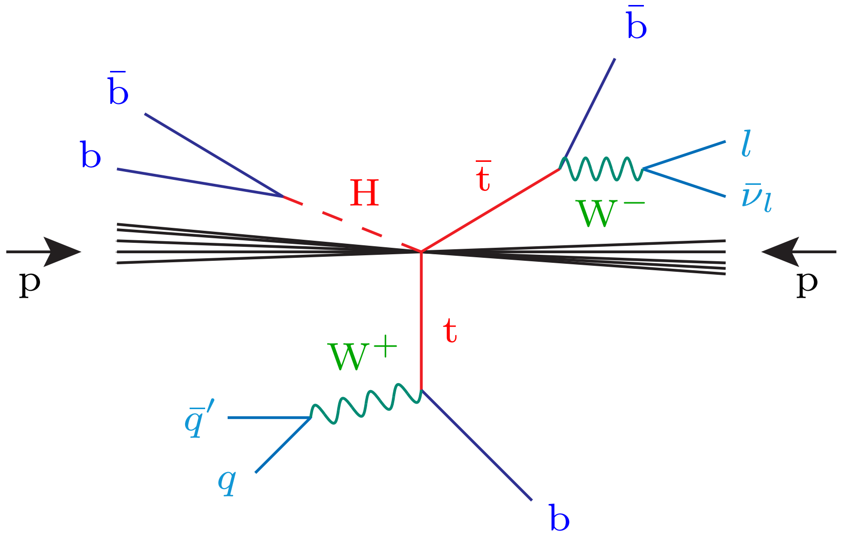
- exponential complexity: $\mathcal{O}(n^4 2^n)$ van Hameren '09 (pure gluon amplitudes)

revival of Feynman diagrams:

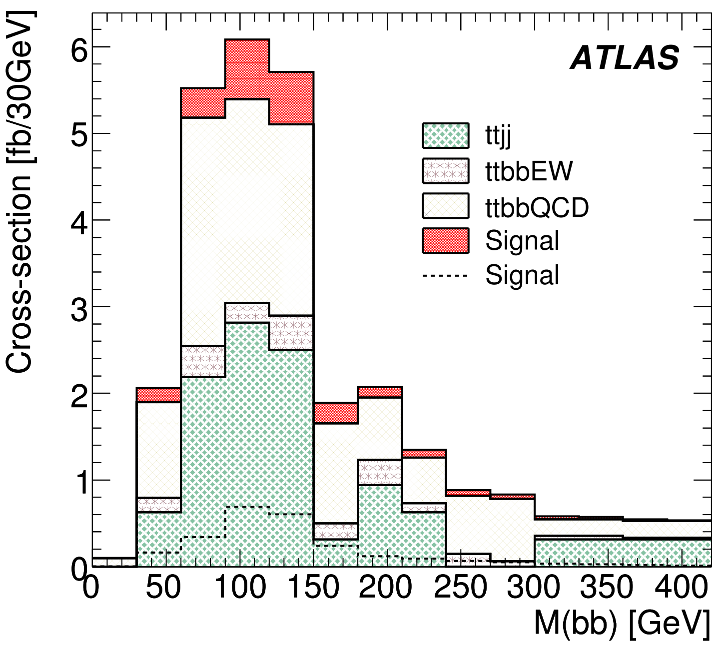
- Feynman diagrams yield faster codes for $2 \to 4$ processes
- allow efficient summation over colours and helicities
- asymptotic behaviour not necessarily relevant for practical purposes
- full automation in progress Cascioli, Maierhofer, Pozzorini '12 OPENLOOPS

Example: $pp \to t\bar{t}b\bar{b}$

Background to $pp \to t\bar{t}H(\to b\bar{b})$



"CSC book", CERN-OPEN-2008-020



- relevance: direct experimental access to $t\bar{t}H$-Yukawa-coupling
- problem: control of background via $pp \to t\bar{t}b\bar{b}, t\bar{t} + \text{jets}$

  need: ▶ improved analysis methods (fat jets, boosted Higgs)

  ▶ NLO predictions for background processes

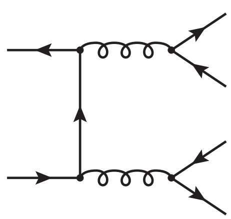
NLO QCD corrections for $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$

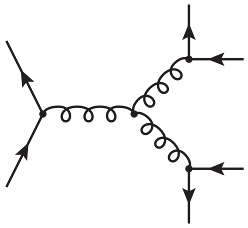
First complete NLO calculation for a $2 \to 4$ hadron-collider process

$q\bar{q} \to \mathrm{t\bar{t}b\bar{b}}$ 5% of cross section

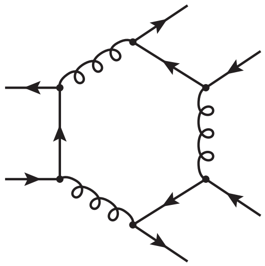
Bredenstein, Denner, Dittmaier, Pozzorini ’08

LO: 7 diagrams

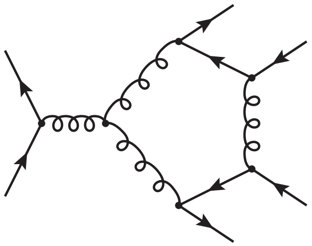




NLO: 188 diagrams



8 hexagons



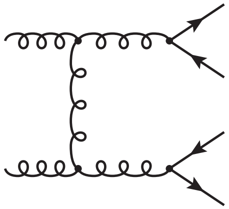
24 pentagons

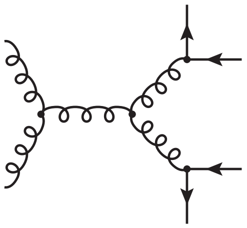
bremsstrahlung diagrams: 64

$\mathrm{gg} \to \mathrm{t\bar{t}b\bar{b}}$ 95% of cross section

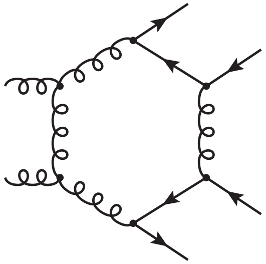
Bredenstein, Denner, Dittmaier, Pozzorini ’09

LO: 36 diagrams

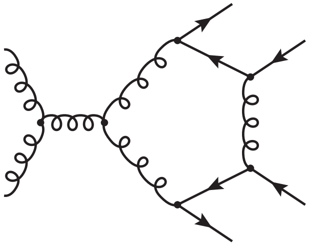




NLO: 1003 diagrams



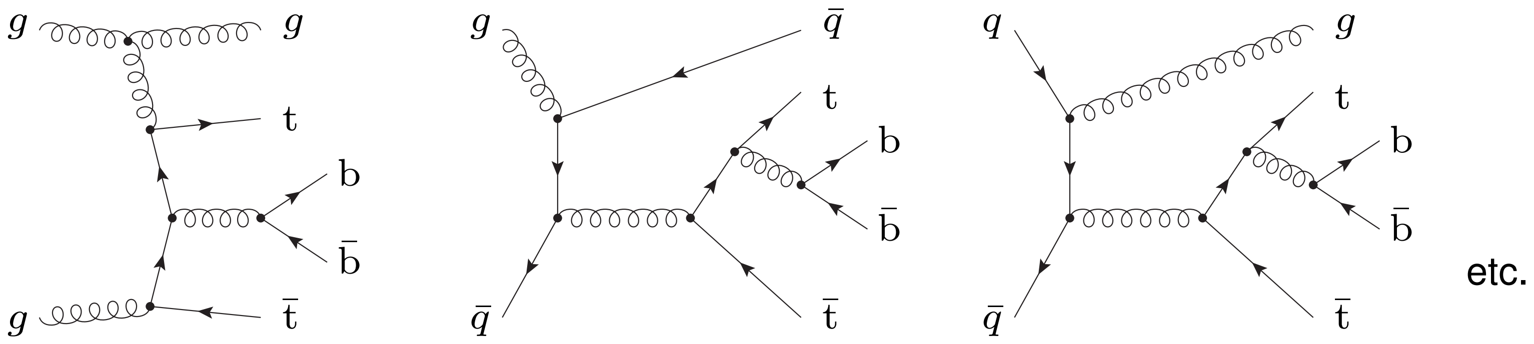
40 hexagons



114 pentagons

bremsstrahlung diagrams: 341

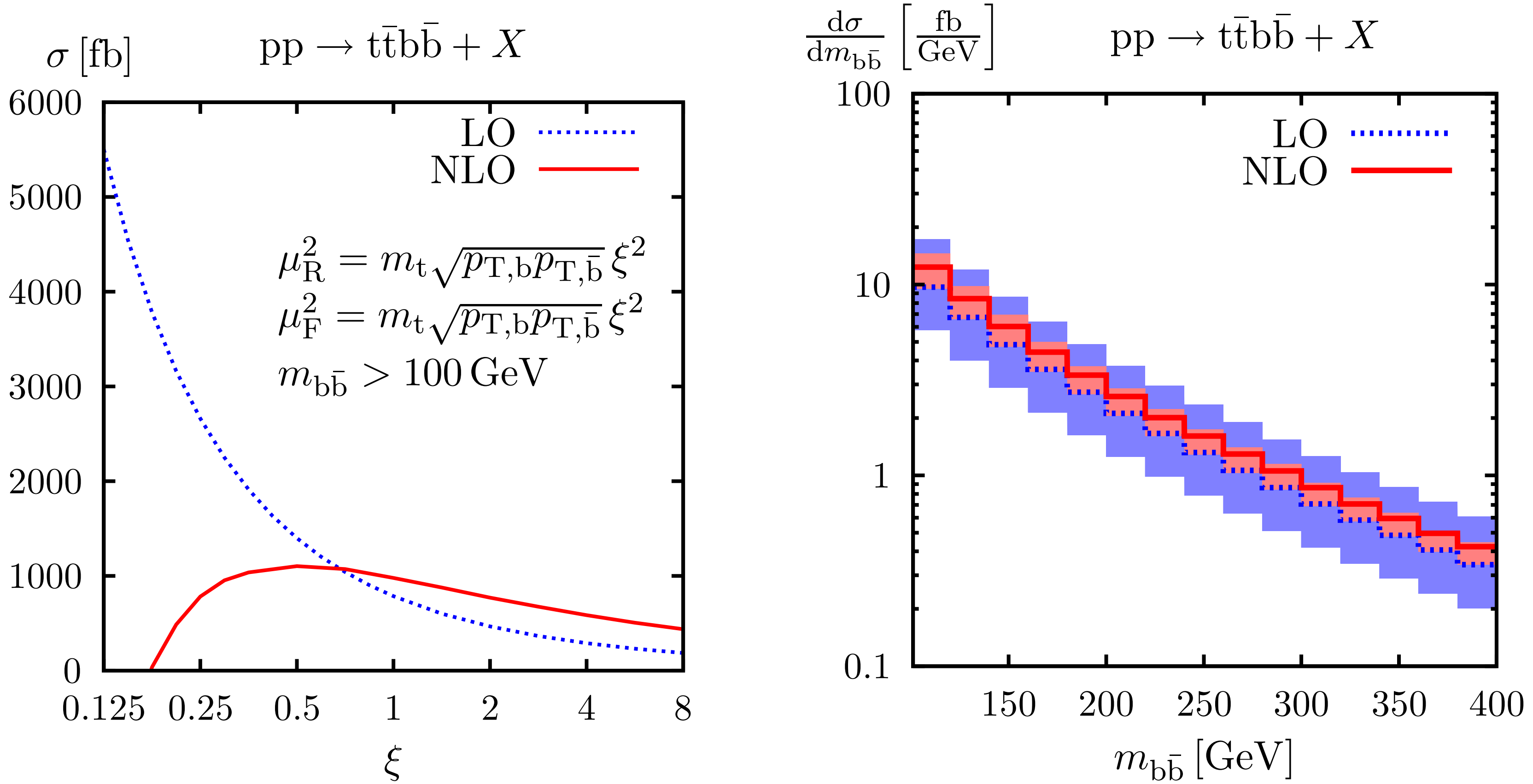
Corrections from real radiation: $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}j}$



- channels: $\mathrm{gg} \to \mathrm{b\bar{b}t\bar{t}g}$, $q\mathrm{g} \to \mathrm{b\bar{b}t\bar{t}}q$, $qq \to \mathrm{b\bar{b}t\bar{t}g}$
- numerical (Monte-Carlo-)integration over 11-dimensional phase space
- fast calculation of amplitudes (bremsstrahlung and LO) needed
- treatment of soft and collinear singularities via subtraction method
  $\Rightarrow$ 30 dipole subtraction terms per channel
  $\Rightarrow$ LO matrix element has to be calculated 30 times for each event
- run times: $\sim 50\,$h on single CPU for 10^7 events
  $\Rightarrow$ 0.5% accuracy for total integrated cross section

Exemplary results for $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$

Bredenstein, Denner, Dittmaier, Pozzorini '09



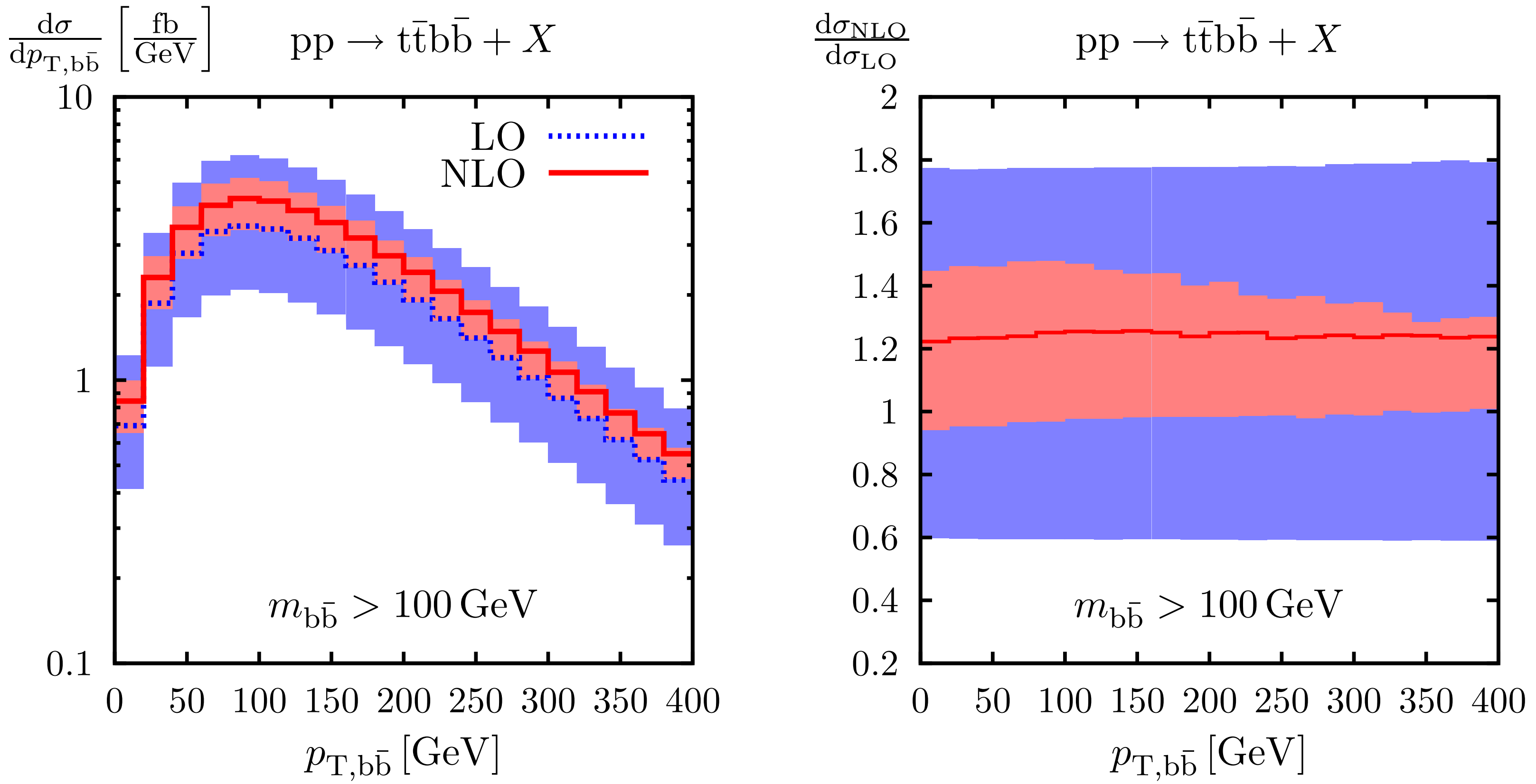
- small NLO correction $K \simeq 1.24$
- reduction of scale uncertainty

$$\Delta_{\mathrm{LO}} \sim 100\% \quad \to \quad \Delta_{\mathrm{NLO}} \sim 20\text{–}30\%$$

Exemplary results for $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$

Distribution in transverse momentum of $\mathrm{b\bar{b}}$ pair

Bredenstein, Denner, Dittmaier, Pozzorini ’09

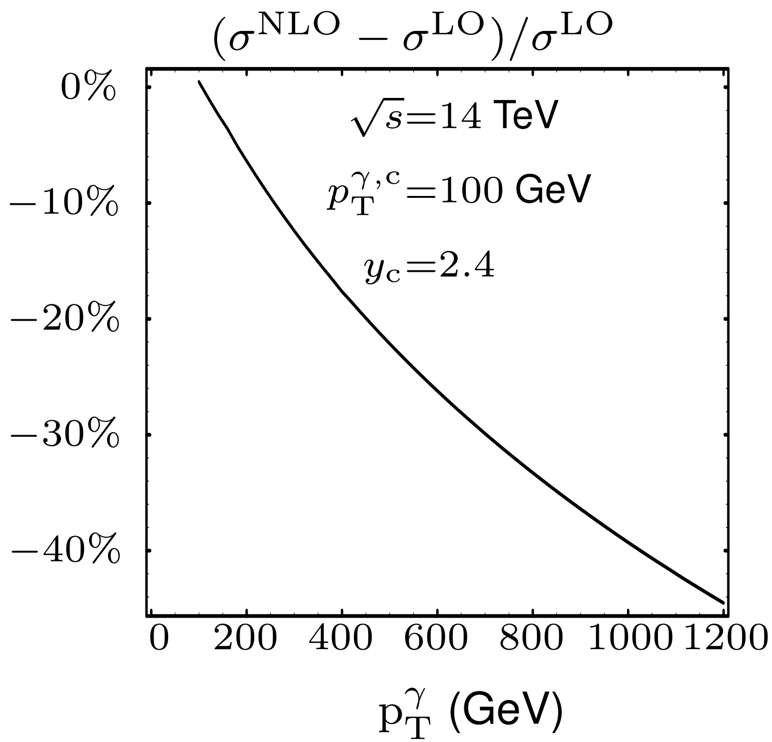


- K-factor almost constant over wide $p_{\mathrm{T,b\bar{b}}}$ range for dynamical scale
- NLO-analysis enables suitable dynamic scale choice
  $\Rightarrow$ improvement of LO prediction via rescaling

Relevance of EWRC

Relevance EW NLO corrections at LHC

- generically: $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \sim$ few %
- EW corrections can be enhanced by high energy scales or kinematic effects
  example: electroweak corrections to $\mathrm{pp} \to Z\gamma + X$ Hollik, Meier ’04



small p_{T}^{γ}

- corrections of $\mathcal{O}(\alpha) \sim 1\%$

$p_{\mathrm{T}}^{\gamma} \gg 100$ GeV

- large negative corrections $\gg 1\%$
- increase with p_{T}^{γ}
- -40% at $p_{\mathrm{T}}^{\gamma} \sim 1\,\mathrm{TeV}$!

- leading NNLO EW corrections might be relevant for some processes
  (Drell-Yan, Z+jet, W+jet) $(40\%)^2 = 16\%$

Origin of large electroweak corrections

Scattering energy $\gg$ characteristic scale of EW corrections:

$E_{\mathrm{CMS}} \gg M_{\mathrm{W}} \approx 80\,\mathrm{GeV}$

$\Rightarrow$ large double logarithms

$$\ln^2\left(\frac{E_{\mathrm{CMS}}^2}{M_{\mathrm{W}}^2}\right) \sim 25 \qquad \text{at} \quad E_{\mathrm{CMS}} \sim 1\,\mathrm{TeV}$$

typical size of corrections:

$$\frac{\alpha}{4\pi s_{\mathrm{w}}^2} \ln^2\left(\frac{E_{\mathrm{CMS}}^2}{M_{\mathrm{W}}^2}\right) \sim 25\% \qquad \text{at} \quad E_{\mathrm{CMS}} \sim 1\,\mathrm{TeV}$$

general feature of hard scattering processes!

Large EW logarithms can be related to mass singularities:

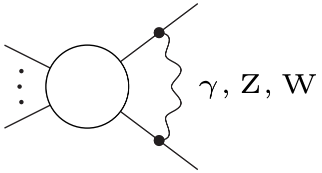
$$M_{\mathrm{W}}/E_{\mathrm{CMS}} \ll 1 \quad \Rightarrow \quad E_{\mathrm{CMS}} \to \infty \quad \text{or} \quad M_{\mathrm{W}} \to 0$$

EW logarithms can be calculated with process-independent methods.

Universal origin of leading EW logarithms

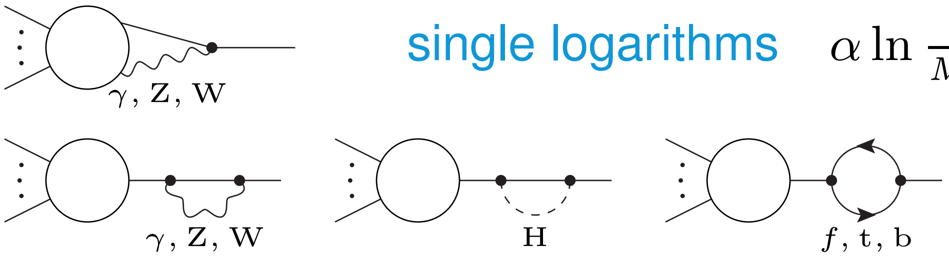
Large EW logarithms are of universal origin:

- infrared logarithms $\Leftrightarrow$ external particles of the process
  mass singularities in virtual corrections related to external lines
  - soft and collinear virtual gauge bosons



double logarithms $\alpha \ln^2 \frac{s}{M_\mathrm{W}^2}$

  - collinear or soft virtual gauge bosons, wave-function renormalization



single logarithms $\alpha \ln \frac{s}{M_\mathrm{W}^2}$

- ultraviolet logarithms $\Leftrightarrow$ parameter renormalization at scale $M_\mathrm{W}^2 \ll s$
  $\Rightarrow$ running of electroweak couplings from M_W to $\sqrt{s}$
  single logarithms $\alpha \ln \frac{s}{M_\mathrm{W}^2}$

Summary on electroweak logarithms

- have been studied by many people

  M. Ciafaloni, P. Ciafaloni, Comelli; Beccaria, Renard, Verzegnassi; Beenakker, Werthenbach; Denner, Pozzorini; Melles; Fadin, Lipatov, Martin; Jantzen, Kühn, Penin, Smirnov; Chiu, Fuhrer, Golf, Kelley, Manohar, ...
- provide estimate for one-loop corrections at level of 5–10%
- useful to estimate electroweak two-loop corrections
- real corrections should be included
  - real photon radiation
  - real massive vector-boson radiation   Baur '06

  $\Rightarrow$ partial cancellation of enhanced corrections
- not reliable for processes with other sources of large contributions

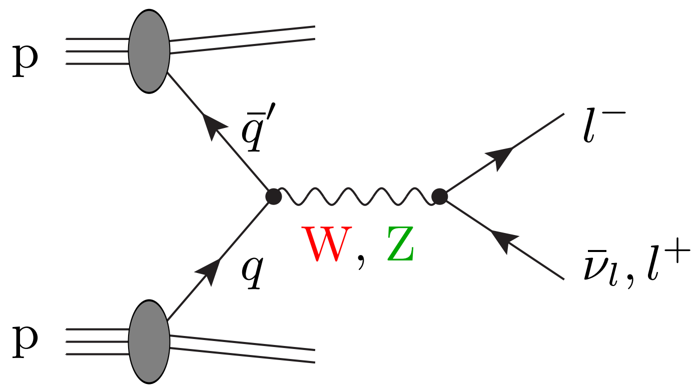
  e.g. large logarithms $\log(t/s) \sim 2\log\theta$ for small θ not included (important for processes with large contributions in forward/backward directions)
- at LHC often sizeable contributions from energies below $1\,\mathrm{TeV}$

$\Rightarrow$ exact calculations of NLO EWRC preferable if possible

Example processes

Single gauge-boson production

Drell–Yan-like W and Z production



large cross sections: $\sigma(\mathrm{W}) = 30\,\mathrm{nb}$
$\sigma(\mathrm{Z}) = 3.5\,\mathrm{nb}$

Physics goals:

- M_Z $\to$ detector calibration by comparing with LEP1 result
- $\sin^2\theta_\mathrm{eff}^\mathrm{lept}$ with $\delta\sin^2\theta_\mathrm{eff}^\mathrm{lept} \sim 0.00014$ $\to$ comparison with results of LEP1 and SLC
- M_W $\to$ improvement to $\Delta M_\mathrm{W} \sim 15\,\mathrm{MeV}(7\,\mathrm{MeV})$, strengthen EW precision tests
  Besson et al. '08
- decay widths Γ_Z and Γ_W from M_{ll} or $M_{\mathrm{T},l\nu_l}$ tails
- search for Z' and W' at high M_{ll} or $M_{\mathrm{T},l\nu_l}$
- information on PDFs, determination of collider luminosity

Known corrections to W/Z production

QCD corrections to W/Z production

- NLO QCD corrections merged with QCD parton showers MC@NLO, POWHEG — Frixione, Webber '02; Frixione, Nason, Oleari '07
- NNLO QCD corrections
  - total cross section — Hamberg, v.Neerven, Matsuura '91; v.Neerven, Zijlstra '92; Harlander, Kilgore '02
  - distributions — Anastasiou et al. '03; Melnikov, Petriello '06 Catani et al. '09
- soft gluon resummation — Balazs, Yuan '97; Ellis, Veseli '98 Landry et al. '02; Cao, Yuan '04

EW corrections to W/Z production

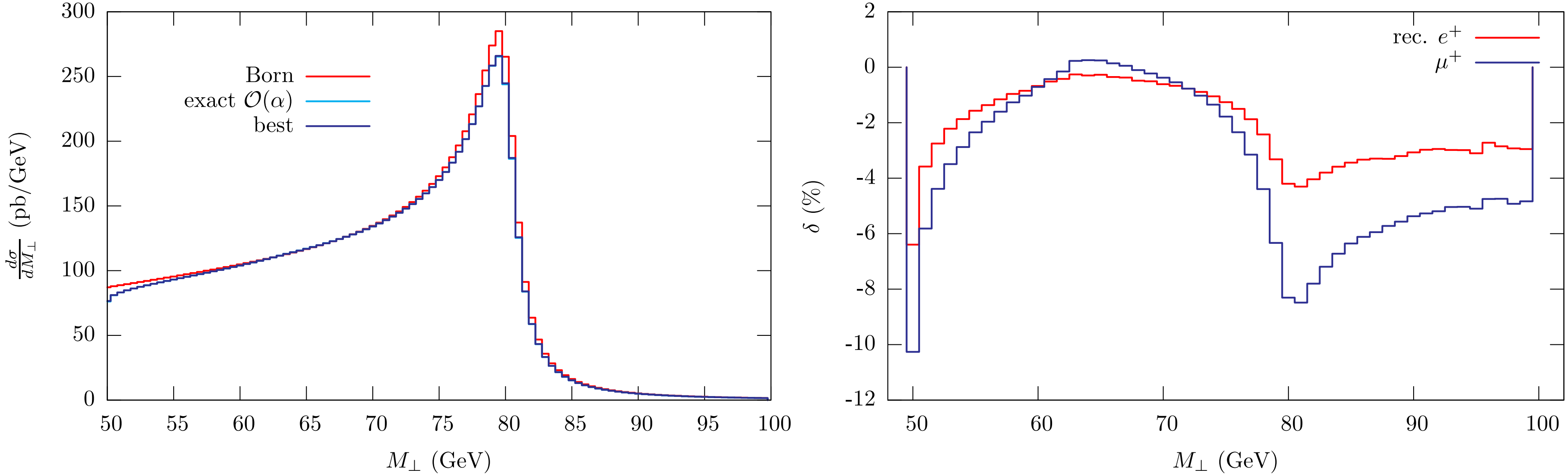
- NLO EW corrections to W production — Baur, Keller, Wackeroth '98; Zykunov '01; Dittmaier, Krämer '02; Baur, Wackeroth '04 Arbuzov et al. '06; Carloni Calame et al. '06
- NLO EW corrections to Z production — Baur, Keller, Sakumoto '97; Baur, Wackeroth '99 Brein, Hollik, Schappacher '99; Baur et al. '02 Zykunov '07; Arbuzov et al. '07 Carloni Calame et al. '07, Dittmaier, Huber '09
- multi-photon radiation via leading logs — Baur, Stelzer '99; Carloni Calame et al. '03, '05 Placzek, Jadach '03; Brensing et al. '07
- photon-induced processes — Dittmaier, Krämer '06; Arbusov, Sadykov '07 Brensing et al. '07

W transverse mass distribution

transverse mass $M_{\mathrm{W,T}} = \sqrt{2p_\perp^l p_\perp^\nu (1 - \cos\phi_{l\nu})}$

- Jacobian peak at W mass relatively insensitive to QCD ISR

Carloni Calame et al. '06 LHC14



- final-state photon radiation distorts Breit–Wigner resonance (kinematic effect!)
  logarithmic corrections $\propto (\alpha/\pi)\log(M_V^2/m_l^2)$
  $\Rightarrow$ shift in extracted W mass: $\delta M_{\mathrm{W}} \sim -170(60)\,\mathrm{MeV}$ for $\mathrm{W} \to \mu\nu(\mathrm{e}\nu)$
  partial KLN cancellation for recombined electrons
- full EW $\mathcal{O}(\alpha)$ corrections: $\delta M_{\mathrm{W}} \sim 10\,\mathrm{MeV}$ Baur, Keller, Wackeroth. '99
- multiple final-state photon radiation: $\delta M_{\mathrm{W}} \sim 10(2)\,\mathrm{MeV}$ Carloni Calame et al. '04

Combination of electroweak and QCD corrections

crucial for W and Z precision measurements but difficult beyond NLO

- simple first attempt: combination of soft-gluon resummation with final-state QED corrections (multiplicative) Cao, Yuan '04 (ResBos-A)
- additive or multiplicative combination of NLO QCD and EW correction
  Balossini et al. '07, '09 (see also Bernaciak, Wackeroth '12)

$$\mathrm{d}\sigma_{\mathrm{QCD}\oplus\mathrm{EW}} = \mathrm{d}\sigma_{\mathrm{QCD}} + \{\mathrm{d}\sigma_{\mathrm{EW}} - \mathrm{d}\sigma_{\mathrm{LO}}\}_{\mathrm{HERWIGPS}}$$

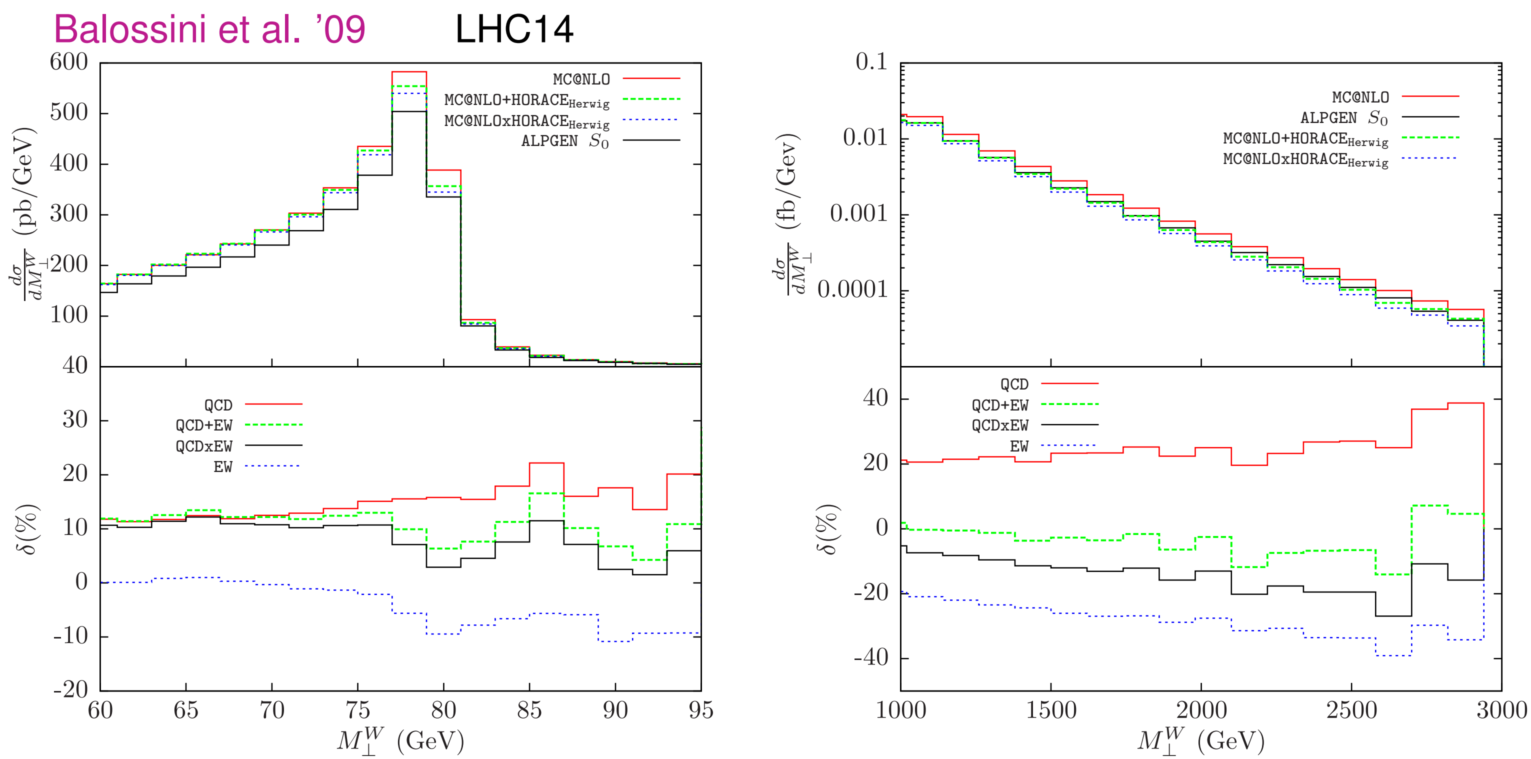
$$\mathrm{d}\sigma_{\mathrm{QCD}\otimes\mathrm{EW}} = \left(1 + \frac{\mathrm{d}\sigma_{\mathrm{QCD}} - \{\mathrm{d}\sigma_{\mathrm{LO}}\}_{\mathrm{HERWIGPS}}}{\mathrm{d}\sigma_{\mathrm{LO/NLO}}}\right)\{\mathrm{d}\sigma_{\mathrm{EW}}\}_{\mathrm{HERWIGPS}}$$

  EW = HORACE, QCD = MC@NLO Frixione, Webber '02

  prescriptions agree at $\mathcal{O}(\alpha_\mathrm{s}) + \mathcal{O}(\alpha)$ but differ at $\mathcal{O}(\alpha\alpha_\mathrm{s})$

- beyond additive approximation full two-loop $\mathcal{O}(\alpha\alpha_\mathrm{s})$ analysis needed
  for Z production some corrections exist:
  - virtual $\mathcal{O}(\alpha\alpha_\mathrm{s})$ correction to quark–gauge-boson vertex Kotikov, Kühn, Veretin '07
  - virtual $\mathcal{O}(\alpha\alpha_\mathrm{s})$ of QED $\times$ QCD type Kilgore,Sturm '11

Transverse W-mass distribution



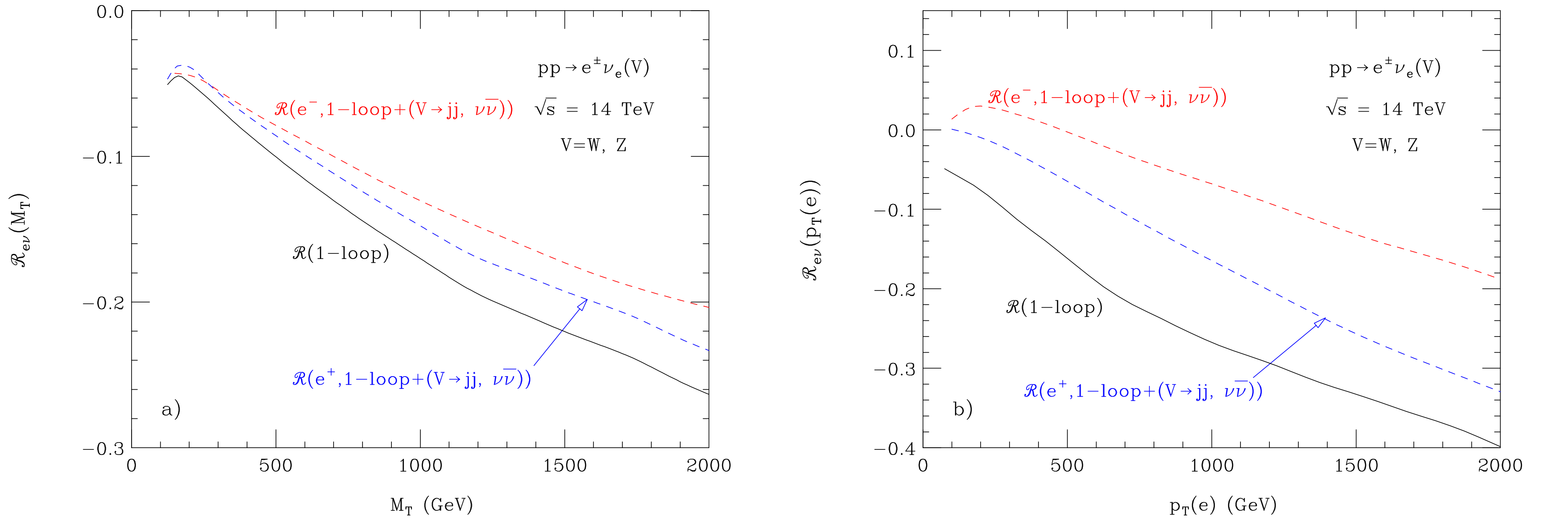
- corrections relative to LO+PS (ALPGEN S0)
- $M_{\mathrm{W,T}} \sim M_{\mathrm{W}}$: negative EW corrections compensate positive QCD corrections
  EW corrections mandatory around Jacobian peak (-10%)
- $M_{\mathrm{W,T}} \gg M_{\mathrm{W}}$: large negative EW corrections (Sudakov logarithms) cancel positive QCD corrections
- different ways of combining QCD and EW corrections differ at per-cent level
  $\Rightarrow \mathcal{O}(\alpha\alpha_{\mathrm{s}})$ calculation needed

Effects of real weak-boson radiation

- Virtual EW corrections enhanced by large logarithms at high energy scales
- for realistic cuts real massive gauge-boson radiation partially cancels virtual EW corrections

Baur '06

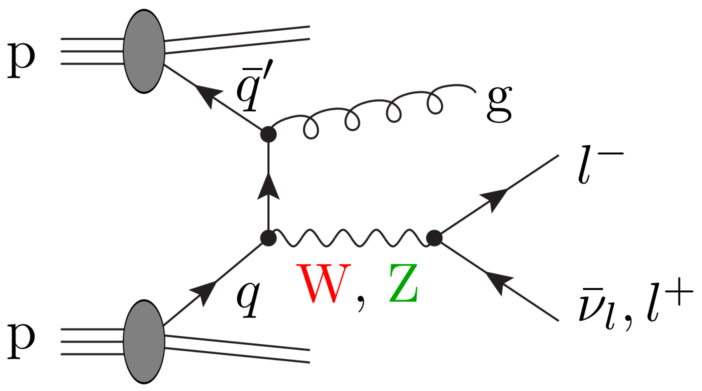
transverse $e\nu$ mass | transverse electron momentum

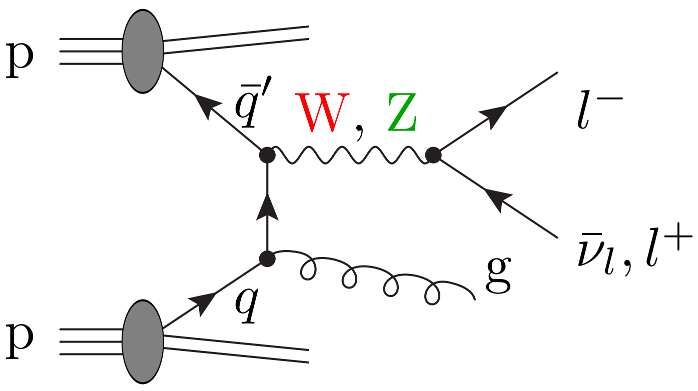


- $M_T(e\nu) = 2\,\mathrm{TeV}$: reduction of corrections from -26% to $-23\%/-22\%$
- $p_T(e) = 1\,\mathrm{TeV}$: reduction of corrections from -28% to $-17\%/-7\%$

Gauge-boson plus jet production

Gauge-boson + jet production





- important contribution to single V production
  $\Rightarrow$ measurement of M_V, Γ_V, electroweak mixing angle $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$
- tests of jet dynamics in QCD
- constraints on parton distribution functions (PDFs)
- source of high-energy leptons and/or missing transverse momentum
  $\Rightarrow$ background to new physics

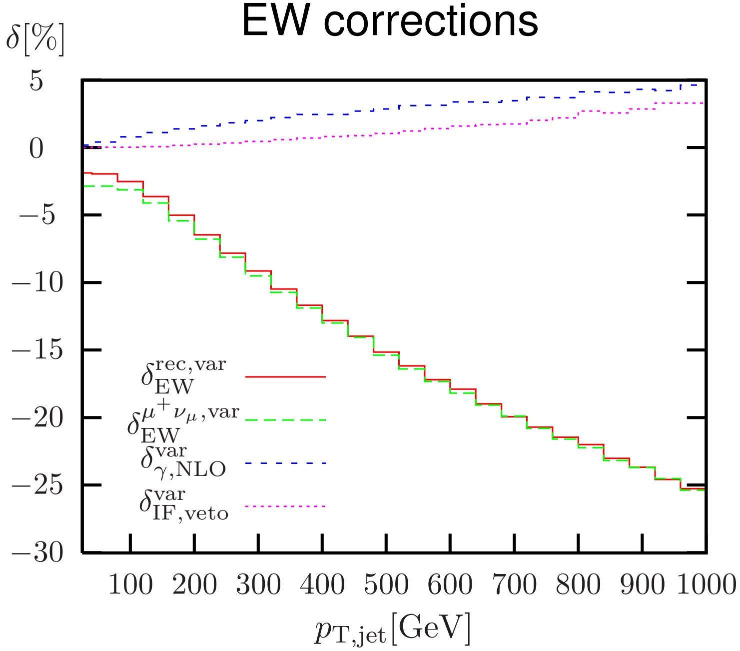
Gauge-boson + jet production

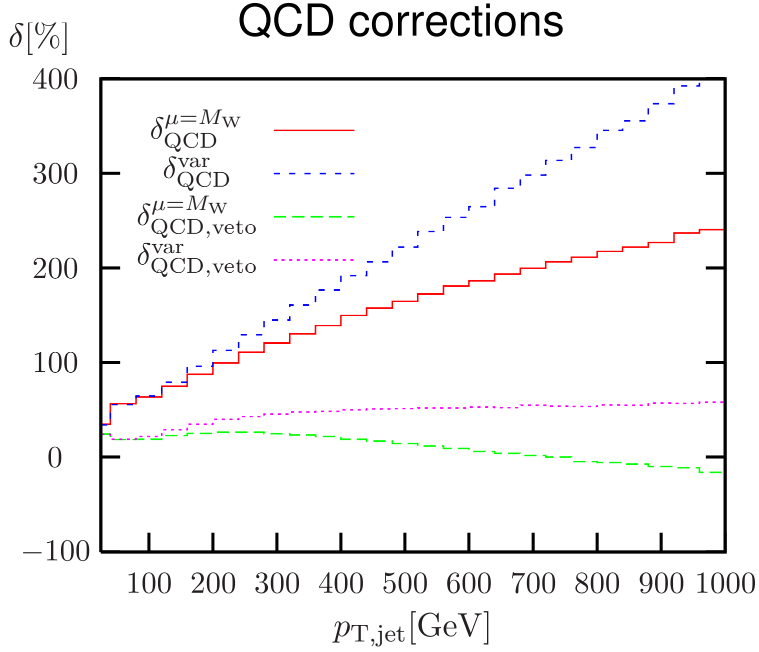
EW corrections

- $\mathrm{pp} \to V + \mathrm{jet} + X \quad (V = \gamma, \mathrm{Z})$
  - weak $\mathcal{O}(\alpha)$ correction (stable Z) Maina, Moretti, Ross '04
    $\delta_{\mathrm{weak}} \sim -(5{-}15)\%$ for $p_{\mathrm{T}} \lesssim 500\,\mathrm{GeV}$
  - (NLO + NNLL) EW corrections (stable Z) Kühn, Kulesza, Pozzorini, Schulze '04, '05
  - EW and QCD NLO corrections for $\mathrm{pp} \to l^+l^- + \mathrm{jet} + X$,
    i.e. $\mathrm{pp} \to \mathrm{Z} + \mathrm{jet} + X$ including leptonic decays Denner, Dittmaier, Kasprzik, Mück '11
- $\mathrm{pp} \to \mathrm{W} + \mathrm{jet} + X$
  - EW corrections for stable W: Kühn et al. '07; Hollik, Kasprzik, Kniehl '07
    $\delta_{\mathrm{weak}} \sim -30\%$ for $p_{\mathrm{T}} \sim 2000\,\mathrm{GeV}$
    photo production appreciably contributes to relative corrections $(+10\%@2\,\mathrm{TeV})$
    Hollik et al. '07
  - EW and QCD NLO corrections for $\mathrm{pp} \to l\nu + \mathrm{jet} + X$,
    i.e. $\mathrm{pp} \to \mathrm{W} + \mathrm{jet} + X$ including leptonic decays Denner, Dittmaier, Kasprzik, Mück '10

Jet transverse momentum in $\mathrm{pp} \to \mathrm{W} + \mathrm{jet} + X$

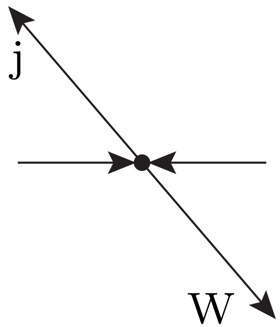
Denner, Dittmaier, Kasprzik, Mück ’11



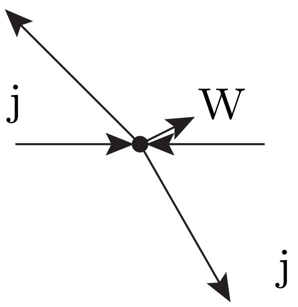


- large electroweak corrections for high p_T
  Sudakov logarithms
- 5% photon-induced corrections at $1\,\mathrm{TeV}$
- huge QCD corrections owing to new subprocess $\mathrm{pp} \to 2\,\mathrm{jets} + \mathrm{W}$ with two opposite hard jets and soft W
  veto on 2nd jet reduces corrections considerably

LO process

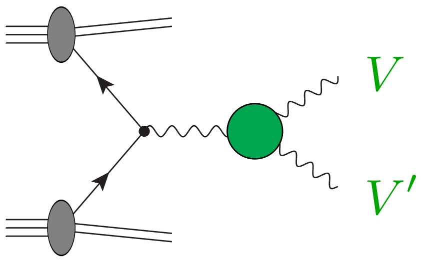


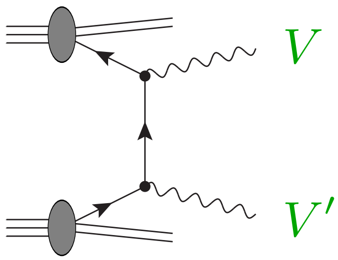
new NLO process



Gauge-boson pair production

Gauge-boson pair production





$V, V' = \gamma, \mathrm{Z}, \mathrm{W}^\pm$

$$\sigma(\mathrm{WW}) \sim 100\,\mathrm{fb}$$
$$\sigma(\mathrm{W}^\pm\mathrm{Z}) \sim 30/20\,\mathrm{fb}$$
$$\sigma(\mathrm{ZZ}) \sim 15\,\mathrm{fb}$$

Physics issues:

- triple-gauge-boson couplings at high momentum transfer
- dynamics of longitudinal massive gauge bosons at high energies
  $\mathrm{W_L}, \mathrm{Z_L} \sim$ Goldstone bosons $\quad\rightarrow$ window to scalar sector
- important class of background processes to many searches
  (e.g. $\mathrm{H}\to VV\to 4f$, supersymmetry)

NLO QCD corrections available for full process including leptonic decays

Dixon, Kunszt, Signer ’99, Campbell, Ellis ’99; De Florian, Signer ’00

EW corrections to gauge-boson pair production

- $\mathrm{pp}(\to \mathrm{W}\gamma) \to l\bar{\nu}\gamma + X$ Accomando, Denner, Pozzorini '01; Accomando, Denner, Meier '05

  $\mathcal{O}(\alpha)$ correction in pole approximation

  $\hookrightarrow\ \delta\ \sim\ -10\%\,(-27\%)$ for $p_{\mathrm{T},\gamma} \gtrsim 250\,\mathrm{GeV}\ (700\,\mathrm{GeV})$

- $\mathrm{pp} \to \mathrm{Z}\gamma + X$ Hollik, Meier '04 and $\mathrm{pp}(\to \mathrm{Z}\gamma) \to ll\gamma + X$ Accomando, Denner, Meier '05

  complete $\mathcal{O}(\alpha)$ correction for on-shell Z bosons in pole approximation

  $\hookrightarrow\ \delta\ \sim\ -10\%$ for $M_{\gamma\mathrm{Z}}$ distribution

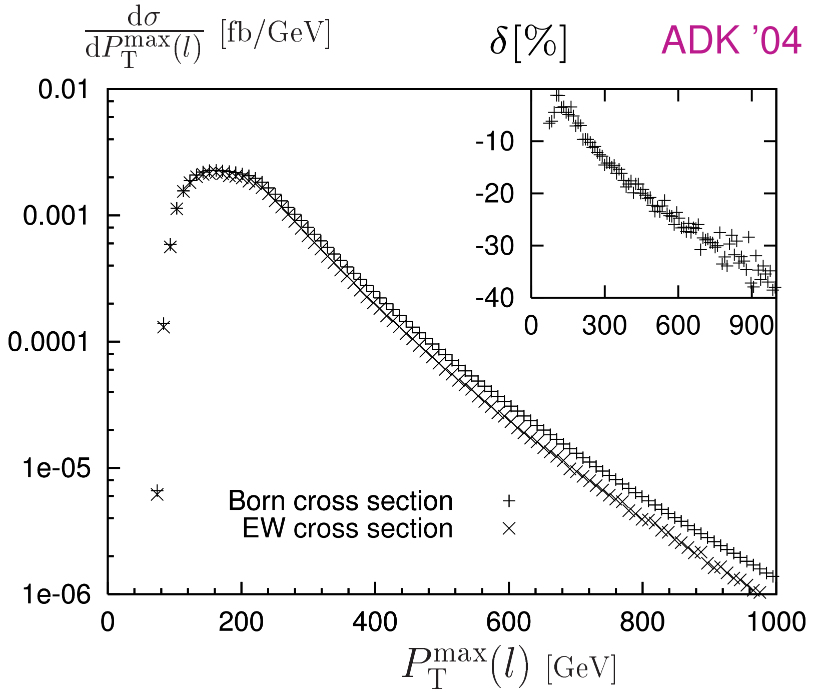
- $\mathrm{pp}(\to \mathrm{WW}, \mathrm{WZ}, \mathrm{ZZ}) \to 4\,\mathrm{leptons} + X$

  Accomando, Denner, Pozzorini '01
  Accomando, Denner, Kaiser '04

  $\mathcal{O}(\alpha)$ correction in high-energy and pole approximations

large negative EW corrections
(Sudakov logarithms)
for large energy scales

$\mathrm{pp} \to \mathrm{WZ} \to \mathrm{e}\nu_{\mathrm{e}}\mu^+\mu^-$ at $\sqrt{s} = 14\,\mathrm{TeV}$

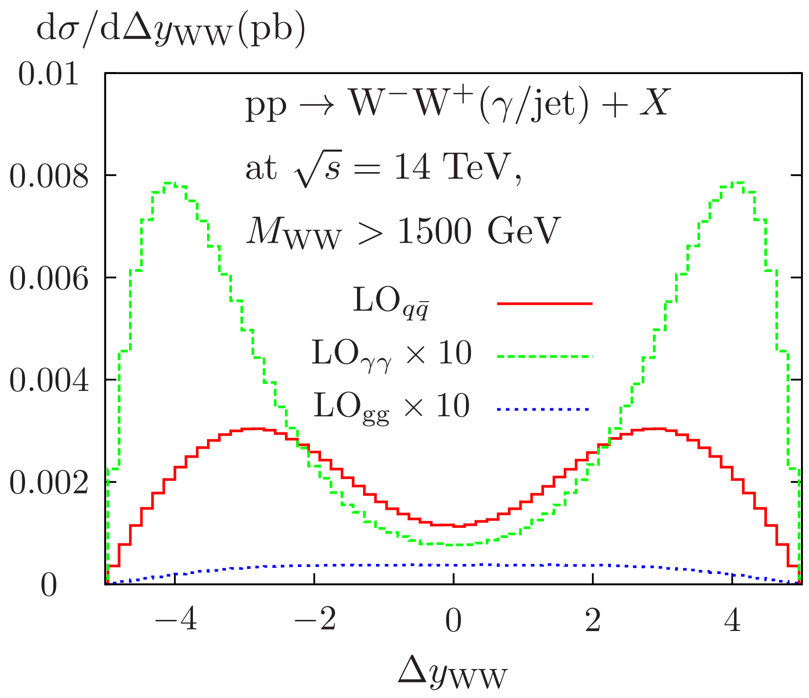


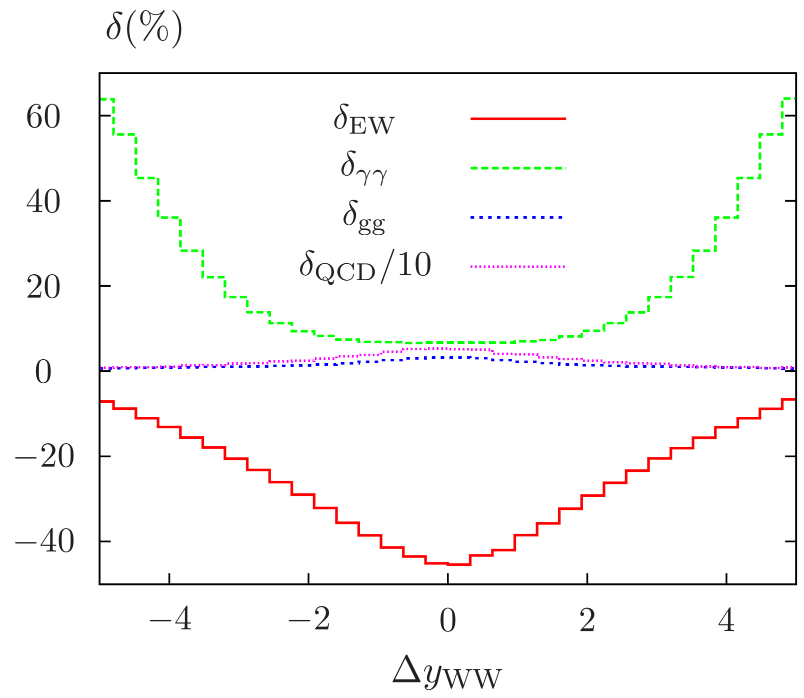
EW corrections to gauge-boson pair production (2)

- $\mathrm{pp} \to \mathrm{WW}, \mathrm{WZ}, \mathrm{ZZ} + X$ (on-shell gauge bosons) Bierweiler, Kasprzik, Kühn, Uccirati '12

  including
  - complete EW and QCD NLO corrections
  - photon- and gluon-induced processes: $\gamma\gamma \to \mathrm{WW}$, $\mathrm{gg} \to \mathrm{WW}$
  - radiation of massive vector bosons: $qq \to \mathrm{WW}V$

distribution in rapidity difference of W bosons (sensitive to anomalous couplings)





dramatic distortion of distribution at level of 50% (mimics anomalous couplings)

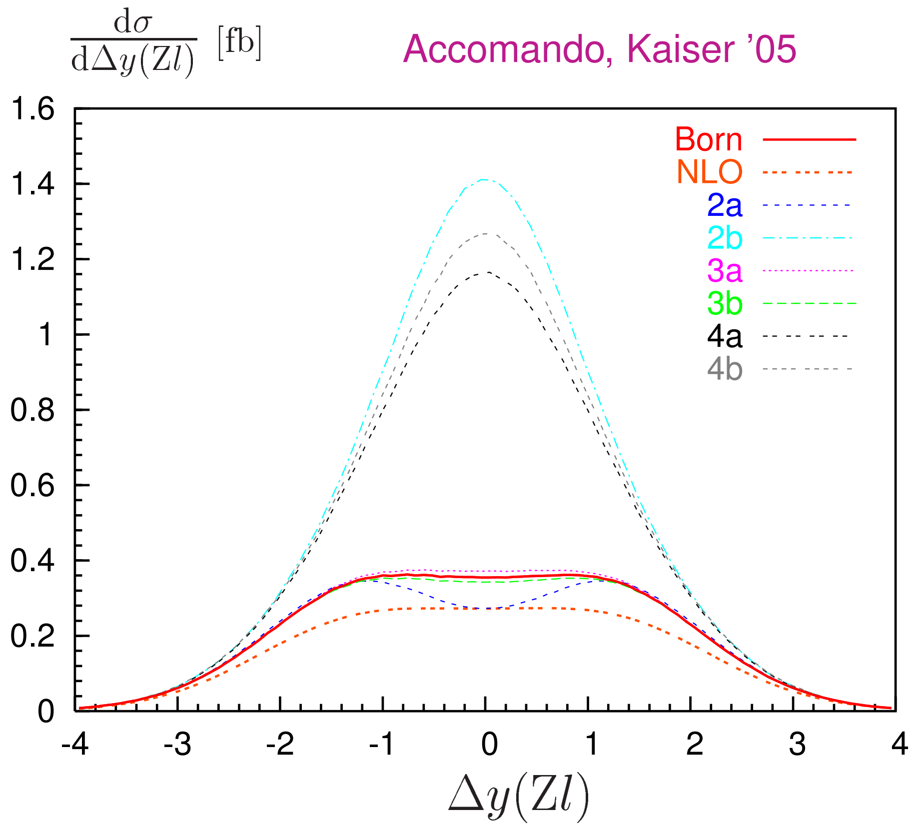
Electroweak corrections vs anomalous couplings

$\text{pp} \to \text{WZ} \to l\nu_l l'\bar{l}'$:

distribution in rapidity difference of Z boson and lepton from W decay $\Delta y(Zl)$

NLO = NLO electroweak: $\sim -20\%$

2a/2b: $\Delta g_1^Z = \pm 0.02$,   3a/3b: $\Delta\kappa_\gamma = \pm 0.04$,   4a/4b: $\lambda = \pm 0.02$



Conclusions

Conclusions

NLO corrections

- important for reliable predictions of cross sections and distributions
- typically some 10%, but may be strongly enhanced
- rapid progress in calculational techniques during recent years
  - successes of unitarity-based techniques (first $2 \to 5$ results)
  - improvement of diagrammatic techniques
- state of the art:
  $2 \to 4$ calculations, first $2 \to 5$ calculations available

EW NLO corrections

- typically at level of few $\%$ to 10%
  $\hookrightarrow$ important for precise measurements
- strongly enhanced in some kinematic regions
  (high energy scales, resonance regions)