QCD and electroweak physics at the LHC

Stefano Pozzorini
CERN

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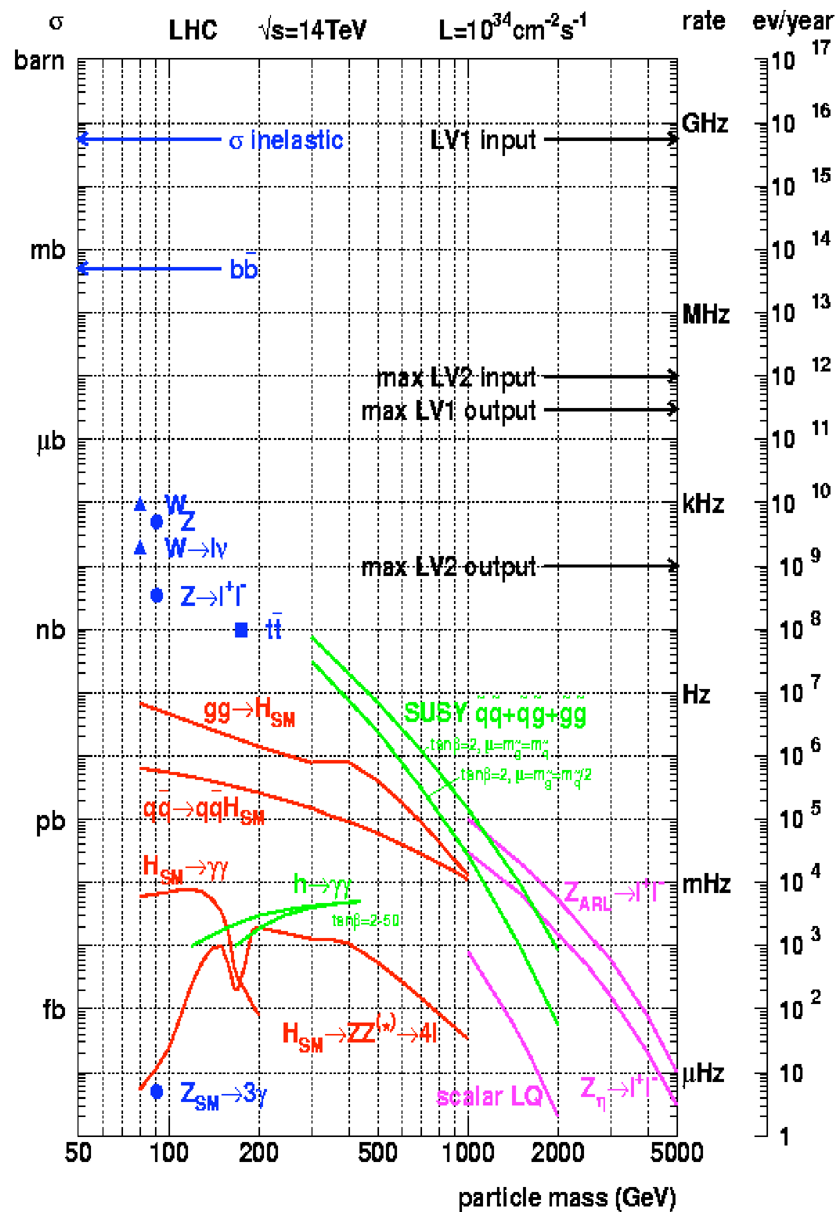
Outline of the talk

(1) **Introduction** - (some of the) activities of the EW/QCD working group

(2) **QCD hard scattering** - from LO to NNLO

(3) **EW corrections** - selected topics

(1) The EW/QCD working group and the LHC



SM (mostly) without Higgs and top

- gauge bosons (Drell Yan, GB pairs)
- jets

Well-known SM reactions

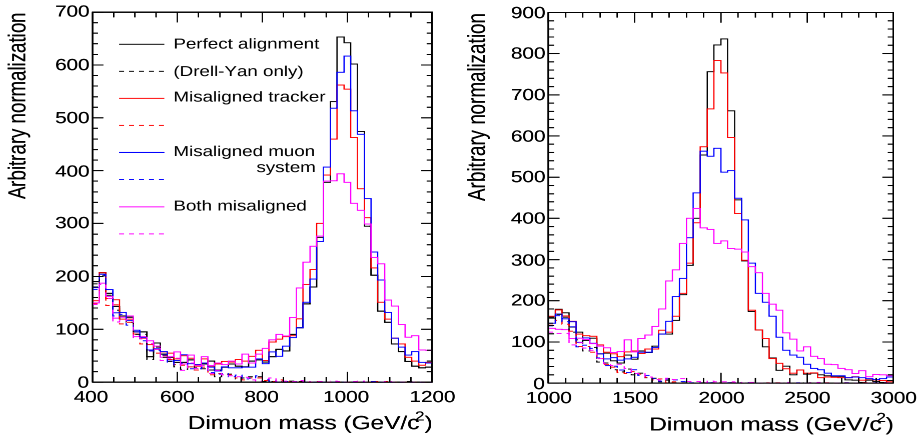
- large cross sections, clean signatures
- good theoretical description (input parameters, (N)NLO cross sections)

Importance of these reactions

- detector calibration
- MC calibration
- measurements of luminosity, PDFs and parameters (α_S, M_W, $\sin^2(\theta_{\rm eff})$, TGCs,...)
- large backrounds in NP searches

Signals and backgrounds

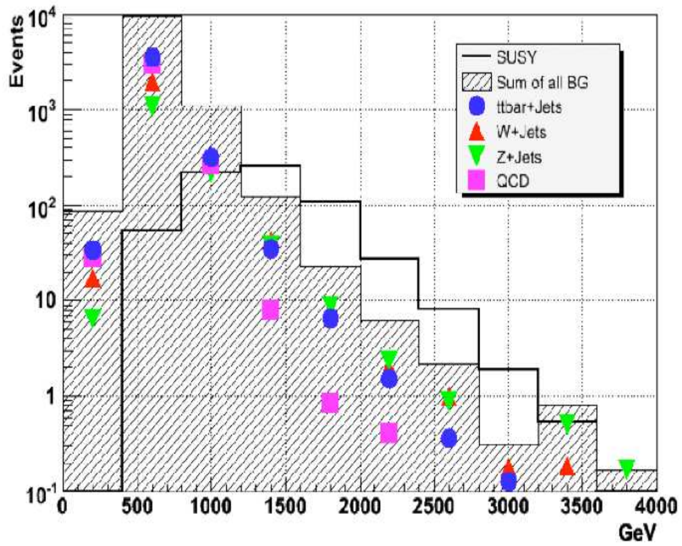
$Z' \to \mu^+\mu^-$ in CMS



Trivial backrounds

- Two-body decays with sharp invariant-mass or Jacobian peaks
- non-hadronic final state
- backround from data, role of theory prediction marginal

SUSY searches in multi-jet + $\not{E}_T$ final states



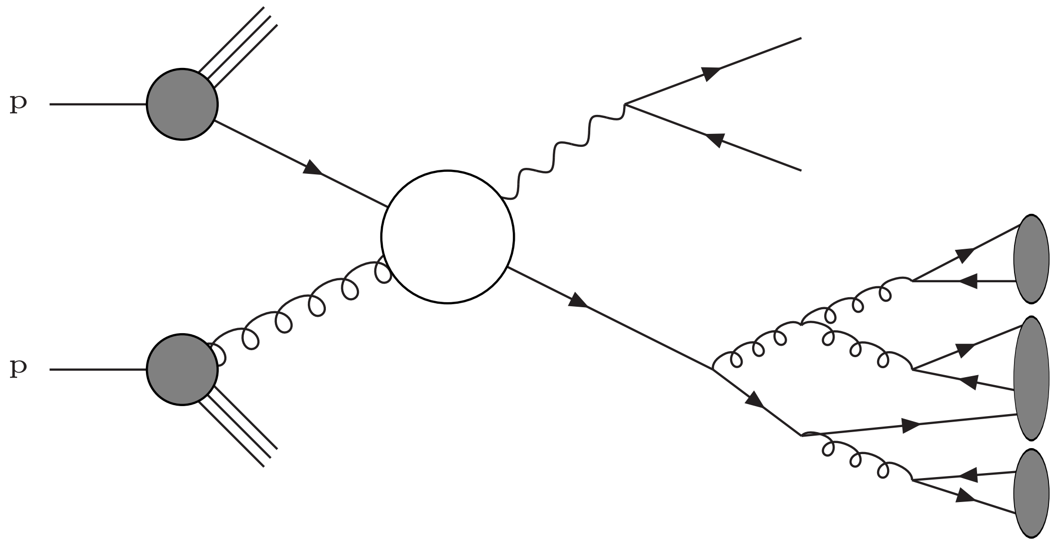
Challenging backgrounds

- jets and missing-energy in final state
- broader S distribution with shape similar as B
- requires solid prediction of B and undestanding of uncertainty
- must be normalized and validated with data control samples in signal-free regions
- extrapolation into signal region driven by theory

Tools for hadronic interactions - theoretical expertise within the Helmholtz Alliance

Structure of the proton

- NNLO splitting functions Moch/Vermaseren/Vogt
- NNLO MRST PDFs Martin/Stirling/Thorne/Watt



Accurate partonic cross section

- **LO, NLO, NNLO predictions** (this talk)
- Resummations

Monte Carlo event generators (HERWIG, SHERPA)

- Showering and hadronization
- matching between partons and jets at LO and NLO
- Underlying events

Input parameters and fits

- precise α_S from $e^+e^- \rightarrow 3j$ at NNLO Gehrmann-De Ridder/ Gehrmann/Glover/Heinrich;Weinzierl
- GFITTER

(2) QCD hard scattering

Everything involves QCD

- also purely EW reactions induced by quark scattering (at LO) receive (N)NLO QCD contributions from the gluons inside the proton

(N)NLO QCD contributions can be very large

- large gluon density at the LHC
- large size of strong coupling $\alpha_S(M_Z) \simeq 0.12$

Size of (N)NLO can be estimated

- through $\mu_{\mathrm{R,F}}$-dependence
- typically strong dependence from running of $\alpha_S(\mu_R)$

Importance of computing (N)NLO

- the estimates can fail (known only a posteriori)
- description of jet structure in terms of partonic constituents

Experimentalists need differential cross sections

- avoid inclusive K factors whenever possible
- experimental analysis require acceptance cuts
- cuts or jet vetos can have a strong impact on size of (N)NLO corrections and scale uncertainties

Importance of describing multi-particle final state

- signatures with many decay produts from heavy unstable particles
- high probability of hard-jet emission

$\sigma(W+Nj)/\text{pb}$	$\sigma(1)$	$\sigma(2)$	$\sigma(3)$	$\sigma(4)$	$\overline{\sigma(N+1)/\sigma(N)}$
TEVATRON	230	37	5.7	0.75	0.13
LHC	3400	1130	340	100	0.3

(2.1) LO predictions

Several automatic algorithms for multi-particle final states

- Feynman diagrams up to $2 \to 6$ (MADGRAPH,CompHEP,AMEGIC++/SHERPA,GRACE,...)
- off-shell recursions up to $2 \to 8$ or more (HELAC/PHEGAS,ALPHA/ALPGEN, O'MEGA/WHIZARD, ...)

  Berends/Giele '88; Caravaglios/Mangano/Moretti/Pittau '99; Draggiotis/Kleiss/Papadopoulus '02

- MHV/on-shell recursions Cachazo/Svrcek/Witten '04; Britto/Cachazo/Feng/Witten '05

time [s] for 10^4 points	BG	BCF	CSW
$gg \to 2g$	0.28	0.33	0.26
$gg \to 3g$	0.48	0.51	0.55
$gg \to 4g$	1.04	1.32	1.75
$gg \to 5g$	2.69	7.26	5.96
$gg \to 6g$	7.19	59.1	30.6
$gg \to 7g$	23.7	646	195
$gg \to 8g$	82.1	8690	1890
$gg \to 9g$	270	127000	29700

CPU efficiency for colour-dressed helicity amplitudes

- MHV/on-shell methods (BCF,CSW) yields compact analytic expressions
- but off-shell recursions (BG) are faster

Duhr/Höche/Maltoni '06; Dinsdale/Ternick/Weinzierl '06

LO amplitudes

Advantages

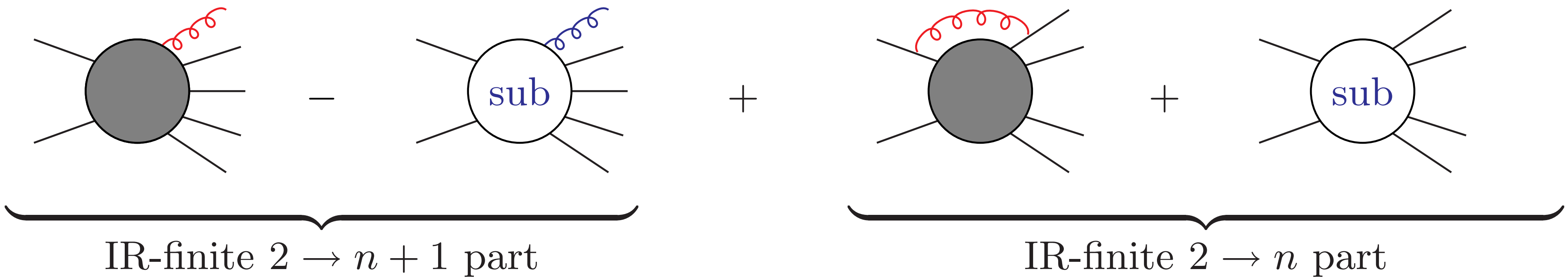
- good estimate in presence of multiple hard final states
- multi-purpose (many processes, many models)
- can be merged with parton showers (CKKW in HERWIG/SHERPA, MLM in ALPGEN)

Limitations

- large scale uncertainties
- especially from high powers of α_S associated with large jet multiplicities
- additional large uncertainties not described by scale variations (e. g. π^2 factors)

(2.2) NLO calculations

Loops and bremsstrahlung for $2 \to n$ process - treatment of IR singularities



Dipole subtraction

Frixione/Kunszt/Signer '96; Catani/Seymour '97

+ Dittmaier/Trocsanyi '02; Weinzierl/Phaf '01

- real and virtual parts divergent
- subtract local counterterm in $(n+1)$-PS and add back to n-PS
- PL event generators, arbitrary cuts and distributions

Automatization

- universal recipe in terms of trees
- parton-level automatization

  Hasegawa/Moch/Uwer;Frederix/Gehrmann/Greiner '08
- merging with parton shower

  Dinsdale/Ternick/Weinzierl'07; Gleisberg/Krauss'08

Bottleneck: one-loop matrix elements

Status of NLO for $2 \to 2$ processes

- fully automatized (e.g. FeynArts/FeynCalc/FormCalc)
- available and implemented for all SM processes (EVENT/JETRAD/MCFM/DISENT/DIPHOX/HQQB/NLOJET++/VBFNLO,etc.)
- matching with PS (MC@NLO/POWHEG) implemented for various processes

Multi-leg processes at NLO: technical challenges

Complexity of n-particle processes

- large number of diagrams $[\mathcal{O}(10^3)]$ and colour structures (grows like $n!$ or faster)
- many kinematic invariants, polarization states and Dirac/helicity structures
- tensor loop integrals of high rank (from ggg-couplings and ferm. propagators)

$$\int \frac{q^{\mu_1}\dots q^{\mu_R}}{(q^2-m_0^2)\dots((q-p_{N-1})^2-m_{N-1}^2)} = \sum_{i_1,\dots,i_R=1}^{N-1} T^{(R)}_{i_1\dots i_R} p_{i_1}^{\mu_1}\dots p_{i_R}^{\mu_R} + g^{\mu_i\mu_j}\,\text{terms}$$

- many particles $\Rightarrow$ high tensor rank $\Rightarrow$ many covariants coefficients $T^{(R)}_{i_1\dots i_R}$

Sources of increasing complexity

- External states with colour and mass, external gluons

Numerical instabilities from inverse Gram determinants

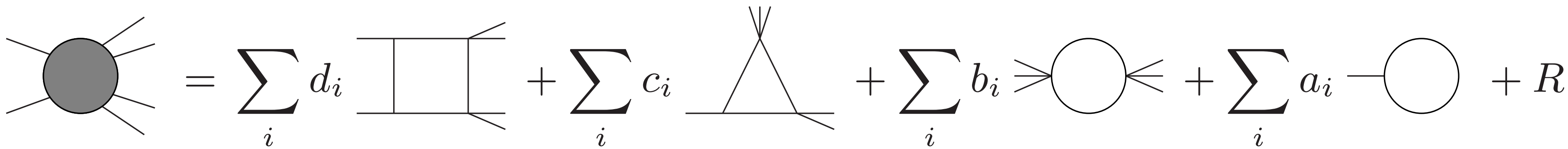
- reduction $T^{(R)} \to T^{(R-1)}$ requires inversion of $Z_{ij} = (2p_ip_j)$
- numerical instabilities from $1/\det(Z)$ in PS regions where $\det(Z) \to 0$
- problems start at $2 \to 3$ and can become serious at $2 \to 4$

Goals for NLO programs

- reliable predictions: **numerical stability**
- **sufficient speed**: distributions require $\gtrsim$ 1 event/sec!

Reduction methods

Any one-loop amplitude reducible to small set of known scalar integrals



We need fast and stable algotithms to compute d_i, c_i, b_i, a_i and rational part R

(A) Diagrammatic approach

- express amplitude through diagrams, insert Feynman rules
- huge number of tensor integrals explicitly reduced to small set of scalar boxes, triangles, etc.

Techniques to handle multi-leg tensor loop integrals

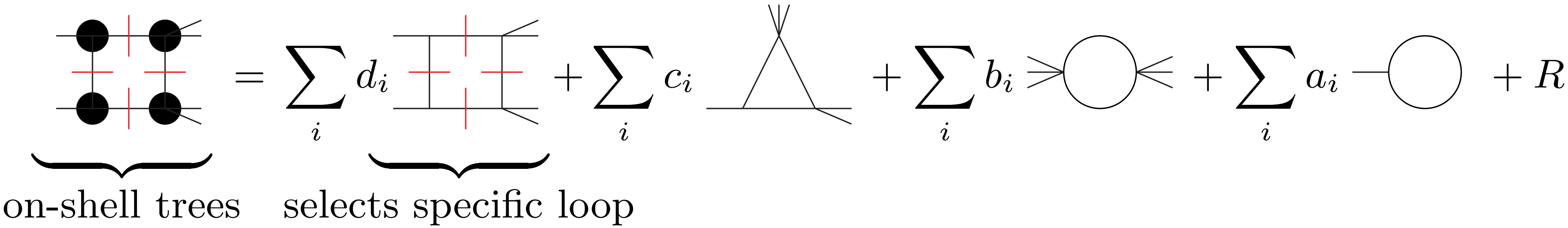
- Reduction of tensor integrals to scalar integrals Passarino/Veltman '79; Stuart et.al. '88-90; v.Oldenborgh/Vermaseren '90; Ezewa et.al. 92'; Denner '93; Campbell et.al. '96; Devaraj/Stuart '97; GRACE collab. '03; del Aguila/Pittau '04; v.Hameren et.al. '05; Denner/Dittmaier '05;
- Alternative reductions introducing scalar integrals in $D > 4$ Davydychev '91; Bern at.al. '93; Tarasov '96; Fleischer et.al. '99; Binoth et.al. '99/'05; Duplanic/Nizic '03; Giele/Glover/Zanderighi '04 Ellis/Giele/Zanderighi '06
- Reduction of pentagons, hexagons, etc. to boxes, triangles, bubbles Melrose '65 v.Neerven/Vermaseren '84'; v.Oldenborgh/Vermaseren '90; Davydychev '91; Bern et.al. '93; Denner '93; Campbell et.al. '96; Suzuki et.al. '02; Tramontano '02; Denner/Dittmaier '02-05; GRACE coll. '02-03;
- Numerical integration Ferroglia et.al. '02; Binoth et.al. '02-05; Nagy/Soper '03; de Doncker et.al. '04; Kurihara/Kaneko '05; Denner/Dittmaier '05; Anastasiou/Beerli/Daleo '05-07; Lazopoulus at.al. '07;

Lot of progress in the recent years

- full generality
- improved numerical stability avoiding $\det(Z)$ or expanding in small $\det(Z)$
- various groups and methods
- emphasis on efficiency, numerical stability and applications

(B) New methods based on generalized unitarity cuts

(Quadruple) branch cuts of full amplitude and its loop decomposition



Bern/Dixon/Dunbar/Kosower; Britto/Cachazo/Feng; Forde; Berger/Bern/Dixon/Forde/Kosower; Anastasiou/Britto/Feng/Kunszt/Mastrolia; Ossola/Pittau/Papadopoulus; Ellis/Giele/Kunszt/Melnikov/Zanderighi;

In practice

- Coefficients d_i, c_i, b_i, a_i expressed in terms of on-shell tree amplitudes
- exploit compact expressions and fast algorithms for multi-leg trees
- additional tricks for cut-free (R) terms: on-shell states in $D > 4$, factorization properties,...

Status

- Proven to be powerful for gg $\to n$g and $\gamma\gamma \to 4\gamma$ virtual amplitudes
- efficiency and numerical stability for cross sections still to be assessed
- many new ideas and strategies, first LHC applications on horizon

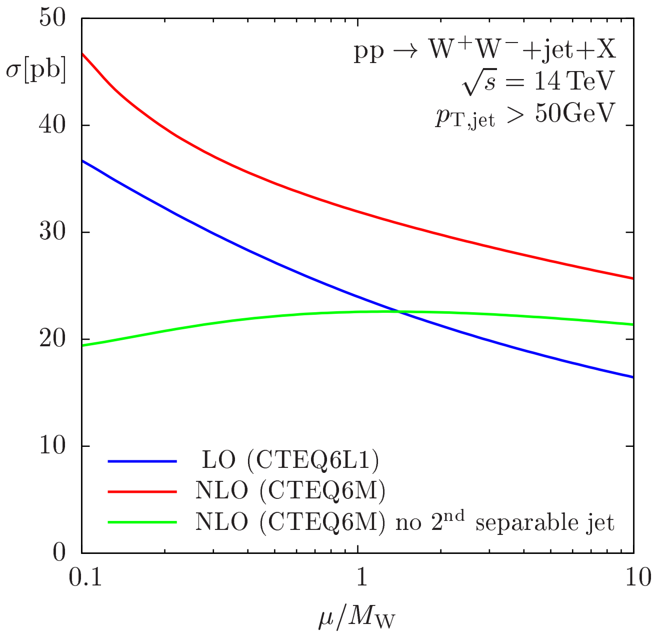
$2 \to 3$ NLO cross sections for LHC (*contrib. from Helmholtz Alliance)

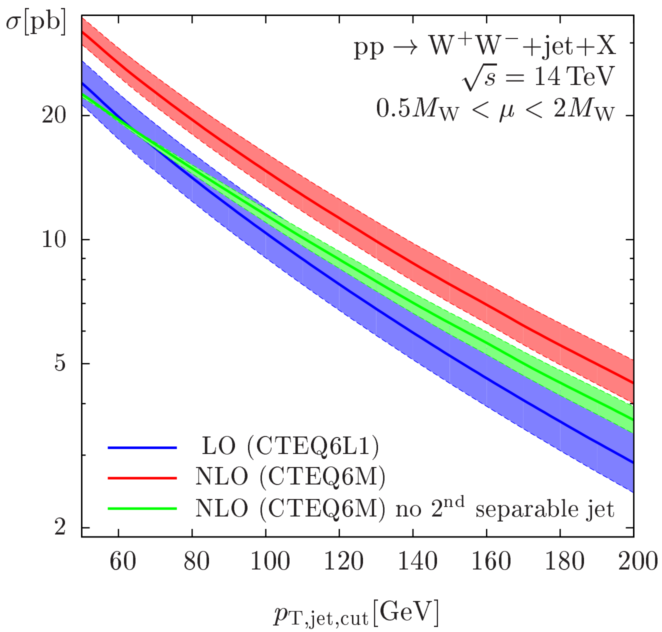
Many signal and background calculations in the recent few years

- *$pp \to t\bar{t}H, b\bar{b}H$ Beenakker/Dittmaier/Krämer/Plümper/Spira/Zerwas; Dawson/Reina/Wackeroth/Orr/Jackson; Peng/Wen-Gan/Hong-Shen/Ren-You/Yi
- *$pp \to HHH$ Plehn/Rauch Binoth/Karg/Kauer/Rückl
- *$pp \to Hjj$ Del Duca/ Kilgore/Oleari/Schmidt/Zeppenfeld; Campbell/Ellis/Zanderighi
- $pp \to jjj$ Bern/Dixon/Kosower; Kunszt/Signer/Trocsanyi; Giele/Kilgore/Nagy
- $pp \to Vjj$ Bern/Dixon/Kosower; Ellis/Veseli; Campbell/Ellis;
- *$pp \to VVj$ Dittmaier/Kallweit/Uwer; Campbell/Ellis/Zanderighi; Binoth/Guillet/Karg/Kauer/Sanguinetti
- *$pp \to VVV$ Lazopoulos/Melnikov/Petriello; Hankele/Zeppenfeld; Binoth/Ossola/Papadopoulos/Pittau
- $pp \to V + b\bar{b}$ Cordero/Reina/Wackeroth
- *$pp \to t\bar{t}j$ Dittmaier/Uwer/Weinzierl
- $pp \to t\bar{t}Z$ Lazopoulus/McElmurry/Melnikov/Petriello

almost all based on Feynman diagrams

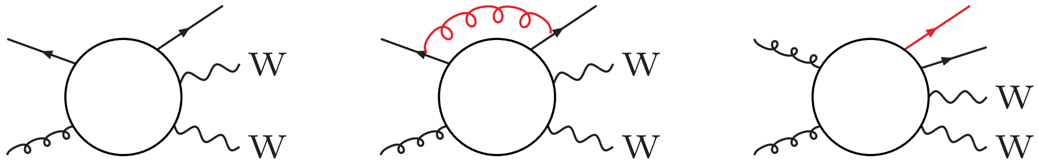
NLO QCD corrections to $pp \to WWj$ [Dittmaier/Kallweit/Uwer '07; Campbell/Ellis/Zanderighi '07]





Important background

- $H \to WW$ (GF/WBF) and new physics (SUSY)
- anomalous couplings in $pp \to WW$



Cross section at LHC ($p_{T,j}^{max} > p_{T,cut}$, $R = 1$)

- small LO scale dependence (25% for $\frac{1}{4} < \frac{\mu}{M_W} < 4$)
- not reduced at NLO!
- NLO correction > LO scale uncertainty!

Stabilization through 2nd-jet veto ($p_{T,j}^{min} < p_{T,cut}$)

- reduces size of correction and NLO scale uncertainty
- NLO consistent with LO uncertainty band

Example of strong cut dependence at NLO!

- WBF cuts can increase NLO corrections up to +70% (WWj dominant BG) Campbell/Ellis/Zanderighi '07

Towards $2 \to 4$ NLO cross sections for the LHC

Very few $2 \to 4$ calculations, only for e^+e^- and $\gamma\gamma$ colliders

- $e^+e^- \to 4f$ (EW) Denner/Dittmaier/Roth/Wieders '05
- $e^+e^- \to HH\nu\bar{\nu}$ (EW) Boudjema/Fujimoto/Ishikawa/Kaneko/Kurihara/Shimizu/Kato/Yasui '05
- $\gamma\gamma \to t\bar{t}b\bar{b}$ (QCD) Lei/Wen-Gan/Liang/Ren-You/Yi '07

Results for LHC urgently needed

- most interesting signals involve heavy particles decaying into jets, leptons, photons
- many multi-particle backgrounds

$2 \to 4$ **is a time consuming businnes**

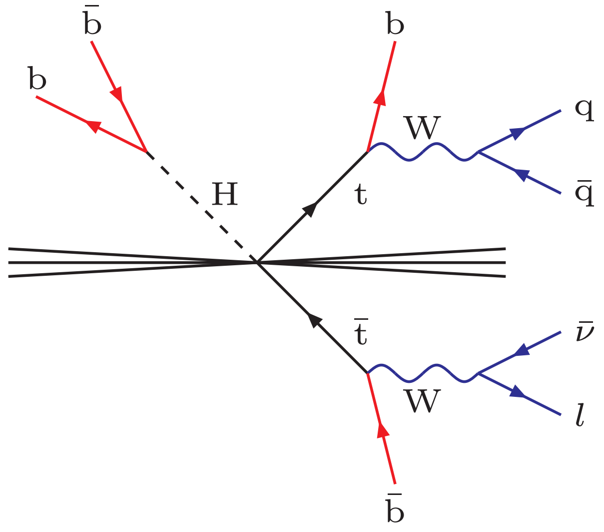
- many months of man power for a single process
- importance of setting right priorities

Les Houches '05 prioritized wishlist

	Reaction	background for	existing calculations
1.	VVj	t$\bar{\text{t}}$H, new physics	WWj: Dittmaier/Kallweit/Uwer '07; WWj: Campbell/Ellis/Zanderighi '07; WWj: Binoth/Guillet/Karg/Kauer/Sanguinetti (in progress)
2.	t$\bar{\text{t}}$b$\bar{\text{b}}$	t$\bar{\text{t}}$H	$q\bar{q}$-channel cross section completed Bredenstein/Denner/Dittmaier/SP '08
3.	t$\bar{\text{t}}$jj	t$\bar{\text{t}}$H	$\emptyset$
4.	VVb$\bar{\text{b}}$	VBF$\to$ H $\to VV$, t$\bar{\text{t}}$, NP	$\emptyset$
5.	VVjj	VBF$\to$ H $\to VV$	**VBF:** Jäger/Oleari/Zeppenfeld '06 + Bozzi '07
6.	Vjjj	new physics	one-loop amplitudes completed Ellis/Giele/Kunszt/Melnikov/Zanderighi '08
7.	VVV	new physics	ZZZ: Lazopoulos/Melnikov/Petriello '07; WWZ: Hankele/Zeppenfeld '07 VVV: Binoth/Ossola/Papadopoulos/Pittau '07

First (partial) results for $2 \to 4$ processes

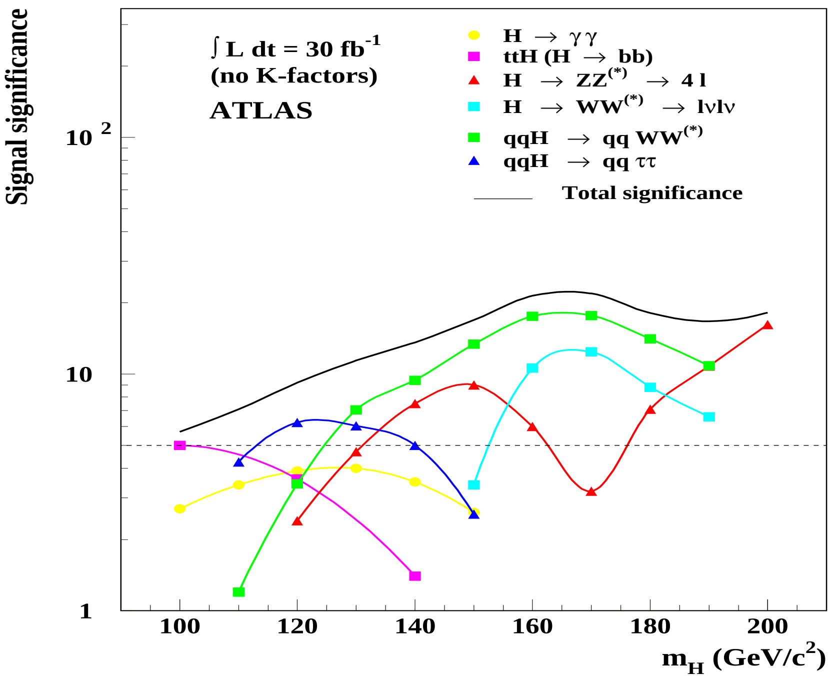
$t\bar{t}H$ production at the LHC and its $t\bar{t}b\bar{b}$ background



Associated $t\bar{t}H(H \to b\bar{b})$ production

- can be observed in $H \to b\bar{b}$ channel
- exploits large $BR(H \to b\bar{b})$ for light H
- measurement of top Yukawa coupling

ATLAS '03



Proposed analysis (ATLAS TDR)

- select final state $b\bar{b}b\bar{b}jjl\nu$ (4 b-quarks!)
- reconstruct $t\bar{t}b\bar{b}$
- select region $|m_{b\bar{b}} - M_H| < 30\,\text{GeV}$

Richter-Was/Sapinski, ATL-PHYS-98-132

Background to pp $\to t\bar{t}H$

Background processes

- $t\bar{t}b\bar{b}$ (QCD+EW), $t\bar{t}jj$
- large $\sigma_{\rm B}$ (underestimated in TDR)

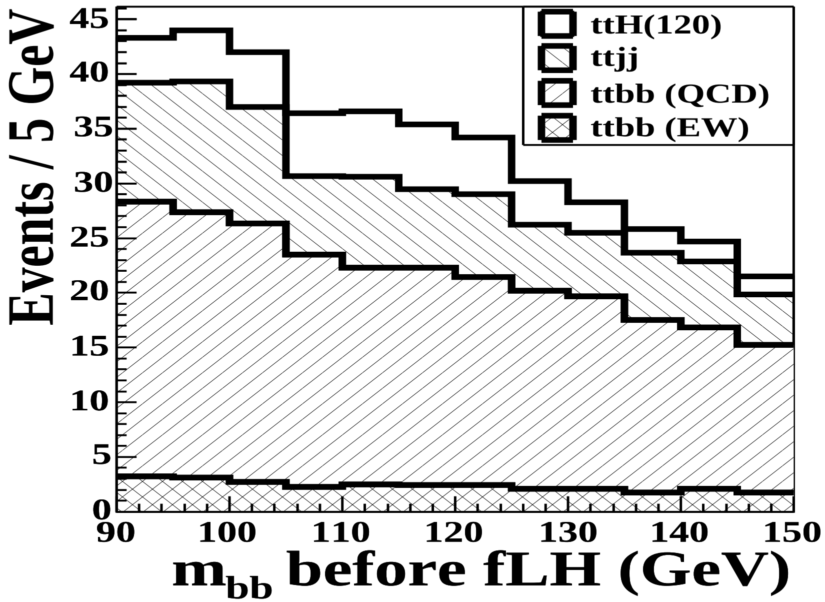
Stat. and syst. uncertainties of B

- small $\Delta B_{\rm stat}$ with $1/\sqrt{B} < 10\%$
- small $S/B \sim 0.2$ requires $\Delta B_{\rm syst} < 20\%$! (not considered in TDR)

Strategy

- direct measurement of B impossible (S and B have similar shape)
- measure B outside signal region and extrapolate with theory predictions
- theory uncertainty at LO > factor 2

$t\bar{t}H$ impossible without $t\bar{t}b\bar{b}$ at NLO



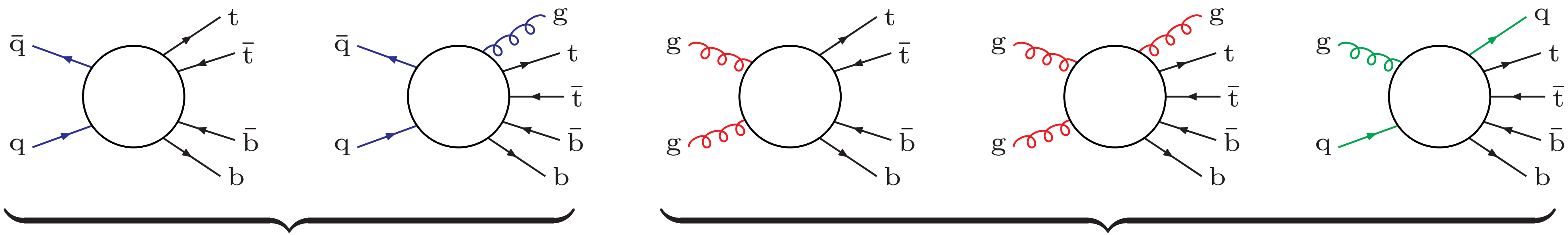
 # events and stat. sign. (30 fb^{-1})

$M_{\rm H}$(GeV)	110	120	130
$t\bar{t}$H	60.9	41.9	25.5
$t\bar{t}b\bar{b}$(QCD)	167.3	145.8	128.7
$t\bar{t}jj$	66.2	54.6	41.6
$t\bar{t}b\bar{b}$(EW)	21.8	18.4	15.2
$S/\sqrt{B}$	3.8	2.8	1.9
S/B	0.24	0.19	0.14

Cammin/Schumacher, ATL-PHYS-2003-024

NLO QCD corrections to $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ [Bredenstein/Denner/Dittmaier/SP '08]

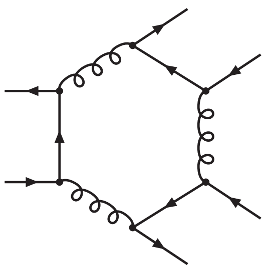
Quark-antiquark and gluon induced processes



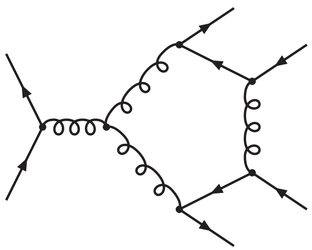
$q\bar{q}$: done

gg,qg: in progress

Sample diagrams in the $q\bar{q}$-channel



8 hexagons



24 pentagons

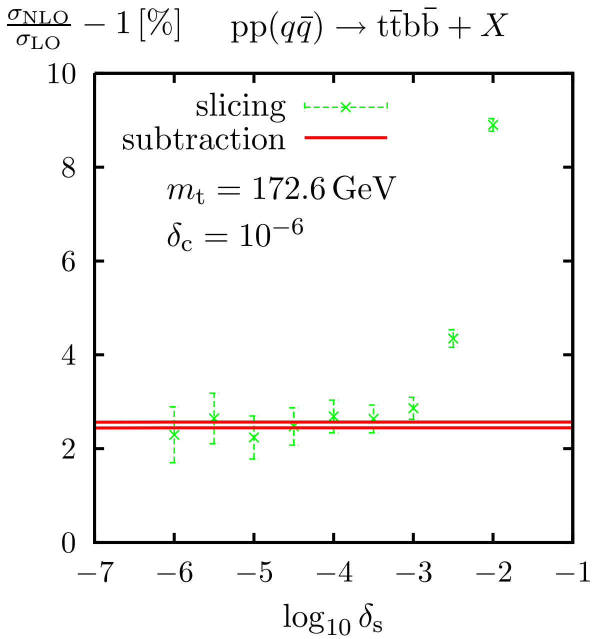
etc.

diagrams and impact on σ_{LO}

	$q\bar{q}$	gg	qg
LO	7	38	
virtual	188	1003	
real	66	393	66
$\sigma/\sigma_{\mathrm{tot}}$	5%	95%	

$q\bar{q}$ channel is simpler than gg and only 5% of σ but demonstrates feasibility of NLO

Technical aspects



Precision (consistency checks)

- UV, soft and collinear cancellations
- 2 completely independent calculations
- 10-digit agreement for single PS points
- permille agreement after PS integration with $\mathcal{O}(10^8)$ events

Runtime and stat. precision $\Delta\sigma/\sigma_{LO}$

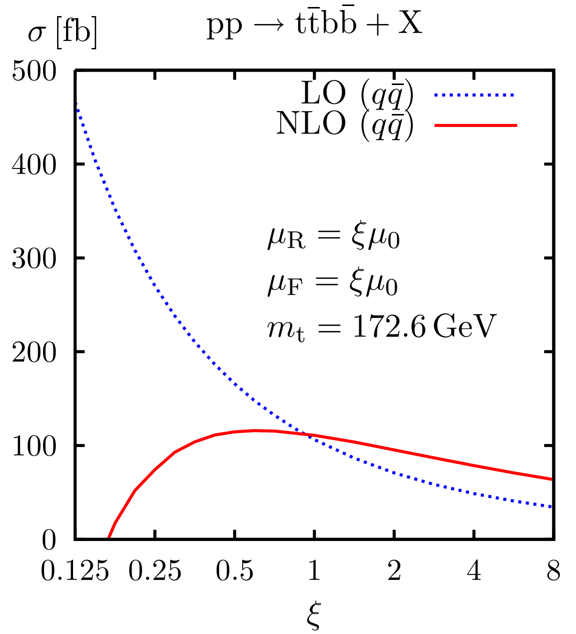
	σ/σ_{LO}	# events	$\Delta\sigma/\sigma_{LO}$	runtime
tree	74%	6.7×10^7	3×10^{-4}	66min
virtual	−3%	0.34×10^7	2.5×10^{-4}	12h
real	33%	13×10^7	5×10^{-4}	34h

on single 3GHZ Intel Xeon processor

Speed of calculation

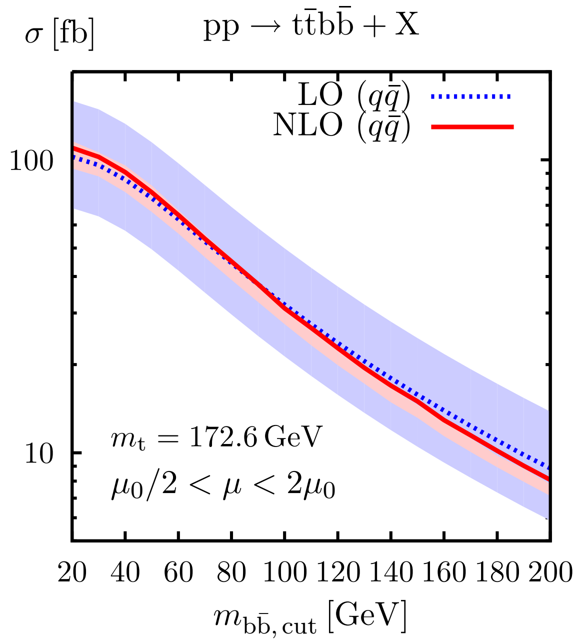
- virtual corrections @ 13 ms/event!
- for same precision $(\Delta\sigma/\sigma)$ virtual corrections require less CPU-time than real corrections (scale-dependent statement!)

Reduction of scale depedence at NLO ($q\bar{q}$ channel)



Total cross section ($p_{\mathrm{T},b} > 20\,\mathrm{GeV}$, $y_b < 2.5$)

- central scale $\mu_0 = m_\mathrm{t}$
- huge LO dependence: up to factor 4 (from $\alpha_\mathrm{S}(\mu_\mathrm{R})^4$)
- stabilization at NLO (close to maximum)



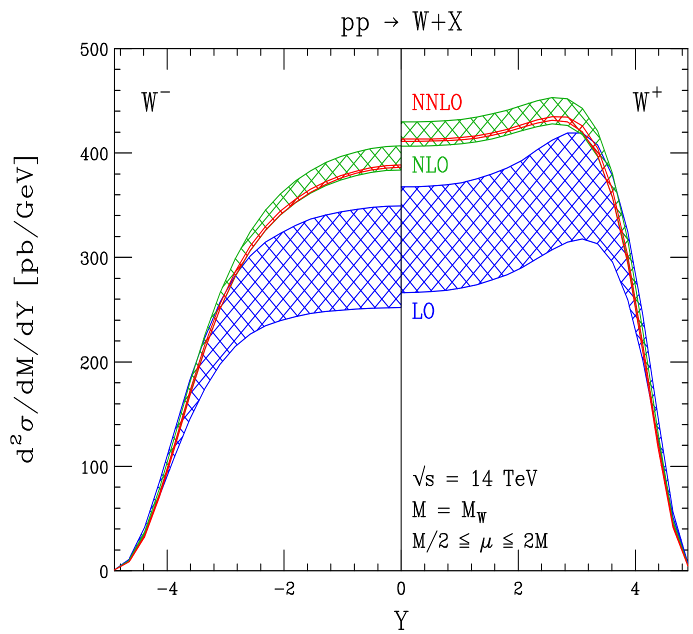
Dependence on $\mathrm{b\bar{b}}$ invariant mass

- strong reduction of scale dependence
- NLO consistent with LO uncertainty band
- shape of $m_{\mathrm{b\bar{b}}}$ distorted by corrections

(2.3) NNLO calculations

NNLO is important when

- NLO corrections and scale uncertainties are large
- percent precision needed for benchmark measurements



Anastasiou/Dixon/Melnikov/Petriello '04

Existing results for $pp \to H, W, Z$

- inclusive cross section

  Harlander '00; Catani/de Florian/Grazzini '01;

  Harlander/Kilgore '01-02; Anastasiou/Melnikov '02;

  Ravindram/Smith/van Neerven '03

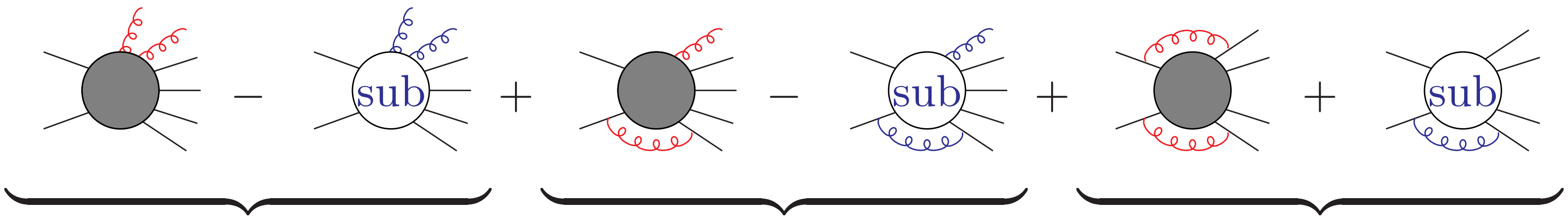
- differential distributions, selection cuts

  Anastasiou/Melnikov/Petriello '05; Anastasiou/Dissertori/

  Stöckli 07; Catani/Grazzini '07-08

IR divergences NNLO

Loops and bremsstrahlung for $2 \to n$ process



IR-finite $2 \to n+2$ part   IR-finite $2 \to n+1$ part   IR-finite $2 \to n$ part

Intricate structure of IR singularities (single and double unresolved partons)

- general subtraction scheme for IR singularities not available
- but a lot of progress in this direction Kosower, Weinzierl, Frixione, Grazzini, Gehrmann-De Ridder, Gehrmann, Glover, Daleo, Maitre, Somogyi, Trocsanyi, Del Duca

Recent achievements

- full NNLO completed for $e^+e^- \to jjj$ Gehrmann-De Ridder/Gehrmann/Glover/Heinrich '07; Weinzierl '08
- full NNLO completed for pp $\to$ singlet Catani/Grazzini '07-08
- first step towards NNLO subtraction for pp $\to j + X$ Daleo/Gehrmann/Maitre '08

2-loop matrix elements for $2 \to 2$

$\mathrm{pp} \to \mathrm{j} + X$ Anastasiou et.al.; Bern et.al.

- important for PDFs and α_S

$\mathrm{pp} \to \mathrm{t\bar{t}}$ Czakon/Mitov/Moch '07; Czakon '08;

- important for precise m_{t} measurement
- $q\bar{q}$-channel completed, gg-channel in progress

$\mathrm{pp} \to \mathrm{WW}$ Chachamis/Czakon/Eiras '08

- large BG to $H \to WW$ and relevant to search for anomalous couplings
- $M_{\mathrm{W}} \to 0$ limit completed, M_{W}-dependence coming soon

Strategy for 2-loop master integrals $I(M)$ with $M \neq 0$ Chachamis/Czakon/Eiras '08

- remove mass-complexity computing $\lim_{M\to 0} I(M)$ (automatized MB method)
- generate system of DEs

$$\frac{\partial}{\partial M} I_i(M) = \sum_j C_{ij} I_j(M)$$

- power expansion in M with up to 11 terms
- improve precision/check convergence with numerical solution of DE

(3) EW corrections - selected topics

Typical size

- $\alpha \sim \alpha_S^2$ suggests NLO EW $\sim$ NNLO QCD
- relevant for precision measurements: PDFs, luminosity, $M_{\mathrm{W}}, \sin^2(\theta), \ldots$

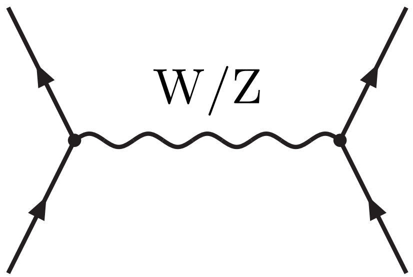
In some kinematic regions NLO EW strongly enhanced and this can require higher orders

- real γ bremsstrahlung distorts leptonic distributions $\Rightarrow \ln(m_l^2/M^2)$
- Virtual W/Z effects distort tail of p_{T} distributions $\Rightarrow \ln(p_{\mathrm{T}}^2/M_{\mathrm{W}}^2)$

In the follwing consider two examples

- Drell-Yan
- pp $\rightarrow V$j

(3.1) Drell-Yan processes pp $\to Z/W \to l\bar{l}/l\bar{\nu}_l$



NLO EW (and NNLO QCD) available

- for Z production: Baur/Keller/Sakumoto '97; Baur/Wackeroth '99; Brein/Hollik/Schappacher '99; Baur et.al '02; Arbuzov et.al. '06;
- for W production: Hollik/Wackeroth '97; Baur/Keller/Wackeroth '98; Dittmaier/Krämer '02; Baur/Wackeroth '04; Arbuzov et.al. '05; Carloni Calame et.al. '06; Brensing/Dittmaier/Krämer/Mück '08

Important for measurement of luminosity from Z/W **counting**
(talks by Hasko Stenzel/ATLAS and Thomas Marteen/CMS)

- 5% precision (dominated by PDF uncertainty) might improve up to 3%

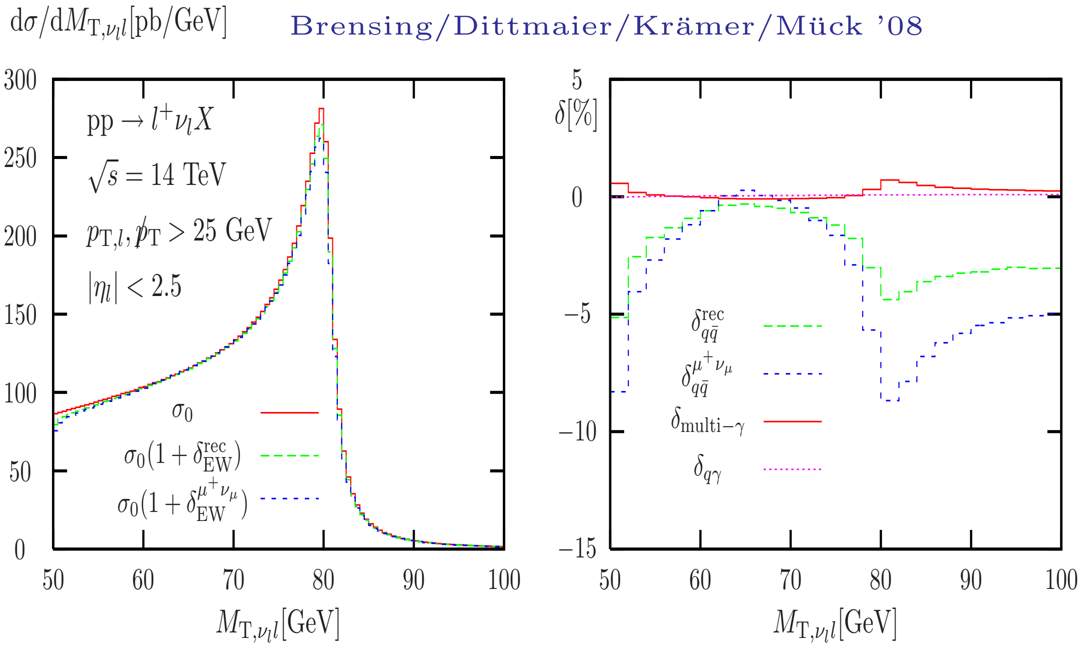
Recent progress on theory side (talk by Oleg Veretin)

- complete $\mathcal{O}(\alpha\alpha_S)$ virtual two-loop for Z production Kotikov/Kühn/Veretin '07
- must be combined with bremstrahlung counterpart

DY permits precision measurements competitive with present accuracy

- $\delta M_\mathrm{W} \sim 15\,\mathrm{MeV}$ and $\delta \sin^2(\theta_\mathrm{eff}) \sim 14\text{–}20 \times 10^{-5}$

M_W from Jacobian peak of $M_\mathrm{T}(\mathrm{W})$ distribution



NLO EW corrections

- strong distortion around peak due to $\ln(M_\mathrm{W}^2/m_l^2)$ from collinear γ
- large shift: $\delta M_\mathrm{W} \sim -170\,\mathrm{MeV}$ in μ channel Carloni Calame et.al. '06;

Multiple-γ emission

- parton shower Carloni Calame et.al. '06 or QED resummation Brensing/Dittmaier/Krämer/Mück '08
- shift: $\delta M_\mathrm{W} \sim 10\,\mathrm{MeV}$ in μ channel Carloni Calame et.al. '06;

Combination of EW and QCD

- EW $\otimes$ HERWIG QCD shower (HORACE) Vicini et. al. '07;Balossini et. al. '07
- Complete $\mathcal{O}(\alpha\alpha_S)$ corrections?

pp $\to \nu_l l^+(+\gamma)$ at $\sqrt{s} = 14\,\text{TeV}$ Les Houches procs. '06

$M_{\text{T},\nu_l l}$/GeV	50–∞	100–∞	200–∞	500–∞	1000–∞	2000–∞
σ_0/pb	2112.2(1)	13.152(2)	0.9452(1)	0.057730(5)	0.0054816(3)	0.00026212(1)
$\delta_{\mu+\nu_\mu}$/%						
DK	−2.75(1)	−5.03(2)	−7.98(1)	−14.43(1)	−21.99(1)	−32.15(1)
HORACE	−2.77(1)	−5.08(1)	−8.01(1)	−14.44(1)	−21.99(1)	−32.16(1)
SANC	−2.76(2)	−5.06(2)	−7.96(2)	−14.41(2)	−21.94(2)	−32.12(2)
WGRAD	−2.69(1)	−4.84(1)	−7.96(1)	−14.48(1)	−22.03(1)	−32.3(1)

High-energy tail of $M_\text{T}(W)$ distribution

- large NLO EW effects resulting from $\ln^2(\hat{s}/M_\text{W}^2)$
- several-percent estimated uncertainty from $\ln^4(\hat{s}/M_\text{W}^2)$ two-loop terms

Studied in great detail for the case of neutral Drell-Yan (Z/γ)

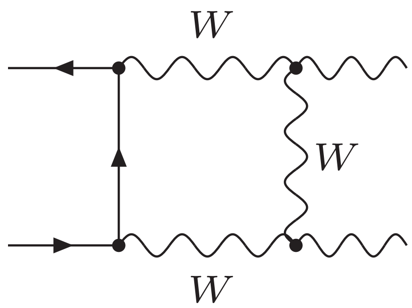
- complete calculation of two-loop $\ln(\hat{s}/M_\text{W}^2)$-terms

  Kühn/Moch/Penin/Smirnov '00-03; Jantzen/Kühn/Penin/Smirnov '04-05; Jantzen/Smirnov '06;

- estimated residual uncertainty of $\mathcal{O}(10^{-3})$

Basic properties of EW Sudakov logarithms

Origin of $\ln(Q^2/M_W^2)$



- when $Q^2 \gg M_W^2$ the Z/W bosons behave as “quasi-massless”
- coupling to external lines produce soft/collinear logarithms

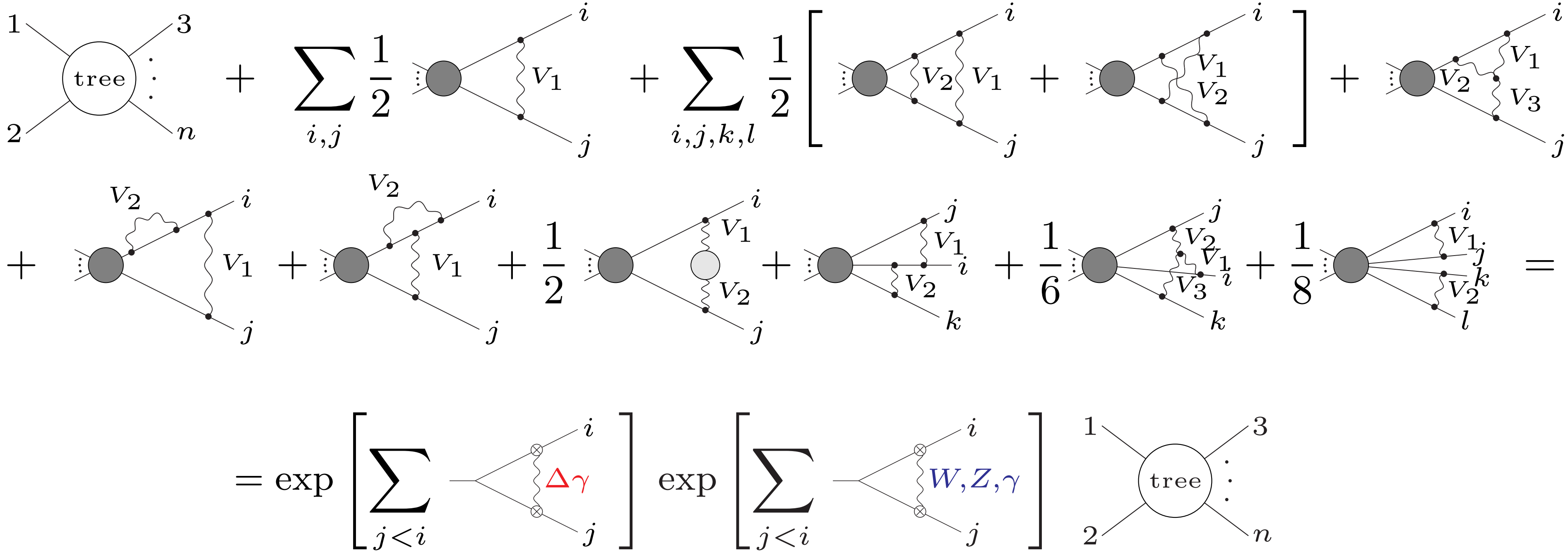
Analogies with soft/collinear singularities in QCD

- affect all hard scattering processes ($Q^2 \gg 100\,\mathrm{GeV}$) with EW interacting particles
- universality and factorization at one loop Denner, SP ’01

$$\alpha\left[C_2 \underbrace{\ln^2\left(\frac{s}{M_W^2}\right)}_{\text{soft,coll}} + C_1 \underbrace{\ln\left(\frac{s}{M_W^2}\right)}_{\text{soft,coll}} + \tilde{C}_1 \underbrace{\ln\left(\frac{s}{\mu_R^2}\right)}_{\text{UV}} + C_0\right]$$

practical consequence: compact formula for $C_2, C_1, \tilde{C}_1$, universally applicable, easy to implement into MC!

Two-loop exponentiation



Fadin/Lipatov/Martin/Melles '00; Melles '00-04; Kühn/Moch/Penin/Smirnov '00-03

Jantzen/Kühn/Penin/Smirnov '04-05 Melles/Hori/Kawamura/Kodaira '00; Beenakker/Werthenbach '00,'02;

Denner/Melles/SP '03; SP '04; Denner/Jantzen/SP '06-08;

- analogies with QCD
- simple formulae for practical applications at colliders

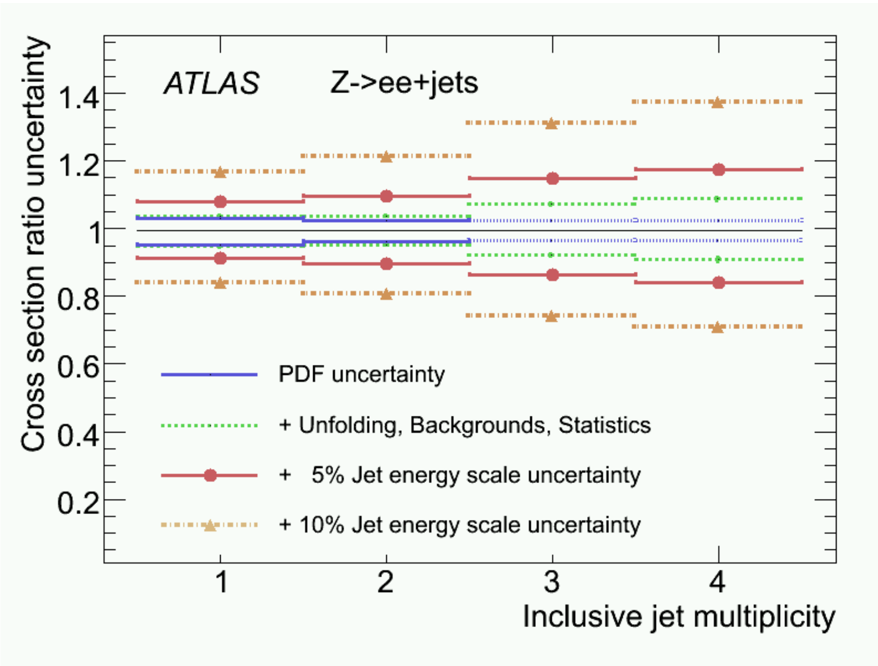
(3.2) $pp \to Vj$

ATLAS measurement of Z+jets cross section (talk by Ulla Blumenschein)

Blumenschein/Segura, Atlas Standard Model CSC Note: ATL-COM-PHYS-2008-064

Importance of $pp \to W/Z + \text{jets}$

- large BG to SM and BSM reactions
- validate/tune MC event generators



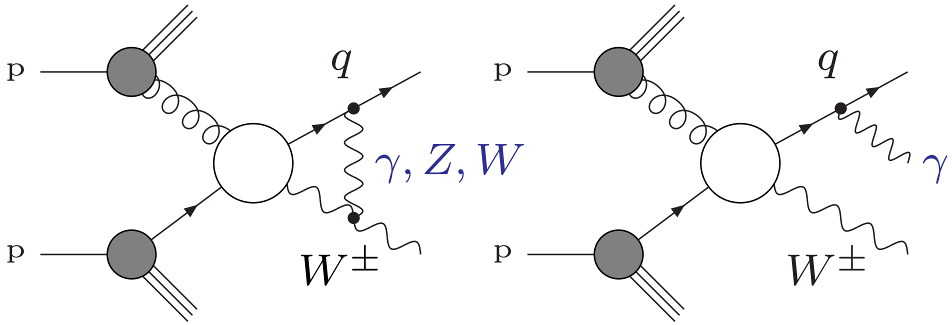
Analysis

- fully-simulated signal and background Monte Carlo samples with 1fb^{-1}
- study reconstruction of leptons and $\not{E}_T$ in multi-jet final state.
- quantify stat. and syst. uncertainties
- $1\ \text{fb}^{-1}$
- including all backgroungds (QCD,tt)
- systematics dominated by JES-uncertainty

Results assuming 5% JES resolution

- $\delta\sigma(pp \to Z + j) \sim 8\%$
- $\delta\sigma(pp \to Z + 4j) \sim 15\%$

EW corrections to pp→Wj



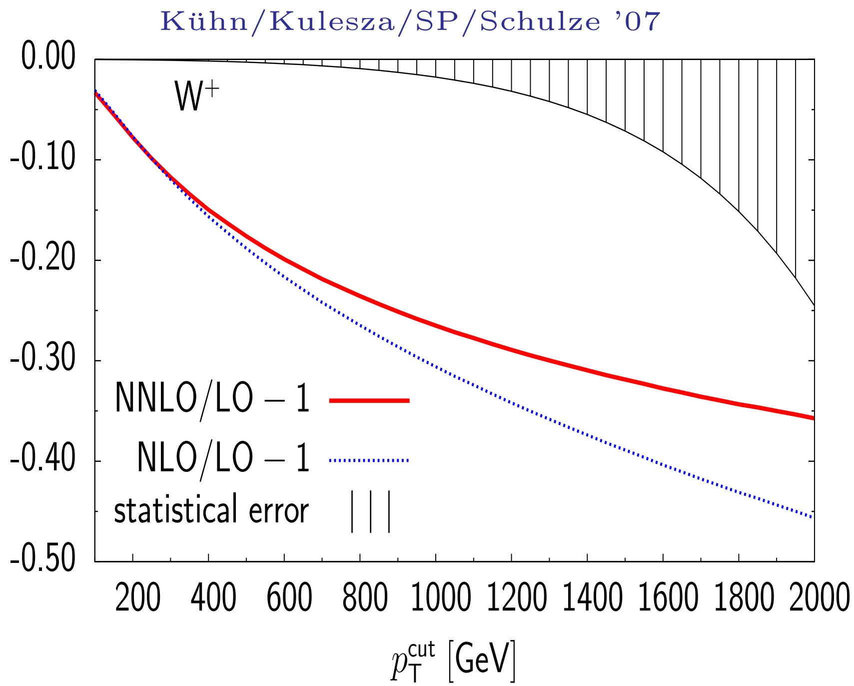
Two independent calculations

- NLO EW + dominant two-loop

  Kühn/Kulesza/SP/Schulze '07

- NLO EW + photon-induced processes

  Hollik,Kasprzik,Kniehl '07



One- and two-loop corrections to p_T distribution

- $-27\% + 3\% = -24\%$ at $p_T \sim 1$ TeV
- $-42\% + 9\% = -33\%$ at $p_T \sim 2$ TeV

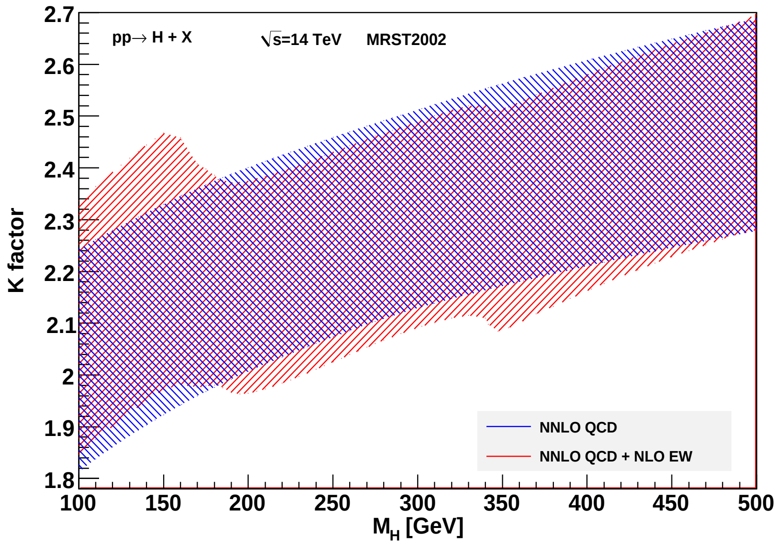
Two-loop $\simeq$ experimental error!

Two-loop EW corrections to pp(gg) → H

(talk by Sandro Uccirati Actis/Passarino/Sturm/Uccirati 0809.1301 [hep-ph], 0809.3667 [hep-th])

Calculation

- all fermionic and bosonic diagrams
- exact M_{H}-,m_{t}-,M_{W}-,M_{Z}-dependence (previous results based on $M_{\mathrm{H}}/M_{\mathrm{W}}$-expansion)
- consistent description of W → WW threshold (complex-mass scheme)



NNLO plus two-loop EW result

- combined with HNNLO code Catani/Grazzini '07-'08
- NNLO predictions shifted by [-2%,+6%]
- largest effect around WW threshold

Conclusions

QCD for multi-particle processes

- excellent LO tools
- NLO pushed up to $2 \to 3$ and will soon break the $2 \to 4$ barrier thanks to lot of theoretical progress

QCD at NNLO

- major progress from inclusive to differential $2 \to 1$ predictions
- good prospects for $2 \to 2$

EW corrections

- NLO studied for various $2 \to 2$ reactions important for benchmark measurements
- large effects in lepton distributions and high-p_{T} regions can require higher orders

The theoretical expertise within the Helmholtz Alliance is providing major contributions in all these areas