E I S A

European Institute for Sciences and Their Applications

Corfu Summer Institute

16th Hellenic School and Workshops on Elementary Particle Physics and Gravity

Corfu, Greece 2016

Electroweak Physics at the LHC

— Lecture 4 —

Higgs Physics

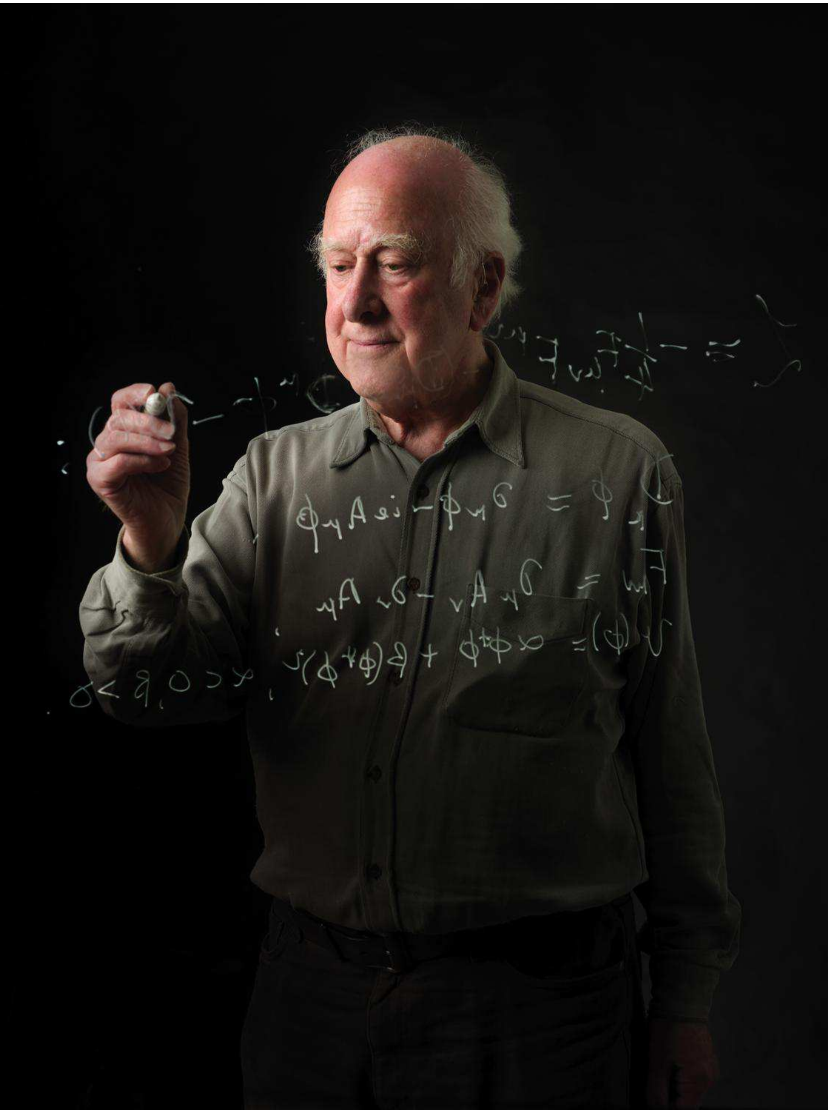
Stefan Dittmaier

Albert-Ludwigs-Universität Freiburg

Contents

Higgs production at the LHC

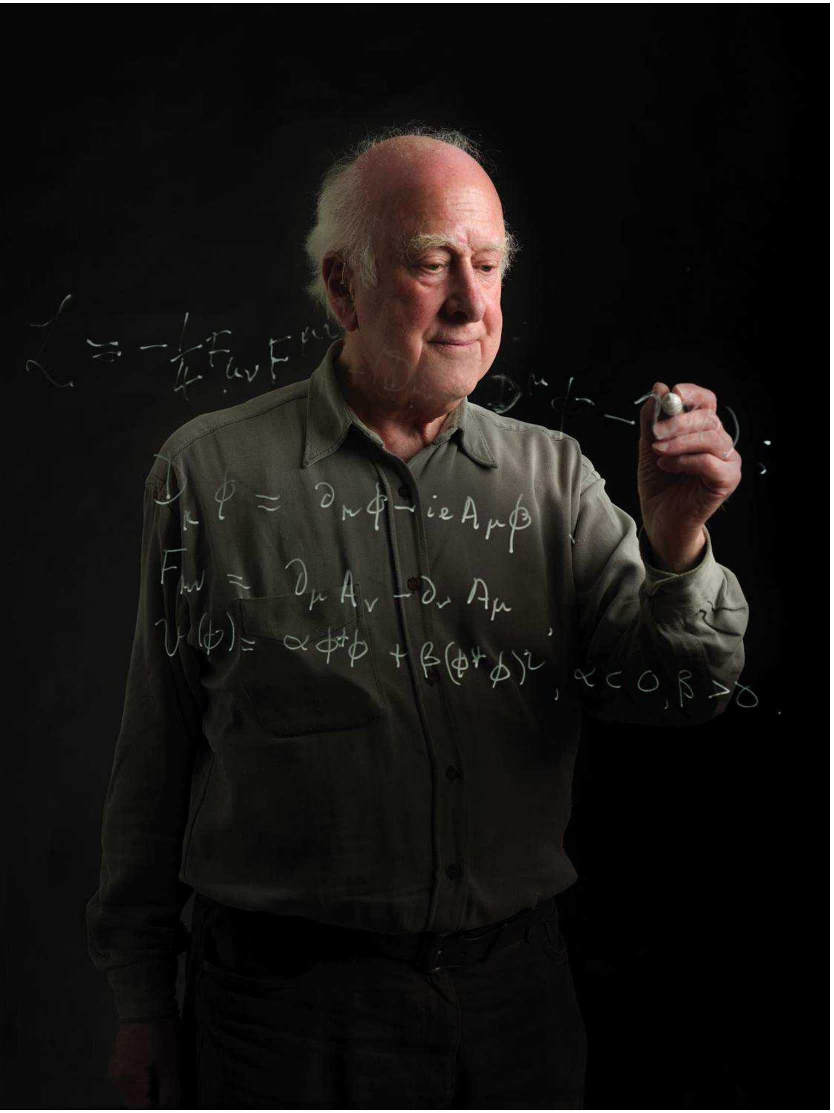
The Higgs mechanism – particles masses and Higgs couplings



Peter Higgs

... describing the "‘Abelian Higgs model"’

The Higgs mechanism – particles masses and Higgs couplings



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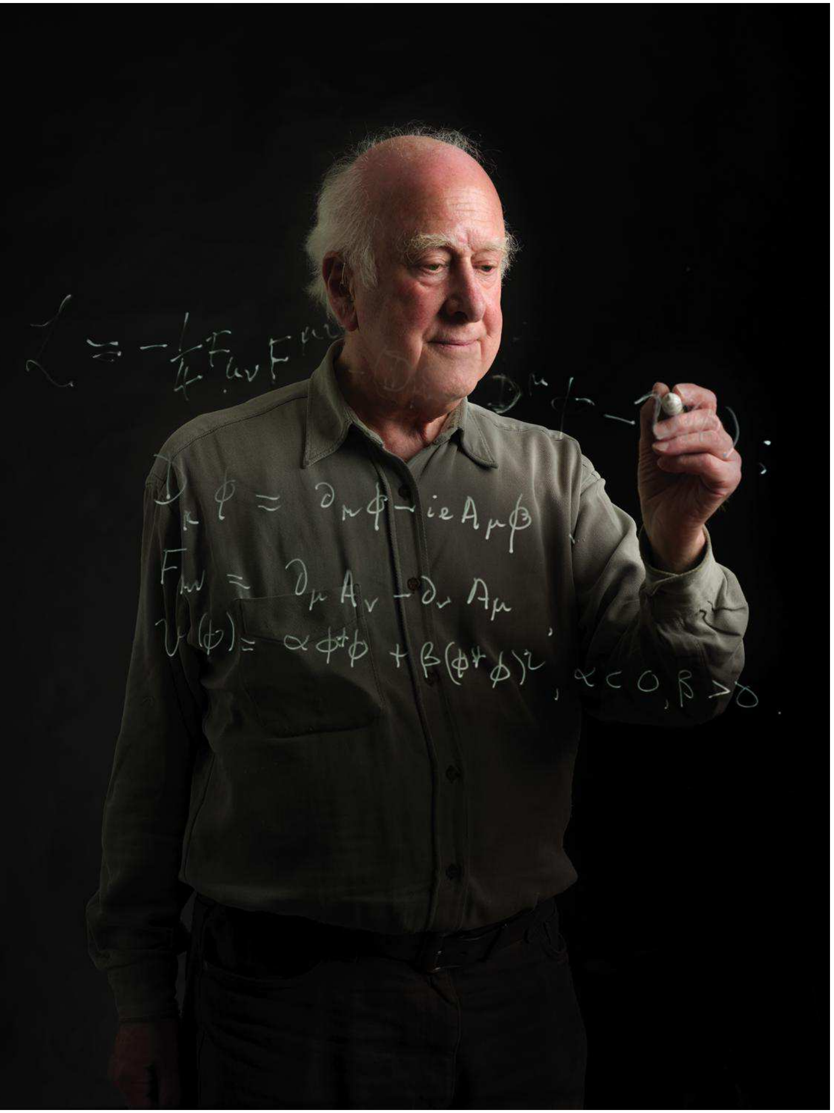

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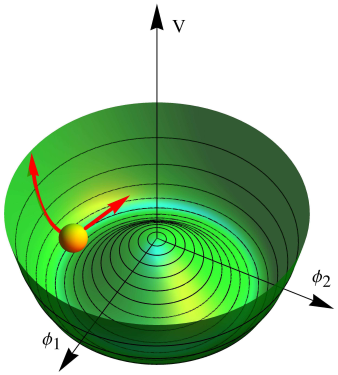


Splitting the Higgs field ϕ:

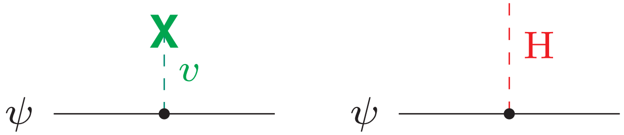
$$\phi(x) = \underbrace{\phi_{\min}}_{=v} + \underbrace{H(x)}$$

vacuum part

Higgs field excitation
↪ generates Higgs particle

Coupling of field ψ to ϕ:

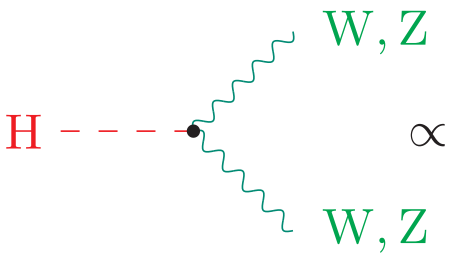
$$g\phi(x)\psi(x)^2 = \underbrace{gv}_{=m}\,\psi(x)^2 + gH(x)\psi(x)^2 + \ldots$$



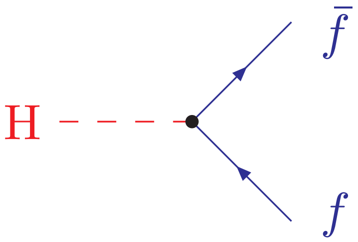
↪ Particle ψ receives mass $m = vg$
via interaction with ϕ

Higgs search at the LHC

Higgs bosons couple proportional to particle masses:



$\propto M_W$

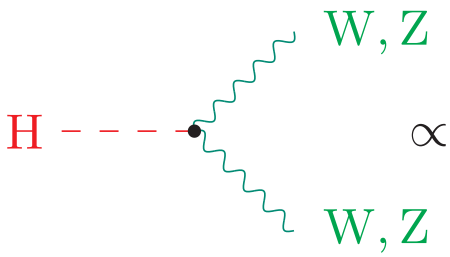


$\propto m_f$

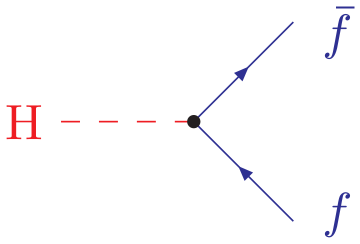
⇒ Higgs production via couplings to W/Z bosons or top-quarks

Higgs search at the LHC

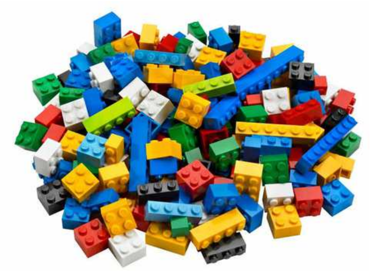
Higgs bosons couple proportional to particle masses:



$\propto \; M_\mathrm{W}$

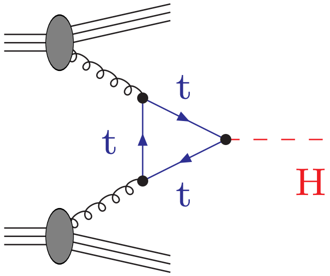


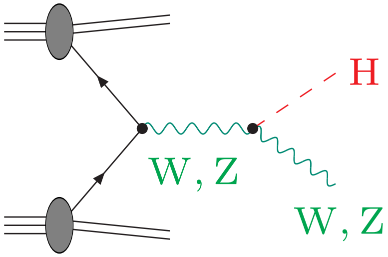
$\propto \; m_f$

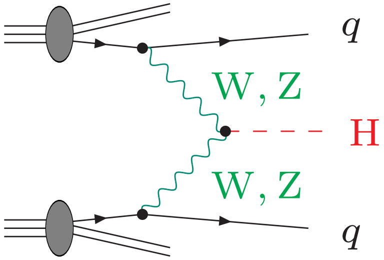


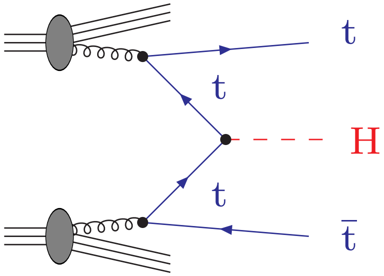
⇒ Higgs production via couplings to W/Z bosons or top-quarks

Processes at hadron colliders $(\mathrm{p\bar{p}}/\mathrm{pp})$:



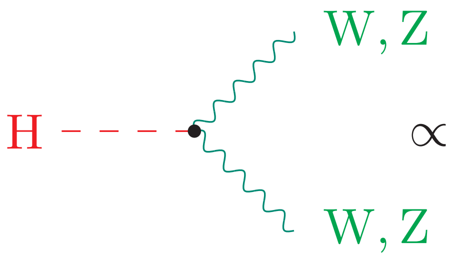




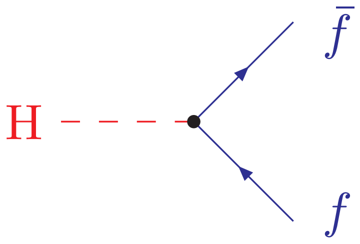


Higgs search at the LHC

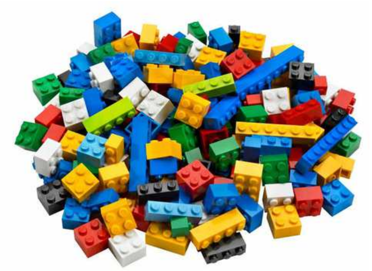
Higgs bosons couple proportional to particle masses:



$\propto M_W$



$\propto m_f$



⇒ Higgs production via couplings to W/Z bosons or top-quarks

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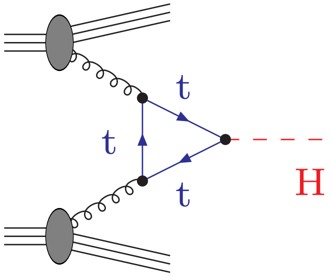
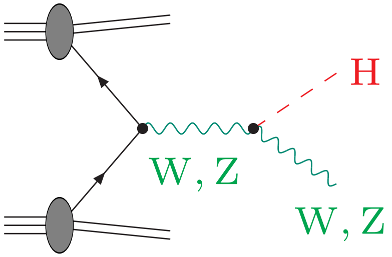
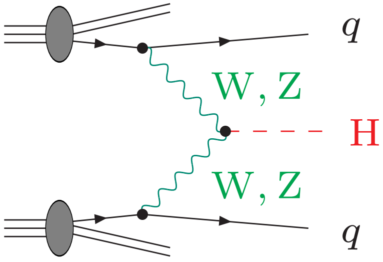
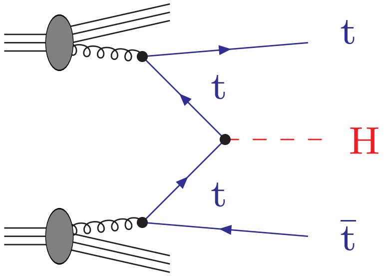
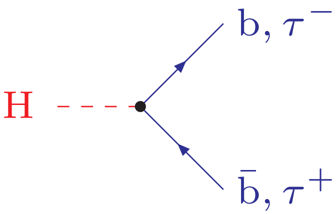


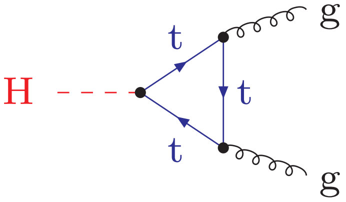


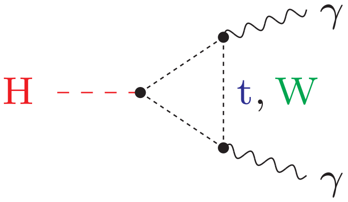


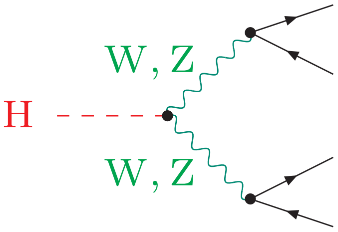


Decay channels for Higgs bosons of moderate mass ($M_H \lesssim 300\,\mathrm{GeV}$):









Branching ratios of the SM Higgs boson

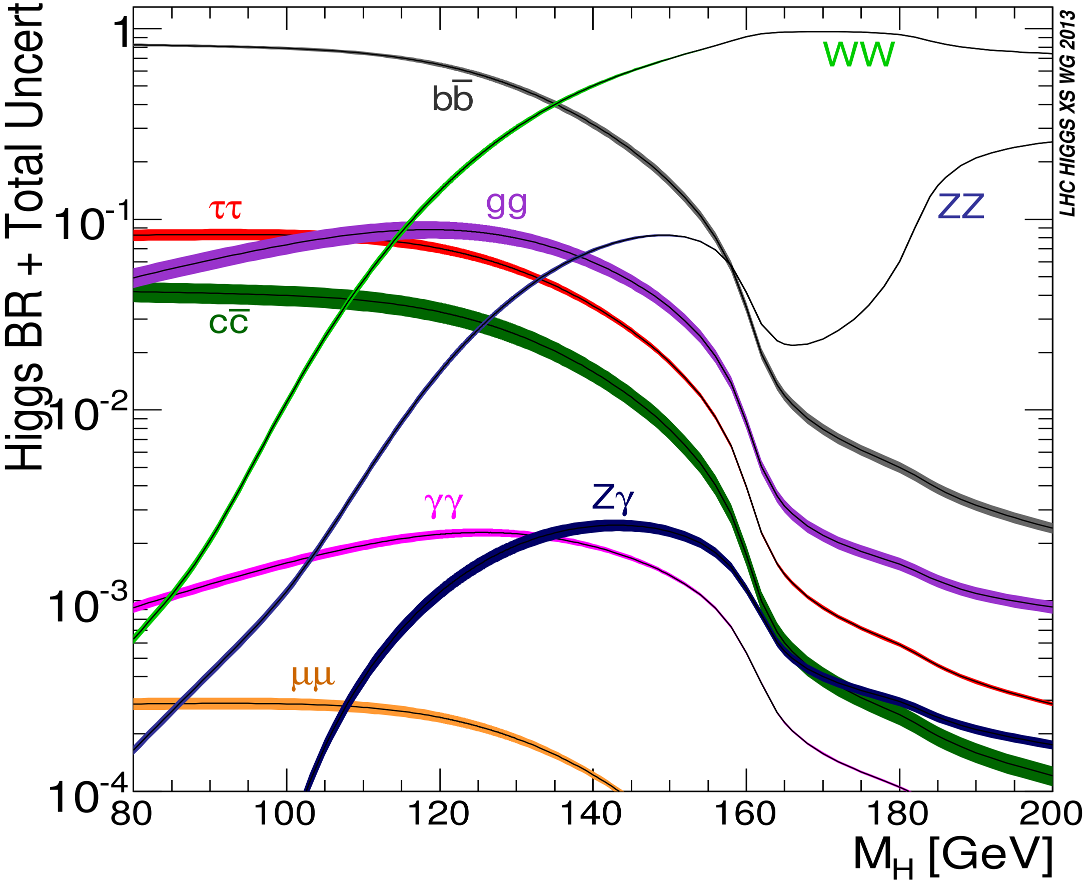
LHC Higgs XS WG '10–'13

$$\mathrm{BR}_{\mathrm{H}\to X} = \frac{\Gamma_{\mathrm{H}\to X}}{\Gamma_{\mathrm{H,tot}}}$$

Many decay channels open

at $M_\mathrm{H} = 126\,\mathrm{GeV}$

$\hookrightarrow$ good for couplings analysis !



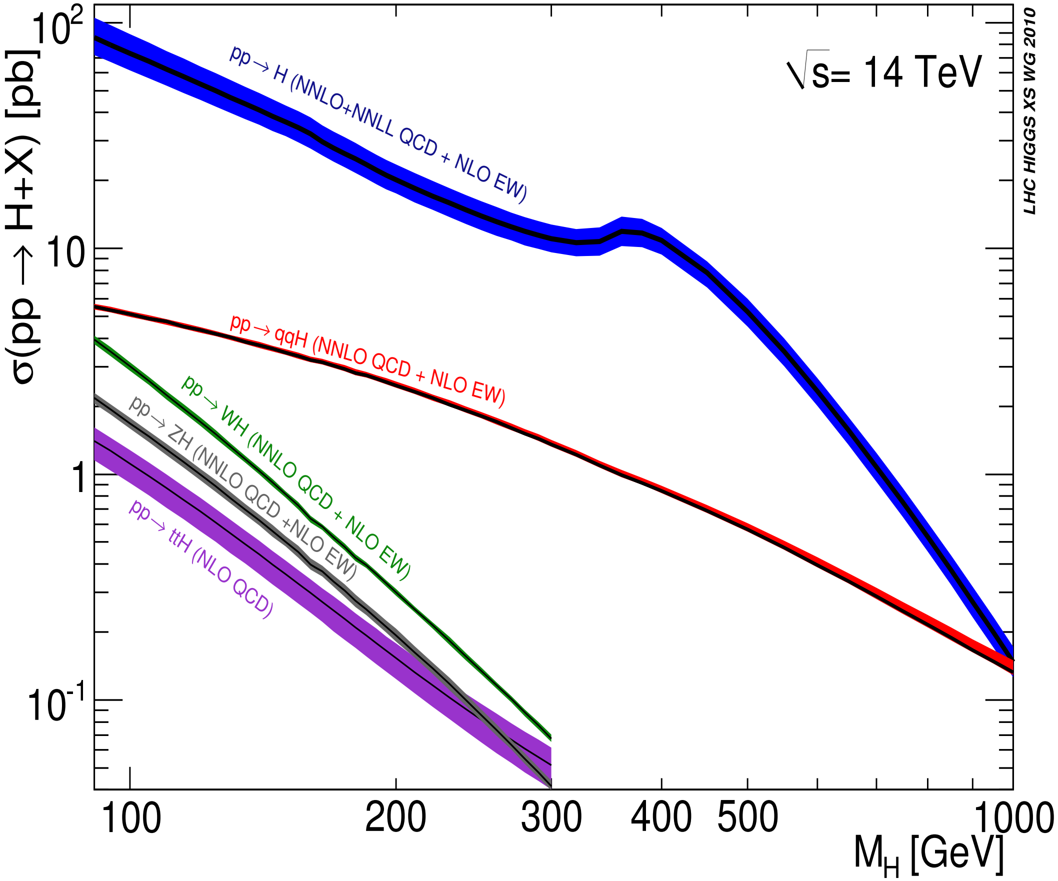
Parametric + theoretical uncertainty:

$M_\mathrm{H}[\mathrm{GeV}]$	$\mathrm{H}\to$ $\mathrm{b\bar{b}}$	$\tau^+\tau^-$	$\mathrm{c\bar{c}}$	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%	$< 0.1\%$	$< 0.1\%$

$\leftarrow$ dominated by $\delta\Gamma_{\mathrm{H}\to\mathrm{b\bar{b}}}$

SM Higgs XS predictions
for the LHC at $\sqrt{s} = 14\,\mathrm{TeV}$

LHC Higgs XS WG 2010–



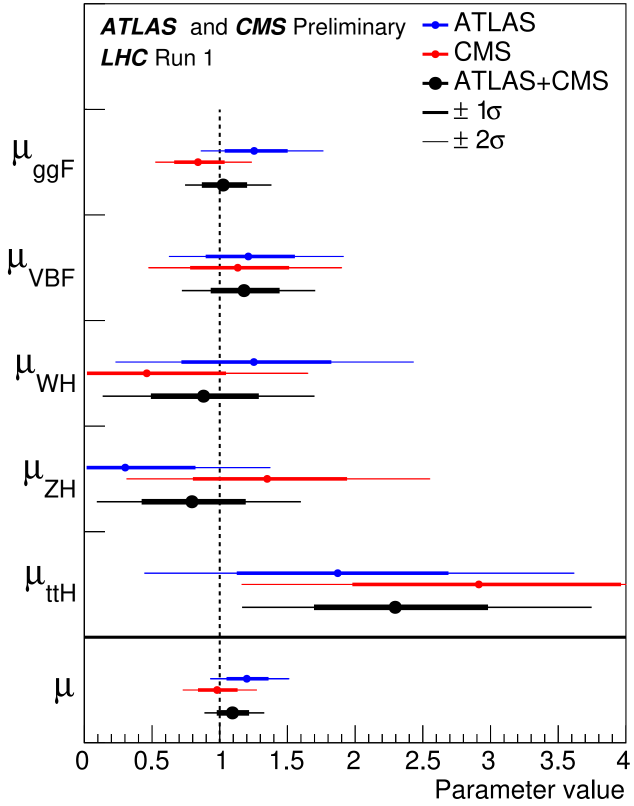
Rough numbers:

$M_{\mathrm{H}} = 125\,\mathrm{GeV}$	Uncertainties		NLO/NNLO/NNNLO	
	scale	PDF4LHC	QCD	EW
ggF	$\boxed{3\%}$	7%	$>100\%$	5%
VBF	1%	3%	5%	5%
WH	1%	4%	20%	7%
ZH	4%	4%	35%	5%
ttH	9%	9%	20%	$\boxed{1\text{–}2\%}$

☐ = not yet in plot

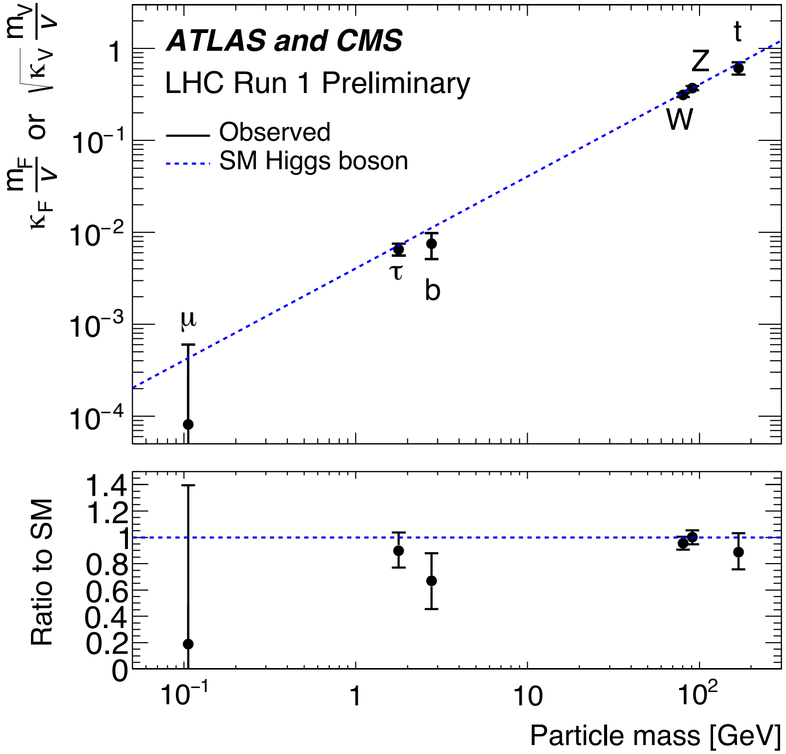
First analyses of the Higgs profile @ Run 1

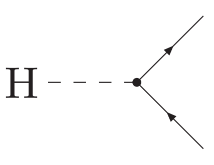
Signal strength:



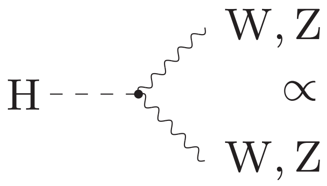
$$\mu = \frac{\sigma_{\exp}}{\sigma_{\rm SM}}$$

Coupling strength:





$\propto \ \kappa_f$



$\propto \ \kappa_V$

Compatibility with Standard Model !   ⇒ Higher precision @ Run 2 !

Tools for Higgs Physics

Cross Section

ggF
HIGLU (NNLO QCD+NLO EW)
iHixs (NNLO QCD+NLO EW)
FeHiPro (NNLO QCD+NLO EW)
HNNLO, HRes (NNLO+NNLL QCD)
SusHi (NNLO QCD)
RGHiggs (NNLO+NNNLL QCD)
ggHiggs (approx. NNNLO QCD)

VBF
VV2H (NLO QCD)
VBFNLO (NLO QCD)
HAWK (NLO QCD+EW)
VBF@NNLO (NNLO QCD)

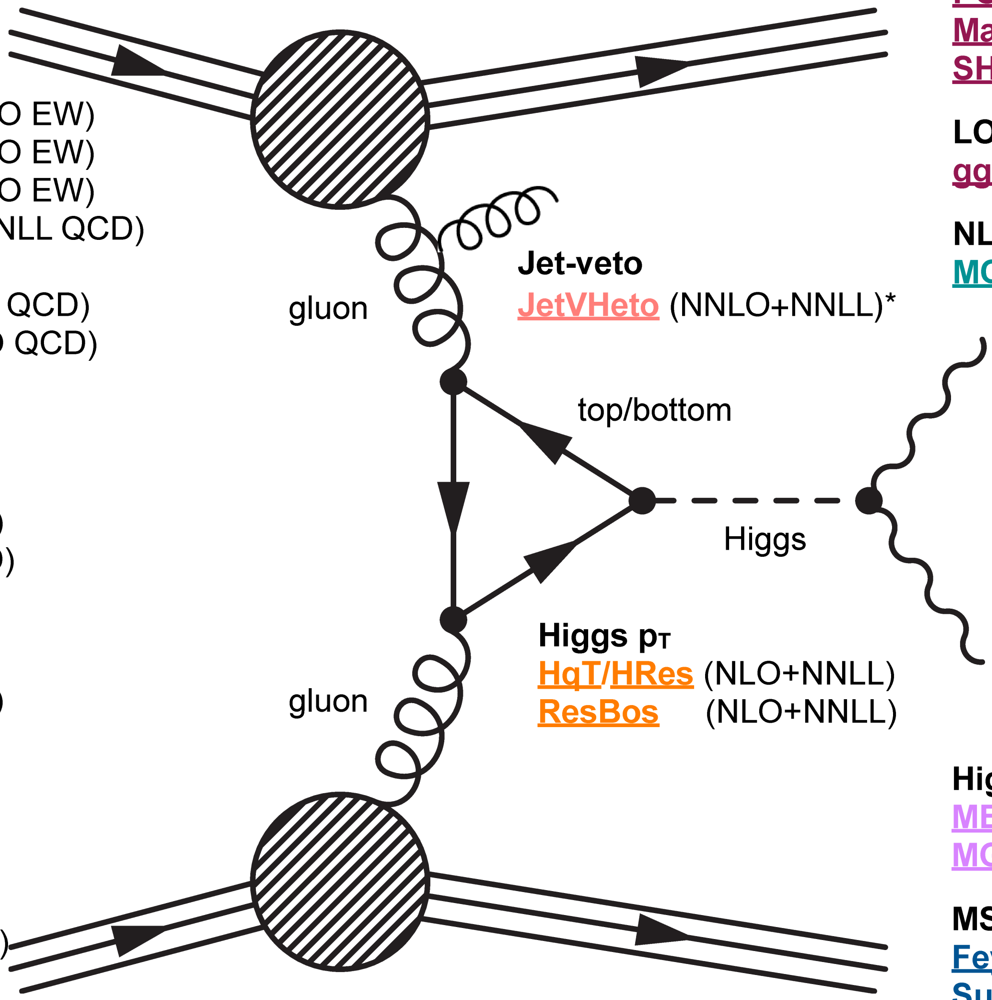
WH/ZH
V2HV (NLO QCD)
HAWK (NLO QCD+EW)
VH@NNLO (NNLO)

ttH
HQQ (LO QCD)

bbH
bbh@NNLO (NNLO QCD)

HH
HPAIR (NLO QCD)

+ private codes.



Jet-veto
JetVHeto (NNLO+NNLL)*

Higgs p_T
HqT/HRes (NLO+NNLL)
ResBos (NLO+NNLL)

PDF: MSTW, CTEQ, NNPDF, etc.
LHAPDF, HOPPET, APFEL

NLO MC
POWHEG MiNLO
MadGrapn5_aMC@NLO
SHERPA MEPS@NLO

LO MC
gg2VV

NLO ME
MCFM, MG5_aMC@NLO

Higgs Decay
HDECAY (NLO++)
Prophecy4f (NLO)

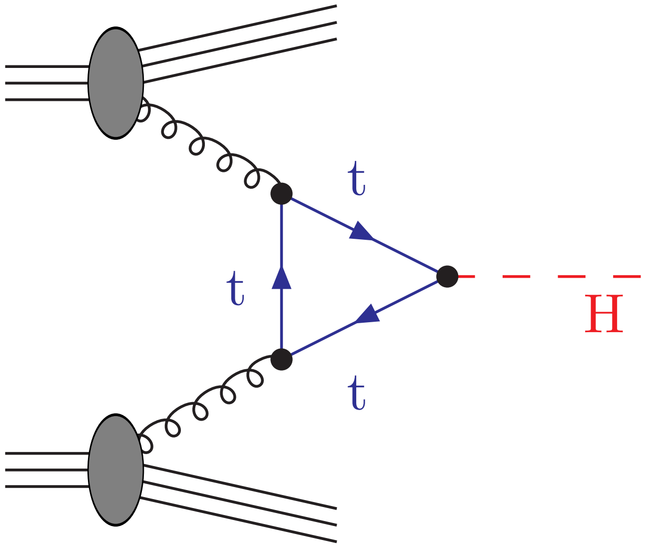
Higgs Properties
MELA/JHU, MEKD
MG5_aMC@NLO (HC)

MSSM/2HDM
FeynHiggs, CPSuperH
SusHi+2HDMC
HIGLU+HDECAY

* NLO+NNLL in differential

Compiled by R. Tanaka, Jan. 2014

Higgs production via gluon fusion



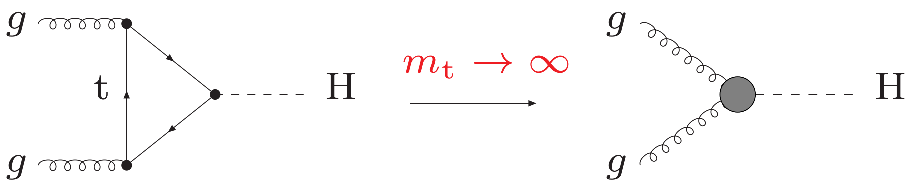
Corrections to Higgs-boson production via gluon fusion

- QCD corrections:
  - full NLO, NNLO via expansions

$$K = \frac{\sigma_{\mathrm{NNLO}}}{\sigma_{\mathrm{LO}}} \sim 2.0$$

Graudenz, Spira, Zerwas '93
Djouadi, Graudenz, Spira, Zerwas '95
...
Marzani et al. '08
Pak, Rogal, Steinhauser '09
Harlander, Ozeren '09

  - NNNLO in limit $m_{\mathrm{t}} \to \infty$



Chetyrkin et al. '98,'06; Moch/Vogt '05;
Schröder/Steinhauser '06; Baikov et al. '09;
Gehrmann et al. '10,'12; Duhr/Gehrmann '13;
Li/Zhu '13; Kilgore '13; Hoeschele et al.'13;
Buehler/Lazopoulos '13;
Anastasiou et al. '13–'16

  - resummations

Catani et al. '03; Moch, Vogt '05
Laenen, Magnea '05; Idilbi, Ji, Ma, Yuan '05
Ravindran '05,'06; Ravindran, Smith, v.Neerven '0
Ahrens, Becher, Neubert, Yang '08,'11
Berger et al. '10; Stewart, Tackmann '11
Banfi, (Monni,) Salam, Zanderighi '12
Becher, Neubert '12; Schmidt, Spira '15

- EW corrections
  - complete NLO correction known $\sim \mathcal{O}(5\%)$

Aglietti, Bonciani, Degrassi, Vicini '04,'06
Degrassi, Maltoni '04
Actis, Passarino, Sturm, Uccirati '08

  - mixed $\mathcal{O}(\alpha\alpha_{\mathrm{s}})$ corrections for small M_{H}

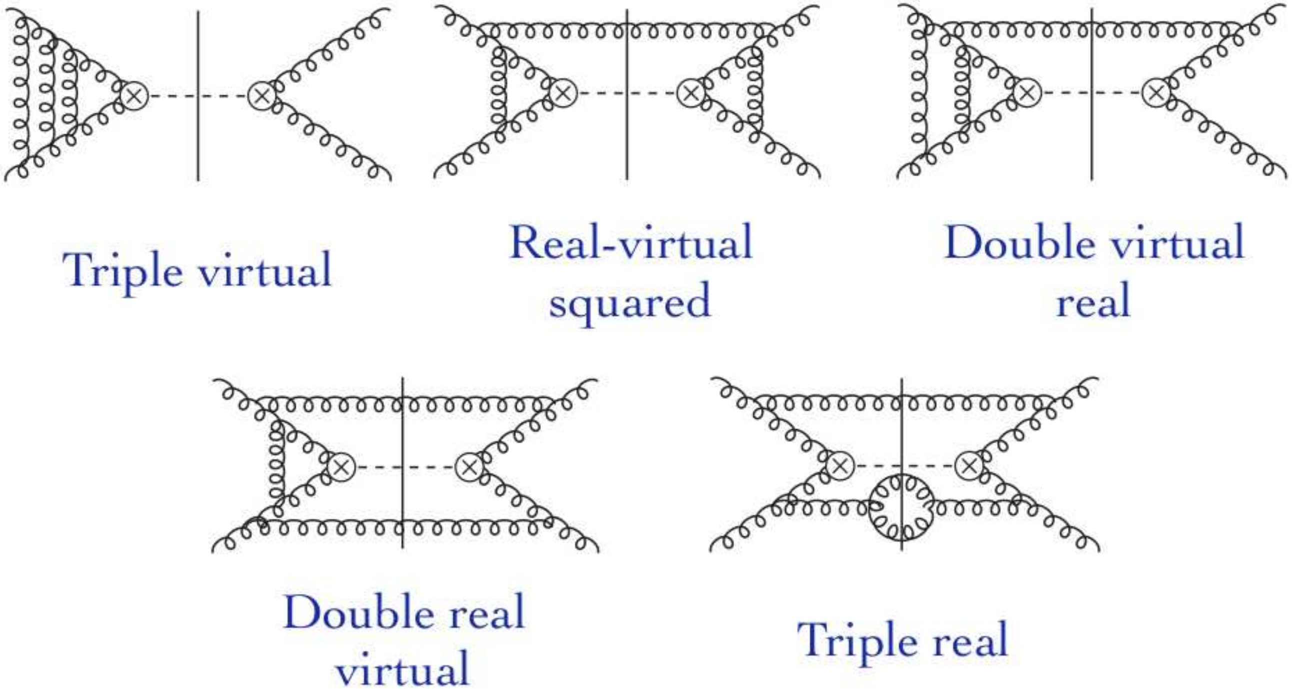
Anastasiou, Boughezal, Petriello '08

Towards $gg \to H$ @ NNNLO QCD

- great theory effort, many ingredients
  (Wilson coefficients, 3-loop amplitudes, hard emission contributions, etc.)

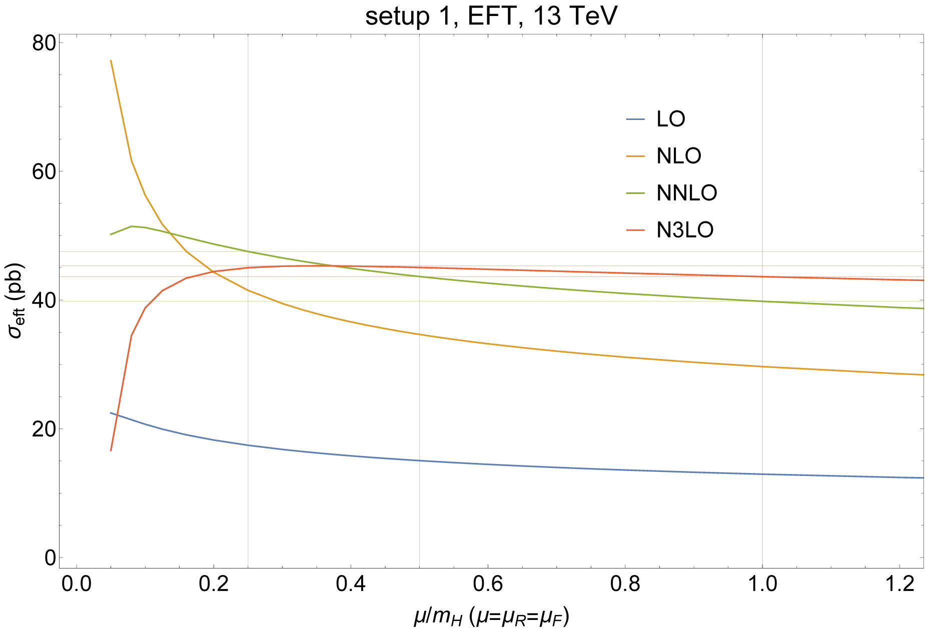
Chetyrkin et al. ’98,’06; Moch/Vogt ’05; Schröder/Steinhauser ’06; Baikov et al. ’09; Gehrmann et al. ’10,’12; Anastasiou et al. ’13,’14; Duhr/Gehrmann ’13; Li/Zhu ’13; Kilgore ’13; Hoeschele et al.’13; Buehler/Lazopoulos ’13; ...

- approximate NNNLO result upon including asymptotics in threshold and high-energy resummation Bonvini et al. ’14
- full NNNLO cross section Anastasiou et al. ’15,’16



$gg \to H$ @ NNNLO QCD + resummations + NLO EW

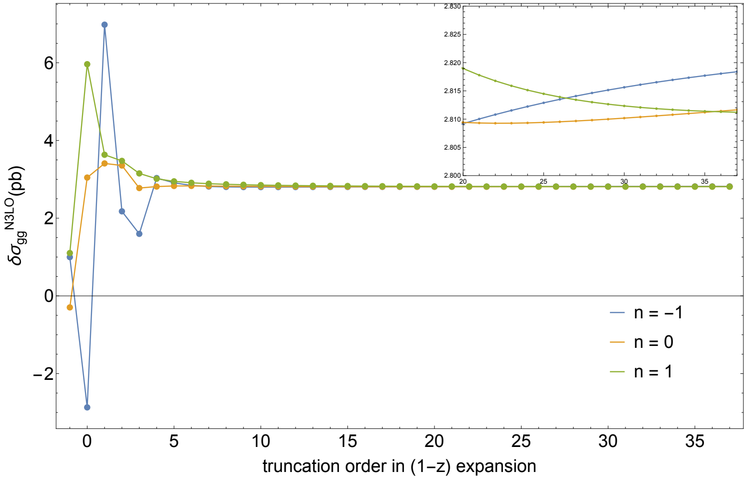
Anastasiou et al. '16



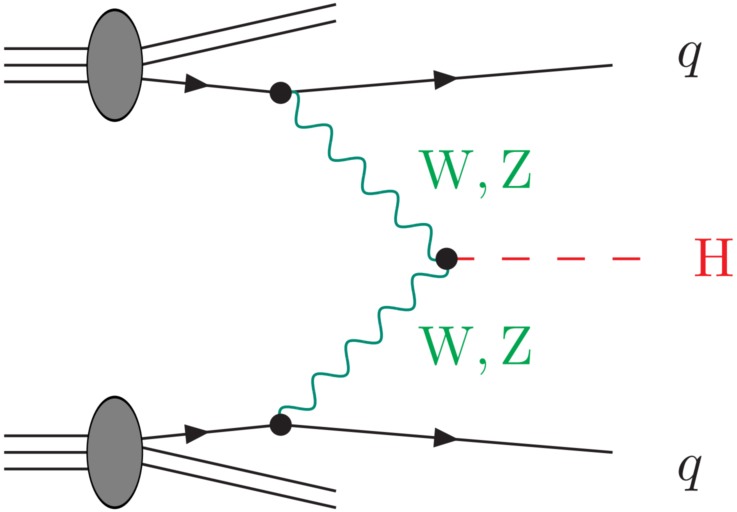
- correction:
  $$\frac{\Delta\sigma_{\rm NNNLO}}{\sigma_{\rm NNLO}} \sim 3\% \text{ @ } \mu = M_{\rm H}/2$$
- scale uncertainty:
  9% @ NNLO $\;\to\;$ $\sim 2\%$ @ NNNLO
- full TH uncertainty: ~ 5–6%
- PDF$\oplus\alpha_{\rm s}$ uncertainty: ~ 3–4%

Details / comments:

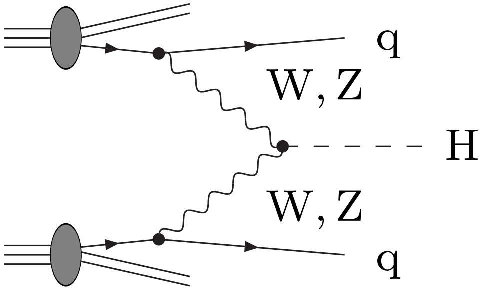
- total XS obtained from expansion in $z = \frac{M_{\rm H}^2}{\hat{s}}$:
  $$\frac{\hat\sigma^{(3,N)}_{ij}}{z^{n+1}} = \delta_{ig}\delta_{jg}\frac{\hat\sigma^{(3)}_{\rm virt+soft}}{z^{n+1}} + \sum_{k=0}^{N} c^{(k)}_{ij}(1-z)^k$$
  $\hookrightarrow$ convergence depends on N and n
- several uncertainty sources of $\sim 1\%$:
  $1/m_{\rm t}$ expansion, quark mass effects, QCD$\otimes$EW,
  NNNLO/NNLO PDF mismatch, $(1-z)^k$ expansion



Higgs production via vector-boson fusion



A multi-leg example: Higgs production via weak vector-boson fusion (VBF)



colour exchange between quark lines suppressed

$\Rightarrow$ small QCD corrections

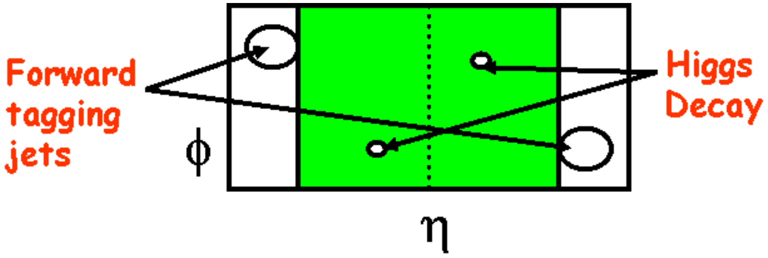
Han, Valencia, Willenbrock ’92; Spira ’98;
Djouadi, Spira ’00; Figy, Oleari, Zeppenfeld ’03

$\hookrightarrow$ t-channel approximation (vertex corrections)

VBF cuts and background suppression:

- 2 hard “tagging” jets demanded:
  $p_{\mathrm{Tj}} > 20\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 4.5$
- tagging jets forward–backward directed:
  $\Delta y_{\mathrm{jj}} > 4, \quad y_{\mathrm{j1}} \cdot y_{\mathrm{j2}} < 0.$

signature $=$ Higgs + 2jets



$\hookrightarrow$ Suppression of background

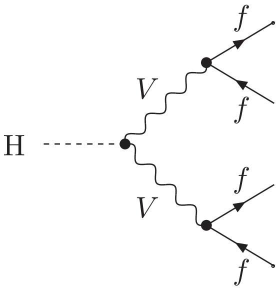
- from other (non-Higgs) processes,
  such as $\mathrm{t\bar{t}}$ or WW production Zeppenfeld et al. ’94-’99
- induced by Higgs production via gluon fusion,
  such as $gg \to gg\mathrm{H}$ Del Duca et al. ’06; Campbell et al. ’06

Work on radiative corrections to the production of Higgs+2jets

- NLO QCD corrections to VBF in DIS-like approximation
  Han et al. '92; Spira '98; Djouadi, Spira '00; Figy et al. '03; Berger, Campbell '04; Nason, Oleari '09
- (full) NLO QCD+EW corrections to VBF
  $\hookrightarrow$ NLO QCD $\sim$ NLO EW $\sim 5{-}10\%$
  Ciccolini, Denner, S.D. '07
  Figy, Palmer, Weiglein '10 (DIS-like EW)
- NNLO QCD corrections to VBF in DIS-like approximation
  $\hookrightarrow$ NNLO QCD $\sim 5\%$
  Bolzoni, Maltoni, Moch, Zaro '10; Cacciari et al. '15
- NNNLO QCD corrections to VBF in DIS-like approximation
  $\hookrightarrow$ NNLO QCD $\sim 0.1{-}0.2\%$
  Dreyer, Karlberg '16
- NLO QCD corrections to $\mathrm{gg} \to \mathrm{Hgg}$, etc.
  Campbell, R.K.Ellis, Zanderighi '06
  $\hookrightarrow$ contribution to VBF $\sim 5\%$
  Nikitenko, Vazquez '07
  (NLO scale uncertainty $\sim 35\%$)
- QCD loop-induced interferences between VBF and Hgg-initiated channels
  $\hookrightarrow$ impact $\lesssim 10^{-3}\,\%$ (negligible!)
  Andersen, Binoth, Heinrich, Smillie '07
  Bredenstein, Hagiwara, Jäger '08
- loop-induced VBF in gg scattering
  Harlander, Vollinga, Weber '08
  $\hookrightarrow$ impact $\sim 0.1\%$
- SUSY QCD+EW corrections
  Hollik, Plehn, Rauch, Rzehak '08
  $\hookrightarrow$ $|\mathrm{MSSM} - \mathrm{SM}| \lesssim 1\%$ for SPS points $(2{-}4\%$ for low SUSY scales)

Generic NLO electroweak diagrams for $\mathrm{H} \to VV \to 4f$,
$\mathrm{pp}(VV \to \mathrm{H}) \to \mathrm{H} + 2\mathrm{jets}$,
$\mathrm{pp} \to \mathrm{H}V \to \mathrm{H} + 2\ell$

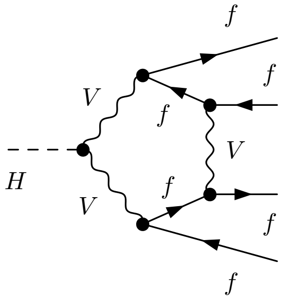
Lowest order:



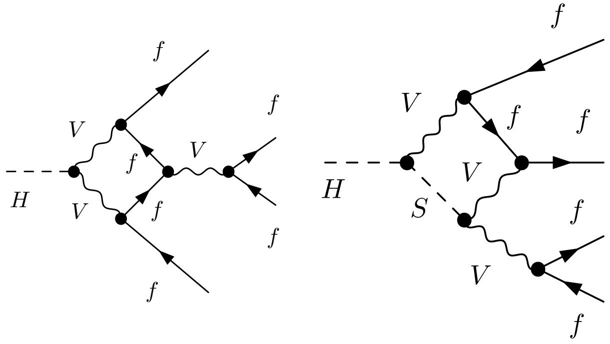
Typical one-loop diagrams:

diagrams = $\mathcal{O}(200\text{—}400)$

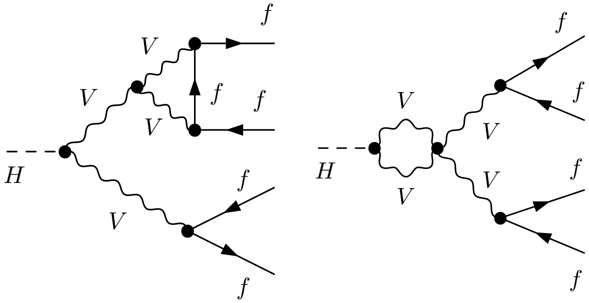
pentagons



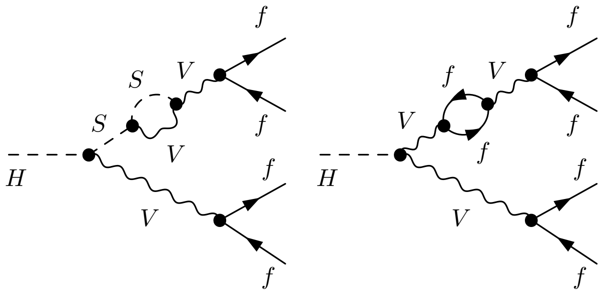
boxes



vertices



self-energies

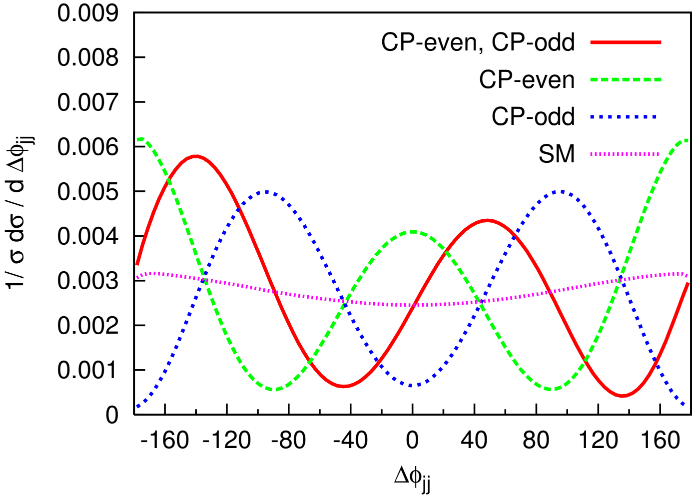


$+$ tree graphs with real gluon or photons

Distribution in the azimuthal angle difference $\Delta\phi_{\mathrm{jj}}$ of the tagging jets

Sensitivity to non-standard effects:

Hankele, Klämke, Zeppenfeld, Figy ’06



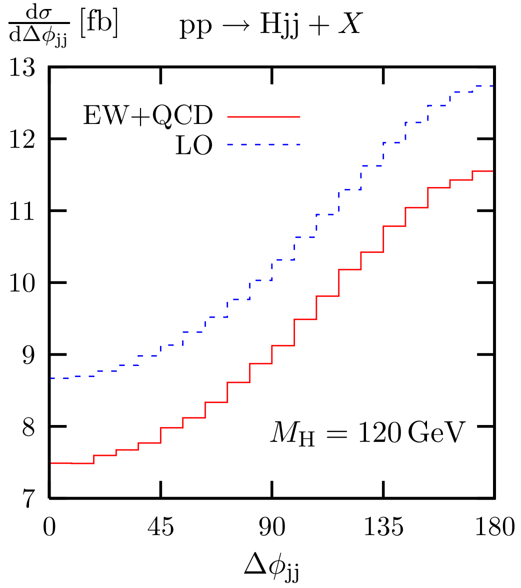
(Individual contributions without SM)

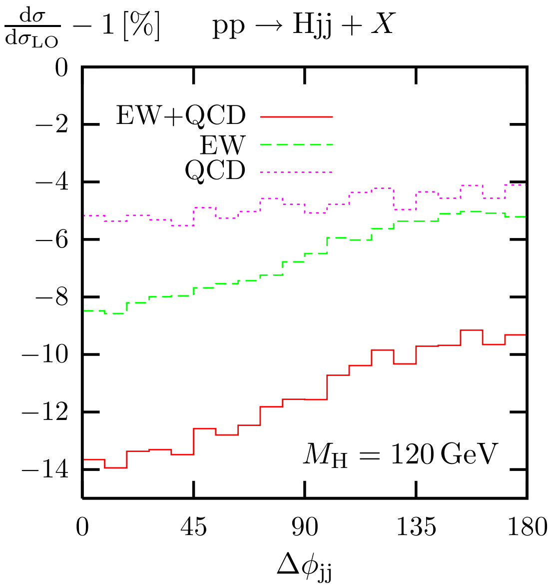
CP-even: $\mathcal{L} \propto HW^{+}_{\mu\nu}W^{-,\mu\nu}$

CP-odd: $\mathcal{L} \propto H\tilde{W}^{+}_{\mu\nu}W^{-,\mu\nu}$

Corrections to the $\Delta\phi_{\mathrm{jj}}$ distribution:

Ciccolini, Denner, S.D. ’07



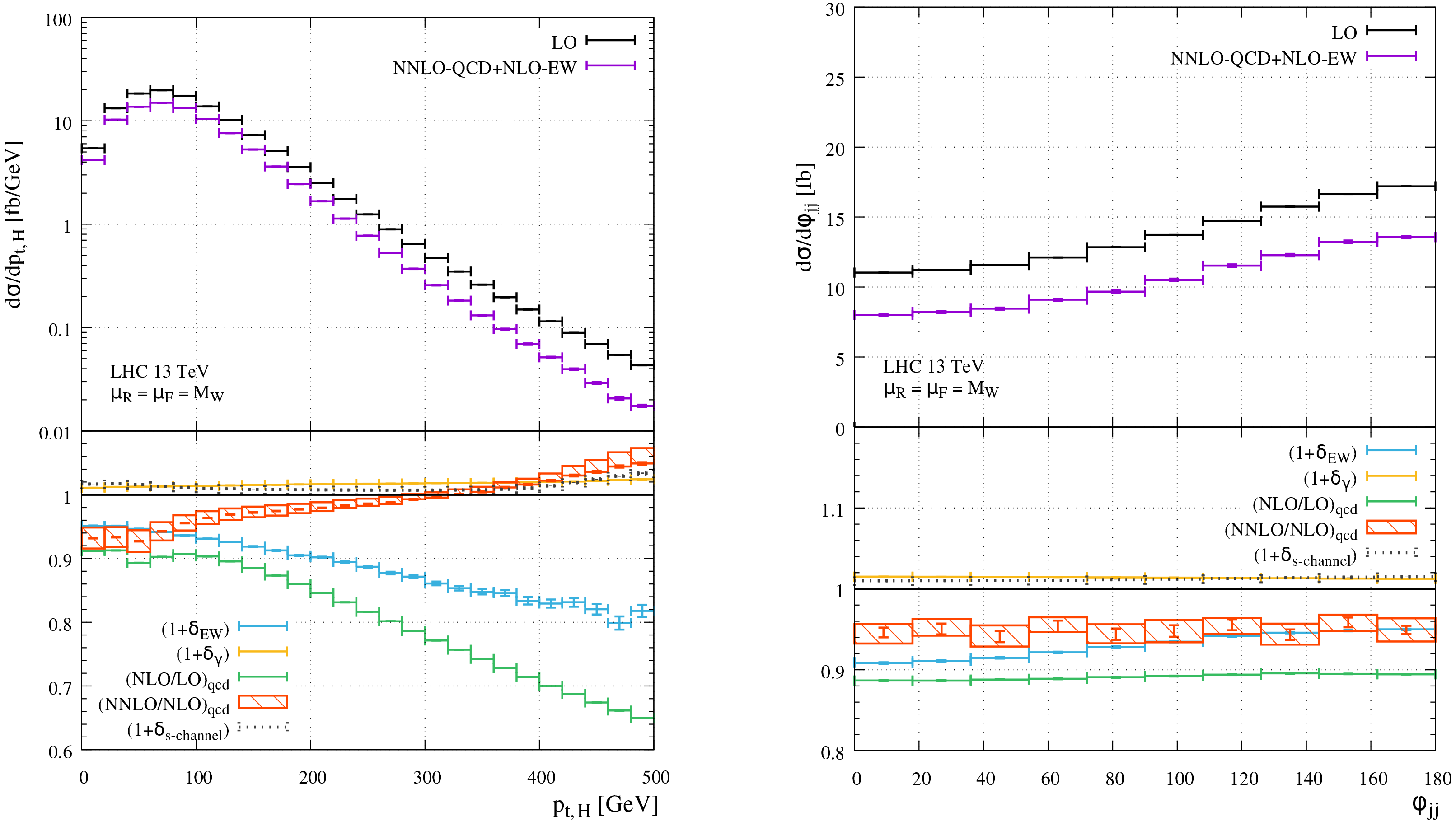


HAWK

Neglected corrections could be misinterpreted as non-standard couplings

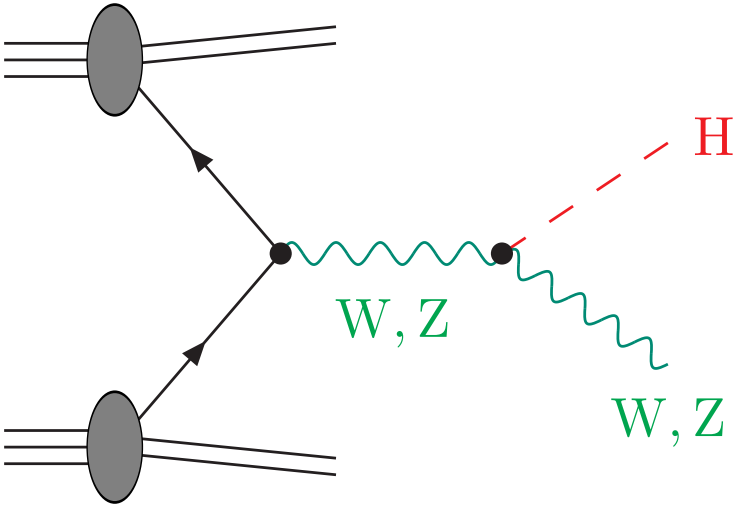
Fiducial cross sections @ NNLO QCD + NLO EW

LHC Higgs XS WG ’16 (to appear in YR4)

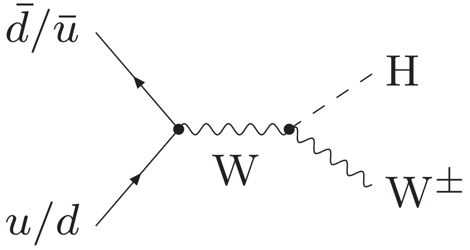


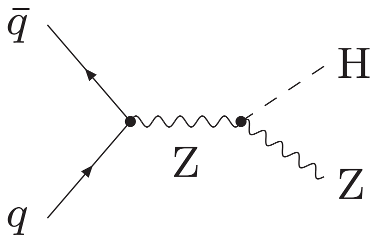
- scale uncertainty $\sim\ 1{-}2\%$
- (N)NLO QCD and NLO EW corrections $\sim\ 5{-}20\%$
- γ-induced and s-channel contributions $\sim\ 1.5\%$

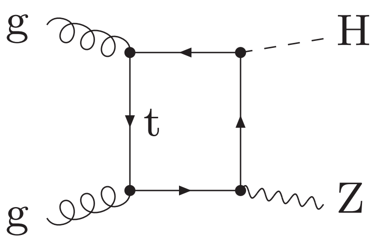
Production via Higgs-strahlung



Current status of theoretical predictions







- NLO QCD: corrections entirely Drell–Yan like
  Han, Willenbrock '91; Ohnemus, Stirling '93; Baer, Bailey, Owens '93
  V2VH (Spira); MCFM (Campbell, R.K.Ellis)
- NLO EW: total cross section, stable W/Z bosons
  Ciccolini, S.D., Krämer '03

  differential cross sections, via HAWK with W/Z decays
  Denner, S.D., Kallweit, Mück '11
- NNLO QCD:

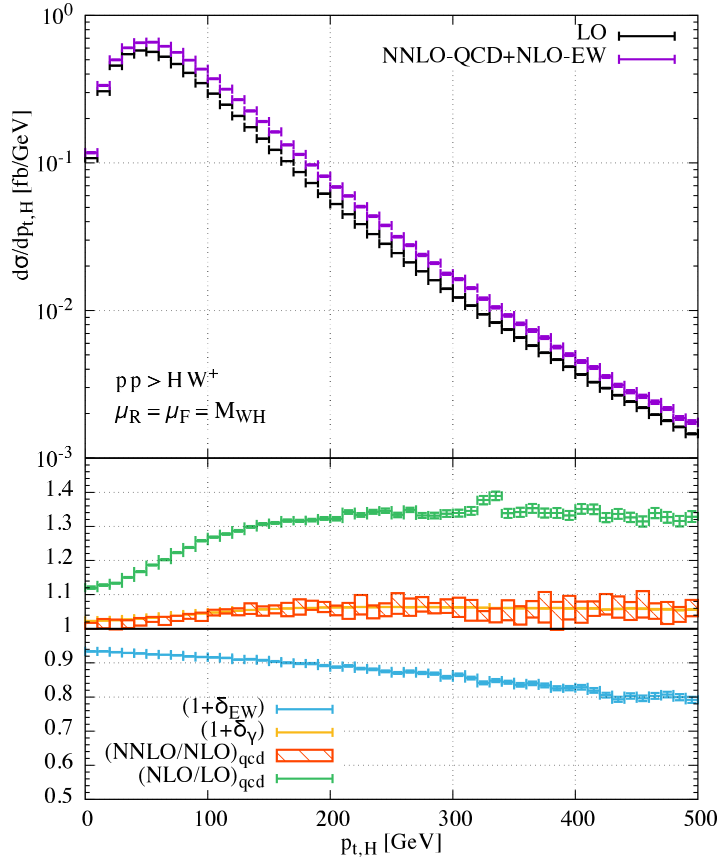
  total cross section, stable W/Z bosons
  Drell–Yan-like part, $gg \to ZH$
  Brein, Djouadi, Harlander '03 (VH@NNLO)

  differential VH XS, with W/Z/H decays, Drell–Yan-like part
  Ferrera, Grazzini, Tramontano '11–'14

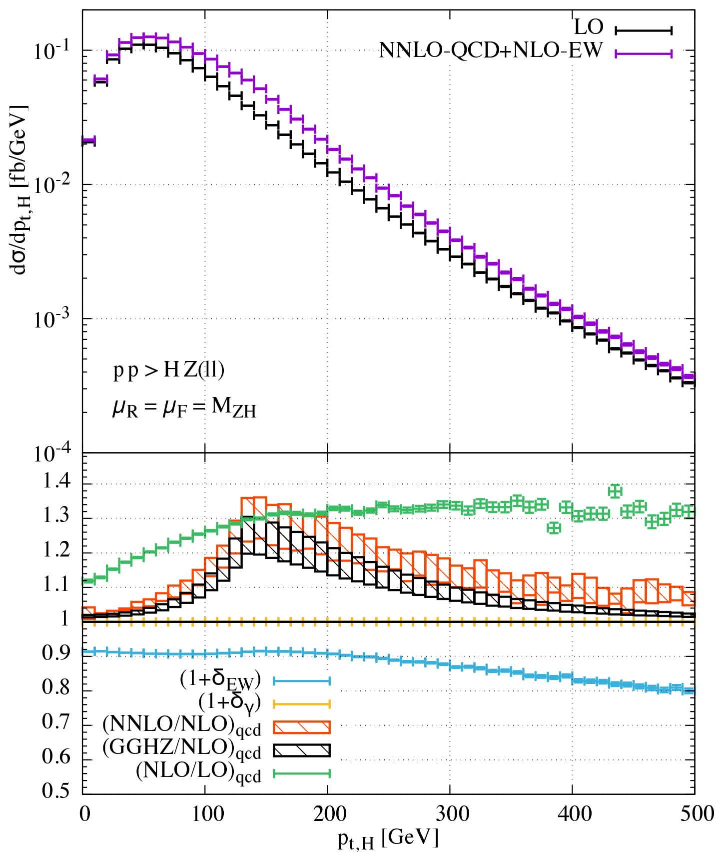
  total cross section, non-Drell–Yan-like parts
  Brein, Harlander, Wiesemann, Zirke '11
- NLO+NLL QCD ($gg \to ZH$): total cross section, gg channel
  Altenkamp et al. '12, Harlander et al. '14

Fiducial cross sections @ NNLO QCD + NLO EW

LHC Higgs XS WG ’16 (to appear in YR4)



$\mathrm{pp} \to \mathrm{W}^+(\to \ell^+\nu_\ell)\mathrm{H}$:

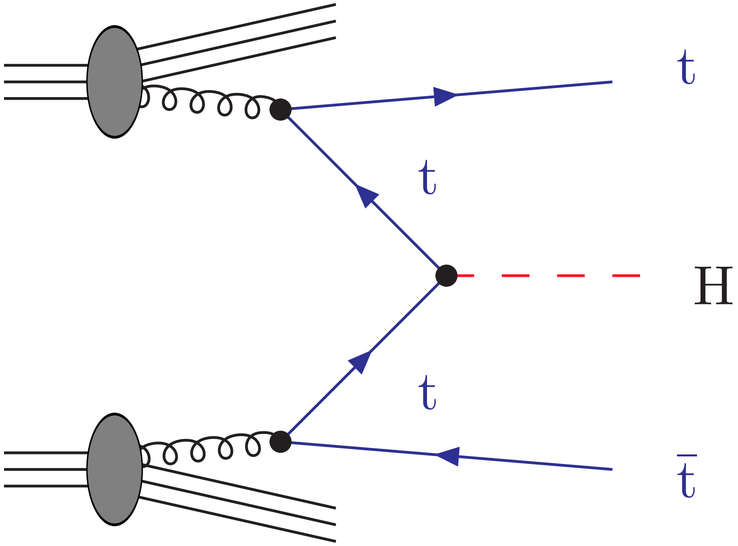


$\mathrm{pp} \to \mathrm{Z}(\to \ell^+\ell^-)\mathrm{H}$:

- scale uncertainty: $\mathrm{WH} \sim 1\%, \qquad \mathrm{ZH} \sim 2\%$
- NNLO QCD / NLO EW corrections $\sim 5\text{–}15\%$
- $\mathrm{gg} \to \mathrm{ZH(LO)} \sim 10\text{–}20\%$
- γ-induced: $\quad \mathrm{WH} \lesssim 5\%, \qquad \mathrm{ZH} < 0.1\%$

Note:
$p_{\mathrm{T,H}} \gtrsim 200\,\mathrm{GeV}$ interesting
in “boosted Higgs analysis”

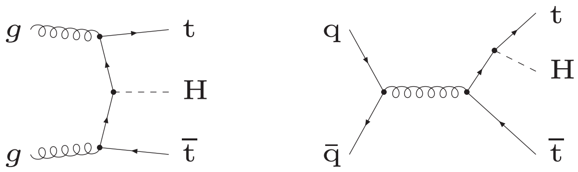
Production of $\mathrm{t\bar{t}H}$ final states



Survey of LO/NLO contributions to $\mathrm{t\bar{t}H}$ production

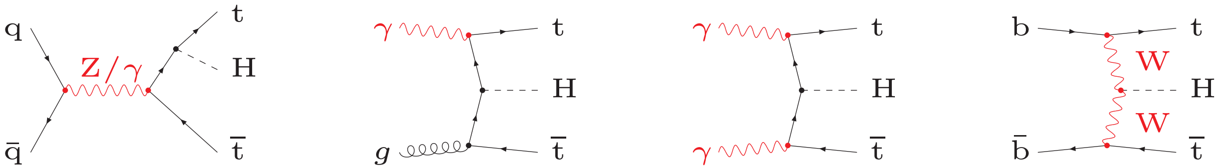
- QCD tree:

  $\mathcal{M}_{\mathrm{QCD},0}$



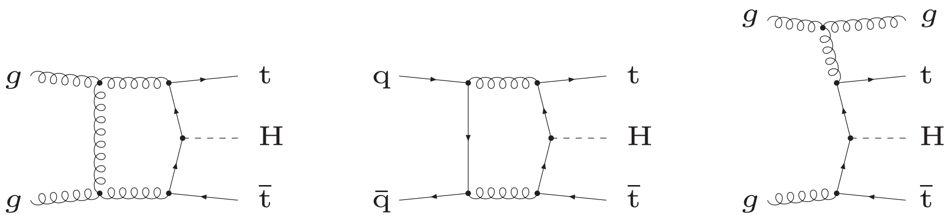
- EW tree:

  $\mathcal{M}_{\mathrm{EW},0}$



- QCD NLO:

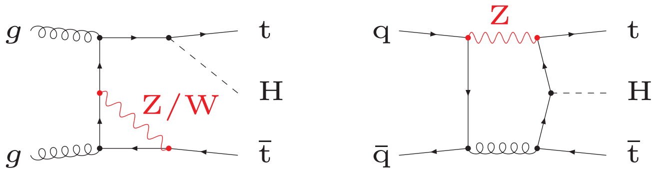
  $\mathcal{M}_{\mathrm{QCD},1}$



etc.

- Weak NLO:

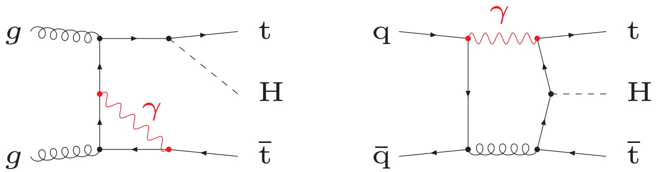
  $\mathcal{M}_{\mathrm{weak},1}$



$$\& \quad \mathcal{M}^{q\bar{q}}_{\mathrm{QCD},1} \times \left(\mathcal{M}^{q\bar{q}}_{\mathrm{weak},0}\right)^* \quad + \quad \ldots$$

- Photonic NLO:

  $\mathcal{M}_{\mathrm{phot},1}$



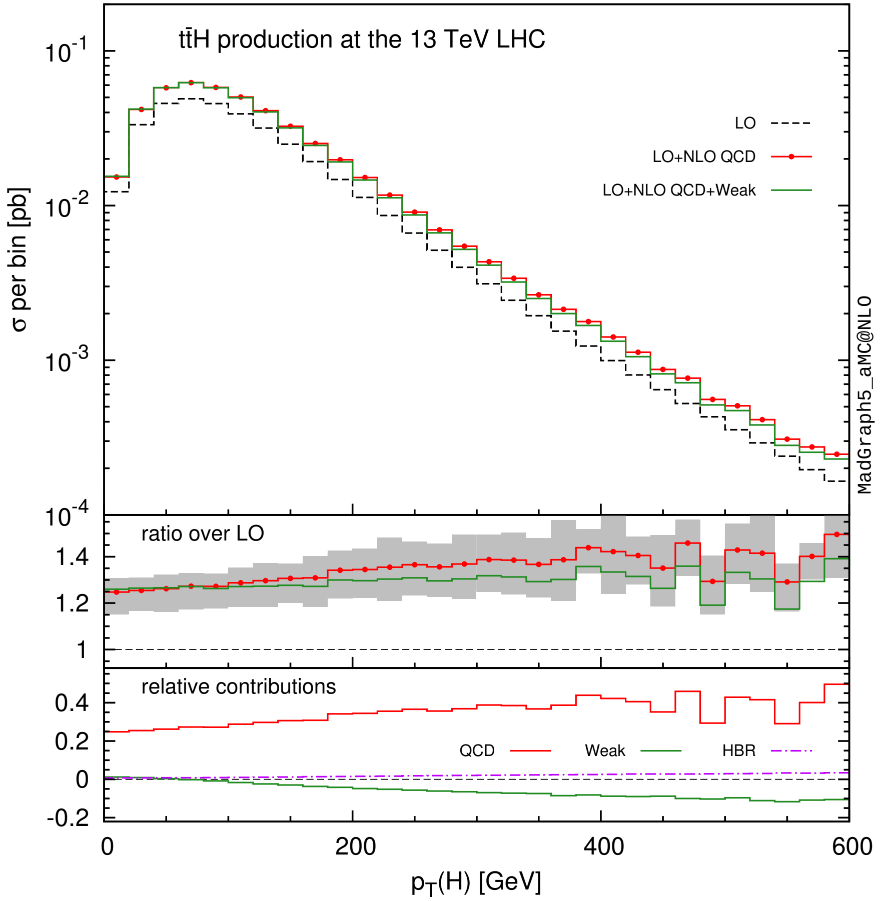
$$\& \quad \mathcal{M}^{q\bar{q}}_{\mathrm{QCD},1} \times \left(\mathcal{M}^{q\bar{q}}_{\mathrm{phot},0}\right)^* \quad + \quad \ldots$$

Known corrections to $\mathrm{t\bar{t}H}$ production

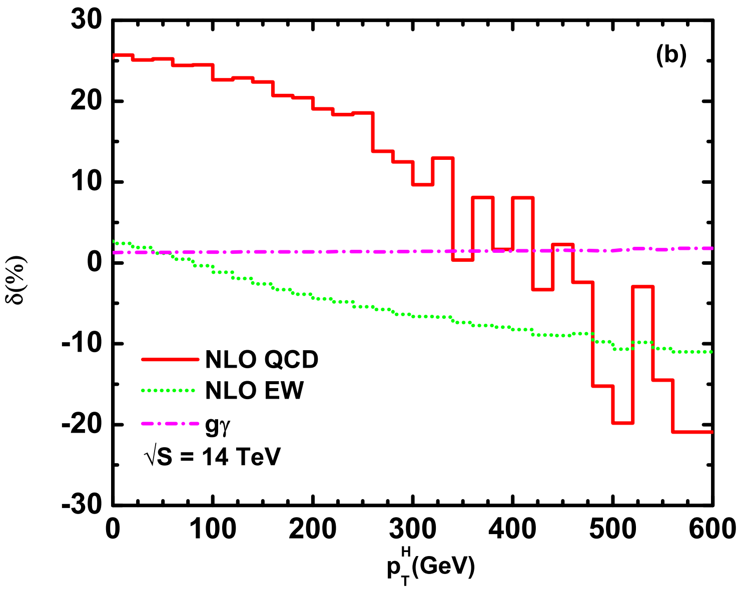
- NLO QCD corrections
    - ◇ $\mathrm{pp} \to \mathrm{t\bar{t}H}$ Beenakker et al. ’01,’02; Dawson et al. ’01,’02
    - ◇ $\mathrm{pp} \to \mathrm{WWb\bar{b}H}$ with leptonic W-boson decays
      Denner, Feger ’15
- QCD parton-shower matching via *aMC@NLO, PowHel, MadSpin, Sherpa*
  Frederix et al. ’11; Garzelli et al. ’11; Artoisenet et al. ’12; LHC HXS WG ’13
- EW corrections
    - ◇ EW tree + EW NLO + real $\mathrm{W/Z/H}$ emission (HBR) in *MadGraph5 aMC@NLO*
      Frixione et al. ’14,’15
    - ◇ EW tree + EW NLO with *FeynArts/FormCalc/LoopTools*
      Zhang et al. ’14

NLO EW corrections to the $p_{\mathrm{T,H}}$ distribution in $\mathrm{t\bar{t}H}$ production

Frixione et al. ’14



Zhang et al. ’14



- EW corrections $\sim 1{-}2\%$ for σ_{tot}
- weak corrections grow to $\sim -10\%$ for $p_{\mathrm{T,H}} \gtrsim 400{-}500\,\mathrm{GeV}$
- EW corrections mostly swamped by QCD uncertainties

Higgs profiling at the LHC

— Higgs couplings and effective field theory approach —

“Profiling” = detailed & precise coupling measurements

But: Couplings analyses based on simple rescalings strongly limited
(no consistent QFT)

$\hookrightarrow$ Statements more precise than $5{-}10\%$ are nonsense !

Solutions:

- analyses in specific models
- model-independent analyses in effective field theories: $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_i}{\Lambda^2} Q_i$

  $\hookrightarrow$ fit of 59 dim-6 operators

Buchmüller, Wyler ’86; Grzadkowski et al. ’10; ...

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  Buchmüller, Wyler ’86; Grzadkowski et al. ’10; ...

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\epsilon^{\alpha\beta\gamma}\epsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\epsilon^{\alpha\beta\gamma}\epsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\epsilon^{\alpha\beta\gamma}\epsilon_{jk}\epsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\epsilon^{\alpha\beta\gamma}(\tau^I\epsilon)_{jk}(\tau^I\epsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\epsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

- many Higgs observables $+$ elektroweak precision tests
- QCD+EW correcturen $+$ new operators $\rightarrow$ hard work

Example: anomalous HVV couplings

Hankele, Klämke, Zeppenfeld, Figy ’06

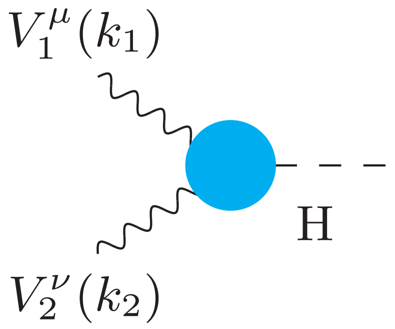
↪ derived from SU(2)×U(1)-invariant dim-6 operators

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i, \qquad \mathcal{O}_{WW} = \Phi^\dagger W_{\mu\nu}W^{\mu\nu}\Phi, \qquad \mathcal{O}_{BB} = \Phi^\dagger B_{\mu\nu}B^{\mu\nu}\Phi,$$

$$\mathcal{O}_{\tilde{W}W} = \Phi^\dagger \tilde{W}_{\mu\nu}W^{\mu\nu}\Phi, \qquad \mathcal{O}_{\tilde{B}B} = \Phi^\dagger \tilde{B}_{\mu\nu}B^{\mu\nu}\Phi,$$

↪ CP-violating couplings involve $\tilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}V^{\rho\sigma}$

Modified HVV Feynman rules



$$= \underbrace{\mathrm{i}\,a^{(1)}_{HV_1V_2}}_{\mathrm{SM}}g^{\mu\nu} + \mathrm{i}a^{(2)}_{HV_1V_2}\Big[k_1^\nu k_2^\mu - (k_1k_2)g^{\mu\nu}\Big] + \mathrm{i}a^{(3)}_{HV_1V_2}\epsilon^{\mu\nu k_1k_2}$$

Explicit insertions:

$$a^{(2)}_{HWW} = \frac{2g}{M_{\mathrm{W}}}\,d, \qquad a^{(2)}_{HZZ} = \frac{2g}{M_{\mathrm{W}}}\,(c_{\mathrm{W}}^2 d + s_{\mathrm{W}}^2 d_B)$$

$$a^{(2)}_{HZ\gamma} = \frac{2g}{M_{\mathrm{W}}}\,c_{\mathrm{W}}s_{\mathrm{W}}(d - d_B), \qquad a^{(2)}_{H\gamma\gamma} = \frac{2g}{M_{\mathrm{W}}}\,(s_{\mathrm{W}}^2 d + c_{\mathrm{W}}^2 d_B)$$

$$a^{(3)}_{HV_1V_2} = a^{(2)}_{HV_1V_2}\Big|_{d\to\tilde{d},\,d_B\to\tilde{d}_B}$$

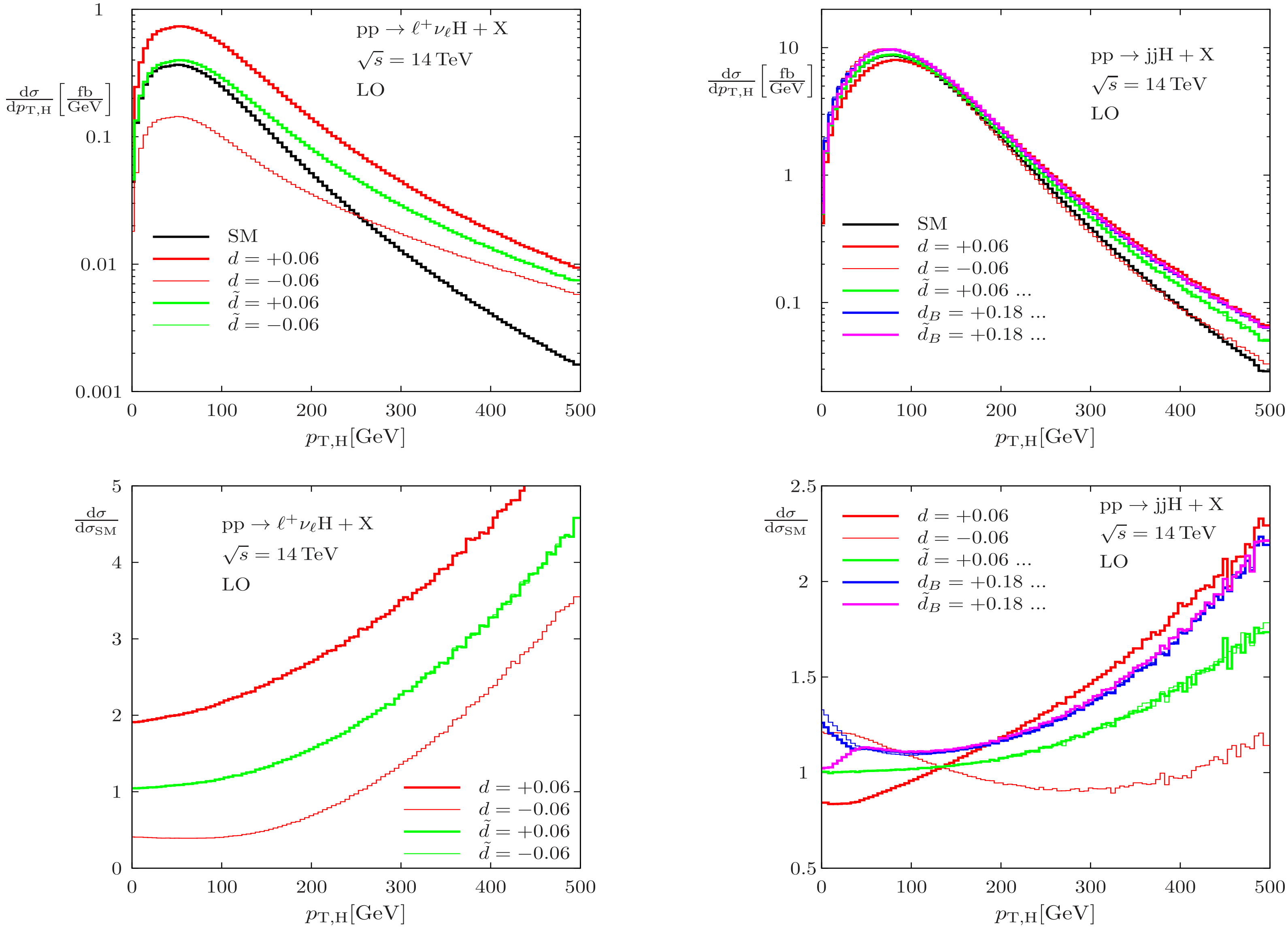
($g = e/s_{\mathrm{W}}$ = gauge coupling)

where $d \propto f_{WW},\quad d_B \propto f_{BB},\quad \tilde{d} \propto f_{\tilde{W}W},\quad \tilde{d}_B \propto f_{\tilde{B}B}$

Anomalous effects in $p_{\mathrm{T,H}}$ spectra in Higgs-strahlung and VBF (no formfactor)

$\mathrm{W^+H}$ (acc. cuts)

VBF (with VBF cuts)



HAWK '12/'13

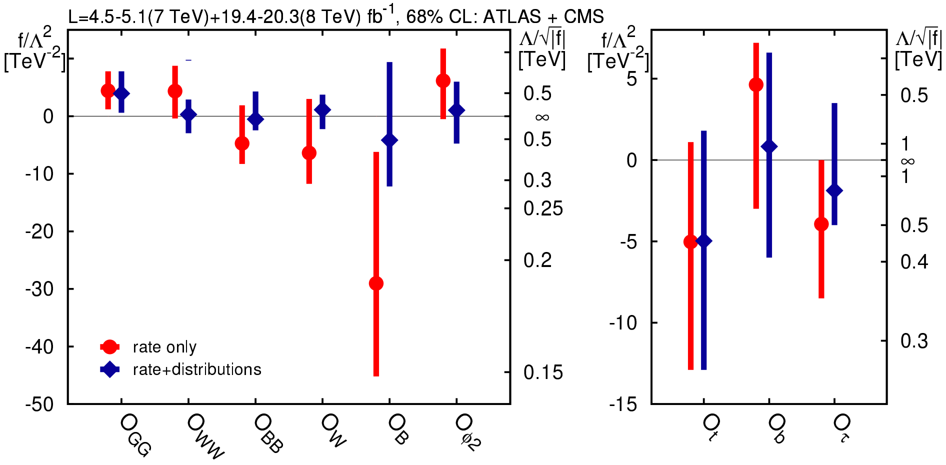
LO shown

NLO QCD available

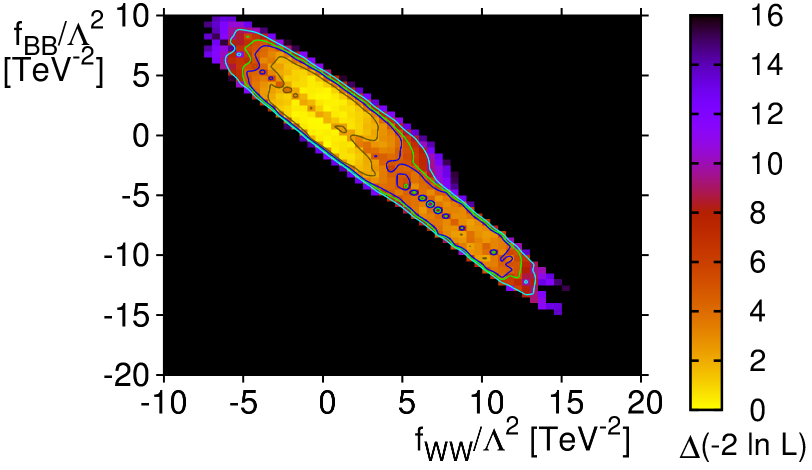
NLO EW planned

Impact of anomalous couplings larger in WH production than in VBF !

First analyses – an example



SFITTER ’15



... still strongly simplified:

few operators, fit to Higgs signal strength, missing corrections, ...

Perspectives:

- precision calculations challenging
  ↪ include QCD + EW corrections to sufficient precision
- interesting exp. analyses expected:
  differential Higgs XS, vector-boson scattering, ...
- global analysis of LHC data ?

The idea:

$f_i = ??$ fitted

$f_i \approx 0$, SM $=$ ok

$f_i \neq 0$, new physics !

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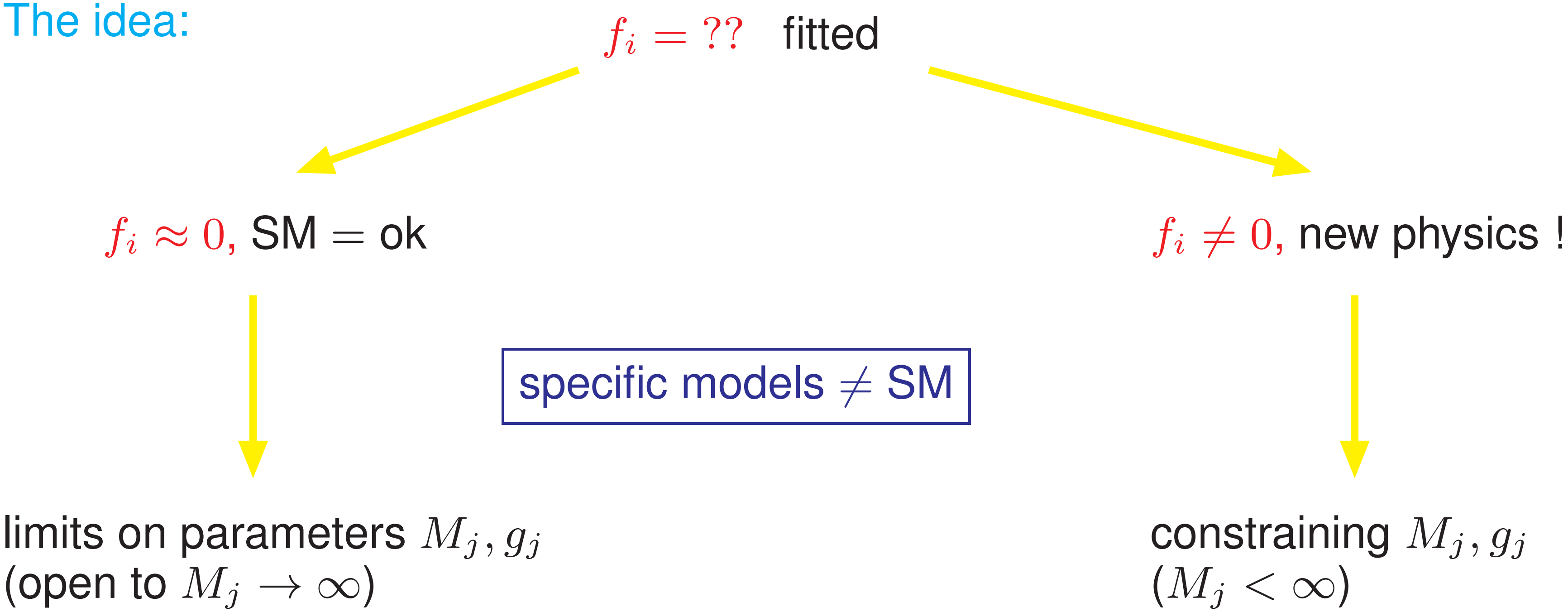

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specific models $\neq$ SM

limits on parameters M_j, g_j
(open to $M_j \to \infty$)

constraining M_j, g_j
$(M_j < \infty)$

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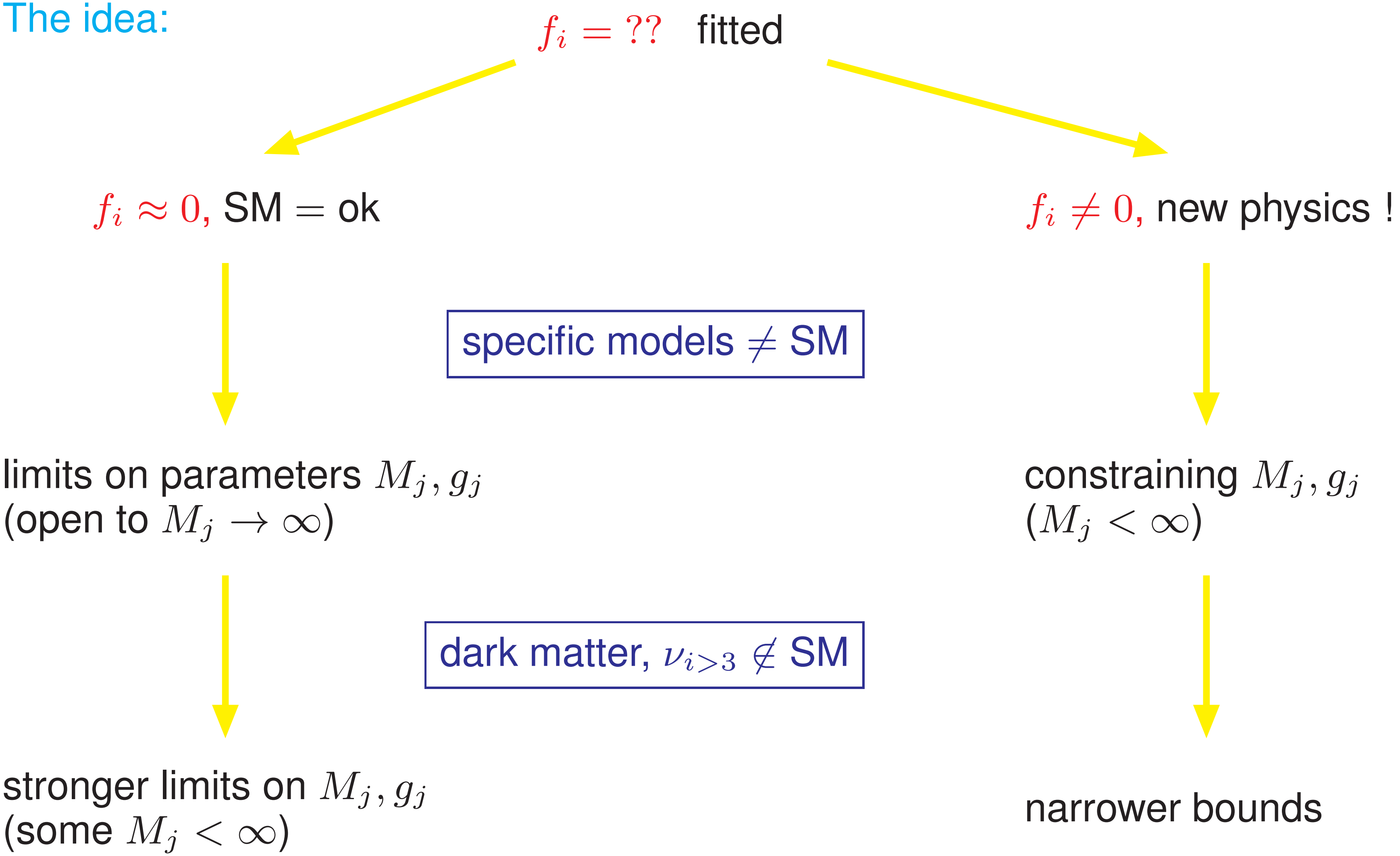

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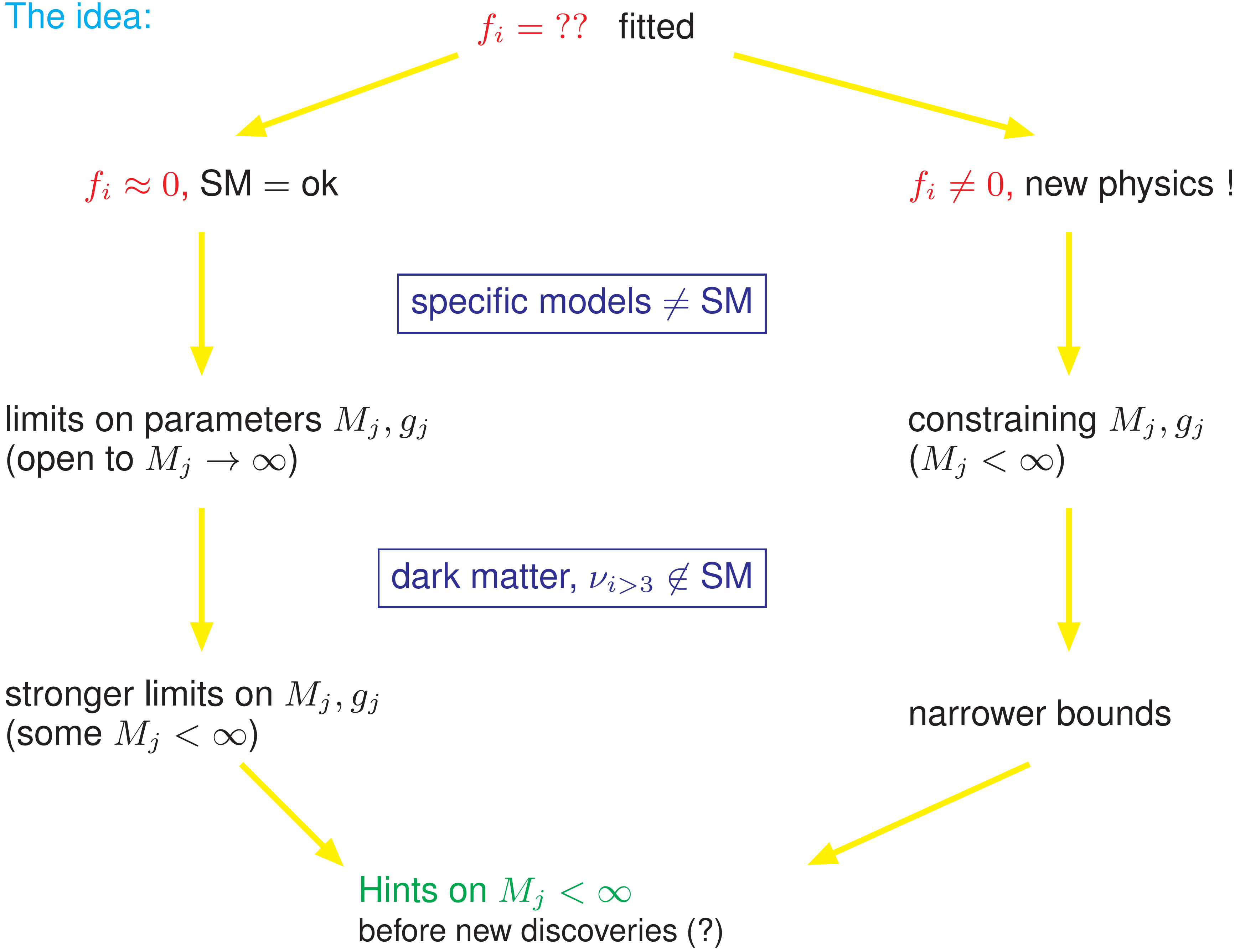
$(M_j < \infty)$

dark matter, $\nu_{i>3} \notin$ SM

stronger limits on M_j, g_j
(some $M_j < \infty$)

narrower bounds

The idea:



$f_i = ??$ fitted

$f_i \approx 0$, SM $=$ ok

$f_i \neq 0$, new physics !

specific models $\neq$ SM

limits on parameters M_j, g_j
(open to $M_j \to \infty$)

constraining M_j, g_j
$(M_j < \infty)$

dark matter, $\nu_{i>3} \notin$ SM

stronger limits on M_j, g_j
(some $M_j < \infty$)

narrower bounds

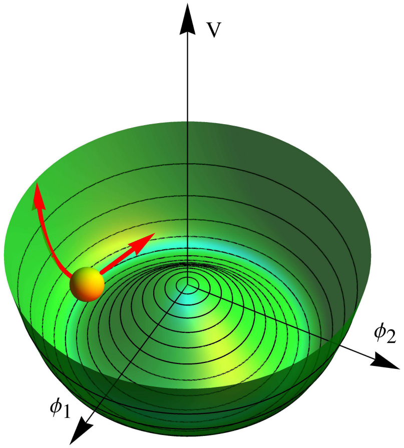
Hints on $M_j < \infty$
before new discoveries (?)

Higgs profiling at the LHC

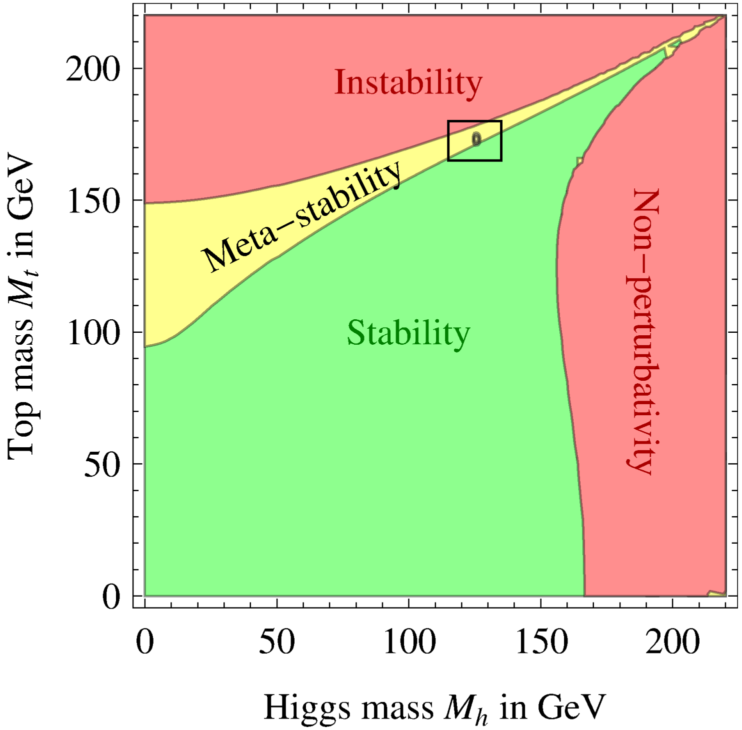
— Higgs self-coupling —

Higgs self/coupling λ – window to new physics ?

$$V(H) = \frac{1}{2}M_H^2 H^2 + \frac{v}{4}\lambda H^3 + \frac{1}{16}\lambda H^4$$



Degrassi et al. ’12



SM prediction: $\lambda(M_H^2) \propto M_H^2$ with “running” $\lambda(\mu)$ in the range $v < \mu < \Lambda = M_{NP}$

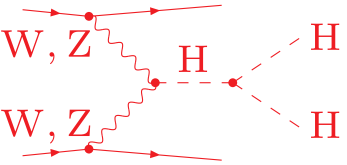
Note: $M_H = 126\,\text{GeV}$ SM escapes problems !

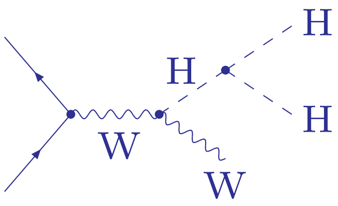
- $\lambda(\mu) < 0$: vacuum instability
- $\lambda(\mu) \to \infty$: triviality, non-perturbativity, ... consistency problem

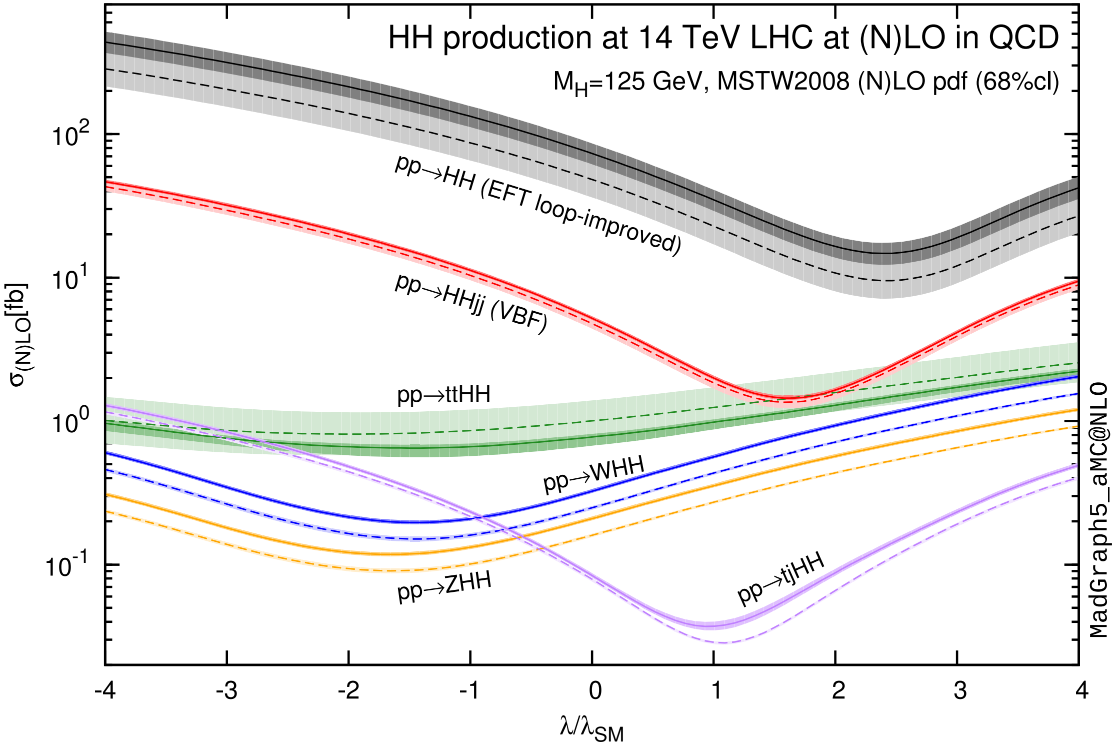
$\Rightarrow$ Exp. challenge: measuring λ in Higgs pair production

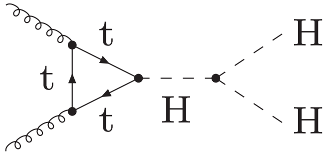
Higgs self/coupling λ – window to new physics ?

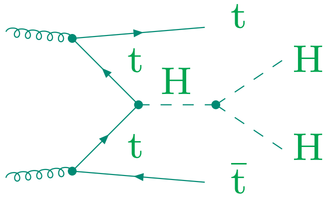
Maltoni et al. ’14











SM prediction: $\lambda(M_{\mathrm{H}}^2) \propto M_{\mathrm{H}}^2$ with “running” $\lambda(\mu)$ in the range $v < \mu < \Lambda = M_{\mathrm{NP}}$

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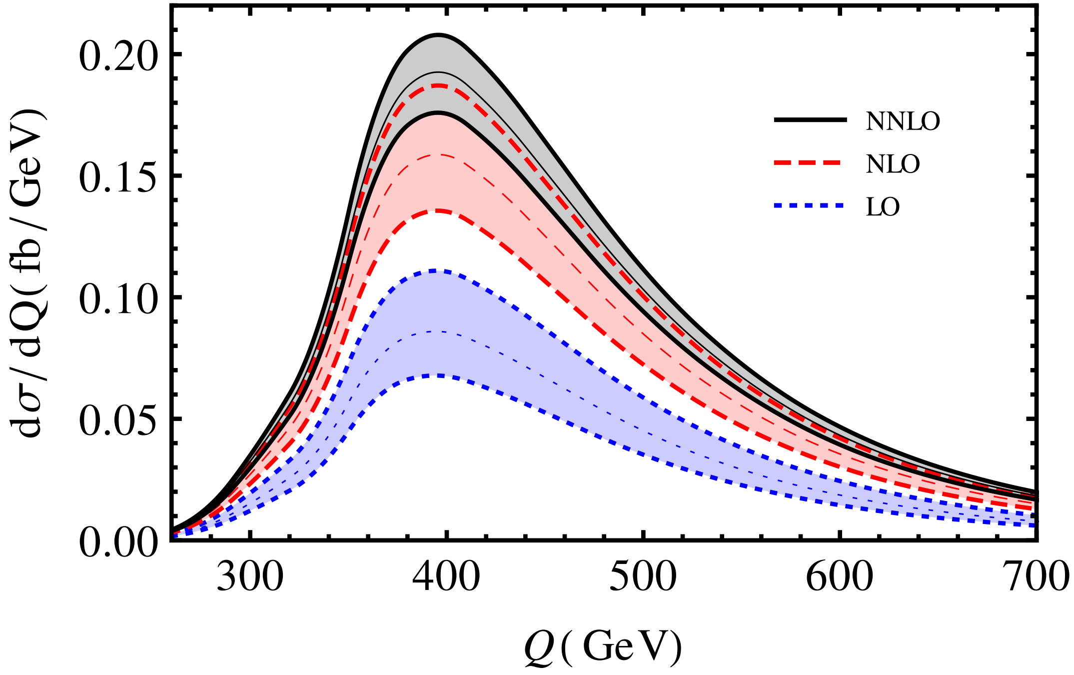
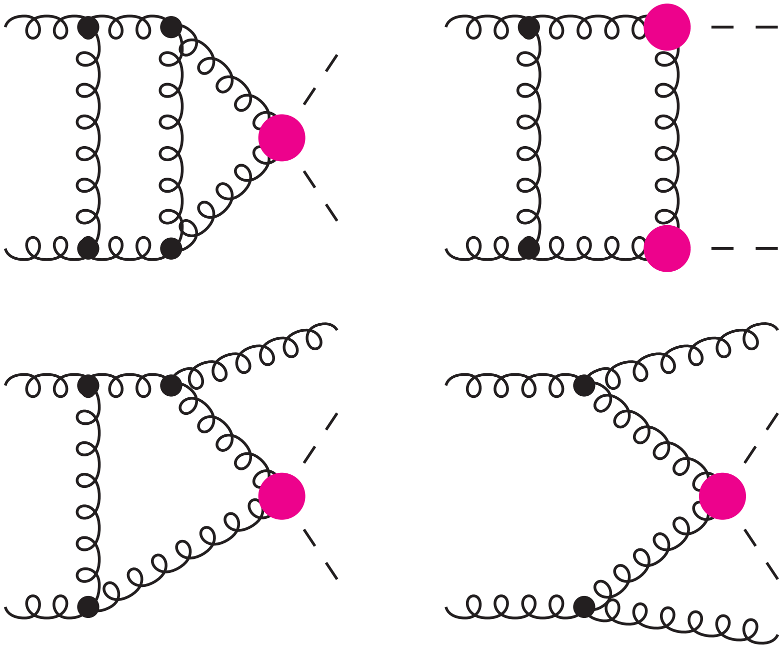
$\Rightarrow$ Exp. challenge: measuring λ in Higgs pair production

More precision for $\mathrm{pp(gg)} \to \mathrm{HH}$



deFlorian, Mazzittelli '13



- LO Eboli et al. '87; Glover, van der Bij '88 $\sigma_{\mathrm{LO}}(m_{\mathrm{t}})$
- NLO: $m_{\mathrm{t}} \to \infty$ Dawson, S.D., Spira '98 $+100\%$

  $1/m_{\mathrm{t}}$ expansion Grigo et al. '13,'15; Degrassi et al. '16 -14%

  full m_{t} dependence Maltoni et al. '14; Borowka et al. '15
- NNLO ($1/m_{\mathrm{t}}$ expansion): $+20\%$

  deFlorian et al. '13; Grigo et al. '14,'15
- QCD parton shower effects / resummations

  Li et al. '13; Maierhöfer et al. '14; Frederix et al. '14 Shao et al. '13; deFlorian et al. '15

TH uncertainty:

(@ 14 TeV)

$\Delta_{\mathrm{scale}} \sim 6\%$

$\Delta_{\mathrm{PDF}+\alpha_{\mathrm{s}}} \sim 8\%$

Higgs profiling at the LHC

— Higgs width and interferometry —

Total Higgs width Γ_{H} from $\mathrm{pp} \to \mathrm{ZZ} \to 4\ell$

Caola, Melnikov '13; Campbell, R.K.Ellis, Williams '13

Problem: $\Gamma_{\mathrm{H}}^{\mathrm{SM}} \approx 0.004\,\mathrm{GeV} \ll \mathcal{O}(1\,\mathrm{GeV}) \sim$ exp. resolution

$\hookrightarrow$ Γ_{H} not directly measureable

Idea: separate on-shell (signal) and off-shell XS for $gg \to \mathrm{H}^{(*)} \to \mathrm{Z}^{(*)}\mathrm{Z}^{(*)} \to 4\ell$

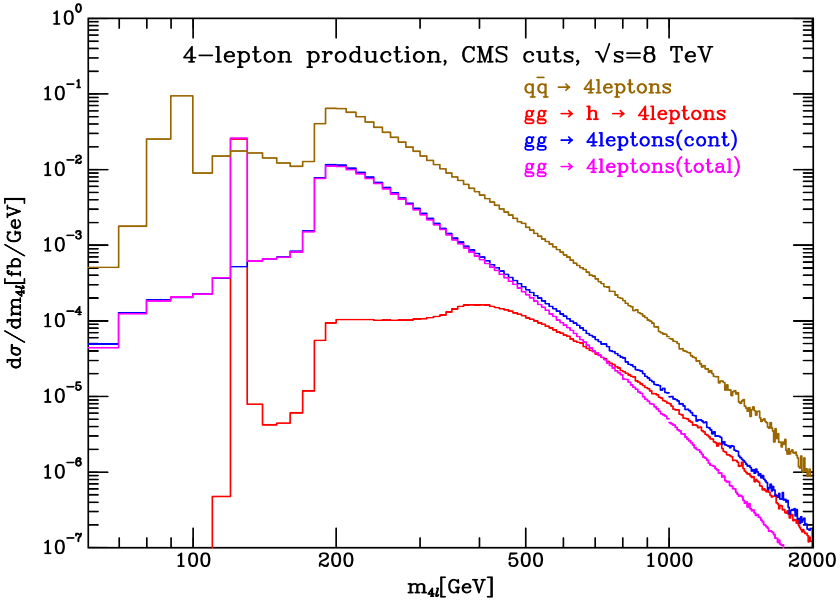
- signal:

$$\sigma_{\mathrm{H}}^{\mathrm{sig}} \propto \frac{g_i^2 g_f^2}{\Gamma_{\mathrm{H}}} \qquad \text{for } i \to \mathrm{H} \to f$$

- off-shell ($M_{4\ell} > M_{\mathrm{H}} +$ some GeV):

$$\sigma_{\mathrm{H}}^{\mathrm{off}} = \underbrace{\sigma_{\mathrm{H}}^{\mathrm{off}}}_{\propto g_i^2 g_f^2} + \underbrace{\sigma_{\mathrm{H}}^{\mathrm{int}}}_{\propto g_i g_f} = (\Gamma_{\mathrm{H}}\text{-independent})$$

Campbell et al. '13 (see also Kauer, Passarino '12,'13)



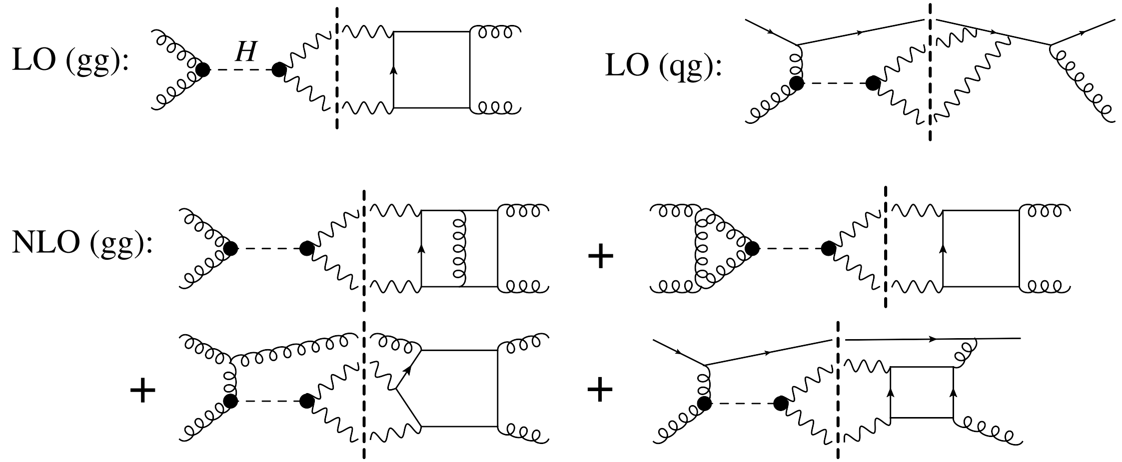
Uniform rescaling of Higgs couplings, keeping $\sigma_{\mathrm{H}}^{\mathrm{sig}}$ unchanged:

$$\sigma_{4\ell}^{\mathrm{exp}} \overset{!}{=} \sigma_{4\ell}(\Gamma_{\mathrm{H}}) \equiv \sigma_{qq\to4\ell} + \sigma_{\mathrm{H}}^{\mathrm{sig}} + \sigma_{\mathrm{H}}^{\mathrm{off}} \times \frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} + \sigma_{\mathrm{H}}^{\mathrm{int}} \times \sqrt{\frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}}}$$

$$\Rightarrow \Gamma_{\mathrm{H}} < \begin{cases} (4.5\text{--}7.5)\Gamma_{\mathrm{H}}^{\mathrm{SM}} & \text{with ATLAS 8TeV data} \\ 2.4\Gamma_{\mathrm{H}}^{\mathrm{SM}} & \text{with CMS 7\&8TeV data} \end{cases}$$

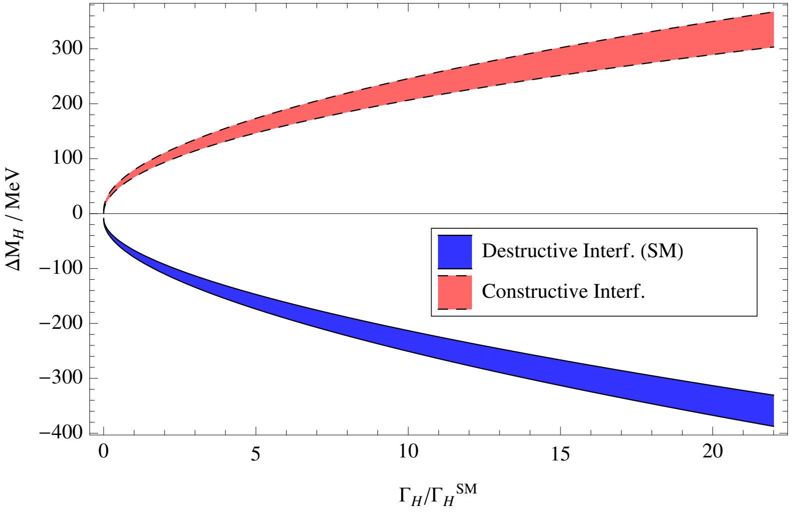
Total Higgs width Γ_{H} from $\mathrm{pp} \to \gamma\gamma$ Dixon, Li ’13

Interference between signal $\mathrm{gg} \to \mathrm{H} \to \gamma\gamma$ and bkg $\mathrm{gg} \to \gamma\gamma$ shifts Higgs mass peak:



Dicus, Willenbrock ’88;
Dixon, Siu ’03;
Martin ’12,’13;
de Florian et al. ’13;
Dixon, Li ’13

Mass shift $\Delta M_{\mathrm{H}} = M_{\mathrm{H}}^{\gamma\gamma} - M_{\mathrm{H}}^{\mathrm{ZZ}}$ depends on Γ_{H}: Dixon, Li ’13



Rough behaviour: $\Delta M_{\mathrm{H}} \propto \sqrt{\Gamma_{\mathrm{H}}}$

Sensitivity:

$\Delta M_{\mathrm{H}} \sim 1\,\mathrm{GeV} \quad \Leftrightarrow \quad \Gamma_{\mathrm{H}} \sim 200\Gamma_{\mathrm{H}}^{\mathrm{SM}}$

Result from LHC data @ Run 1:

$$\Delta M_{\mathrm{H}} = \begin{cases} +1.47 \pm 0.72\,\mathrm{GeV} & \text{(ATLAS)} \\ -0.89^{+0.56}_{-0.57}\,\mathrm{GeV} & \text{(CMS)} \end{cases}$$