Higgs Physics – Lecture 4

Future Directions in Higgs Physics at the LHC

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Course on Physics at the LHC – LIP, 26 May 2014

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Outlook

Introduction

Where do we stand

Answers and questions at the end of run-I

Future LHC Higgs Physics:

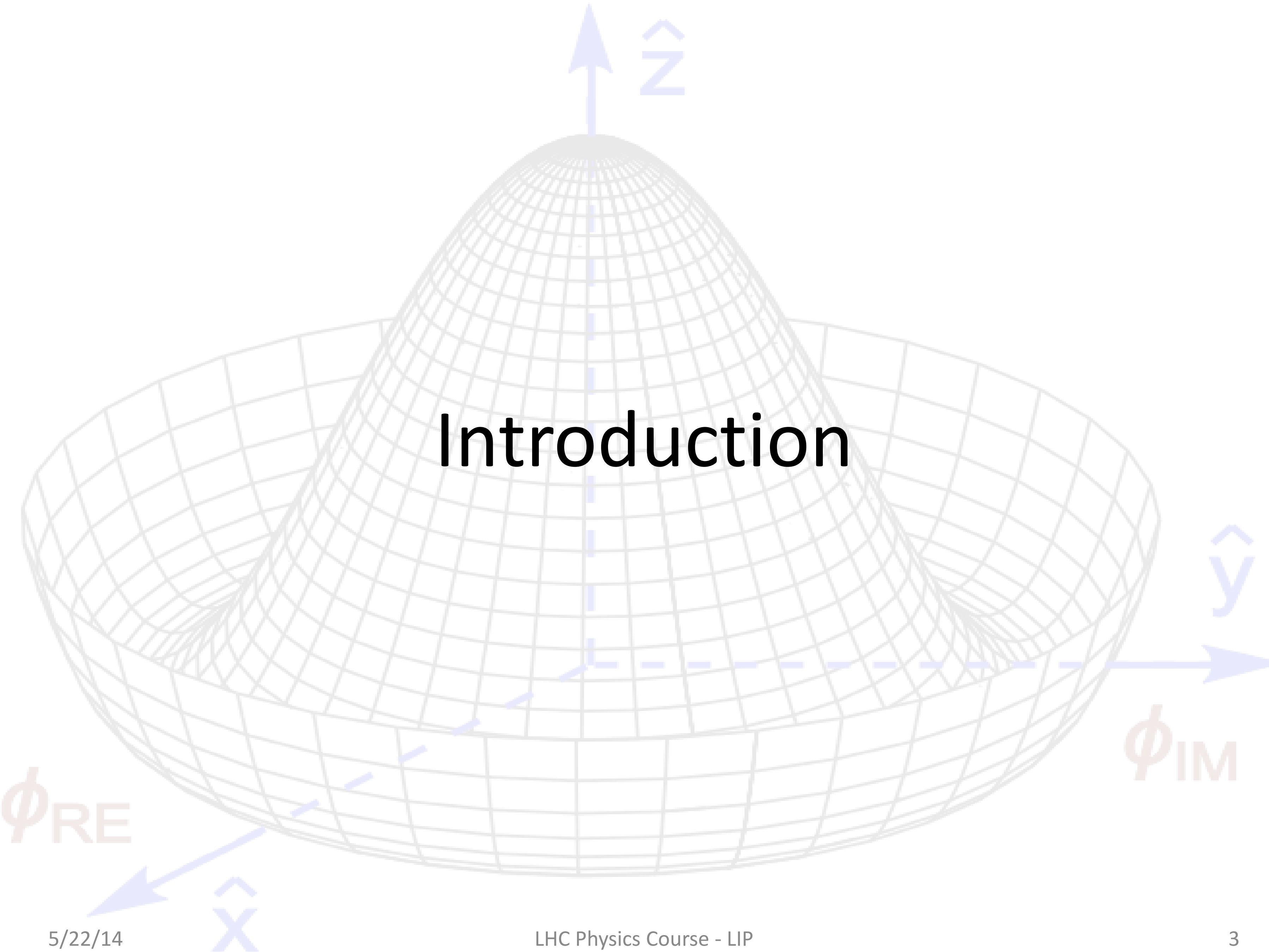
LHC Machine scenarios

Precision Higgs Measurements

Higgs sector Searches

Higgs physics at future accellerators

Introduction



Higgs lectures so far…

- Lecture 1 – overview of theory and history
- Lecture 2 – some search channels in detail
- Lecture 3 – channel combination and properties of observed Higgs
- This lecture – try to get overview and look ahead

$$\boxed{\mathcal{L}_{EW} = \mathcal{L}_g + \mathcal{L}_f + \mathcal{L}_h + \mathcal{L}_y.}$$

Electroweak Lagrangian before spontaneous symmetry breaking

$$\mathcal{L}_g = -\frac{1}{4}W^{a\mu\nu}W^a_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu}$$

Electroweak gauge bosons: B^0 W^0 $W^\pm$

$$\mathcal{L}_f = \overline{Q}_i i\not{D} Q_i + \overline{u}_i i\not{D} u_i + \overline{d}_i i\not{D} d_i + \overline{L}_i i\not{D} L_i + \overline{e}_i i\not{D} e_i$$

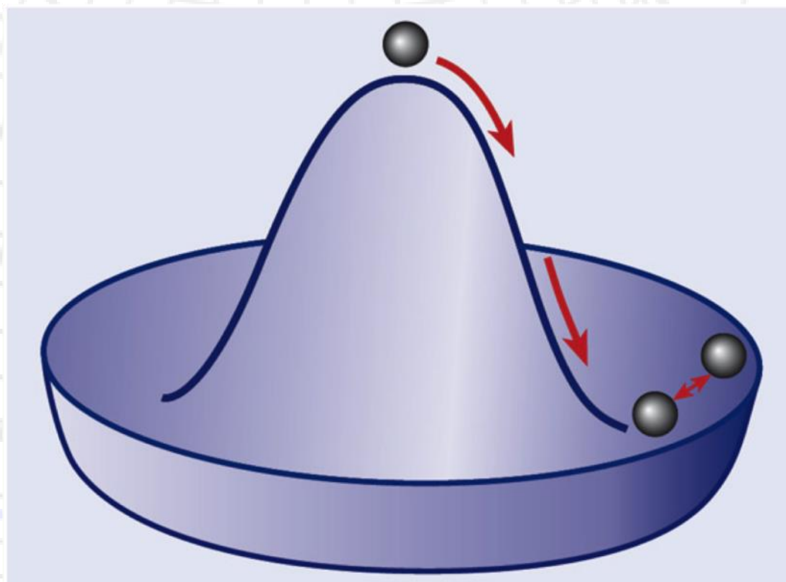
Fermion kinetic terms

$$\mathcal{L}_h = |D_\mu h|^2 - \lambda \left(|h|^2 - \frac{v^2}{2}\right)^2$$

Higgs term (note: vacuum expectation value zero before symmetry breaking)

$$\mathcal{L}_y = -y_{u\,ij}\epsilon^{ab}\,h_b^\dagger\,\overline{Q}_{ia}u_j^c - y_{d\,ij}\,h\,\overline{Q}_i d_j^c - y_{e\,ij}\,h\,\overline{L}_i e_j^c + h.c.$$

Yukawa interaction term between Higgs field and fermions



Massive Higgs boson: transverse oscillation mode

Spontaneous symmetry breaking:
New bosons γ and Z^0 from W^0 and B^0

$$\begin{pmatrix}\gamma \\ Z^0\end{pmatrix} = \begin{pmatrix}\cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W\end{pmatrix}\begin{pmatrix}B^0 \\ W^0\end{pmatrix}$$

$$\mathcal{L}_{EW} = \mathcal{L}_K + \mathcal{L}_N + \mathcal{L}_C + \mathcal{L}_H + \mathcal{L}_{HV} + \mathcal{L}_{WWV} + \mathcal{L}_{WWVV} + \mathcal{L}_Y$$

After sym. breaking

$$\mathcal{L}_K = \sum_f \overline{f}(i\partial\!\!\!/ - m_f)f - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} + m_W^2 W^+_\mu W^{-\mu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu + \frac{1}{2}(\partial^\mu H)(\partial_\mu H) - \frac{1}{2}m_H^2 H^2$$

Kinetic terms: notice boson masses (Z,W,H)!

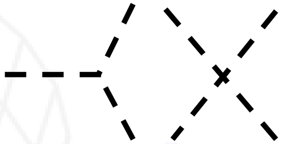
$$\mathcal{L}_N = eJ^{em}_\mu A^\mu + \frac{g}{\cos\theta_W}(J^3_\mu - \sin^2\theta_W J^{em}_\mu)Z^\mu$$

$$\mathcal{L}_C = -\frac{g}{\sqrt{2}}\left[\overline{u}_i\gamma^\mu\frac{1-\gamma^5}{2}M^{CKM}_{ij}d_j + \overline{\nu}_i\gamma^\mu\frac{1-\gamma^5}{2}e_i\right]W^+_\mu + h.c.$$

Neutral and charged current terms: fermions and gauge boson interactions

$$\mathcal{L}_H = -\frac{gm_H^2}{4m_W}H^3 - \frac{g^2m_H^2}{32m_W^2}H^4$$

Higgs boson 3- and 4-point self-interaction



$$\mathcal{L}_{HV} = \left(gm_W H + \frac{g^2}{4}H^2\right)\left(W^+_\mu W^{-\mu} + \frac{1}{2\cos^2\theta_W}Z_\mu Z^\mu\right)$$

Higgs boson interaction with gauge bosons

Gauge boson self interaction:

$$\mathcal{L}_{WWV} = -ig[(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})(A^\nu\sin\theta_W - Z^\nu\cos\theta_W) + W^-_\nu W^+_\mu(A^{\mu\nu}\sin\theta_W - Z^{\mu\nu}\cos\theta_W)]$$

$$\mathcal{L}_{WWVV} = -\frac{g^2}{4}\Big\{[2W^+_\mu W^{-\mu} + (A_\mu\sin\theta_W - Z_\mu\cos\theta_W)^2]^2 - [W^+_\mu W^-_\nu + W^+_\nu W^-_\mu + (A_\mu\sin\theta_W - Z_\mu\cos\theta_W)(A_\nu\sin\theta_W - Z_\nu\cos\theta_W)]^2\Big\}$$

$$\mathcal{L}_Y = -\sum_f \frac{gm_f}{2m_W}\overline{f}fH$$

Yukawa interactions between Higgs and fermions: note fermion masses!


Repubblica.it
Cern, scoperta la "particella di Dio"
« PRECEDENTE
Foto 1 di 19
SUCCESSIVO
Higgs boson-like particle discovery claimed at LHC
THANH NIEN ONLINE
DIỄN ĐÀN CỦA HỘI LIÊN HIỆP THANH NIÊN VIỆT NAM
Chính trị - Xã hội
Quốc phòng
Thế giới trẻ
Kinh tế
Thế giới
Văn nghệ
Giáo dục
Công nghệ
Chủ nhật, 08/07/2012, 10:35:36 GMT+7
RSS
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Quảng cáo
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Khoa học
Sân bóng của các hạt nhân
Ngày 4.7 tại Genova, Thụy Sĩ, Viện Nghiên cứ
mới được cho là tương ứng với hạt Higgs
5 thập niên qua. Nếu thông tin này hoàn toàn
tương đương với việc Christophe Columbus
SAY GOD PARTICLE
ONE MORE GODDAMN TIME
The New York Times
U.S.
N.Y. / REGION
BUSINESS
Le boson d
99,9999 %
Le Monde.fr | 04.07.2012
Physicists Find Elusive Particle Seen as
PHYSIK
Haarscharf am gottverdammten Teilchen vorbei
Die Belege scheinen überwältigend: Forscher könnten ein neues Teilchen gefunden haben. Unklar ist, ob es das Higgs-Boson ist, der letzte Baustein im Weltbild der Physik.
theguardian
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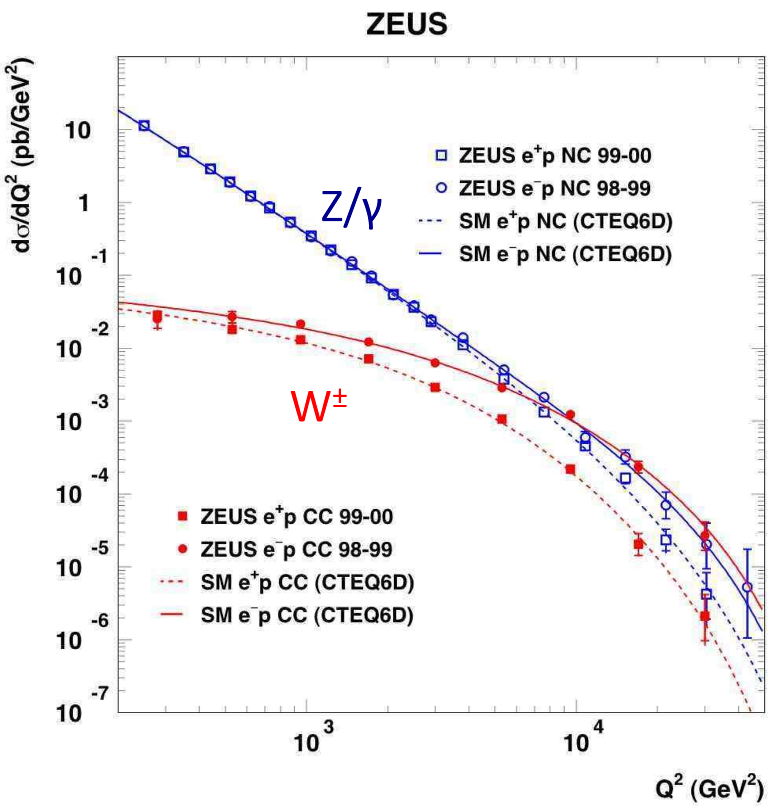
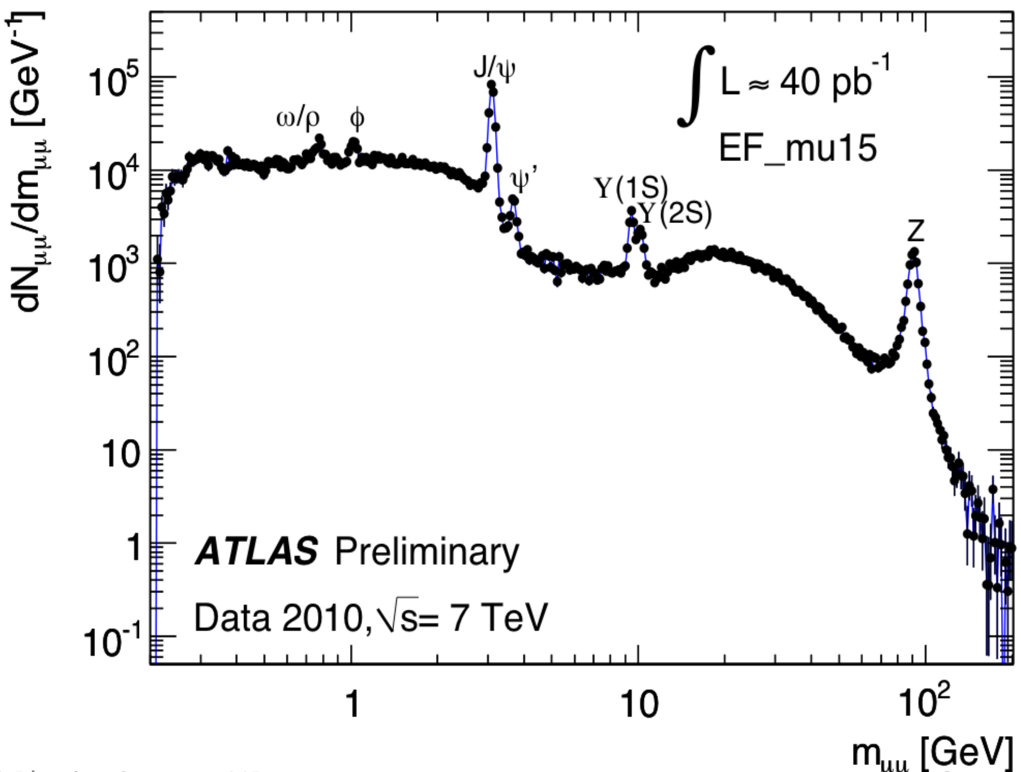
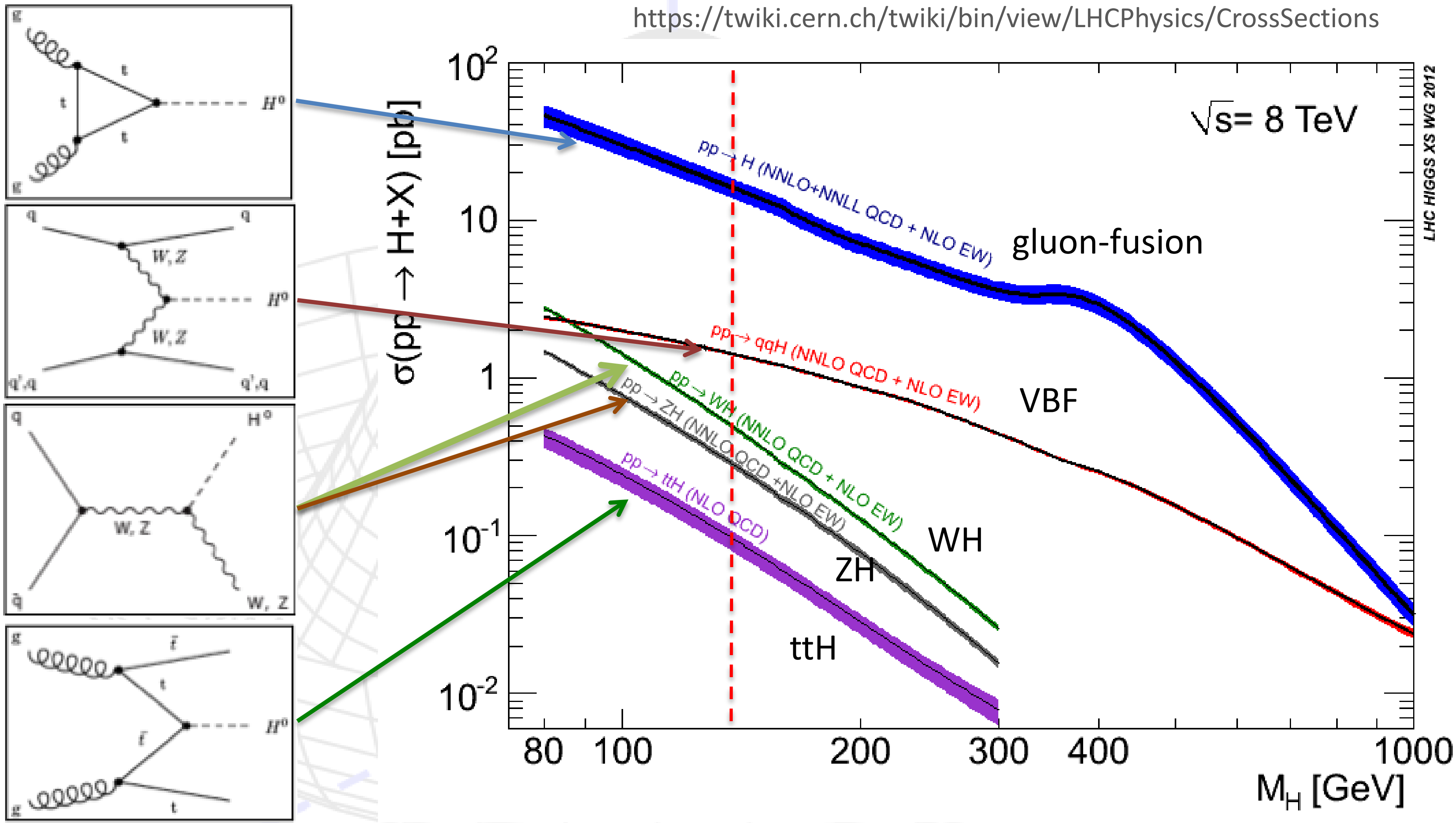
Comment is free
The Higgs boson discovery is another giant leap for humankind
The Cern discovery of the Higgs particle is up there with putting man on the moon – something all humanity can be proud of
Scientists in Geneva on Wednesday applauded the discovery of a

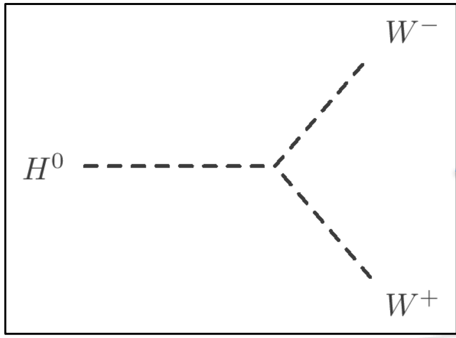
Why does it matter?

- Because it's real!
  - Data shows Higgs mechanism (or something like it) needed in the theory
- Because it may lead us to new discoveries and a new understanding of Nature!
  - "There is nothing so practical as a good theory" (Kurt Lewin)

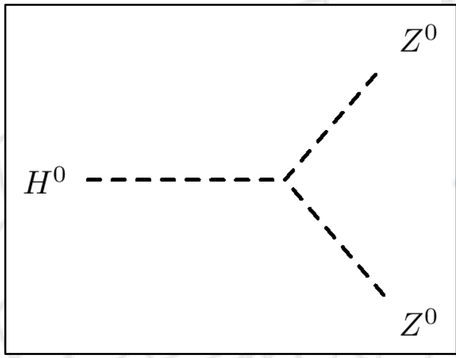




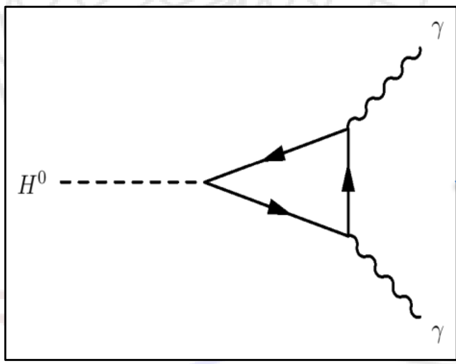

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections
$\sqrt{s}$= 8 TeV
LHC HIGGS XS WG 2012
pp → H (NNLO+NNLL QCD + NLO EW)
gluon-fusion
pp → qqH (NNLO QCD + NLO EW)
VBF
pp → WH (NNLO QCD + NLO EW)
WH
pp → ZH (NNLO QCD +NLO EW)
ZH
pp → ttH (NLO QCD)
ttH
σ(pp → H+X) [pb]
M_H [GeV]
W,Z
W, Z
H⁰



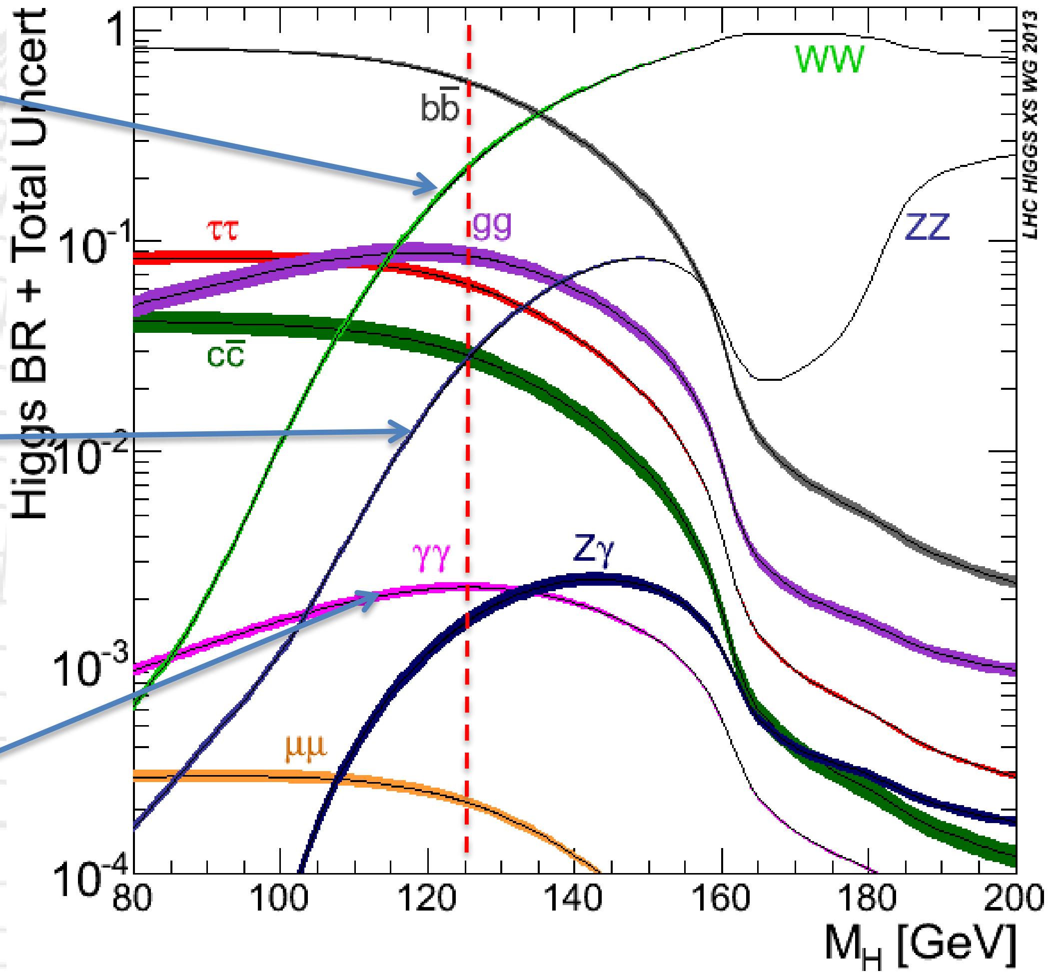
W^-
H^0
W^+



Z^0
H^0
Z^0

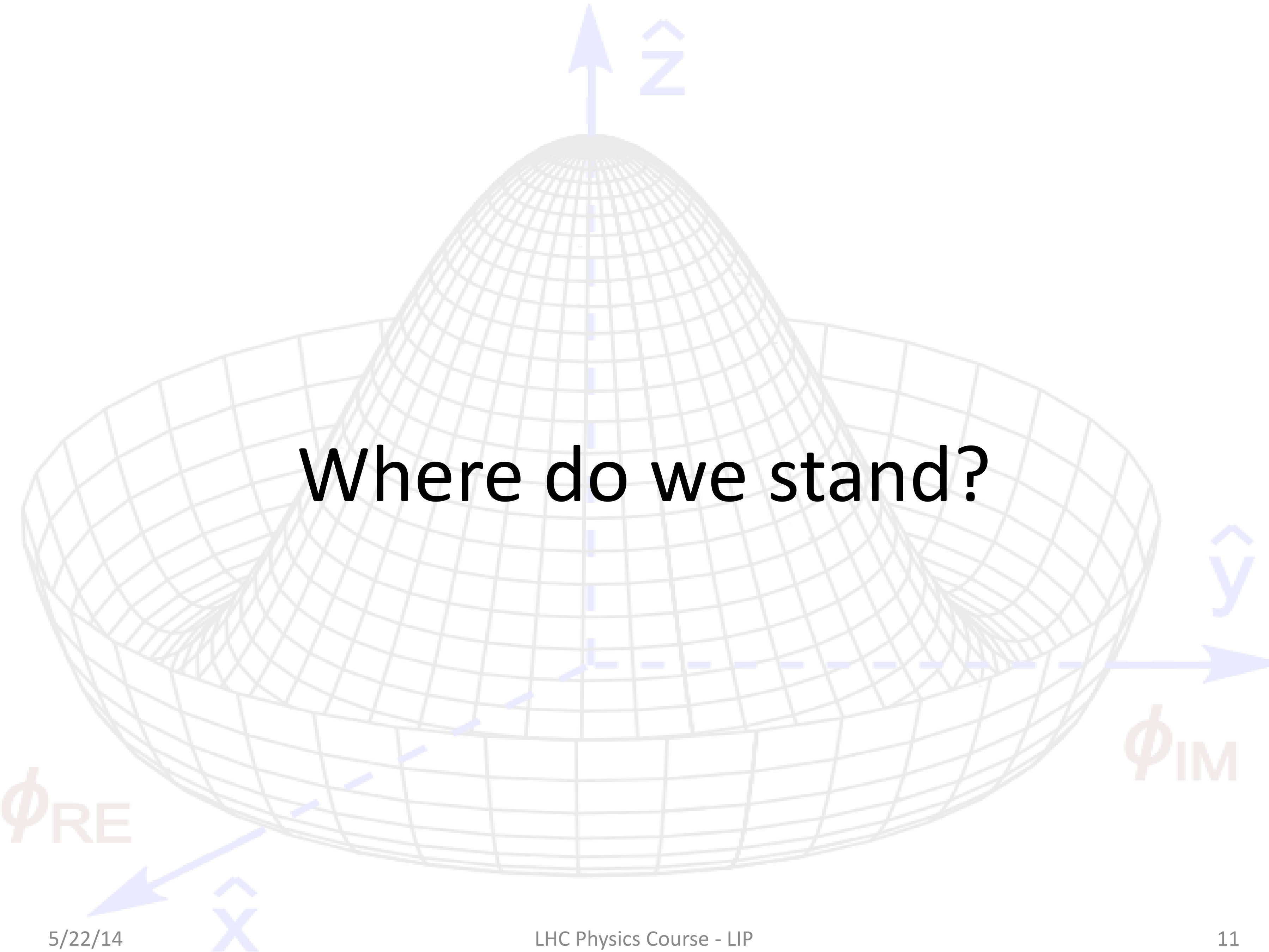


γ
H^0
γ



Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
WW
bb̄
ττ
gg
ZZ
cc̄
γγ
Zγ
μμ
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]

Where do we stand?



Questions and answers at the end of Run I

- Most modes available with current lumi explored
- Precision: obvious signal in bosonic decays
  - Mass around 125GeV – some questions
  - Signal strength consistent with SM – some questions
  - Main alternatives to $J^P = 0^+$ discarded – questions remain
- Fermion couplings probably seen in $H \to \tau\tau$ (4σ)
- Evidence for VBF production (3σ)
- Mainly indirect sensitivity to ttH coupling through loops
- Many direct searches for other Higgses turned out nothing (yet)

	H→γγ	H→WW	H→ZZ	H→bb	H→ττ	H→Zγ	H→μμ	H→cc	H→HH	H→inv
ggF	✔	✔	✔		✔	✔	✔			
VBF	✔	✔	✔		✔	✔	✔			✔
VH	✔	✔	✔	✔	✔					✔
ttH	✔	✔	✔	✔	✔					

Higgs boson mass

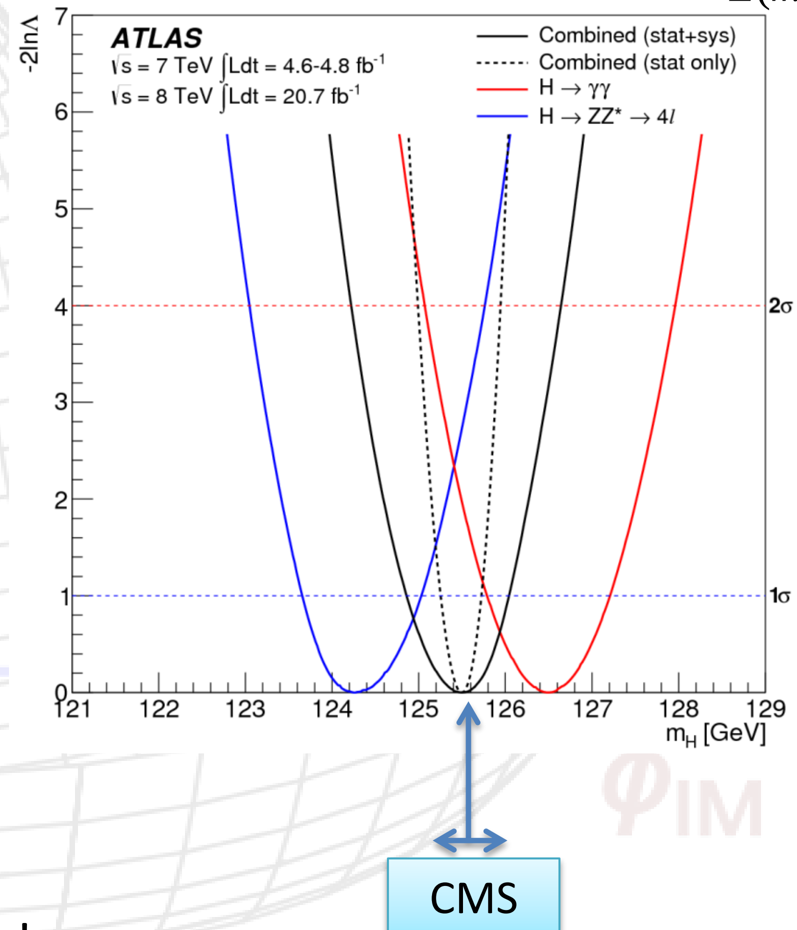
- **Mass:** around 125GeV
  - Used to be the only unknown SM-Higgs parameter, remember? ☺
- ATLAS: arXiv:1307.1427
  - $m_H^{H\to 4l}$ = 124.3 ±0.6(stat) ±0.5(sys)
  - $m_H^{H\to\gamma\gamma}$ = 126.8 ±0.2(stat) ±0.7(sys)
  - Assuming single resonance: m_H = 125.5 ±0.2(stat) $^{+0.5}_{-0.6}$(sys)
- Tension between channels!
  - Compatibility P=1.5% (2.4σ)
  - Rises to 8% with square syst.prior

BUT:

- CMS: arXiv:1312.5353
  - $m_H^{H\to 4l}$ = 125.6 ±0.4(stat) ±0.6(sys)
- CMS: CMS-PAS-HIG-13-005
  - $m_H^{H\to\gamma\gamma}$ = 125.4 ±0.5(stat) ±0.6(sys)

$$L = \frac{L(m_H)}{L(\hat{m}_H)}$$

ATLAS: arXiv:1307.1427



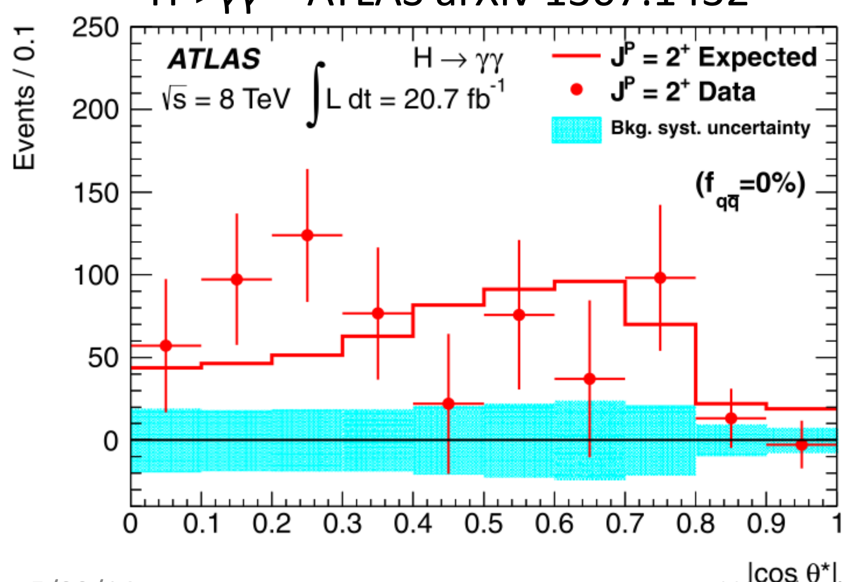
- Doesn't look like two different resonances!...

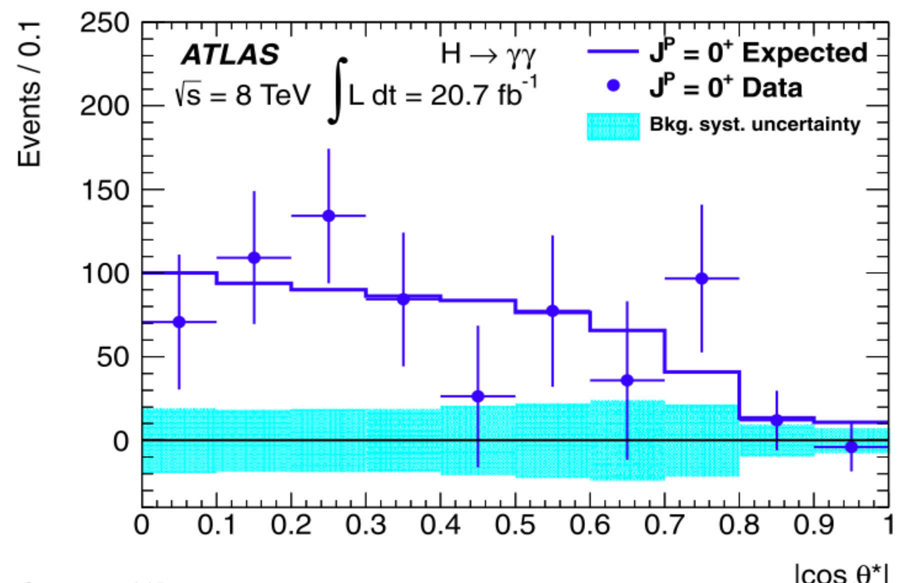
Spin and Parity

- Pure $J^P = 0^-, 1^+, 1^-$, and 2^+ excluded with 97.8, 99.97, 99.7, and 99.9% Confidence Level (ATLAS arXiv 1307.1432)
- But note: Higgs could have CP-violating component!

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

H->γγ – ATLAS arXiv 1307.1432





Direct Evidence of Fermion Couplings

- **Challenging** channels at the LHC!
  - Huge backgrounds (H->bb,H->ττ)
  - Or low rate: H->μμ

- ATLAS:

  4.1σ evidence of H->ττ decay 3.2σ exp.

  $\mu = \boldsymbol{\sigma_{obs.}/\sigma_{SM}} = 1.4 \pm 0.3(stat) \pm 0.4(sys)$

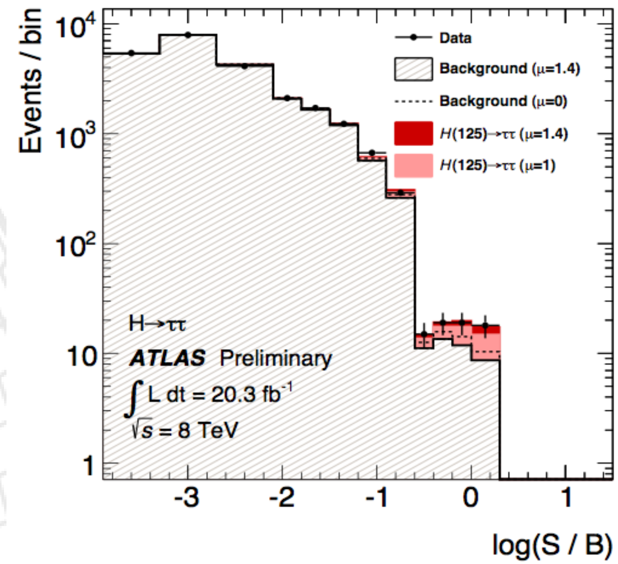
- CMS:
  - Combination of H->bb and H->ττ:

  3.8σ evidence (obs.) 4.4σ (expected)

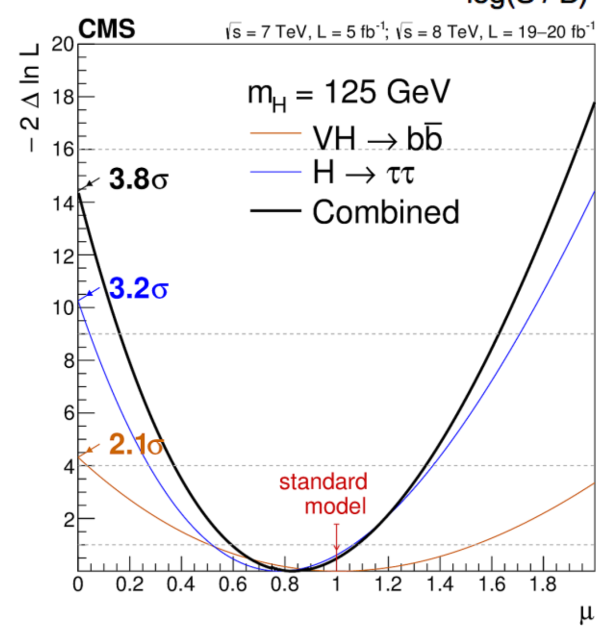
  $\mu = \boldsymbol{\sigma_{obs.}/\sigma_{SM}} = 0.83 \pm 0.24$

CMS 1401.6527

Channel ($m_H = 125\,\mathrm{GeV}$)	Significance (σ) Expected	Significance (σ) Observed	Best-fit μ
$VH \to b\bar{b}$	2.3	2.1	1.0 ± 0.5
$H \to \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24



ATLAS-CONF-2013-108



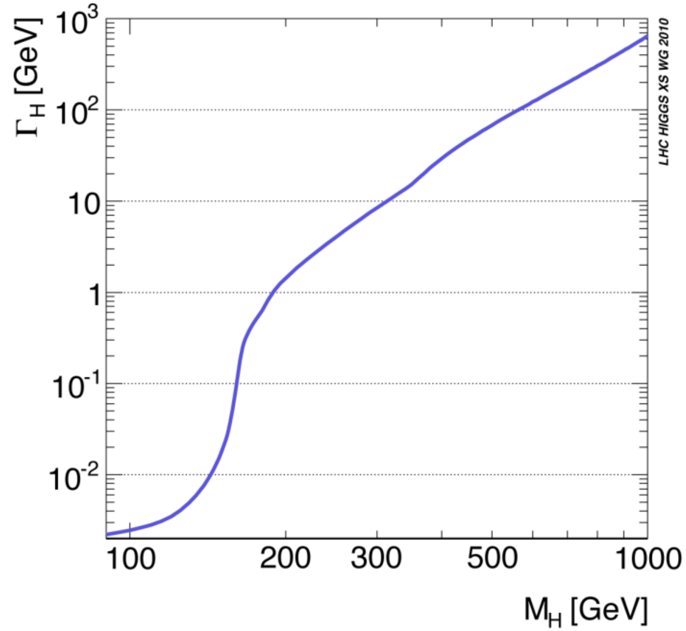
CMS 1401.6527

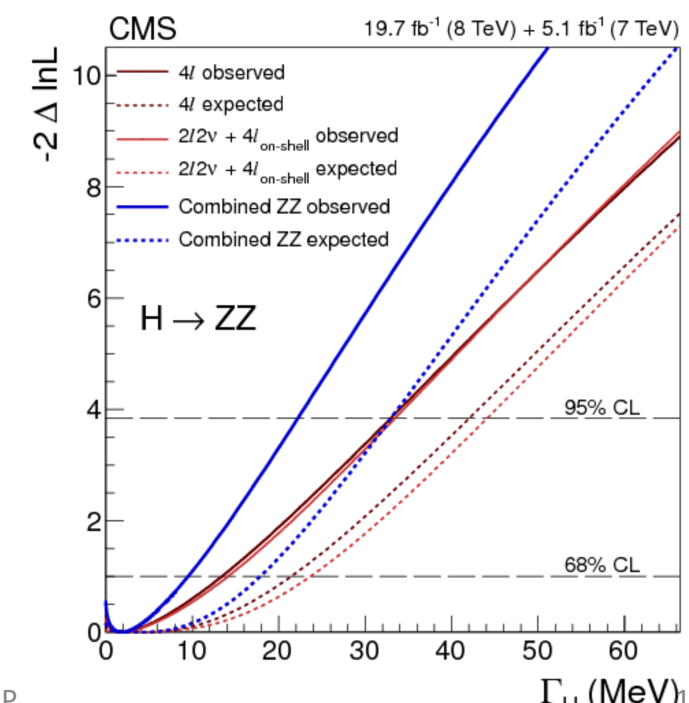
Higgs Width

- Total width not measurable at the LHC
  - Hadronic decays invisible in huge jet background
- Sensitivity can be achieved through "interferometric" measurement
  - **Use gg→H→ZZ with Z on- or off-shell**
- Proof of principle done, although still very far from theoretically expected value (4MeV)
  - **Γ_H < 22 MeV at 95% CL**

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}$$

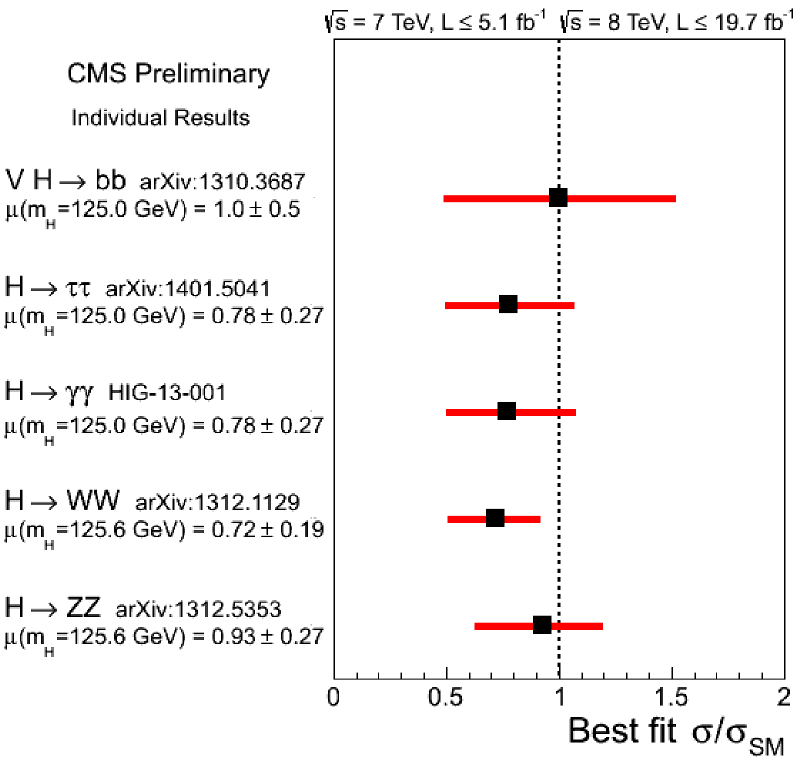
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$$

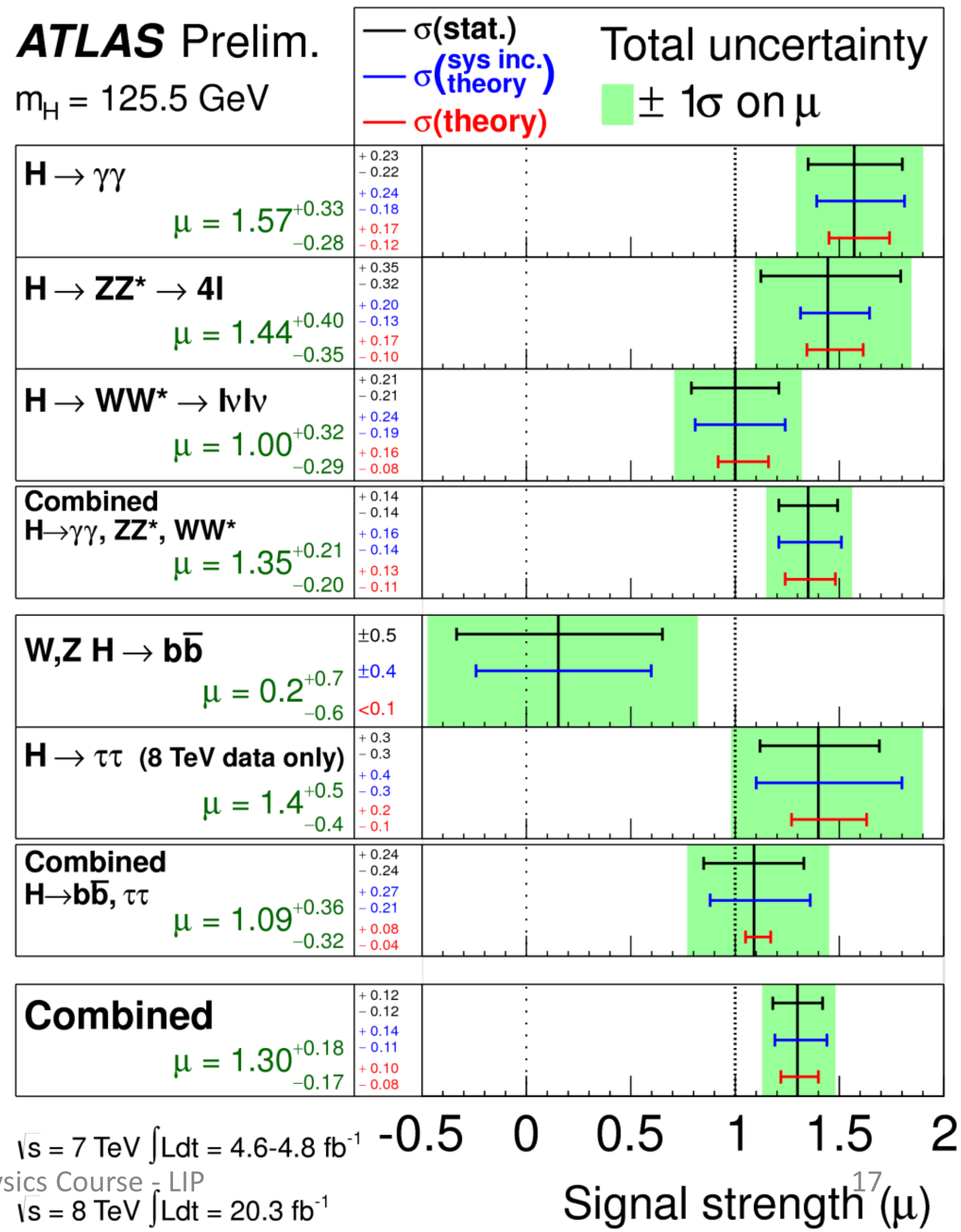




http://arxiv.org/pdf/1405.3455.pdf

Signal strength





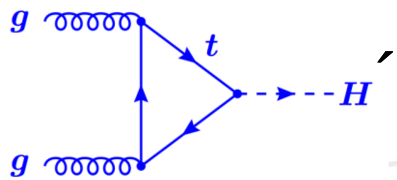
$$m = \frac{s_{meas}}{s_{SM}}$$

Take-home messages:

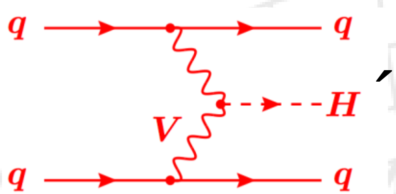
- Need more data!
- **Always run two experiments!**

Combining Higgs Channels

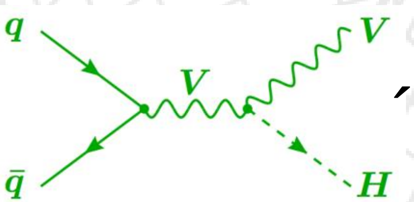
Production



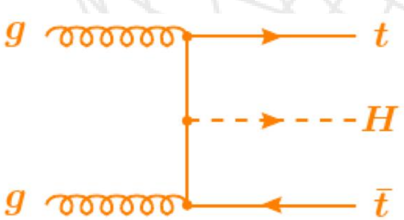
´ k_g^2



´ $k_{W/Z}^2$



´ $k_{W/Z}^2$

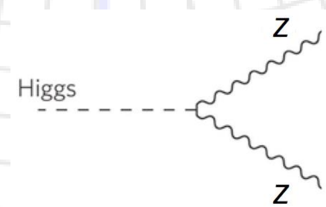


´ k_t^2

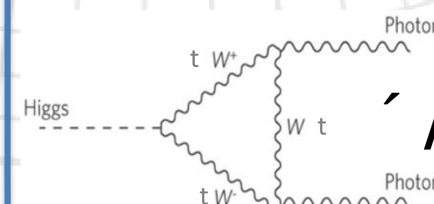
×

Decay

´ k_W^2



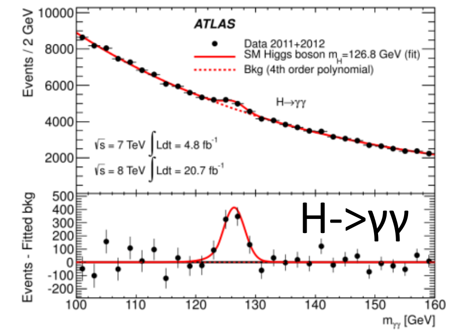
´ k_Z^2

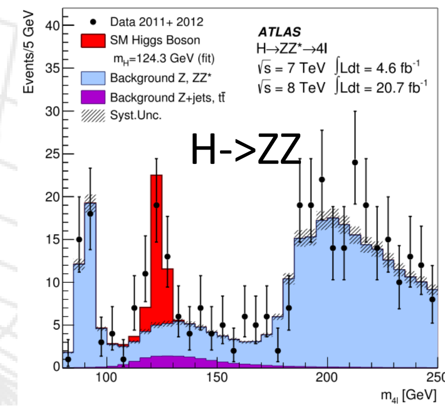


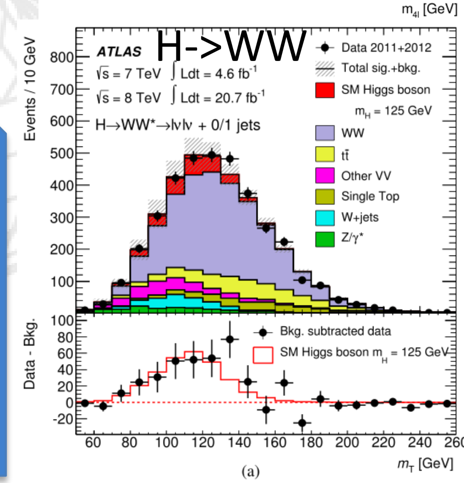
´ k_g^2

FIT

Backgrounds +







A bit more technically

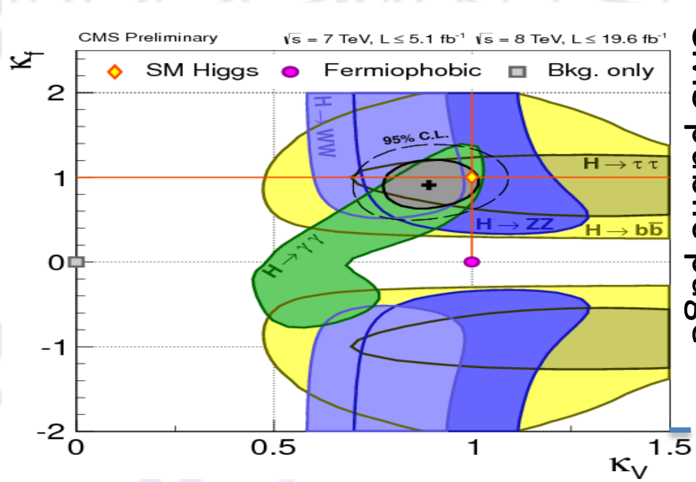
- **Assumptions:**
  - Single resonance (at $m_H = 125.5\text{GeV}$)
  - No modification of tensor structure of SM Lagrangian:
    - i.e. H has $J^P = 0^+$
  - Narrow width approximation holds
    - i.e. rate for process i ➔ H ➔ f is: $s \times BR = \dfrac{s_{i\to H} \times G_{H\to f}}{G_H}$

- **Free parameters** in framework:
  - Coupling scale factors: κ_j^2
  - Total Higgs width: κ_H^2 $\quad s_i = k_i^2 \times s_i^{SM}; G_f = k_f^2 \times G_f^{SM}; G_H = k_H^2 \times G_H^{SM}$
  - Or ratios of coupling scale factors: $\lambda_{ij} = \kappa_i / \kappa_j$

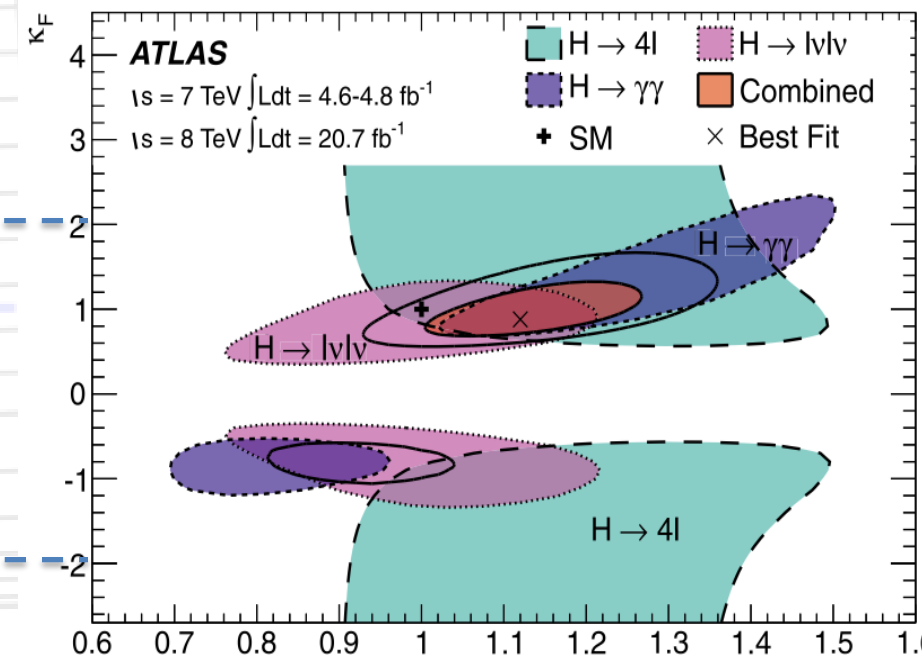
- Tree-level motivated framework
  - Useful for **studying deviations** in data with respect to expectations
    - E.g. extract coupling scale factor to weak bosons κ_V by setting $\kappa_W = \kappa_Z = \kappa_V$
  - Not same thing as fitting a new model to the data

Fermion and Boson couplings from fit

- Set one scale factor for all fermions (**κ_F** = κ_t = κ_b= κ_τ =…) and one for all vector bosons (**κ_V** = κ_Z = κ_W)
- Assume **no new physics**
- Strongest constraint to κ_F comes form gg->H loop
- ATLAS and CMS fits within 1-2σ of SM expectation (compatibility P=12%)
- Note ATLAS and CMS κ_V different – see signal strength below

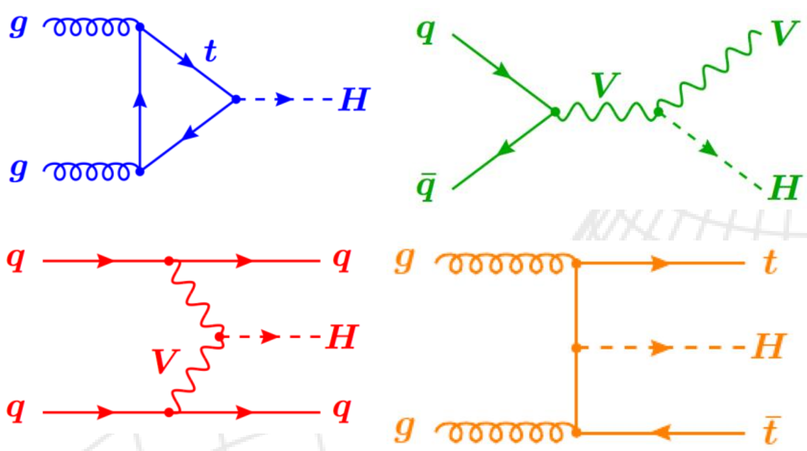


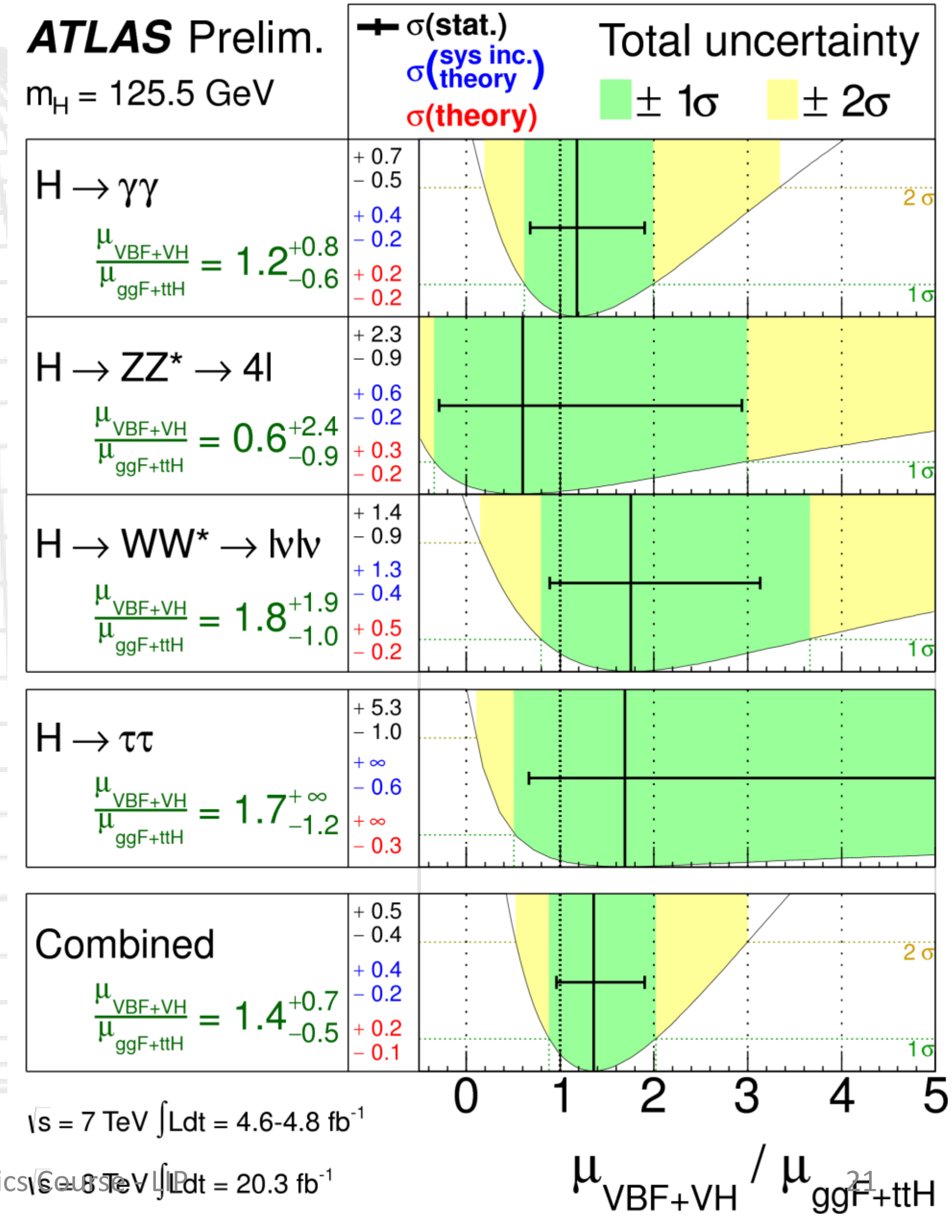
CMS public page



ATLAS 1307.1427

Production Modes

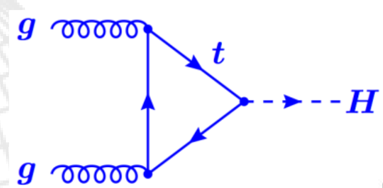


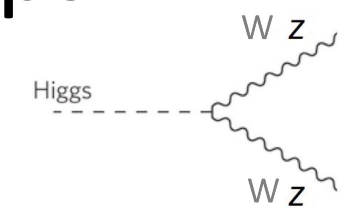


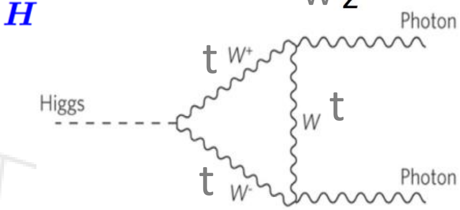
- Combination of channels allows consistency checks
- Evidence for VBF production (3σ)
- Sensitivity to top Yukawa coupling only through loops so far

New Physics in the Loops?

- New heavy particles may show up in **loops**
  - Dominant **gluon-fusion** through a (mostly) top loop production for H->ZZ, H->WW and H->γγ
  - **H->γγ decay** through top and W loops (and interference)



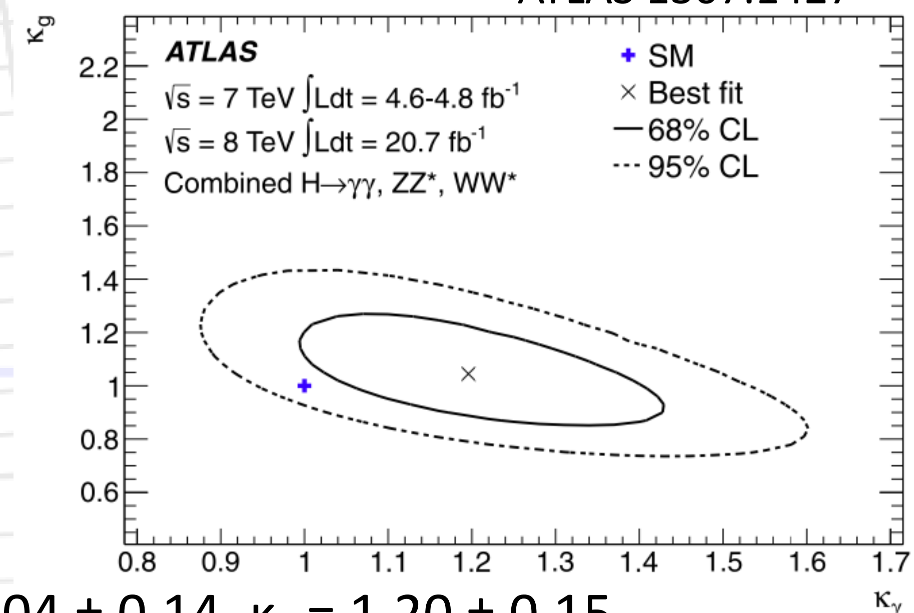




ATLAS 1307.1427

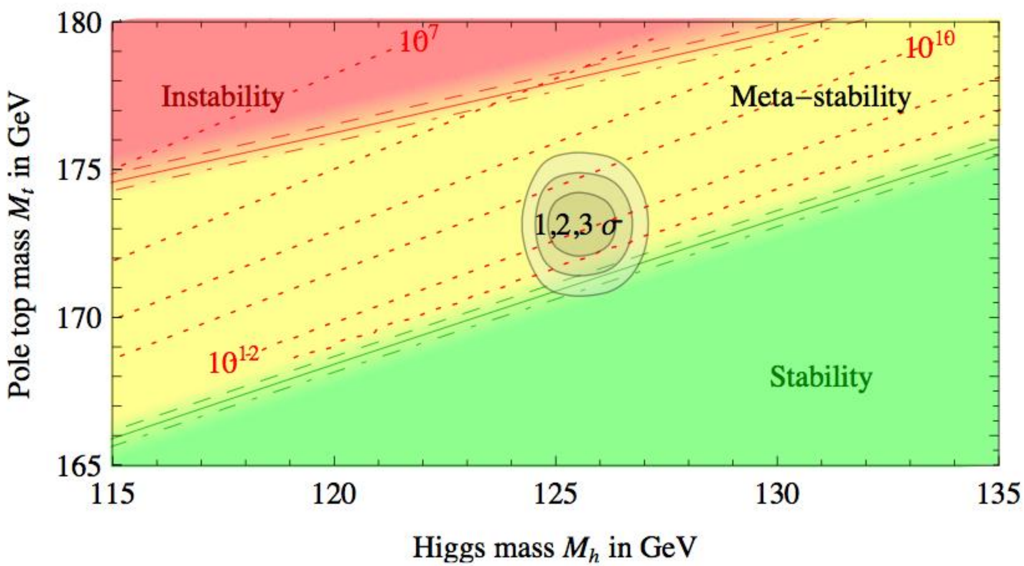
- Assume no change in Higgs width and SM couplings to known particles

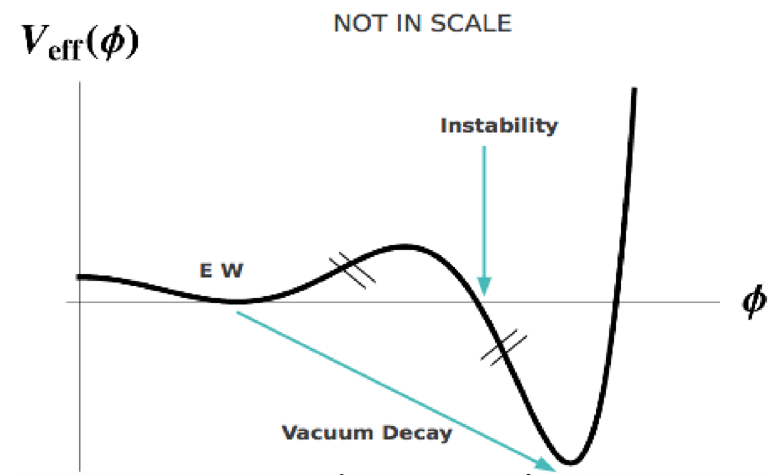
- Introduce effective coupling scale factors:
  - κ_g and κ_γ for ggH and Hγγ loops



- Best fit values: $\kappa_g = 1.04 \pm 0.14$, $\kappa_\gamma = 1.20 \pm 0.15$
- Fit within 2σ of SM (compatibility P=14%)

A bit of fun…

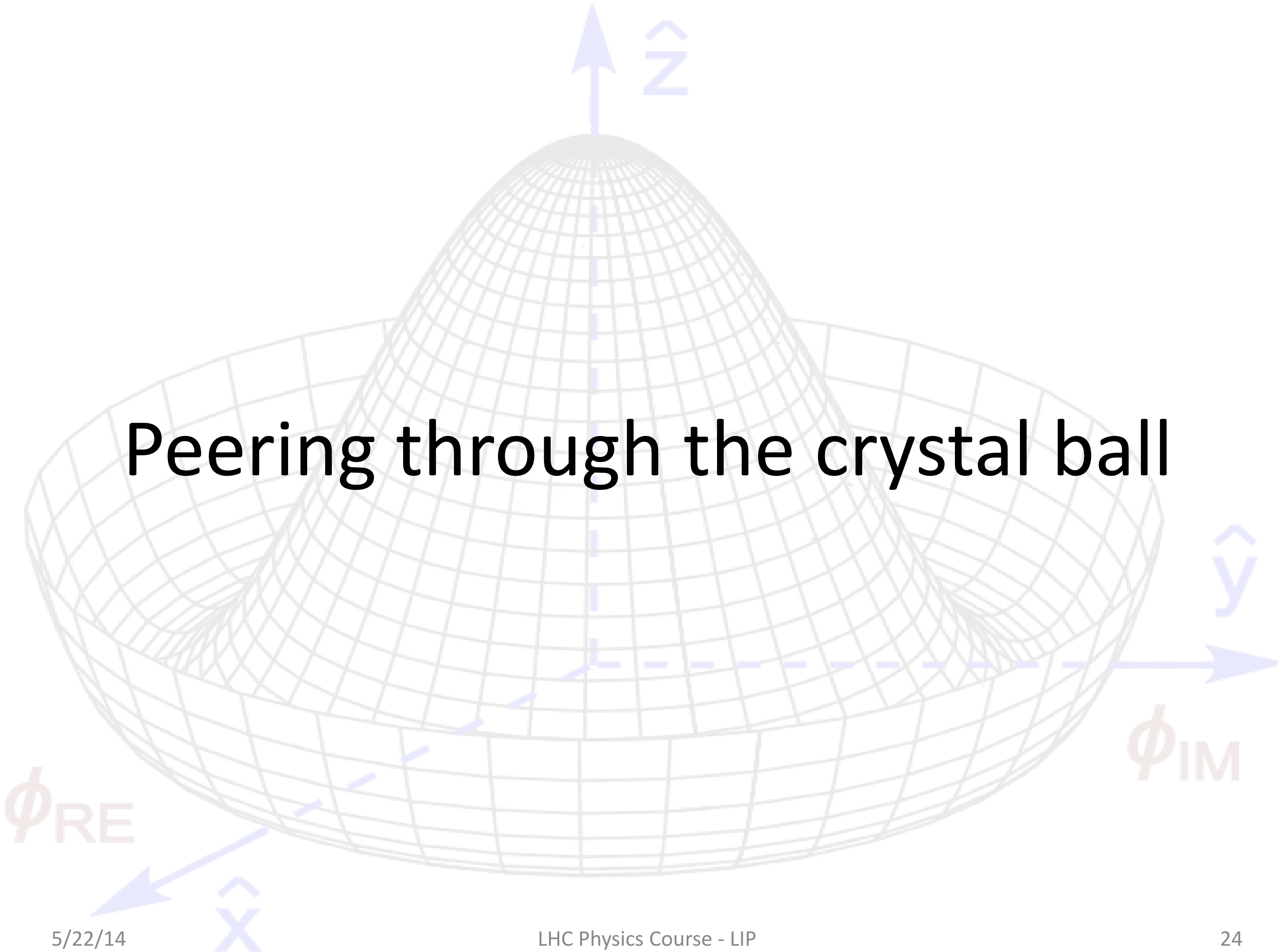




RG-improved potential

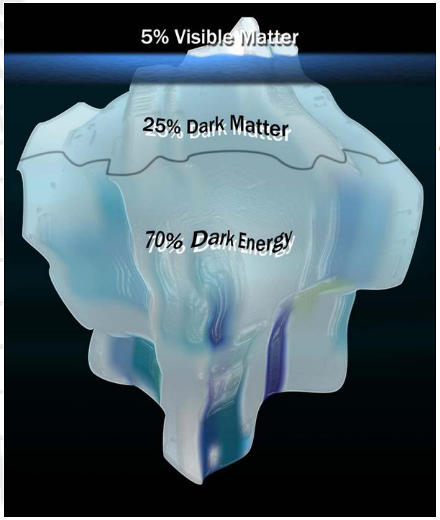
- What if…
  - At higher orders, Higgs potential doesn't have to be stable
  - Depending on m_t and m_H second minimum can be lower than EW minimum ⇒ tunneling between EW vacuum and true vacuum?!
- "For a narrow band of values of the top quark and Higgs boson masses, the Standard Model Higgs potential develops a shallow local minimum at energies of about 10^{16} GeV, where primordial inflation could have started in a cold metastable state", I. Masina, arXiv:1403.5244 [astro-ph.CO]
- See also: V. Brachina, Moriond 2014 (Phys.Rev.Lett.111, 241801 (2013)), G. Degrassi et al, arXiv:1205.6497v2

Peering through the crystal ball

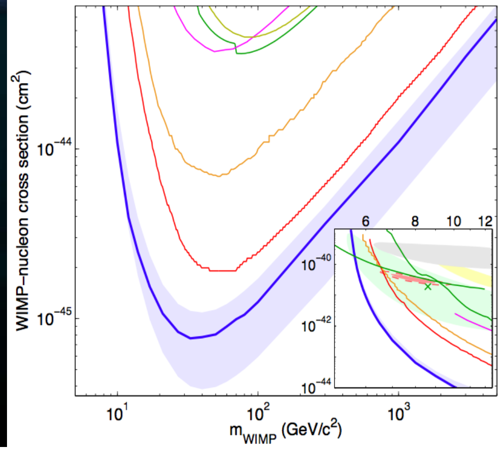


So, where do we stand?

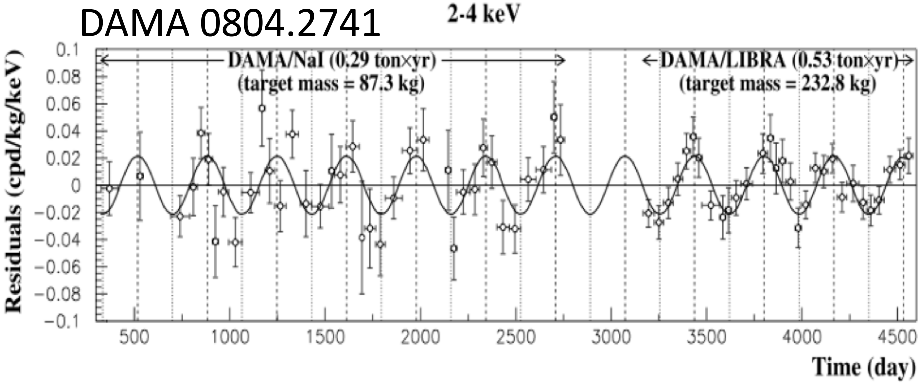
- We have found the **missing piece** of the Standard Model puzzle
- The current data show us a **SM-like** Higgs boson
  - Each channel not so well measured
  - But combination fits well with expectations
- **Is this the end of the story?**



LUX 1310.8214



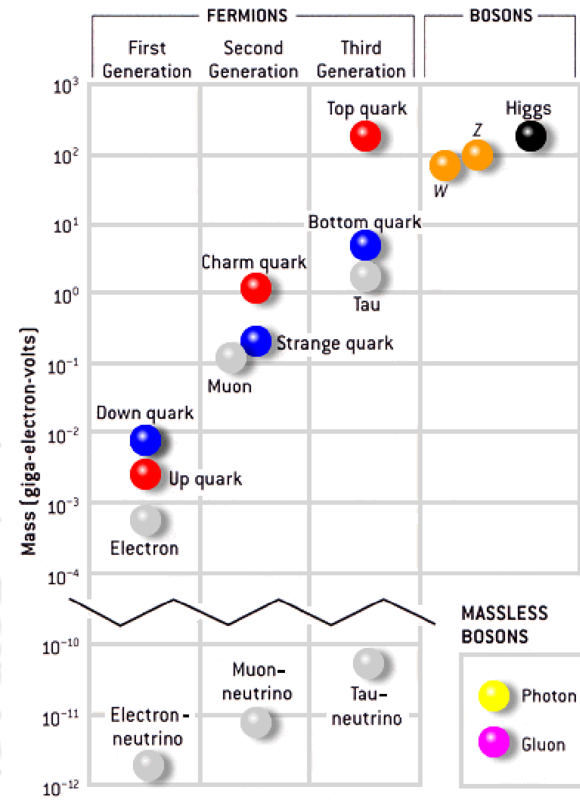
DAMA 0804.2741

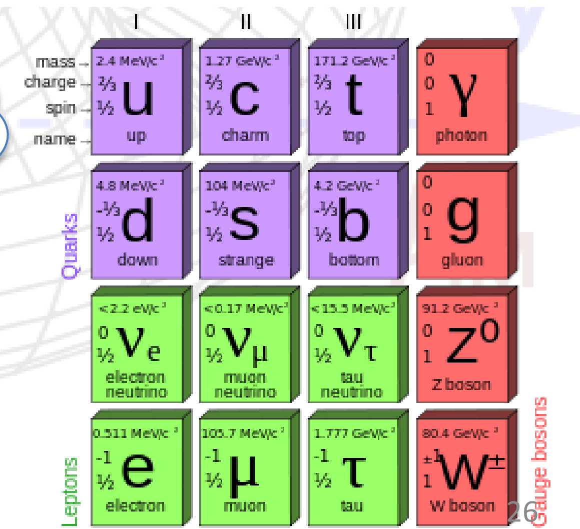


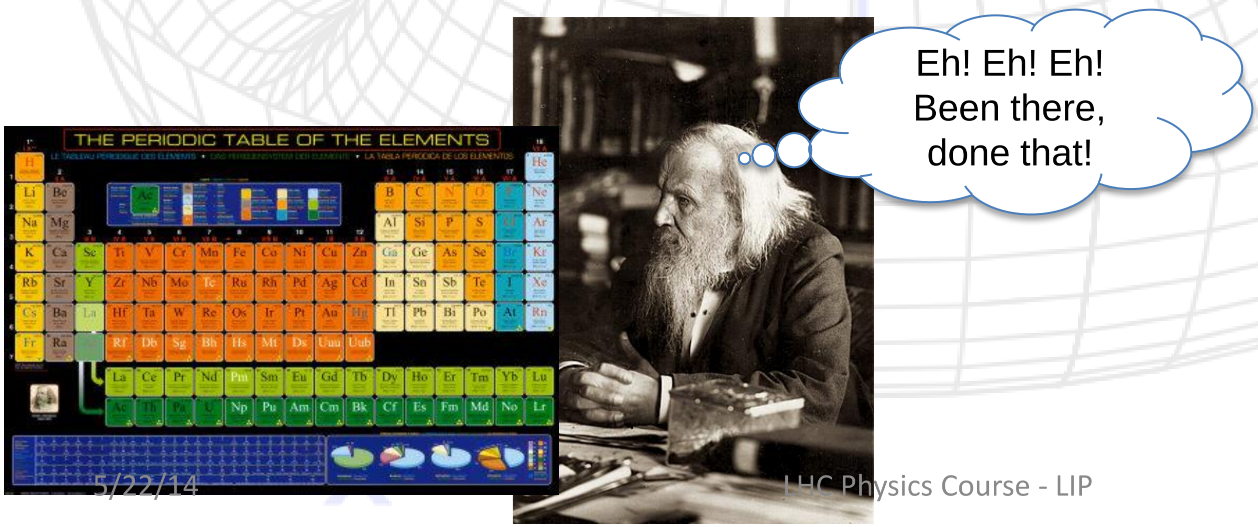
Discovery → Precision! (& a few more channels)

Many questions…

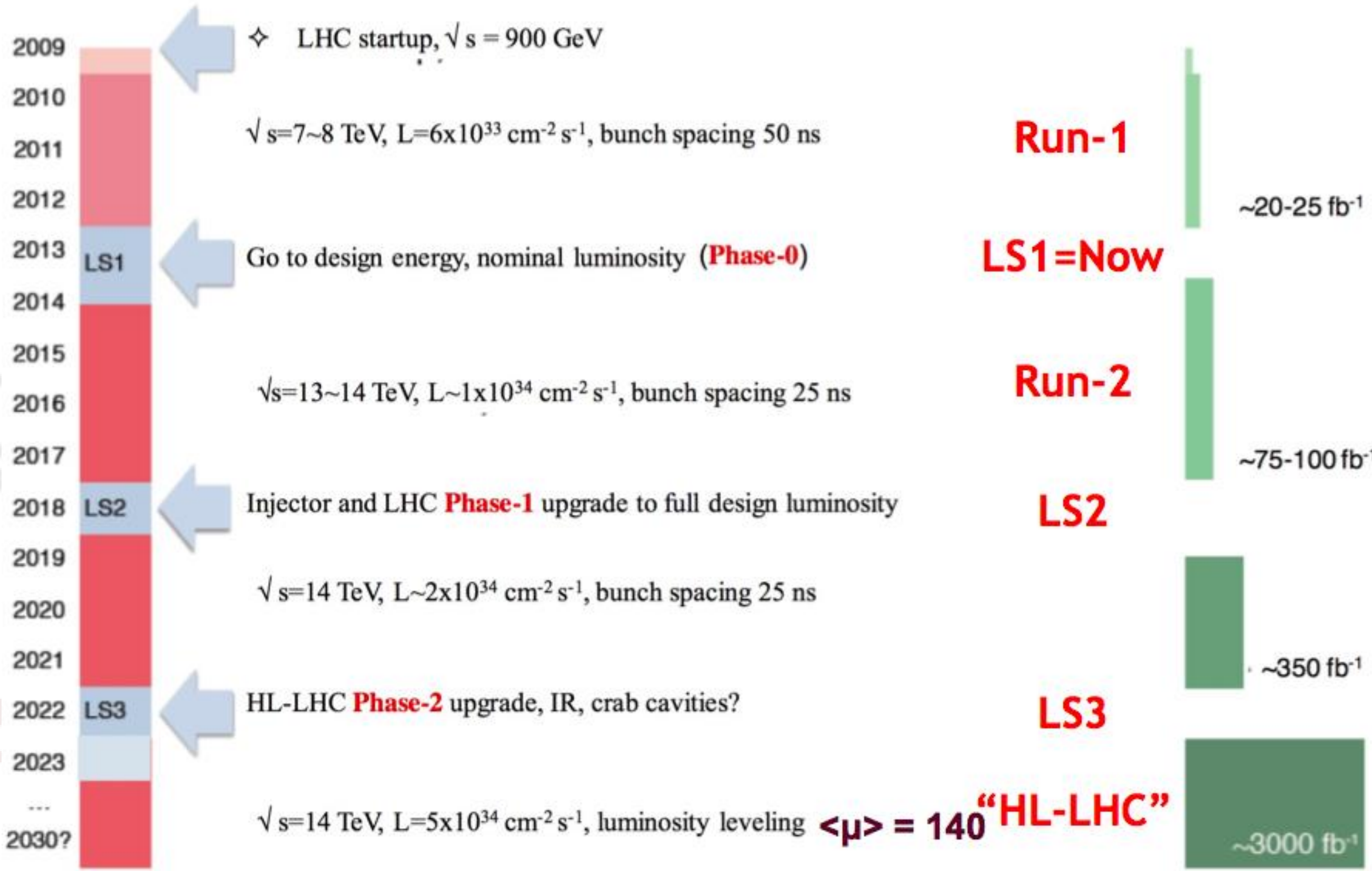
- Higgs mechanism says **how** to give mass to fundamental particles
- It doesn't say **why** fermion masses and Yukawa couplings are so different:
  - 10^{-10}GeV (ν) – 10^{2}GeV (t)
- Top mass at the EW scale. Does it play a special role in breaking it?
- (And by the way… why 3 families of leptons and quarks?)
- What is the underlying theory?





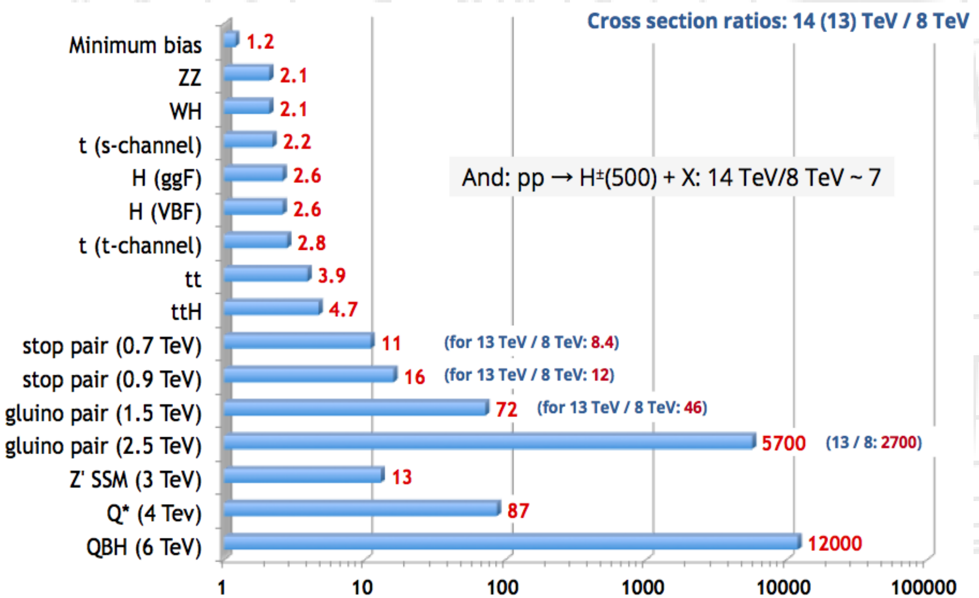


Future LHC Running

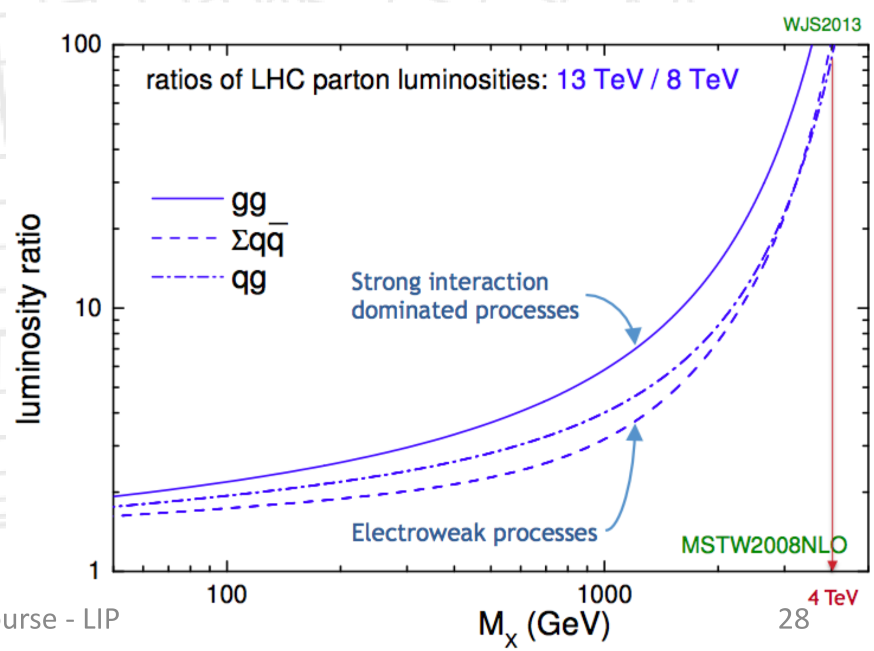


Not only more luminosity

- Higher centre of mass energy gives access to higher masses
- Hugely improves potential for discovery of heavy particles
- Increases cross sections limited by phase space
  - E.g. ttH increases faster than background (factor 4)
- But may make life harder for light states
  - E.g. only factor 2 increase for WH/ZH, H→bb and more pileup
  - Could be compensated by use of boosted jet techniques (jet substructure)



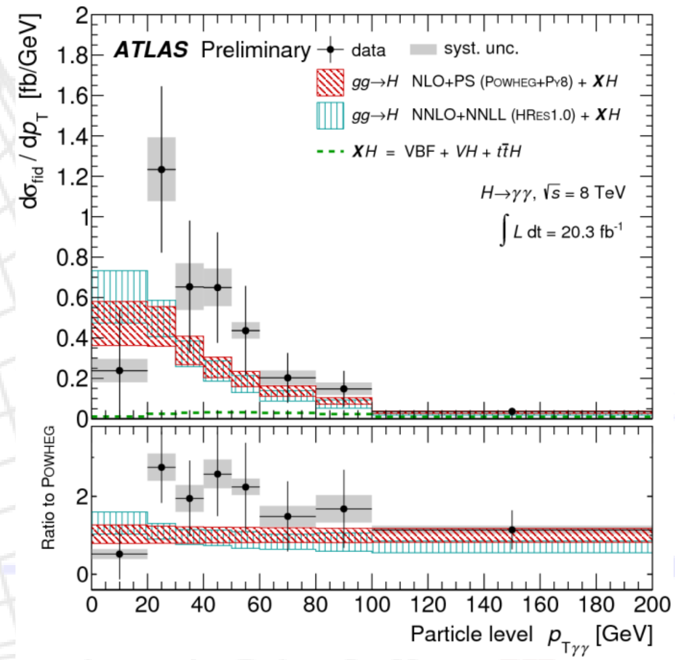
http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html



Run II/High-Lumi LHC Programme

Precision AND searches!

- Precision:
  - Continue to look for deviations wrt Standard Model
- Differential cross sections:
  - New physics in loops could modify event kinematics
- Complete measurement of properties:
  - E.g. CP quantum numbers:
  - Sensitivity in H→ZZ and VBF
  - Search for CP violatin in Higgs sector
- Search for rare decay modes:
  - H→HH to access self coupling (long term!)
- Search for additional Higgs bosons:
  - E.g. 2-Higgs Doublet Model is a natural extension and predicted in SUSY



Direct BSM Higgs Searches (ATLAS)

- FCNC in $t \to cH$, $H \to \gamma\gamma$ - upper limit on BR: Obs.(Exp.): 0.83%(0.53%) x SM for 125 GeV at 95% CL [ATLAS-CONF-2013-081]
- $H \to ZZ \to ll\nu\nu$: Excl. 320 - 560 GeV [ATLAS-CONF-2012-016]
- $H \to ZZ \to llqq$: Excl. 300 - 310, 360 - 400 GeV. at 145 GeV 3.5 x SM [ATLAS-CONF-2012-017]
- $H \to WW \to l\nu jj$: at 400 GeV Obs.(Exp.) 2.3(1.6) x SM [ATLAS-CONF-2012-018]
- Higgs in SM with 4th fermion generation: model ruled out [ATLAS-CONF-2011-135]
- Fermiophobic H to diphoton Model ruled out [ATLAS-CONF-2012-013]
- MSSM neutral H [JHEP: JHEP02(2013)095]
- NMSSM a1 to $\mu\mu$ [ATLAS-CONF-2011-020]
- NMSSM H to a0a0 to 4γ [ATLAS-CONF-2012-079]
- $H^{\pm} \to cs$ [EPJC73 (2013) 2465]
- 2HDM WW($l\nu l\nu$) [ATLAS-CONF-2013-027]

'It is an old maxim of mine that when you have excluded the impossible, whatever remains, however improbable, must be the truth.'

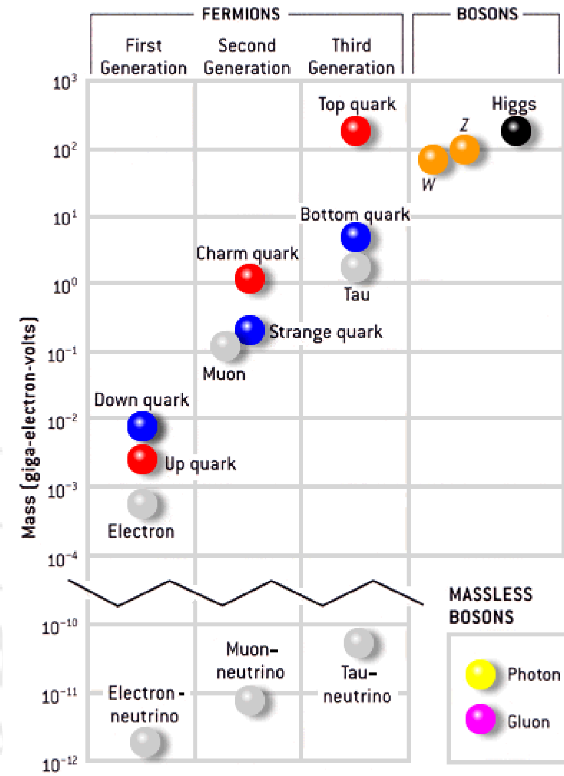
Sherlock Holmes

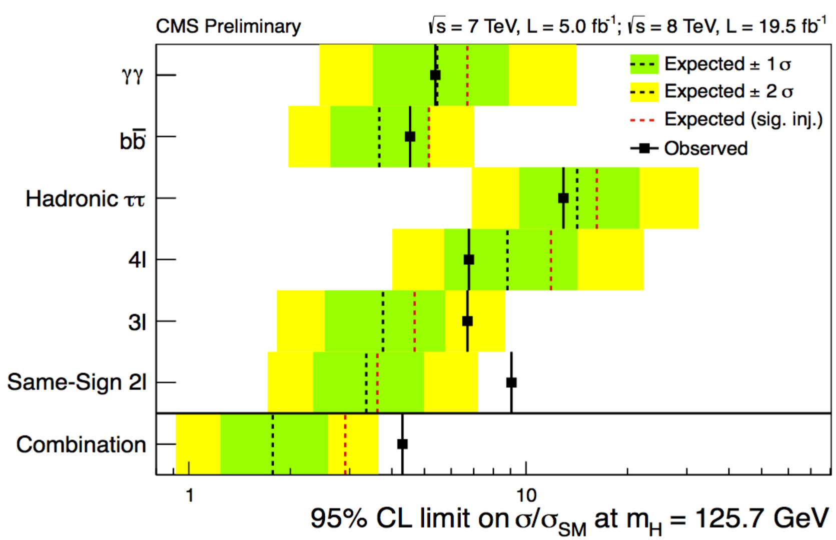
-The Beryl Coronet

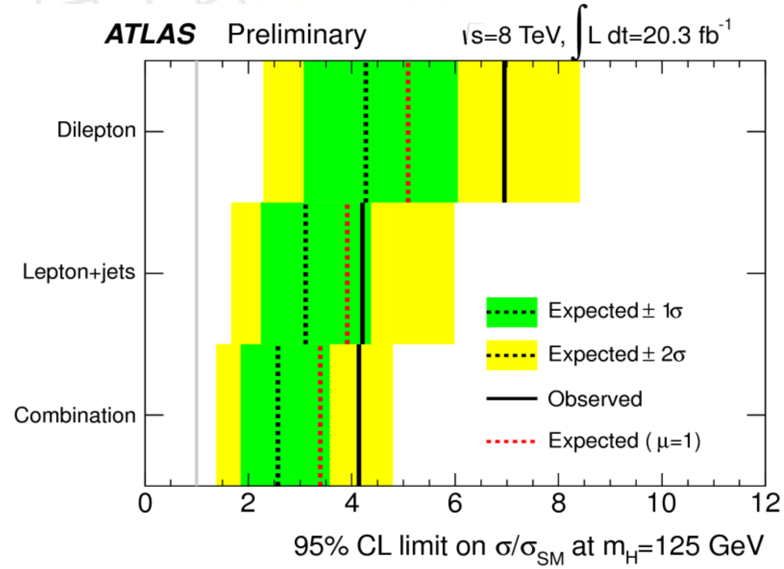
"THE PIPE WAS STILL BETWEEN HIS LIPS."

An example: ttH

- Indirect constraints on top-Higgs Yukawa coupling from loops in ggH and ttH vertices
  - Assumes no new particles contribute to loops
- Top-Higgs Yukawa coupling can be measured directly
  - Allows probing for New Physics contributions in the ggH and γγH vertices
- Top Yukawa coupling $Y_t = \sqrt{2}M_t/vev = 0.996 \pm 0.005$
  - Does this mean top plays a special role in EWSB?

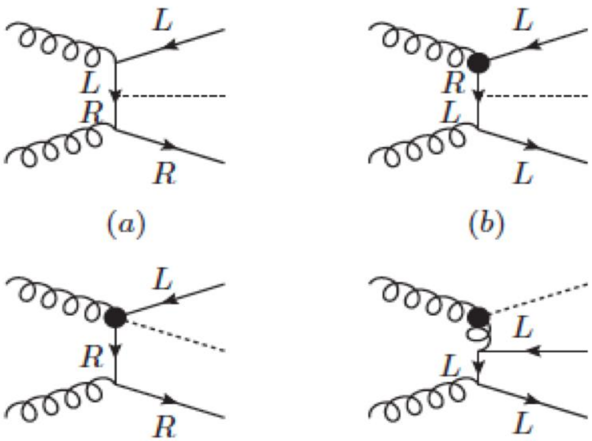




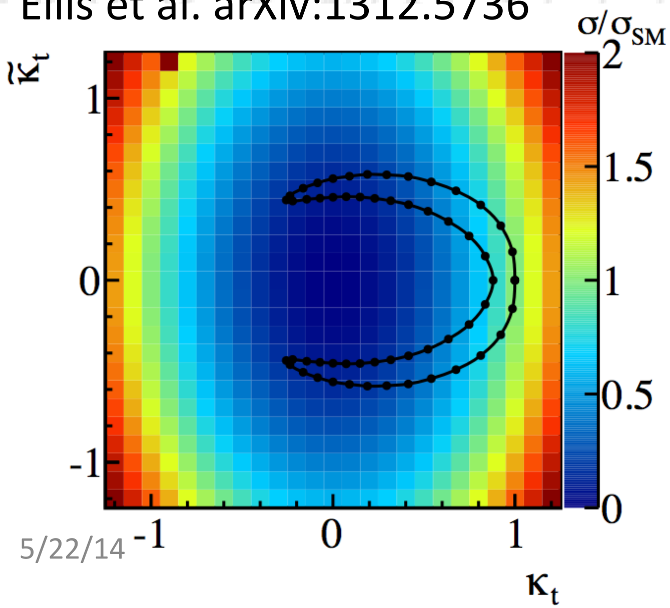


Sensitivity to New Physics

Degrande et al. arXiv:1205.1065



Ellis et al. arXiv:1312.5736

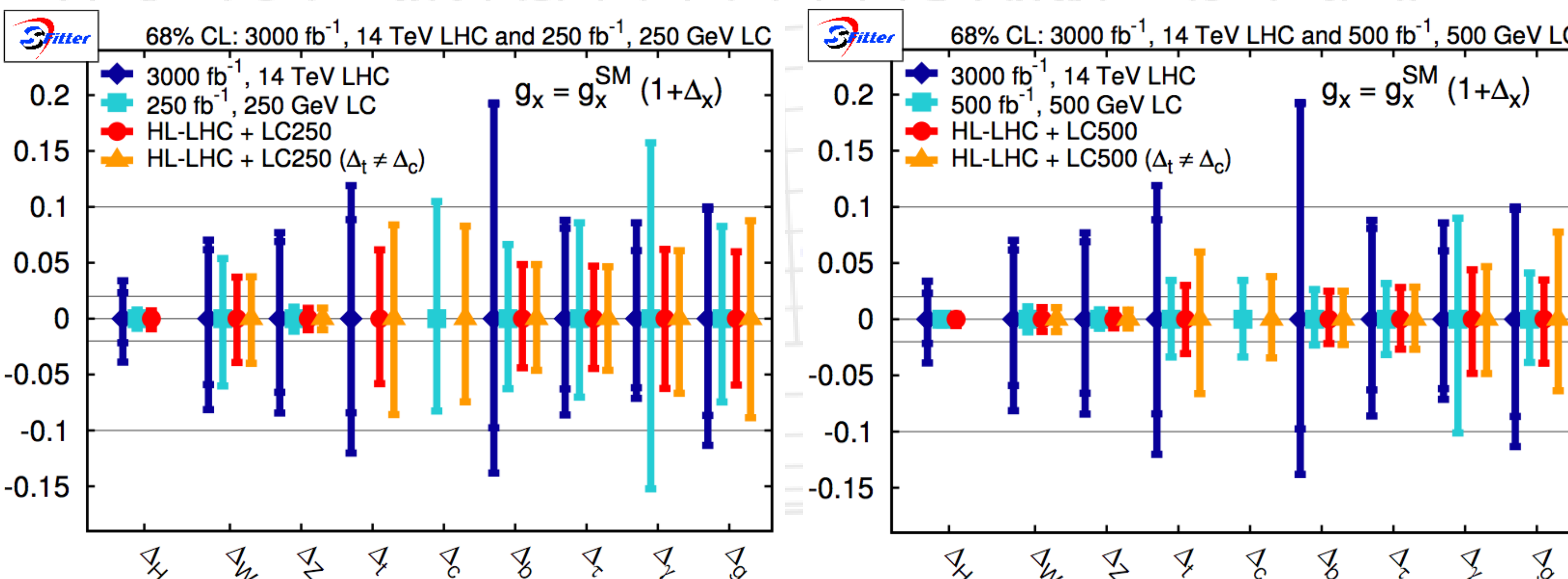


- Effective top-Higgs Yukawa coupling may deviate from SM due to new higher-dimension operators
  - Change **event kinematics –** go differential!
- ttH sensitive new physics: little Higgs, composite Higgs, Extra Dimensions,…
- In the presence of CP violation, Higgs-top coupling have scalar (κ_t)and pseudoscalar ($\tilde{\kappa}_t$)components
  - Strong dependence on ttH cross section
  - Note: Indirect constraints from electron electric dipole moment not taken into account (give $|\tilde{\kappa}_t| < 0.01$)

Future experimental programme

High-Luminosity LHC plus Linear Collider are "**dream team**" for Higgs properties!

- LHC ($\sqrt{s}$=14TeV and L=3000fb^{-1}) **systematics limited**
- Total width only at Linear Collider ($\sqrt{s}$=250GeV, L=250fb^{-1}: ≈10% accuracy)
- 2nd generation couplings (Δ_c, Δ_μ) challenging at LHC but possible at LC
- Δ_{top} opens up for LC500 ($\sqrt{s}$=500GeV, L=500fb^{-1}): ≈3-7% from HL-LHC + LC500
- Precision of **HL-LHC + LC** limited by LC statistical uncertainty, not systematics!
- **NOTE:** Not yet clear what machine will follow the LHC… but Higgs physics is a big part of it's physics motivation!



Klute et al, arXiv: 1301.1322

Summary

- Recapitulation:
  - Electroweak symmetry breaking
  - Higgs boson in Electroweak Lagrangian
  - Practical implications
  - Higgs boson production and decay at the LHC
- The landscape at the end of LHC run I
  - Higgs properties: mass, spin, couplings
  - Review of statistical combination of Higgs channels
  - The power of combining different channels – examples
  - Implications of Higgs measurements beyond Higgs sector
- Future Higgs measurements at LHC and beyond
  - Fundamental questions at the end of run I
  - Future LHC running – luminosity, energy, and physics reach
  - Higgs physics in future LHC analyses – Precision and Searches
  - An example: associated production with top-quark pair – SM and BSM
  - Precision of Higgs properties at future colliders