CHARGED HIGGS PRODUCTION IN POWHEG

KAROL KOVAŘÍK

INSTITUT FÜR THEORETISCHE PHYSIK, KIT

Karlsruhe Institute of Technology

OUTLINE

1. Monte Carlo meets NLO - POWHEG method

2. Charged Higgs in BSM

3. Charged Higgs production @ NLO

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1. Monte Carlo meets NLO

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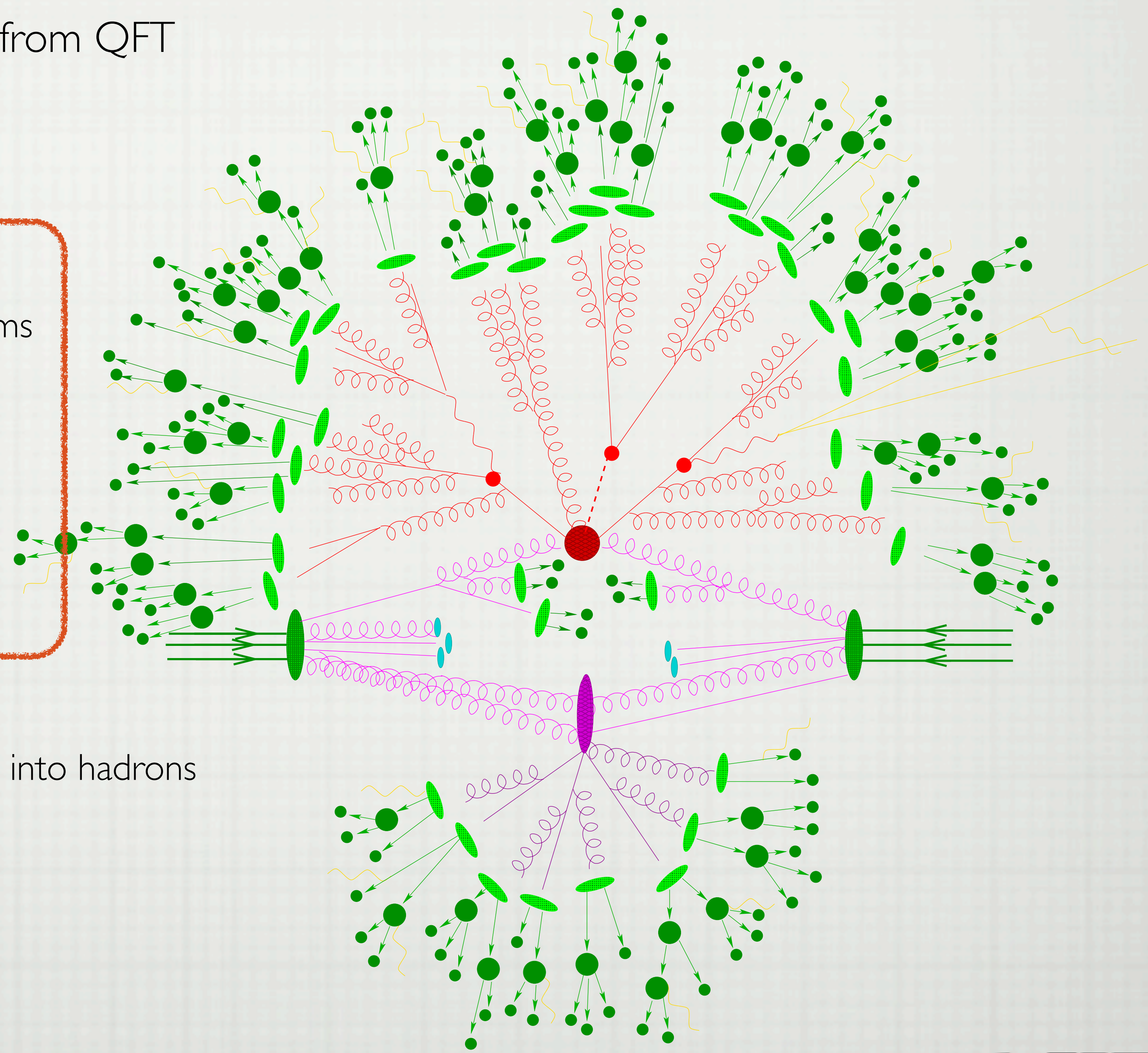
- **MC generators**
  - Complicated machinery needed to go from QFT to simulating real events
  - A lot of moving parts
    - **hard matrix element**
      - QFT calculations using Feynman diagrams
      - most rigorous part of MC
    - **parton showers**
      - generating soft & collinear radiation
      - makes ME more realistic
    - **hadronisation**
      - using color information to turn partons into hadrons
      - very model dependent
    - **underlying event**



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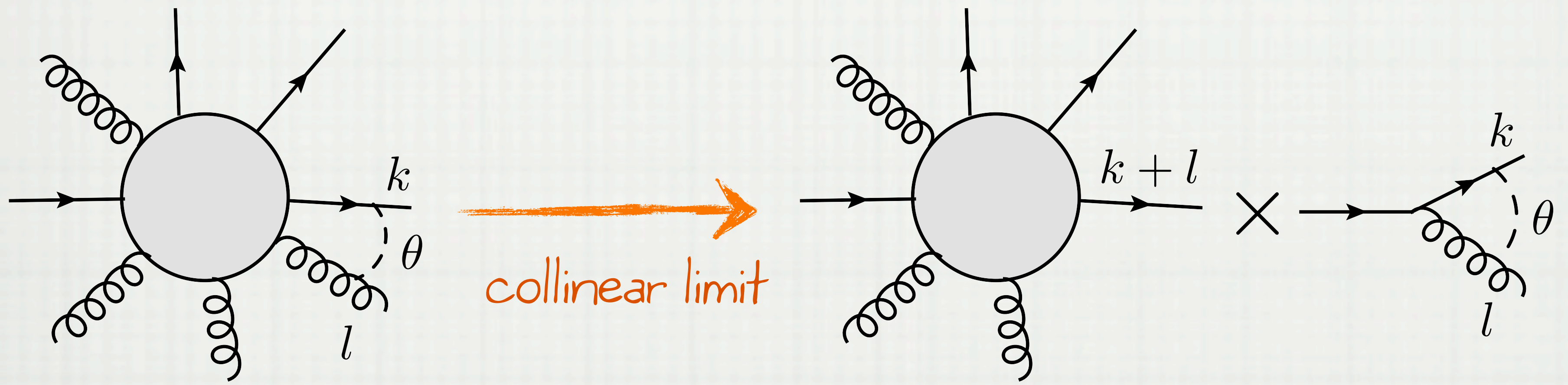
- **Parton showers**
  - New particles (mainly gluons) radiated due to collinear & soft enhancement
  - Collinear radiation universal - easy to automatize for any process



  - Phase-space factorizes

$$|M_{n+1}|^2 d\Phi_{n+1} \to |M_n|^2 d\Phi_n \frac{\alpha_s}{2\pi}\frac{dt}{t} P_{q,qg}(z)\, dz\, \frac{d\phi}{2\pi}$$

hardness: $t = Q^2 \;\text{ or }\; p_T^2 \;\text{ or }\; E^2\theta^2$

energy fraction: $z = \dfrac{k^0}{k^0 + l^0}$

Altarelli-Parisi splitting function: $P_{q,qg}(z) = C_F \dfrac{1+z^2}{1-z}$

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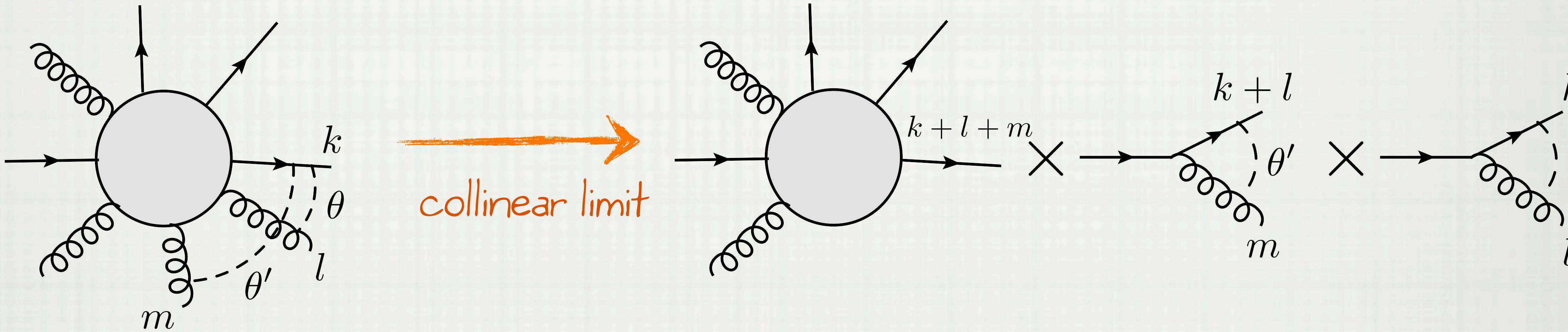
- **Parton showers**
  - Factorization works even for multiple collinear particles - *just iterate previous formula*



  - Ordering in hardness - first emission harder than the second (can mean different things depending on definition of t)

$$|M_{n+1}|^2 d\Phi_{n+1} \to |M_{n-1}|^2 d\Phi_{n-1} \times \frac{\alpha_s}{2\pi}\frac{dt'}{t'}P_{q,qg}(z')\,dz'\,\frac{d\phi'}{2\pi} \times \frac{\alpha_s}{2\pi}\frac{dt}{t}P_{q,qg}(z)\,dz\,\frac{d\phi}{2\pi}\theta(t'-t)$$

  - Factor $\frac{\alpha_s(t)}{2\pi}\frac{dt}{t}P_{q,qg}(z)\,dz\,\frac{d\phi}{2\pi}$ looks & smells like a probability - why not interpret it like one ?

  - Probability of emission between t and t+dt

$$d\mathcal{P}_{i,jk} \sim \frac{\alpha_s(t)}{2\pi}\frac{dt}{t}P_{i,jk}(z)\,dz\,\frac{d\phi}{2\pi}$$

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- **Parton showers**
  - Probability of NO emission can be expressed in terms of emission probability

$$\begin{aligned}\mathcal{P}_{\text{nothing}}(T_0 < t < T_n) &= \lim_{n\to\infty}\prod_{i=0}^{n-1}\mathcal{P}_{\text{nothing}}(T_i < t < T_{i+1})\\ &= \lim_{n\to\infty}\prod_{i=0}^{n-1}(1-\mathcal{P}_{\text{emission}}(T_i < t < T_{i+1}))\\ &= \exp\Big(-\int_{T_0}^{T_n}\frac{d\mathcal{P}_{\text{emission}}}{dt}dt\Big)\end{aligned}$$

  - Sudakov form factor - NO emission probability between t_h and t_l

$$\Delta_i(t_h,t_l) = \exp\left[-\sum_{(j,k)}\int_{t_l}^{t_h}\frac{dt'}{t'}\int dz\frac{\alpha_s(t')}{2\pi}P_{i,jk}(z)\right]$$

  - Probability of first branching at hardness t = no branching until t & emission at t

$$\boxed{d\mathcal{P}_i(t_I,t) = \frac{\alpha_s(t)}{2\pi}\frac{dt}{t}P_{i,jk}(z)\,dz\,\frac{d\phi}{2\pi}\times\exp\Big[-\sum_{(j,k)}\int_t^{t_I}\frac{dt'}{t'}\int dz\frac{\alpha_s(t')}{2\pi}P_{i,jk}(z)\Big]}$$

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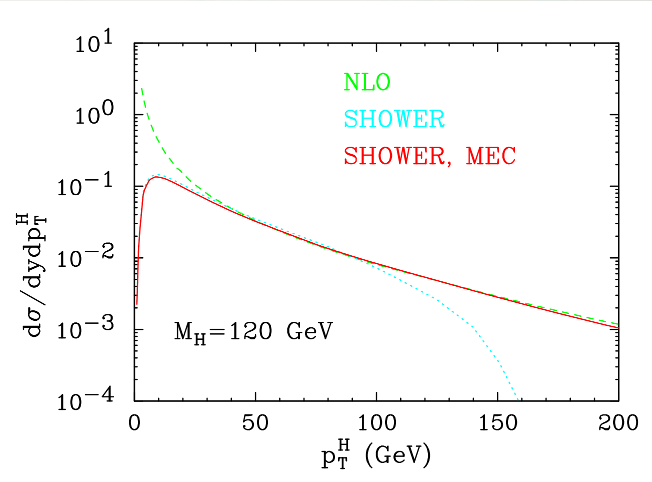
- **NLO cross-sections**
  - NLO cross-sections complicated objects - combining 2 types of processes
    - virtual (loop) corrections - containing UV & IR divergence

      - same phase-space as tree-level Φ_B
    - real emission corrections - containing IR divergence

      - phase-space with n+1 particles Φ_R



$$d\sigma = \Big(B(\Phi_B) + \hat{V}(\Phi_B)\Big) d\Phi_B + R(\Phi_R) d\Phi_R$$

  - Cancellation of UV divergence 'simple' through renormalization of couplings constants etc.
  - Cancellation of IR divergence only in sufficiently inclusive quantities (!)
  - To cancel IR singularities in each part separately, one introduces auxiliary subtraction terms & one has to factorize the phase-space $\Phi_R(\Phi_B, \Phi_{\rm rad})$

$$\sigma = \int d\Phi_B \Big[B(\Phi_B) + \hat{V}(\Phi_B) + \int d\Phi_{\rm rad} C(\Phi_R(\Phi_B, \Phi_{\rm rad}))\Big] + \int d\Phi_R \Big[R(\Phi_R) - C(\Phi_R)\Big]$$

  - Imperfect cancellation of singularities for exclusive quantities e.g. in a Monte Carlo

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MONTE CARLO

- **NLO cross-sections & parton shower**
  - How to use NLO cross-sections in parton showers ?
  - In parton shower language an equivalent of a NLO cross-section is a cross-section with one emission

$$d\sigma = d\Phi_B B(\Phi_B)\left(\underbrace{\Delta_i(t_I,t_0)}_{\text{no emission}} + \sum_{(j,k)} \Delta_i(t_I,t)\underbrace{\frac{\alpha_s(t)}{2\pi}}_{\text{one emission}} P_{i,jk}(z)\frac{dt}{t}dz\frac{d\phi}{2\pi}\right)$$

  - Expanding in α_s we get

$$d\sigma = d\Phi_B B(\Phi_B)\left(1 - \sum_{(j,k)} \int \frac{dt'}{t'} \underbrace{\int dz}_{\text{virtual corrections}} \frac{\alpha_s(t')}{2\pi} P_{i,jk}(z) + \sum_{(j,k)} \frac{\alpha_s(t)}{2\pi} \underbrace{P_{i,jk}(z)}_{\text{real corrections}}\frac{dt}{t}dz\frac{d\phi}{2\pi}\right)$$

  - Shower cross-section contains approximate virtual & real corrections in the collinear limit
    NOTE: Sudakov form-factor resums universal part of the virtual(!) correction
  - Goal of NLO Monte Carlos is to recover exact NLO cross-sections when we expand the parton shower cross-section in α_s

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- **MC@NLO method**
  - Main idea - do not modify the shower algorithm
    - add difference between exact NLO and approximate (MC) NLO
  - Modified MC@NLO shower cross-section (with correct NLO expansion)

$$d\sigma = \underbrace{d\Phi_B \bar{B}^{MC}(\Phi_B)}_{\text{S event}} \Bigg(\underbrace{\Delta^{MC}(t_I, t_0) + \Delta_i^{MC}(t_I, t) \frac{R^{MC}(\Phi)}{B(\Phi_B)} d\Phi_{\rm rad}^{MC}}_{\text{unmodified shower}} \Bigg) + \underbrace{\Big(R(\Phi) - R^{MC}(\Phi) \Big) d\Phi}_{\text{H event}}$$

where the modified Born contains also the virtual corrections

$$\bar{B}^{MC}(\Phi_B) = B(\Phi_B) + \left[V(\Phi_B) + \int R^{MC}(\Phi) d\Phi_{\rm rad}^{MC} \right]$$

  - Both S-event & H-event are generated separately with probabilities

$$\sigma_S = \int |\bar{B}^{MC}(\Phi_B)| d\Phi_B \qquad\qquad \sigma_H = \int |R - R^{MC}| d\Phi$$

the S-event is then passed to the shower before one adds the H-event

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- **POWHEG method**
  - Main idea - replace the parton shower approximation for no radiation and the first (hardest) emission by the full NLO calculation
  - Separate the real emission into singular and regular part

$$R = R^S + R^F$$

  - POWHEG cross-section with the hardest emission

$$d\sigma = d\Phi_B \bar{B}^S(\Phi_B)\left(\Delta^S_{t_0} + \Delta^S_t \frac{R^S(\Phi)}{B(\Phi_B)} d\Phi_{\rm rad}\right) + R^F d\Phi_R$$

where the modified Born contains also the virtual corrections

$$\bar{B}^S = B + V + \int R^S d\Phi_{\rm rad}$$

  - Modified Sudakov form-factor & modified shower generating emission only with lower p_T than the first emission

$$\Delta^S_t = \exp\left[-\int \theta(t_r - t)\frac{R^S(\Phi_B, \Phi_{\rm rad})}{B(\Phi_B)} d\Phi_{\rm rad}\right]$$

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MONTE CARLO

- **MC@NLO**

- No need to modify shower algorithm
- Implementation of NLO not Monte Carlo independent (need analytical expression for $R^{MC}(\Phi)$)
  - MC@NLO works with Herwig
  - aMC@NLO works with Pythia
- H-event often has negative weights as
$$R < R^{MC}$$

- **POWHEG**

- Modified shower algorithm requires new Monte Carlo to be constructed
- POWHEG can be coupled to any SMC
- always positive weights
- simple inclusion of new processes with POWHEG-BOX framework

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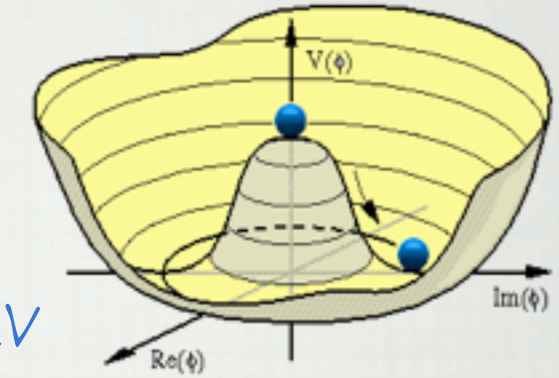
2. Charged Higgs in BSM

CHARGED HIGGS

- **Higgs sector of the Standard model**
  - Higgs field in a SU(2)-doublet

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ v + h + i\chi \end{pmatrix} \qquad \langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Higgs VEV



  - Lagrangian of the Higgs field in SM

$$\mathcal{L} = (D^\mu \Phi)^\dagger (D_\mu \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

Higgs kinetic term   Higgs mass term   Higgs self-interaction

  - Interaction of Higgs with vector bosons through covariant derivative

$$D_\mu = i\partial_\mu - g\frac{1}{2}\vec{\tau}.\vec{W} - g'\frac{Y}{2}B_\mu$$

  - Masses of vector bosons - result of EWSB and gauge symmetry

$G^\pm\ G^0$ - Goldstone bosons act as longitudinal polarizations of W & Z-bosons

$$M_W^2 = \frac{1}{4}g^2 v^2 \qquad M_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2 \qquad M_W/M_Z = \cos\theta_W$$

  - Yukawa interactions of Higgs with fermions

$$\mathcal{L}_{\text{Yuk.}} \sim h_t\, \bar{t}_R (t,b)_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} + h_b\, \bar{b}_R (t,b)_L \begin{pmatrix} -\phi^0 \\ \phi^- \end{pmatrix} + h.c.$$

$$h_i = \frac{\sqrt{2}\, m_i}{v} = \frac{g\, m_i}{\sqrt{2} m_W}$$

Standard Model

- one doublet
- 4 dof
- h^0 - physical Higgs
- no charged Higgs

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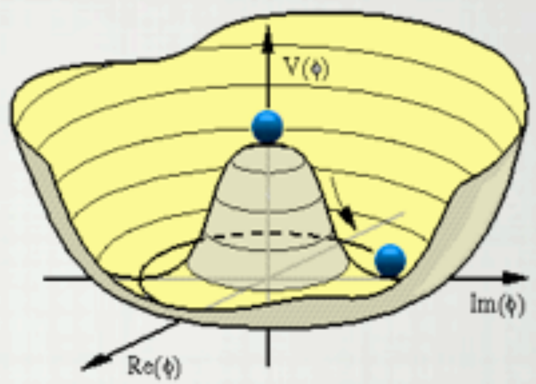
- **extending the Higgs sector**
  - adding extra Higgs fields (singlets, doublets, triplets...)

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \qquad \Phi_i = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_i^+ \\ v_i + h_i + i\chi_i \end{pmatrix}$$

Two Higgs doublet model - 2HDM



  - Higgs self-interaction - the most general Higgs potential in 2HDM

$$V \sim \lambda_1(|\Phi_1|^2 - v_1^2)^2 + \lambda_2(|\Phi_2|^2 - v_2^2)^2 + \lambda_3[(|\Phi_1|^2 - v_1^2) + (|\Phi_2|^2 - v_2^2)]^2$$
$$+\lambda_4[|\Phi_1|^2|\Phi_2|^2 - |\Phi_1^\dagger\Phi_2|^2] + \lambda_5[Re(\Phi_1^\dagger\Phi_2) - v_1v_2]^2 + \lambda_6[Im(\Phi_1^\dagger\Phi_2)]^2$$

  - mixing between two doublets

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1^0 \\ h_2^0 \end{pmatrix} \quad \begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix} \quad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

$$\tan\alpha = f(v_1, v_2, \lambda_1, \lambda_2, \lambda_3, \lambda_5) \qquad \tan\beta = \frac{v_2}{v_1}$$

  - simple kinetic term - simple interaction with vector bosons

$$\mathcal{L}_{\text{kin}} \sim (D^\mu\Phi_1)^\dagger(D_\mu\Phi_1) + (D^\mu\Phi_2)^\dagger(D_\mu\Phi_2)$$

same as in the SM

$$M_W^2 = \frac{1}{4}g^2(v_1^2 + v_2^2) \qquad M_Z^2 = \frac{1}{4}(g^2 + g'^2)(v_1^2 + v_2^2) \qquad M_W/M_Z = \cos\theta_W$$

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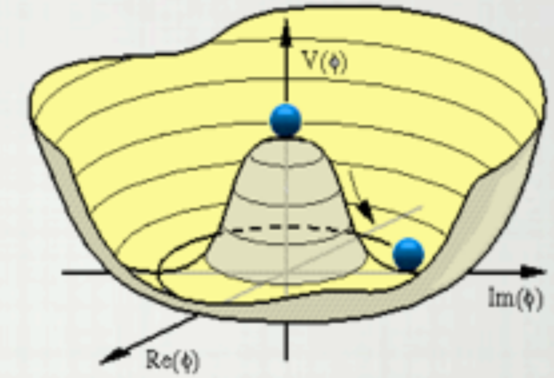

- **2HDM & Yukawa interactions**
  - Standard Model Yukawa interactions (3rd gen. quarks)

$$\mathcal{L}_{\text{Yuk.}} \sim h_t\,\bar{t}_R(t,b)_L\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} + h_b\,\bar{b}_R(t,b)_L\begin{pmatrix}-\phi^0\\ \phi^-\end{pmatrix} + h.c.$$

  - **2HDM type I** - only one doublet couples to fermions

$$\mathcal{L}_{\text{Yuk.}} \sim \frac{\sqrt{2}m_t}{v_2}\,\bar{t}_R(t,b)_L\begin{pmatrix}\phi_2^+\\ \phi_2^0\end{pmatrix} + \frac{\sqrt{2}m_b}{v_2}\,\bar{b}_R(t,b)_L\begin{pmatrix}-\phi_2^0\\ \phi_2^-\end{pmatrix} + h.c.$$

charged Higgs coupling to fermions - 2HDM type I

$$\mathcal{L}_{H^+ff} \sim \bar{t}\left(h_t\cot\beta P_L - h_b\cot\beta P_R\right)b\,H^+$$

  - **2HDM type II** - different doublets couples to up-type/down-type fermions

$$\mathcal{L}_{\text{Yuk.}} \sim \frac{\sqrt{2}m_t}{v_2}\,\bar{t}_R(t,b)_L\begin{pmatrix}\phi_2^+\\ \phi_2^0\end{pmatrix} + \frac{\sqrt{2}m_b}{v_1}\,\bar{b}_R(t,b)_L\begin{pmatrix}-\phi_1^0\\ \phi_1^-\end{pmatrix} + h.c.$$

charged Higgs coupling to fermions - 2HDM type II

$$\mathcal{L}_{H^+ff} \sim \bar{t}\left(h_t\cot\beta P_L + h_b\tan\beta P_R\right)b\,H^+$$

<u>2HDM type I & II</u>

- two doublets
- 8 dof
- h^0, H^0, A^0 - physical Higgses
- charged Higgs

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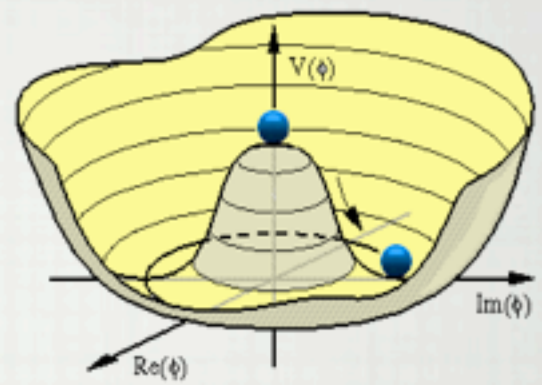
CHARGED HIGGS

- **SM vs 2HDM vs MSSM**
  - Standard Model free params in Higgs sector

$$m_h, \lambda$$ 2 parameters



  - 2HDM - free params in Higgs sector

$$m_h, m_H, m_A, m_{H^+}, \tan\beta, \alpha, \lambda_5$$ 7 parameters

  - MSSM - free params in Higgs sector
    - Higgs potential constrained by SUSY

$$V = (m_{H_1}^2 + \mu^2)|H_1|^2 + (m_{H_2}^2 + \mu^2)|H_2|^2 - m_{12}^2(H_1 H_2 + H_1^\dagger H_2^\dagger) + \frac{1}{8}(g^2 + g'^2)(|H_1|^2 - |H_2|^2)^2 + \frac{1}{2}g^2|H_1^\dagger H_2|^2$$

    - only 3 free parameters

$$m_A, \tan\beta, \mu$$ 3 parameters

$$m_{h^0,H^0}^2 = \frac{1}{2}\left[m_{A^0}^2 + m_Z^2 \mp \sqrt{(m_{A^0}^2 + m_Z^2)^2 - 4m_{A^0}^2 m_Z^2 \cos^2\beta}\right]$$

$$m_{H^\pm}^2 = m_{A^0}^2 + m_W^2$$

$$\tan 2\alpha = \frac{m_{A^0}^2 + m_Z^2}{m_{A^0}^2 - m_Z^2}\tan 2\beta$$

charged Higgs coupling to fermions – MSSM

$$\mathcal{L}_{H^+ff} \sim \bar{t}\left(h_t \cot\beta P_L + h_b \tan\beta P_R\right) b\, H^+$$

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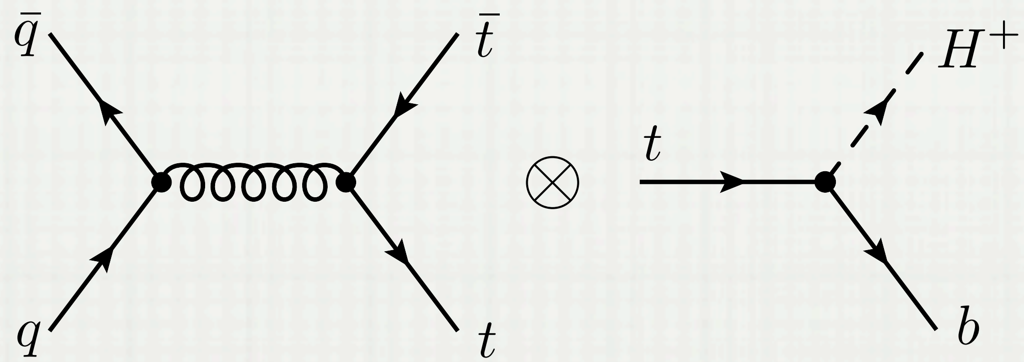
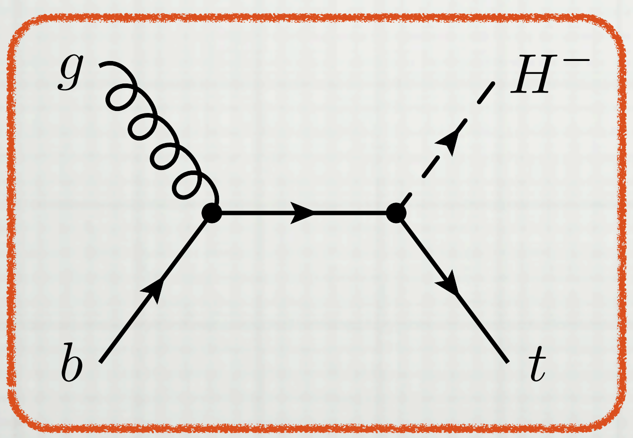
CHARGED HIGGS

- **Charged Higgs @ colliders**
  - leading production process in the case $m_H < m_t$

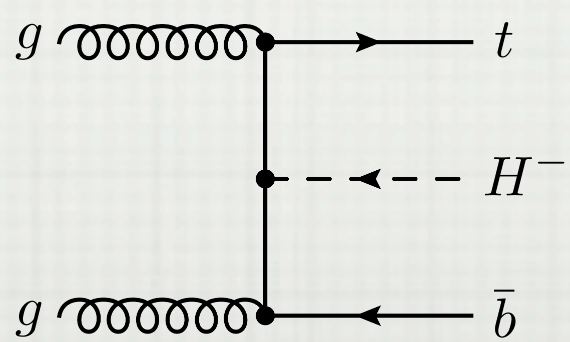


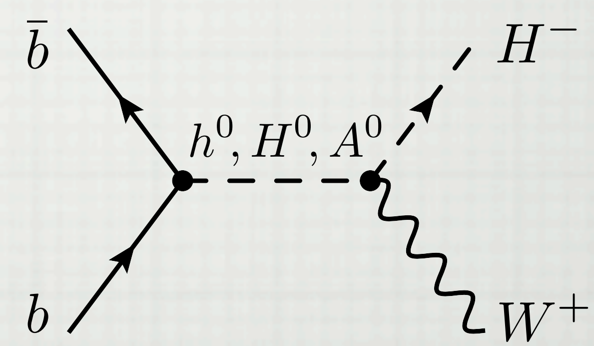
$t\bar{t}$ production + top quark decay

  - leading production process in the case $m_H > m_t$



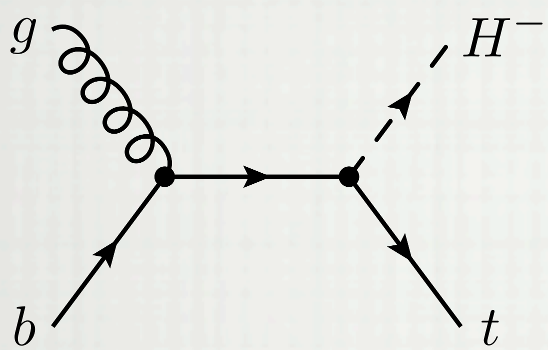
gb -> tH





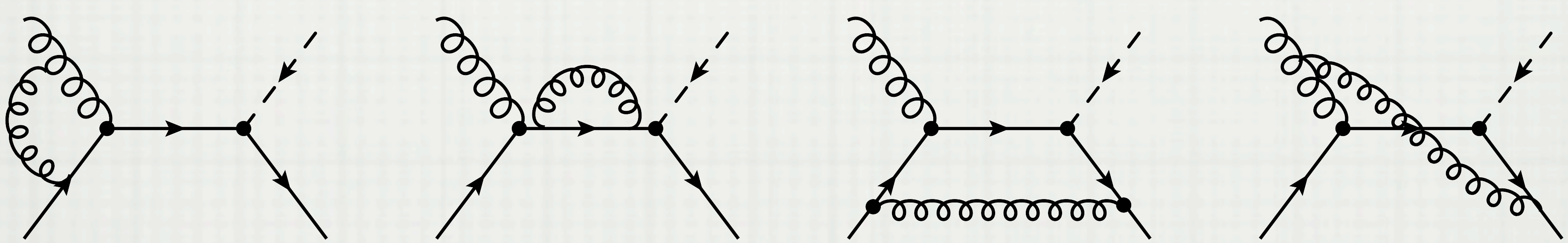
CHARGED HIGGS

- **Charged Higgs production @ NLO**

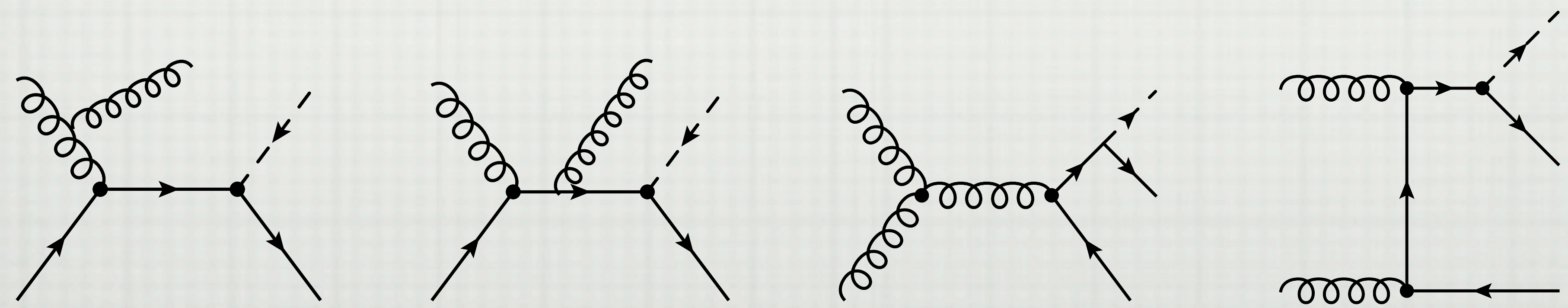


- NLO includes virtual corrections with UV & IR divergence
- Cancellation of UV divergence via renormalization
- NLO includes real corrections with IR divergence - cancel IR divergence
- NLO stabilizes renormalization scale dependence

- Virtual corrections

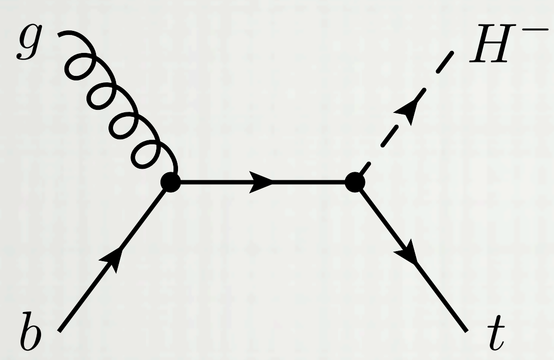


- Real corrections



CHARGED HIGGS

- **Charged Higgs production @ NLO**



- NLO includes virtual corrections with UV & IR divergence
- Cancellation of UV divergence via renormalization
- NLO includes real corrections with IR divergence - cancel IR divergence
- NLO stabilizes renormalization scale dependence

- 2HDM parameters

$$m_H = 300\ \text{GeV} \qquad \tan\beta = 10 \qquad \sqrt{s}_{\text{TEV}} = 1.96\,\text{TeV} \qquad \sqrt{s}_{\text{LHC}} = 7\,\text{TeV}$$

- typical Bjorken x

$$x_a x_b = \frac{(k_1+k_2)^2}{s} > \frac{(m_t+m_H)^2}{s} \qquad x_{\text{TEV}} \sim 0.3 \qquad x_{\text{LHC}} \sim 0.07$$

Scenario	LO	Scale unc.	NLO	Scale unc.	PDF error
Tevatron 2HDM-I	$3.229.10^{-6}$	$+1.306.10^{-6}(40\%)$ $-0.901.10^{-6}(28\%)$	$6.218.10^{-6}$	$+1.388.10^{-6}(22\%)$ $-1.201.10^{-6}(19\%)$	$+4.448.10^{-5}(72\%)$ $-2.362.10^{-5}(38\%)$
Tevatron 2HDM-II	$1.303.10^{-5}$	$+0.524.10^{-5}(40\%)$ $-0.365.10^{-5}(28\%)$	$2.506.10^{-5}$	$+0.565.10^{-5}(23\%)$ $-0.484.10^{-5}(19\%)$	$+1.792.10^{-5}(72\%)$ $-0.952.10^{-5}(38\%)$
LHC 2HDM-I	$1.577.10^{-3}$	$+0.379.10^{-3}(24\%)$ $-0.304.10^{-3}(19\%)$	$2.189.10^{-3}$	$+0.162.10^{-3}(7\%)$ $-0.199.10^{-3}(9\%)$	$+0.356.10^{-3}(16\%)$ $-0.304.10^{-3}(14\%)$
LHC 2HDM-II	$6.366.10^{-3}$	$+1.514.10^{-3}(24\%)$ $-1.237.10^{-3}(19\%)$	$8.821.10^{-3}$	$+0.651.10^{-3}(7\%)$ $-0.802.10^{-3}(9\%)$	$+1.433.10^{-3}(16\%)$ $-1.223.10^{-3}(14\%)$

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3. Charged Higgs in POWHEG

POWHEG

- **POWHEG-BOX framework**
  - general framework to include NLO calculations in shower Monte Carlos
  - automatic generation of NLO real corrections (NLO virtual corrections supplied by user)
  - automated dipole subtraction in the FKS scheme

- **Processes included**
  - Single vector boson production + decay [Alioli, Nason, Oleari, Re, arXiv: 0805.4802 [hep-ph]]
  - Vector boson + 1 jet production + decay [Alioli, Nason, Oleari, Re, arXiv: 1009.5594 [hep-ph]]
  - Single top (s & t -channel) [Alioli, Nason, Oleari, Re, arXiv: 0907.4076 [hep-ph]]
  - Single top with W [Re, arXiv: 1009.2450 [hep-ph]]
  - Higgs boson production in gluon fusion [Alioli, Nason, Oleari, Re, arXiv: 0812.0578 [hep-ph]]
  - Higgs boson production in vector boson fusion [Nason, Oleari, arXiv: 0911.5299 [hep-ph]]
  - Jet pair production [Alioli, Hamilton, Nason, Oleari, Re, arXiv: 1012.3380 [hep-ph]]
  - Heavy quark pair production [Frixione, Nason, Ridolfi, Re, arXiv: 0707.3088 [hep-ph]]
  - ZZ, WW, WZ production [Melia, Nason, Rontsch, Zanderighi, arXiv: 1107.5051 [hep-ph]]
  - $Wb\bar{b}$ production [Oleari, Reina, arXiv: 1105.4488 [hep-ph]]
  - Charged Higgs boson production with a top quark [KK, Klasen, Nason, Weydert, arXiv: 1203.1341 [hep-ph]]

AND MORE...

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POWHEG

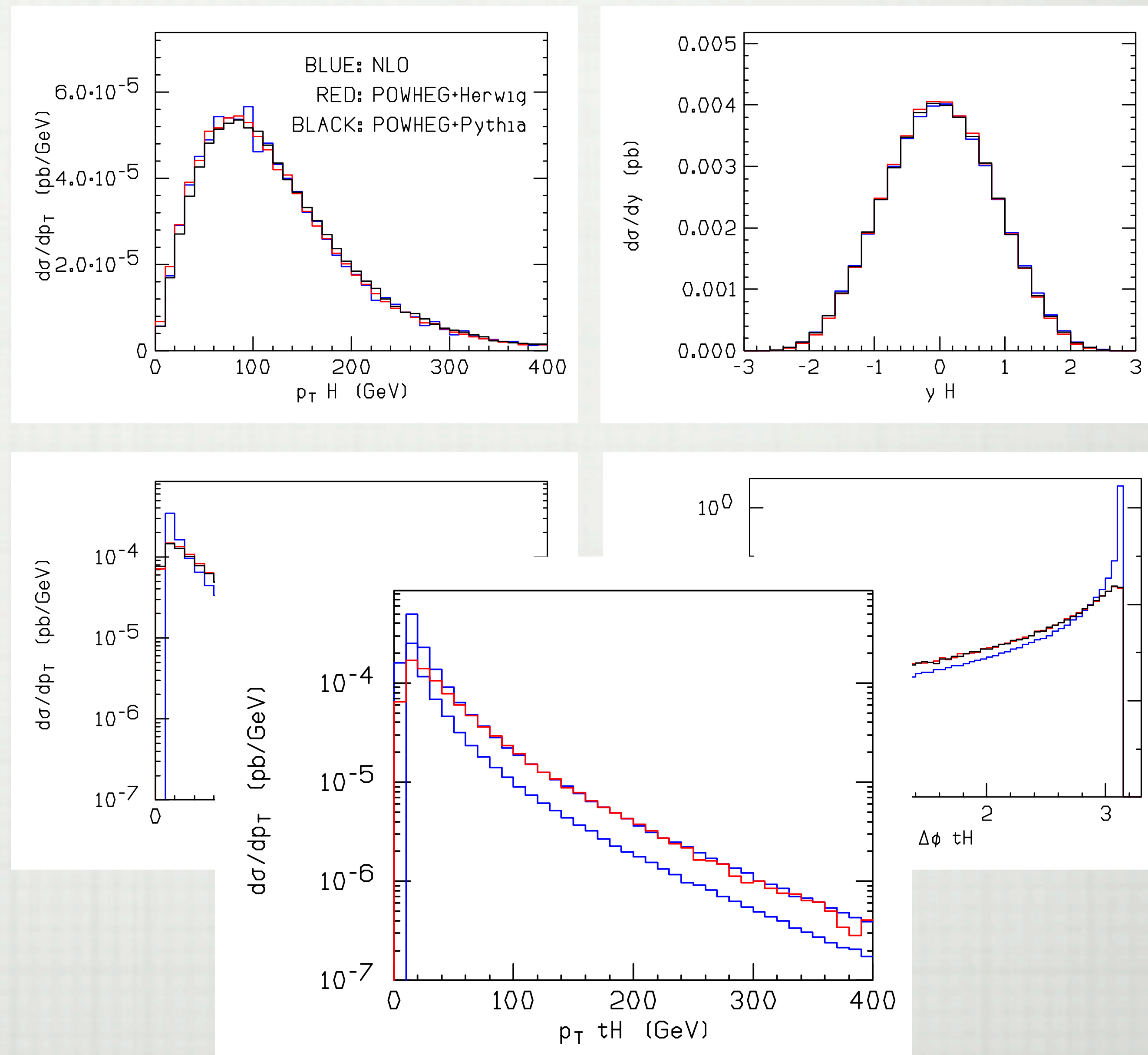
- **Charged Higgs production @ LHC**

  - comparison of NLO cross-section with POWHEG coupled to Pythia or Herwig

    2HDM type-II

    $m_H = 300\,\mathrm{GeV} \quad \tan\beta = 10 \quad \sqrt{s} = 7\,\mathrm{TeV}$

  - shower resummation works for $p_T^{tH} \to 0$
  - results for Pythia (pT ordered showers) and Herwig (angle ordered showers) compatible
  - difference between NLO and POWHEG in high pT tail within uncertainty



scale uncertainty

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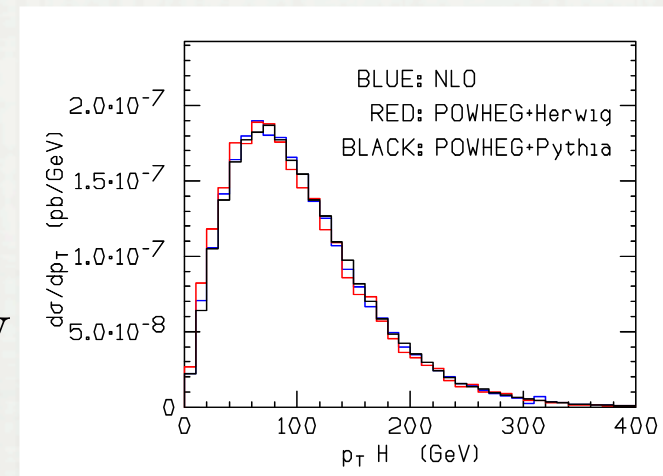
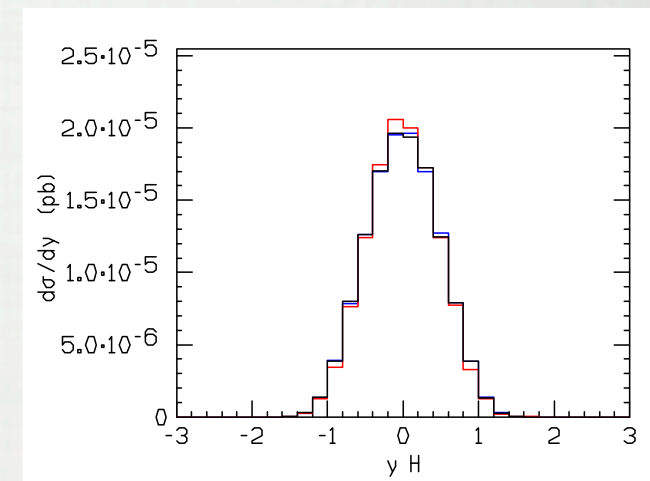
POWHEG

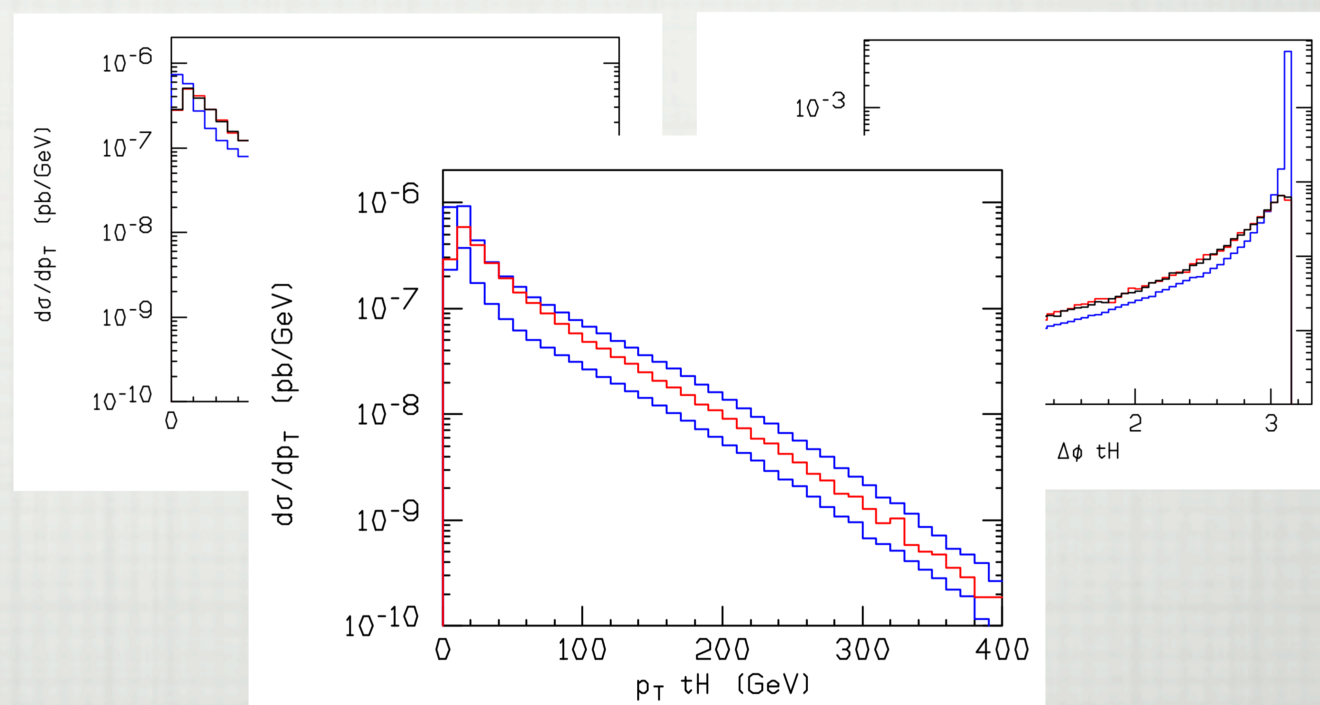
- **Charged Higgs production @ Tevatron**
  - comparison of NLO cross-section with POWHEG coupled to Pythia or Herwig

    2HDM type-II

    $m_H = 300\,\mathrm{GeV}\quad \tan\beta = 10 \quad \sqrt{s} = 1.96\,\mathrm{TeV}$
  - shower resummation works for $p_T^{tH} \to 0$
  - results for Pythia (pT ordered showers) and Herwig (angle ordered showers) compatible
  - different shape of p_T tH compared to LHC due to different contributing partons



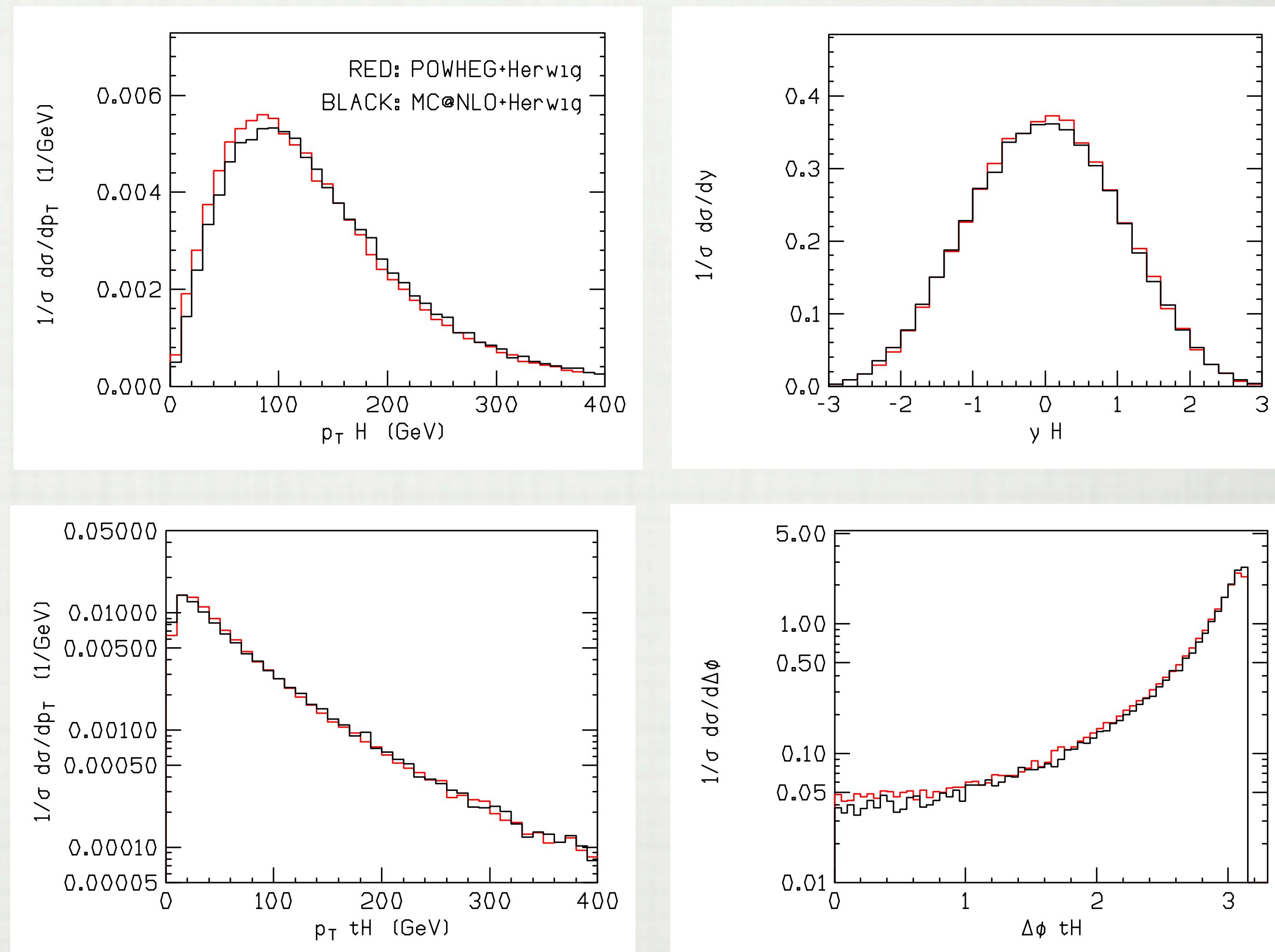




scale uncertainty

POWHEG

- **Charged Higgs production - POWHEG vs MC@NLO**
  - comparison of implementations into POWHEG & MC@NLO both coupled to angular ordered Herwig
    [Weydert et al., arXiv: 0912.3430 [hep-ph]]
  - all distributions between POWHEG & MC@NLO compatible both for LHC and Tevatron
  - different NLO normalization due to renormalization scheme differences - different treatment of the top mass



POWHEG

- **Charged Higgs production - low Higgs mass**
  - For Higgs masses $m_H < m_t + m_b$ we face the same problem as the single top production in Wt channel
    [Tait, hep-ph/9909352] [Campbell, Tramontano, hep-ph/0506289] [Frixione et al., arXiv: 0805.3067 [hep-ph]]
  - @ NLO charged Higgs production in association with a top quark interferes with $t\bar{t}$ production and a subsequent decay of the top quark
    - the two production processes are formally inseparable (but one can try)
  - NLO real corrections to the charged Higgs production with a top quark contains $t\bar{t}$ production with top quark decay

2->3 real corrections

  - 3 possible treatments of the top quark resonance
    - diagram removal (DR)
    - diagram subtraction (DS)
    - no subtraction

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POWHEG

- **Charged Higgs production - low Higgs mass**
  - Separating real emission contribution from partons a,b in 2 categories
    1. contributions via tt̄ production $\mathcal{M}_{ab}^{t\bar{t}}$
    2. remainder $\mathcal{M}_{ab}^{tH^-}$

    the whole real emission $\mathcal{M}_{ab} = \mathcal{M}_{ab}^{t\bar{t}} + \mathcal{M}_{ab}^{tH^-}$
  - Squaring the matrix element

$$|\mathcal{M}_{ab}|^2 = |\mathcal{M}_{ab}^{tH^-}|^2 + 2\mathrm{Re}(\mathcal{M}_{ab}^{tH^-}\mathcal{M}_{ab}^{t\bar{t}*}) + |\mathcal{M}_{ab}^{t\bar{t}}|^2 = \mathcal{S}_{ab} + \mathcal{I}_{ab} + \mathcal{D}_{ab}$$

integrable IR singularities

No IR singularities but doubly resonant

  - Ultimate Goal:

    Having both tH and tt̄ production processes @ NLO and retaining the interference

- **Diagram Removal (DR)**
  - Remove resonant diagrams at the amplitude level (not gauge invariant)

$$\mathcal{M}_{ab} = \mathcal{M}_{ab}^{tH^-}$$

  - No doubly resonant contributions and no interference

$$|\mathcal{M}_{ab}|^2 = \mathcal{S}_{ab} + \cancel{\mathcal{I}_{ab} + \mathcal{D}_{ab}}$$

  - One can add tt̄ production @ NLO - losing only the interference

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POWHEG

- **Charged Higgs production - low Higgs mass**
  - Separating real emission contribution from partons a,b in 2 categories

    1. contributions via tt̄ production $\mathcal{M}_{ab}^{t\bar{t}}$
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integrable IR singularities

No IR singularities but doubly resonant

  - Ultimate Goal:

    Having both tH and tt̄ production processes @ NLO and retaining the interference

- **Diagram Subtraction (DS)**
  - Remove resonant contribution at the cross-section level

$$d\sigma_{H^-t}^{\mathrm{sub}} = \frac{f_{\mathrm{BW}}(m_{H-\bar{b}})}{f_{\mathrm{BW}}(m_t)} \left|\tilde{\mathcal{A}}^{(t\bar{t})}\right|^2$$

  - Difficult to add tt̄ production @ NLO consistently - retaining some interference

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POWHEG

- **Charged Higgs production - low Higgs mass**
  - Separating real emission contribution from partons a,b in 2 categories
    1. contributions via tt̄ production $\mathcal{M}_{ab}^{t\bar{t}}$
    2. remainder $\mathcal{M}_{ab}^{tH^-}$

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integrable IR singularities

No IR singularities but doubly resonant

  - Ultimate Goal:

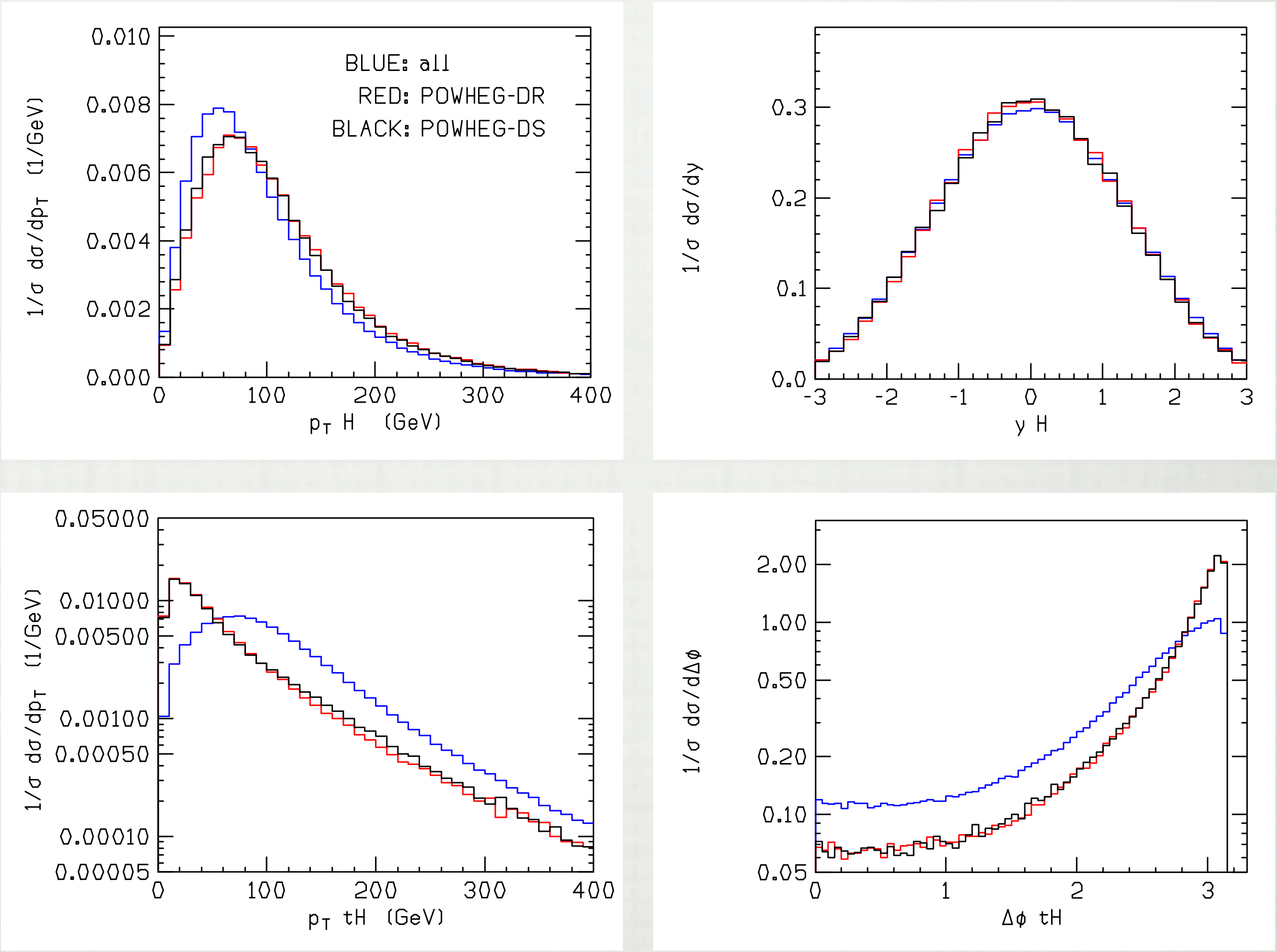
    Having both tH and tt̄ production processes @ NLO and retaining the interference

- **No subtraction**
  - Nothing is subtracted and we use the fact that doubly resonant contribution IR safe - importance sampling for resonance region
  - After events are generated one can remove events near resonance and replace them with tt̄ production @ NLO consistently - retaining NLO & interference

POWHEG

- **Charged Higgs production - low Higgs mass**
  - Comparison of the 3 implemented methods

1. Both subtraction methods DR & DS compatible
2. Interference effect are small - negligible
3. No subtraction leads to much harder distribution of p_T of the top-Higgs pair
4. Total cross-section in all methods is continuous over the threshold $m_H = m_t$



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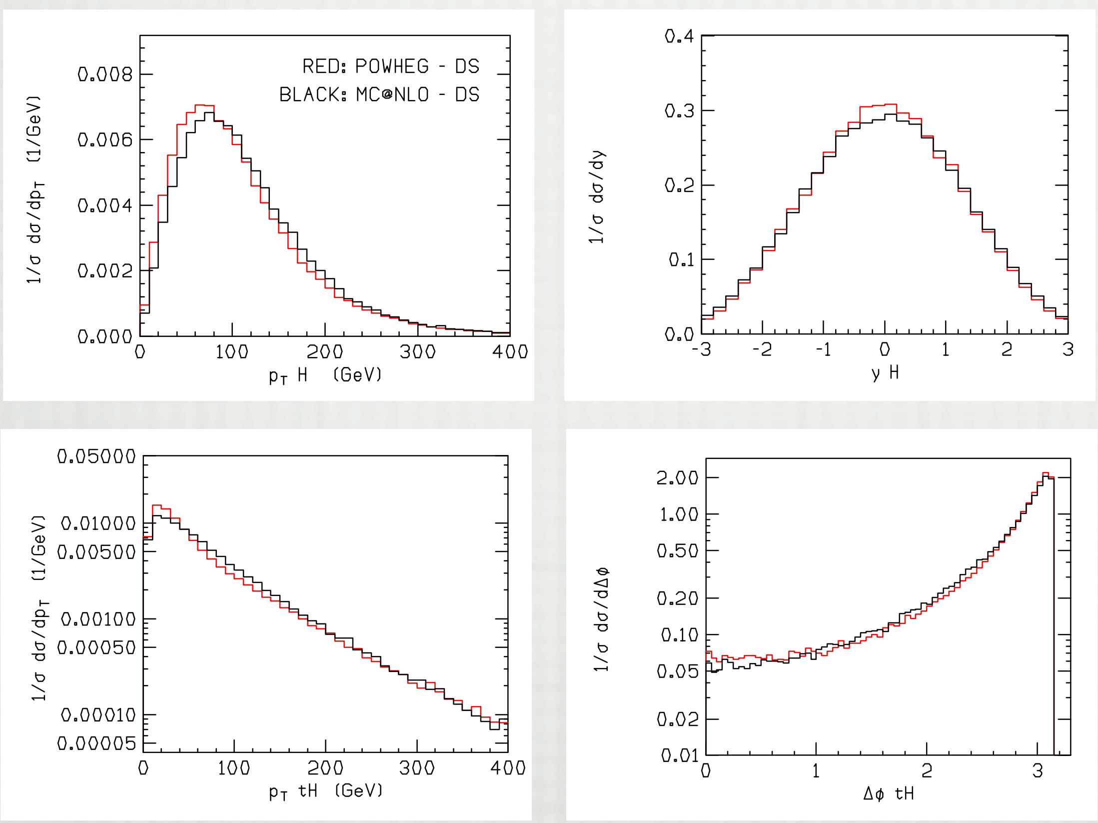
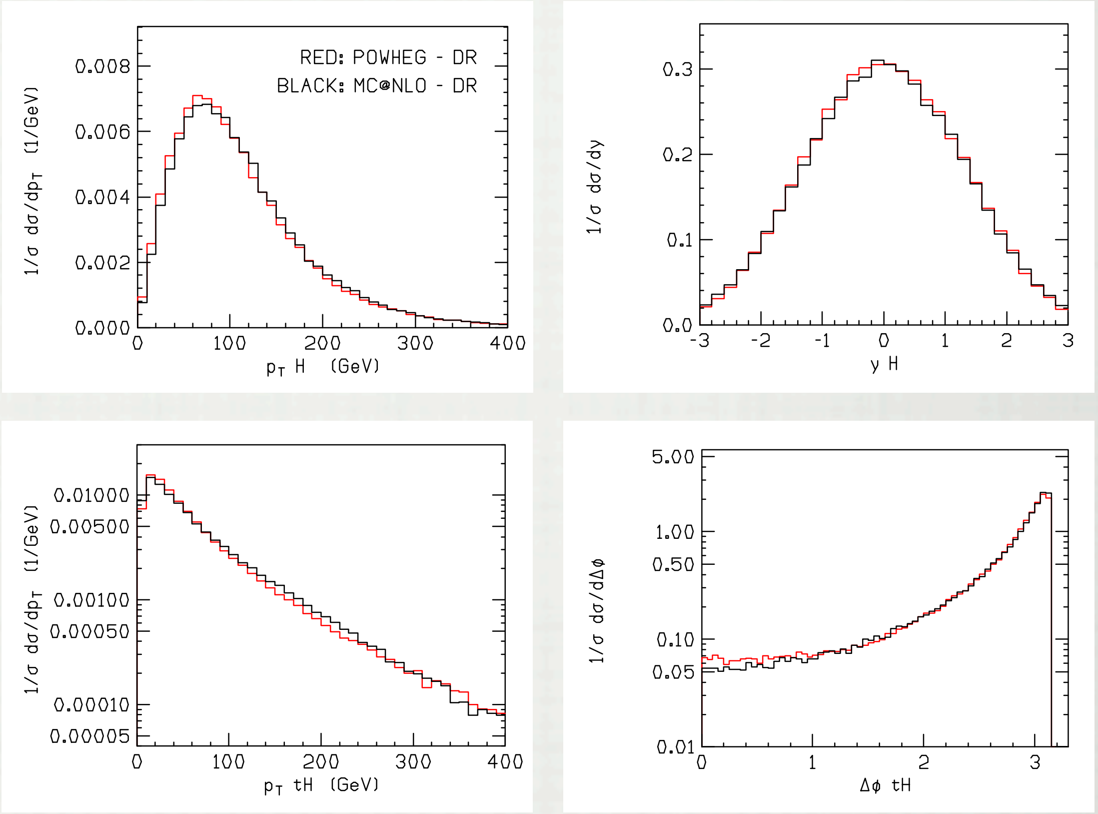
POWHEG

- **Charged Higgs production - low Higgs mass**
  - DR & DS implemented in POWHEG compatible with MC@NLO for all distributions and LHC & Tevatron





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CONCLUSIONS

- NLO Monte Carlo generators are becoming standard
- Many Standard Model and even some BSM processes already included
- Leading production of charged Higgs boson now included in POWHEG

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THANK YOU