Associated Production of Higgs Bosons and Heavy Quarks in Two Photon Collisions at NLO

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Outline

- Introduction
- Born results
- NLO calculations
- Outlook

Introduction

Laser back-scattering technique

$\longrightarrow$ A future Linear Collider could be run in two photon mode

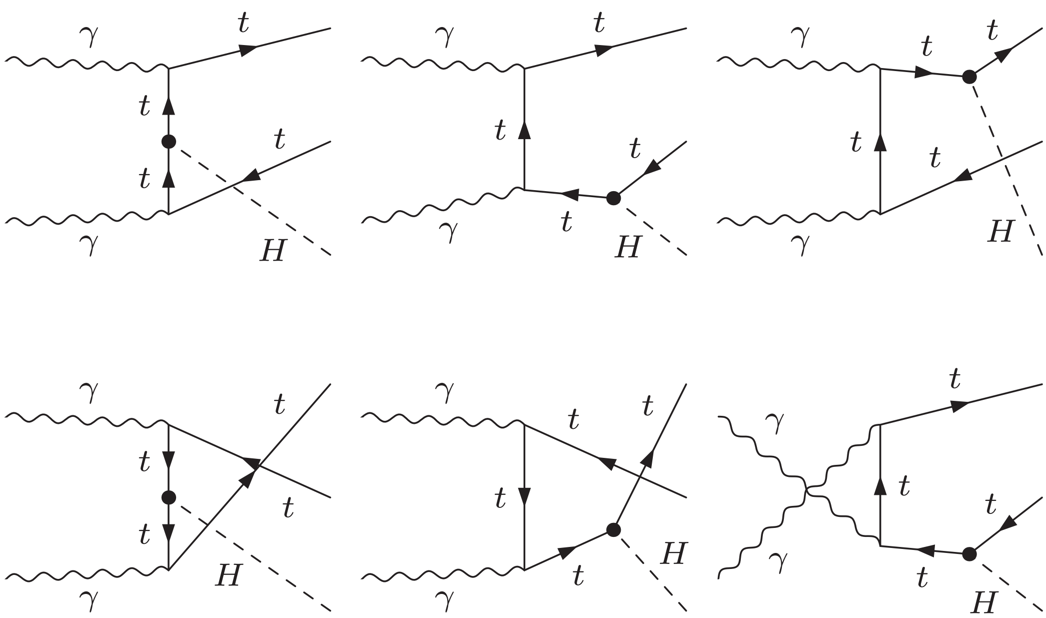
$\longrightarrow$ Processes which proceed via two photon collisions can be studied

$\longrightarrow$ Calculate cross sections of subprocesses and integrate over photon distributions

It turns out that the photon collider is a very useful tool

In this work: $\gamma\,\gamma \to t\,\bar{t}\,H$ at $\mathcal{O}(\alpha_s)$

Born niveau diagrams:

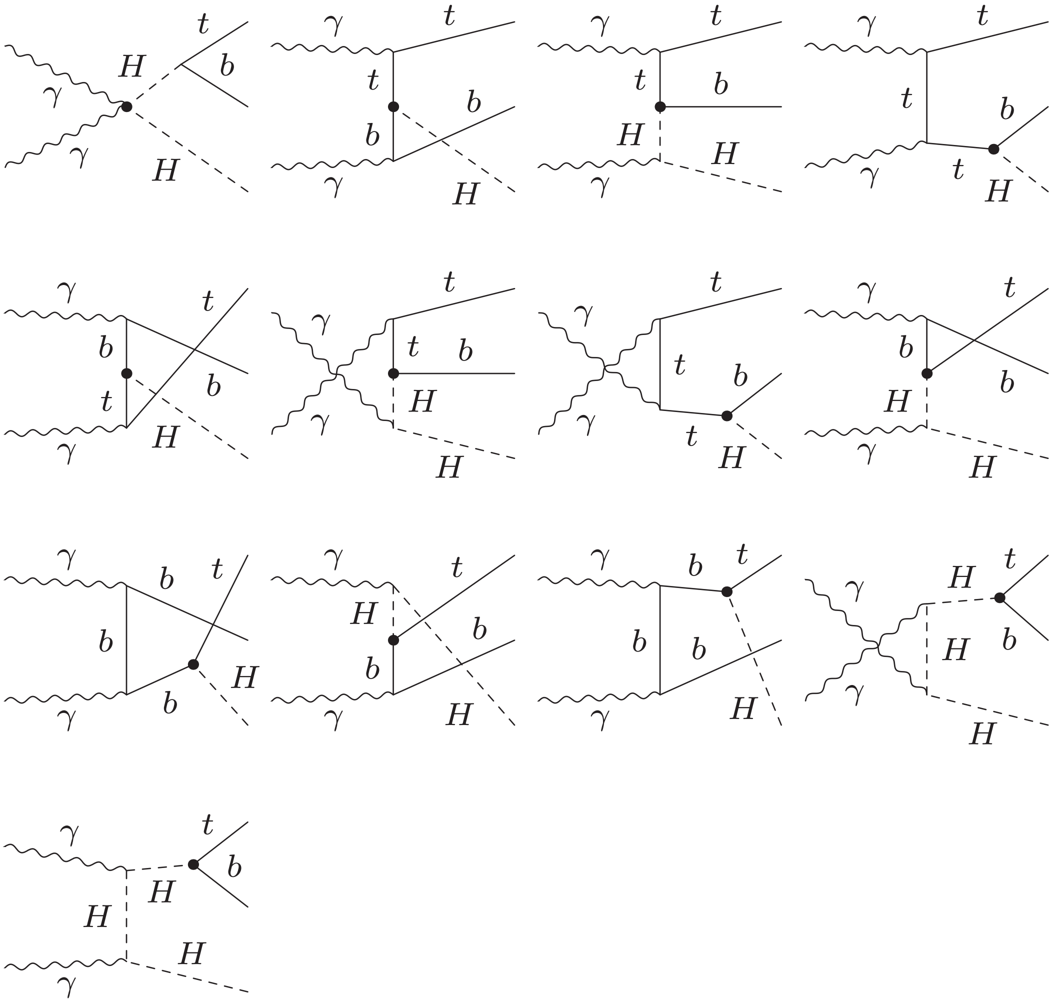


→ Check on results given in literature
→ Good test of applied methods

Associated Higgs production also possible in e^+e^--collisions: → Compare results

Then one could consider: $\gamma\,\gamma \to t\,\bar{b}\,H^- \;/\; \bar{t}\,b\,H^+$ at $\mathcal{O}(\alpha_s)$

Born niveau diagrams:



Known results for $\gamma\gamma$ collisions

- All cross sections known at LO
  $\rightarrow Q\bar{Q}H$: [Boos *et al.*], [Cheung]
  $\rightarrow Q\bar{Q}\Phi$: [Guo *et al.*]
  $\rightarrow tbH^{\pm}$: [He *et al.*], [Kanemura *et al.*]

- $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_{ew})$ results known for $Q\bar{Q}H$
  $\rightarrow$ [Hui *et al.*]

Known results for e^+e^--collisions

- All cross sections known at LO
  $\rightarrow$ [Djouadi *et al.*], . . .

- QCD results:
  $\rightarrow$ $Q\bar{Q}H$: [Dittmaier *et al.*], [Dawson *et al.*]
  $\rightarrow$ $Q\bar{Q}\Phi$: [Dawson *et al.*], [Dittmaier *et al.*]

- SUSY-QCD results:
  $\rightarrow$ $Q\bar{Q}\Phi$: [Zhu], [Häfliger *et al.*]

- Full $\mathcal{O}(\alpha_s)$ results also known for $t\bar{b}H^-/\bar{t}bH^+$:
  $\rightarrow$ [Kniehl *et al.*]

- $\mathcal{O}(\alpha_{ew})$ results known for $Q\bar{Q}H$:
  $\rightarrow$ [Belanger *et al.*], [Denner *et al.*], [You *et al.*]

Relevance: $\gamma\,\gamma \to Q\,\bar{Q}\,H$ resp. $\gamma\,\gamma \to Q\,\bar{Q}\,\Phi$

- Direct measurement of Yukawa couplings

Relevance: $\gamma\,\gamma \to t\,\bar{b}\,H^- \,/\, \bar{t}\,b\,H^+$

- Direct investigation of $\tan\beta$
- Proof of new physics beyond Standard Model (if $H^\pm$ too heavy to be produced in pairs)

Relevance: NLO corrections

- Increase of precision for prediction
- In particular, reduction of scheme and scale dependences

Born results

- First given in [Boos *et al.*], [Cheung] in 1992
- Also calculated by [Guo *et al.*] in 2000
- Recalculated by [Hui *et al.*] in 2004

$\longrightarrow$ Recent results differ from results published in 1992; results of 2000?

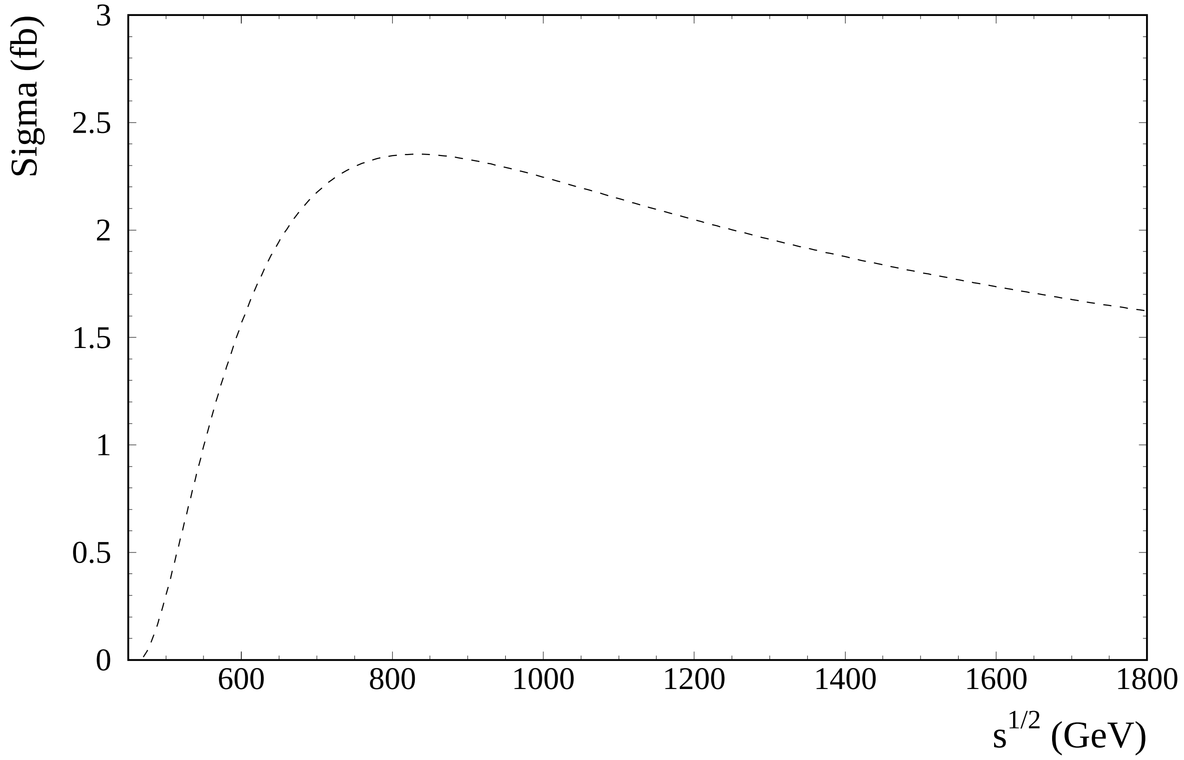
$\longrightarrow$ New and independent calculation desirable

Cross section of subprocess

Calculation:

- Fully automated computation with `FeynArts3.2/FormCalc3.2`

Results:



$M_H = 115$ GeV

Cross section of full process

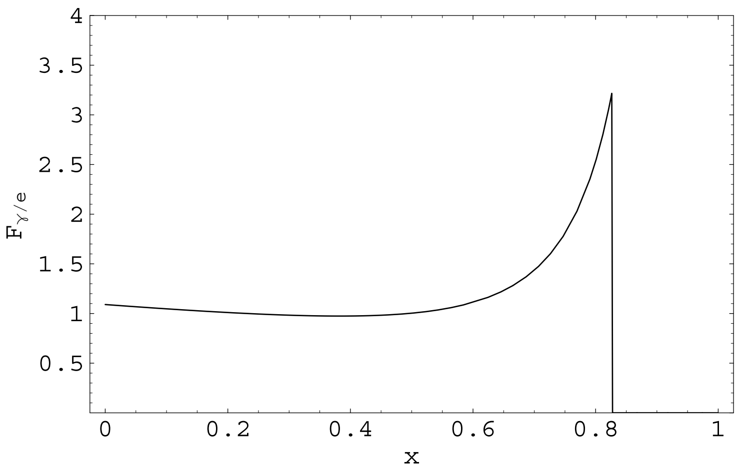
Calculation:

$$\sigma(s) = \int_{x_l}^{x_u} dx_1 \int_{x_l \cdot \frac{x_u}{x_1}}^{x_u} dx_2 \, F(x_1) \, F(x_2) \, \hat{\sigma}(x_1 x_2 s)$$

$$x_u \quad \hat{=} \quad \text{upper limit given by energy spectrum}$$

$$x_l = \frac{(2m_t + M_H)^2}{x_u s}$$

$$\hat{\sigma} \quad \hat{=} \quad \text{cross section of subprocess}$$



Energy spectrum of back-scattered photon
versus energy fraction of incident electron

- Integration over photon distributions carried out together with phase space integration
- Independent calculation of Gudrun Heinrich based on `CompHEP` and a self-made routine for the integration over photon distributions

Results:

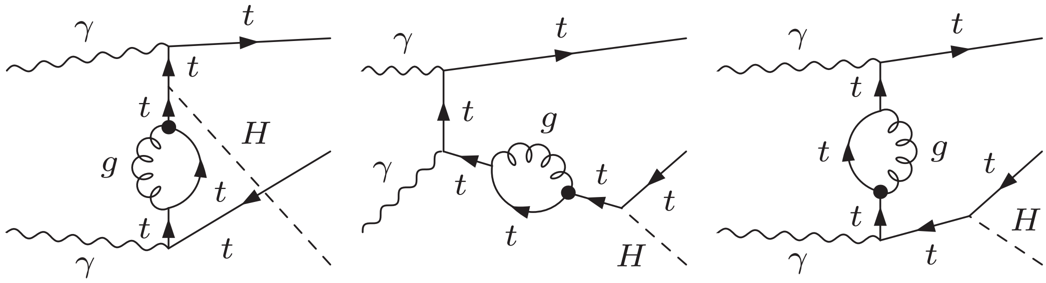
m_t [GeV]	M_H [GeV]	$\sqrt{s}$ [GeV]	σ [fb]
120	60	500	0.390(8)
		1000	2.18(6)
		2000	2.39(1)
150	60	1000	2.74(0)
		2000	3.42(1)
	140	1000	0.311(7)
		2000	0.805(8)
180	140	1000	0.341(2)
		2000	1.05(5)

$\longrightarrow$ In agreement with G. H. and with [Hui *et al.*]
$\longrightarrow$ Variation of parameters does not seem to resolve the problem

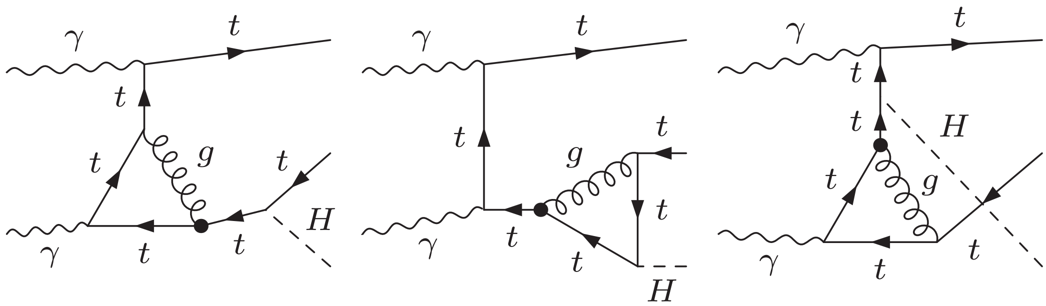
NLO calculations

Diagrams for NLO QCD corrections

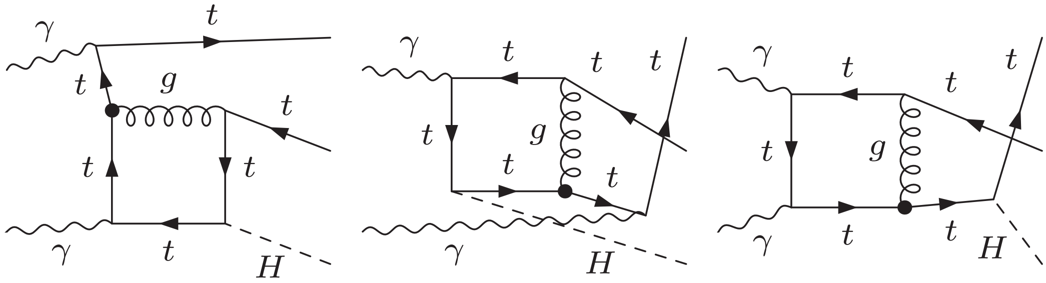
Self-energy corrections



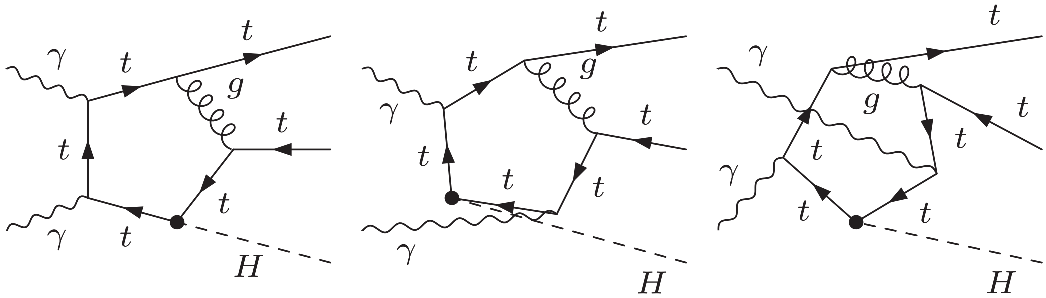
Vertex corrections



Boxes



Pentagons



→ 5-point tensor integrals of rank 3 occur

→ Soft singularities occur which have to be cancelled against IR singularities arising from soft gluon radiation at tree level

Calculations

- Use FeynArts/FormCalc to generate diagrams
- Reduce N-point tensor integrals to "basis" set of scalar integrals [Giele *et al.*]
- Use FORM to perform reduction
- Work in framework of dipole subtraction method [Catani *et al.*]
- Use FORTRAN to integrate over phase space and photon distributions
- Optimisation necessary (Calculate functions only once)

Problem: Exceptional phase space configurations

- Reimplement everything directly in `FORTRAN` ($\longrightarrow$ `FORTRAN90`)
- Again optimise (store integrals when calculated)
- Use methods of [Ellis *et al.*] in order to treat exceptional phase space configurations
- Provide results for "basis" set of scalar integrals $\longrightarrow$ Reduction to master integrals

Independent calculation based on different reduction method performed by Gudrun Heinrich as a strong check on results

Tensor reduction method - [Giele *et al.*]

Notation:

$$I_N^{\mu_1\mu_2\cdots\mu_m}(D;\{q_i\},\{\nu_i\}) = \int \frac{d^D l}{i\pi^{D/2}} \frac{l^{\mu_1} l^{\mu_2}\cdots l^{\mu_m}}{d_1^{\nu_1} d_2^{\nu_2}\cdots d_N^{\nu_N}}$$

$$d_i = (l+q_i)^2 + i0$$

Davydychev decomposition:

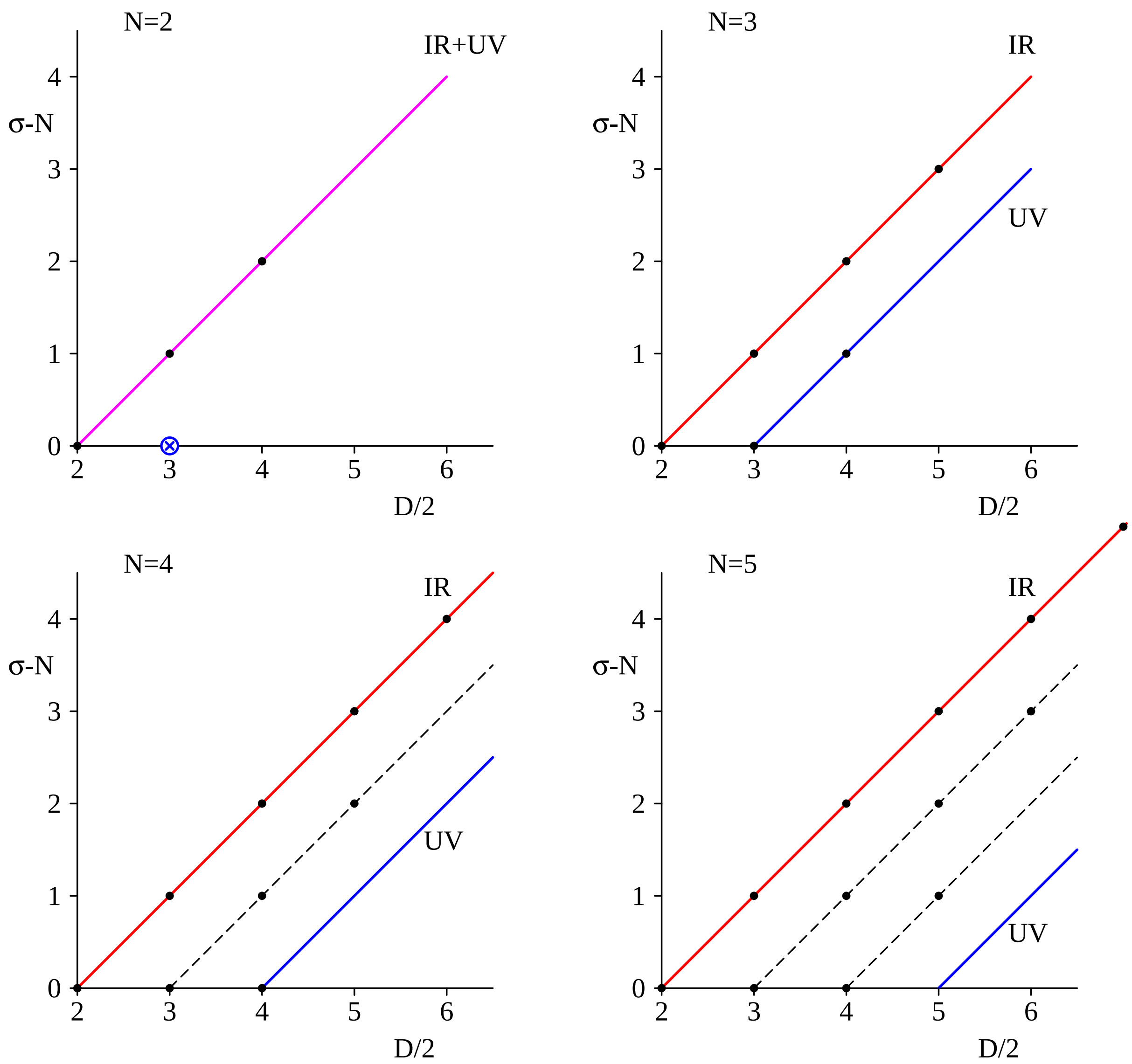
$$I_N^{\mu_1\mu_2\cdots\mu_m}(D;\{q_i\},\{1\}) =$$

$$\sum_{\lambda,x_1,x_2,\ldots,x_N} \delta_{(2\lambda+\sum_i x_i - m)} \left(-\frac{1}{2}\right)^{\lambda} x_1! x_2! \cdots x_N!$$

$$\times \quad \left\{ g^{\lambda} q_1^{x_1} q_2^{x_2} \cdots q_N^{x_N} \right\}^{\mu_1\mu_2\cdots\mu_m}$$

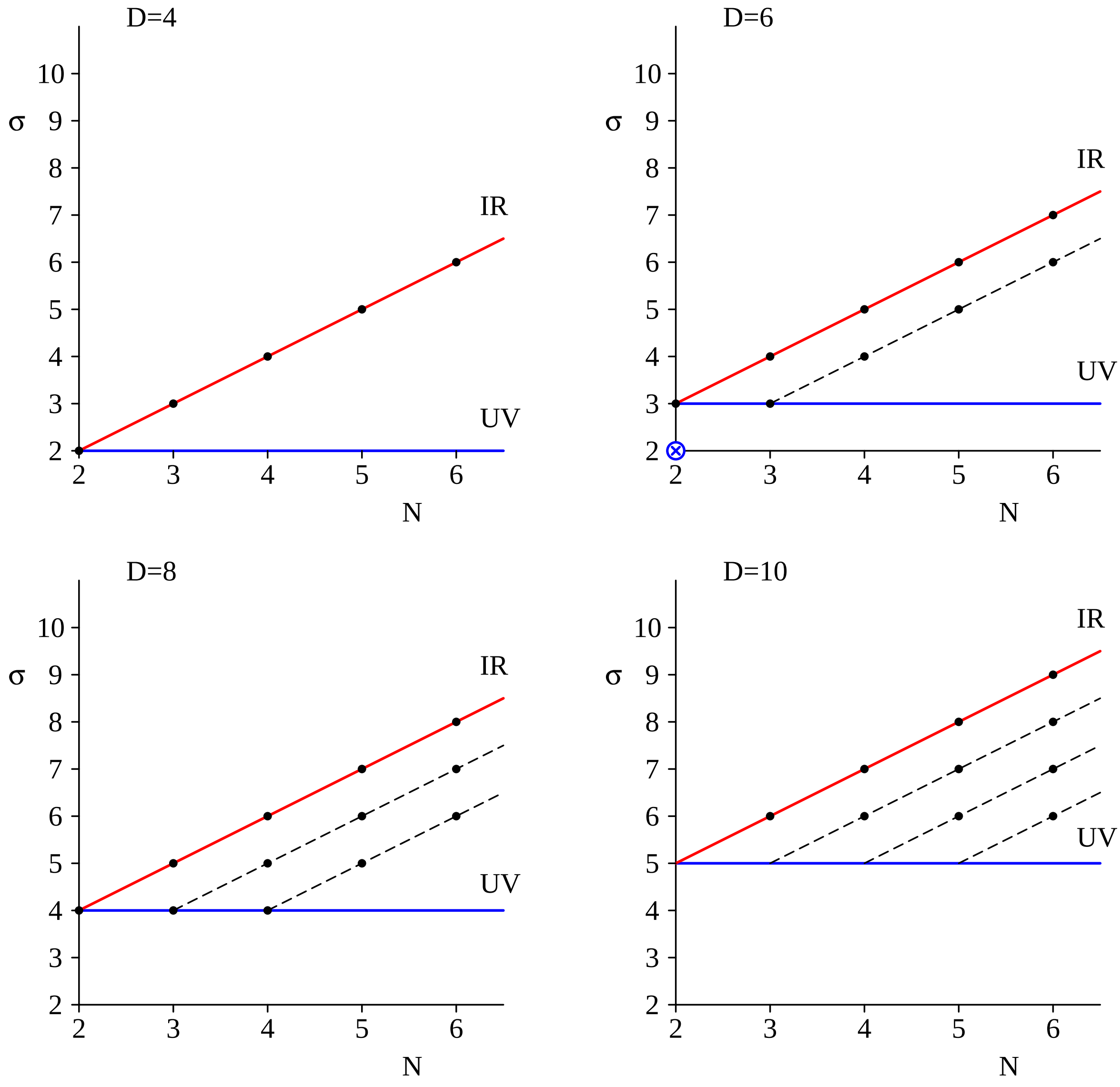
$$\times \quad I_N\left(D + 2(m-\lambda); \{q_i\}, \{1+x_i\}\right)$$

Produced integrals (1):



$$\text{N fixed;} \quad \sigma = \nu_1 + \nu_2 + \cdots + \nu_N$$

Produced integrals (2):



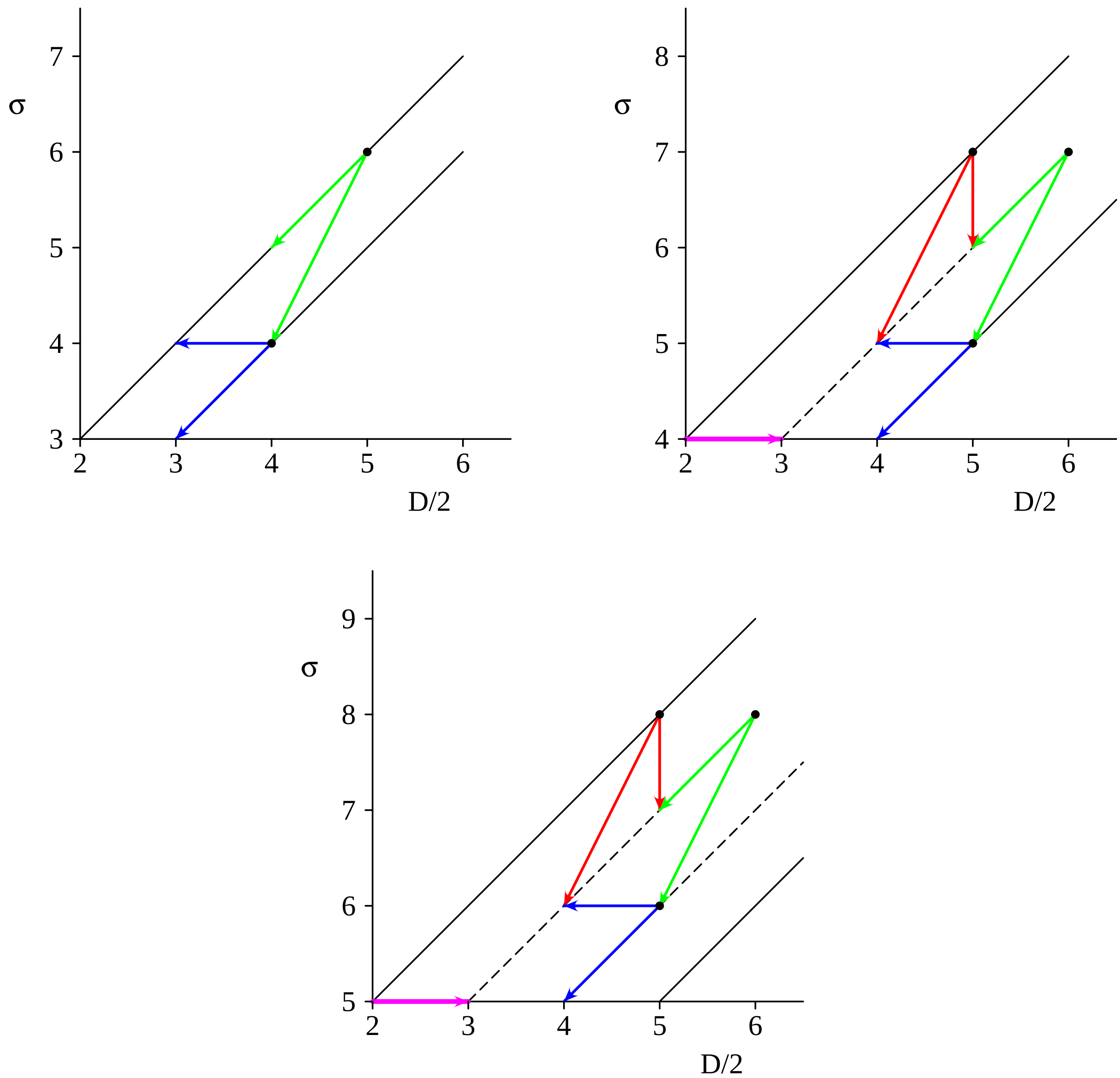
D fixed; $\sigma = \nu_1 + \nu_2 + \cdots + \nu_N$

- Read off "basis" set of UV-divergent integrals
- Derive recursion relations for finite and IR-divergent integrals

$\longrightarrow$ "Basis" set of integrals,

$$
\begin{aligned}
\mathcal{A}_M(p_1, p_2, \ldots, p_M) = & \\
& \sum_{\nu_1\nu_2\nu_3} K^{IR}_{\nu_1\nu_2\nu_3} I^{IR}_3(D = 2(\sigma - 1); \nu_1, \nu_2, \nu_3) \\
+ & \sum_{\{\nu_\ell\}} K^{fin}_{\{\nu_\ell\}} \tilde{I}^{UV}_N (D = 2\sigma; \{\nu_\ell\}) \\
+ & \sum_{\text{triangles}} K^{fin}_3 I^{fin}_3 (D = 4; 1, 1, 1) \\
+ & \sum_{\text{boxes}} K^{fin}_4 I^{fin}_4 (D = 6; 1, 1, 1, 1) \\
+ & \sum_{\text{pentagons}} K^{fin}_5 I^{fin}_5 (D = 6; 1, 1, 1, 1, 1) \\
+ & \sum_{i=1}^{8} K^{UV}_i \mathcal{I}^{UV}_i
\end{aligned}
$$

Recursion relations:



$$\mathrm{N} = 3,\ 4,\ 5; \quad \sigma = \nu_1 + \nu_2 + \cdots + \nu_N$$

- Need to know coefficients of IR-divergent triangles in D dimensions
  $\longrightarrow$ Analytic instead of numeric methods

- Obtained IR-divergent contribution to amplitude is quite complex
  $\longrightarrow$ Hard to cancel IR-divergences analytically

$\longrightarrow$ Direct determination of IR-divergent contribution without use of recursion relations possible

Generalization of formalism to include masses:
$\longrightarrow$ [Dittmaier]

Outlook

Todo list:

- Provide expressions for end points of reduction
- Construct real part according to dipole subtraction method
- Cancel divergences analytically
- Perform phase space integration
- Perform various checks
- . . .