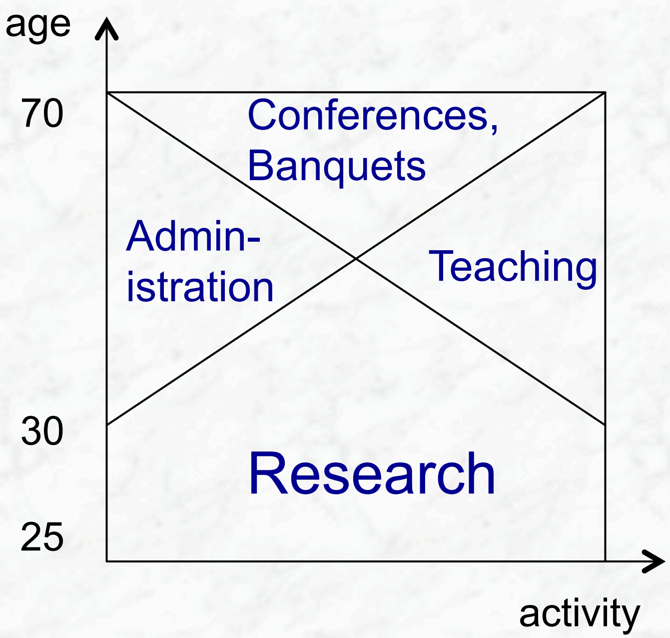
Conference Summary

Higgs Couplings 2014

Karl Jakobs
Physikalisches Institut
Universität Freiburg / Germany

- At this conference more than 30 talks were given
- I do not attempt to summarize all results in detail and I had to make a selection; I would in no way be capable of giving justice and fair credit to the fantastic amount of work presented during the last days
- My apologies to those speakers whose results I have omitted
  It is not intended as a reflection of the relative importance !



Helmut Schmidt,
German Chancellor, 1974-1982

„Wer Visionen hat, sollte zum Arzt gehen"

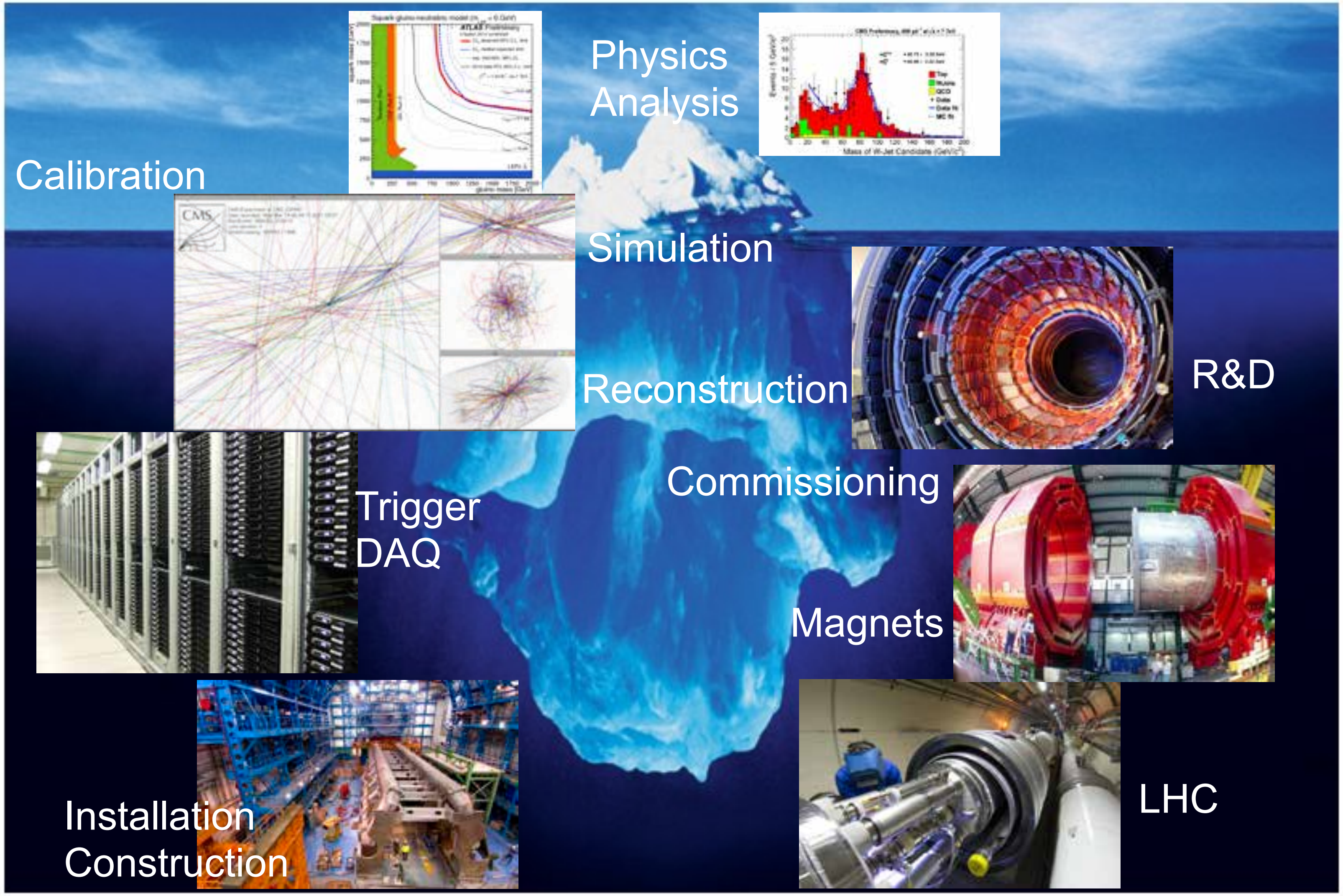
In 2012 the Higgs boson was like …

……a newborn child in the particle family;

After a long and painful way to discovery the world celebrated the arrival of a

“Higgs-like particle”

After a huge effort from many people over a long time, we arrived at physics analysis



H. Bachacou

$H \rightarrow \gamma\gamma$ (historical mode)

Photon decay modes of the intermediate mass Higgs
ECFA Higgs working group
C.Seez and T. Virdee
L. DiLella, R. Kleiss, Z. Kunszt and W. J.Stirling

Presented at the LHC Workshop, Aachen, 4 - 9 October 1990
by C. Seez, Imperial College, London.

CERN 90-10
ECFA 90-133
Volume II
3 December 1990

A report is given of studies of:
(a) $H \rightarrow \gamma\gamma$ (work done by C. Seez and T. Virdoe)
(b) $W H \rightarrow \gamma\gamma$ (work done by L. DiLella, R. Kleiss, Z. Kunszt and W. J. Stirling)
for Higgs bosons in the intermediate mass range ($90 < m_{\gamma\gamma} < 150$ GeV/c^2).
The study of the two photon decay mode is described in detail.

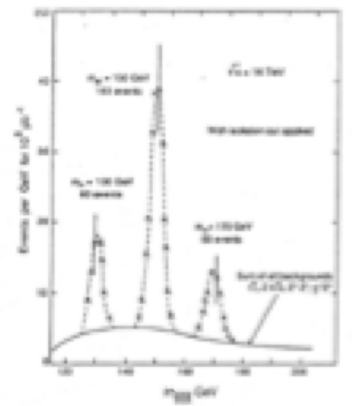


Fig. 10

SEARCH FOR $H \rightarrow Z^*Z^* \rightarrow$ 4 LEPTONS AT LHC

Higgs Study Group

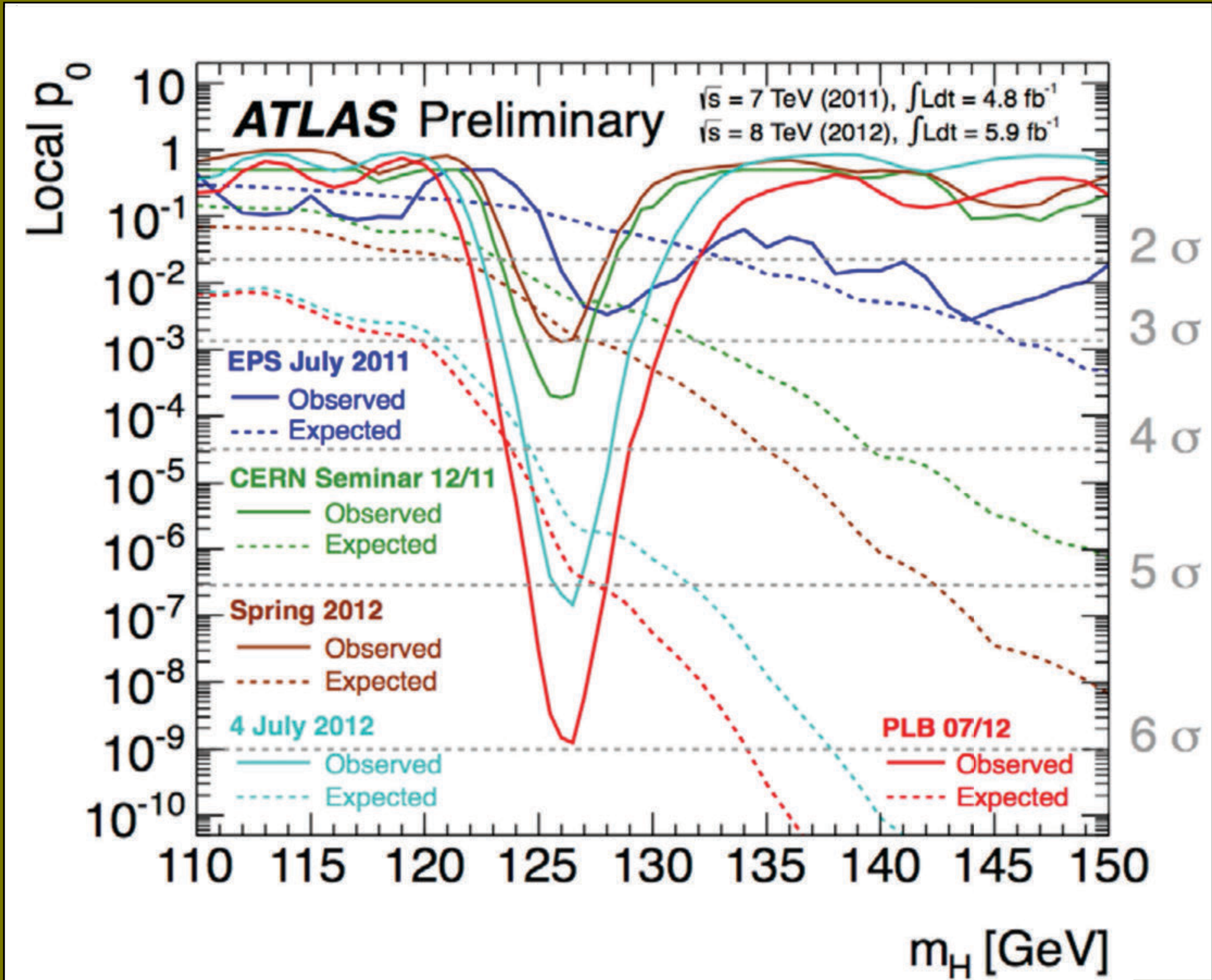
M. Della Negra, D. Froidevaux, K. Jakobs, R. Kinnunen,
R. Kleiss, A. Nisati and T. Sjöstrand

CERN 90-10
ECFA 90-133
Volume II
3 December 1990

In Section 2, we discuss the simulation of the Higgs signal, and we study the backgrounds from $t\bar{t}$, $Zb\bar{b}$ and Z^*Z^*, γ^*Z^*, in Section 3. Finally, in Section 4, we present and discuss the results, and we conclude in Section 5.

Evolution of the excess with time

Evolution of the excess with time



Citation: J. Beringer *et al.* (Particle Data Group), PR D86, 010001 (2012) and 2013 partial update for the 2014 edition (URL: http://pdg.lbl.gov)

GAUGE AND HIGGS BOSONS

γ

$I(J^{PC}) = 0,1(1^{--})$

Mass $m < 1 \times 10^{-18}$ eV
Charge $q < 1 \times 10^{-35}$ e
Mean life τ = Stable

g or gluon

$I(J^{P}) = 0(1^{-})$

Mass $m = 0$ [a]
SU(3) color octet

W

$J = 1$

Charge = ± 1 e
Mass $m = 80.385 \pm 0.015$ GeV
$m_Z - m_W = 10.4 \pm 1.6$ GeV
$m_{W^+} - m_{W^-} = -0.2 \pm 0.6$ GeV
Full width $\Gamma = 2.085 \pm 0.042$ GeV
$\langle N_{\pi^\pm} \rangle = 15.70 \pm 0.35$
$\langle N_{K^\pm} \rangle = 2.20 \pm 0.19$
$\langle N_{p} \rangle = 0.92 \pm 0.14$
$\langle N_{\text{charged}} \rangle = 19.39 \pm 0.08$

$$H^0$$

Z

$J = 1$

Charge = 0
Mass $m = 91.1876 \pm 0.0021$ GeV [d]
Full width $\Gamma = 2.4952 \pm 0.0023$ GeV
$\Gamma(\ell^+ \ell^-) = 83.984 \pm 0.086$ MeV [b]
$\Gamma(\text{invisible}) = 499.0 \pm 1.5$ MeV [e]
$\Gamma(\text{hadrons}) = 1744.4 \pm 2.0$ MeV
$\Gamma(\mu^+ \mu^-)/\Gamma(e^+ e^-) = 1.0009 \pm 0.0028$
$\Gamma(\tau^+ \tau^-)/\Gamma(e^+ e^-) = 1.0019 \pm 0.0032$ [f]

Higgs Bosons — H^0 and $H^\pm$

H^0 Mass $m = 125.9 \pm 0.4$ GeV

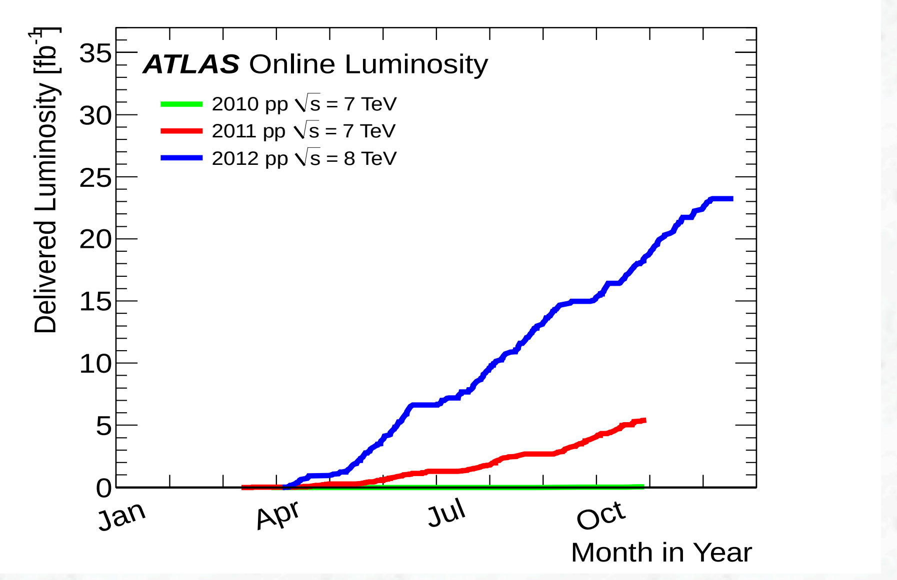
H^0 signal strengths in different channels [n]

Combined Final States = 1.07 ± 0.26 (S = 1.4)
$W W^*$ Final State = 0.88 ± 0.33 (S = 1.1)
$Z Z^*$ Final State = $0.89^{+0.30}_{-0.25}$
$\gamma\gamma$ Final State = 1.65 ± 0.33
$b\bar{b}$ Final State = $0.5^{+0.8}_{-0.7}$
$\tau^+\tau^-$ Final State = 0.1 ± 0.7


Steve Meyers (early 2012):
“The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics.”

Key ingredients to this success story

1. The accelerator



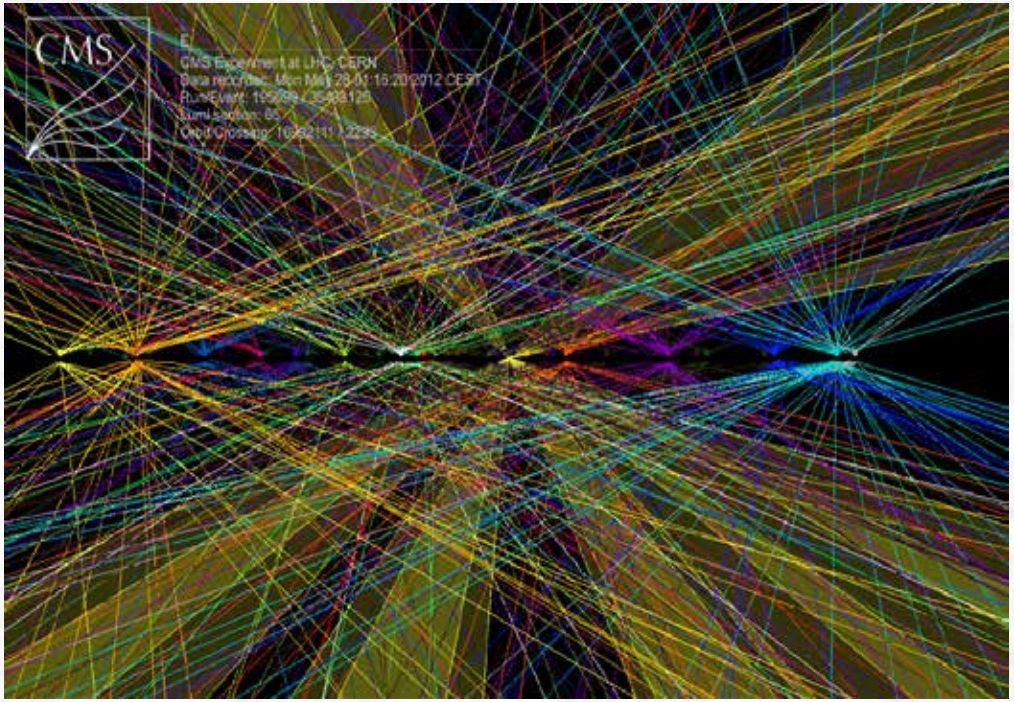
- World record on instantaneous luminosity on 22. April 2011: $4.7\ 10^{32}\ cm^{-2}\ s^{-1}$ (Tevatron record: $4.0\ 10^{32}\ cm^{-2}\ s^{-1}$)

- 2012: regularly above $6\ 10^{33}\ cm^{-2}s^{-11}$

The key ingredients to this success story

1. The accelerator

2. The detectors



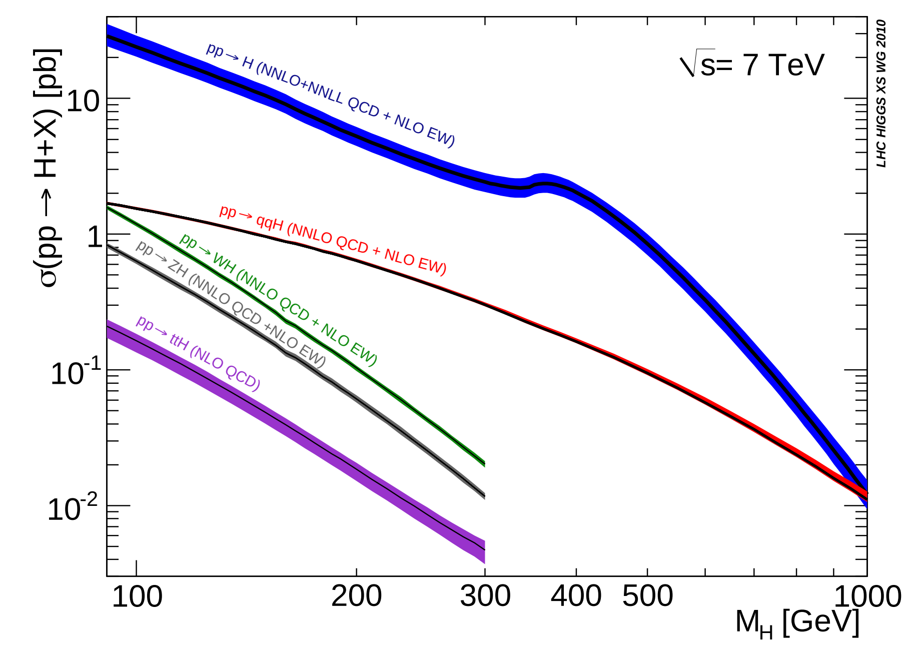
- Working channels > 99%
- Data recording efficiency ~93-94%
- Data quality
- Speed of data analysis
- Had to cope with high luminosity

The key ingredients to this success story

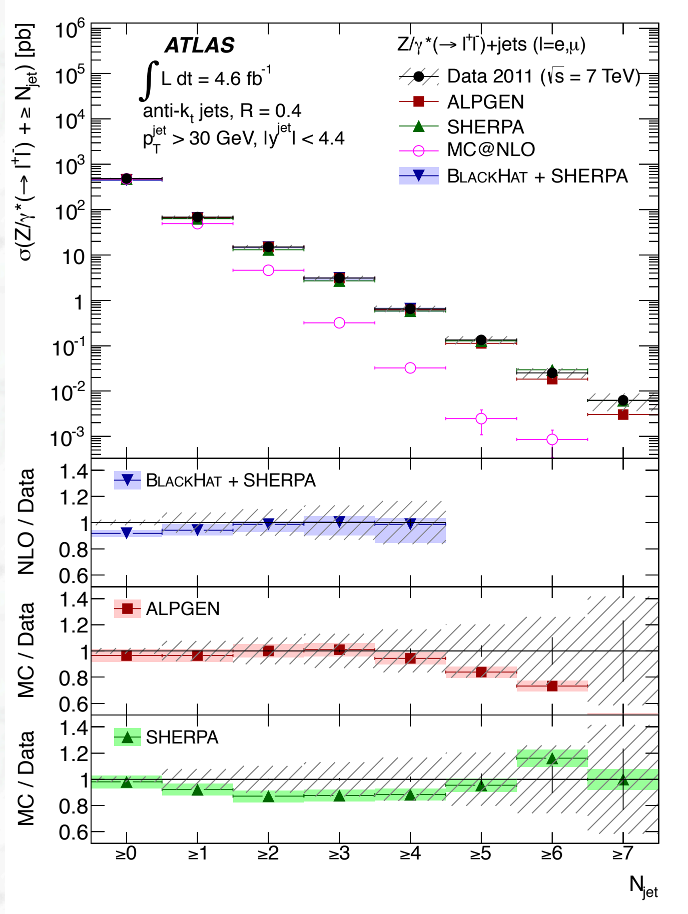
1. The accelerator

2. The detectors

3. Theory, including advances in Monte Carlo simulation



- The overwhelming progress in (N)NLO calculations for signal and background processes



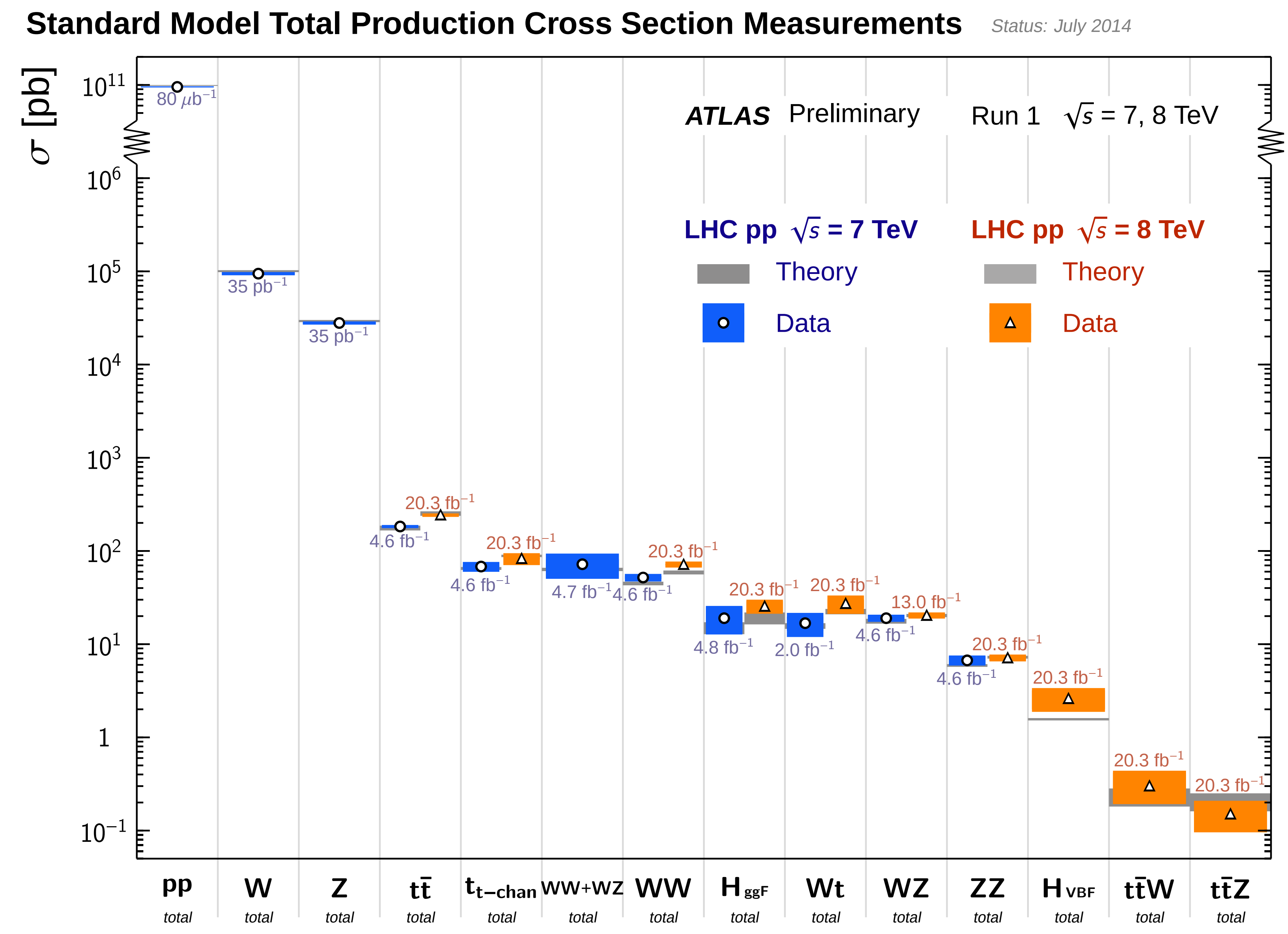
- Improved Monte Carlos simulations

  ALPGEN, MC@NLO, POWHEG, SHERPA, …

- The "Higgs *cross section group*"

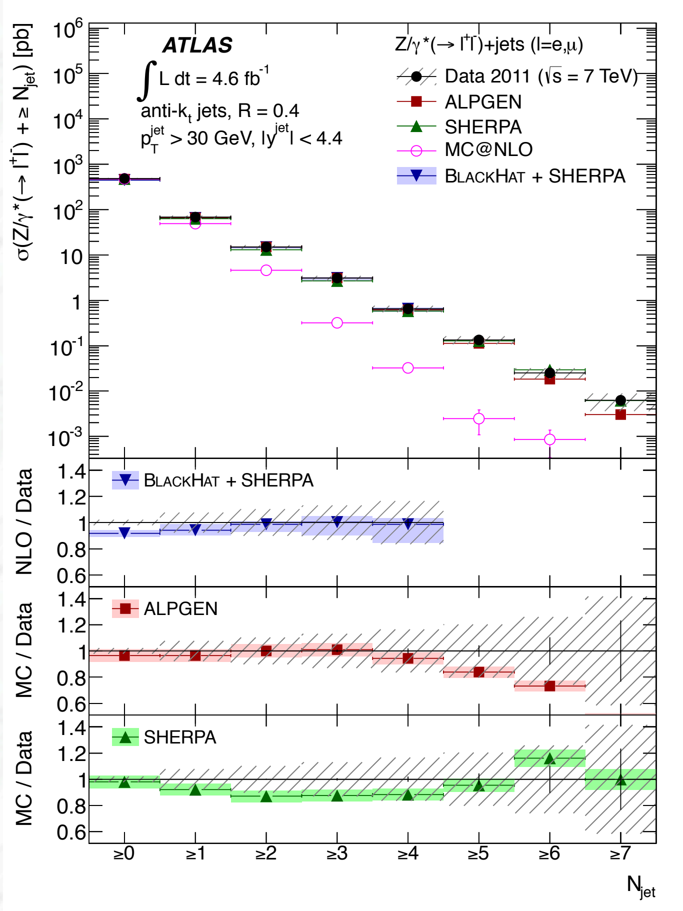
  A big success story !! HXSWG

  * Central values for the production processes
  * Theoretical uncertainties
  * Differential distributions
  * Guidance / benchmark scenarios on coupling measurements
  * Guidance in spin/CP measurements



Standard Model Total Production Cross Section Measurements
Status: July 2014
σ [pb]
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
Theory
Data
LHC pp √s = 8 TeV
Theory
Data
80 μb⁻¹
35 pb⁻¹
35 pb⁻¹
4.6 fb⁻¹
20.3 fb⁻¹
4.6 fb⁻¹
20.3 fb⁻¹
4.7 fb⁻¹
4.6 fb⁻¹
20.3 fb⁻¹
4.8 fb⁻¹
20.3 fb⁻¹
2.0 fb⁻¹
20.3 fb⁻¹
4.6 fb⁻¹
13.0 fb⁻¹
4.6 fb⁻¹
20.3 fb⁻¹
20.3 fb⁻¹
20.3 fb⁻¹
20.3 fb⁻¹
pp total
W total
Z total
tt̄ total
t t−chan total
WW+WZ total
WW total
H ggF total
Wt total
WZ total
ZZ total
H VBF total
tt̄W total
tt̄Z total

- The overwhelming progress in (N)NLO calculations for signal and background processes



- Improved Monte Carlos simulations

  ALPGEN, MC@NLO, POWHEG, SHERPA, …

- The Higgs *“cross section group”*

  A big success story !!

  HXSWG

* Central values for the production processes
* Theoretical uncertainties
* Differential distributions
* Guidance / benchmark scenarios on coupling measurements
* Guidance in spin/CP measurements

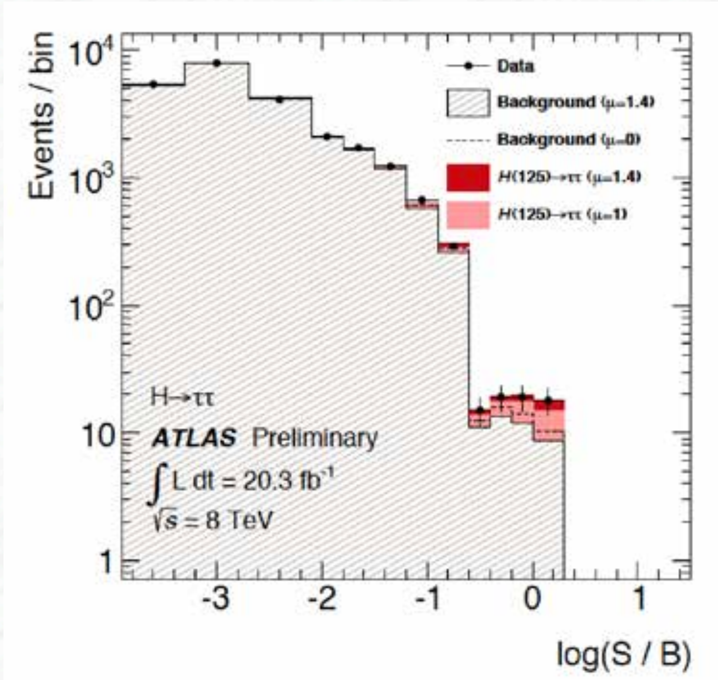
The key ingredients to this success story

1. The accelerator

2. The detectors

3. Theory, including advances in Monte Carlo simulation

4. Analysis Techniques



- Multivariate Techniques (Neutral networks, Boosted Decision Trees, …) ←Tevatron
- Data-driven background estimates, control region fits ← Tevatron
- Statistical methods (profile likelihood methods)
- Energy flow techniques

Where do we stand after two years?

What aspects of the Higgs boson have we learned about in the last two years?

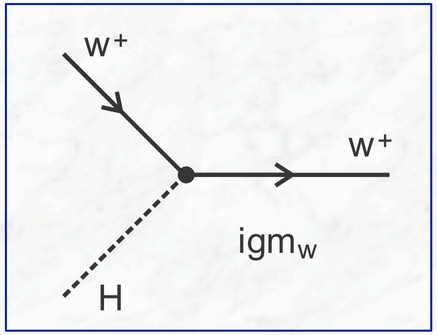
- Clear signals in bosonic decays
- Differential cross-section measurements
- Signals in fermionic decays

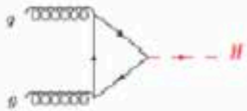
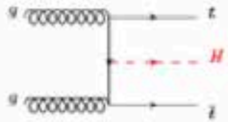
- Higgs boson profile:

  - Precision mass measurements
  - Extensive coupling measurements
  - Off-shell behaviour
  - Discrete quantum numbers (spin, CP)

- Search for brother or sister particles, i.e. additional Higgs bosons

Couplings to boson



Mode	ggF	VBF	VH	ttH
				
$\gamma\gamma$	✓	✓	✓	✓
ZZ	✓	✓	✓	
WW	✓	✓	✓	✓

✓ LHC analysis + “Signal seen”

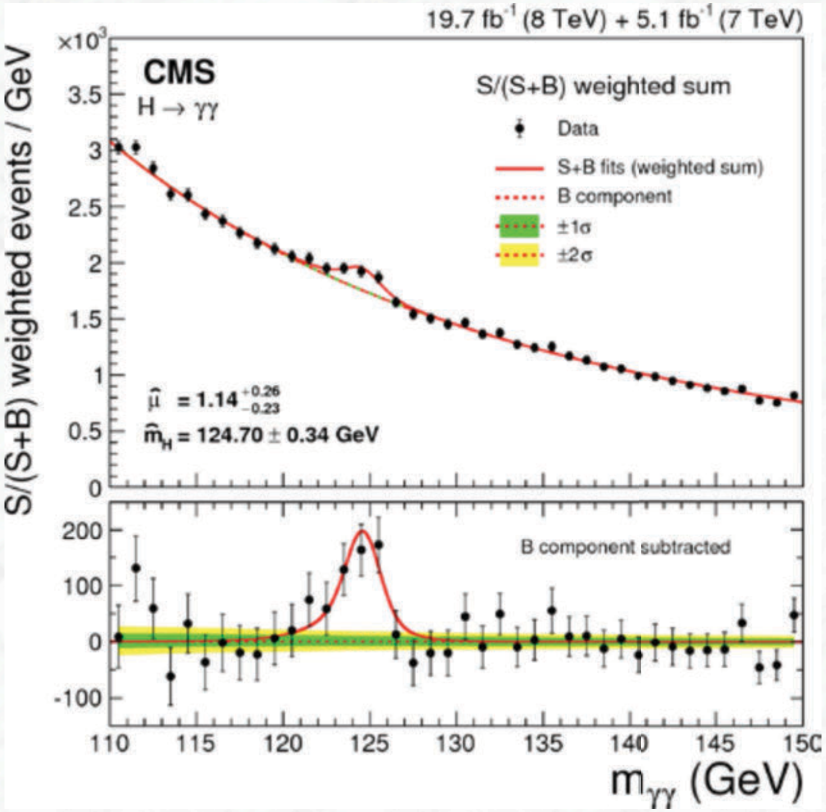
✓ LHC analysis

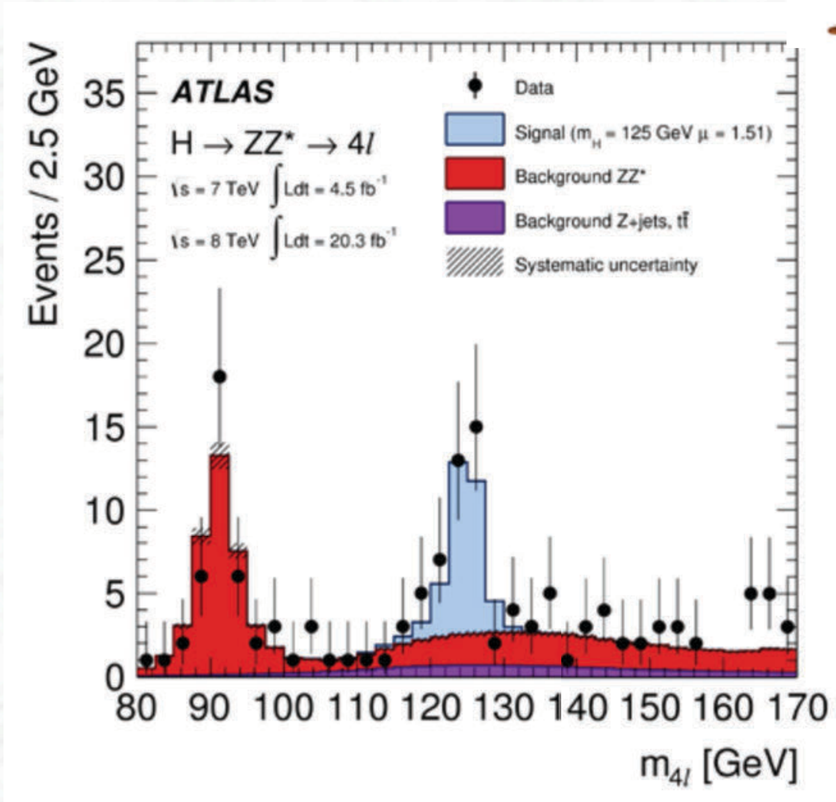
Categorisation in all channels

→ information on production mode
→ couplings

Signals in the bosonic decay modes

A. Calandri
A. Massironi



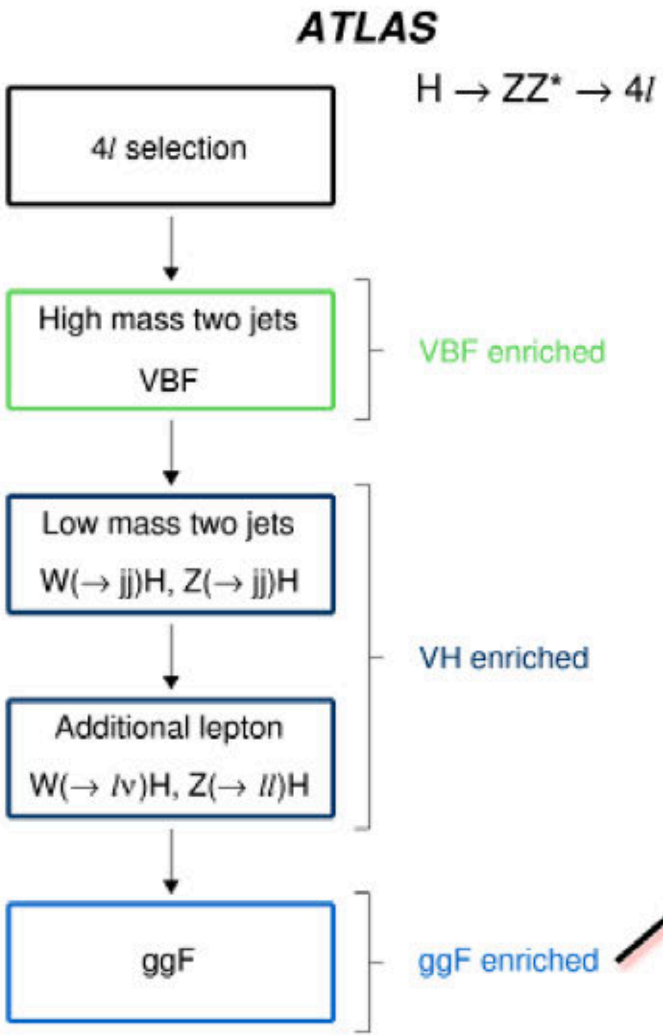


5.7σ

>7σ

Categorisation, example H → ZZ*→ 4l decays

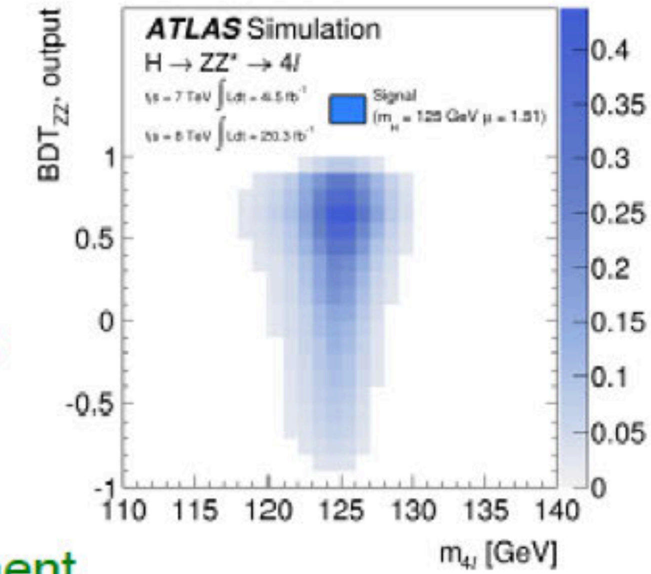
Event categorization:

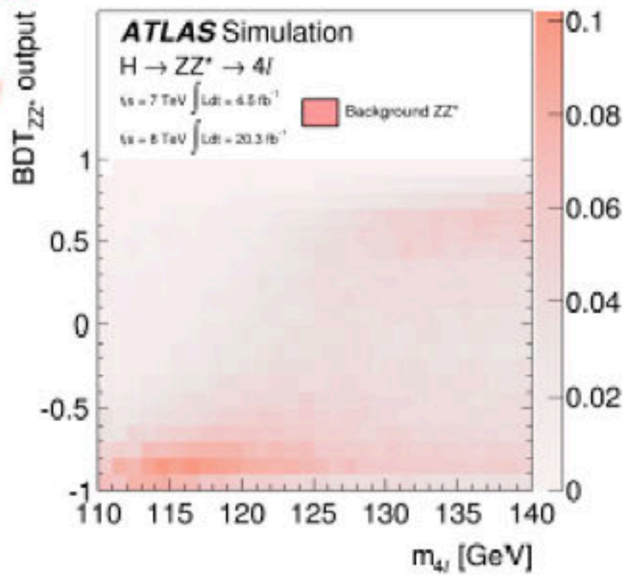


BDT vs mass

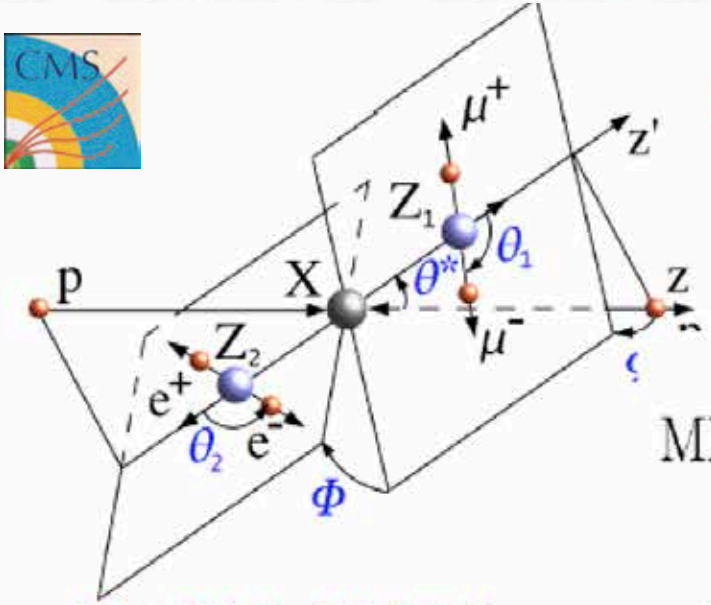
BDT variables:

- $P_T(4l)$
- $\eta(4l)$
- Matrix Element Discriminant





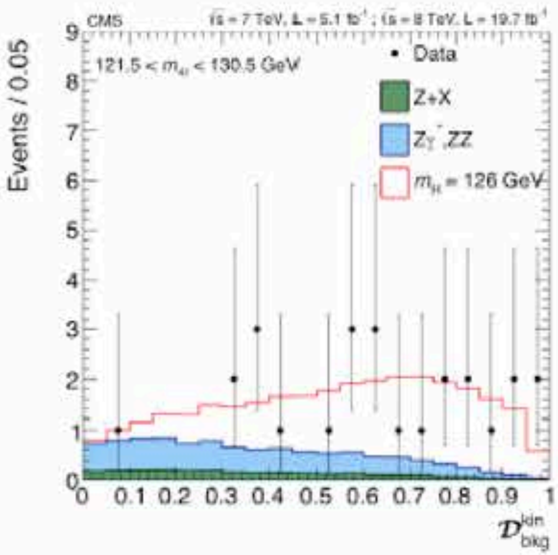
Matrix-element / multivariate analysis techniques



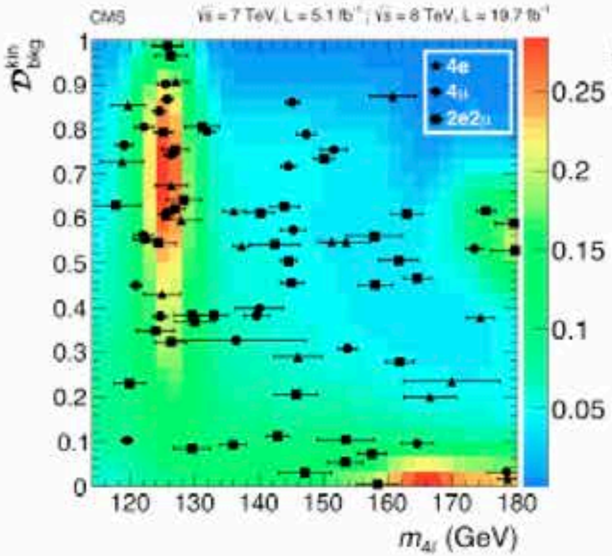
MELA: Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to ZZ background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

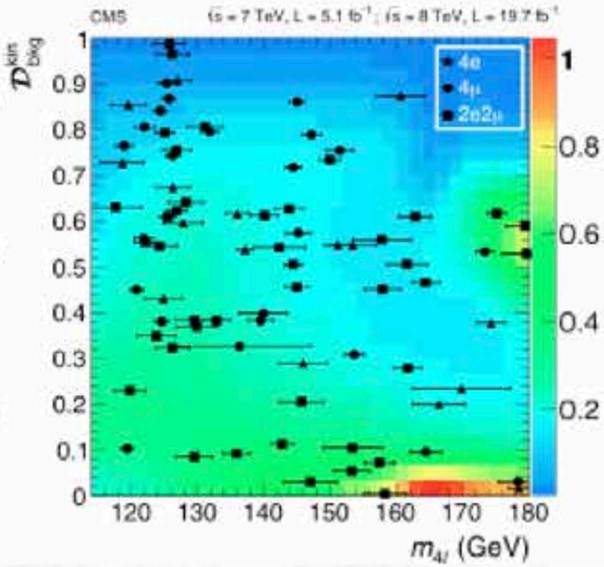
M_{4l} = 121.5 – 130.5 GeV



Colours are signal + BG

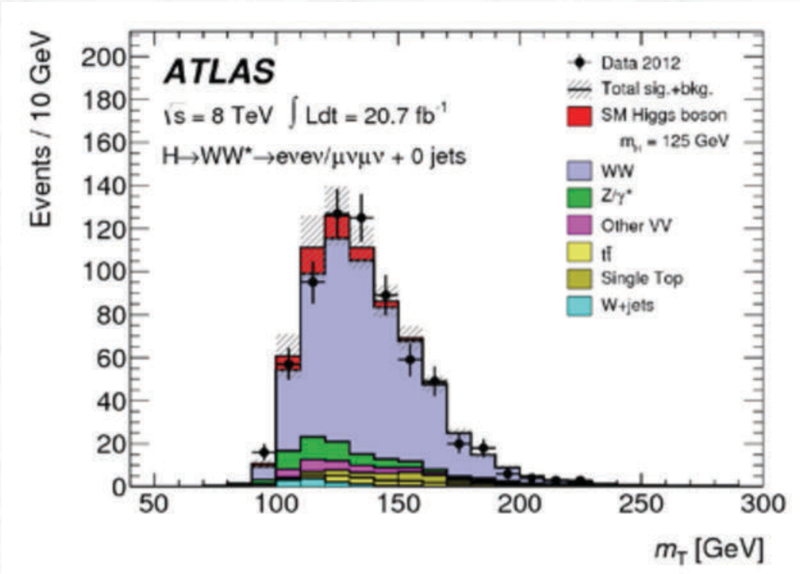


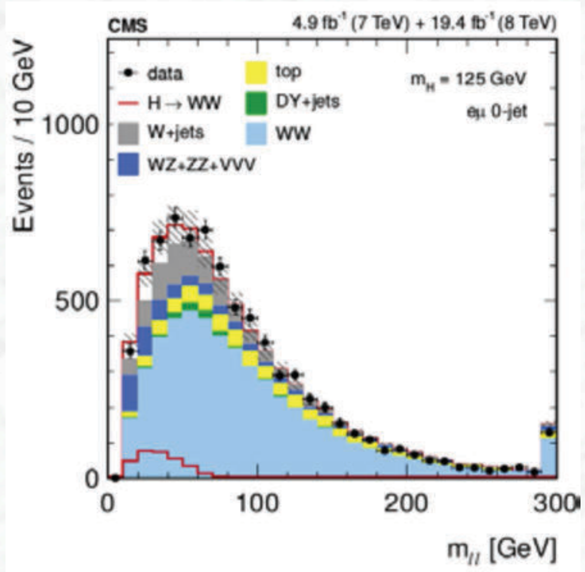
Colours are BG only

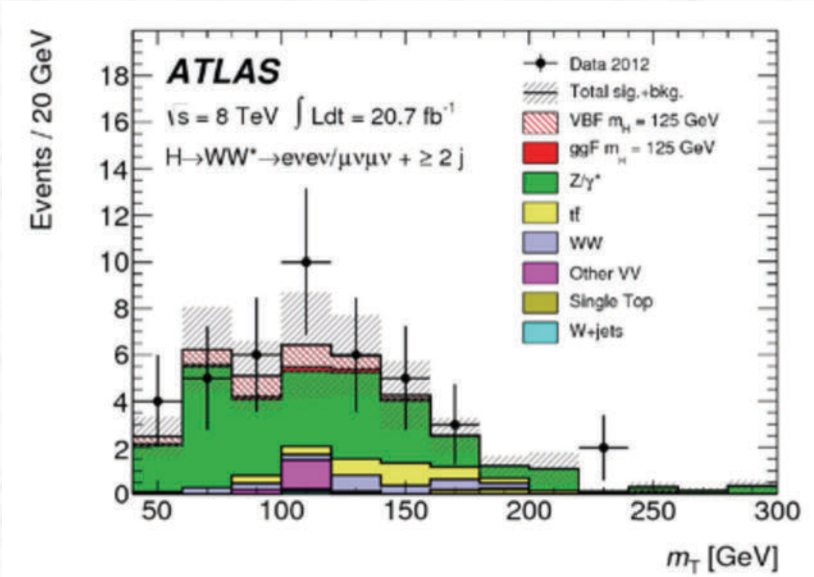


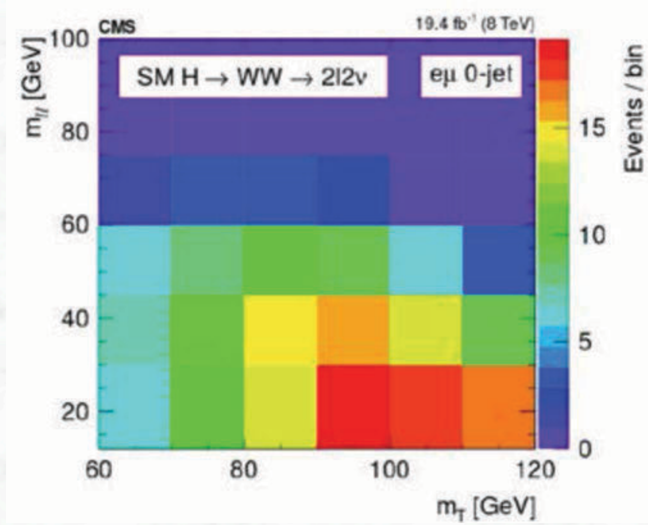
H → WW→ lν lν signals

A. Calandri
A. Massironi









Summary of “final” Run-1 results

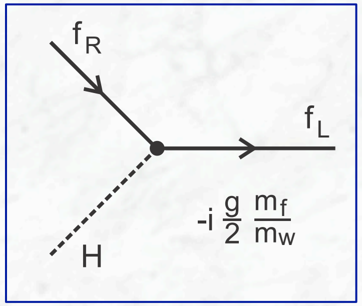
	ATLAS m [GeV]	ATLAS μ	CMS m [GeV]	CMS μ
$H \rightarrow \gamma\gamma$	126.0 ± 0.50	1.17 ± 0.27	124.70 ± 0.34	$1.14^{+0.26}_{-0.23}$
$H \rightarrow ZZ^* \rightarrow 4l$	124.51 ± 0.52	$1.44^{+0.40}_{-0.34}$	125.6 ± 0.45	$0.93^{+0.29}_{-0.25}$
$H \rightarrow WW^* \rightarrow l\nu l\nu$	125.5*	$0.99^{+0.31}_{-0.28}$	125 ± 4	$0.72^{+0.20}_{-0.18}$

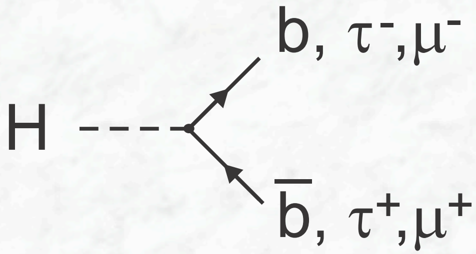
- Signals established with high significance in both experiments
- Signal strengths appear to be well consistent with the Standard Model expectations (high $\gamma\gamma$ signal yields “normalized”)
- Clear evidence in VBF sub-categories (later)
- Differential distributions measured (later)
- Mass determined with high precision (later)

* non-final results yet, publication in preparation

Couplings to fermions ?

- Search for H → ττ and H → bb decays
- Search for the rare H → μμ decay

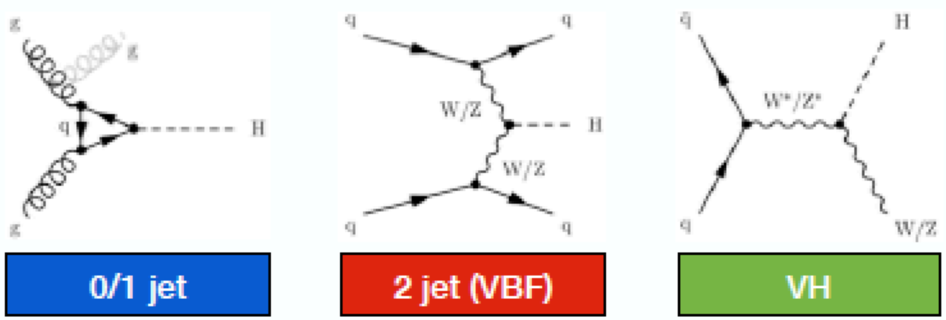




Search for H → τ τ decays

R. Manzoni
KG Tan

- A challenging analysis, focus on VBF and "boosted" topologies
- Multivariate analysis in ATLAS
- Complex models to estimate backgrounds
  (embedding of Z → τ τ events, use of control regions, e.g. 0-jet category)
- Complex fit models

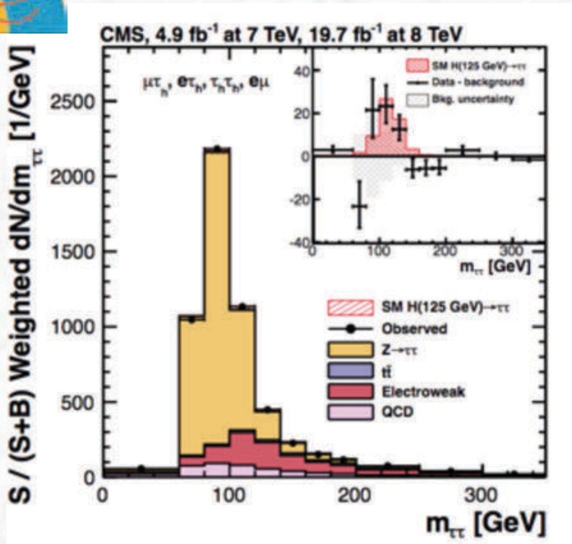


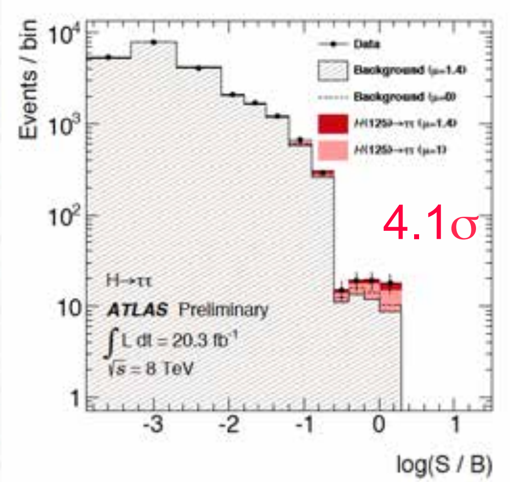
0 jet		1 jet		2 jet (VBF tag)	
low τ p_T	high τ p_T	low boost	high boost	loose	tight
$H \rightarrow \mu\tau_h, e\tau_h, \tau_h\tau_h, e\mu, \mu\mu, ee$					
ZH			WH		

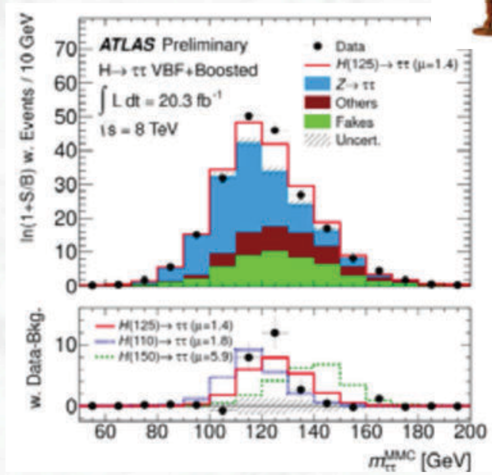
Boosted (Large Higgs p_T)	VBF (VBF tag)
$H \rightarrow \mu\tau_h, e\tau_h, \tau_h\tau_h, e\mu, \mu\mu, ee$	

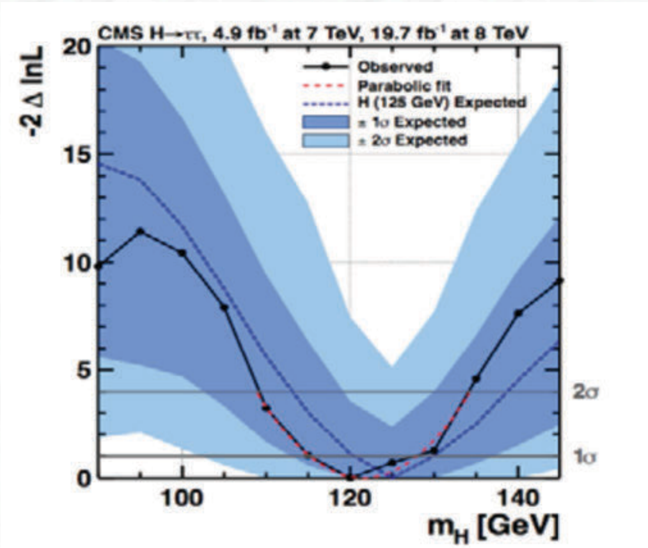
Clear evidence for H → τ τ decays in both experiments

R. Manzoni
KG Tan









Signal strength (all sub-channels):

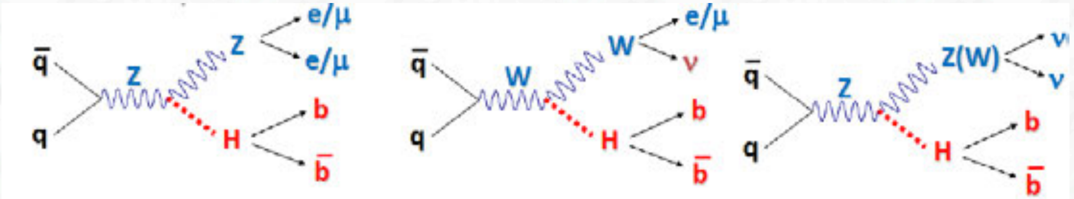
ATLAS: $\mu = 1.4\ ^{+0.5}_{-0.4}$

CMS: $\mu = 0.78 \pm 0.27$

$m_H = 122 \pm 7$ GeV

R. Manzoni
KG Tan

Search for H → bb decays

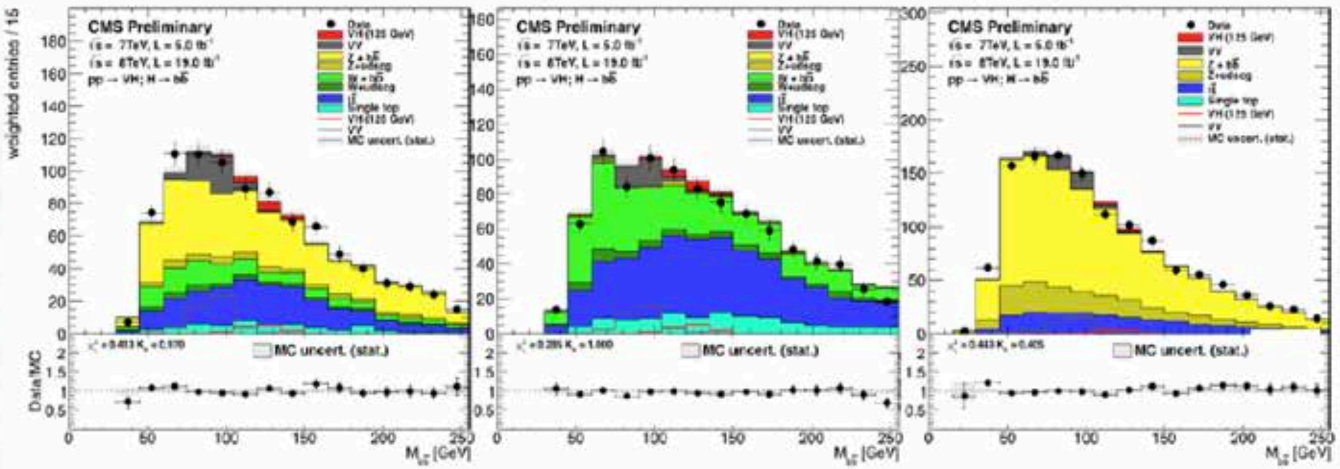


- All what was said for H → $\tau\tau$ applies here as well;
  (challenges, categorization, background normalization, complexity of the fit,… frustration of students,…)

0-lepton
- Require large E_T^{miss} and corresponding p_T^{miss}
- Missing energy and jets are back-to-back

1-lepton
- Require some E_T^{miss}
- Use transverse mass between neutrino and lepton

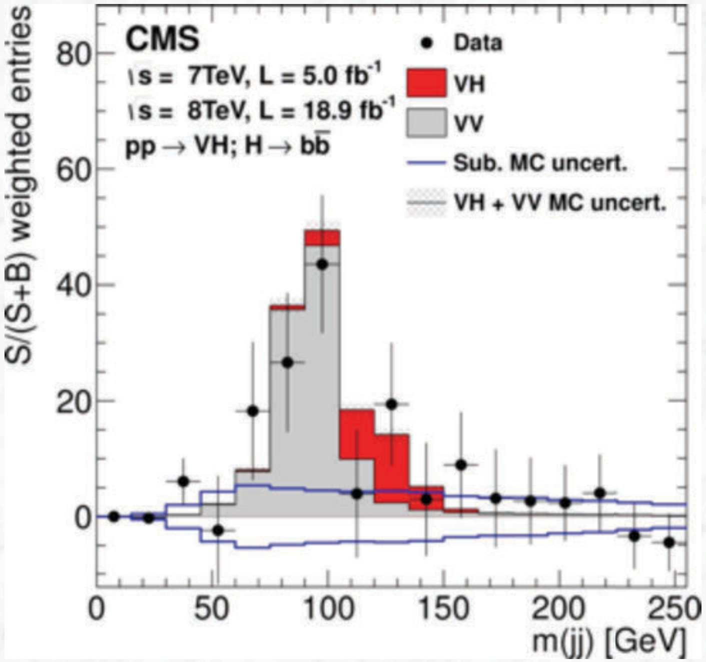
2-lepton
- Require less E_T^{miss}
- Use invariant mass of the oppositely charged lepton pair

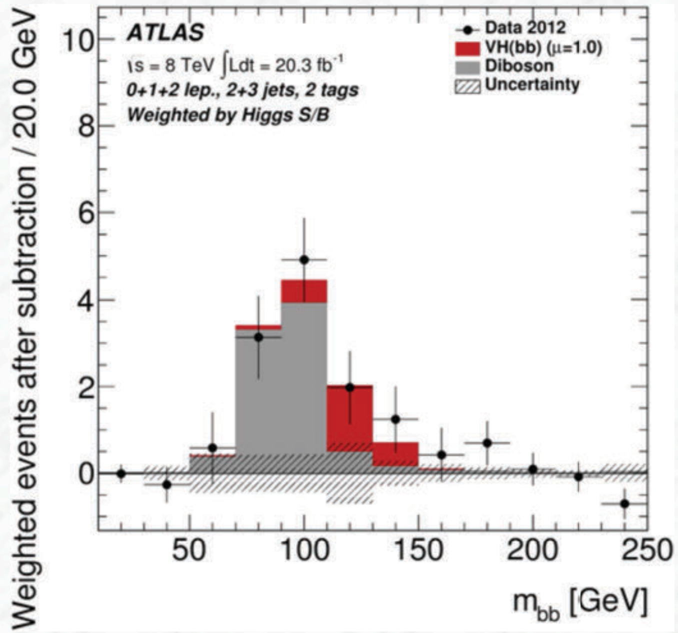


MAJOR BACKGROUNDS

Z+bb, tt — W+jets, tt — Z+bb

Hints / evidence for H → bb decays

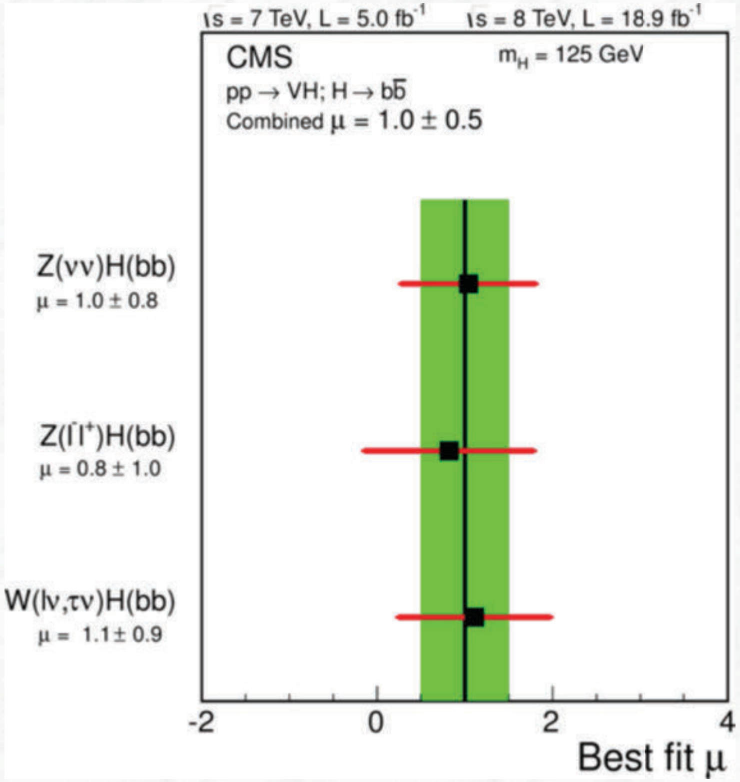


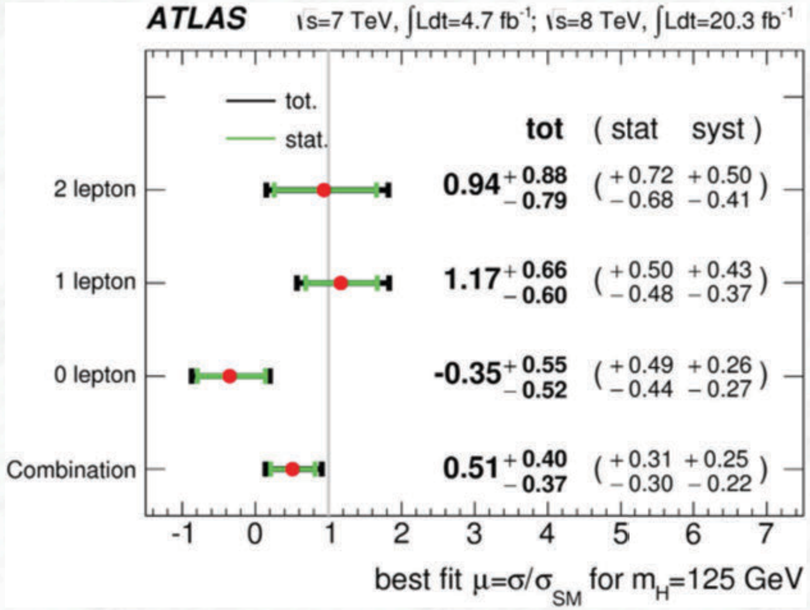


Signal strength (all sub-channels):

CMS: $\mu = 1.0 \pm 0.5$ ATLAS: $\mu = 0.51^{+0.40}_{-0.37}$

Hints / evidence for H → bb decays





Signal strength (all sub-channels):

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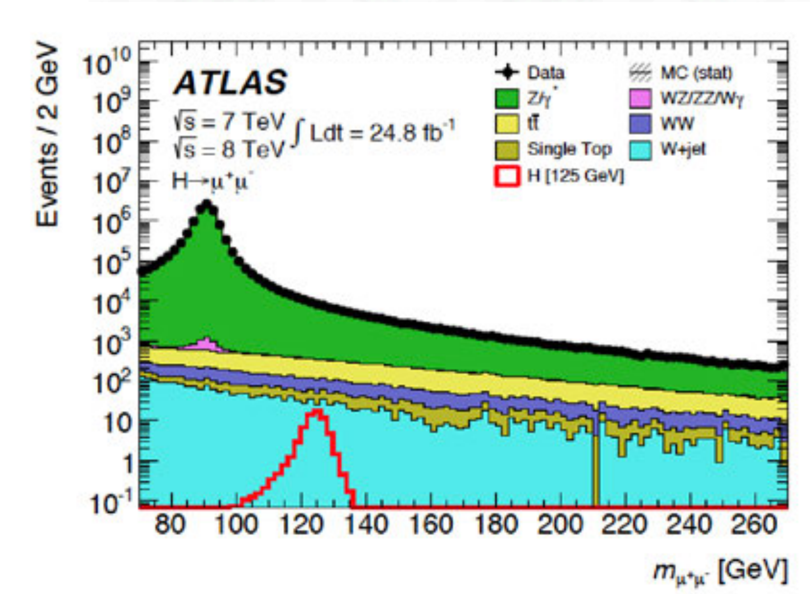
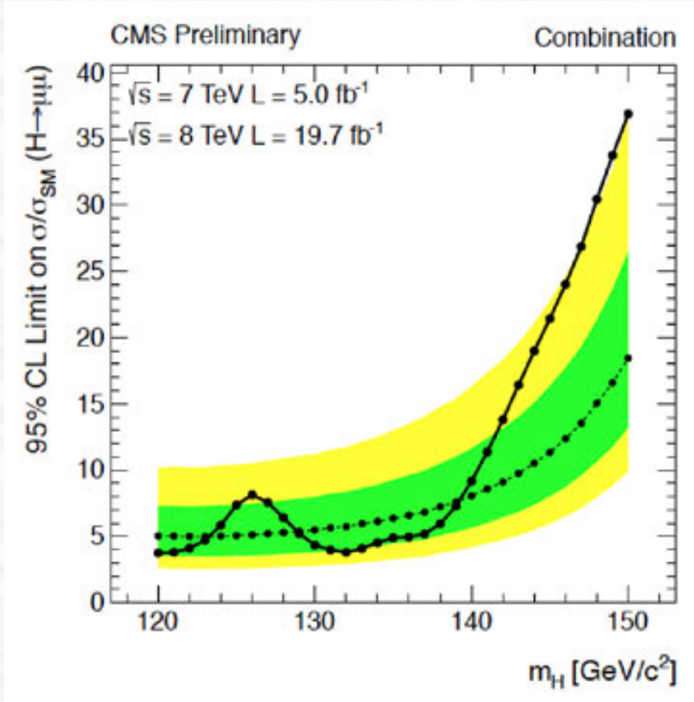
Results on the search for H→ $\mu\mu$

R. Manzoni
KG Tan





m_H = 125 GeV:

Observed 95% CL:	ATLAS:	7.0 σ_{SM}	CMS:	7.4 σ_{SM}
Expected (no Higgs):		7.2 σ_{SM}		5.1 σ_{SM}

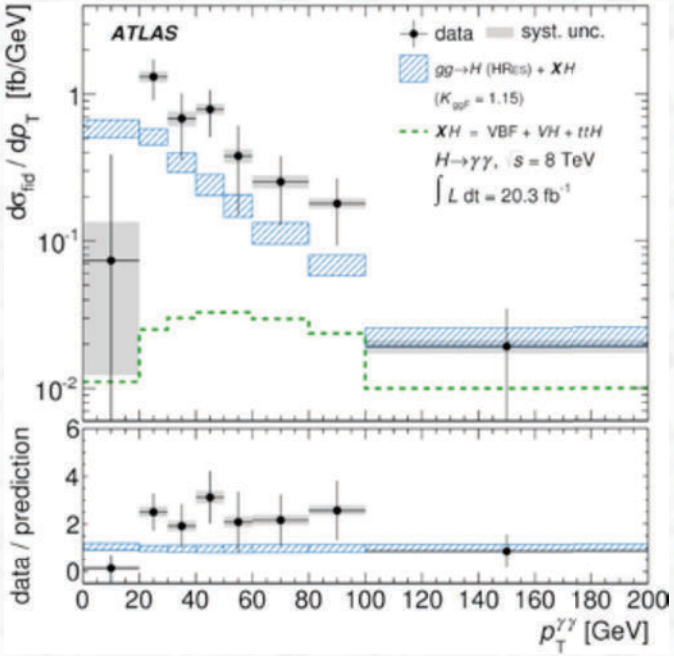
No evidence for "universal" fermion couplings

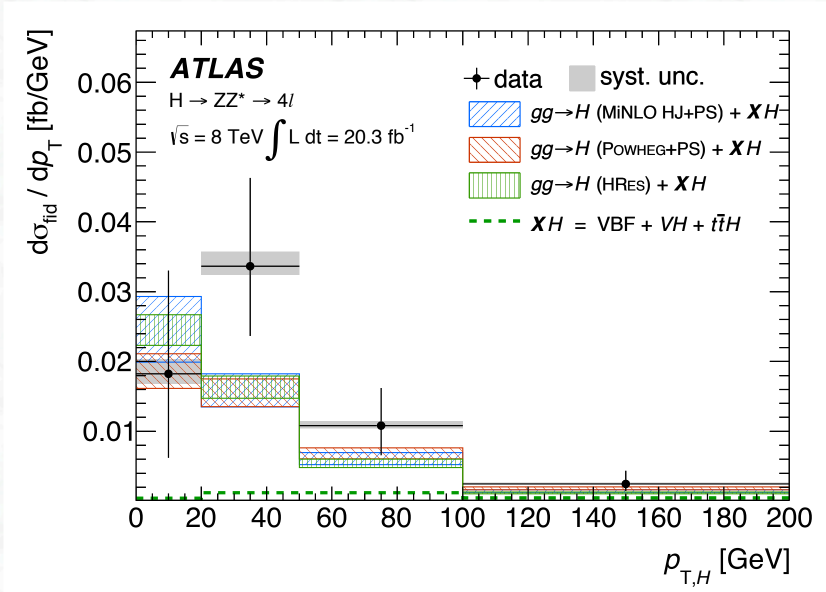
Summary of “final” Run-1 results of signal strength

	m [GeV]	μ ATLAS	m [GeV]	μ CMS
H → γγ	126.0 ± 0.50	1.17 ± 0.27	124.70 ± 0.34	$1.14^{+0.26}_{-0.23}$
H → ZZ* → 4l	124.51 ± 0.52	$1.44^{+0.40}_{-0.34}$	125.6 ± 0.45	$0.93^{+0.29}_{-0.25}$
H → WW* → lνlν	125.5*	$0.99^{+0.31}_{-0.28}$	125 ± 4	$0.72^{+0.20}_{-0.18}$
H → ττ	-	$1.4^{+0.5}_{-0.4}$	122 ± 7	0.78 ± 0.27
H → bb	-	$0.51^{+0.40}_{-0.37}$	-	1.0 ± 0.5

* non-final results yet, publication in preparation

Differential cross-section measurements





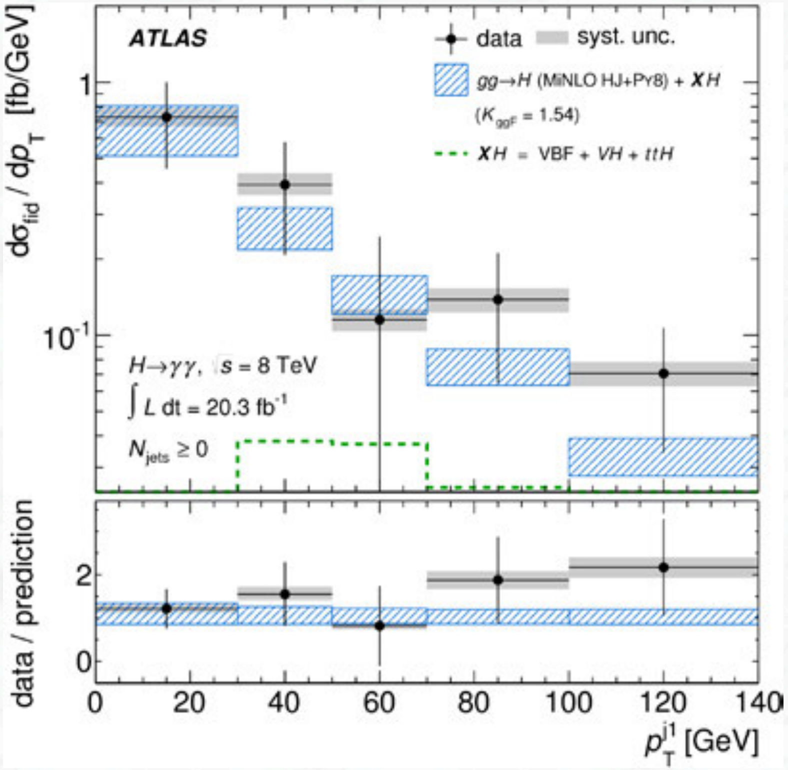
- First fiducial, differential cross-section measurements in bosonic channels
- Good agreement within present experimental and theoretical uncertainties, (… except normalization?)

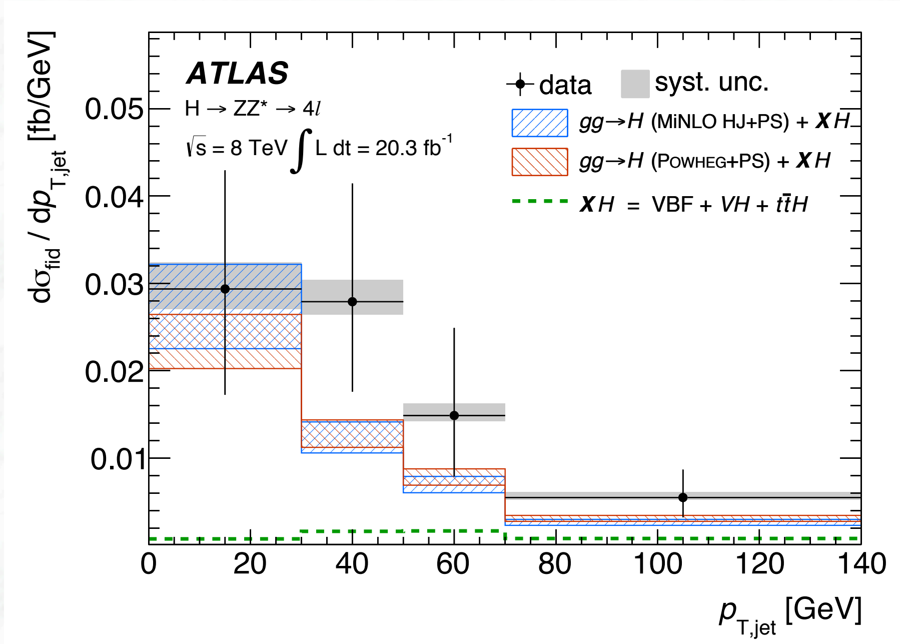
- Large future potential: probe Higgs boson kinematics, jet activity, VBF contributions, spin-CP nature, …

  → could become the "common ground" between experiment and theory for future measurements

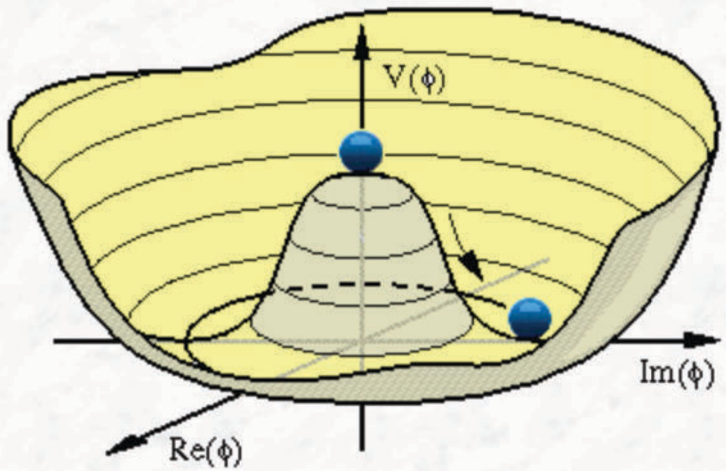
G. Artoni

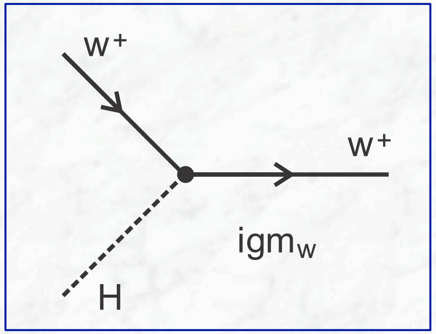
Differential cross-section measurements (cont.)

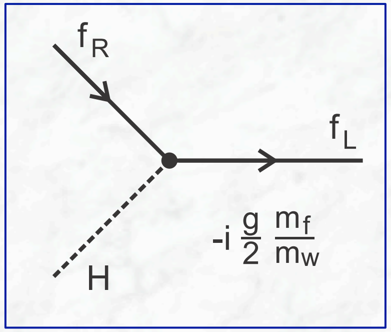




The Higgs Boson Profile







The Higgs Boson Profile

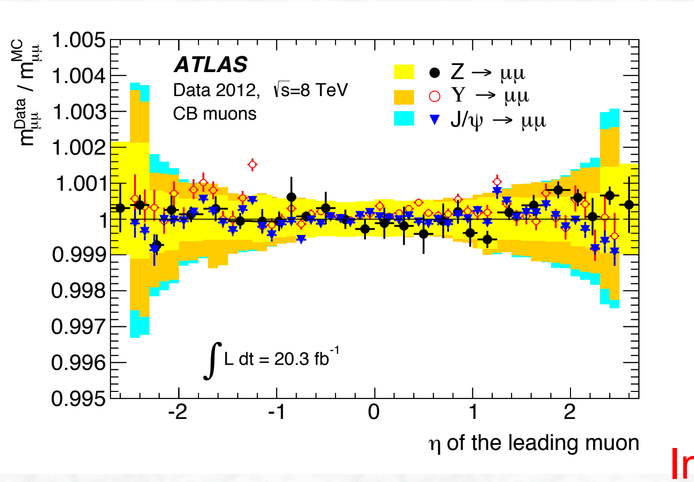
Channel/ Measurement	$\gamma\gamma$	ZZ	WW	$\tau\tau$	bb
Mass	✓	✓			
Couplings	✓	✓	✓	✓	✓
Off-shell Behaviour		✓	✓		
Spin-Parity	✓	✓	✓		

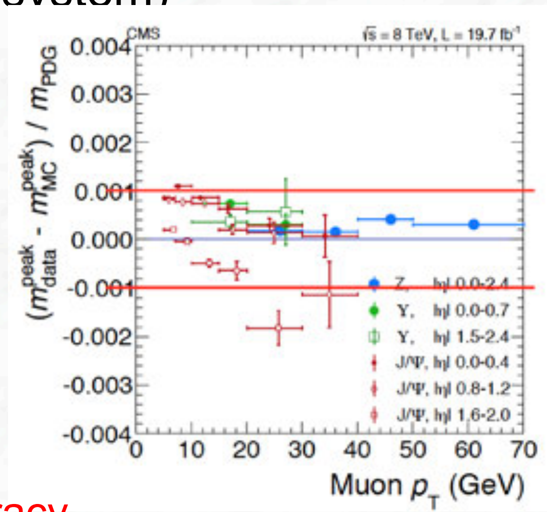
✓ Significant contribution of this channel to the measurement

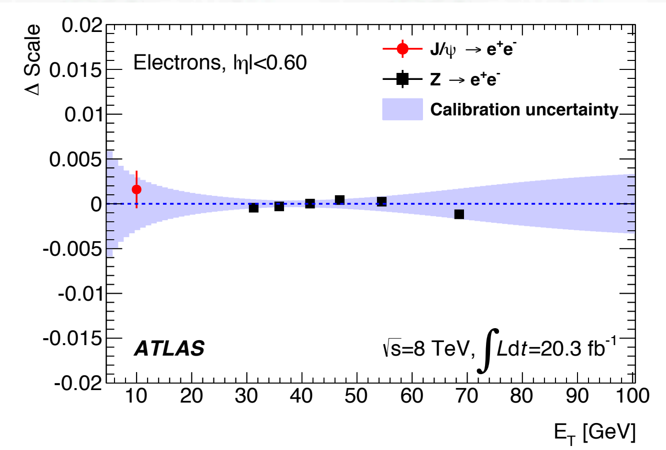
Measurement of the Higgs-boson mass

A. Martelli
R. Turra

- Huge calibration effort by both collaborations to fix the lepton (e,μ) and photon energy scales as function of p_T and η
- Impressive accuracy reached (high statistics Z, Y, J/ψ samples, high performance tracking detectors, redundancy (ATLAS muon system)



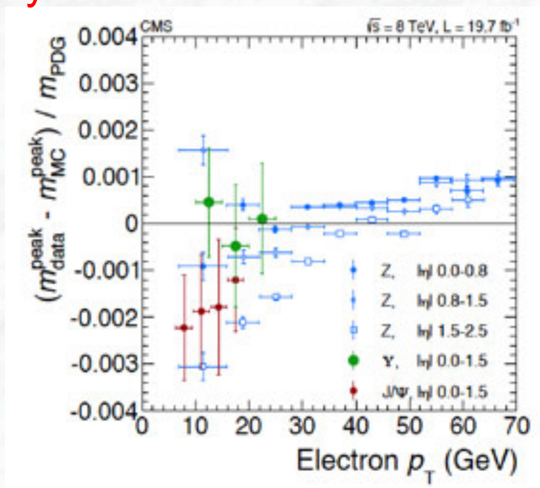




Impressive accuracy reached

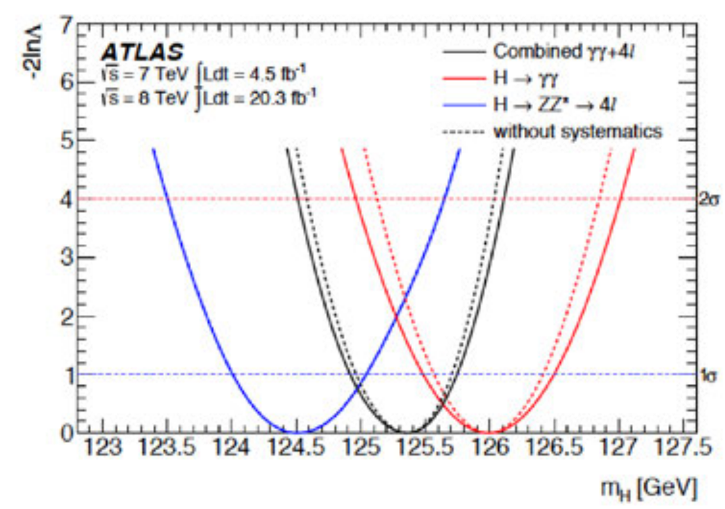
0.1 – 0.3%

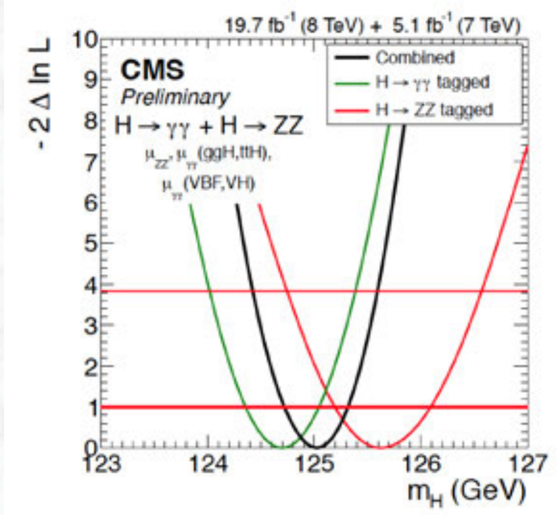
(huge effort)



Measurement of the Higgs-boson mass

A. Martelli
R. Turra





- Systematic uncertainties reduced by a factor of ~3
- m_{4l} and $m_{\gamma\gamma}$ as independent nuisance parameters
- e/γ energy scale fully correlated

ATLAS:	$m_H = 125.36 \pm 0.37$ (stat) ± 0.18 (syst) GeV
CMS:	$m_H = 125.03\,^{+0.26}_{-0.27}$ (stat) $^{+0.13}_{-0.15}$ (syst) GeV

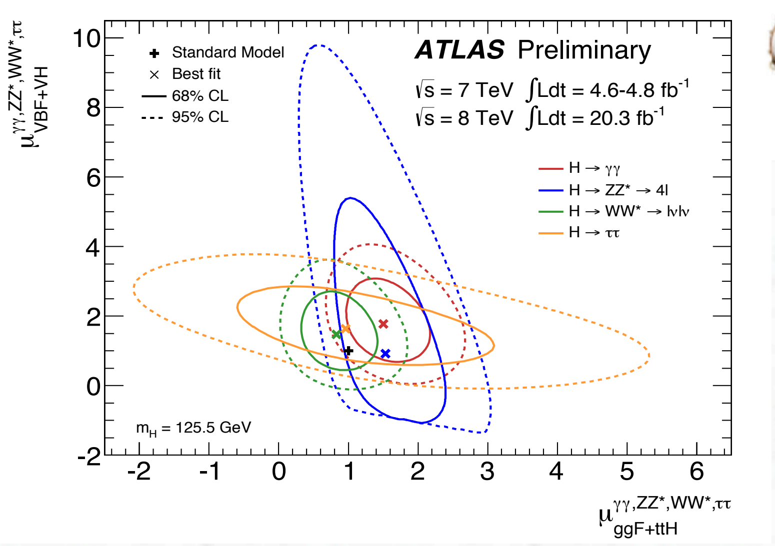
- Compatibility between channels 2.0σ (ATLAS) and 1.6σ (CMS)

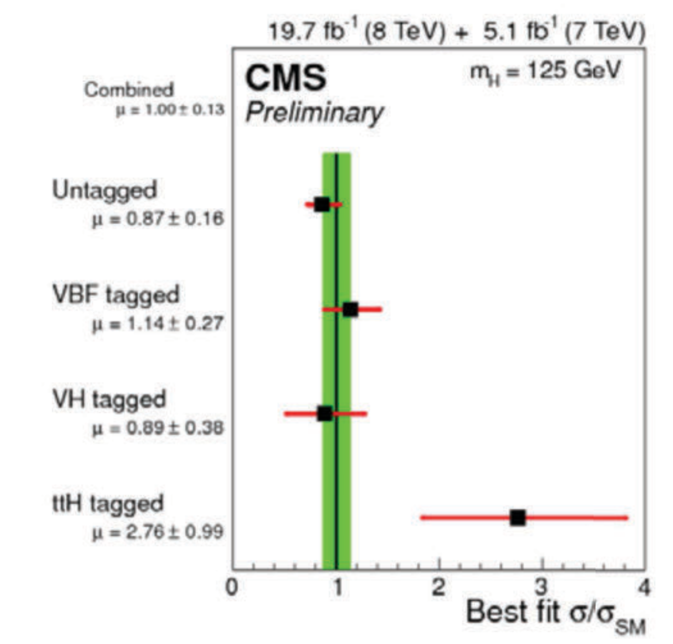
- Future: further reduction of statistical and systematic uncertainties !
  "modest requirements" from theory side; but parametric uncertainty in Higgs sector, e.g. branching ratios at 125 GeV

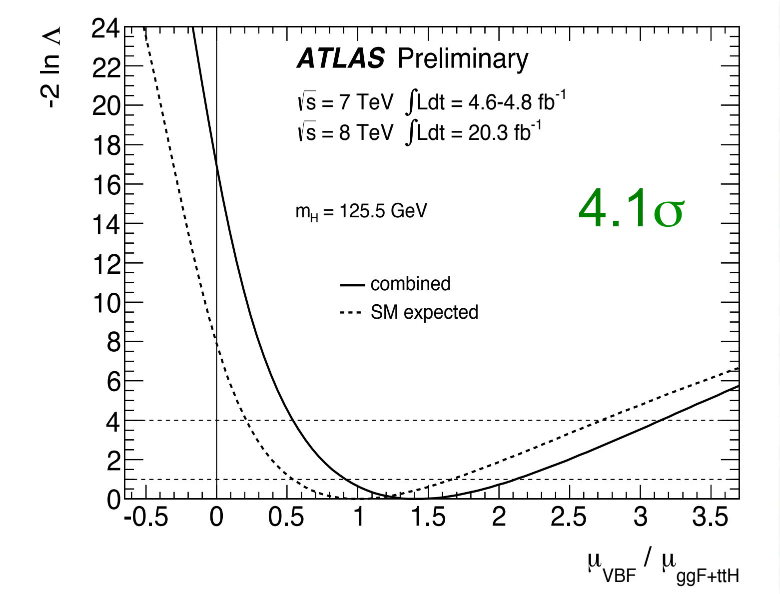
Towards Higgs Boson Couplings

Gluon fusion versus vector boson fusion

Hongtao Yang
André David



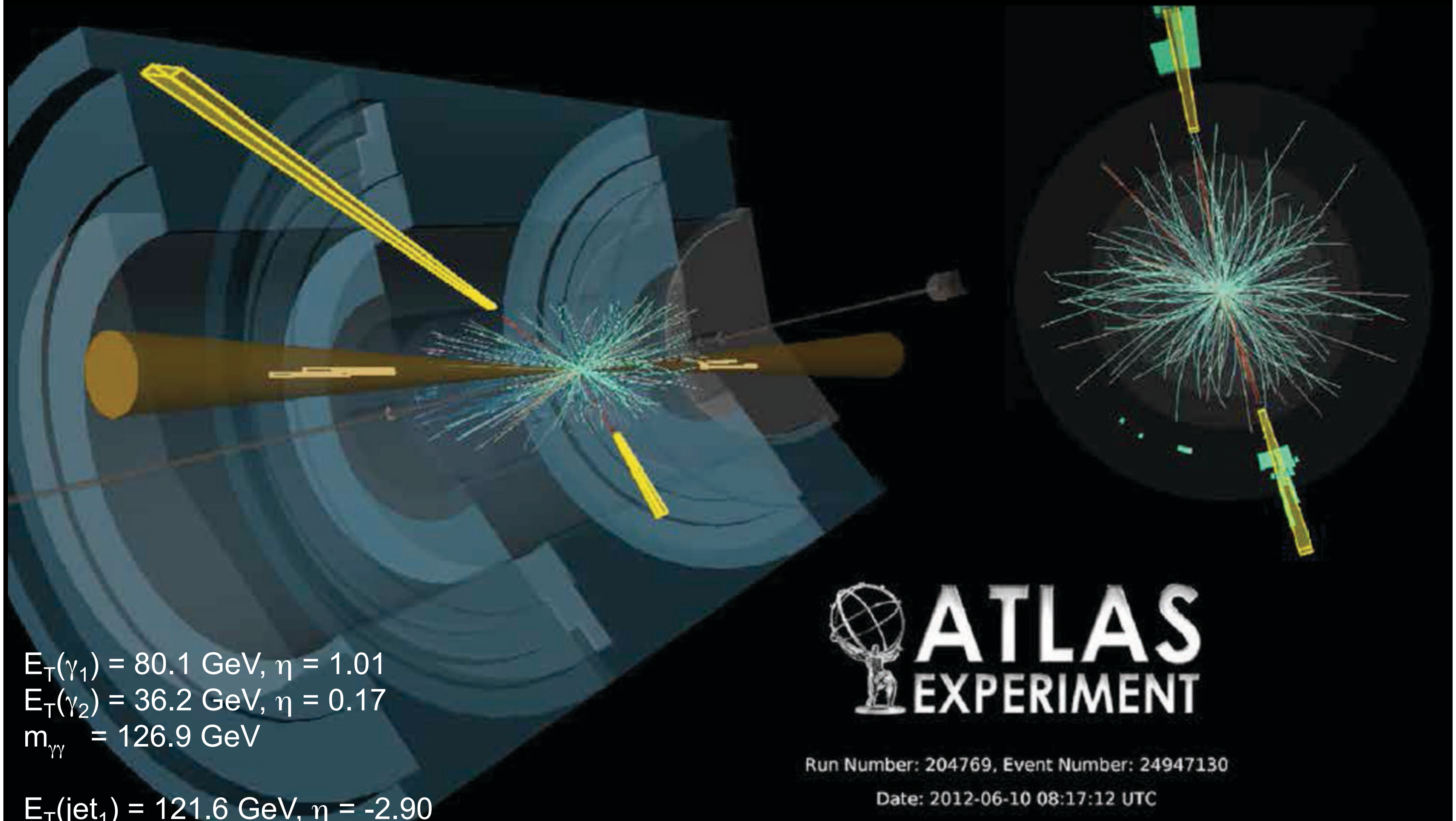




ATLAS + CMS:

Evidence for all Higgs boson production modes

$H \rightarrow \gamma\gamma$ VBF candidate event



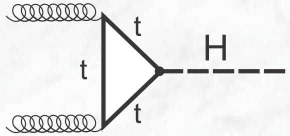
$E_T(\gamma_1)$ = 80.1 GeV, η = 1.01
$E_T(\gamma_2)$ = 36.2 GeV, η = 0.17
$m_{\gamma\gamma}$ = 126.9 GeV

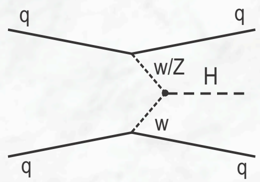
$E_T(\text{jet}_1)$ = 121.6 GeV, η = -2.90
$E_T(\text{jet}_2)$ = 82.8 GeV, η = 2.72
m_{jj} = 1.67 TeV

Higgs boson couplings

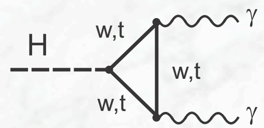
- Production and decay involve several couplings

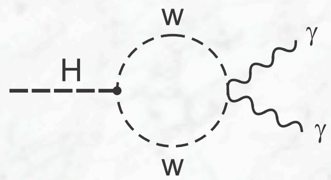
Production:





Decays: e.g H → γγ (good example)
(Decay widths depends on W and top-coupling,
destructive interference)





- Benchmarks defined by LHC cross section working group (leading-order tree-level framework):

  - Signals observed originate from a single resonance;
    (mass assumed here is 125.5 GeV)

  - Narrow width approximation: → rates for given channels can be decomposed as:

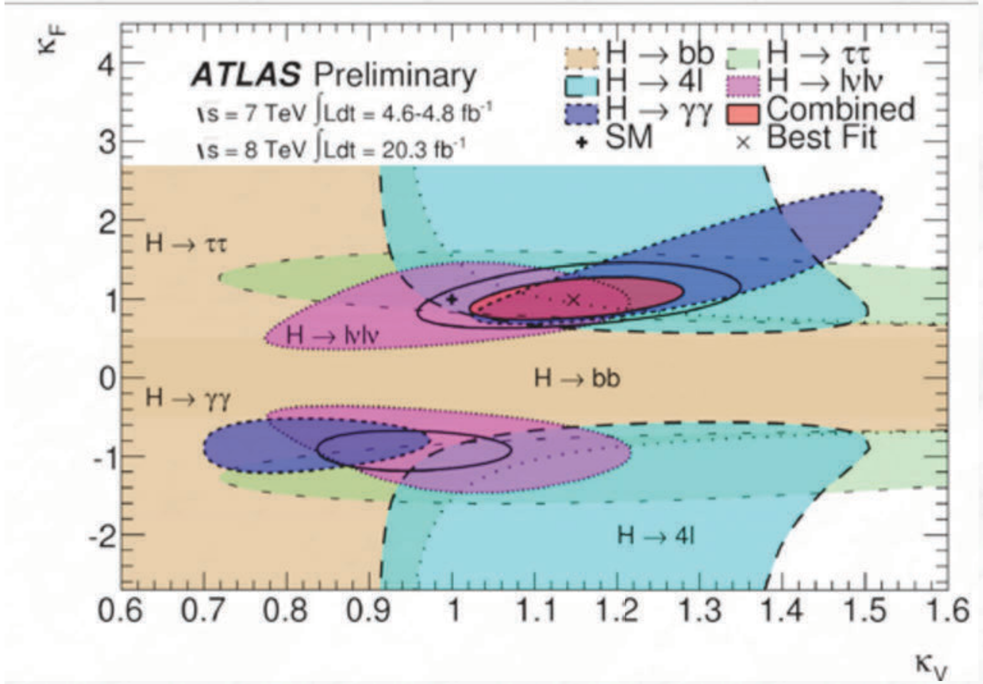
$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

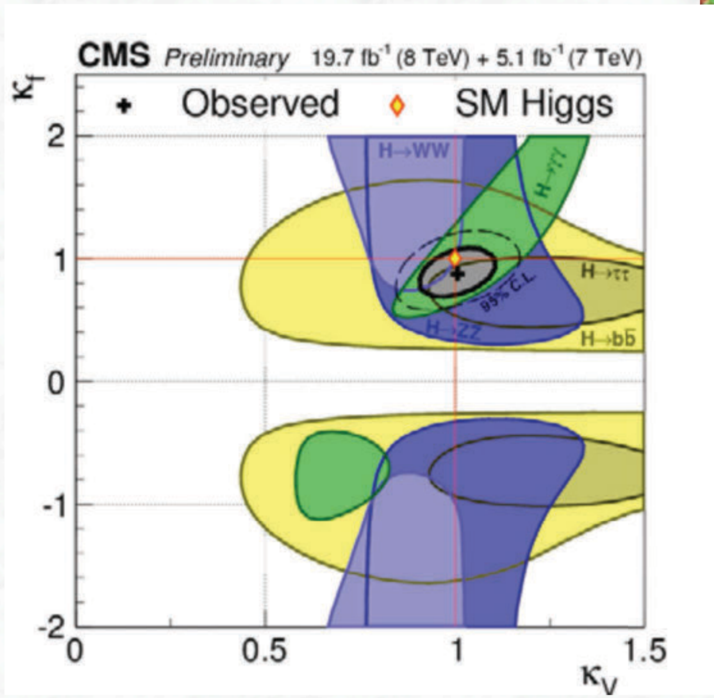
i, f = initial, final state
Γ_f, Γ_H = partial, total width

  - Modifications to coupling strength are considered (coupling scale factors κ),
    tensor structure of Lagrangian assumed as in Standard Model

Fermion vs. vector-boson coupling scale factors - in the LO κ-framework-

Hongtao Yang
André David



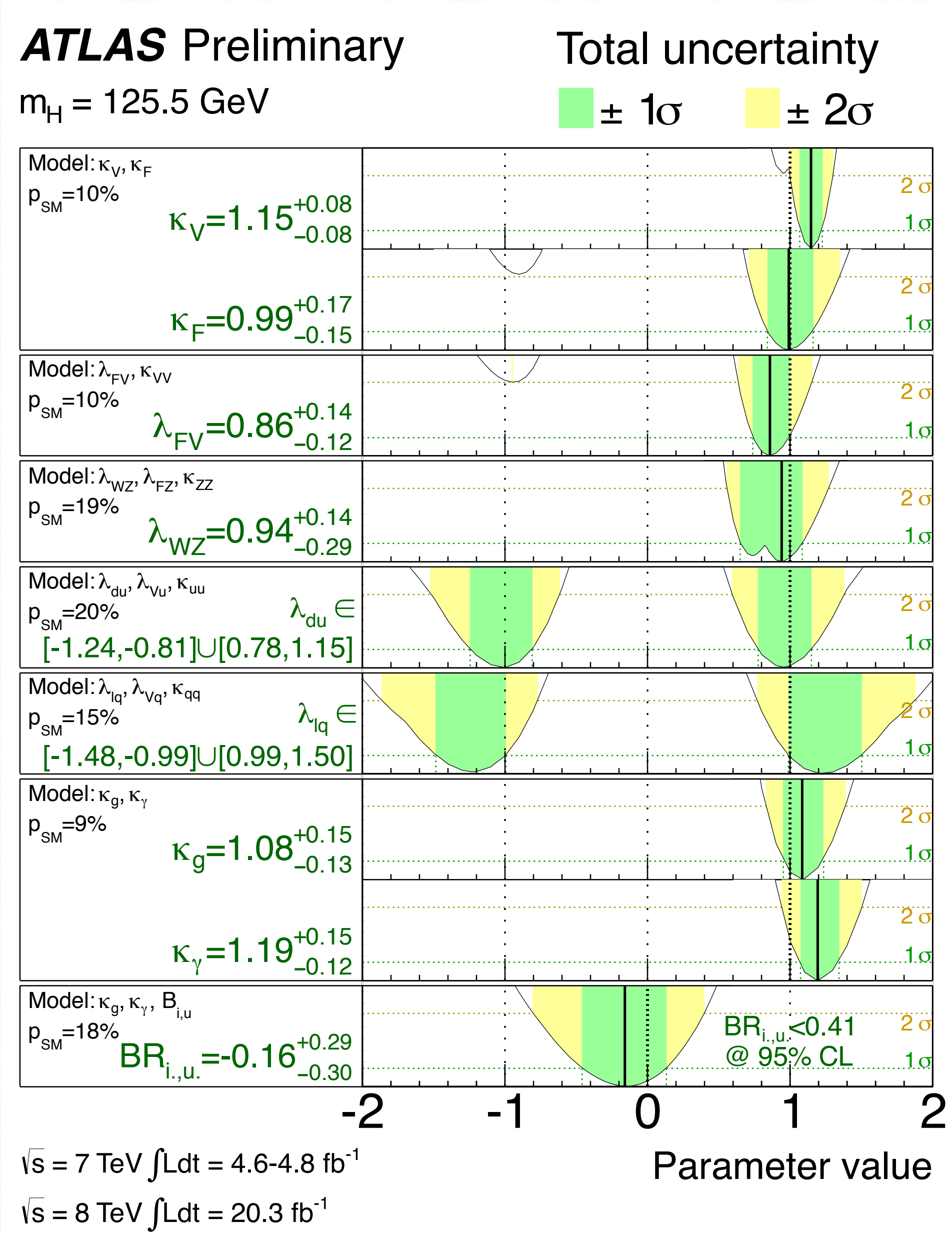


- Good agreement with Standard Model expectation

- Degeneracy between rel. sign broken by H → $\gamma\gamma$

Summary of ATLAS results for various scenarios

Hongtao Yang



Fermion and vector boson scale factors

Test of custodial symmetry

Up- to down-type quark couplings

Lepton / quark couplings

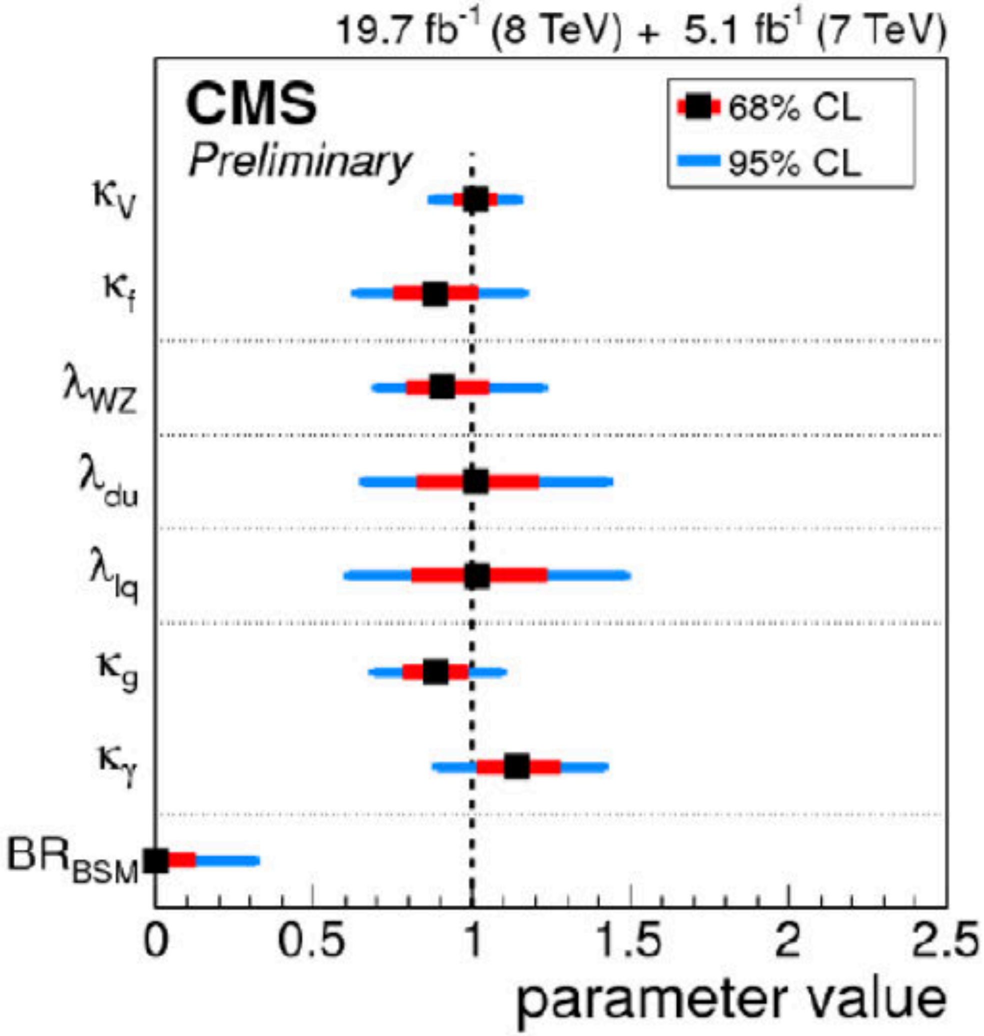
Contributions to ggF production and gg decay loops

Invisible and undetectable decays

Summary of CMS results for various scenarios

André David

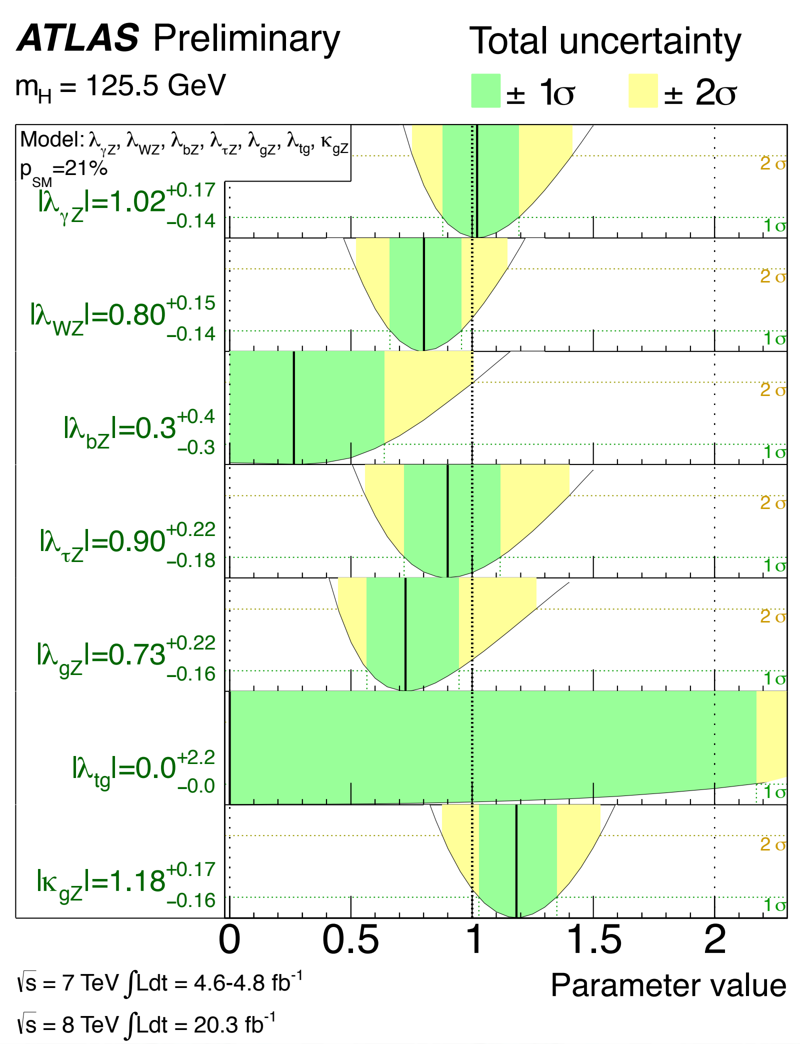
- Summary of the fits of six **benchmarks models** probing:
  - Fermions and vector bosons.
  - Custodial symmetry.
  - Up/down fermion coupling ratio.
  - Lepton/quark coupling ratio.
  - BSM in loops: gluons and photons.
  - Extra width: BR_{BSM}.
- **No significance deviations from SM.**

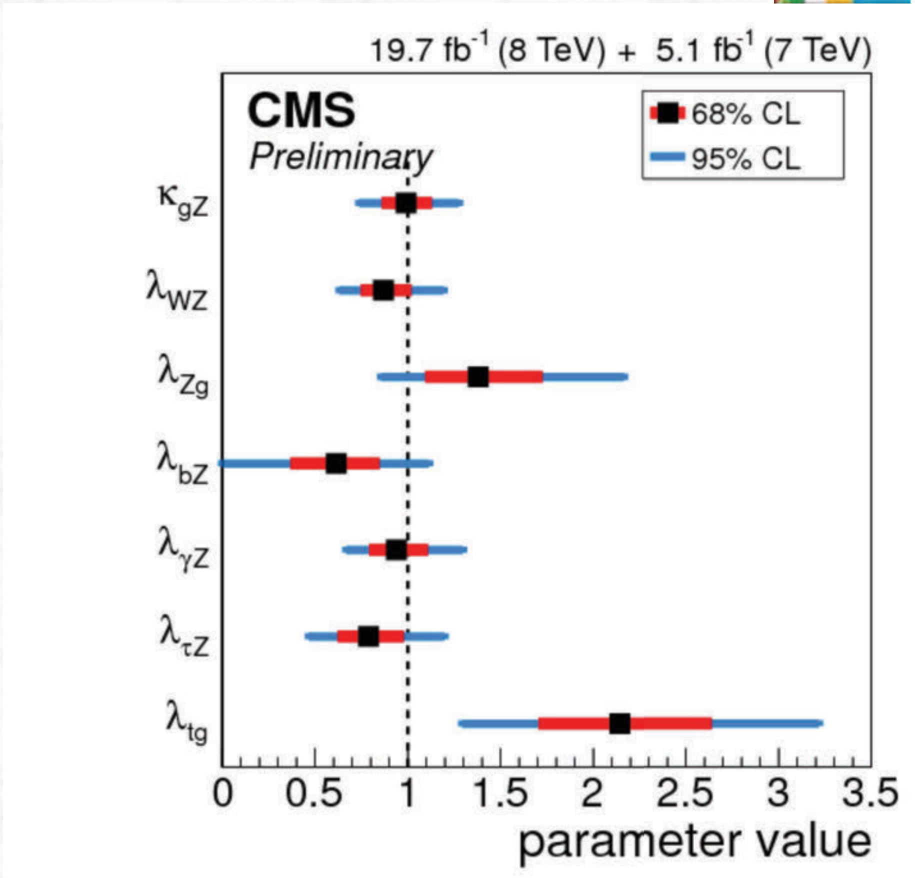


$\lambda_{xy} = \kappa_x/\kappa_y$

Ratio of couplings, generic model

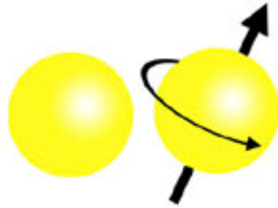
Hongtao Yang
André David





- Coupling scale factors to W, Z, t, b, and τ are treated independently;
- Effective scale factors for the gg → H and H → γγ loops
- Only ratios of couplings accessible

Spin and CP



Wolfgang Pauli und Niels Bohr bei der wissenschaftlichen Untersuchung der Kreiselbewegung (1952, anlässlich der Eröffnung des Instituts für Theoretische Physik in Lund / Schweden)

- If Standard Model Higgs boson: $J^P = 0^+$

  → strategy is to falsify other hypotheses (0^-, 1^-, 1^+, 2^-, 2^+)

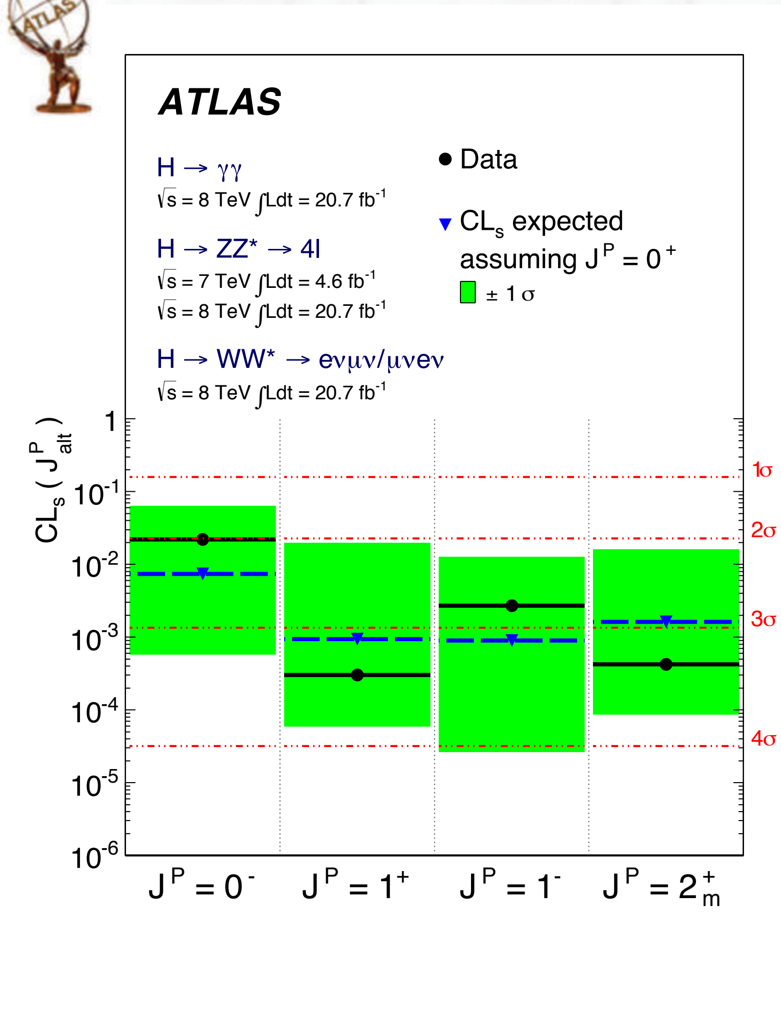
  Spin 1: dis-favoured by observed $H \rightarrow \gamma\gamma$ decays, Landau-Yang theorem

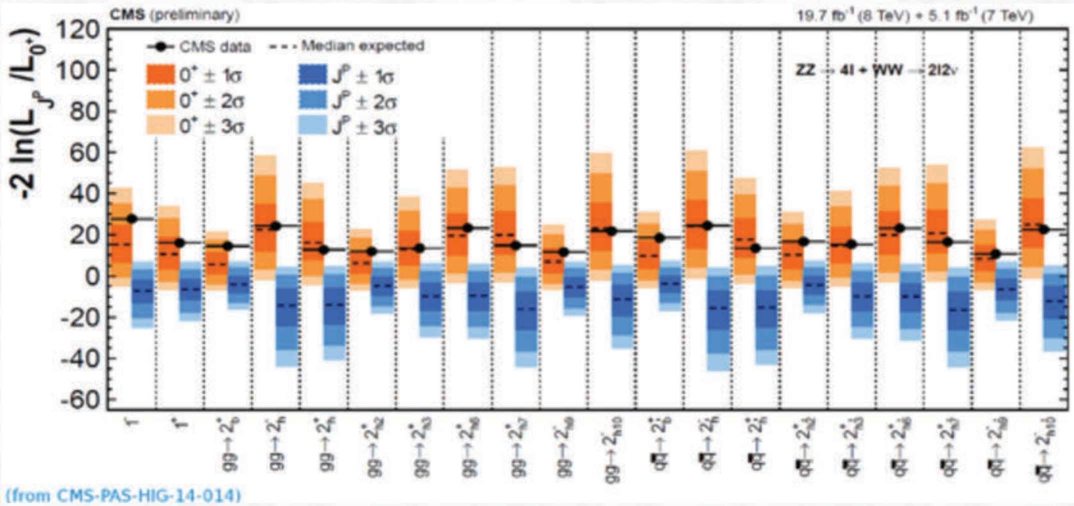
  Spin 2: consider graviton-like tensor, equivalent to a Kaluza-Klein graviton

- Angular distributions of final state particles show sensitivity to spin

Meng Xiao
Johannes Mattmann

Result on different J^{CP} hypothesis tests





Are theorists satisfied? Can we stop looking at spin-2 models?

Meng Xiao
Johannes Mattmann

Phenomenology of anomalous couplings: spin 0

- Interaction between a spin 0 Higgs and two gauge bosons V_1, V_2 (Z, W, γ, g), expansion up to q^2
  - q^4 and higher orders not considered assuming small anomalous couplings

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{V_1V_2}} + \underbrace{\frac{\kappa_1^{\mathrm{V_1V_2}} q_{\mathrm{V_1}}^2 + \kappa_2^{\mathrm{V_1V_2}} q_{\mathrm{V_2}}^2}{\left(\Lambda_1^{\mathrm{V_1V_2}}\right)^2}}_{\text{Λ_1 term, leading momentum expansion}} \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V_1}}^* \epsilon_{\mathrm{V_2}}^* + \underbrace{a_2^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} f^{*(\mathrm{V_2}),\mu\nu}}_{\text{a_2 term, CP even state}} + \underbrace{a_3^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} \tilde{f}^{*(\mathrm{V_2}),\mu\nu}}_{\text{a_3 term, CP odd state}}$$

- SM value for couplings

	a_1	q^2/Λ_1^2	a_2	a_3
HZZ(WW)	2	$10^{-3} - 10^{-2}$	$10^{-3} - 10^{-2}$	$< 10^{-10}$
HZγ	-	$10^{-3} - 10^{-2}$	~ 0.0035	$< 10^{-10}$
H$\gamma\gamma$	-	-	$\sim$ -0.004	$< 10^{-10}$

- Mesuarements

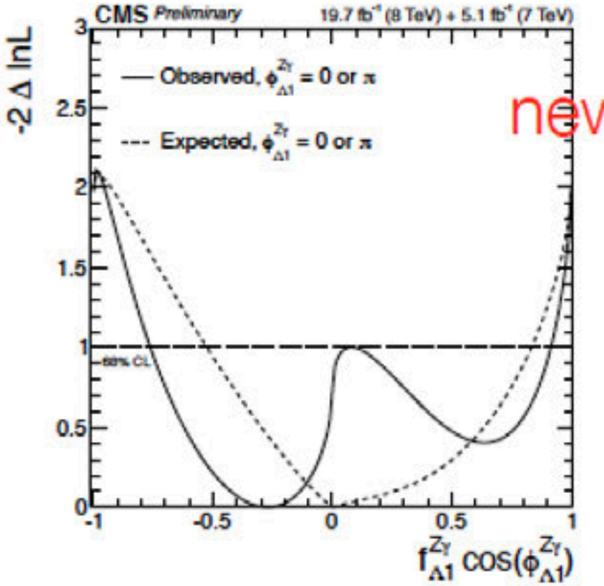
1) hypothesis test, pure 0^- (a_3), 0_h^+ (a_2) states
   - CMS: 99.9% (0^-), 95% CL (0_h^+)
   - ATLAS: 97.8% CL (0^-)

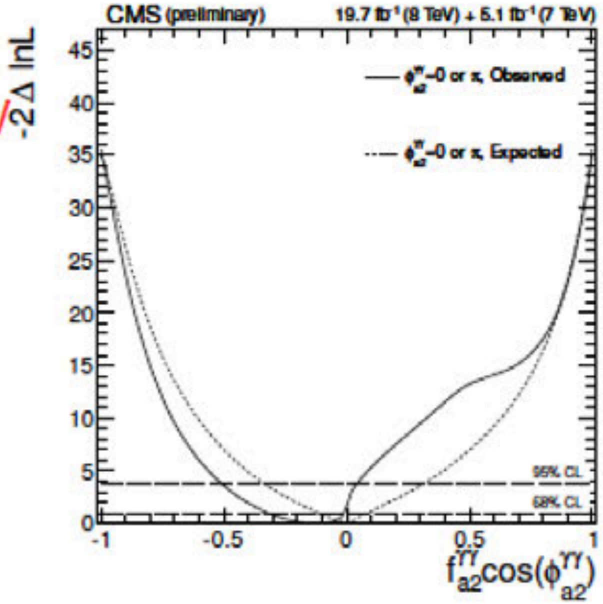
2) measure 11 anomalous couplings (10 in CMS-PAS-HIG-14-014 + 1 new)

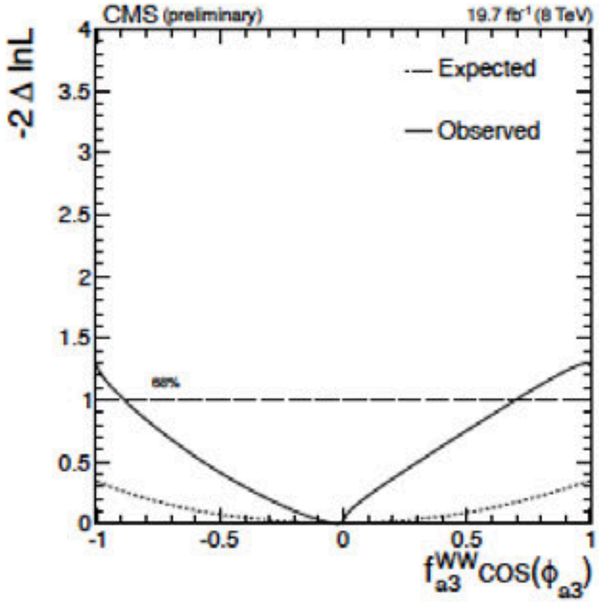
Phys.Lett. B726 (2013) 120–144

Phys.Rev.Lett. 110 (2013) 081803
Phys.Rev. D89 (2014) 092007

CMS results: HWW, HZγ, Hγγ anomalous couplings







	Parameter	Observed	Expected	$f^{VV}_{ai} = 1$ vs 0
	$f^{WW}_{\Lambda 1}\cos(\phi^{WW}_{\Lambda 1})$	$0.64^{+0.36}_{-0.11}$ $[-1.00, 0.44] \cup [0.49, 1.00]$	$0.00^{+0.36}_{-1.00}$ $[-1.00, 0.43] \cup [0.48, 1.00]$	100% (81%)
HWW	$f^{WW}_{a2}\cos(\phi^{WW}_{a2})$	$0.44^{+0.56}_{-0.53}$ $[-1.00, -0.58] \cup [-0.25, 1.00]$	$0.00^{+1.00}_{-0.13}$ $[-1.00, -0.56] \cup [-0.24, 1.00]$	100% (50%)
	$f^{WW}_{a3}\cos(\phi^{WW}_{a3})$	$-0.03^{+0.73}_{-0.87}$ $[-1.00, 1.00]$	$0.00^{+1.00}_{-1.00}$ $[-1.00, 1.00]$	26% (56%)
	$f^{Z\gamma}_{\Lambda 1}\cos(\phi^{Z\gamma}_{\Lambda 1})$	$-0.27^{+0.34}_{-0.49}$ $[-1.00, 1.00]$	$0.00^{+0.83}_{-0.53}$ $[-1.00, 1.00]$	26% (16%)
HZγ	$f^{Z\gamma}_{a2}\cos(\phi^{Z\gamma}_{a2})$	$0.00^{+0.14}_{-0.20}$ $[-0.49, 0.46]$	$0.00^{+0.51}_{-0.51}$ $[-0.78, 0.79]$	<0.01% (0.01%)
	$f^{Z\gamma}_{a3}\cos(\phi^{Z\gamma}_{a3})$	$0.02^{+0.21}_{-0.13}$ $[-0.40, 0.51]$	$0.00^{+0.51}_{-0.51}$ $[-0.75, 0.75]$	<0.01% (<0.01%)
Hγγ	$f^{\gamma\gamma}_{a2}\cos(\phi^{\gamma\gamma}_{a2})$	$-0.12^{+0.11}_{-0.20}$ $[-0.51, 0.04]$	$0.00^{+0.09}_{-0.11}$ $[-0.34, 0.32]$	<0.01% (<0.01%)
	$f^{\gamma\gamma}_{a3}\cos(\phi^{\gamma\gamma}_{a3})$	$0.02^{+0.13}_{-0.06}$ $[-0.32, 0.35]$	$0.00^{+0.11}_{-0.15}$ $[-0.40, 0.37]$	<0.01% (<0.01%)

- a_i real, ϕ_*=0,π
- Consistent with SM
- H->4l from pure HZγ*, Hγ*γ* excluded at > 99.99% CL

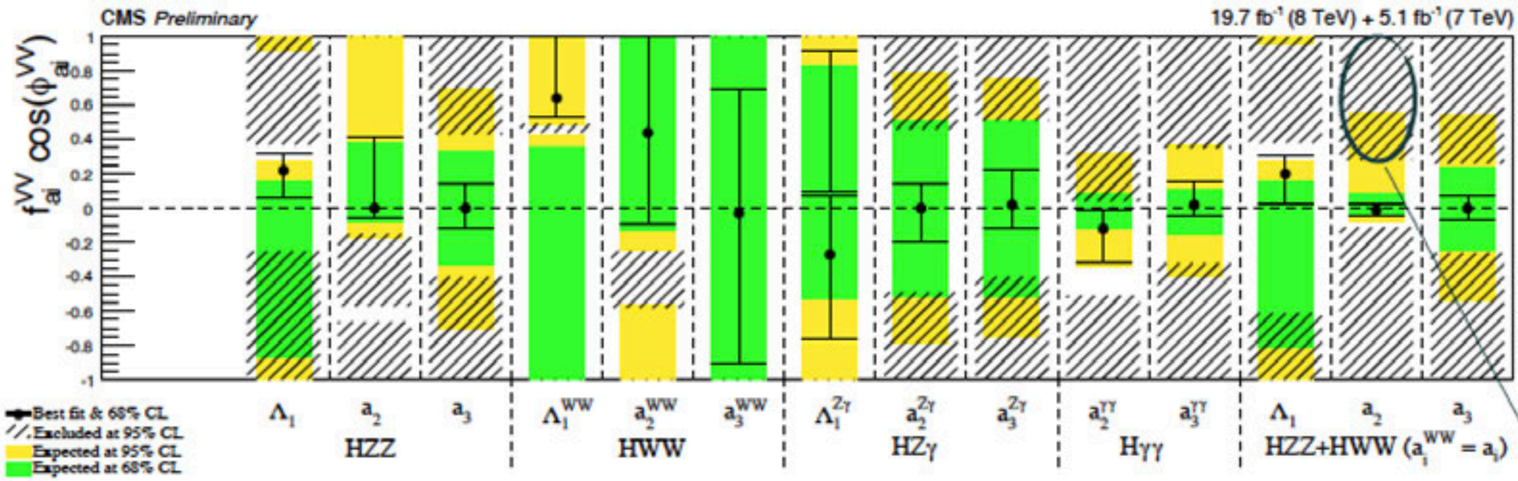
More plots for all the other parameters in backup

CMS results summary

Meng Xiao
Johannes Mattmann

HWW+ZZ, $a_i^{ZZ} = a_i^{WW}$

Parameter	Observed	Expected	$f_{ai}^{VV} = 1$ vs 0
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.20^{+0.11}_{-0.18}$ $[-0.61, 0.38]$	$0.00^{+0.16}_{-0.81}$ $[-1, 0.27] \cup [0.95, 1]$	0.86% (13%)
$f_{a2}\cos(\phi_{a2})$	$-0.01^{+0.03}_{-0.04}$ $[-0.11, 0.28]$	$0.00^{+0.09}_{-0.03}$ $[-0.08, 0.55]$	0.07% (0.31%)
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.07}_{-0.07}$ $[-0.26, 0.26]$	$0.00^{+0.24}_{-0.24}$ $[-0.54, 0.54]$	<0.01% (0.09%)



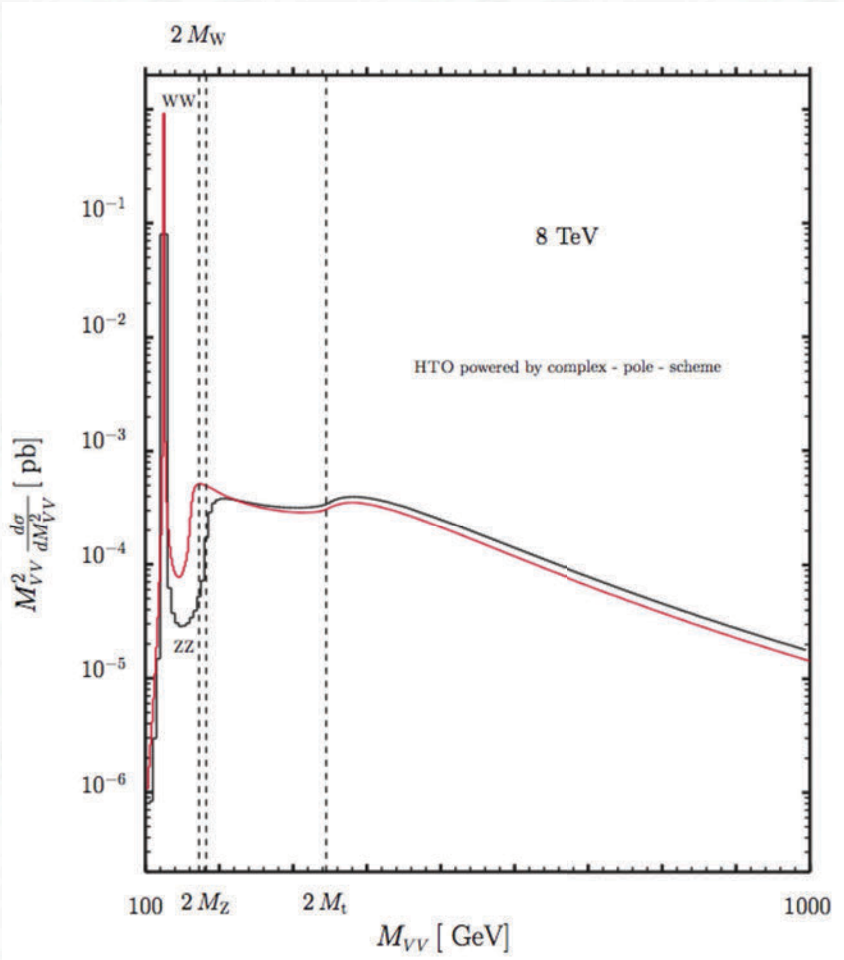
— Consistent with SM
— when assuming $a_i^{ZZ} = a_i^{WW}$
—pure 0_h^+ excluded at 99.93% CL
—pure 0^- excluded at 99.99% CL

Region not excluded in either HZZ or HWW
Constraint from HZZ HWW correlation

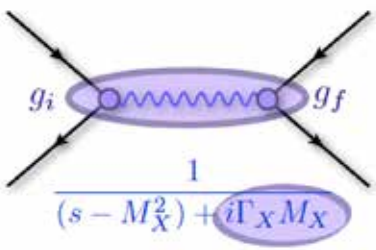
- A good start to investigate the CP-structure
- Limited by number of events
- Potential in Run-2, including fermionic channels

Off-shell cross sections, Higgs boson width

C. Williams
S. Hoeche
C. Charlon

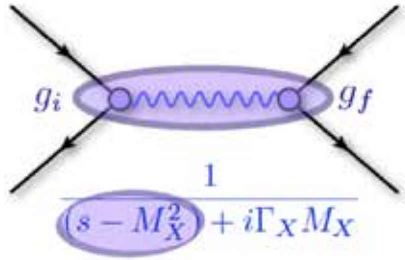


N. Kauer and G. Passarino, JHEP 08 (2012) 116



In the resonance region the "on-shell" cross section is dominated by the width.

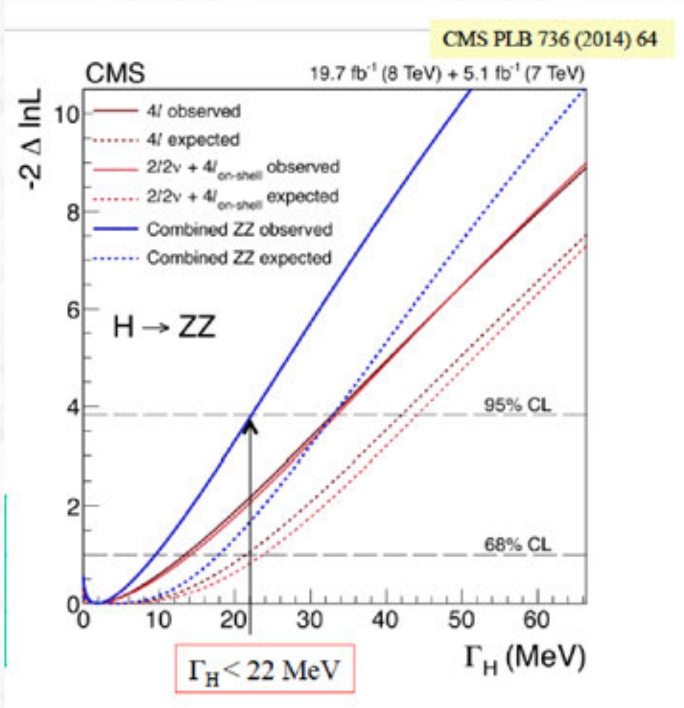
$$\sigma^{on}_{i\to X\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_X}$$

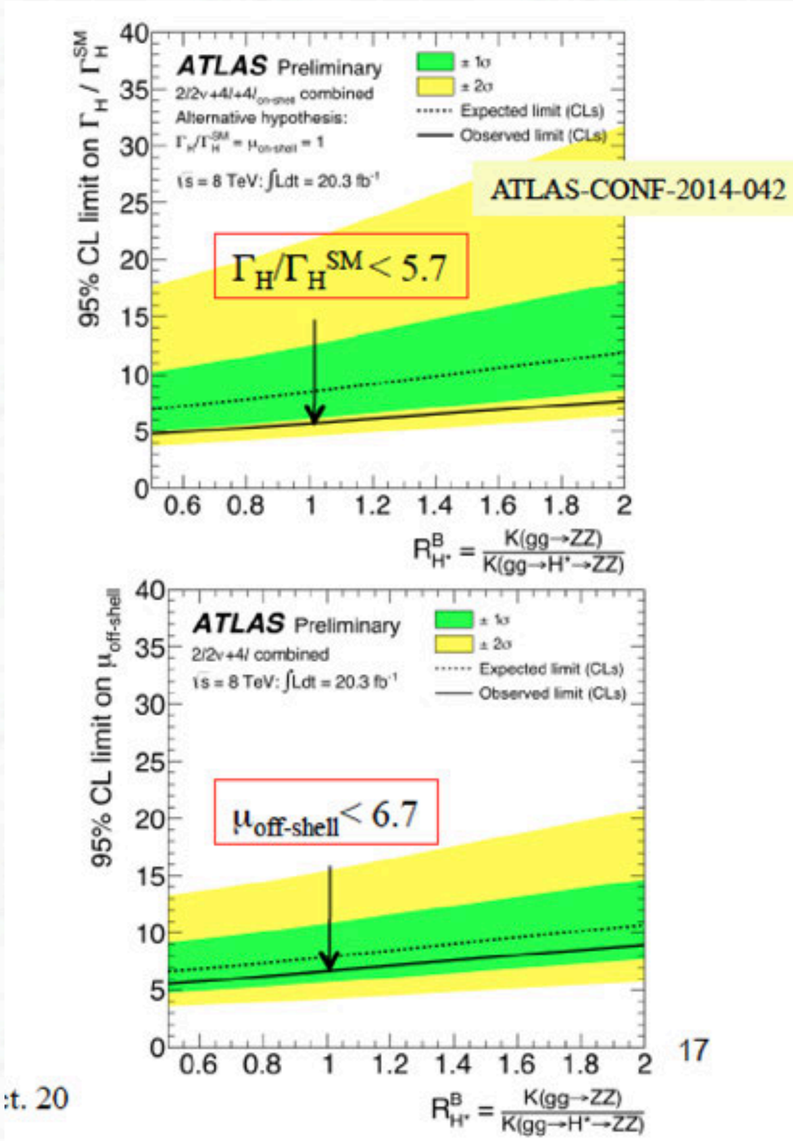


Away from the resonance region, the "off-shell" cross section does not depend on the width.

$$\sigma^{off}_{i\to X\to f} \sim g_i^2 g_f^2$$

Experimental results





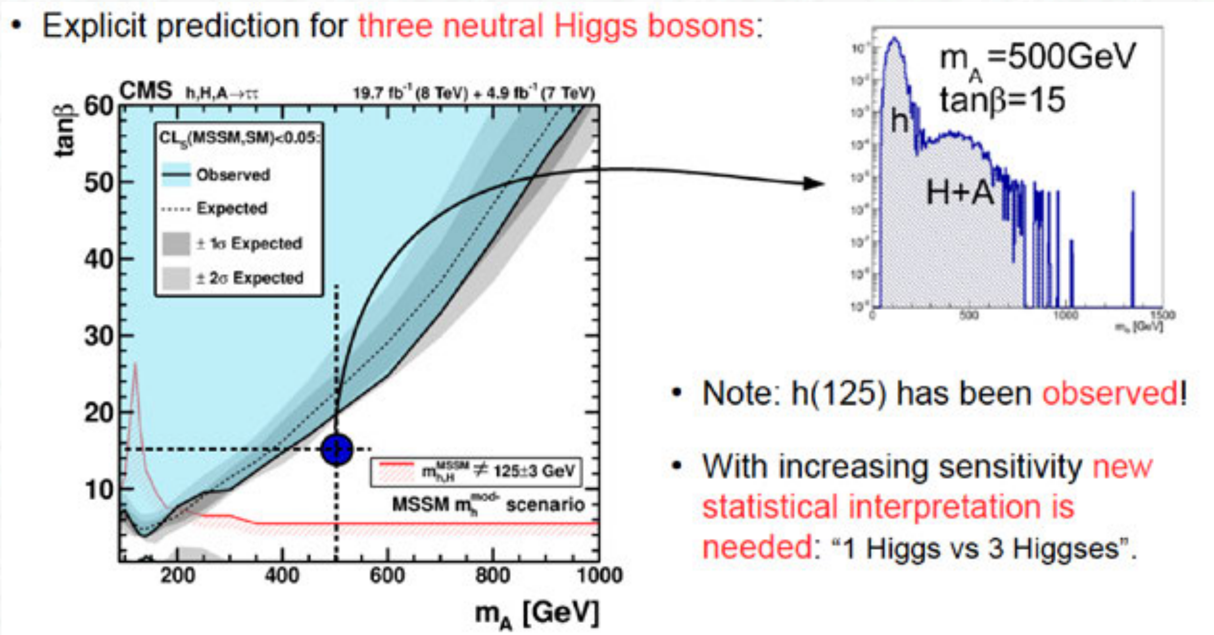
Interesting Idea

- Off-shell cross sections can be used to constrain the couplings (ATLAS µ-off-shell < 6.7)
- Bounds on width obtained by rescaling the SM → sensitivity to values of 5-7 SM values
- Future: improved calculations in off-shell region needed
  interpretation in Effective Field Theory?

R. Wolf
M. Hoffmann

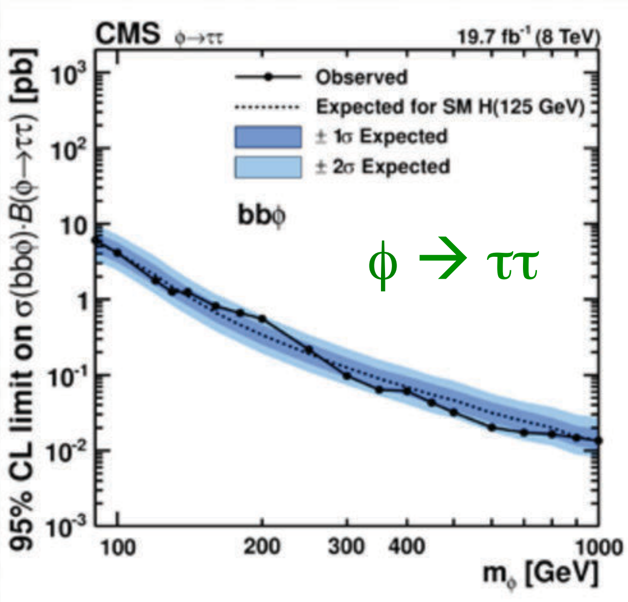
Additional Higgs Bosons ?

- All canonical searches ($\phi \rightarrow \tau\tau$, $\phi \rightarrow$ bb, $H^+ \rightarrow \tau\,\nu$, …. done)
- Additional searches for exotic decays, e.g. $h \rightarrow \tau\,\mu$ started
- Change in interpretation paradigm: h(125 GeV) Higgs boson should be taken into account in model interpretations, e.g. MSSM

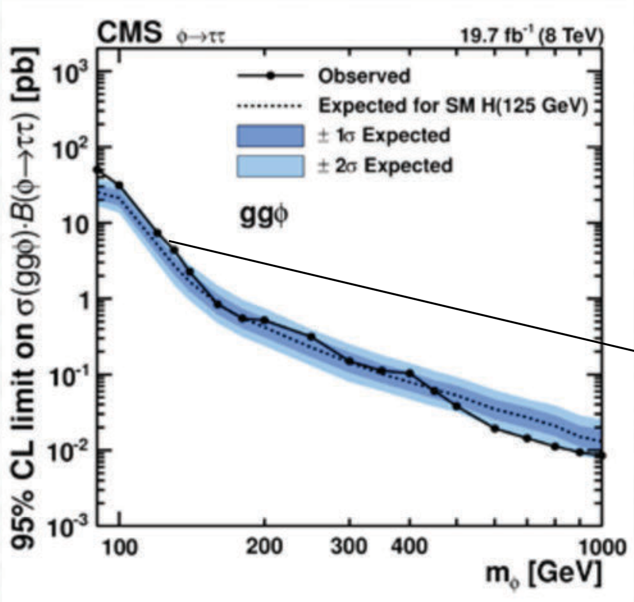


Limits on cross sections

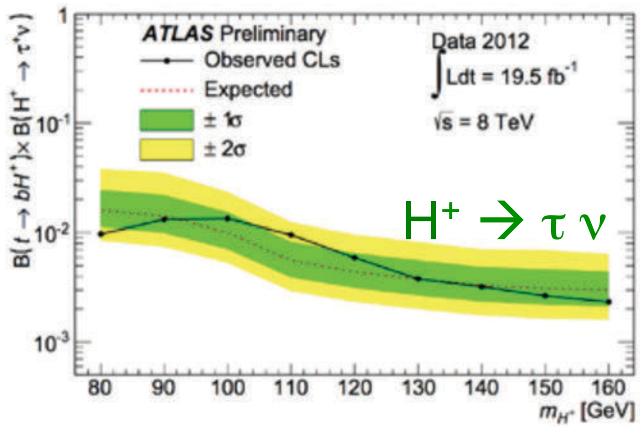
R. Wolf
M. Hoffmann



$\phi \rightarrow \tau\tau$

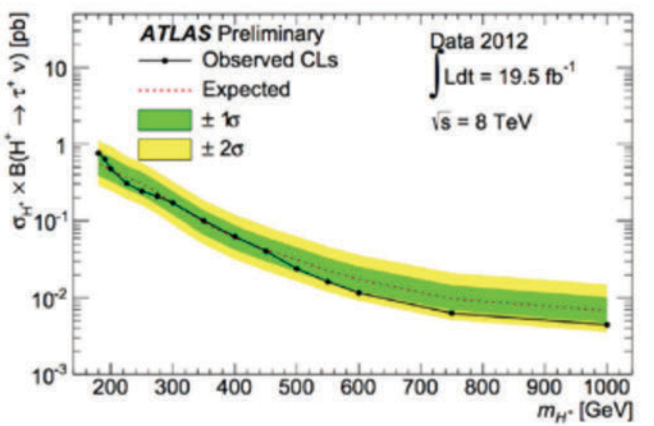


sensitivity to h(125) GeV at ~2.5σ



$H^+ \rightarrow \tau\,\nu$

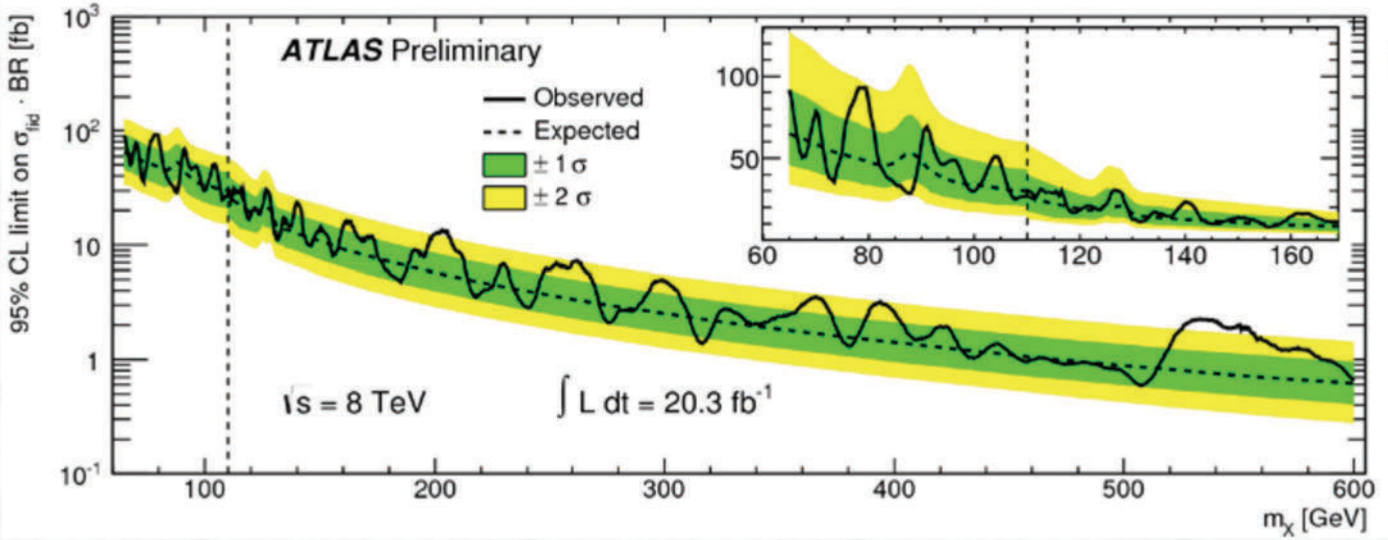
Upper limits on
Br(t → bH±) × Br(H± → τν)
- 1.3% - 0.23%



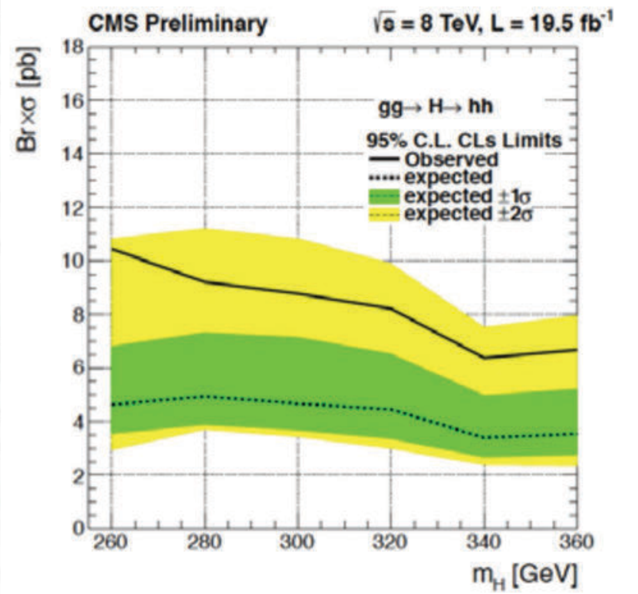
Upper limits on
σ(pp → tH± + X)×Br(H± → τν)
- 0.76 pb - 4.5 fb

R. Castello
A. Kaplan
J. Alison

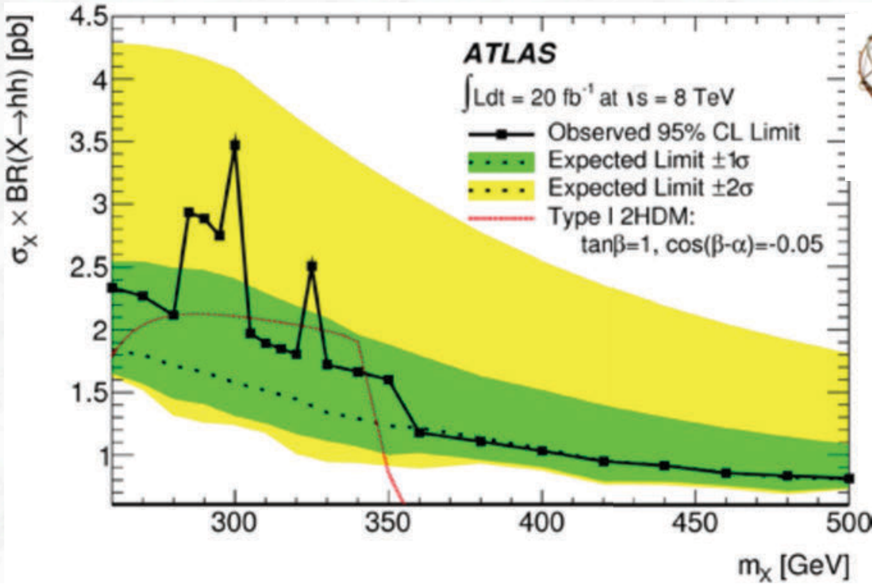
- Search for heavy object H → γγ



- Search for heavy object H → hh → γγ bb
(several channels combined)



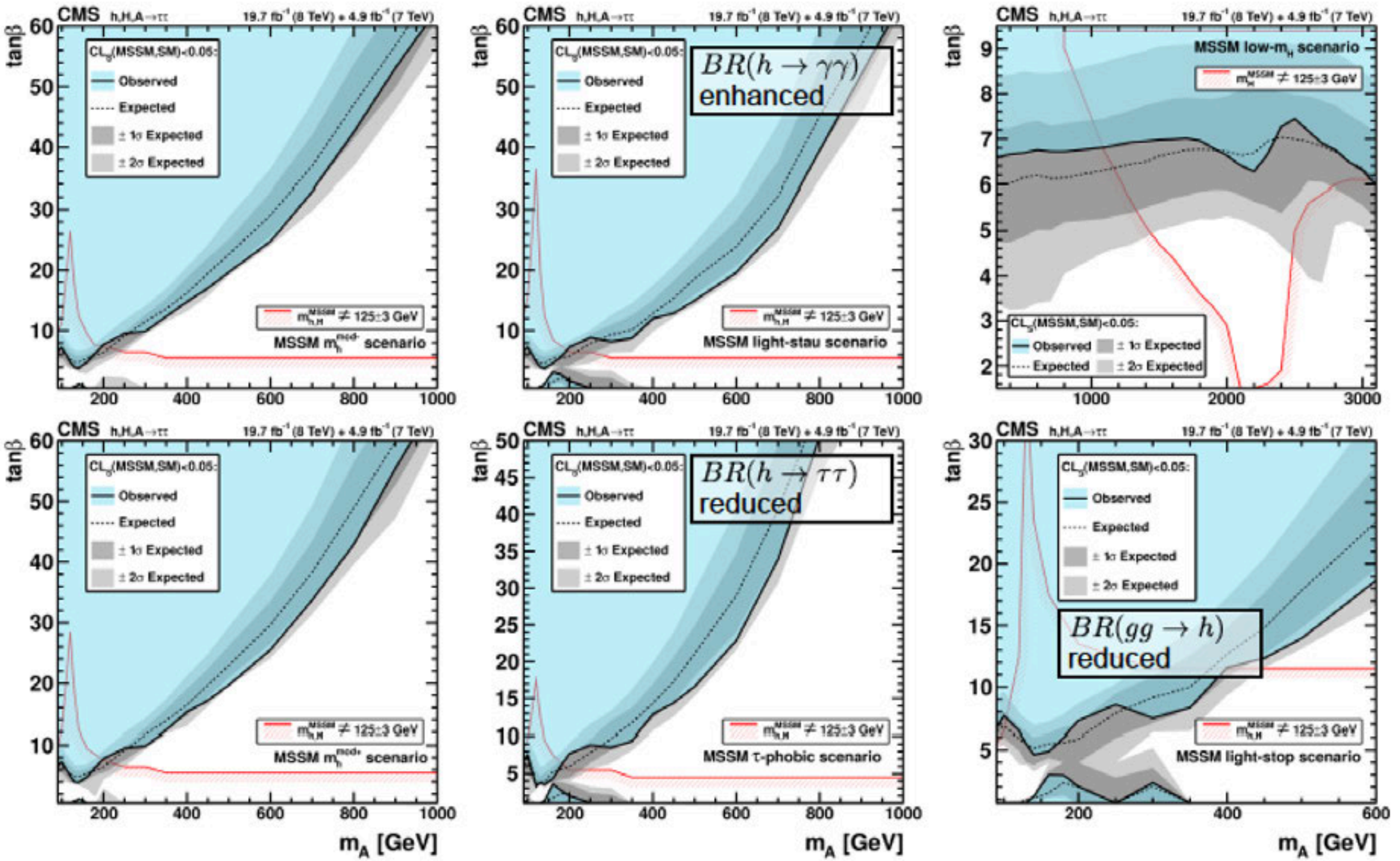
(mx = 300 GeV~ 2.1σ after look-elsewhere)



MSSM interpretations

R. Wolf

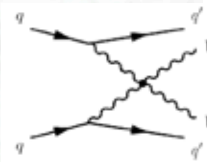
Complete Set of Benchmark Scenarios (arXiv:1302.7033)

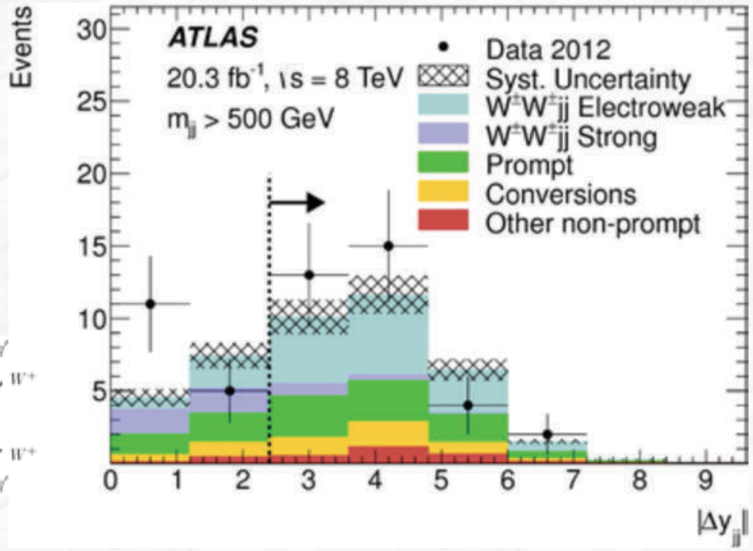


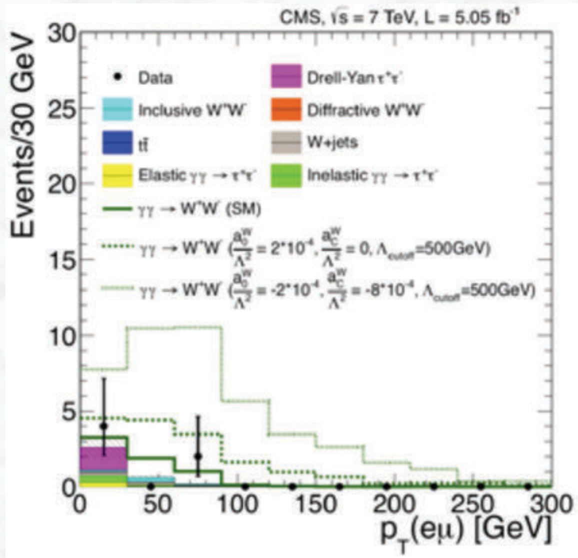
Vector Boson Fusion / Scattering

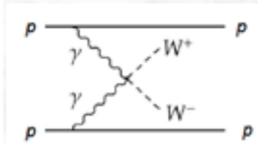
- Important to understand electroweak symmetry breaking → B. Jäger
- First “beautiful” experimental results appear → N. Chanon

  - Like-sign WW scattering, evidence for el.weak contributions
    → potential for 5σ observation in Run-2





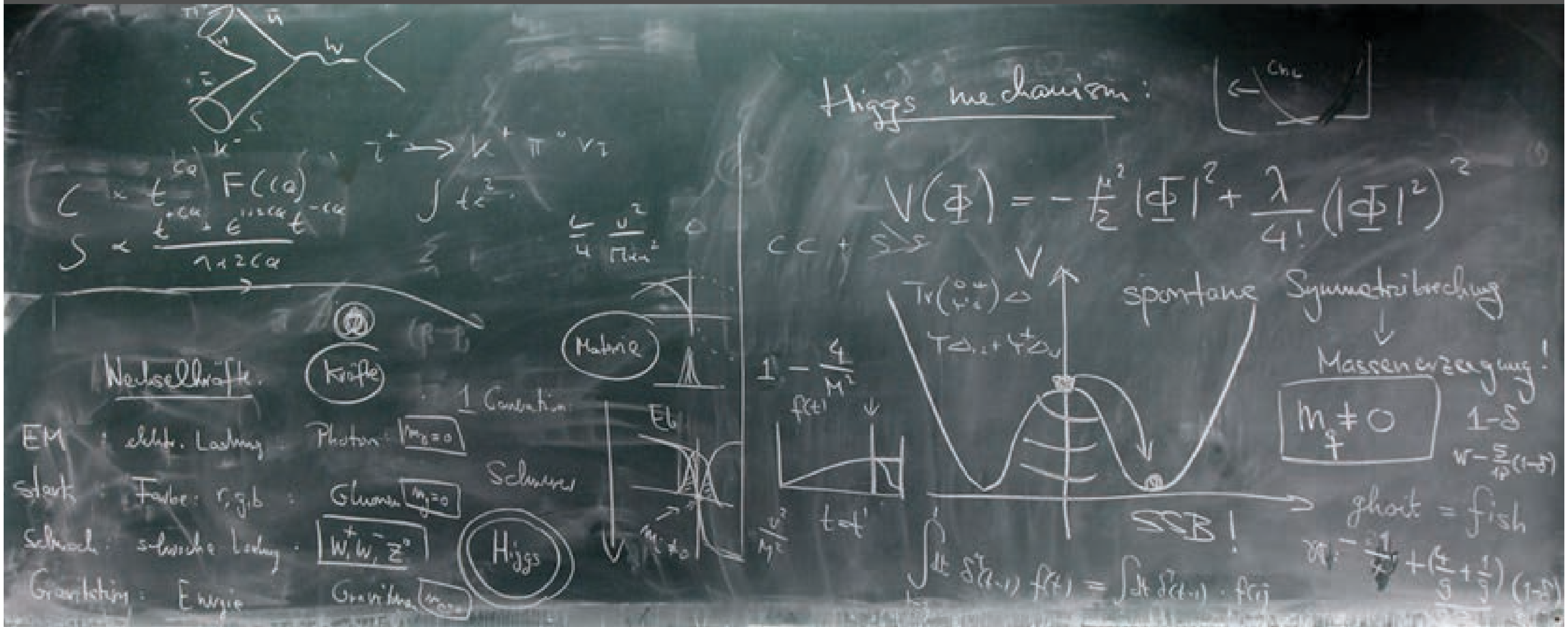




- Exclusive $\gamma\gamma$ → WW production gives so far best limits on $WW\gamma\gamma$ coupling

➔ Important research field in Run-2 and HL-LHC

Theory


Higgs mechanism :
spontane Symmetriebrechung
Massenerzeugung!
SSB!
Materie
Kräfte
Wechselkräfte
EM
stark
Schwach
Photon
Higgs
ghost = fish

Many interesting theory talks presented at this workshop

- It seems that the theoretical progress keeps pace with experimental progress;

- Important work on the (N)NLO front

  - Approximate N^3LO calculation of gluon-fusion progress → S. Forte
  - NLO and NNLO calcualtion for Higgs boson pair production → M. Steinhauser
  - NLO calculations for vector boson scattering → B. Jäger

- Progress in Resummation, Higgs p_T spectrum

  - HRes (treatment of heavy quarks) → M. Grazzini
    → A. Vicini

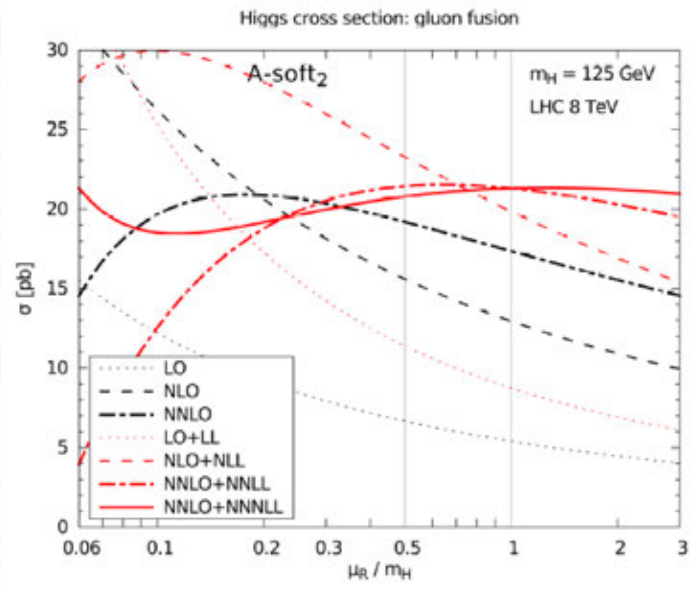
- Exclusive Jet bins / Jet veto efficiencies → A. Banfi

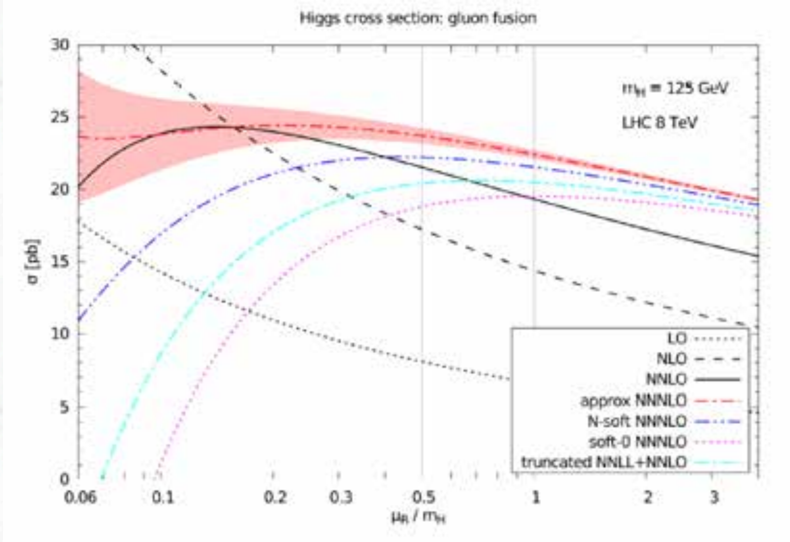
- Off shell cross sections, Interferometry → C. Williams
  S. Hoeche

- Higgs mass and potential, UV behaviour, naturalness → W. Skiba

S. Forte
M. Grazzini

- Continuous progress on theoretical calculations;
  N^3NLO (Anastasiou et al, 2014) and N^3LL resummation (almost) (Bonvini et al).





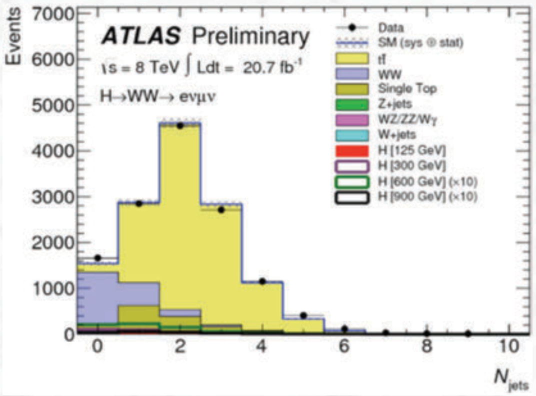
- Uncertainties might decrease slowly (μ_R, μ_F, pdf, α_s)
- Inclusion of top and bottom mass effects at NNLO+NNLL desirable in HRes (p_T^H)

Future: would be nice to come up with an updated **"cross-section recommendation"** and the **related uncertainties** at 8 and 13 TeV
→ Higgs cross section working group

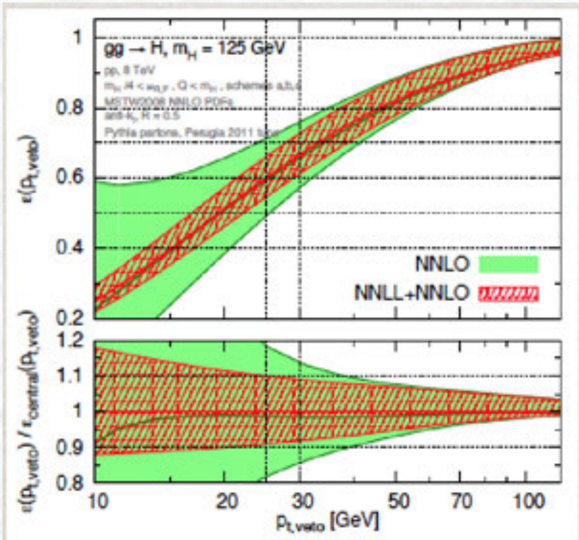
→ Experiments: measurement of unfolded differential distributions (P_T^H et al.. is essential to validate / test also Monte Carlo modelling)

Jet Vetos and Substructure

A. Banfi



- Experimental motivation is very clear;
- Split into jet bins
  → increase of sensitivity
  → separate background components
  (data-driven estimates)

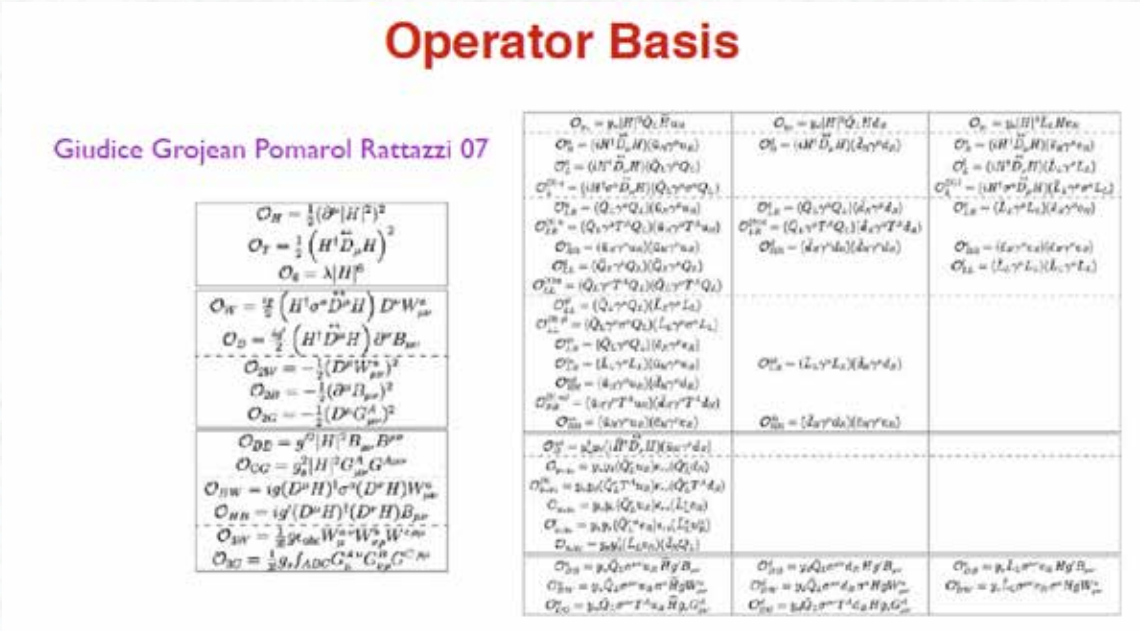


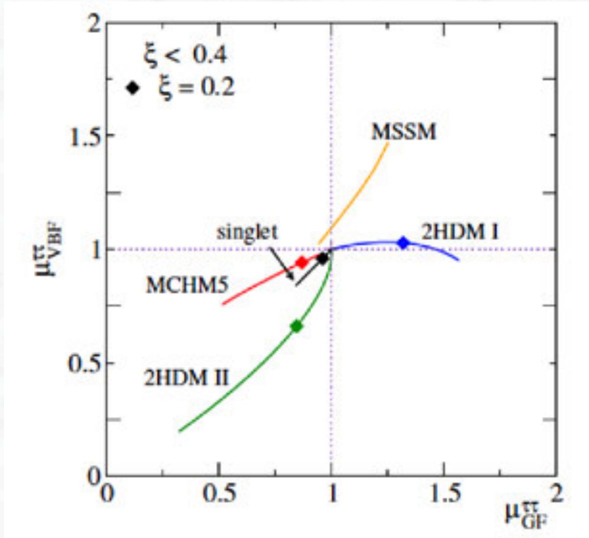
- Resummation of large logarithms needed to reduce uncertainties on jet-veto efficiencies,
  but uncertainties are still sizeable at NNLO+NNLL;
- Inclusion of top- and bottom-mass effects sightly increases uncertainty

- Boosted Jets (important for Run 2):
  New insights from analytical resummation methods
  → potential for improved tools / taggers

- Higgs Boson Couplings Beyond the Standard Model → E. Massó
  Effective Field theory approach as a model-independent approach to study deviations from the SM

- Global Fits to Higgs signal strength and couplings → D. Lópes-Val





→ We (experimentalists and theorists) need an interface / dictionary

Analysis Tools

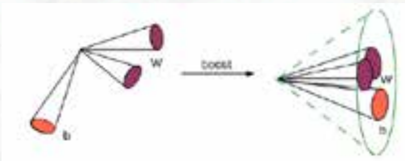
- Tools to describe BSM Higgs boson production → A. Vicini

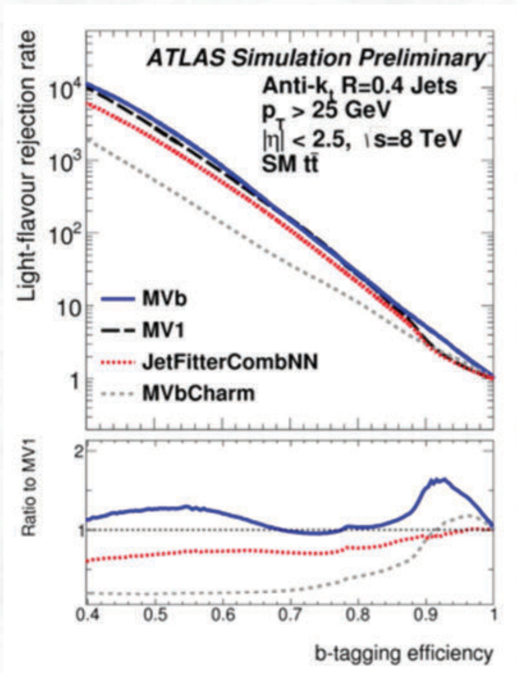
  - MSSM and beyond, e.g. general 2HDM
  - Anomalous couplings
  - Include effective Field theory approach

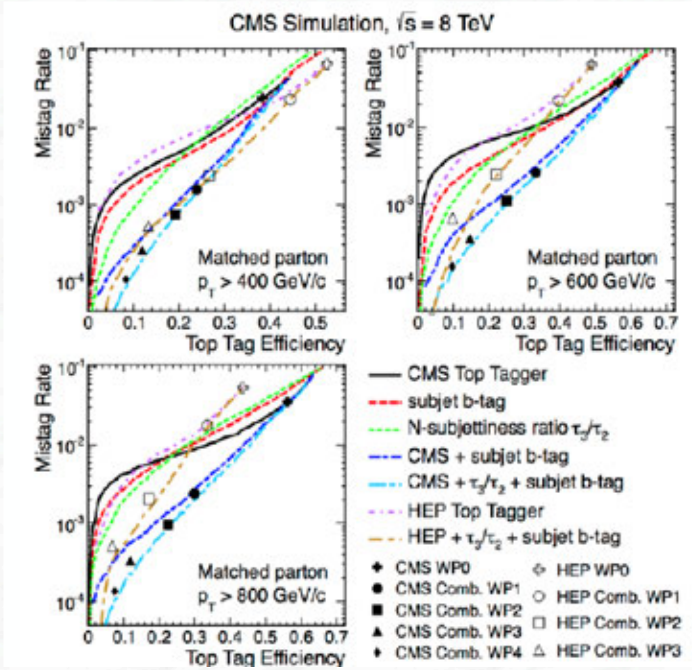
- Matrix element methods in Higgs phenomenology → M. Spannovsky

- B-tagging at high luminosity → D. Jennens, S. Zenz

- Top taggers / Boosted jets







Future Colliders

- Several talks on Higgs boson potential at future colliders
- Higgs couplings at future hadron colliders — I. Law
- Higgs couplings at future lepton colliders ILC — K. Fujii
- Experimental studies of hh production — J. Alison
  Higgs boson self coupling
- Future precision Higgs measurement an EW observables — B. Hennig

A personal view:

- Important to explore full LHC potential in medium and log term (Run-2, HL-LHC)
- Potential of HL-LHC need to be better understood, more work to be done,
  e.g. Higgs boson self coupling
  high priority issues: Higgs profile, Vector boson scattering, Searches …. Higgs portal
- Decision on next machine will depend on Run-2 outcome, …

M. Kado (Santander)

Towards Run-2

Precision
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- Off Shell couplings and width
- Interferometry

Rare decays
- $Z\gamma$, $\gamma\gamma^*$
- Muons $\mu\mu$
- LFV $\mu\tau$, $e\tau$

$$H^0$$

Is the SM minimal?
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H in the final state (ZH, WH, HH)

…and More!
- FCNC top decays
- Di-Higgs production
- Trilinear couplings prospects
- Etc…

One of the first goals : focus our efforts to extract most of the physical content of our data!

Maximization of Physics Output and Interpretation requires a close collaboration between experimentalists and theorists

HXSWG

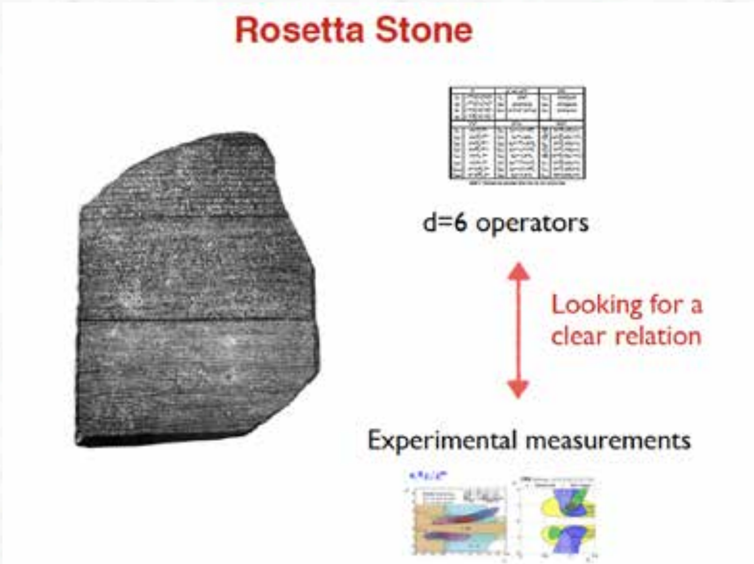
The Higgs cross section working group must continue to play a key rôle:

- Predictions of cross sections
- Related uncertainties !
- PDF uncertainteis must be addressed (how much can they be reduced if LHC data are included)

- Differential distributions
- Framework for CP-mixture

- Effective Field theory approach !

- Further interfaces might also be discussed there (unfolded fiducial cross-section)



THANKS to the Organizers of the Conference for the fantastic meeting !
In particular to Giampiero and Chiara

… and to all Speakers for presenting such a wealth of interesting and exiting results !