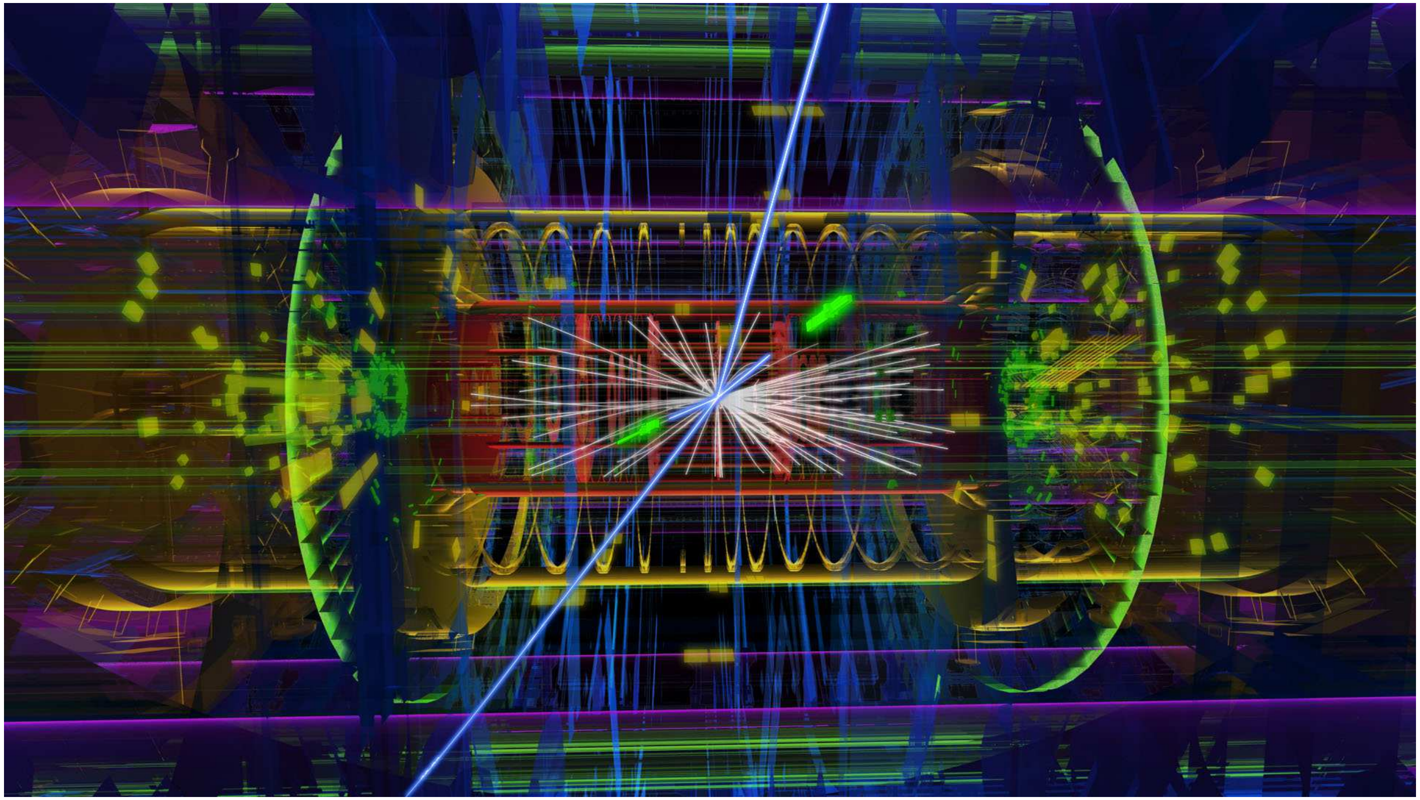


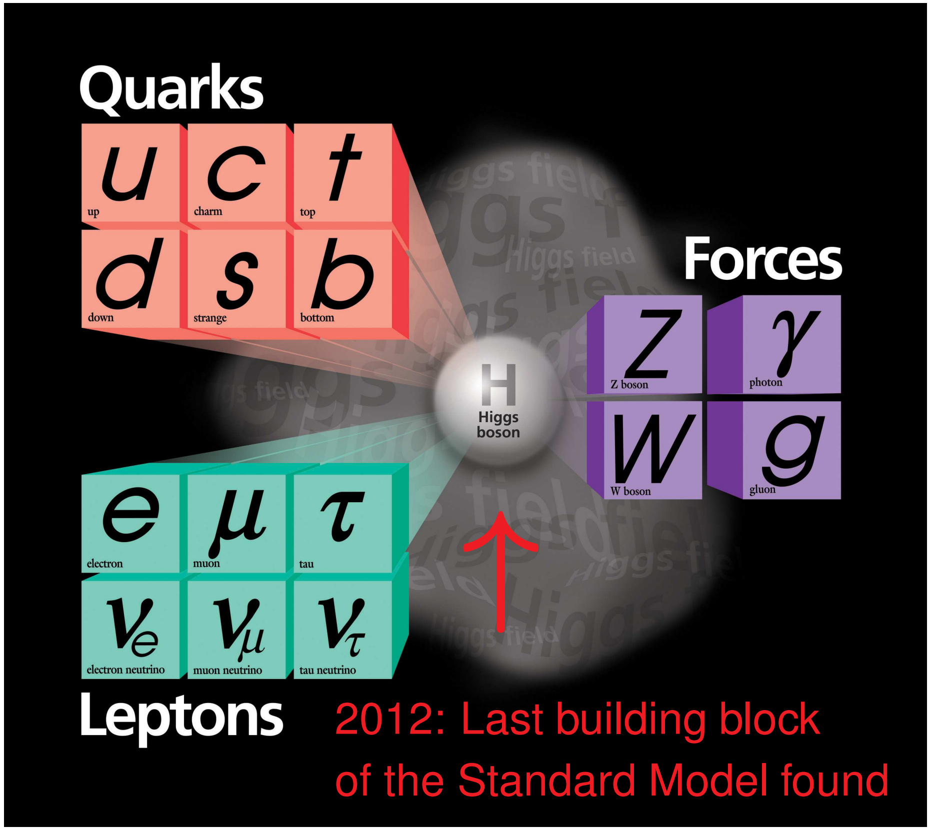
Towards Higgs Precision Physics at the LHC

Stefan Dittmaier
Albert-Ludwigs-Universität Freiburg

Status quo of particle phenomenology

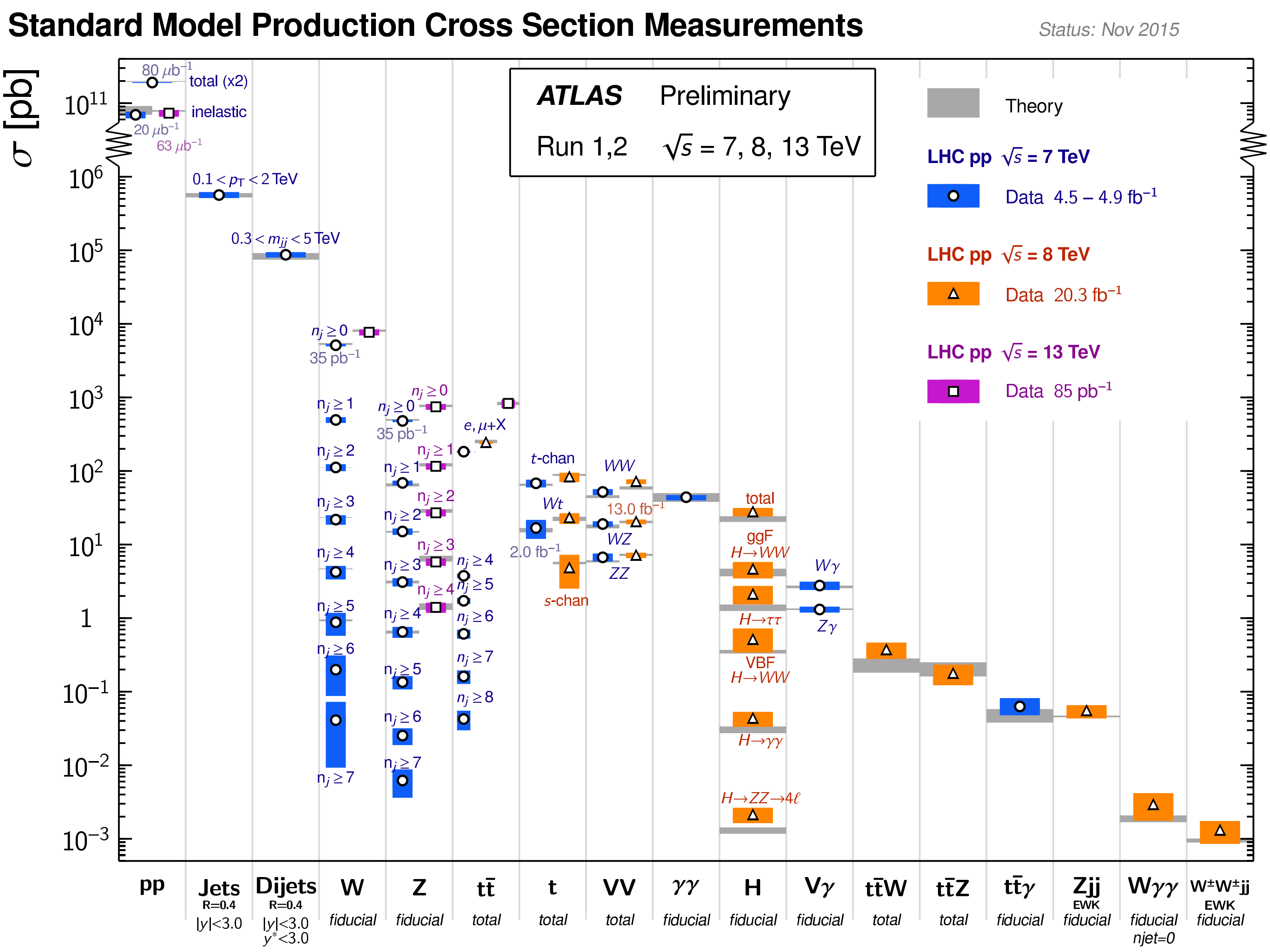
Francois Englert Peter Higgs

2013



2012: Last building block of the Standard Model found

Standard Model carved in stone ??



Good overall agreement between theory & experiment !

Mission and prospects for LHC Run 2

Run 1 of LHC = great success !

- All SM particles rediscovered + discovery of Higgs boson
- SM cross sections measured → agreement with SM predictions
- New-particle searches extended to TeV scale → no new particle yet

↪ New physics (if there) manifests itself in small & subtle effects.

⇒ Higher precision in experiment & theory neccessary !

... (to be) delivered by Run 2 of LHC:

- higher energy: $13{-}14\,\mathrm{TeV}$
- higher luminosity: $\sim 300\,\mathrm{fb}^{-1}$
- particular importance:
  - search for new particles (e.g. $\gamma\gamma$ resonance real?)
  - profiling the Higgs boson with precision (more decay channels, coupling structures)
  - precision physics with SM particles

Mission and prospects for LHC Run 2

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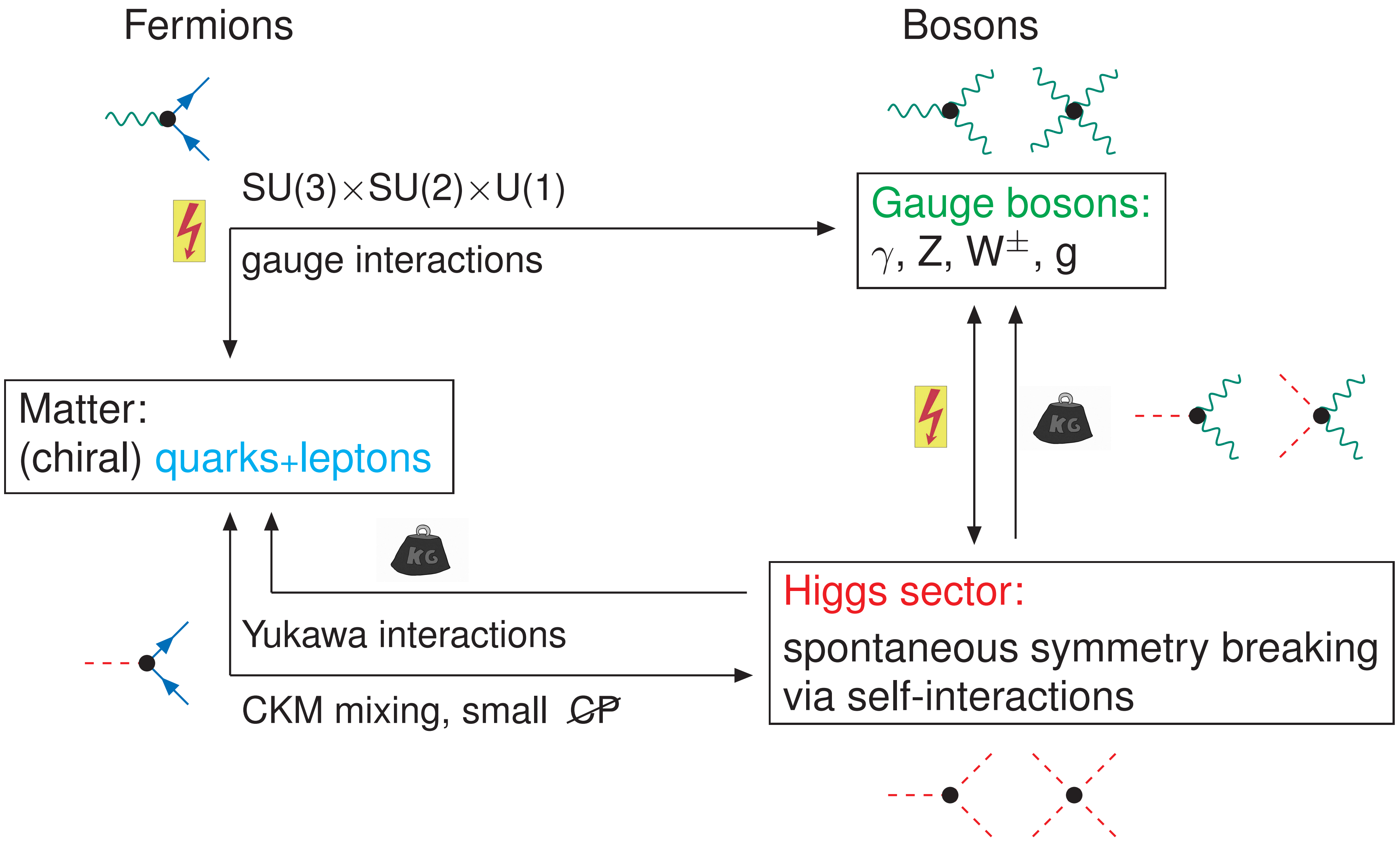
Contents

Predicting LHC processes

Structure and elementary interactions of the Standard Model



Fermions

Bosons

SU(3)×SU(2)×U(1)

gauge interactions

Gauge bosons:
γ, Z, $W^{\pm}$, g

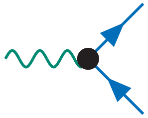
Matter:
(chiral) quarks+leptons

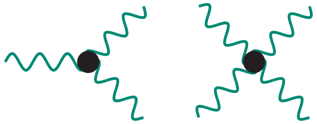
Yukawa interactions

CKM mixing, small $\cancel{CP}$

Higgs sector:
spontaneous symmetry breaking
via self-interactions

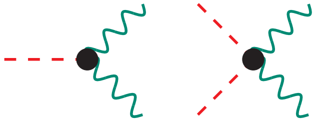
Structure and elementary interactions of the Standard Model

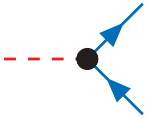




Test of the model

⇔ Exp. reconstruction of the $\underbrace{\text{elementary couplings}}_{\text{Feynman rules}}$





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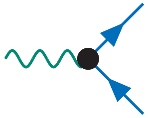

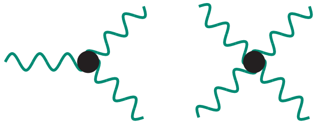

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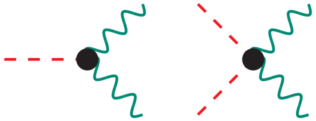
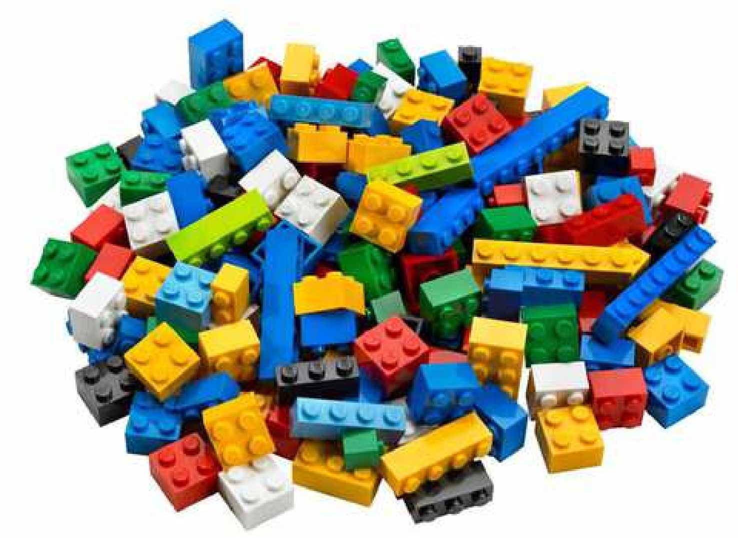
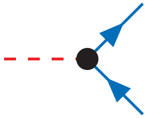
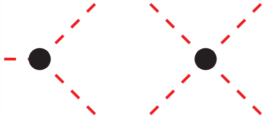
Building blocks for particle reactions









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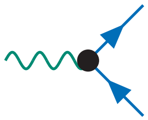

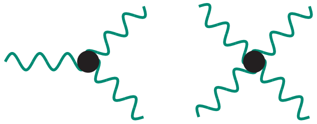

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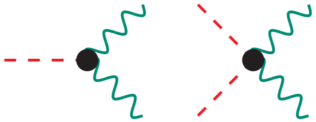
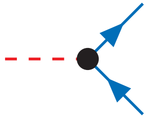
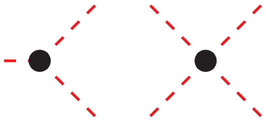


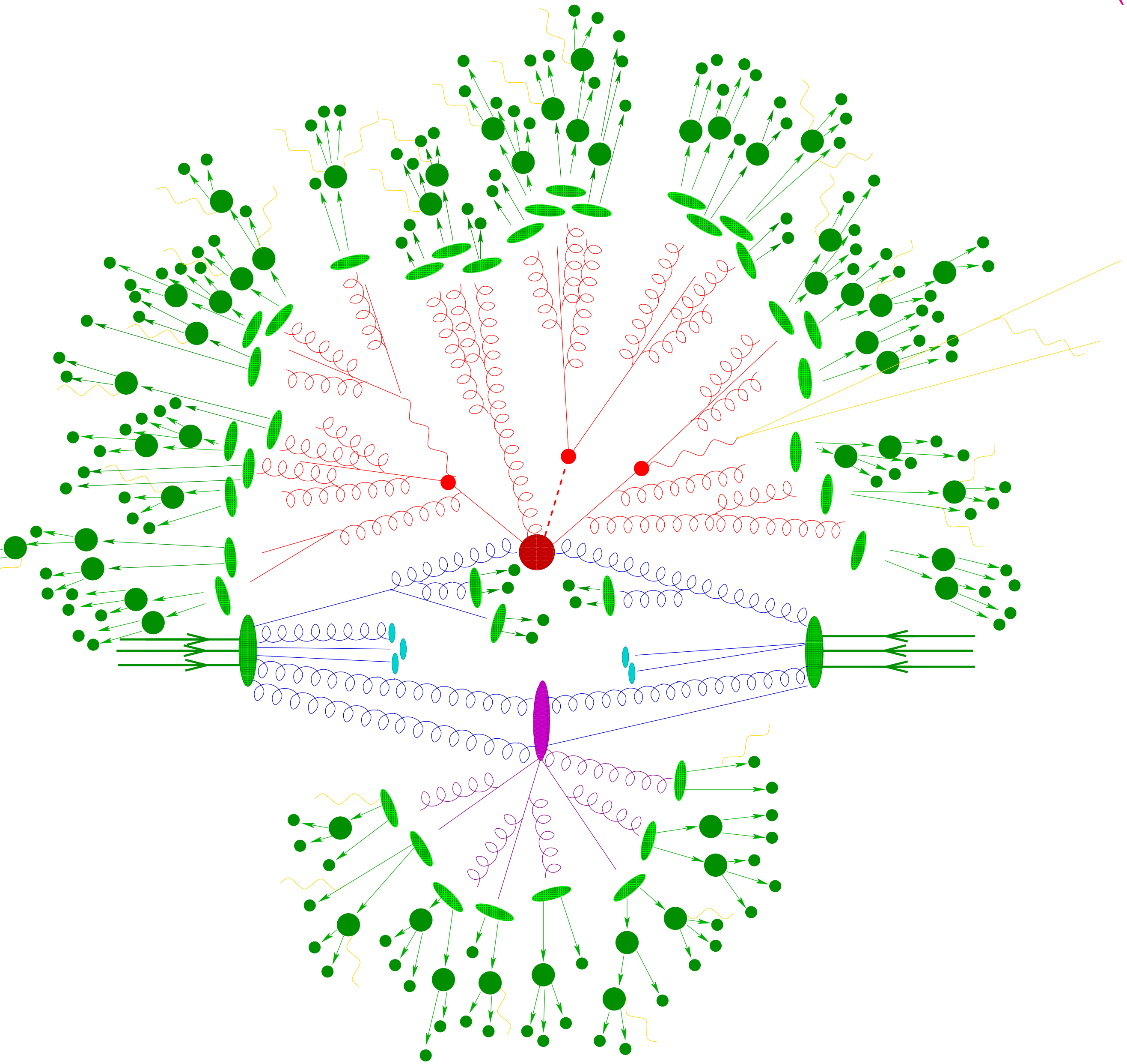




Standard Model extensions → more fields, more particles, more interactions, ...

Illustration of hard and soft parts in an event simulation

(designed by Sherpa)



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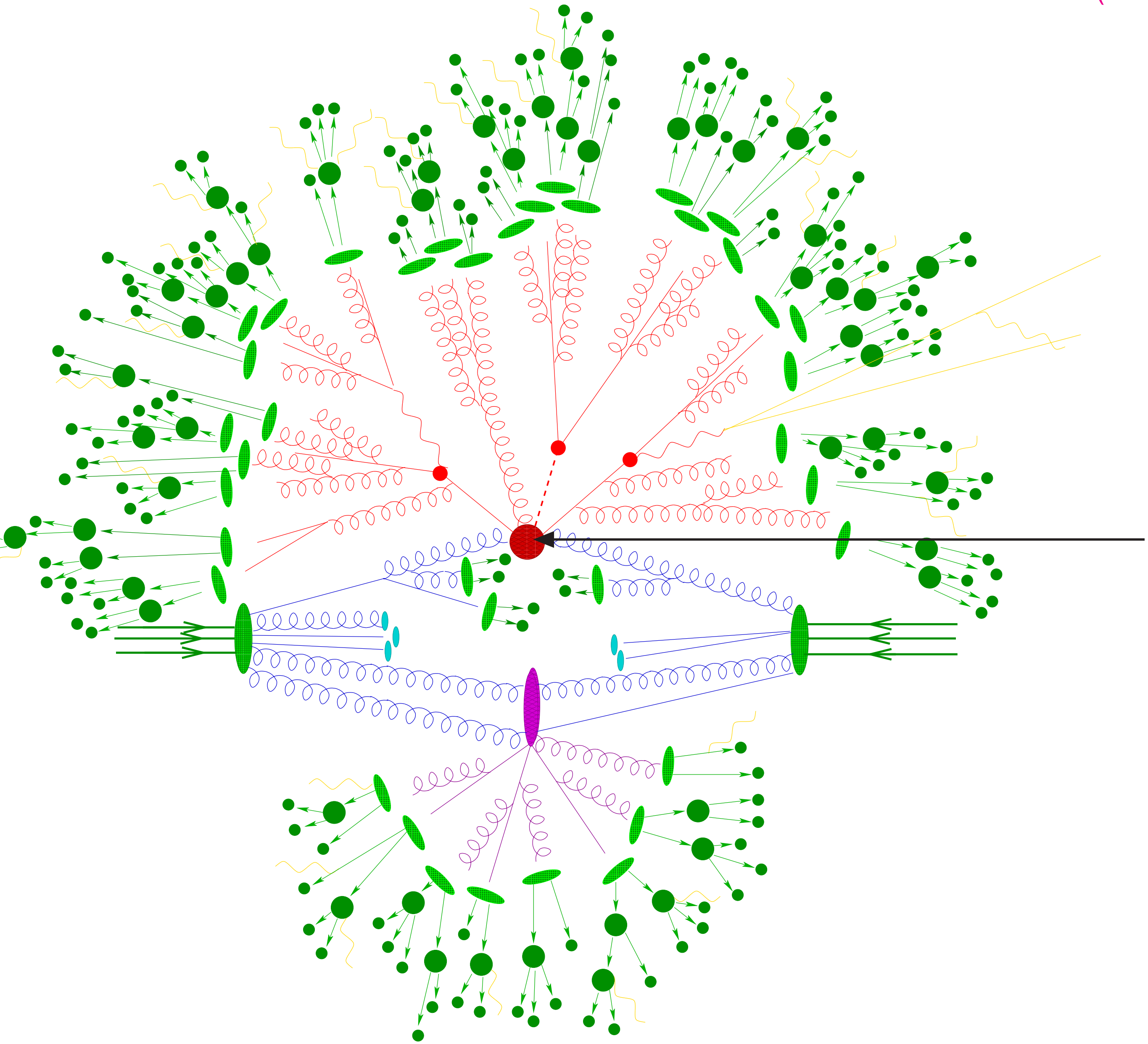

Hard partonic scattering

= perturbative part

→ considered in this talk

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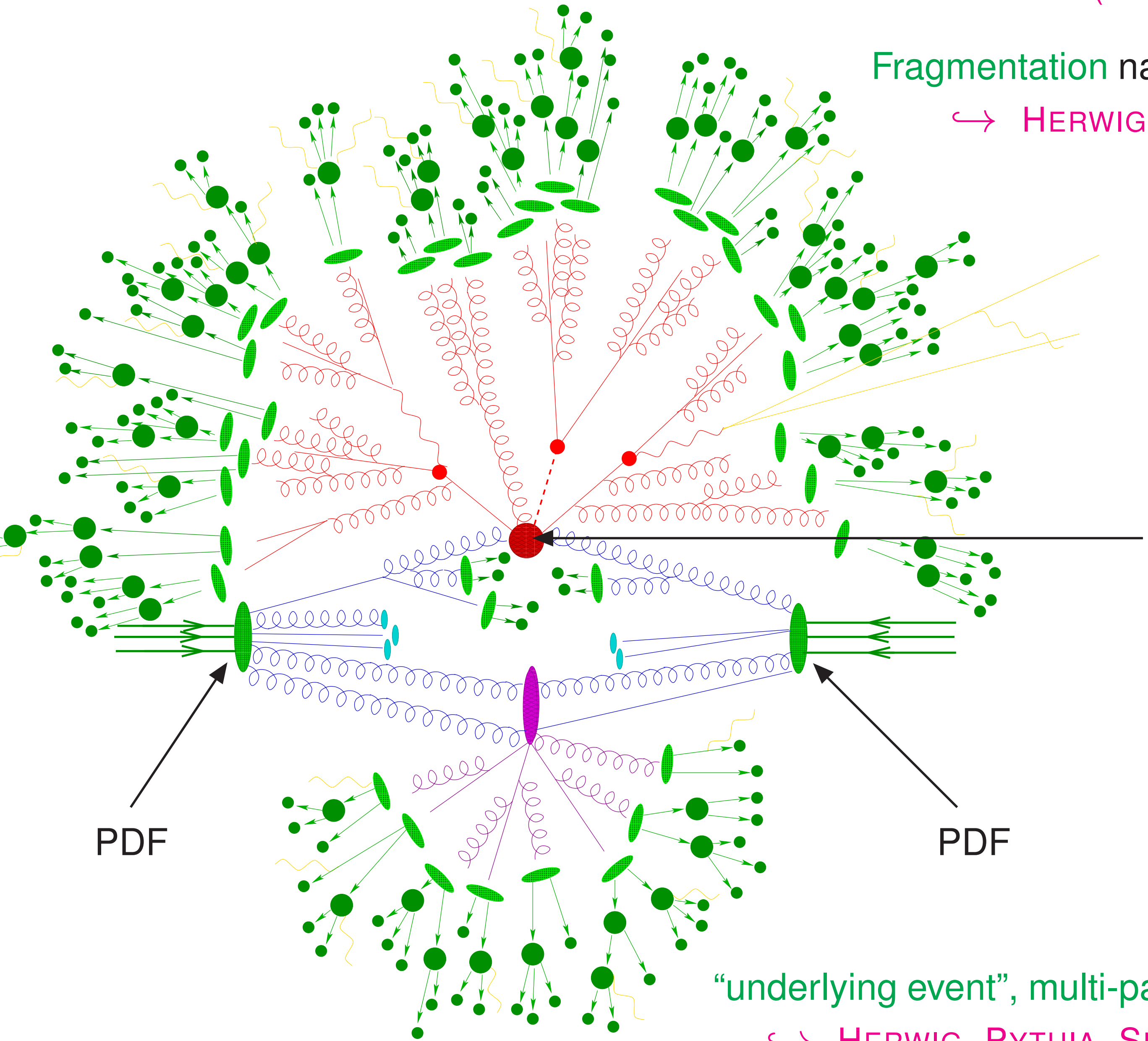


Fragmentation nach parton shower

↪ HERWIG, PYTHIA, SHERPA

Hard partonic scattering
= perturbative part
→ considered in this talk

PDF

PDF

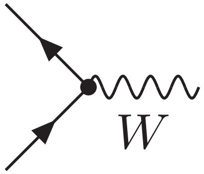
“underlying event”, multi-parton scattering

↪ HERWIG, PYTHIA, SHERPA

Perturbative predictions for particle processes

LO cross sections

– stable particles
– partonic final states



Perturbative predictions for particle processes

LO cross sections

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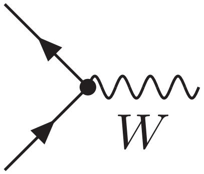
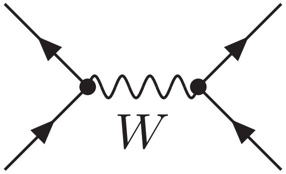
↓

LO improvements

– particle decays
– off-shell contributions
– universal corrections





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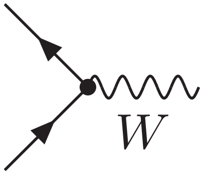

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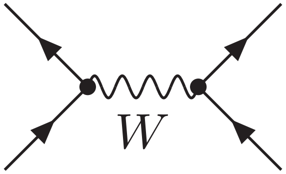

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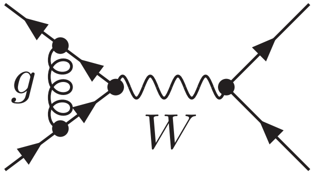
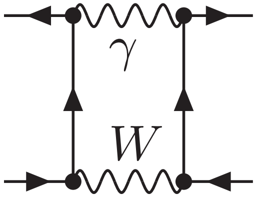
NLO cross sections

– QCD+EW corrections
– hard jets / LO Jet structure
– γ radiation





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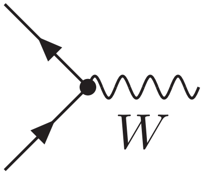

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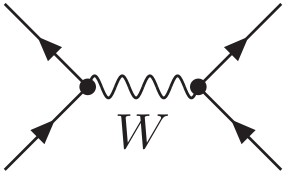

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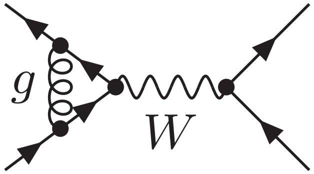

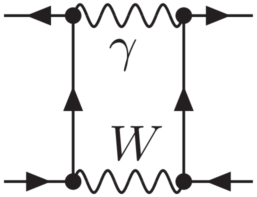

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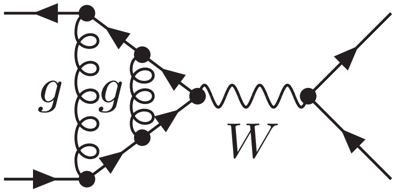
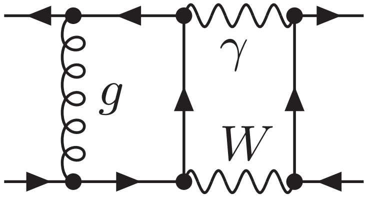
NNLO cross sections

– QCD (+EW?) corrections
– QCD × EW corrections
– more hard jets / NLO jet structure





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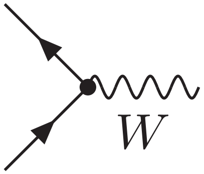

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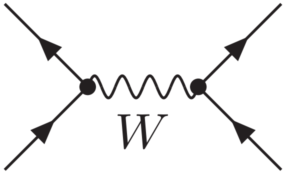

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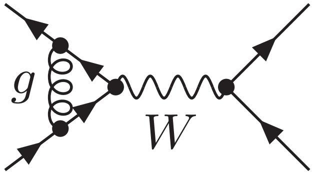

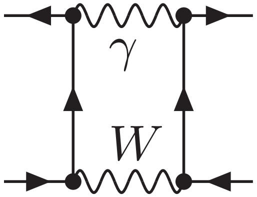

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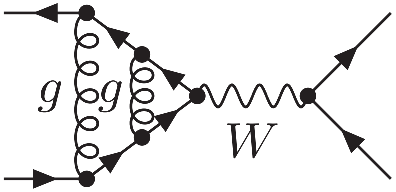

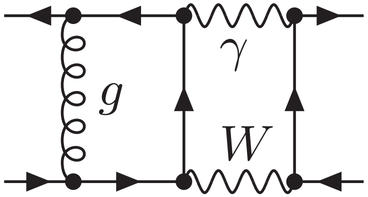

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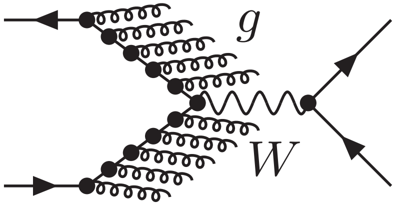
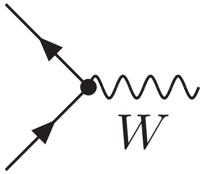
Analyt. QCD resummations

– reduced scale dependence
– elimination of perturb. artifacts
– for special observables



Perturbative predictions for particle processes

LO cross sections



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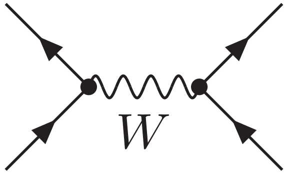

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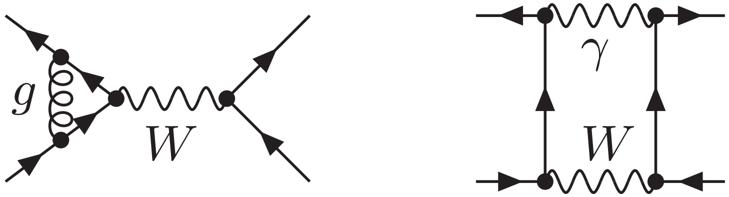
NLO cross sections



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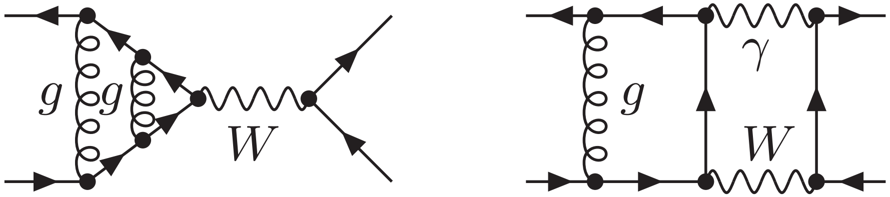
NNLO cross sections



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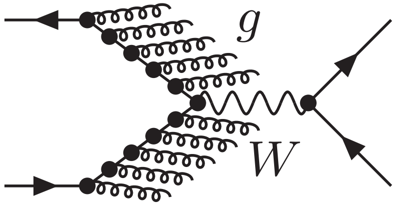
Analyt. QCD resummations



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Precise pseudo-observables

σ, $\mathrm{d}\sigma/\mathrm{d}X$, M, Γ, A_{FB}, etc.

Perturbative predictions for particle processes

LO cross sections

– stable particles
– partonic final states

↓

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LHC = “Long and Hard Calculations” (T.Binoth)

Challenges in N...LO predictions

Algebraic complexity

LO: problem solved up to $2 \to \sim 10$ particles

NLO: problem solved up to $2 \to\ 4$, first results for > 6 external particles

NNLO: several $2 \to 2$ examples in QCD ($\mathrm{t\bar{t}}$, $\mathrm{W{+}jet}$, $\mathrm{W}\gamma$, WW, etc.)

N$^{>2}$LO: “static quantities"’, $1 \to 2$, $2 \to 1$ (e.g. $\mathrm{gg} \to \mathrm{H}$ @ NNNLO QCD)

Challenges in N...LO predictions

Algebraic complexity

The “NLO revolution”: NLO for ≥ 6 particle processes

$\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$	EW	[Denner, S.D., Roth Wieders ’05]
$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$	QCD	[Bredenstein, Denner, S.D., Pozzorini ’09,’10; Bevilacqua et al. ’09]
$\mathrm{pp} \to \mathrm{t\bar{t}} + 2j$	QCD	[Bevilacqua, Czakon, Papadopoulos, Worek ’10,’11]
$\mathrm{pp} \to \mathrm{t\bar{t}t\bar{t}}$	QCD	[Bevilacqua, Worek ’12]
$\mathrm{pp} \to \mathrm{b\bar{b}b\bar{b}}$	QCD	[Greiner, Guffanti, Reiter, Reuter ’11]
$\mathrm{pp} \to \mathrm{WWb\bar{b}}$	QCD	[Denner, S.D., Kallweit, Pozzorini ’10-’12; Bevilacqua et al. ’10]
$\mathrm{pp} \to \mathrm{WW} + 2j$	QCD	[Melia, Melnikov, Rontsch, Zanderighi ’10,’11; Greiner et al. ’12]
$\mathrm{pp} \to \mathrm{W/Z} + 3j$	QCD	[Ellis, Melnikov, Zanderighi ’09,’10; Berger et al. ’09,’10]
$\mathrm{pp} \to \mathrm{W/Z} + 4j$	QCD	[Berger et al. ’11,’12]
$\vdots$		
$\mathrm{e^+e^-} \to 7j$	QCD	[Becker et al. ’12]
$\vdots$		
$\mathrm{pp} \to \mathrm{W/Z} + 5j$	QCD	[Bern et al. ’13; Goetz, Reuschle, Schwan, Weinzierl ’14]
$\mathrm{pp} \to \mathrm{WWb\bar{b}H}$	QCD	[Denner, Feger ’15]
$\mathrm{pp} \to \mathrm{WWb\bar{b}} + j$	QCD	[Bevilacqua, Hartanto, Kraus, Worek ’15]
$\mathrm{pp} \to \mathrm{WW/ZZ} \to 4\ell$	EW	[Biedermann et al. ’16; Billoni et al. ’16]

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$\mathrm{pp} \to \mathrm{b\bar{b}b\bar{b}}$	QCD	
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$\vdots$		
$\mathrm{e^+e^-} \to 7j$	QCD	
$\vdots$		
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Challenges in N...LO predictions

Algebraic complexity

Loop integrals

NLO: problem solved

NNLO: many examples (but with few scales), many masses arbitrarily complicated

N$^{>2}$LO: mostly vacuum graphs

Challenges in N...LO predictions

Algebraic complexity

Loop integrals

IR singularities

NLO: problem solved

NNLO: successful proposals (antenna / jettiness / q_{T} / residue subtraction, etc.)

Challenges in N...LO predictions

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Loop integrals

IR singularities

Unstable particles @ NLO

$\hookrightarrow$ Problem: resummation of decay widths $\oplus$ gauge invariance !

Solutions at NLO:

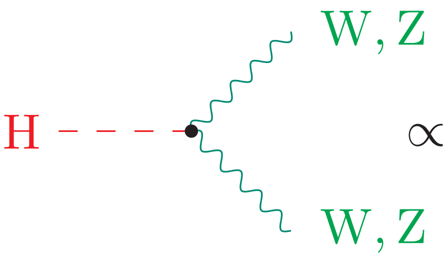
$$\left.\begin{array}{l}\text{– “Pole scheme”} \\ \text{– Effective field theory}\end{array}\right\} \to \text{Systematic expansions about resonance}$$

- “Complex-mass scheme”
  $\hookrightarrow$ complex masses & couplings, complete phase space, more work

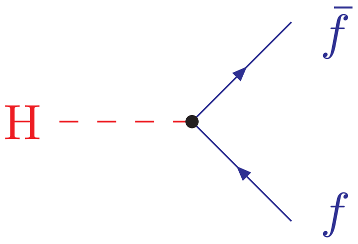
Higgs production at the LHC

Higgs search at the LHC

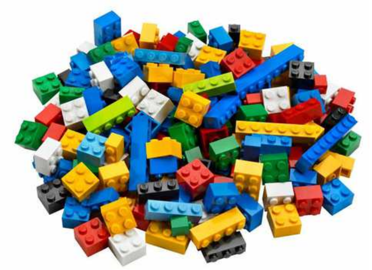
Higgs bosons couple proportional to particle masses:



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



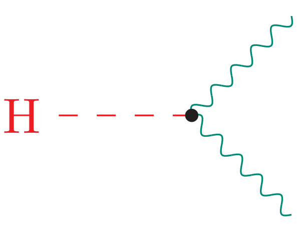
$\propto \; m_f$



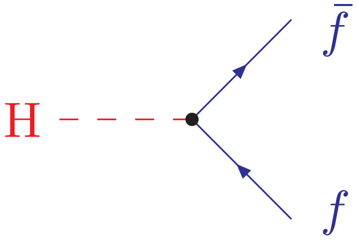
⇒ Higgs production via couplings to W/Z bosons or top-quarks

Higgs search at the LHC

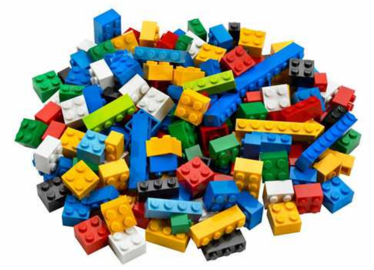
Higgs bosons couple proportional to particle masses:



$\propto M_\mathrm{W}$

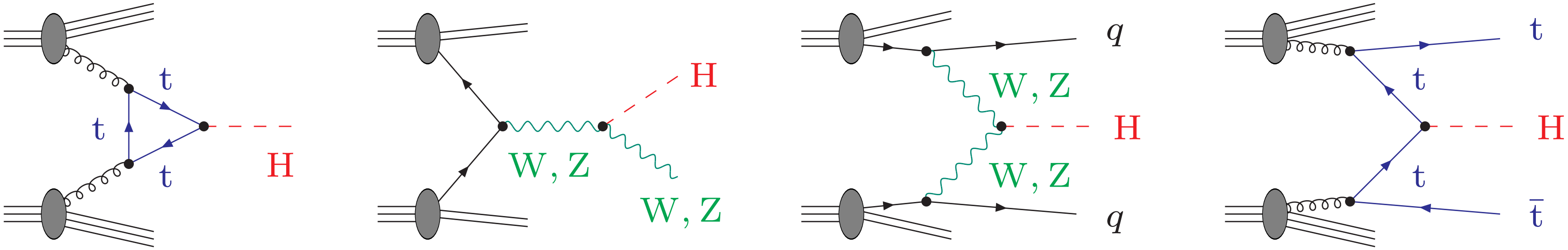


$\propto m_f$



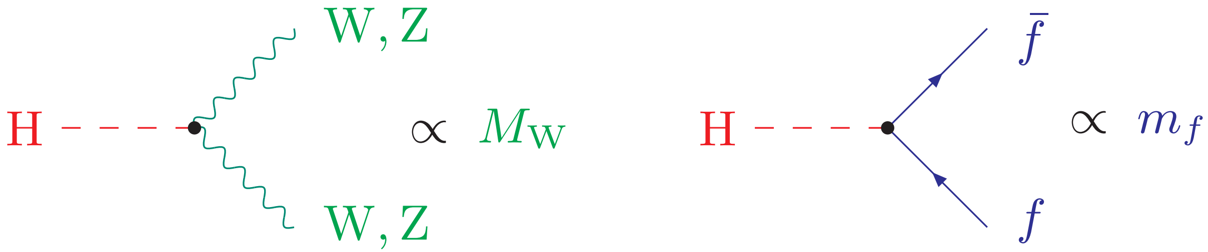
⇒ Higgs production via couplings to W/Z bosons or top-quarks

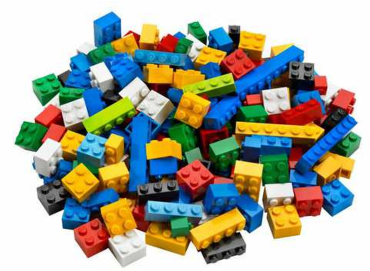
Processes at hadron colliders ($\mathrm{p\bar{p}/pp}$):



Higgs search at the LHC

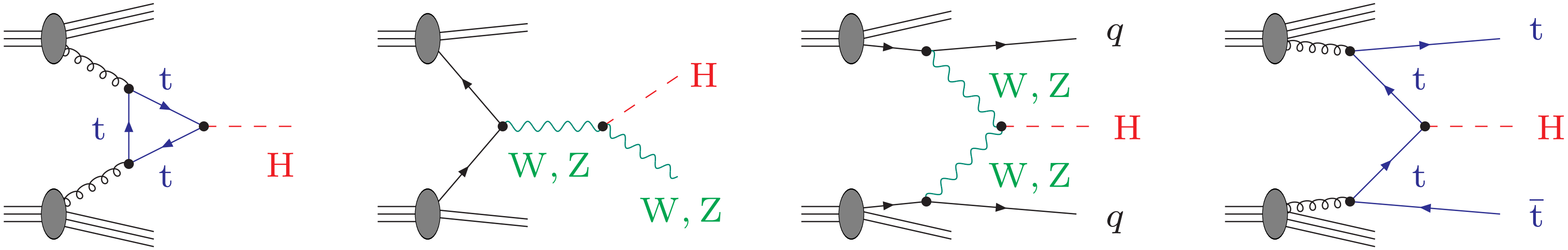
Higgs bosons couple proportional to particle masses:



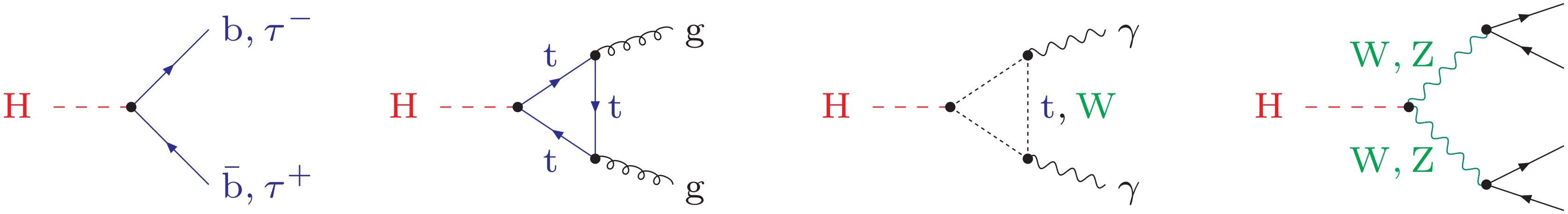


⇒ Higgs production via couplings to W/Z bosons or top-quarks

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



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



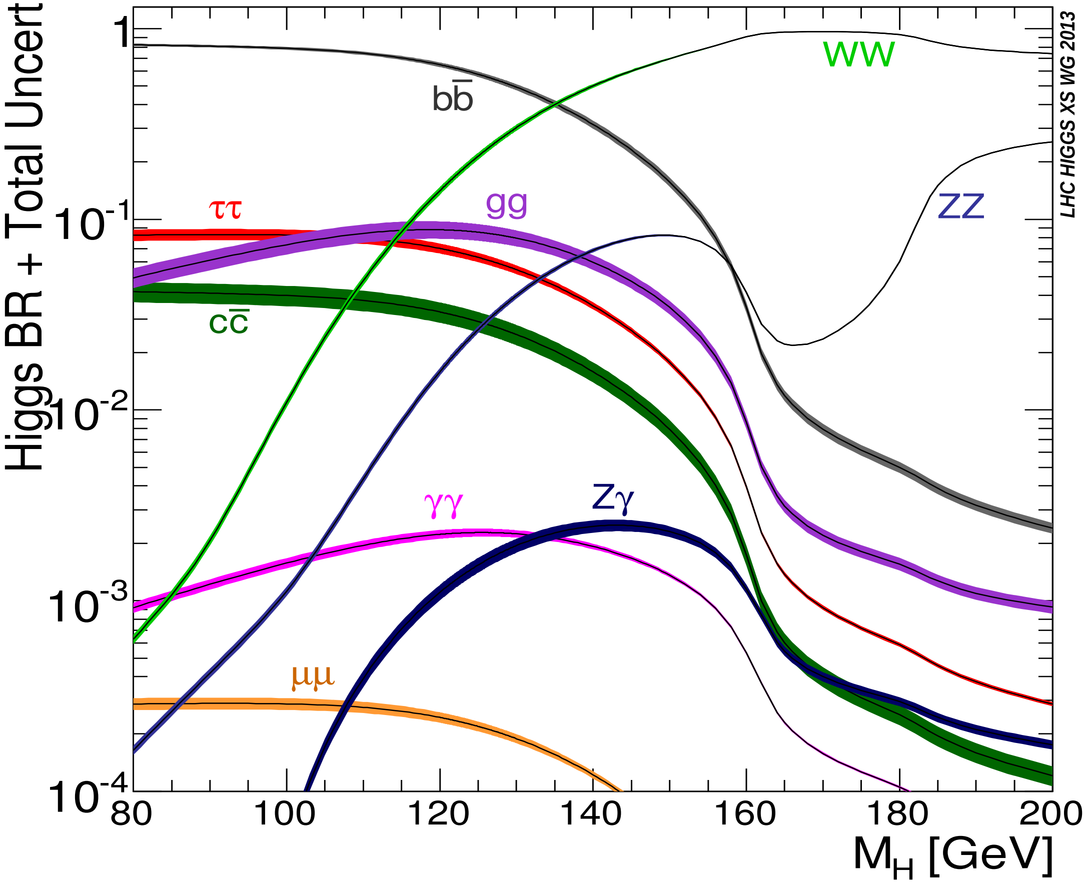
Branching ratios of the SM Higgs boson

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 !



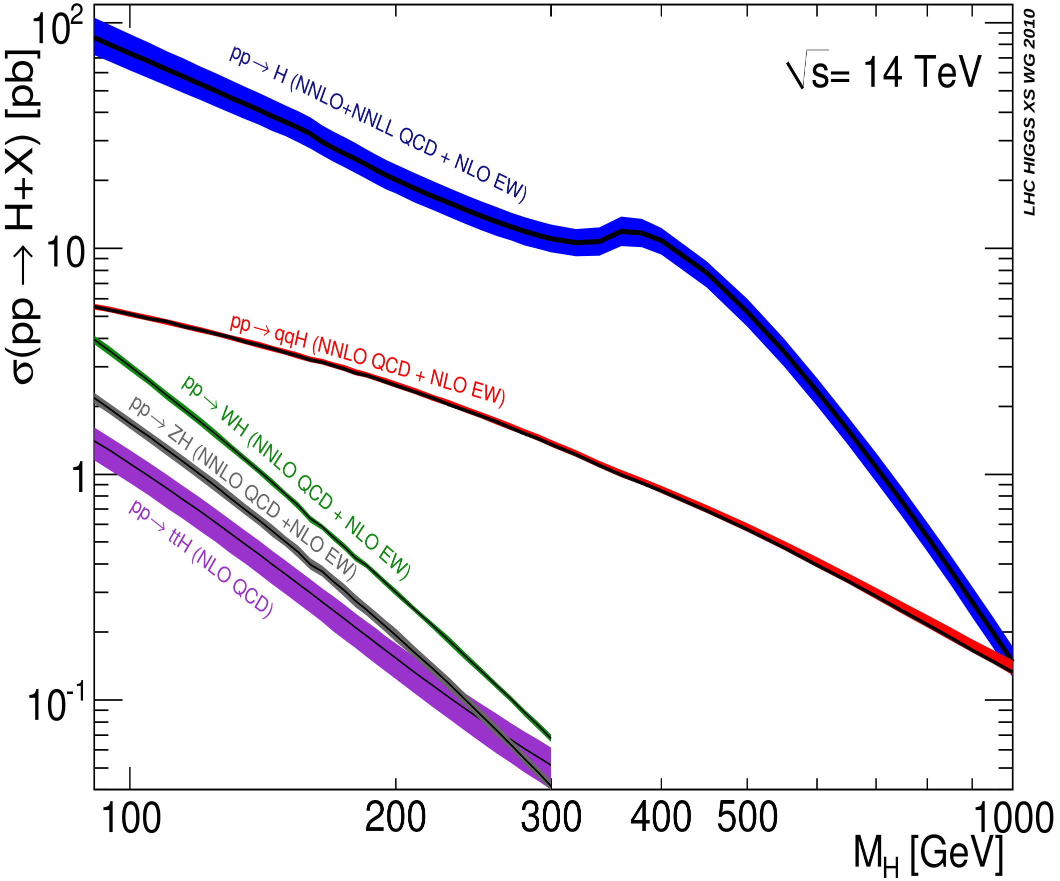
Parametric + theoretical uncertainty:

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

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

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

LHC Higgs XS WG 2010–



Rough numbers:

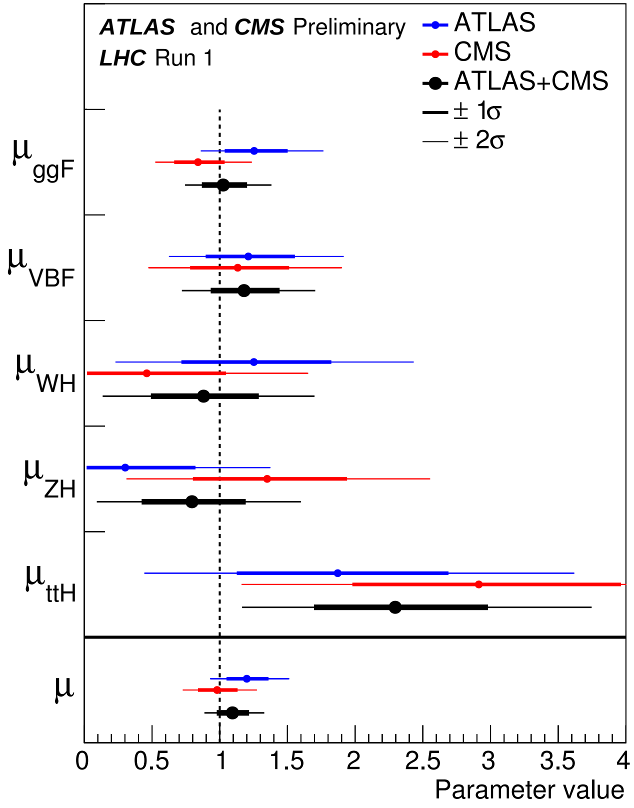
$M_{\mathrm{H}} = 125\,\mathrm{GeV}$	Uncertainties		NLO/NNLO/NNNLO	
	scale	PDF4LHC	QCD	EW
ggF	$\boxed{3\%}$	7%	$>100\%$	5%
VBF	1%	3%	5%	5%
WH	1%	4%	20%	7%
ZH	4%	4%	35%	5%
ttH	9%	9%	20%	$\boxed{1\text{–}2\%}$

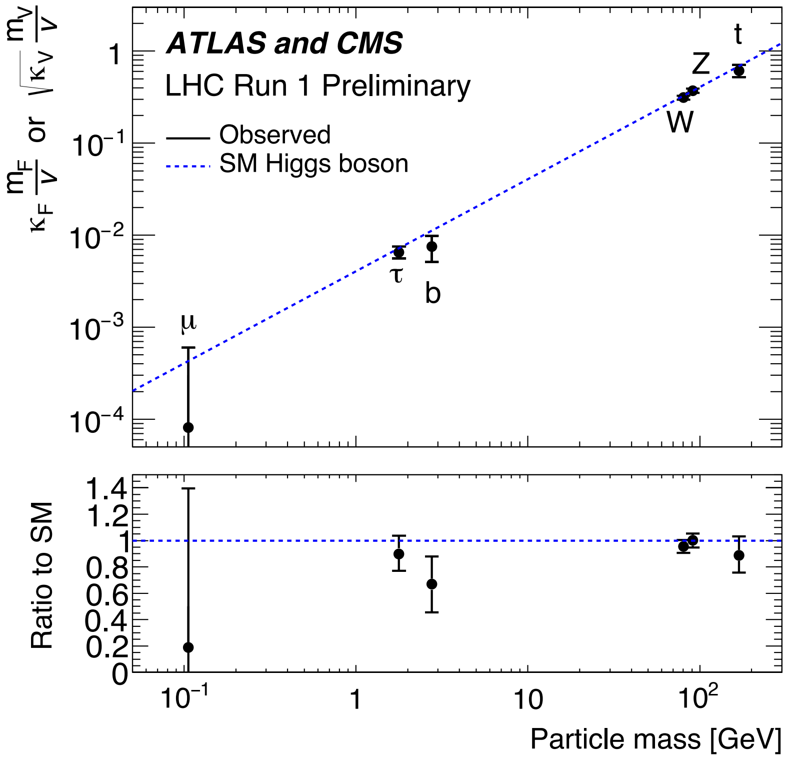
☐ = not yet in plot

First analyses of the Higgs profile @ Run 1

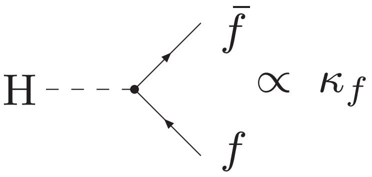
Signal strength:

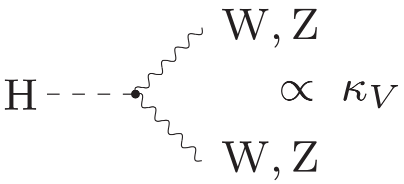
Coupling strength:





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





Compatibility with Standard Model ! $\Rightarrow$ 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)

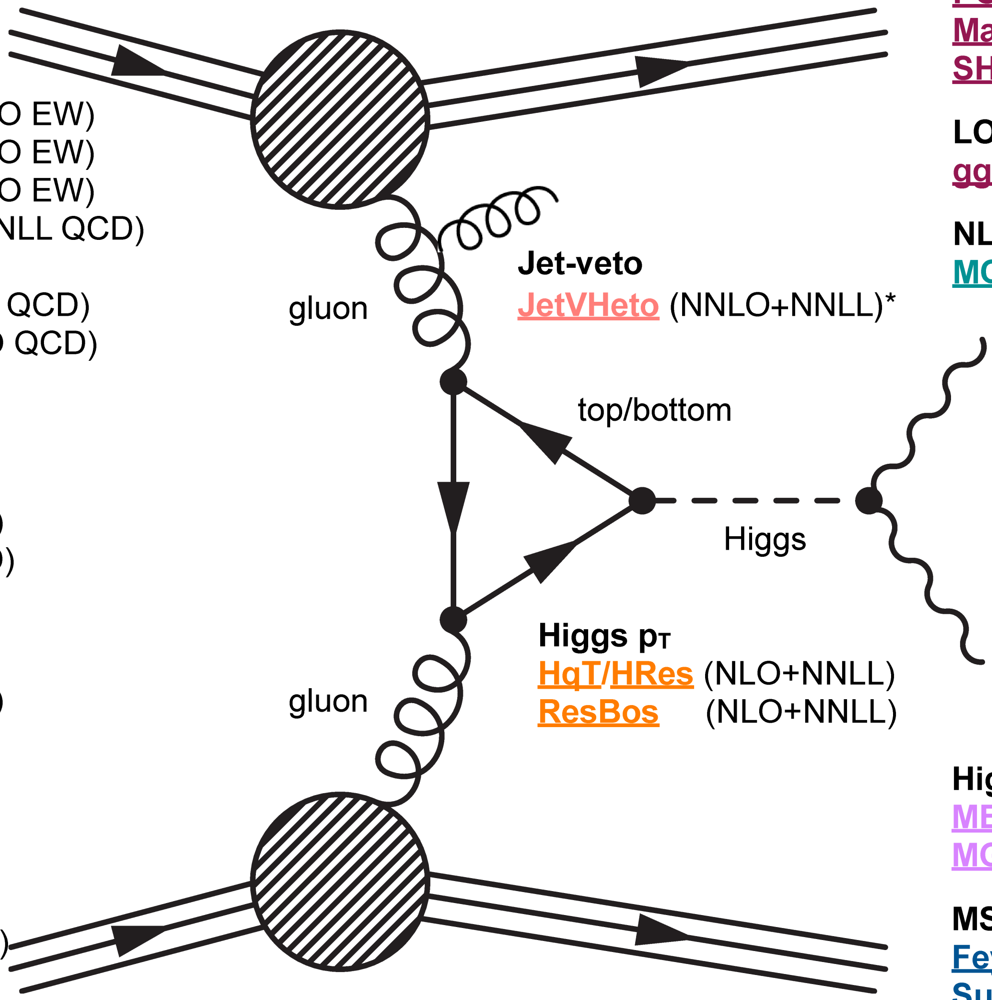
WH/ZH
V2HV (NLO QCD)
HAWK (NLO QCD+EW)
VH@NNLO (NNLO)

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)

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)

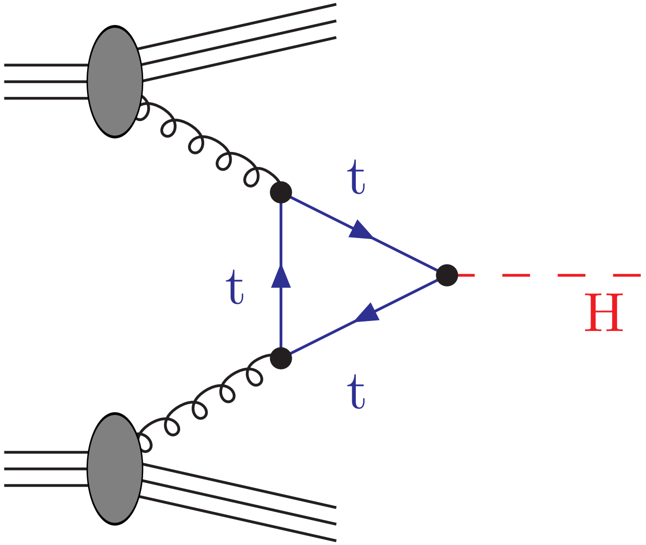
MSSM/2HDM
FeynHiggs, CPSuperH
SusHi+2HDMC
HIGLU+HDECAY

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

* NLO+NNLL in differential

Compiled by R. Tanaka, Jan. 2014

Higgs production via gluon fusion



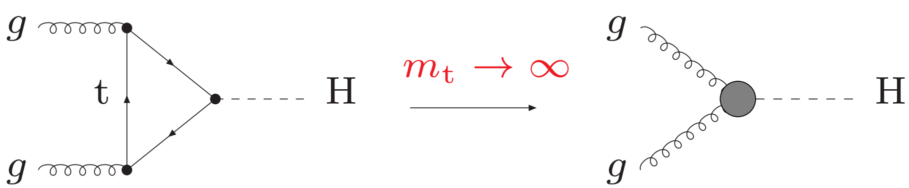
Corrections to Higgs-boson production via gluon fusion

- 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 ’06
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

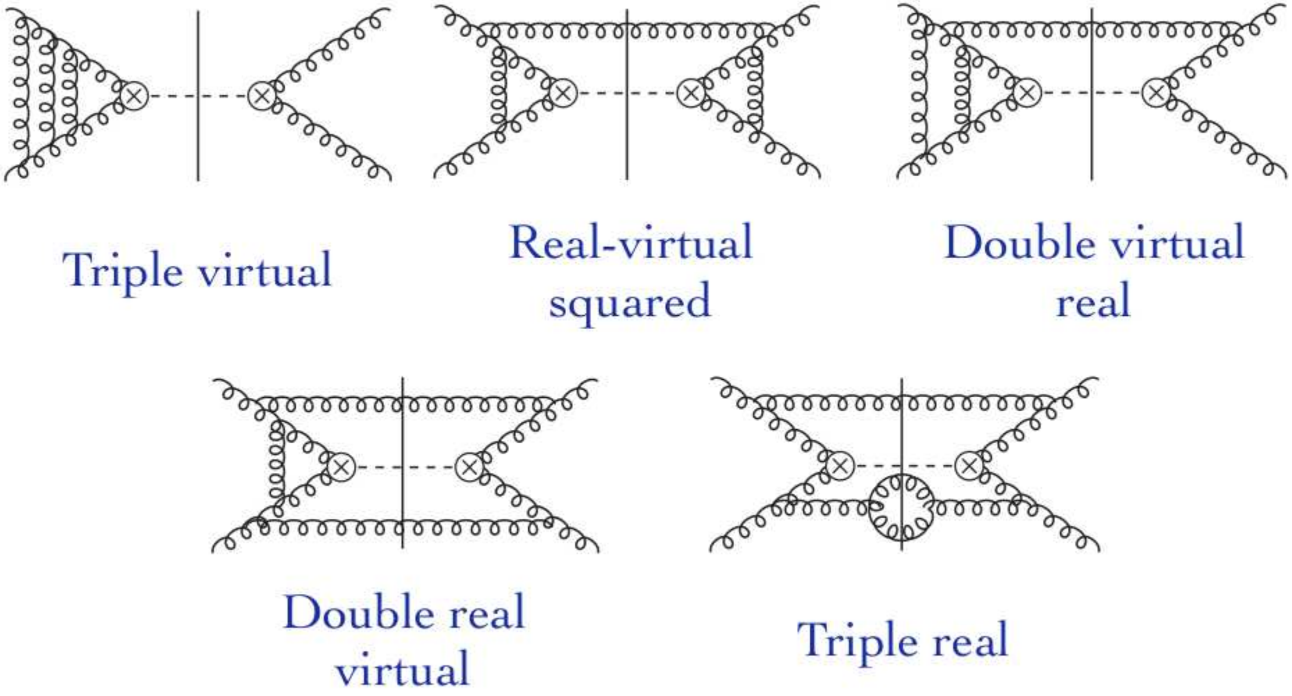
Towards $gg \to H$ @ NNNLO QCD

- 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; ...

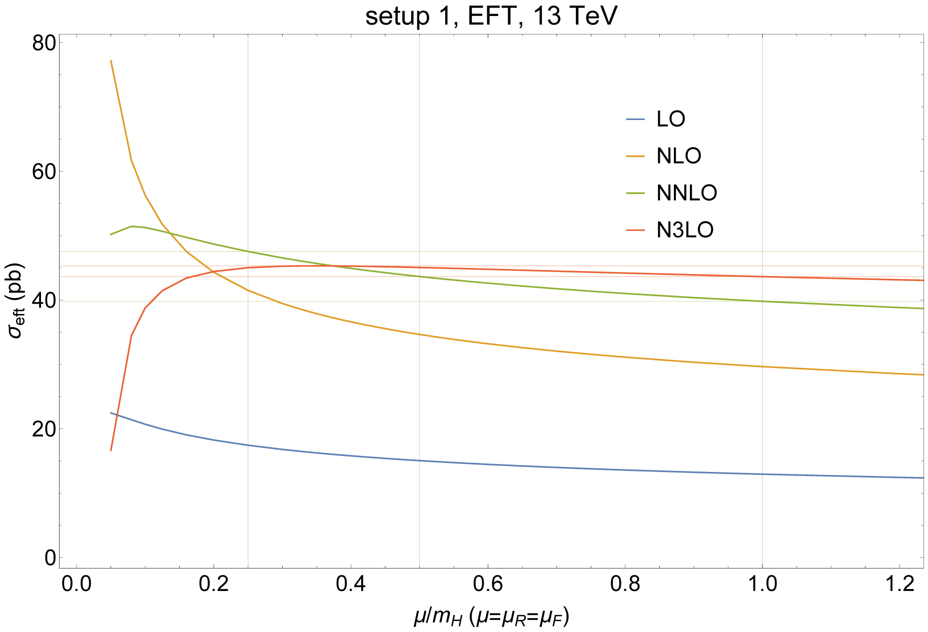
- approximate NNNLO result upon including asymptotics in threshold and high-energy resummation Bonvini et al. ’14

- full NNNLO cross section Anastasiou et al. ’15,’16



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

Anastasiou et al. '16



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

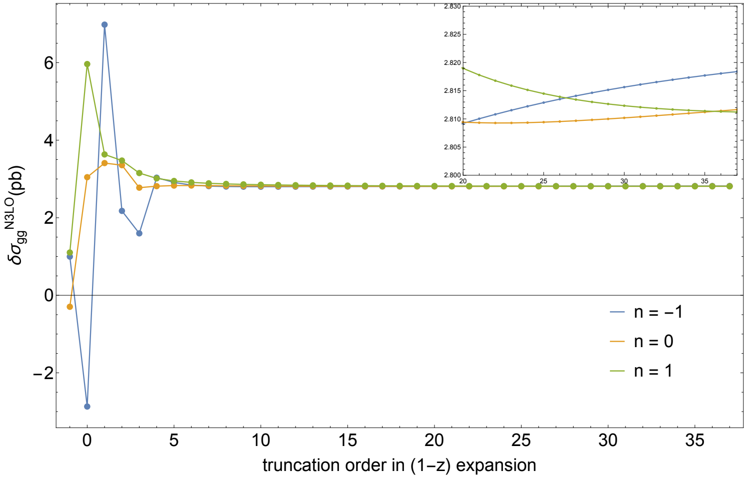
Details / comments:

- total XS obtained from expansion in $z = \frac{M_{\mathrm{H}}^2}{\hat{s}}$:

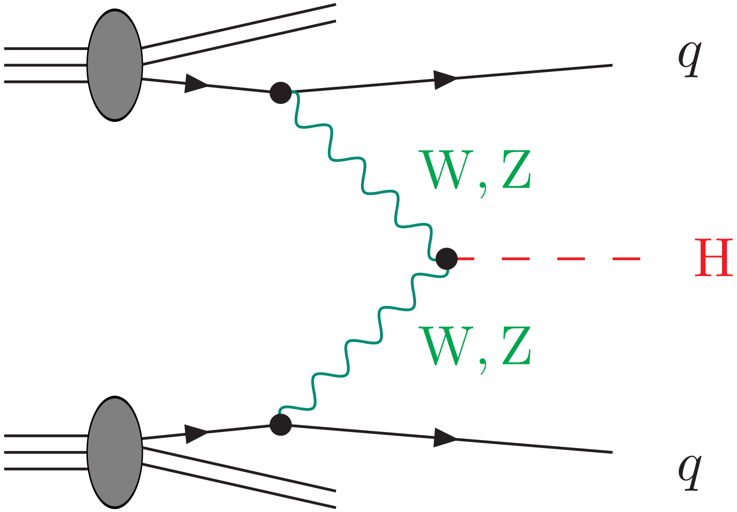
$$\frac{\hat{\sigma}^{(3,N)}_{ij}}{z^{n+1}} = \delta_{ig}\delta_{jg}\frac{\hat{\sigma}^{(3)}_{\mathrm{virt+soft}}}{z^{n+1}} + \sum_{k=0}^{N} c^{(k)}_{ij}(1-z)^k$$

  $\hookrightarrow$ convergence depends on N and n

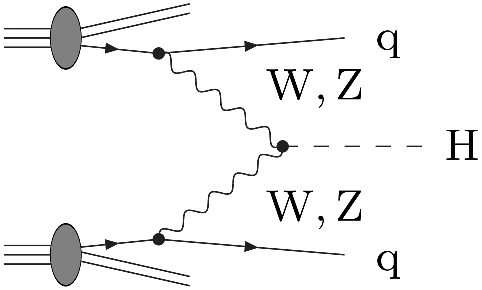
- several uncertainty sources of $\sim 1\%$:
  $1/m_{\mathrm{t}}$ expansion, quark mass effects, QCD$\otimes$EW,
  NNNLO/NNLO PDF mismatch, $(1-z)^k$ expansion



Higgs production via vector-boson fusion



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



colour exchange between quark lines suppressed

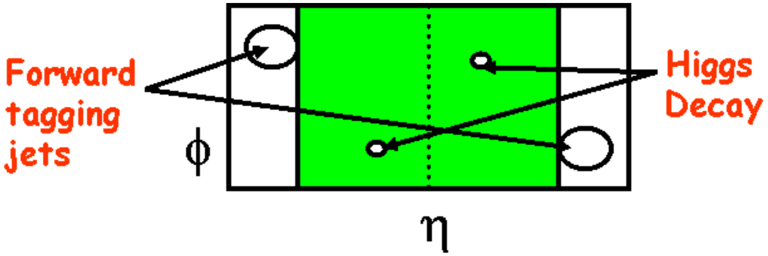
$\Rightarrow$ small QCD corrections

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

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

VBF cuts and background suppression:

signature $=$ Higgs + 2jets



- 2 hard “tagging” jets demanded:

  $p_{\mathrm{Tj}} > 20\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 4.5$

- tagging jets forward–backward directed:

  $\Delta y_{\mathrm{jj}} > 4, \quad y_{\mathrm{j1}} \cdot y_{\mathrm{j2}} < 0.$

$\hookrightarrow$ 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 $gg \to Hgg$, 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 $\sim 0.1\%$

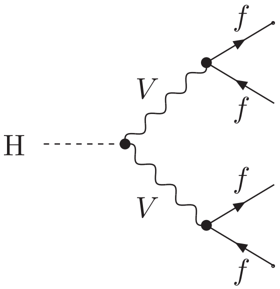
- SUSY QCD+EW corrections

  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 $\mathrm{H} \to VV \to 4f$, $\mathrm{pp}(VV \to \mathrm{H}) \to \mathrm{H} + 2\mathrm{jets}$, $\mathrm{pp} \to \mathrm{H}V \to \mathrm{H} + 2\ell$

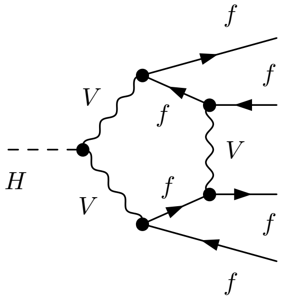
Lowest order:



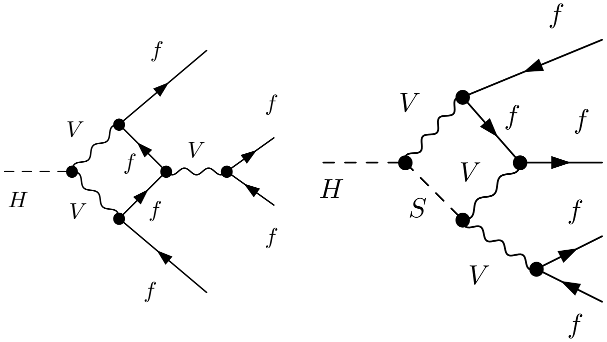
Typical one-loop diagrams:

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

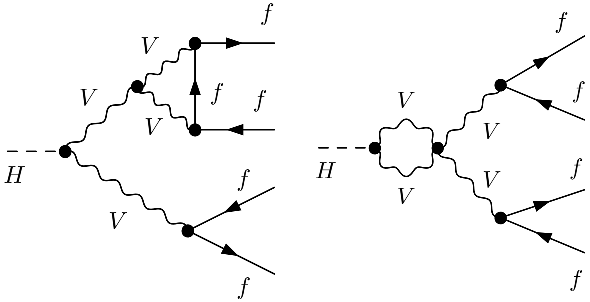
pentagons



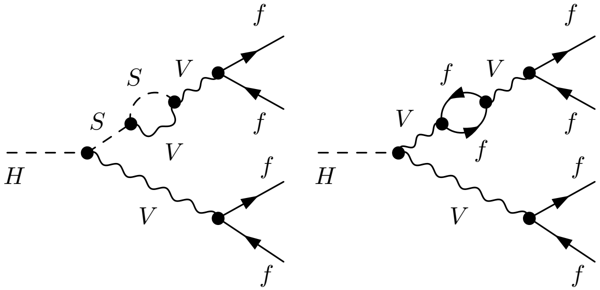
boxes



vertices



self-energies

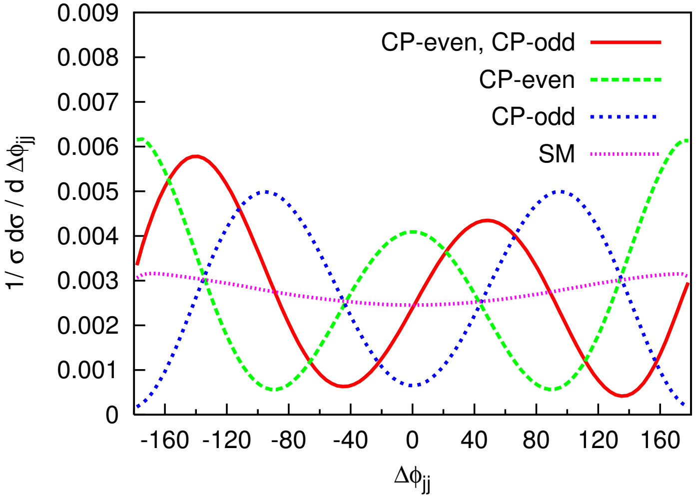


$+$ tree graphs with real gluon or photons

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

Sensitivity to non-standard effects:

Hankele, Klämke, Zeppenfeld, Figy ’06



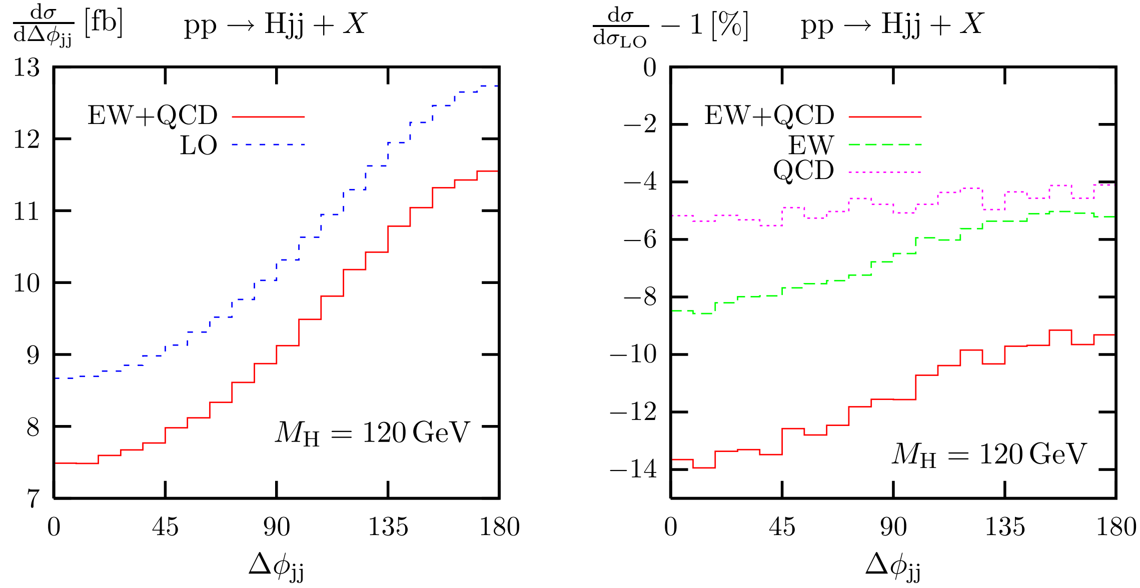
(Individual contributions
without SM)

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

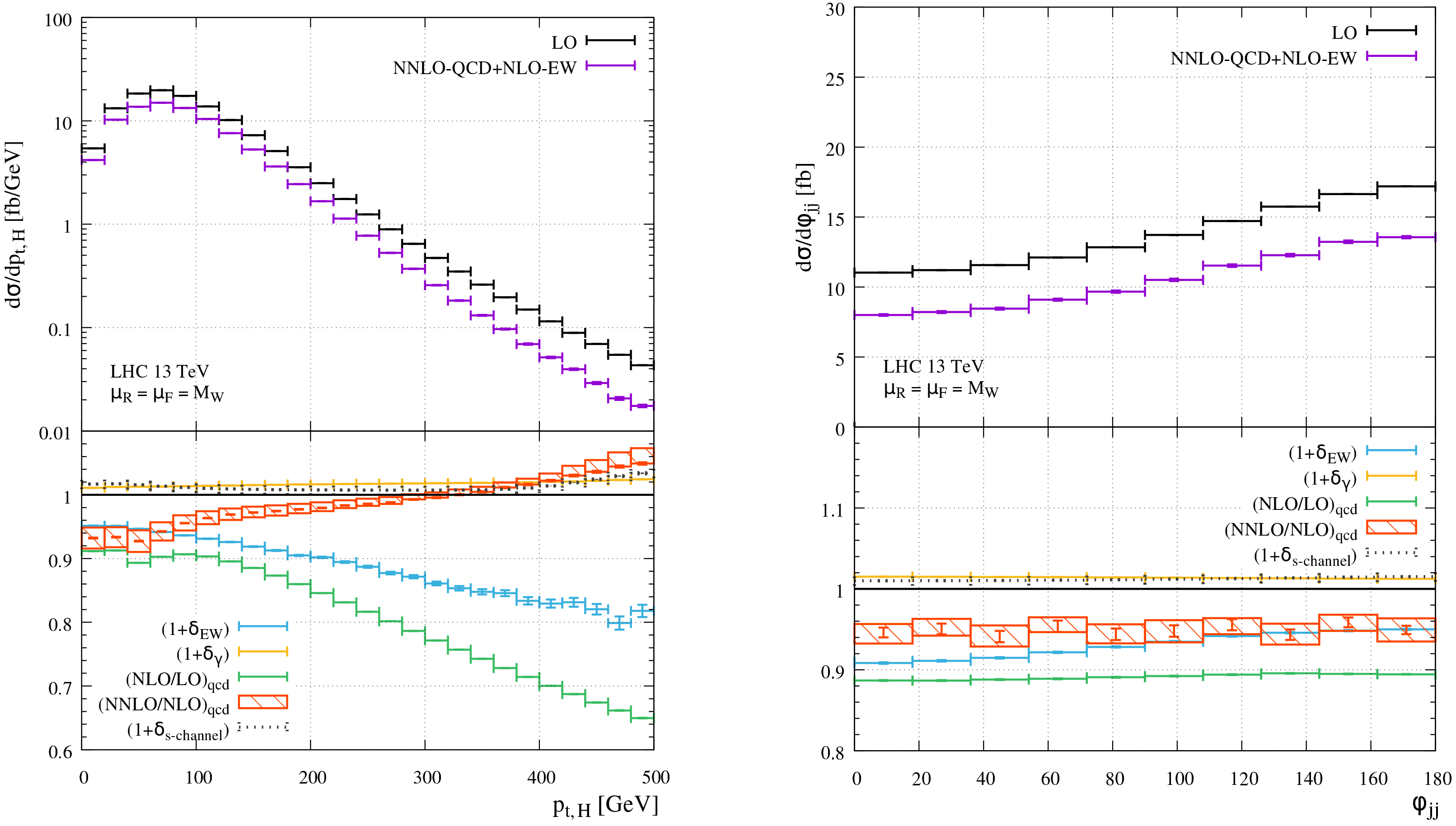


HAWK

Neglected corrections
could be misinterpreted
as non-standard couplings

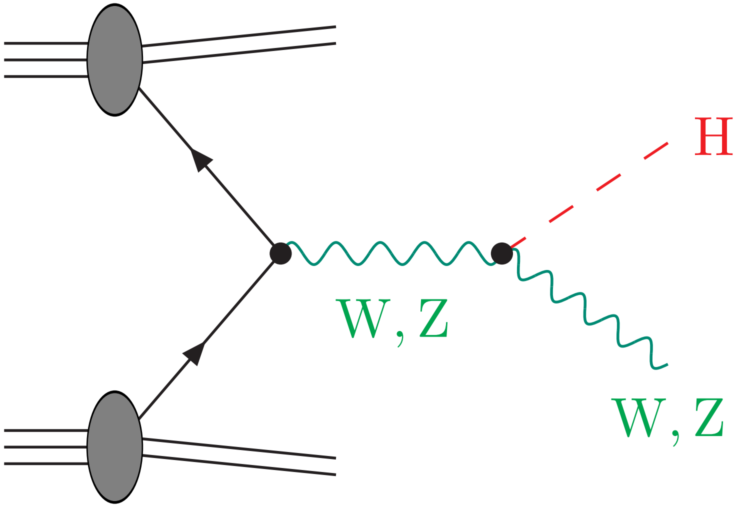
Fiducial cross sections @ NNLO QCD + NLO EW

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

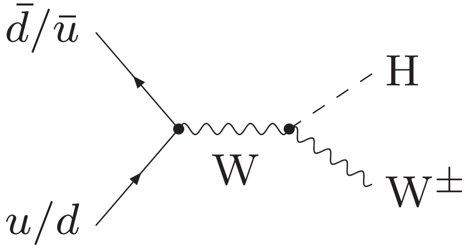


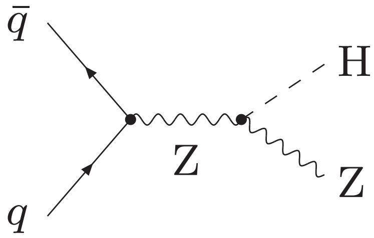
- scale uncertainty $\sim\ 1-2\%$
- (N)NLO QCD and NLO EW corrections $\sim\ 5-20\%$
- γ-induced and s-channel contributions $\sim\ 1.5\%$

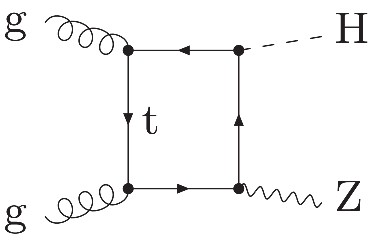
Production via Higgs-strahlung



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, $\mathrm{gg} \to \mathrm{ZH}$
  Brein, Djouadi, Harlander '03 (VH@NNLO)

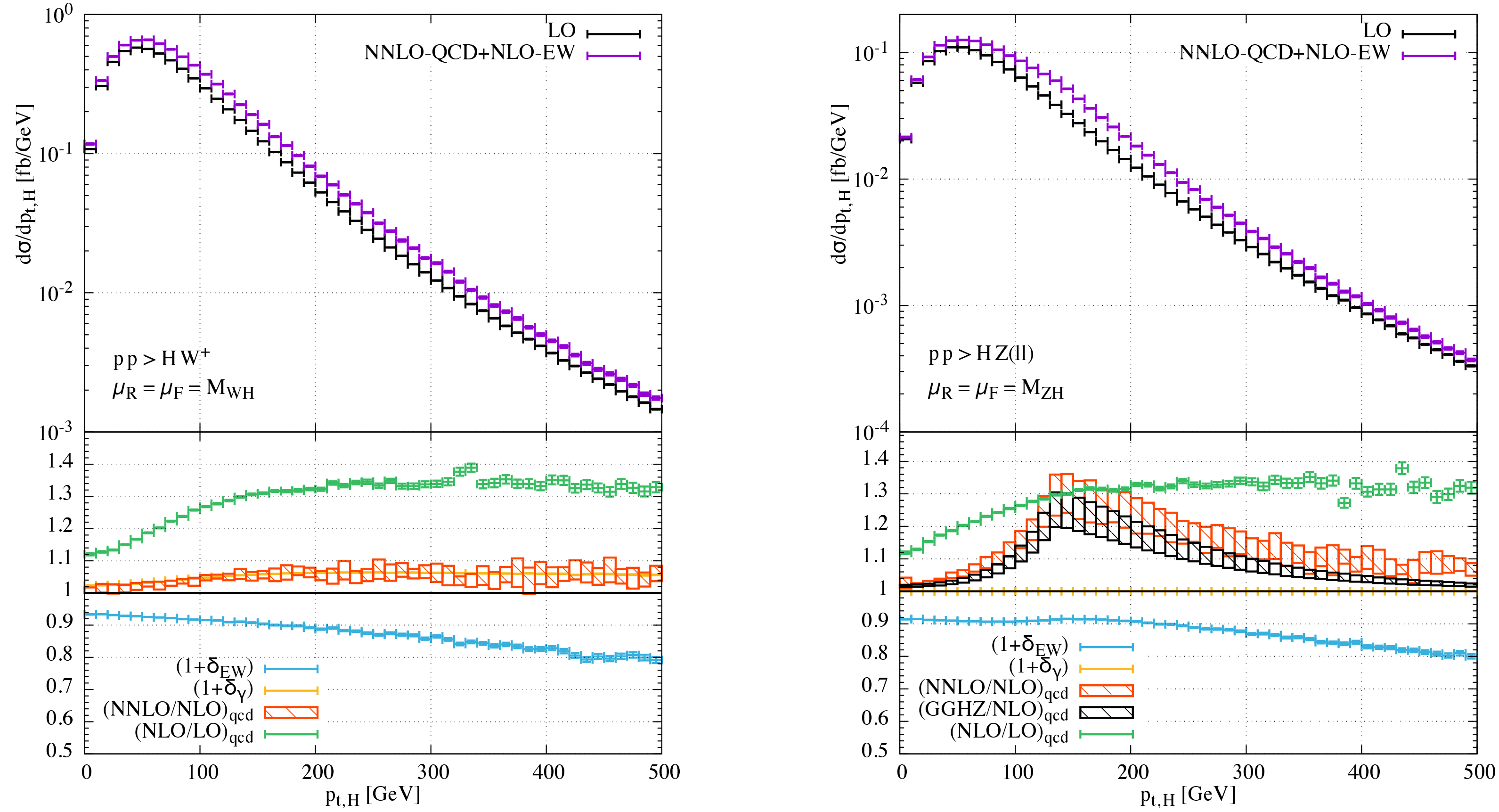
  differential VH XS, with W/Z/H decays, Drell–Yan-like part
  Ferrera, Grazzini, Tramontano '11–'14

  total cross section, non-Drell–Yan-like parts
  Brein, Harlander, Wiesemann, Zirke '11
- NLO+NLL QCD ($\mathrm{gg} \to \mathrm{ZH}$): 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)

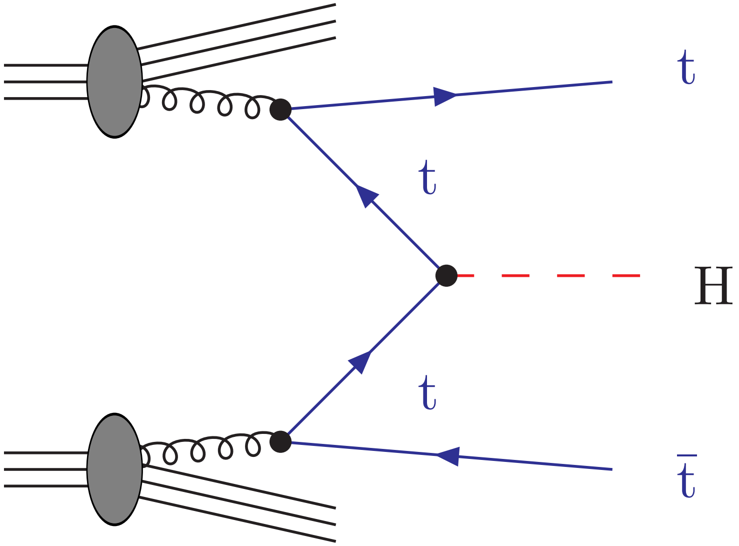
$\mathrm{pp} \to \mathrm{W}^+(\to \ell^+\nu_\ell)\mathrm{H}$: $\mathrm{pp} \to \mathrm{Z}(\to \ell^+\ell^-)\mathrm{H}$:



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

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

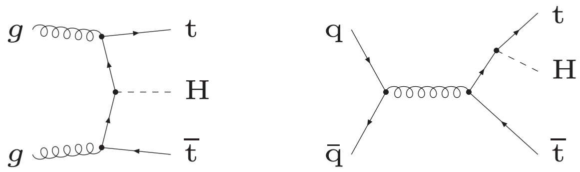
Production of $t\bar{t}H$ final states



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

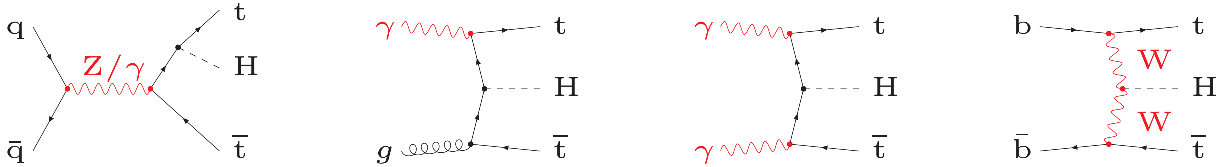
- QCD tree:

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



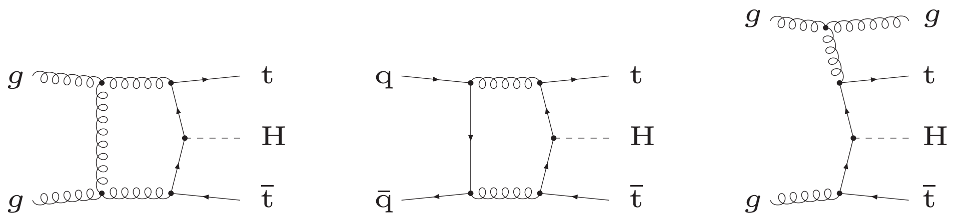
- EW tree:

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



- QCD NLO:

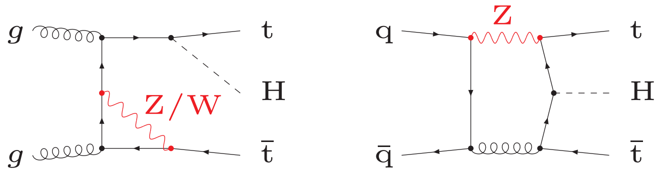
  $\mathcal{M}_{\mathrm{QCD},1}$



etc.

- Weak NLO:

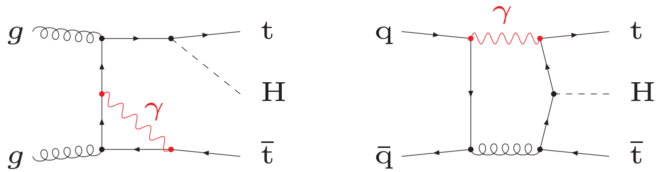
  $\mathcal{M}_{\mathrm{weak},1}$



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

- Photonic NLO:

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



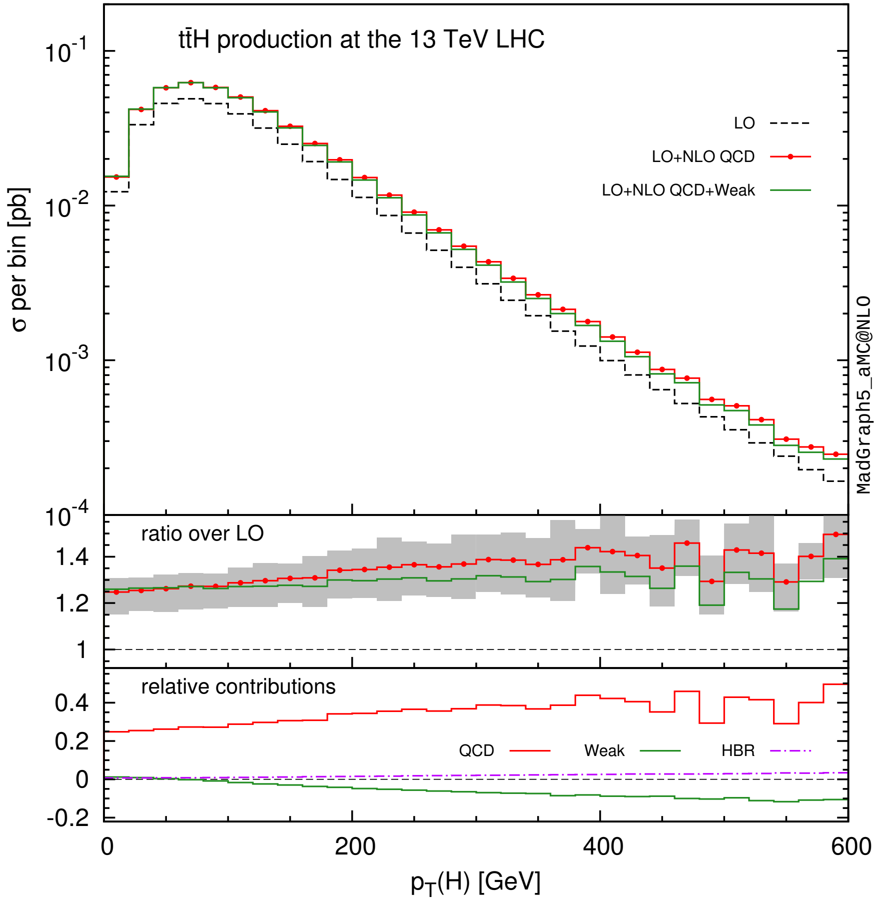
$\& \quad \mathcal{M}^{q\bar{q}}_{\mathrm{QCD},1} \times \left(\mathcal{M}^{q\bar{q}}_{\mathrm{phot},0}\right)^* \quad + \quad \ldots$

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

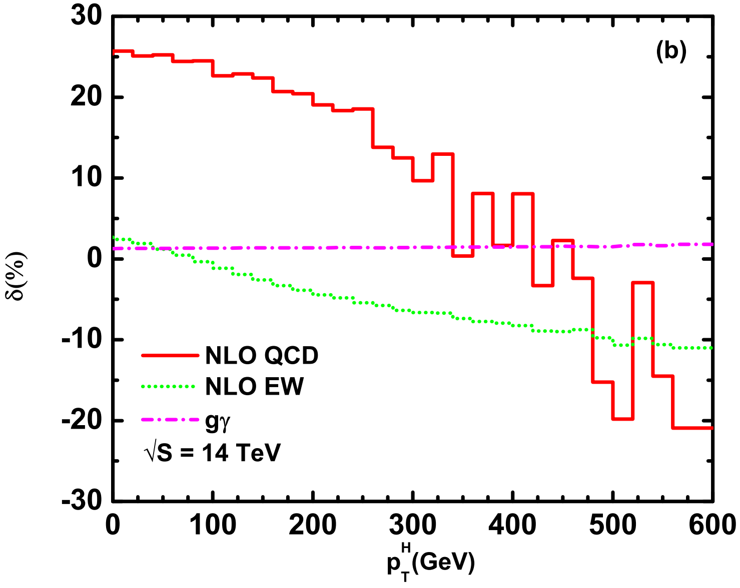
- NLO QCD corrections
  - $pp \to t\bar{t}H$ Beenakker et al. ’01,’02; Dawson et al. ’01,’02
  - $pp \to WWb\bar{b}H$ with leptonic W-boson decays
    Denner, Feger ’15
- QCD parton-shower matching via *aMC@NLO, PowHel, MadSpin, Sherpa*
  Frederix et al. ’11; Garzelli et al. ’11; Artoisenet et al. ’12;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

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

Solutions:

- analyses in specific models
- model-independent analyses in effective field theories: $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_i}{\Lambda^2} Q_i$
  ↪ fit of 59 dim-6 operators

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

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  $\hookrightarrow$ fit of 59 dim-6 operators

  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

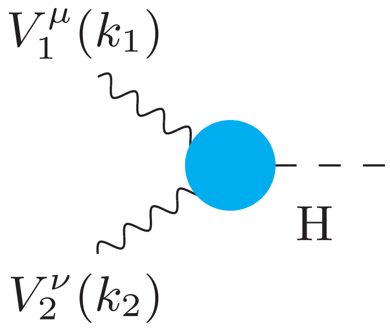
↪ derived from SU(2)×U(1)-invariant dim-6 operators

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

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

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

Modified HVV Feynman rules



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

Explicit insertions:

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

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

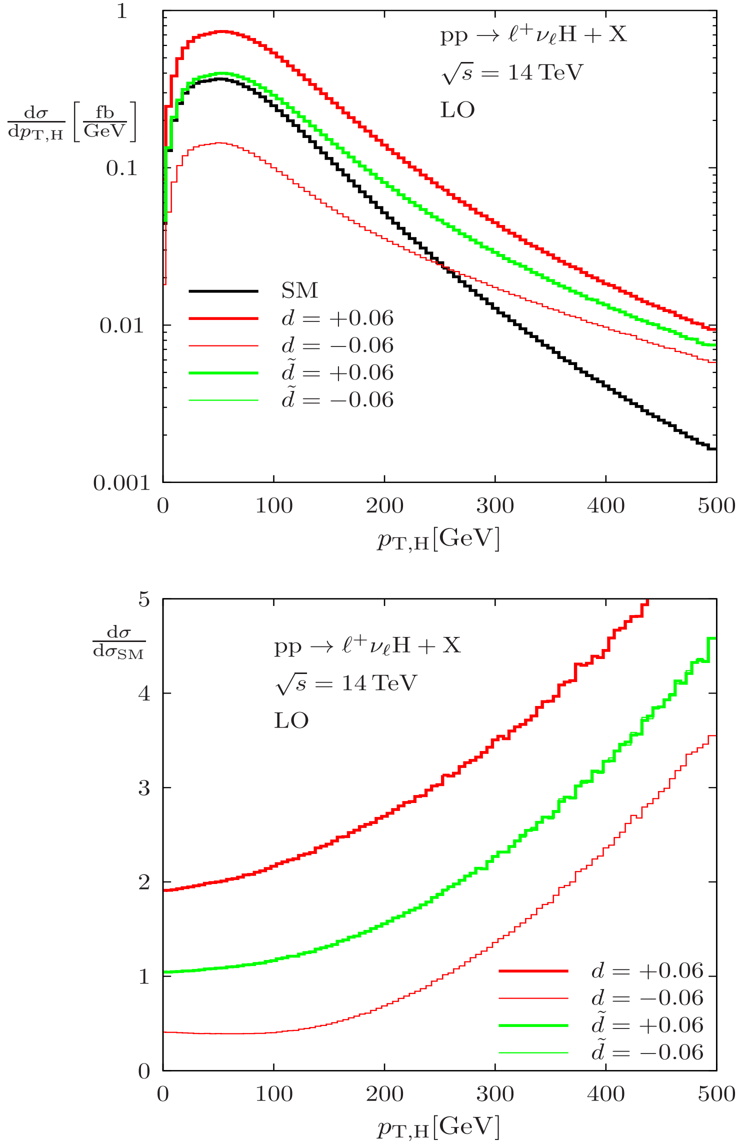
$$a^{(3)}_{HV_1V_2} = a^{(2)}_{HV_1V_2}\Big|_{d\to\tilde{d},\,d_B\to\tilde{d}_B}$$

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

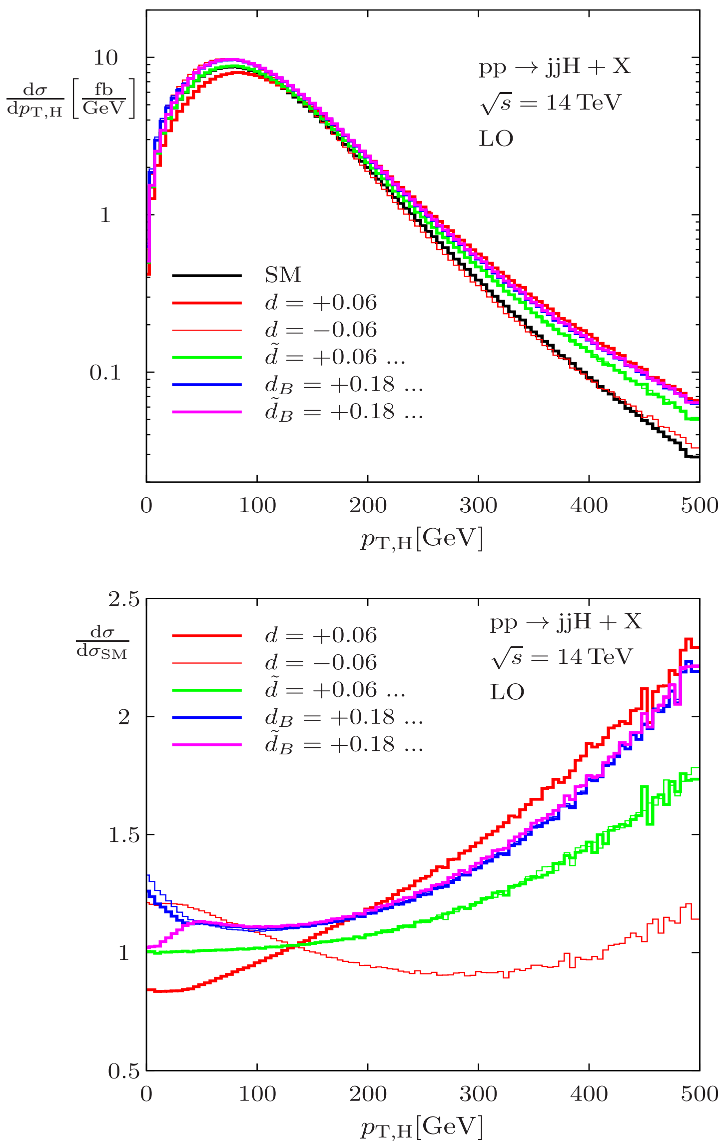
where $d \propto f_{WW}$, $d_B \propto f_{BB}$, $\tilde{d} \propto f_{\tilde{W}W}$, $\tilde{d}_B \propto f_{\tilde{B}B}$

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

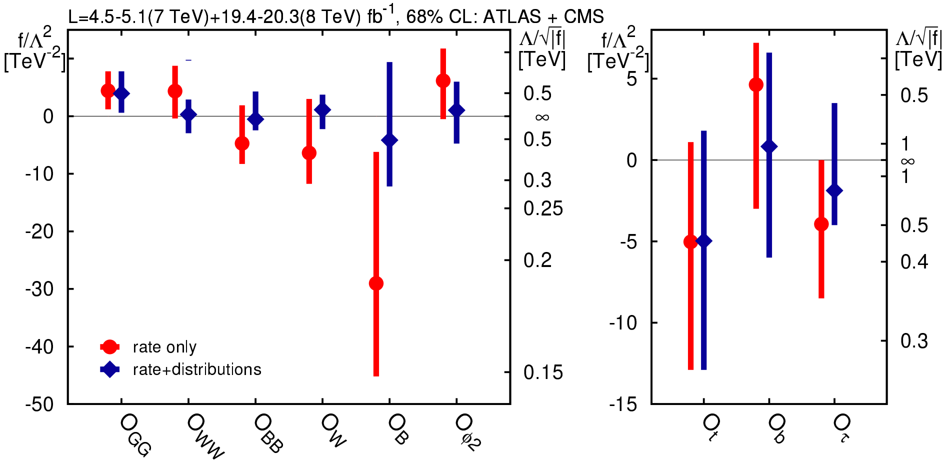
NLO QCD available

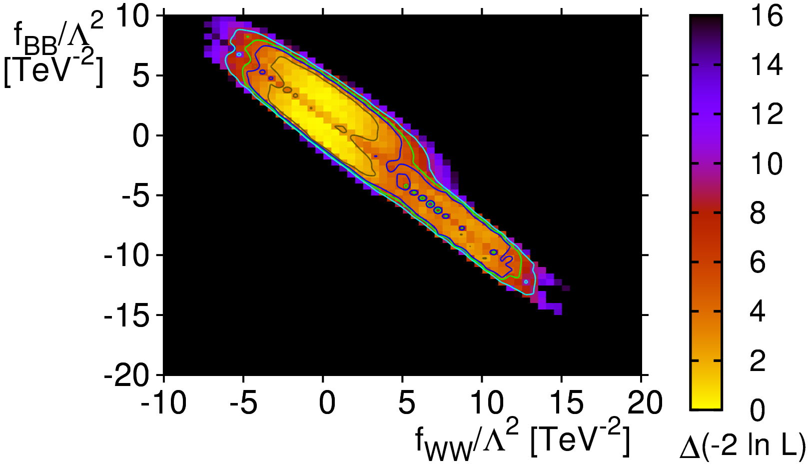
NLO EW planned

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
  $\hookrightarrow$ 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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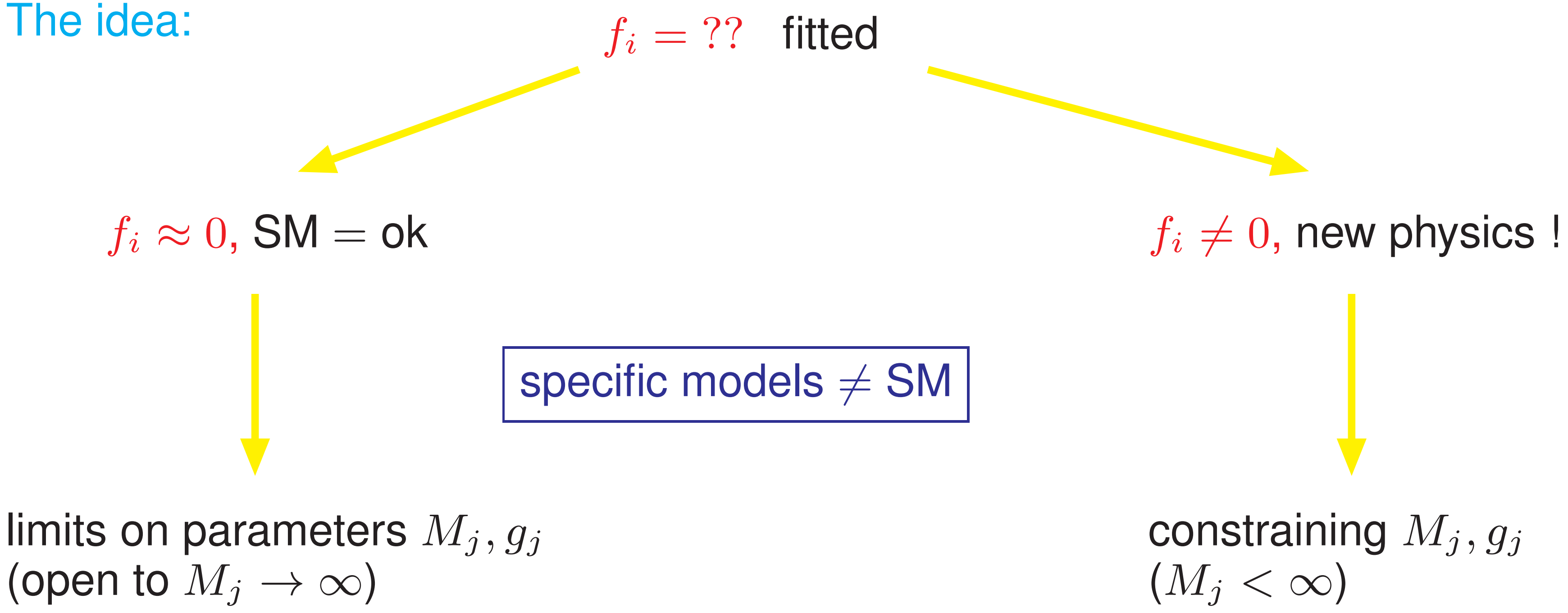

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specific models $\neq$ SM

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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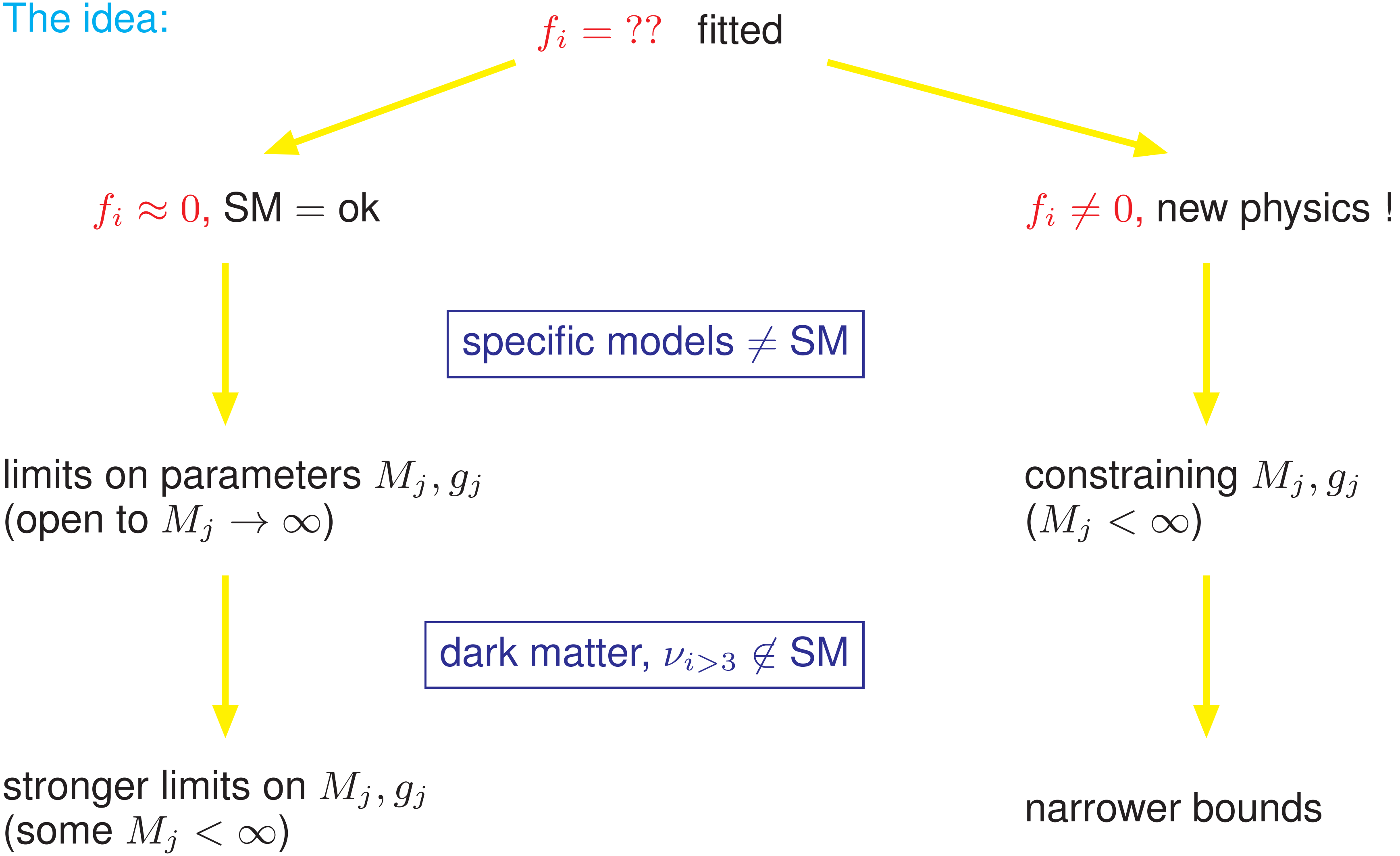

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dark matter, $\nu_{i>3} \notin$ SM

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

narrower bounds

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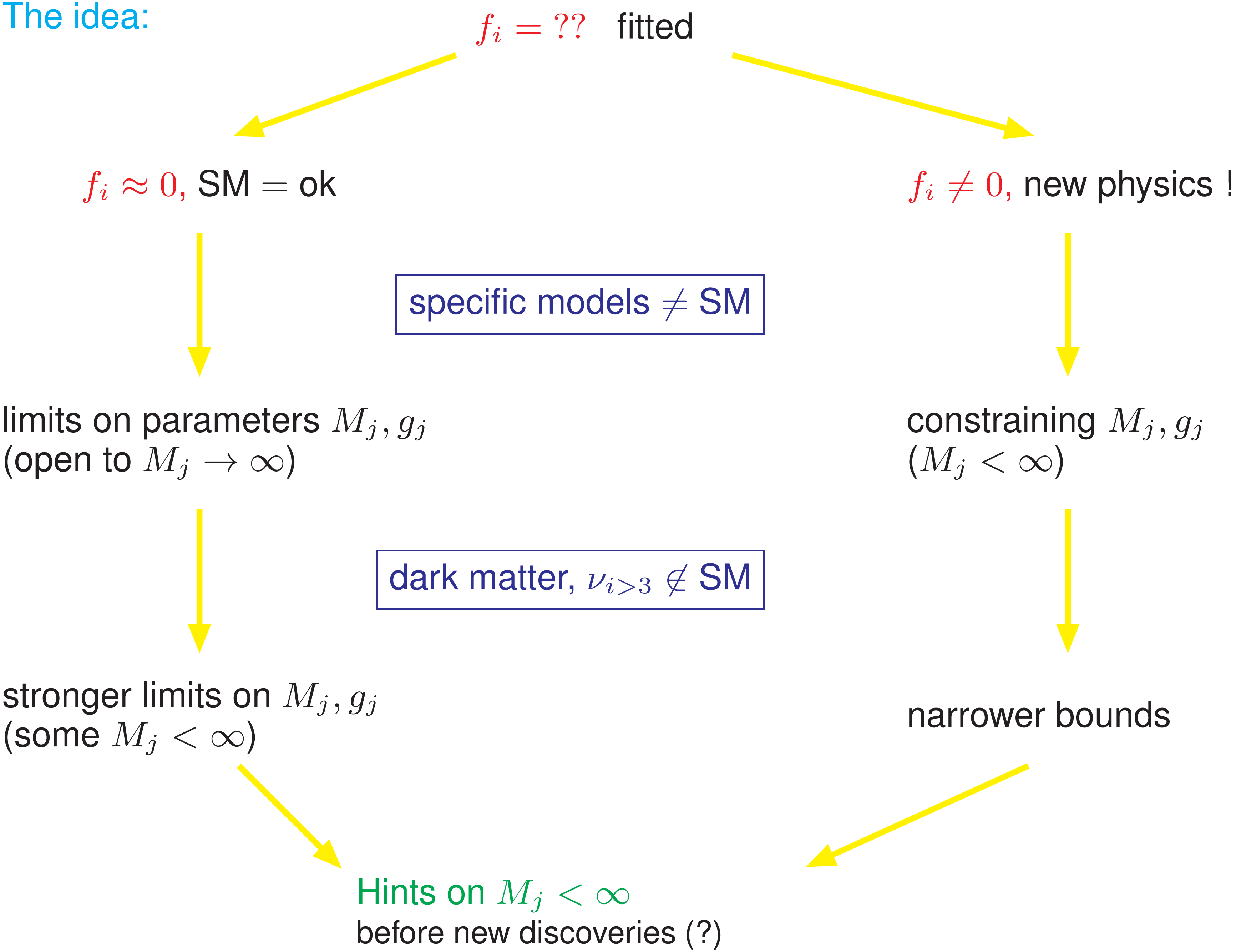

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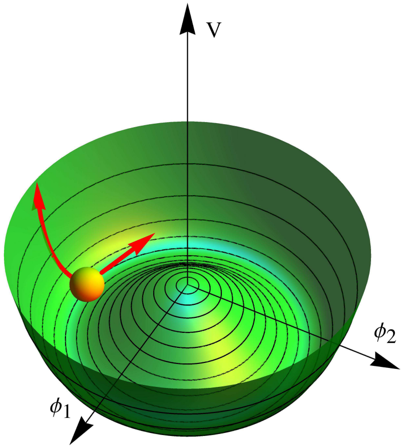
Hints on $M_j < \infty$
before new discoveries (?)

Higgs profiling at the LHC

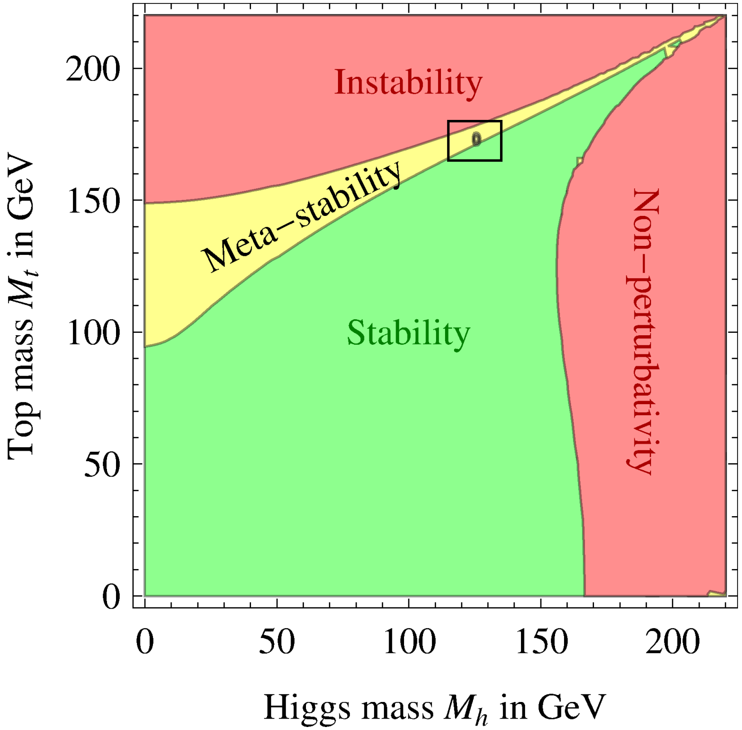
— Higgs self-coupling —

Higgs self/coupling λ – window to new physics ?

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



Degrassi et al. ’12



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

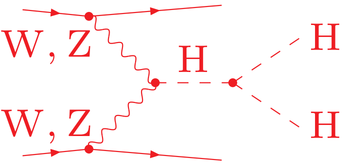
Note: $M_\mathrm{H} = 126\,\mathrm{GeV}$ SM escapes problems !

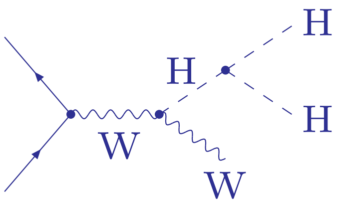
- $\lambda(\mu) < 0$: vacuum instability
- $\lambda(\mu) \to \infty$: triviality, non-perturbativity, ... consistency problem

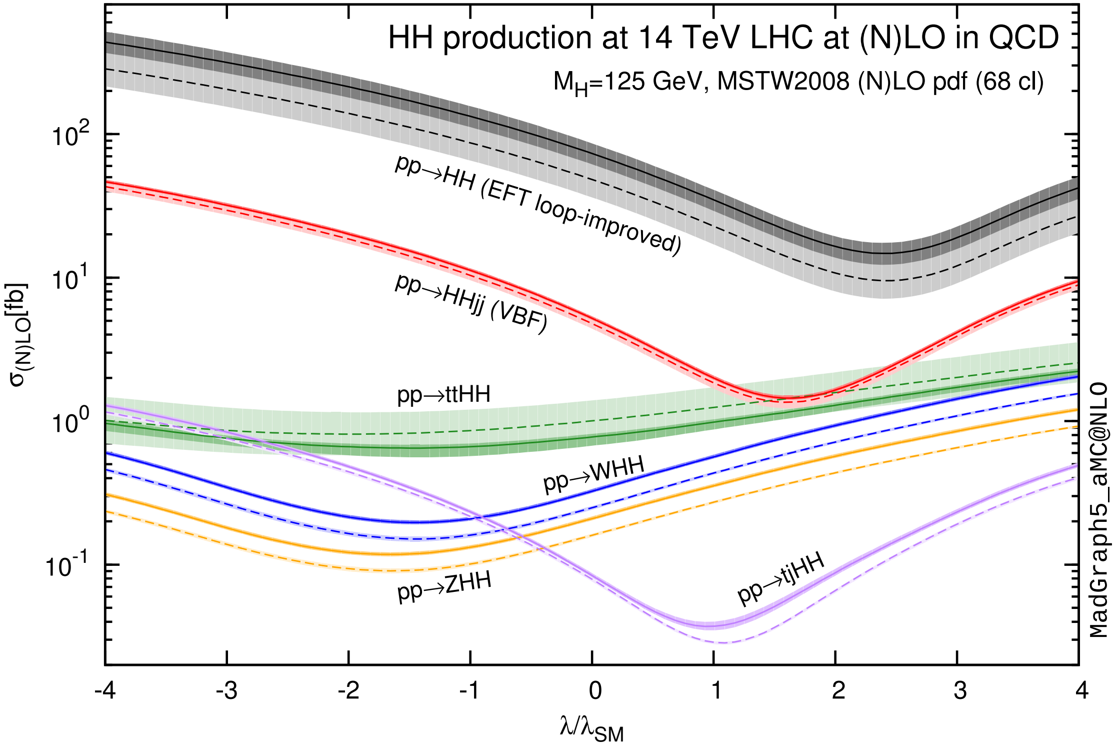
$\Rightarrow$ Exp. challenge: measuring λ in Higgs pair production

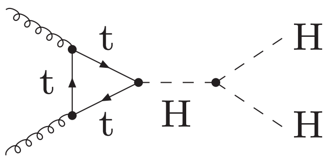
Higgs self/coupling λ – window to new physics ?

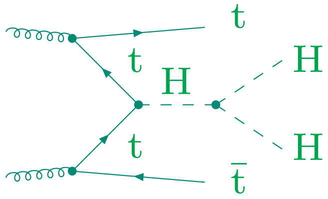
Maltoni et al. ’14











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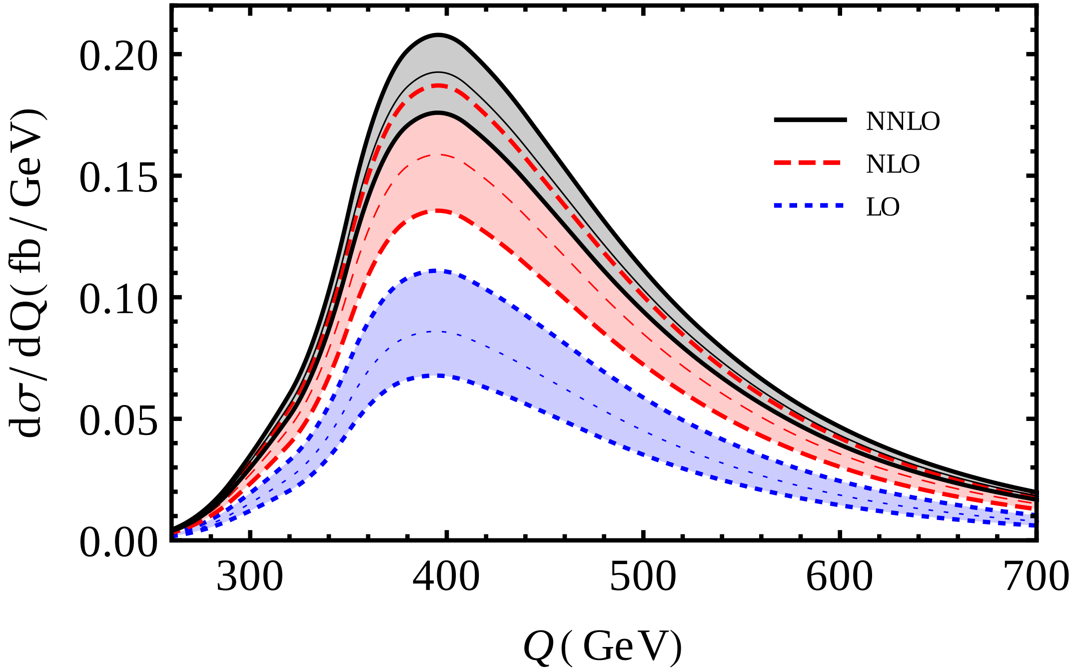
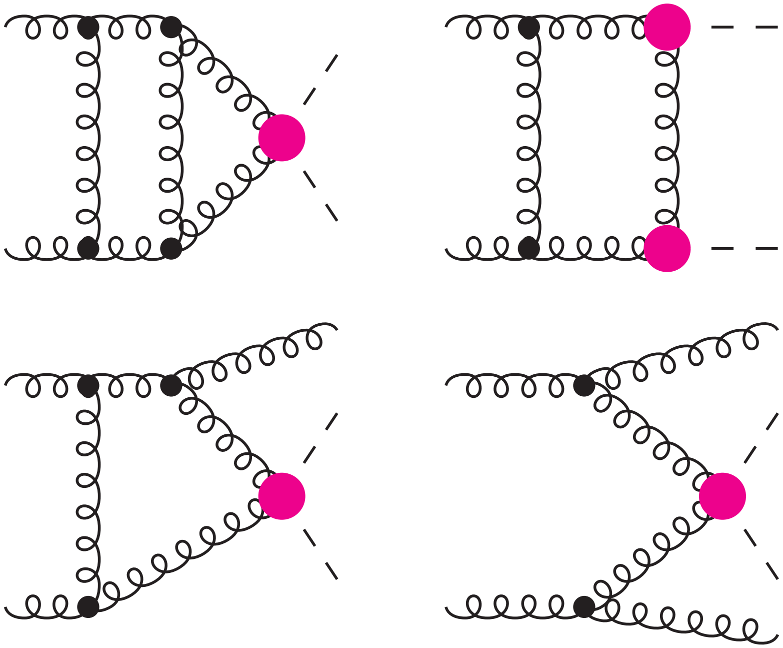
More precision for $\mathrm{pp(gg)} \to \mathrm{HH}$



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): deFlorian et al. '13; Grigo et al. '14,'15 $+\,20\%$
- 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 $\mathrm{gg} \to \mathrm{H}^{(*)} \to \mathrm{Z}^{(*)}\mathrm{Z}^{(*)} \to 4\ell$

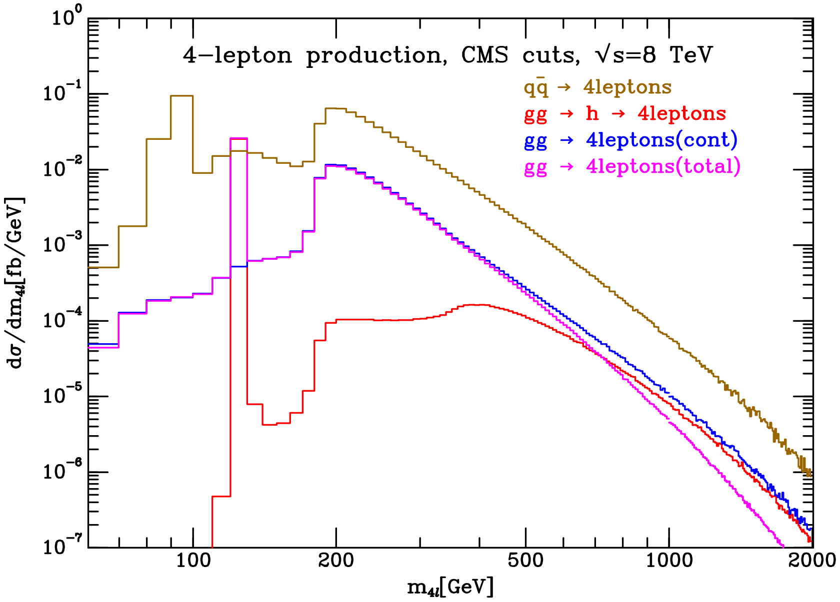
- signal:

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

- 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)



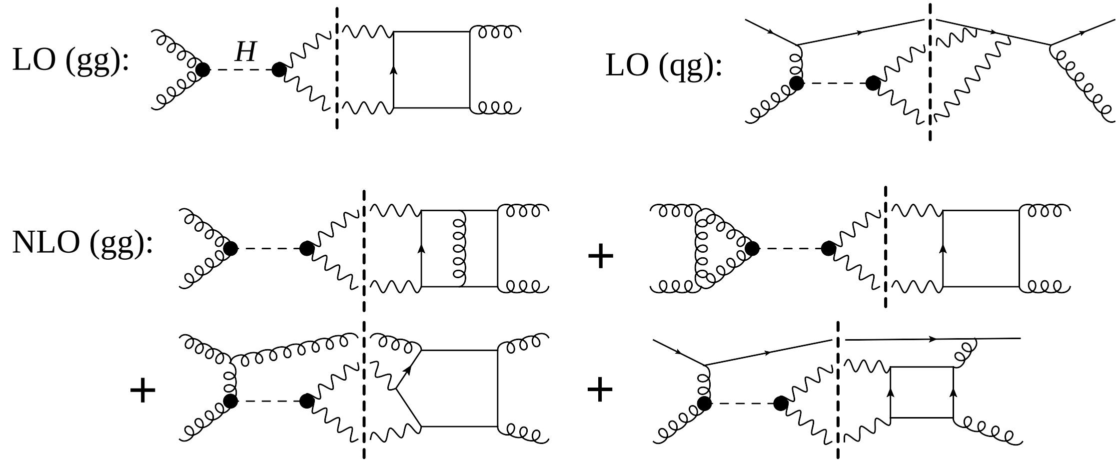
Uniform rescaling of Higgs couplings, keeping $\sigma_\mathrm{H}^\mathrm{sig}$ unchanged:

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

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

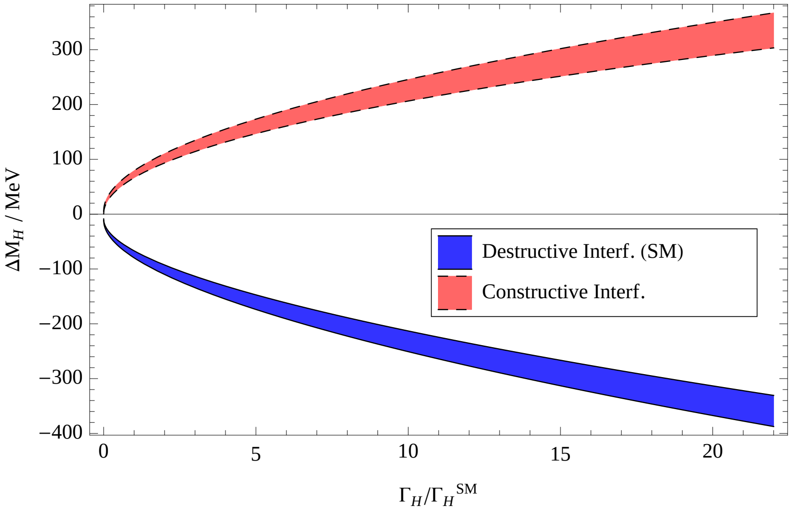
Total Higgs width Γ_H from $\mathrm{pp} \to \gamma\gamma$ Dixon, Li ’13

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:

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

Conclusions

Higgs physics @ LHC in Run 2

... in theory:

- higher precision for Higgs production and decay

  $\hookrightarrow$ SM predictions $\oplus$ effective dim-6 operators
- more precise predictions in non-standard models (singlet, doublet, triplet, SUSY, etc.)

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“In ~~football as in watchmaking~~, talent and elegance mean nothing without rigour and precision.”
particle theory
[Lionel Messi]

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... in experiment:

- Higgs cross sections more precisely and differentially

  ↪ model-independent couplings analysis in effective field theory
- particle / Higgs searches in mass range $M \sim 1{-}10\,\mathrm{TeV}$ = terra incognita !

  ↪ stringent tests of non-standard models

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+ complementary results from other SM processes (vector-boson scattering, etc.)

+ results form non-collider-based experiments ($\boldsymbol{\nu}$, DM, astroparticle physics)

Higgs physics @ LHC in Run 2

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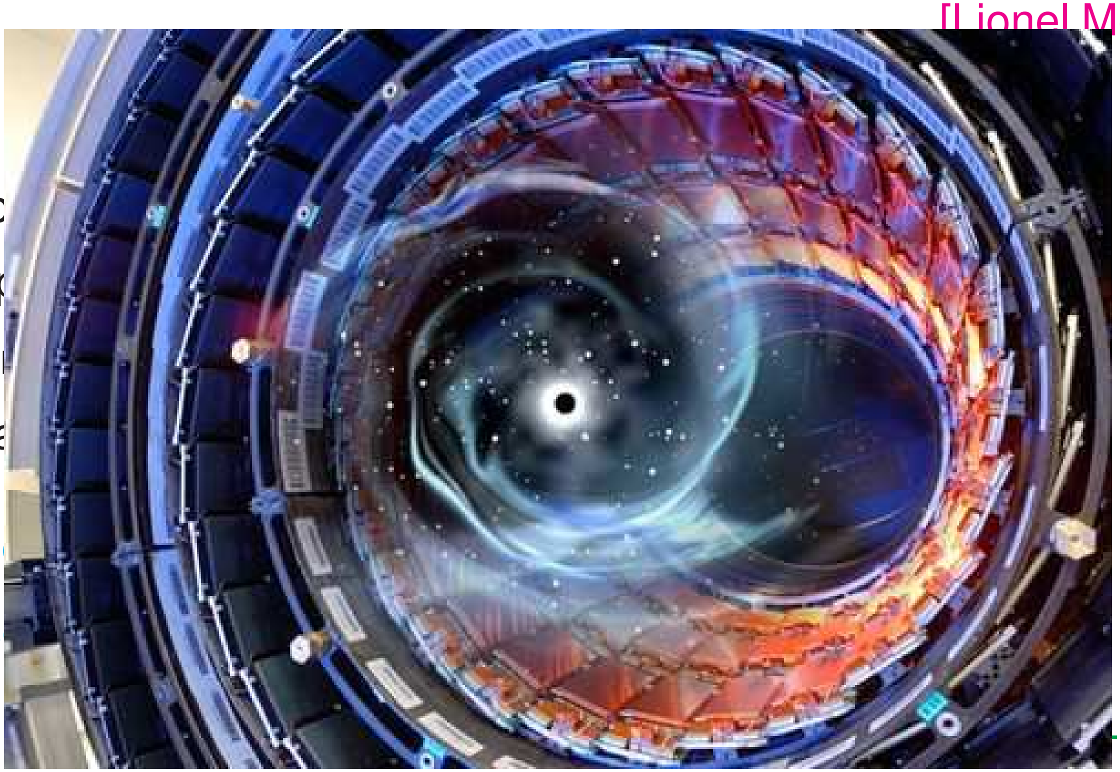

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  ↪ model-independent cou
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  ↪ stringent tests of non-sta

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-LHC

Backup slides

Electroweak effects in PDFs

Analogy to QCD-improved parton model:

Collinear splittings $q \to q\gamma$, $\gamma \to q\bar{q}$ lead to quark mass singularities

- absorption of $\alpha \ln m_q$ singularities via factorization into redefined PDFs
- $\mathcal{O}(\alpha)$ corrections to all PDFs
  $\hookrightarrow$ typical impact: $\Delta(\mathrm{PDF}) \lesssim 0.3\%\ (1\%)$ for $x \lesssim 0.1\ (0.4)$, $\mu_{\mathrm{fact}} \sim M_{\mathrm{W}}$
- photon PDF
  $\hookrightarrow$ typically add $\mathcal{O}(1\%)$ to cross sections, but with large uncertainties

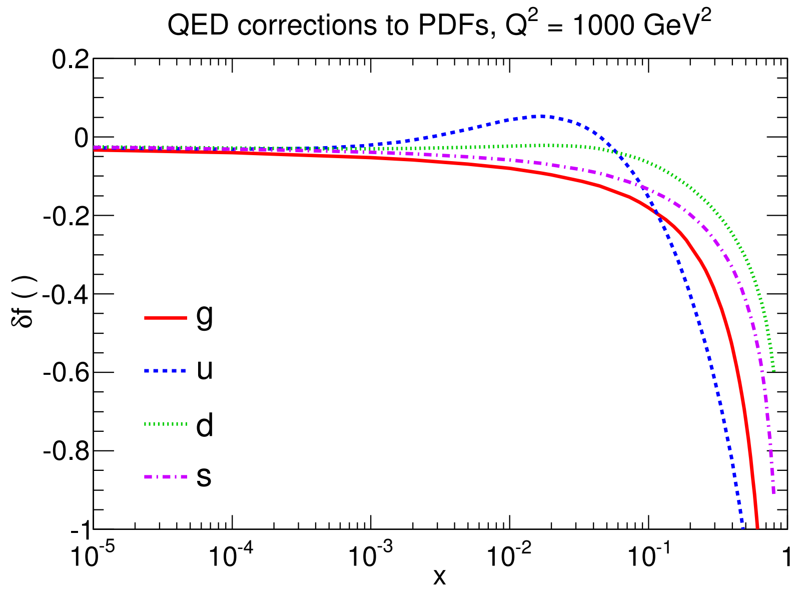
NNPDF2.3QED = NNPDF set with $\mathcal{O}(\alpha)$ corrections

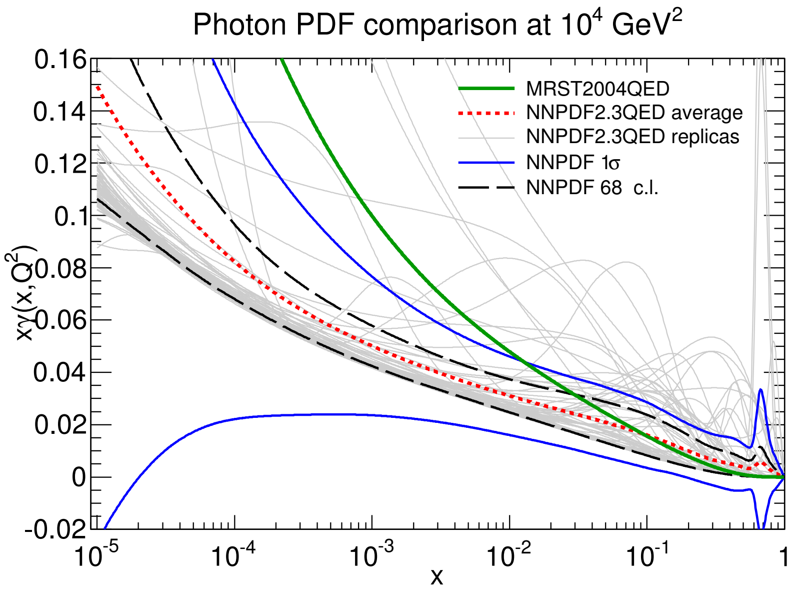
Ball et al. [NNPDF collaboration] '13

- currently best PDF prediction at (N)NLO QCD + NLO EW
- PDF samples for error estimate provided
- photon PDF fitted to DIS and Drell–Yan data $(10^{-5} \lesssim x \lesssim 10^{-1})$
  $\hookrightarrow$ better future constraints via $\gamma\gamma \to \mu^+\mu^-, \mathrm{W}^+\mathrm{W}^-$ for larger x ?
- but: (small) scheme ambiguity remains in $\mathcal{O}(\alpha)$

Electroweak effects in PDFs (continued)

NNPDF2.3QED PDF set

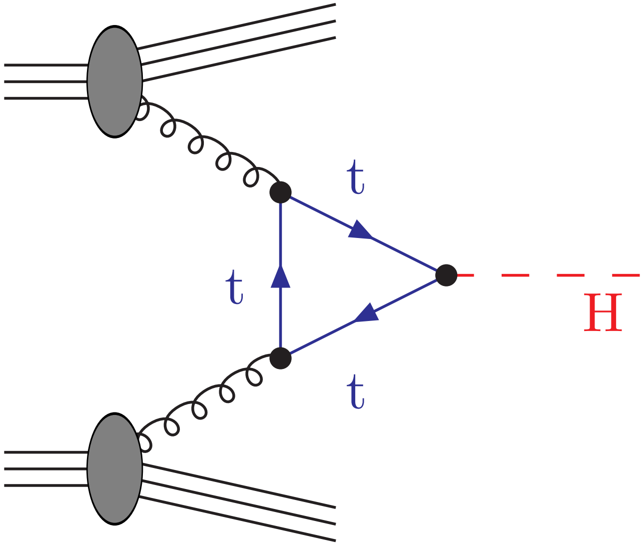

QED corrections to PDFs, Q^2 = 1000 GeV^2


Photon PDF comparison at 10^4 GeV^2

Photon PDF:

- agreement with old $\gamma_{\rm MRST}(x)$ for $x \gtrsim 0.03$, but $\gamma_{\rm NNPDF}(x) < \gamma_{\rm MRST}(x)$ for smaller x
- lack of experimental information for $x \gtrsim 0.1$
  $\hookrightarrow$ constrained via $\gamma\gamma \to \mu^+\mu^-, \mathrm{W}^+\mathrm{W}^-$ for larger x in the future ?

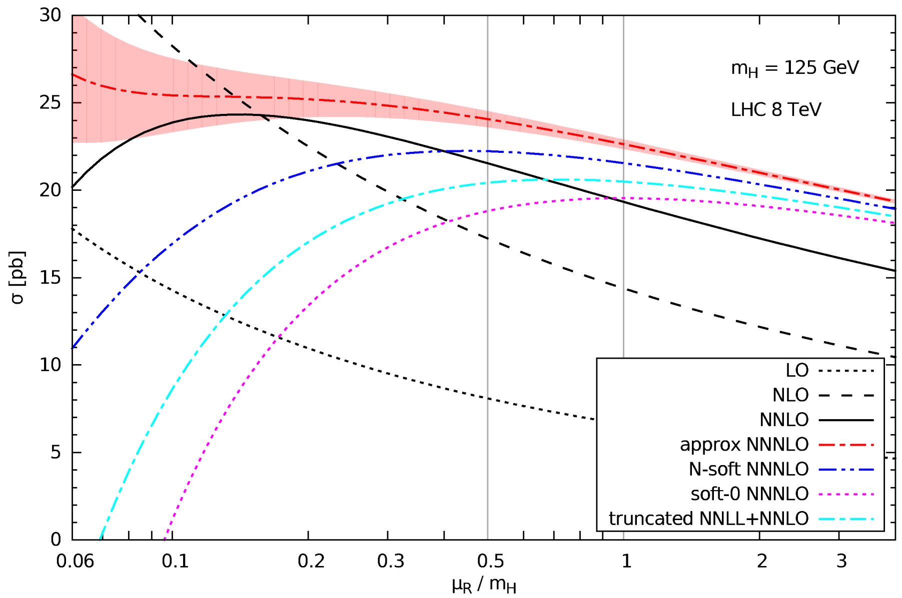
Higgs production via gluon fusion



gg → H @ NNNLO QCD

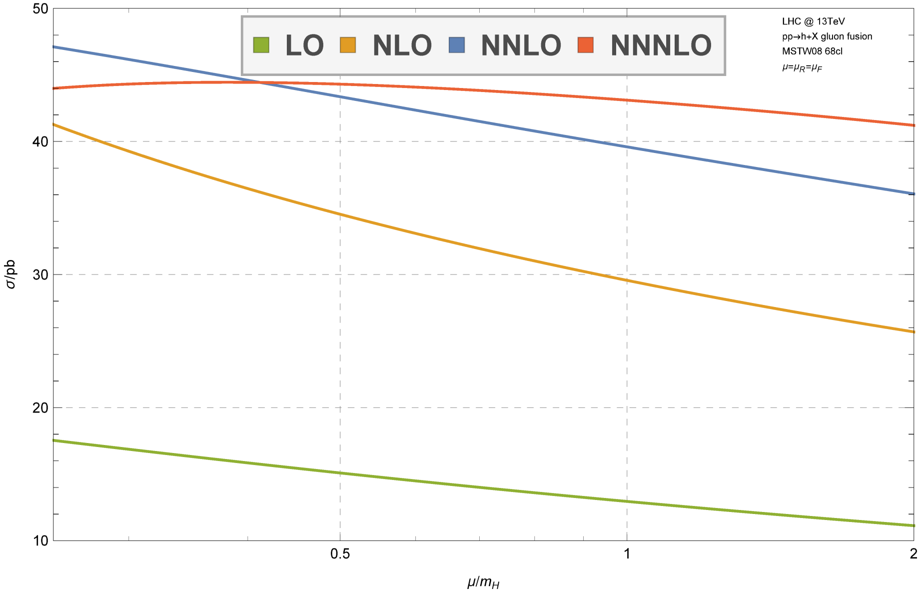
Approximated result:

Bonvini et al. ’14



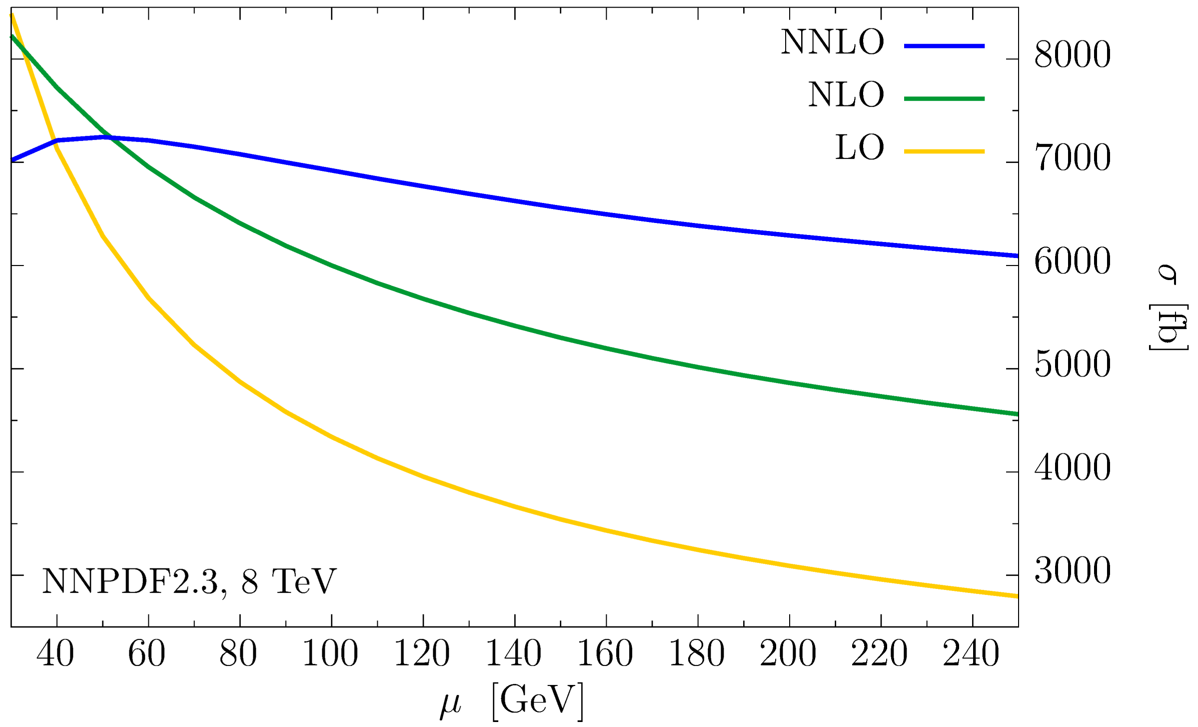
Full result:

Anastasiou et al. ’15



Another ingredient: Higgs + 1 jet @ NNLO QCD Boughezal et al. ’13,’15; Chen et al. ’14

- $p_{\mathrm{T,H}}$ spectrum @ NNLO QCD → e.g. MC reweighting
- stabilization of predicted jet multiplicities (0-jet, 1-jet, 2-jet inclusive)



Boughezal et al. ’15

$\sqrt{s} = 8\,\mathrm{TeV}$

$p_{\mathrm{T,jet}} > 30\,\mathrm{GeV}$

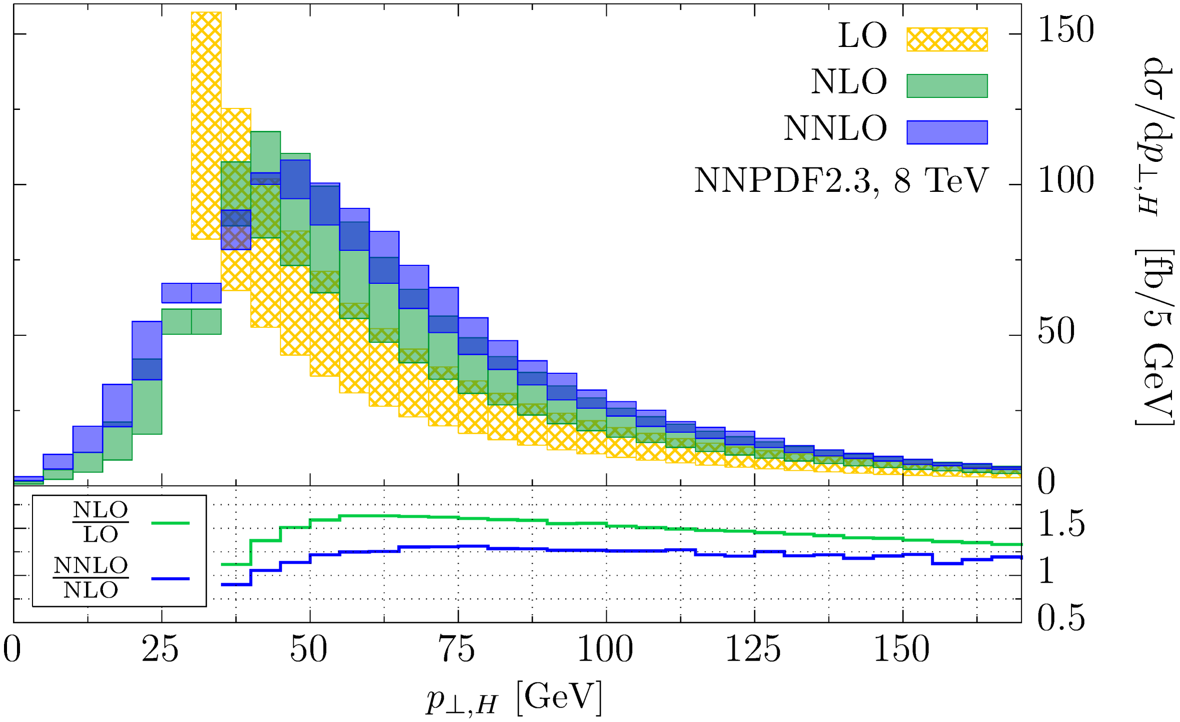
corrections: LO $\xrightarrow{+23\%}$ NLO $\xrightarrow{+5\%}$ NNLO for $\mu = M_{\mathrm{H}}/2$

uncertainties: PDF: 5%

scale: 44% LO, 23% NLO, 9% NNLO

Higgs + 1 jet @ NNLO QCD – some details

- major obstacle: isolation and cancellation of IR singularities
  - ◇ Boughezal et al.:
    - sector-improved residue subtraction Czakon ’10; Czakon, Heymes ’14
    - jettiness subtraction Boughezal, Liu, Petriello ’15; Gaunt et al. ’15
  - ◇ Chen et al. (gg channel): antenna subtraction Gehrmann–de Ridder, Gehrmann, Glover ’05
- K factor $p_{\mathrm{T,H}}$-dependent:



Boughezal et al. ’15