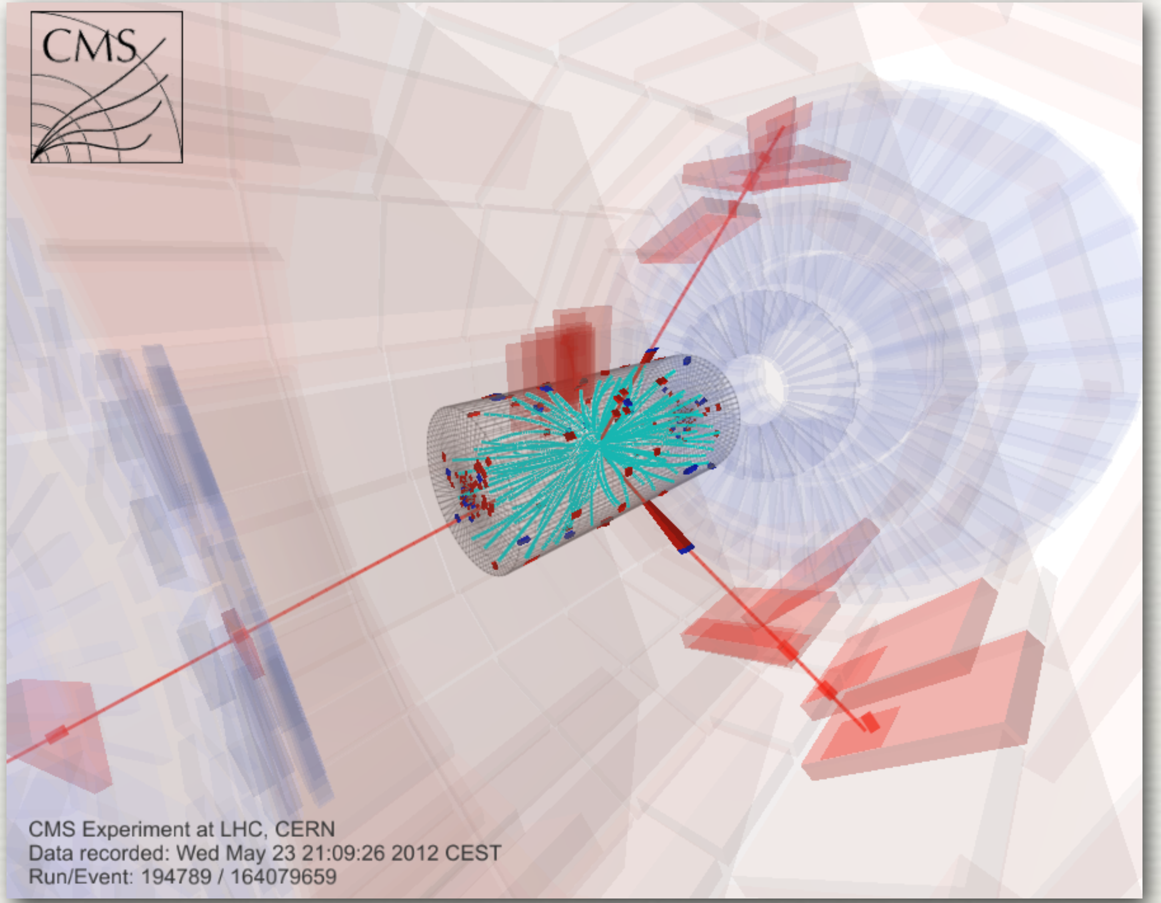
LHC Searches & Higgs Results



Andre Sznajder(UERJ)

Outline

- Standard Model
- The LHC and Experiments
- SM Higgs search
  - decays into bosons
  - decays into fermions
  - high mass exclusion
- Higgs properties
  - mass
  - couplings
  - spin & parity
  - width
- BSM Higgs search
- Future Perspectives

Prelude ...

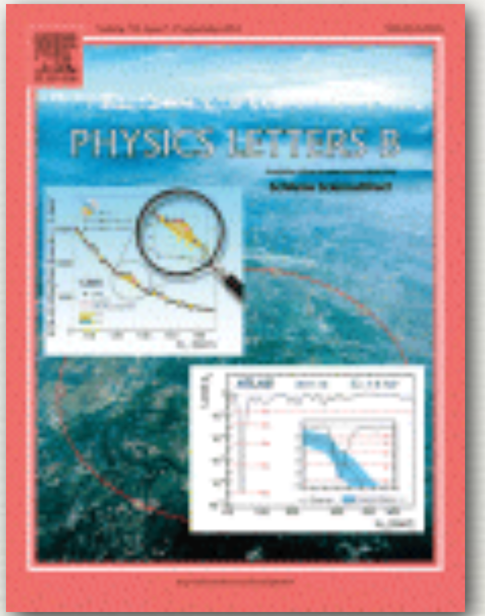
On July 4th 2012 ATLAS and CMS collaborations announced the discovery of a new boson around 125GeV

Results followed by updates focusing on answering the questions:

- if the new boson is "the Standard Model Higgs boson"
- if there are any hints for the physics beyond SM?

Answers provided as:

- measurements of the new boson properties: mass, spin-parity ...
- searches for additional Higgs like bosons in a wide mass range

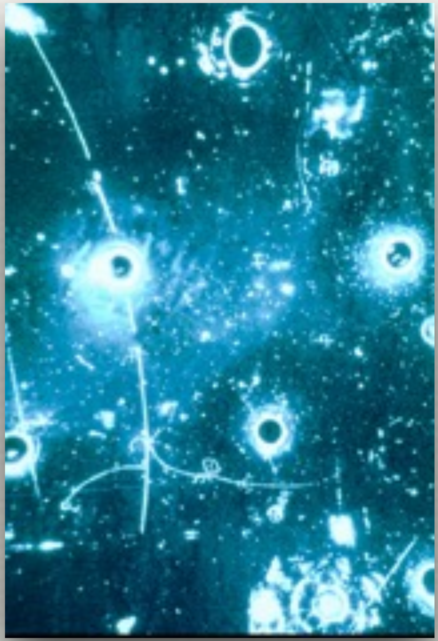


- **ATLAS: Phys.Lett. B716 (2012) 1-29**
- **CMS: Phys.Lett. B716 (2012) 30-61**

Electroweak Theory

In the mid 60‘s Glashow-Salam-Weinberg proposed a unification of the weak and electromagnetic interactions based a $SU(2)_L$ x $U(1)_Y$ gauge theory

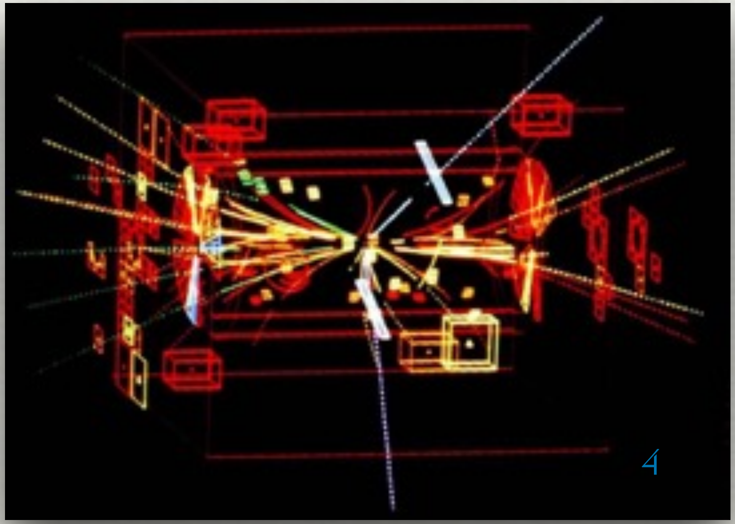
- fermions are doublets or singlets under $SU(2)_L$
- Z and γ emerge as a mix of the two groups gauge fields
- Lagrangian contains neutral current as well as charged describing, e.g., beta decay and neutrino scattering



Neutral current event in the Gargamelle bubble chamber

Weak interaction is short ranged => W and Z bosons are massive

problem: mass terms ($m_W^2 W^+_\mu W^{-\mu}$)break gauge invariance   => loss of renormalizability and unitarity



W/Z discovery at UA1 & UA2 experiments

The Higgs/BEH Mechanism

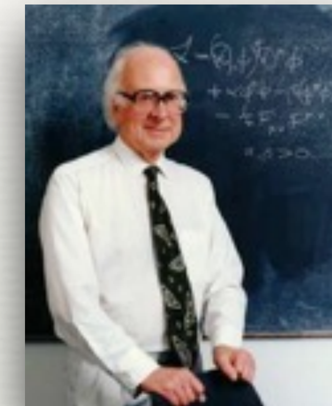
Problem of gauge bosons masses solved by Spontaneous Symmetry Breaking (SSB) mechanism elaborated by several authors at the beginning of the 60s

F. Englert

R. Brout
(1928-2011)

[P.W. Higgs,
"Broken symmetries, massless particles and gauge fields",
Phys.Lett.12(1964)132]

[P.W. Higgs,
"Broken symmetries and the masses of gauge bosons",
Phys.Rev.Lett.13(1964)508]



P.W. Higgs

[F. Englert and R. Brout,
"Broken symmetry and the mass of gauge vector mesons",
Phys.Rev.Lett.13(1964)321]

[G.S.Guralnik, C.R.Hagen, T.W.B.Kibble,
"Global conservation laws and massles particles", **Phys.Rev.Lett.13(1964)585]**

G.S. Guralnik

C.R. Hagen

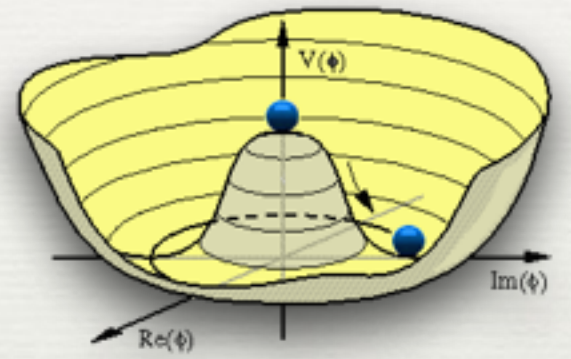
T.W.B. Kibble

The Higgs Mechanism

The Higgs Mechanism applied to the $SU_L(2) x U_Y(1)$ local gauge theory is able to give mass to the gauge bosons

- gauge symmetry of the model is preserved while ground state of the scalar field "spontaneously" breaks the symmetry
- minimal solution uses a doublet of complex scalar fields (4 degrees of freedom) – and has a non-zero vacuum expectation value(VEV)
- one component corresponds to an electrically neutral scalar particle – the "Higgs boson"
- remaining three components add a new degree of freedom (longitudinal polarization) of massive $W^{\pm}$ and Z bosons

Higgs Potential



$$L_{Higgs} = (D_\mu \Phi)^+ (D^\mu \Phi) - m^2 |\Phi|^2 - \lambda |\Phi|^4$$

$$m_H = \sqrt{2\lambda} v \qquad m_W = \frac{1}{2}\frac{ev}{\sin^2\Theta_W} \qquad m_Z = \frac{1}{2}\frac{ev}{\sin\Theta_W \cos\Theta_W} \qquad m_\gamma = 0$$

The Standard Model

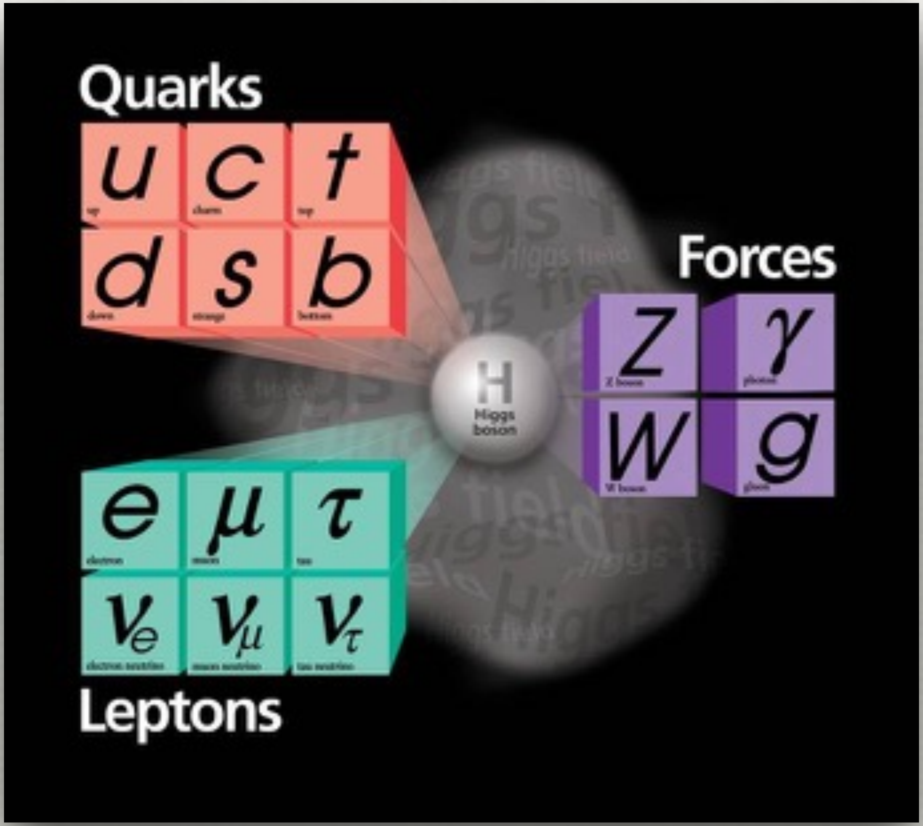
The SM reflects our current understanding of elementary particles and the forces acting between them (with the exception of gravity).

Matter

- three generations of fermions
- in each generation
  - 2 quarks (Q = +2/3,-1/3)
  - 1 charged lepton (Q = -1)
  - 1 neutrino (Q = 0)

Forces

- the strong force (8 gluons)
- the electromagnetic force (photon)
- the weak force (W, Z)



Higgs field gives mass to electroweak gauge bosons and fermions(Yukawa couplings)

Why is the Higgs important ?

The Higgs boson presents much more than just another new particle. It is a fundamental component of the standard model !

- the SM accurately describes decades of experimental measurements but its conceptual basis rely on the Higgs mechanism
- it describes the way elementary particles acquire mass. In a world with massless fermions atoms would not exist, the electron would be massless !!!

It changes our view on the nature of elementary particles

- mass is no more an intrinsic property of particle. It's rather a result of an interaction with an external field !
- "break the paradigm" that interactions are dictated by gauge symmetries

SM Lagrangian

$$\mathcal{L} = -\tfrac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$W^{\pm}, Z, \gamma$ kinetic energies and self-interactions

$$+\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)L$$
$$+\bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)R$$

lepton and quark kinetic energies and their interactions with $W^{\pm}, Z, \gamma$

$$+\left|\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)\phi\right|^{2}$$
$$-V(\phi)$$

$W^{\pm}, Z, \gamma$ and Higgs masses and couplings

$$-(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.)$$

lepton and quark masses and coupling to Higgs

L ... left–handed fermion (l or q) doublet
R ... right–handed fermion singlet

$\mathcal{L}$ from QCD:

$$\mathcal{L} = \underbrace{\bar{q}\left(i\gamma^{\mu}\partial_{\mu} - m\right)q}_{E_{kin}(q)} - g\underbrace{(\bar{q}\gamma^{\mu}T_a q)G^a_{\mu}}_{\text{Interaction } q,\, g} - \underbrace{\frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu}}_{E_{kin}(g)}$$

$E_{kin}(q)$

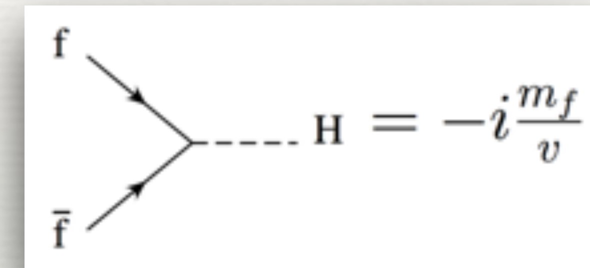
Interaction q, g

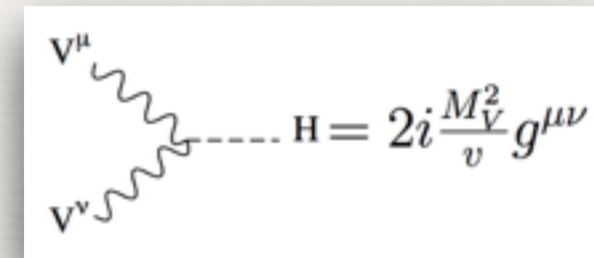
$E_{kin}(g)$ includes self-interaction between gluons

- Higgs mass is a free parameter of the model
- If we know the mass all Higgs interactions to elementary particles are determined by the model
- Higgs to fermions Yukawa couplings introduced by hand

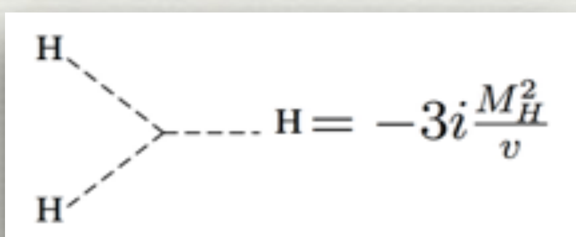
Higgs Boson Interactions

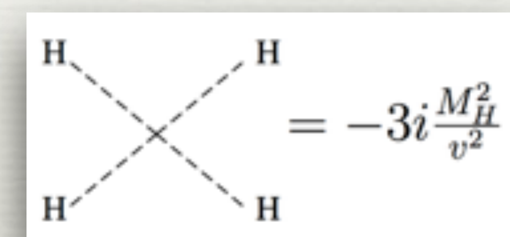
Directly couple with the mass of elementary particles

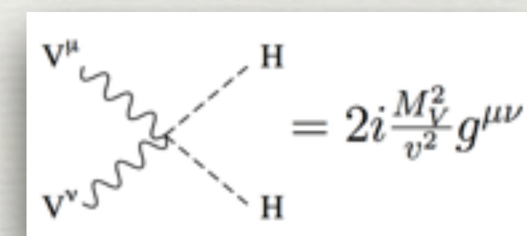




Self couplings

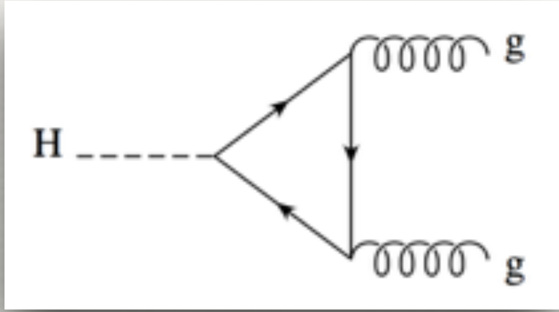






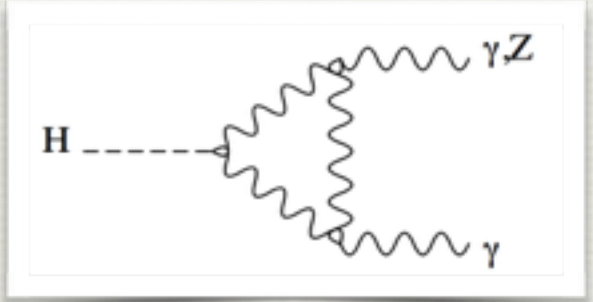
Couplings to Massless Bosons

Takes place through loops of massive particles

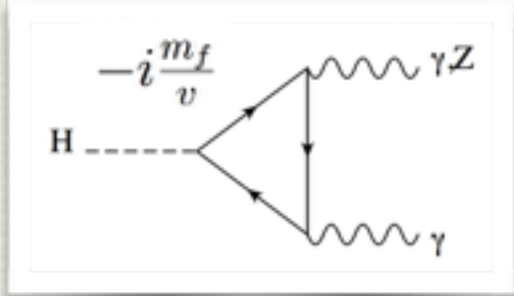


all fermions contributes, but top quark dominates due to its large mass

Opposing effects (interference)

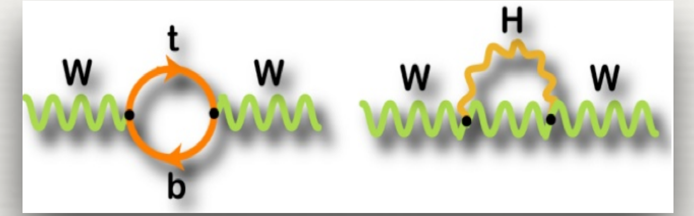


+

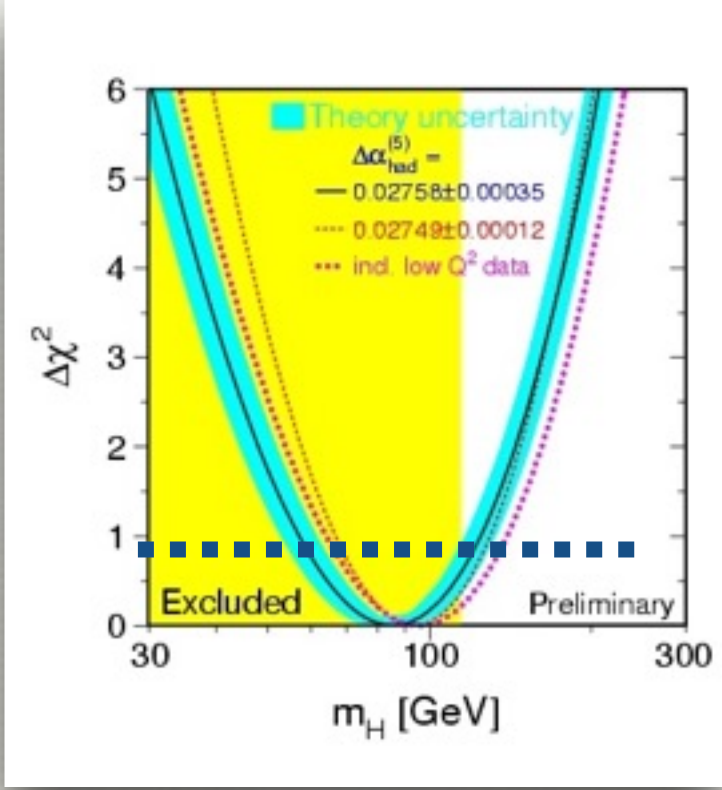


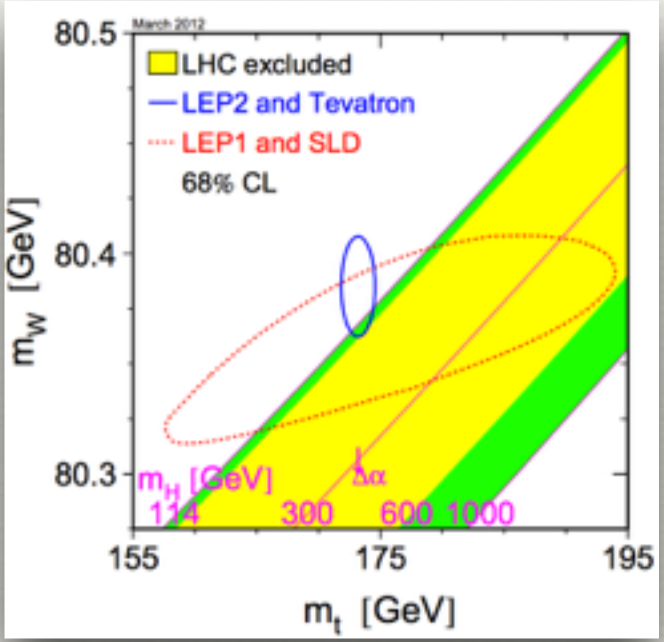
Indirect Higgs Measurements

Until LHC, the only way to observe the Higgs boson has been through indirect measurements, i.e. to see its loop effects on other SM quantities. Find mH bounds from best Standard Model fits to all existing data.



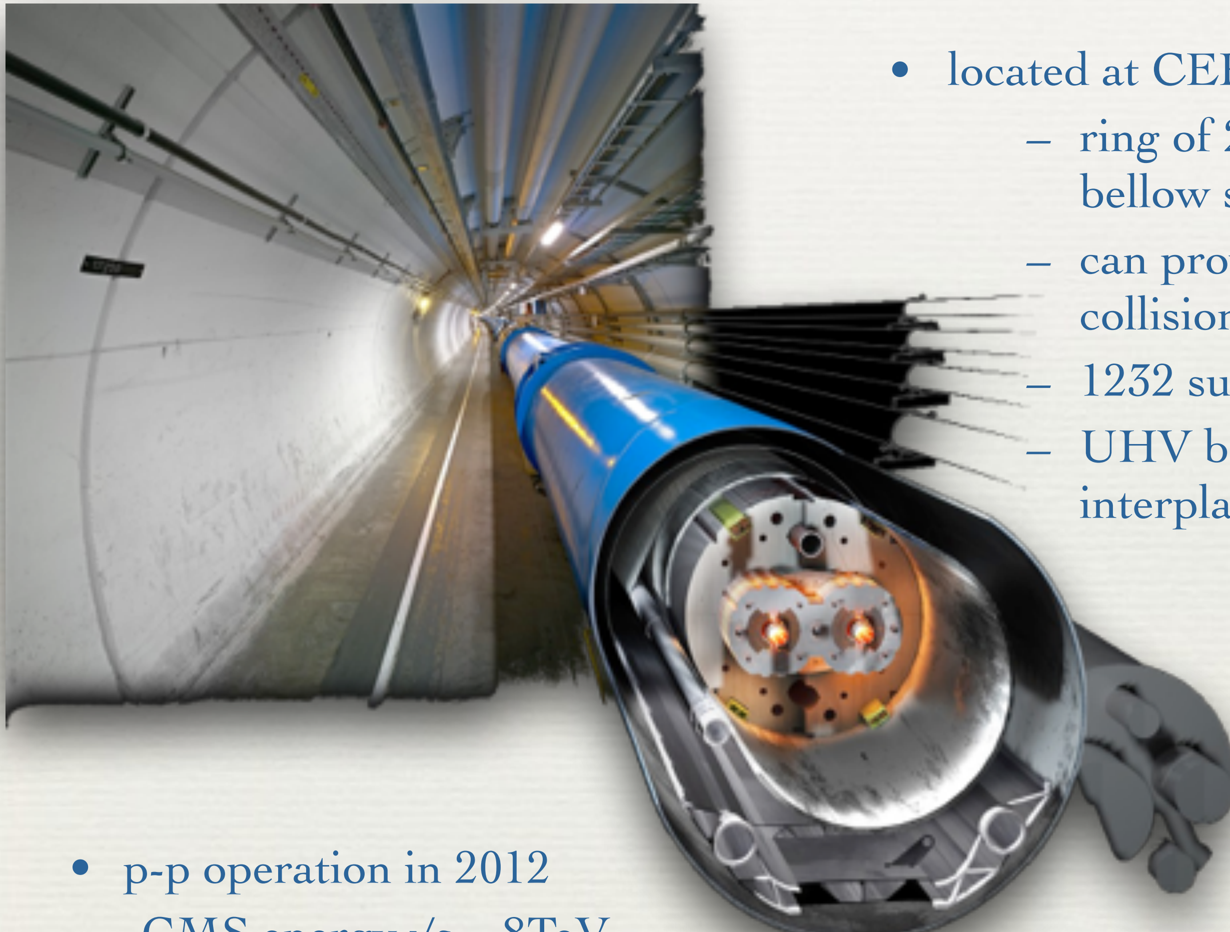
quadratic dependence on $\mathbf{m_t}$ but only logarithmic dependence on $\mathbf{m_H}$ still precision measurements gives some sensitivity





LHC

The world's most powerful accelerator



- located at CERN near Geneva
  - ring of 27 km circumference and 100m bellow surface
  - can provide p-p, Pb-Pb (and p-Pb) collisions in 4 interaction regions
  - 1232 superconducting dipoles(–271.25 °C)
  - UHV beam pipes as empty as interplanetary space (10^{-13} *atm*)

- p-p operation in 2012
  - CMS energy $\sqrt{s}$ = 8TeV
  - ≈1400 bunches / beam with 50ns bunch spacing
  - peak luminosity of 7×10^{33} $cm^{-2}s^{-1}$ (10^9 collisions / s)

$$L = \frac{N_b^2 n_b f_{\rm rev} \gamma_r}{4\pi \varepsilon_n \beta *} F$$

N_b = number of proton per bunch
n_b = number of bunches

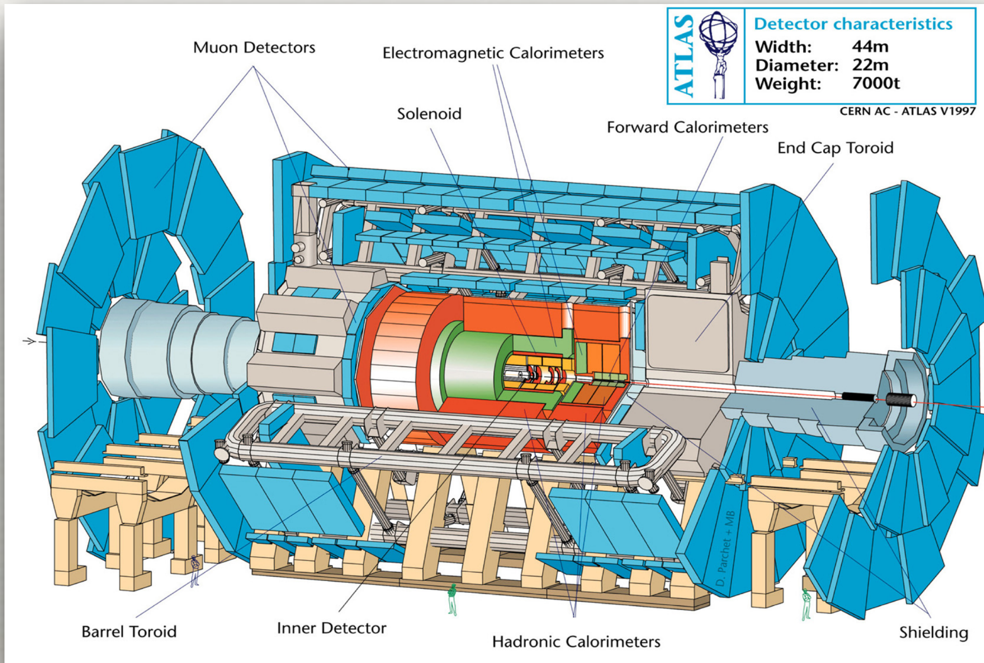
f_{rev} = rotation frequency (~ 11Hz)
F = crossing angle factor

Rms transverse beam size $=\sqrt{\varepsilon \beta / \gamma}$
ε_n = renorm. transverse emittance
$\beta *$ = optics at beam crossing (m)
γ_r = relativistic factor

LHC Experiments

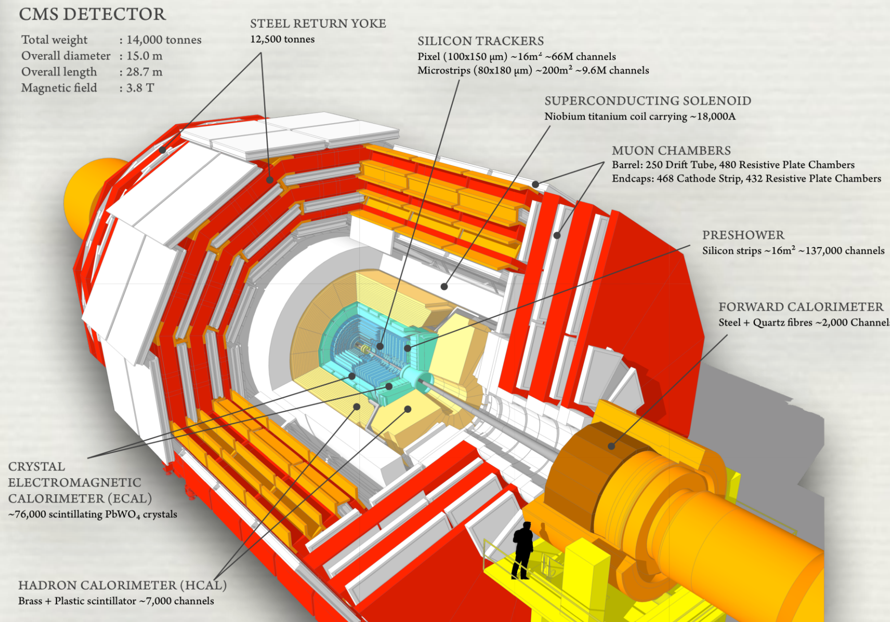
- General purpose experiments: ATLAS and CMS (cover wide range of physics from SM measurements to BSM)
- Specialized experiments: Alice(heavy ions) and LHCb (B physics) ...

ATLAS & CMS Experiments



ATLAS

CMS

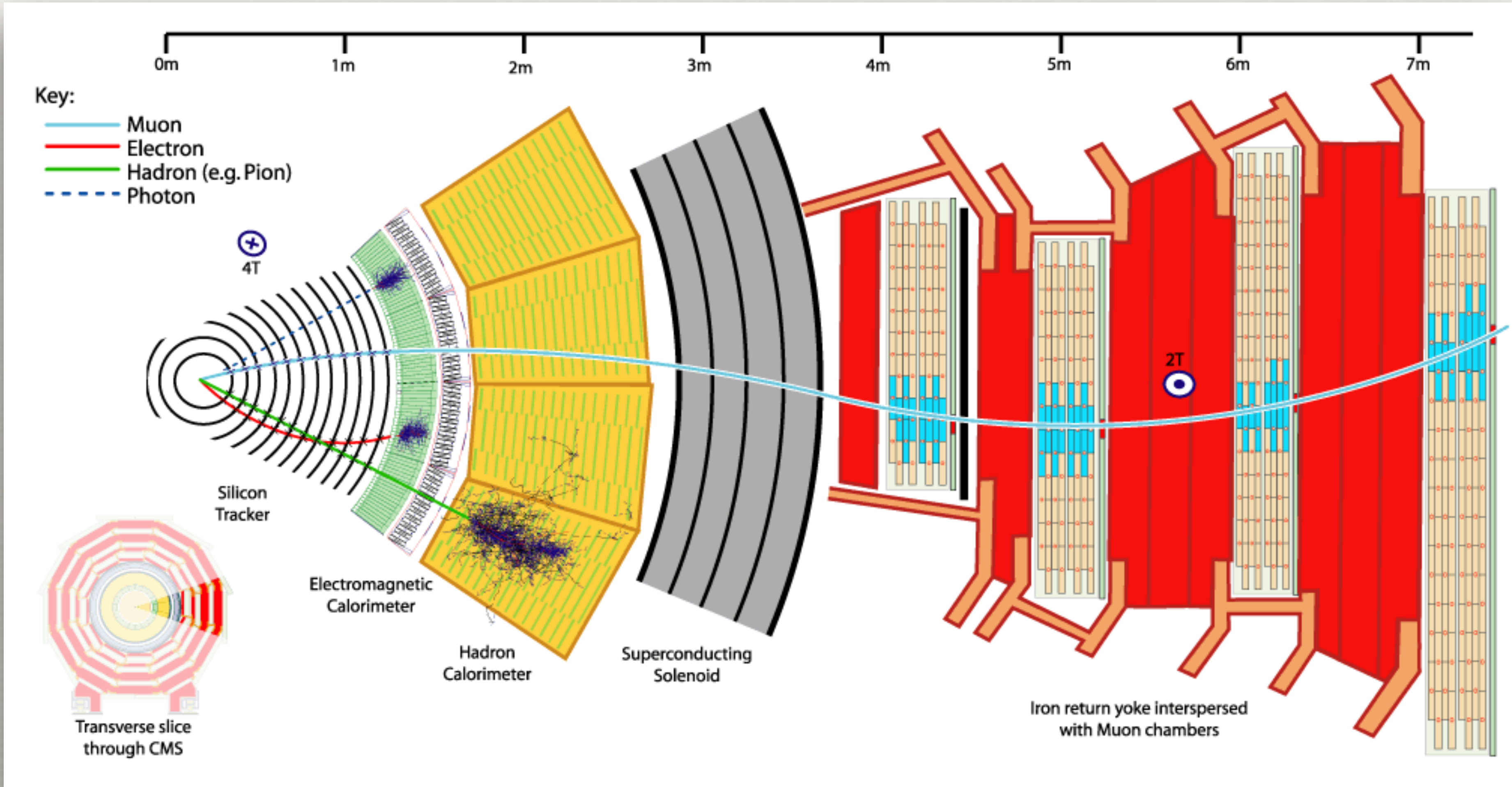


	ATLAS	CMS
Weight	7000t	12500t
Diameter	22 m	15 m
Lenght	46 m	22 m
Magnetic field	2 T	4 T

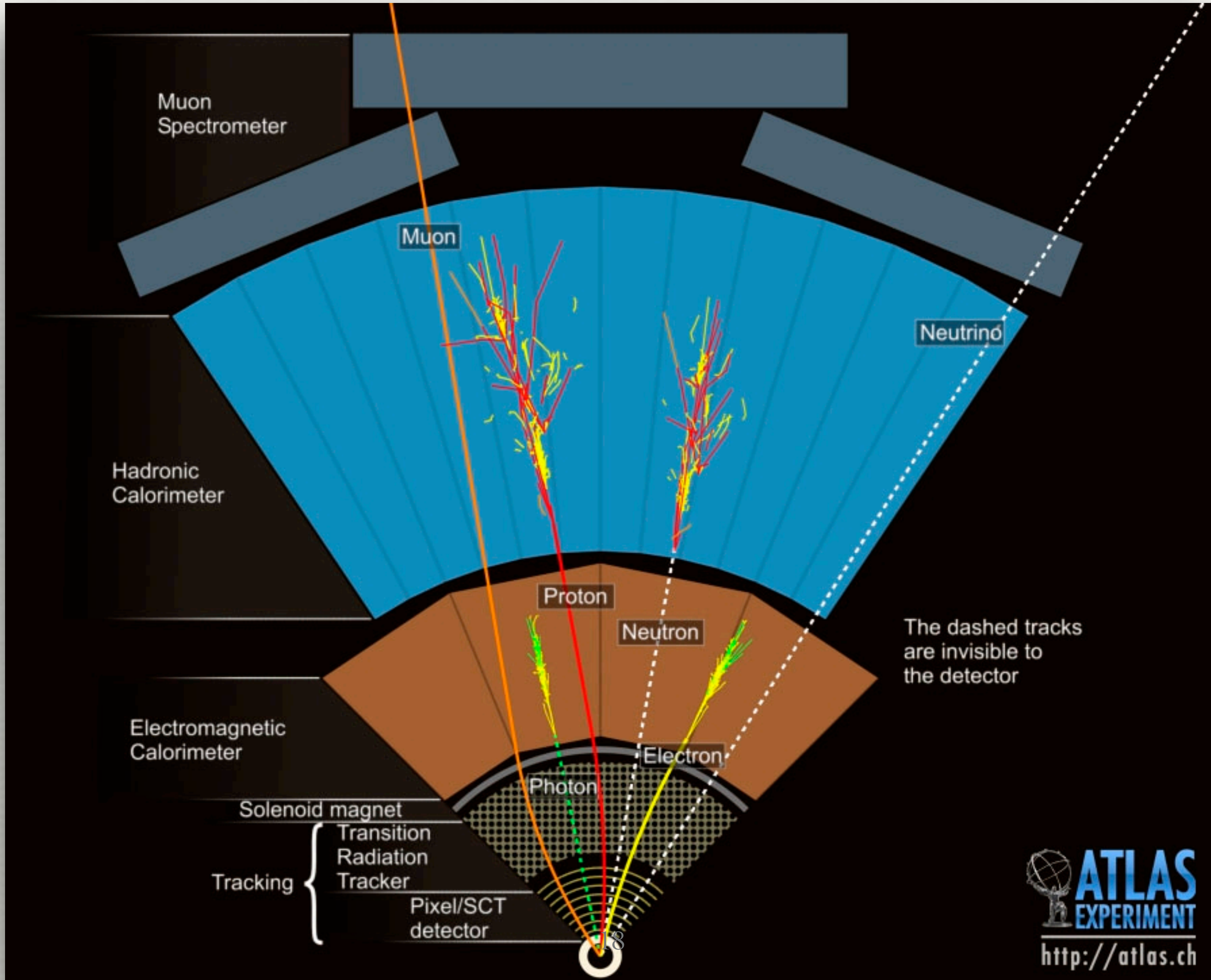
ATLAS vs CMS

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\times10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\times10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} + 0.005$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Cu+scintillator (5.8λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID+MS)	$\sigma/p_T \approx 1\%$ @ 50GeV to 5% @ 1TeV (ID+MS)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)

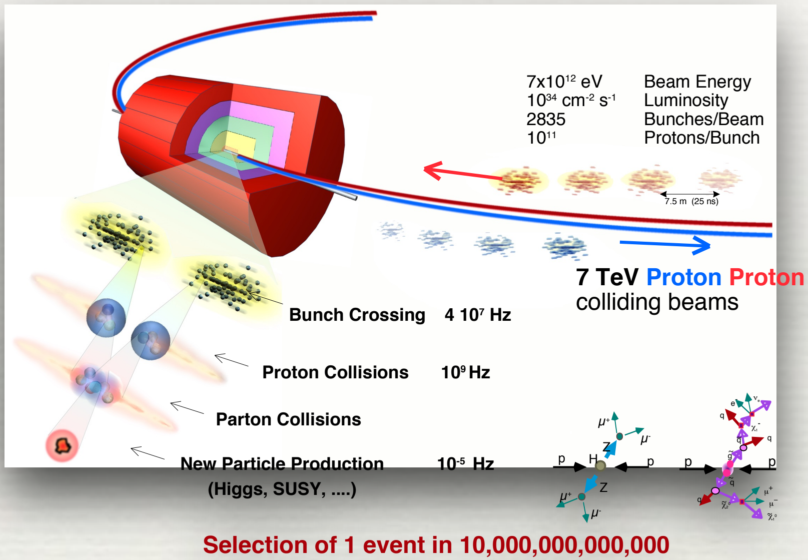
CMS Particle Detection

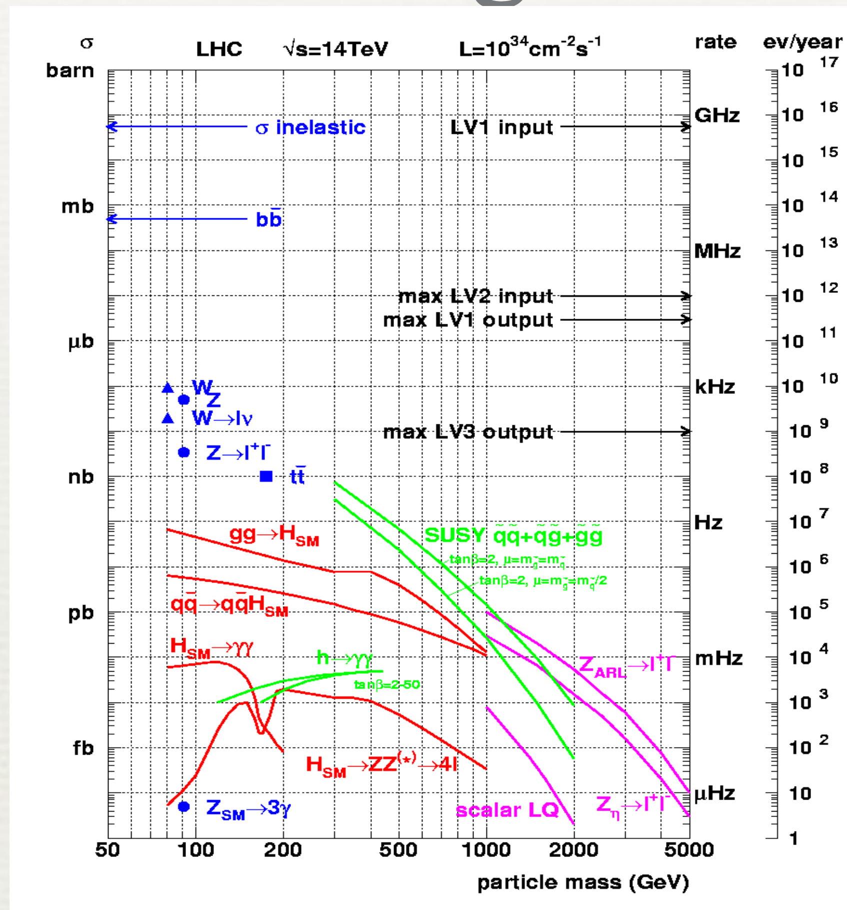


ATLAS Particle Detection



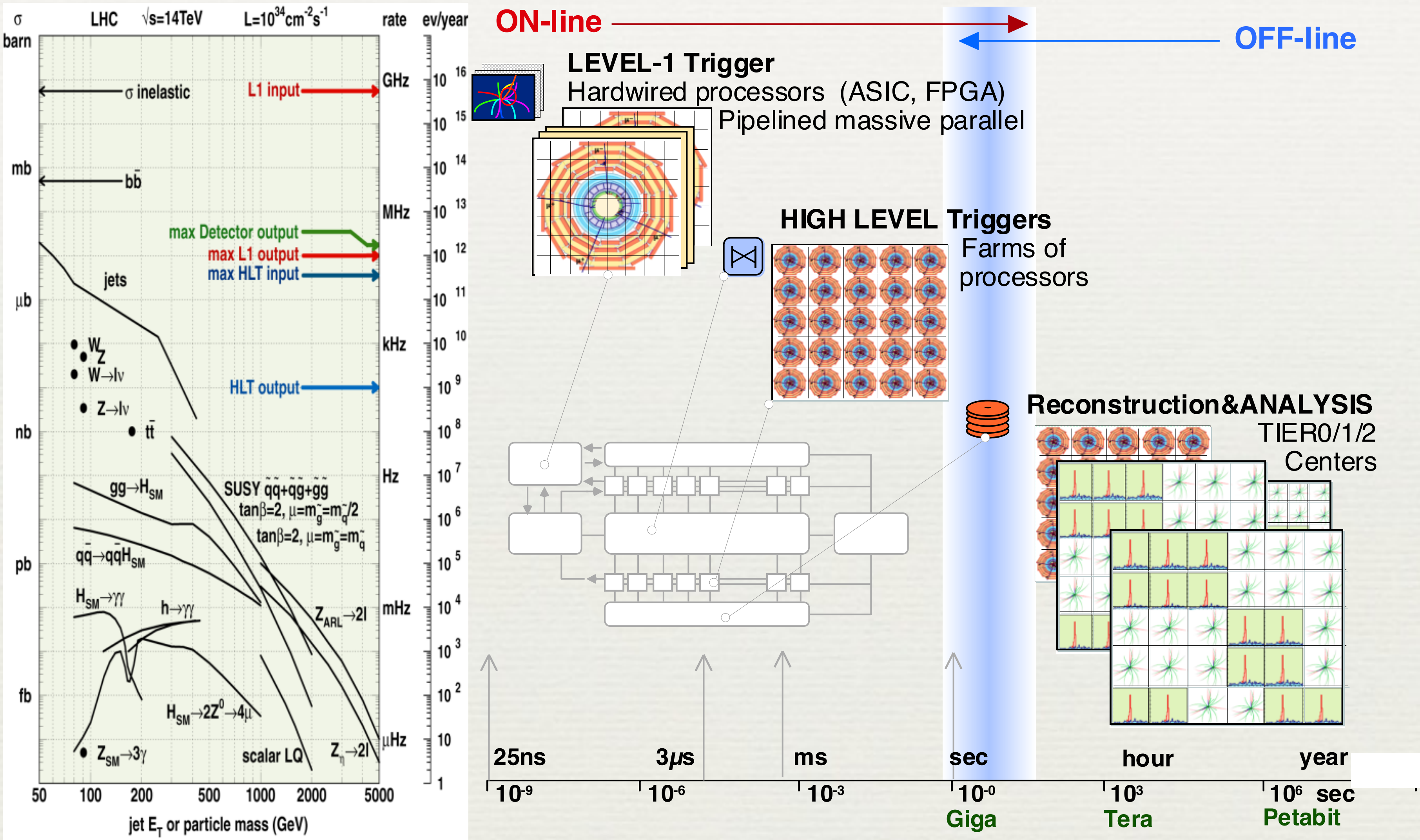
Experimental Challenges





- reduce rate from 20 million collisions per bunch crossings / s (10^9Hz) to a few 100Hz
- production rate for a light Higgs boson is about 0.1Hz
- data reduction done in stages: trigger(HW) / filter(SW)
- critical component of the experiment!

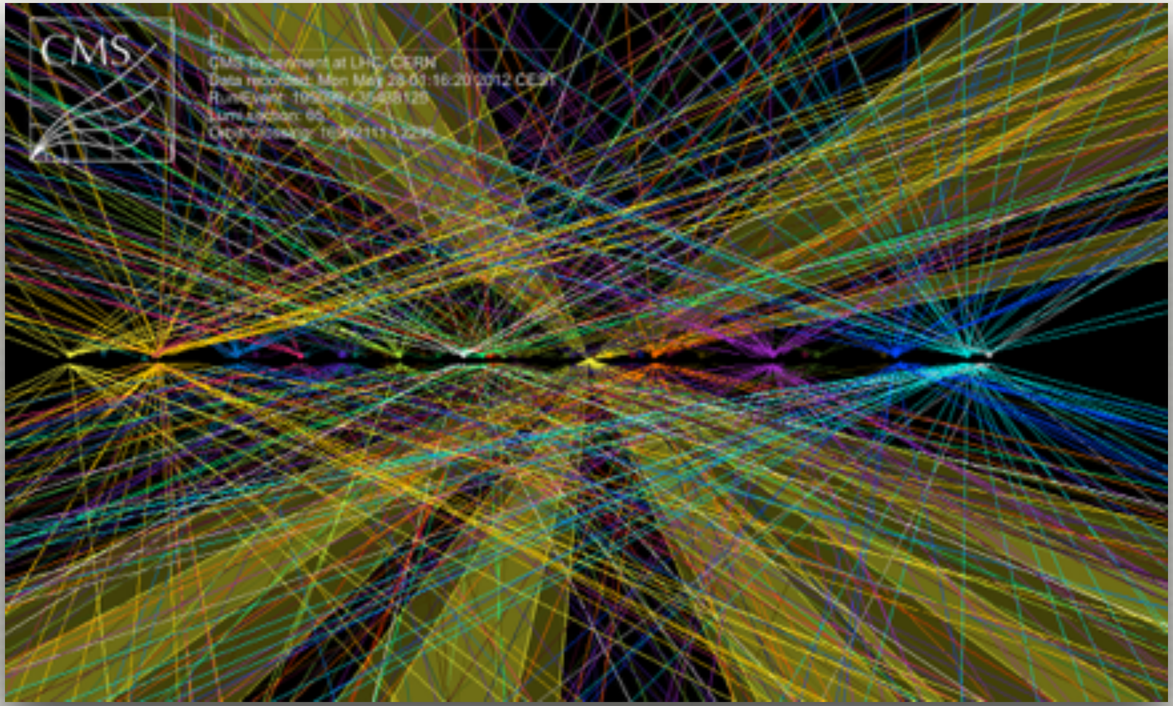
Event Selection Stages

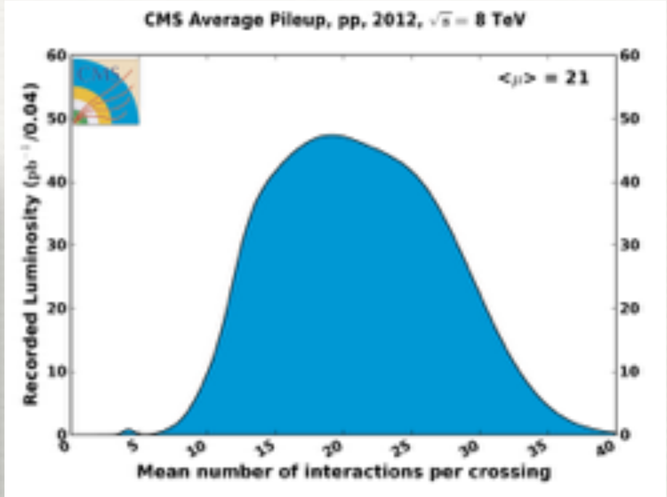


Experimental Challenges

Multiple collisions generates in average 25 events per bunch crossing !

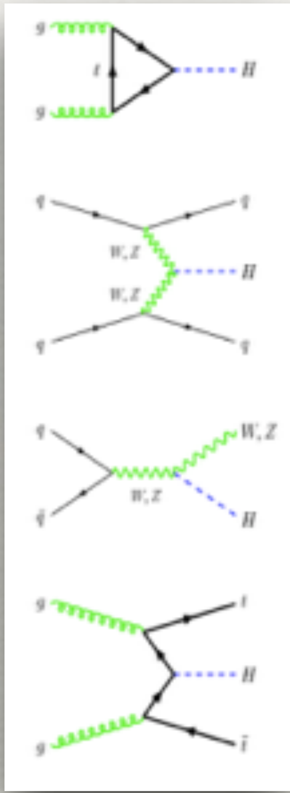
Reconstruction of the 100s of charged particles
in the high-granularity silicon tracking device





Higgs Production Modes @ LHC

Production % @125GeV



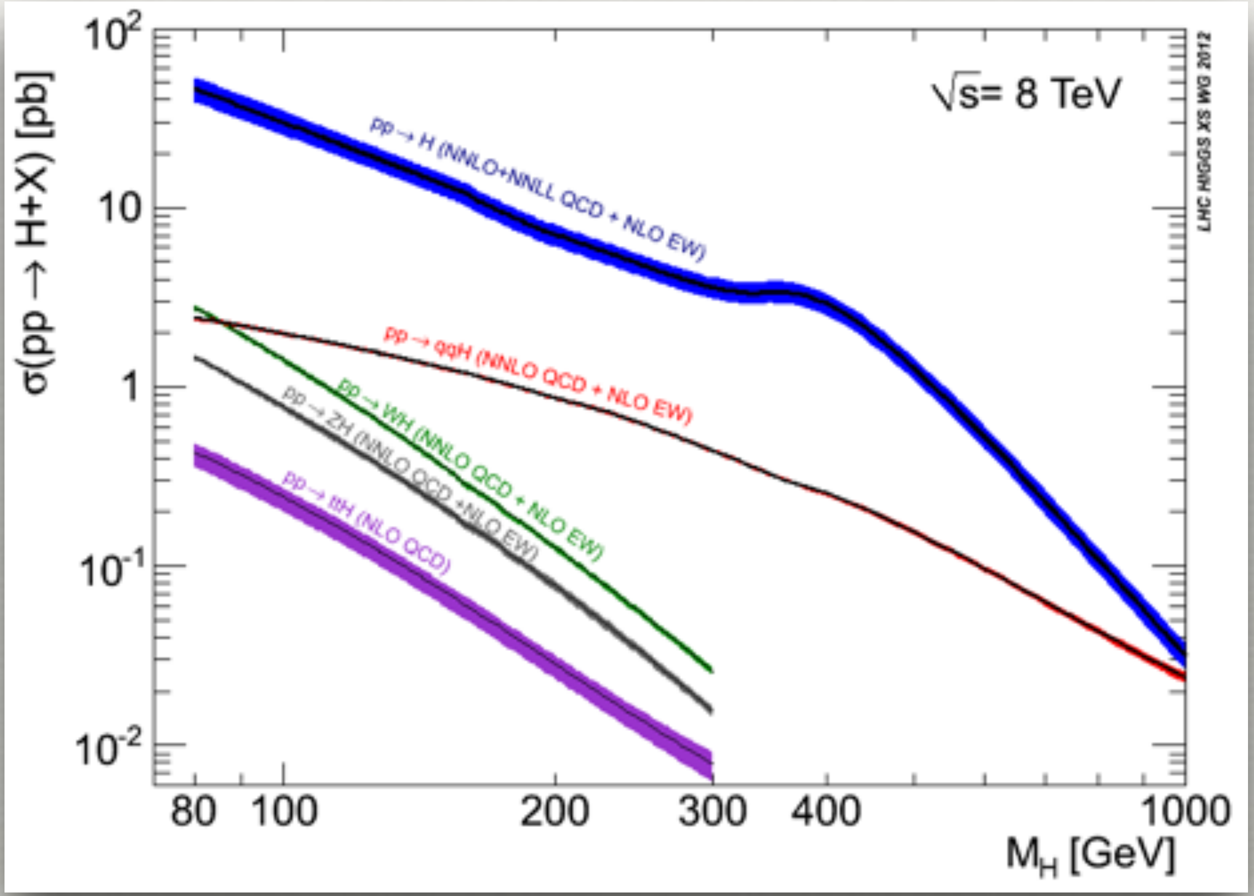
"gluon fusion" (ggF): ≈87.5%

"vector boson fusion" (VBF): ≈7%

"associated production" (VH): ≈5%

"tt fusion": <1%

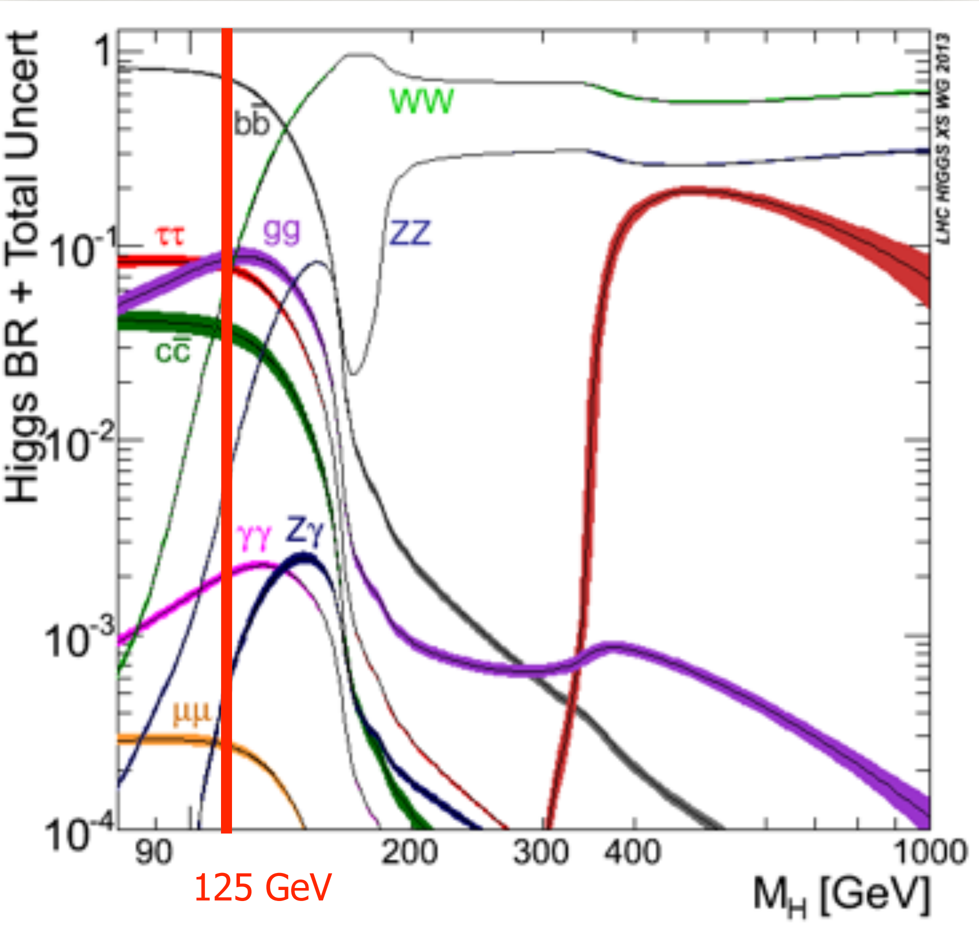
Higgs Production Cross Section



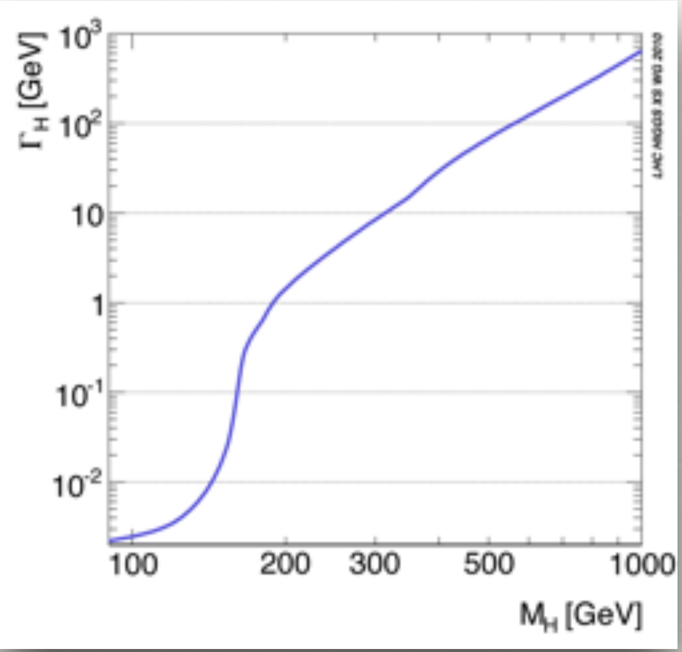
LHC Higgs XSWG:

arXiv:1101.0593, arXiv:1201.3084, arXiv:1307.1347

Higgs Decay Modes & Width



LHC Higgs XS WG:
arXiv:1101.0593,
arXiv:1201.3084,
arXiv:1209.0040



Main contributions:

Low mass: **H→γγ, H→ZZ and H→WW**

Intermediate/high mass: **H→WW, H→ZZ** **(clean leptonic decay signatures)**

Channel Characteristics

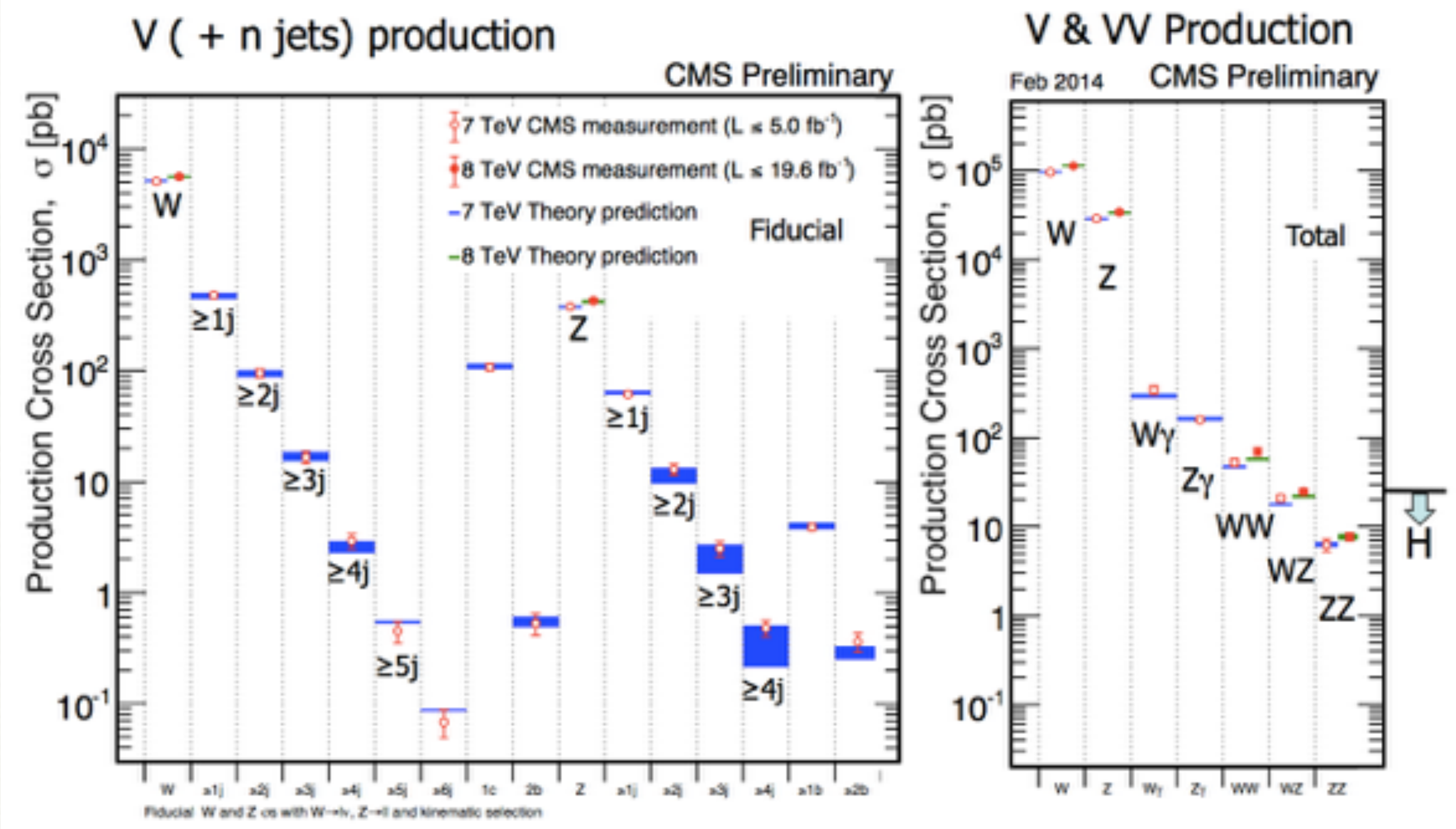
- The decay branching ratio determines the m_H range where a channel is significant
- Final state objects determine the channel resolution for mH

$$m_H = \sqrt{E_H^2 - \vec{p}_H^{\,2}} = \sqrt{\sum E_i^2 - \sum \vec{p}_i^{\,2}}$$

Channel	m_H range (GeV/c²)	Data used 7+8 TeV (fb^{-1})	m_H resolution
H -> γγ	110-150	5.1+19.6	1-2%
H -> tautau	110-145	4.9+19.6	15%
H -> bb	110-135	5.0+19.0	10%
H -> WW -> lnulnu	110-600	4.9+19.5	20%
H -> ZZ -> 4l	110-1000	5.1+19.6	1-2%

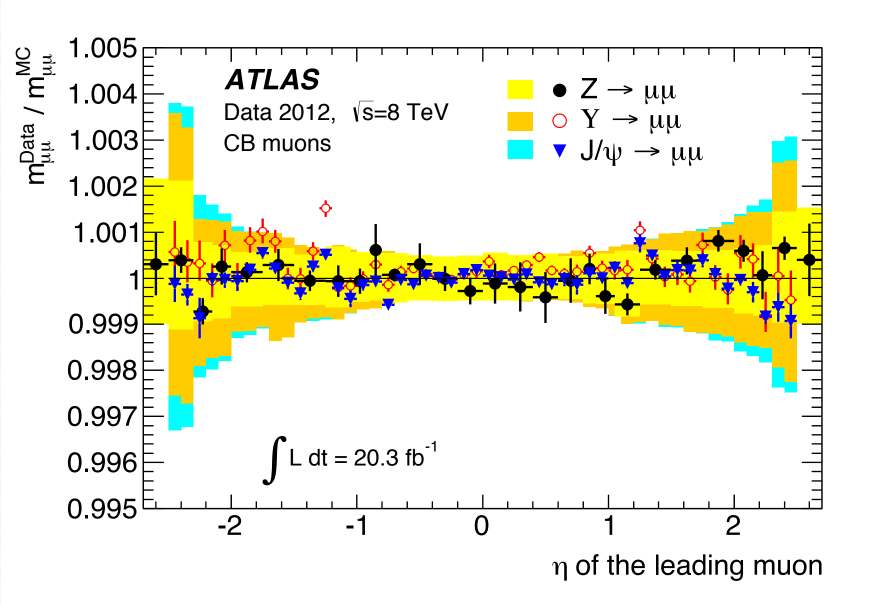
Understanding the Backgrounds

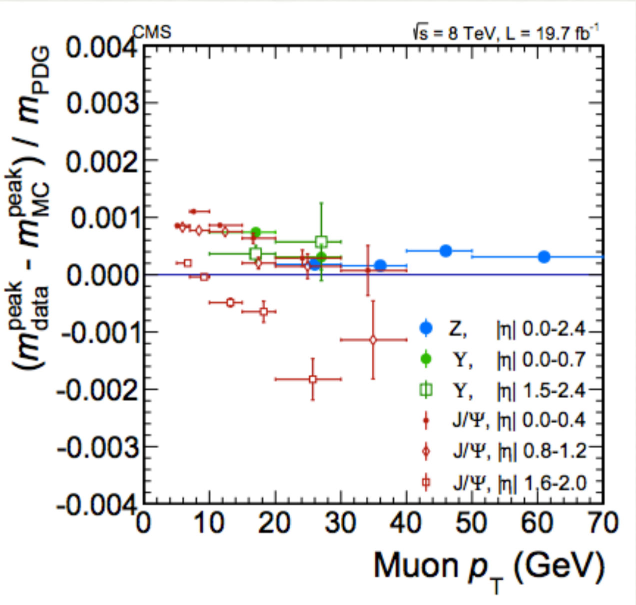
- Validate and tune MC simulations on production cross section measurements
- All theoretical expectations calculated at NLO or higher



Standard Candles: Z, J/ψ ,ϒ decays

- **Z, J/ψ** ,ϒ -> l^+l^- , γγ decays in data are standard candles to calibrate photon, electron and muon energy scales
- Large source of clean events with well described mass peak.
- Energy measurements are corrected to match mass distributions between data and MC.

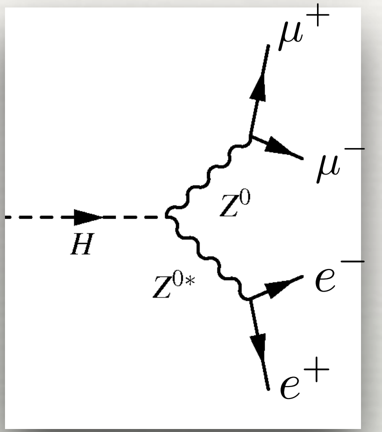


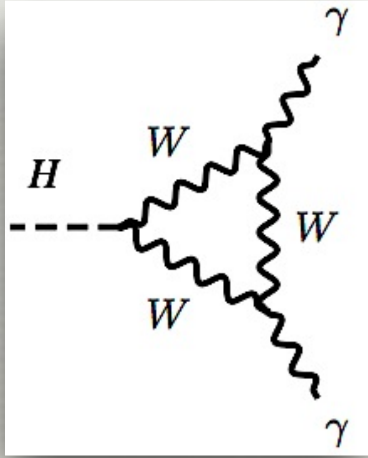


High Resolution Channels

- Only high resolution physics objects (no jets or neutrinos)
- Full reconstruction of final state (model independence)

Channel	BR(mH=125GeV)	Resolution
H→ZZ→4l	0.0276%	1-2%
H→γγ	0.228%	1-2%
H→Zγ→2lγ	0.01%	1-2%
H→μμ	0.0219%	1-2%





$H \rightarrow ZZ^* \rightarrow 4\ell$

The Higgs golden channel

Signatures:

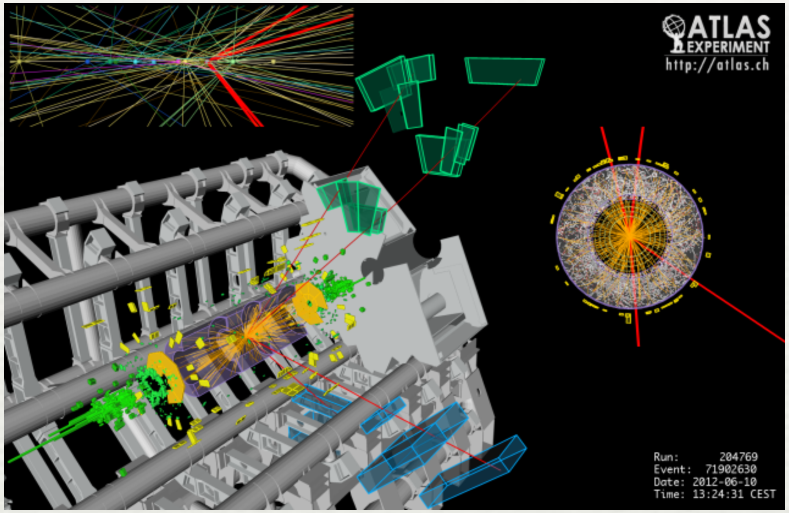
- two electrons or muons pairs, isolated from hadronic activity and categorized in: 4e,2e2μ,4μ
- very high S/B ratio channel

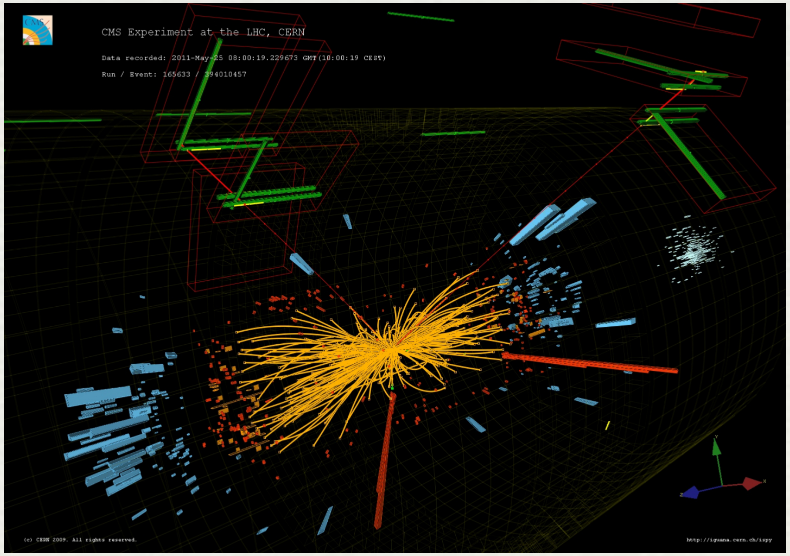
Challenges:

- need high efficiencies for lepton reconstruction and ID
- small branching fraction
- low Pt for at least 1 or 2 leptons (Z^* yields low pT)

Methods:

- Z candidates formed from same-flavor & opposite-sign leptons
- FSR photon recovery to improve m_{ZZ} resolution
- For lepton pair closest to the Z-mass require: **40 (50)< mll < 120(106) GeV CMS(ATLAS)**

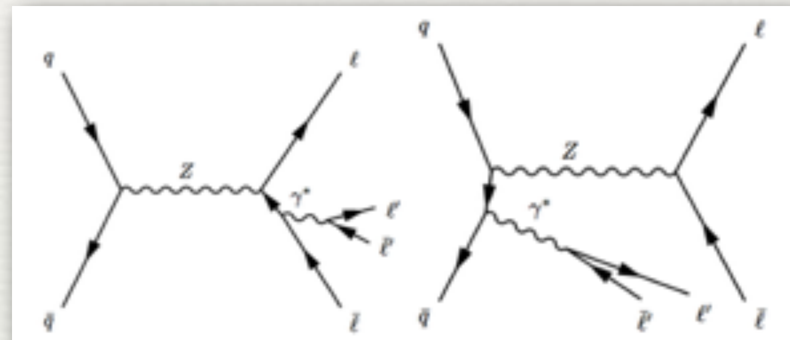




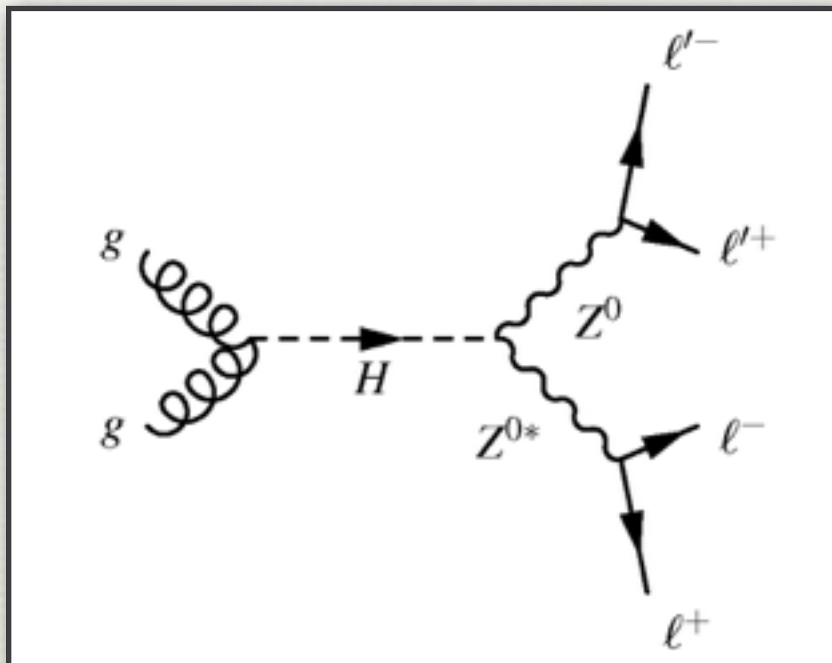
$H \to ZZ^* \to 4\ell$

Golden channel has clean experimental signature and allows full reconstruction of the final state

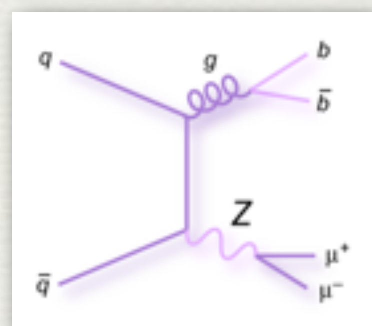
irreducible background
($qq \to Z\gamma^*$, $qq \to ZZ$, $gg \to ZZ$)

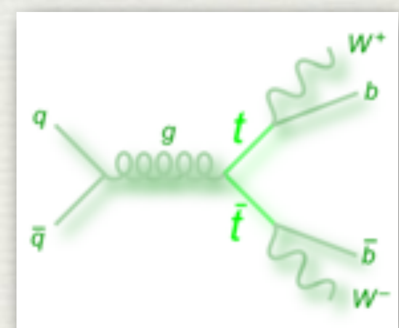


signal $H \to ZZ^* \to 4l$



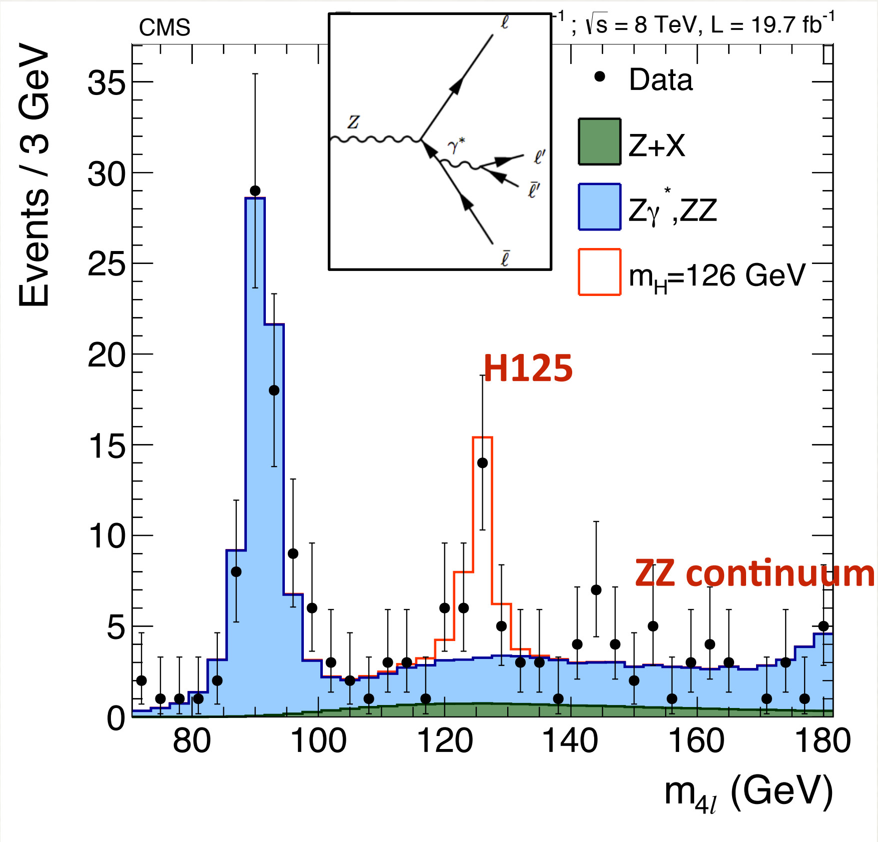
reducible background
(Z+jets, ttbar, Z+γ+jets, WZ+jets, ...)

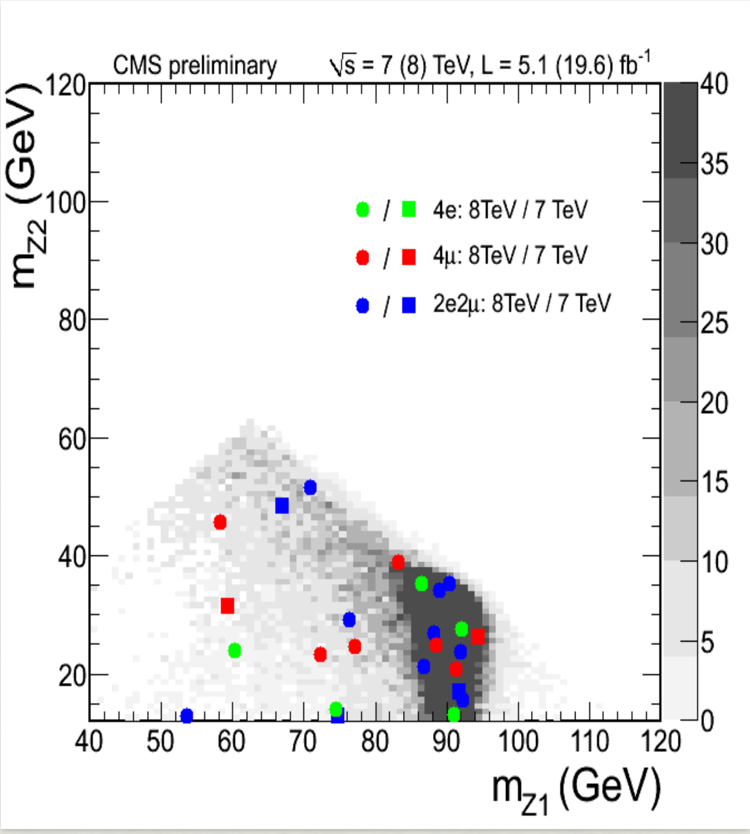




H→ZZ*→4l (CMS)

Mass spectra shows a clean signal peak at ~126 GeV and very good control of the dominant ZZ background

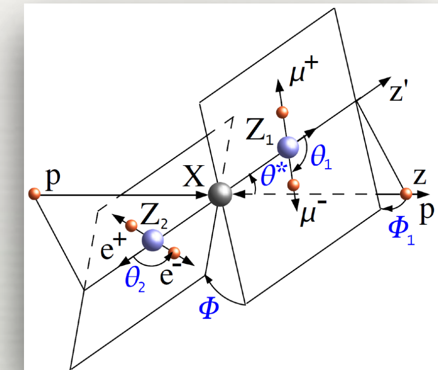




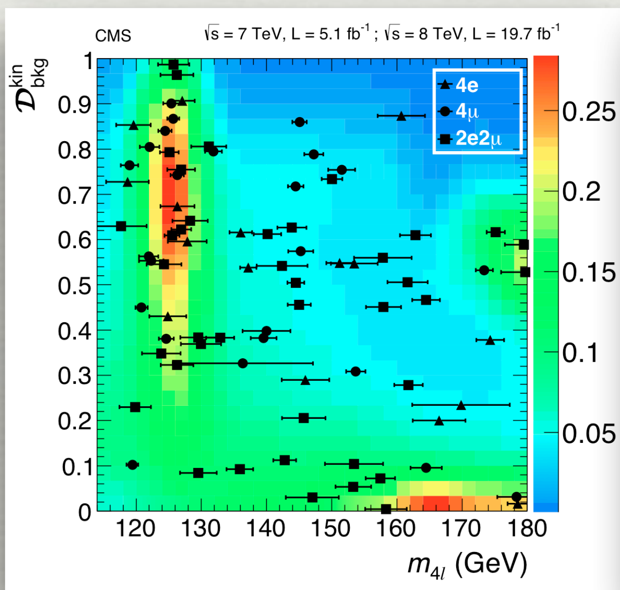
H→ZZ*→4l (CMS)

Matrix Element Likelihood Analysis (MELA) uses kinematic inputs to build a kinematic discriminant for signal to background discrimination using {m1,m2,θ1,θ2,θ*,Φ,Φ1}

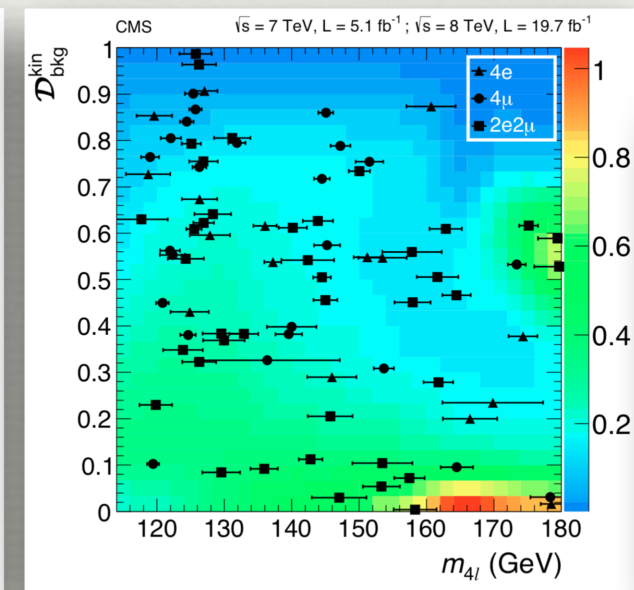
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

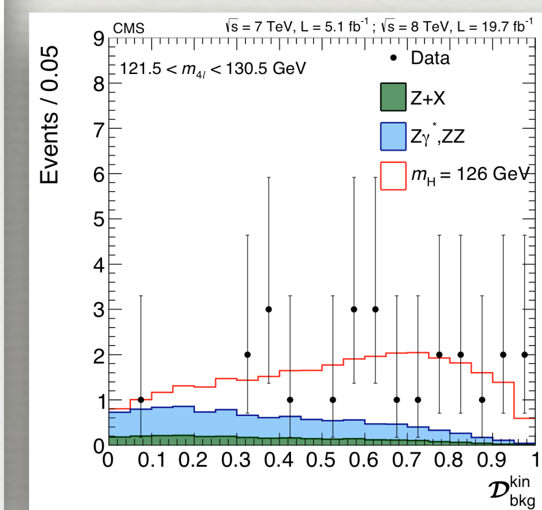


Signal + Background



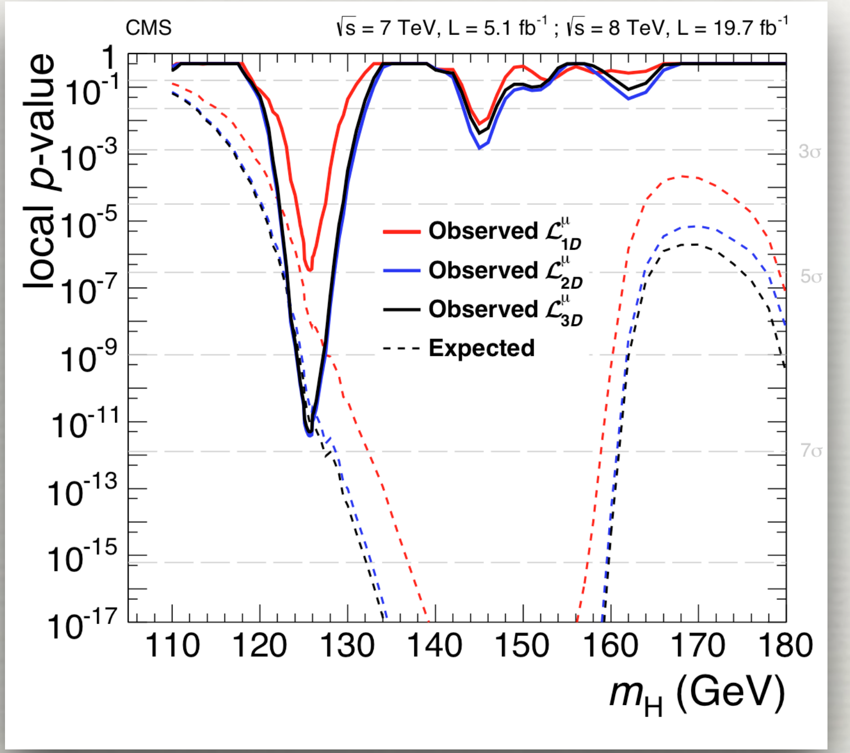
Background only



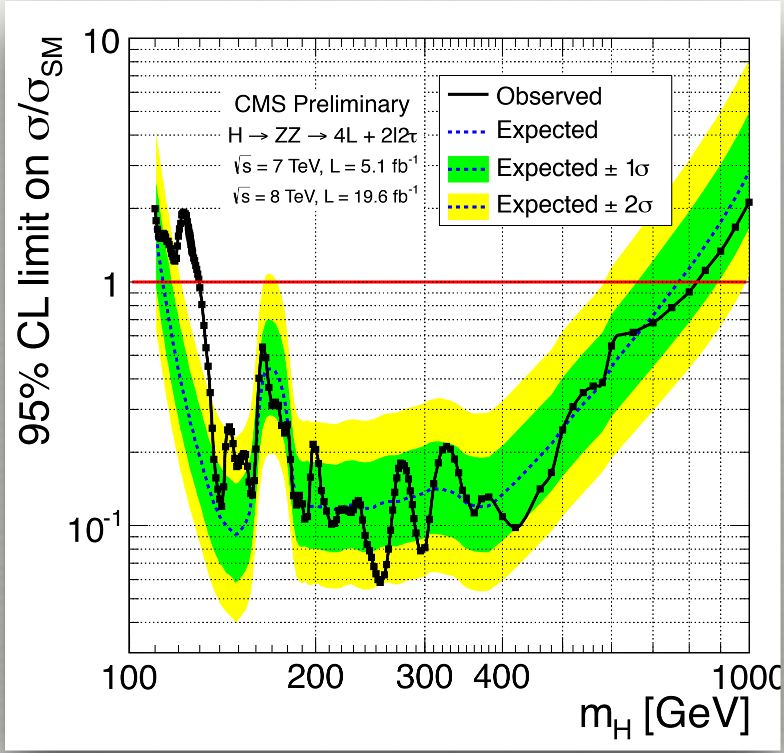


H→ZZ*→4l (CMS)

Low mass region



High mass region



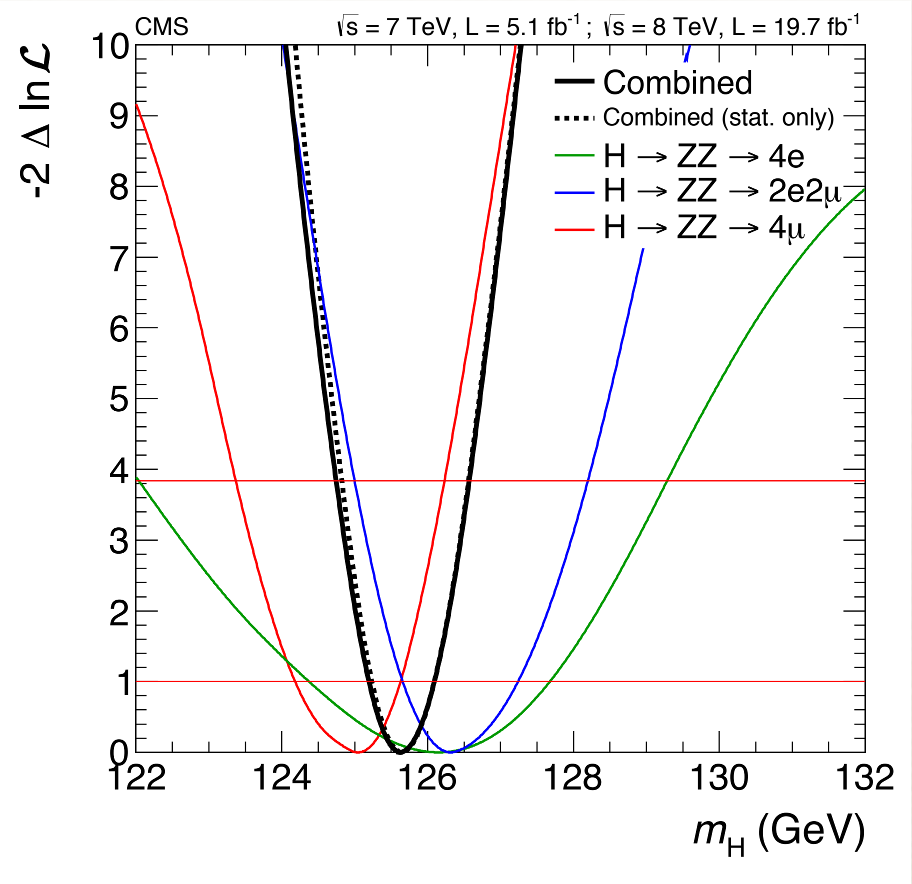
- Largest signal observed @ 125 GeV
- Local significance 6.8 σ
- Expected significance 6.7 σ
- Fitted μ = σ/σ$_{SM}$ @ 125 GeV

SM Higgs excluded @95%CL:[130,827]GeV

Phys.Rev. D89 (2014) 092007

$H \to ZZ^* \to 4l$ (CMS)

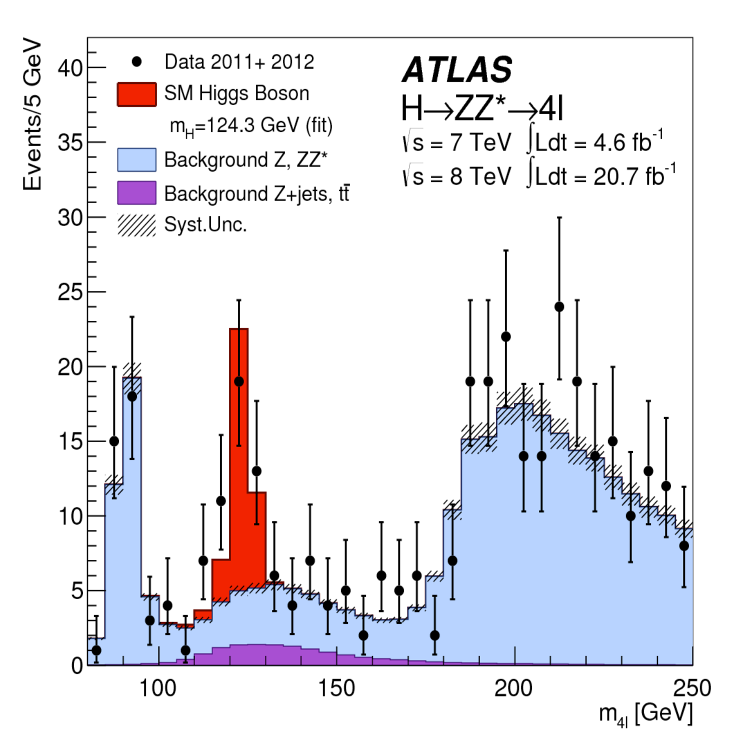
- Simultaneous fit across three final state categories
- Dominant systematic uncertainty due to lepton momentum scale (~1-3% on mass peak).
- Systematics include acceptance and efficiency uncertainties for electrons and muons

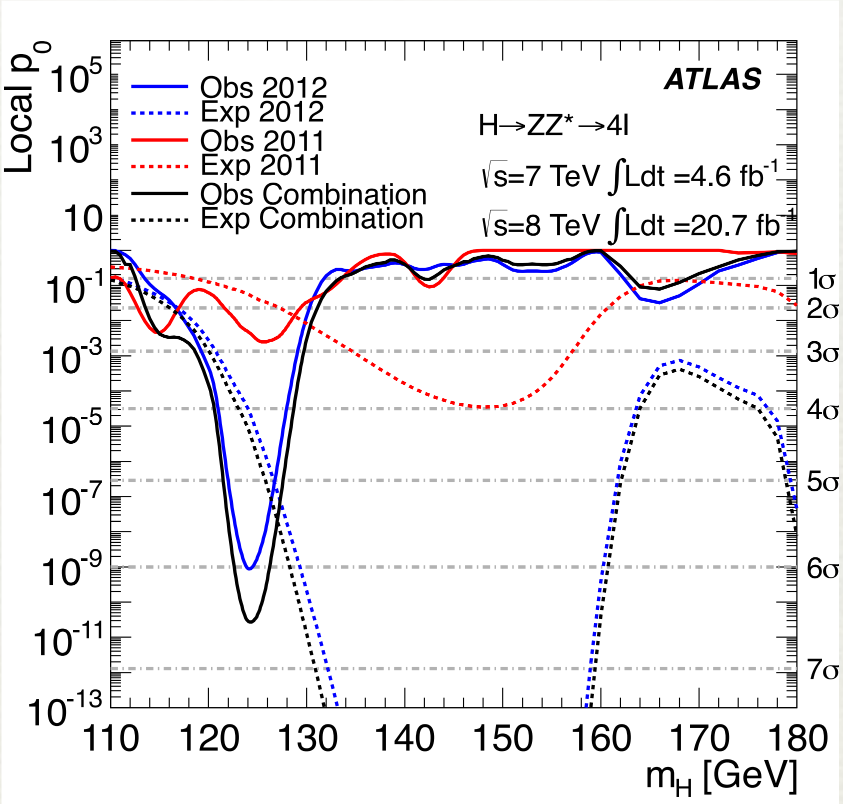


$$\mathbf{m_H = 125.59^{+0.43}_{-0.41}\ (stat)^{+0.16}_{-0.18}\ (syst)\ GeV}$$

H→ZZ*→4l (ATLAS)

- Simultaneous fit across three final state categories ggH , qqH and VH
- Significance of the observed peak is 6.6σ for the combined 7 TeV and 8 TeV data, to be compared with 4.4σ expected from SM Higgs boson production at this mass





H→γγ

Signatures:

- two photons isolated from hadronic activity
- additional two tag jets in case of VBF production

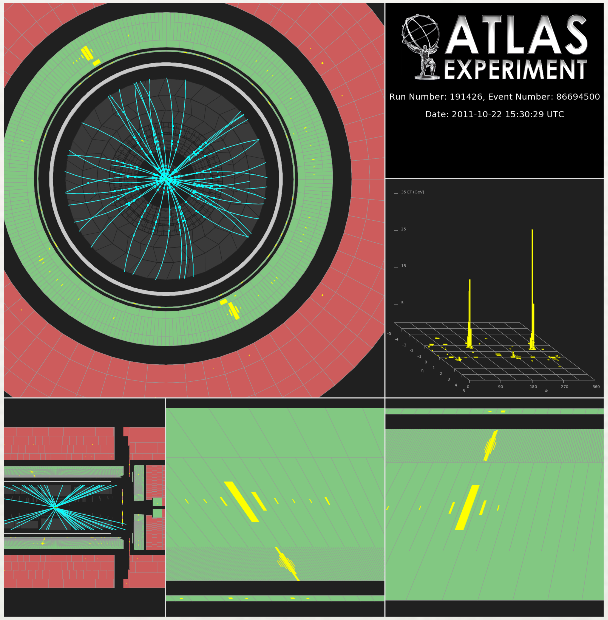
Challenges:

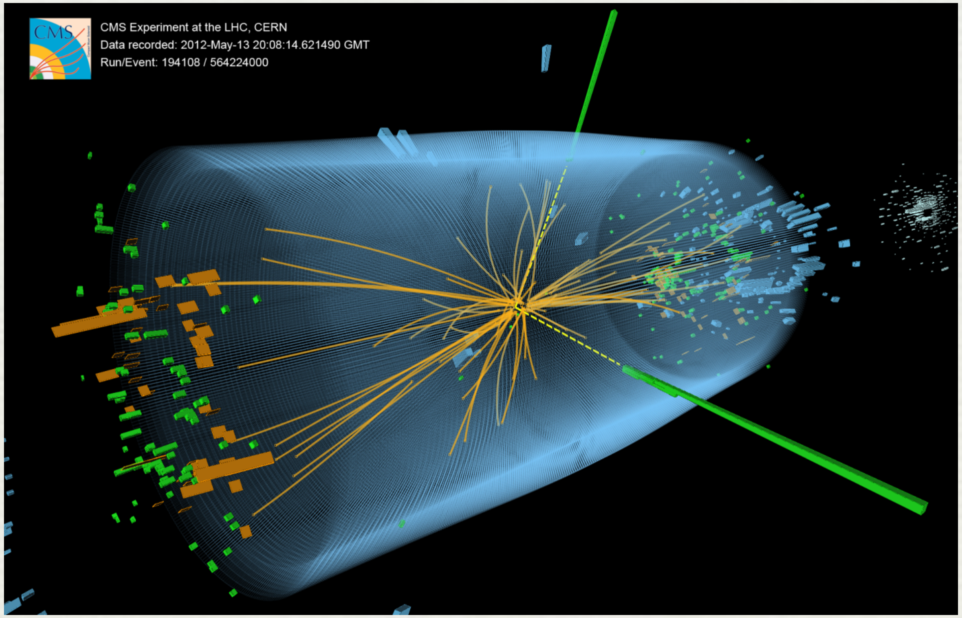
- small peaking signal on a large falling background (BR~0.2%)
- discrimination from large jet related backgrounds
- photon energy resolution
- $\gamma \rightarrow e^+e^-$ conversions in the detector

Method:

- Categorize events with two high P_T photons based on the properties of the di-photon pair

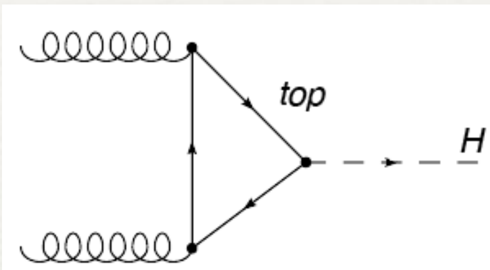
$$\mathbf{m}_{\gamma\gamma} = \sqrt{\mathbf{2E^1_\gamma E^2_\gamma(1 - \cos\theta)}}$$

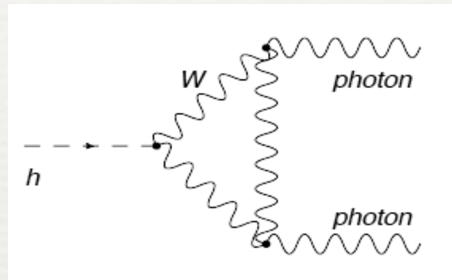


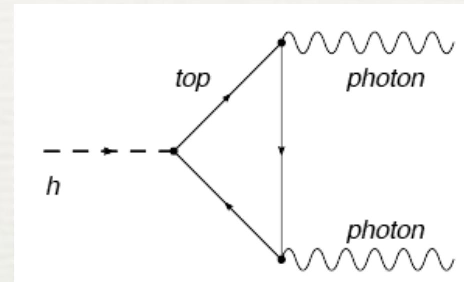


H→γγ

Signal H → γγ



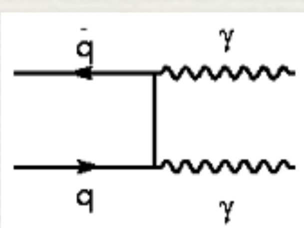


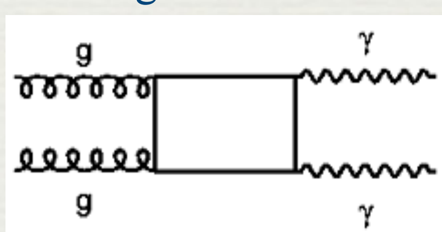


Background composition:

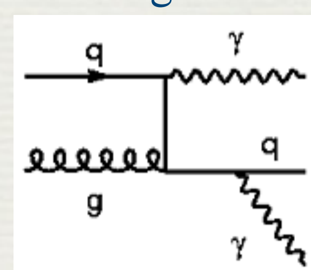
- prompt-prompt (irreducible) : pp->γγ (~70%)
- prompt-fake (reducible) : pp->γ+jet (~30%)
- fake-fake (reducible) : pp->jet+jet (<1%)

Irreducible QCD background

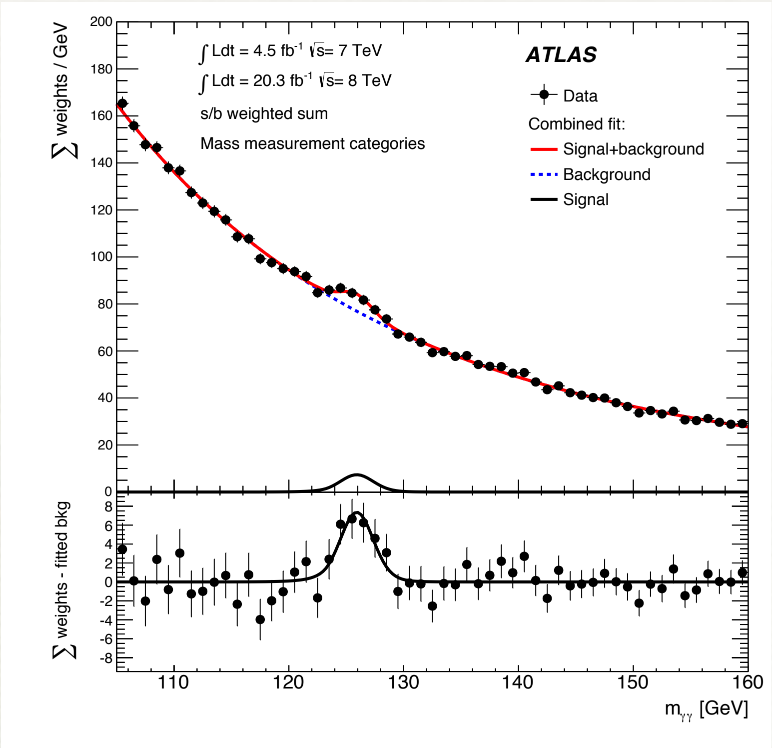




Reducible background (Compton)

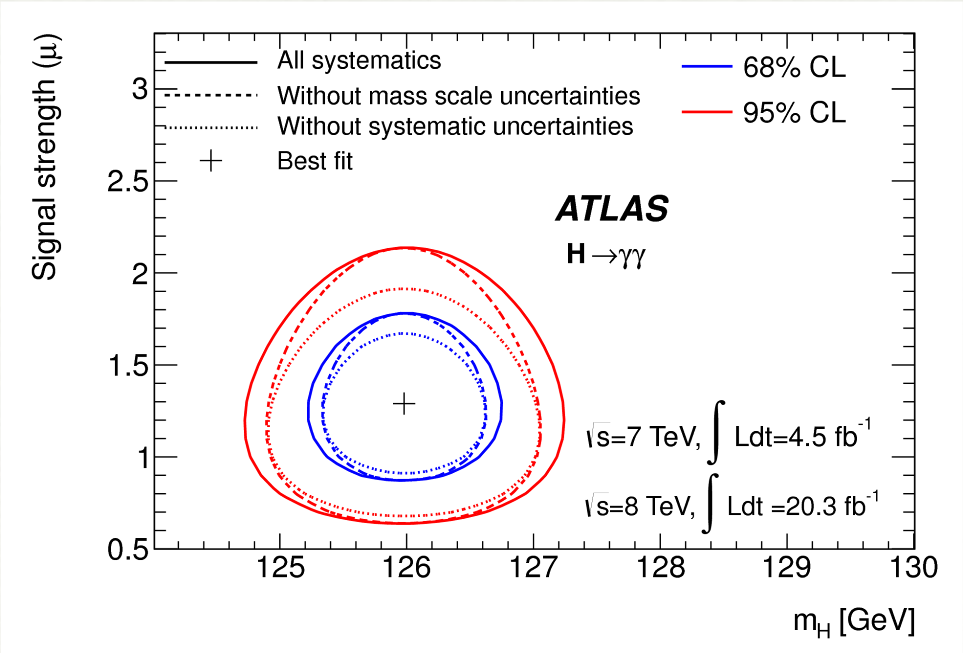


H→γγ (ATLAS)



PRD 90, 052004 (2014)

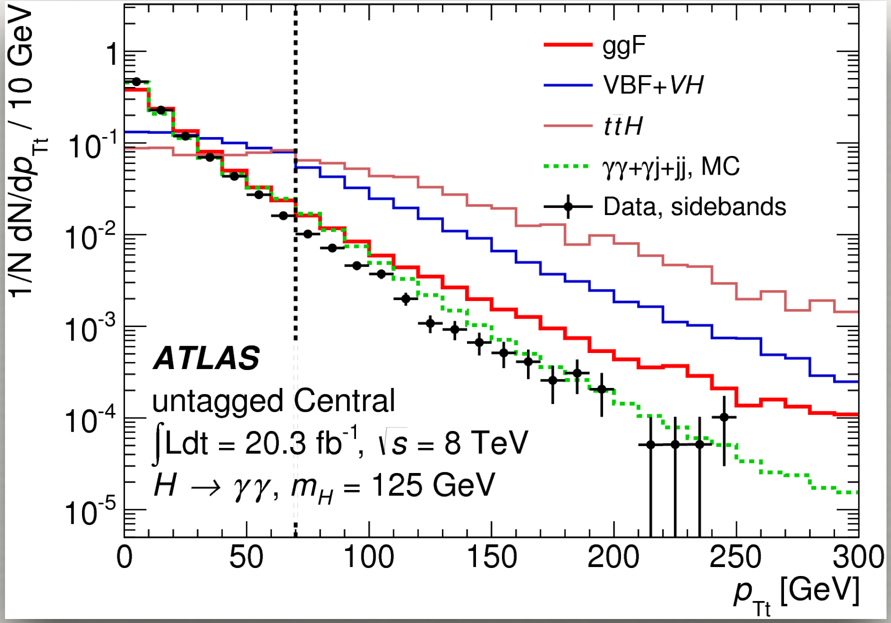
- Signal (fit to MC)- sum of Gaussians or CB function
- background (data-driven) – "discrete profiling" or bias study methods

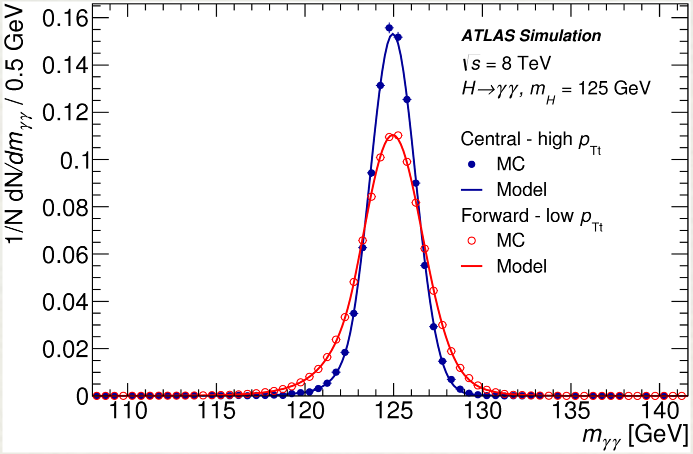


H→γγ (ATLAS)

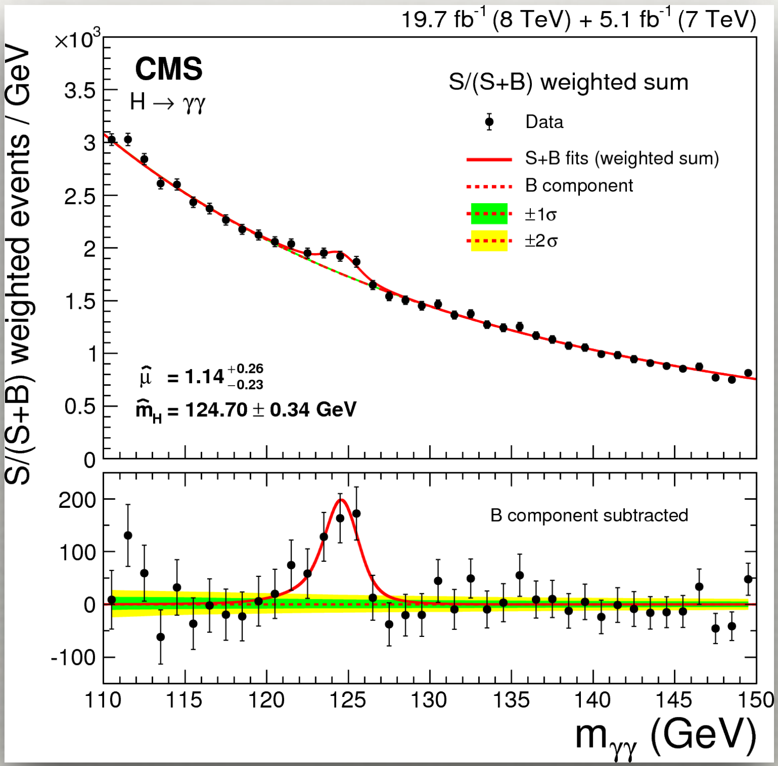
Dedicated analysis for mass measurement with events are split into 10 event categories:

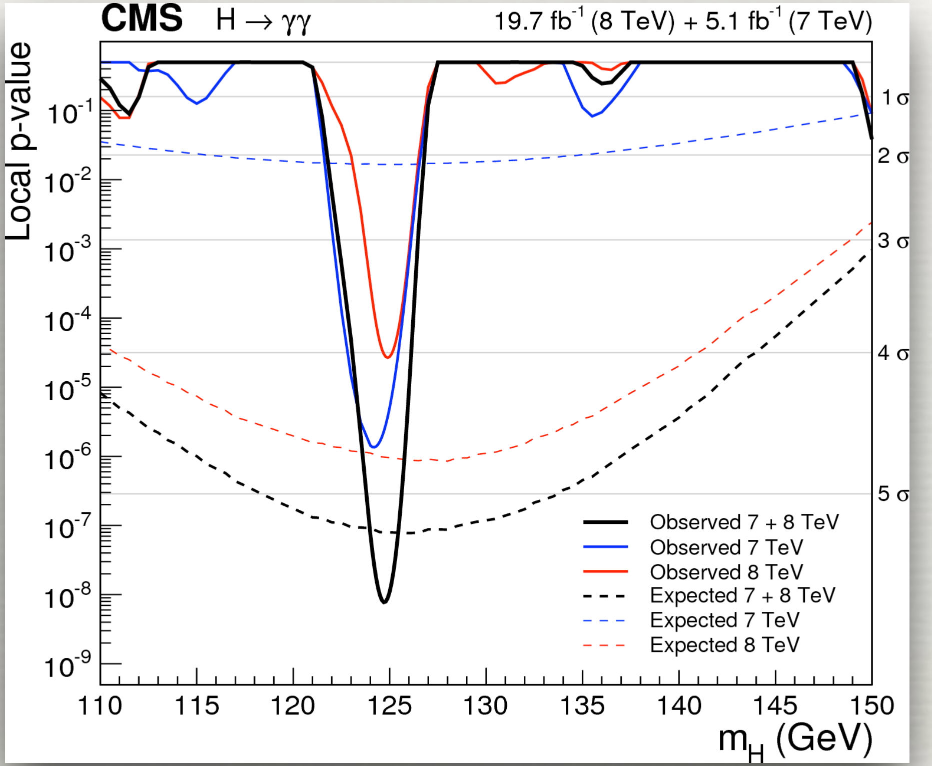
- converted/unconverted photons
- photon η
- diphoton P_T transverse to thrust
- different S/B, resolution between the categories
- smallest energy scale systematics in highest resolution (central) categories





H→γγ (CMS)

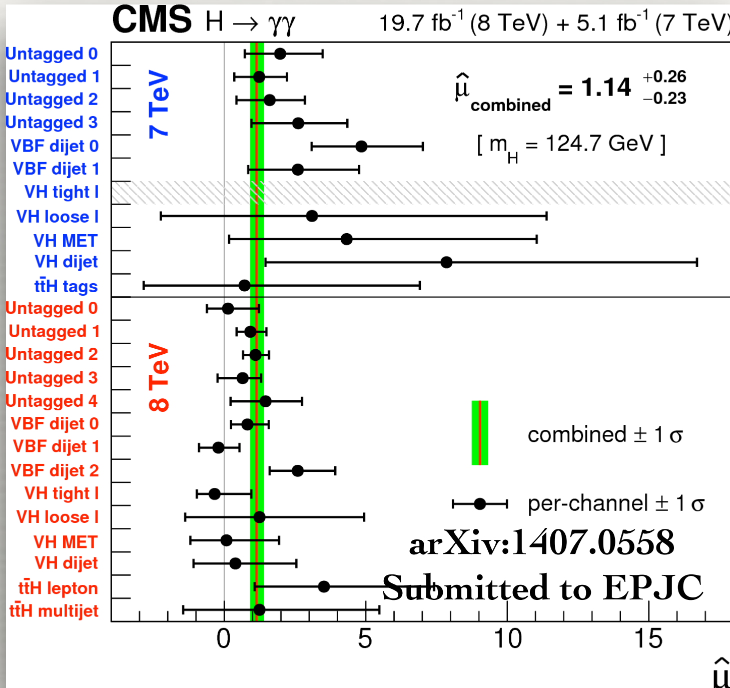




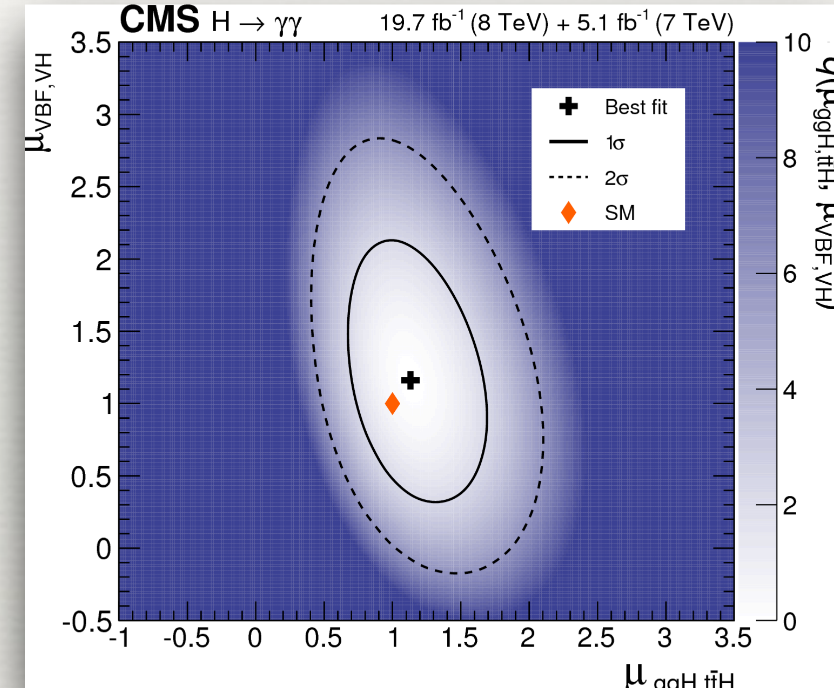
- Largest signal observed around 125 GeV (standalone discovery)
- Local significance 5.7 σ
- Expected significance 5.2 σ
- Fitted $\mu = \sigma/\sigma_{SM}$ at 125 GeV +-1.14 +0.26 -0.23

H→γγ (CMS)

Many exclusive channels addressing all production modes
Untagged mode split into categories with decreasing s/b with MVA



arXiv:1407.0558
Submitted to EPJC

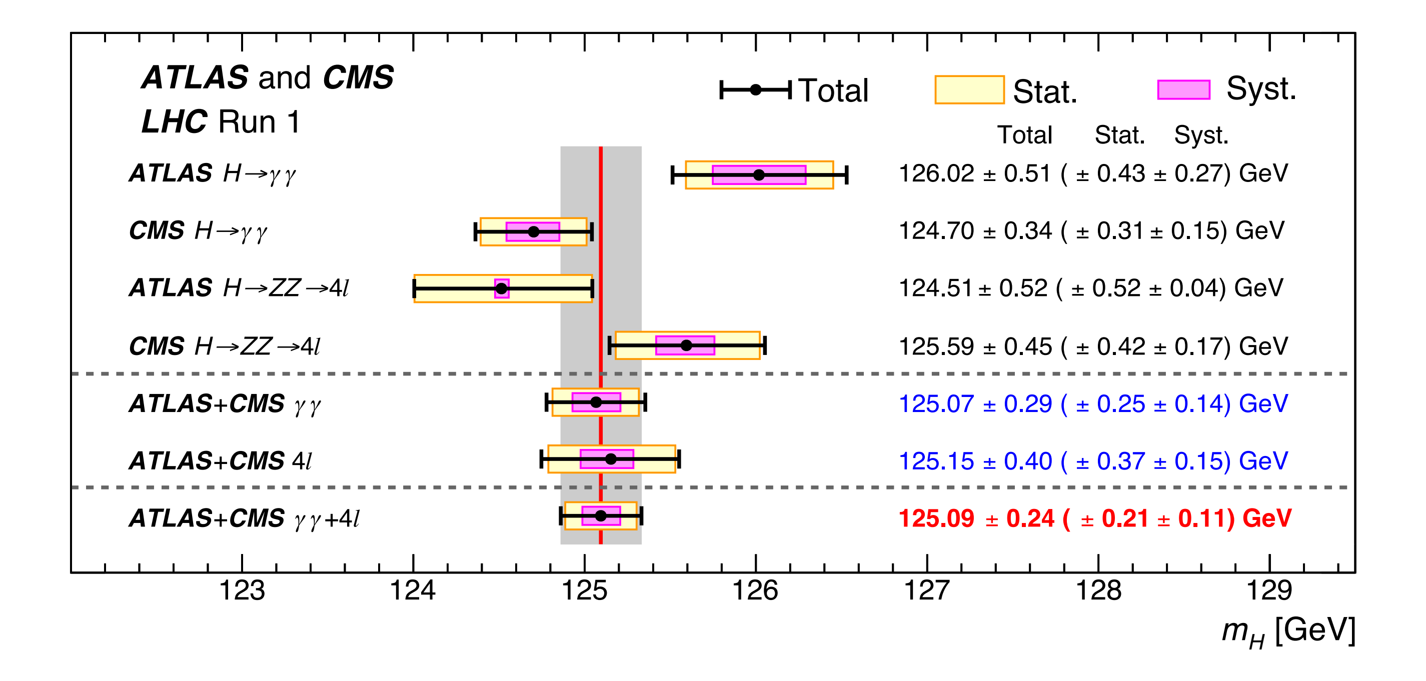


Results of the fit for individual production modes:

Process	$\hat{\mu}$	Uncertainty total	stat	systematic theo	systematic exp
ggH	$1.12^{+0.37}_{-0.32}$	0.34	0.30	0.13	0.09
VBF	$1.58^{+0.77}_{-0.68}$	0.73	0.69	0.20	0.15
VH	$-0.16^{+1.16}_{-0.79}$	0.97	0.97	0.08	
tt̄H	$2.69^{+2.51}_{-1.81}$	2.2	2.1	0.4	

Higgs Mass Combination

ATLAS and CMS combined measurement of the Higgs boson mass paper published in Phys. Rev. Lett. 114, 191803 (2015)



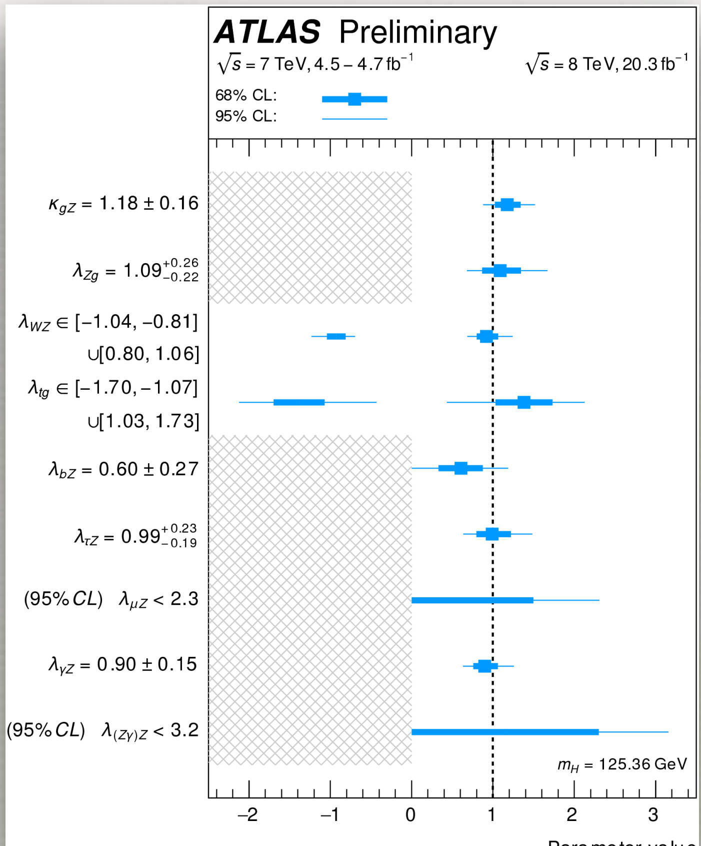
$$\mathbf{m_H = 125.09 \pm 0.21\ (stat)}$$
$$\mathbf{\pm 0.11\ (scale)}$$
$$\mathbf{\pm 0.02\ (other)}$$
$$\mathbf{\pm 0.01\ (theory)}$$
$$\mathbf{GeV}$$

- Statistical uncertainty dominates
- Scale uncertainties larger than systematic
- Expect improvements with more data !
- Interference not included in theory uncertainty

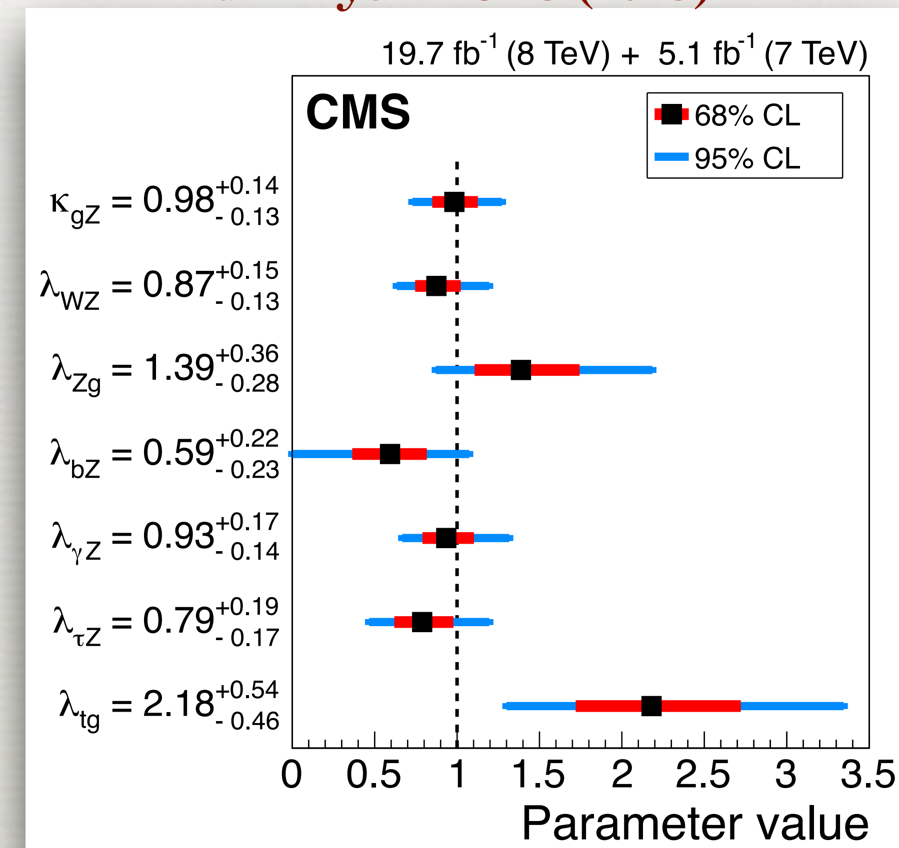
Higgs Couplings

Higgs mass determines all its couplings under SM ⇒ test for deviations

ATLAS-CONF-2015-007



Eur. Phys. J. C 75 (2015) 212



Reading List

- "Combined measurement of the Higgs Boson Mass in pp collisions at sqrt(s)=7 and 8 TeV with the ATLAS and CMS Experiments" - Phys. Rev. Lett. 114, 191803 (2015)
- "Measurement of the Higgs boson mass from the H$\gamma\gamma$ and H->ZZ*->4l channels in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector" - PRD 90, 052004 (2014)
- "Measurement of the properties of a Higgs boson in the four-lepton final state" - CMS - PRD 89, 092007 (2014)
- "Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV" - CMS - Eur. Phys. J. C 75 (2015) 212
- "Observation of the diphoton decay of the Higgs boson and measurement of its properties" - CMS - EPJC 74 (2014) 3076

Low Resolution Channels

- Involves low resolution physics objects (jets and/or neutrinos)
- Incomplete reconstruction of final state (model dependence)

Channel	BR(mH=125GeV)	Resolution
$H \rightarrow bb$	57.7%	10%
$H \rightarrow \tau\tau$	6.32%	10-20%
$H \rightarrow WW \rightarrow 2l2\nu$	0.756%	20%

$H \to WW \to l\nu l\nu$

The most sensitive channel around $2xM_w$

Signature:

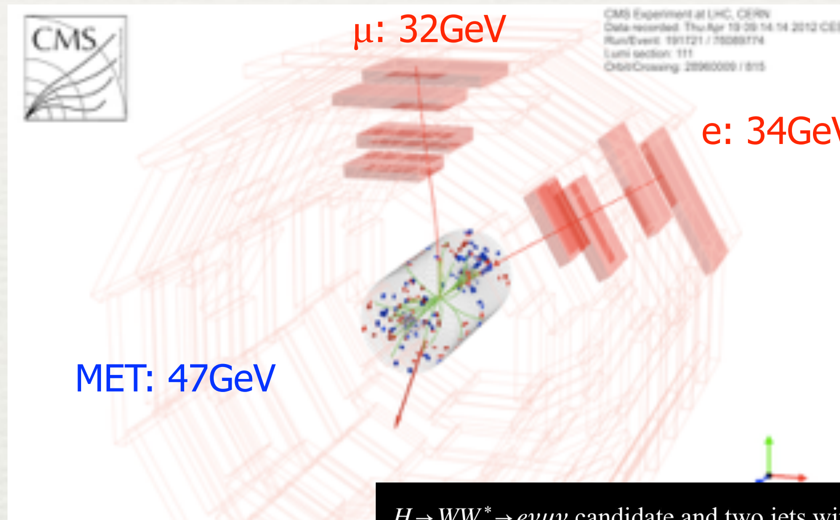
- 2 high p_T isolated leptons
- large missing transverse energy due to neutrinos

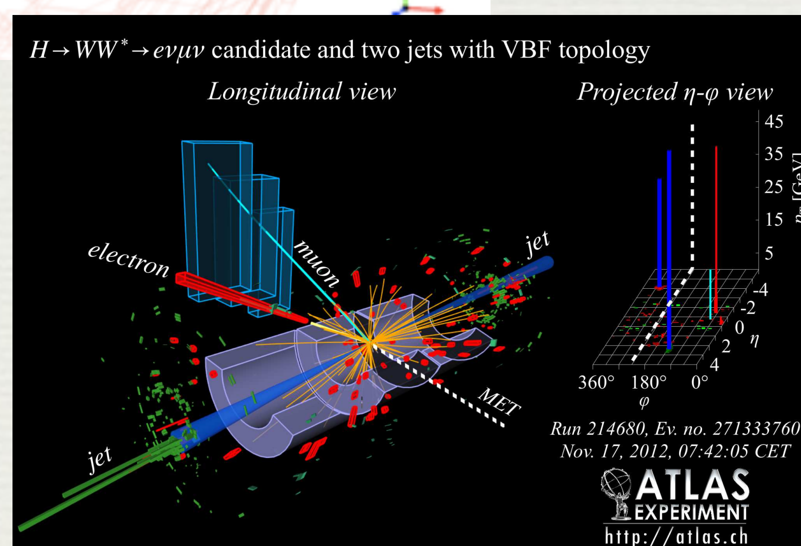
Challenges:

- no mass peak !
- very good understanding of backgrounds: WW, W/Z +jets, top and Drell-Yan

Methods:

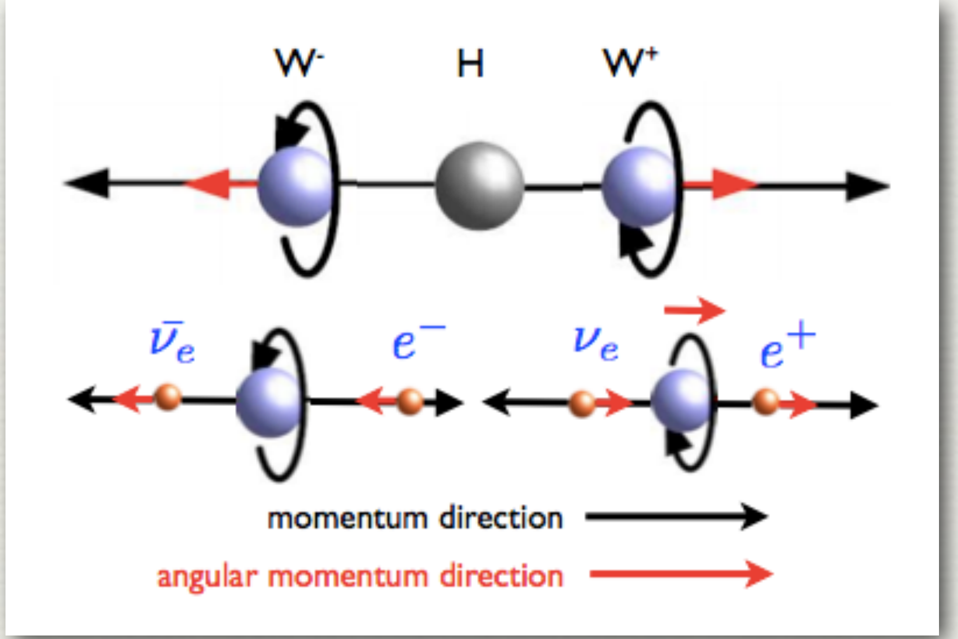
- Scalar Higgs + (V-A) favors small opening angles between leptons
- enhance sensitivity by subdividing into 0,1,2 jets categories

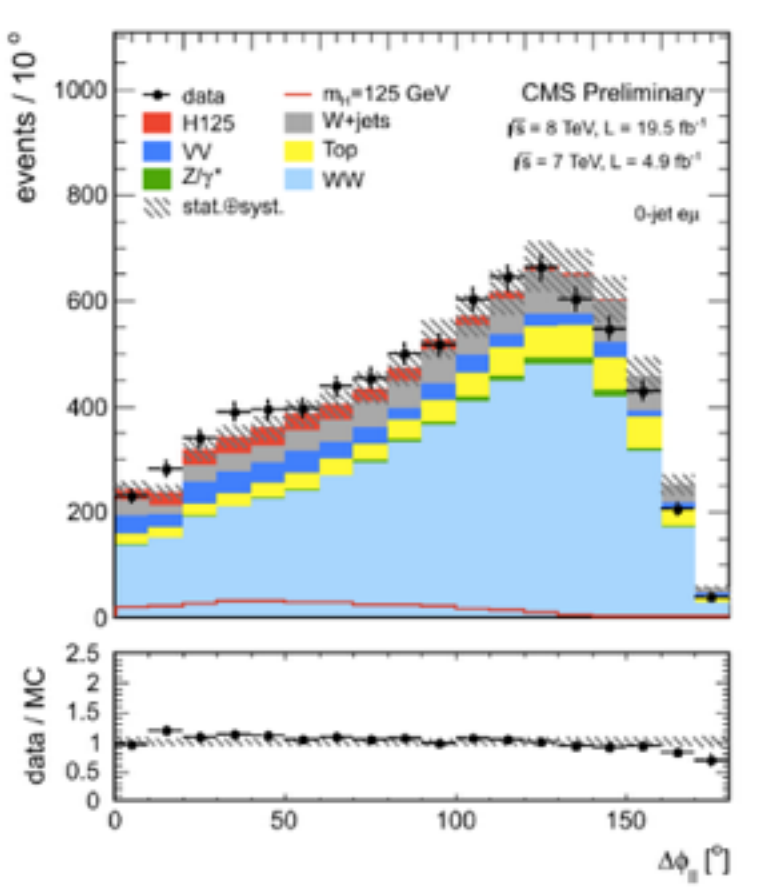




H→WW→lνlν

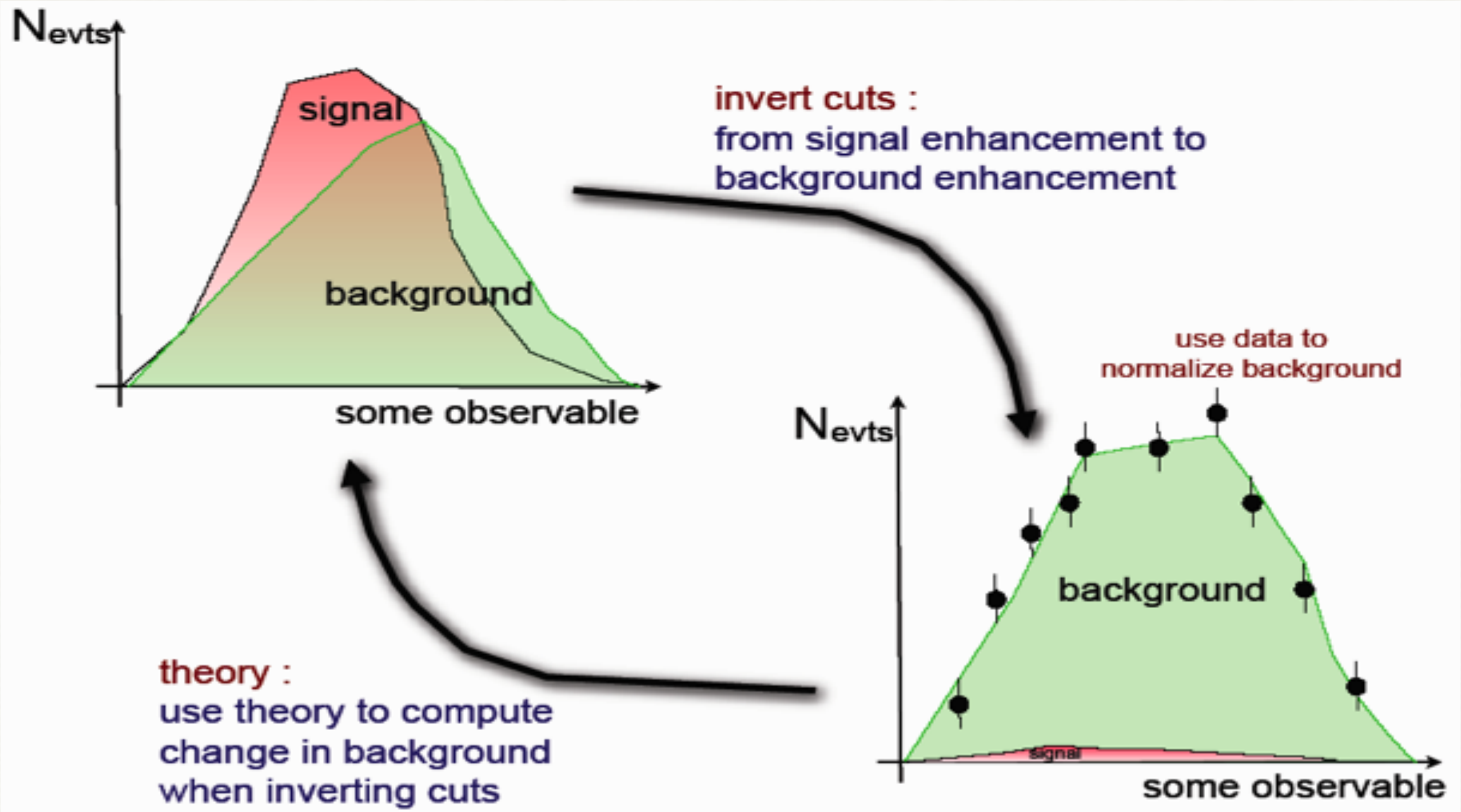
Higgs decay kinematics => scalar decay and V-A structure of W decay lead to a small opening angle between leptons





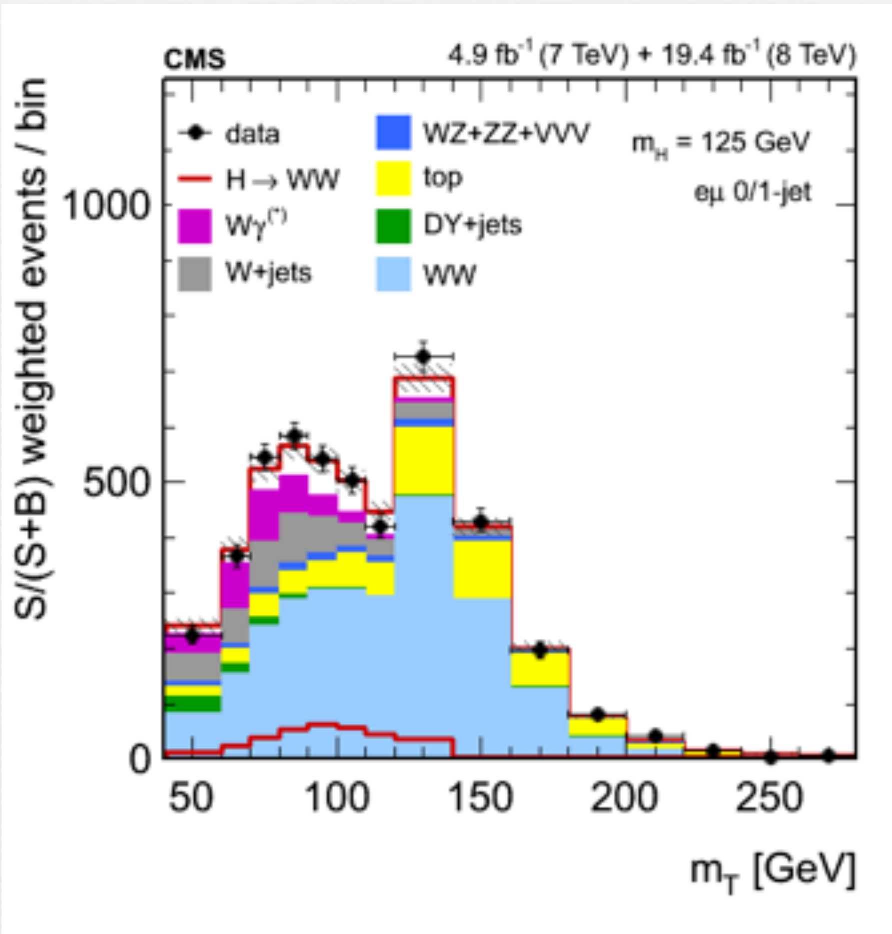
H→WW→lνlν

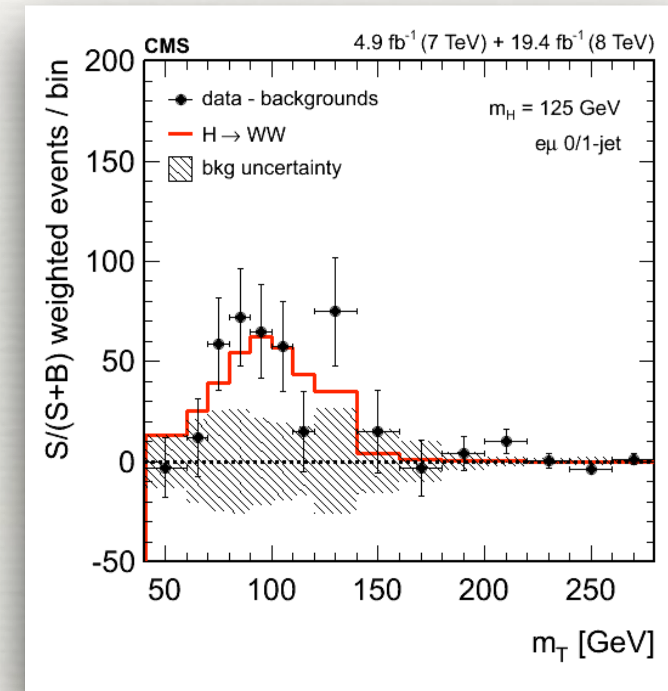
Data driven background estimation



H→WW→lνlν (CMS)

- Events with 0- and 1-jet and different flavour leptons (7+8 TeV Data)
- A significant excess observed …

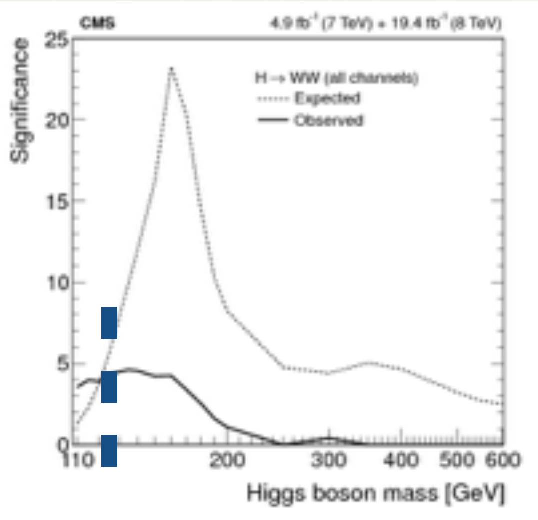


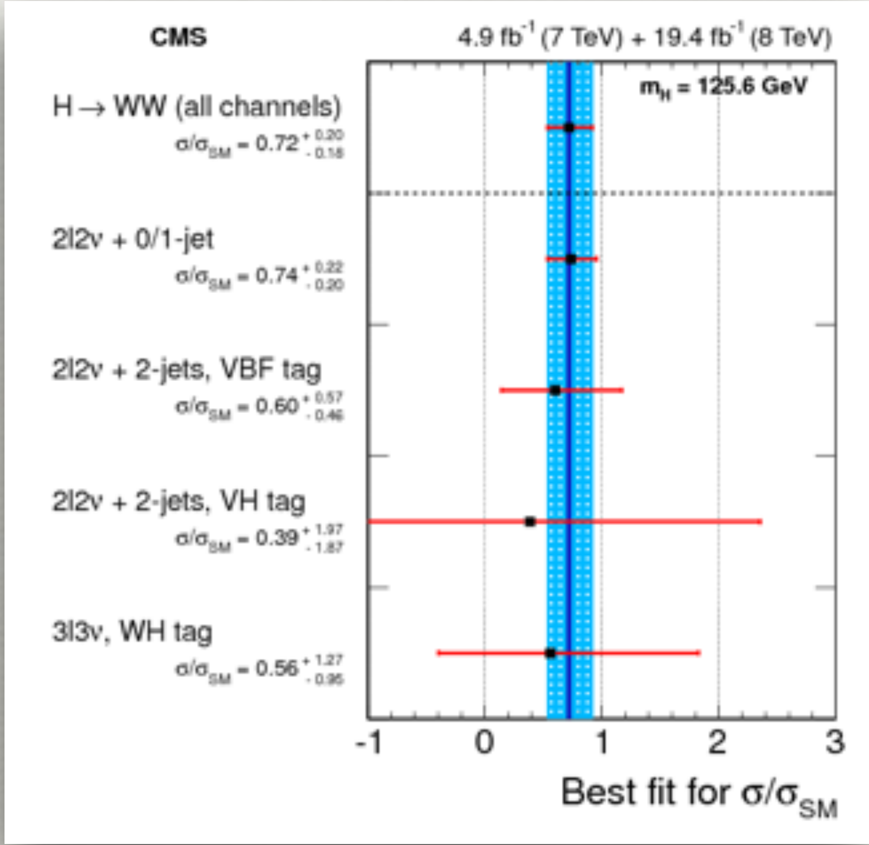


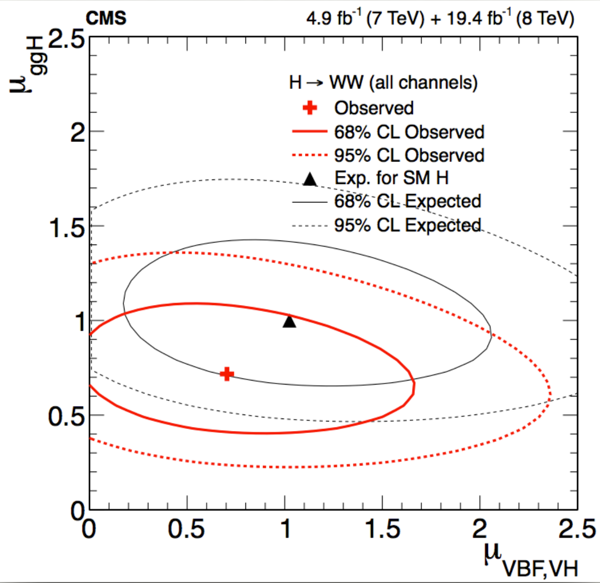
$$M_T = \sqrt{2p_T^{\ell\ell} E_T^{miss} \cos(\Delta\phi_{\ell\ell} - E_T^{miss})}$$

H→WW→lνlν (CMS)

- Several categories combined: 0jet, 1 jet, VBF, VH
- Broad evidence of signal around 125 GeV
- Expected(observed) significance: 5.8σ(4.3 σ)
- Fitted σ/σ_{SM} = 0.72



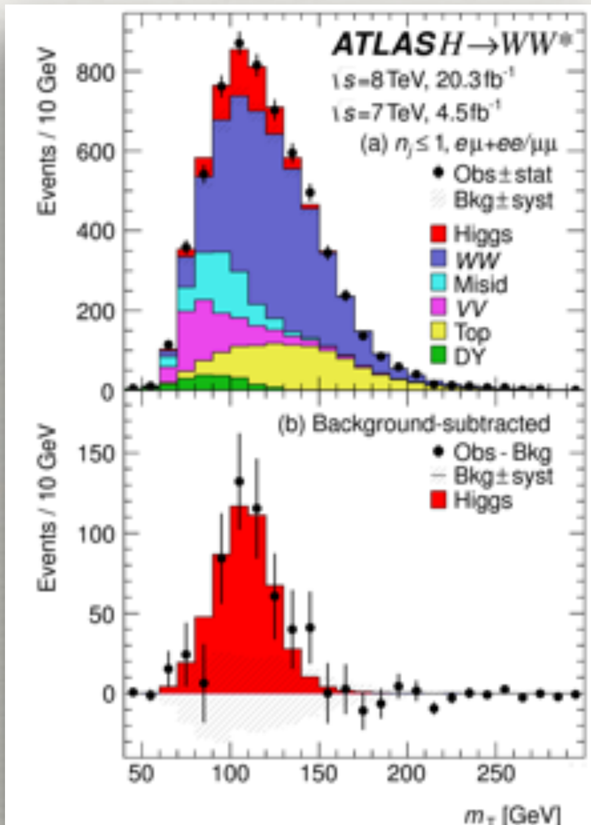


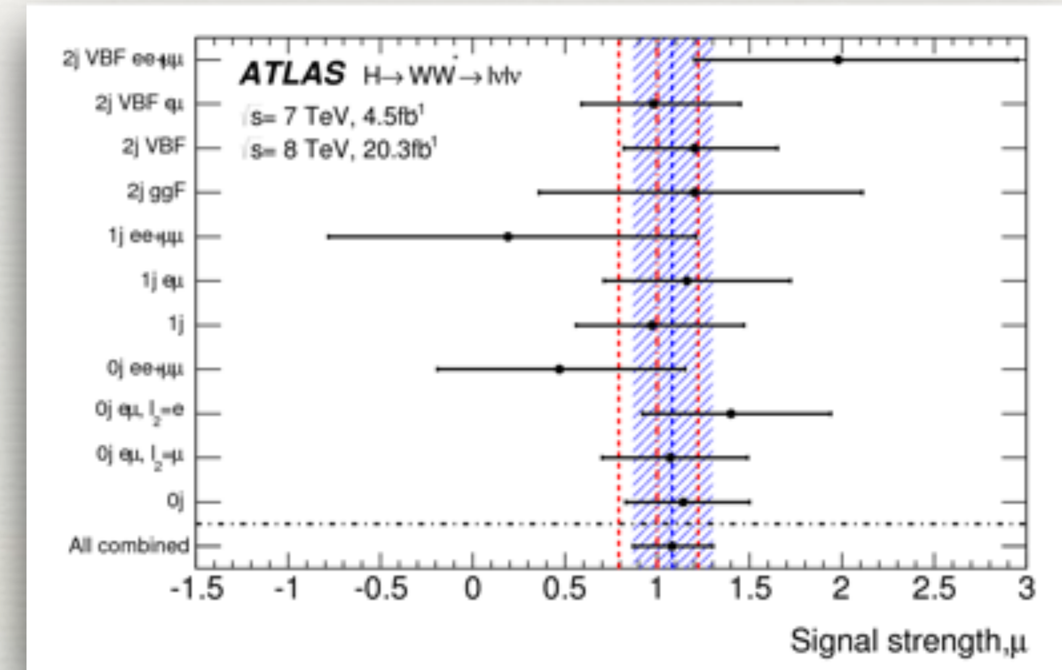


JHEP 01 (2014) 096

H→WW→lνlν (ATLAS)

ATLAS results are very similar …





$$\sigma/\sigma_{SM} = 1.09^{+0.16}_{-0.15}\,(\text{stat.})^{+0.17}_{-0.14}\,(\text{syst.})$$

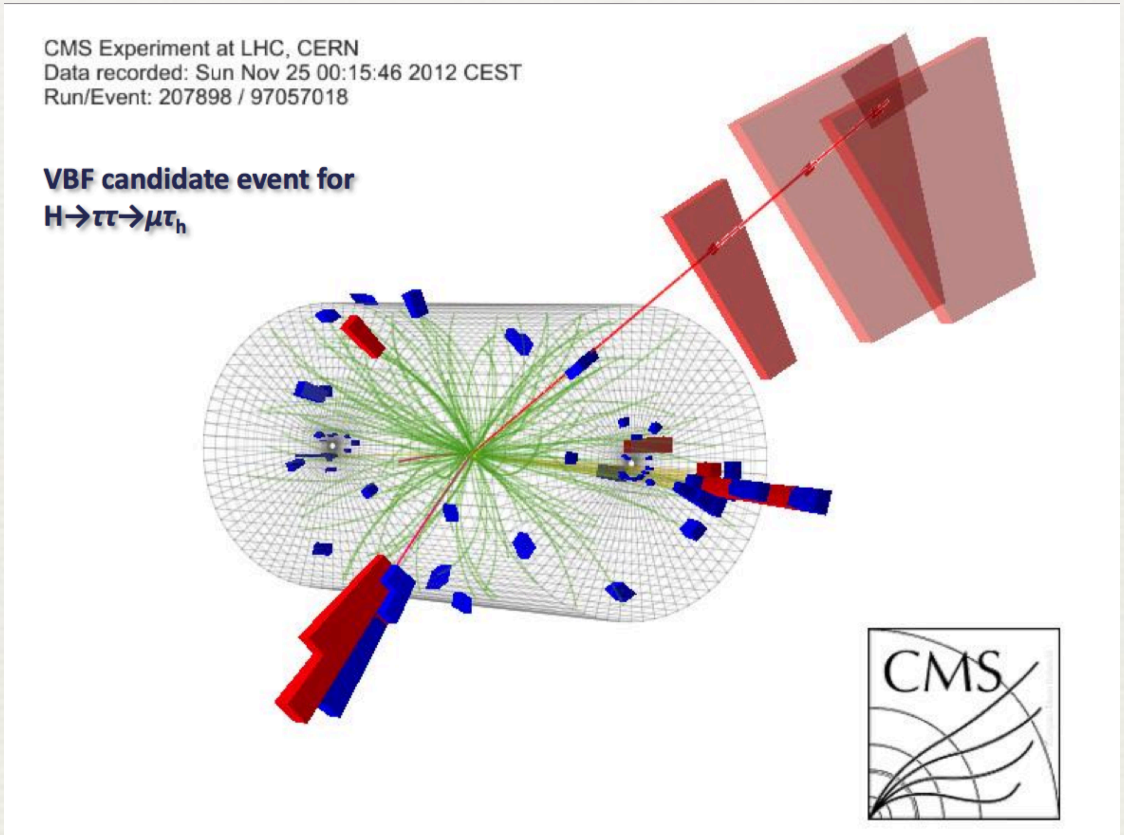
H →ττ

Large rates with medium mass resolution

Signature:
- e, μ, τ_H from tau decay
- MET from tau neutrinos

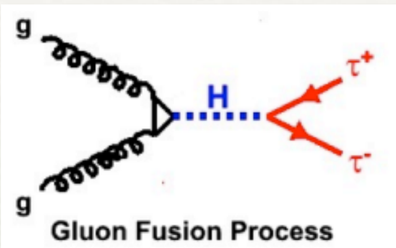
Challenges:
- Reconstruct corrected ττ invariant mass
- Separate the Higgs peak from the DY decay

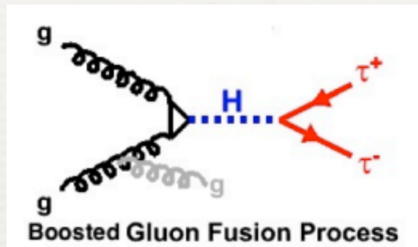
Methods:
- Use many categories to increase the sensitivity
- Template fit of $m_{\tau\tau}$ shape

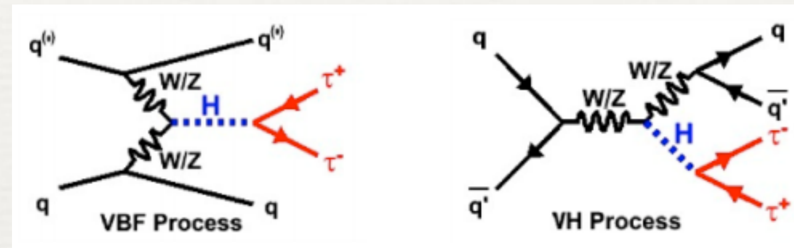


$H \to \tau\tau$ (CMS)

Complicated analysis, many different sub-channels







- 0-jet
- 1-jet boosted
- 2-jet VBF
- VH (use leptonic decays of V)

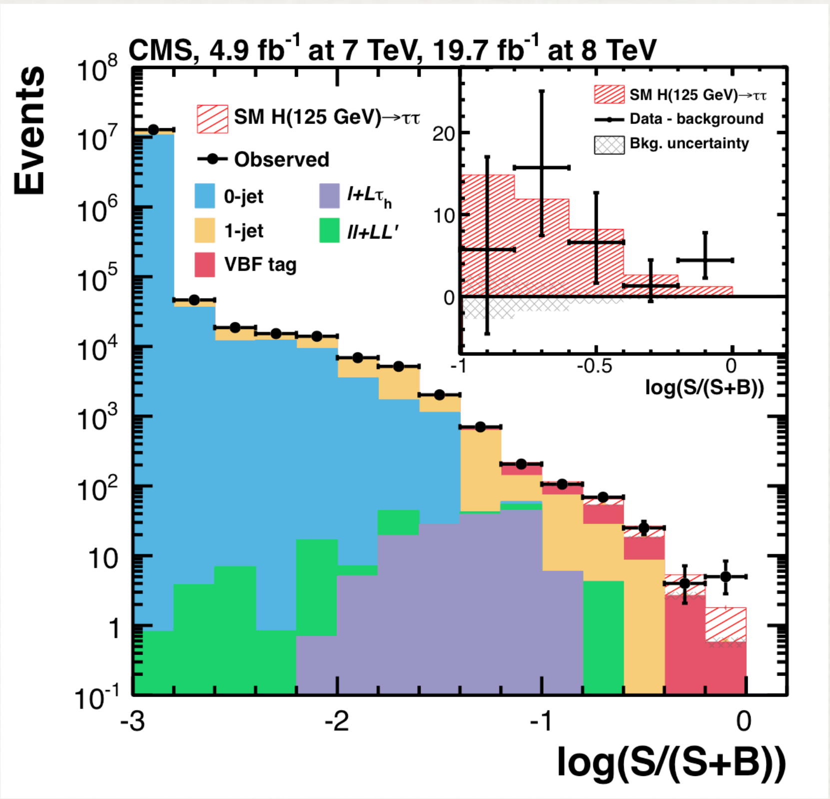
$\otimes$

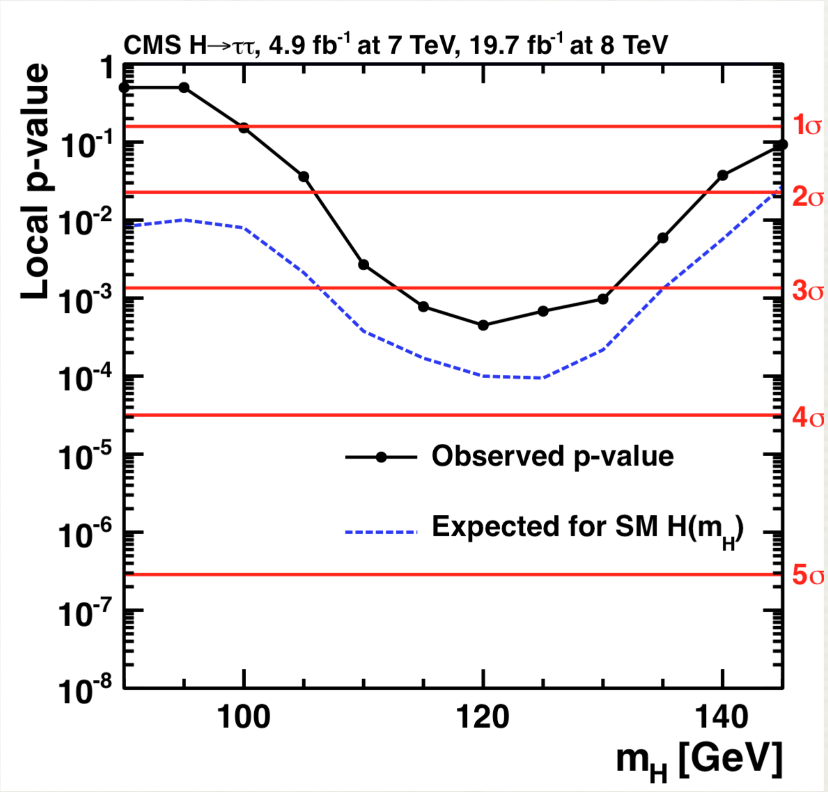
$$H \to \tau\tau \to \ell\ell + 4\nu \ (12\%)$$
$$H \to \tau\tau \to \ell\tau_h + 3\nu \ (46\%)$$
$$H \to \tau\tau \to \tau_h\tau_h + 2\nu \ (42\%)$$

H →ττ (CMS)

- Broad evidence of signal near 125GeV with expected(observed) significance: 3.2σ(3.7σ)
- Fitted signal strength σ/σ_{SM} = 0.78 ± 0.27
- Evidence of Higgs coupling to τ leptons !

JHEP 1405 (2014) 104





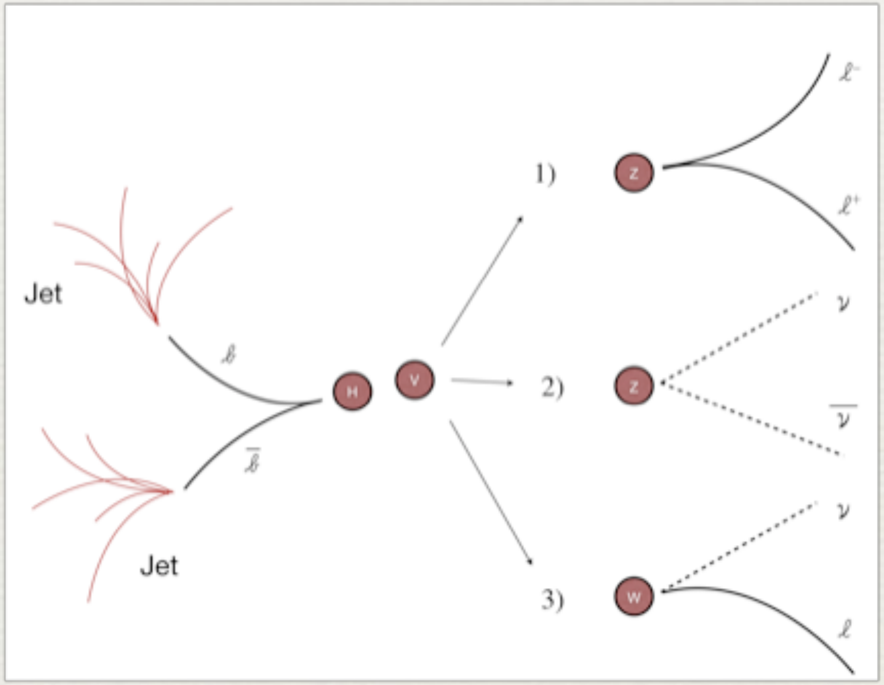
H→bb

QCD background too large so needs additional tag

Signature:
- b-jets identified through displaced tracks
- leptons and MET from b-decay

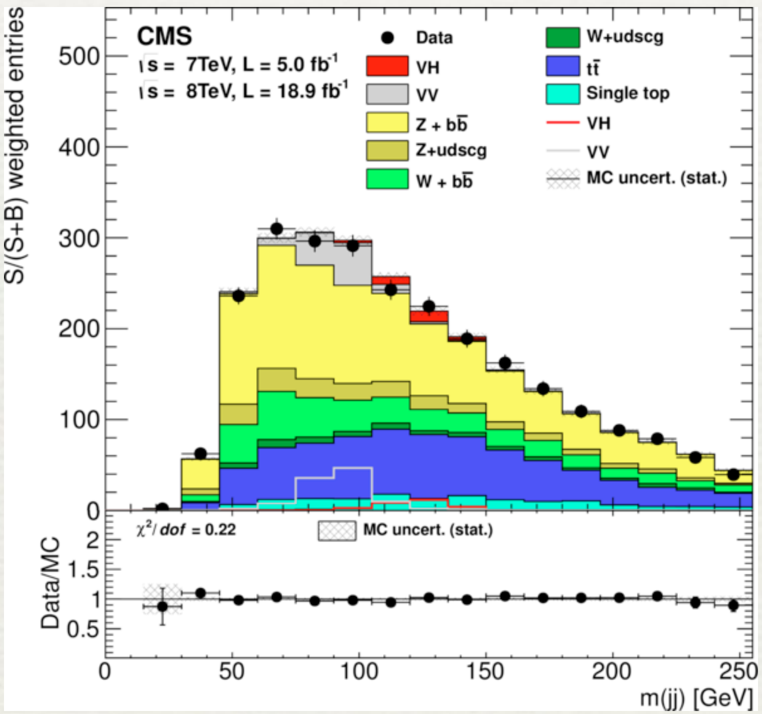
Challenges:
- largest number of Higgs decays but too much QCD background
- main backgrounds are W/Z+jets and top

Methodology:
- categorize in associated prod : VH , ttH
- go to high pT where Higgs is enhanced
- MVA based analyses to enhance sensitivity

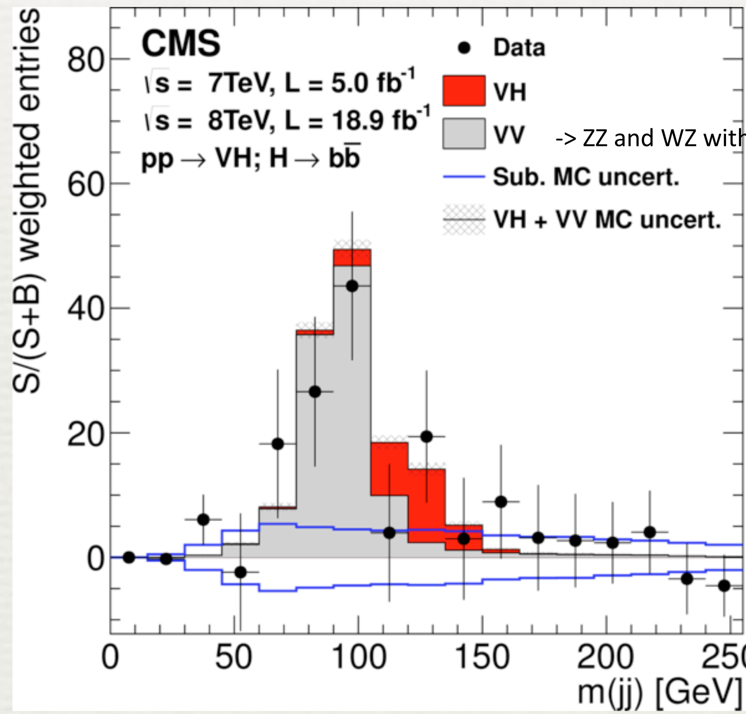


VH , H→bb (CMS)

S/B weighted mass distribution



Background subtracted (except VV)

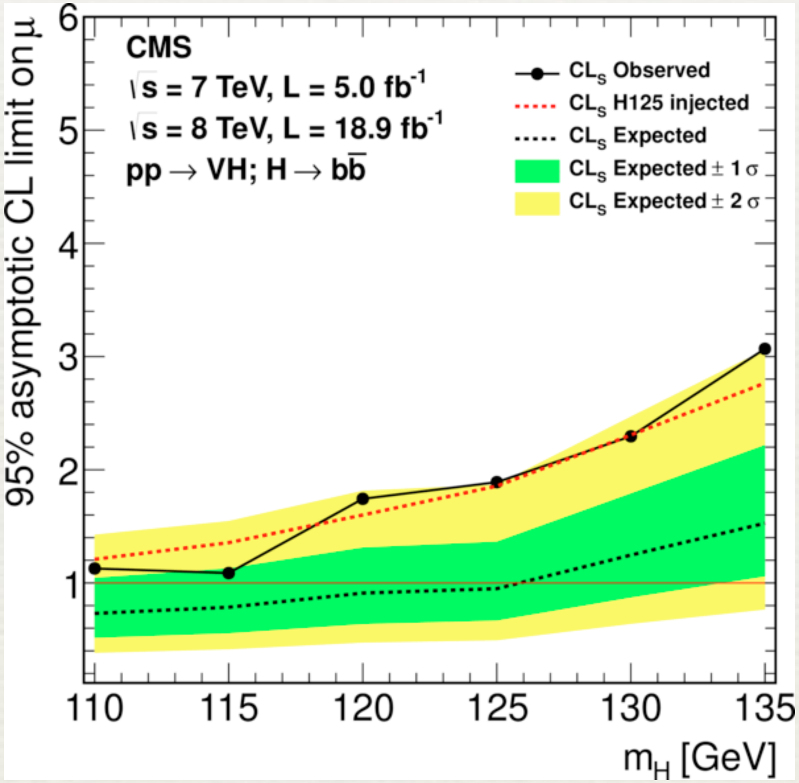


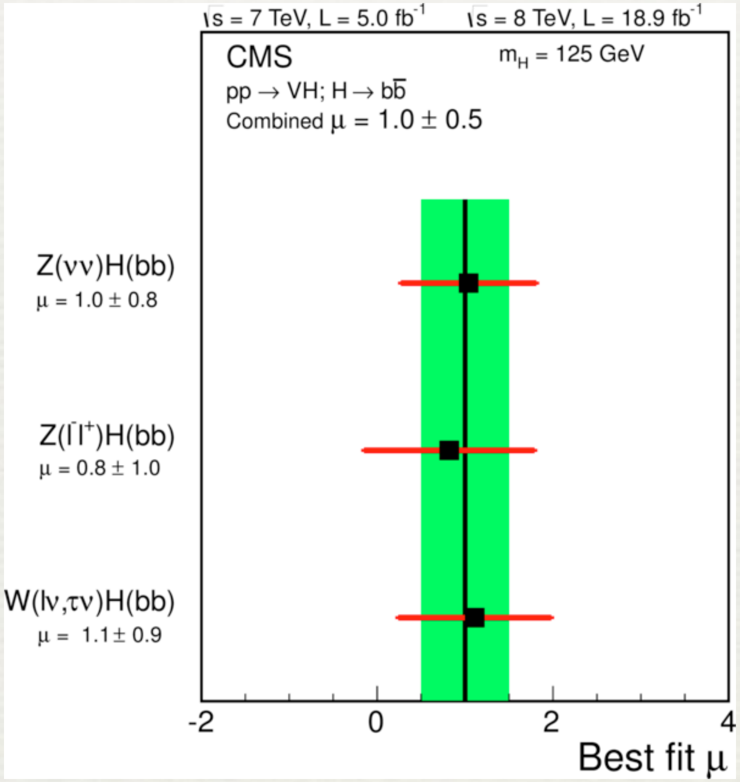
Phys. Rev. D 89, 012003

VH , H→bb (CMS)

- Excess of events near 125 GeV
- expected(observed) significance: 2.1σ(2.1σ)
- Fitted σ/σ_{SM} = 1.0 ± 0.5
- Combined with Hττ gives 3.8σ significance ⇒ evidence of Higgs coupling to down type fermions NATURE PHYS. 10(2014)

Phys. Rev. D 89, 012003

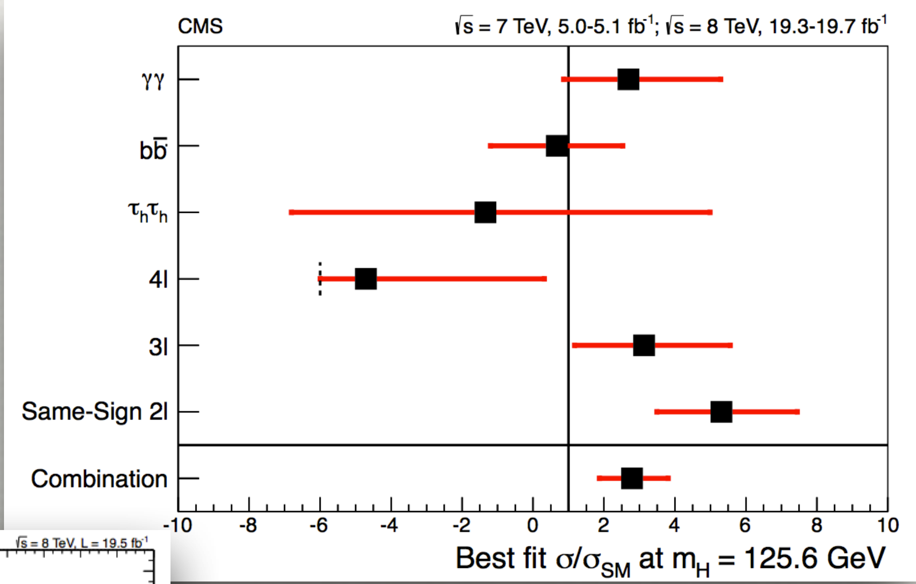




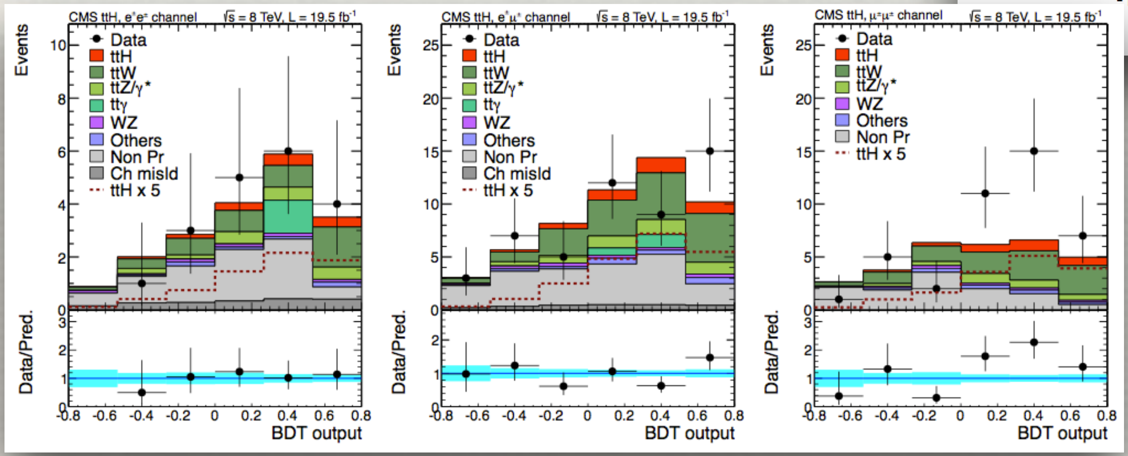
ttH (CMS)

Search for ttH production in Hbb, γγ, multi leptons

- Some excess of events near 125 GeV (~2σ above SM)
- expected(observed) significance: 1.1σ(3.4σ)
- Fitted σ/σ_{SM} = 2.8 ± 1.0
- Excess driven by the same sign di-lepton search

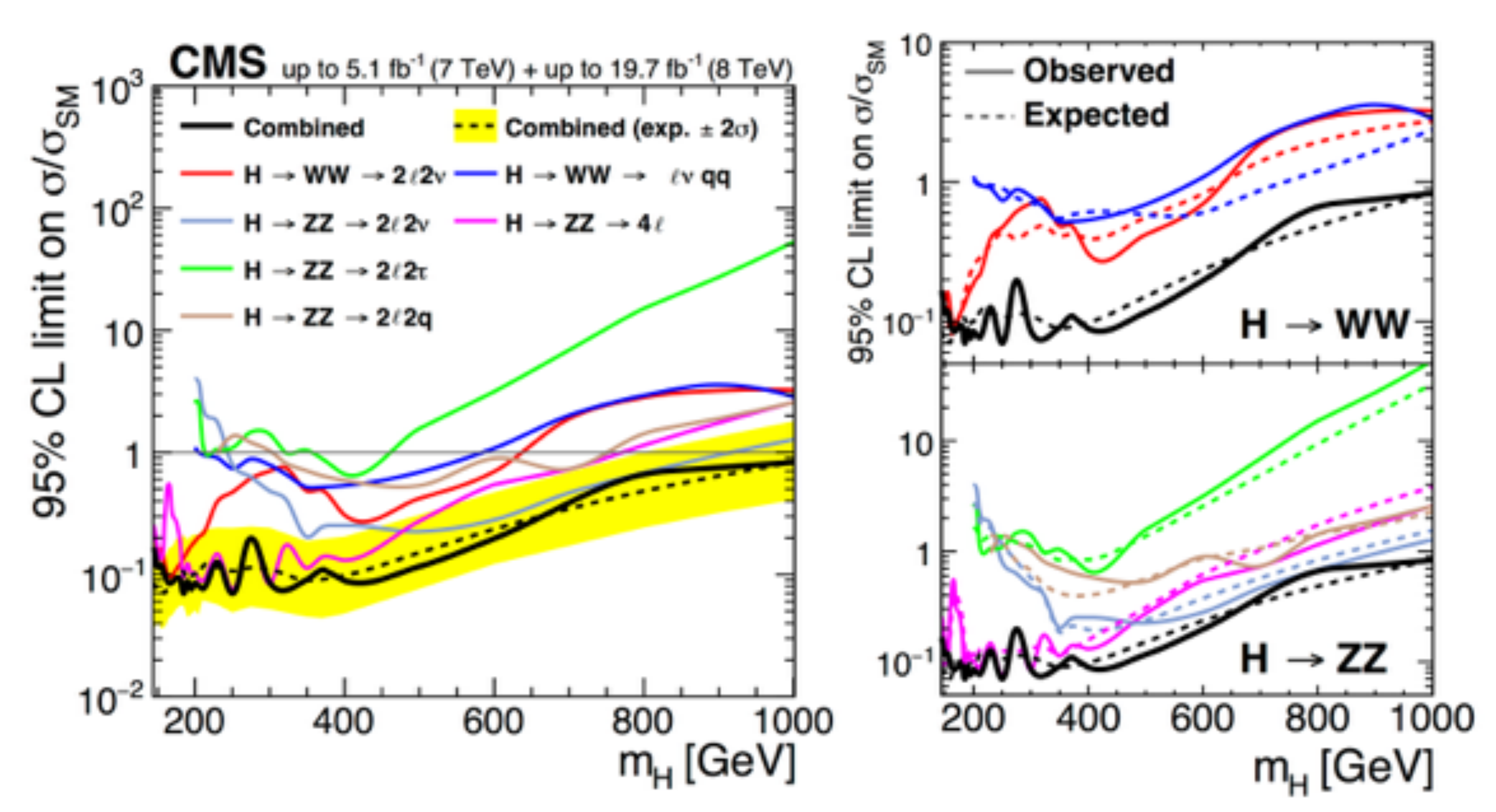


JHEP 09 (2014) 087



High Mass SM Higgs Search

High mass search with channels WW & ZZ exclude a SM-like Higgs boson in the range 145 $< m_H <$ 1000 GeV



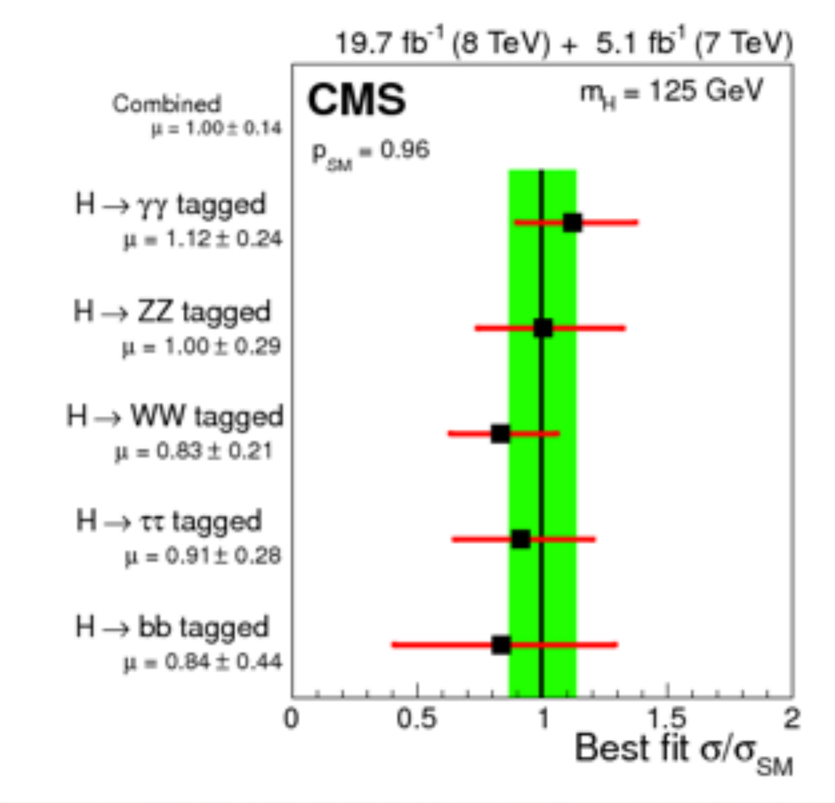
SM Higgs Properties

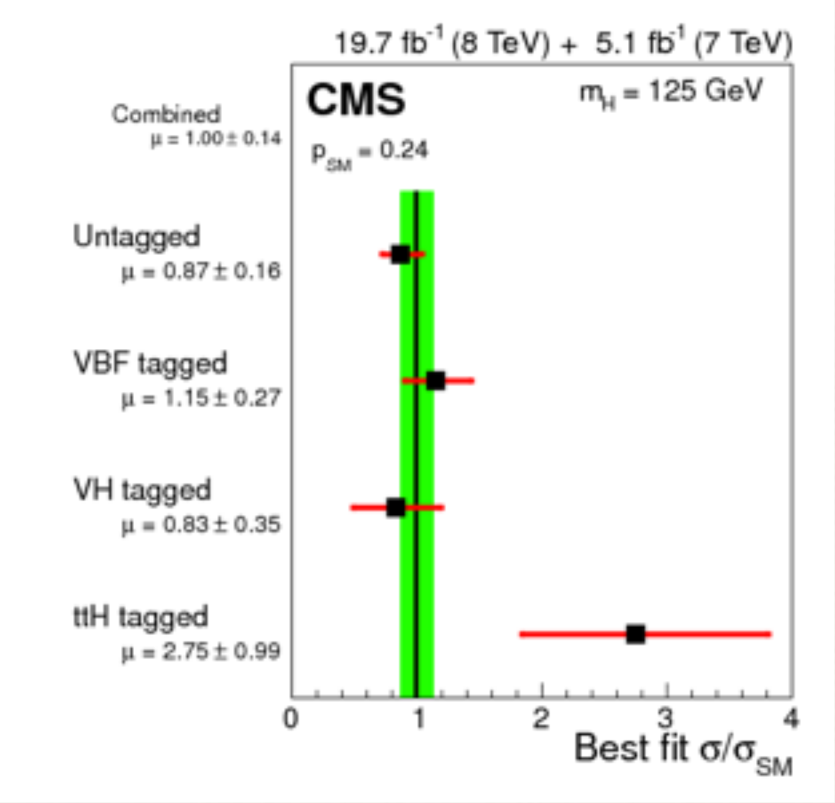
- All channels are combined
- Profile likelihood fits are carried out with all nuisances profiled
- Cross sections, branching ratios and recommendations taken from the LHC cross section WG:

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

Higgs Signal Strengh (CMS)

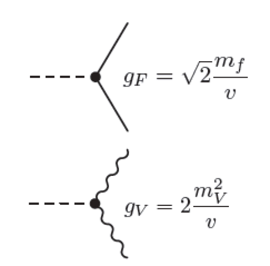
- Combined $\mu = \sigma/\sigma_{SM} = 1.00 \pm 0.09(\text{stat}) \pm 0.08(\text{theo}) \pm 0.07(\text{syst})$
- Signal strengths in different channels and production modes are consistent with the SM



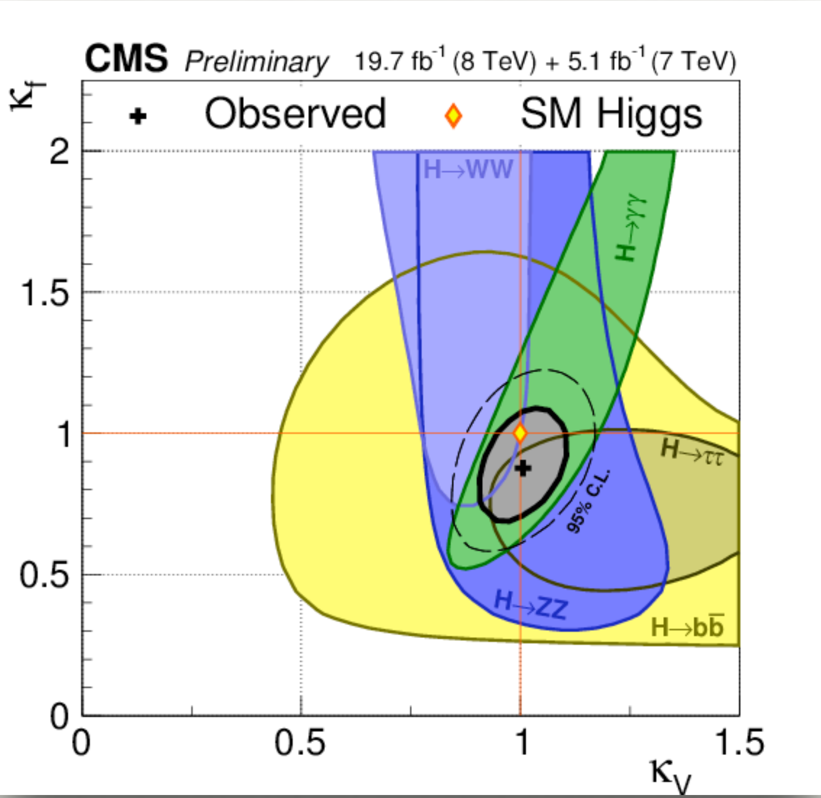


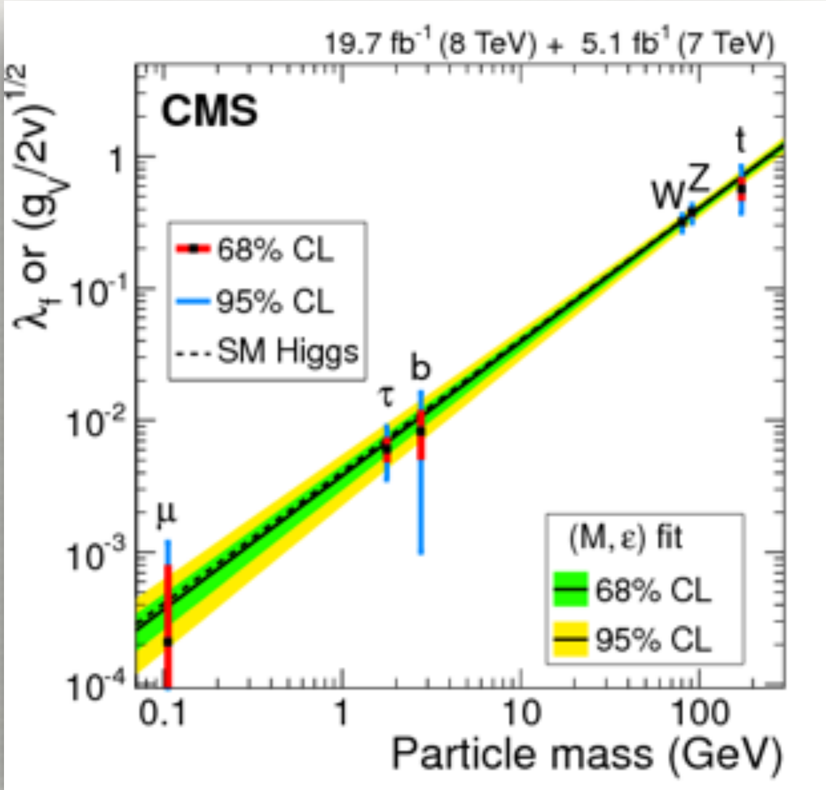
Higgs Couplings (CMS)

- Vector and fermion couplings are scaled by factors $\mathbf{k_f}$ and $\mathbf{k_v}$
- Couplings are proportional to particle masses as expected in SM
- Results agree with SM within ~1σ



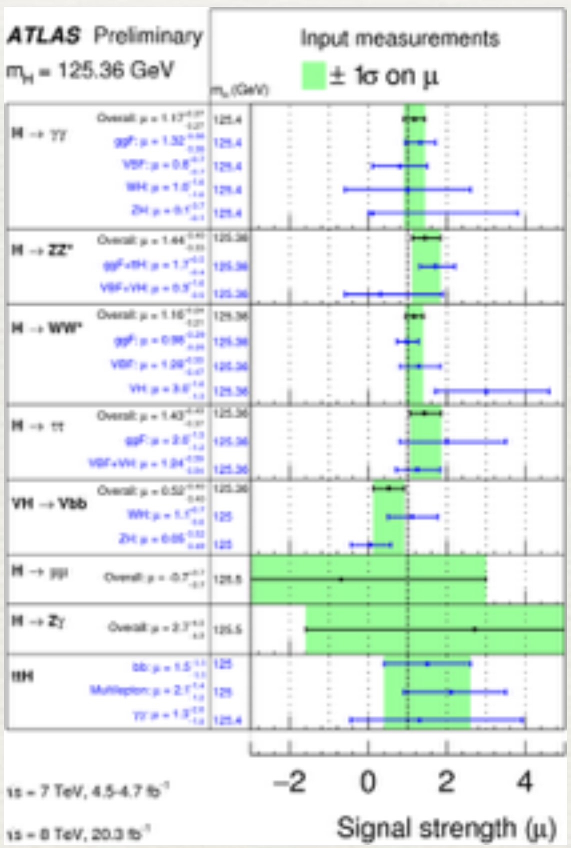
Eur. Phys. J. C 75 (2015) 212



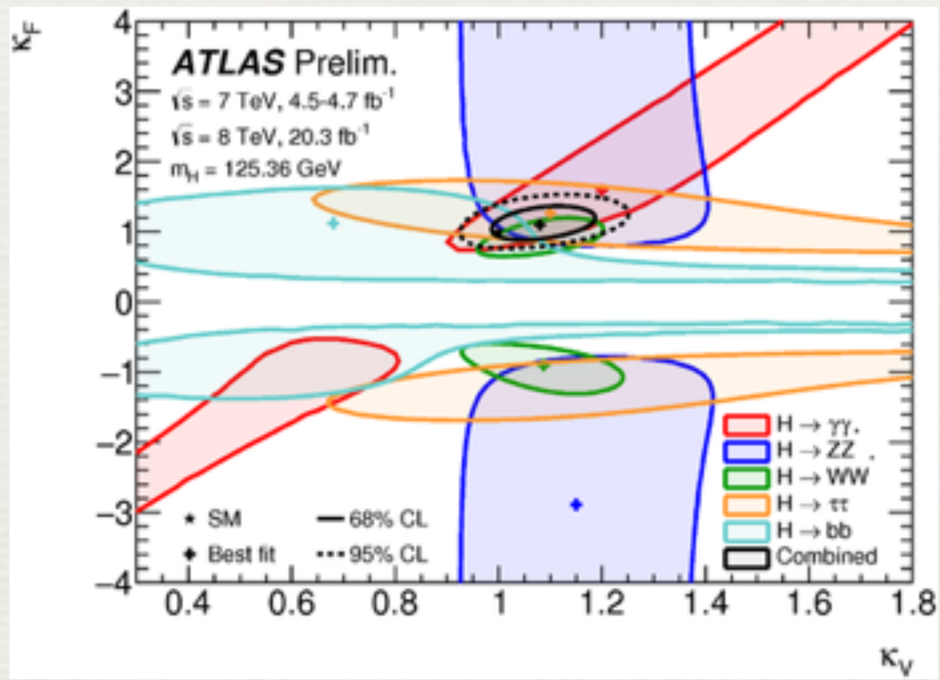


Higgs Signal Strength and Couplings (ATLAS)

- Summary of the signal-strength measurements, as published, from individual analyses
- Coupling scale factors for fermions and bosons, assuming only SM contributions to the total width

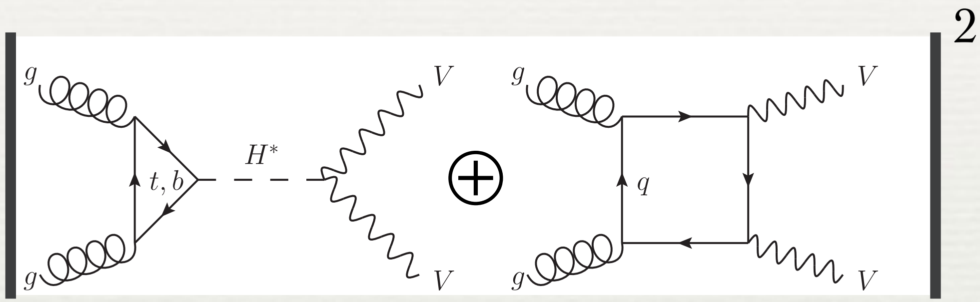


ATLAS-CONF-2015-007

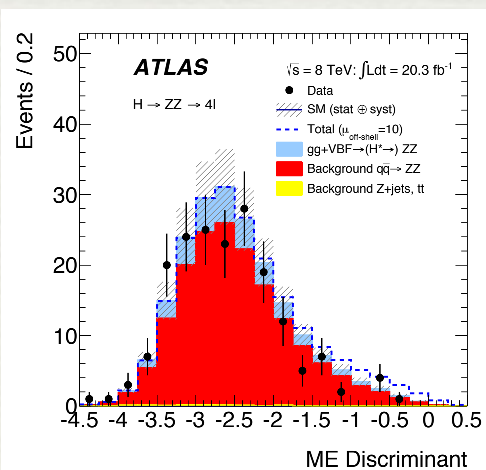


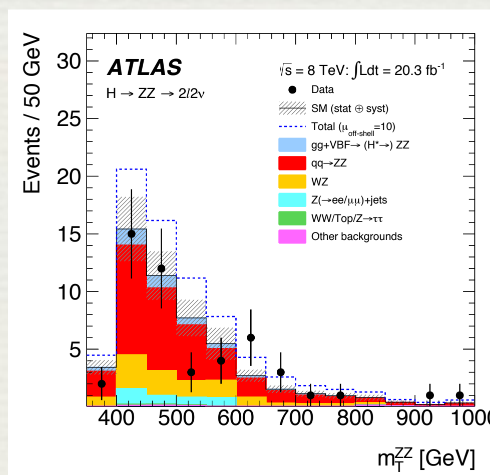
Higgs Off-shell Analysis (ATLAS)

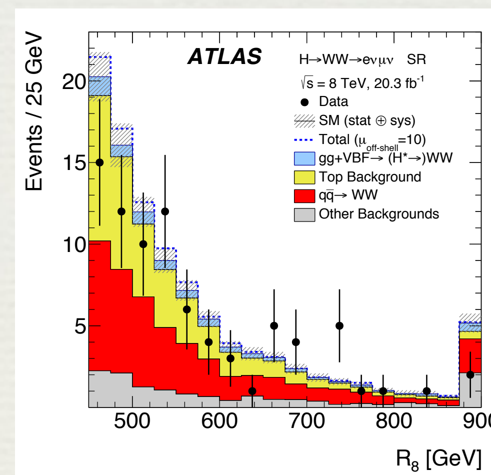
Measure Higgs signal strength for $m_{VV} >> 2M_V$ (V=W,Z) and look for couplings deviations at high energies



Considered the decay channels ZZ->4l , ZZ->2l2v and WW->2l2v



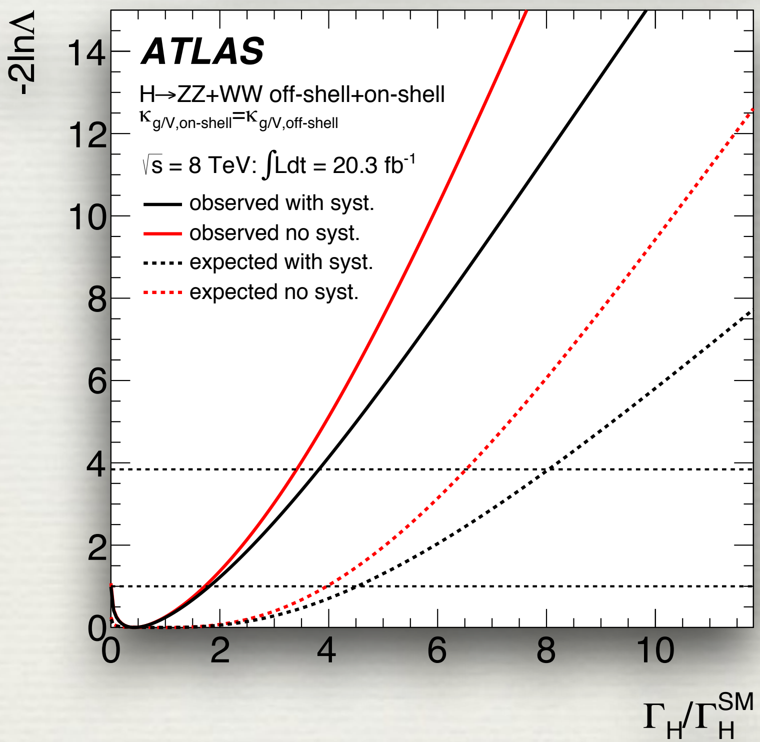




Higgs Off-shell Analysis (ATLAS)

Assume SM value for signal strengths off-shell ratio for μ_{ggH} / μ_{qqH}

$R^B_{H^*}$	Observed 0.5	Observed 1.0	Observed 2.0	Median expected 0.5	Median expected 1.0	Median expected 2.0	Assumption
$\mu_{\text{off-shell}}$	5.1	**6.2**	8.6	6.7	**8.1**	11.0	$\mu^{gg\to H^*}_{\text{off-shell}}/\mu^{VBF}_{\text{off-shell}}=1$
$\mu^{gg\to H^*\to VV}_{\text{off-shell}}$	5.3	**6.7**	9.8	7.3	**9.1**	13.0	$\mu^{\text{VBF } H^*\to VV}_{\text{off-shell}}=1$

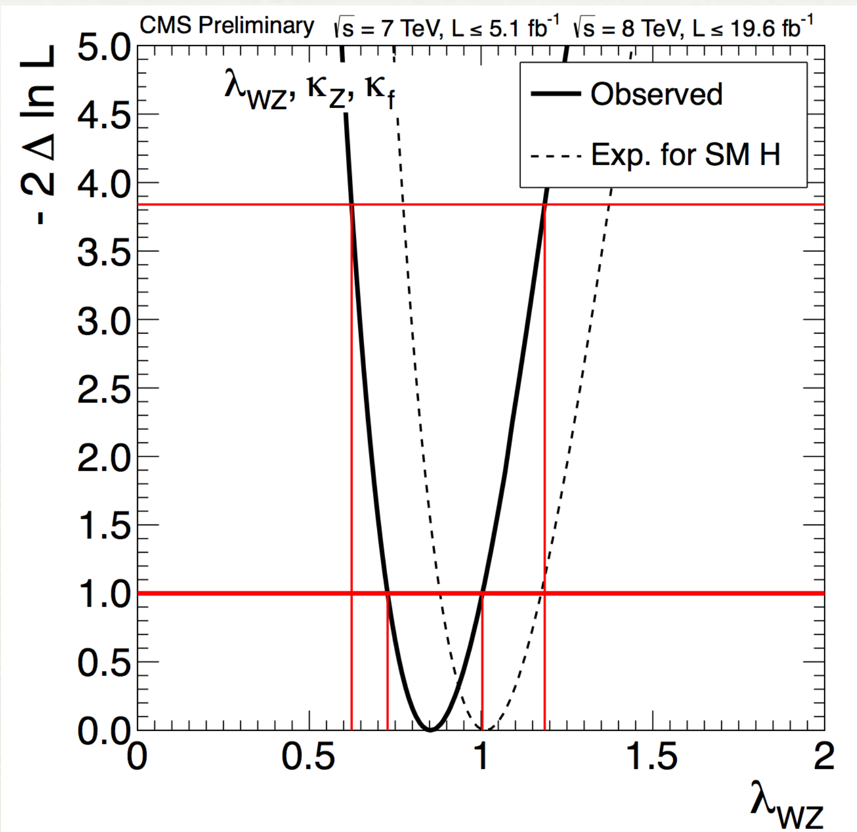


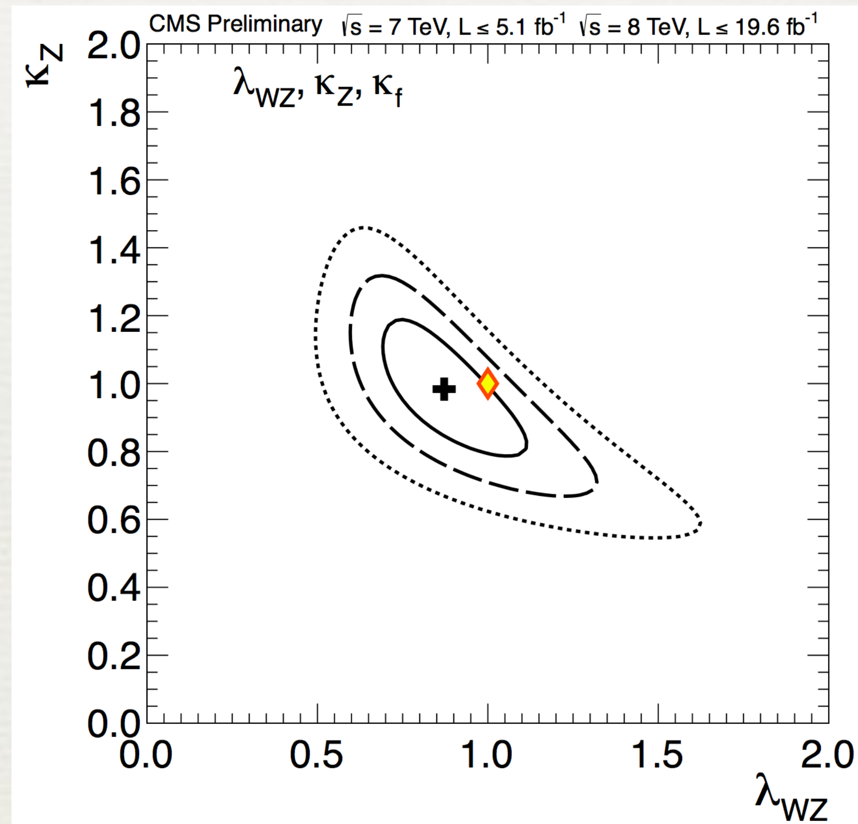
Eur. Phys. J. C (2015) 75:335

Observed(expected) 95% CL upper limits on Γ_H/Γ_H^{SM} **< 5.5(8.0)** for the combined off-shell ZZ and WW analyses

Custodial Symmetry Test

Modify the SM Higgs boson couplings to the W and Z bosons introducing two scaling factors k_W and k_Z and perform combinations to assess if $\lambda_{WZ} = k_W/k_Z = 1$





CMS-PAS-HIG-13-005

95% CL interval for λ_{WZ} : [0.62,1.19]

Statistics In Nutshell: Exclusion , Evidence & Discovery

H0: null hypothesis (ex: no Higgs)
H1: alternate hypothesis (ex: existence of the Higgs)

Quantify the level for which the hypotheses are accepted or rejected

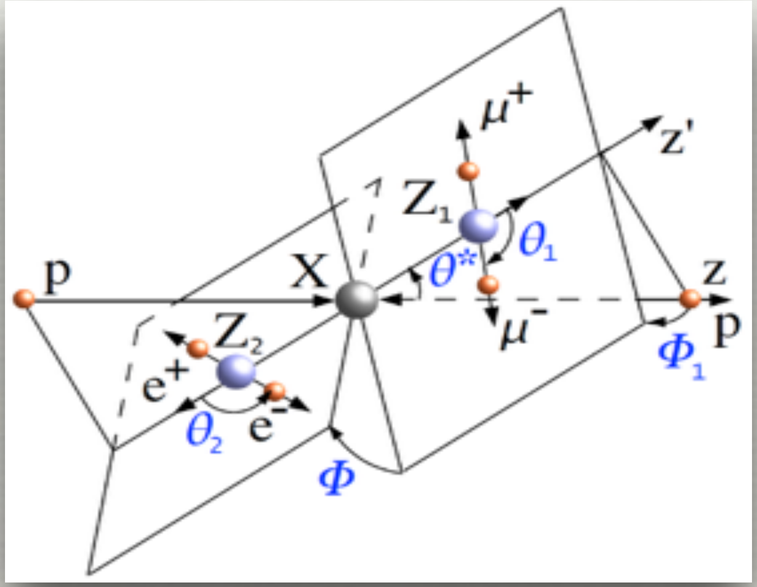
- Confidence level for the exclusion :
  - significance $< 3\sigma$
- Signal significance (p-value):
  - $3\sigma =<$ significance $< 5\sigma$ → evidence
  - significance $>= 5\sigma$ → discovery

Higgs Boson Spin-Parity

- The spin-parity of the Higgs boson candidate can be probed using angular distributions
- Mainly use diboson channels H→ZZ and H→WW
- The presence of the H →γγ decay excludes the spin 1 hypothesis (Yang's Theorem)
- Hypothesis testing is performed for different alternatives: spin 0^-, spin 1 and spin 2

RESULTS:

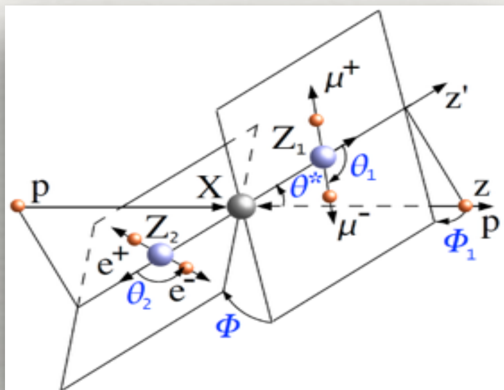
- Strong exclusion of a spin 1 resonance
- Spin 0^- excluded at > 3σ level
- Graviton like resonances excluded at >3σ

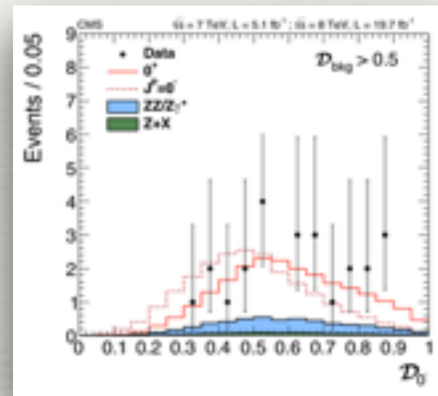


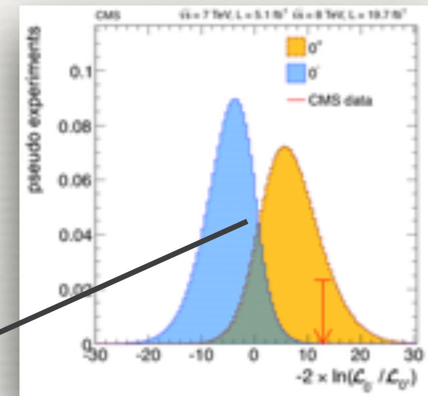
Higgs Boson Spin-Parity(CMS)

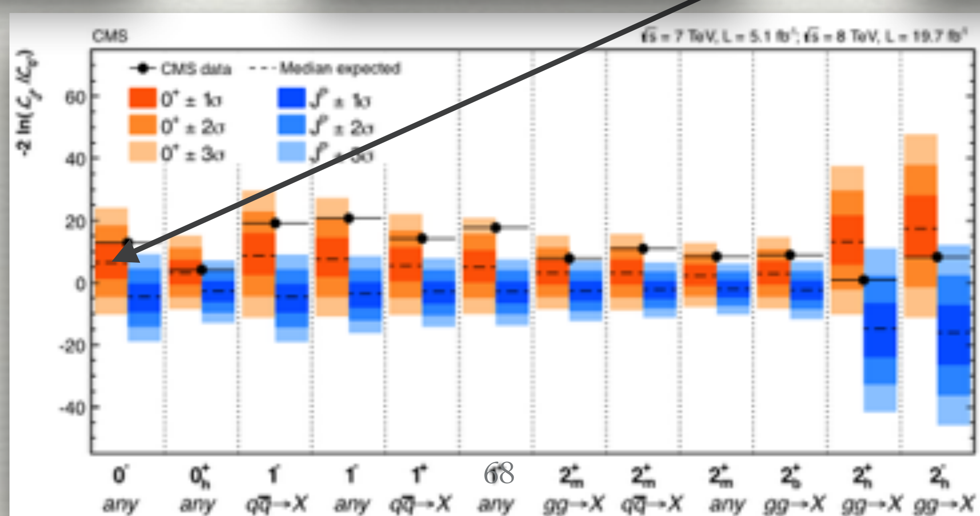
Spin-parity measurement with **Matrix Element Likelihood Analysis** (MELA)

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



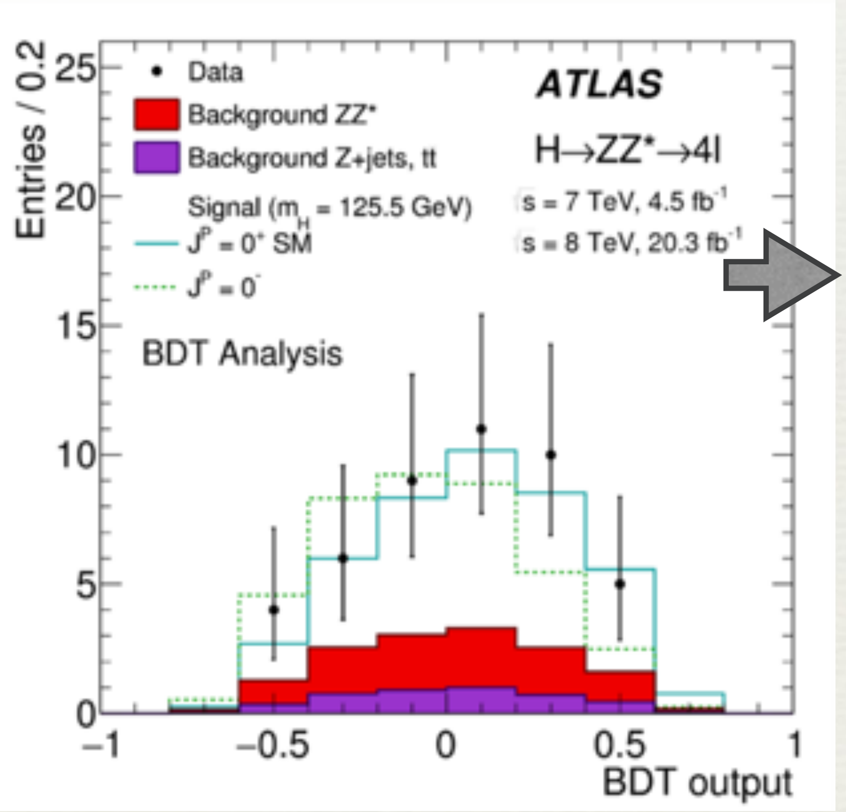


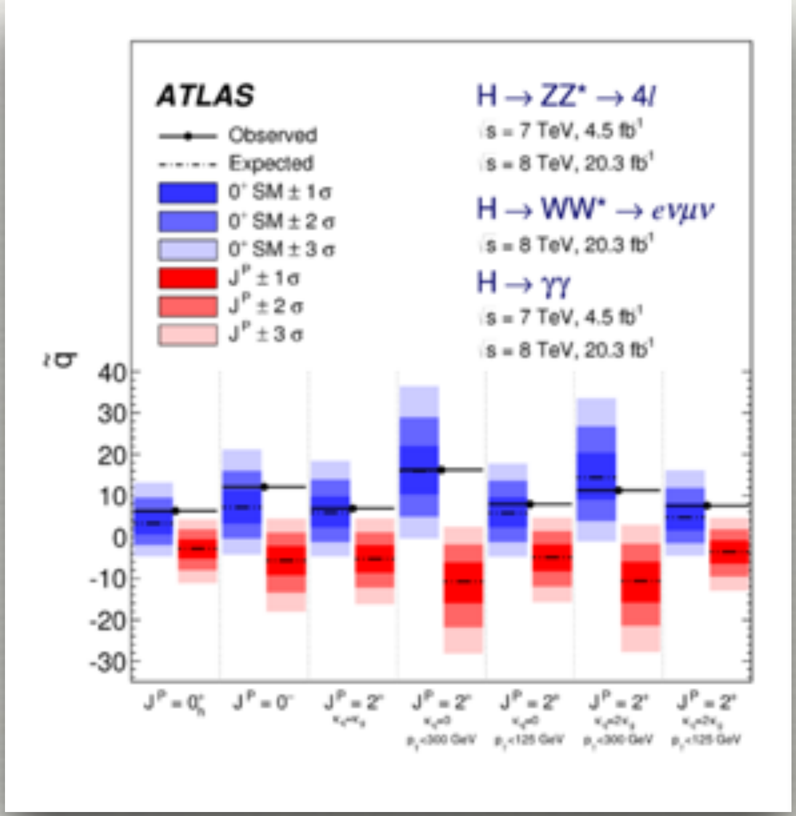




Higgs Boson Spin-Parity(ATLAS)

- Uses the decay angles and invariant masses, combined to build a BDT discriminant
- Distributions of the test statistic ˜q for the SM Higgs boson and for the JP alternative hypotheses favors the former

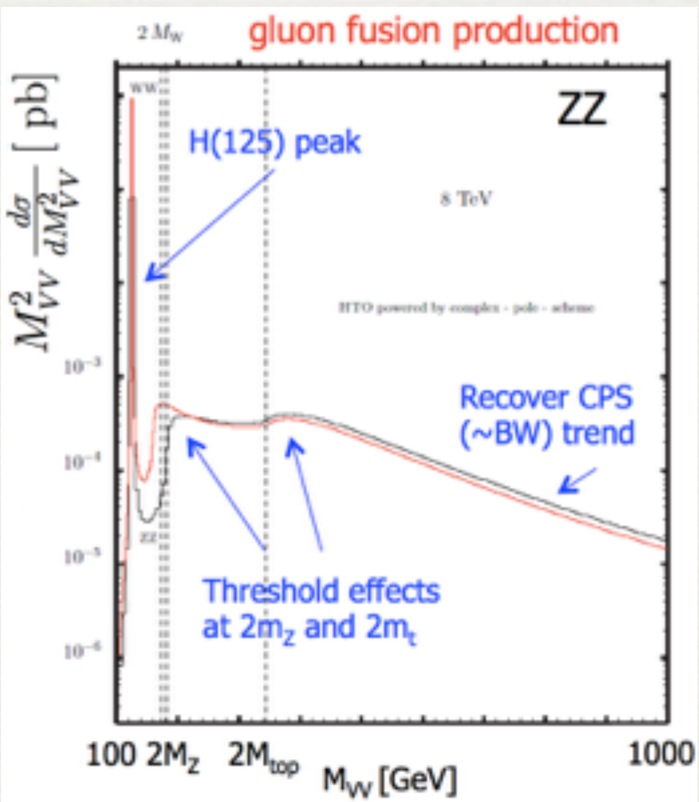




Higgs Width from off-shell ZZ

- Direct measurement limited by experimental mass resolution O(2GeV) while SM expectation $\Gamma_{H125} = 4$ MeV
- Narrow width approximation not adequate for Higgs to VV. Off-shell contribution is sizeable at high ZZ mass (~7.6% cross section increase)

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



- From cross section ratio derive width information
- Assume couplings are unchanged between on-shell and off-shell F. Caola, K. Melnikov (Phys. Rev. D88 2013 , 054024)

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}$$

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

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

Ratio (off-shell / on-shell) $\propto \Gamma$

Higgs Width from off-shell ZZ (CMS)

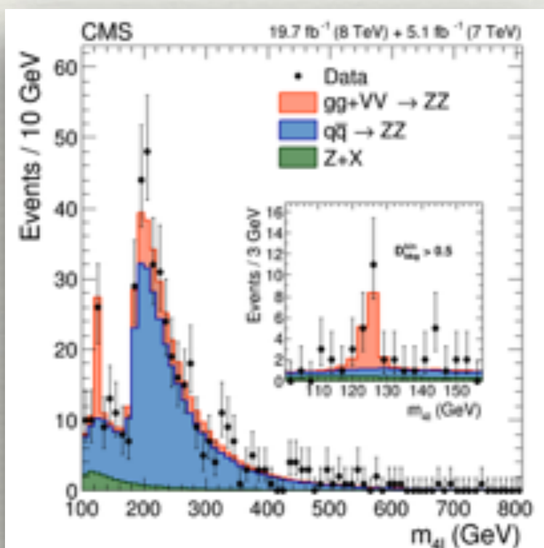
- Use MELA for ggZZ and qqZZ discrimination including interference
- 2D likelihood analysis using discriminator versus m4l for separating on-shell and off-shell regions

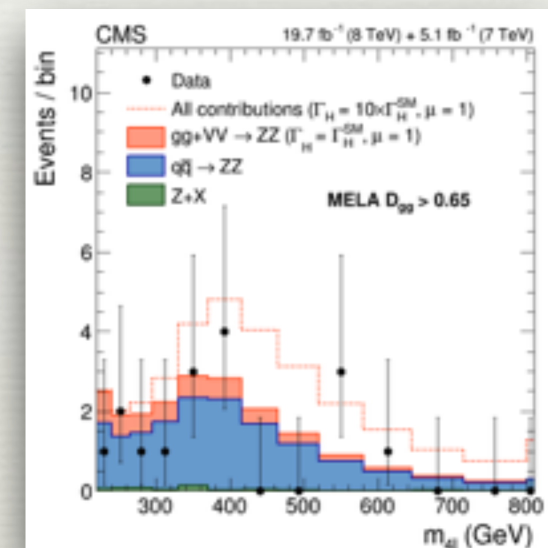
Observed(expected) @ 95% C.L : $\Gamma_H < 4.2(8.5)\ \Gamma_{HSM}$

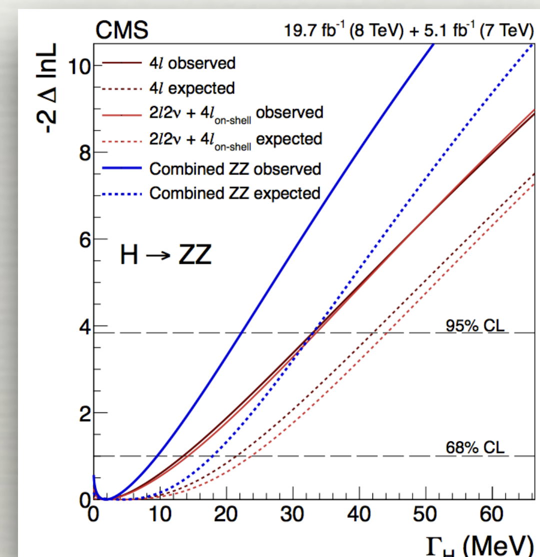
Under the peak

Far from the peak (>220GeV)

Phys. Lett. B 736 (2014) 64



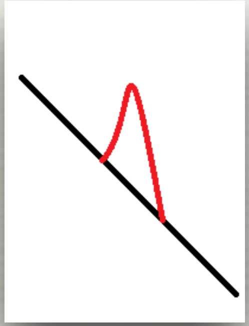




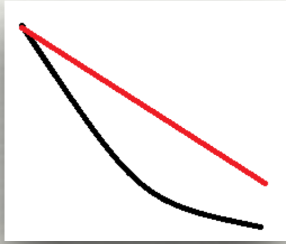
BSM Searches

All searches corresponds to looking for discrepancies between predicted and observed distributions !

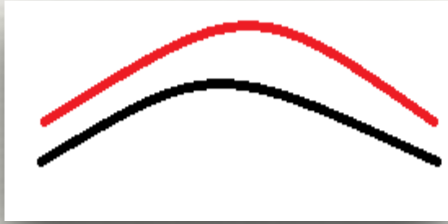
Resonance

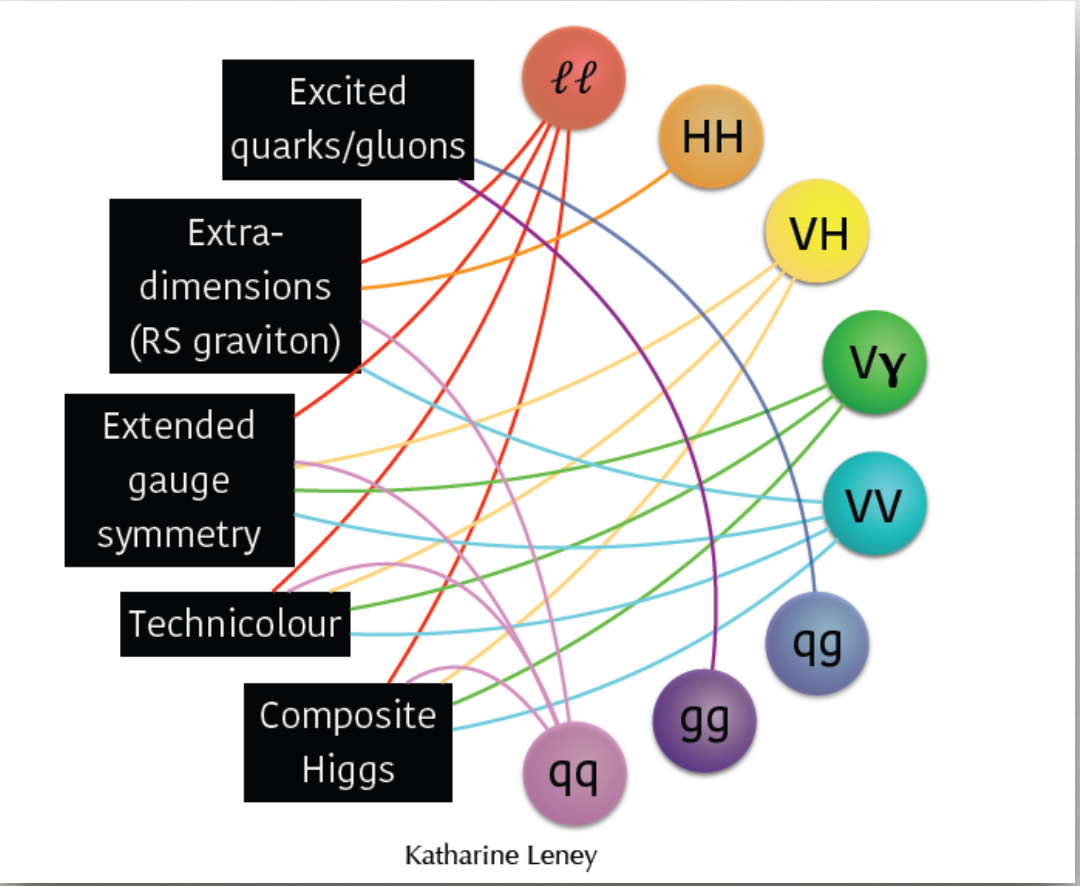


Shape



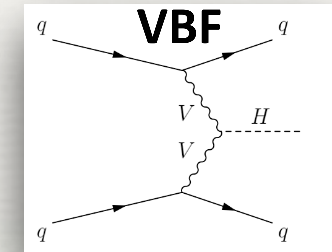
Rate



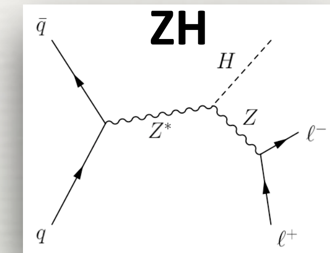


Higgs to Invisibles

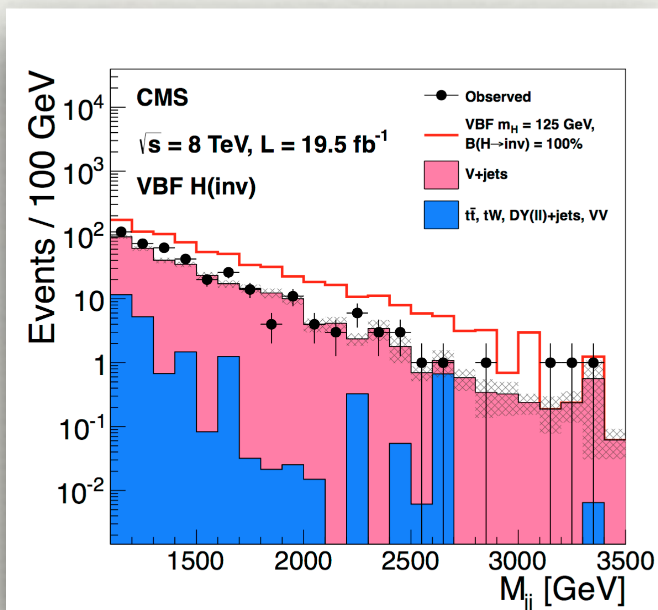
The Higgs boson could decay to invisible particles, such as dark matter candidates. Exploit VBF qqH and ZH with Zll(bb) production modes



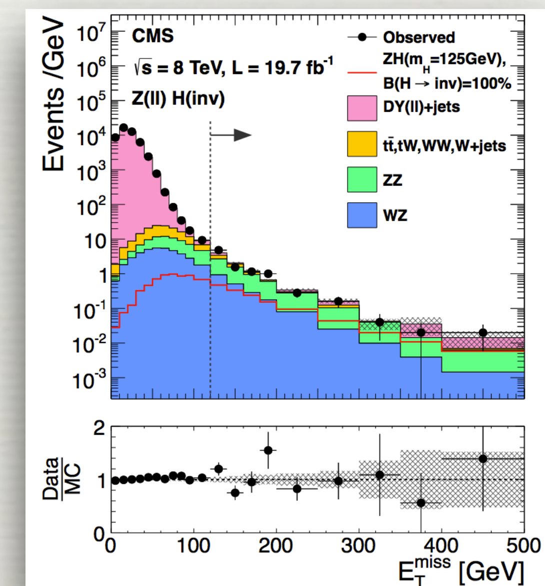
Eur. Phys. J. C 74 (2014) 2980



Search for VBF jets plus MET



Search for l^+l^- plus MET



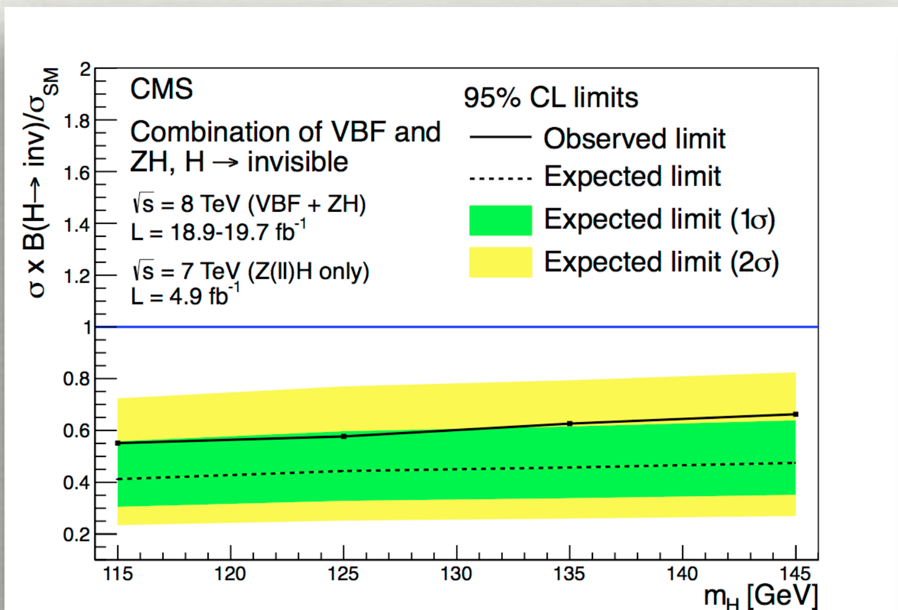
Higgs to Invisibles

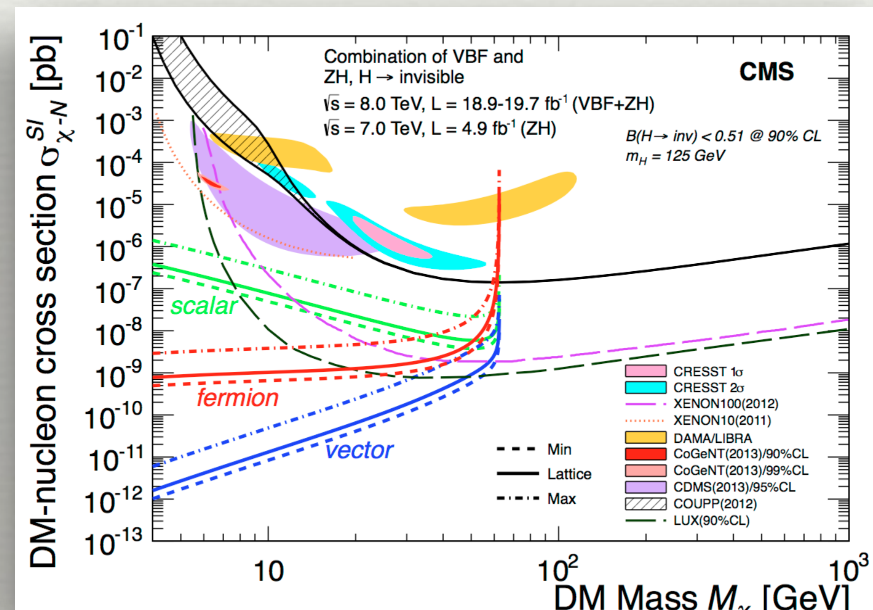
No signal observed and limits are derived . Combined exclusion and Dark Matter interpretation…

Eur. Phys. J. C 74 (2014) 2980

Combined observed(expected) limit:
BR(H_{inv}) < 0.58 (0.44) @ 95% CL

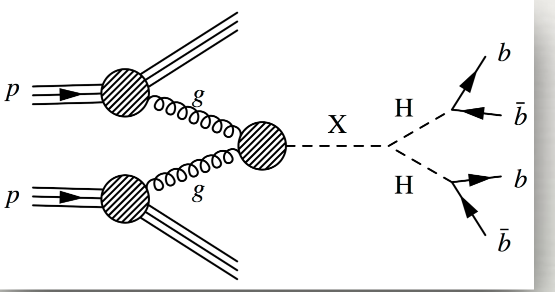
These limits can be interpreted in a Higgs portal model in which the DM couples to the Higgs

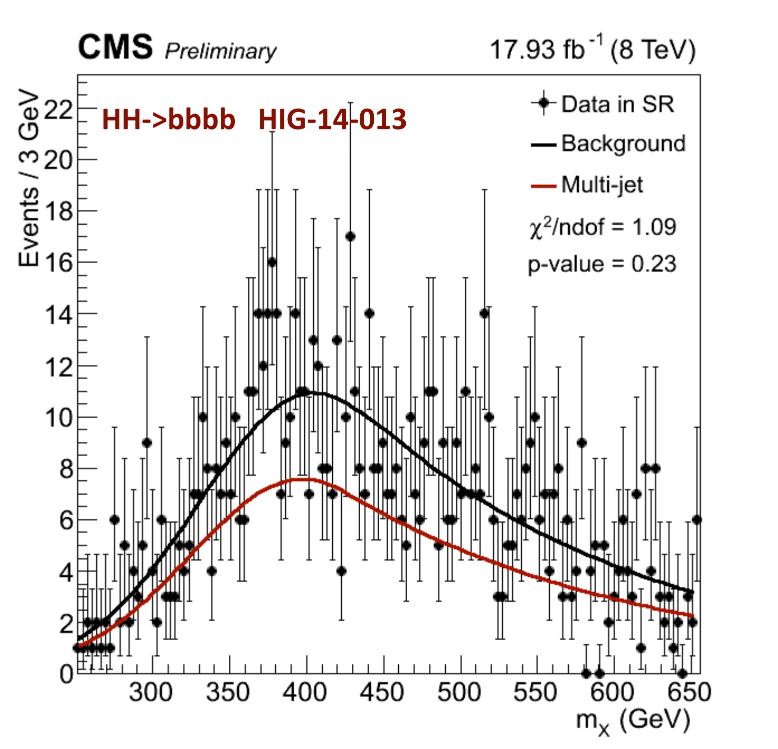


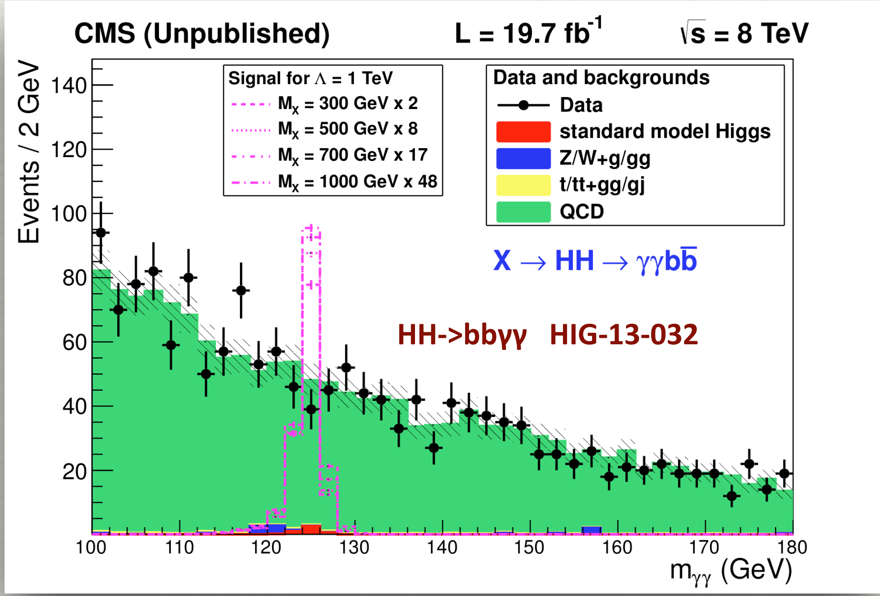


X→HH

Search for the resonant production of two Higgs bosons from radion or graviton decay

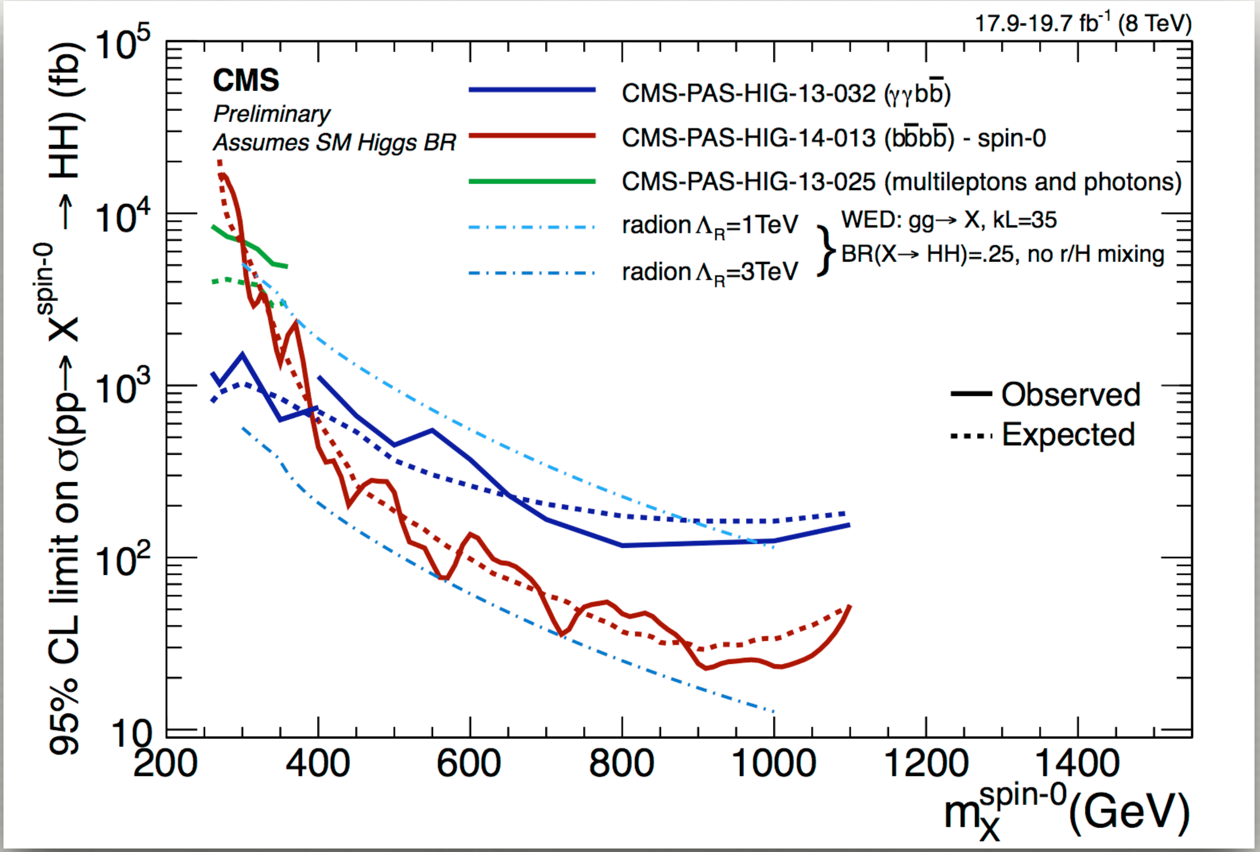






X→HH

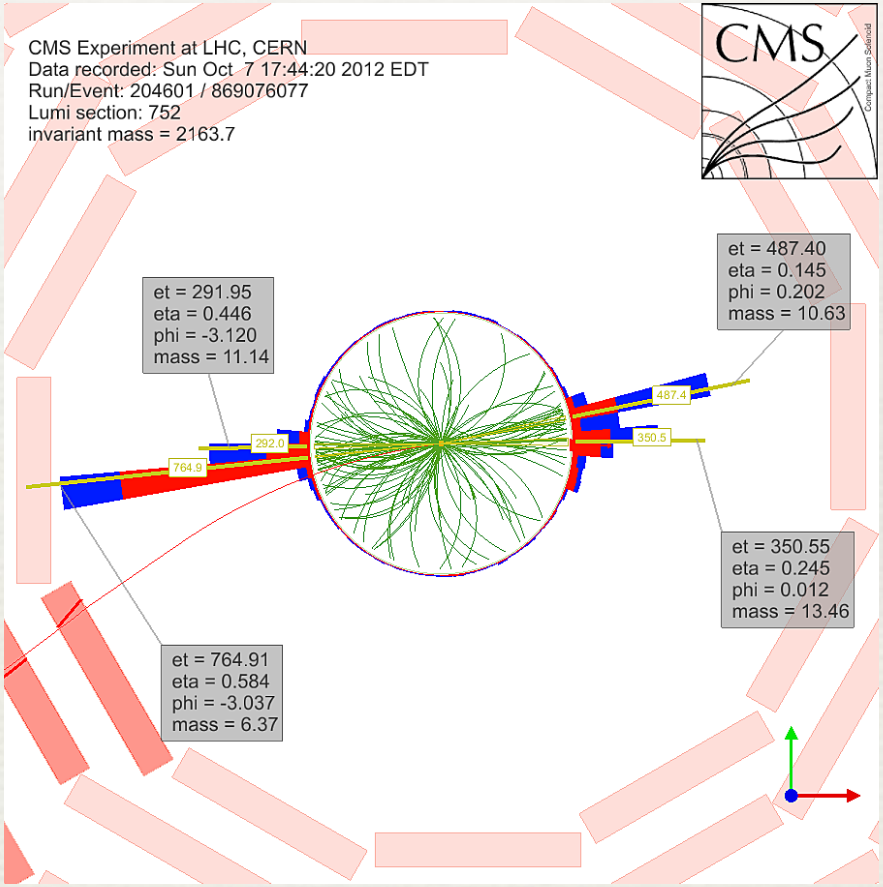
No signal observed, derive limits on **σ.BR** , assuming BR(X->HH)=25% for this plot.

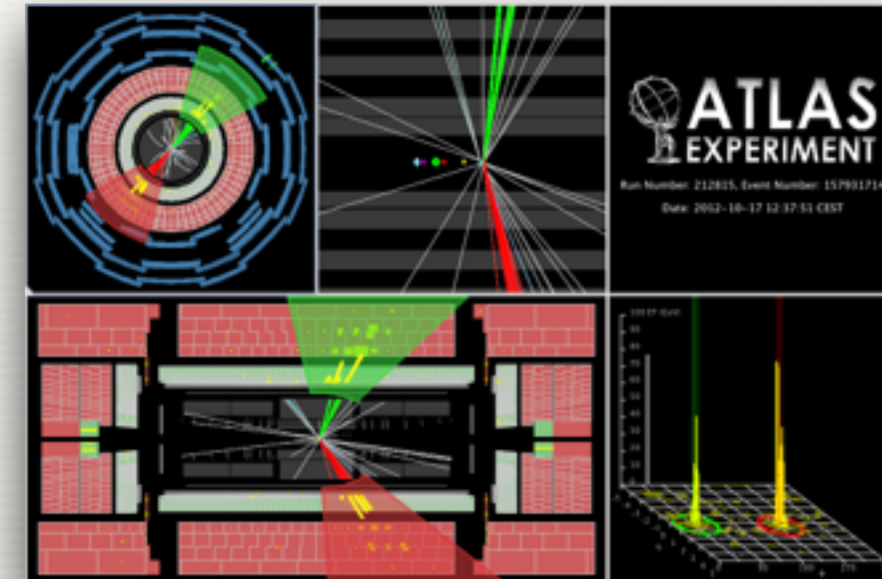


Complementary: bbγγ more sensitive at lower masses, 4b at higher masses

High Mass Di-boson Search

Search for high mass diboson resonances with boson tagged jets (W/Z jets)





Atlas event selected by the WW, WZ and ZZ cuts, with dijet invariant mass m_{jj}=2.0TeV. Leading jet has P_T= 1.1 TeV and m_j = 93.7 GeV while subleading jet has p_T=0.9TeV and m_j=92.8GeV

High Mass Di-boson Search(ATLAS)

Search for high mass diboson resonances with boson tagged jets (W/Z jets)

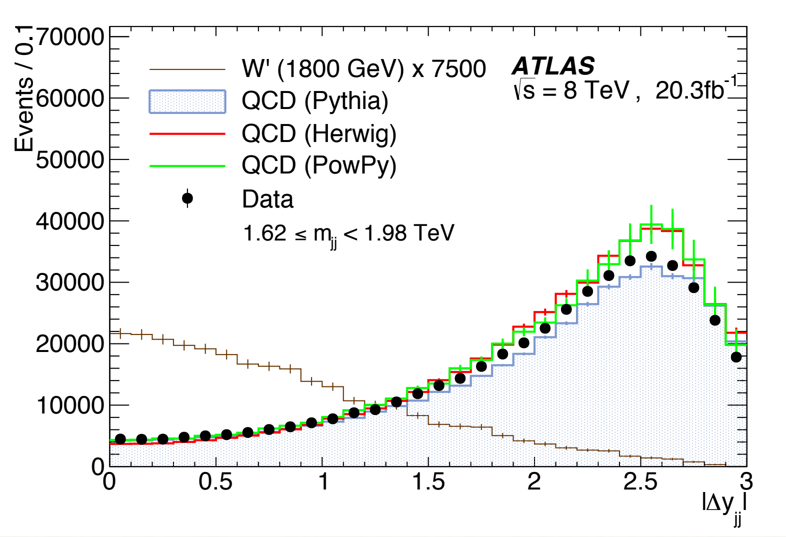
- Fat jets reconstructed using the Cambridge–Aachen (C/A) algorithm with a radius R = 1.2
- Fat Jets are then groomed to reduce pile-up contribution and identify the subjets pair associated with the boson decays: $W \rightarrow q\tilde{q}'$ or $Z \rightarrow q\tilde{q}$
- Selected subjets are then filtered: the original topological cluster constituents of that pair taken together and clustered using the C/A algorithm with a small radius R= 0.3
- Filtered jets are calibrated using (E,η) dependent correction from simulation.The calibrated jet 4-momentum is used as the W or Z boson 4-momentum
- Narrow mass windows of 26 GeV chosen to optimise sensitivity to signal events and are centred at either M_W=82.4 GeV or M_Z=92.8 GeV , which is where simulation peaks

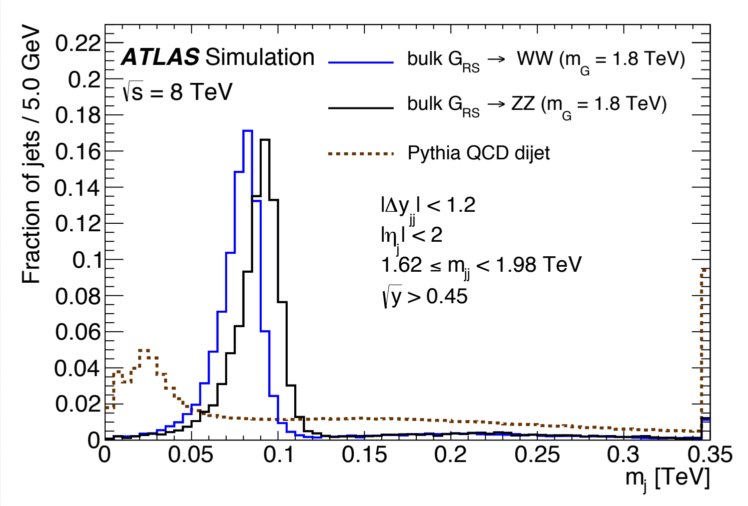
High Mass Di-boson Search(ATLAS)

High-mass resonances decaying to a pair of boosted vector bosons . The subsequent bosons hadronic decay are recognized as two large-radius massive jets with large momentum, typically balanced in pT.

Selection Cuts:

- ungroomed jet Pt greater than 540GeV.
- no electron with ET > 20 GeV with $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$
- no muon with pT>20GeV in the region $|\eta| < 2.5$
- leading jets must have $|\eta|<2.0$ and $|\Delta\eta|<1.2$
- leading jets satisfy boson tag $|m_j - m_V| < 13$GeV



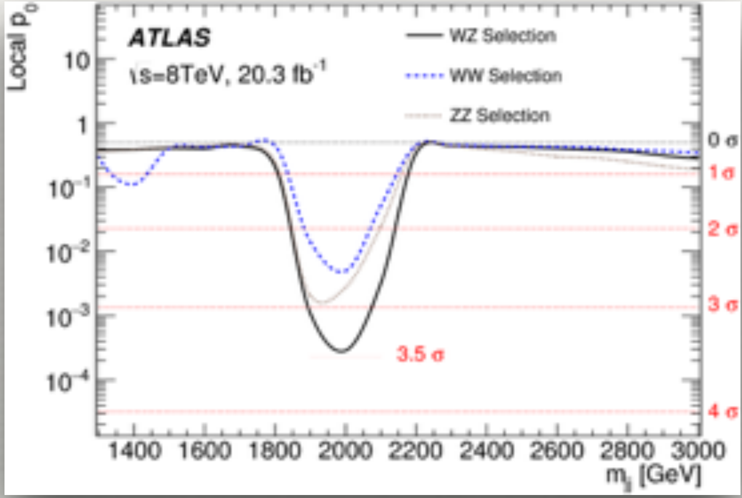


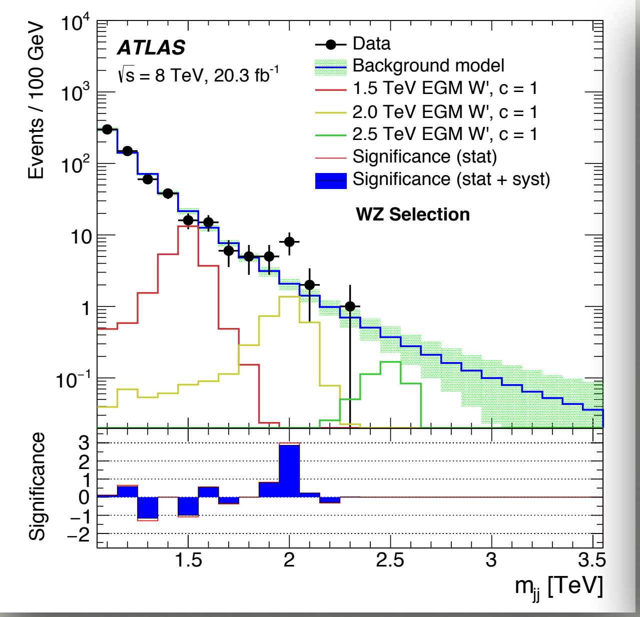
High Mass Di-boson Search(ATLAS)

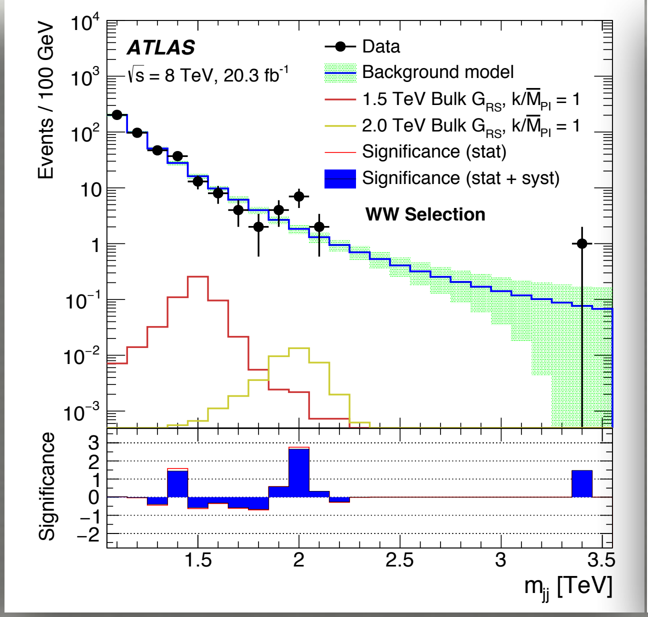
CERN-PH-EP-2015-115

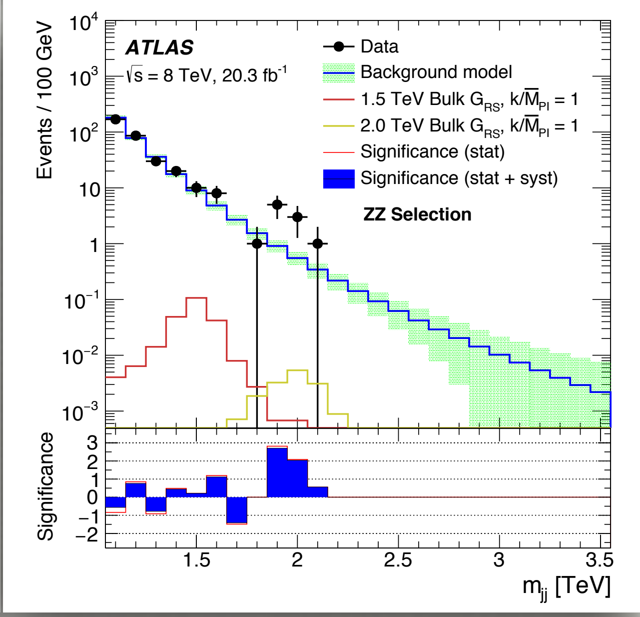
- Signal significance (p-value) for WZ, WW and ZZ selections

- Dijet mass distributions with bin by bin significance compared with EGM(SSM) W' model





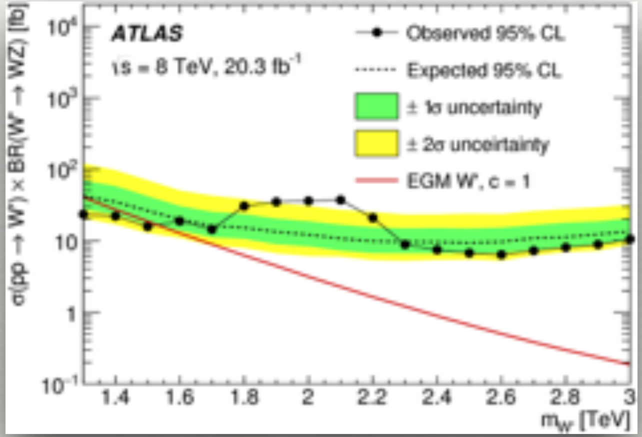




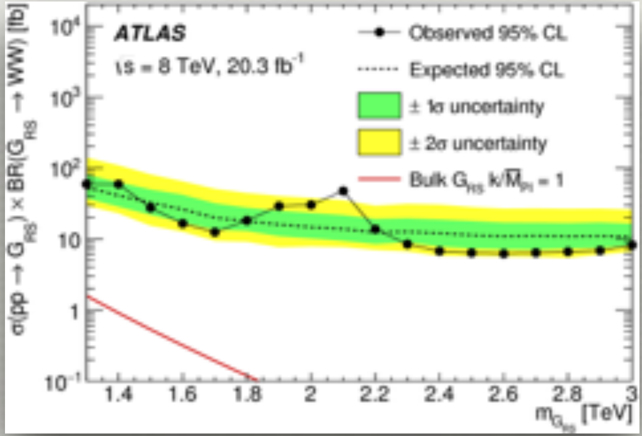
High Mass Di-boson Search(ATLAS)

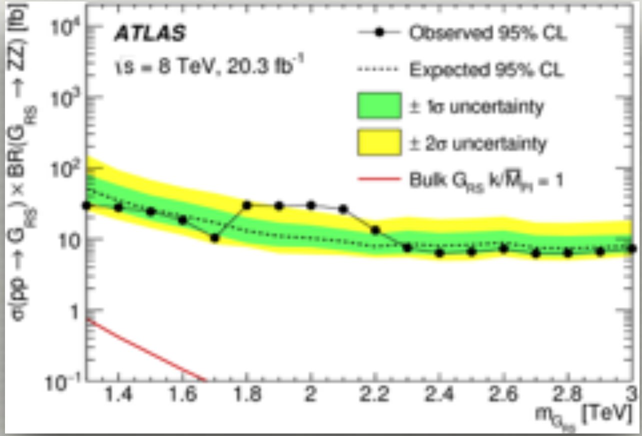
Exclusion limits @ 95%CL on the σ.BR for: CERN-PH-EP-2015-115

- WZ final state of a new heavy gauge boson W′ with couplings of EGM(SSM) model in the mass range [1.3,1.5]TeV



- WW and ZZ final states of Kaluza–Klein excitations of the graviton in a bulk RS model

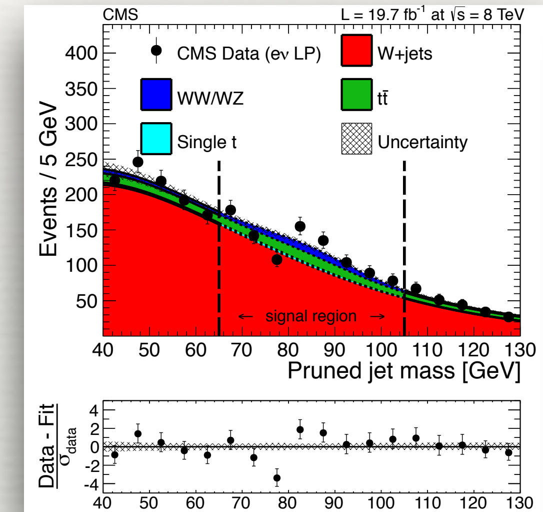


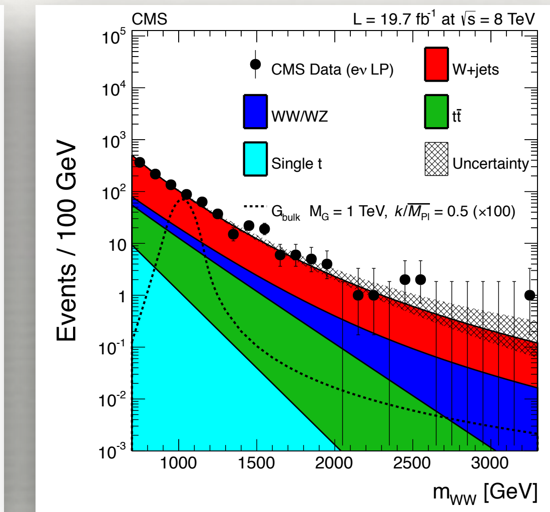


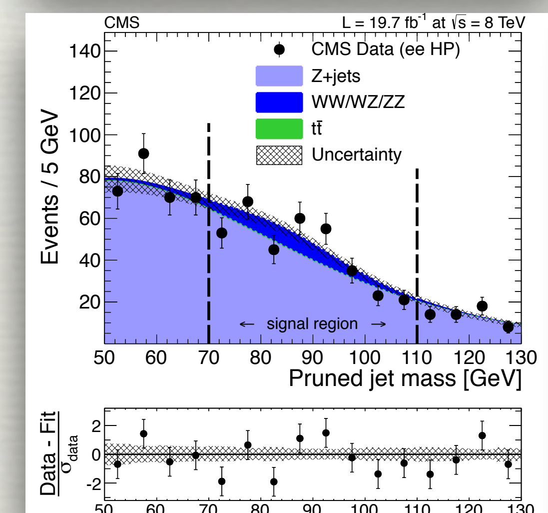
High Mass Di-boson Search(CMS)

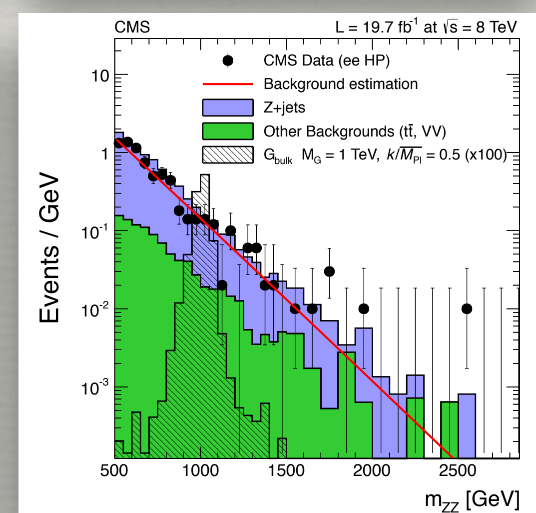
Search for new resonances decaying to WW, ZZ or WZ in which sub-sequentially one of the vector bosons decays leptonically and the other hadronically.

- Non-resonant W jets background prediction extracted from a fit to the side bands.
- MC resonant shapes are corrected using the differences between data and simulation in the W peak position and width measured in the control region
- A jet is identified as W-jet if its pruned mass falls in the range [65,105]GeV and similarly a Z-jet is required to have a pruned mass in [70,110]GeV.
- Reject V jet candidates with $\tau_{21} > 0.7$ because jets coming from hadronic W/Z decays are characterized by lower values of τ_{21} compared to the SM backgrounds



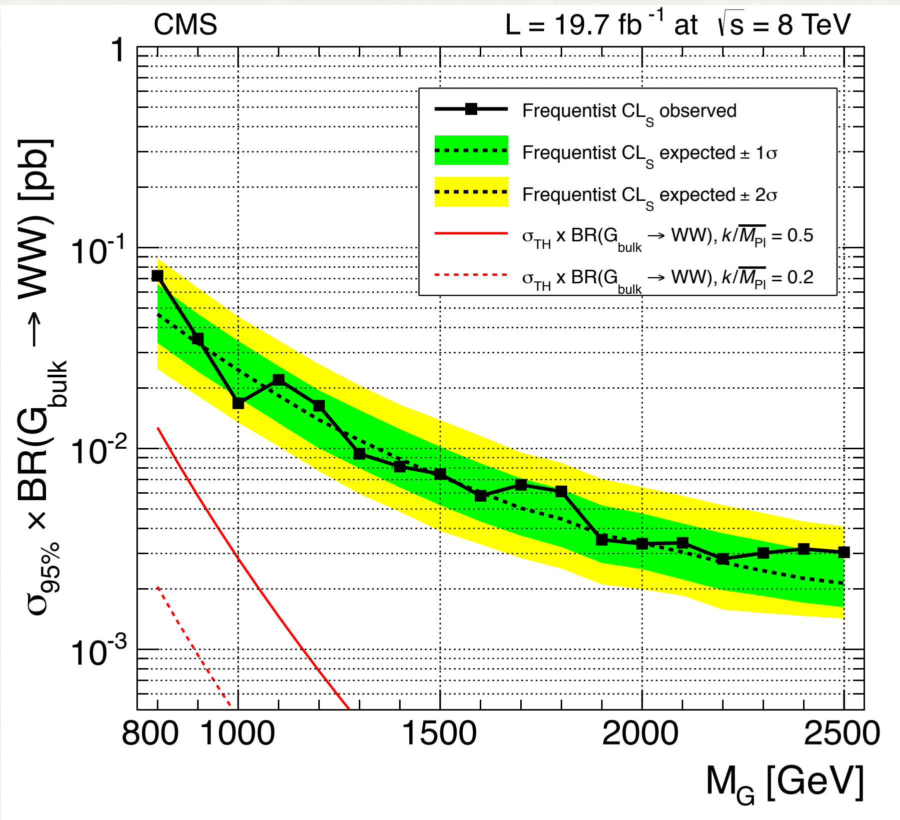


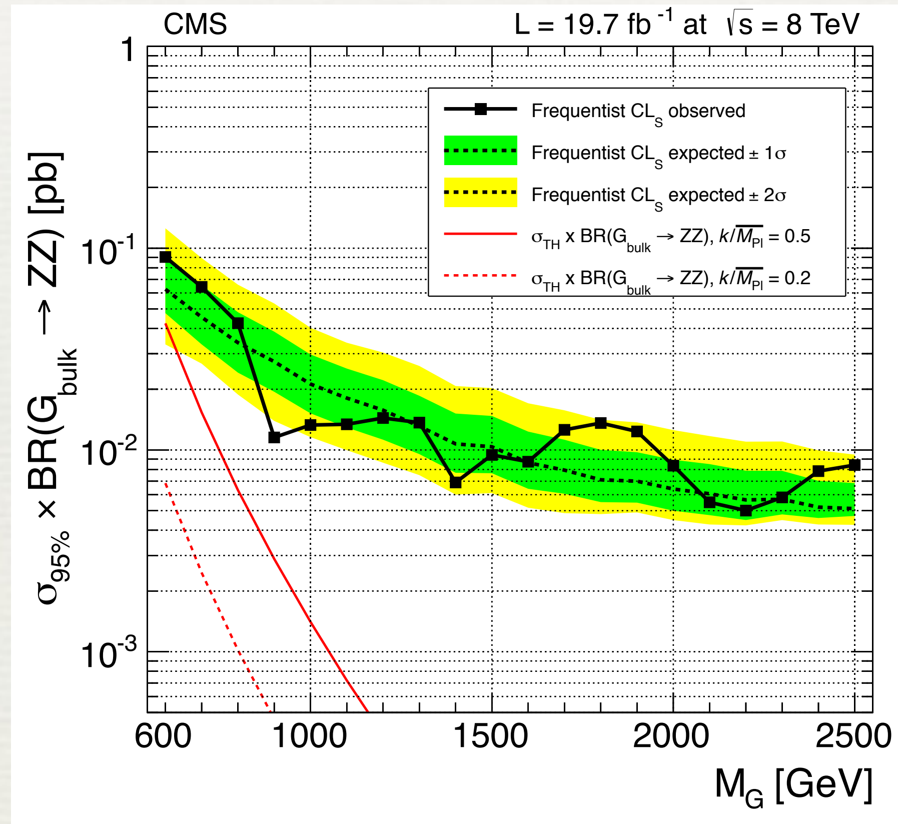




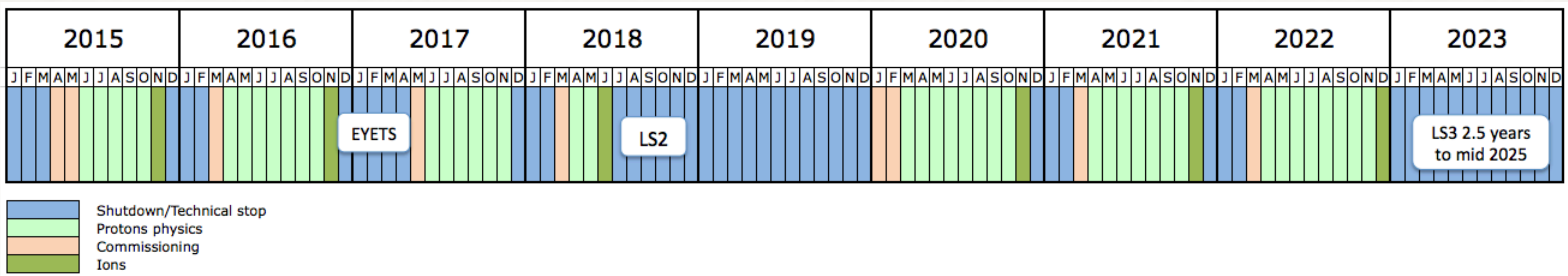
High Mass Di-boson Search(CMS)

Upper limits at 95% confidence level are set on the Bulk Graviton model production cross for resonance masses between 600 and 2500 GeV

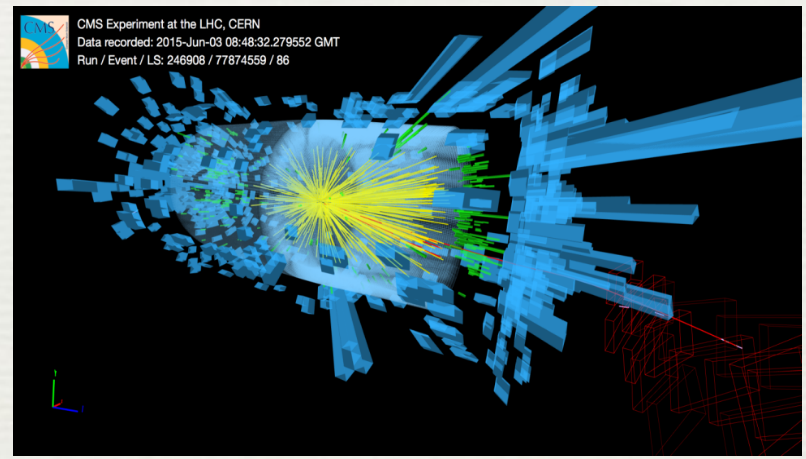




Run 2 and Beyond

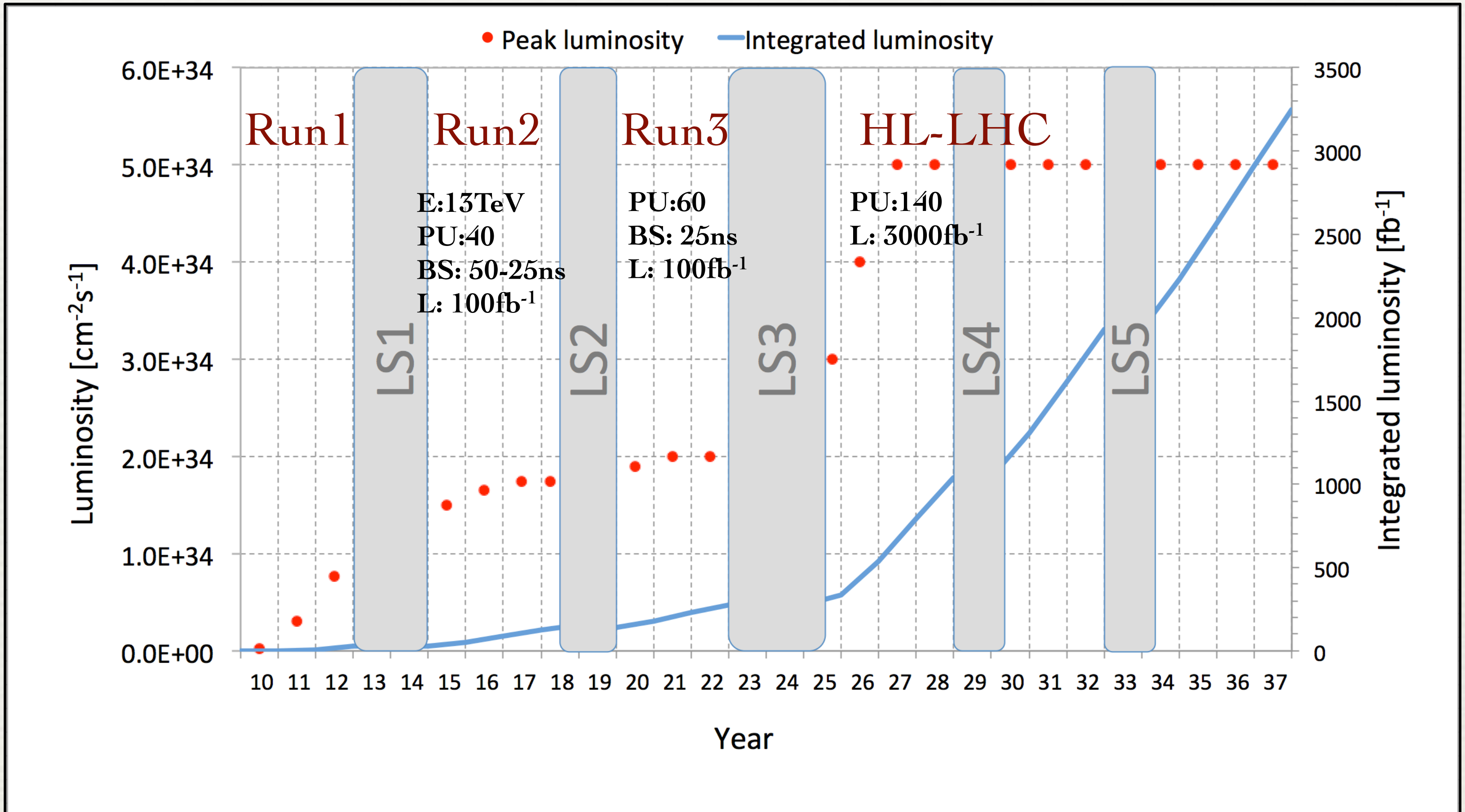


Run2 Start on June/03, 2015, with stable beams @6.5TeV

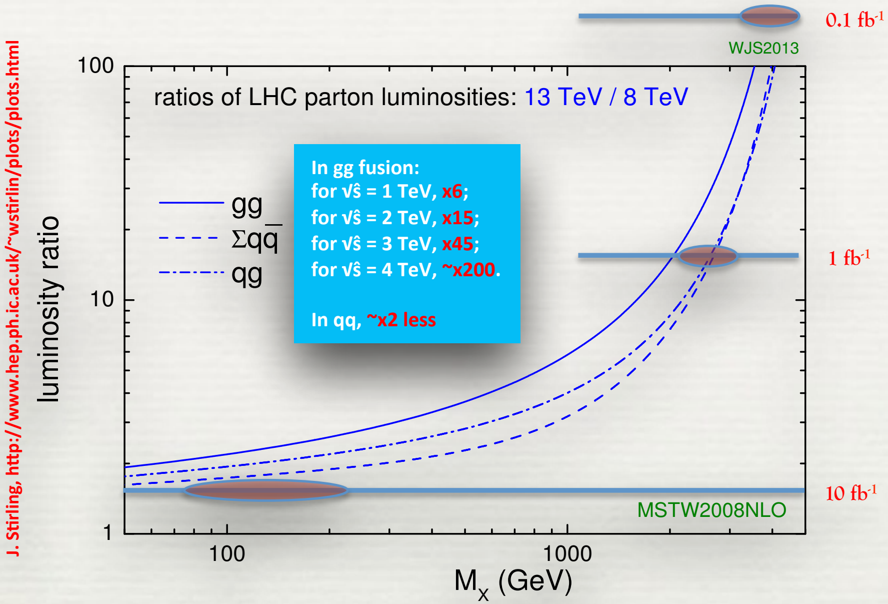


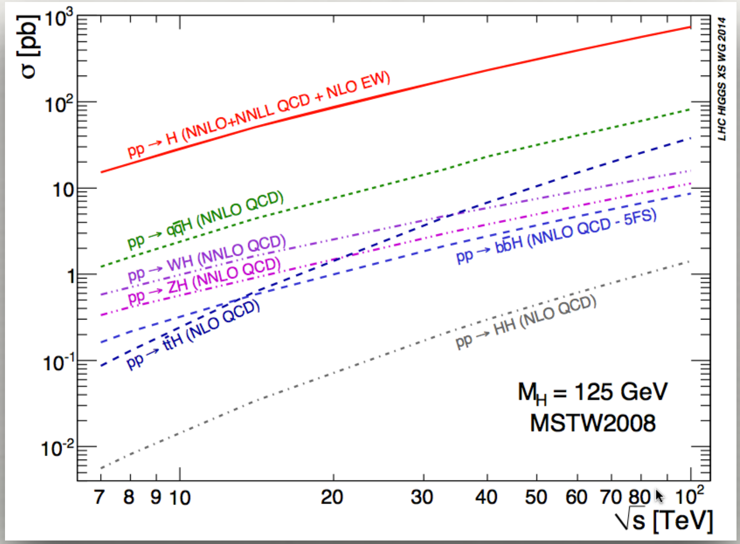
2015 Phase	Days	Efficiency	Int.Lumi
Initial Low Lumi	7	20%	~ few pb-1
50ns	21	20%	~ 0.5 fb-1
25ns	70	30%	~ 8 fb-1

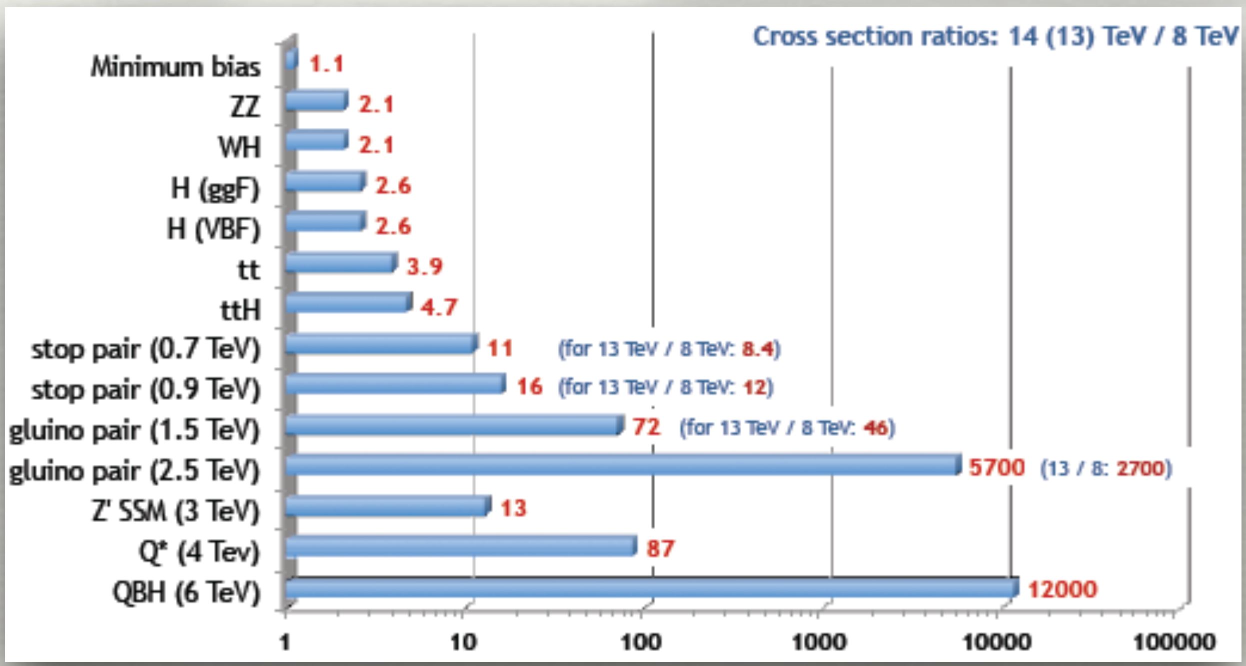
LHC Luminosity Evolution



8TeV→13TeV : What Changes ?

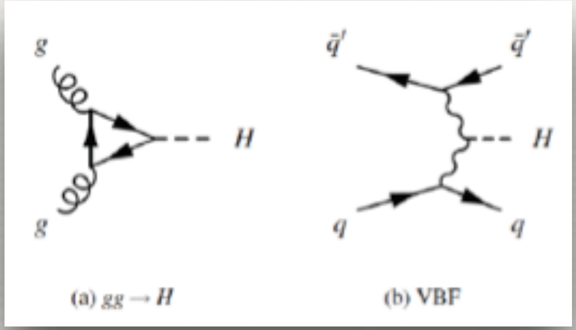


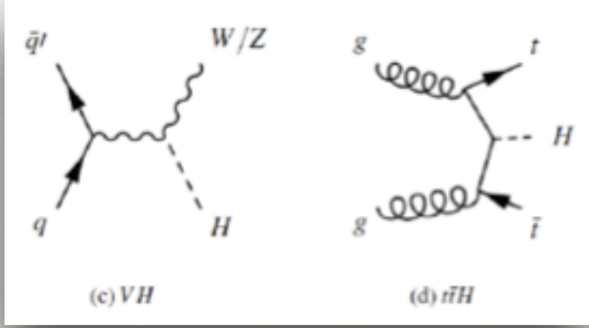




Higgs Production (13TeV)

- SM Higgs is light, so the gluon fusion cross section doesn't get that much boost (x2, 19.1 → 43.6 pb)
- Background cross sections also increase





σ [pb] at m_H=125.5 GeV	8 TeV	13 TeV	Ratio
ggF	19.1	43.62	2.6
VBF	1.6	3.727	2.6
WH	0.7	1.362	2.1
ZH	0.4	0.8594	2.1
ttH	0.1	0.5027	4.7

Higgs Physics Prospects

Run 2 and 3 (starting in 2015):

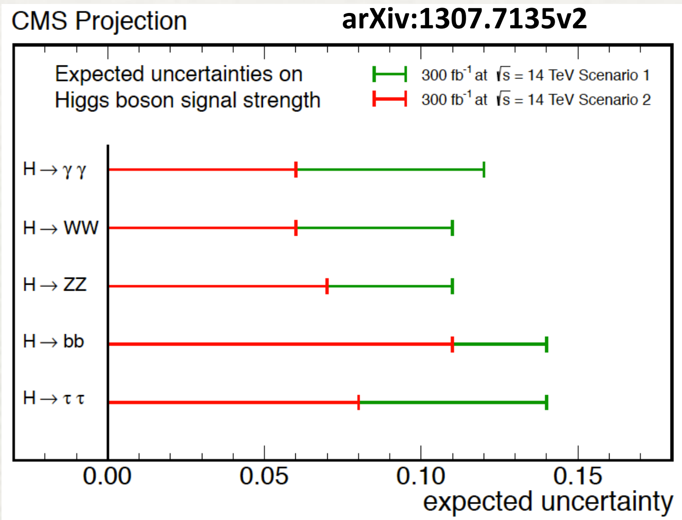
- Re-discovery of the Higgs
- Measure Higgs properties
  - cross section (also differential)
  - mass & width
  - couplings to bosons, fermions, ttH & EFT
- Searches for BSM Higgs
  - additional boson in EWK singlet model
  - search for $H \rightarrow hh$ and $A \rightarrow Zh$ in 2HDM
  - search for H+, dark matter

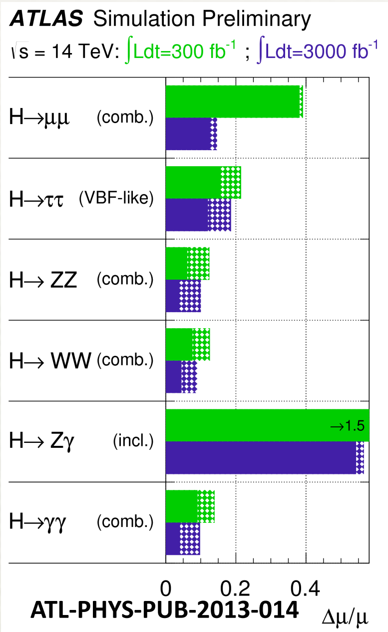
High Luminosity-LHC (from 2025):

- Precision measurements (2x improvement)
- Searches for
  - rare decays,
  - anomalous couplings
  - CP-violation in Higgs
- Search for BSM decays
  - invisible
  - $t \rightarrow cH$
- VV scattering
- HH production & self-coupling

Higgs Signal Strength (300fb^{-1})

Higgs signal strength $\mu=\sigma/\sigma_{SM}$ with 300 fb^{-1} gives 2x factor improvement in precision measurement





CMS:

- Extrapolated from 2011/12 results
- scenario 1 and 2 ≈ upper and lower bounds
- precision of **6-14%** on μ

ATLAS:

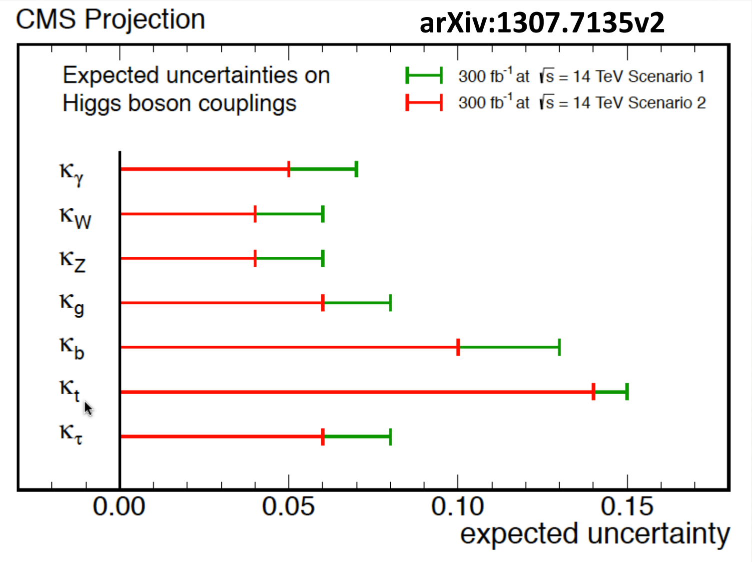
- Based on parametric simulation
- precision of **6-20%** on μ
- Hbb not yet included

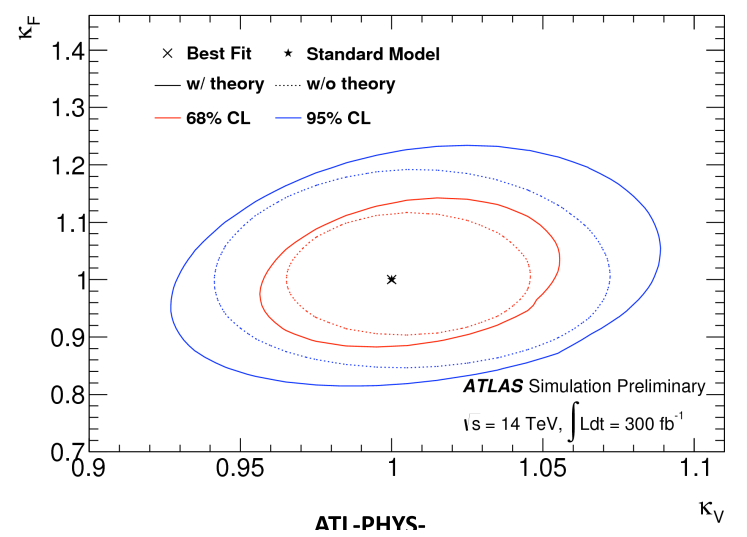
Higgs Couplings (300fb^{-1})

Assumes no extra BSM Higgs decays so absolute couplings can be extracted and minimal coupling fit.

$$\kappa_V = \kappa_Z = \kappa_W$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$$





ATLAS

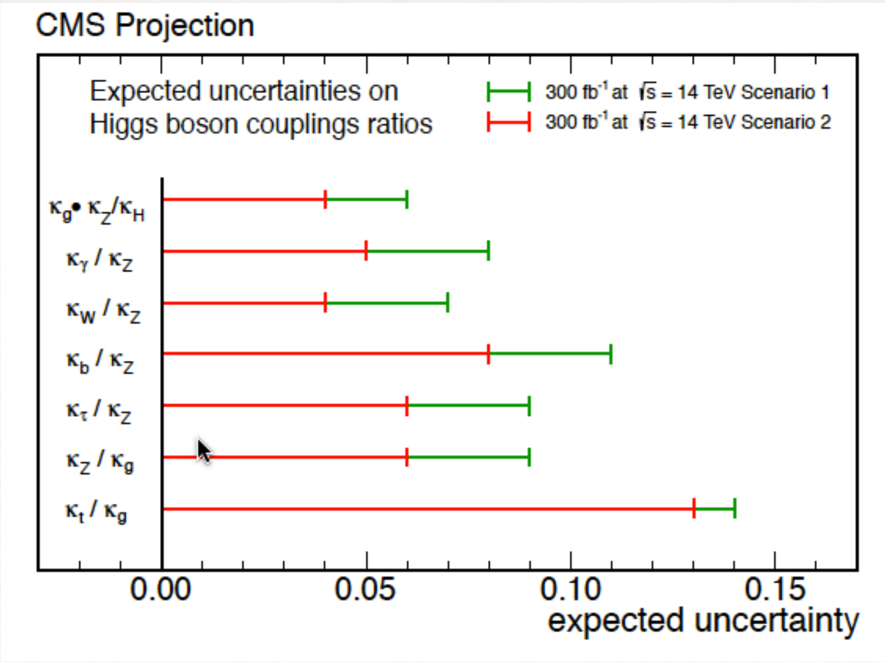
Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None
2	$\kappa_V = \kappa_Z = \kappa_W$	3.3%	2.8%	2.7%
	$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$	8.6%	7.5%	7.1%

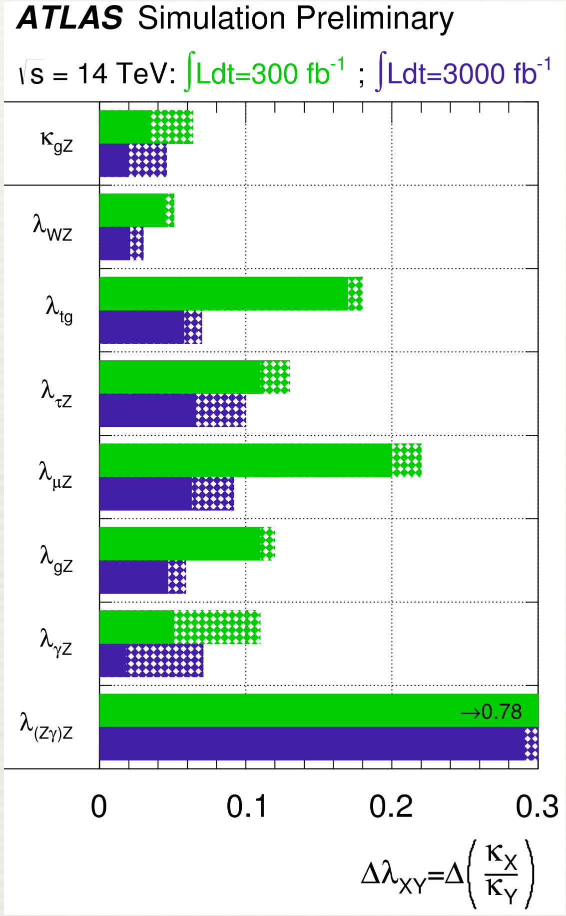
CMS:

- uncertainties on K_i limited by theoretical uncertainties on production and decay rates
- $\sigma(\kappa_V) \approx$ 3-6% $\sigma(\kappa_F) \approx$ 5-15%

Higgs Partial Width Ratios (300fb^{-1})

No assumption on the total Higgs width . Take ratios so many experimental and theoretical uncertainties cancel





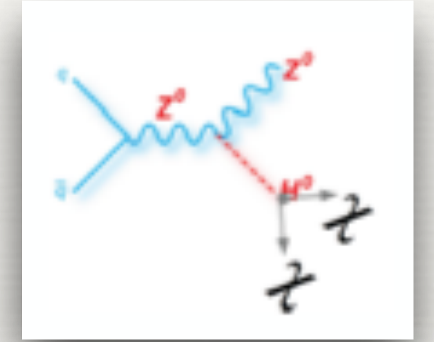
CMS:

With 300 fb-1 the uncertainties on the Higgs coupling scale factor ratios are expected in the range 4-15%

Higgs Mass (300fb^{-1})

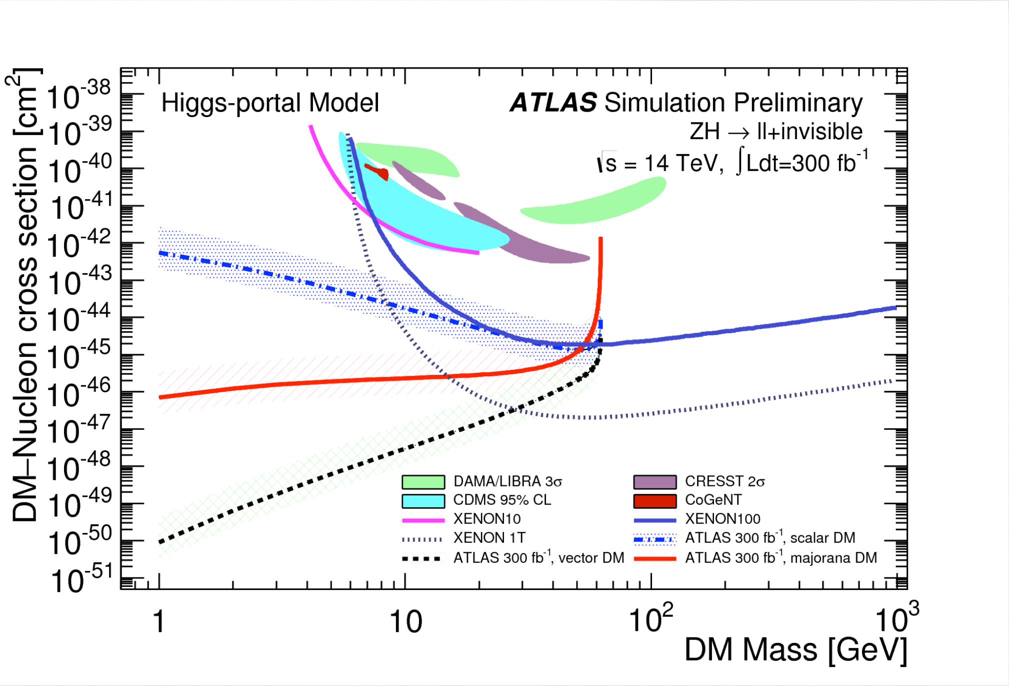
- Increase in Higgs cross section (2x) from 8 TeV to 14 TeV the **statistical uncertainty** is expected to be reduced to:
    - 50 MeV with 300 fb-1
    - 15 MeV with 3000 fb-1
- Precision of the future measurement will likely be dominated by systematics.
- Energy/momentum scale of photons, electrons and muons should improve with increasing statistics.
- Making optimistic assumption that systematics also scales with statistics, the expected **systematic uncertainty** is:
    - 70 MeV with 300 fb-1
    - 25 MeV with 3000 fb-1
- ATLAS 1999 TDR estimates that a relative precision of **0.07%** is achievable with 300 fb^{-1}
- CMS 2007 TDR projects a statistical uncertainty of **0.1%** with 300 fb^{-1}

Invisible Higgs ($300 fb^{-1}$)



Invisible Higgs can be seen as as a portal to Dark Matter

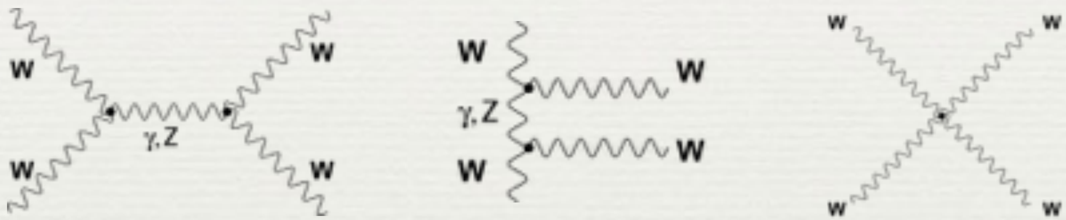
- Indirect constraints:
  - from Higgs coupling fit
  - BR(H->inv) < 28% @ 95% CL
- Direct search:
  - ZHee/μμ+ETmiss
  - BR(H->inv) < 32% @ 95% CL
- Possible to convert the limits on BR(Hinv) into the strenght of the interaction between dark matter and Higgs boson, $\lambda_{H\chi\chi}$
- Bound on $\lambda_{H\chi\chi}$ can be mapped into scattering cross section of dark matter on a nuclei
- Limits from ATLAS at low mass better than those from direct detection limits degrade as m_χ approches $m_H/2$

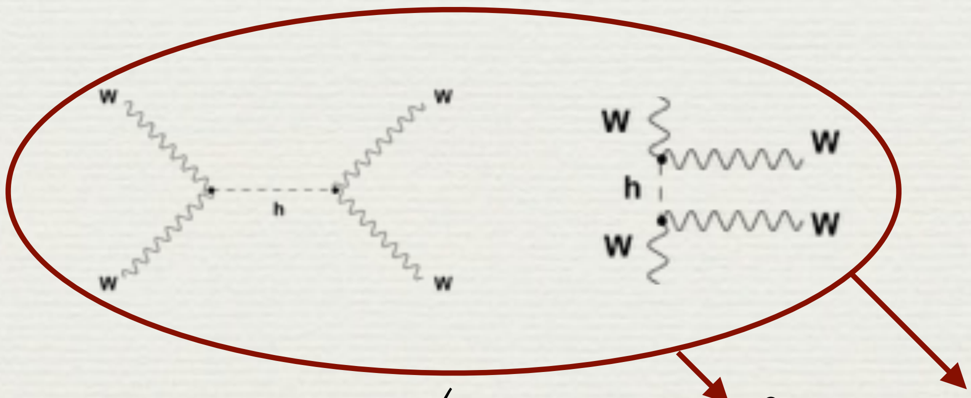


VV Scattering(3000fb^{-1})

HighWithout the Higgs, $W_LW_L \rightarrow W_LW_L$ violates unitarity at $\sqrt{s}$ ~ O(1TeV)

- W, Z masses (longitudinal degrees of freedom) arise from the Higgs mechanism
- Higgs exchange diagrams cancels the divergence making the amplitude finite.
- Complementary to Higgs coupling analysis



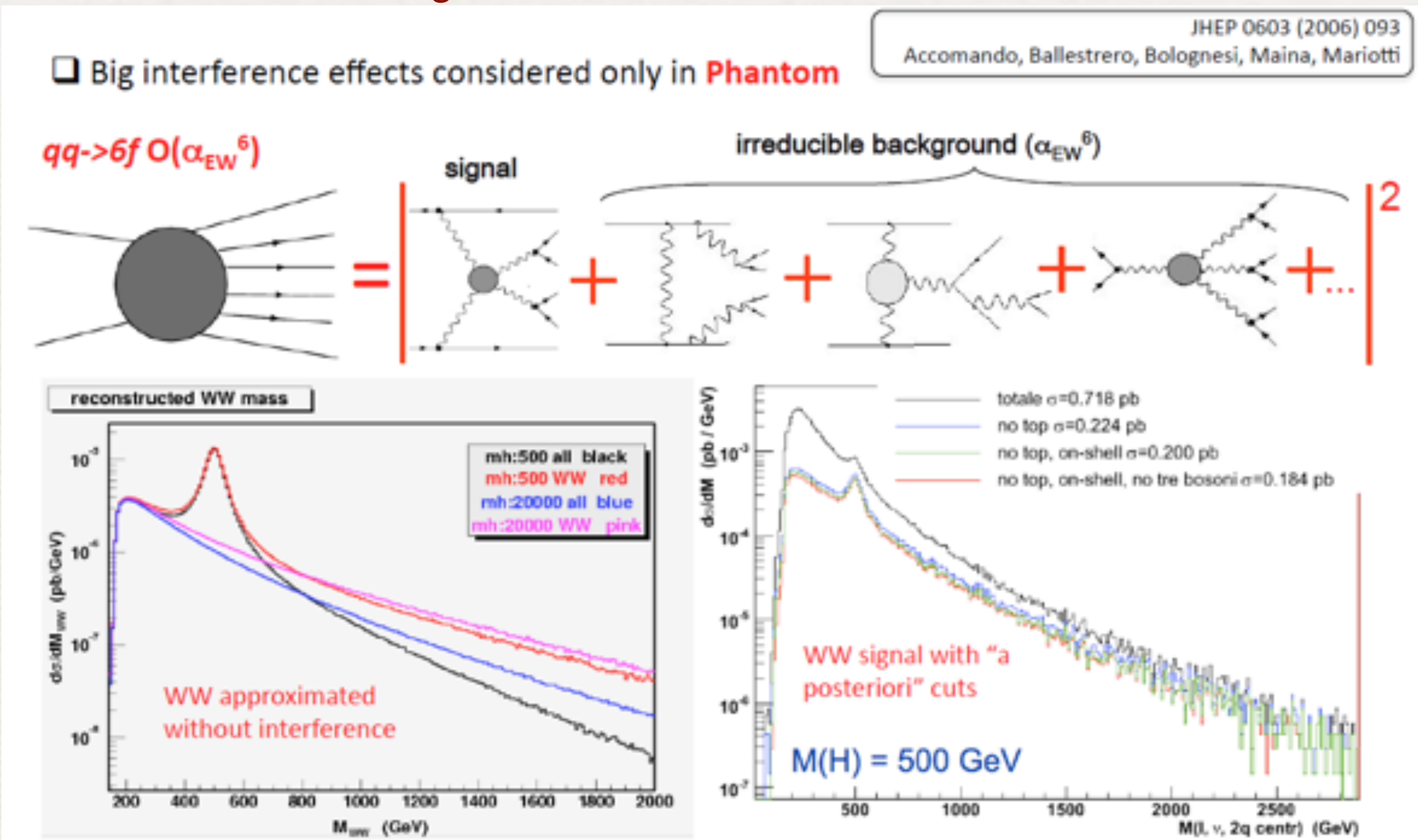


$$A\left(W_L^+W_L^- \;-\; W_L^+W_L^-\right) \approx \frac{1}{v^2}\left(-s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2}\right)$$

VV Scattering: Interference

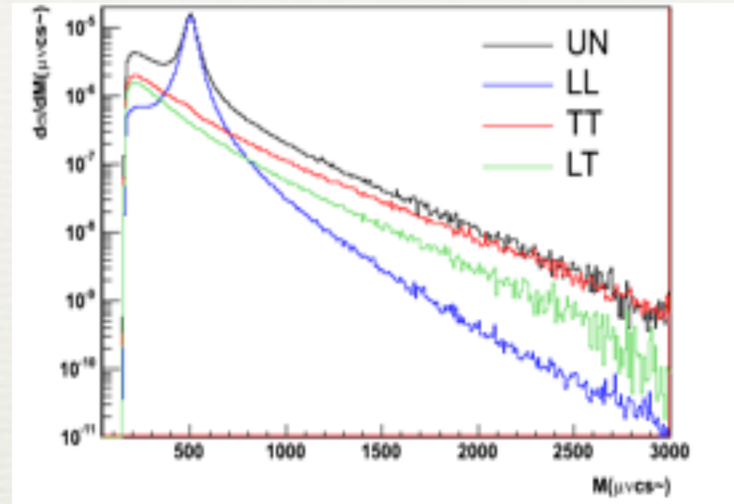
Large interference between signal and irreducible background !

Need to use the full set of diagrams **(signal+irr.background)** and impose kinematics cuts to isolate phase space regions where signal dominates over background

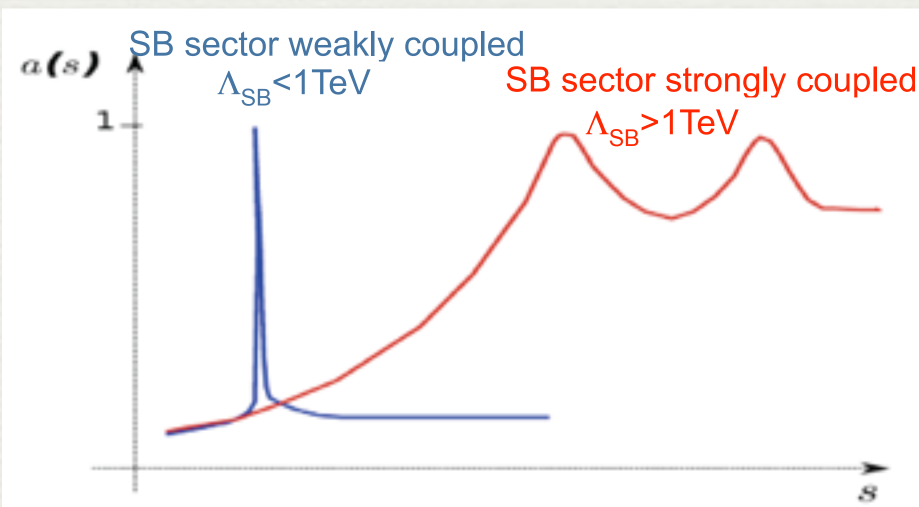


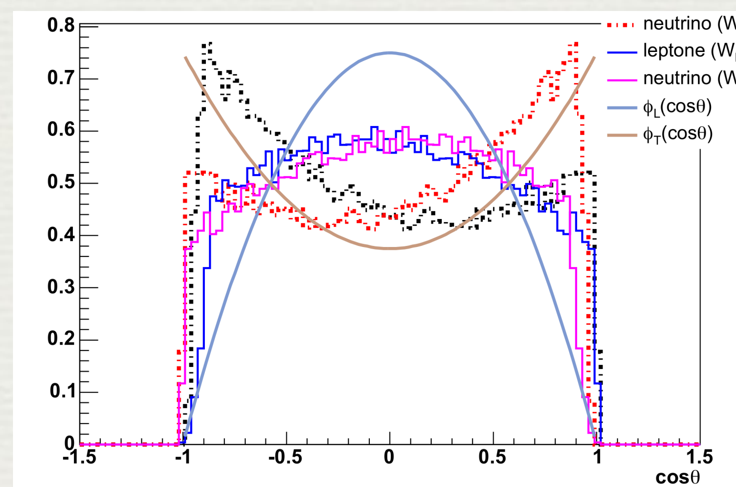
VV Scattering as a EWSB probe

VV Scattering spectrum, σ(VV→VV) is a fundamental probe to test the nature of the Higgs boson and EWSB



- Some BSM models predict TeV resonances "paired" with a light scalar particle(H125) ⇒ search for resonances in VBF spectrum
- Contrary to what one expects LL does not dominate at high mVV , but angular analysis can help …

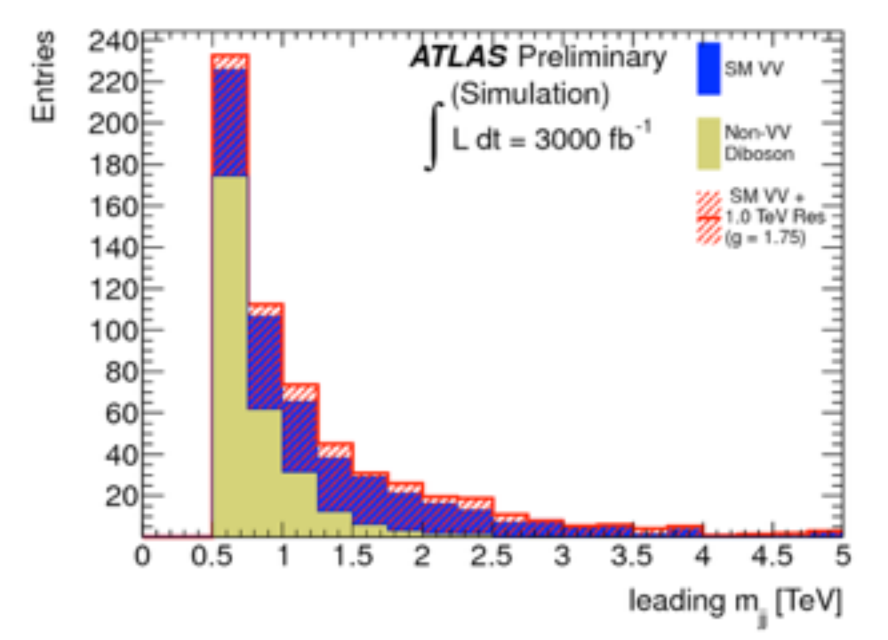




VV Scattering as a EWSB probe

VV Scattering expectations in the fully leptonic mode for 300 and 3000fb^{-1}

- Very low cross section (in 20fb^{-1} CMS expects 0.1 signal events >1TeV)
- Main background is VV+jets
- Sensitivity to anomalous couplings in VBS
- HL-LHC should be able to provide answers to most benchmark cases.



model	$300\,fb^{-1}$	$3000\,fb^{-1}$
$m_{resonance} = 500$ GeV, $g = 1.0$	2.4σ	7.5σ
$m_{resonance} = 1$ TeV, $g = 1.75$	1.7σ	5.5σ
$m_{resonance} = 1$ TeV, $g = 2.5$	3.0σ	9.4σ

Conclusions

- The discovery of the new particle has been confirmed with more data. Now measuring its properties.
- The spin/parity is compatible with a 0+ state (scalar) !
- Mass of the new particle is m_H=125.1 ± 0.2 GeV
- Decays into fermion (τ+b channels) observed with combined significance > 3σ
- Search for rare decays & processes is going on…
- The couplings to bosons and fermions consistent with SM at ~20-30% precision level => Surprises still possible !!!
- A new energy domain with a vast potential for new physics discoveries and precision measurements will open with the Run 2 and Run 3 at √s=13 TeV
- Similar results and projections from ATLAS and CMS in spite of the differences in the assumptions