Recent Developments In Theory

Stefan Dittmaier
Albert-Ludwigs-Universität Freiburg

Particle theory in the Helmholtz Alliance "Physics at the Terascale"

Lines of research reflected in the position description of the Theory Fellows:

- Precision calculations for high-energy colliders
- New physics – construction and phenomenological studies of models
- Monte Carlo event generators / tools – support and development

$\hookrightarrow$ Large variety of theoretical studies by Alliance member institutes / universities:

- (non-)Higgs phenomenology — Bonn, Freiburg, Hamburg, KIT, Mainz, MPI, RWTH, Siegen, Wuppertal
- SUSY phenomenology — Bonn, Dresden, Freiburg, MPI, RWTH, Würzburg
- Top-quark physics — DESY, Hamburg, HUB, KIT, Mainz, MPI, RWTH
- High-energy flavour physics — DESY, Dortmund, KIT, Mainz, RWTH, Siegen
- Identified hadrons at high energies and DIS — DESY, Hamburg, Mainz

...

. . .   (*incomplete* list continued)   . . .

- EW precision calculations — DESY, Freiburg, Hamburg, HUB, KIT, MPI, RWTH, Würzburg
- Two- and multi-loop calculations
  DESY, Hamburg, KIT, Mainz, Siegen, Wuppertal, Würzburg
- NLO multi-leg techniques, computations, and automation
  DESY, Freiburg, KIT, MPI, RWTH, Wuppertal
- IR structure of QCD, NNLO subtraction, QCD resummations
  Hamburg, Mainz, RWTH
- Monte Carlo generators (Helac/Phegas, Herwig, Sherpa, Whizard)
  Dresden, Freiburg, KIT, Siegen, Wuppertal, Würzburg
- Parton showers — KIT, Mainz, RWTH
- PDFs — DESY, Dortmund, Freiburg
- New-physics (non-SUSY) models and studies
  Bonn, DESY, Freiburg, Hamburg, KIT, RWTH, Würzburg
- Astroparticle physics / cosmology
  Bonn, DESY, MPI

$\Rightarrow$ Broad alliance activities at the research frontier

Intention of the talk:

- no comprehensive overview, but
- illustration of some selected topics from the area "precision calculations"
  $\hookrightarrow$ motivation ("why"), techniques / concepts ("how"), recent results ("what")

Contents

Results from ...

... the multi-loop frontier (Jet event shapes and Higgs-boson production)

... the multi-leg frontier (NLO QCD predictions for ttbb production at the LHC)

Concluding remarks

Disclaimer:
The selection of topics is certainly subjective and in part due to the organizers who selected me as a speaker.
Any omission of related work or citations is not intentional. I declare that I tried my best...

Results from the multi-loop frontier

1. Jet event shapes

Jet event-shape observables at e^+e^- colliders

- characterize the topology of hadronic events
  without referring to details of the hadronic particle content
- allow for crucial tests of jet dynamics predicted by QCD
- sensitive to $\alpha_s(Q)$ at variable scale $Q = \sqrt{s}$

α_s from hadronic event shapes — status 2006

Bethke '06

Q[GeV]	$\alpha_s(M_Z)$	Δ_{EXP}	Δ_{TH}
14.0	$0.120\ ^{+0.010}_{-0.008}$	0.002	$^{+0.009}_{-0.008}$
22.0	$0.118\ ^{+0.009}_{-0.008}$	0.003	$^{+0.009}_{-0.007}$
35.0	$0.123\ ^{+0.008}_{-0.006}$	0.002	$^{+0.008}_{-0.005}$
44.0	$0.123\ ^{+0.008}_{-0.006}$	0.003	$^{+0.007}_{-0.005}$
58.0	0.123 ± 0.007	0.003	0.007

Q[GeV]	$\alpha_s(M_Z)$	Δ_{EXP}	Δ_{TH}
91.2	0.121 ± 0.006	0.001	0.006
133	0.120 ± 0.007	0.003	0.006
161	0.118 ± 0.008	0.005	0.006
172	0.114 ± 0.008	0.005	0.006
183	0.121 ± 0.006	0.002	0.005
189	0.121 ± 0.005	0.001	0.005
195	0.122 ± 0.006	0.001	0.006
201	0.124 ± 0.006	0.002	0.006
206	0.124 ± 0.006	0.001	0.006

Note: $\Delta_{TH} > \Delta_{EXP}$

with TH $=$ QCD NLO$\oplus$resummations

$\hookrightarrow$ high motivation for recent QCD calculations at NNLO and NNLL

Gehrmann et al. '07–'09; Weinzierl '08,'09; Becher, Schwartz '08

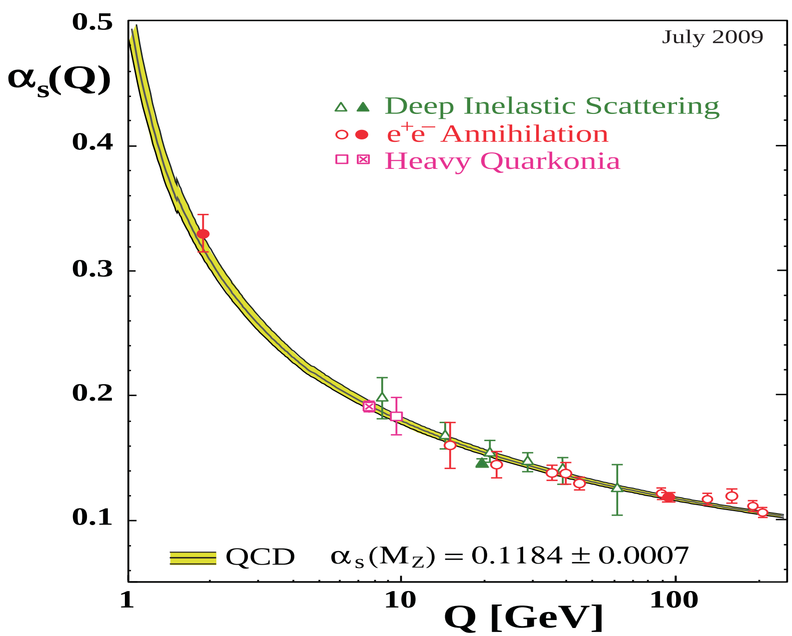
Jet event shapes and α_s determination in 2009

Bethke '09

Process	Q[GeV]	$\alpha_s(Q)$	$\alpha_s(M_Z)$	excl. mean $\alpha_s(M_Z)$	std. dev.
τ-decays	1.78	0.330 ± 0.014	0.1197 ± 0.0016	0.11818 ± 0.00070	0.9
DIS [F_2]	$2-15$	–	0.1142 ± 0.0023	0.11876 ± 0.00123	1.7
DIS [ep $\to$ jets]	$6-100$	–	0.1198 ± 0.0032	0.11836 ± 0.00069	0.4
$Q\overline{Q}$ states	7.5	0.1923 ± 0.0024	0.1183 ± 0.0008	0.11862 ± 0.00114	0.2
Υ decays	9.46	$0.184^{+0.015}_{-0.014}$	$0.119^{+0.006}_{-0.005}$	0.11841 ± 0.00070	0.1
e^+e^- [jets&shps]	$14-44$	–	0.1172 ± 0.0051	0.11844 ± 0.00076	0.2
e^+e^- [ew]	91.2	0.1193 ± 0.0028	0.1193 ± 0.0028	0.11837 ± 0.00076	0.3
e^+e^- [jets&shps]	$91-208$	–	0.1224 ± 0.0039	0.11831 ± 0.00091	1.0

World average:

$$\alpha_s(M_Z) = 0.1184 \pm 0.0007$$



Theory prediction for jet event shapes ($e^+e^- \to n\,\text{jets},\ n \geq 3$)

$$y \;=\; \text{thrust } T \;=\; \max_{\vec{n}} \sum_i |\vec{p}_i \cdot \vec{n}| \,/\, \sum_i |\vec{p}_i|, \quad \text{etc.}$$

$$\frac{1}{\sigma_{\text{had}}}\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y} \;=\; \underbrace{\alpha_s\, C^{\text{QCD}}_{\text{LO}} + \alpha_s^2\, C^{\text{QCD}}_{\text{NLO}}} \;+\; \underbrace{\alpha_s^3\, C^{\text{QCD}}_{\text{NNLO}}}$$

R.K.Ellis, Ross, Terrano '81; Kunszt '81
Vermaseren, Gaemers, Oldham '81
Giele, Glover '92; Catani, Seymour '96

Gehrmann-DeRidder, Gehrmann,
Glover, Heinrich '07–'09; Weinzierl '08,'09

$+$ NLL resummation $+$ NLL/NNLO matching ($+$ NNLL resummation for T)

NLL resummation: Catani, Turnock, Webber, Trentadue '91,'93

NLL/NNLO matching: Gehrmann, Luisoni, Stenzel '08

NNLL resummation for T: Becher, Schwartz '08

$+$ non-perturbative hadronization effects

Korchemsky, Sterman '95; Dokshitzer, Webber '95,'97
Dokshitzer, Lucenti, Marchesini, Salam '98

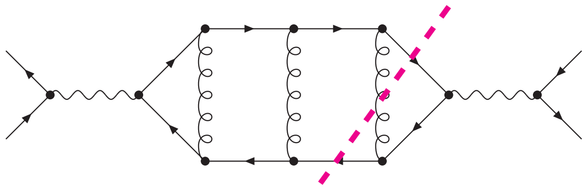
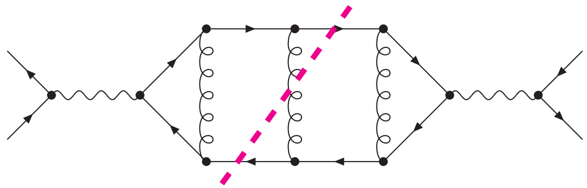
$$+\; \underbrace{\alpha\, C^{\text{EW}}_{\text{LO}} + \alpha\alpha_s\, C^{\text{EW}}_{\text{NLO}} + \alpha^2\alpha_s\, C^{\text{ISR}}_{\text{LL}}}$$

Denner, S.D., Gehrmann, Kurz '09
(partial results from Carloni-Calame, Moretti, Piccinini, Ross '08)

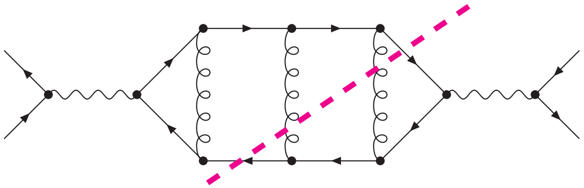
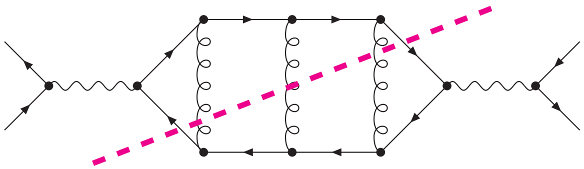
Recent NNLO QCD results already included in α_s fit to event shapes
Gehrmann, Luisoni, Stenzel '08; Dissertori et al. '08; Bethke et al. '08; Davison, Webber '08

General structure of $e^+e^- \to 3\text{jets}$ at NNLO QCD

$$\Delta\sigma_{\text{NNLO}} = F_{\text{flux}} \int d\Phi_3 \left[2\,\text{Re}\left\{ \mathcal{M}^{(2\to3)}_{\text{2-loop}} \mathcal{M}^{(2\to3)*}_{\text{tree}} \right\} + \left| \mathcal{M}^{(2\to3)}_{\text{1-loop}} \right|^2 \right]$$

$$+ F_{\text{flux}} \int d\Phi_4 \, 2\,\text{Re}\left\{ \mathcal{M}^{(2\to4)}_{\text{1-loop}} \mathcal{M}^{(2\to4)*}_{\text{tree}} \right\} + F_{\text{flux}} \int d\Phi_5 \left| \mathcal{M}^{(2\to5)}_{\text{tree}} \right|^2$$

Major difficulties:

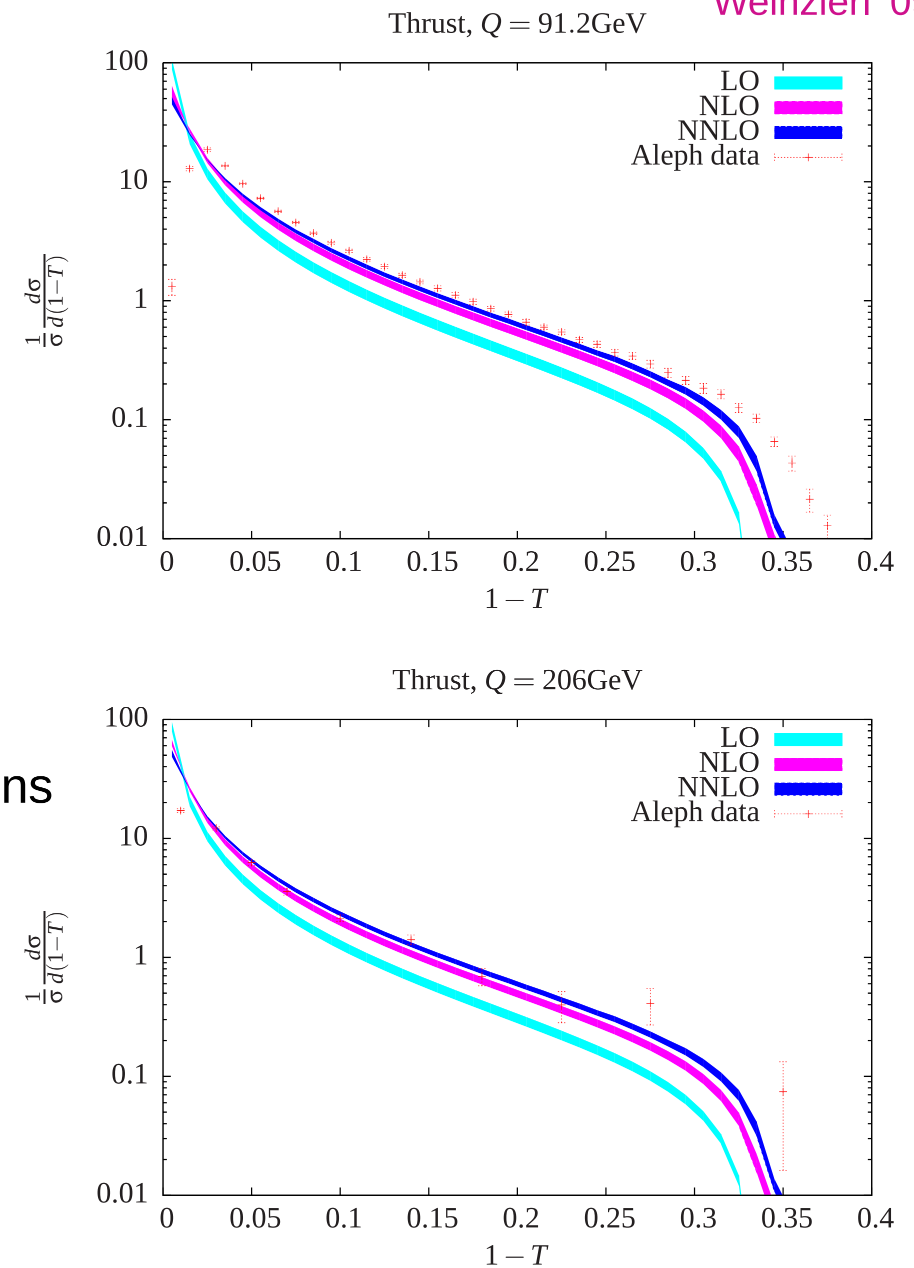
- 2-loop amplitudes $\mathcal{M}^{(2\to3)}_{\text{2-loop}}$ Garland, Gehrmann, Glover, Koukoutsakis, Moch, Remiddi, Uwer, Weinzierl '02
- extraction and cancellation of IR (soft / collinear) singularities
  $\hookrightarrow$ in particular: single and double unresolved limits in real emission amplitudes
  Weinzierl, Kilgore, Frixione, Grazzini, Gehrmann-DeRidder, Gehrmann, Glover, Heinrich, Del Duca, Somogyi, Trocsanyi, Catani '03–'09

Thrust distribution at LEP in NNLO QCD

Weinzierl '09

- reduction of scale dependence
  in LO $\longrightarrow$ NLO $\longrightarrow$ NNLO
  $\hookrightarrow$ reduction of theoretical uncertainty in α_s fit

- further corrections, not included in plots on rhs:
  - ◇ improvements via resummations (available up to NLL and NLL)
  - ◇ hadronization effects
  - ◇ electroweak corrections (available up to NLO)

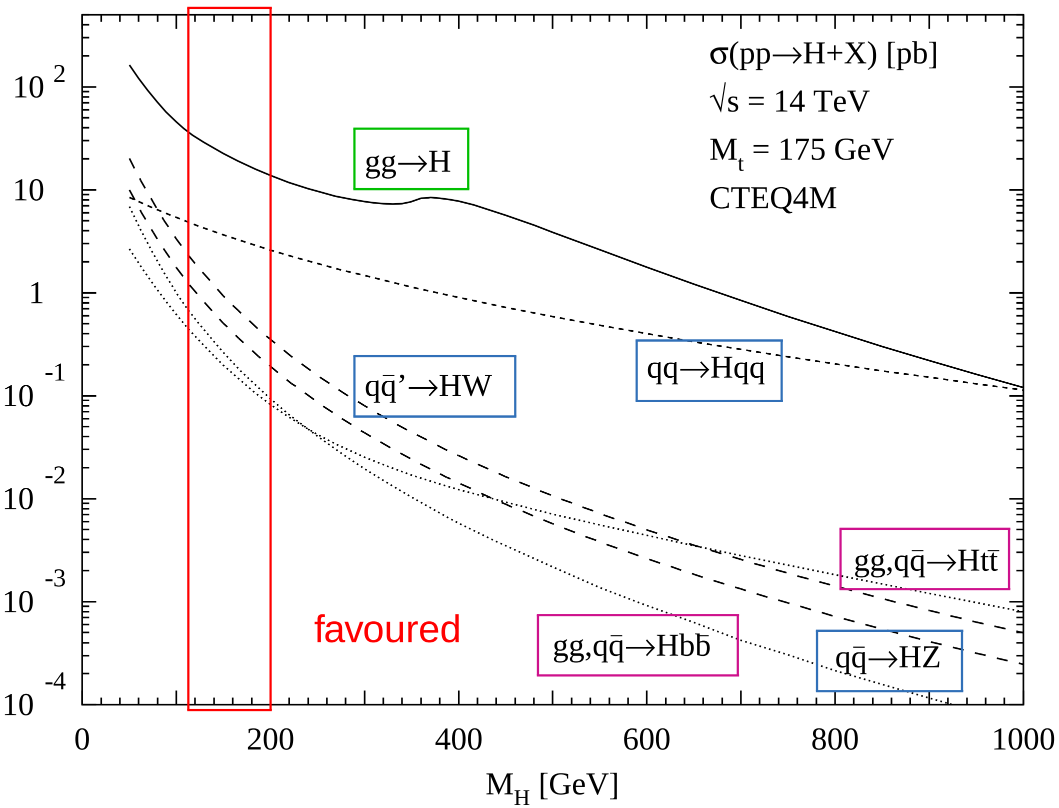


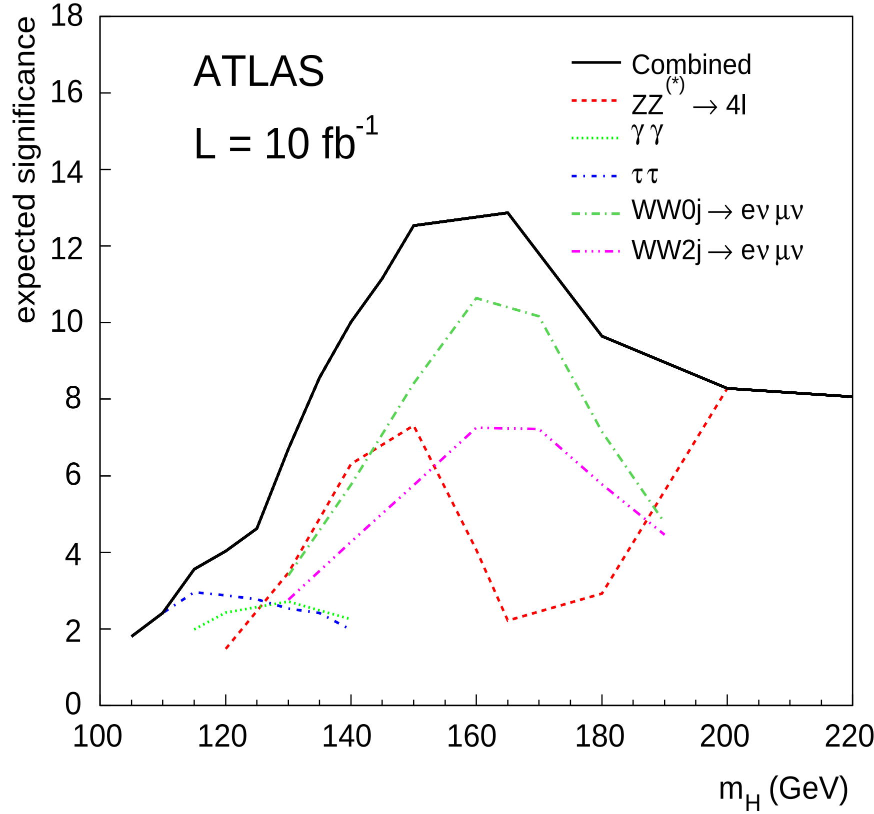
Results from the multi-loop frontier

2. Higgs-boson production

Cross sections and significance of the Higgs signal at the LHC

(not only) Spira et al.





Typical size of perturbative corrections at next-to-leading order (NLO):

QCD: $\mathcal{O}(\alpha_s) \sim 10{-}100\%$ Electroweak: $\mathcal{O}(\alpha) \sim 10\%$

$\hookrightarrow$ calculate / control higher orders to reduce theoretical uncertainty down to the level of PDF ($q\bar{q} \sim 5\%$, $gg \sim 5{-}10\%$) and experimental uncertainties

Complication: task requires "multi-loop" or "multi-leg" computations

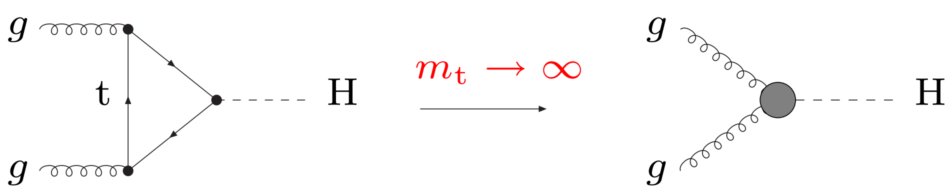
A multi-loop example: Higgs-boson production via gluon fusion at the LHC

- QCD corrections:
  - ◇ complete NLO correction known
    Graudenz, Spira, Zerwas ’93
    Djouadi, Graudenz, Spira, Zerwas ’95
  - ◇ NNLO correction known as expansion for $m_{\mathrm{t}} \to \infty$ matched with $\hat{s} \to \infty$

$$K = \frac{\sigma_{\mathrm{NNLO}}}{\sigma_{\mathrm{LO}}} \sim 2.0$$

Harlander, Kilgore ’01,’02
Catani, de Florian, Grazzini ’01
Anastasiou, Melnikov ’02
Ravindran, Smith, v.Neerven ’03,’04
Anastasiou, Melnikov, Petriello ’04
Marzani et al. ’08
Pak, Rogal, Steinhauser ’09
Harlander, Ozeren ’09

  - ◇ resummations / virtual / soft terms to NNNLO in limit $m_{\mathrm{t}} \to \infty$

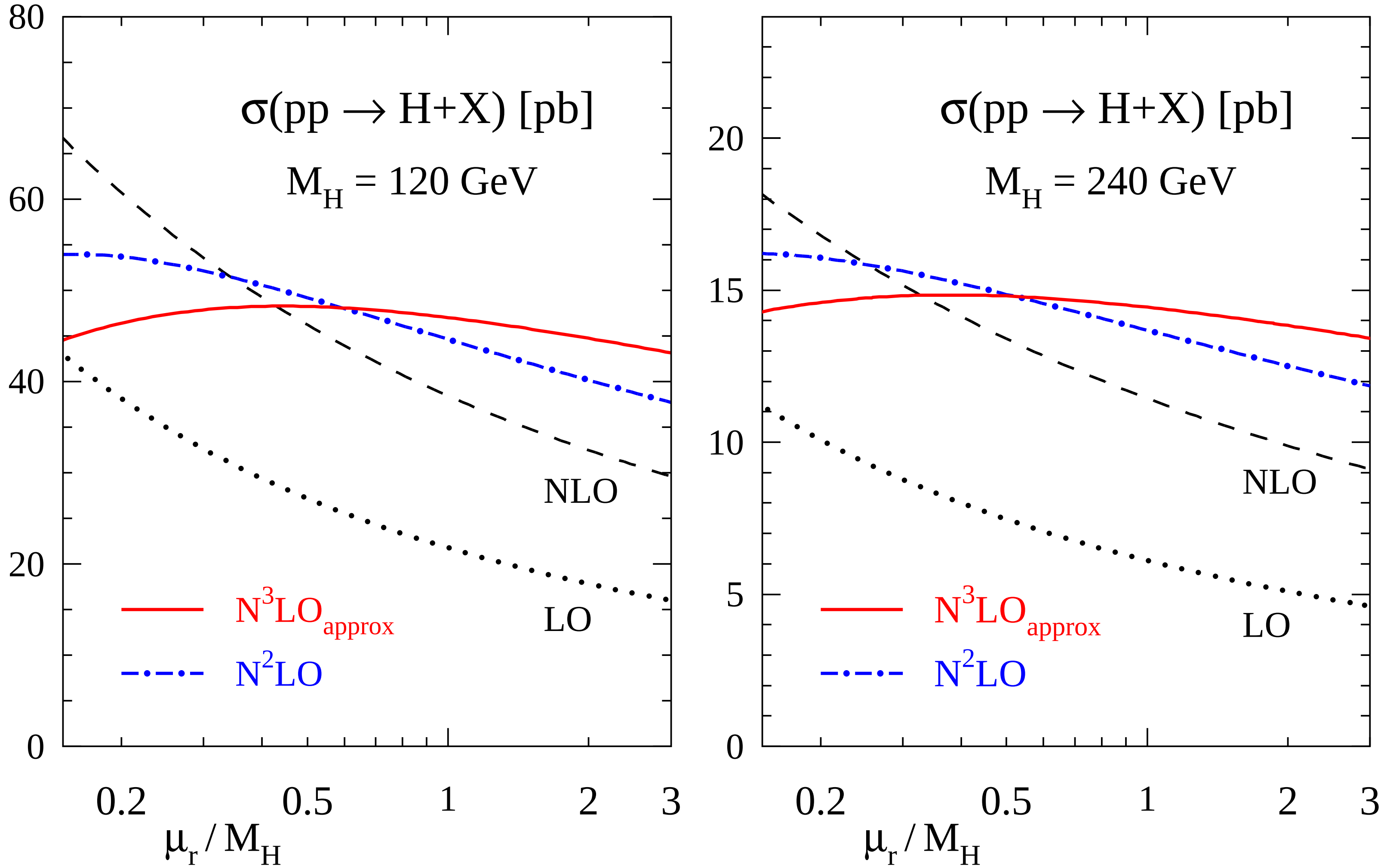


Catani et al. ’03; Moch, Vogt ’05
Laenen, Magnea ’05; Idilbi, Ji, Ma, Yuan ’05
Ravindran ’05,’06; Ravindran, Smith, v.Neerven
Ahrens, Becher, Neubert, Yang ’08

- EW corrections
  - ◇ complete NLO correction known $\sim \mathcal{O}(5\%)$
    Aglietti, Bonciani, Degrassi, Vicini ’04,’06
    Degrassi, Maltoni ’04
    Actis, Passarino, Sturm, Uccirati ’08
  - ◇ mixed $\mathcal{O}(\alpha\alpha_{\mathrm{s}})$ corrections for small M_{H}
    Anastasiou, Boughezal, Petriello ’08

QCD scale dependence of predictions for inclusive $gg \to \mathrm{H}$

Moch, Vogt '05



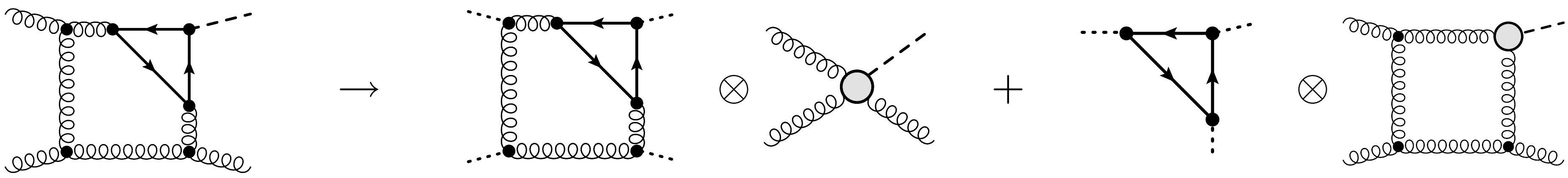
Reduction of renormalization-scale dependence with increasing orders !

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

Recent error estimate with MSTW2008 NNLO: $\delta_{\mathrm{PDF}} \lesssim 3\%$ de Florian, Grazzini '09

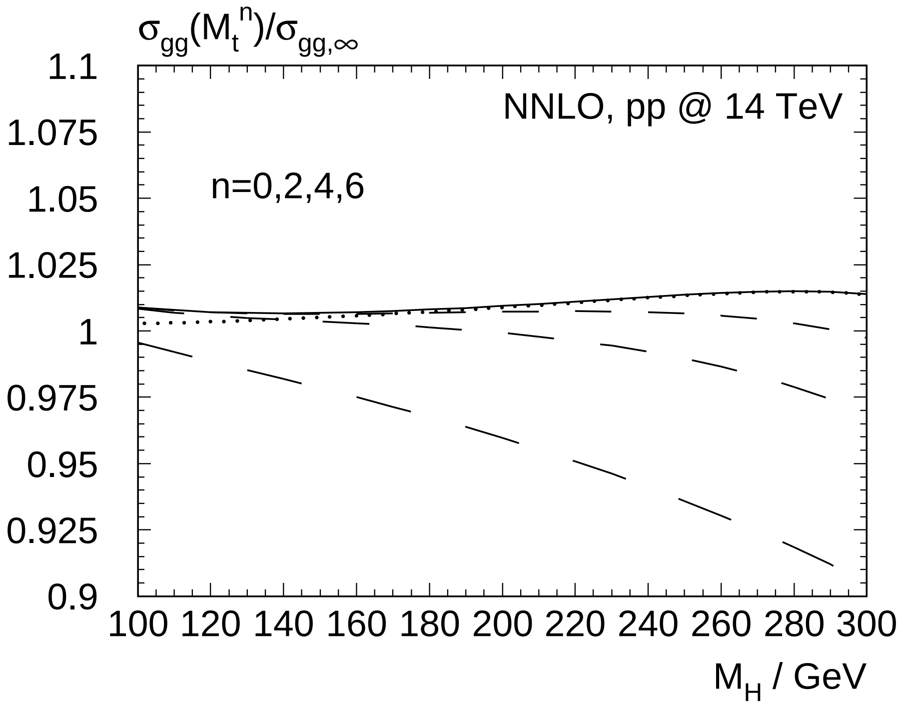
Improved $1/m_t$ expansion at NNLO QCD Harlander, Ozeren '09

Heavy-top expansion (here illustrated for real–virtual part of NNLO)



with proper matching of the soft ($\hat{s} \to M_H^2$) and high-energy ($\hat{s} \to \infty$) limits
Marzani et al. '08

yields full m_t dependence of cross section within $\mathcal{O}(0.5\%)$:



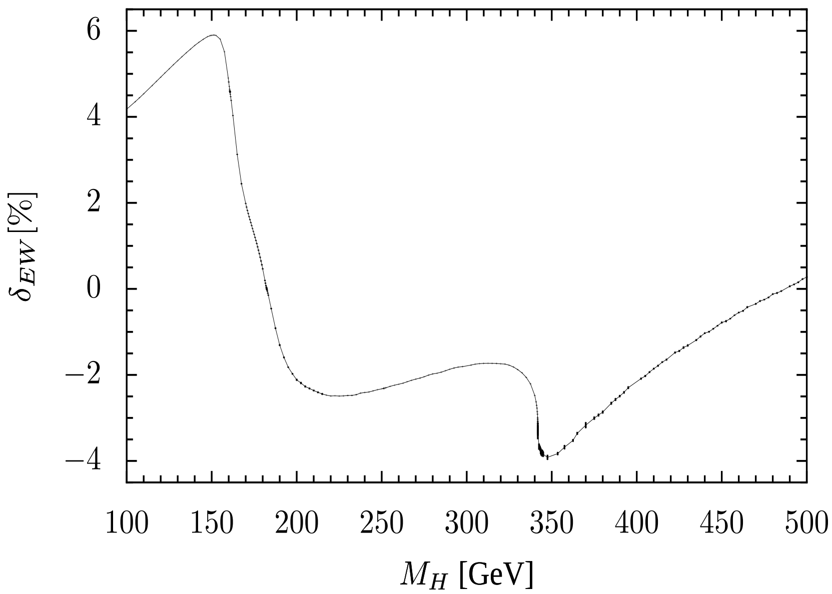
$\sigma_{gg,\infty}$ = pure $m_t \to \infty$ limit for NNLO part

$\sigma_{gg}(M_t^n)$ includes NNLO terms of $\mathcal{O}(1/m_t^n)$
(dashes: $n = 0, 2, 4$; solid line: $n = 6$)

NLO EW corrections

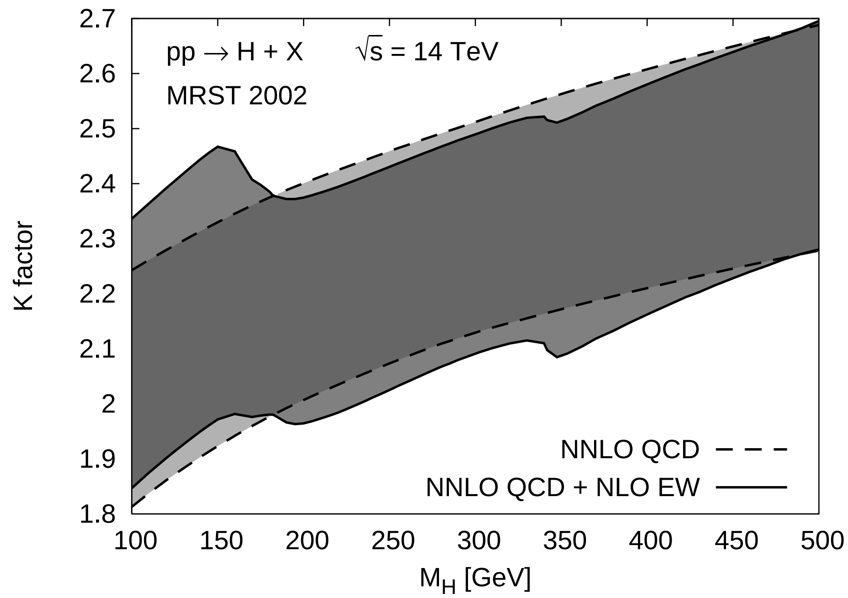
Actis, Passarino, Sturm, Uccirati '08

Correction to partonic cross section:

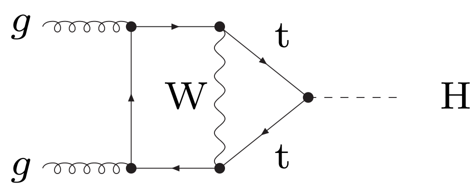


K factors for pp cross section:

(band width: $M_\mathrm{H}/2 < \mu_{\mathrm{R/F}} < 2M_\mathrm{H}, \quad \mu_\mathrm{R}/2 < \mu_\mathrm{F} < 2\mu_\mathrm{R}$)



EW corrections ...



etc.

- matter at the 5% accuracy level
- show non-trivial structures near WW, ZZ, $\mathrm{t\bar{t}}$ thresholds

  $\hookrightarrow$ finite widths of particles in loops required (otherwise unphysical peaks)
- mixed $\mathcal{O}(\alpha\alpha_\mathrm{s})$ corrections for small M_H Anastasiou, Boughezal, Petriello '08

  suggest factorization of QCD and EW corrections within good accuracy

Results from the multi-leg frontier

$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$ **at NLO QCD**

At the LHC the background to some signals probably cannot be measured !

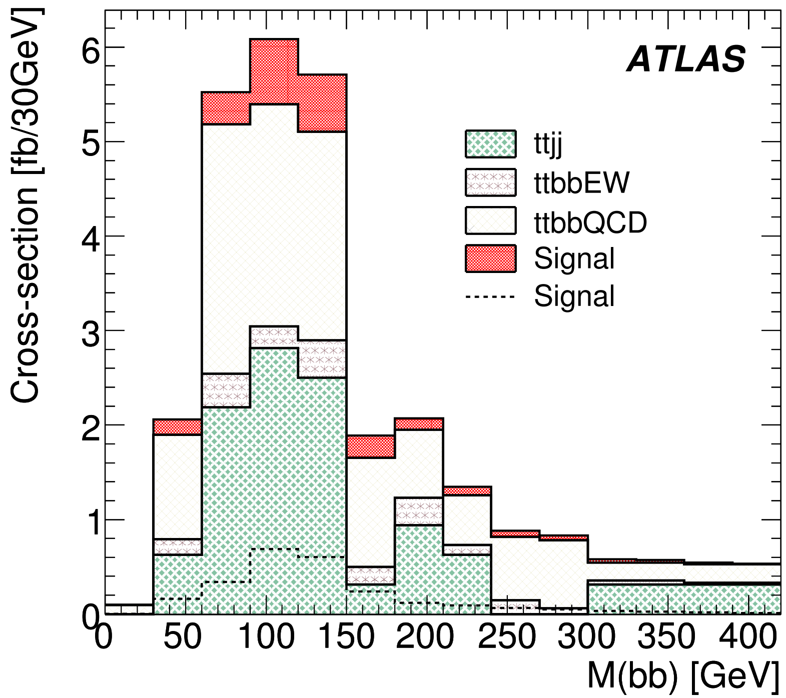
$\hookrightarrow$ precise predictions for many "multi-leg" background processes required

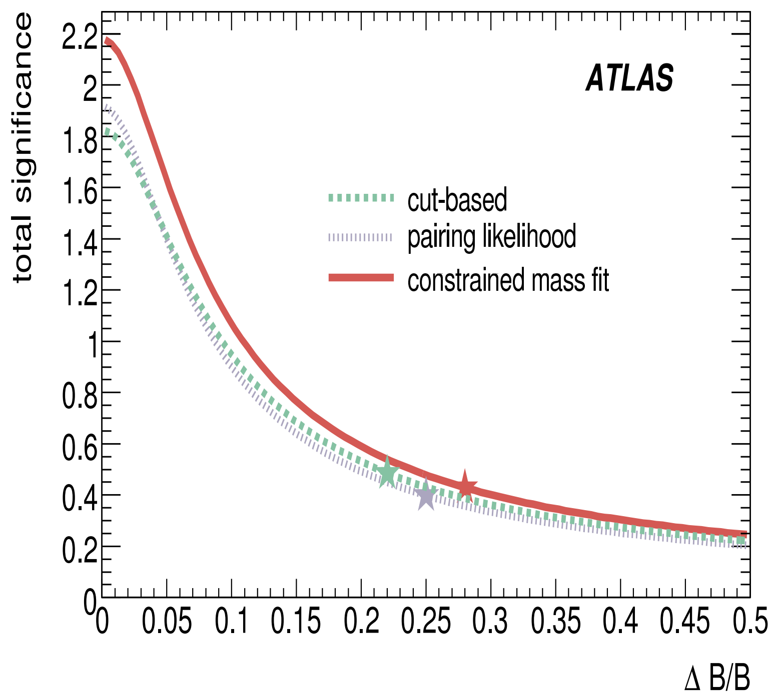
Examples for important missing NLO predictions for background:

	background for	"Les Houches wishlist '05"
$pp \to VV + jet$	$t\bar{t}H$, new physics	
WW+jet: S.D., Kallweit, Uwer '07,'09; Campbell, R.K.Ellis, Zanderighi '07; Binoth et al. (in progress) Wγ+jet: Campanario, Englert, Spannowsky, Zeppenfeld '09		
$pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$	
Bredenstein, Denner, S.D., Pozzorini '08,'09; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09		
$pp \to t\bar{t} + 2jets$	$t\bar{t}H$	
$pp \to VVb\bar{b}$	VBF $\to H \to VV$, $t\bar{t}H$, new physics	
$pp \to VV + 2jets$	VBF $\to H \to VV$	
VBF: Jäger et al. '06,'09; Bozzi et al. '07		
$pp \to V + 3jets$	$t\bar{t}$, new physics	
W+3jets: R.K.Ellis, Melnikov, Zanderighi '09; Berger et al. '09		
$pp \to VVV$	SUSY tri-lepton	
Lazopoulos et al. '07; Binoth, Ossola, Papadopoulos, Pittau '08; Hankele, Zeppenfeld '08		
$pp \to b\bar{b}b\bar{b}$	Higgs and new physics	(added 2007)
$q\bar{q}$: Binoth, Greiner, Guffanti, Guillet, Reiter, Reuter '09		

$\hookrightarrow$ Many long-termed NLO calculations for theorists !
(several 10^4 diagrams, many "(wo)men-decades")

Signal and background for $t\bar{t}H(\rightarrow b\bar{b})$ at ATLAS "CSC book",CERN-OPEN-2008-020





- low signal/background ratio:
  $S/\sqrt{B} = 1.8{-}2.2$ without systematic errors for $M_{\rm H} = 120\,{\rm GeV}$ and $L = 30\,{\rm fb}^{-1}$
  $\hookrightarrow$ background uncertainty $\Delta B/B$ kills significance (see plot on r.h.s.)
  $\hookrightarrow$ challenge for theory, NLO indispensible, but still further tricks required!

- particularly problematic:
  - ◇ shapes of signal and background similar
  - ◇ large combinatorial background from $b\bar{b}$ misassignment

Complications in NLO corrections to many-particle processes:

- huge amount of algebra, long final expressions

  $\hookrightarrow$ computer algebra / automation / new “unitarity-based” techniques

- multi-dimensional phase-space integration

  $\hookrightarrow$ Monte Carlo techniques, e.g. multi-channel

- complicated structure of singularities and matching of virtual and real corrections

  $\hookrightarrow$ subtraction and slicing techniques

- numerically stable evaluation of one-loop integrals with up to 5,6,. . . external legs

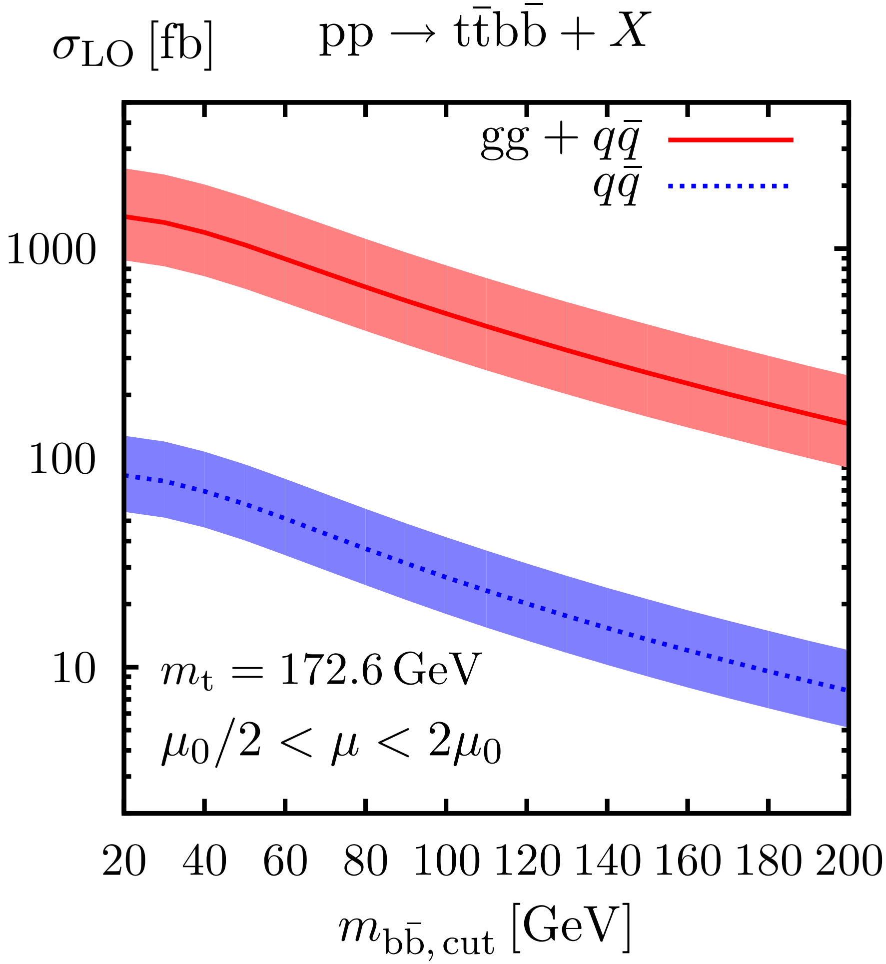
  $\hookrightarrow$ techniques to solve problems with inverse kinematical (e.g. Gram) det’s

- treatment of unstable particles, issue of complex masses

  $\hookrightarrow$ e.g. “complex-mass scheme”

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

LO cross section as function of the lower cut on the $\mathrm{b\bar{b}}$ invariant mass:



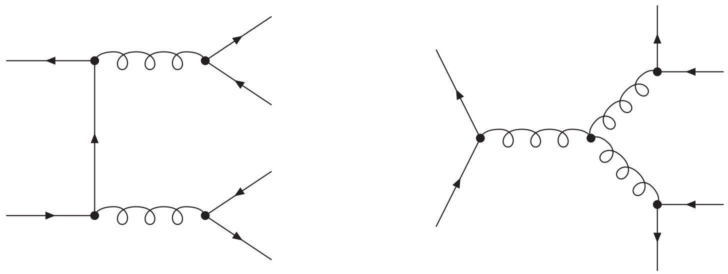
- Scale uncertainty = $\mathcal{O}(100\%)$
  $\hookrightarrow$ NLO corrections indispensible

- gg fusion strongly dominates over $q\bar{q}$ annihilation

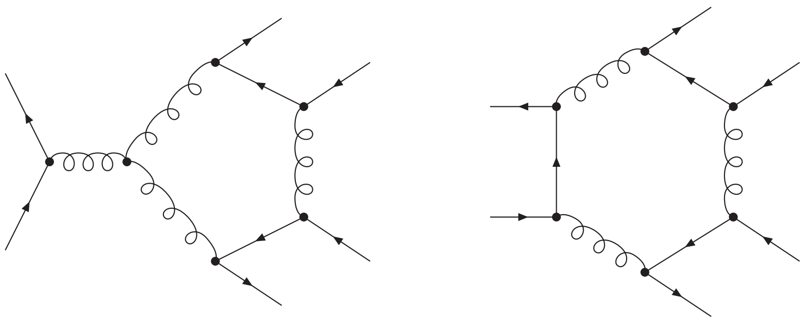
NLO QCD corrections to $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$

from $q\bar{q} \to \mathrm{t\bar{t}b\bar{b}}$ to $\mathrm{gg} \to \mathrm{t\bar{t}b\bar{b}}$

LO: 7 tree diagrams



NLO: $\mathcal{O}(200)$ diagrams
(24 pentagons, 8 hexagons)



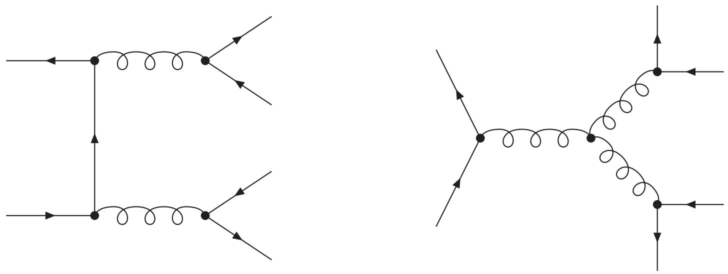
ranks of tensor loop integrals ≤ 3

$\hookrightarrow$ already tough

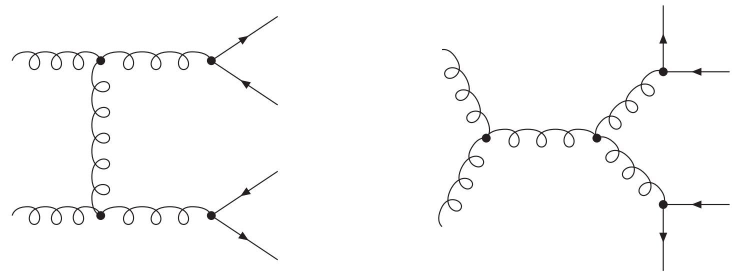
NLO QCD corrections to $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$

from $q\bar{q} \to \mathrm{t\bar{t}b\bar{b}}$ to $\mathrm{gg} \to \mathrm{t\bar{t}b\bar{b}}$

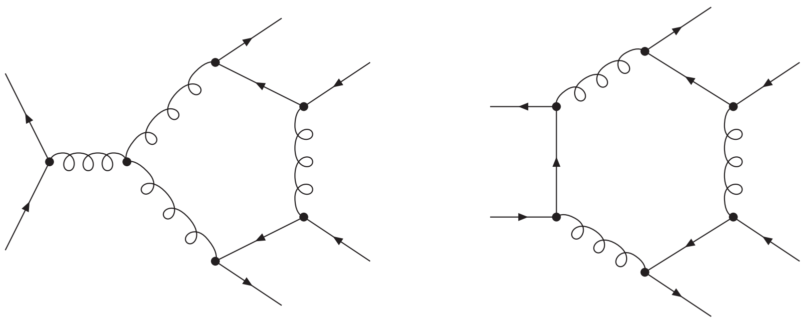
LO: 7 tree diagrams



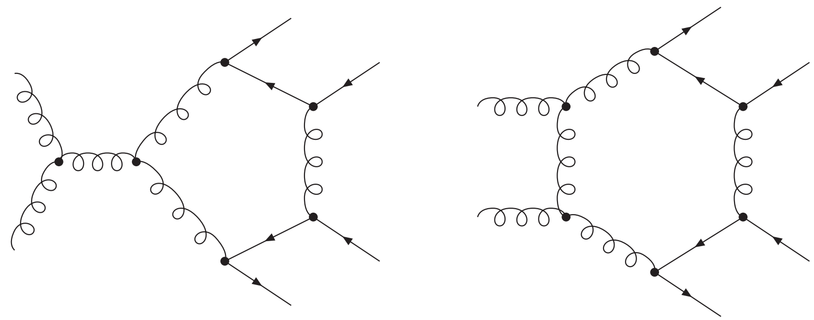
LO: 36 tree diagrams



NLO: $\mathcal{O}(200)$ diagrams
(24 pentagons, 8 hexagons)



NLO: $\mathcal{O}(\gtrsim 1000)$ diagrams
(> 100 pentagons, 40 hexagons)



ranks of tensor loop integrals ≤ 3

$\hookrightarrow$ already tough

ranks ≤ 4

$\hookrightarrow$ algebraically more complex than $q\bar{q}$ by 1–2 orders of magnitude

Calculation of loops via Feynman diagrams Bredenstein, Denner, S.D., Pozzorini '08,'09

- two independent calculations of all ingredients
- algebraic reductions done in *Mathematica*
  one of the two versions builds on *FormCalc* (Hahn, Perez-Victoria '98)

$$\mathcal{M}^{(\Gamma)}_{gg\to t\bar{t}b\bar{b}} = \underbrace{\mathcal{C}^{(\Gamma)}}_{\text{colour structure for (sub)graph }\Gamma} \sum_{k=1}^{502} \overbrace{F_k^{(\Gamma)}(\{p_i\cdot p_j\})}^{\text{invariant functions containing loop integrals}} \underbrace{\hat{\mathcal{M}}_k(\{p_i\})}_{\text{standard spinor structures}}$$

$\hat{\mathcal{M}}_1 = [\bar{u}_t \gamma^\mu \not{p}_1 \not{\epsilon}_1 \not{\epsilon}_2 v_{\bar{t}}]\,[\bar{u}_b \gamma_\mu v_{\bar{b}}]$, etc.

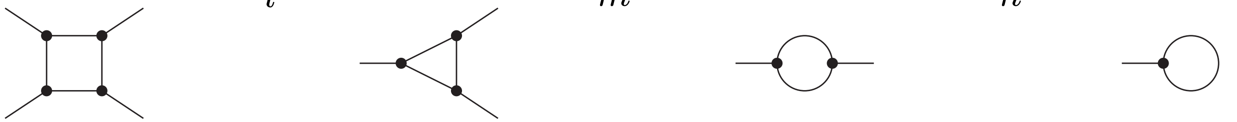
  factorization of colour structure from (sub)graph Γ
  $\hookrightarrow$ all colour channels calculated simultaneously

- loop integrals: Denner, S.D. '02,'05
  - ◇ 5-/6-point integrals directly reduced to 4-point integrals
  - ◇ 3-/4-point integrals by default reduced a la Passarino–Veltman,
    stabilization via dedicated expansion methods for small Gram determinants
- runtime for virtual corr. per point on a 3GHz processor: $\sim 10\text{ms}$ for $q\bar{q}$, $\sim 160\text{ms}$ for gg
  $\hookrightarrow$ procedure is very stable and fast

Calculation via the "OPP method" Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09

The basic idea of "unitarity-based loop methods":

$$\mathcal{M}_1 = \sum_k d_k \underbrace{D_0(k)} + \sum_l c_l \underbrace{C_0(l)} + \sum_m b_m \underbrace{B_0(m)} + \sum_n a_n \underbrace{A_0(n)} + \underbrace{R}_{\text{rational terms}}$$



D_0, C_0, B_0, A_0 = scalar one-loop integrals

d_k, c_l, b_m, a_n = algebraic coefficients determined from tree (sub)amplitudes via generalized unitarity cuts (fixed loop momentum!)

$\hookrightarrow$ efficient recursive techniques available

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

- reduction at the integrand level with *CutTools* Ossola, Papadopoulos, Pittau '07,'08
- one-loop amplitudes for fixed loop momentum via *Helac-1Loop* van Hameren, Papadopoulos, Pittau '09
- rational terms via special Feynman rules
- Monte Carlo tricks (colour sum, LO sampling with reweighting by loops)
  $\hookrightarrow$ increases efficiency a lot
- numerical stabilization via quadruple precision for problematic points

Variants of unitarity-based methods

Different groups – different applications (espcially for determining R)

- *CutTools* (Ossola, Papadopoulos, Pittau '07,'08) $\longrightarrow$ amplitudes on wishlist, VVV and $\mathrm{t\bar{t}b\bar{b}}$ cross sections
- *Rocket* (R.K.Ellis, Melnikov, Zanderighi '08,'09) $\longrightarrow$ multi-gluon amplitudes, $\mathrm{W}+3j$ cross section (leading colour)
- *BlackHat* (Berger et al. '08,'09) $\longrightarrow$ $\mathrm{W}+3j$ cross section
- Lazopoulos '08 $\longrightarrow$ multi-gluon amplitudes
- Giele, Winter '09 $\longrightarrow$ multi-gluon amplitudes

“Feynmanians”	**versus**	**“Unitarians”**
– factorial groth in # diagrams with $N =$ # of external particles		+ algebraic expense increases with power of N
+ simultaneous treatment of colour and spin channels		– algebraic work proportional to # colour and # of helicity channels
+ particle masses fully supported		• generalization to masses in progress
+ numerical stability via dedicated analytical methods		• stability enforced via multiple precision $\hookrightarrow$ works up to now, but . . .
• full automation possible		+ automation seems easier

Main achievements:

$\mathrm{e^+e^-} \to 4f$ NLO EW	$\mathrm{pp} \to \mathrm{W{+}3jets}$ NLO QCD
$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ NLO QCD	$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ NLO QCD

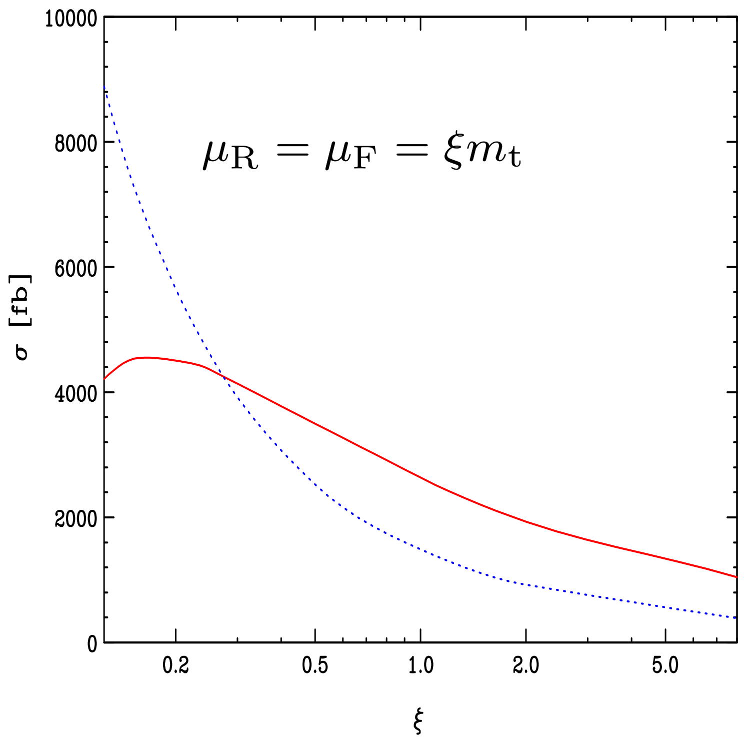
My opinion/expectations about performance:

superior for fermions/masses and not too many external legs	superior for many gluons

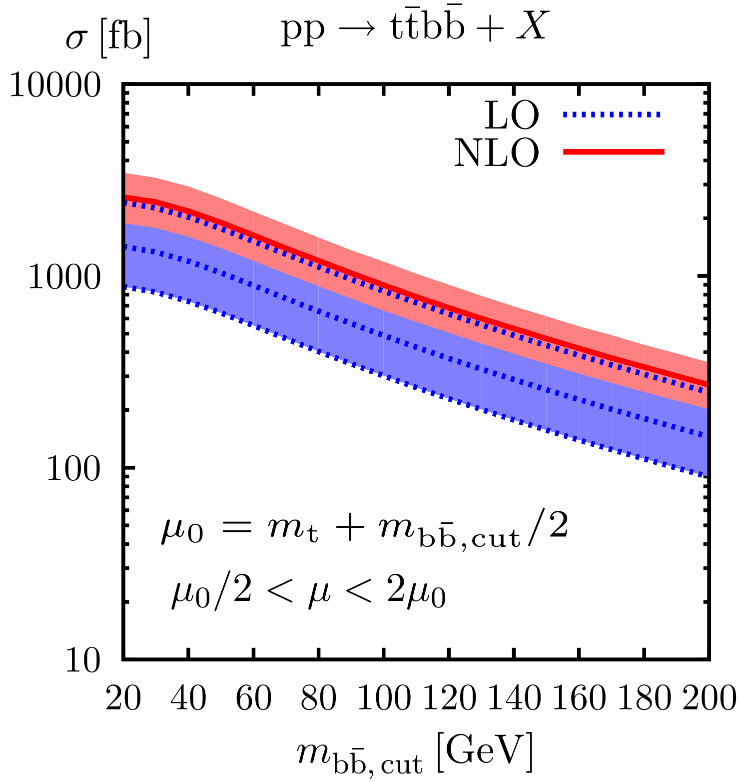
$\hookrightarrow$ For $2 \to 4$ reactions best choice depends on specific processes.

NLO QCD corrections to integrated cross sections

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09



Bredenstein, Denner, S.D., Pozzorini '09



Main results:

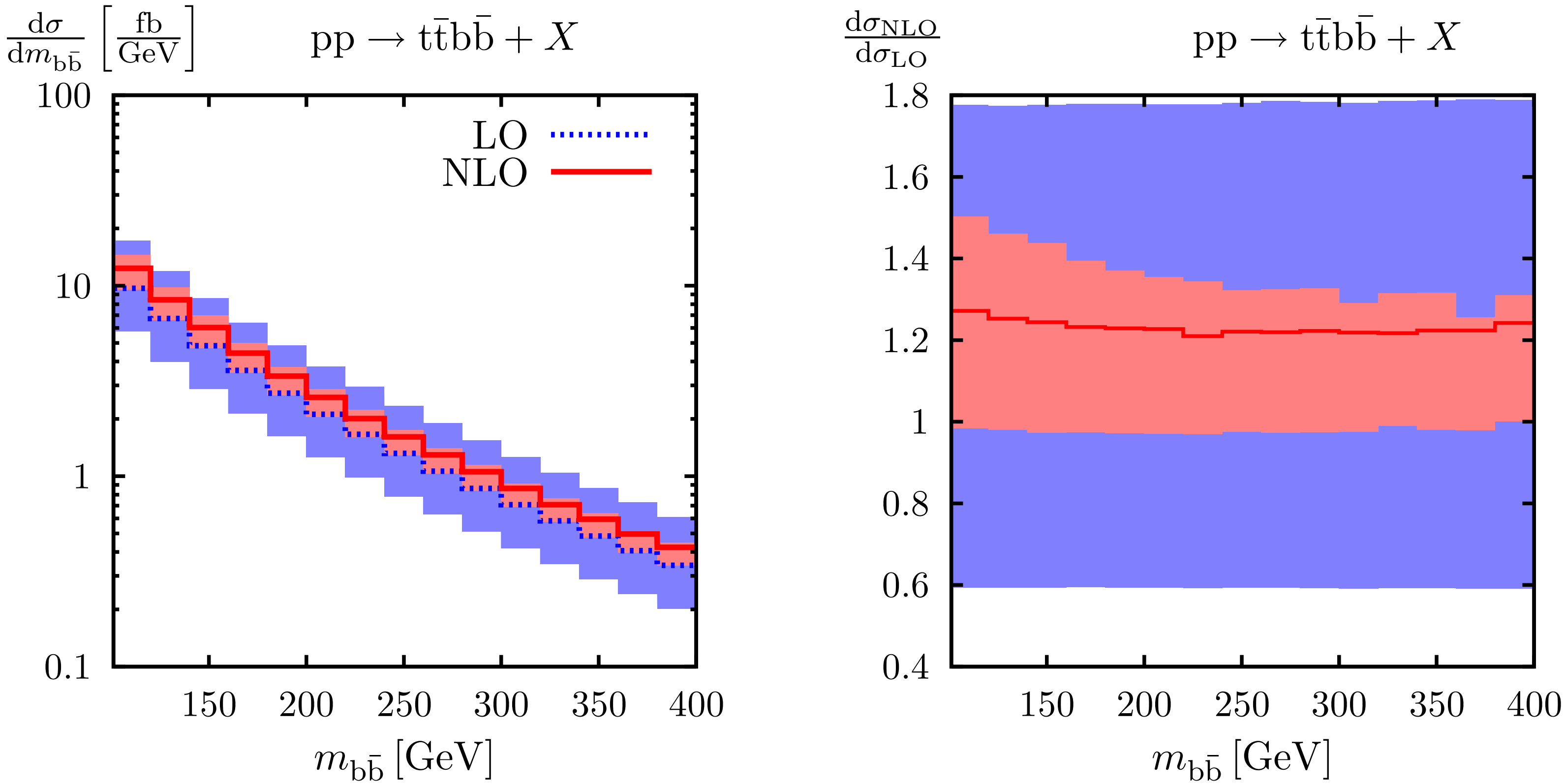
- results of the two groups agree
- correction very large at central scale $\mu_{R/F} = m_t$: $K = 1.77$
- NLO scale dependence still large: $\sim 33\%$ for $\mu_0/2<\mu_{R/F}<2\mu_0$ ($\sim 70\%$ at LO)

$\hookrightarrow$ further theoretical and/or phenomenological tricks necessary to stabilize analysis

More results on $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$

- Improvements on scale choice and selection cuts:

Bredenstein, Denner, S.D., Pozzorini '09



$\hookrightarrow$ reduced K factor ~ 1.2 and NLO scale dependence $\sim 21\%$
for new central scale $\mu_0^2 = m_\mathrm{t}\sqrt{p_{\mathrm{T,b}}\, p_{\mathrm{T,\bar{b}}}}$

- Another idea under discussion:

Butterworth et al. '08; ATL-PHYS-PUB-2009-08

fat jets containing $\mathrm{b\bar{b}}$ pairs from high-p_T Higgs (successful in WH/ZH revival!)

$\hookrightarrow$ $S/\sqrt{B} = 4.1$ for $M_\mathrm{H} = 120\,\mathrm{GeV}$ and $L = 100\,\mathrm{fb}^{-1}$ seems feasible

Plehn, Salam, Spannowsky '09

Concluding remarks

Concluding remarks

Alliance members are very active at a broad theory frontier:

- New physics
- Monte Carlo event generators / tools
- Precision calculations

$\hookrightarrow$ exemplary topics discussed in this talk:

- ◇ "multi-loop calculations" (jet event shapes, Higgs-boson production)
- ◇ "multi-leg" computations ($\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$)

Alliance provides fruitful environment for research in theory:

- Theory Fellowships and Young Investigator Groups
- support of workshop / collaborative initiatives
- LHC-D working groups / workshops and DESY Analysis Centre
- schools and VTI seminars

$\hookrightarrow$ interface between theory and experiment

Concluding remarks

Alliance members are very active at a broad theory frontier:

- New physics
- Monte Carlo event generators / tools
- Precision calculations

$\hookrightarrow$ exemplary topics discussed in this talk:

- ◇ "multi-loop calculations" (jet event shapes, Higgs-boson production)
- ◇ "multi-leg" computations ($\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$)

Alliance provides fruitful environment for research in theory:

- Theory Fellowships and Young Investigator Groups
- support of workshop / collaborative initiatives
- LHC-D working groups / workshops and DESY Analysis Centre
- schools and VTI seminars

$\hookrightarrow$ interface between theory and experiment

"Wir leben alle auf dieser Erde, aber eben auf verschiedenen Spielhälften."
(Klaus Augenthaler)