Quark-mass effects in Higgs-boson production in gluon fusion

Project A1a

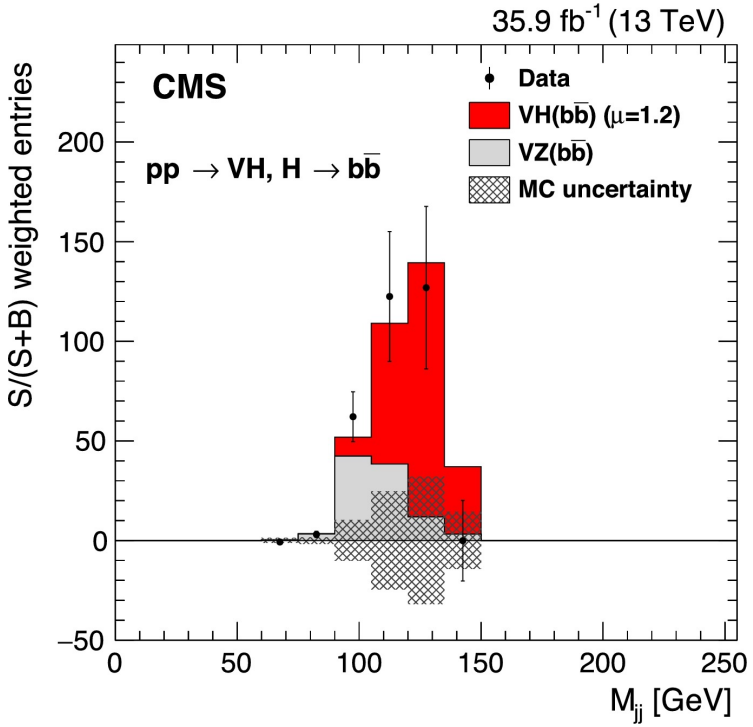
M. Czakon, R. Harlander

CRC TRR 257 meeting, Karlsruhe, March 17th 2019

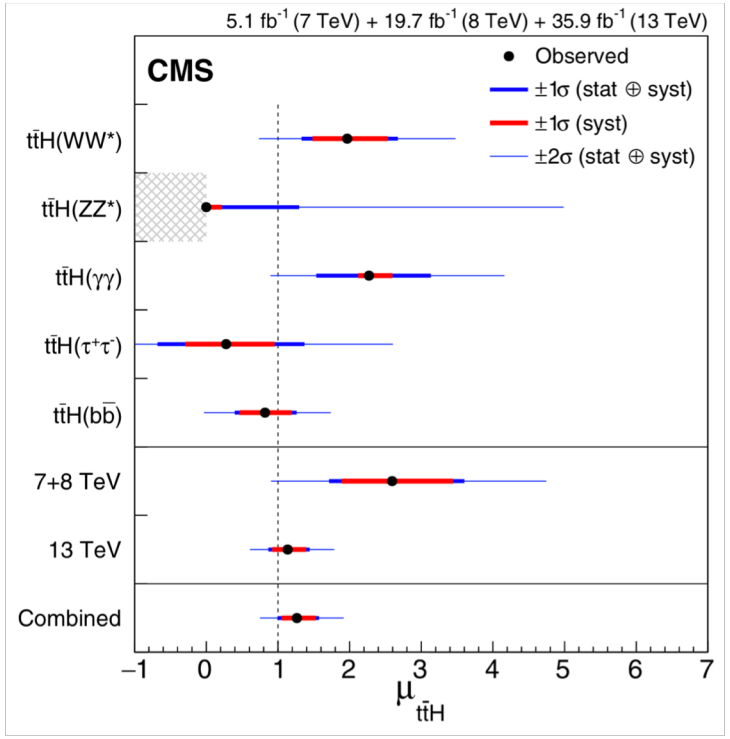
Plan:

- Status
- Some open problems in Higgs-boson production description:
  - Total inclusive cross section
  - Differential cross section
  - Kinematical limits
  - Resummation and bottom Yukawa coupling
- Semi-numerical methods
- Conclusions

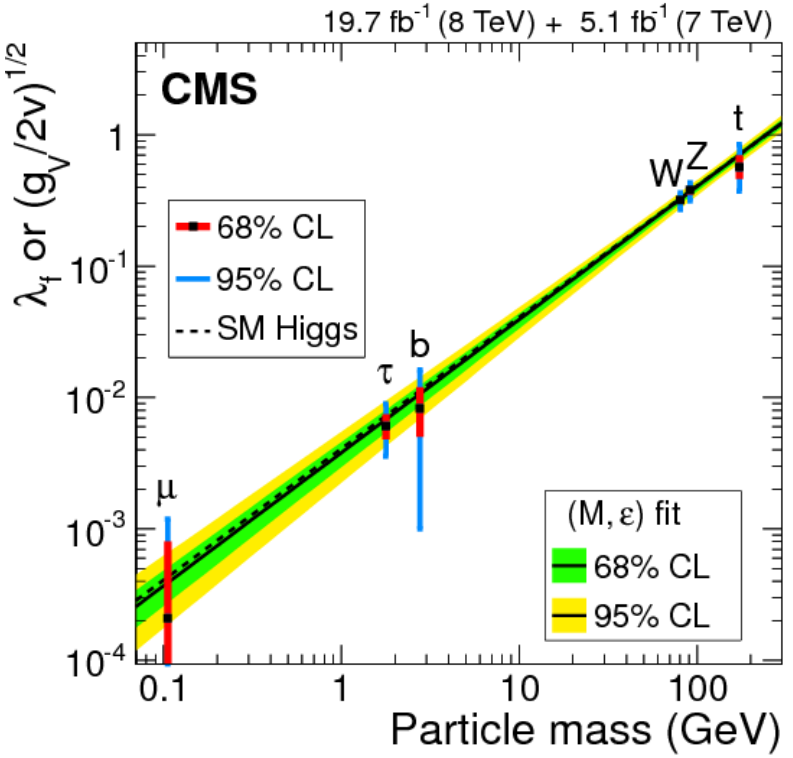
Status experiment



PLB 780 (2018) 501



PRL 120 (2018) 231801



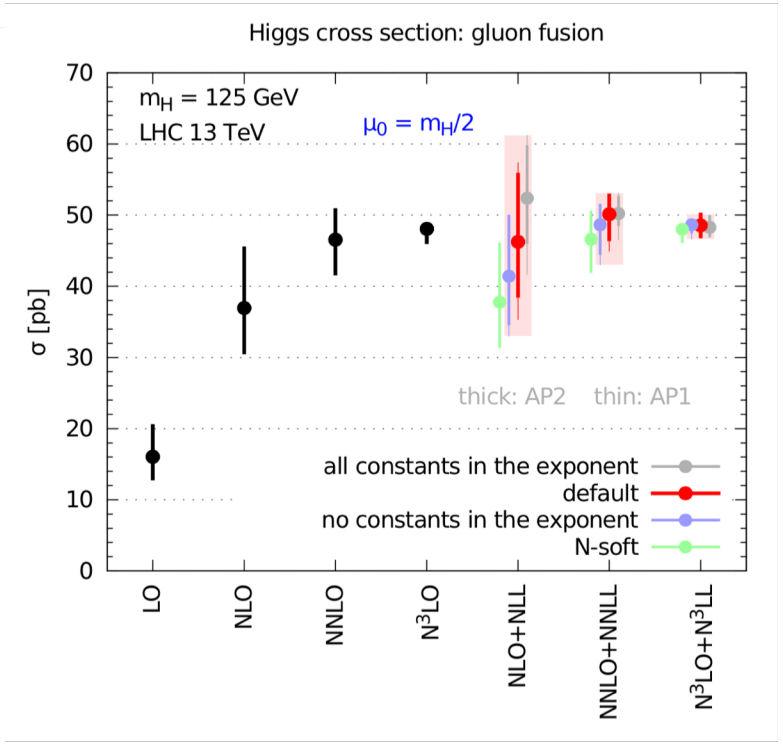
Status theory

Handbook of LHC Higgs cross sections:
4. Deciphering the nature of the Higgs sector
Report of the LHC Higgs Cross Section Working Group `16

LHC @13 TeV

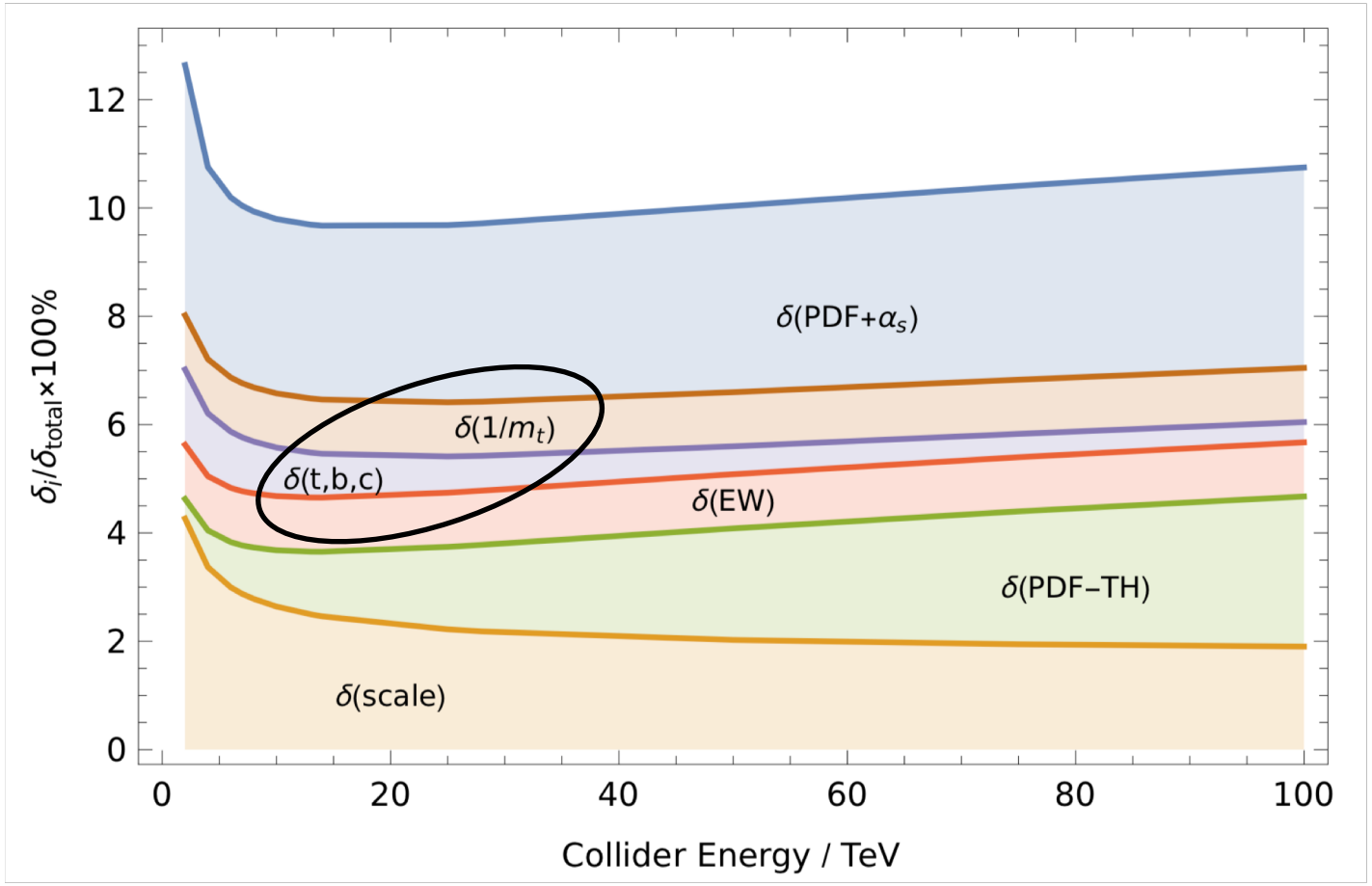
$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\,(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\,(\text{PDF+}\alpha_s)\,.$$

$$\begin{aligned}
48.58\,\text{pb} = \quad & 16.00\,\text{pb} && (+32.9\%) && (\text{LO, rEFT}) \\
& + 20.84\,\text{pb} && (+42.9\%) && (\text{NLO, rEFT}) \\
& - \ 2.05\,\text{pb} && (-4.2\%) && ((t,b,c), \text{exact NLO}) \\
& + \ 9.56\,\text{pb} && (+19.7\%) && (\text{NNLO, rEFT}) \\
& + \ 0.34\,\text{pb} && (+0.7\%) && (\text{NNLO}, 1/m_t) \\
& + \ 2.40\,\text{pb} && (+4.9\%) && (\text{EW, QCD-EW}) \\
& + \ 1.49\,\text{pb} && (+3.1\%) && (\text{N}^3\text{LO, rEFT})
\end{aligned}$$



Status theory

Higgs Physics
at the HL-LHC and HE-LHC
Report from Working Group 2
on the Physics of the HL-LHC,
and Perspectives at the HE-LHC `19



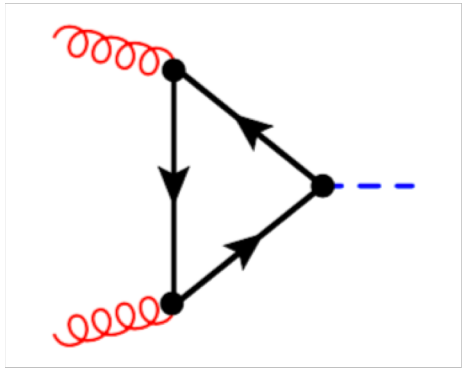
– Missing higher-order effects of QCD corrections beyond N3LO (δ(scale)).
– Missing higher-order effects of electroweak and mixed QCD-electroweak corrections at and beyond O(α_S α) (δ(EW)).
– Effects due to finite quark masses neglected in QCD corrections beyond NLO (δ(t,b,c) and δ(1/mt))
– Mismatch in the perturbative order of the parton distribution functions (PDF) evaluated at NNLO
and the perturbative QCD cross sections evaluated at N3LO (δ(PDF-TH)).

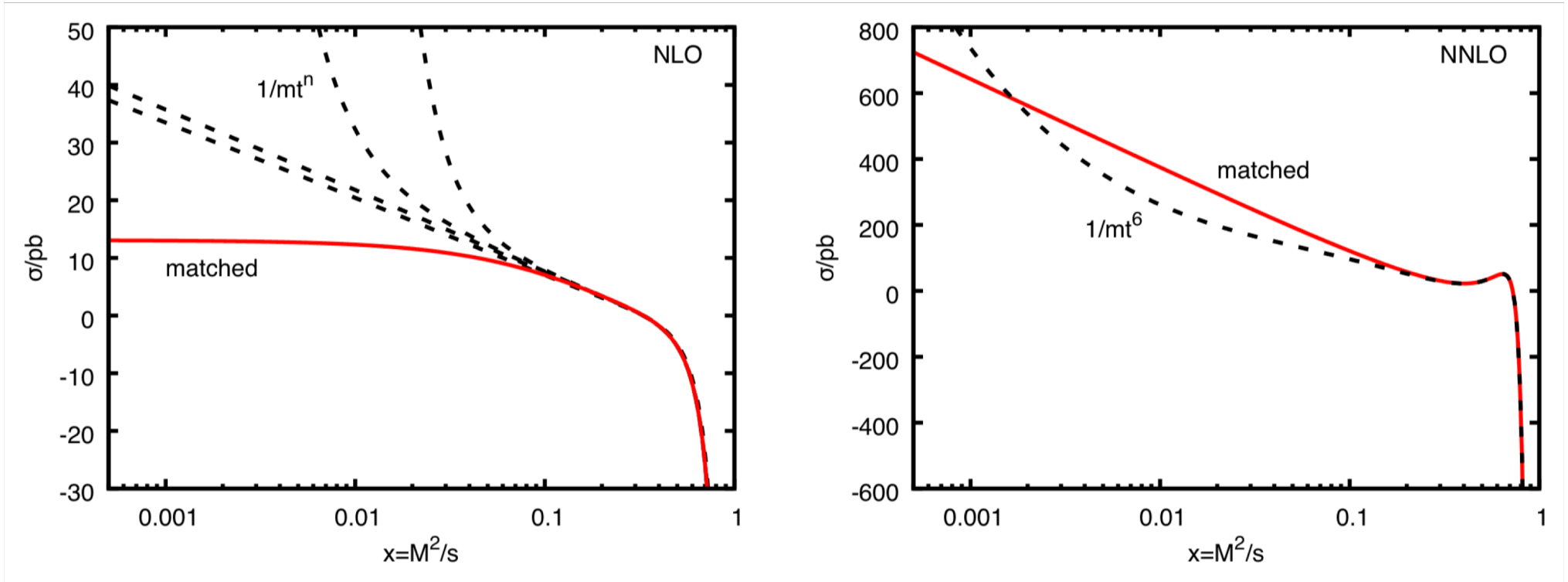
Top quark mass & inclusive cross section gg -> H + X

Exploiting the large mass expansion

RH, Ozeren, `09
RH, Neumann, Ozeren, M. Wiesemann, `12
RH, Mantler, S. Marzani, K. Ozeren, `10

Marzani, Ball, Del Duca, Forte, Vicini `08
Pak, Rogal, Steinhauser `10





Top quark mass & inclusive cross section gg -> H + X

…and the high-energy limit

RH, Ozeren, `09
RH, Neumann, Ozeren, M. Wiesemann, `12
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Marzani, Ball, Del Duca, Forte, Vicini `08
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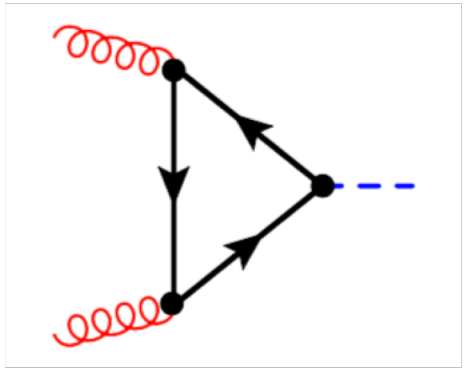


$$\Delta_{gg}(N,\tau,\mu_{\rm F}) = h(0,\tau,\gamma_s,\gamma_s)R^2(\gamma_s)\left(\frac{M_H^2}{\mu_{\rm F}^2}\right)^{2\gamma_s}$$

$$R = 1 + \mathcal{O}\left(\left(\frac{\alpha_s}{N}\right)^3\right)$$

$$h(N,\tau,M_1,M_2) = M_1 M_2 \int_0^1 d\zeta \zeta^{N-1} \int_0^\infty d\xi_1 \xi_1^{M_1-1} \int_0^\infty d\xi_2 \xi_2^{M_2-1} \int_0^{2\pi} \frac{d\varphi}{2\pi} M_H^2 \sigma^{\rm off}(\zeta,\tau,\xi_1,\xi_2,\varphi),$$

$$\xi_i = \frac{|\mathbf{k}_i|^2}{M_H^2}, \quad \zeta = \frac{M_H^2}{2(k_1\cdot k_2 - \mathbf{k}_1\cdot\mathbf{k}_2)}$$

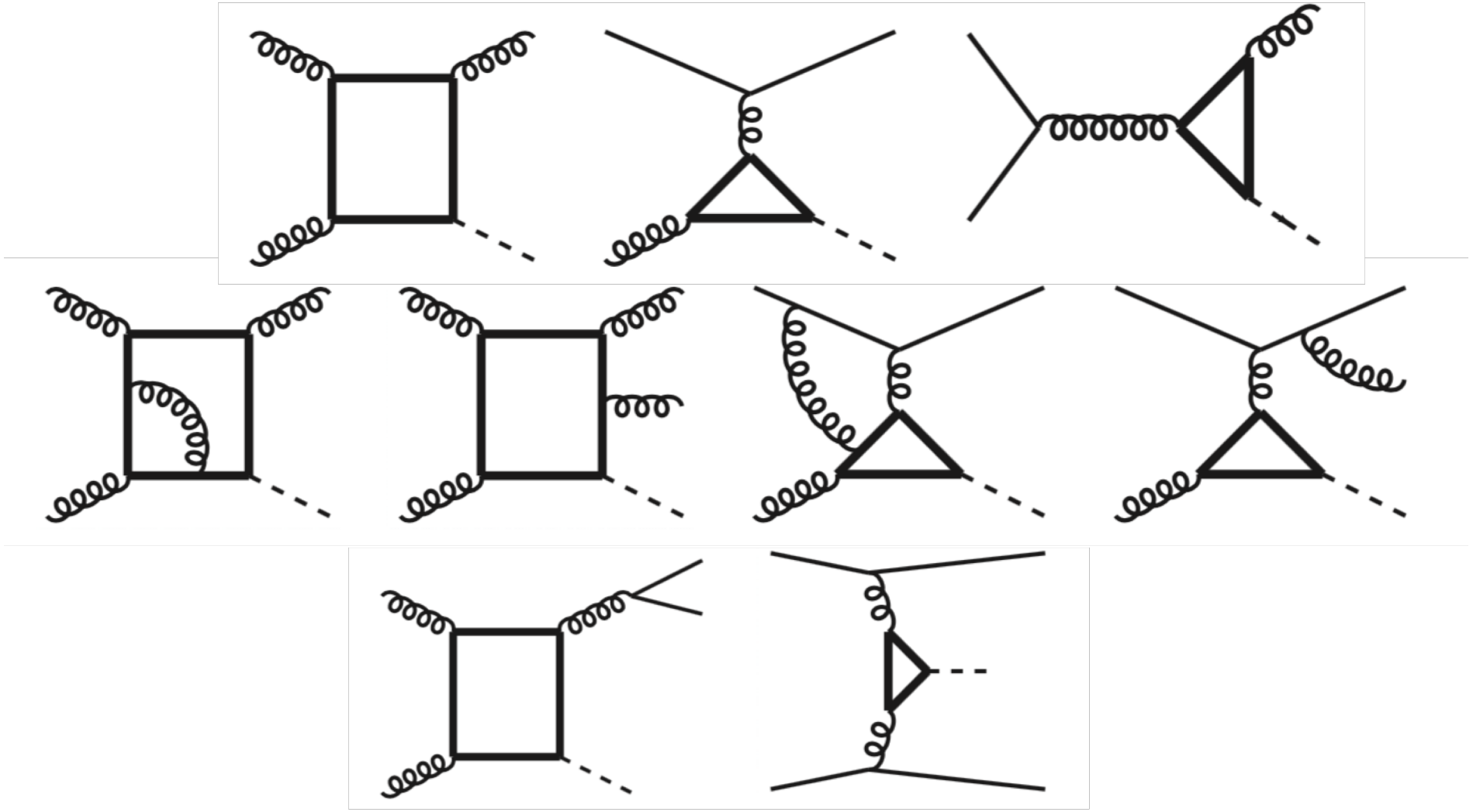
$$M_1 = M_2 = \gamma_s\left(\frac{\alpha_s}{N}\right)$$

$$\gamma_s\left(\frac{\alpha_s}{N}\right) = \sum_{k=1}^{\infty} c_k \left(\frac{C_A\alpha_s}{\pi N}\right)^k, \quad c_k = 1,0,0,2\zeta(3),\ldots$$

- Extend beyond leading high-energy behavior ?
- How about threshold behavior ?

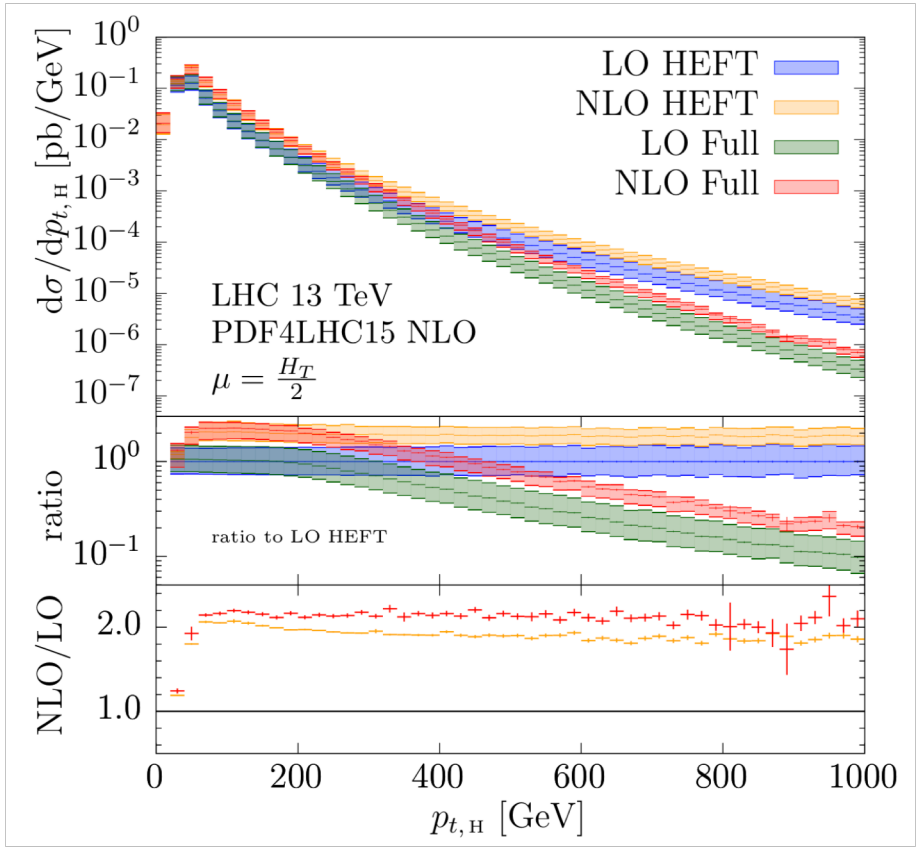
Higgs + jet studies with mass effects @ NLO

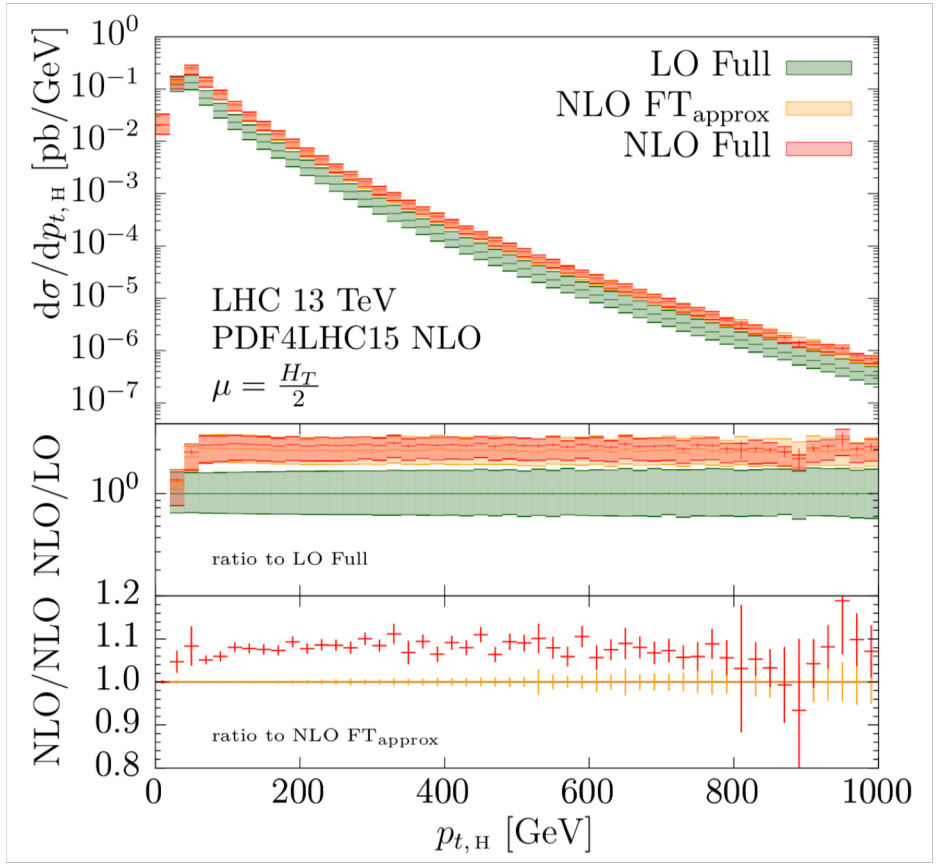
- Complicated two-loop amplitudes



Higgs + jet studies with mass effects @ NLO

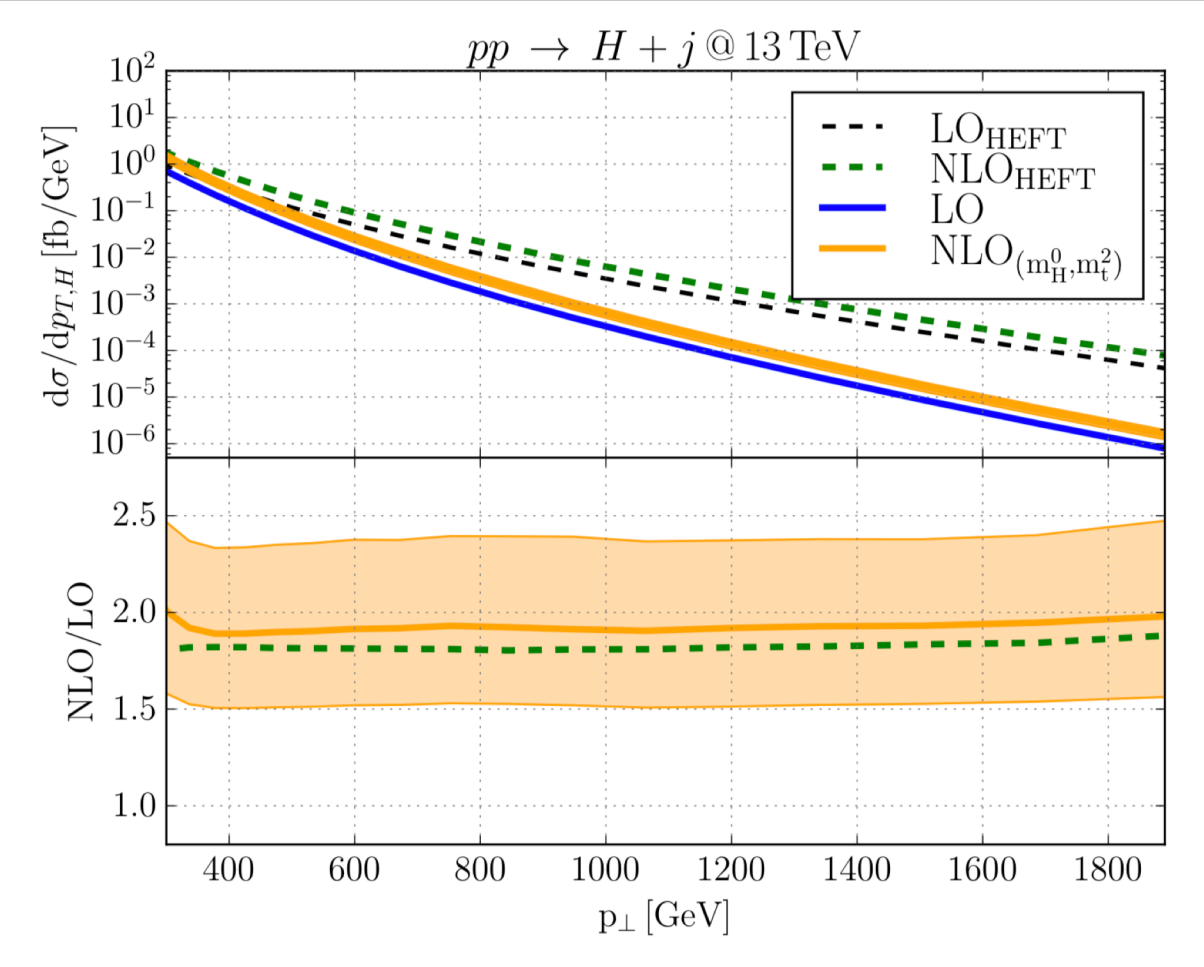
- Exact numerical result using sector decomposition for two-loop amplitiudes Jones, Kerner, Luisioni `18





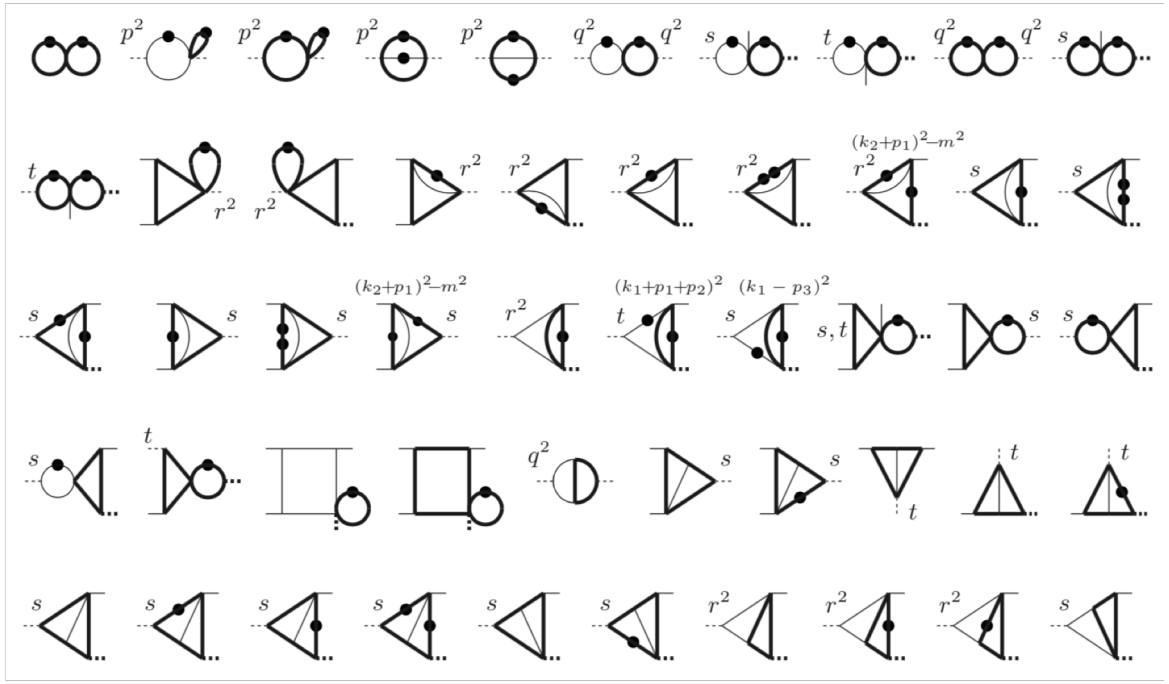
Higgs + jet studies with mass effects @ NLO

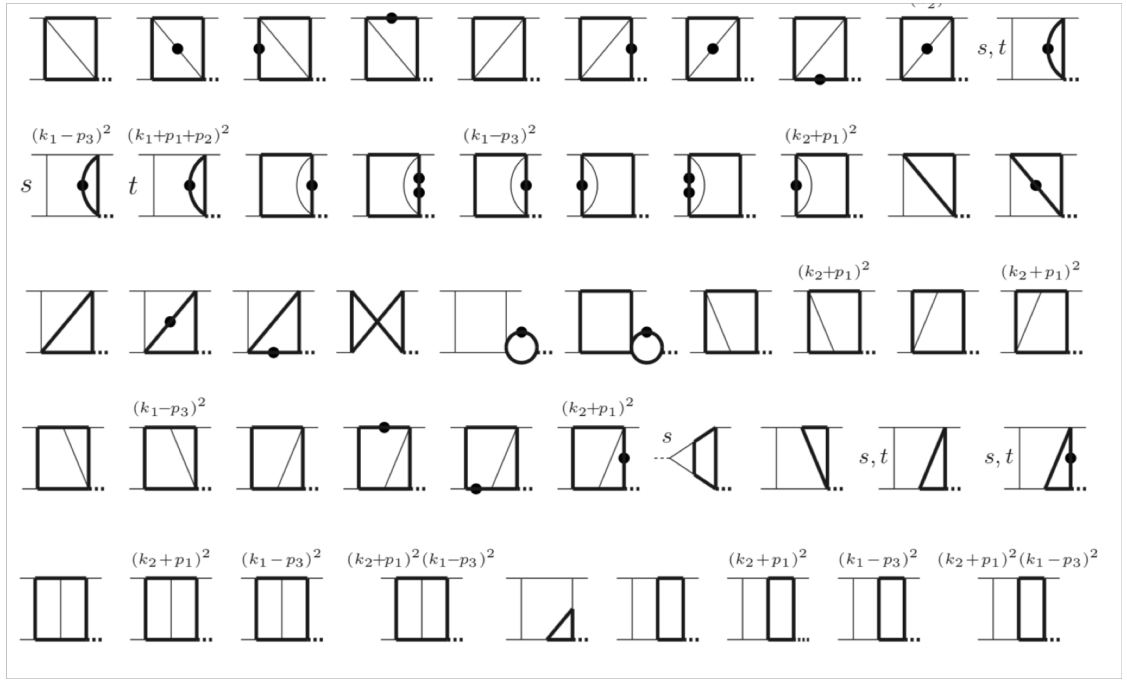
- Results using full two-loop amplitudes for nearly massless top quarks and exact real radiation Lindert, Kudashkin, Melnikov, Wever `18



Higgs + jet studies with mass effects @ NLO

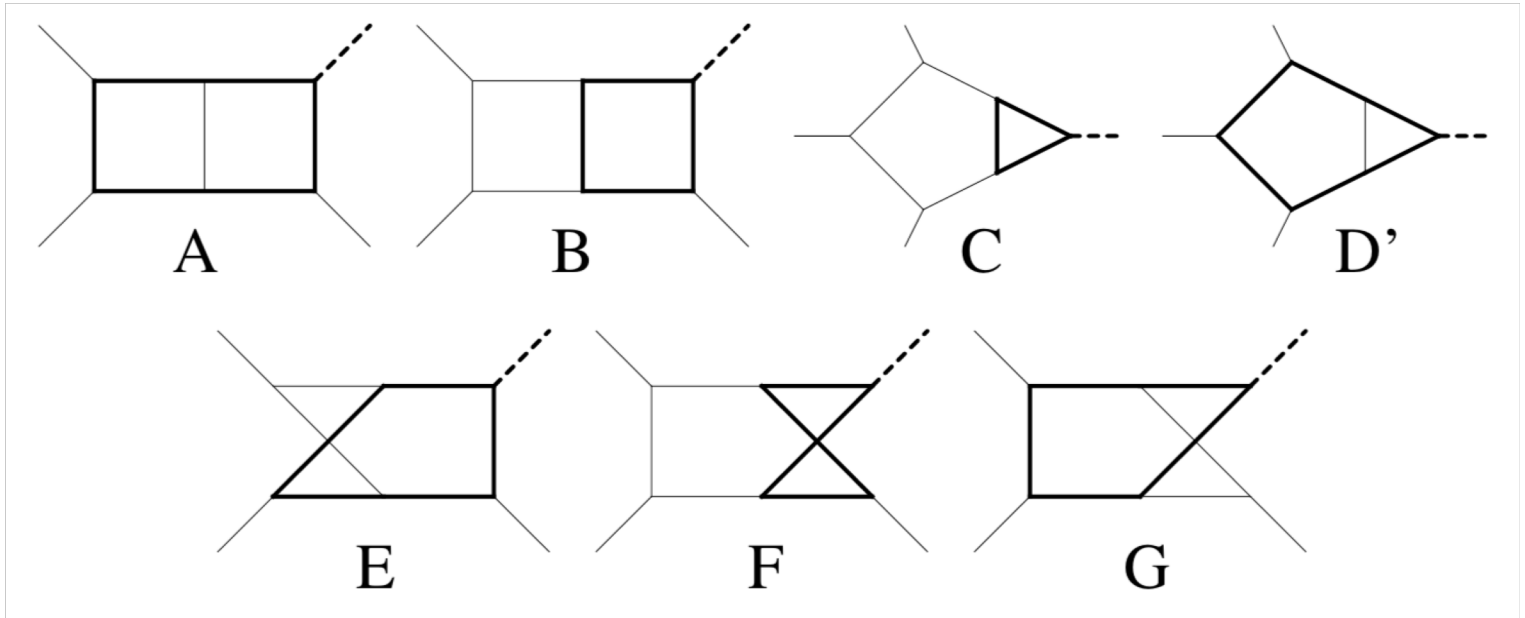
- Exact two-loop amplitudes in the planar approximation
  Bonciani, Del Duca, Frellesvig, Henn, Moriello, Smirnov `16





Higgs + jet studies with mass effects @ NLO

- Exact two-loop amplitudes and some non-planars
  Bonciani, Del Duca, Frellesvig, Henn, Moriello, Smirnov `18



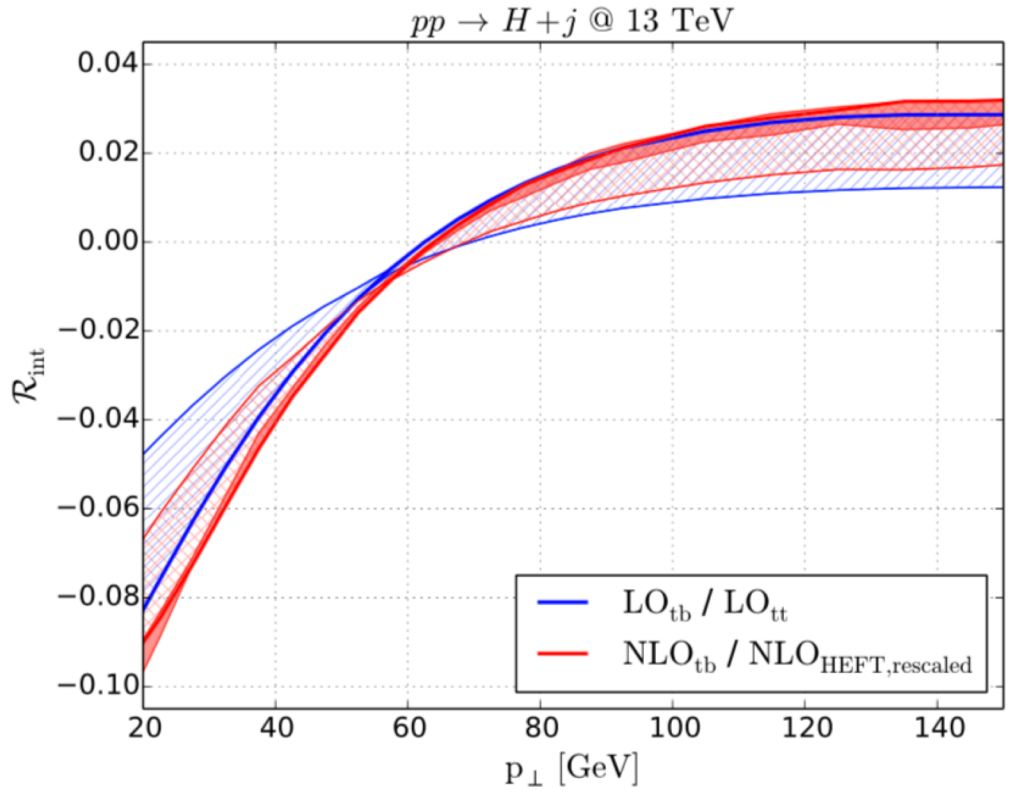
- Elliptic polylogs

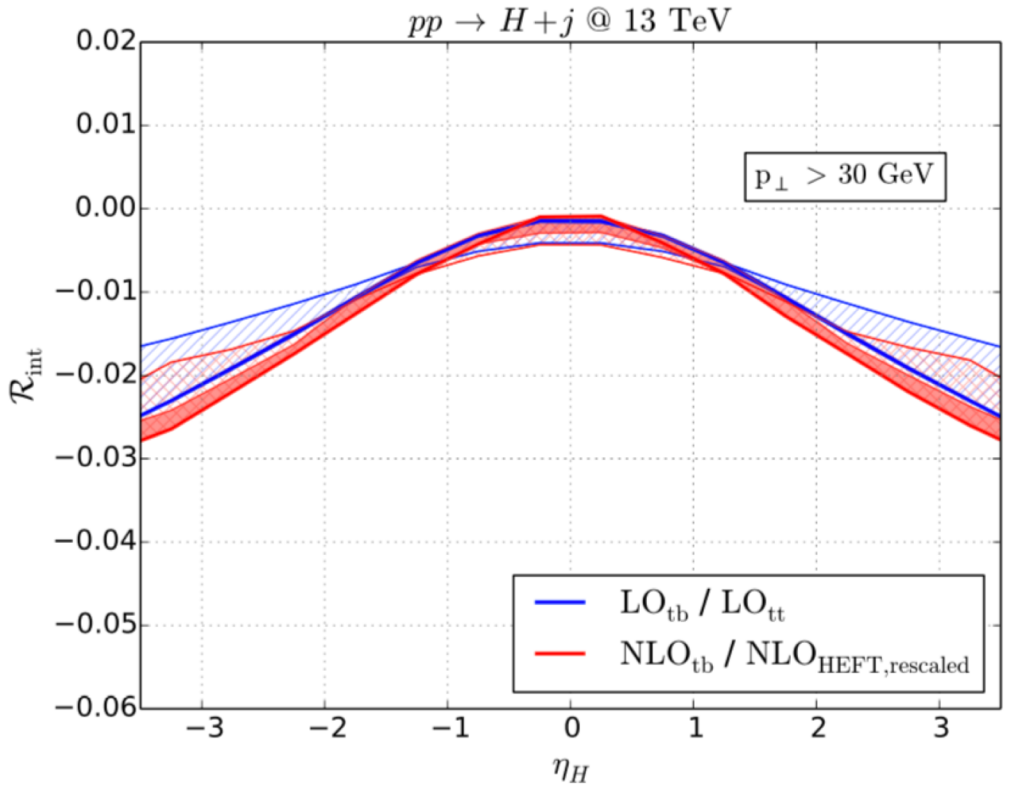
$$A_{66}\big|_{\text{max cut}} \propto \int \frac{dz}{s\sqrt{P_{4;1}(z)}}$$

$$P_{4;1} \equiv \left((m_H^2+z)^2 - 4m_H^2 m_t^2\right)\left(4m_t^2 tu/s + (t+z)^2\right)$$

Top-bottom-loop interference for Higgs + jet

Lindert, Melnikov, Tancredi, Wever `17





- Integrate to obtain the effect on the inclusive cross section ?

Cross sections with mass effects: summary

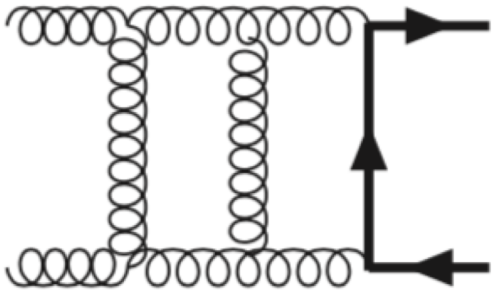
- 3-loop 3-points amplitudes and 2-loop 4-point amplitudes allow to evaluate the missing mass effects at NNLO by means of a direct Monte Carlo integration using an NNLO subtraction scheme, e.g. STRIPPER MC `10, MC and Heymes `14

- Do we have to wait for the complete analytic results ?

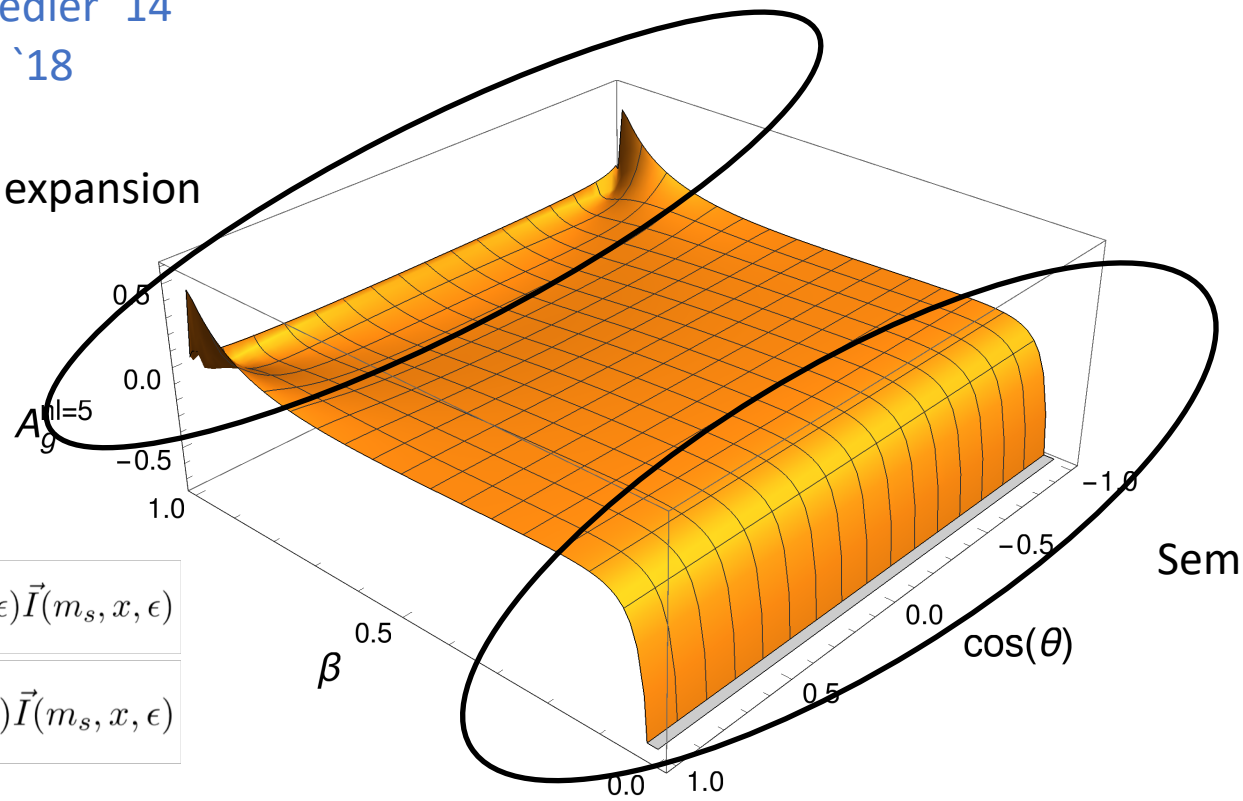
Semi-numerical methods

- Numerical solution of differential equations
- Example: top-quark pair production in hadron collisions

MC `08
Bärnreuther, MC, Fiedler `14
Chen, MC, Poncelet `18



Analytic high-energy expansion



Semi-numerical threshold expansion

$$m_s \frac{\partial}{\partial m_s} \vec{I}(m_s, x, \epsilon) = A^{(m_s)}(m_s, x, \epsilon) \vec{I}(m_s, x, \epsilon)$$

$$x \frac{\partial}{\partial x} \vec{I}(m_s, x, \epsilon) = A^{(x)}(m_s, x, \epsilon) \vec{I}(m_s, x, \epsilon)$$

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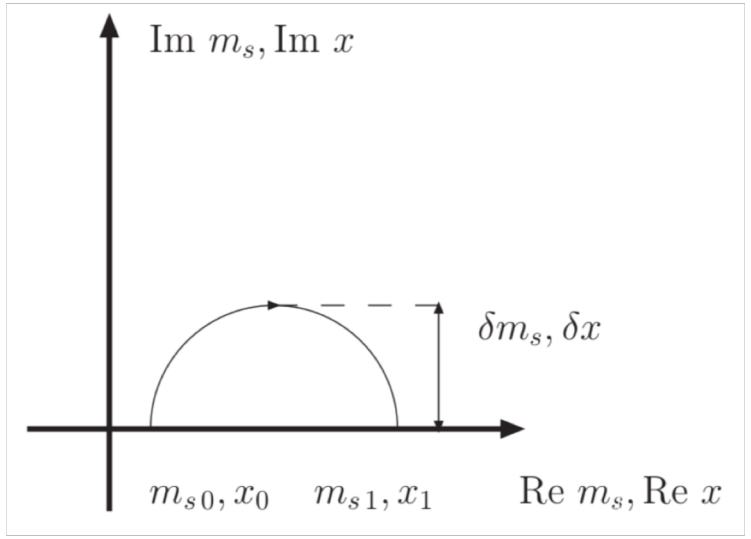

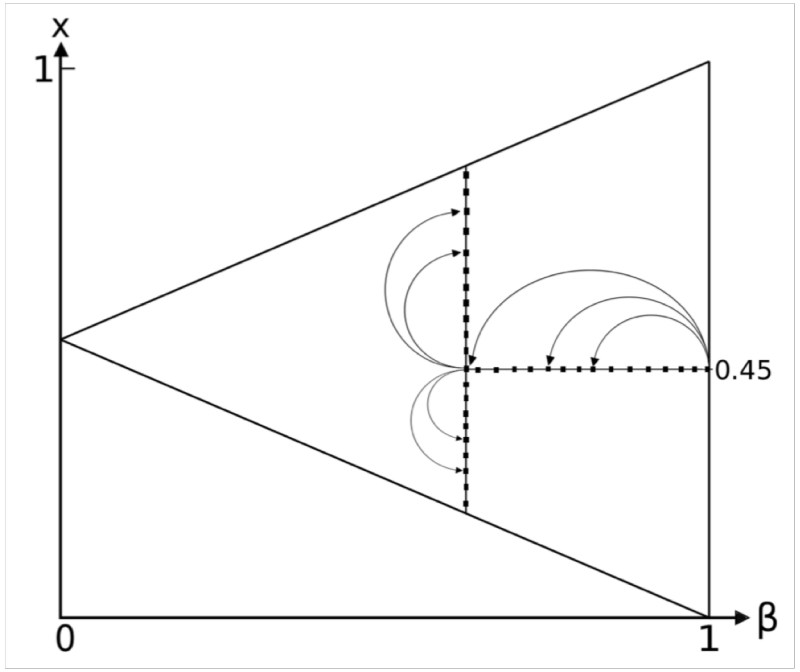

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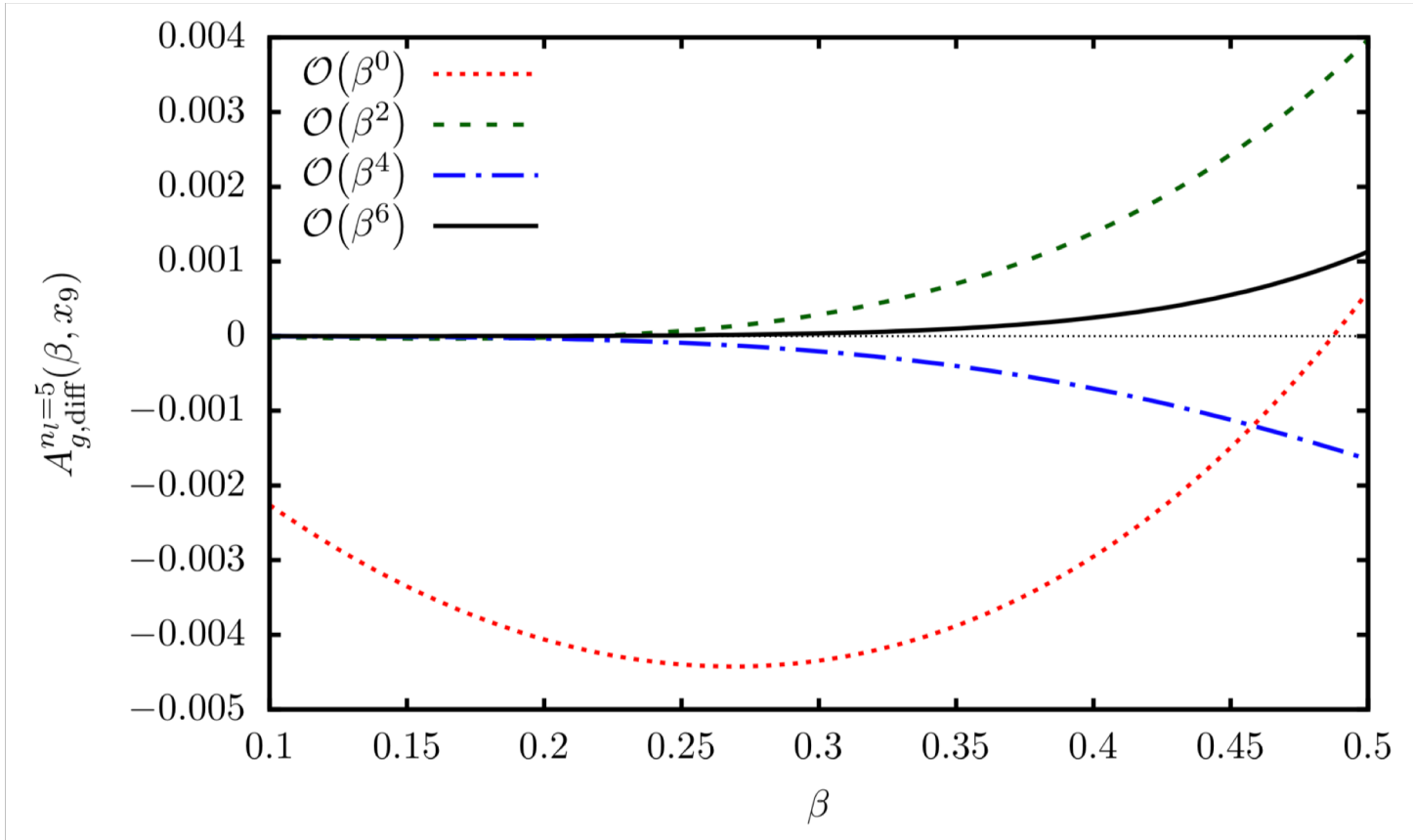
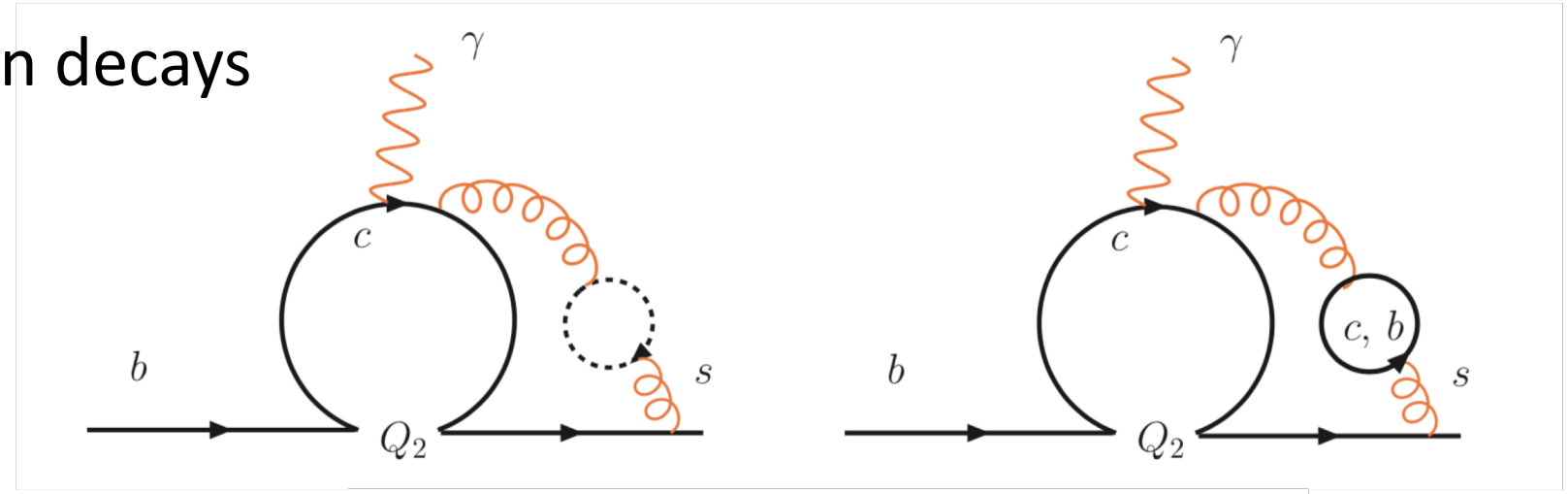
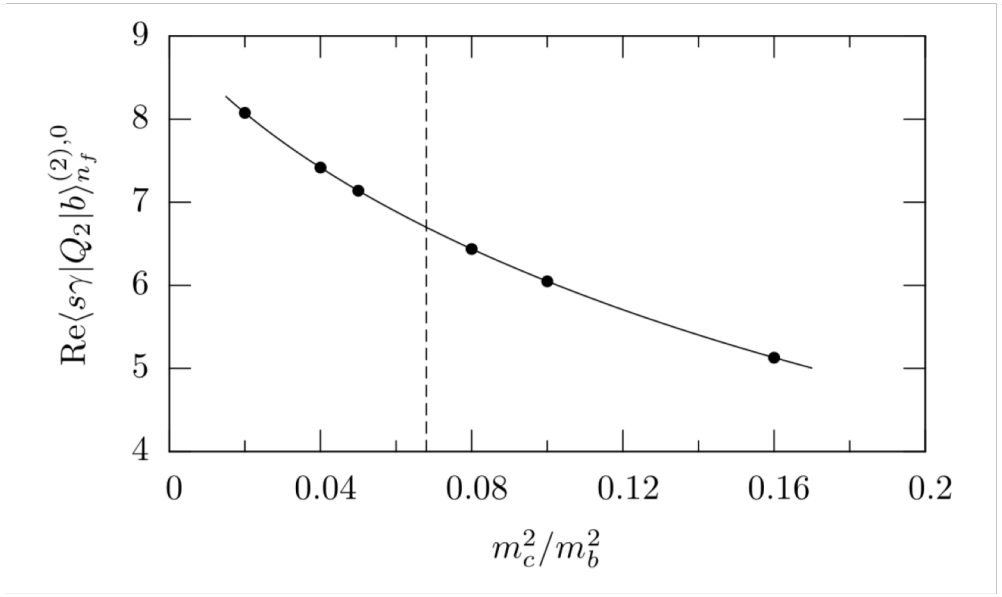


Semi-numerical methods

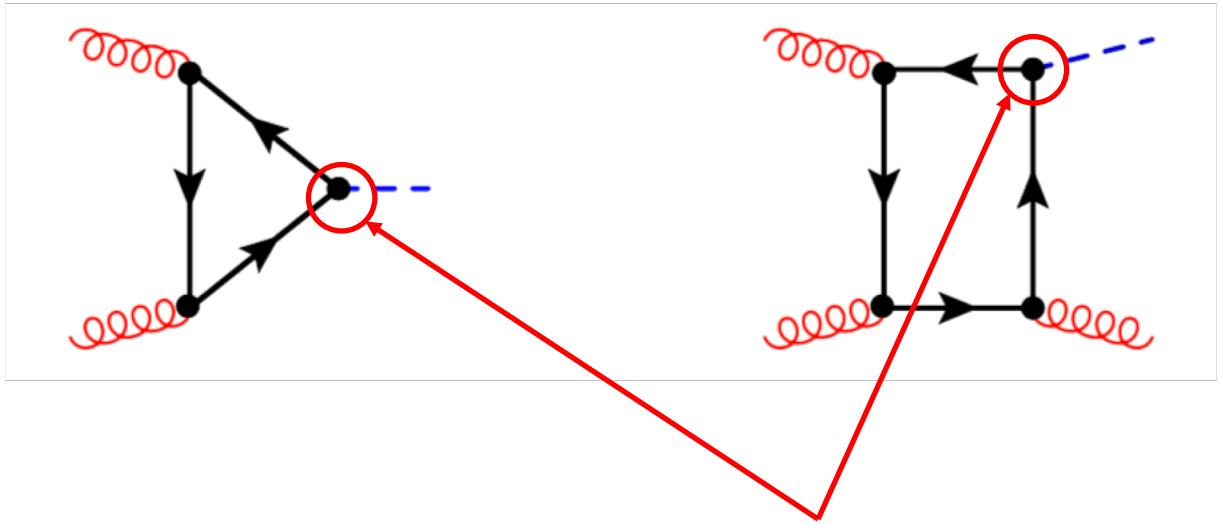
- Numerical solution of differential equations
- Example: Rare B-meson decays



Boughezal, MC, Schutzmeier `07
MC, Fiedler, Huber, Misiak, Schutzmeier, Steinhauser `15
Misiak et al `15



One last question…



- How to renormalize the bottom Yukawa coupling ?

- Hints from subleading Sudakov resummation ? Melnikov, Penin `16

Conclusions

- In principle, one can obtain both total and differential cross sections using purely numerical methods
- However, there is potential for physical insight by analytic methods in high-energy, threshold and other regimes
- Progress expected through synergy between the two approaches

Conclusions

Methodologically related to:	
• Subtraction methods	A1a, B1a
• Massive virtual amplitudes	A3b, B1b
• Evaluation of master integrals	C1a, C1b
Relevant input to Higgs-boson physics analyses:	
• Bottom-mass effects in BSM theories	A3a, A3b
• Mass effects in Higgs-boson production	A1b

Links to other projects:

- A1b - Higgs boson physics with higher order QCD corrections within the Higgs Effective Theory
- A3b - Precision predictions for Higgs boson properties as a probe for New Physics
- B1a - Production of colour-singlet final states through N3LO QCD
- B1b - Precision top-quark physics at the LHC