The Latsis Symposium 2013

Nature at the energy frontier

Zurich, June 3-6 2013

Theory perspectives on future accelerators

Michelangelo L. Mangano

TH Unit, Physics Department, CERN

michelangelo.mangano@cern.ch

Introduction

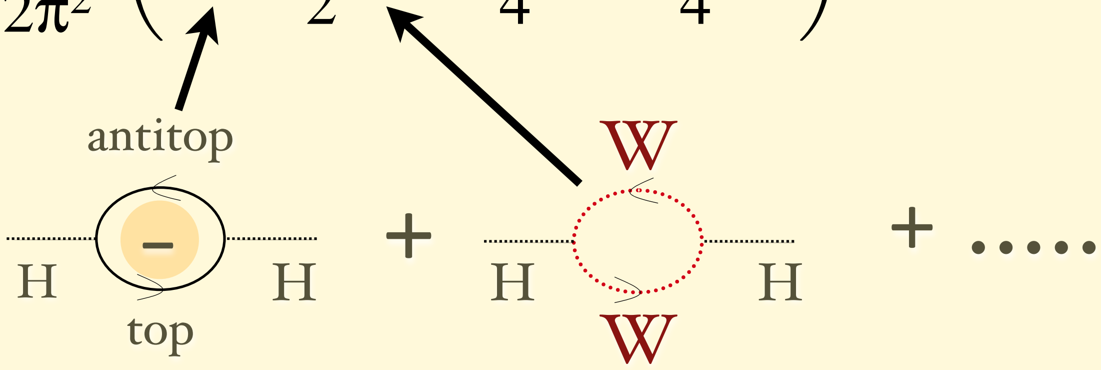
- In spite of the Higgs discovery, the origin of EW symmetry breaking remains a huge mistery
- The observation of the Higgs where the SM predicted it would be, its SM-like properties, and the lack, at the LHC, of BSM phenomena observed up to the TeV scale, make the naturalness issue as puzzling as ever

Hierarchy, or naturalness, problem

Hierarchy, or naturalness, problem

Calculating the radiative corrections to the Higgs mass in the SM poses an intriguing puzzle:

$$m_H^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2}\left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2\right)\Lambda^2 \sim m_0^2 - (115\mathrm{GeV})^2\left(\frac{\Lambda}{400\mathrm{GeV}}\right)^2$$

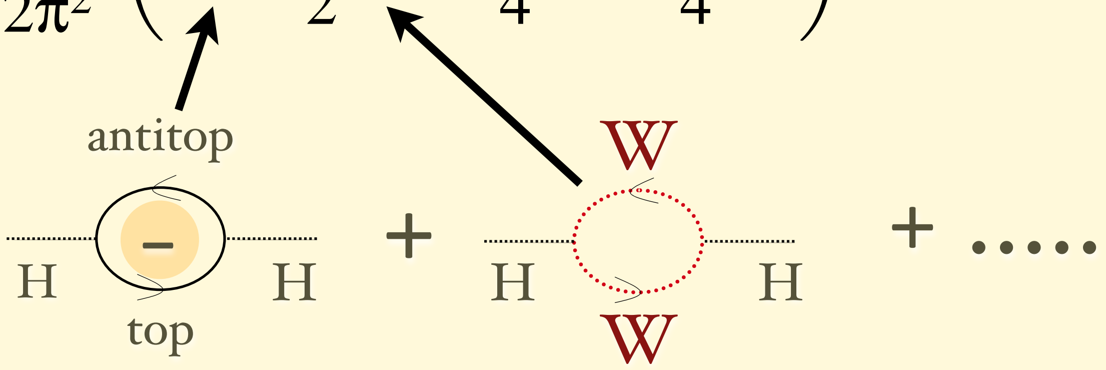


Λ= scale up to which no BSM dynamics appears

Hierarchy, or naturalness, problem

Calculating the radiative corrections to the Higgs mass in the SM poses an intriguing puzzle:

$$m_H^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2}\left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2\right)\Lambda^2 \sim m_0^2 - (115\mathrm{GeV})^2\left(\frac{\Lambda}{400\mathrm{GeV}}\right)^2$$



Λ= scale up to which no BSM dynamics appears

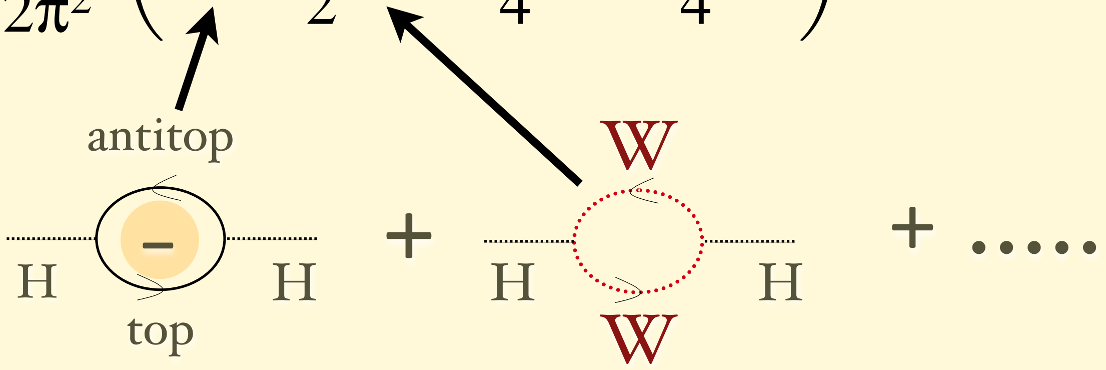
renormalizability =>

$$m_H^2(v) \sim m_H^2(\Lambda) - (\Lambda^2 - v^2) \quad , \quad v = \langle H \rangle \sim 250\mathrm{GeV}$$

Hierarchy, or naturalness, problem

Calculating the radiative corrections to the Higgs mass in the SM poses an intriguing puzzle:

$$m_H^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2}\left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2\right)\Lambda^2 \sim m_0^2 - (115\mathrm{GeV})^2\left(\frac{\Lambda}{400\mathrm{GeV}}\right)^2$$



Λ= scale up to which no BSM dynamics appears

renormalizability =>

$$m_H^2(v) \sim m_H^2(\Lambda) - (\Lambda^2 - v^2) \quad , \quad v = \langle H \rangle \sim 250\mathrm{GeV}$$

Assuming Λ can extend up to the highest energy beyond which quantum gravity will enter the game, 10^{19} GeV, keeping m_H below 1 TeV requires a fine tuning among the different terms at a level of 10^{-34}:

$$\frac{m_H^2(\Lambda) - \Lambda^2}{\Lambda^2} \sim \frac{v^2}{\Lambda^2} = O(10^{-34}) \text{ if } \Lambda \sim M_{Planck}$$

extremely **unnatural** if it is to be an accident !!

We are therefore led to speculate the existence of **new phenomena at a scale of the order of the TeV**, to introduce new contributions to the Higgs self-energy equation, which cancel the quadratic growth with Λ in a natural **way**

More in general ....

Tie the Higgs mass to some symmetry which protects it against quadratic divergencies

Supersymmetry

H (scalar) ↔ fermion

$$\delta m_e = \frac{\alpha_{em}}{3\pi} m_e \log\frac{\Lambda}{m_e}$$

Gauge symmetry

H (scalar) ↔ 5th component of a gauge bosons in 5 dimensions or more

=> extra dimensional theories

Global symmetry

$H \to H + a \Rightarrow L(H)=L(\partial H)$

=> Little Higgs theories, Technicolor
H=pseudo-goldstone boson

- Lack of evidence for new physics from the LHC at the TeV scale raises an issue of **fine tuning**.
  - The higher the scale of the phenomena solving the hierarchy problem, the higher the degree of fine tuning required to keep the scale of weak interactions at 100 GeV.
  - The solutions to the naturalness problem are themselves becoming “unnatural”.

Way outs

Way outs

- BSM particles are already being created at the LHC, but are hiding well:
  - compressed spectra: low MET, low ET, long lifetime heavy particles, ...
  - RPV
  - ....

Way outs

- BSM particles are already being created at the LHC, but are hiding well:
  - compressed spectra: low MET, low ET, long lifetime heavy particles, ...
  - RPV
  - ....
- BSM is less “conventional”, fine-tuning or direct search constraints less tight
  - NMSSM
  - non-degenerate squarks
  - ....

Way outs

- BSM particles are already being created at the LHC, but are hiding well:
  - compressed spectra: low MET, low ET, long lifetime heavy particles, ...
  - RPV
  - ....
- BSM is less “conventional”, fine-tuning or direct search constraints less tight
  - NMSSM
  - non-degenerate squarks
  - ....
- Naturalness is an ill guided principle ⇒ Anthropic principle

- I strongly disfavour the last option
  - that "naturalness" is a problem, is more than an aesthetic issue: to the extent that there are new phenomena between the weak scale and the Plank scale (e.g. the sectors related to nu masses, to CPV, DM, etc), the Higgs is coupled, directly or indirectly, to them, receiving quadratic corrections to its mass. Renormalization itself cannot absorb all these contributions coming from many different scales, unless there is some dynamics acting at all scales. But this would be BSM physics.
  - there could be "infinitely" many theories that are anthropically more likely than the SM. Even if finely tuned at the per mille level, a SUSY universe reduces the naturalness problem by many orders of magnitude. Anthropic reasoning could be appropriate to defend a finely-tuned SUSY or composite-Higgs model, but does not obviously apply to the SM.
- Of course accepting that anthropic selection applies to a "natural" but fine-tuned BSM universe, leaves open the possibility that the scale of new phenomena is well above the TeV ....

- Confidence in the appearance of new physics at the LHC at 14 TeV remains fully justified:

- Confidence in the appearance of new physics at the LHC at 14 TeV remains fully justified:
  - exploration of the "way outs" listed before (NMSSM, RPV, compressed spectra, push to higher mass all conventional searches, ...)

- Confidence in the appearance of new physics at the LHC at 14 TeV remains fully justified:
    - exploration of the “way outs” listed before (NMSSM, RPV, compressed spectra, push to higher mass all conventional searches, ...)
    - WIMP DM in the LHC range is still a sensible thing to expect: how far and how conclusively can one push its search ?

- Confidence in the appearance of new physics at the LHC at 14 TeV remains fully justified:
  - exploration of the "way outs" listed before (NMSSM, RPV, compressed spectra, push to higher mass all conventional searches, ...)
  - WIMP DM in the LHC range is still a sensible thing to expect: how far and how conclusively can one push its search ?
  - flavour physics remains alert for new phenomena (CPV, LFV, ...)

- Confidence in the appearance of new physics at the LHC at 14 TeV remains fully justified:
  - exploration of the "way outs" listed before (NMSSM, RPV, compressed spectra, push to higher mass all conventional searches, ...)
  - WIMP DM in the LHC range is still a sensible thing to expect: how far and how conclusively can one push its search ?
  - flavour physics remains alert for new phenomena (CPV, LFV, ...)
- Whether new particles can be seen or not at 14 TeV, the most concrete and urgent questions now are

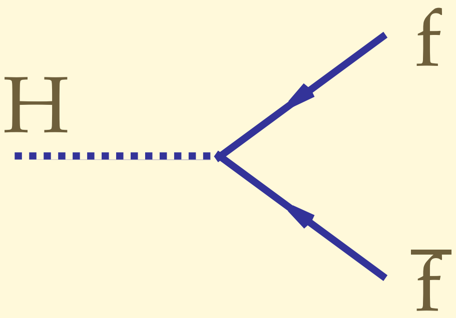
- Confidence in the appearance of new physics at the LHC at 14 TeV remains fully justified:
    - exploration of the "way outs" listed before (NMSSM, RPV, compressed spectra, push to higher mass all conventional searches, ...)
    - WIMP DM in the LHC range is still a sensible thing to expect: how far and how conclusively can one push its search ?
    - flavour physics remains alert for new phenomena (CPV, LFV, ...)
- Whether new particles can be seen or not at 14 TeV, the most concrete and urgent questions now are
    - up to which scale do Higgs interactions behave SM-like ?

- Confidence in the appearance of new physics at the LHC at 14 TeV remains fully justified:
    - exploration of the "way outs" listed before (NMSSM, RPV, compressed spectra, push to higher mass all conventional searches, ...)
    - WIMP DM in the LHC range is still a sensible thing to expect: how far and how conclusively can one push its search ?
    - flavour physics remains alert for new phenomena (CPV, LFV, ...)
- Whether new particles can be seen or not at 14 TeV, the most concrete and urgent questions now are
    - up to which scale do Higgs interactions behave SM-like ?
    - are there any hints of natural solutions to the hierarchy problem?

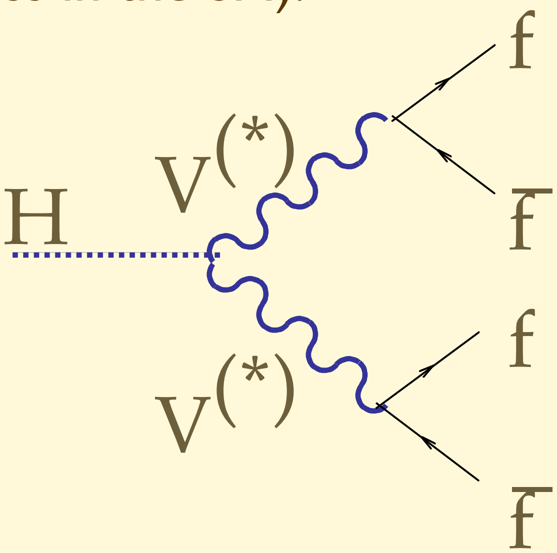
- Confidence in the appearance of new physics at the LHC at 14 TeV remains fully justified:
  - exploration of the "way outs" listed before (NMSSM, RPV, compressed spectra, push to higher mass all conventional searches, ...)
  - WIMP DM in the LHC range is still a sensible thing to expect: how far and how conclusively can one push its search ?
  - flavour physics remains alert for new phenomena (CPV, LFV, ...)
- Whether new particles can be seen or not at 14 TeV, the most concrete and urgent questions now are
  - up to which scale do Higgs interactions behave SM-like ?
  - are there any hints of natural solutions to the hierarchy problem?
- What is the need for precision measurements of the Higgs sector, what are the possible implications of these measurements, what do they probe, how do they bear on the naturalness problem ?

Higgs couplings

Tree level (proportional to particle's mass in the SM):



~ m_f / v



~ m_V / v

Modifications, possibly breaking the linear relation coupling-mass, are common in BSM models (although constrained, e.g., by EW precision tests, in addition today to direct BR measurements). For example:

SUSY:

hbb, hττ, hμμ ∝ tanβ δ(**hVV**)/**hVV** ∝ $m^2(h)/m^2(H)$

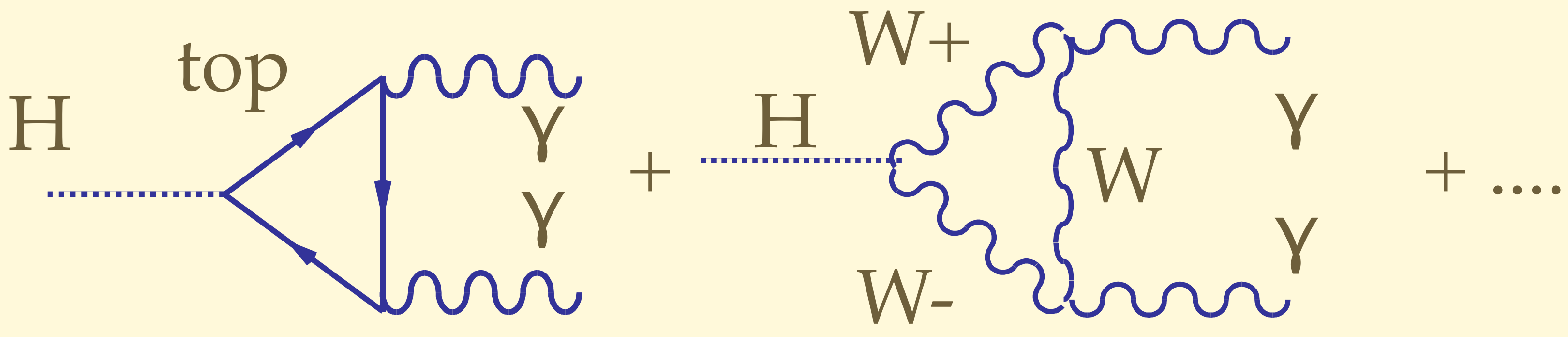
... more complex deviations in models with extended Higgs structures (e.g. NMSSM)

Composite Higgs models:

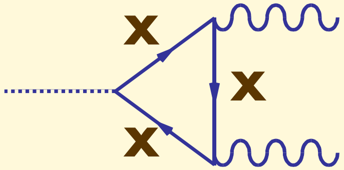
δ(**hVV**)/**hVV** ∝ $\xi = v^2/f^2$, f being the "decay constant" of the strong interactions which the Higgs would be a pseudo goldstone boson of

Higgs couplings

Loop level (in the SM, proportional to mass of particles in the loop)



Modifications can arise both from modif's of the tree-level couplings, and from possible new states present in the loops.



Comments:

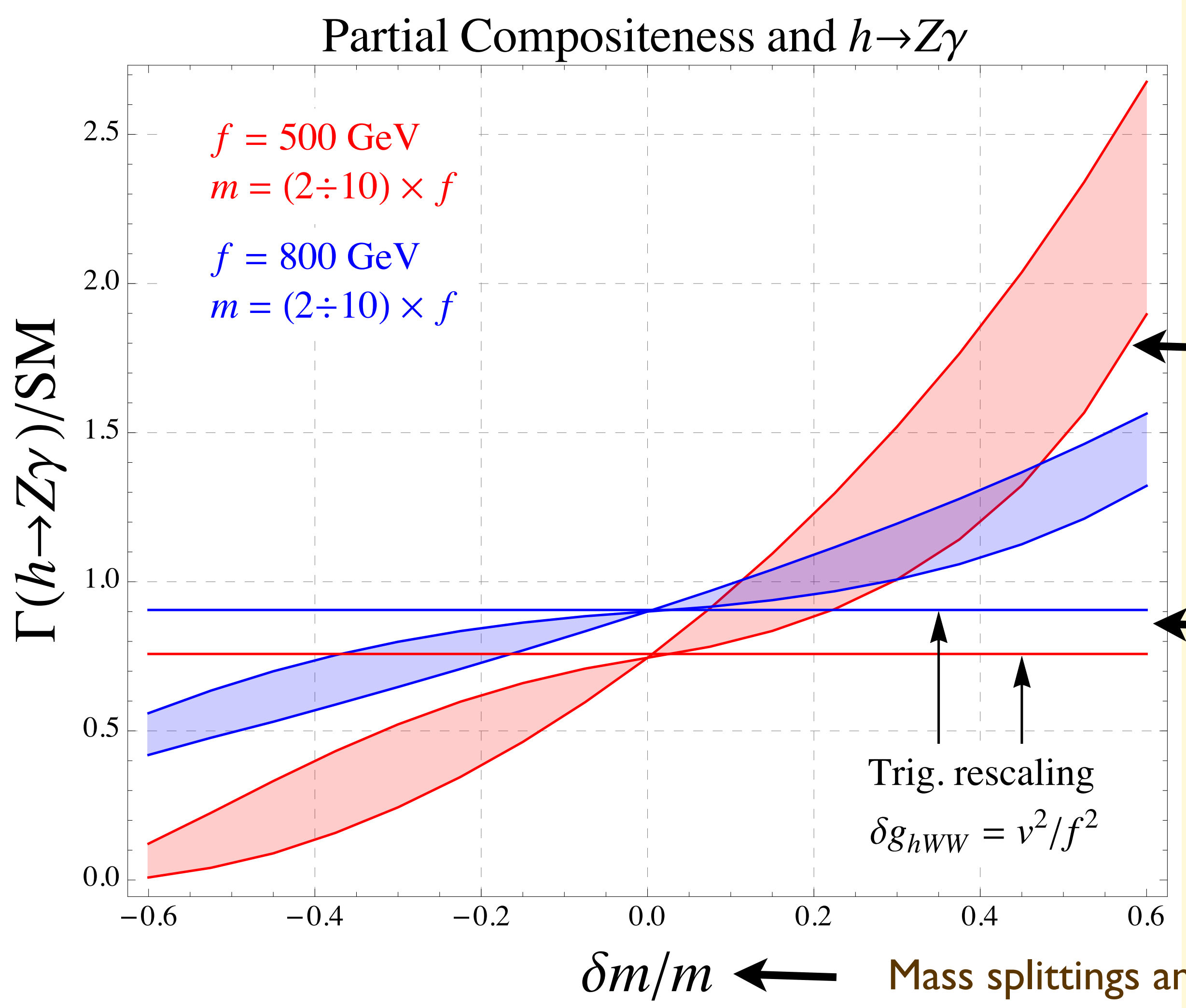
- Loop-induced couplings, which in the SM are fully determined by the tree-level ones, add important new information in the presence of BSM
- Cancellations of different contributions may take place. It is necessary to **resolve** what circulates in the loop, e.g. using different probes such as

H→Zγ vs H→γγ

- Precision measurements of super-rare decays like H→Zγ are therefore very important, although beyond the reach of either the nominal LHC, or LC, programmes

Example

Preliminary result of study by Azatov, Contino, Di Iura, Galloway, to appear soon. Private communication from the authors.



Much larger impact on B(H→Zγ), also for multi-TeV masses of new fermions: potential for visible effects even when B(H→WW)=SM to within %

Impact on B(H→WW) small, and independent of δm/m

Mass splittings among the new fermions of the strongly interacting sector

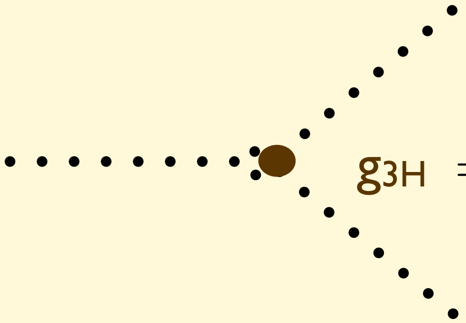
Higgs selfcouplings

The Higgs sector is defined in the SM by two parameters, **μ** and **λ**:

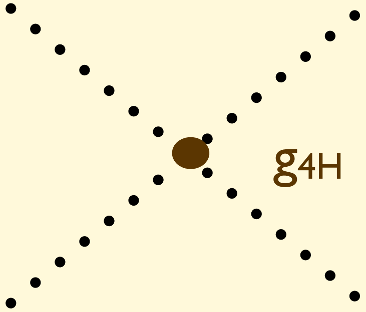
$$V_{SM}(H) = -\mu^2 \, |H|^2 + \lambda \, |H|^4$$

$$\frac{\partial V_{SM}(H)}{\partial H}|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}|_{H=v} \quad \Rightarrow \quad \begin{array}{rcl} \mu & = & m_H \\ \lambda & = & \dfrac{m_H^2}{2v^2} \end{array}$$

These relations uniquely determine the strength of Higgs selfcouplings in terms of m_H



$g_{3H} \Rightarrow 6\lambda \, v = \frac{3m_H^2}{v}$ ~O(m_{top})



$g_{4H} \Rightarrow 6\lambda = \frac{3m_H^2}{v^2}$ ~O(1)

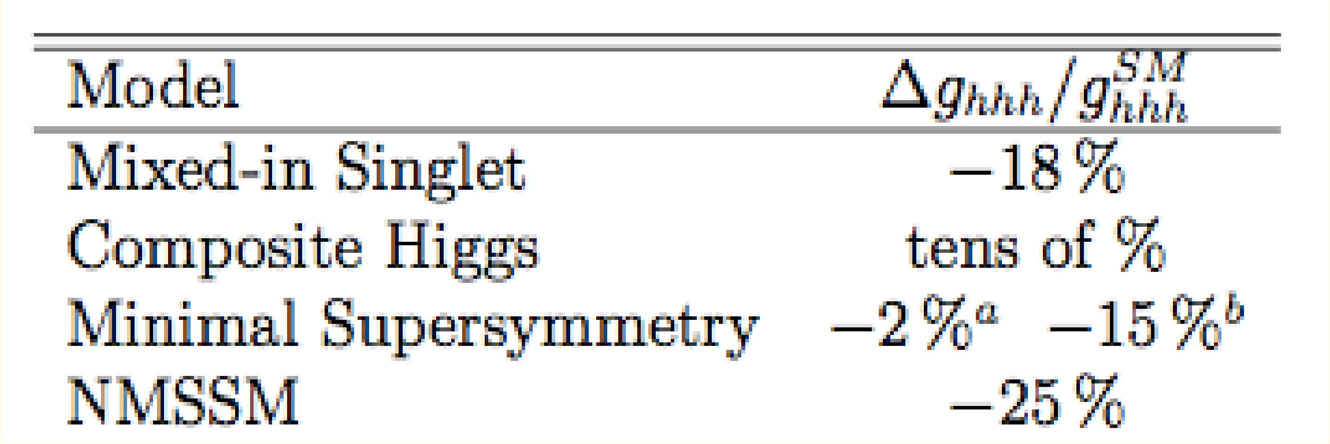
Testing these relations is therefore an important test of the SM nature of the Higgs mechanism

Higgs selfcouplings

The values of g_{3H} and g_{4H} can differ from the SM in several classes of BSM scenarios. For example: R.Gupta et al, arXiv:1305.6397

- Non-minimal Higgs sectors, like 2HDM, NMSSM
- Dynamical Higgs models (Pseudo-Nambu-Goldstone-boson, like little Higgs, ...)

Requiring that the **direct** manifestations of these models not be visible(*) at the LHC 14TeV/300fb-1(nor to affect EW precision measurements), allows deviations of the Higgs selfcoupling from the SM value as large as ~20%, which sets a possible target for future sensitivities:



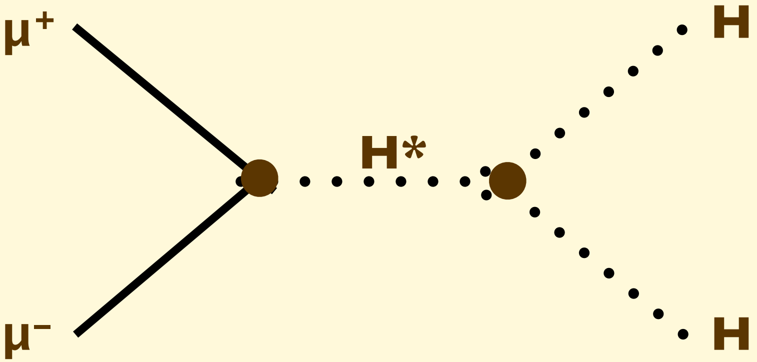
Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $\;-15\,\%^b$
NMSSM	$-25\,\%$

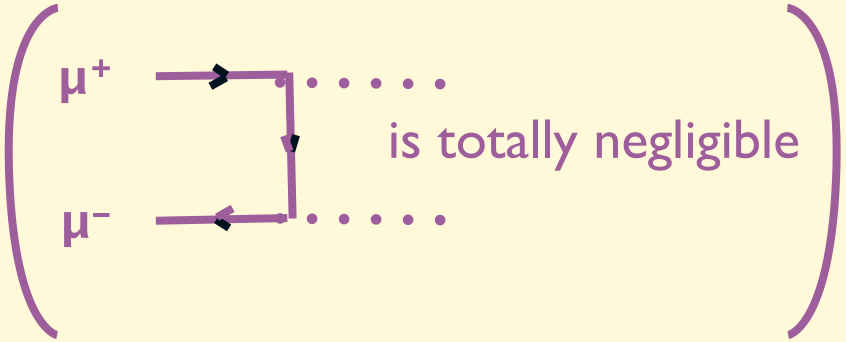
R.Gupta et al, arXiv:1305.6397

(*) of course having both direct evidence of new states and a deviation in HHH couplings is even better!

Higgs pair production

The only clean way to probe the triple H coupling is at a muon collider, at $\sqrt{S} > 2\ m_H$:

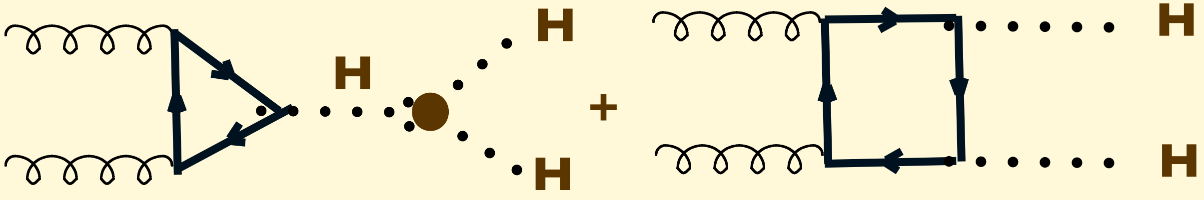




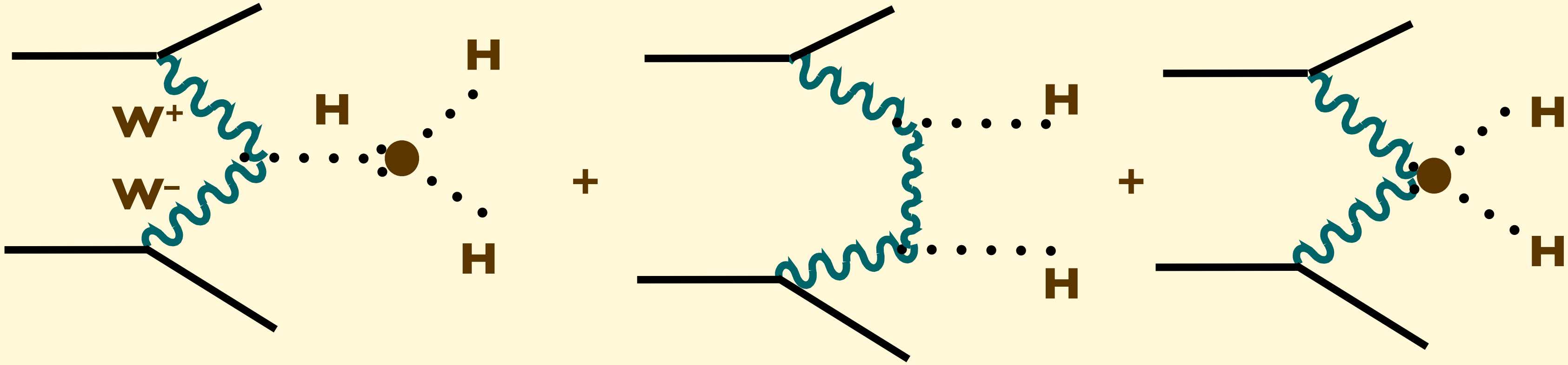
is totally negligible

For HH production in hadronic collisions, the HHH coupling is always mixed with other processes:

gg fusion:



VBF:



In the SM this causes accidental cancellations among diagrams, small rates, and typically suppressed sensitivity to the HHH coupling

Higgs pair production

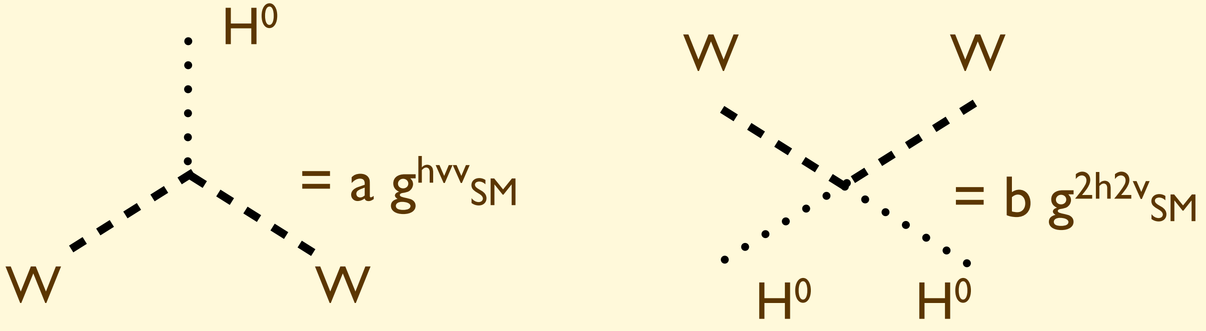
Beyond the SM, in addition to the Higgs selfcoupling, HH production tests the couplings of the Higgs to new physics, the unitarity of WW scattering, etc

H pairs allow to probe Higgs interactions in regions of Q^2 away from the Higgs pole.

The dynamics of Higgs pair production therefore goes well beyond the mere determination of Higgs self-couplings, and is a powerful probe of the nature of EWSB

Particularly true of strongly coupled, composite Higgs models, where the rate for double Higgs production in both gg and vector boson fusion is much enhanced relative to the SM.

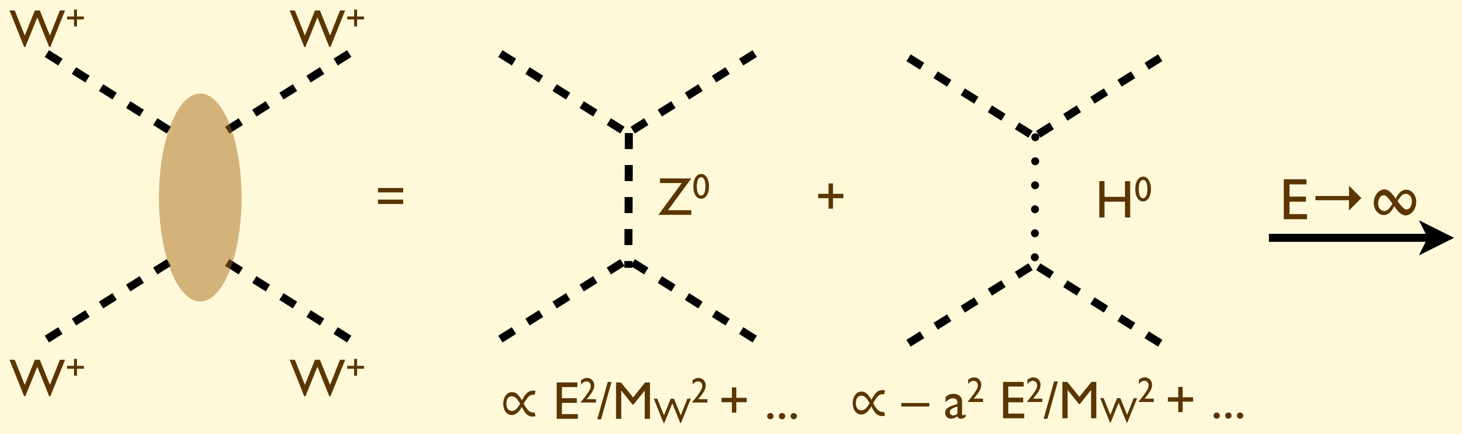
High-energy WW scattering



$= a\, g^{hvv}_{SM}$

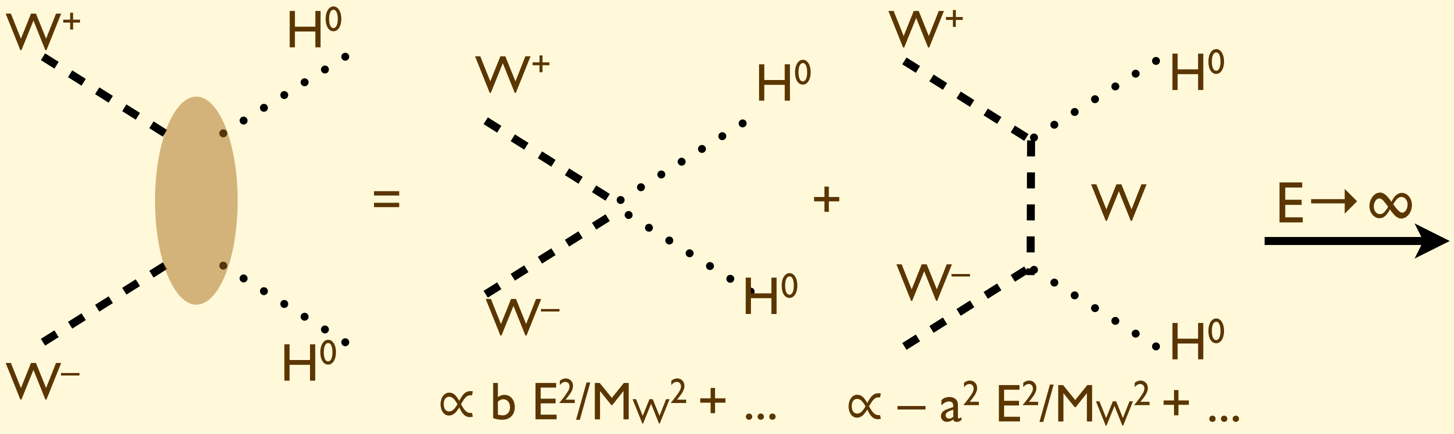
$= b\, g^{2h2v}_{SM}$

- a=b=1 in the SM
- In general, a,b≠1 and a≠b



$\propto E^2/M_W{}^2 + \ldots$ $\quad \propto - a^2\, E^2/M_W{}^2 + \ldots$

$\mathbf{(1 - a^2)}\ E^2 / M_W{}^2 + \ldots$



$\propto b\, E^2/M_W{}^2 + \ldots$ $\quad \propto - a^2\, E^2/M_W{}^2 + \ldots$

$\mathbf{(b - a^2)}\ E^2 / M_W{}^2 + \ldots$
+ threshold terms
proportional to
HHH coupling

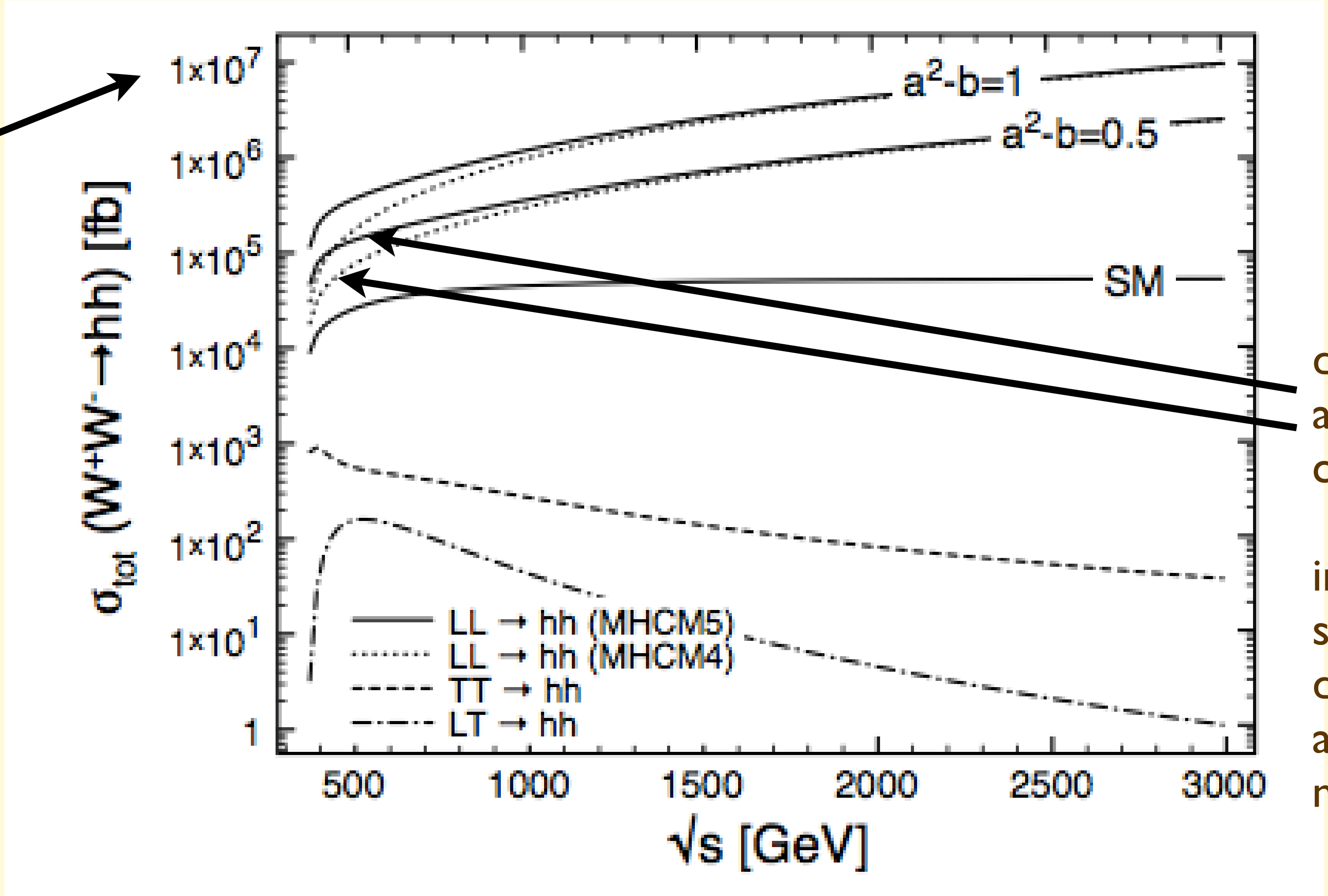
High-energy WW scattering

In more detail:

$$\frac{d\sigma_{LL\to LL}/dt}{d\sigma_{TT\to TT}/dt}\Big|_{90^o} = \frac{(1-a^2)^2}{2304}\,\frac{s^2}{M_W^4} \qquad \frac{d\sigma_{LL\to hh}/dt}{d\sigma_{TT\to hh}/dt} = \frac{2s^2}{g^4v^4}\,\frac{(b-a^2)^2}{(a^4+(b-a^2)^2)}$$

Example: WW→HH

R.Contino et al, arXiv:1002.1011v2



partonic
cross
sections

different
anomalous HHH
couplings:

invariant mass
spectrum of HH
discriminates
among BSM
models

Example: WW scattering in PNGB models based on SO(5)/SO(4), where a=√(1–ξ) and b=1–2ξ with ξ=(v/f)^2 :

R.Contino et al, arXiv:1002.1011v2

$$\frac{d\sigma(W_L W_L)/dt}{d\sigma(W_T W_T)/dt}\Big|_{90^\circ} = \left(\frac{\xi}{48}\,\frac{E^2_{CM}(WW)}{M_W^2}\right)^2 \sim 4\xi^2\left(\frac{E_{CM}(WW)}{800\ \mathrm{GeV}}\right)^4$$

and therefore it takes CM energies of the WW pair well above the TeV to have sensitivity in the range ξ<<1.

In pp collisions at 14 TeV, with 300 fb^{-1}, the statistics drops once M(WW)~1 TeV, and one is sensitive to values ξ≳0.5 (cfr ξ≳0.3 w. 1000 fb^{-1} at CLIC 3TeV)

Since the reach in ξ scales like ~ 1/ E^2 , the sensitivity will improve to O(0.05) at ~50 TeV, and to O(0.01) at ~100 TeV.

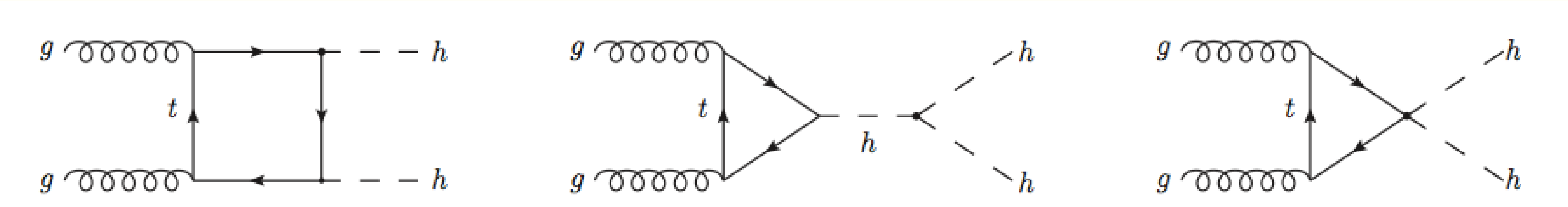
This is the reason why the SSC was designed for 40 TeV: it's the energy at which one can start doing quantitative checks of the proper behaviour of high-energy WW scattering

The need to perform this measurement remains today as strong as it ever was, as is the need to attain energies in the range of at least 30-40 TeV for compelling results.

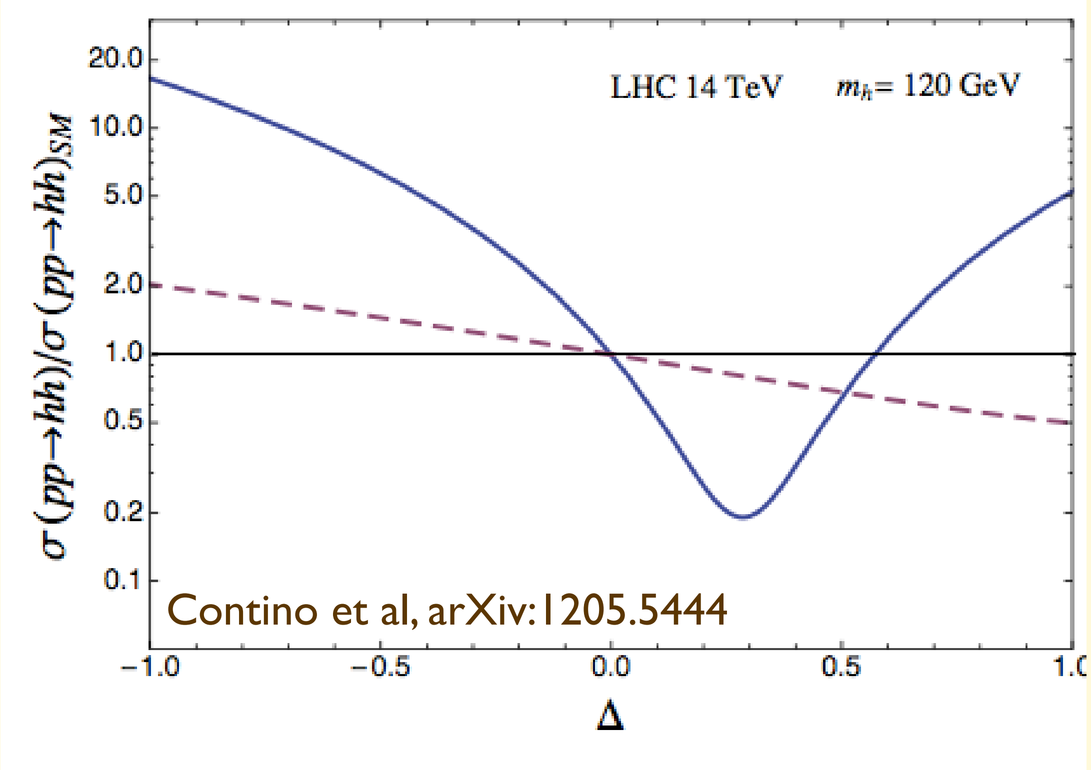
Higgs pair production in gg fusion

A typical feature of composite Higgs models is the appearance of a ttHH effective coupling, which contributes to gg→HH

Grober and Muhlleitner, arXiv:1012.1562



$$A \sim \frac{m_t^2}{v^2} \qquad A \sim g_{3H} \frac{m_t^2}{v^2} \frac{m_H^2}{\hat{s}} \log^2\left(\frac{\hat{s}}{m_t^2}\right) \qquad A \sim g_{ttHH} \frac{m_t^2}{v^2} \log^2\left(\frac{\hat{s}}{m_t^2}\right)$$



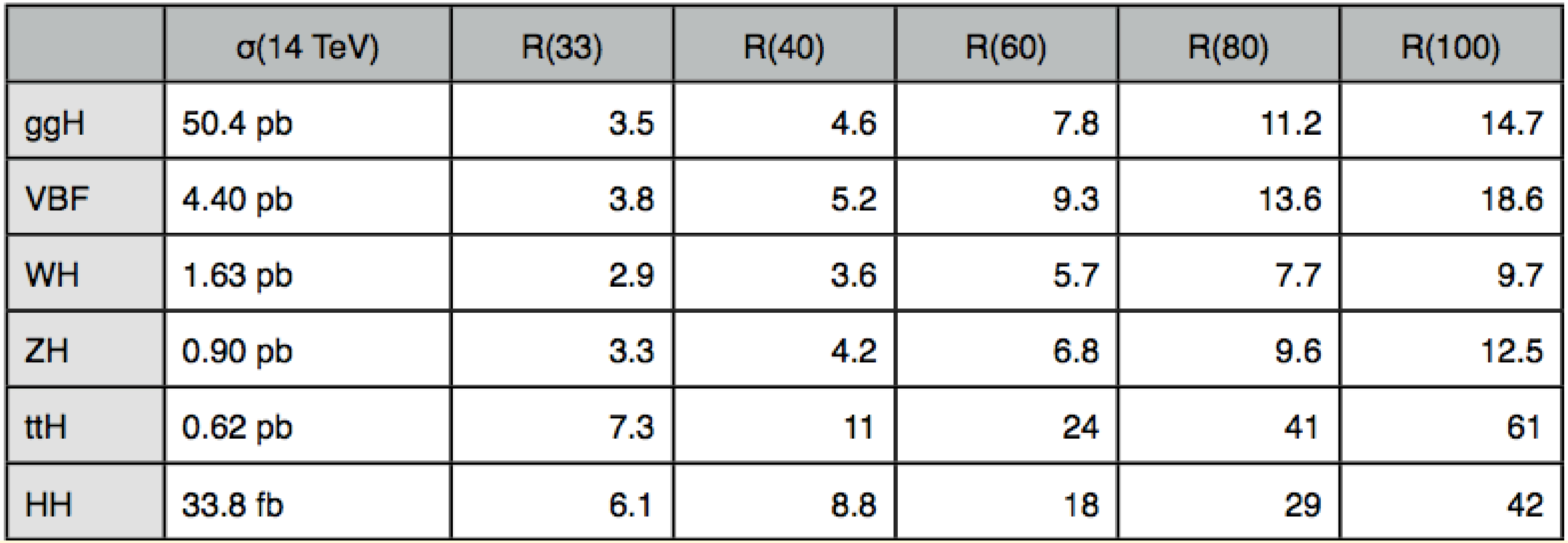
Contino et al, arXiv:1205.5444

g_{ttHH} = Δ (y_{top} / v)
g_{3H} = g_{3H}^{SM}

g_{ttHH} = 0
g_{3H} = (1+Δ) g_{3H}^{SM}

Higgs rates at high energy

NLO rates **R(E)** = σ(E TeV)/σ(14 TeV)

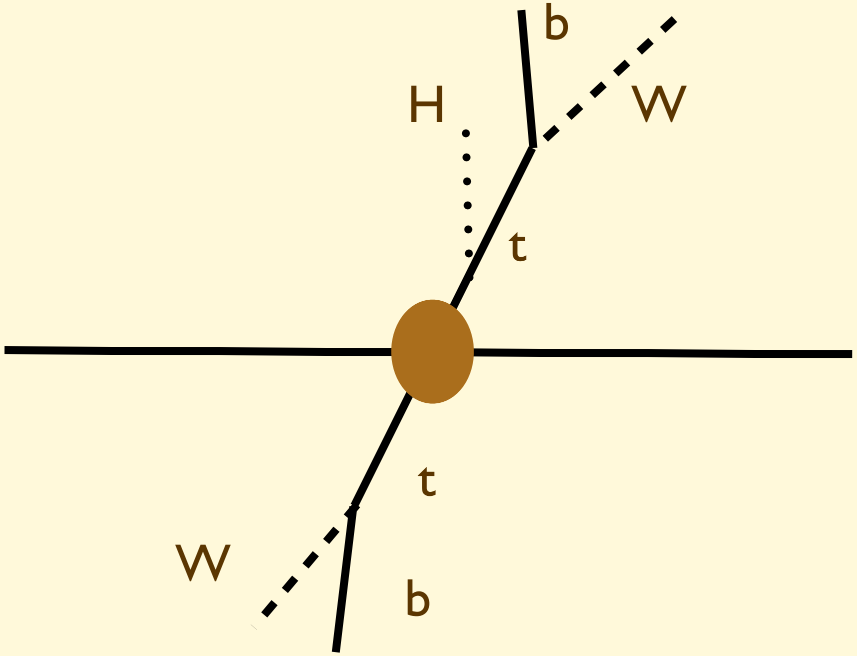


	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

In several cases, the gains in terms of "useful" rate are much bigger.

E.g. when we are interested in the large-invariant mass behaviour of the final states.

Example: ttH at large pt(top)



- Reduced backgrounds
- Reduced combinatorics

⇒ more reliable measurement of y_{top}

pp→ttH	**14 TeV**	**33 TeV** (33/14)	**60 TeV** (60/14)	**100 TeV** (100/14)
σ_{TOT}	0.4 pb	2.8 pb (x 7)	9.7 pb (x 24)	25 pb (x 60)
$\sigma(p_T^{top} > 0.5\ \text{TeV})$	1.6 fb	26 fb (x 16)	120 fb (x 75)	400 fb (x 250)

(LO rates)

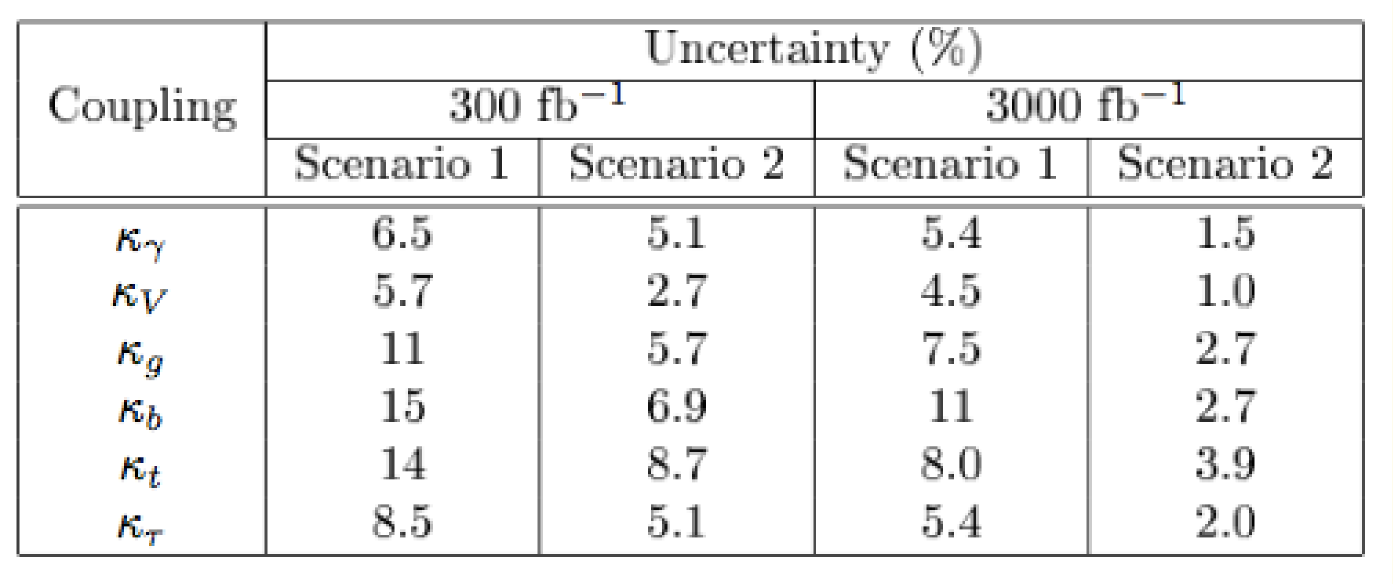
Remarks

- No realistic and complete studies are available, as yet, of
  - the performance in the measurement of Higgs couplings, self-couplings and other properties, by possible LHC detectors at the ultimate luminosities and at energies higher than 14 TeV
  - the various scenarios outlined above
  - the overall requirements on the theory side to match the possible experimental accuracies and optimize the discovery potential
- While effective lagrangians provide a useful tool to assess the "low-energy" impact of SM modifications, and e.g. compare different colliders, this approach cannot evaluate the interplay between the measurement of deviations from SM Higgs properties, and direct observation of new states responsible for these deviations. This is crucial to compare experiments at "low-energy" (ILC, CLIC) with the LHC and future hadron colliders.

Challenges for theory

Recent assessments of Higgs measurement potential, at HL-LHC

CMS submission to Strategy Group,
https://indico.cern.ch/contributionDisplay.py?contribId=177&confId=175067



Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Plus $H\mu\mu$ coupling to better than 5% at 3000fb^{-1}

Scenario 1: same systematics as 2012 (TH and EXP)
Scenario 2: half the TH syst, and scale with 1/sqrt(L) the EXP syst

Note: assume no invisible Higgs decay contributing to the Higgs width

Note: results of scenario 2 @ 3000/fb are overall as powerful as LC@500GeV !!

- Such progress will require a coordinated effort on different fronts:
  - improved higher-order perturbative calculations
  - improved overall modeling of the final state descriptions
  - improved PDF inputs

- Such progress will require a coordinated effort on different fronts:
  - improved higher-order perturbative calculations
  - improved overall modeling of the final state descriptions
  - improved PDF inputs
- All of the above applies to
  - Higgs and BSM signals
  - backgrounds
  - all ancillary processes required to
    - validate/tune MCs
    - extract PDFs directly from LHC data

- Such progress will require a coordinated effort on different fronts:
  - improved higher-order perturbative calculations
  - improved overall modeling of the final state descriptions
  - improved PDF inputs
- All of the above applies to
  - Higgs and BSM signals
  - backgrounds
  - all ancillary processes required to
    - validate/tune MCs
    - extract PDFs directly from LHC data
- Dedicated measurements will also be required to validate the theoretical calculations, extract PDFs, fine tune parameters, test theoretical systematics, ...

- Such progress will require a coordinated effort on different fronts:
  - improved higher-order perturbative calculations
  - improved overall modeling of the final state descriptions
  - improved PDF inputs
- All of the above applies to
  - Higgs and BSM signals
  - backgrounds
  - all ancillary processes required to
    - validate/tune MCs
    - extract PDFs directly from LHC data
- Dedicated measurements will also be required to validate the theoretical calculations, extract PDFs, fine tune parameters, test theoretical systematics, ...
- More in general, the search of "well-hidden" BSM processes will have to rely more and more on direct comparisons with precise SM calculations

Examples of recent progress, future needs, challenges and opportunities

Example: precision Higgs physics

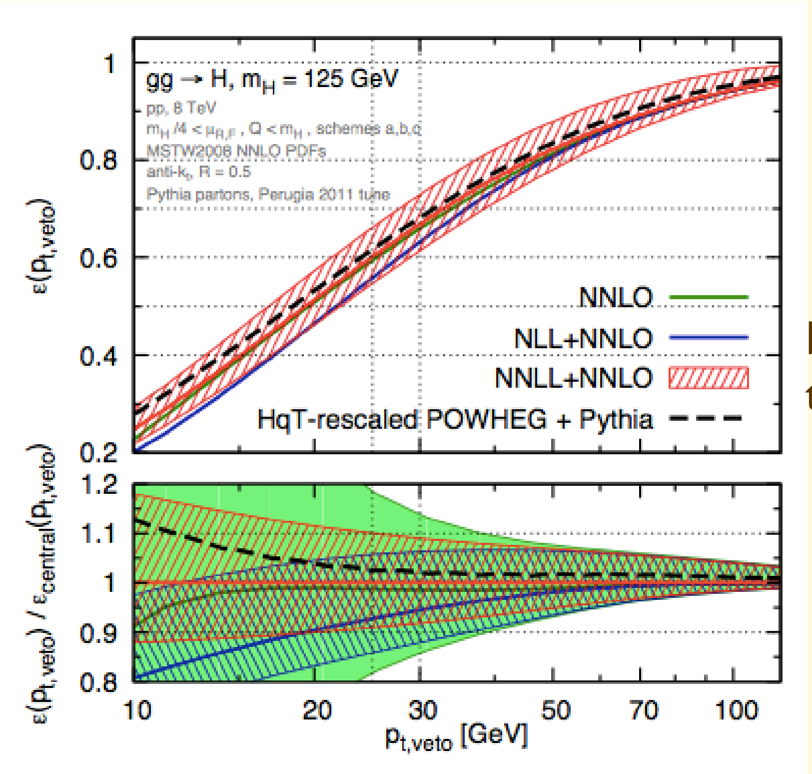
Theoretical uncertainties on production rates (Higgs XS WG, arXiv:1101.0593)

14 TeV	δ(pert. theory)	δ(PDF, α_S)
gg→H	± 10 %	± 7%
VBF (WW→H)	± 1 %	± 2%
qq→WH	± 0.5 %	± 4%
(qq,gg)→ZH	± 2 %	± 4%
(qq,gg)→ttH	± 8 %	± 9%

Improve with higher-loop calculations:
gg->H @ NNNLO
ttH @ NNLO

Improve with dedicated QCD measurements, and appropriate calculations

Theoretical uncertainties on modeling of selection cuts.



Ex. jet veto efficiency, required to reduce bg's to H→WW*

Banfi, Monni, Salam, Zanderighi, arXiv:1206.4998

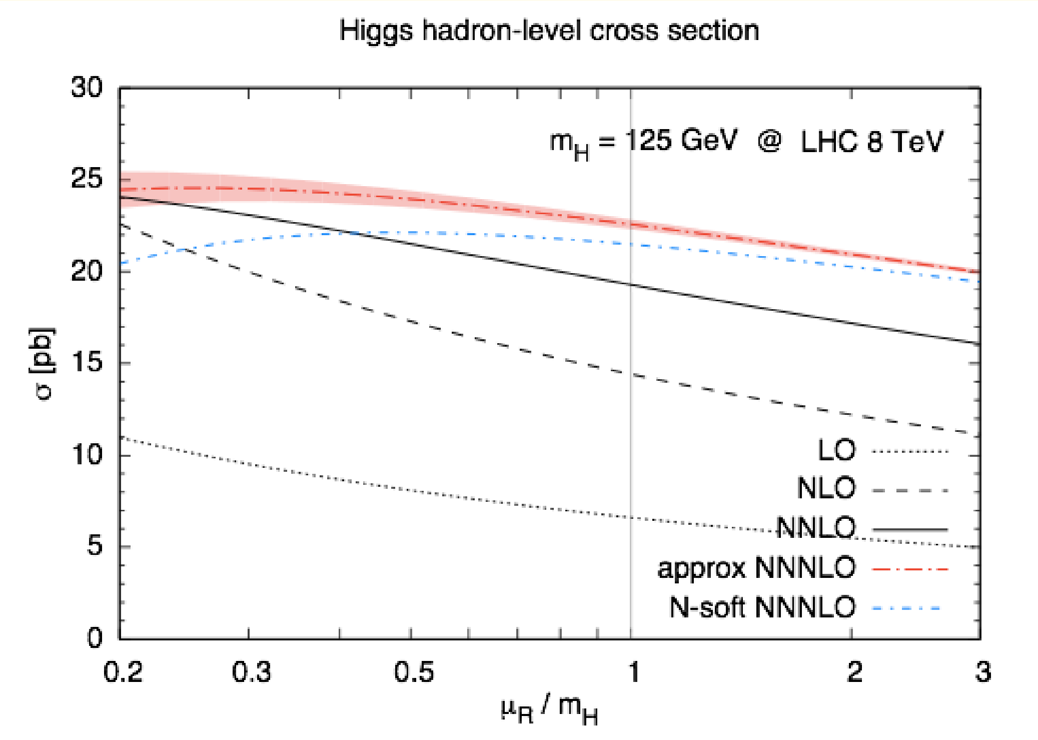
Ongoing theoretical progress for σ(gg→H)

- First steps towards the cross section at NNNLO: triple soft limits, O(ϵ) expansion of NNLO, ...

Anastasiou, Buehler, Duhr, Herzog, arXiv:1208.3130
Anastasiou, Duhr, Dulat, Mistlberger, arXiv:1302.4379
Hoschele, Hoff, Pak, Steinhauser, Ueda, arXiv:1211.6559

- Approximate NNNLO from structure of leading large-x and small-x singularities

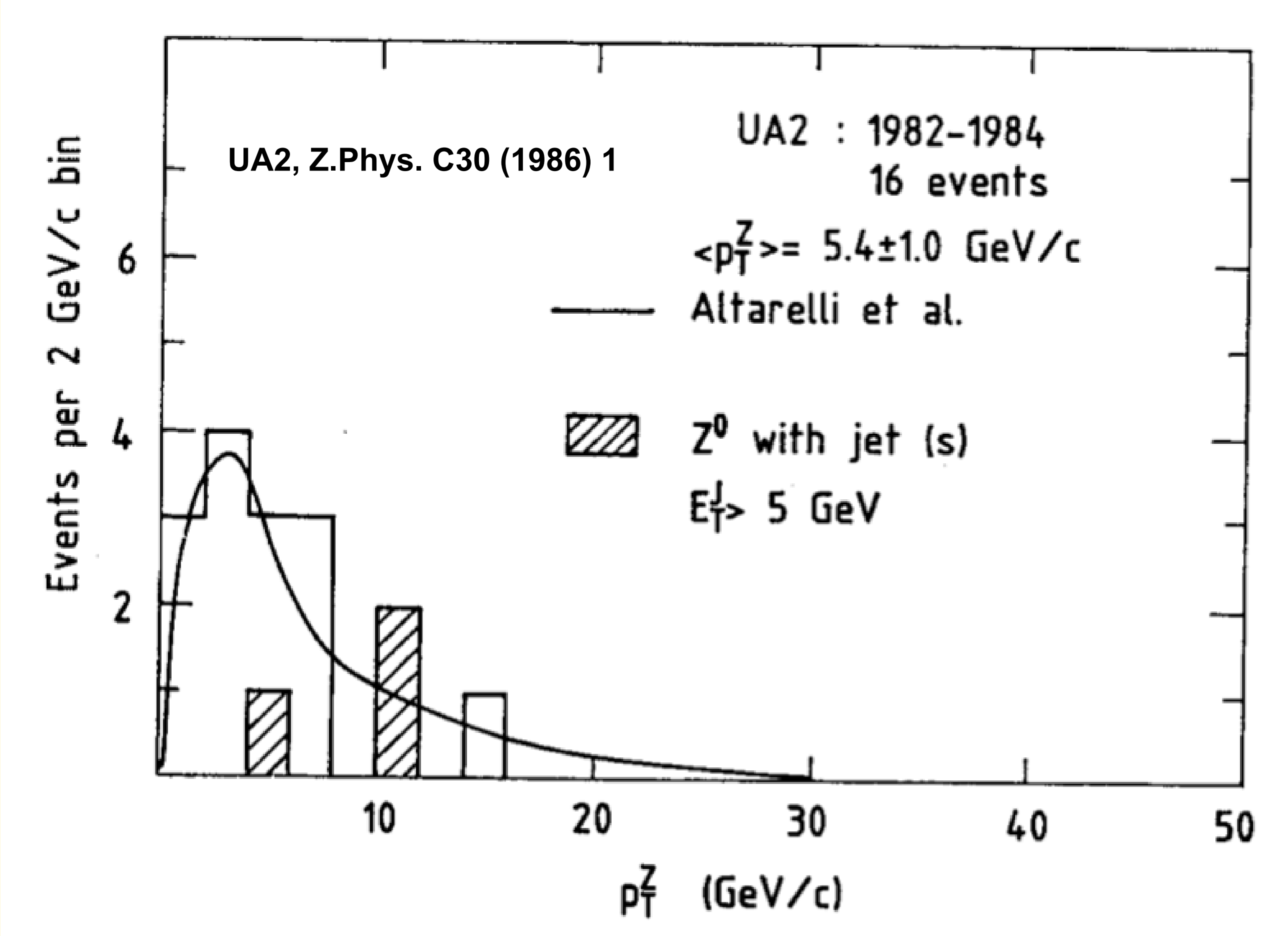
R. Ball etal, arXiv:1303.3590

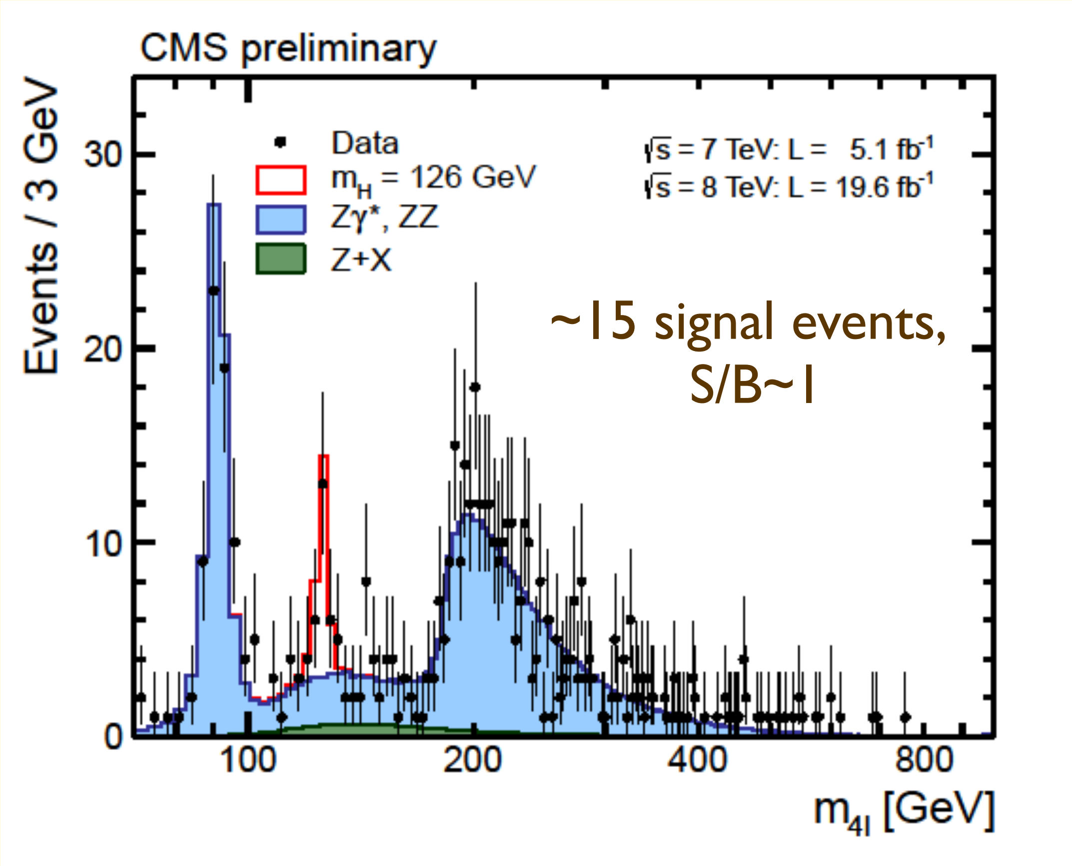


Towards experimental constraints on Higgs production dynamics ....

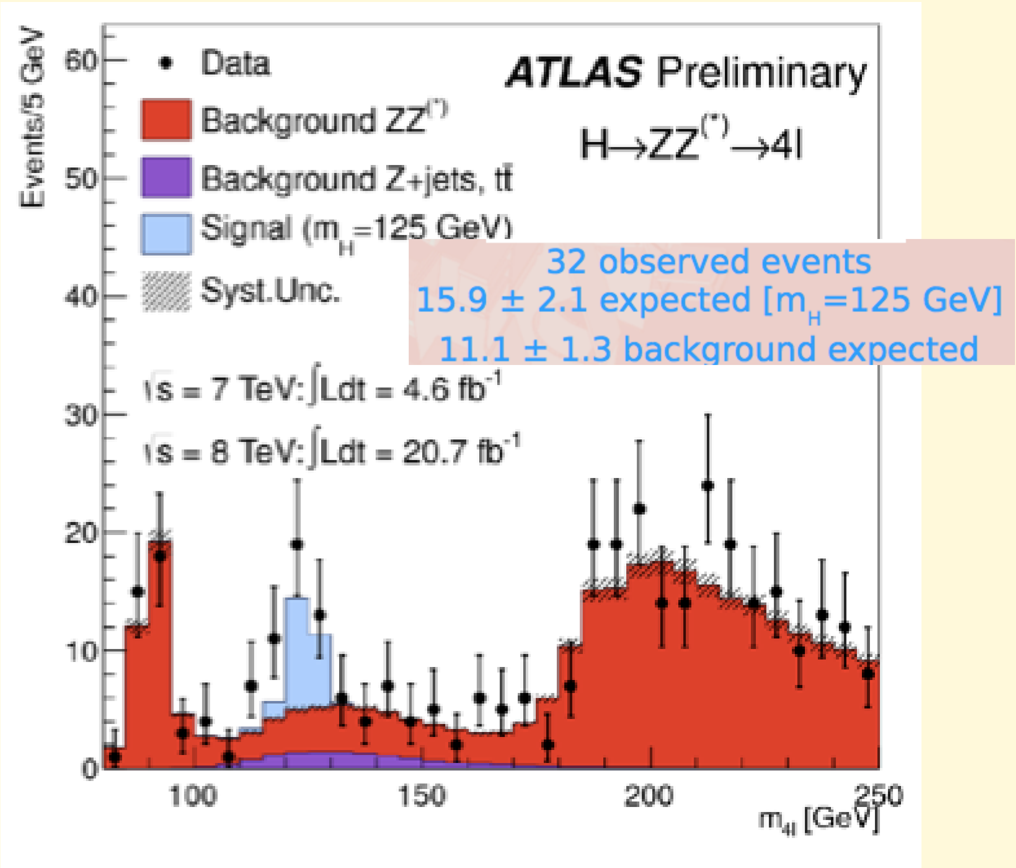
Towards experimental constraints on Higgs production dynamics ....

To put it in perspective, the study of W/Z production properties started like this ....., from a score of events:





~15 signal events,
S/B~1

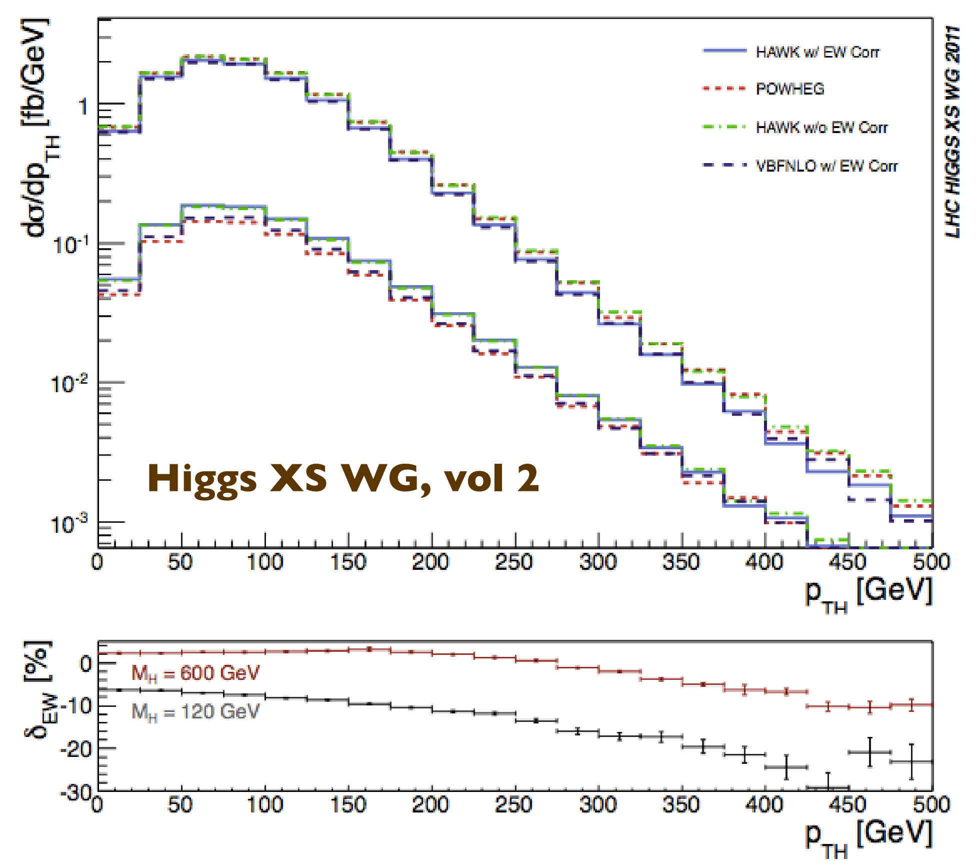


32 observed events
15.9 ± 2.1 expected [m$_H$=125 GeV]
11.1 ± 1.3 background expected

There is enough to start plotting pt(H), N$_{jet}$ distribution in H production, etc.

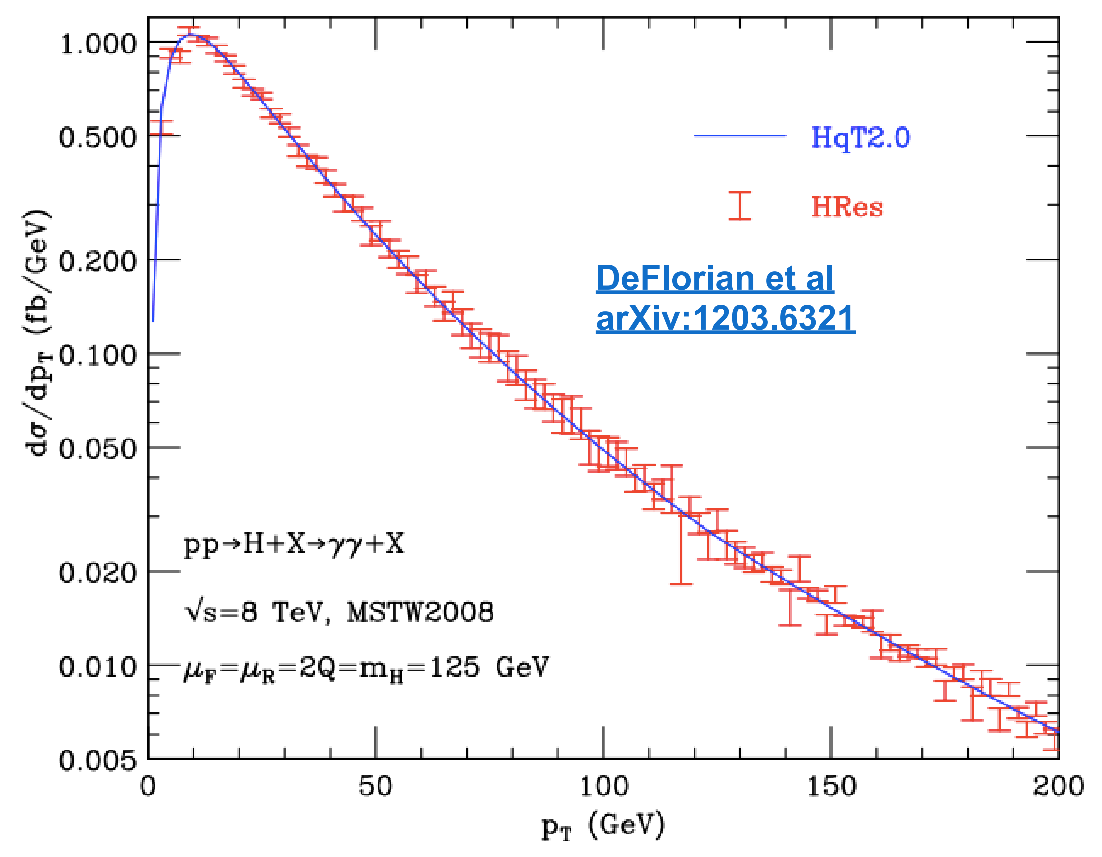
$p_T(H)$: qq → qq H vs gg → H

qq → qq H



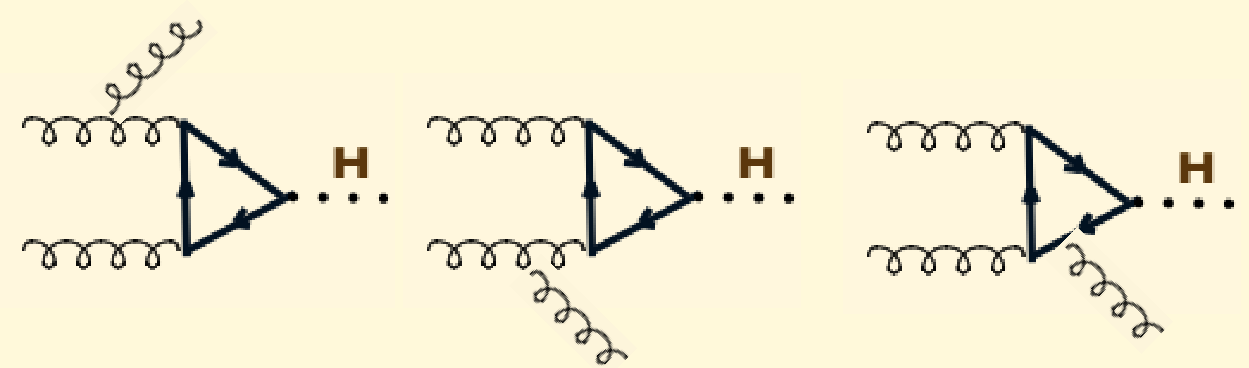
- p_T(peak)~60 GeV
- Large size of EW corrections

gg → H



- p_T(peak)~10 GeV

gg→H at $p_T > m_{top}$ resolves the inside of the production triangle, an alternative probe to its components



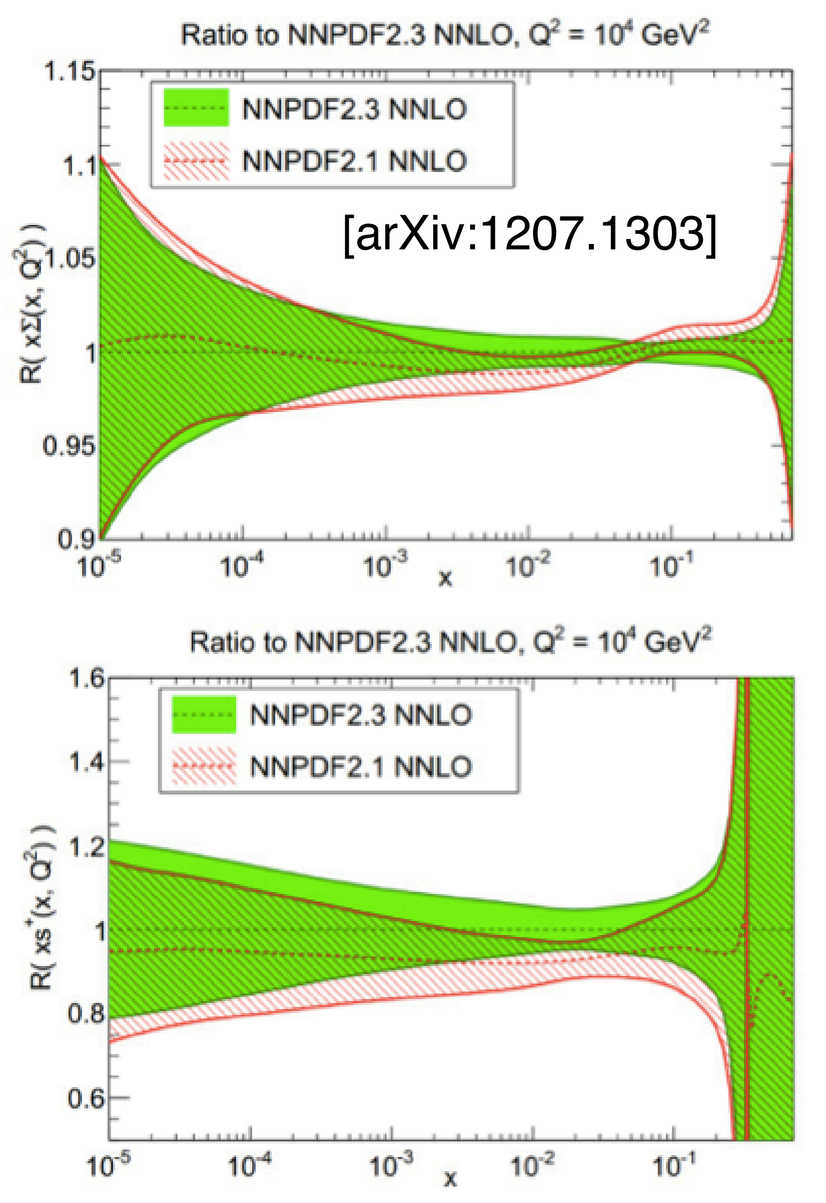
PDF progress

NNPDF2.3: First publicly available PDF set that includes LHC data in the fit.
Global fit, includes all relevant LHC data that were available with full covariance matrix

- ATLAS Inclusive Jets, 36pb^{-1}
- ATLAS W/Z lepton rapidity distributions, 36pb^{-1}
- CMS W lepton asymmetry, 840pb^{-1}
- LHCb W rapidity distributions, 36pb^{-1}

Impact of LHC data:

- Moderate effect from LHC data, generally less than half a sigma in central values.
- Largest impact is for Singlet and strange distributions.
- Expect more substantial improvements with 2011 and 2012 data.

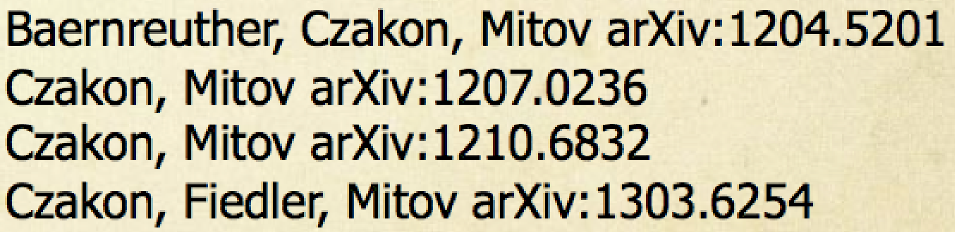


[arXiv:1207.1303]

Further progress from more data, and more accurate (NNLO) theory for a variety of processes probing different flavours and ranges of x and Q.

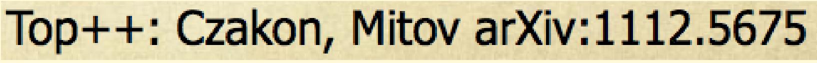
Recent progress in NNLO

- **Two long-awaited milestone calculations in progress, delivering first results:**
  - **Jet production**. Completed so far:
    - gg initial state: A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover, J. Pires, **arXiv:1301.7310**
  - **H+jet,** Boughezal, Caola, Melnikov, Petriello, Schulze, arXiv:1302.6216
  - **σ(tt)** (Czakon, Mitov et al): full results available for total cross section, at NNLO+NNLL



Baernreuther, Czakon, Mitov arXiv:1204.5201
Czakon, Mitov arXiv:1207.0236
Czakon, Mitov arXiv:1210.6832
Czakon, Fiedler, Mitov arXiv:1303.6254

    - implemented in a numerical code

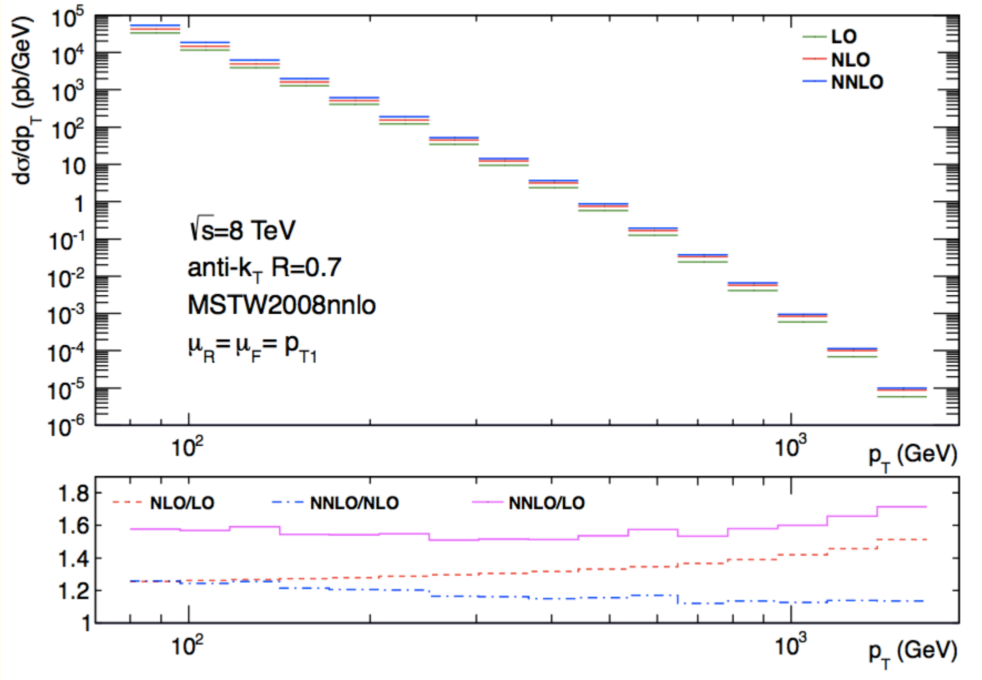


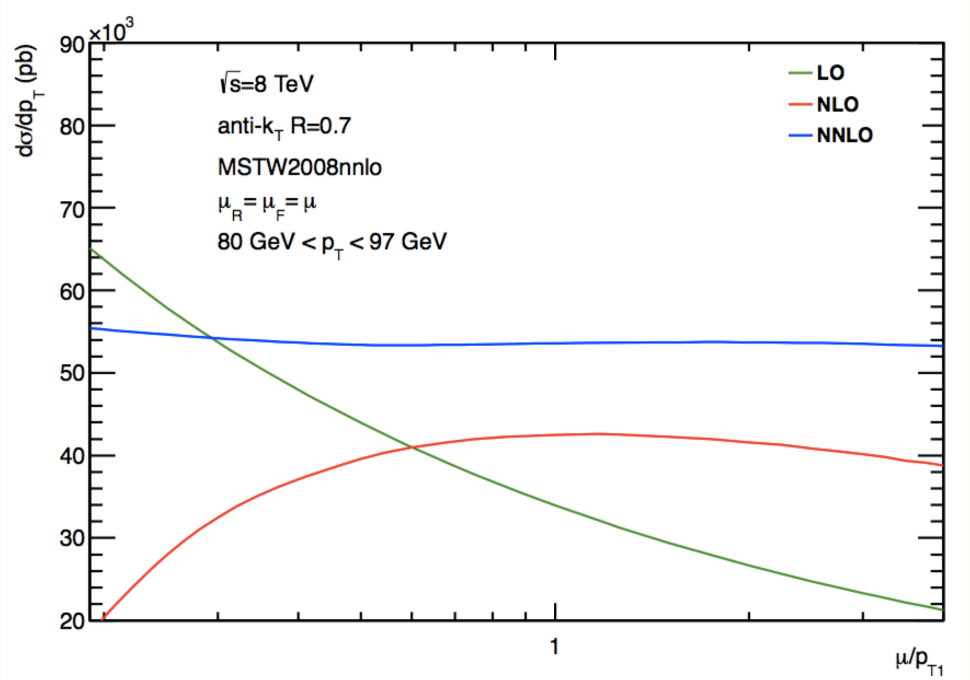
Top++: Czakon, Mitov arXiv:1112.5675

    - first NNLO result for production of coloured final state in hadron collisions, first direct probe of gluon PDF known to NNLO

Inclusive jet cross section at NNLO

“Second order QCD corrections to jet production at hadron colliders: the all-gluon contribution”, A. Gehrmann-De Ridder, T. Gehrmann, E.W. N. Glover, J. Pires, arXiv:1301.7310





NNLO/NLO ~ 1.2

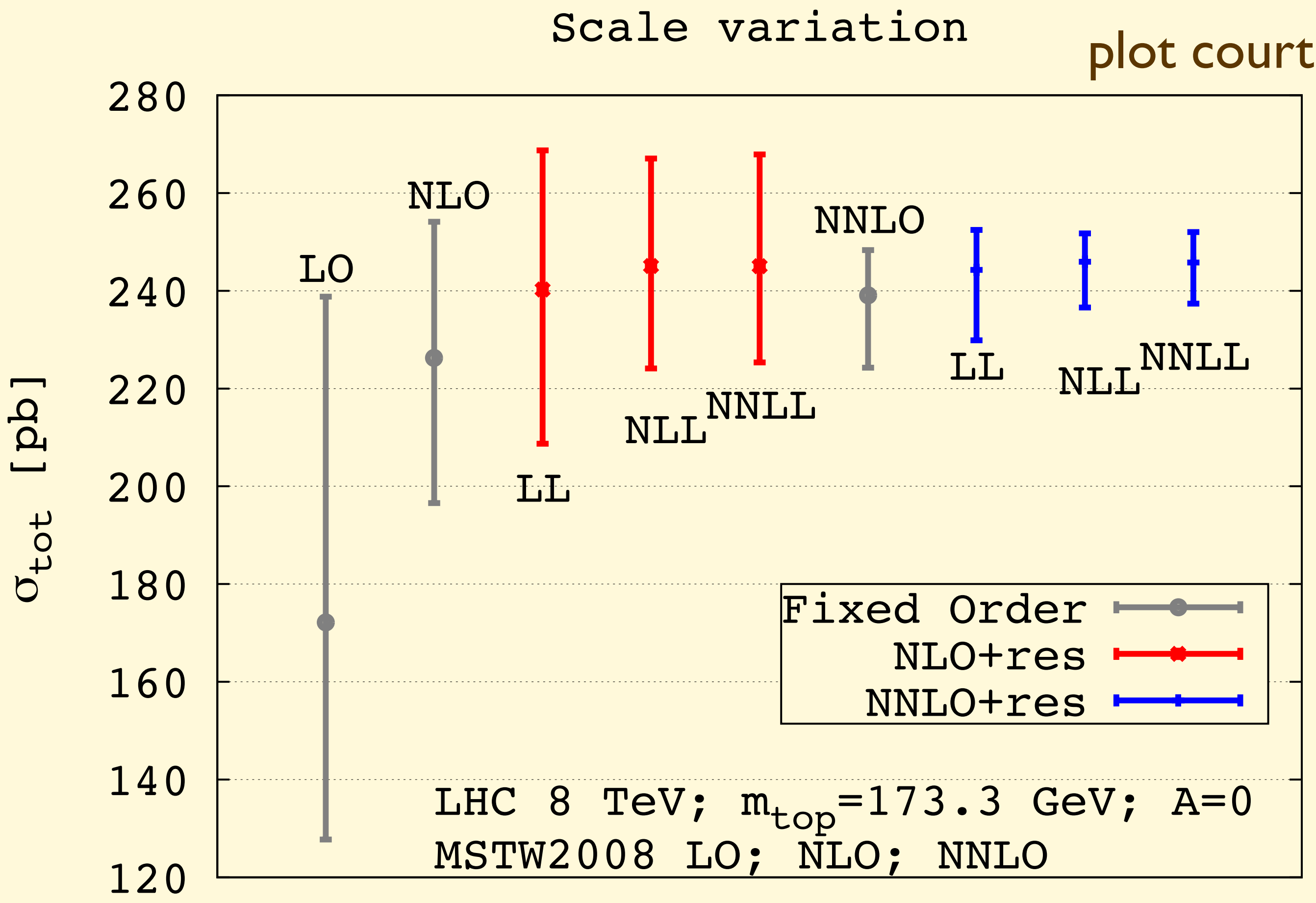
NNLO scale systematics ~ few % ...

- does this survive if $\mu_F \neq \mu_R$?

Notice that NNLO outside the NLO scale-variation band

At this level of precision, there are other things one should start considering. E.g. non-perturbative systematics and EW corrections

Inclusive tt cross section at NNLO



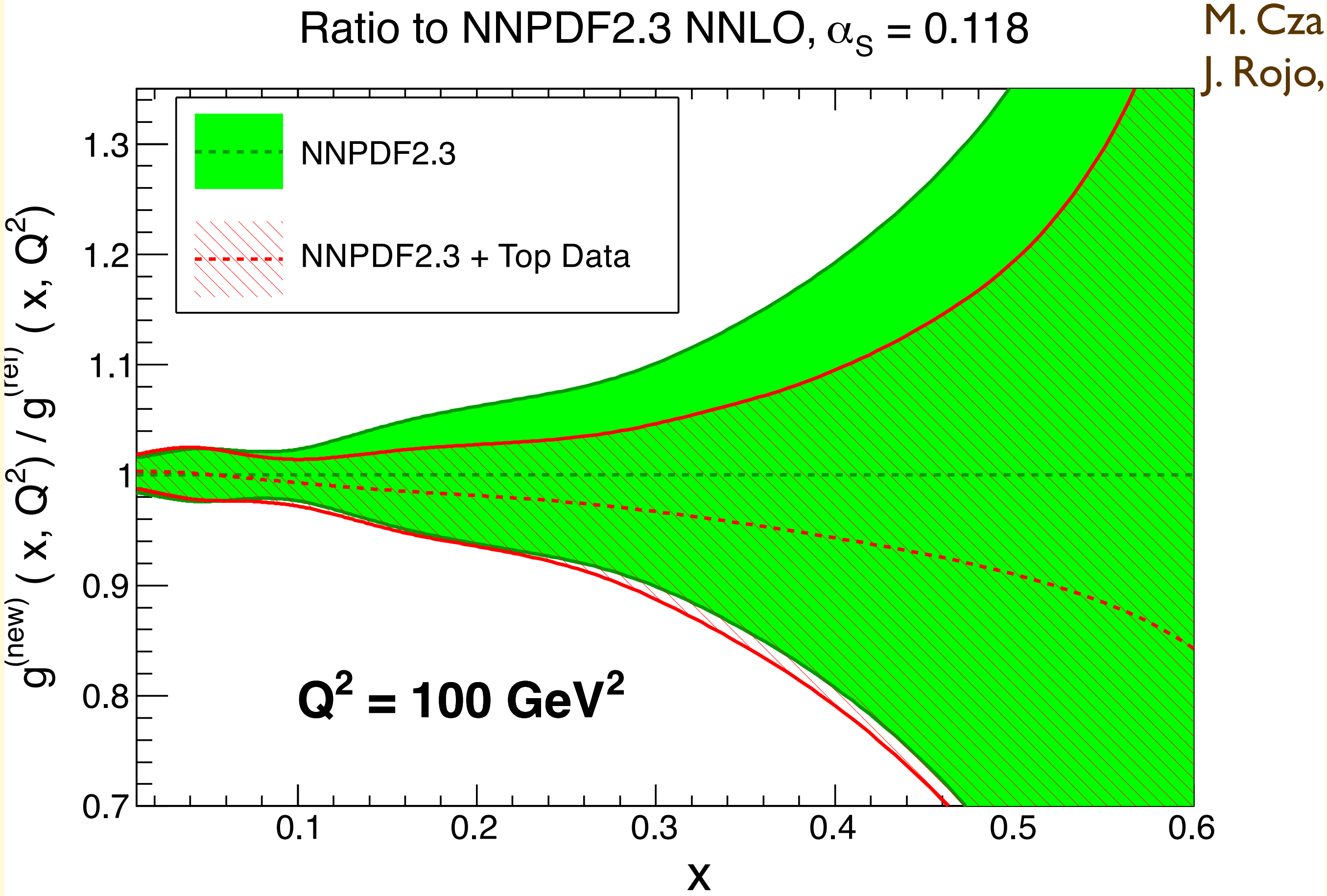
plot courtesy of A.Mitov

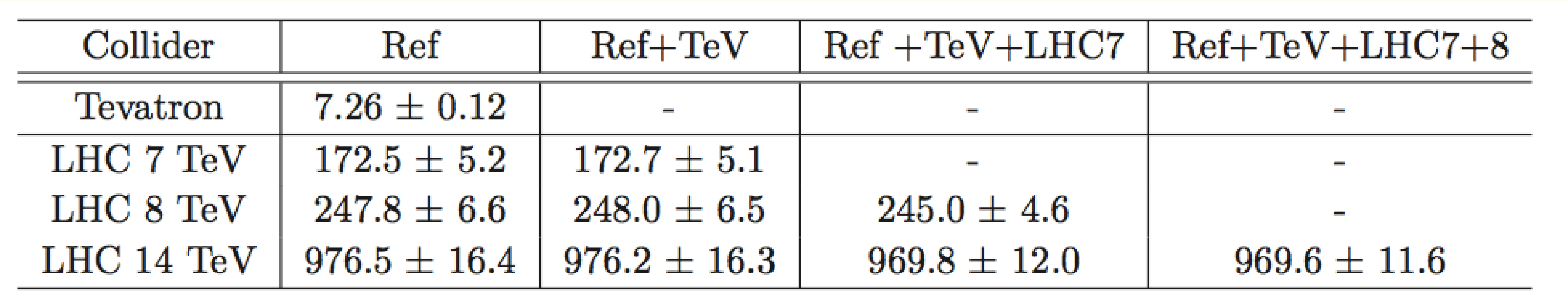
TH and parametric uncertainties are all of similar size:

- **Scale**: Independent μ_R , μ_F variation, ➡ 3%
  $0.5\ \mu_0 < \mu_{R,F} < 2\ \mu_0$ at $\mu_0 = m_{top}$,
  with $0.5 < \mu_R / \mu_F < 2$
- **PDF** (at 68%CL) ➡ 2-3%
- **$\Delta\alpha_s$** = ±0.0007 ➡ 1.5%
- **Δm_{top}** = ± 1 GeV ➡ 3%

Constraining the gluon PDF with LHC σ(tt)

M. Czakon, MLM, A. Mitov, J. Rojo, arXiv:1303.7215





Collider	Ref	Ref+TeV	Ref +TeV+LHC7	Ref+TeV+LHC7+8
Tevatron	7.26 ± 0.12	-	-	-
LHC 7 TeV	172.5 ± 5.2	172.7 ± 5.1	-	-
LHC 8 TeV	247.8 ± 6.6	248.0 ± 6.5	245.0 ± 4.6	-
LHC 14 TeV	976.5 ± 16.4	976.2 ± 16.3	969.8 ± 12.0	969.6 ± 11.6

x-range relevant for gg→H is smaller. Direct probe: $d\sigma/dp_T$ (Z), to be calculated at NNLO

Other important measurements and calculations, ancillary to precision studies and searches

- NLO→NNLO
- EW boson interactions at high energy (WW scattering, triple/ quadruple gauge boson couplings)
- EW radiative corrections to hard processes at the highest Q^2
  - jet cross sections, W/Z+jets, top production, Higgs production
- Exploration of extreme kinematical regions (large-x, co-existence of different mass scales and large Sudakov effects, ...), to control theory predictions for highest Q^2 exotic BSM processes, improve accuracy of PDFs at large x, ...
- Ever more precise measurements of m(W) and m(top)
- .....

Concluding remarks

Concluding remarks

- The key outcome of the Higgs observation and other LHC findings is a confirmation of the relevance of the hierarchy problem. The future of accelerator physics should be tailored to address this question.

Concluding remarks

- The key outcome of the Higgs observation and other LHC findings is a confirmation of the relevance of the hierarchy problem. The future of accelerator physics should be tailored to address this question.
- Obvious priorities include:

Concluding remarks

- The key outcome of the Higgs observation and other LHC findings is a confirmation of the relevance of the hierarchy problem. The future of accelerator physics should be tailored to address this question.
- Obvious priorities include:
    - Precision studies of Higgs properties:

Concluding remarks

- The key outcome of the Higgs observation and other LHC findings is a confirmation of the relevance of the hierarchy problem. The future of accelerator physics should be tailored to address this question.
- Obvious priorities include:
  - Precision studies of Higgs properties:
    - H decay branching ratios, very rare H decay modes, including flavour violating ones

Concluding remarks

- The key outcome of the Higgs observation and other LHC findings is a confirmation of the relevance of the hierarchy problem. The future of accelerator physics should be tailored to address this question.
- Obvious priorities include:
  - Precision studies of Higgs properties:
    - H decay branching ratios, very rare H decay modes, including flavour violating ones
    - H production and interactions at large Q^2

Concluding remarks

- The key outcome of the Higgs observation and other LHC findings is a confirmation of the relevance of the hierarchy problem. The future of accelerator physics should be tailored to address this question.
- Obvious priorities include:
    - Precision studies of Higgs properties:
        - H decay branching ratios, very rare H decay modes, including flavour violating ones
        - H production and interactions at large Q^2
    - Dig deeper in the search of well-hidden BSM processes, and extend mass reach going to higher energy

Concluding remarks

- The key outcome of the Higgs observation and other LHC findings is a confirmation of the relevance of the hierarchy problem. The future of accelerator physics should be tailored to address this question.
- Obvious priorities include:
  - Precision studies of Higgs properties:
    - H decay branching ratios, very rare H decay modes, including flavour violating ones
    - H production and interactions at large Q^2
  - Dig deeper in the search of well-hidden BSM processes, and extend mass reach going to higher energy
- The fact that no BSM has been seen as yet implies that, if anything will be seen, it will take a lot of luminosity and/or energy to study it in detail!

Concluding remarks

- The key outcome of the Higgs observation and other LHC findings is a confirmation of the relevance of the hierarchy problem. The future of accelerator physics should be tailored to address this question.
- Obvious priorities include:
  - Precision studies of Higgs properties:
    - H decay branching ratios, very rare H decay modes, including flavour violating ones
    - H production and interactions at large Q^2
  - Dig deeper in the search of well-hidden BSM processes, and extend mass reach going to higher energy
- The fact that no BSM has been seen as yet implies that, if anything will be seen, it will take a lot of luminosity and/or energy to study it in detail!
- The same is true for a complete study of the EWSB sector.

Concluding remarks

Concluding remarks

- The difficulty and timescales of necessary theoretical calculations match the challenge of building the experiments, and of doing precise measurements. It will be a tough ride for the whole community, mitigated only by the occasional excitement of a fresh discovery.

Concluding remarks

- The difficulty and timescales of necessary theoretical calculations match the challenge of building the experiments, and of doing precise measurements. It will be a tough ride for the whole community, mitigated only by the occasional excitement of a fresh discovery.
- It took 40 years to wrap up the SM, it may take longer to tackle the next layer. The future plan must ensure a continued interest and excitement, justified by new and challenging measurements, to fill possibly long discover-less periods!

Concluding remarks

- The difficulty and timescales of necessary theoretical calculations match the challenge of building the experiments, and of doing precise measurements. It will be a tough ride for the whole community, mitigated only by the occasional excitement of a fresh discovery.
- It took 40 years to wrap up the SM, it may take longer to tackle the next layer. The future plan must ensure a continued interest and excitement, justified by new and challenging measurements, to fill possibly long discover-less periods!
- Experimentalists often want from theorists a good physics case to justify some future facility. We can give many physics cases: whether they're good, it's a different story. So far theorists have been mostly right with the SM (mtop, CKM and CPV, mHiggs), but mostly wrong with BSM, which is where we are moving towards now. Exptl's should take the lead again, and revamp the excitement of the exploration of the unknown, motivated by the pleasure of meeting tough technological challenges, making exciting and unique measurements, and pushing the frontier of knowledge.

Concluding remarks

- The difficulty and timescales of necessary theoretical calculations match the challenge of building the experiments, and of doing precise measurements. It will be a tough ride for the whole community, mitigated only by the occasional excitement of a fresh discovery.
- It took 40 years to wrap up the SM, it may take longer to tackle the next layer. The future plan must ensure a continued interest and excitement, justified by new and challenging measurements, to fill possibly long discover-less periods!
- Experimentalists often want from theorists a good physics case to justify some future facility. We can give many physics cases: whether they're good, it's a different story. So far theorists have been mostly right with the SM (mtop, CKM and CPV, mHiggs), but mostly wrong with BSM, which is where we are moving towards now. Exptl's should take the lead again, and revamp the excitement of the exploration of the unknown, motivated by the pleasure of meeting tough technological challenges, making exciting and unique measurements, and pushing the frontier of knowledge.
- In my view, the current theoretical perspective justifies a call for a fast track approach to (a hadron collider at) the highest possible energy, with an interim filled by the fullest exploitation of the LHC, pushing further the discovery reach and the precision measurements, and possibly by a Japanese e^+e^- Higgs factory