State-of-the-Art Calculations for Top, Higgs, Jet production

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Plan of the talk

I will review some of the recent calculations that regard

- Top production
- Higgs production

More comments —> B. Mistlberger' talk

- Jet production

More comments —> R. Boughezal' talk

I apologise in advance ...

Theoretical framework: Perturbative QCD

At LHC hadronic collisions $h_1 + h_2 \to Q\bar{Q} + X$

we rely on Factorization Theorem

PDFs: Universal Part

Evolution with Fact scale predicted by the theory

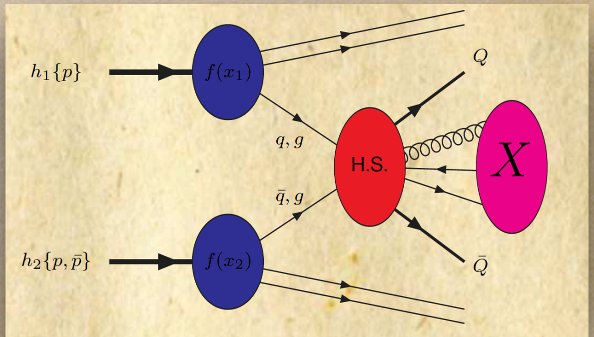
Partonic CS: Process-dep Part

Calculation in PT Theory

$$\sigma_{h_1,h_2} = \sum_{i,j} \int_0^1 dx_1 \int_0^1 dx_2 \, f_{i,h_1}(x_1,\mu_F) \, f_{j,h_2}(x_2,\mu_F) \, \hat{\sigma}_{ij}(\hat{s}, m^2, \alpha_S(\mu_R), \mu_F, \mu_R)$$

NNLO
- S. Moch, J. Vermaseren, A. Vogt, Nucl. Phys. B688 (2004) 101
- A. Vogt, S. Moch, J. Vermaseren, Nucl. Phys. B691 (2004) 129

NNNLO
- S. Moch, B. Ruijl, T. Ueda, J. Vermaseren, A. Vogt, Phys. Lett. B782 (2018) 627
- J. Davis, B. Ruijl, T. Ueda, J. Vermaseren, A. Vogt, Nucl. Phys. B915 (2017) 335
- S. Moch, B. Ruijl, T. Ueda, J. Vermaseren, A. Vogt, JHEP 10 (2017) 041



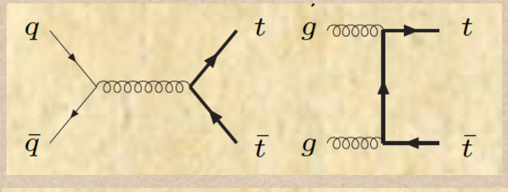
Top Quark Production

- With a mass of m=173.3 GeV, the top quark is the heaviest particle produced so far at colliders and since it couples strongly to the Higgs boson, it is important for the understanding of the Electroweak symmetry breaking!
- Top mass is a crucial input parameter of the SM

See Vicini's talk

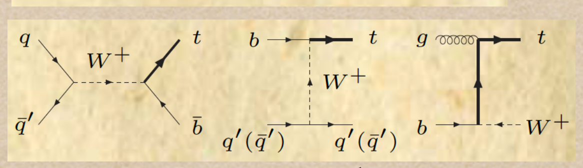
- Top quarks are produced at hadron colliders via two mechanisms:

Pair production:



Main production mechanism at LHC
CS = 900 pb @ 13TeV

Single top production:



Main channel for single-top @ LHC
~ 80% @ 13 TeV …

- Top quark does not hadronize: opportunity to study the spin properties and interaction vertices
- Theoretical predictions forTop-pair production are known at NNLO+NNLL (+NLOew). They are very accurate and they can be used to constrain the gluon pdf at large x

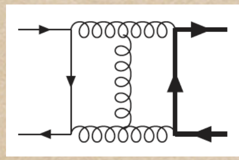
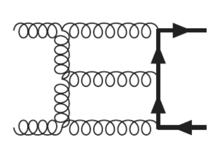
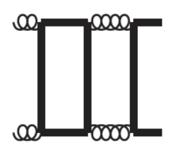
M. Czakon, M. L. Mangano, A. Mitov and J. Rojo, JHEP 07 (2013) 167

NNLO QCD corrections to Top-pair Production

- In 2013 the total production CS was calculated at NNLO in QCD (stable tops)

  P. Baernreuther, M. Czakon and A. Mitov, Phys. Rev. Lett. 109 (2012) 132001
  M. Czakon and A. Mitov, JHEP 1212 (2012) 054, JHEP 1301 (2013) 080
  M. Czakon, P. Fiedler and A. Mitov, Phys. Rev. Lett. 110 (2013) 252004

  - Virtual: Two-loop matrix elements for $q\bar{q} \to t\bar{t}\,,\ gg \to t\bar{t}$

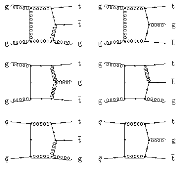
    Elliptic integrals

    M. Czakon, Phys. Lett. B664 (2008) 307
    R.B.,A. Ferroglia, T. Gehrmann, D. Maitre, C. Studerus, JHEP 07 (2008) 129
    R.B.,A. Ferroglia, T. Gehrmann, C. Studerus, JHEP 08 (2009) 067
    R.B.,A. Ferroglia, T. Gehrmann, A. von Manteuffel, C. Studerus, JHEP 01 (2011) 102
    R.B.,A. Ferroglia, T. Gehrmann, A. von Manteuffel, C. Studerus, JHEP 12 (2013) 038
    P. Baernreuther, M. Czakon, P. Fiedler, JHEP 02 (2014) 078

    One-loop times One-loop

    J. G. Koerner, Z. Merebashvili, M. Rogal, Phys. Rev. D77 (2008) 094011
    B. Kniehl, Z. Merebashvili, J. G. Korner, M. Rogal, Phys. Rev. D78 (2008) 114011
    C. Anastasiou, S. M. Aybat, Phys. Rev. D78 (2008) 114006

  - Real virtual: One-loop matrix elements for $t\bar{t} + 1\text{parton}$

    S. Dittmaier, P. Uwer, and S. Weinzierl, Phys. Rev. Lett. 98 (2007) 262002
    G. Bevilacqua, M. Czakon, C. Papadopoulos, M. Worek, Phys. Rev. D84 (2011) 114017
    K. Melnikov and M. Schultze, Nucl. Phys. B840 (2010) 129

  - Double real: Tree-Level metrix elements for $t\bar{t} + 2\text{partons}$

- The three contrib. are separately divergent. IR subtraction terms: STRIPPER

  M. Czakon, Phys. Lett. B693 (2010) 259; Nucl. Phys. B849 (2011) 250
  R. Boughezal, K. Melnikov, F. Petriello, Phys. Rev. D85 (2012) 034025

- QCD corrections to processes that involve at lest two large energy scales ($\hat{s}, m_t^2 \gg \Lambda^2_{QCD}$) are characterised by a logarithmic behaviour in the vicinity of the boundary of the phase space

$$\sigma \sim \sum_{n,m} C_{n,m}\, \alpha_S^n \ln^m (1-\rho) \qquad m \leq 2n$$

Even if $\alpha_S \ll 1$ (pert region) we can have at all orders $\alpha_S \ln(1-\rho) \sim \mathcal{O}(1)$

→ Log Contributions have to be resummed: now @ NNLL

M. Cacciari, M. Czakon, M. L. Mangano, A. Mitov, and P. Nason, Phys. Lett. B 710 (2012) 612

- Also the EW NLO corrections were included in the analysis

M. Czakon, D. Heymes, A. Mitov, D. Pagani, I. Tsinikos, M. Zaro, JHEP 1710 (2017) 186

- The NNLO+NNLL corrections were implemented in a MC integrator: TOP++

$$\sigma = 245.8 \text{ pb} \pm 3\% \pm 2.5\% \qquad @\ 8 \text{ TeV}$$

M. Czakon, A. Mitov, Comp. Phys. Commun. 185 (2014) 2930

- Very recently New NNLO calculation of the total CS

(except virtual two-loop corrections, one-loop with OPENLOOPs)

★ The IR subtraction terms with Qt subtraction formalism

S. Catani, S. Devoto, M. Grazzini, S. Kalweit, J. Mazzitelli, H. Sargsyan, PRD 99 (2019) 051501

The total CS is not the only observable that registered a big activity of the theory community

- Distributions (stable tops) @ NNLO: $m_{t\bar{t}}$ distrib., p_T disturb. of the top, Rapidity distribution of the top, A_{FB} for Tevatron, A_C at LHC

M. Czakon, P. Fiedler, D. Heymes, A. Mitov, JHEP 05 (2013) 034
M. Czakon, D. Heymes, A. Mitov, Phys. Rev. Lett. 116 (2016) 082003
M. Czakon, D. Heymes, A. Mitov, D. Pagani, I. Tsinikos, M. Zaro, JHEP 1710 (2017) 186

- Top Decay and NWA: NNLO+NNLL+EW corrections to the total CS were calculated with stable tops. However top decay in b+W NWA (resonant contributions)

Distrib. and Spin corr. @NLO

K. Melnikov, M. Schulze, JHEP 0908 (2009) 049
K. Melnikov, M. Schulze, Phys. Lett. B700 (2011) 17
W. Bernreuther, Z.-G. Si, Nucl. Phys. B837 (2010) 90
W. Bernreuther, Z.-G. Si, Phys. Rev. D86 (2012) 034026

Top decay @NNLO

J. Gao, C. S. Li, H. X. Zhu, Phys. Rev. Lett. 110 (2013) 042001
M. Brucherseifer, F. Caola, K. Melnikov, JHEP 1304 (2013) 59

Spin corr. @NNLO

M. Czakon, D. Heymes, A. Mitov, D. Pagani, I. Tsinikos, M. Zaro, Phys. Rev. D98 (2018)

- NLO+PS

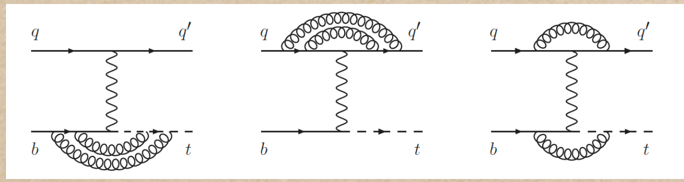
J. M. Campbell, R. K. Ellis, P. Nason, E. Re, JHEP 04 (2015) 104

NNLO QCD corrections to Single-Top production

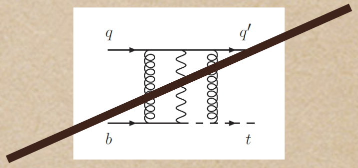
- Single top production is important because:
  - it gives the opportunity to check the tWb vertex (SM vs. Anom. vertex contr)
  - it involves CKM matrix elem. V_{bt} (direct access to the parameter)
- The bigger contribution to the CS comes from t-channel: the bigger theory effort was devoted to this channel !

T-channel single top @ NNLO:

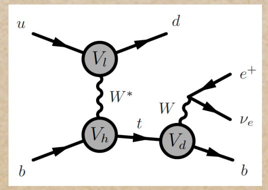
- QCD Corrections worked out neglecting "cross-talking terms" (stable top)



M. Brucherseifer, F. Caola, K. Melnikov, Phys. Lett. B736 (2014) 58



- QCD Corrections in production and top decay and diff distributions



E. L. Berger, J. Gao, C.-P. Yuan, H. X. Zhu, Phys. Rev. D94 (2016) 071501
E. L. Berger, J. Gao, H. X. Zhu, JHEP 1711 (2017) 158

- NLO+PS

S. Alioli, P. Nason, C. Oleari, E. Re, JHEP 09 (2009) 111
T. Jezo, P. Nason, JHEP 1512 (2015) 065

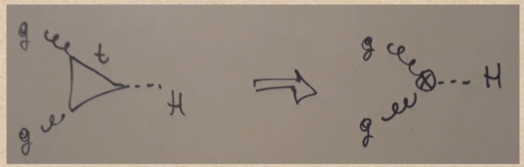
Higgs Production at the LHC

- The state-of-the-art is for sure represented by the total ggF CS known at the NNNLO in QCD! Nice convergence of the pt series: moderate increase of the central value but sizeable reduction in the scale dependence w.r.t. NNLO. At 13 TeV and Higgs mass of 125 GeV

$$\sigma = 48.58 \text{ pb}^{+2.22 \text{ pb } (4.56\%)}_{-3.27 \text{ pb } (-6.72\%)} \pm 1.56 \text{ pb}(3.2\%)$$

C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog, A. Lazopoulos, B. Mistlberger, JHEP 1615 (2016) 058

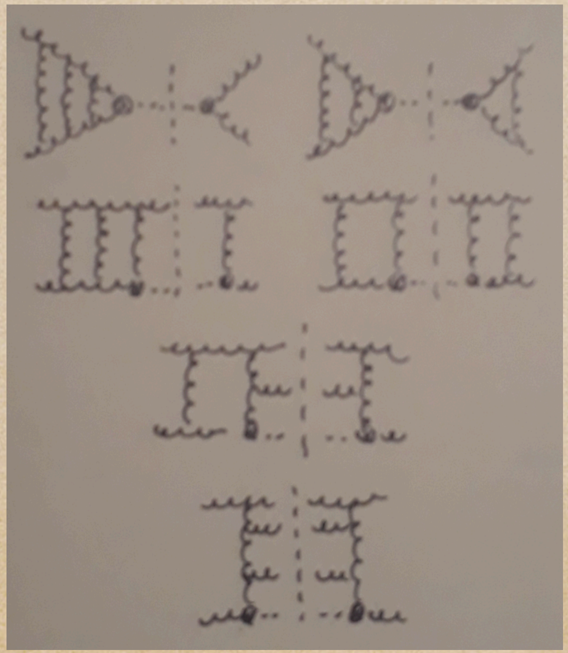
- The calculation was done in the $m_t \to \infty$ limit



- Inclusive calculation (integration over the whole phase space) with reverse unitarity

C. Anastasiou, K. Melnikov, Nucl. Phys. B646 (2002) 220

It turns out that this is an interesting obs by itself, H+j →



P. A. Baikov, K. G. Chetyrkin, A. V. Smirnov, V. A. Smirnov, M. Steinhauser, Phys. Rev. Lett. 102 (2009)
T. Gehrmann, E. W. N. Glover, T. Huber, N. Ikizlerli, C. Studerus, JHEP 06 (2010) 094

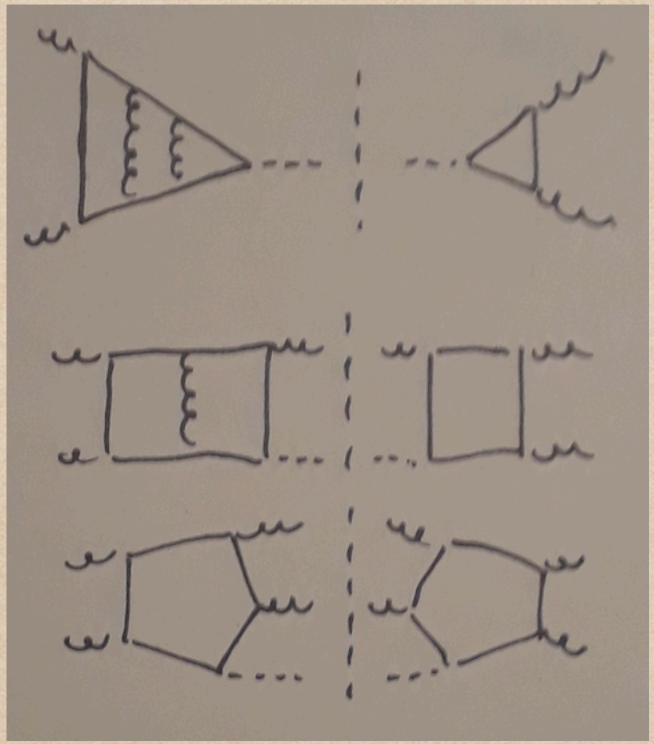
C. Duhr, T. Gehrmann, M. Jaquier, JHEP 02 (2015) 077
F. Dulat, B. Mistlberger, arXiv 1411.3586
W. B. Kilgore, PRD89 (2014) 073008

C. Anastasiou, C. Duhr, F. Dulat, B. Mistlberger, JHEP 07 (2013)
C. Duhr, T. Gehrmann, Phys. Lett. B 727 (2013)
Y. Li, A. Von Manteuffel, R. Schabinger, H. X. Zhu, PRD91 (2015) 032008

The TH prediction includes EW corr.s

Exclusive obs are known at NNLO

- As at the previous order, it would be desirable to have the complete NNLO with finite top mass



... at the moment unknown

It turns out that this is an interesting obs by itself, H+j →

S. P. Jones, M. Kerner, G. Luisoni, Phys. Rev. Lett. 120 (2018) 162001

V. Del Duca, W. Kilgore, C. Oleari, C. Schmidt, D. Zeppenfeld, Phys. Rev. Lett. 87 (2001) 122001
Nucl. Phys. B616 (2001) 367

- The virtual contribution Is not known, while the interference of The two-loop H+j with the one-loop is known numerically

→ Calc Analytically complex: elliptic integrals
Can be done in power expansion ....

- The IR subtraction terms can be calculated with Qt ...

H+jet

- H+j is important in the high- $p_{t,H}$ region ($p_{t,H} \geq m_t$) to disentangle SM from NP contributions. In this regime the top loop is resolved

- In HEFT (infinite top mass) the NNLO QCD corrections are known

R. Boughezal, F. Caola, K. Melnikov, F. Petriello, M. Schulze, JHEP06 (2013) 072
Phys. Rev. Lett. 115 (2015) 082003
X. Chen, T. Gehrmann, E. W. N. Glover, M. Jaquier, Phys. Lett. B 740 (2015) 147
R. Boughezal, C. Focke, W. Giele, X. Liu, F. Petriello, Phys. Lett. B748 (2015) 5

- Power in $1/m_t^2$ corrections at NLO in QCD were also calculated

R. Harlander,T. Neumann, K. J. Ozeren, M. Wiesemann, JHEP 08 (2012) 139
T. Neumann, M. Wiesemann, JHEP 11 (2014) 150

- Small bottom mass interference effects and asymptotic $p_{t,H} \geq 400$ GeV were also calculated

K. Melnikov, L. Tancredi, C. Wever, JHEP 11 (2016) 104; Phys. Rev. D95 (2017) 054012
R. Mueller, D. G. Ozturk, JHEP 08 (2016) 055
J. M. Lindert, K. Melnikov, L. Tancredi, C. Wever, Phys. Rev. Lett. 118 (2017) 252002
K. Kudashkin, K. Melnikov, C. Wever, JHEP 02 (2018) 135
J. M. Lindert, K. Kudashkin, K. Melnikov, C. Wever, Phys. Lett. B782 (2018) 210

- Finally H+j was computed at NLO in QCD with the full top mass dependence

S. P. Jones, M. Kerner, G. Luisoni, Phys. Rev. Lett. 120 (2018) 162001

Calculation:

- Everything except virtual corrections are calculated analytically
- VIRTUAL: reductions to the Master Integrals, the MIs basis is chosen to be composed by quasi-finite integrals (better numeric convergence)

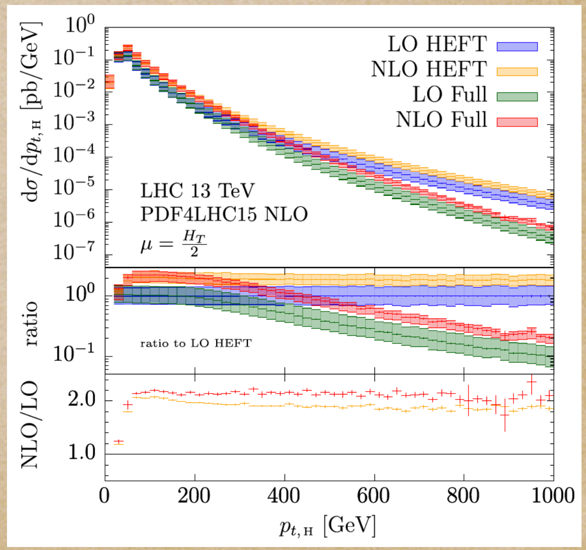
  → MIs are calculated numerically with SecDec

- Total CS: Corrections from LO to NLO are large (Kf=1.8)

  NLOfull/NLOheft ≈ 9%

Theory	LO [pb]	NLO [pb]
HEFT:	$\sigma_{\rm LO} = 8.22^{+3.17}_{-2.15}$	$\sigma_{\rm NLO} = 14.63^{+3.30}_{-2.54}$
$\rm FT_{approx}$:	$\sigma_{\rm LO} = 8.57^{+3.31}_{-2.24}$	$\sigma_{\rm NLO} = 15.07^{+2.89}_{-2.54}$
Full:	$\sigma_{\rm LO} = 8.57^{+3.31}_{-2.24}$	$\sigma_{\rm NLO} = 16.01^{+1.59}_{-3.73}$

- $p_{t,H}$ The bands of scale variations at NLO do not overlap anymore for $p_{t,H} \geq 340$ GeV



Analytic Calculations and Massive Corrections:

Calculation of matrix elements:

$$F_i = \int d^D k_1 d^D k_2 \frac{S_1^{n_1} \ldots S_q^{n_q}}{D_1^{m_1} \ldots D_t^{m_t}} = F_i(x)$$

$$x = s/m^2 \, , \, t/m^2 \ldots$$

- ✦ Observable ⟶ Dim-Reg scalar integrals
- ✦ IBP's ⟶ reduction of these ints to a set of Lin independent Master Integrals
- ✦ Calculation of the Master Integrals

$$\partial_x F = A(x, D)\, F + \Omega(x, D)$$

$$A = \begin{pmatrix} a_{1,1} & 0 & 0 & 0 \\ a_{2,1} & a_{2,2} & 0 & 0 \\ a_{3,1} & a_{3,2} & a_{3,3} & 0 \\ a_{4,1} & a_{4,2} & a_{4,3} & a_{4,4} \end{pmatrix}$$

➡ Only 1st-order diff eqs
Solutions in terms of GPLs
VERY WELL studied

$$A = \begin{pmatrix} a_{1,1} & a_{1,2} & 0 & 0 \\ a_{2,1} & a_{2,2} & 0 & 0 \\ a_{3,1} & a_{3,2} & a_{3,3} & 0 \\ a_{4,1} & a_{4,2} & 0 & a_{4,4} \end{pmatrix}$$

➡ 2nd-order diff eqs
Solutions in terms of Elliptic Integrals

- ✦ Repeated integrations over elliptic kernels of GPLs functions

J. Broedel, C. Duhr, F. Dulat, L. Tancredi, JHEP 1805 (2018) 093; PRD97 (2018) 116009

NB: it is not necessary to have complicated massive cut structure in order to have elliptic integrals

B. Mistlberger, JHEP 1805 (2018) 028

Jet production

- Jet production is the most frequently occurring reaction at LHC
- Jets are important for testing the QCD running coupling to large momentum transfer, for searches of NP in the di-jet mass spectrum, for constraining PDFs
- Di-jet production is known at NNLO:

  NNLO QCD corrections to the purely gluonic channel

  A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover, J. Pires, Phys. Rev. Lett. 110 (2013) 162003

  NNLO QCD corrections to all parton channels at leading Nc (doubly differential in mjj and rapidity difference)

  J. Currie, A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover, A. Huss, J. Pires, Phys. Rev. Lett. 119 (2017) 152001

- Inclusive single jet production is known at NNLO at leading Nc:

  J. Currie, E. W. N. Glover, J. Pires, Phys. Rev. Lett. 118 (2017) 072002

- Dijet and single jet CSs used at NNLO (reduced scale dependence) for constraining pdfs

(See R. Boughezal's talk)

Conclusions

- We presented a limited "selection" of calculations for Top, Higgs and jet production at LHC
- The state-of the art is quite advanced! It includes NNLO and also NNNLO perturbative corrections for key observables
- Possible directions for the future:

  — Computation of massive corrections @ NLO and NNLO

  — higher multiplicity (3 jets @ NNLO, NNLO QCD corr. to Httbar ...)