The Theoretical Challenge

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Università di Torino

Understanding the Higgs - Torino, 28 November 2012

From the Higgs mechnism ...

The quest of a theory for weak interactions:

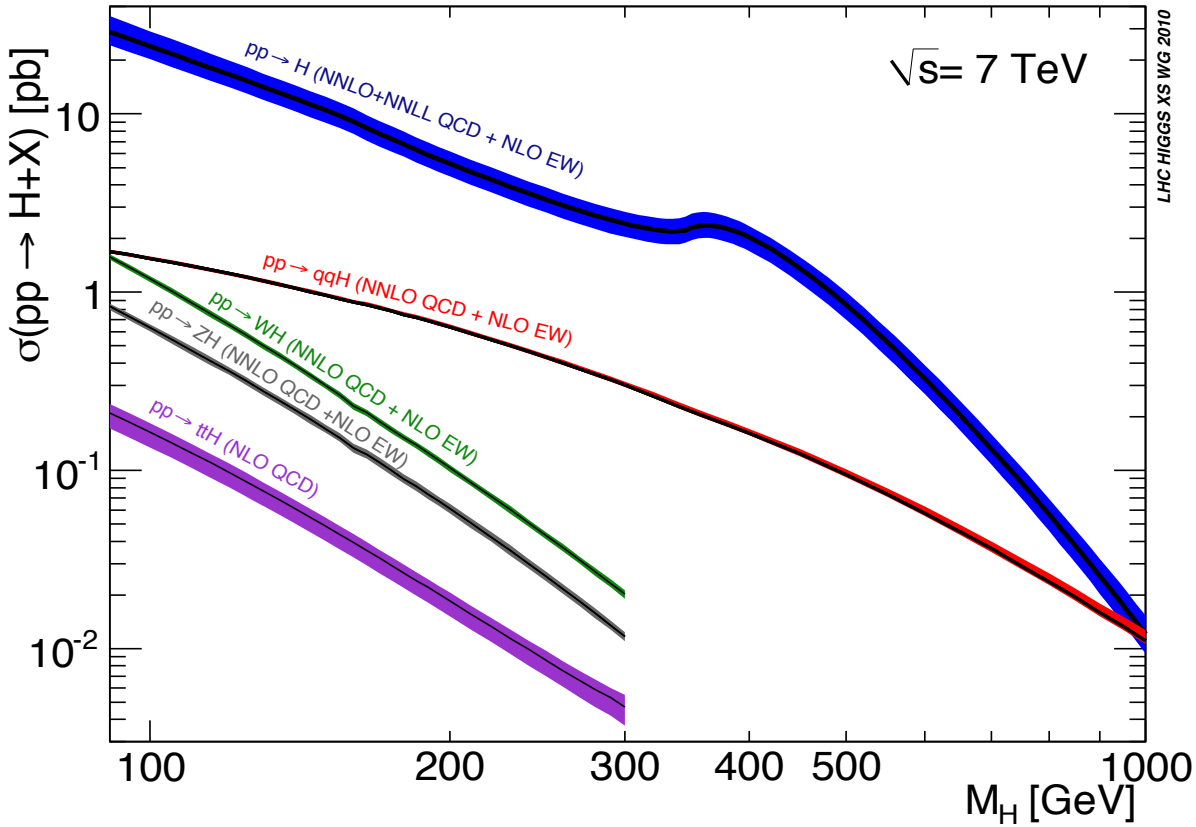
- Yang-Mills theories describe interactions mediated by **massless** bosons (Example: QED, QCD), but ...
- ... Weak interactions are mediated by **massive** particles
- Spontaneous breakdown of local symmetry:
  - Introduction of the Higgs field, which breaks the symmetry of the vacuum
  - All particles which interact with the Higgs field get a mass
  - Quantum excitations of the Higgs field: the Higgs boson

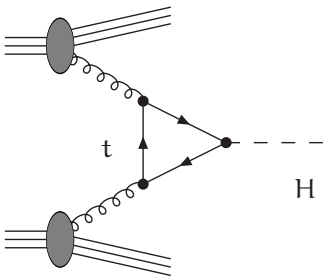
... to Higgs phenomenology

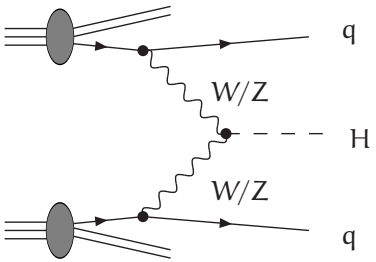
High precision computations:

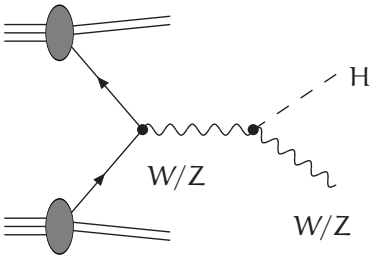
- The Higgs signal: Production cross sections and decay widths
- Background distributions

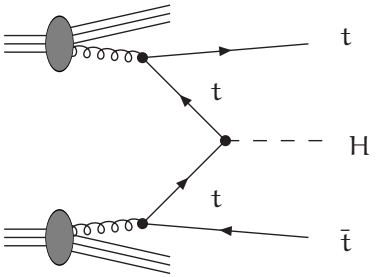
Higgs production channels at the LHC



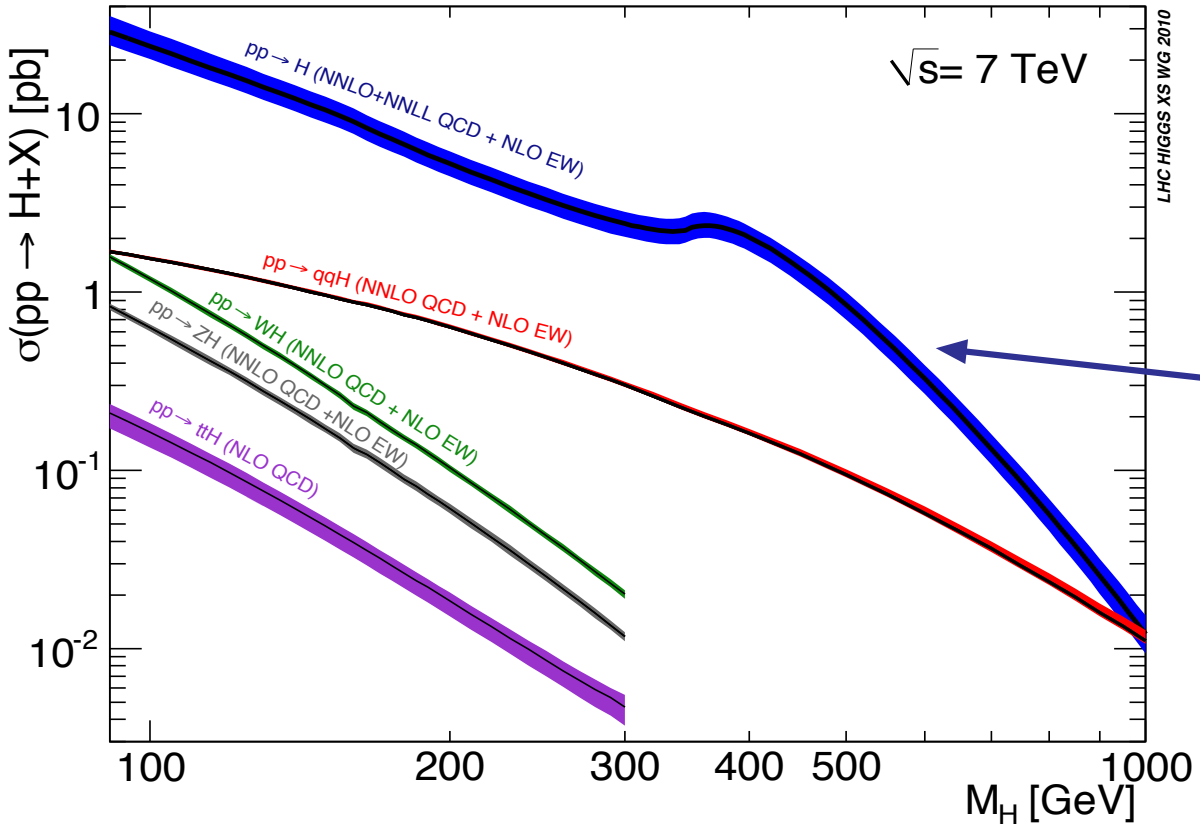




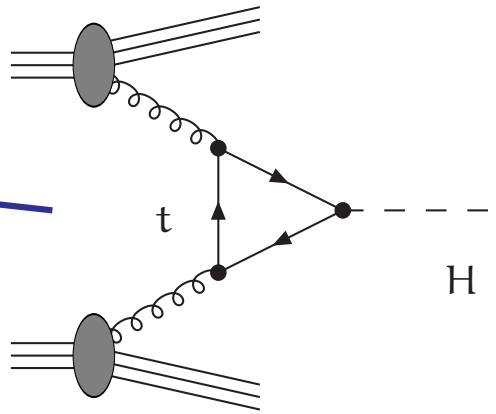


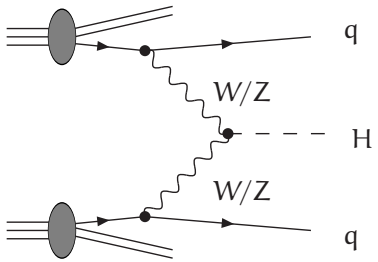


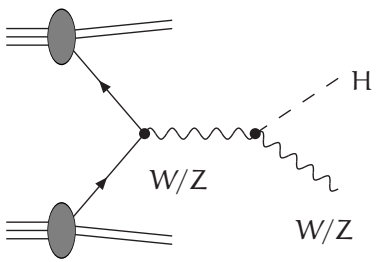
Higgs production channels at the LHC

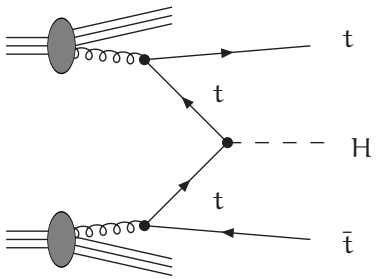


Gluon Fusion

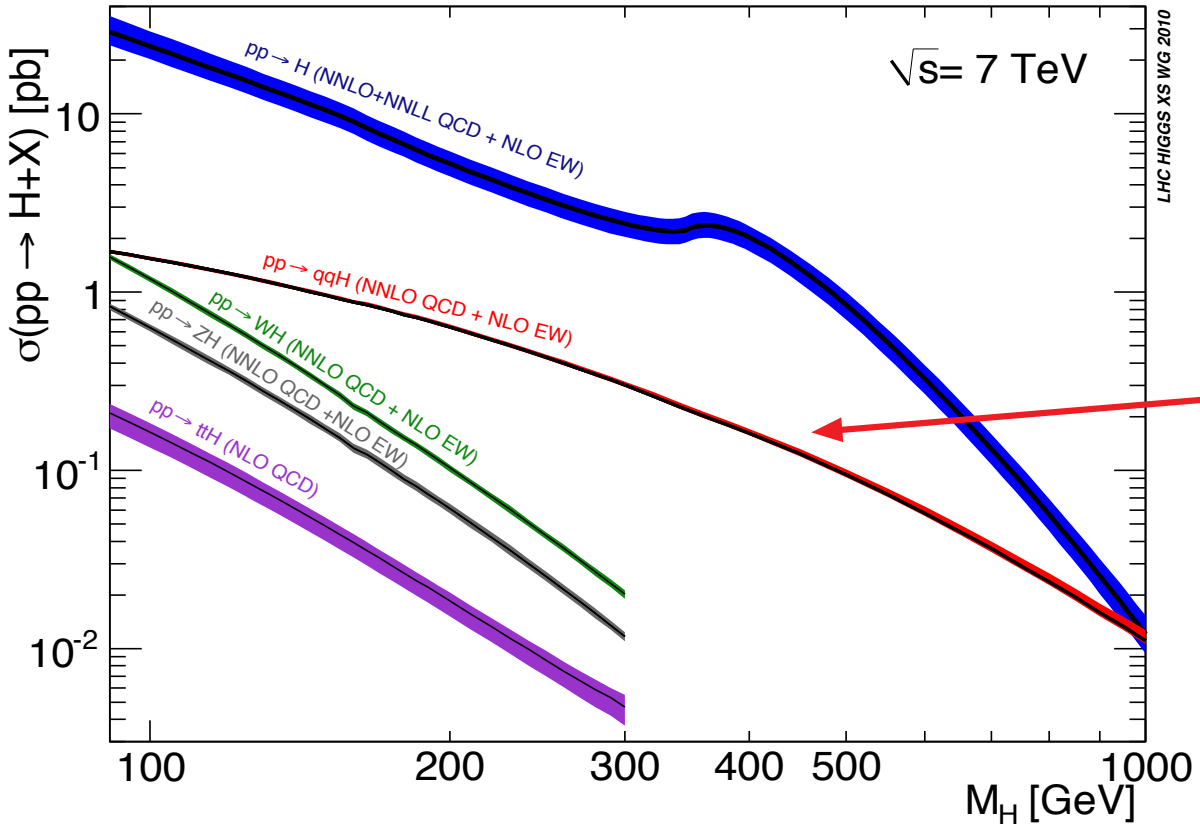








Higgs production channels at the LHC



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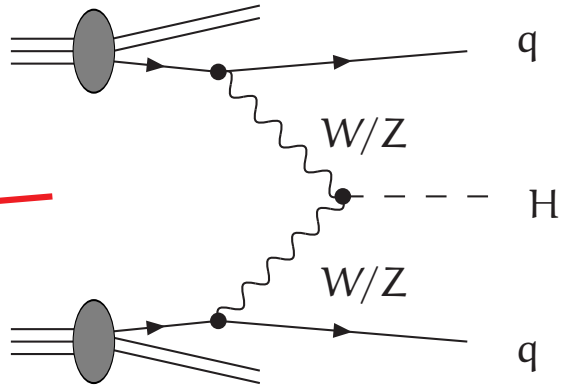

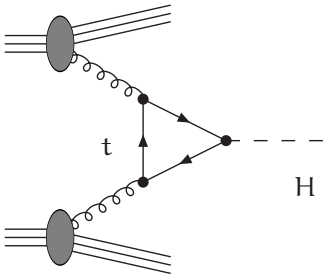

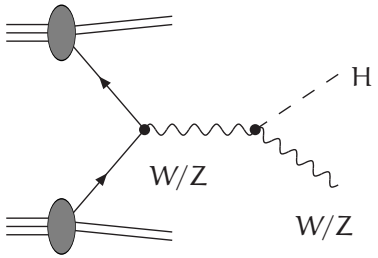

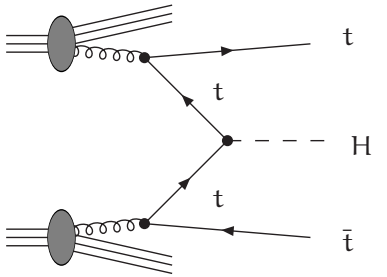

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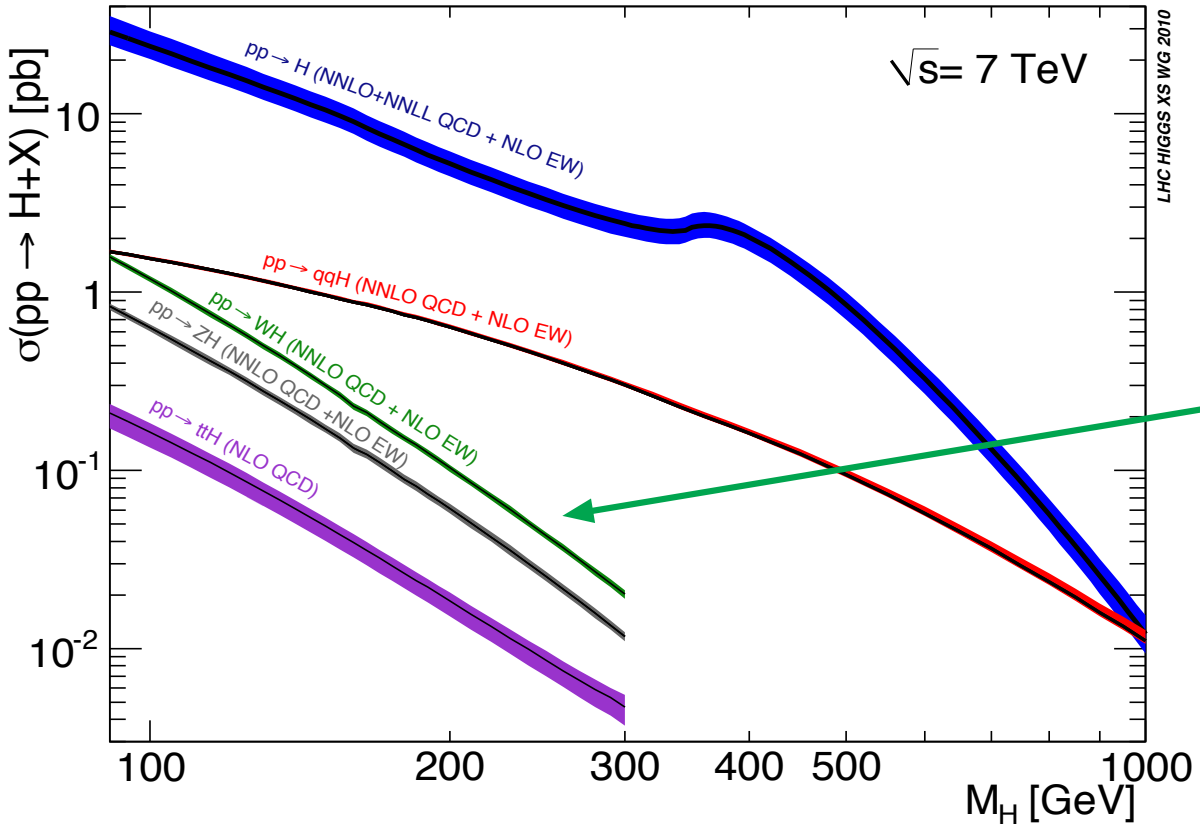
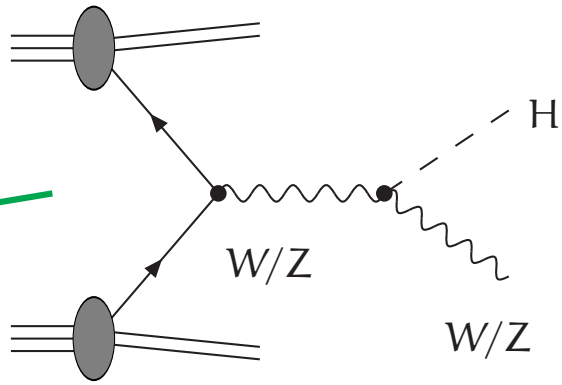
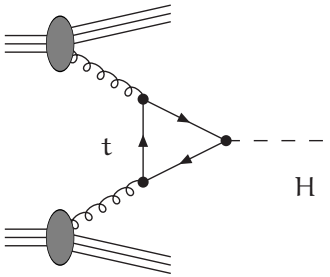
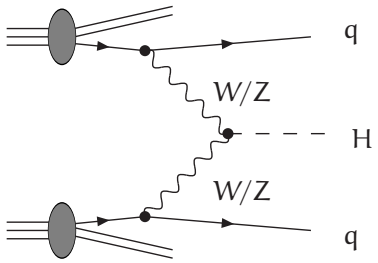
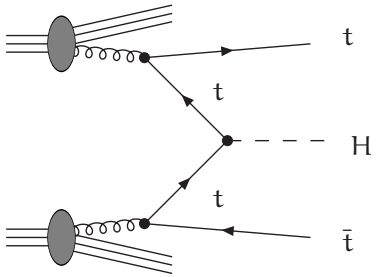


Higgs-strahlung

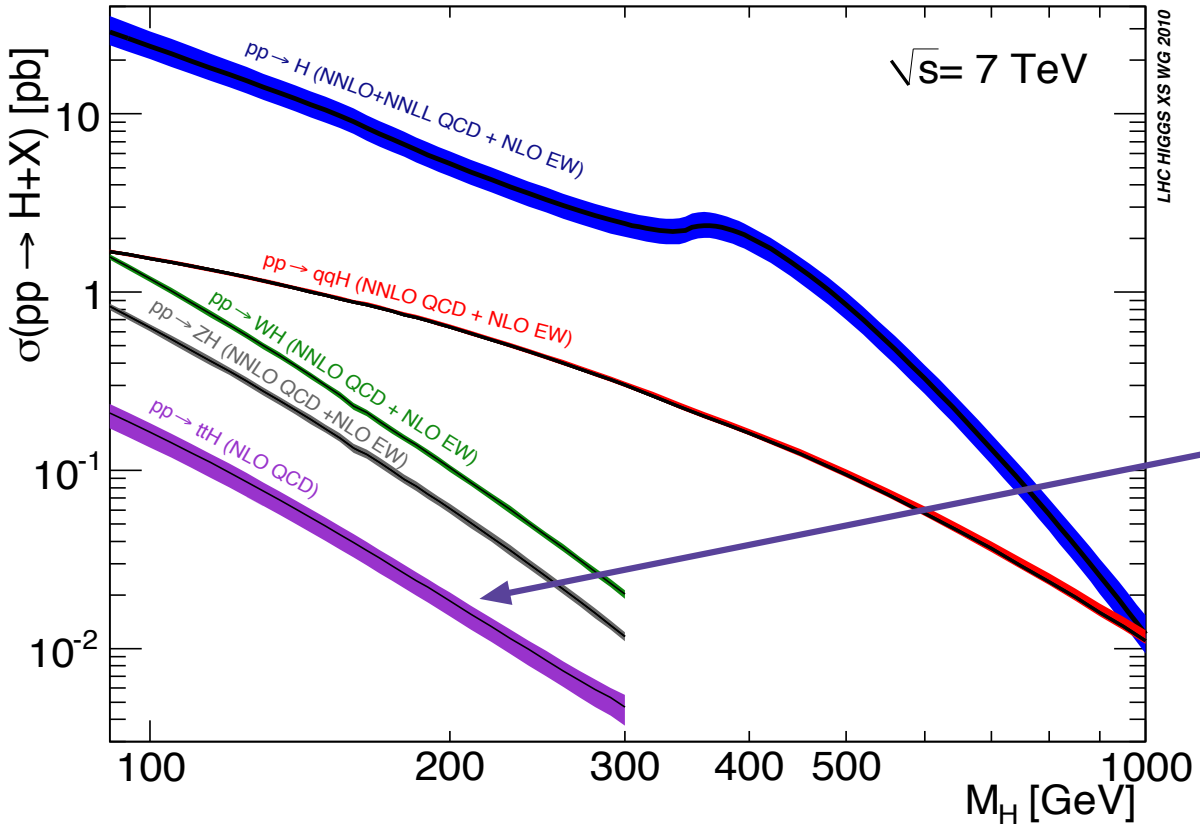




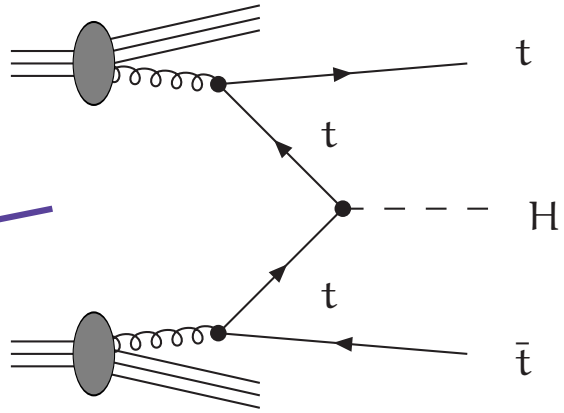


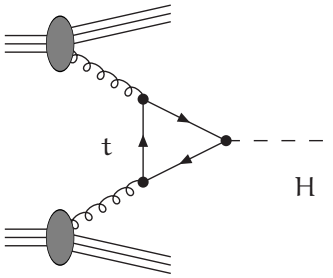


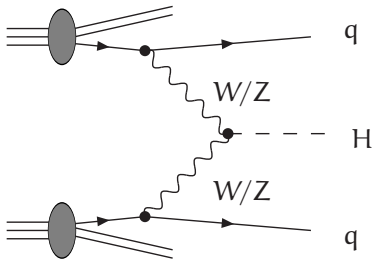
Higgs production channels at the LHC

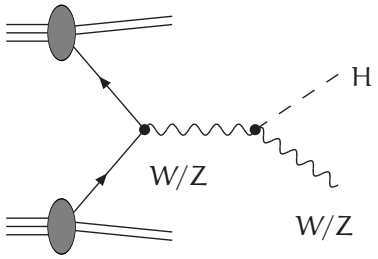


Top associate production

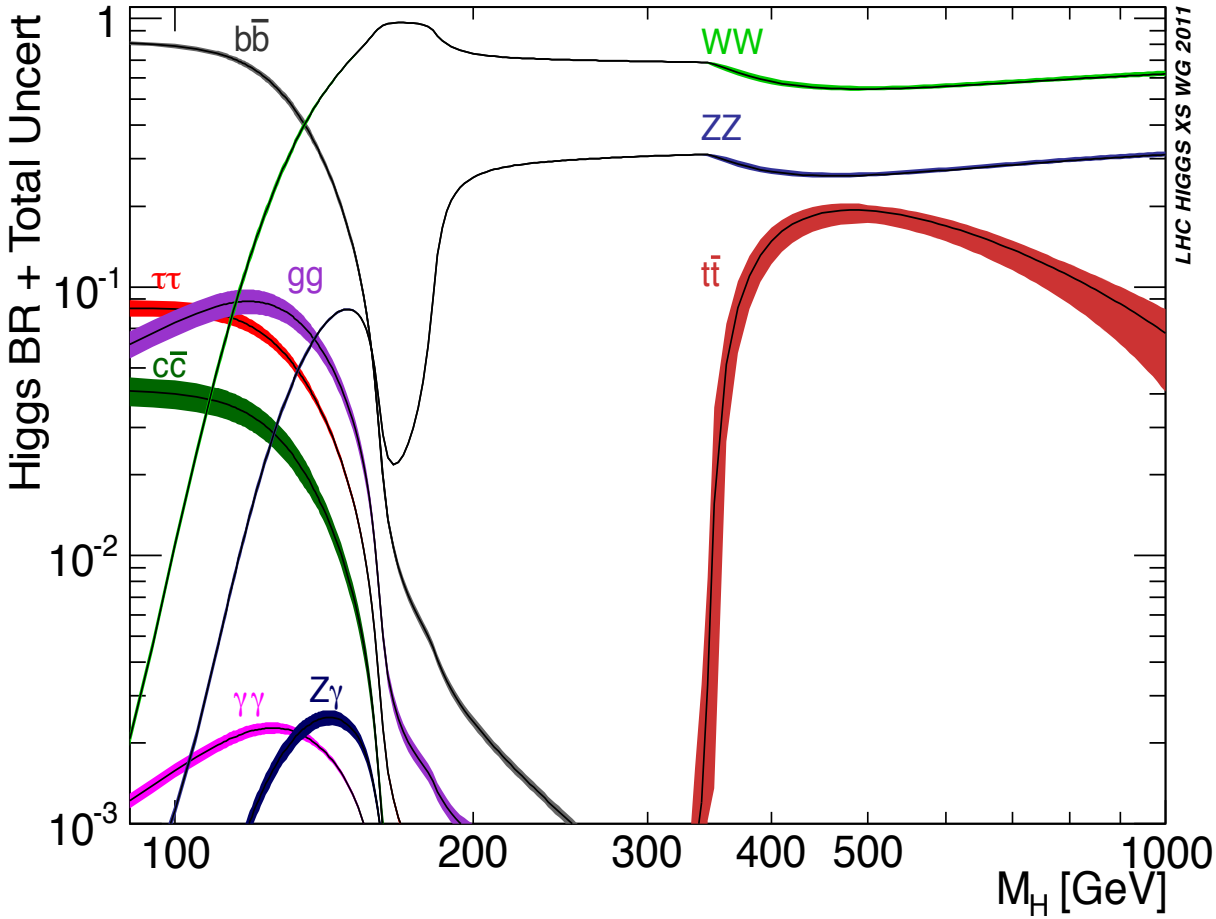


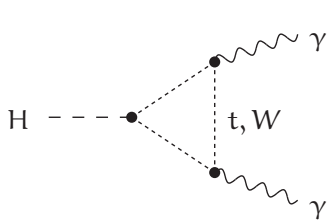


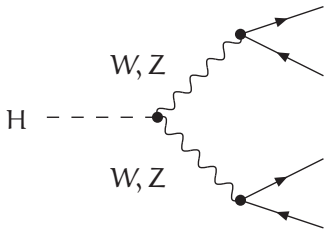


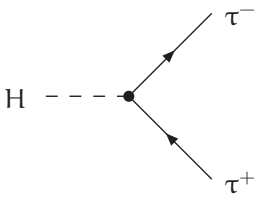


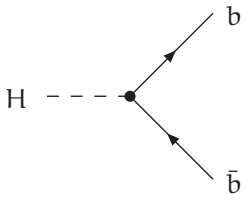
Higgs decay channels at the LHC

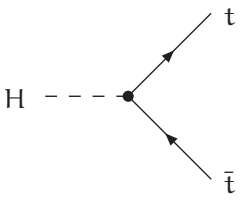












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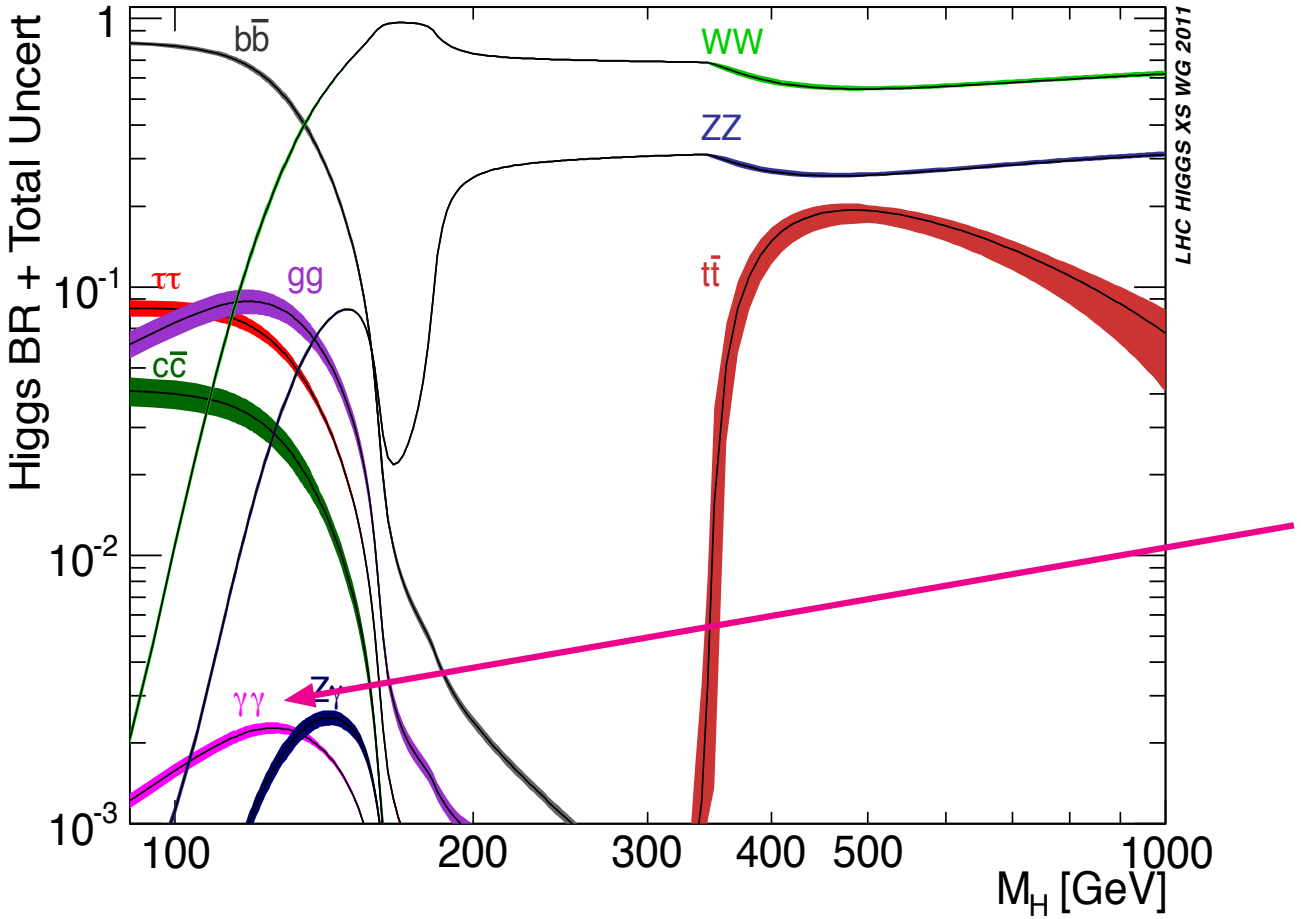
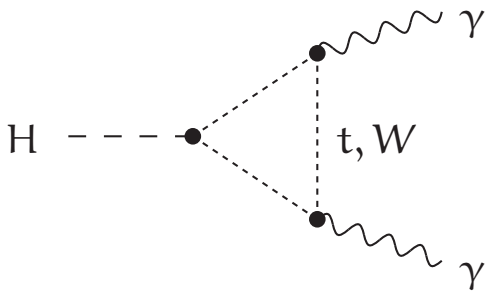
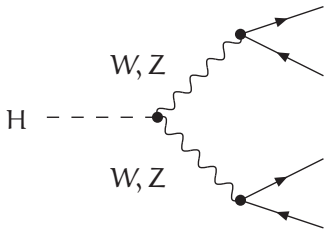
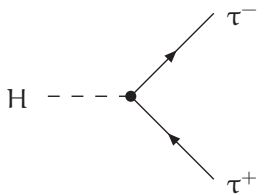
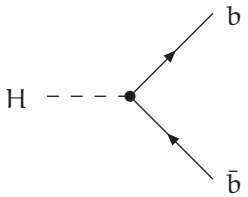


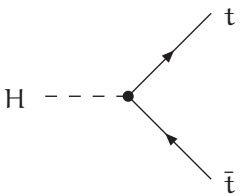
$H \to \gamma\gamma$



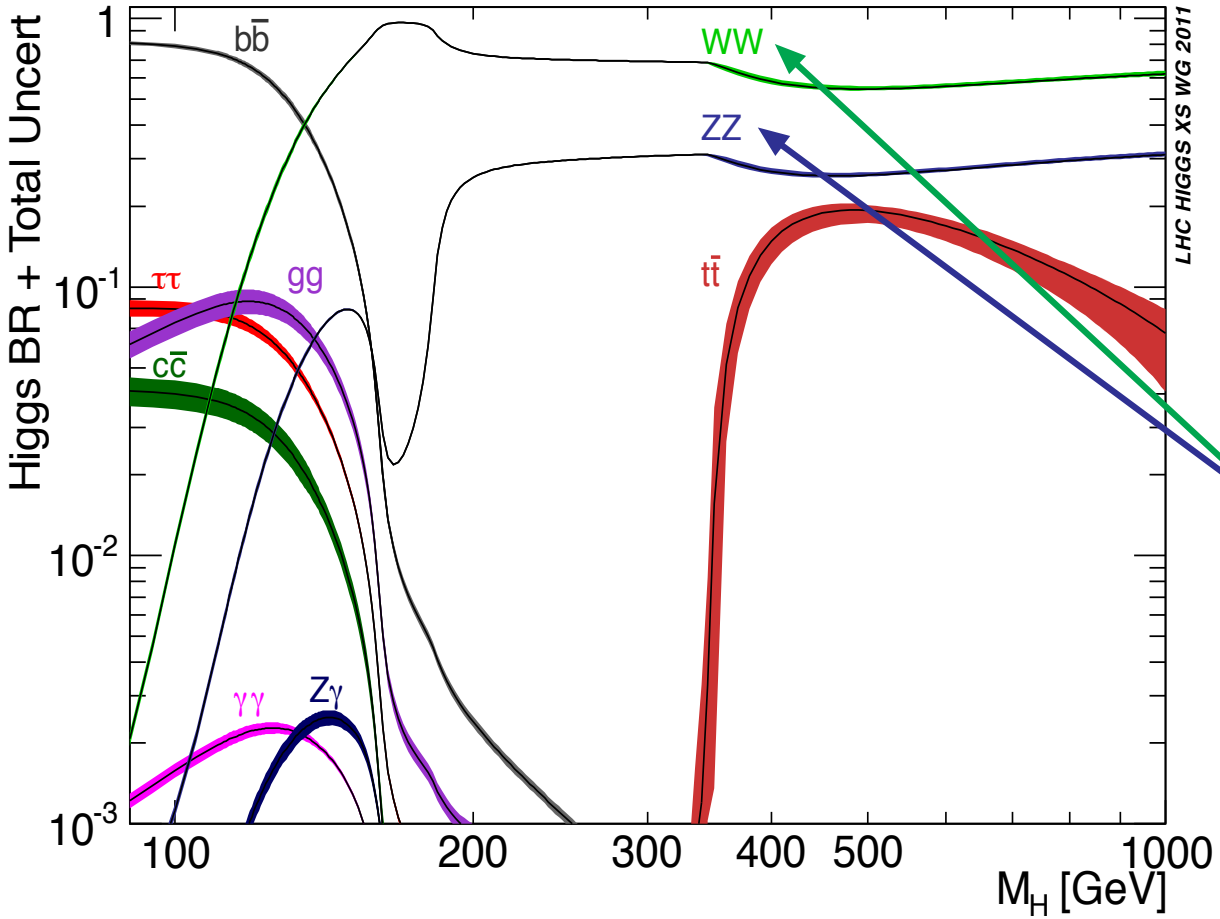






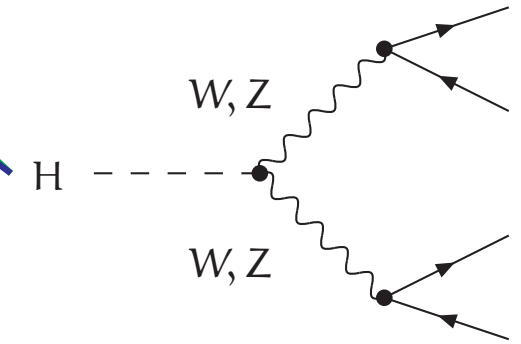


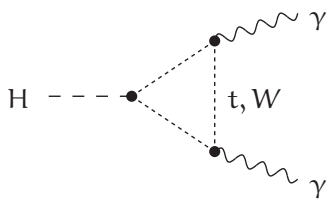
Higgs decay channels at the LHC

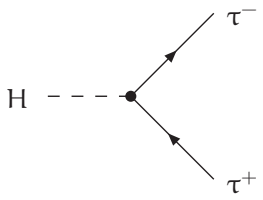


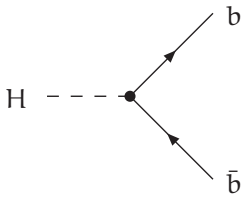
$H \to ZZ \to 4f$

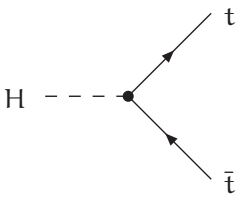
$H \to WW \to 4f$











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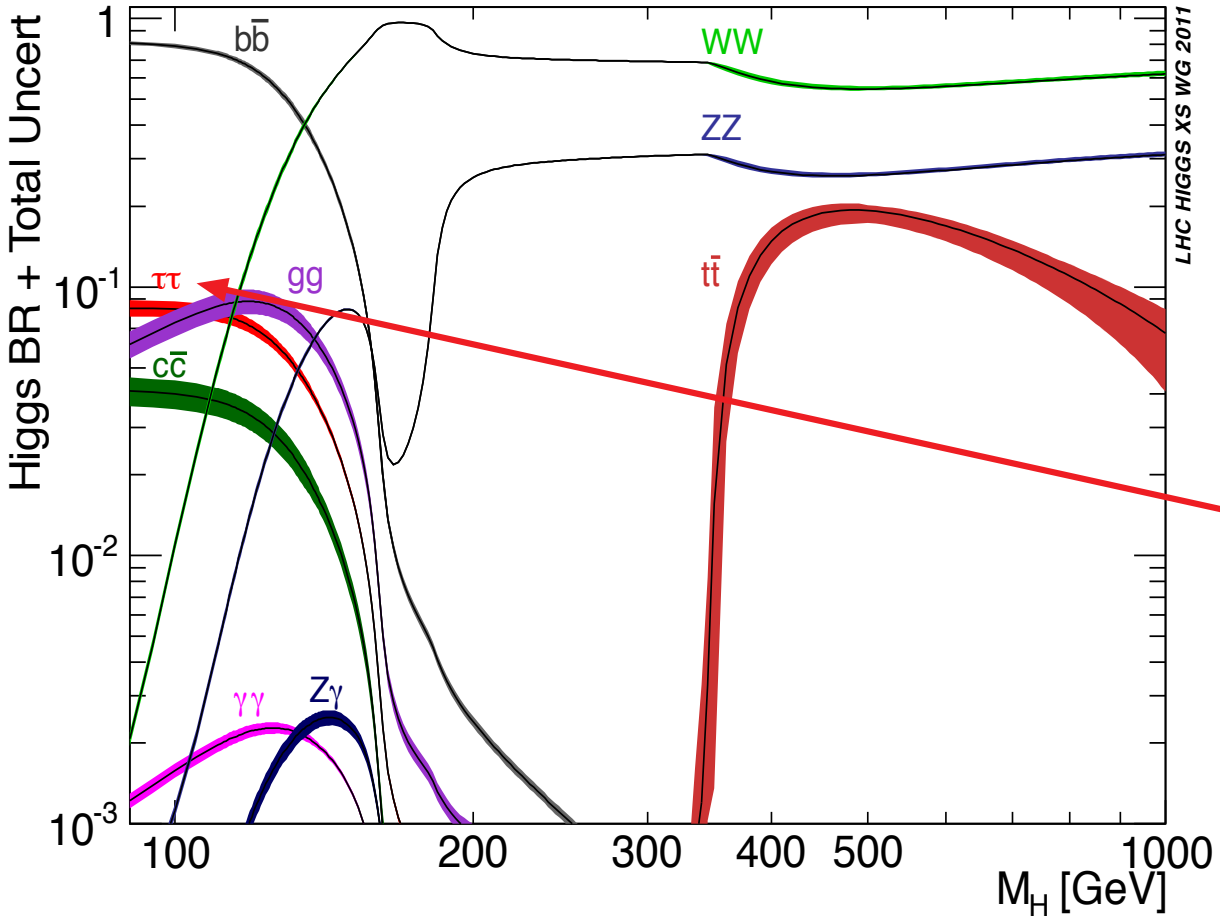
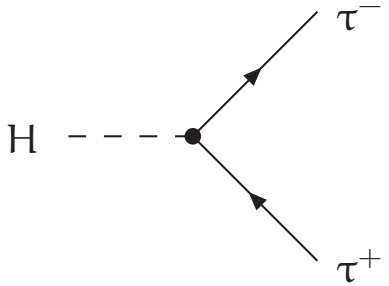
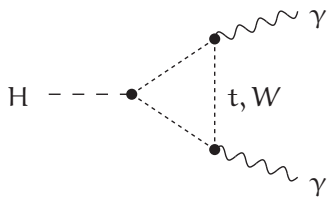
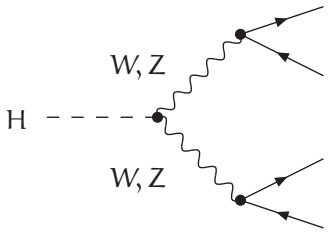
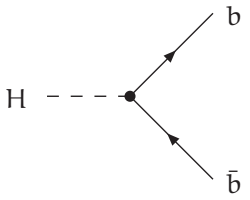


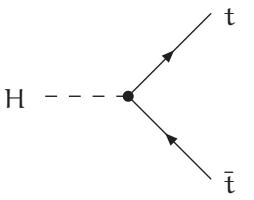
$H \to \tau^-\tau^+$











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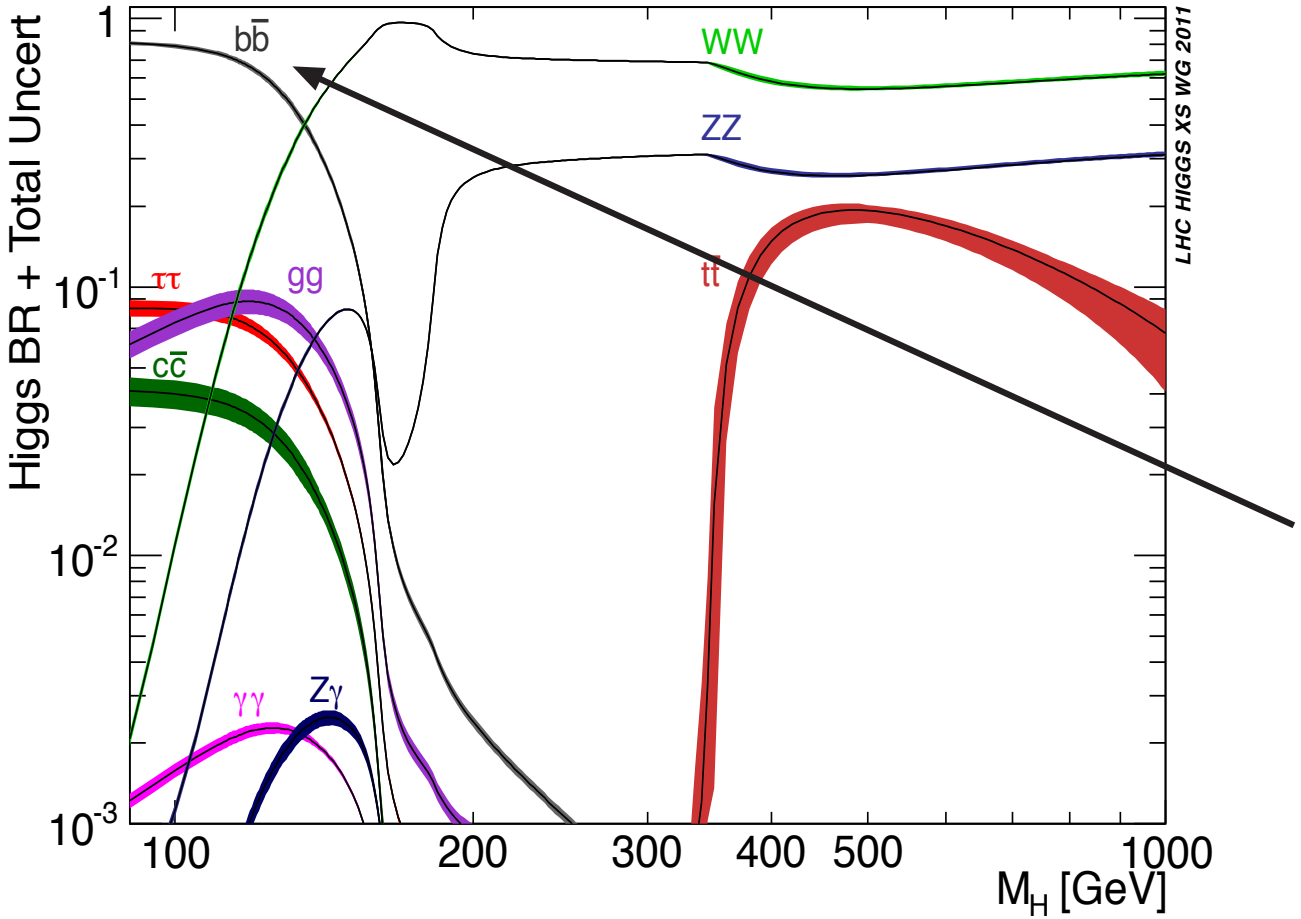
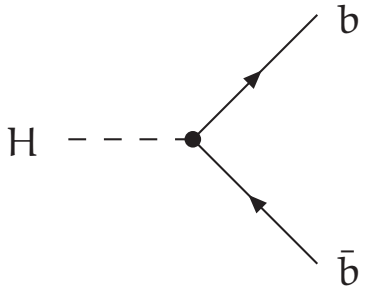
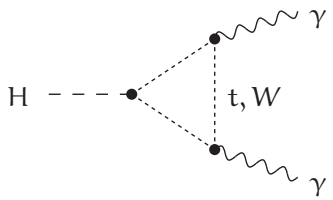
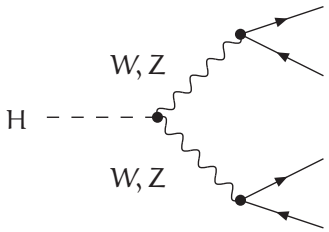
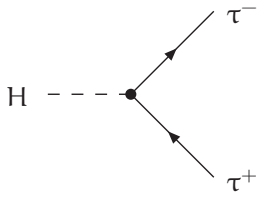


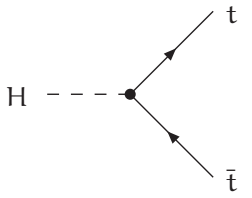
$H \to b\bar{b}$



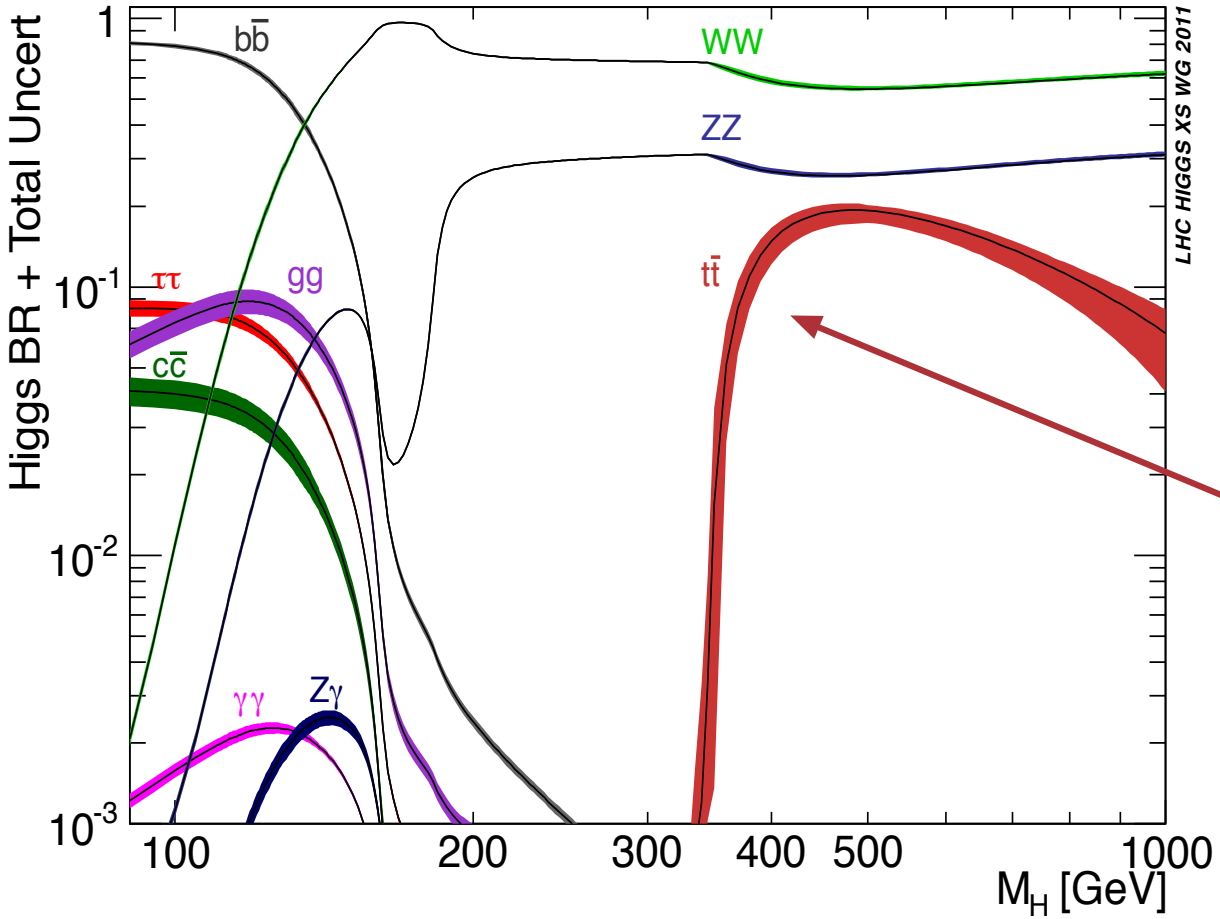




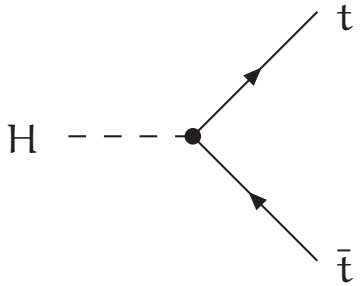


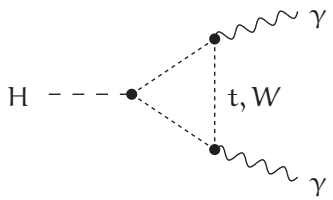


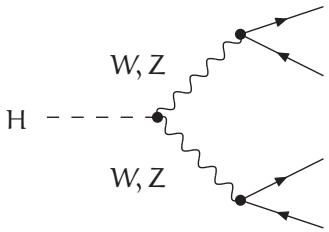
Higgs decay channels at the LHC

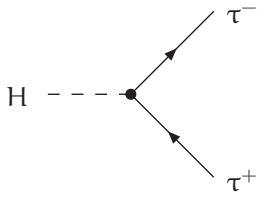


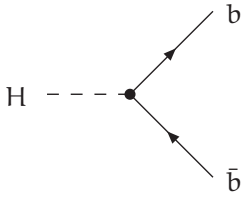
$H \to t\bar{t}$











Structure of the cross-section

Es. : $pp \to jj$

fit of experimental data

$$\overbrace{\sigma_{had}(p_1,p_2)}^{\text{hadronic cross-section}} = \sum_{a,b} \int dx_1 \int dx_2 \quad \overbrace{f_a(x_1,\mu_F^2)\, f_b(x_2,\mu_F^2)}^{\text{Parton Distrubution Functions (PDFs)}}$$

$$\times \Big[\underbrace{\sigma_{ab}^{LO}(x_1p_1, x_2p_2; \mu_R^2) + \sigma_{ab}^{NLO}(x_1p_1, x_2p_2; \mu_R^2, \mu_F^2) + \dots}_{\text{partonic cross-section}} \Big]$$

Es. : $gg \to q\bar{q}$, $q\bar{q} \to q\bar{q}$, $gq \to gq$, etc.

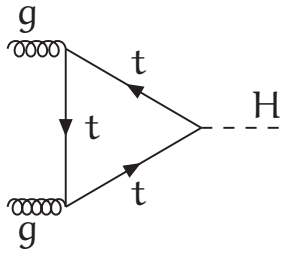
- μ_F^2 $\to$ Factorization scale
- μ_R^2 $\to$ Renormalization scale

All orders computations are scale independent.

Varying the scales $\to$ Estimation of theoretical uncertainty

Gluon Fusion

- Largest production cross section $\rightarrow$ Precise theoretical prediction is important
- Lowest order is a **one loop** calculation:



Georgi-Glashow-Machacek-Nanopoulos '78

  - Strong scale dependence
  - QCD corrections for reliability
- NLO QCD corrections
  - Large M_t limit: Dawson '91, Djouadi-Spira-Zerwas '91

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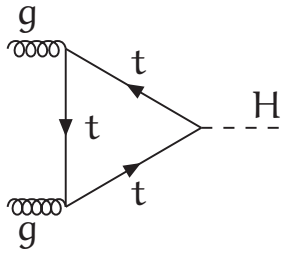

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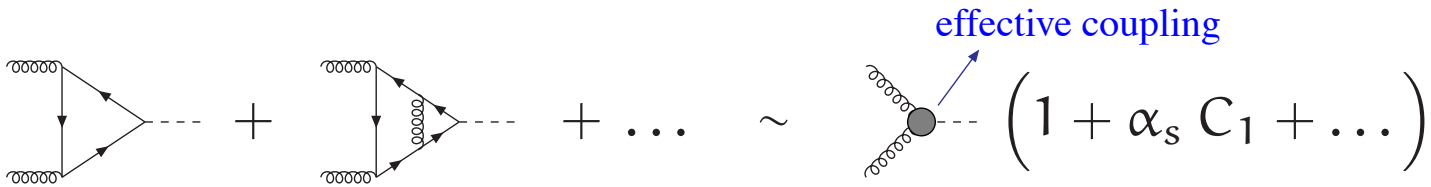

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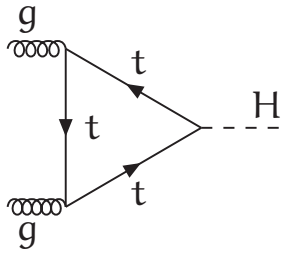

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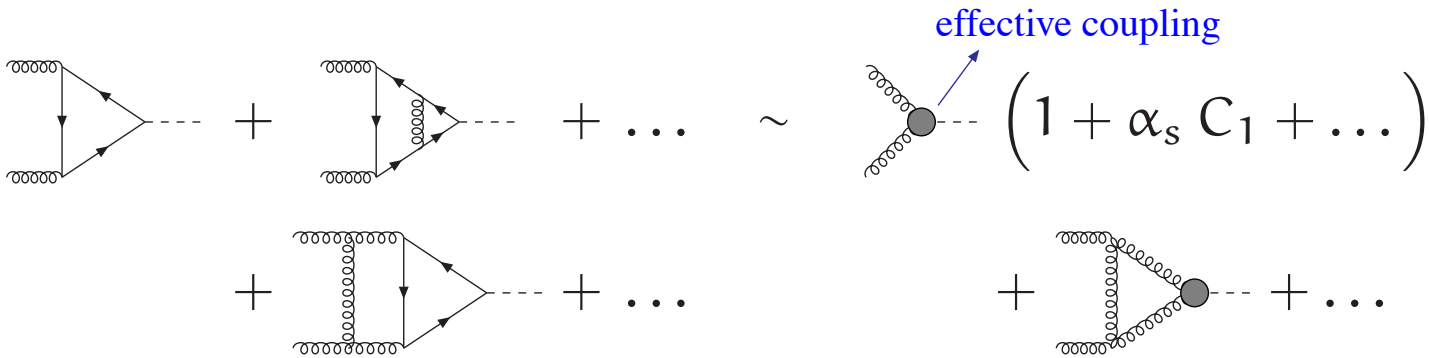

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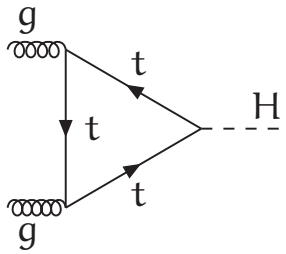
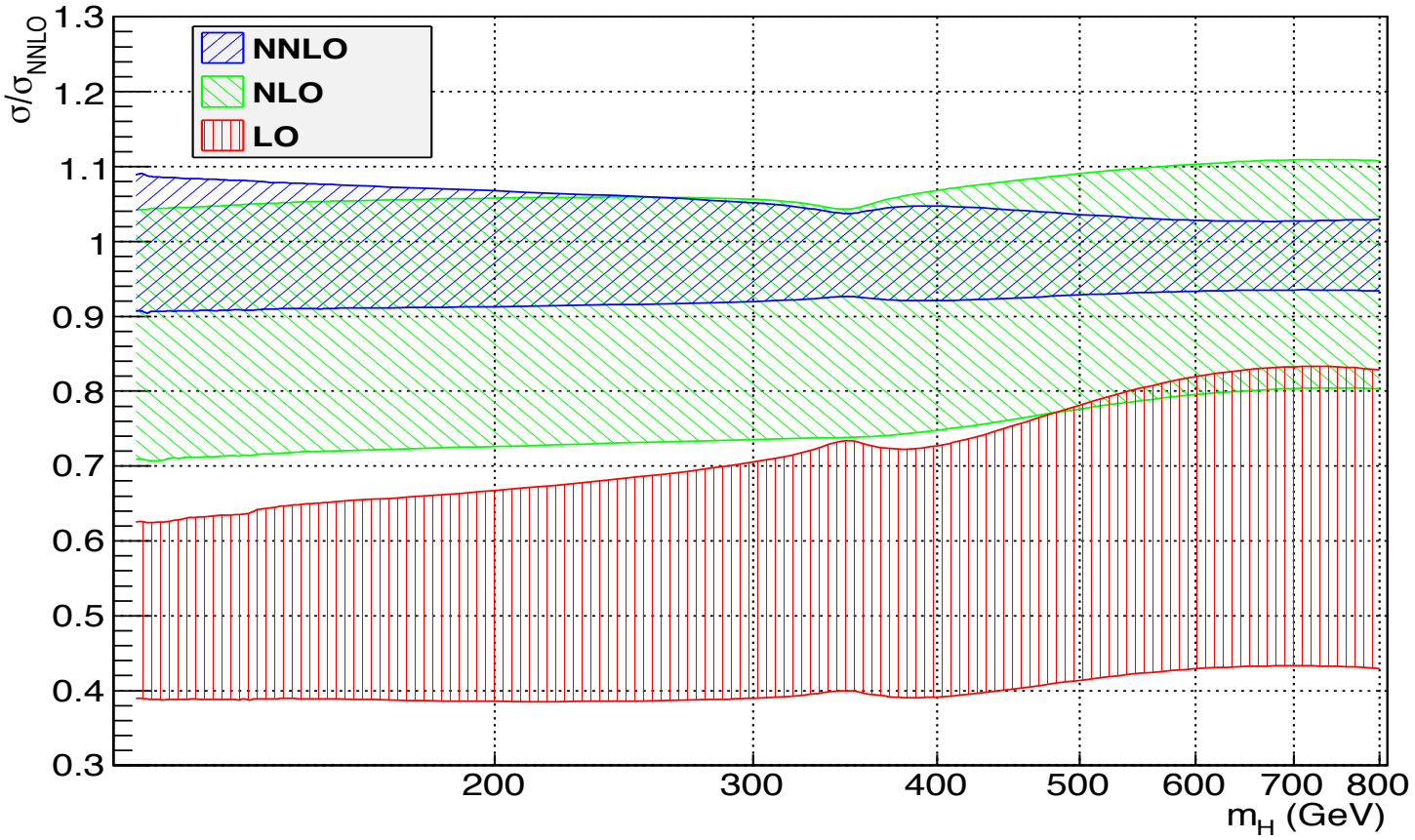


Georgi-Glashow-Machacek-Nanopoulos '78

  - Strong scale dependence
  - QCD corrections for reliability
- NLO QCD corrections $\rightarrow$ **+80**% LO; **Scale dependence 20**%
  - Large M_t limit: Dawson '91, Djouadi-Spira-Zerwas '91
  - Full result: Spira-Djouadi-Graudenz-Zerwas '95, Harlander-Kant '05, Anastasiou-Beerli-Bucherer-Daleo-Kunszt '06, Aglietti-Bonciani-Degrassi-Vicini '06

.

- NNLO QCD corrections $\rightarrow$ **+20%** NLO; **Scale dependence 10%**
  - Large M_t limit: Harlander '00, Catani-de Florian-Grazzini '01, Harlander-Kilgore '01, Anastasiou-Melnikov '02, Ravindran-Smith-van Neerven '03
  - Finite M_t effects: Harlander-Ozeren '09, Pak-Rogal-Steinhauser '09

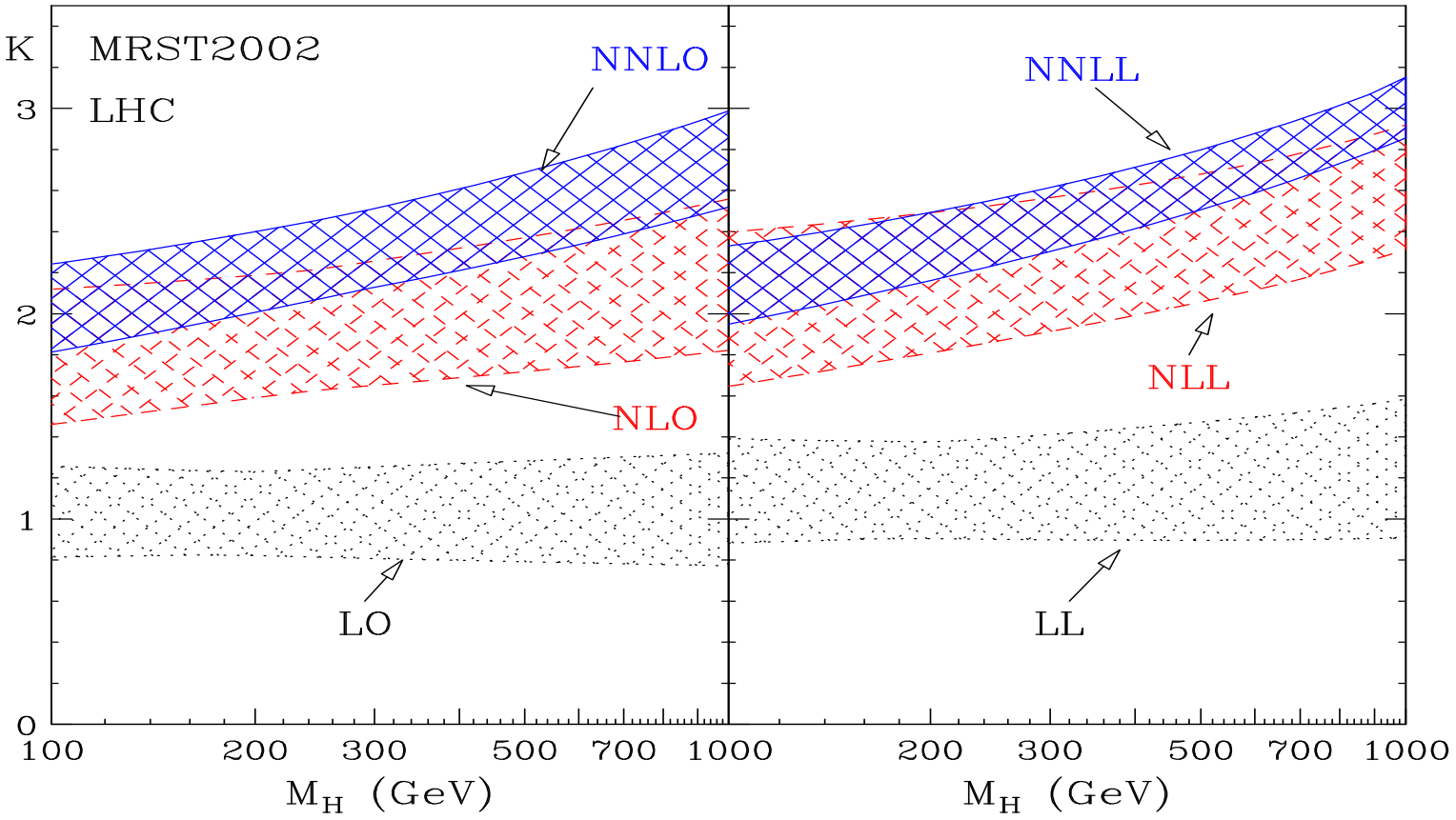


- Soft-gluon resummation NNLL → **+6%** NNLO; **Scale dependence 8%**

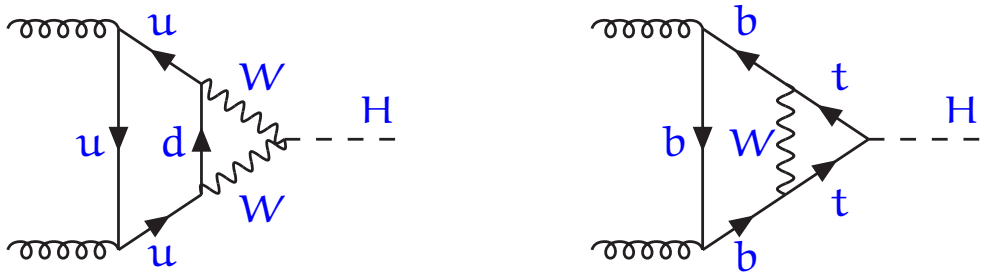
  Catani-de Florian-Grazzini-Nason '03

- Soft-gluon resummation N^3LL → **+8%** NNLO; **Scale dependence 3%**

  Moch-Vogt '05, Laenen-Magnea '06, Idilbi-Ji-Ma-Yuan '06, Ravindran '06, Ahrens-Becher-Neubert-Yang '09



- NLO EW corrections



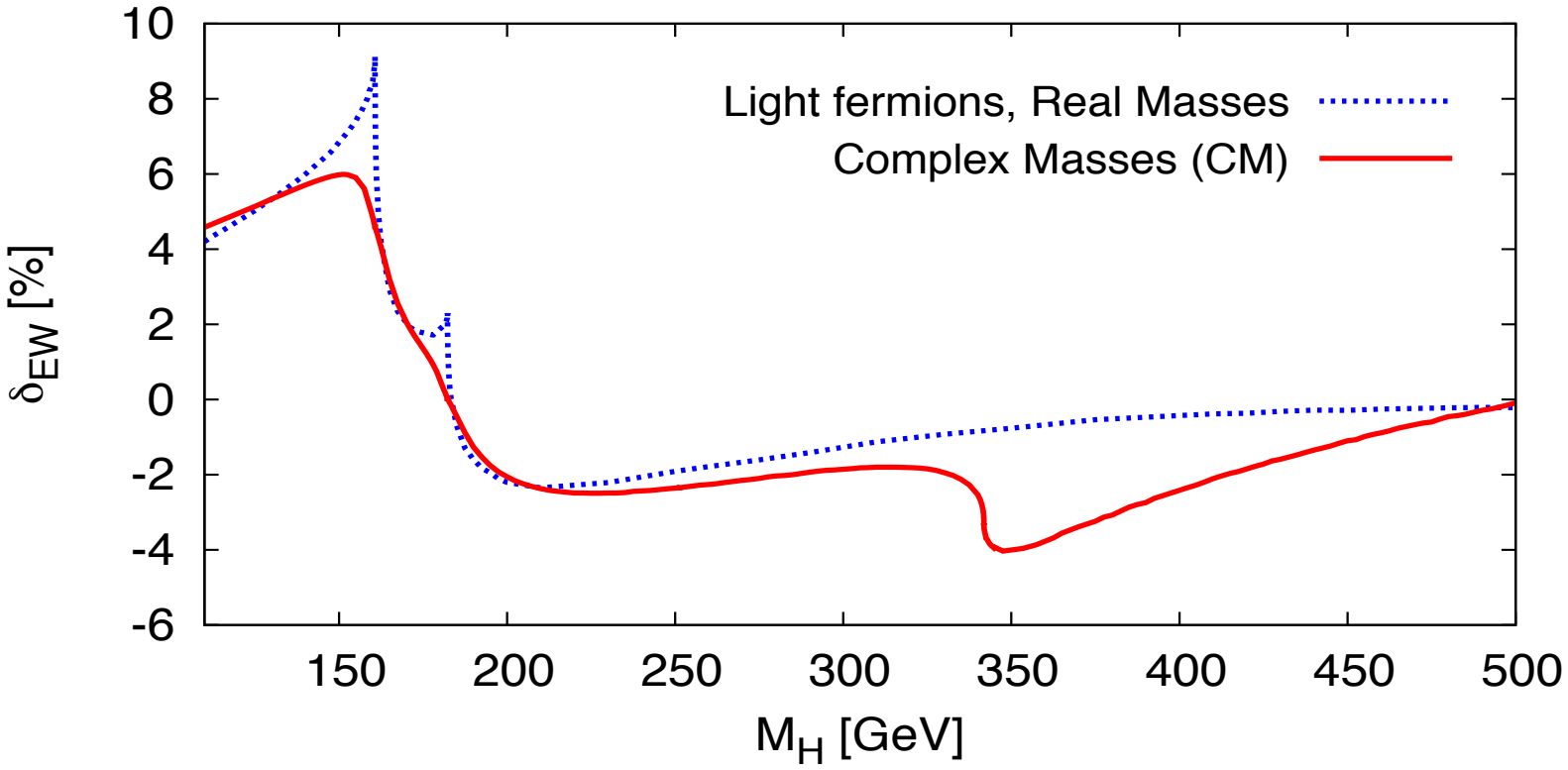
Many massive particles $\longrightarrow$ Potentially large threshold effects

↳ Instable $\longrightarrow$ **Complex masses**

- Dominant contributions enhanced by M_t^2: `Djouadi-Gambino '94`
- Light-quark contributions: `Aglietti-Bonciani-Degrassi-Vicini '04`
- Top-quark contributions (Taylor expansion for $M_H < 2M_W$): `Degrassi-Maltoni '04`
- Full EW Corrections: `Actis-Passarino-Sturm-U. '08`

↳ **Complex mass scheme** $\longrightarrow$ Stabilize behaviour at thresholds

- NLO EW corrections $\rightarrow$ **-4**% $< \delta_{EW} <$ **+6**% ;
  - Dominant contributions enhanced by M_t^2: `Djouadi-Gambino '94`
  - Light-quark contributions: `Aglietti-Bonciani-Degrassi-Vicini '04`
  - Top-quark contributions (Taylor expansion for $M_H < 2M_W$): `Degrassi-Maltoni '04`
  - Full EW Corrections: `Actis-Passarino-Sturm-U. '08`



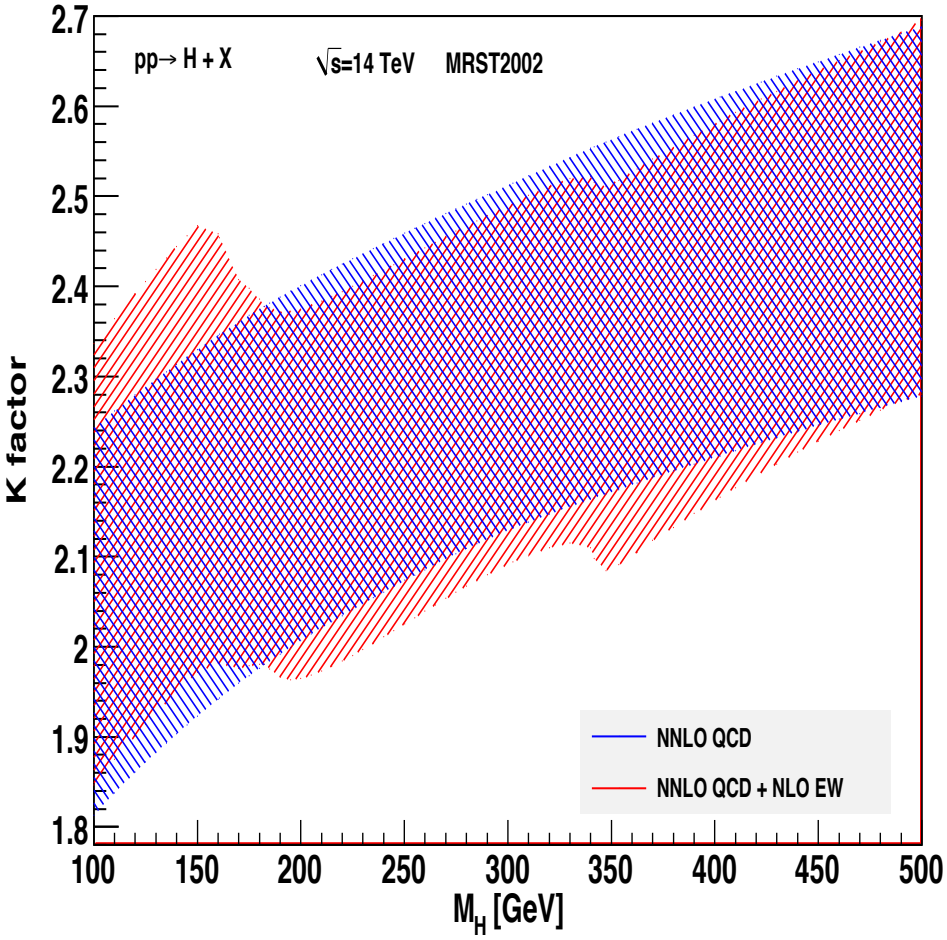
How to combine QCD and EW corrections?

- Partial factorization: $\sigma \sim \sigma^{LO}(1+\delta_{EW}) + \sigma^{NLO}_{QCD} + \sigma^{NNLO}_{QCD} + \dots$
- Complete factorization: $\sigma \sim (\sigma^{LO} + \sigma^{NLO}_{QCD} + \sigma^{NNLO}_{QCD} + \dots)(1+\delta_{EW})$

- Mixed QCD-EW corrections $\mathcal{O}(\alpha\alpha_s)$
  - Light-quark contributions (expansion for $M_H < M_W$): Anastasiou-Boughezal-Petriello '08

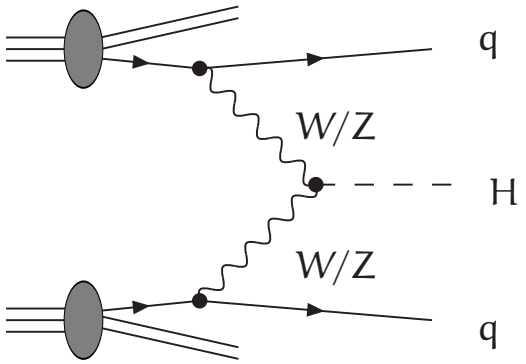
    $\Downarrow$

    Complete factorization
  - EW effects enhanced $\left(K = \frac{\sigma}{\sigma^{LO}}\right)$



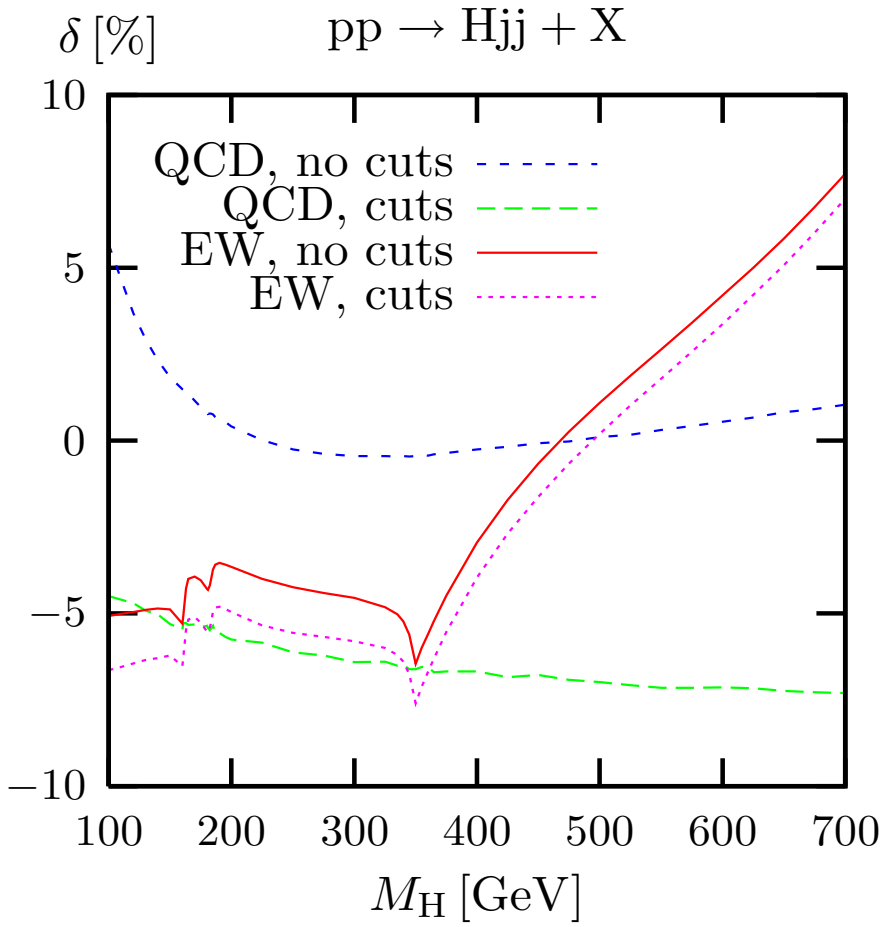
Vector Boson Fusion (VBF)

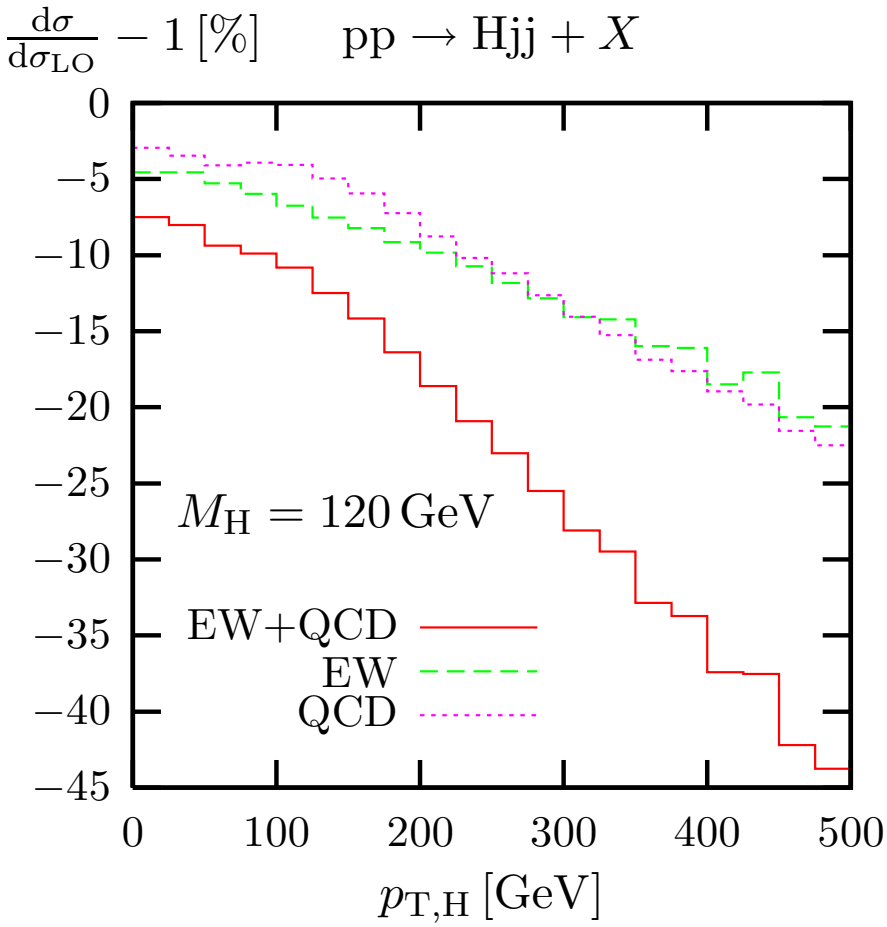
- $pp \to H + 2$ Jets
- Special cuts to reduce other production channel
  - Almost no color exchange between quark lines
  - Reduced QCD effects



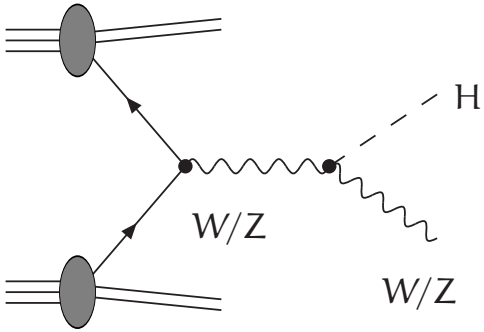
- NLO QCD corrections $\to$ **5-10**% LO; **Scale dependence 5**%
  - Total cross section: `Spira '97`
  - Differential cross sections: `Figy-Oleari-Zeppenfeld '03`
- NNLO QCD corrections $\to$ **1**% NLO; **Scale dependence 2**%
  - Gluon induced contributions: `Harlander-Vollinga-Weber '08`
  - Structure function approximation: `Bolzoni-Maltoni-Moch-Zaro '10`

- NLO EW corrections $\rightarrow$ **5-10**% LO
  - Ciccolini, Denner, Dittmaier '07
  - Same order of QCD correction
  - Large corrections at high energies





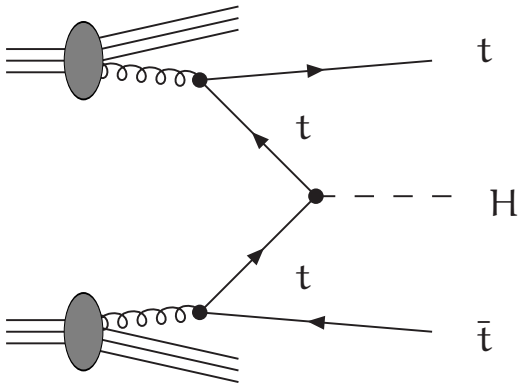
Higgs-strahlung



- $pp \to HW, pp \to HZ$
- Important in the "boosted-Higgs" scenario together with $H \to b\bar{b}$ decay
- NLO QCD corrections $\to$ **30%** LO; **Scale dependence 10%**
  Han-Willenbrock '91, Baer-Bailey-Owens '93, Ohnemus-Stirling '93
- NNLO QCD corrections $\to$ **10%** NLO; **Scale dependence 1-4%**
  - Total cross section: Brein-Djouadi-Harlander '03, Brein-Harlander-Wiesemann-Zirke '11
  - Differential cross sections: Ferrera-Grazzini-Tramontano '11
- NLO EW corrections $\to$ **5-10%** LO
  - Total cross section: Ciccolini-Dittmaier-Krämer '03
  - Differential cross sections: Denner-Dittmaier-Kallweit-Mück '11

Associate Higgs production with $t\bar{t}$

- $pp \to t\bar{t}H$
- Important to check the $t\bar{t}H$ Yukawa coupling
- Suppressed cross section
  - $\to$ Combined with $H \to b\bar{b}$ decay



- NLO QCD corrections $\to$ **10-20**% LO; **Scale dependence 10**%
  - Total cross section:

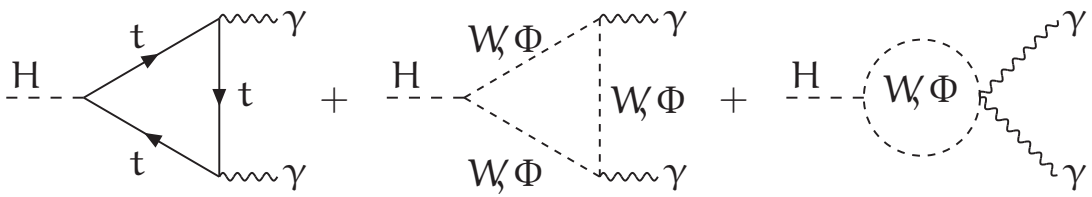
    Beenakker-Dittmaier-Krämer-Plümper-Spira-Zerwas '01,

    Reina-Dawson '01
  - Differential cross sections:

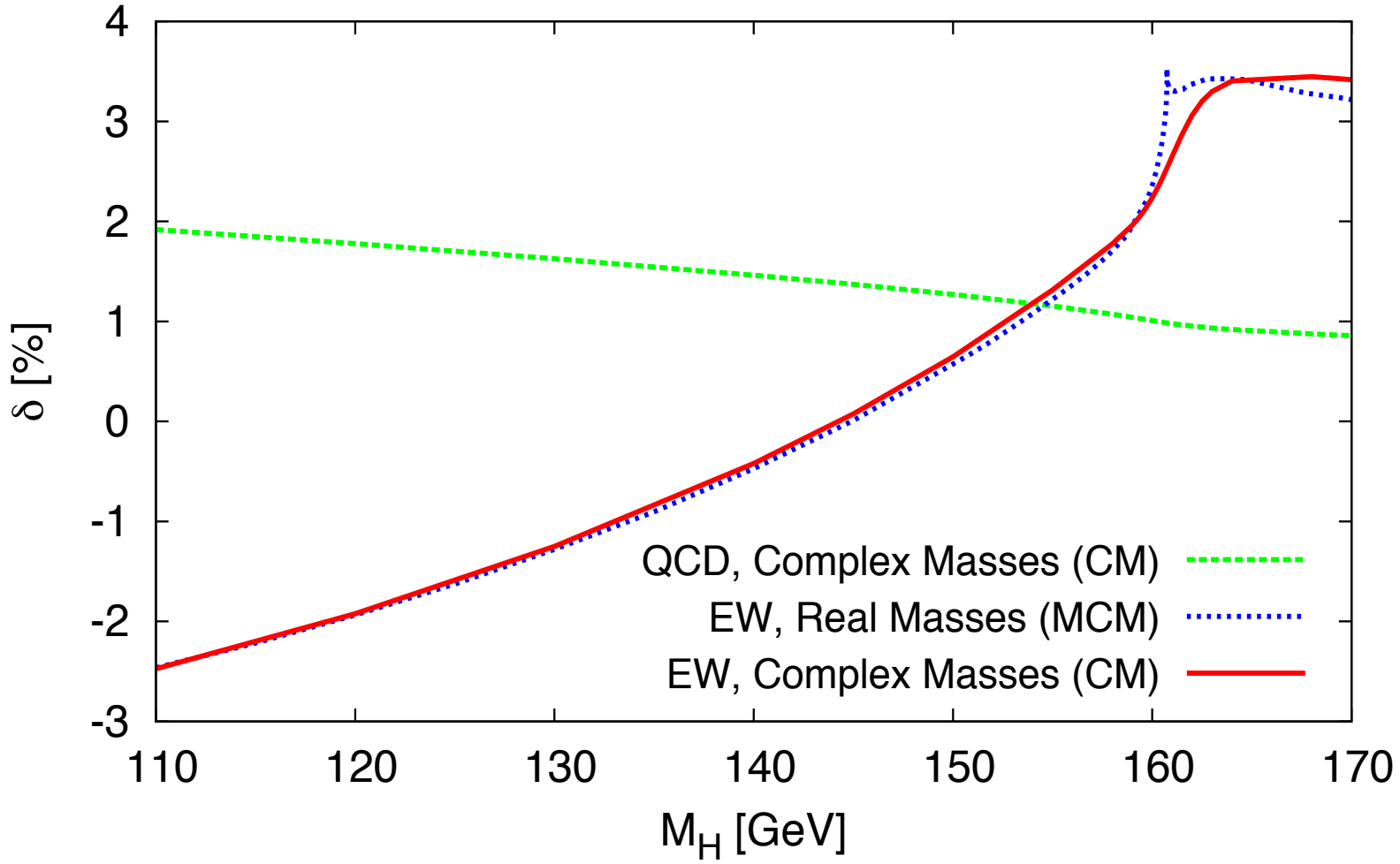
    Beenakker-Dittmaier-Krämer-Plümper-Spira-Zerwas '02
- $pp \to t\bar{t}b\bar{b} \to$ Background to $pp \to t\bar{t}H$, $H \to b\bar{b}$ is Known at NLO QCD

Decay $H \to \gamma\gamma$

- Important for light Higgs
- Potentially large threshold effects



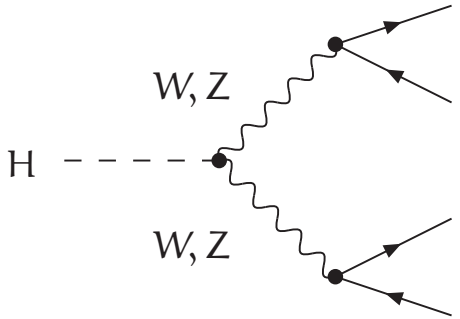
- NLO QCD $\to$ **1-2**% LO
  - Expansion in $M_H/4M_t$: Zheng-Wu '90, Djouadi-Spira-van der Bij-Zerwas '91, Dawson-Kauffman '93, Steinhauser '96
  - Exact computation: Melnikov-Yakovlev '93, Djouadi-Spira-Zerwas '93, Inoue-Najima-Oka-Saito '94, Fleischer-Tarasov-Tarasov '04
- NLO EW $\to$ **-3**% $< \delta_{EW} <$ **+4**%
  - Light fermions contribution: Aglietti-Bonciani-Degrassi-Vicini '04
  - Top-quark and bosonic corrections (m_H<150 GeV): Degrassi-Maltoni '05
  - Complete corrections: Passarino-Sturm-U. '07,'08



- Threshold effects under control
- Background → taken from data, but ...

  ... Theoretical simulations for comparisons and for multivariate analyses

Decay $H \to WW/ZZ \to 4f$



- Relevant at the WW/ZZ threshold
- The W/Z decays have to be taken into account
- Four-fermion final state allows
  to extract spin and CP of the Higgs
- NLO EW corrections $\to$ $< \mathbf{12}\%$ LO;
  - On-shell Vector bosons: `FLeischer-Jegerlehner '81`
  - With full off-shell effects: `Bredenstein-Denner-Dittmaier-Weber '06`
- Background of $H \to WW \to l^+\nu l^-\bar{\nu}$:
  Extrapolated from data using theoretical distributions
- Background of $H \to ZZ \to l^+l^-l'^+l'^-$ and $H \to ZZ \to l^+l^-\nu\bar{\nu}$:
  Taken from theory

High precision in theoretical distributions $pp \to 4l$ needed

Summary of uncertainties for production and decay

		LHC @ $\sqrt{s} = 7$TeV			
		uncertainties		corrections	
	M_H[GeV]	Theory	PDFs	QCD	EW
ggF	< 500	6–10%	8–10%	$> 100\%$	5%
VBF	< 500	1%	2–7%	5%	5%
HW	< 200	1%	3–4%	30%	5–10%
HZ	< 200	1–2%	3–4%	40%	5%
ttH	< 200	10%	9%	5%	?

M_H[GeV]	$H \to$ $b\bar{b}$	$\tau^+\tau^-$	$c\bar{c}$	gg	$\gamma\gamma$	WW	ZZ
120	3%	6%	12%	10%	5%	5%	5%
150	4%	3%	10%	8%	2%	1%	1%
200	5%	3%	10%	8%	2%	$< 0.1\%$	$< 0.1\%$

Towards the next theoretical challenges

- Experiments do not measure total cross sections
  - Differential distributions available for production and decay at NLO

    $\rightarrow$ QCD/EW corrections and uncertainties can change
  - At NNLO not always available

    Ex: Top-mass effects in $gg \rightarrow H$
- Background distributions
  - Big improvement in the last years through NLO automatization:

    Ex.: $pp \rightarrow t\bar{t}b\bar{b}$ $pp \rightarrow t\bar{t}jj$ $pp \rightarrow W^+W^-b\bar{b}$ $pp \rightarrow W^+W^-jj$
  - Some corrections still missing

    Ex.: EW corrections to $pp \rightarrow Z + 2$ jets $\rightarrow$ background to VBF

Towards the next theoretical challenges

- Off-shell effects of unstable final states

  Ex.: $pp \to t\bar{t}H \to W^+W^-b\bar{b}H \to l^+\nu l^-\bar{\nu}b\bar{b}H$

- Link between Parton Shower and fixed order calculations:

  MC@NLO and POWHEG

  - All production channels are available
  - Most of background processes are implemented

- Beyond the Standard Model (without assuming models)

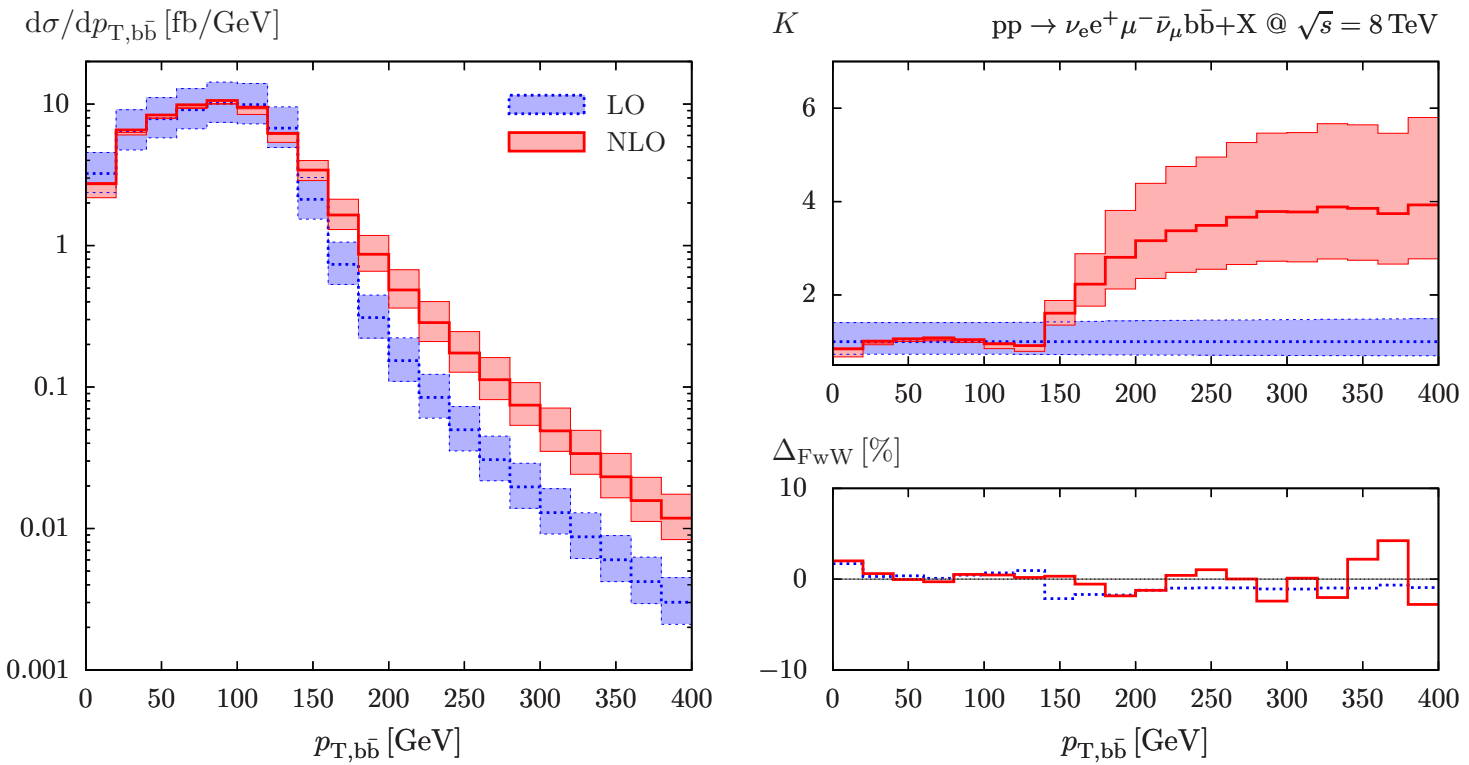
  - Good knowledge of the SM background
  - Effective theory approach

•

$pp \to W^+W^-b\bar{b}$

Background to

$pp \to H(\to b\bar{b})W$



Invariant $b\bar{b}$-Mass distribtution of

$pp \to t\bar{t}b\bar{b}$

Background to $pp \to H(\to b\bar{b})t\bar{t}$