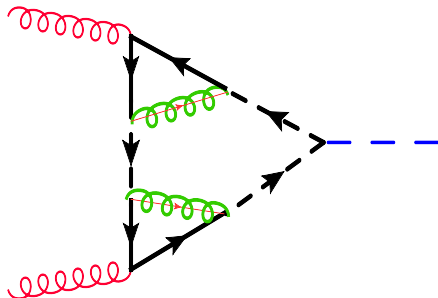
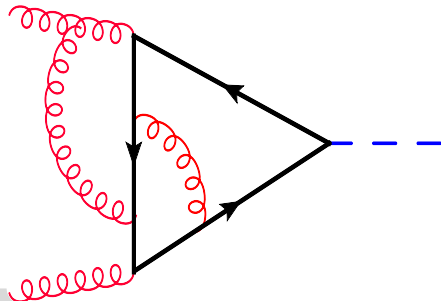


Higgs boson production in the SM and MSSM to NNLO

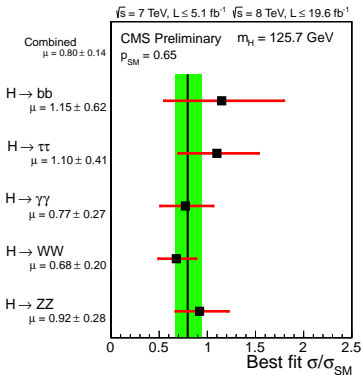
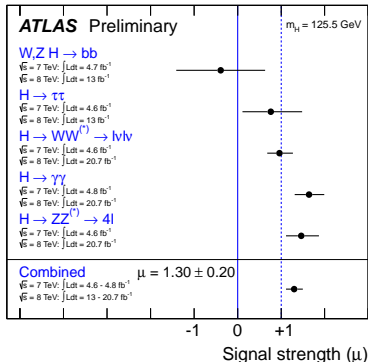
LHCP, Barcelona, May 2013

Matthias Steinhauser | TTP Karlsruhe

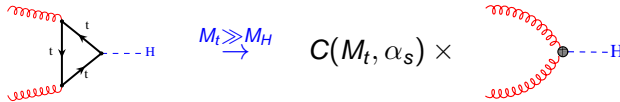


- NNLO MSSM
- Towards N³LO in the SM

Higgs boson discovery



SM:



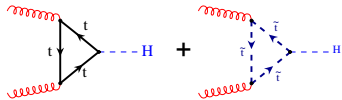
MSSM:

$$C = C(M_t, M_{\text{SUSY}}, \alpha_s)$$

Aim: Compute NNLO corrections in MSSM — as in SM

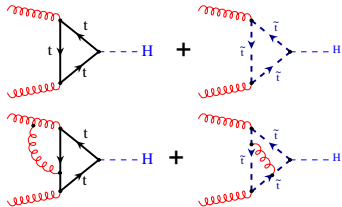
[only gluon fusion]

Gluon fusion in SUSY



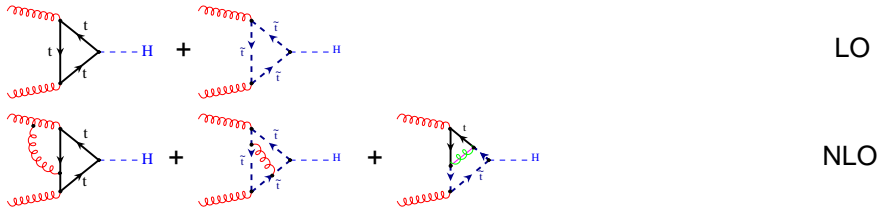
LO

Gluon fusion in SUSY

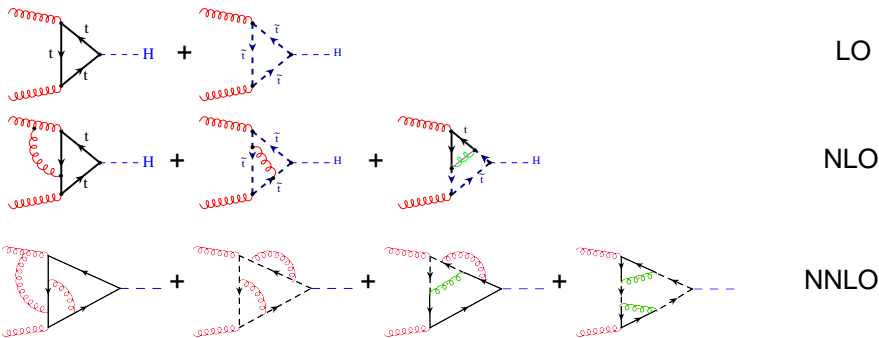


LO

Gluon fusion in SUSY

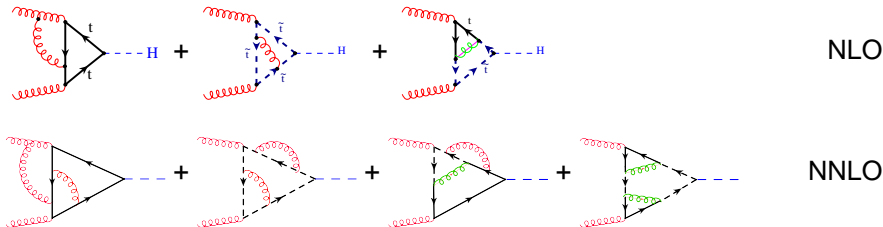


Gluon fusion in SUSY



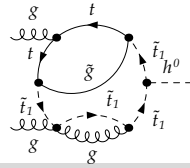
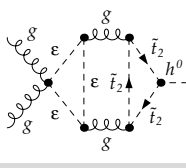
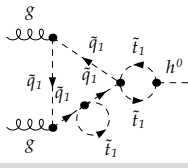
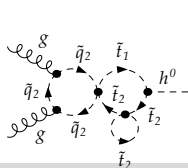
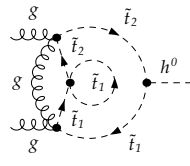
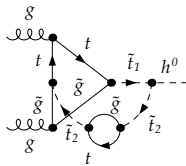
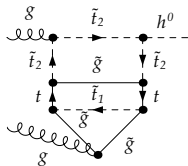
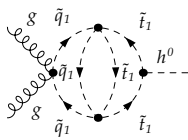
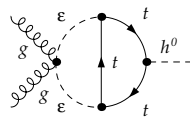
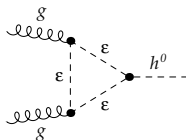
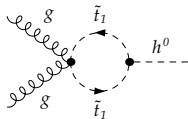
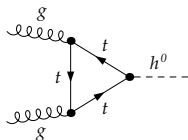
+ 57936 more Feynman diagrams

Gluon fusion in SUSY



- NLO SUSY-QCD, $M_H \ll M_{SUSY}$, (t, \tilde{t}) sector [Harlander, Steinhauser'03'04; Deggrasi, Slavich'08]
- NLO squark loops [Aglietti, Bonciani, Deggrasi, Vicini'07; Mühlleitner, Spira'08]
- NLO SUSY-QCD, (b, \tilde{b}) sector [Anastasiou et al.'07; Deggrasi, Slavich'11; Harlander, Hofmann, Mantler'11]
- NLO SUSY-QCD "full theory" [Anastasiou, Bucherer, Daleo'07; Mühlleitner, Rzehak, Spira]
- NNLO SUSY-QCD, $M_H \ll M_{SUSY}$, (t, \tilde{t}) sector [Pak, Steinhauser, Zerf'10'12]
- SusHi [Harlander, Liebler, Mantler'12]

Coefficient function C to 3 loops (NNLO)



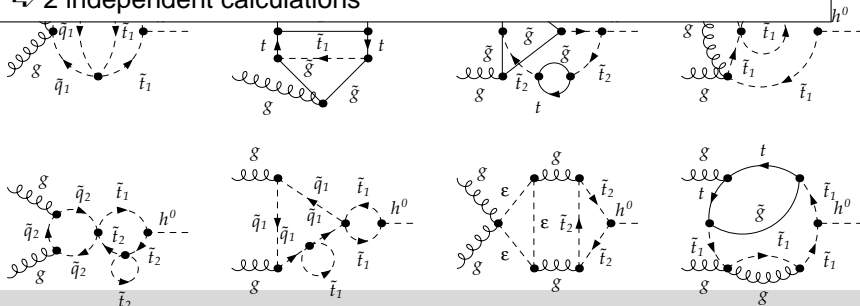
Coefficient function C to 3 loops (NNLO)



$C(M_t, M_{\text{SUSY}}, \alpha_s)$ to 3 loops:

- direct calculation of vertex diagrams [Pak,Steinhauser,Zerf'12]
- 2-point function \oplus low-energy theorem [Kurz,Zerf,Steinhauser'12]

⇒ 2 independent calculations

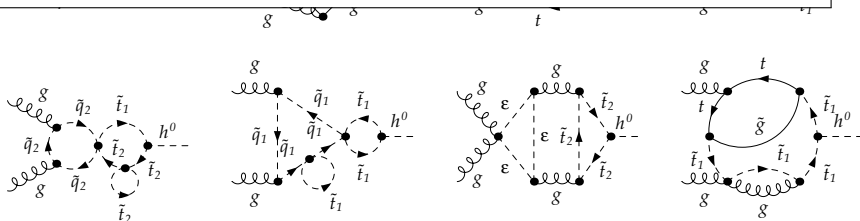


Coefficient function C to 3 loops (NNLO)



Subtleties

- many mass scales: $m_t, m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{q}}, m_{\tilde{g}}$
- $\overline{\text{DR}}$ scheme in MSSM \rightarrow $(\overline{\text{MS}})$ in eff. theory (SM)
- Dimensional Reduction (DRED), ϵ scalar
 - ⇒ new operators in effective theory
- ...



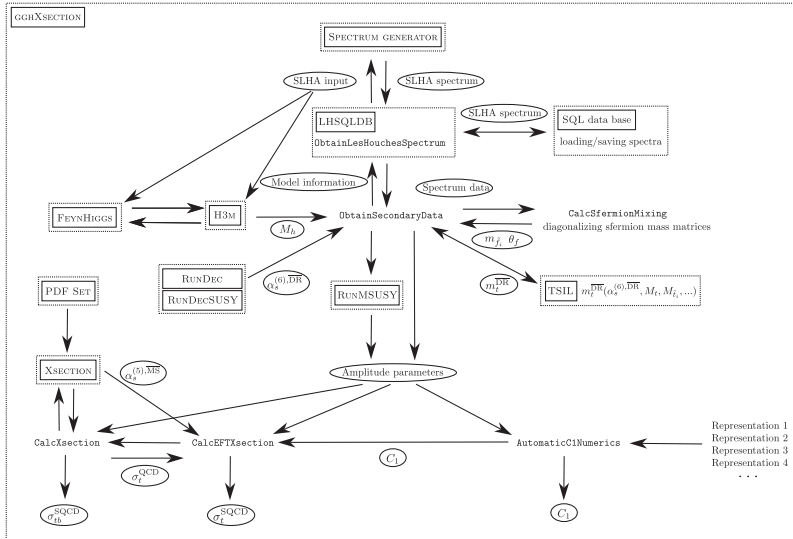
$$\sigma(gg \rightarrow h + X)$$

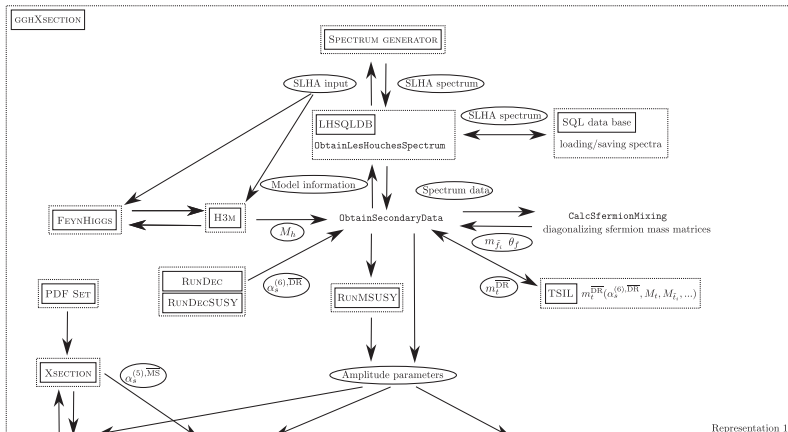
$$\sigma(pp \rightarrow h + X) = (1 + \delta^{\text{EW}}) \times \left[\sigma_{tb}(\mu_s) \Big|_{\text{NLO}} - \sigma_t(\mu_s) \Big|_{\text{NLO}} + \sigma_t(\mu_s, \mu_h) \Big|_{\text{NNLO}} \right]$$

- δ^{EW} : NLO electroweak corrections (SM): [Actis,Passarino,Sturm,Uccirati'08]
- σ_{tb} : NLO top/stop and bottom/sbottom contribution

[Degrassi,Slavich'11; Harlander,Hofmann,Mantler'11]

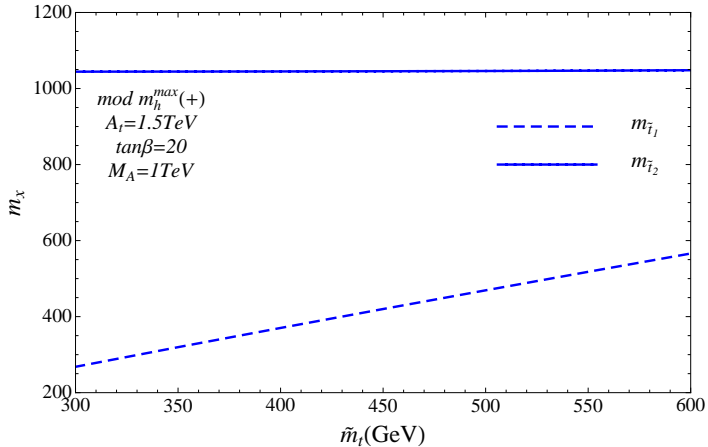
- NNLO: top/stop/sbottom ($m_b = 0$)



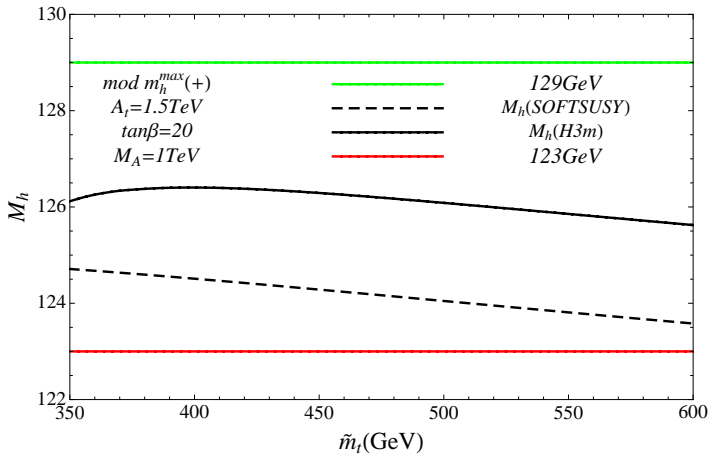


- **softsusy: SUSY spectrum** [Allanach]
- **FeynHiggs** [Frank,Hahn,Heinemeyer,Hollik,Rzehak,Weiglein]
- **H3m: M_h to 3 loops** [Kant,Harlander,Mihaila,Steinhauser]
- **TSIL: stop \overline{DR} -on-shell relation to 2 loops** [Martin,Robertson'05]

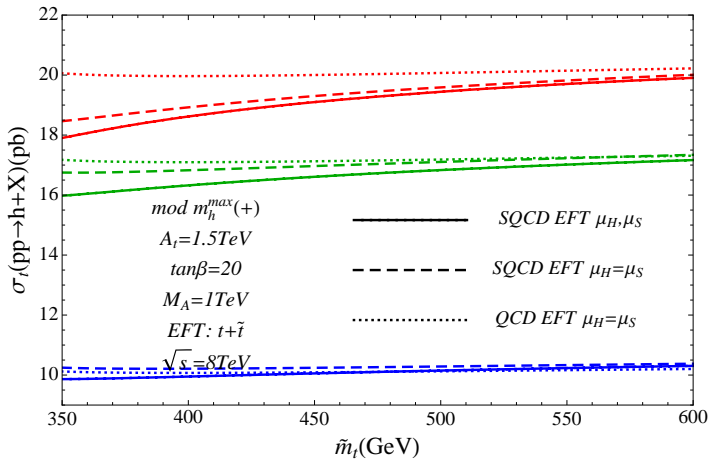
modified m_h^{\max}



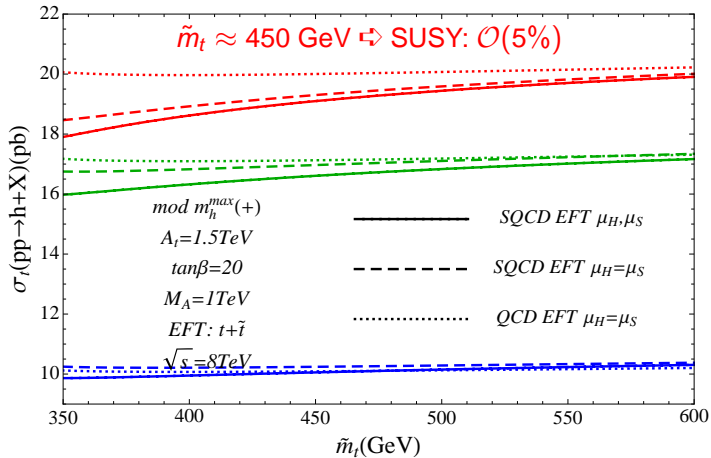
[Pak,Steinhauser,Zerf'12]



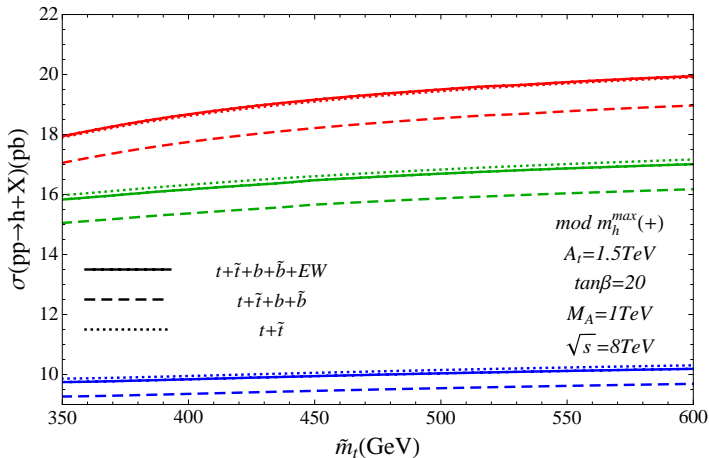
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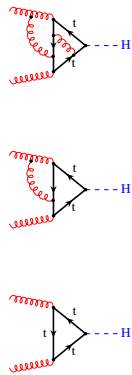
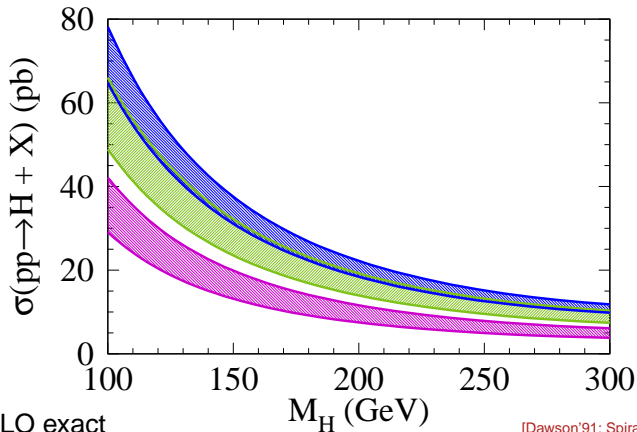


[Pak, Steinhauser, Zerf'12]



[Pak,Steinhauser,Zerf'12]

SM: gluon fusion to NNLO



NLO exact

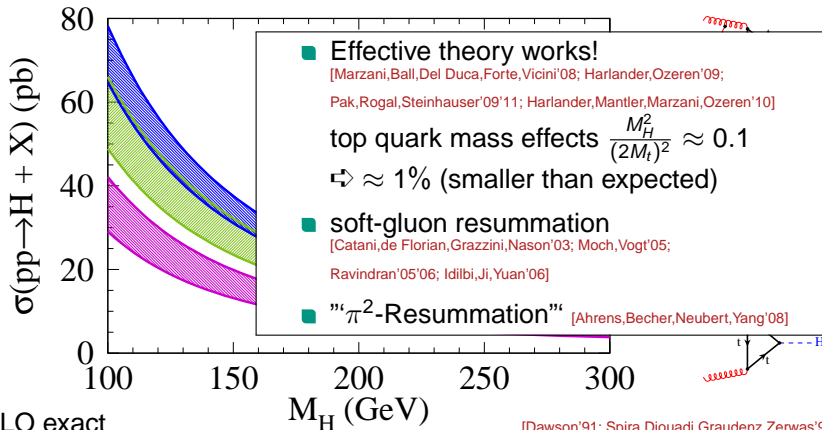
NNLO $m_t \rightarrow \infty$

uncertainty from higher order: $\approx 10\%$

[Dawson'91; Spira,Djouadi,Graudenz,Zerwas'91'93]

[Harlander,Kilgore'02; Anastasiou,Melnikov'02; Ravindran,Smith,v.Neerven'03]

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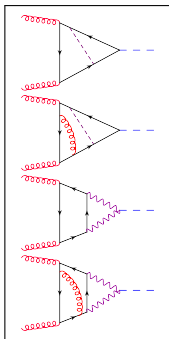
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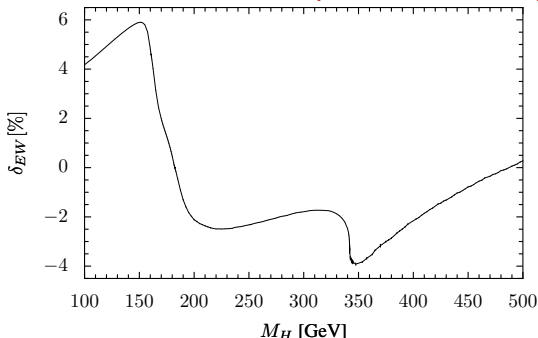
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[Harlander,Kilgore'02; Anastasiou,Melnikov'02; Ravindran,Smith,v.Neerven'03]

Gluon fusion: EW corrections



[Actis, Passarino, Sturm, Uccirati'08]



- EW $\mathcal{O}(G_F m_t^2)$: $\approx 0.5\%$
- EW/QCD $\mathcal{O}(\alpha_s G_F m_t^2)$: $\approx 0.5\%$
- EW $\mathcal{O}(\alpha)$: $\approx 5\%$
- EW/QCD $\mathcal{O}(n_f \alpha \alpha_s)$: $\approx 1\%$ \Leftrightarrow “complete factorization”
- EW to real rad.: $\approx 1\%$

[Djouadi, Gambino'94]

[Steinhauser'98]

[Aglietti et al.'04; Degrassi, Maltoni'04; Actis, Passarino, Sturm, Uccirati'08]

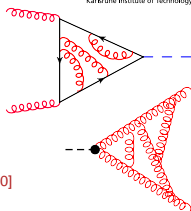
[Anastasiou, Boughezal, Petriello'09]

[... Keung, Petriello'09; Brein'10; Anastasiou, et al.'11]

Towards N³LO in the SM

- Four-loop (N³LO) matching coefficient $C(M_t, \alpha_s)$

[Chetyrkin, Kniehl, Steinhauser'98; Schröder, Steinhauser'04; Chetyrkin, Kühn, Strum'04]



- Three-loop (N³LO) Higgs-gluon-gluon form factor

[Baikov, Chetyrkin, Smirnov, Smirnov, Steinhauser'09; Gehrmann, Glover, Huber, Iklizlerli, Studerus'10]

⇒ virtual N³LO corrections known

- NNLO master integrals computed to $\mathcal{O}(\epsilon)$

[Pak, Rogal, Steinhauser'11; Anastasiou, Buehler, Duhr, Herzog'12]

- NNLO cross section $\sigma(gg \rightarrow H + X)$ to $\mathcal{O}(\epsilon)$

[Höchele, Hoff, Pak, Steinhauser, Ueda'12]

- All infra-red counterterms at N³LO

[Höchele, Hoff, Pak, Steinhauser, Ueda'12]

- $\sigma_{gg}^{\text{soft}}$ at N³LO: expansion around $y = 1 - M_H^2/s \rightarrow 0$
(triple-real contribution)

[Anastasiou, Duhr, Dulat, Mistlberger'13]

- $pp \rightarrow H + \text{jet}$ at NNLO

[Boughezal, Caola, Melnikov, Petriello, Schulze'13]

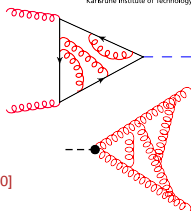
- approximate N³LO → talk by M. Bonvini

[Ball, Bonvini, Forte, Marzani, Ridolfi'13]

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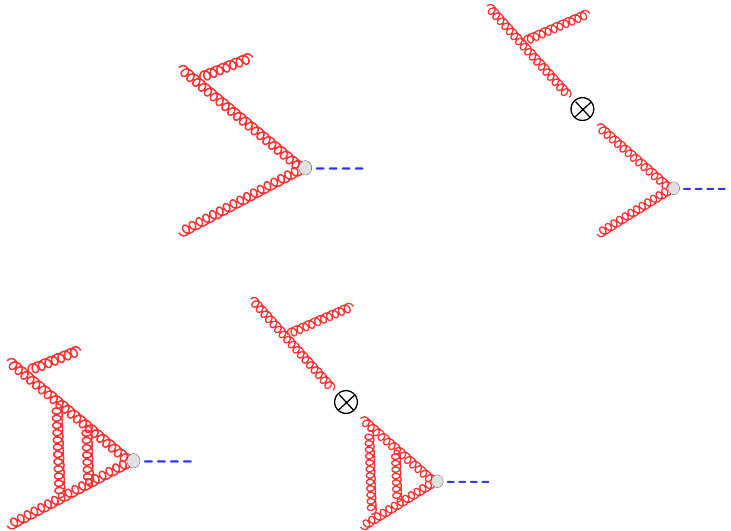
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[Ball, Bonvini, Forte, Marzani, Ridolfi'13]

Collinear singularities from initial state



“Collinear CTs”

- $P_{gg}^{(0)} \otimes \sigma_{gg}^{NNLO}$

- $P_{gg}^{(1)} \otimes \sigma_{gg}^{NLO}$

- $P_{gg}^{(0)} \otimes \sigma_{gg}^{NLO} \otimes P_{gg}^{(0)}$

- $[f \otimes g](x) = \int_0^1 dx_1 dx_2 \delta(x - x_1 x_2) f(x_1) g(x_2)$

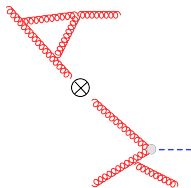
- Mellin space $M_n[f(x)] = \int_0^1 dx x^{n-1} f(x)$

- “Harmonic polylogarithms” (HPLs) up to weight 4

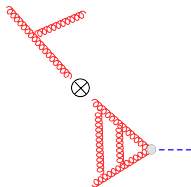
$$\left\{ H_{\vec{w}(4)}, \frac{H_{\vec{w}}}{1-x}, \left[\frac{\ln^k(1-x)}{1-x} \right]_+, \dots \right\} \otimes \left\{ \frac{1}{x}, \frac{1}{1-x}, \frac{1}{1+x} \right\}$$

some are “problematic” for $x \rightarrow 1$

- algorithm which allows unified treatment



[Remiddi, Vermaseren'99]



[Hörschele, Hoff, Pak, Steinhauser, Ueda'12]

⇒ all N³LO collinear counterterms

- NNLO corrections to $gg \rightarrow H + X$ in the MSSM
- first steps towards N³LO in the SM