H^+H^- production in Vector Boson Fusion@NNLO-Qcd

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Why Two-Higgs-Doublet-Model (2HDM)?

- Is the discovery of a light scalar with couplings consistent with SM predictions enough to consider SM as a valid perturbative description all the way to Λ_{Planck} ?

- The Higgs boson as an elementary particle comes with an intrinsic instability of its mass under radiative corrections (*naturalness problem*). On top of that EWSB is realized only by trigger the mass parameter μ^2 for the Higgs potential $\mathcal{V} = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$ to negative values.

- In the context of models of EWSB one can consider multiple $SU(2)_L$ (e.g. 2HDM) doublets as well as additional Higgs singlets and triplets.

- SM Higgs Naturalness problem not explained, but different Higgs-fermions coupling structure provided and the spontaneous breakdown of $SU(2)_L \times U(1)_Y$ to $U(1)_{em}$ can be addressed.

- 2HDM can also be embedded in MSSM (and SUSY theories), thus addressing also naturalness problem.

Structure of 2HDM

Φ_1 and Φ_2 denote two complex $Y = 1$, $SU(2)_L$ doublet scalar fields.

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c. \right]$$

$$+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \frac{1}{2}\lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \frac{1}{2}\lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)$$

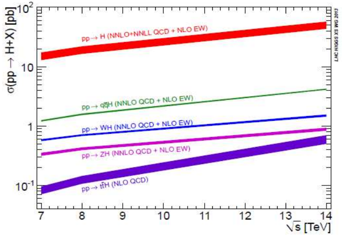
$$+ \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\right] \Phi_1^\dagger \Phi_2 + h.c. \right\}$$

1. Explicit CP-violation from complex parameters.
2. Tree-level MSSM: $\lambda_1 = \lambda_2 = \frac{1}{4}(g^2 + g'^2)$, $\quad \lambda_3 = \frac{1}{4}(g^2 - g'^2)$
   $\lambda_4 = -\frac{g^2}{2}$, $\quad \lambda_5 = \lambda_6 = \lambda_7 = 0$, $m_{12}^2 = m_A^2 \cos\beta \sin\beta$
3. EWSB: 3 Goldstone Bosons $G^\pm, G$ 'eaten' by $W^\pm, Z$,
   2 CP-even scalars h, H ($m_h \leq m_H$), one CP-odd scalar A , charged Higgs pair $H^\pm$.
4. Rich phenomenology is possible!
   CP-violation, FCNC, Scalar charged current, Dark matter

... see A.Nikitenko talk

Why Vector Boson Fusion channel?

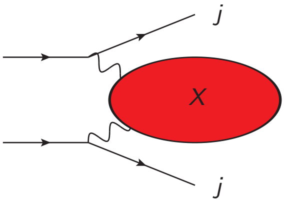
1. SM-Higgs via VBF is the second dominant channel after $gg \to h$



2. Given $p + p \to X + j + j$, with X any set of particles being a color-singlet coupled only via EW (e.g. $H^+H^-, HH, ...$) , then X is produced in $y \sim 0$ region and 2 jets j in forward/backward region
3. Hadronic activity in the central region suppressed (EW LO process!) $\Rightarrow$ clear signature for VBF!
4. Predictions for SM-Higgs in VBF cross-section known with great accuracy (NLO-QCD and NLO-EW available in MC generators, NLO+PS in MG5_aMC, parts of NNLO-QCD also available).

Status of the Art - 2HDM in VBF

$q + q' \to X + j + j$:



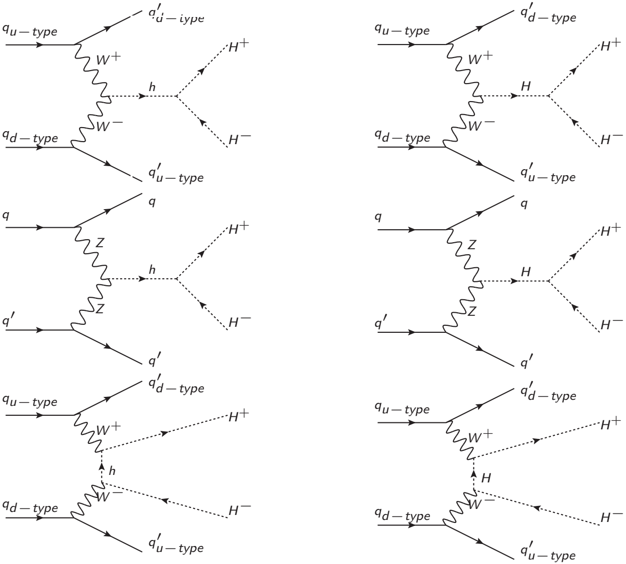
2HDM implemented in MG5_aMC@NLO generator $\Rightarrow$ any process like $p + p \to X + j + j$ (X any scalar color-singlet set coupled only via EW (e.g. H^+H^-, HH, hh, HA, hA...)) can be generated @ NLO+PS!

We aim at further increasing accuracy!

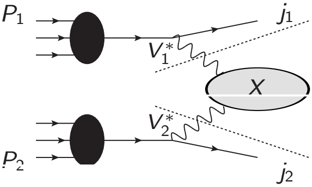
1. implement NNLO-QCD in Structure Function (SF) approach for 2HDM via VBF processes
2. NNLO-QCD partial differential (X-observables)
3. NLO+PS fully differential cross-sections

Case study : $p + p \to H^+ + H^- + j + j$ @ NNLO.

Tree-level Diagrams for H^+H^- production in VBF



Structure Functions (SF) approach to VBF



$X - h, H, H^+H^-, hh, HH, \ldots$

$$d\sigma = \frac{1}{S}\frac{G_F^2 M_{V_1}^2 M_{V_2}^2}{(Q_1^2+M_{V_1}^2)^2(Q_2^2+M_{V_2}^2)} W_{\mu\nu}\left(x_1, Q_1^2, m_{j_1}^2\right) \mathcal{M}^{\mu\rho}_{V_1V_2X}\mathcal{M}_{V_1V_2X}{}^{*\mu\rho}\, W_{\rho\sigma}\left(x_2, Q_2^2, m_{j_2}^2\right)$$

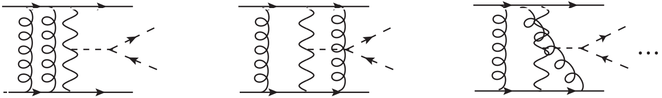
$$\times \frac{d^3p_{j_1}}{(2\pi^3 2E_{j_1})}\frac{d^3p_{j_2}}{(2\pi)^3 2E_{j_2}} ds_1 ds_2 \frac{d^3p_X}{(2\pi)^3} 2E_X (2\pi)^4 \delta^{(4)}(p_1+p_2-p_X-p_{j_1}-p_{j_2})$$

- Being the bulk of the process $V_1^* + V_2^* \to X$ EW, QCD corrections factorize!
- Factorization holds exact up to NLO, at NNLO becomes an approximation.

Structure Functions approach @NNLO

We neglect 2 kinds of diagrams @NNLO.

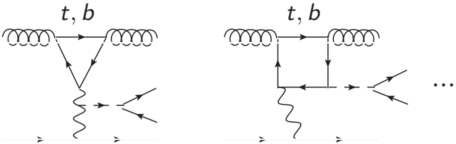
GLUON EXCHANGE ACROSS 2 HADRONIC CURRENTS



$\simeq \frac{1}{N_c^2}$

- $1/N_c^2$ suppressed, gauge invariant
- @NLO typically 10% of DIS-like corrections for SM-Higgs

$t-b$ LOOPS DIAGRAMS



$\simeq 0.001\sigma_{tot}$

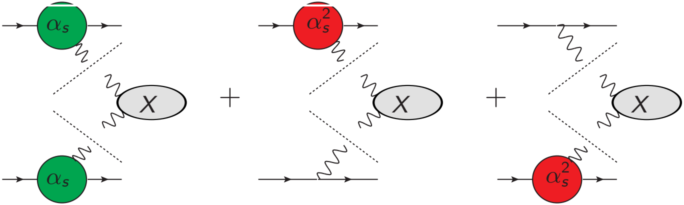
- gauge invariant
- below per-mil of total VBF SM-Higgs cross-section

CC-DIS form factors

$$W_{\mu\nu}(x,Q^2,m^2) = F_1(x,Q^2,m^2)\left(-g_{\mu\nu}+\frac{q_\mu q_\nu}{q^2}\right)+\frac{F_2(x,Q^2,m^2)}{P\cdot q}\left(P_\mu-\frac{P\cdot q}{q^2}q_\mu\right)\left(P_\nu-\frac{P\cdot q}{q^2}q_\nu\right)$$
$$-i\frac{F_3(x,Q^2,m^2)}{2P\cdot q}\epsilon_{\mu\nu\rho\sigma}P^\rho q^\sigma + F_4(x,Q^2,m^2)q_\mu q_\nu + F_5(x,Q^2,m^2)(P_\mu q_\nu + P_\nu q_\mu)$$

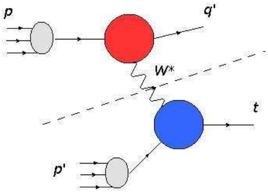
Form factors F_i computed perturbatively thanks to QCD factorization

$$d\sigma_X = \sum_{a,b}\int_{x_1}^1\int_{x_2}^1 \frac{dz_1}{z_1}\frac{dz_2}{z_2} f_a\left(\frac{x_1}{z_1},\mu_F^2\right) f_b\left(\frac{x_2}{z_2},\mu_F^2\right) \times d\hat{\sigma}_{ab\to X}\left(z_1,z_2,\alpha_s(\mu_R^2),\frac{Q^2}{\mu_F^2}\frac{Q^2}{\mu_R^2}\right)$$



- massless current $q_{light} \to q'_{light} + V^*$@NNLO available $\Rightarrow$ ready for VBF!
- but massive current $q_{light} \to q'_{heavy} + V^* \Rightarrow F_i$s 'almost' computed analitically @NNLO.. $p+p \to H^+ + H^- + j + t$ can be explored

Massive Form Factors from SingleTop@NNLO in CC-DIS approach



$$d\sigma \propto \frac{1}{(Q^2+M_W^2)} W_{\mu\nu}(x_1, Q^2, 0) \frac{1}{(Q^2+M_W^2)} W^{\mu\nu}(x_2, Q^2, m_t^2) dQ^2 dW_1^2 dW_2^2$$

- $Q^2 \rightarrow$ virtuality of exchanged boson
- $W_1^2 = 2P_1 \cdot q - Q^2$, $W_2^2 = -2P_2 \cdot q - Q^2 \rightarrow$ hadronic remnants invariant masses
- x_1, x_2 natural DIS variables $x_1 = \frac{Q^2}{W_1^2+Q^2}$, $\quad x_2 = \frac{mt^2+Q^2}{W_2^2+Q^2}$
- Integration over final state quarks and extra-radiation performed analitically in SF! $\mathbf{W^{\mu\nu}(x_2, Q^2, m_t^2)}$ describes **massive** current!
- Integrations over Q^2, W_1^2, W_2^2 performed numerically

Master Integrals : Why and How?

Why?

- Loop and Phase Space integrations performed in (almost) the same way
- Part of the computation can be authomatized (... towards authomatic NNLO?)

How? Computation naturally divided in 3 steps

1. Reduction of scalar matrix elements to *master integrals*
   (automatic via `FIRE` by A.Smirnov)
2. Explicit evaluation of master integrals (MIS)
   via Differential Equations in Canonical Basis (see T.Gehrmann talk!)
3. Plug-in of evaluated MIS into matrix elements, possibly "cosmetics",
   finally Renomarmalization (not trivial because of m_t^2)

CC-DIS Form Factors via MIs: some numbers

bottom-initiated processes (b-nonsinglet channel)

	SubProcess	Feynman diagrams	Phase Space diagrams	Topologies	Phase Space integrals	Masters integrals	
RR	$bW^* \to tgg$	5	21	3	$\mathcal{O}(200)$	11	
	$bW^* \to tq\bar{q}$	2	3	1	$\mathcal{O}(50)$	3	
	$bW^* \to tb\bar{b}$	4	10	1	$\mathcal{O}(120)$	7	18
RV	$bW^* \to tg$	10	20	3	$\mathcal{O}(400)$	21	21
VV	$bW^* \to t$	12	12	5	$\mathcal{O}(500)$	18	18

- $\Rightarrow b + W^* \to t + X|_{\mathcal{O}(\alpha_s^2)}$ described by $\mathcal{O}(60)$ masters.
- Canonical DE for Master Integrals directly linear in all variables.

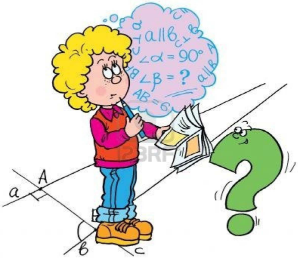
gluon-initiated processes (gluon channel)

- $\mathcal{O}(20)$ new Master Integrals...but more complicated (*quadratic letters!*)
- $\Rightarrow$ remappings to linearize the DEs were needed!...achieved 3 weeks ago!

Conlusions and Outlook

1. Intro to 2HDM and Motivation for interest in Vector Boson Fusion channel for SM and BSM-Higgs(es)
2. Structure Function approach to VBF
3. Analytic massive current $q_{light} + W^* \rightarrow q_{heavy}$ almost available, allows for $H^+ + H^- + t + j$
4. Computation of Massive Form Factors carried out for SingleTop@NNLO: Set of Master Integrals now available, now Renormalization..

Heavy mathematical effort...



$\Rightarrow$

... one more step towards precision physics for the LHC.

Back-up slides

Constraints on the 2HDM potential

1. **Vacuum stability.**
   $\mathcal{V}$ must be bounded from below. No directions in parameters space such that $\mathcal{V} \to -\infty$.

$$\lambda_1, \lambda_2 > 0, \quad \lambda_3 > \sqrt{\lambda_1 \lambda_2}$$

$$\text{If } \lambda_6 = \lambda_7 = 0 \Rightarrow \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}$$

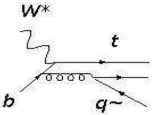
2. **Perturbativity.**
   All λ_i and Yukawa bounded from above : $|\lambda_i| < 4\pi$.
3. **S-matrix Unitarity.**
   Tree-level unitarity of HH and HV scattering sets opper limits on combinations of the λ_i.
4. **Oblique EW parameters.**
   To ensure $\rho \simeq 1$ (custodial simmetry): $m_{H^+}^2 = m_A^2$, $(\lambda_4 = \lambda_5)$.

Phase Space Integrals as Loop Integrals: a diagrammatic example

Reverse unitarity : $\delta_+(q^2) \rightarrow \left(\frac{1}{q^2}\right)_c = \frac{1}{2\pi i}\left(\frac{1}{q^2+i0} - \frac{1}{q^2-i0}\right)$

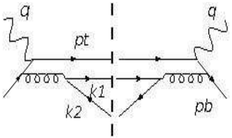
Ex. RR : $\sigma(b + W^* \rightarrow t + q + \bar{q})^{0loops}$

Feynman diagram



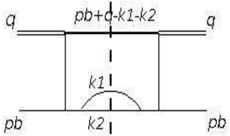
rank-1 tensor

Square modulus * $P_i^{\mu\nu}$



$$\Rightarrow \int d^D k_1 d^D k_2 d^D p_t \delta_+ (k_1)^2\, \delta_+ (k_2)^2\, \delta_+ \left(p_t^2 - m_t^2\right) \delta\left(p_t - (p_b + q - k_1 - k_2)\right) |\mathcal{A}|^2$$

Feynman integral:
2-loop scalar integral over k_1, k_2

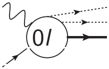


$$\Rightarrow \int d^D k_1 d^D k_2 \frac{1}{k_1^2} \frac{1}{k_2^2} \frac{1}{(p_b + q - k_1 - k_2)^2 - m_t^2} |\mathcal{A}|^2$$

NNLO computation organization

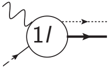
$$\sigma(b + W^* \to t + X)_{\mathcal{O}(\alpha_s^2)} = ???$$

RR: $\sigma(b + W^* \to t + X)^{0loops}_{X=gg,q\bar{q},b\bar{b}}$
$+\sigma(g + W^* \to t + g + \bar{b})$
$+\sigma(q + W^* \to t + q + \bar{b})$



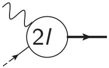
$\to$ 2 Phase Space integration

RV: $\sigma(b + W^* \to t + X)^{1loops}_{X=g}$
$+\sigma(g + W^* \to t + \bar{b})^{1loops}_{X=g}$



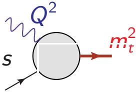
$\to$ 1 Phase Space + 1 Loop integration

VV: $\sigma(b + W^* \to t)^{2loops}$



$\to$ 2 Loop integration

2 $\to$ 1 process, but governed by **3 hard scales s, mt^2, Q^2** !



RR, RV, VV computed via a unique technique:

MASTER INTEGRALS (+ reverse unitarity for phase space integrations)