THE HIGGS BOSON IN THEORY

Babis Anastasiou
ETH Zurich

BEFORE JULY 4

- Theorists had various expectations about how a Higgs discovery would come.
- I would like to take you three years back where we had a grand belief and a grand hope
- Grand belief: physics beyond the Standard Model is inevitable
- Grand hope: physics beyond the Standard Model at the LHC is inevitable.

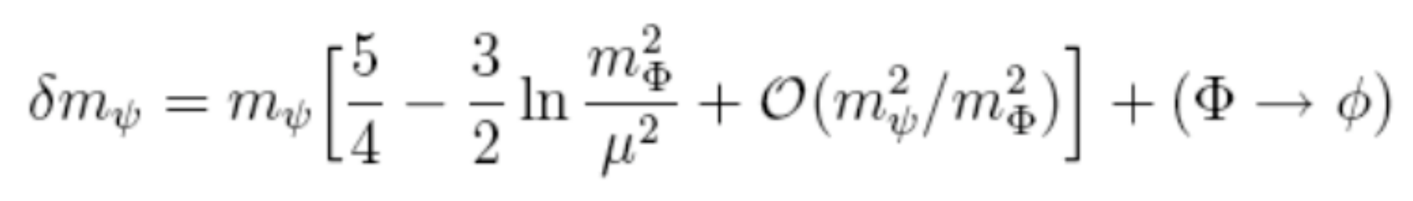
Higgs physics could be different than in the Standard Model

THE SM IS UNPROTECTED

- In naive extensions of the Standard Model, fundamental scalars receive large mass-redefinitions at each order in perturbation theory:

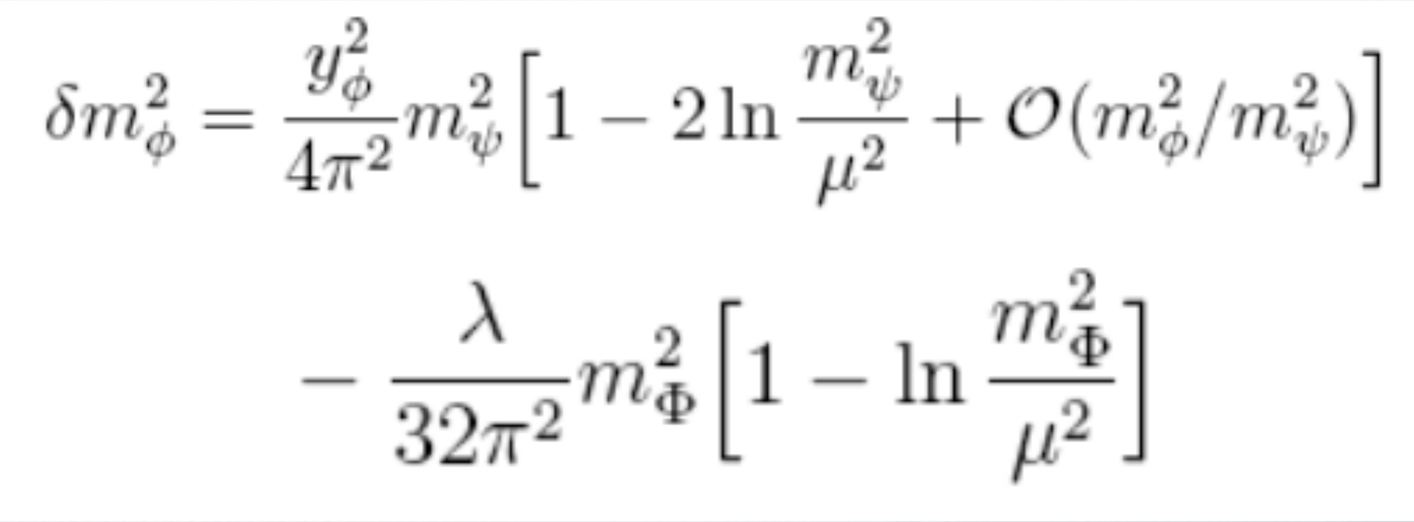
$$
\begin{aligned}
\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{m_\phi^2}{2}\phi^2 \\
+\frac{1}{2}\left(\partial_\mu \Phi\right)^2 - \frac{m_\Phi^2}{2}\Phi^2 \\
+\bar{\psi}\left(i\gamma^\mu \partial_\mu - m_\psi\right)\psi \\
-\frac{1}{4}\lambda\phi^2\Phi^2 - y_\phi \phi\bar{\psi}\psi - y_\Phi \Phi\bar{\psi}\psi
\end{aligned}
$$

- spoiling electroweak precision tests,



$$\delta m_\psi = m_\psi\left[\frac{5}{4} - \frac{3}{2}\ln\frac{m_\Phi^2}{\mu^2} + \mathcal{O}(m_\psi^2/m_\Phi^2)\right] + (\Phi \to \phi)$$

- destabilizing Higgs boson observables at higher orders in perturbation theory.



$$
\begin{aligned}
\delta m_\phi^2 = \frac{y_\phi^2}{4\pi^2} m_\psi^2\left[1 - 2\ln\frac{m_\psi^2}{\mu^2} + \mathcal{O}(m_\phi^2/m_\psi^2)\right] \\
- \frac{\lambda}{32\pi^2} m_\Phi^2\left[1 - \ln\frac{m_\Phi^2}{\mu^2}\right]
\end{aligned}
$$

SOLVING THE HIERARCHY PROBLEM

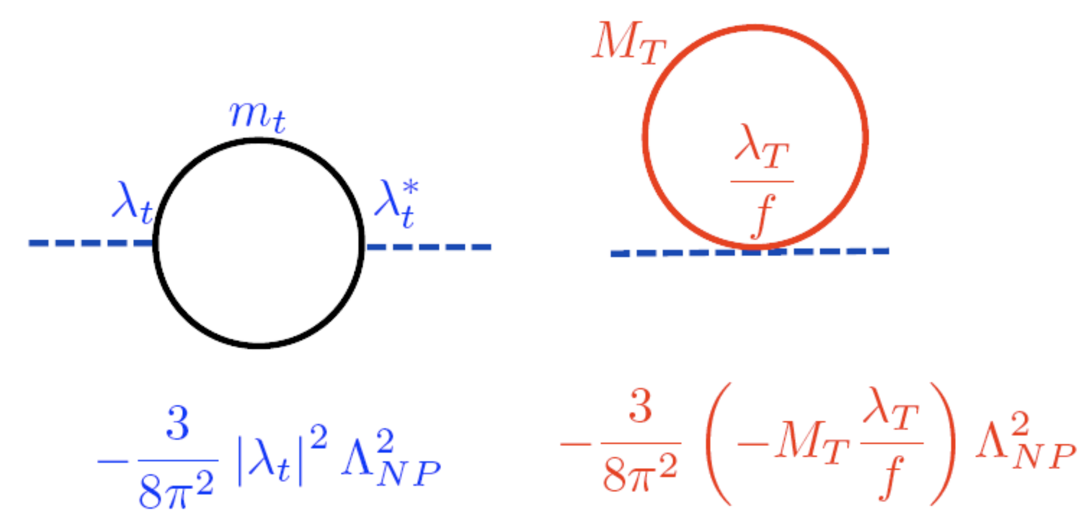
- **No new physics at all:** ***Higgs physics is exactly as in the SM***.
  Not a physics option just a technical option.

- **“accidents”:** there is no new physics at the electroweak scale, but at a higher scale. It requires increasingly fine cancelations the higher the new physics scale.
  Higgs physics does not need to deviate from the SM.
  No scale between the electroweak scale and the ~Planck is special.

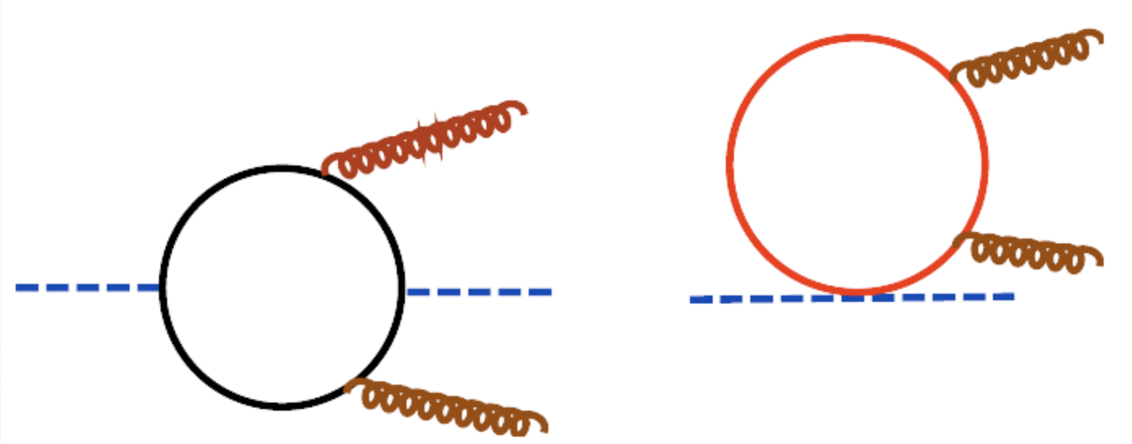
- **broken symmetries or non-perturbative protections at LHC energies:** rich new physics is around the corner - electroweak scale - and stabilizes the Higgs sector up to very high energies. ***Higgs physics may deviate from the SM.***

BUILDING PROTECTIONS AND HIGGS PHYSICS

Heavy particles appear in symmetry multiplets



Such cancelations are passed on loop induced Higgs processes ***(Rattazzi,Low; Falkowski)***



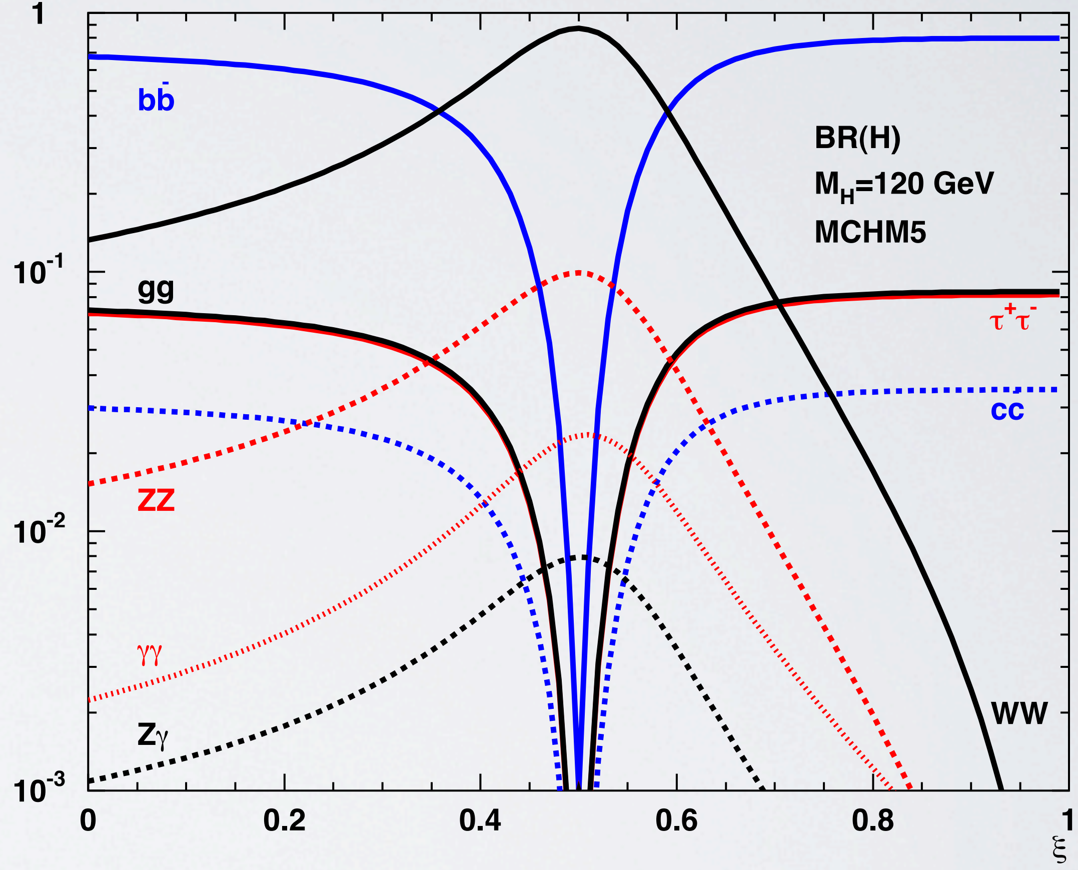
EFFECTS ON HIGGS PHENOMENOLOGY

- Higgs production cross-sections and decay widths are typically smaller than in the SM.

- Some room for enhanced branching ratios (by reducing the $H \to bb$ width or enhancing directly the loop induced decay widths).

- Large excesses over Standard Model rates for Higgs signals are difficult to accommodate.

- Deviations from SM rates for Higgs signals is not meant to be the "smoking gun" of these theories which have a rich spectrum of light new particles.



Espinosa, Grojean, Muhlleitner

SM **Composite Higgs** **"Techni-color"**

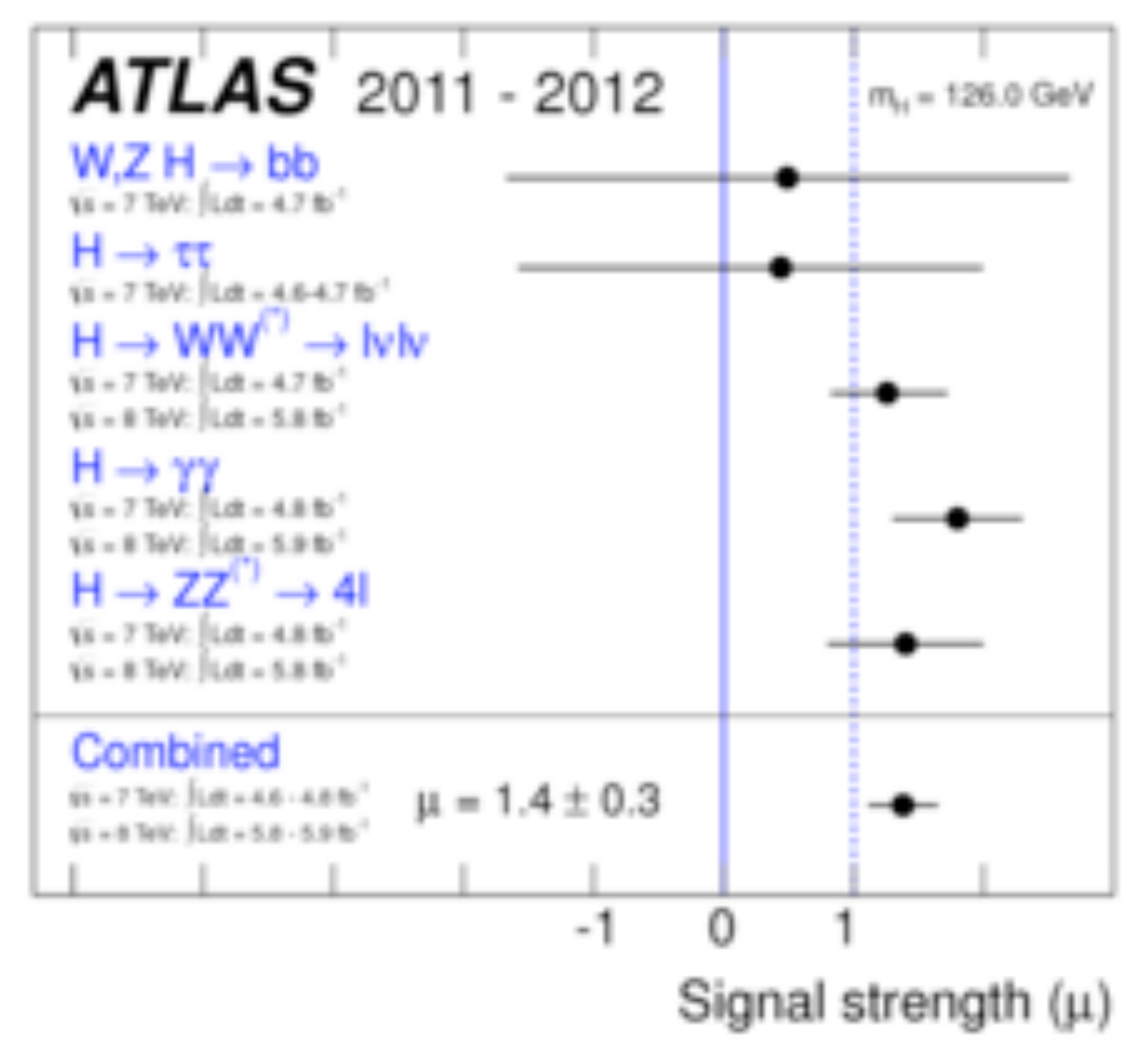
An example of a natural theory

AFTER JULY 4

- ATLAS and CMS found a Higgs boson.
- This is the most difficult discovery in modern particle physics.
- Search for rare events. Cross-sections of a 2-50 fb.
- Clever and mature analyses with very high signal efficiencies.
- The mass is where electroweak precision tests like a Higgs boson to be in the Standard Model.

ATLAS DISCOVERY

- Three channels.
  H→ZZ→llll,
  H→gamma gamma,
  H→WW
  with 8 TeV data.
- Results: a convincing excess in all three channels.
- Consistent with Standard Model
- However, a stronger production is quite possible.



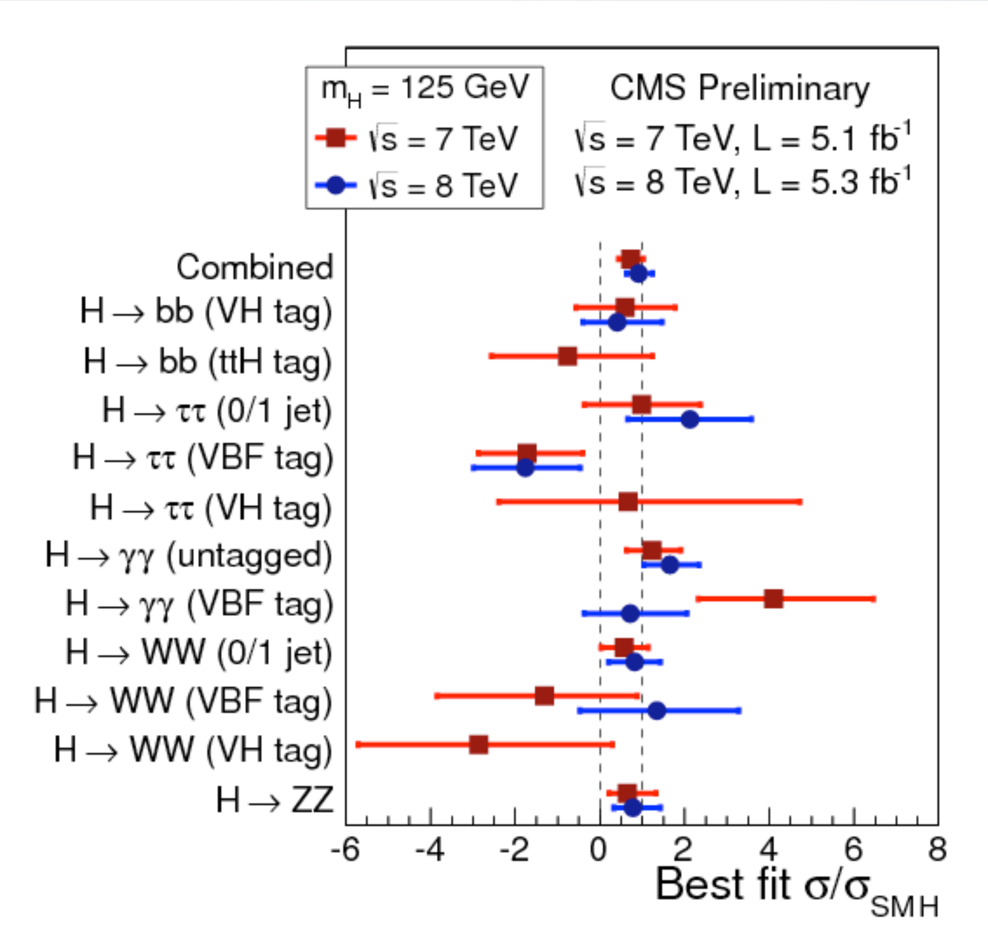
CMS DISCOVERY

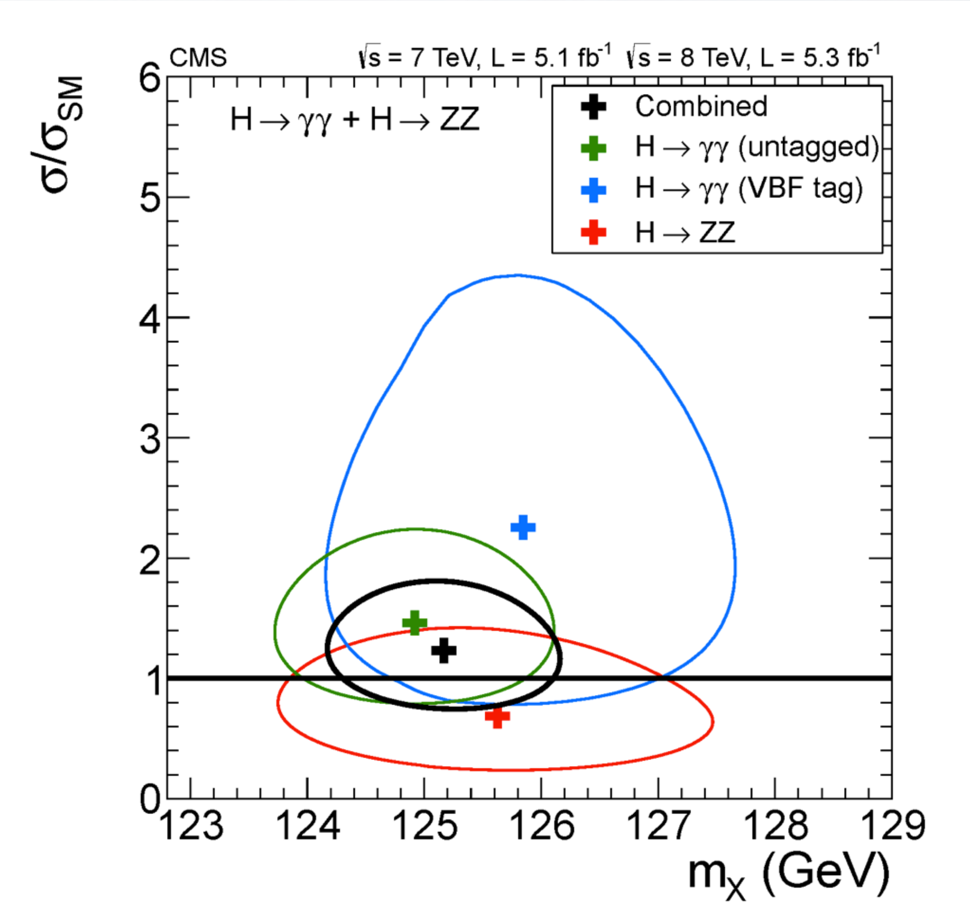
- **H→gamma,gamma,**
  H→ZZ,
  H→WW,
  H→tau tau,
  H→bb with 8 TeV data

- A convincing excess in **H→ZZ,WW,gamma-gamma**

- **H→tau tau** has a very small S/B (~3%).
  e-hadronic seems in tension with a SM Higgs at 125 GeV. mu-hadronic seems OK.

- In WW, the 0-jet mu-e category seems to be consistent with SM or higher rate. Other categories seem to favor a smaller cross-section than SM, but are consistent with one times SM.





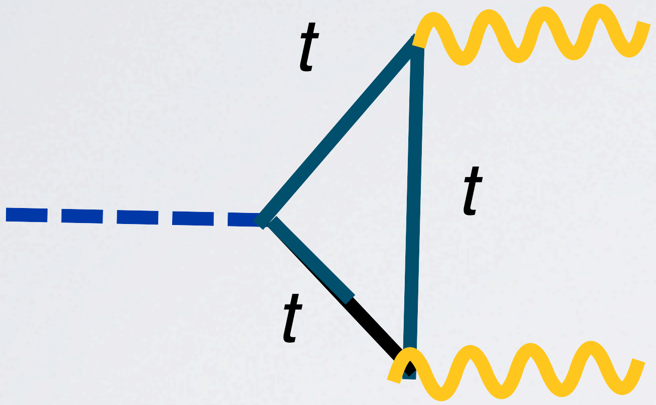
READING OF GENERAL EXPERIMENTAL PICTURE

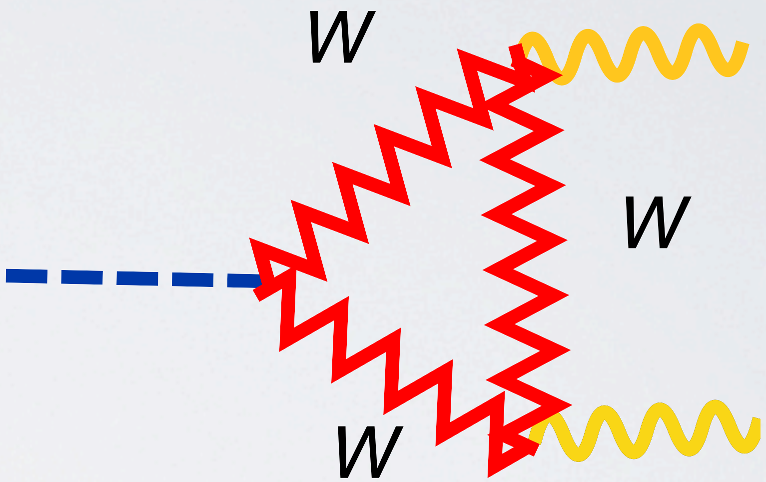
- We have a Higgs boson which is consistent with the Standard Model.
- Is the di-photon branching ratio enhanced? Is the tau-tau coupling reduced? Are the WW and ZZ fine or bigger than the Standard Model?
- We rely on a very small number of events to draw conclusions. We cannot distinguish clearly between data fluctuations and a new physics phenomenon.
- We will know with a better precision (factor of two?) by the end of this LHC run. The picture will be much clearer with the 14TeV run.
- Measurements leave a lot of room for new physics manifesting itself as atypical Higgs interactions.

IMAGINING AHEAD THE OUTCOMES OF FUTURE EXPERIMENTAL UPDATES

- scenario A : The di-photon channel remains high, while other measurements are SM-like.
- scenario B : The tau-tau channel remains low and the di-photon channel remains high
- scenario C: The WW, ZZ, diphoton remain all high (as it appears with ATLAS)
- ...

TWO PHOTON DECAY IN THE STANDARD MODEL





(Light Higgs)

$$N_c Q_t^2 (4/3)$$

$$(-7)$$

Sensitive to new colorless or colored particles

Production via gluon fusion is sensitive to colored new particles only.

SCENARIO A : HIGH DI-PHOTON AND SM-LIKE RATES IN OTHER CHANNELS

- To preserve the SM-like predictions in all other channels, new states should not couple to gluons (leptons, new W bosons, colorless new scalars).

- The mass of these new states is not entirely given by the Higgs vev (e.g. vector-like leptons to produce a negative Yukawa coupling)

- To induce a large modification of the di-photon signal, new states must have a large coupling to the Higgs boson and be relatively light (~ few100s of GeV).

- Trouble with the Higgs potential and vacuum stability (more new physics around ~ 1TeV).

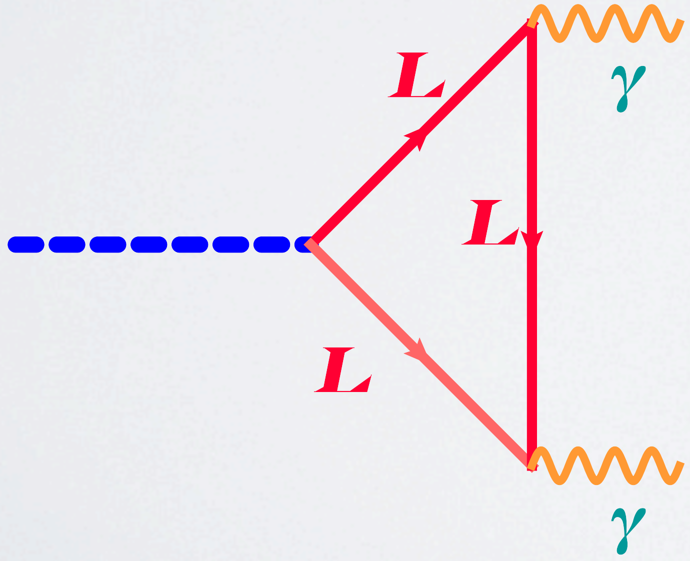
- ...or we should consider a more complicated and very conspiring Higgs sector, with different couplings than in the SM at the tree-level already.

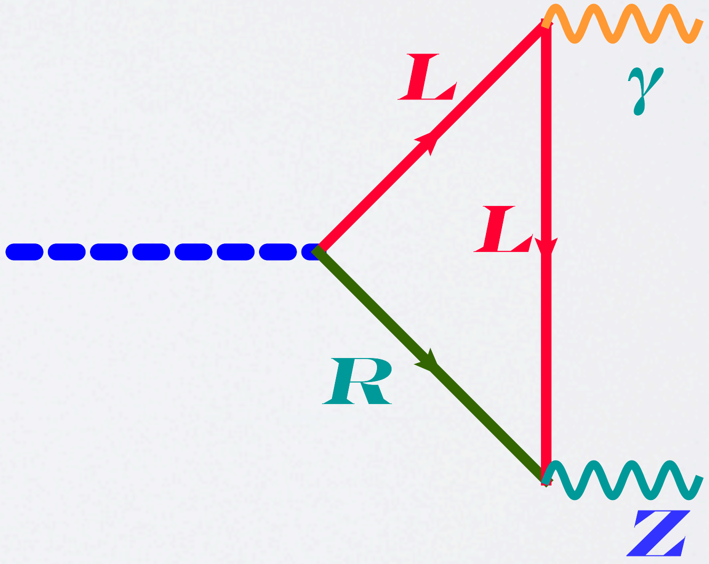
THE DI-PHOTON PUZZLE

- Exotic objects such as colorless scalars, new W's and new leptons can be part of Randall-Sundrum, little Higgs, composite Higgs and supersymmetric models.
- Puzzle: why are they hiding from direct detection so far?
- Could be protected by discrete symmetries which forbid $1 \rightarrow 2$ decays into SM particles besides the Higgs.
- Possible connection with dark matter searches, which may need to be target a smaller amount of missing energy.
- Puzzle: If this anomaly is a manifestation of fully fledged theory with all nice properties, such as dark matter, protecting the Higgs potential and solving the hierarchy problem, why are colored Higgs production and decay protected?

THE BR(H → Z-GAMMA)

- If we have an anomaly in the diphoton channel, the rarer decay to a Z boson and a photon becomes especially important.
- It is sensitive to flavor changing effects while the di-photon decay is not.





SCENARIO B : SMALL BR(H->TAU-TAU)

- The Higgs →tau-tau measurements are very preliminary. Also, they battle against a very low signal/background ratio.
- But, it will be interesting to have a situation where we need to explain a largish/normal BR(H→bb) as TEVATRON suggests, a small BR(H→tau-tau) and an enhanced di-photon channel.
- This would point to some type of tau-partners causing both deviations.
- But, I do not know of a successful model in this direction.

SO?

- It is very hard to make theoretically consistent models which explain a large di-photon rate with a minimal (unnatural) spectrum.
- These attempts have to be completed at some TeV-ish scale with more new physics.
- It is perhaps even harder to use natural models with a rich light spectrum which are not yet excluded.
- But we should keep looking for light top/bottom/tau partners, supersymmetric or not, as vigorously as possible. Light particles are not necessarily easy to detect.

SCENARIO C :
A "GLOBAL" ENHANCEMENT

- What if further data indicates an enhancement to all major signals?

- This is not such a crazy scenario to contemplate: all ATLAS measurements for Higgs processes in 2012 have somewhat high central values.

- I would try to resolve such a situation with perturbative QCD.

- Are perturbative QCD corrections for Higgs production in gluon fusion estimated precisely?

A HIGGS TEST OF PERTURBATIVE QCD

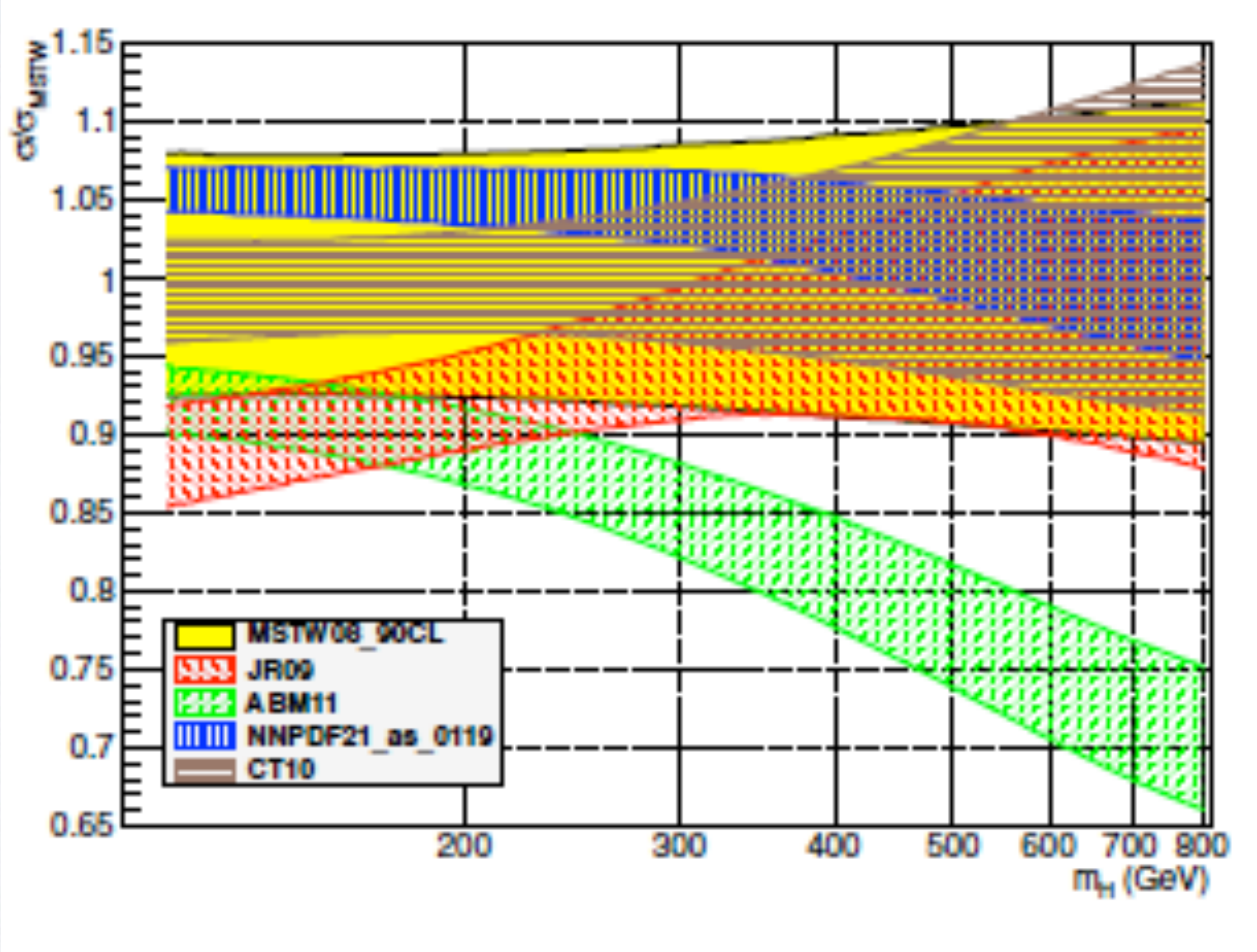
- QCD is diagonal to the electroweak gauge group. Corrections are “global” to all decay final states.

- It will be relatively easy to tell apart shortcomings of perturbative QCD and BSM effects by looking at ratios of cross-sections.

- How much do we trust our perturbative QCD computations?

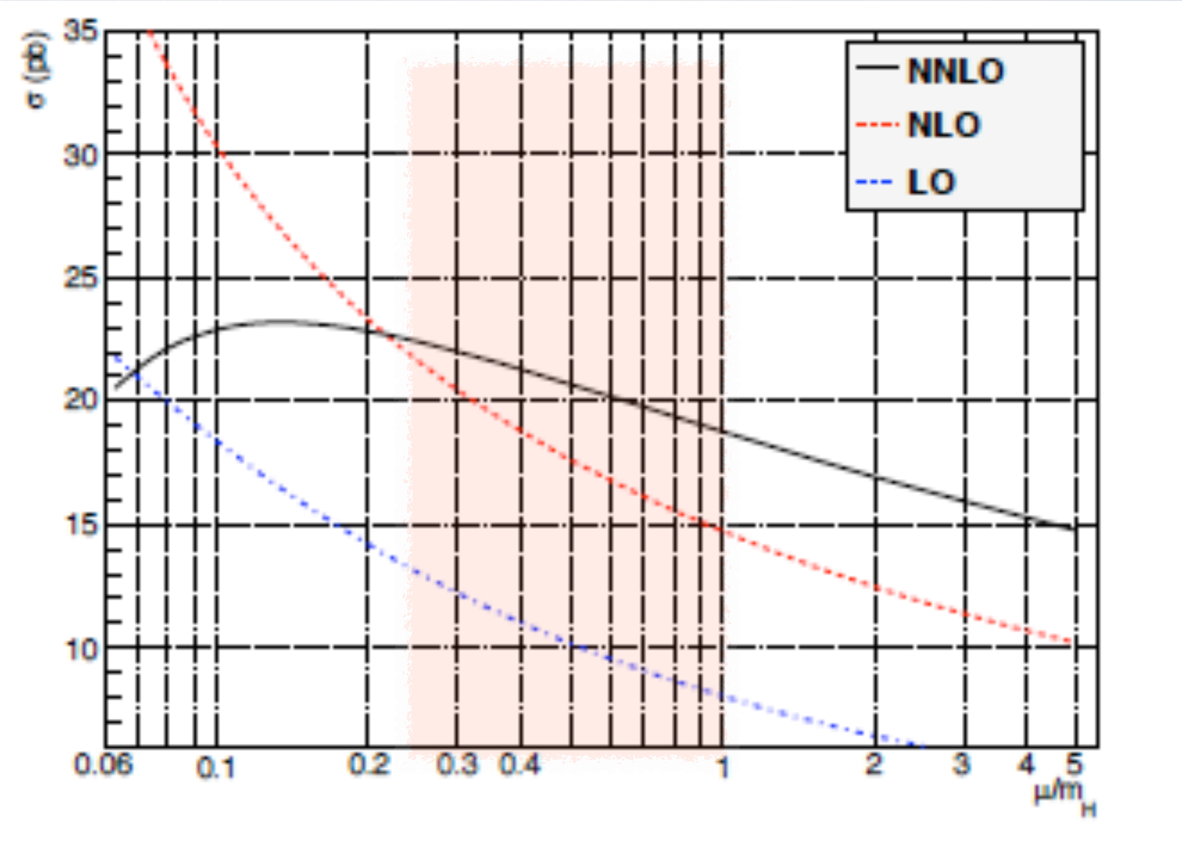
PDF UNCERTAINTIES

- Five NNLO pdf sets
- 68% confidence level uncertainties show discrepancies
- Situation can be ameliorated by adopting the 90%CL uncertainty of MSTW
- Still, ABM11 set is quite different. ABM11 finds a lower value of alpha_s, relies on less data, but not yet shown to disagree with LHC data. Their alpha_s value is in tension with measurements of the Z and W decay widths as well as LEP data and tau decays.
- Important: high precision measurements of top and other SM cross-sections at the LHC.



SCALE VARIATIONS

- The Higgs cross-section has worried us for a long time about its slow perturbative convergence.
- perturbative series converges well for scales around half the Higgs mass
- but very slowly for higher scales.
- should we trust the NNLO computations?
- Let's dissect them



NLO QCD CORRECTIONS

cross-section for gluon fusion via a heavy (top) quark:

$$\sigma \sim \mathcal{L}_{gg}\,(\mu) \times \left(\frac{\alpha_s(\mu)}{\pi}\right)^2$$

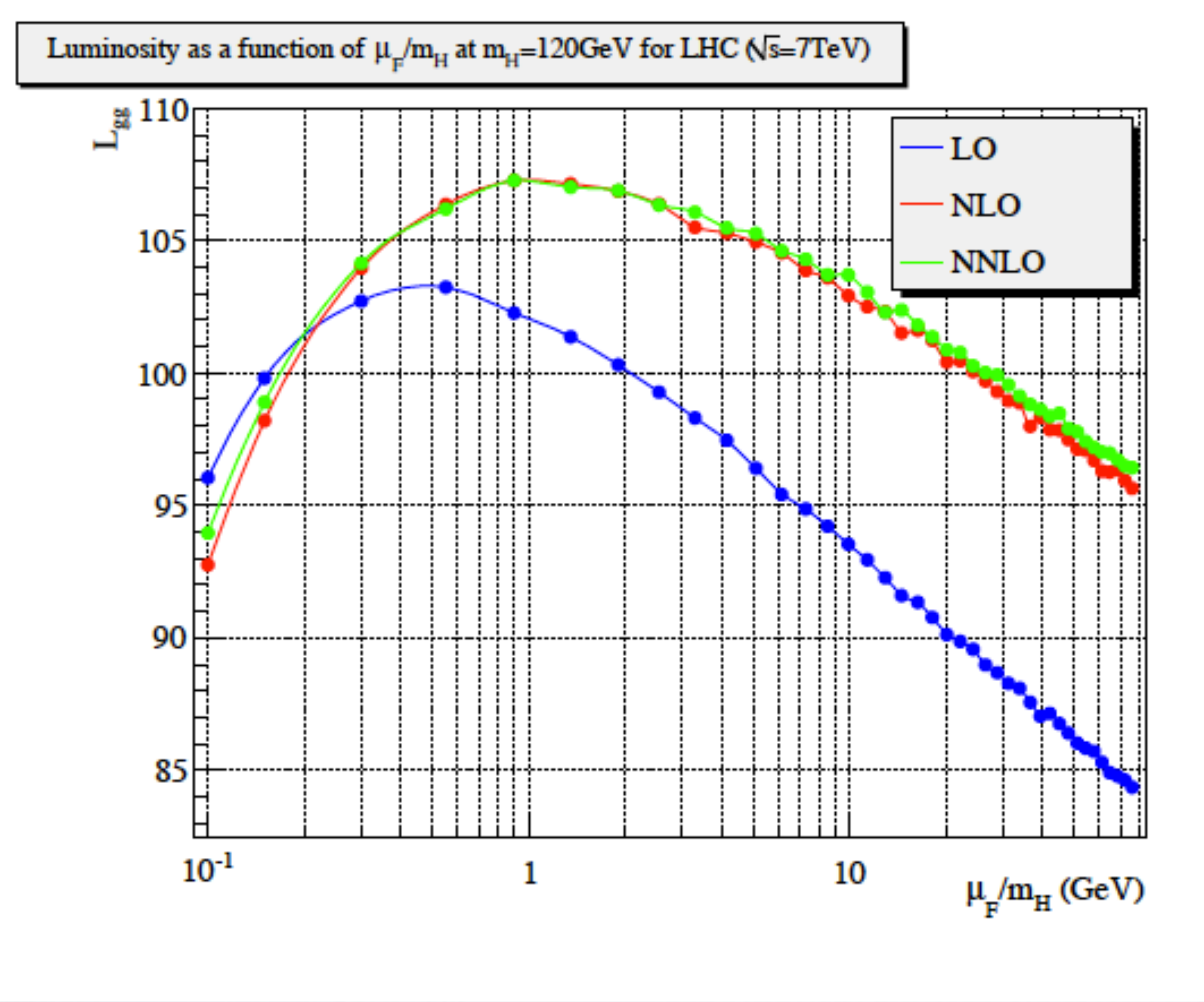
$$\left\{1 + \frac{\alpha_s(\mu)}{\pi}\left[N_c\frac{\pi^2}{3} + \frac{11}{2}\right] + 2\log\left(\frac{\mu^2}{p_T^2}\right) N_c\mathrm{Coll}\left(\frac{p_t^2}{M_h^2}\right) + \mathrm{Reg}\left(\frac{p_t^2}{M_h^2}, \theta\right)\right\}$$

Soft real and virtual corrections $\pi^2, \log\left(\frac{\mu^2}{p_T^2}\right)$

$\frac{11}{2} = 2\,C_1$ Wilson coefficient of Heavy Quark Effective Theory (~ UV nature)

$\mathrm{Reg}\left(\frac{p_t^2}{M_h^2}, \theta\right) \to 0,$ hard, vanishes in $p_t, \theta, \pi - \theta \to 0$

GLUON-GLUON LUMINOSITY



Lgg(Mh=120GeV, LHC7, MSTW08)

- Very stable from NLO to NNLO
- Within 5% from LO for a light Higgs boson at the LHC for reasonable factorization scales.
- ~ 20% higher than LO for large factorization scales

LARGE K-FACTORS

$$\frac{\text{NLO}}{\text{LO}} \sim \underset{\text{NLO/LO gluons and alpha\_s}}{(80\% - 105\%)} \left\{ 1 + 4\% \left[\overset{\pi^2}{9.876} + \underset{\text{Wilson coefficient}}{5.5} \right] + \dots \right\}$$

Bound to have a large K-factor of at least 1.5-1.6 due to pi's and the Wilson coefficient

Milder K-factor if gluon fusion is mediated through a light quark (bottom) as, for example, in large tan(beta) MSSM.

$$\frac{\text{NLO}}{\text{LO}} \sim (80\% - 105\%) \left\{ 1 + 4\% \left[\underset{\pi^2}{9.876} + \overset{\text{Two-loop bottom amplitude.}}{0.9053} \right] + \dots \right\}$$

LARGE K-FACTORS (II)

$$\frac{\text{NLO}}{\text{LO}} \sim (80\% - 105\%) \left\{ 1 + \frac{\alpha_s(\mu)}{\pi}\left[\ldots + 6\log\left(\frac{\mu^2}{p_T^2}\right) + \ldots\right]\right\}$$

NLO/LO gluons
and alpha_s

- Logarithmic enhancement at small transverse momentum
- Integrable: reliable perturbative expansion for inclusive cross-sections.
- The mu scale is arbitrary, but no need to be senseless.
- Choices very different than pt can spoil the perturbative expansion.

$$M_H = 120\,\text{GeV}\ \text{@LHC7} \rightsquigarrow < p_t > \sim 35\,\text{GeV}$$

$$\left\{1 + 4\%\left[\,9.876 \;+\; 5.5 \;+\mathcal{O}(15.)\right] + \ldots\right\} \quad \mu = M_h$$

π^2 *Wilson coefficient* *Pt-Log*

$$\frac{\text{NLO}}{\text{LO}} \sim (80\% - 105\%)$$

$$\left\{1 + 4\%\left[\,9.876 \;+\; 5.5 \;+\mathcal{O}(1.)\right] + \ldots\right\} \quad \mu = \frac{M_h}{4}$$

NLO/LO gluons
and alpha_s

PERTURBATIVE CONVERGENCE?

- Three main worries from the NLO calculation:
  - Large NLO Wilson coefficient ~15-20%
  - Pi^2 = 2 x Nc x (Pi^2/6) term ~ 30-40%
  - Large logs (2 x Nc x Log(pt^2/mu^2)) of transverse momentum (sensitive to mu) ~1% - 80%

- Comforting that the NNLO corrections are mild. The Wilson coefficient has a regular perturbative expansion.

At NNLO:

Wilson coefficient

$$C \sim 1 + (4\%) \cdot 5.5 + (4\%)^2 \cdot 10.$$

Chetyrkin, Kniehl, Steinhauser

PERTURBATIVE CONVERGENCE?

- Half of Pi^2 belongs to a different Wilson coefficient when matching to SCET. It ``exponentiates''. We are left to explain with the other half, which is a smaller (half) concern.

At NNLO and beyond:

Ahrens, Becher, Neubert

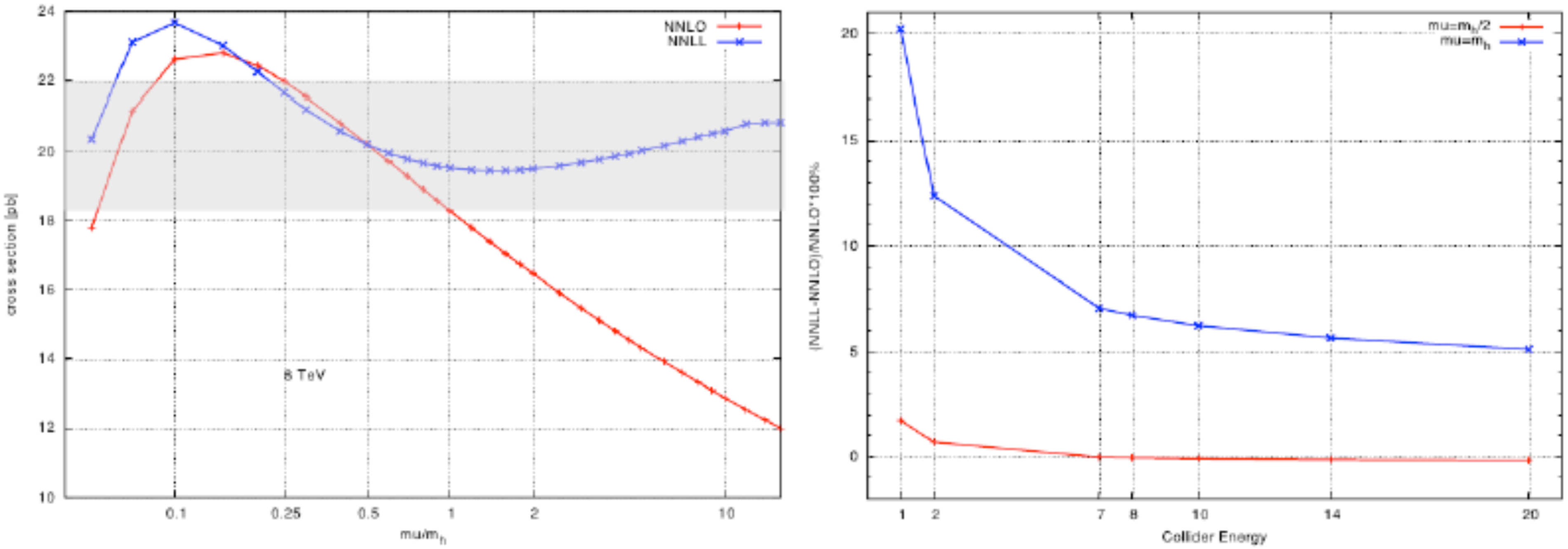
$$1+\frac{\alpha_s}{\pi}\cdot(\pi^2)+\ldots\sim e^{\frac{\alpha_s}{\pi}\cdot\left(\frac{\pi^2}{2}\right)}\left(1+\frac{\alpha_s}{\pi}\left[\frac{\pi^2}{2}\right]\ldots\right)$$

- Logs due to soft radiation exponentiate and can be resummed with NNLL accuracy at all orders.

Catani, de Florian, Grazzini

- Luckily, they yield small corrections beyond NNLO

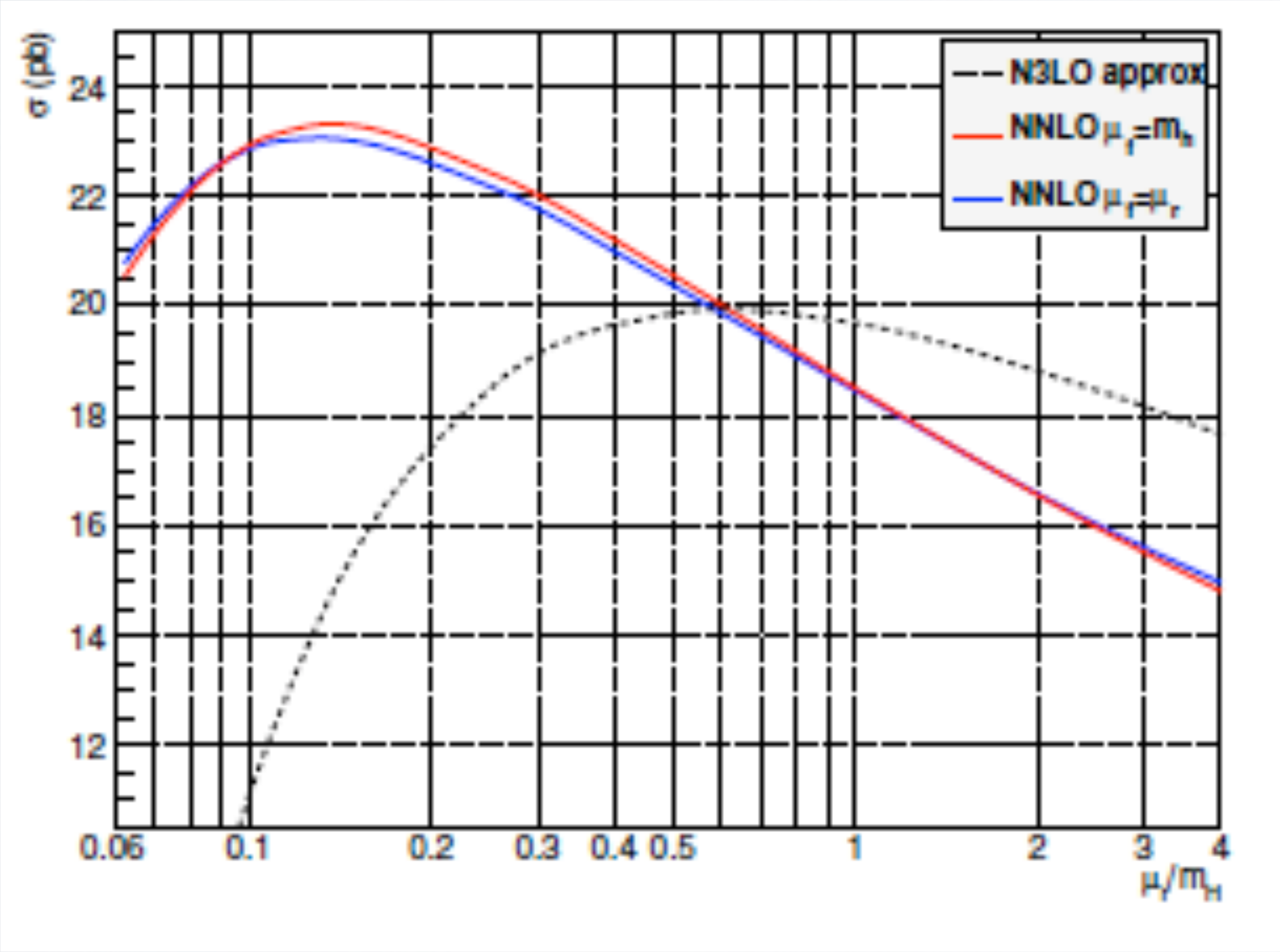
CHECKS AGAINST KNOWN BEYOND NNLO EFFECTS



All numbers for these plots are calculated with the online calculator by M. Grazzini, see http://theory.fi.infn.it/grazzini/hcalculators.html

- NNLO vs NNLL resummation (*Catani, Grazzini, de Florian)* agree very well, over a vast range of collider energies
- Similar observations for SCET-type of threshold resummation (Ahrens, Becher, Neubert)

SOFT LOGS AT NNNLO



The NNLO logarithmic terms are also known.

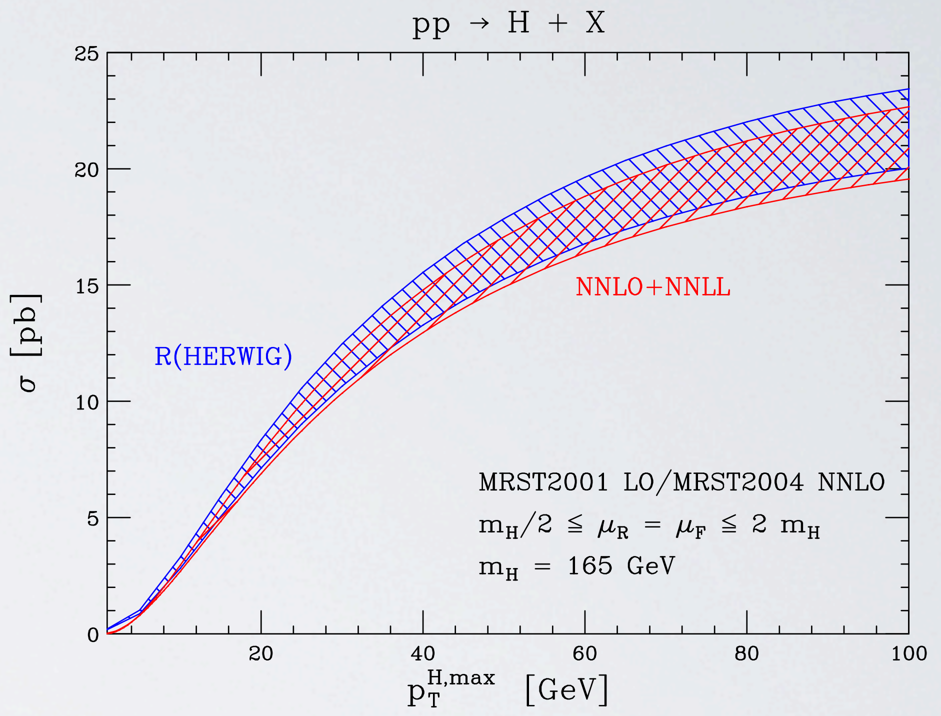
Moch, Vogt

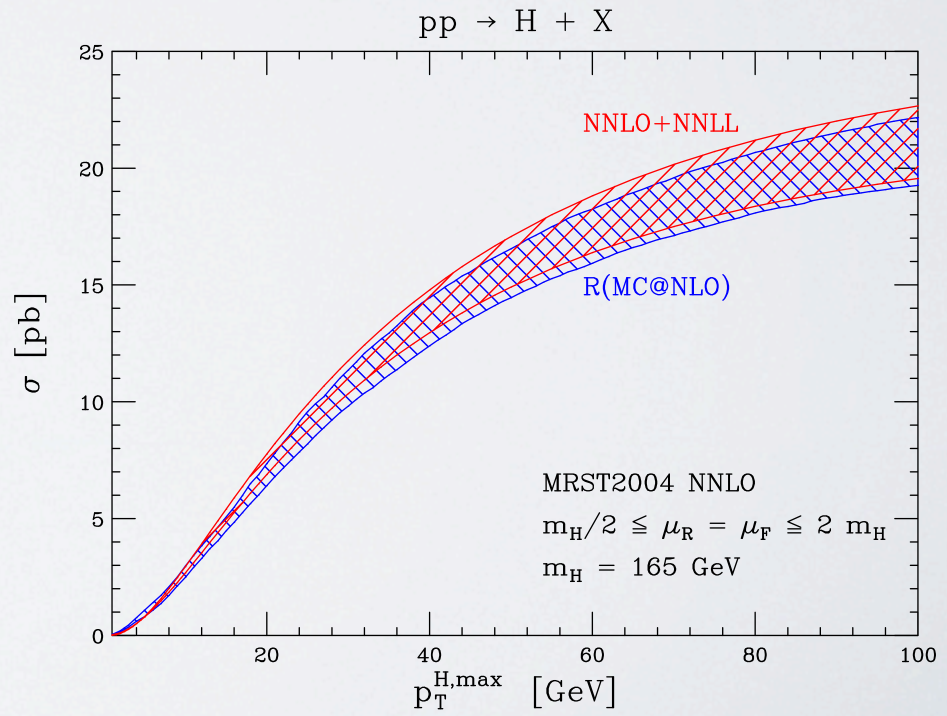
Consistent with NNLO

We have reshuffled/resummed perturbation theory in all sensible ways that we can think of with very consistent results. inspires confidence that we have achieved a very good accuracy which we can trust for the inclusive cross-section

CHECK ON EFFICIENCIES

- Exhaustive comparisons between parton-shower, resummation and fixed order already five years ago.
- Showing a very good agreement in efficiencies for jet vetoes and other cuts. ***CA,Dissertori,Grazzini,Stoeckli,Webber***
- The question of jet vetoes tantalized other theorists for quite some time, fearing that the success of the NNLO vs parton shower comparison and pt-resummation may be an accident.

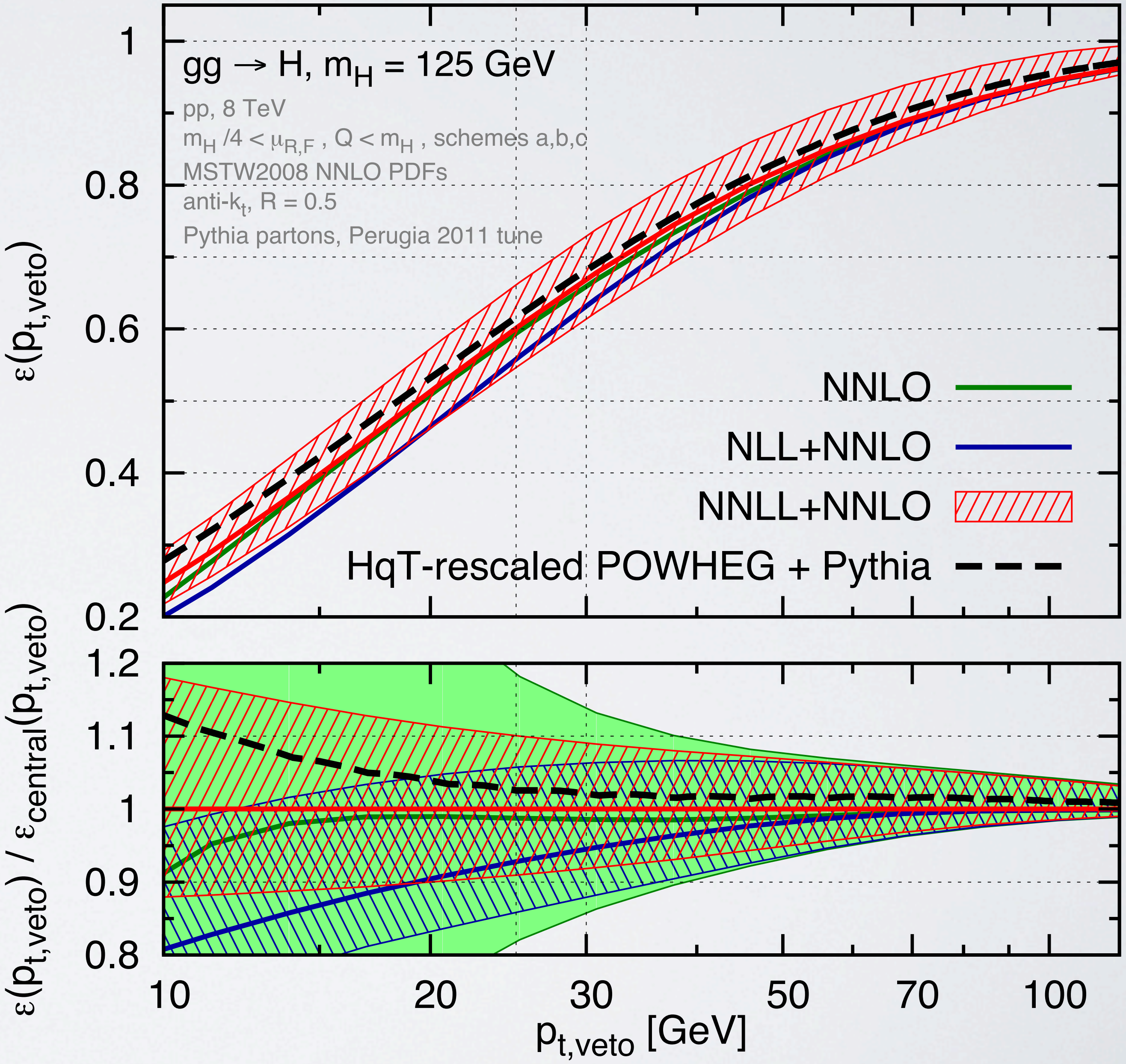




RESUMMED JET-VETO EFFICIENCIES

- Explicit Jet-veto resummation at NNLL matched to NNLO.
  Banfi, Monni, Salam, Zanderighi
- Excellent agreement with fixed order NNLO down to very low veto values
- Lesson I: caution is needed when the matching and resummation are not at the same level of accuracy (NLL-NNLO differs from NNLL-NNLO)
- Lesson II: A poor man's solution to rescale bad Monte-Carlo such that it matches a precisely known distribution is indeed poor!

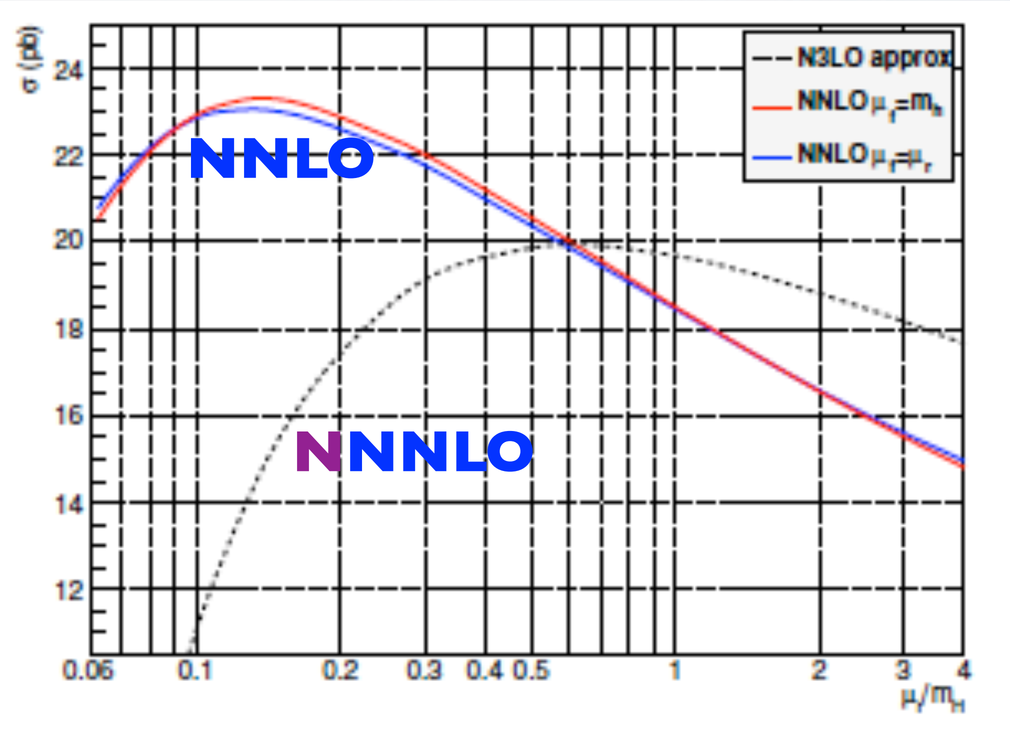
Banfi, Monni, Salam, Zanderighi



(Similar studies with a SCET formalism by ***Becher, Neubert****)*

EVEN BETTER PRECISION?

- The cross-section for gluon fusion is a very important ingredient for Higgs coupling extractions,
- causing the largest theoretical uncertainty.
- shall we go to an NNNLO precision?
- We can now already the precision which we can claim at the next order.
- surprisingly, we can only reduce the scale uncertainty from a 8% down to a 5% if we do so.



NNNLO is necessary to instill more confidence in our existing predictions.

CAN IT BE DONE?

- I believe yes.
- The techniques which were invented for the NNLO calculations in gluon fusion worked effortlessly.
- One order higher is a tremendous leap in technical difficulty**.**
- ***We need a similar leap in cleverness.***
- but we already know much more about the structure of loop and phase-space integrals (unitarity and reverse-unitarity, threshold expansions, non-linear mappings, symbol - coproduct and polylogarithms, etc).

BUT, IS IT THE HIGGS?

- It can be composite, fat, little, ugly, MSSM light, SM, etc, but it must be the Higgs.

- It couples to WW, so it is unlikely to be pseudo-scalar.

- It couples to photons, so it cannot be a vector.

- It is technically allowed to be a spin-2 particle. I do not know of any theory which passes EWPTs with such a light spin-2 resonance.

- We will be confident rather soon. The ZZ,WW decays yield characteristic spin correlations.

- Note, that spin correlations have already been exploited in order to maximize the discovery potential for a CP-even scalar. We would look for spin-2 with different analyses.

SUMMARY

- I found it very hard to stop reading the vastly growing literature, thinking or calculating in order to collect my thoughts and compose my presentation.
- This is an amazing moment in the history of particle physics.
- We have the discovery of a Higgs boson; a particle which is very rare to produce and very delicate on physics at higher energies.
- Data agrees roughly with the SM, but leaves open many possibilities.
  It will be very exciting to do model building once Higgs data is more precise.
- Higgs cross-sections are very well studied. I would desire even more precise QCD predictions.
- A lot of work to be done in measuring Higgs boson couplings and even more difficult processes such as Higgs pair production.
- Higgs data will be very important in deciding the big next steps in accelerator physics.