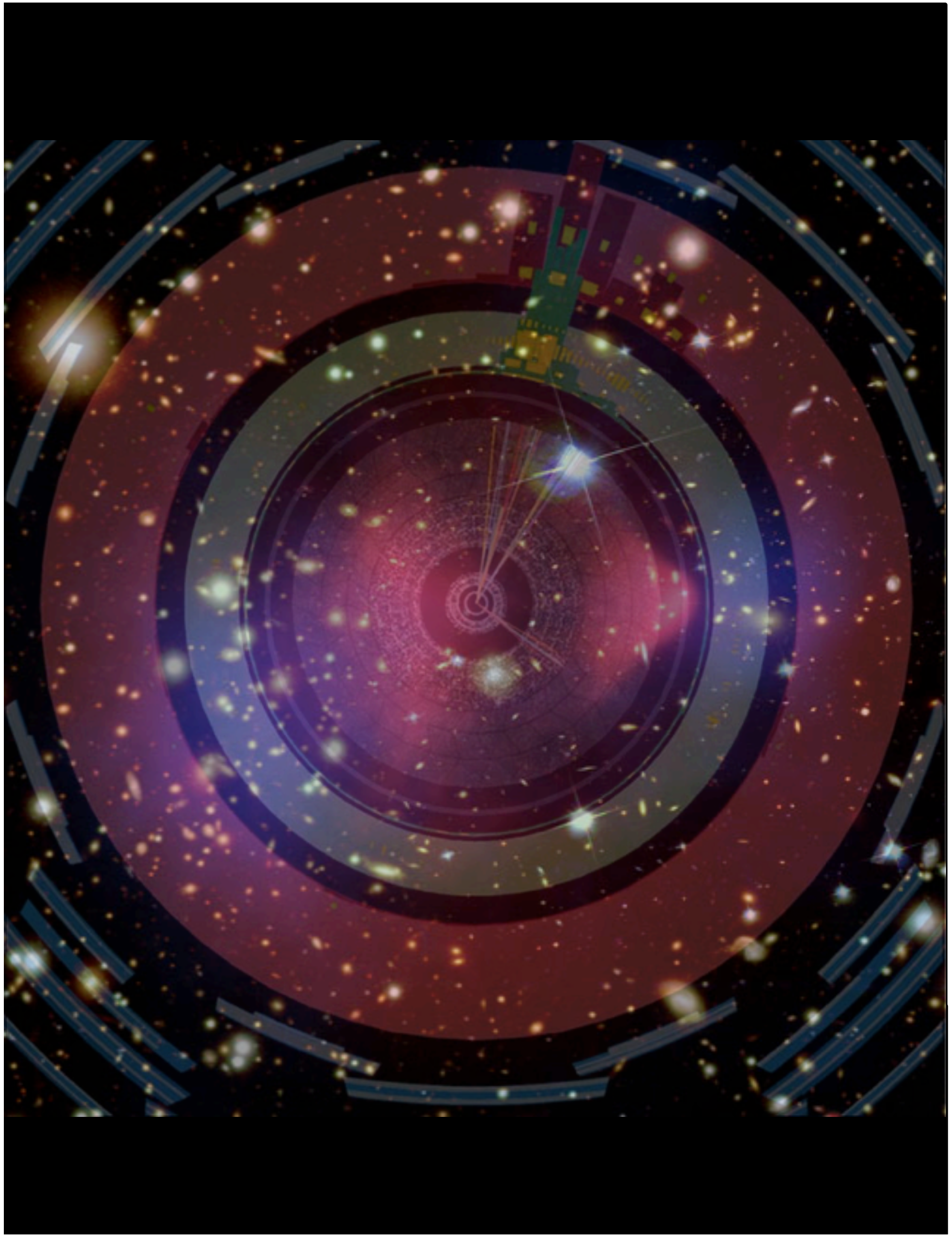


Beyond the Discovery

Exploring Higgs Couplings

Marumi Kado
LAL and CERN

Disclaimer

Apologies for none exhaustive coverage

- Spin, Parity and CP measurements
- Searches for additional states of extended sector
- Searches for exotic Higgs boson decays
- Measurement of fiducial and differential cross sections
- Complete rare decays prospects
- TH Implications (see A. Masiero’s talk)

… Focus on the coupling properties

Three Years of LHC at the Energy Frontier

Two fundamental observations

- The discovery of the approximately 126 GeV (Standard Model-like) Higgs boson: The main missing key piece of the Standard Model!

- Nothing else!

Consequences : See A. Masiero's talk

THE BEH-MECHANISM, INTERACTIONS WITH SHORT RANGE FORCES AND SCALAR PARTICLES

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Entrance of the H^0 in the PDG!

Higgs Bosons — H^0 and $H^\pm$

A REVIEW GOES HERE – Check our WWW List of Reviews

NODE=S055
NODE=S055

CONTENTS:

NODE=S055CNT
NODE=S055CNT

NODE=S055CNT

H^0 (Higgs Boson)

NODE=S055210

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

NODE=S055210

H^0 MASS

NODE=S055HBM
NODE=S055HBM

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT	
125.9±0.4 OUR AVERAGE					
125.8±0.4±0.4	[1] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV	
126.0±0.4±0.4	[2] AAD	12AI	ATLS	pp, 7 and 8 TeV	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
126.2±0.6±0.2	[3] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV	OCCUR=2
125.3±0.4±0.5	[4] CHATRCHYAN	12N	CMS	pp, 7 and 8 TeV	

[1] Combined value from ZZ and $\gamma\gamma$ final states. NODE=S055HBM;LINKAGE=CA

[2] AAD 12AI obtain results based on 4.6–4.8 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 5.8–5.9 fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.9 σ is observed at m_{H^0} = 126 GeV. See also AAD 12DA. NODE=S055HBM;LINKAGE=AA

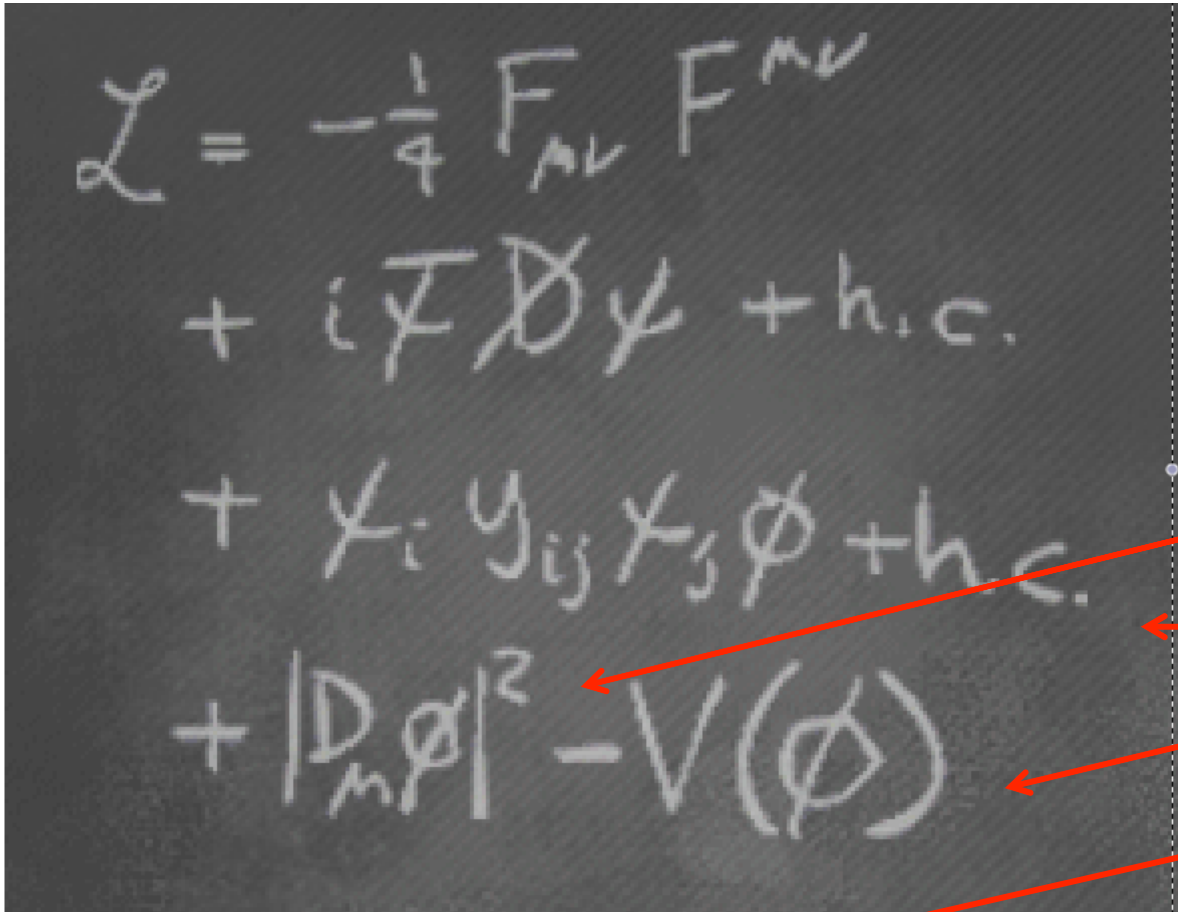
[3] Result based on $ZZ \rightarrow 4\ell$ final states in 5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 12.2 fb^{-1} at E_{cm} = 8 TeV. NODE=S055HBM;LINKAGE=CT

[4] CHATRCHYAN 12N obtain results based on 4.9–5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 5.1–5.3 fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.0 σ is observed at about m_{H^0} = 125 GeV. See also CHATRCHYAN 12BY. NODE=S055HBM;LINKAGE=CH

Inaugural entrance of the Higgs boson in the PDG particle listing !
(not anymore as an hypothetical particle)

$$H^0$$

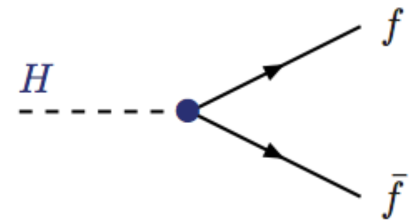
Outline: The Higgs Couplings and Interpretations



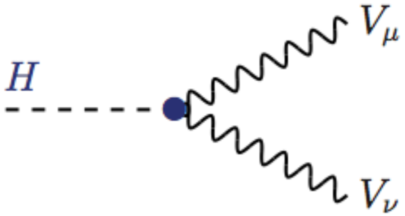
H^0

- Gauge bosons
- Fermions
- Itself
- …and more

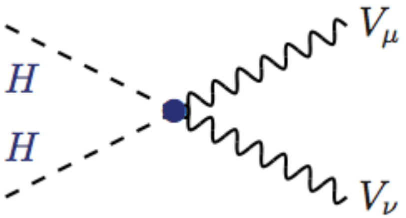
+ Dark matter ?
+ BSM ?



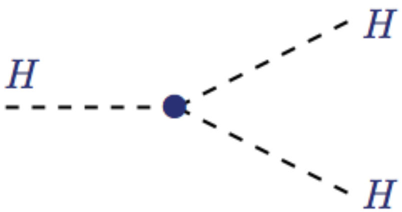
$$g_{Hff} = m_f/v$$



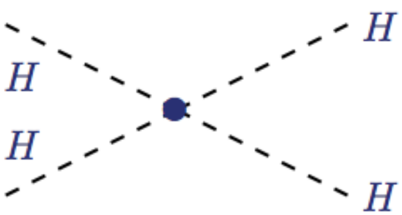
$$g_{HVV} = 2M_V^2/v$$



$$g_{HHVV} = 2M_V^2/v^2$$



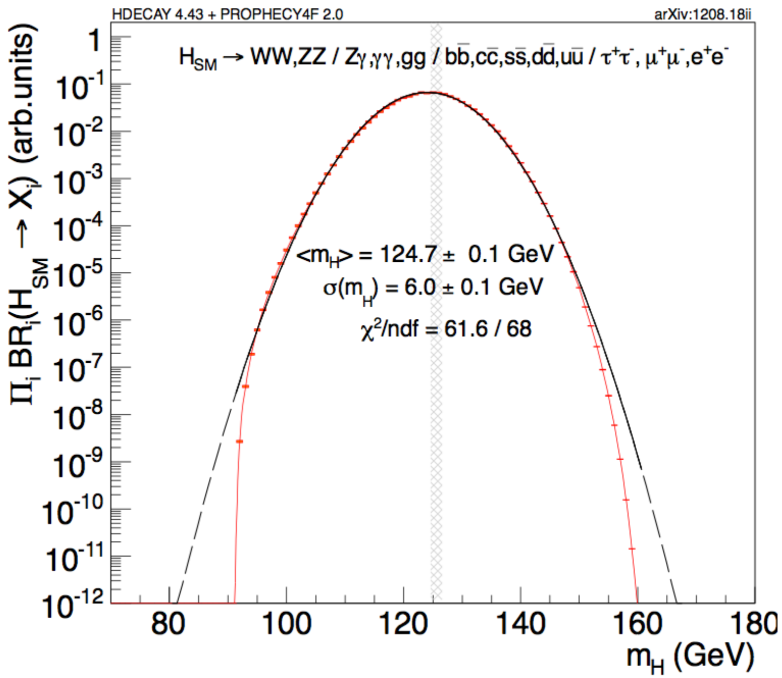
$$g_{HHH} = 3M_H^2/v$$



$$g_{HHHH} = 3M_H^2/v^2$$

Measuring the Coupling Properties of the Observed State

For the time being only test the bosonic and fermionic sector



The Higgs Natural Width Problem

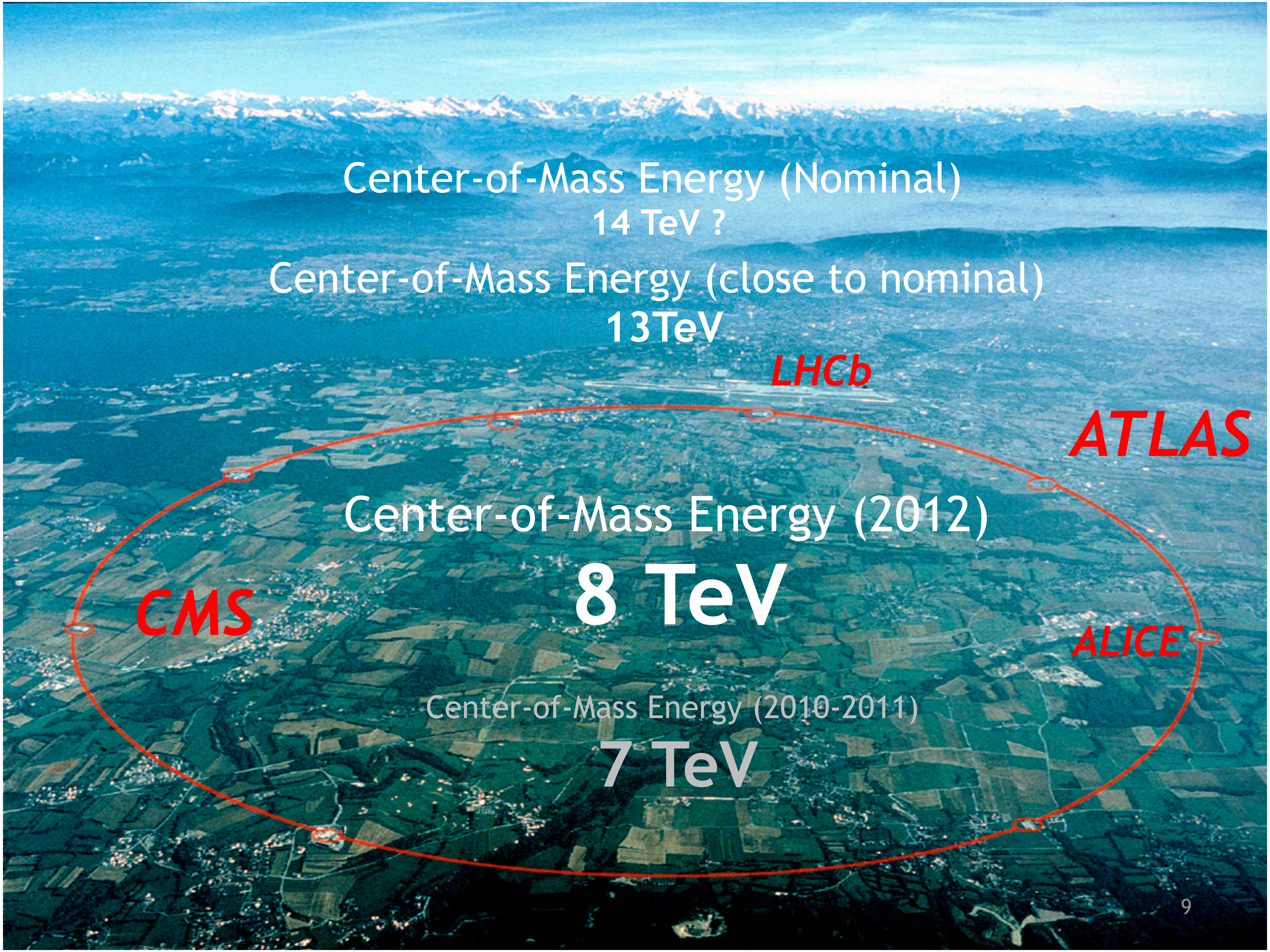
At LHC no direct access to the Higgs total cross section (unlike e^+e^- collider from recoil mass spectrum)

- Total width (4 MeV) too tiny to be meaningfully measured experimentally from lineshape

- New observed state can decay invisibly. Direct search possible at LHC

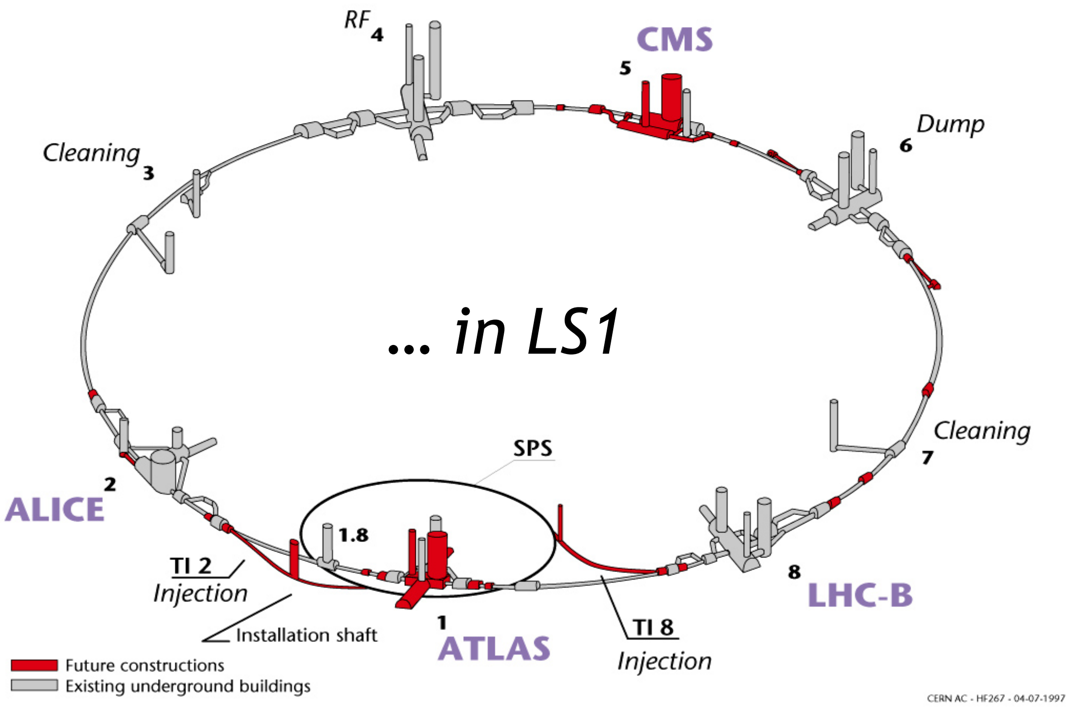
- New observed state can decay to *a priori* visible decay products but not distinguishable from background. In this case no experimental handle

The total width cannot be measured without further assumptions on the couplings of the visible states.



Center-of-Mass Energy (Nominal)
14 TeV ?
Center-of-Mass Energy (close to nominal)
13TeV
LHCb
ATLAS
Center-of-Mass Energy (2012)
8 TeV
CMS
ALICE
Center-of-Mass Energy (2010-2011)
7 TeV

Three Years of LHC operations at the Energy frontier



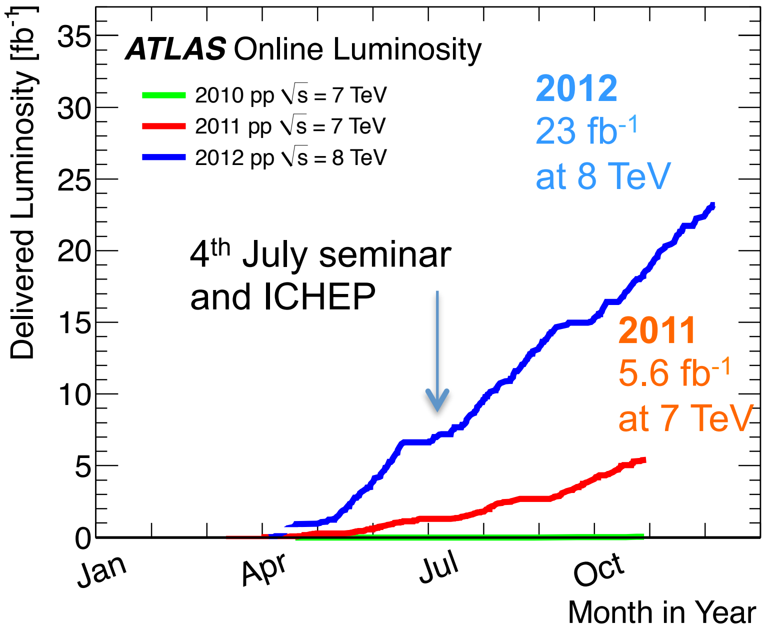
The LHC

- Circumference 27 km
- Up to 175 m underground
- Total number of magnets 9 553
- Number of dipoles 1 232
- Operation temperature 1.9 K (Superfluid He)

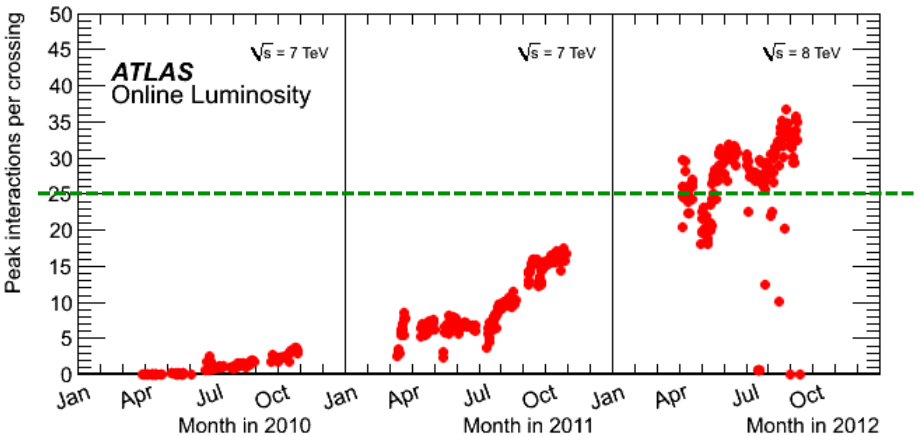
$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Parameter	2010	2011	2012	Nominal
C.O.M Energy	7 TeV	7 TeV	8 TeV	14 TeV
N_p	1.1 10^{11}	1.4 10^{11}	1.6 10^{11}	1.15 10^{11}
Bunch spacing / k	150 ns / 368	50 ns / 1380	50 ns /1380	25 ns /2808
ε (mm rad)	2.4-4	1.9-2.3	2.5	3.75
β* (m)	3.5	1.5-1	0.6	0.55
L ($cm^{-2}s^{-1}$)	2×10^{32}	3.3×10^{33}	~7×10^{33}	10^{34}

The first LHC run



2010
0.05 fb^{-1}
at 7 TeV

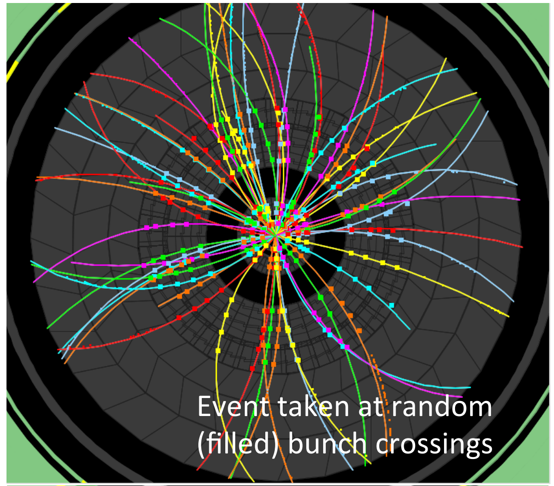


Design value
(expected to be
reached at L=10^{34} !)

2010

O(2) Pile-up events

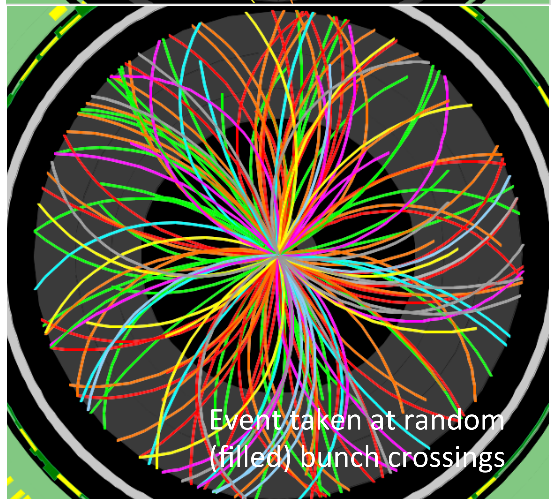
150 ns inter-bunch spacing



2011

O(10) Pile-up events

50 ns inter-bunch spacing

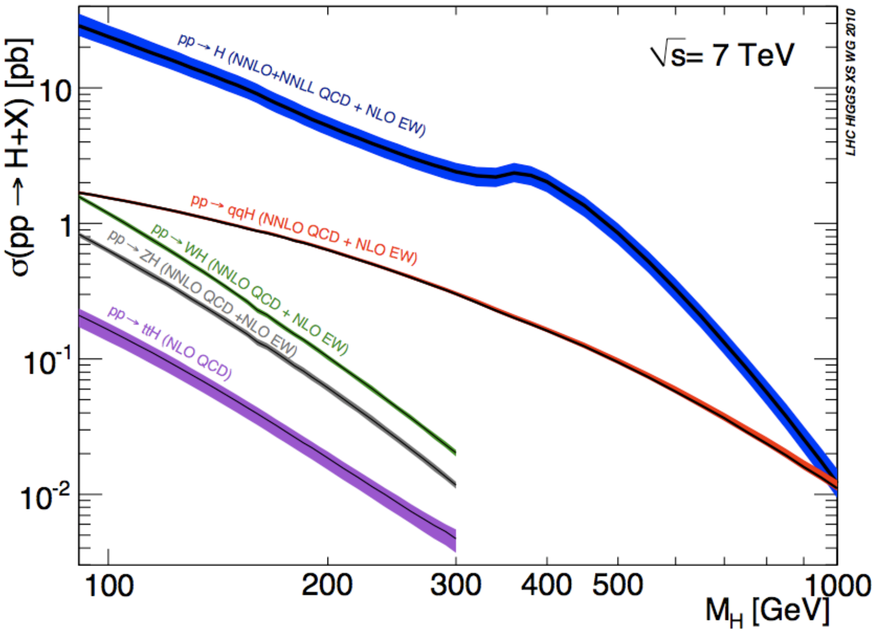


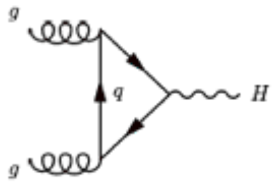
2012

O(20) Pile-up events

50 ns inter-bunch spacing

The Main Production Modes at the LHC

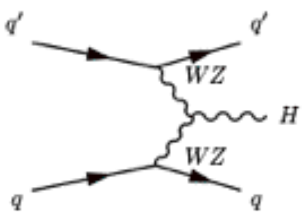




- Gluon fusion process :

Dominant process known at NNnLO TH uncertainty ~O(10%)

~0.5 M events produced!

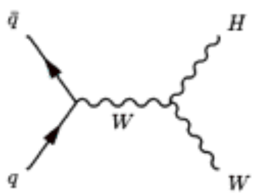


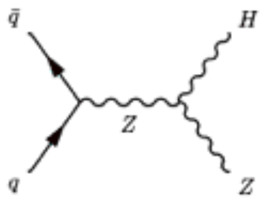
- Vector Boson Fusion :

known at NLO TH uncertainty ~O(5%)

Distinctive features with two forward jets and a large rapidity gap

~40 k events produced!



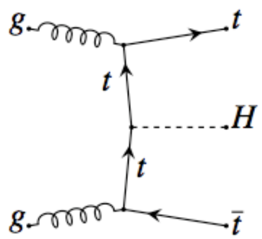


- W and Z Associated Production :

known at NNLO TH uncertainty ~O(5%)

Very distinctive feature with a Z or W decaying leptonically

~20 k events produced!



- Top Associated Production :

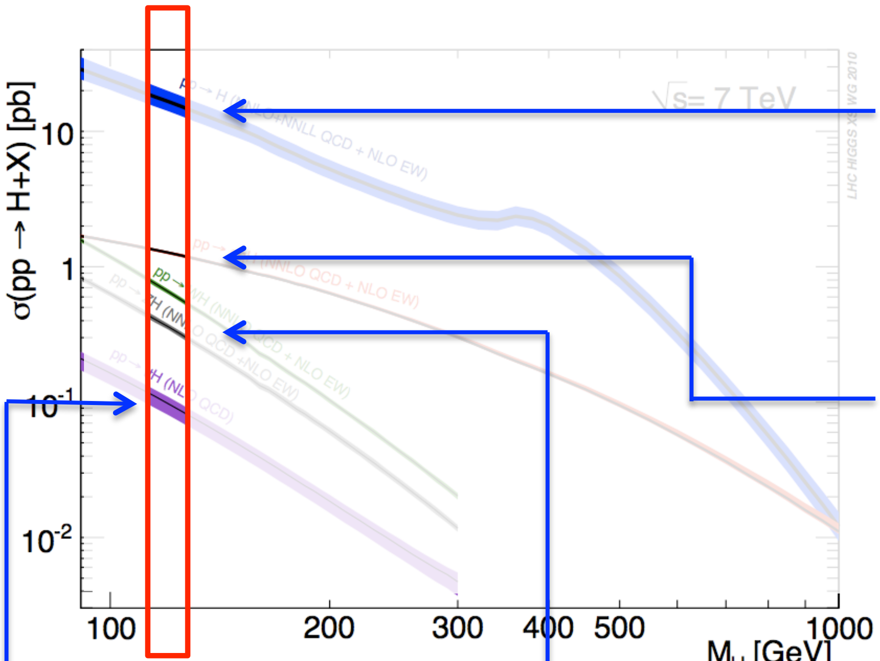
known at NLO TH uncertainty ~O(15%)

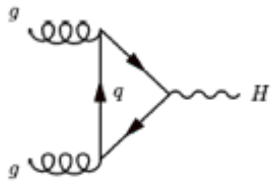
Quite distinctive but also quite crowded

~3 k events produced!

* TH uncertainty mostly from scale variation and PDFs, $\delta\sigma_{PDF\text{-}\alpha s}$~8-10% and $\delta\sigma_{Scale}$~ 7-8%

The Main Production Modes at the LHC





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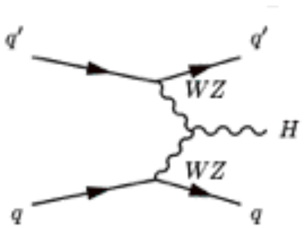
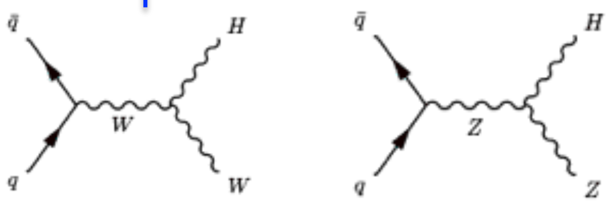


- Vector Boson Fusion :

known at NLO TH uncertainty ~O(5%)

Distinctive features with two forward jets and a large rapidity gap

~40 k events produced!



- W and Z Associated Production :

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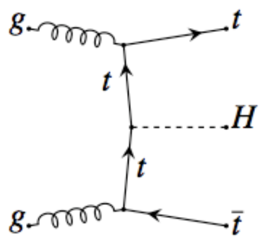
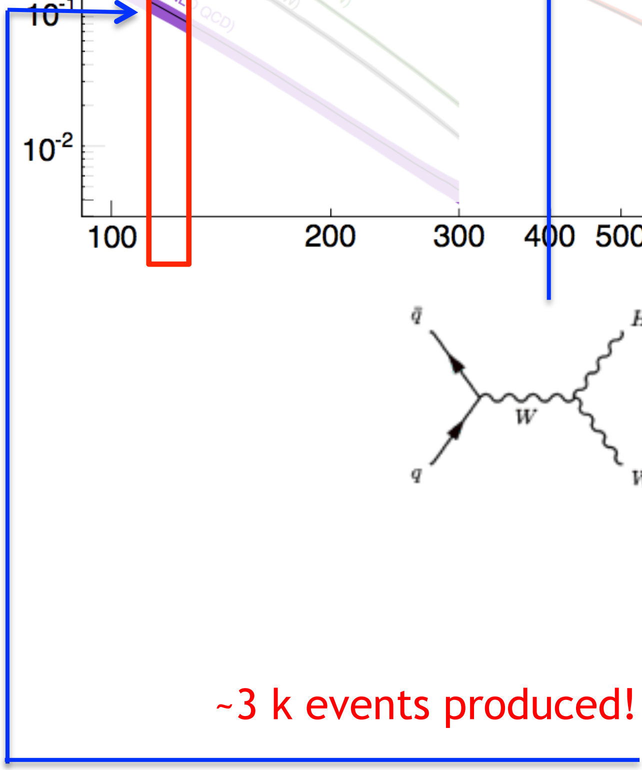
Very distinctive feature with a Z or W decaying leptonically

~20 k events produced!





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Quite distinctive but also quite crowded

* TH uncertainty mostly from scale variation and PDFs, $\delta\sigma_{PDF\text{-}\alpha s}$~8-10% and $\delta\sigma_{Scale}$~ 7-8%

Decay Modes

- Dominant decay mode b (57%)

Very large backgrounds, associated production W,Z H and Boost!

- The $\tau\tau$ channel (6.3%)

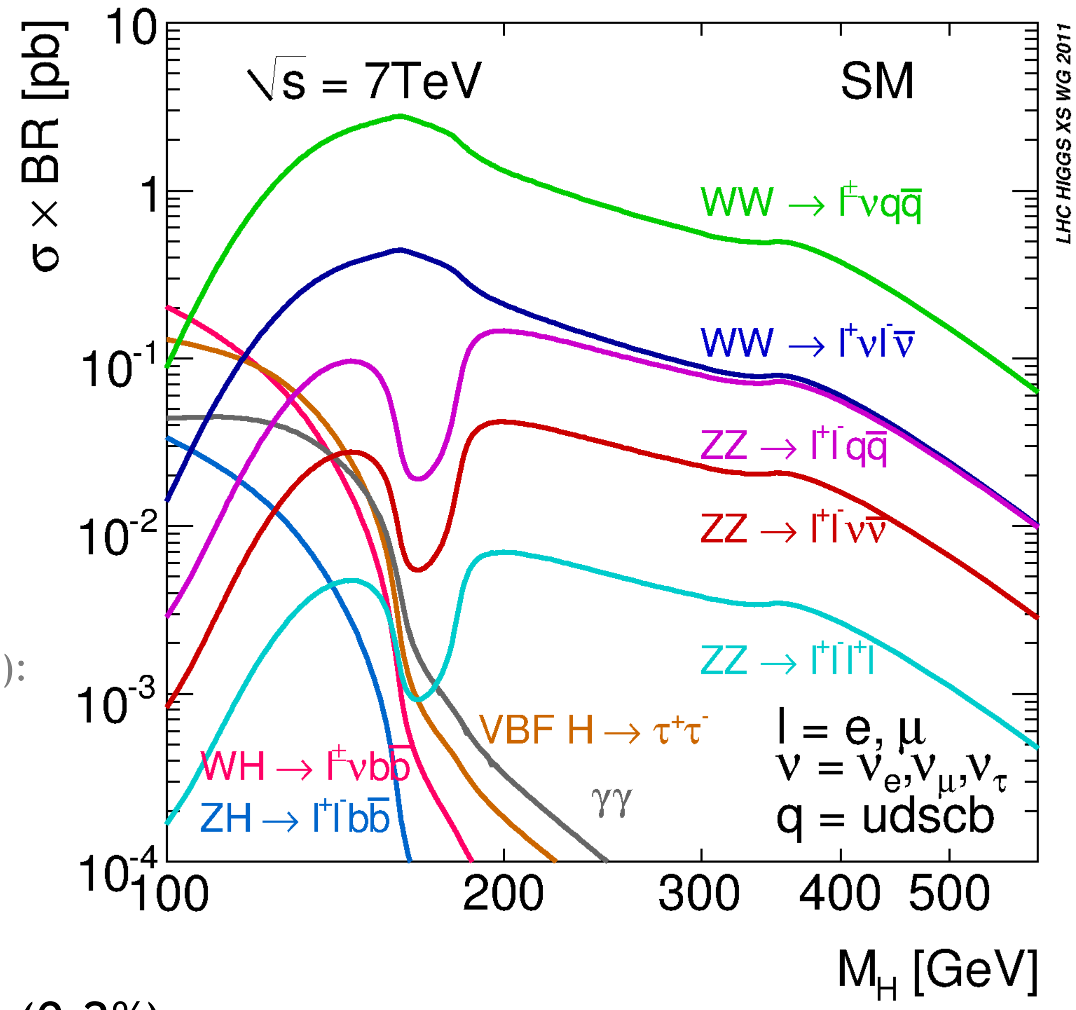
VBF, VH, but also ggF with new mass reconstruction techniques

- The $\gamma\gamma$ channel (0.2%)

Discovery channel, high mass resolution (High stat, and backgrounds)

- The ZZ Channel (3%)
  - Subsequent all leptons decays (low statistics): golden channel
  - llqq and llvv sensitive mostly at high mass

- The WW Channel (22%)
  - Subsequent lvlv very sensitive channel
  - lvqq sensitive mostly at high mass



- The $\mu\mu$ channel (0.02%) and Zγ (0.2%)

Low statistics from the low branching in $\mu\mu$ or both the low branching and subsequent decay in leptons (Zγ)

- The cc channel (3%) Very difficult

Decay Modes

- Dominant decay mode b (57%)

Very large backgrounds, associated production W,Z H and Boost!

- The ττ channel (6.3%)

VBF, VH, but also ggF with new mass reconstruction techniques

- The γγ channel (0.2%)

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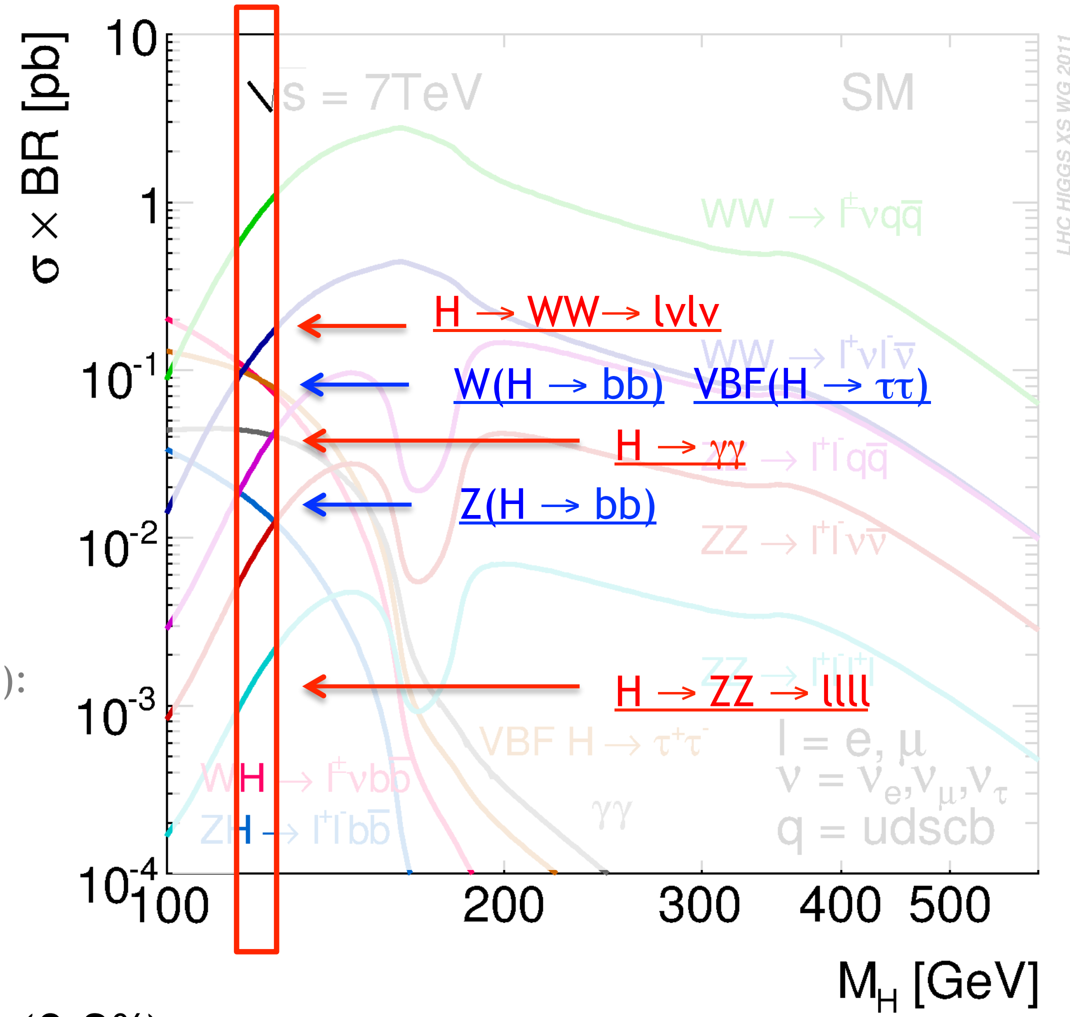


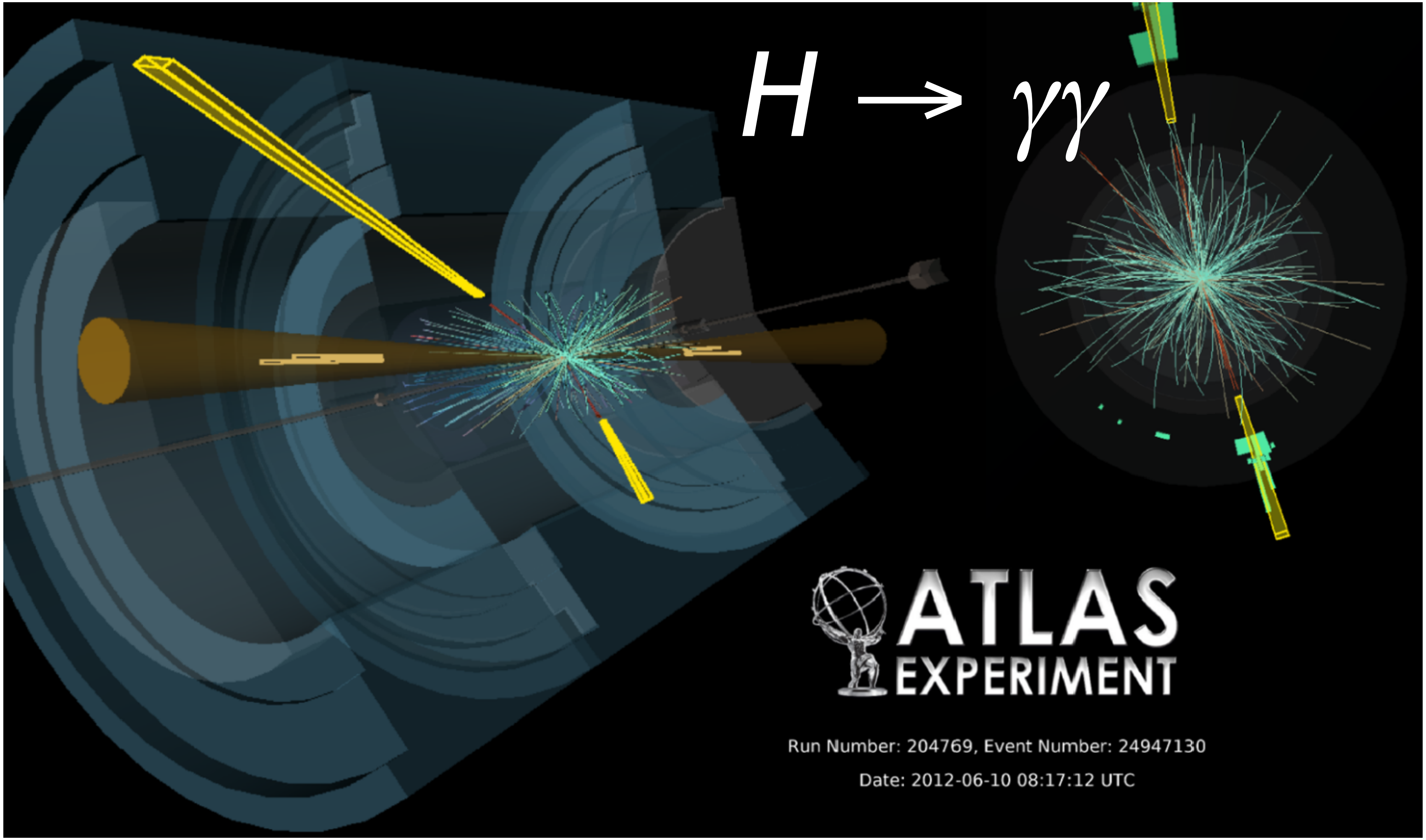
- The μμ channel (0.02%) and Zγ (0.2%)

Low statistics from the low branching in μμ or both the low branching and subsequent decay in leptons (Zγ)

- The cc channel (3%) Very difficult

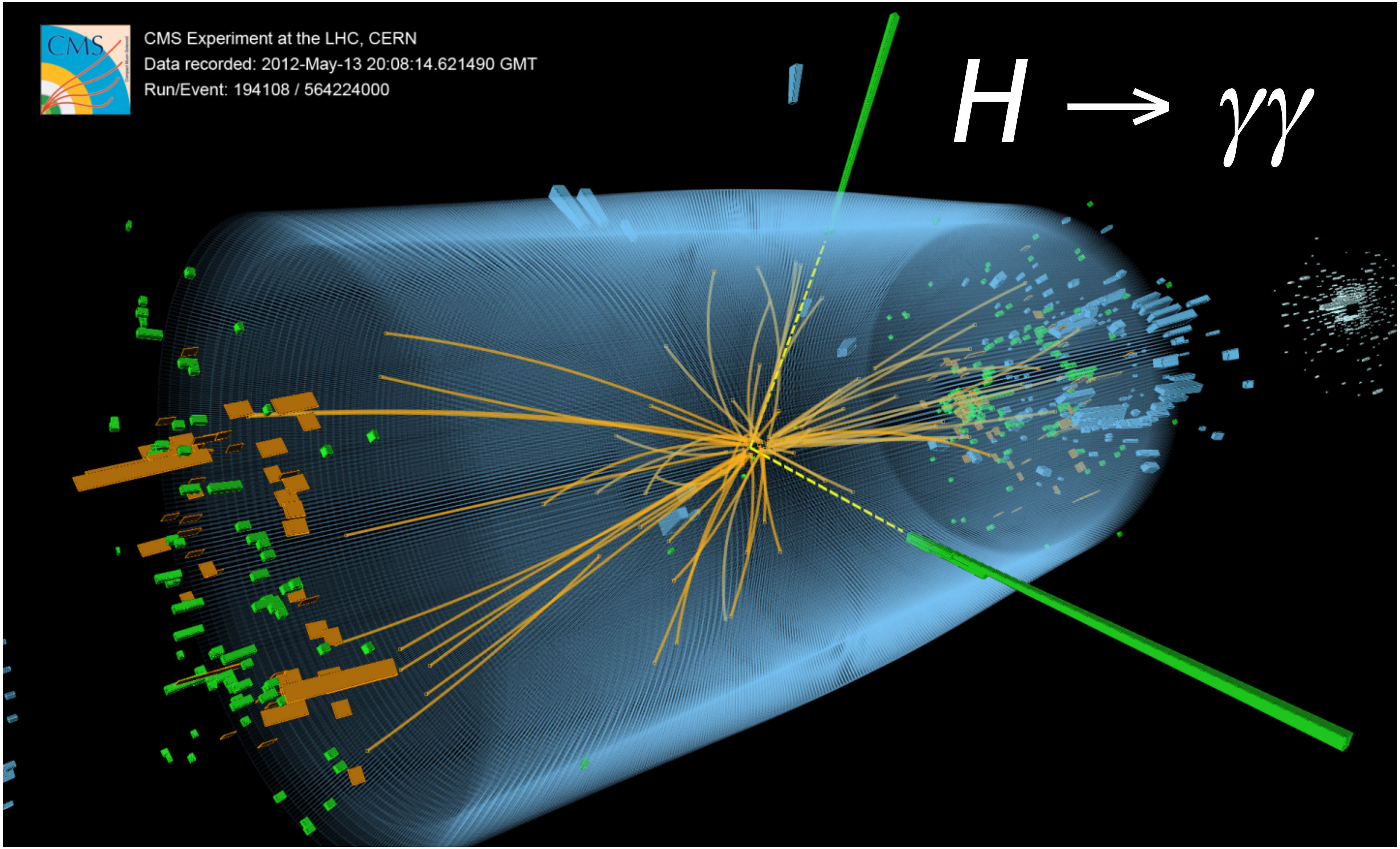
Channels investigated

Channel categories	ATLAS				CMS				TeVatron	
	ggF	VBF	VH	ttH	ggF	VBF	VH	ttH	VH	ggF
$\gamma\gamma$	✓	✓	✓	✓	✓	✓	✓	✓	(inclusive) ✓	
ZZ (llll)	✓	✓			✓	✓			✓	
WW ($l\nu l\nu$)	✓	✓	✓		✓	✓	✓	✓	✓	✓
$\tau\tau$	✓	✓	✓		✓	✓	✓	✓	✓	
H (bb)			✓	✓		✓	✓	✓	✓	
$Z\gamma$	(inclusive) ✓				✓	✓				
$\mu\mu$	(inclusive) ✓									
Invisible	(✓)		✓			✓	✓			



γγ channel basic facts :

- Ns ~ O(500) per experiment
- Signal purity ~ 2% - 60%



γγ channel basic facts :

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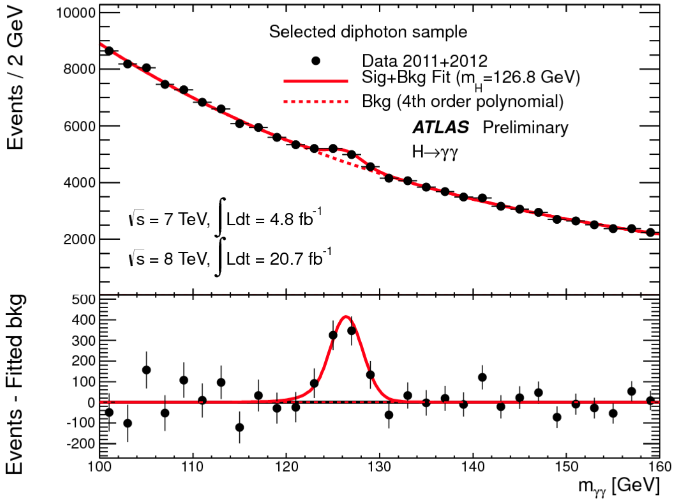
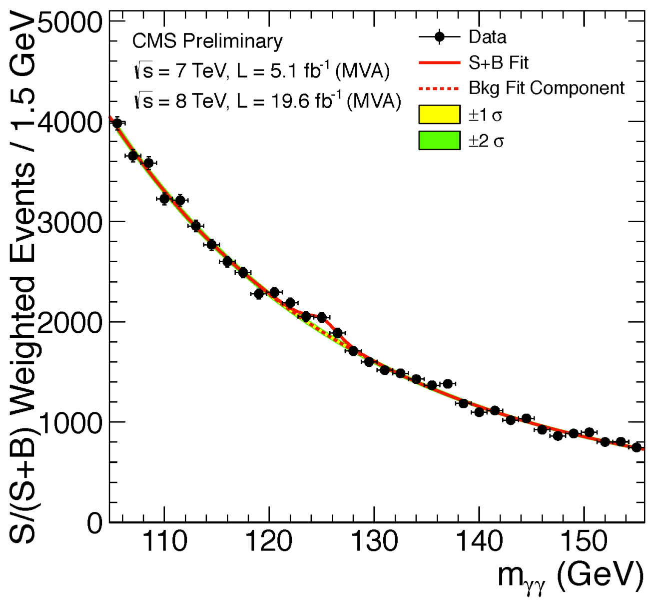
$H \rightarrow \gamma\gamma$



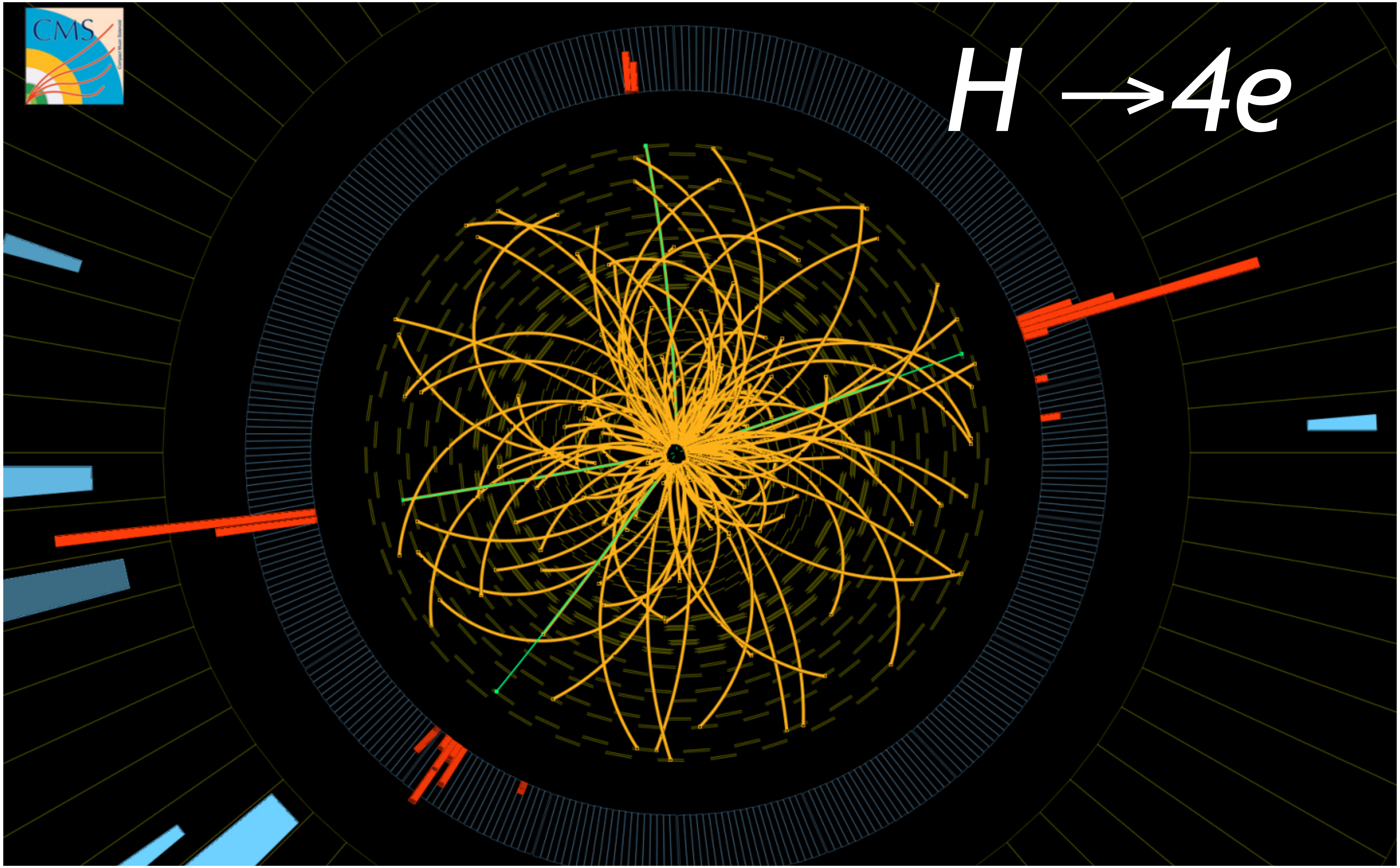


Analysis strategy:

- **Di-photon mass** is the key observable
- two isolated high-p_T photons
  - vertex
    - CMS: from recoiling charged particles
    - ATLAS: from photon pointing (longitudinal ECAL segmentation)
  - split events into exclusive categories:
    - untagged, and further divided into 4/9 classes based on
      - expected mass resolution
      - expected S/B-ratio
    - di-jet tagged (VBF), and further divided into 2 classes based on
      - expected S/B-ratio
    - ATLAS: low mass di-jet tag (VH)
    - MET-tagged (VH)
    - lepton-tagged (VH)
  - background: from $m_{\gamma\gamma}$ distribution (in the sidebands)

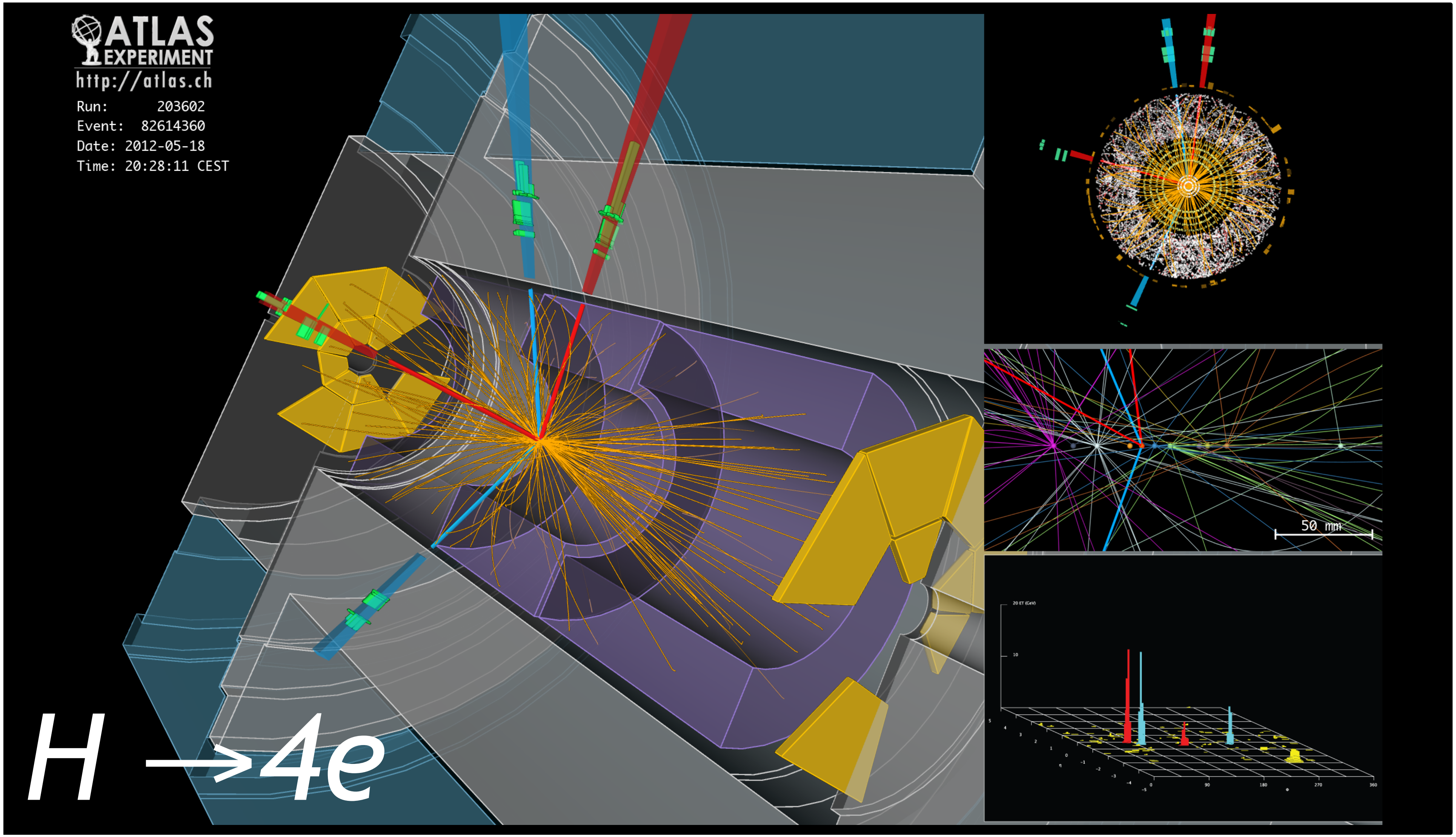
Key Analysis Features to note:

- Small S/B-ratio,
- High event yield
- di-photon mass resolution = 1-2%



4l channel basic facts :

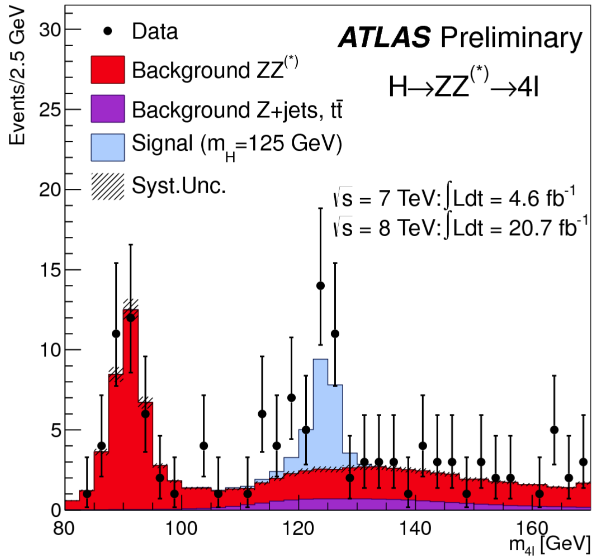
- Ns ~ O(15-20) per experiment
- Signal purity > 1.5

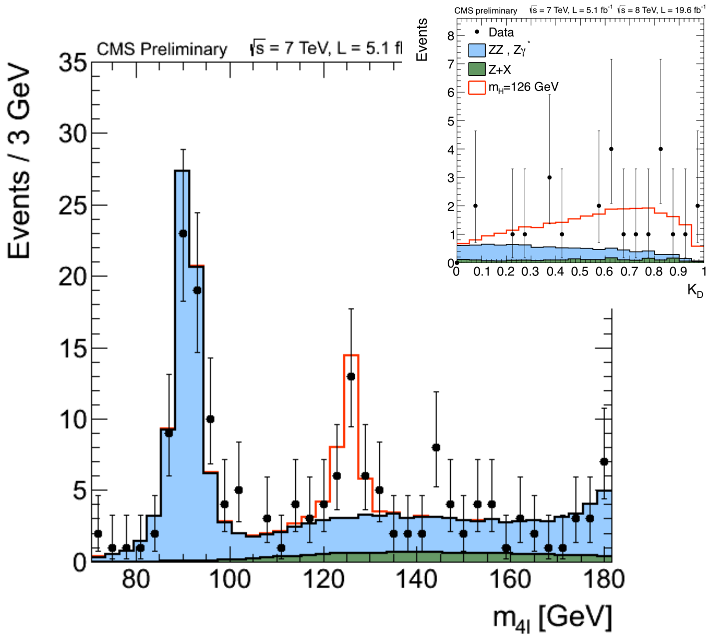


4l channel basic facts :

- Ns ~ O(15-20) per experiment
- Signal purity > 1.5

$$H \to ZZ^{*} \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$$





Analysis strategy:

four prompt leptons (low p_T is important!)

four-lepton mass is the key observable

split events into 4e, 4μ, 2e2μ channels:

Different resolutions and S/B rates

CMS specificities:

- **ME-based discriminant K_D**
- Per event (mass) errors

split events further into exclusive categories:

untagged (CMS: add a 3rd observable: **four-lepton p_T/m**)

di-jet tagged (CMS: add a 3rd observable: $\mathbf{V_D(m_{jj}, \Delta\eta_{jj})}$)

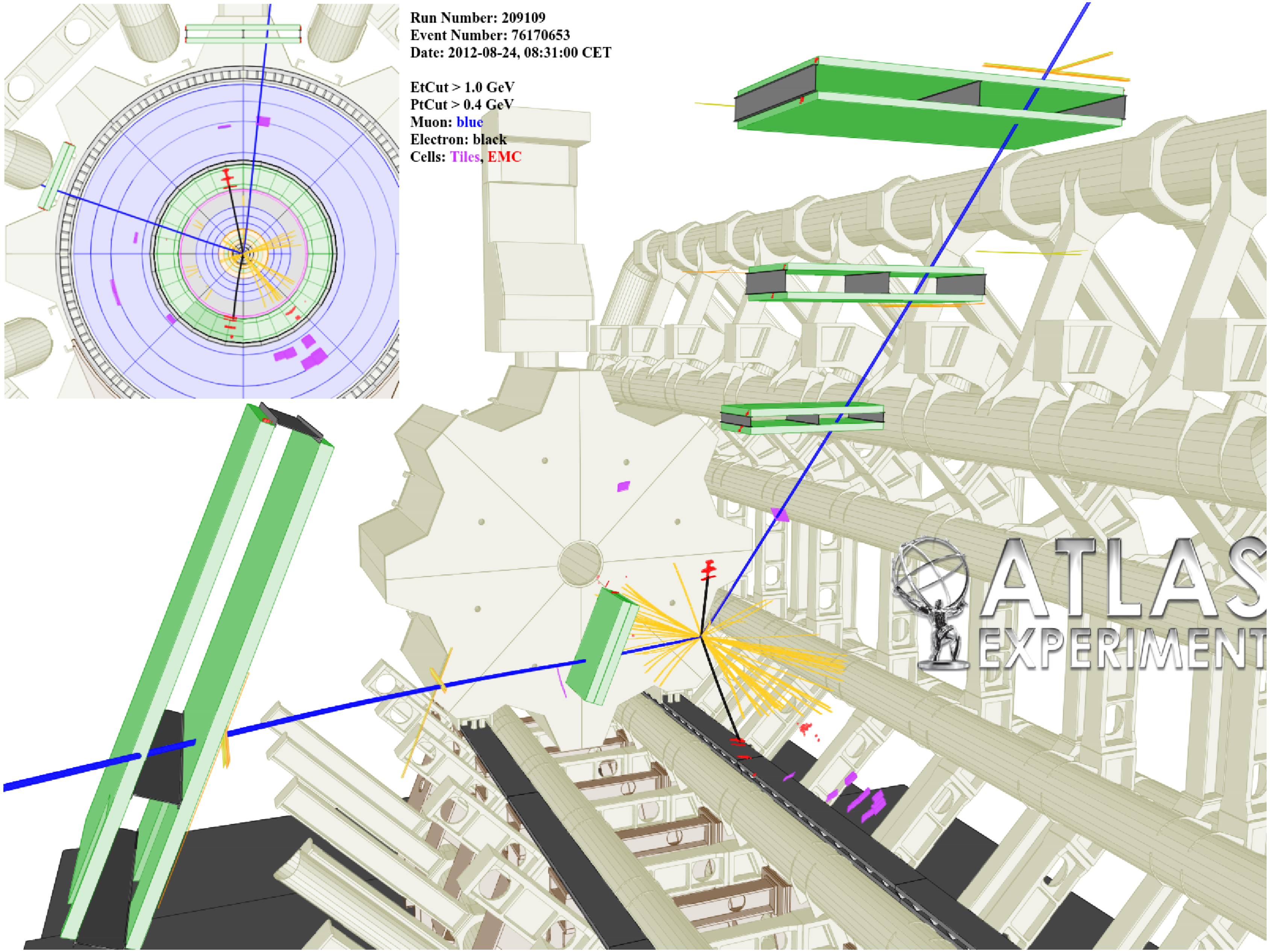
Analysis key features:

High S/B-ratio,

But small event yield

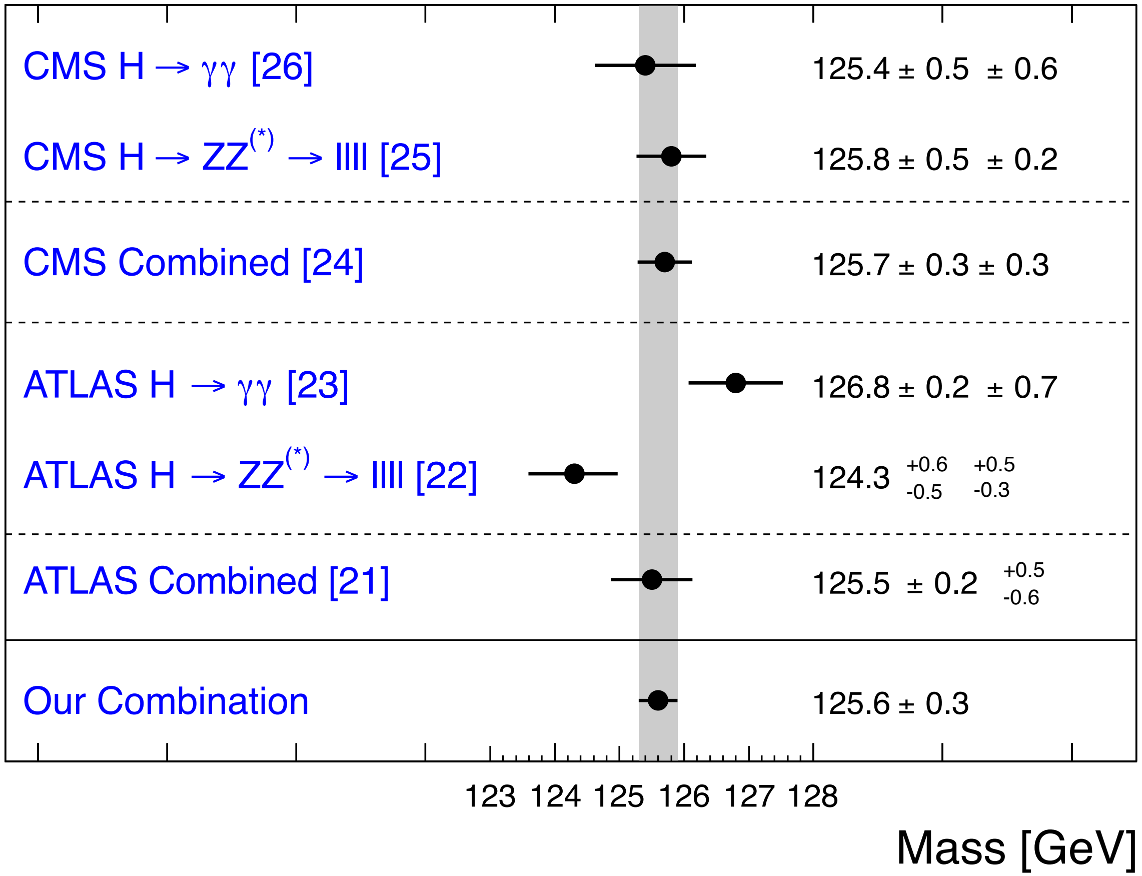
mass resolution = 1-2%

$H \rightarrow 4l$ Single Highest Purity Candidate Event ($2e2\mu$)



The Mass of the Higgs Particle

Review of mass measurements across channels and experiments



Final word on mass and μ from both ATLAS and CMS will require final Run I calibration

- Unofficial combination

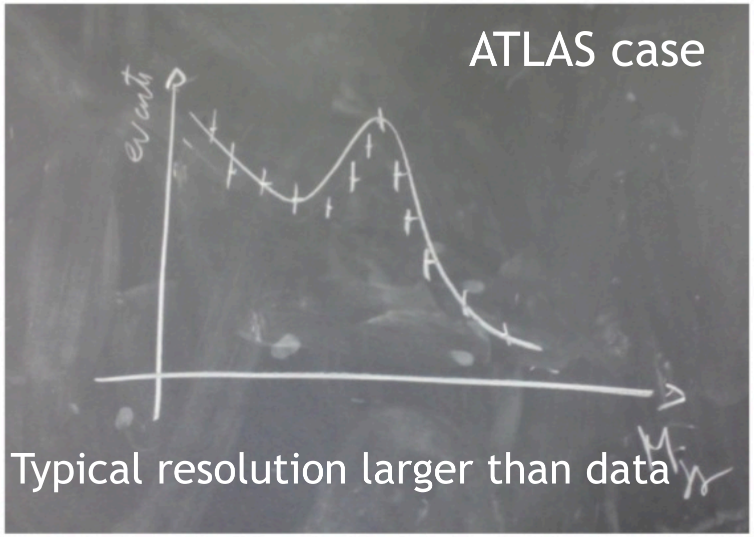
χ^2 Probability of 13%

The long standing ATLAS "excess" in diphoton rate

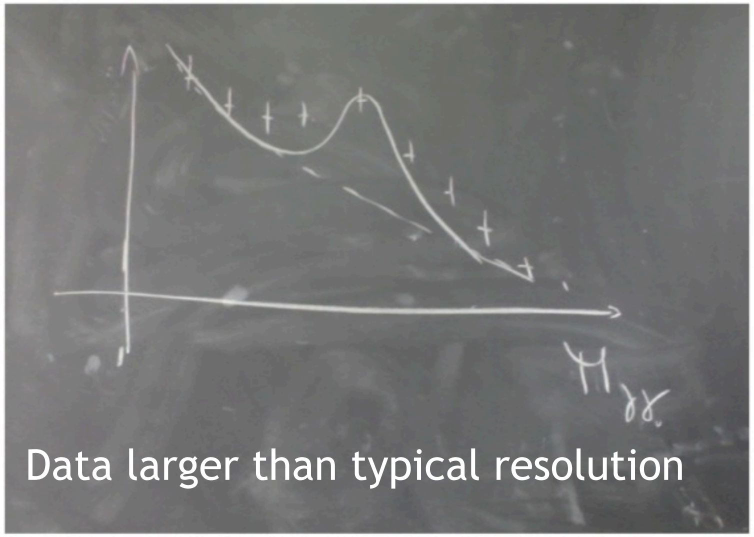
The compatibility in the signal strength parameter between the data and the SM Higgs boson signal plus background hypothesis is estimated with the test statistic $\lambda(\mu)$ with $\mu = 1$ [4], and is found to be at the 2.3 σ level.

The results reported above are extracted from a fit in which the mass resolution uncertainty, which is ~20%, is treated as a nuisance parameter with a Gaussian constraint. As a check, the fit was repeated with no constraint on the mass resolution parameter, giving $\mu = 1.49 \pm 0.33$ (1.8 σ compatibility with the SM Higgs boson signal hypothesis). This fit prefers a narrower mass resolution than the nominal one by 1.8 σ, which is better than the resolution corresponding to a perfectly uniform calorimeter. Dedicated studies revealed no indication that the systematic uncertainty on the resolution is underestimated; the large pull in this test fit can also be a statistical effect arising from background fluctuations.

Higher prob. to overestimate μ

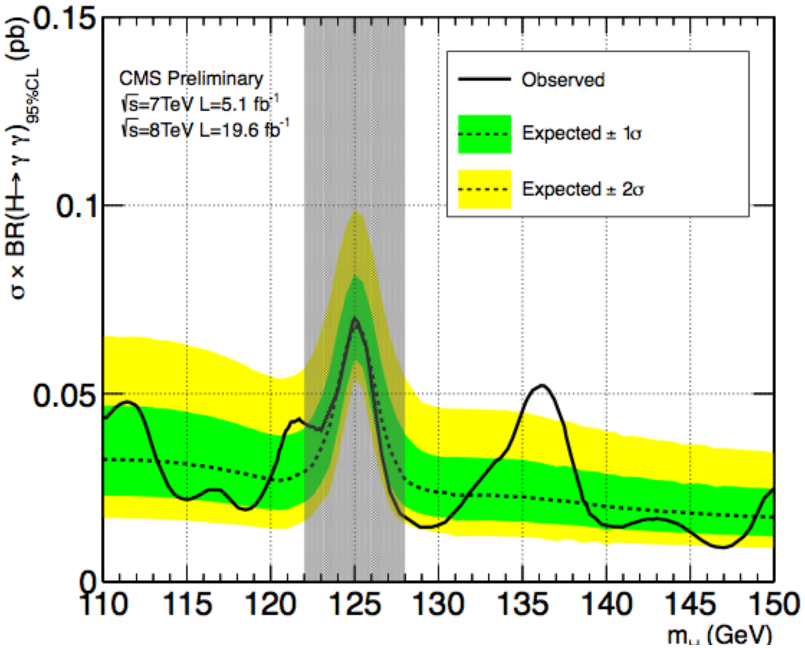


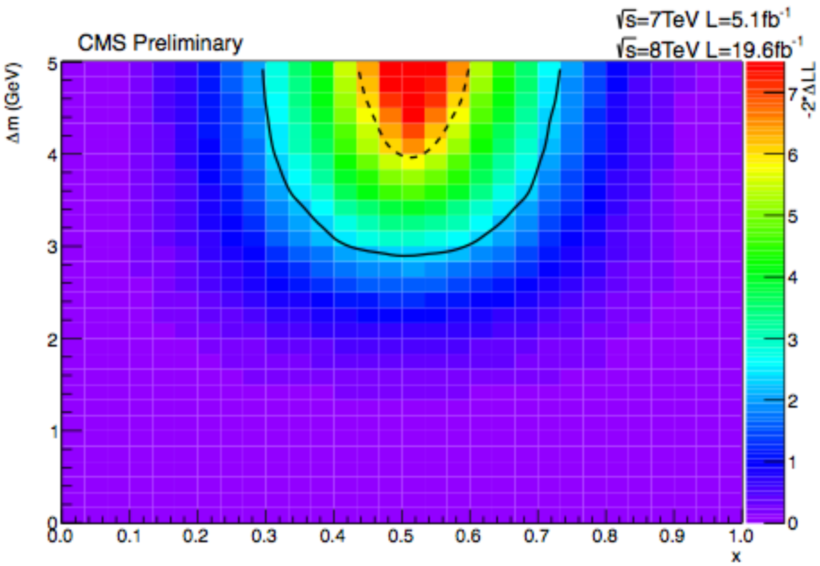
Higher prob. To underestimate μ



(Conditionnal) Probability for a fluctuation in the mass also higher

$H \to \gamma\gamma$



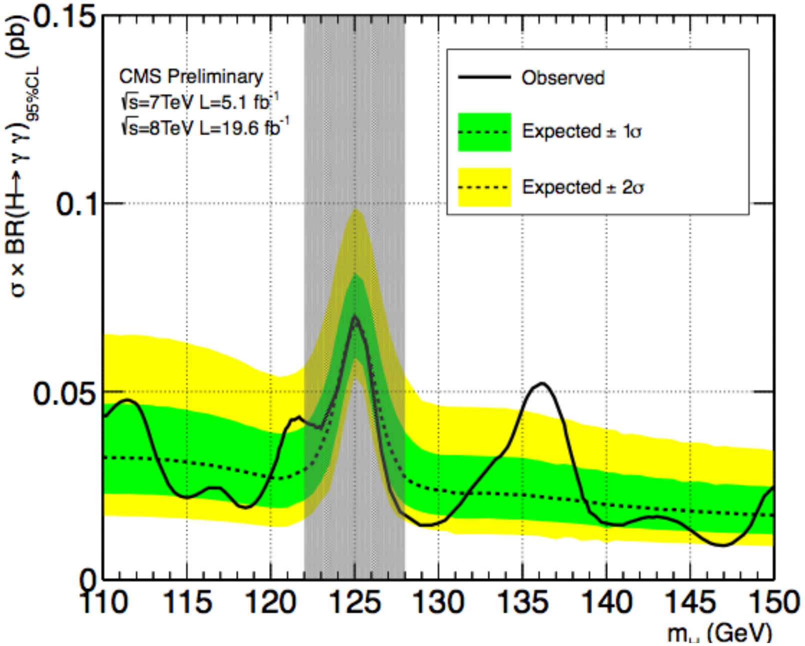


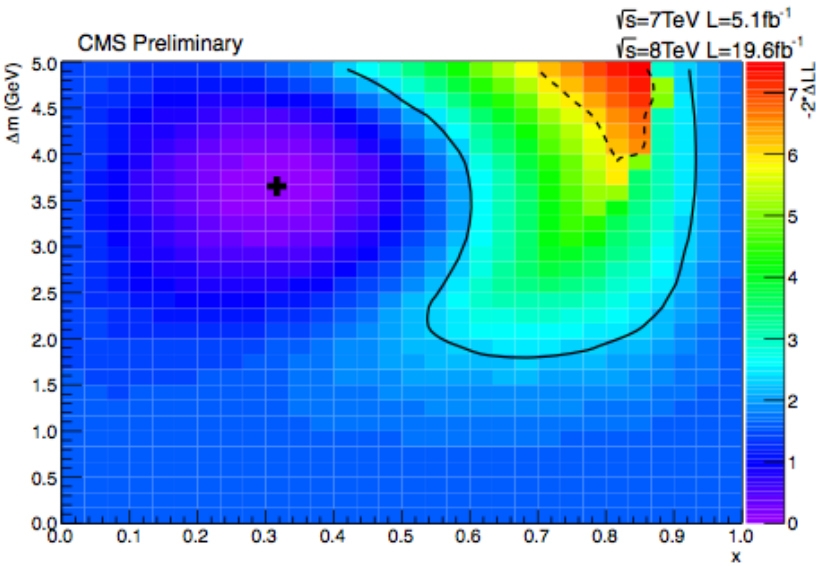
- CMS estimate of the potential presence of two nearly degenerate states (CMS-PAS-HIG-13-016)

- CMS obs. (exp.) limit on natural width 6.9 (5.9) GeV

- CMS limit on higher mass states (an excess at around 136 GeV <2 s.d. with LEE)

$H \to \gamma\gamma$





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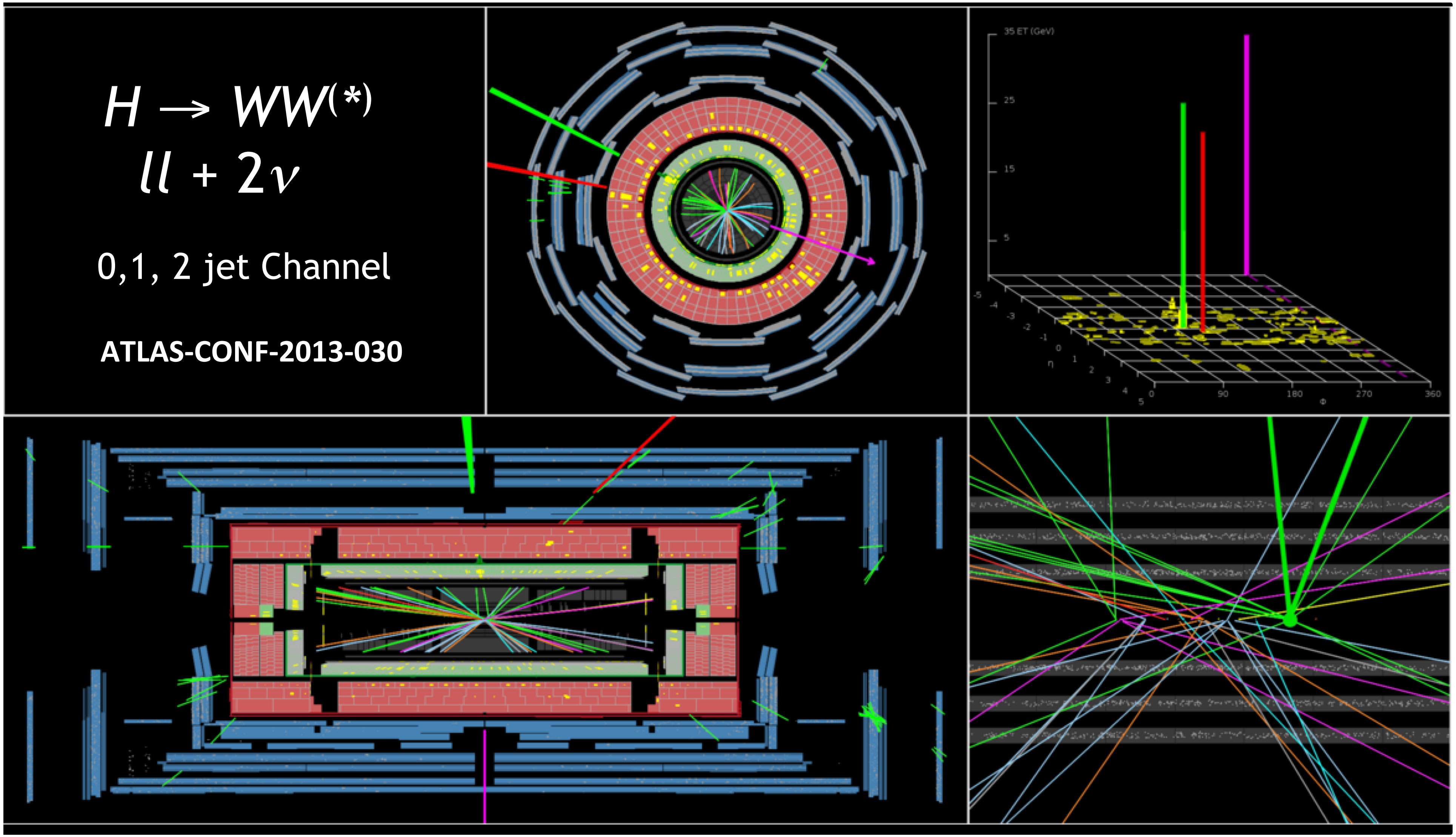
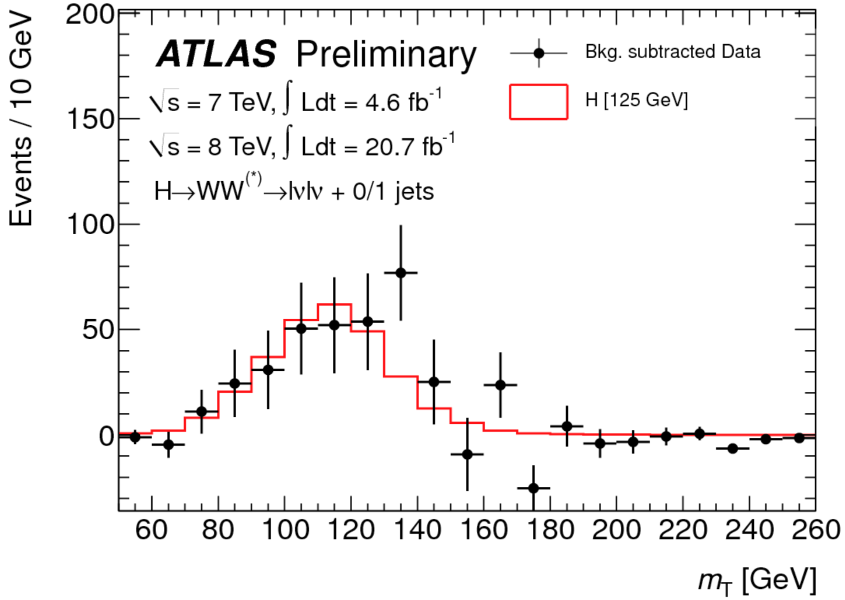
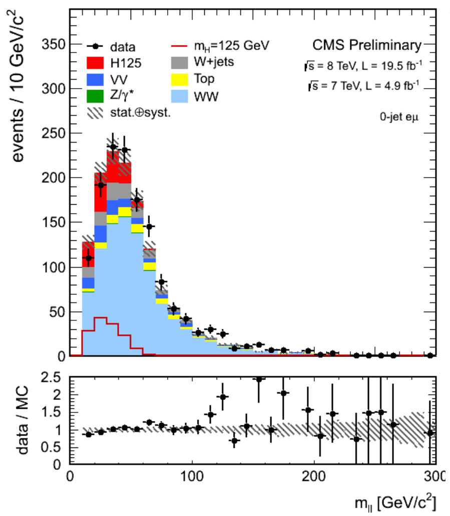


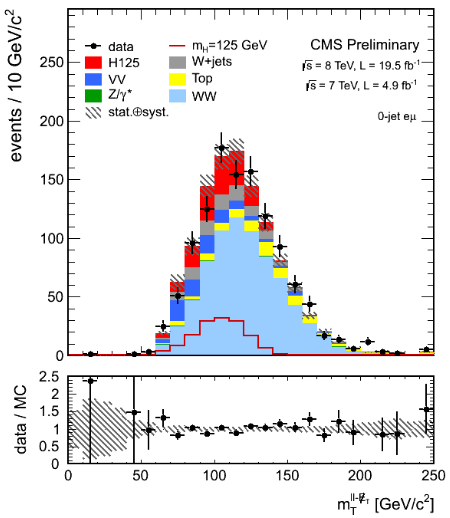
lvlv channel basic facts :

- Ns ~ O(300) per experiment
- Signal purity ~ 5% and 40%

$H \rightarrow WW^{*} \rightarrow \ell^{+}\upsilon\ell^{-}\upsilon$







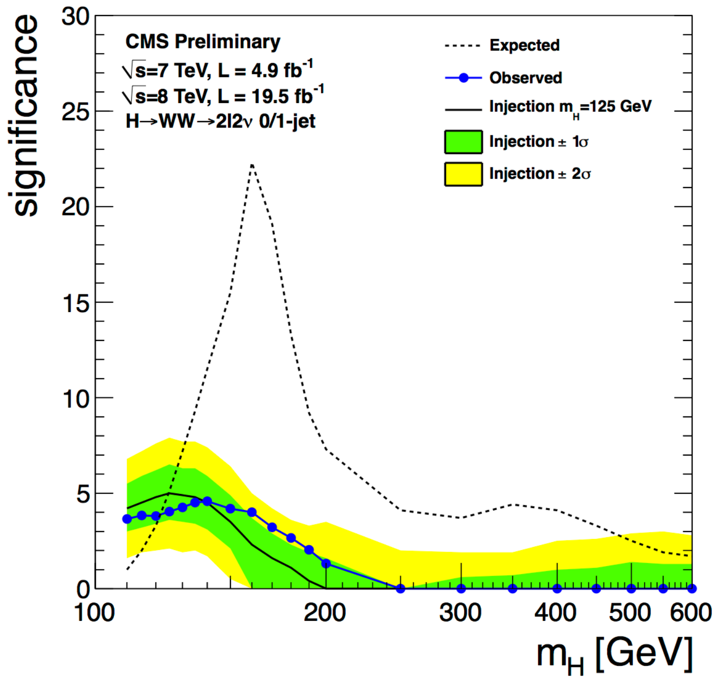
- Analysis strategy:
  - two prompt high-p_T leptons
  - Use spin-0 and V-A structure of W decay
  - MET
  - split events into ee, μμ, eμ channels:
    - different S/B rates: Drell-Yan in ee/μμ !
  - split events further into 0/1-jet:
    - different S/B rates: ttbar in 1-jet !
  - **ATLAS: m_T-distribution**
  - **CMS:**
    - Different-flavor: **2D distribution $N(m_{ll}, m_T)$**
    - Same-flavor dileptons: **cut-based analysis**
  - Backgrounds (for low mass Higgs):
    - WW, tt, W+jets, DY+jets, Wγ: from control regions
    - ZW, ZZ: from MC (very small contribution)

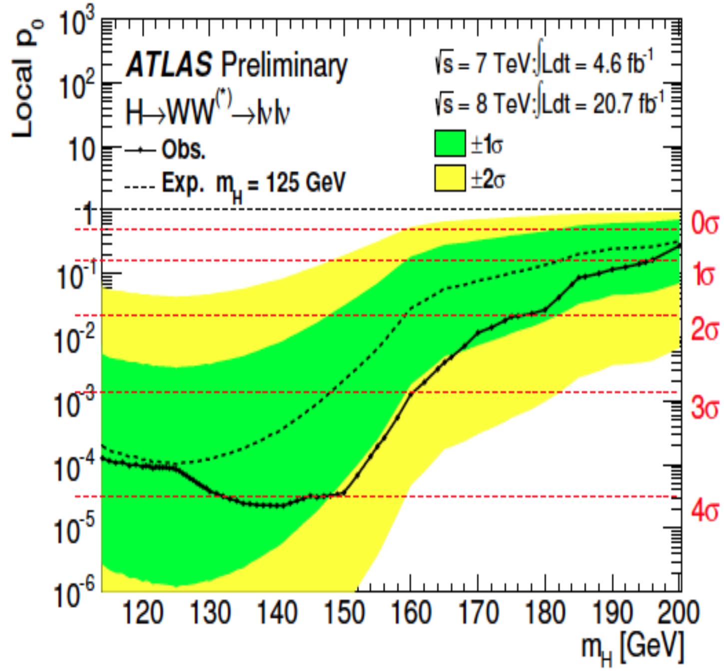
- Analysis features to note (m_H=125):
  - Fair S/B
  - Fair signal event yield (200 events)
  - Poor mass resolution ≈20%

Background Uncertainties

TH uncertainty on the WW kinematics

$$\mu_{obs} = 1.01 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{theo. syst.}) \pm 0.12\,(\text{expt. syst.}) \pm 0.04\,(\text{lumi.}) = 1.01 \pm 0.31.$$

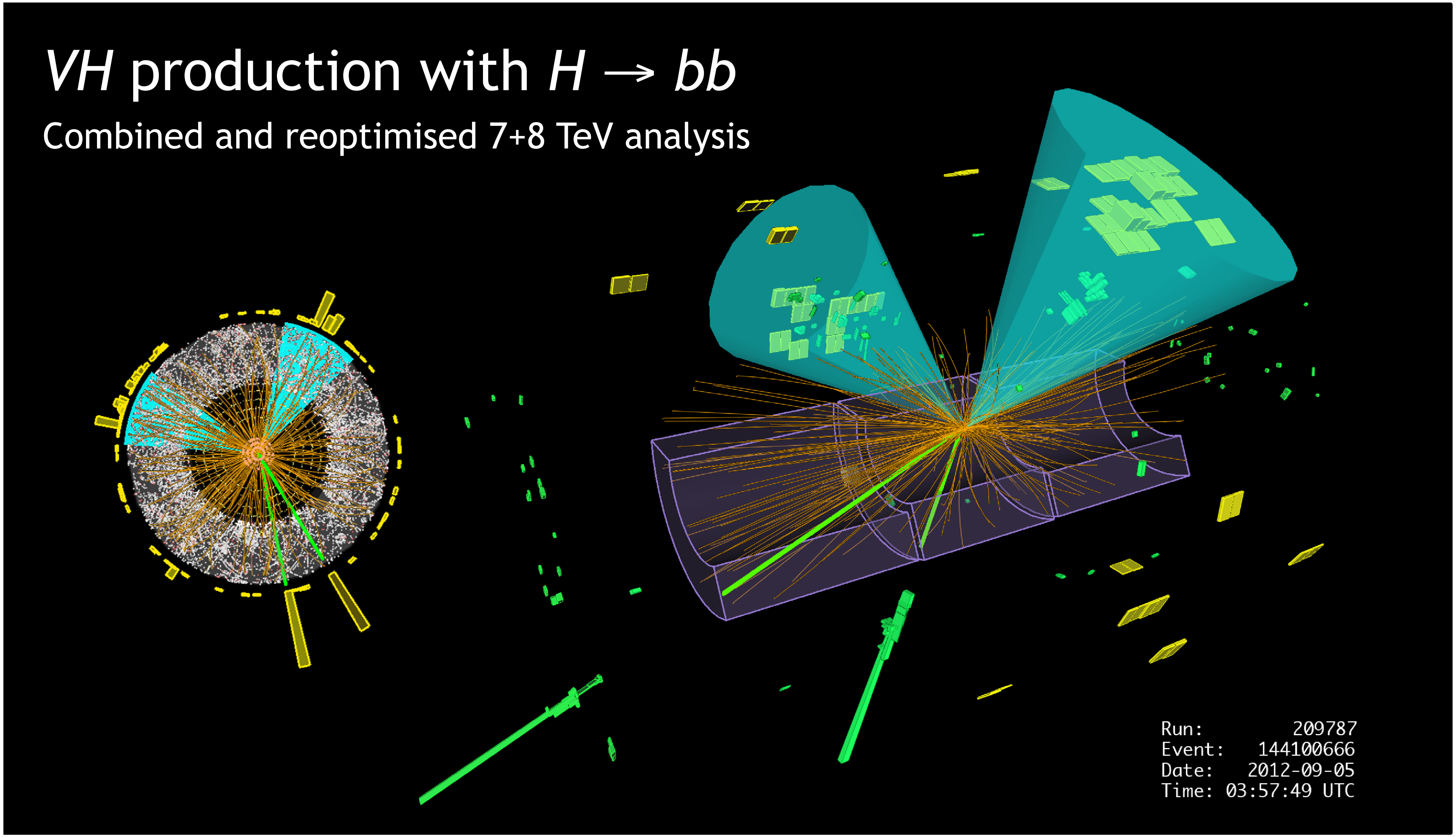




NNLO calculation underway!!!

(m = 125) **Z_{obs} = 4.0 σ**
Z_{exp} = 5.0 σ

(m = 125) **Z_{obs} = 3.8 σ**
Z_{exp} = 3.7 σ

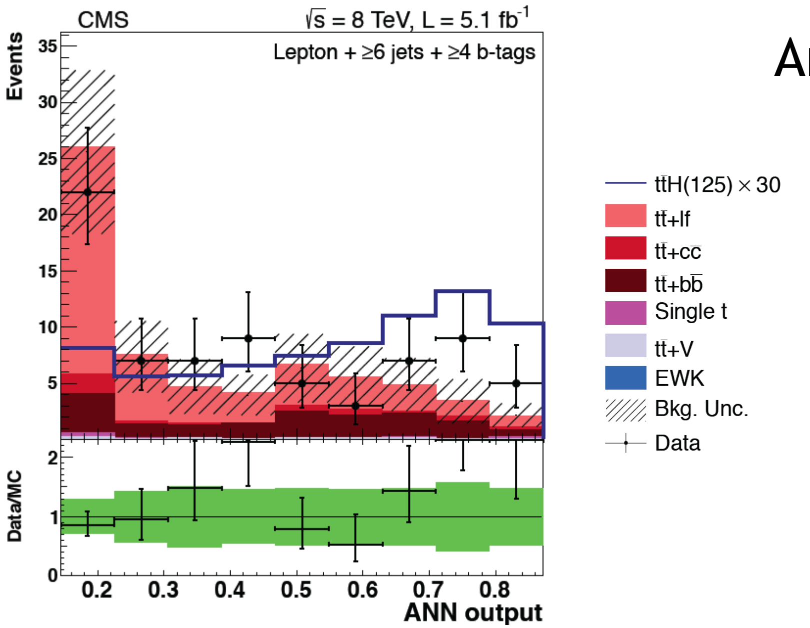


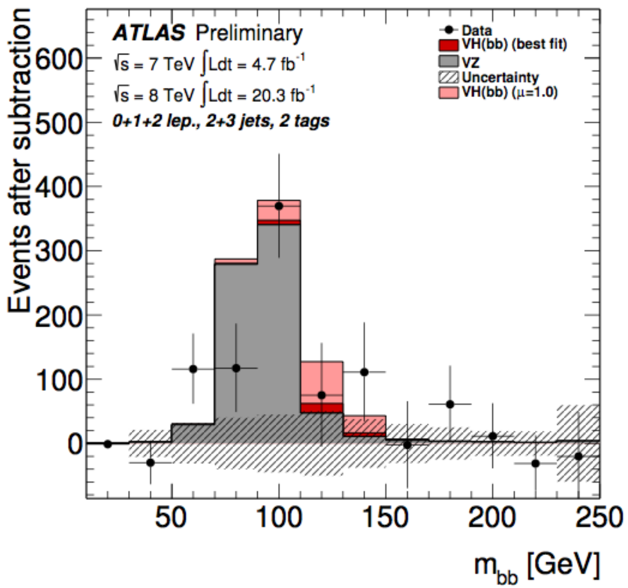
VH(bb) channel basic facts sheet :

VH(bb) channel basic facts :

- Ns ~ O(100) per experiment
- Signal purity ~ 1% - 15%

$VH \to Vbb$





Analysis strategy:

- Channels separated in 0 (MET), 1 (MET) and 2 leptons
- With two b-tagged jets (using 0 and 1 for control)
- Further categorize in pT of the V
- Mass reconstruction is Key
- Simulation ISR and gluon splitting is also Key
- Diboson reconstruction also important element

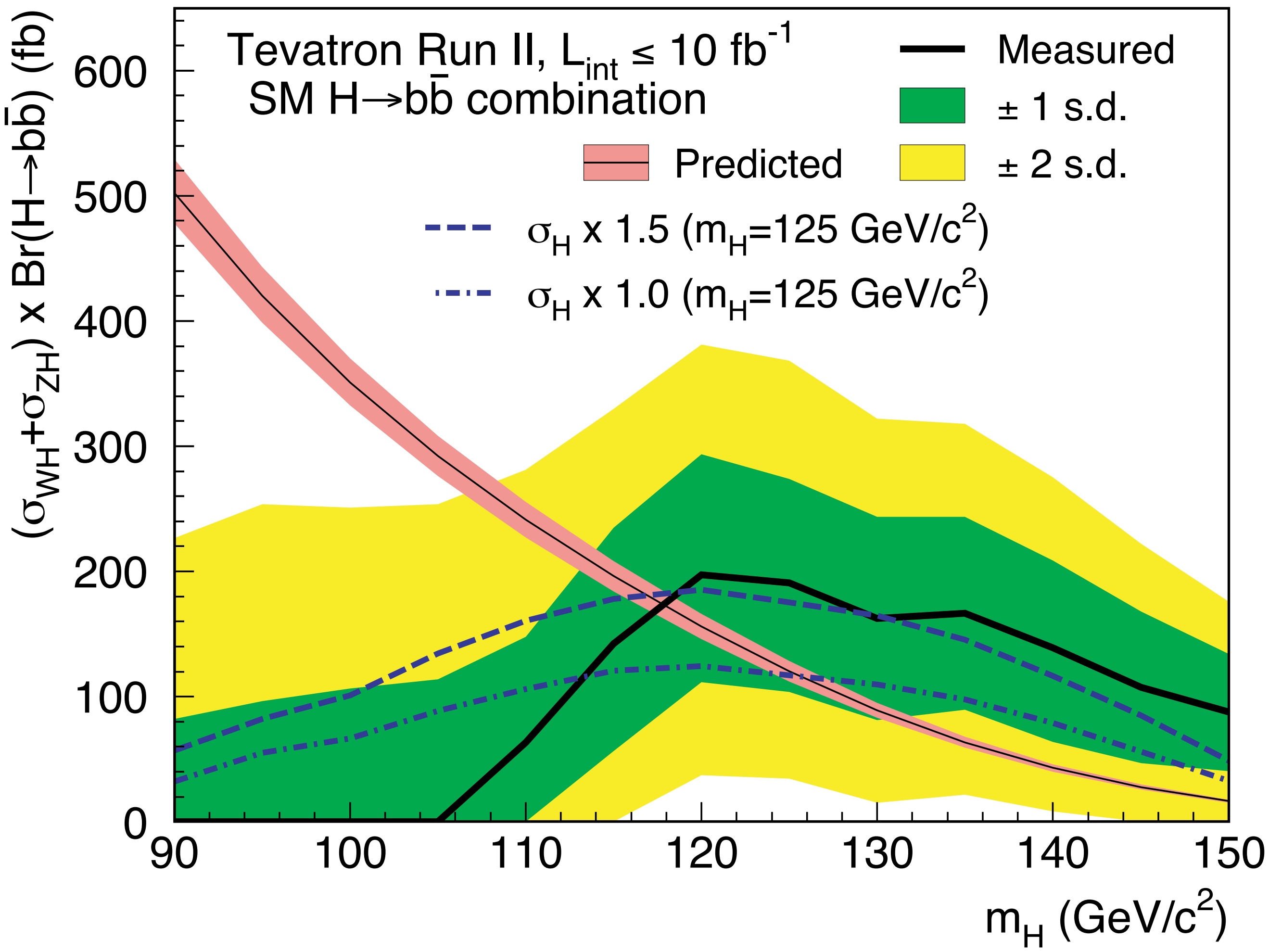
- Main Backgrounds:
  - V+bb and top
  - Uses mainly control regions except

Key Analysis features:

- Low S/B-ratio
- small signal event yield
- Higgs is on falling slope of Z-decays
- poor mass resolution ≈15%

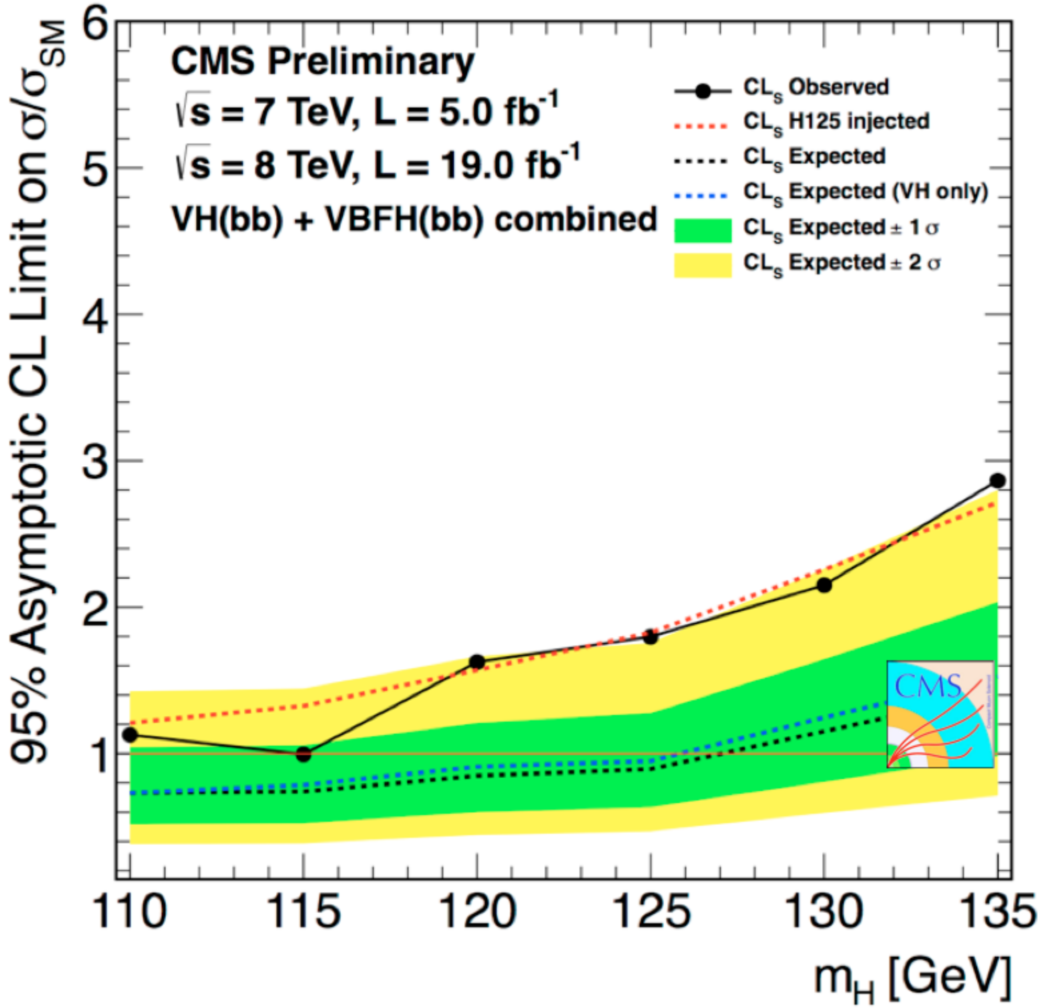
$VH \to Vbb$

VH(bb) at the Tevatron



~~$VH \rightarrow V$~~ $\quad (H \rightarrow bb)$

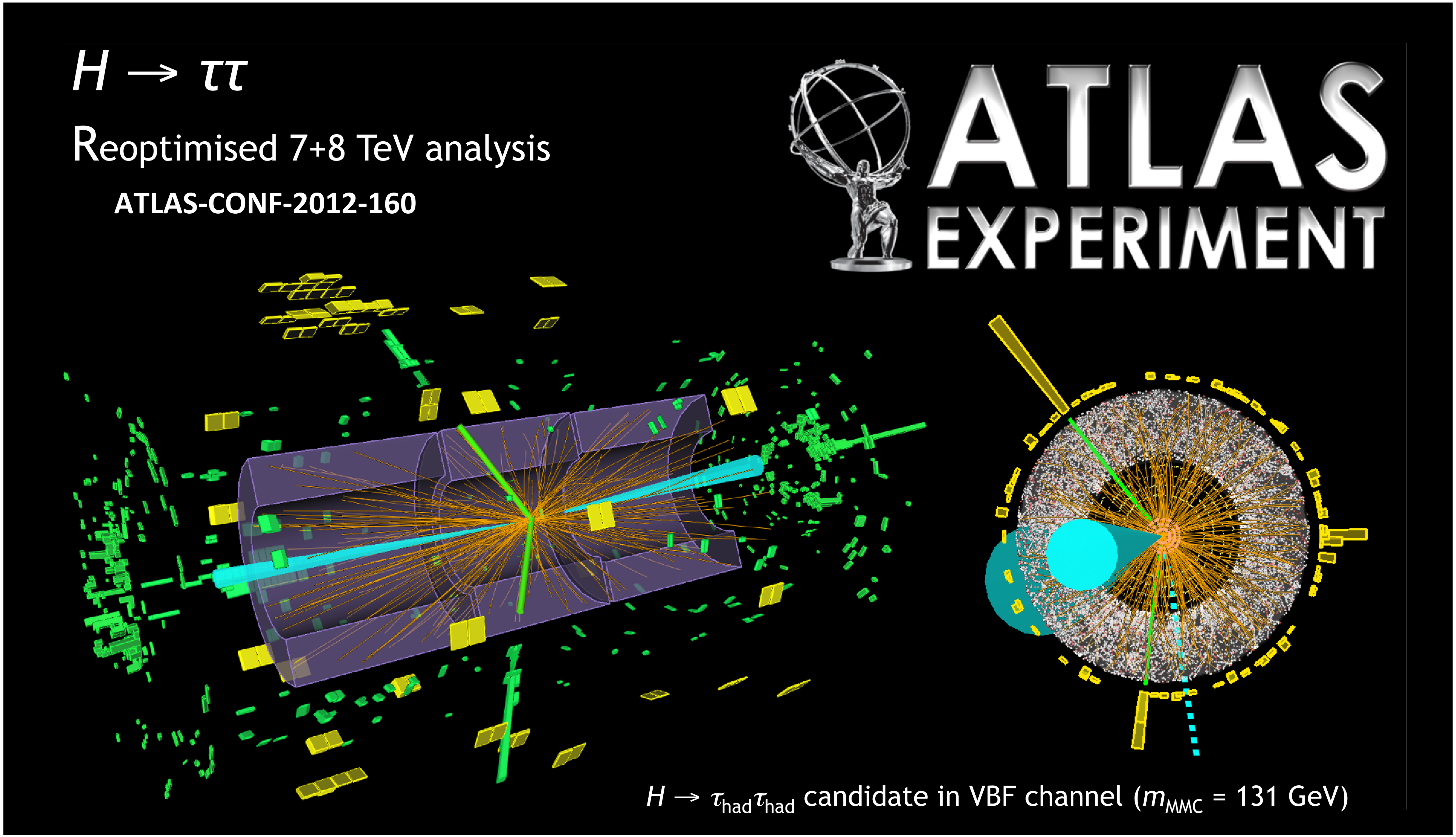
CMS with VBF analysis combined



Latest News
(Last week)

ATLAS and CMS announce the results of their searches in the Tau Tau channel:

Unambiguous observation of coupling of the Higgs particle to fermions

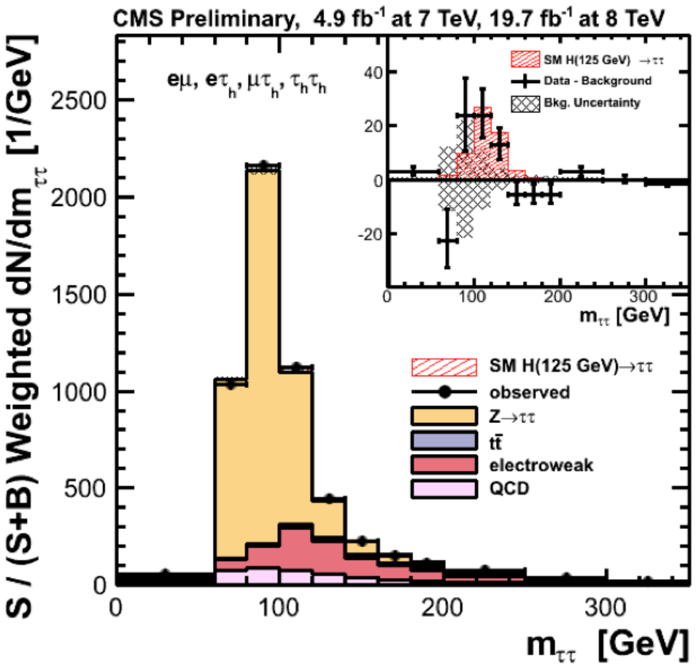


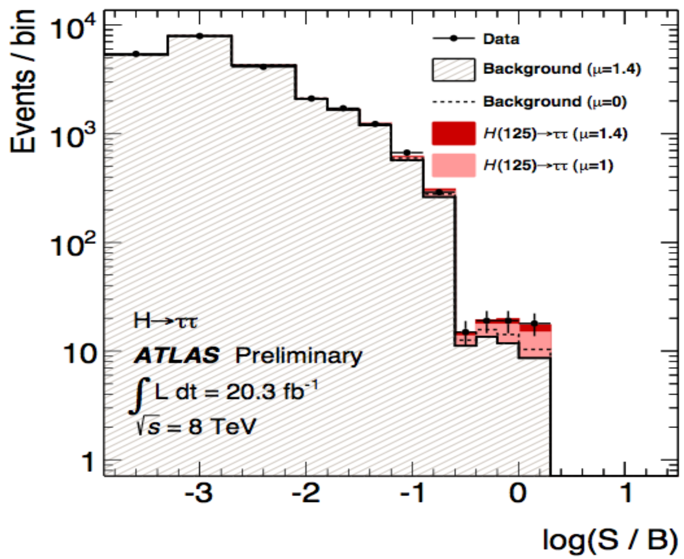
ττ channel basic facts sheet :

ττ channel basic facts :

- Ns ~ O(500) per experiment
- Signal purity ~ 0.3% - ~O(1)

$H \to \tau^+\tau^-$





Analysis strategy:

- di-tau candidates: $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$
- MET
- **DiTau mass (including MET)**: key distribution

split events into jet categories:

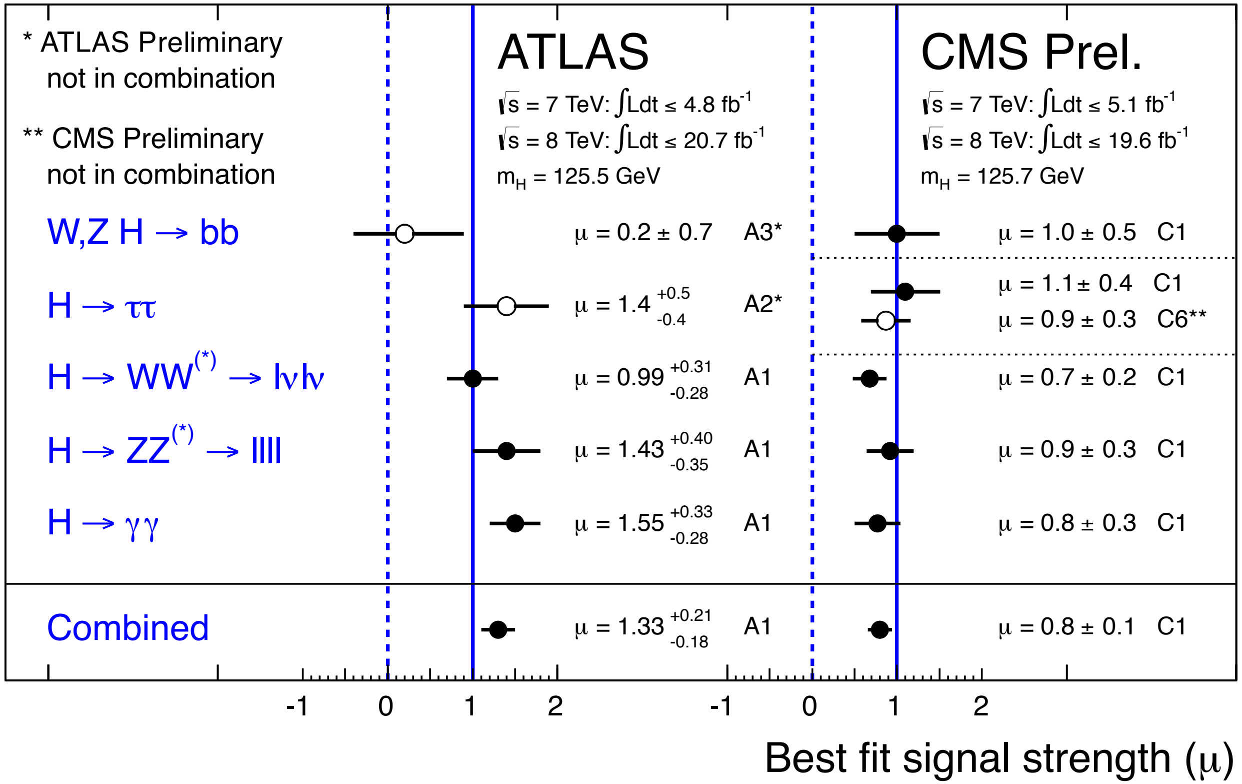
- **2-jets (VBF-tag)**: best S/B-ratio
- **VH Lepton tag (not combined)**
- **1-jet (ggF, VH)**: acceptable S/B-ratio
- untagged: mostly control region (S/B≅0)

- ATLAS uses MVA approach
- Backgrounds:
  - $Z\to\tau\tau$: $Z\to\mu\mu$ (data) with embedding
  - $Z\to ee$, W+jets, ttbar: MC for shapes, data for normalization
  - QCD: from control regions

Key Analysis features:

- Decent S/B-ratio
- Relatively small signal event yield
- Higgs is on falling slope of Z-decays
- poor mass resolution ≈15%

Channel categories	ATLAS				CMS				Tevatron
	μ (125.5 GeV)	Z exp	Z obs	M (GeV)	μ	Z exp	Z obs	M (GeV)	μ (at 125 GeV)
$\gamma\gamma$	1.5±0.4	4.1	7.4	126.8±0.2±0.7	0.8±0.3	3.9	3.2	125.4±0.5±0.4	$6.0^{+3.4}_{-3.1}$
ZZ (llll)	1.6±0.3	4.4	6.6	124.3±0.5±0.5	0.9±0.3	7.1	6.7	125.8±0.5±0.2	-
WW (lνlν)	1.0±0.3	3.8	3.8	-	0.7±0.2	5.3	3.9	-	1.6±1.2
$\tau\tau$	1.4±0.5	3.2	4.1	-	0.9±0.3	3.6	3.4	115^{+8}_{-2}	$1.7^{+2.3}_{-1.7}$
W,Z H (bb)	0.2±0.7	1.4	0.3	-	1.1±0.6	2.2	2.0	-	1.6±0.7
Combination	1.30±0.20	7.3	10	125.5±0.2±0.6	0.80±0.14	-	-	125.7±0.3±0.3	1.4±0.6

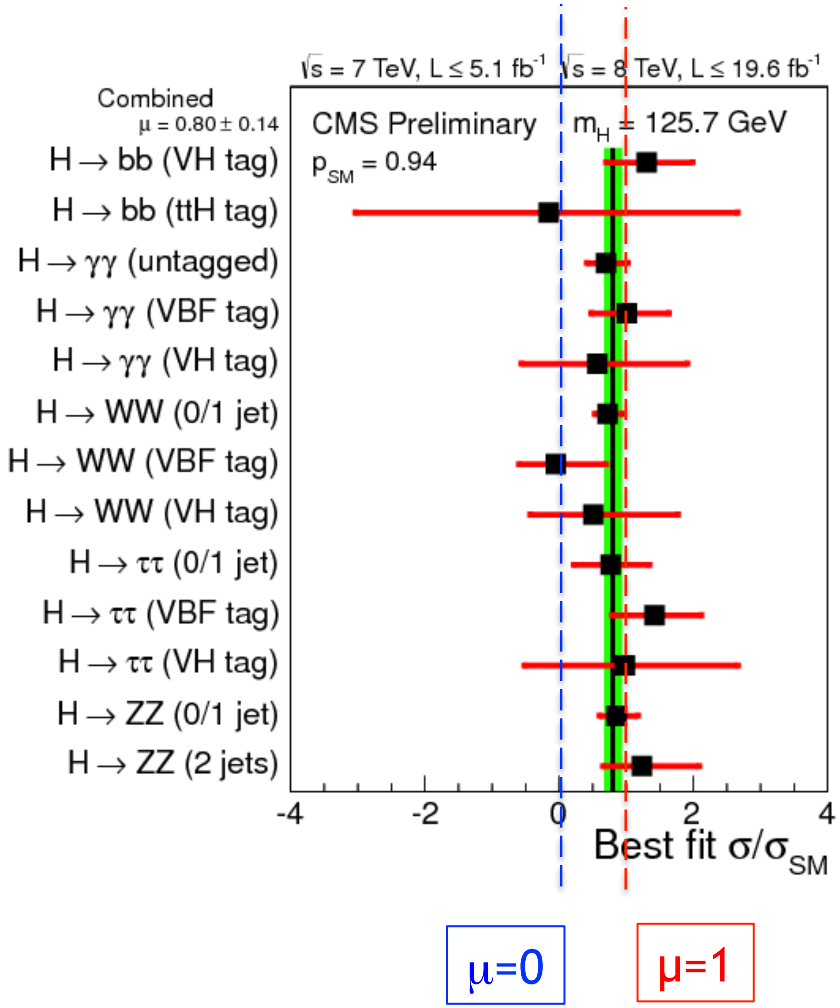


Measurement of Coupling Properties

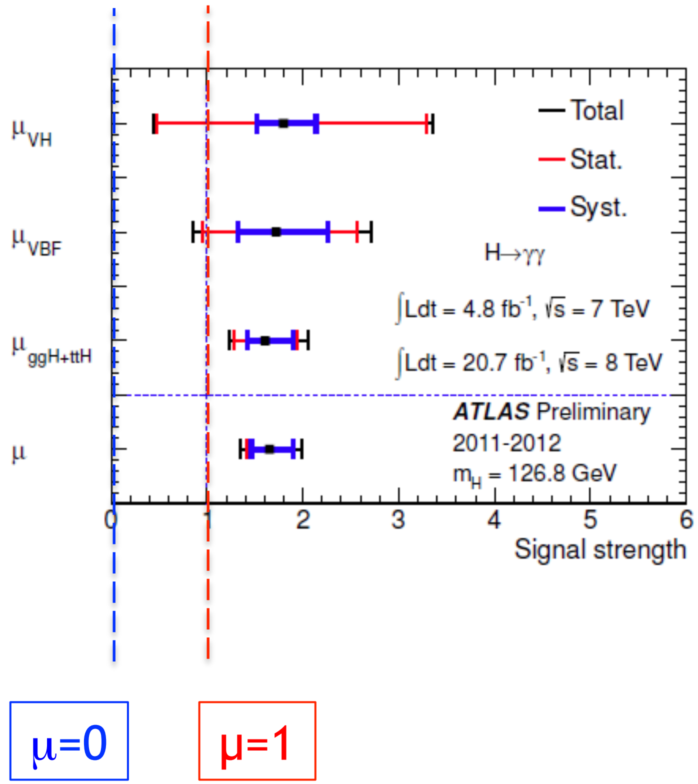
How the fit works

$$n_s^c = \mu\left(\sum_{i\in\{ggF,VBF,VH,ttH\}} \mu^i \sigma_{SM}^i \times A^{ic} \times \varepsilon^{ic}\right) \times \mu^f Br^f \times L^c$$

Sub-channel signal strengths

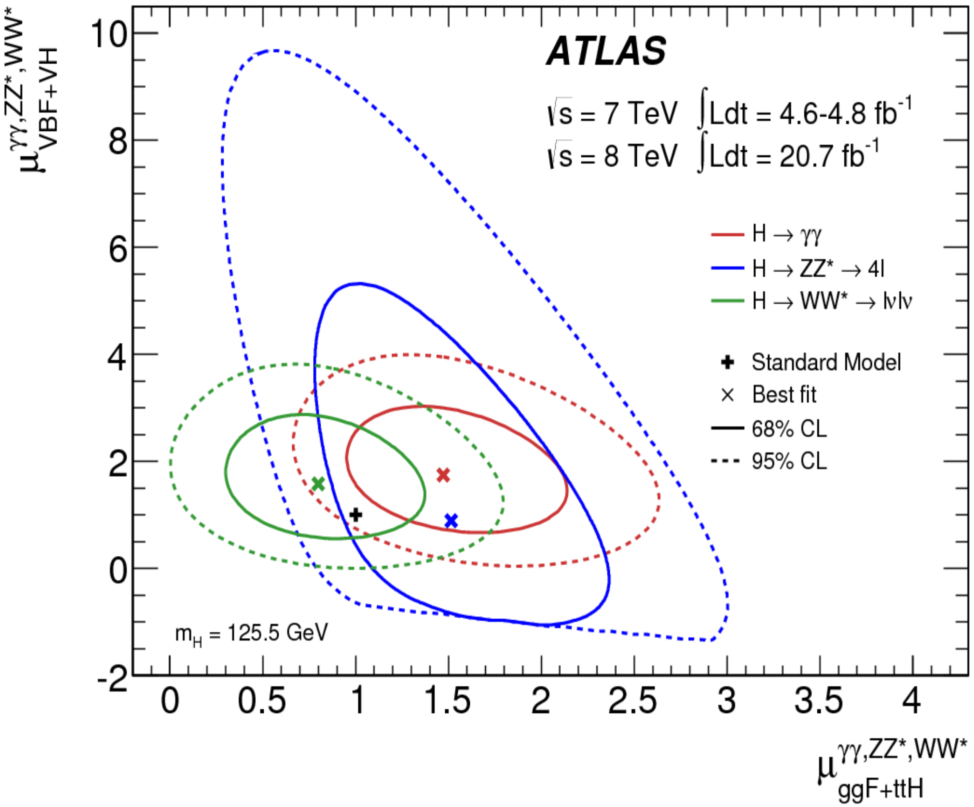


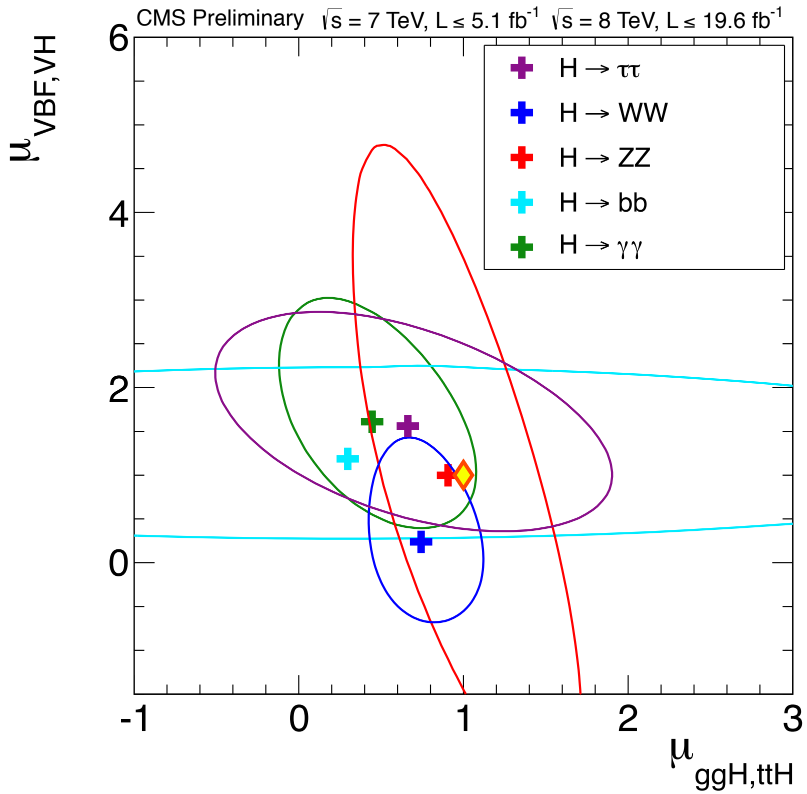
Production mode signal strengths (per channel)



Production Signal Strengths

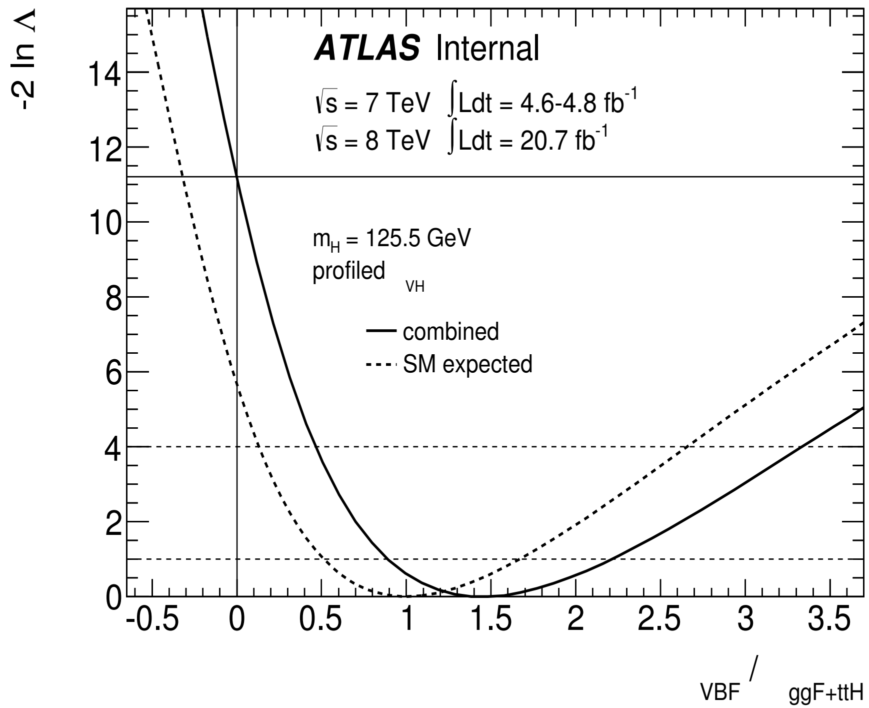
For individual channels



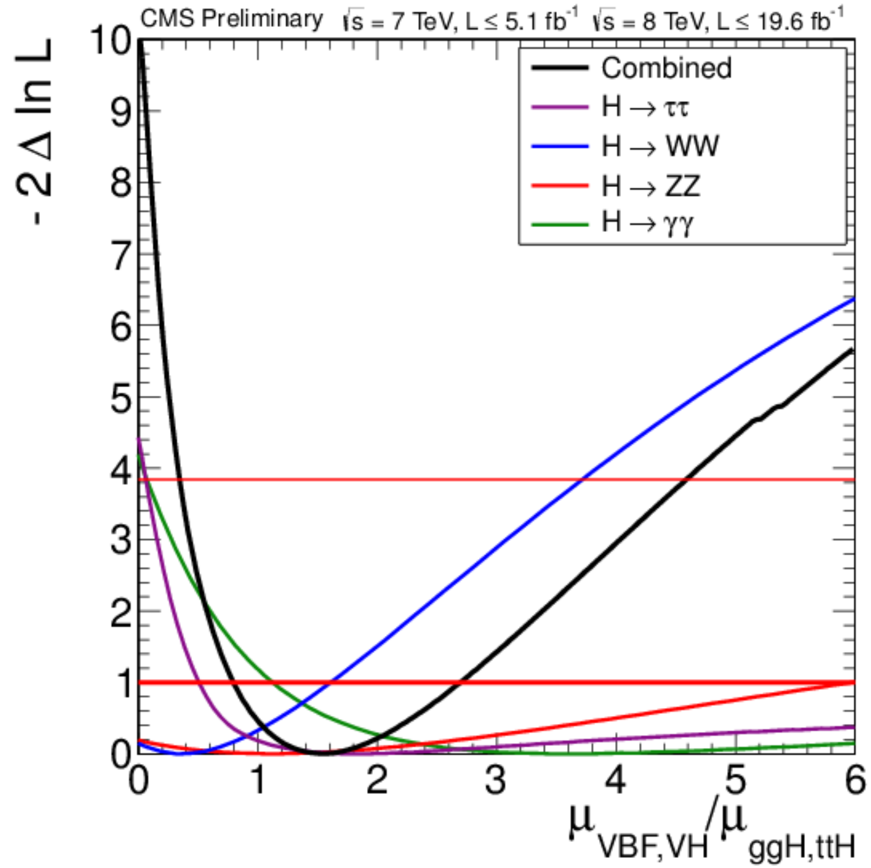


Evidence for VBF production

From the ratio of individual production signal strengths



Evidence for VBF(,VH) production



Coupling Properties (Deviations) Measuremens

Further re-parameterization of the n_s^c yields per categories

- Assuming narrow width approximation
- Assume the same tensor structure of the SM Higgs boson : $J^{CP} = 0^{++}$
- Link to an effective Lagrangian and use scale factors

$$\mathcal{L} = \kappa_W \frac{2m_W{}^2}{v} W_\mu^+ W_\mu^- H + \kappa_Z \frac{m_Z{}^2}{v} Z_\mu Z_\mu H - \sum_f \kappa_f \frac{m_f}{v} f\bar{f}H$$
$$+ c_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^a_{\mu\nu} H + c_\gamma \frac{\alpha}{\pi v} A_{\mu\nu} A_{\mu\nu} H$$

Parameterize μ_i and μ_f as a function of κ's

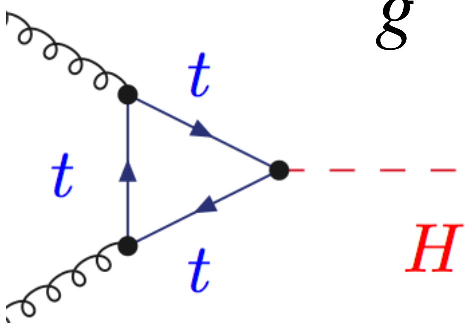
For example, the main contribution (ggF) to the gg channel can be written as:

$$\sigma \cdot \mathrm{BR}\,(gg \to H \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

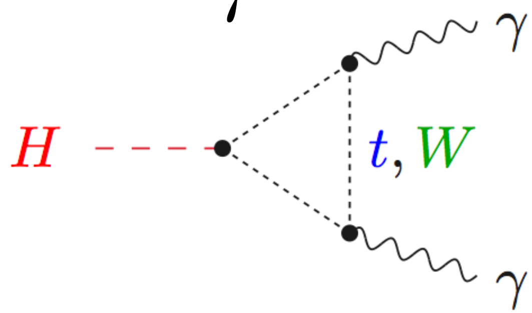
Relating Couplings and Event Yields

Scale factors of loop induced couplings w.r.t. SM

κ_g



κ_γ

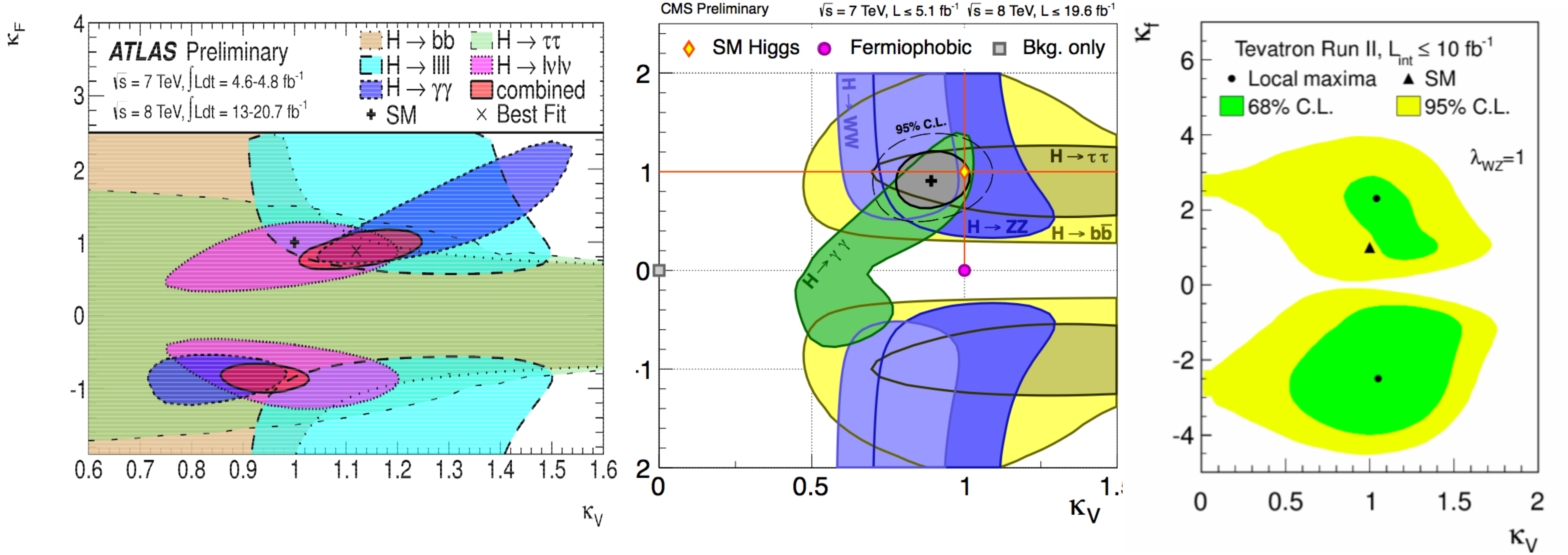


- Loop expression ambiguity :
  - Can be expressed in terms of k_F and k_V (Assuming the SM field content)
  - Or treated effectively (Allowing for possible additional particles)

$$\kappa_g^2(\kappa_b, \kappa_t, m_H) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt}(m_H) + \kappa_b^2 \cdot \sigma_{ggH}^{bb}(m_H) + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}(m_H)}{\sigma_{ggH}^{tt}(m_H) + \sigma_{ggH}^{bb}(m_H) + \sigma_{ggH}^{tb}(m_H)}$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}(m_H)}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}(m_H)}$$

Main results I : Probing the coupling to SM particles

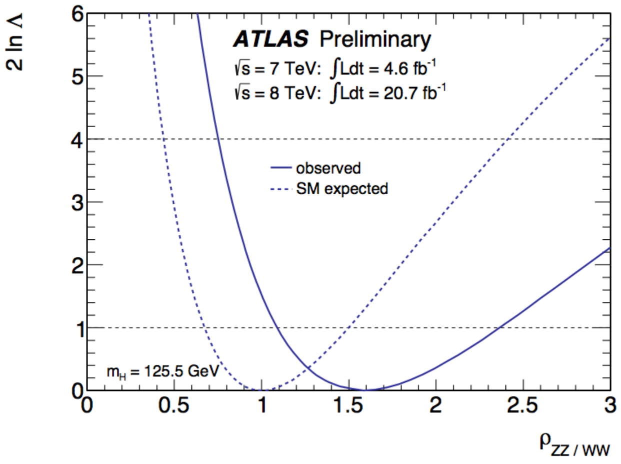


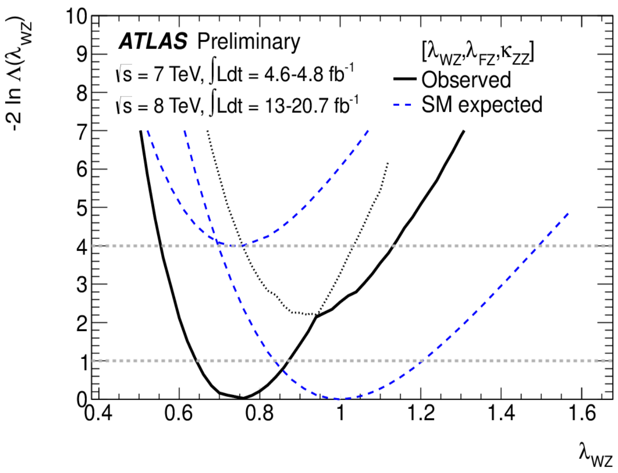
- By convention sign on the fermion yukawa strength multiplier (relying on the $\gamma\gamma$ strength primarily)… ambiguity inspired tH analyses

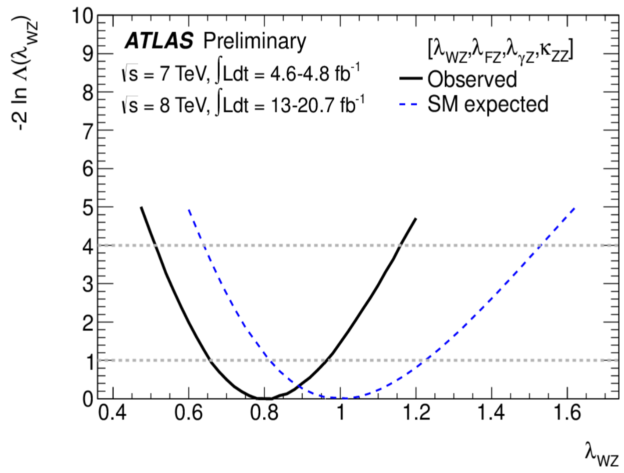
- Checking the direct and indirect couplings to fermions

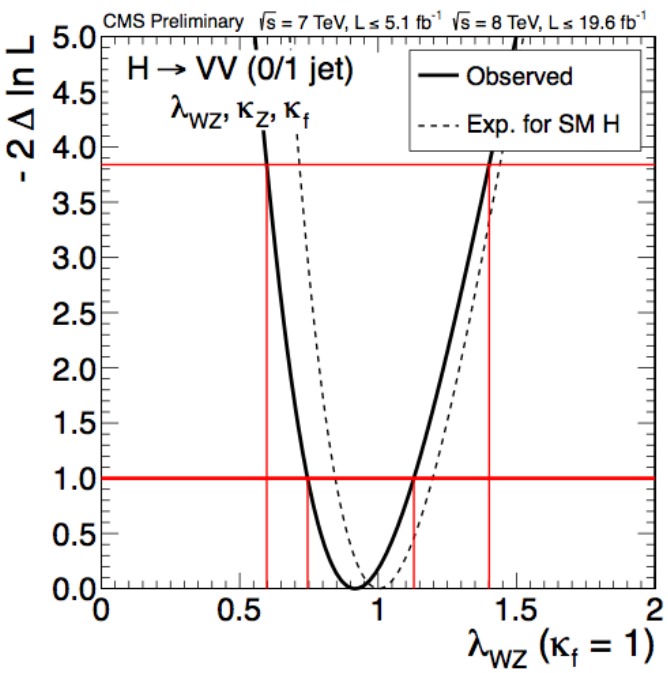
- Checks of specific composite models

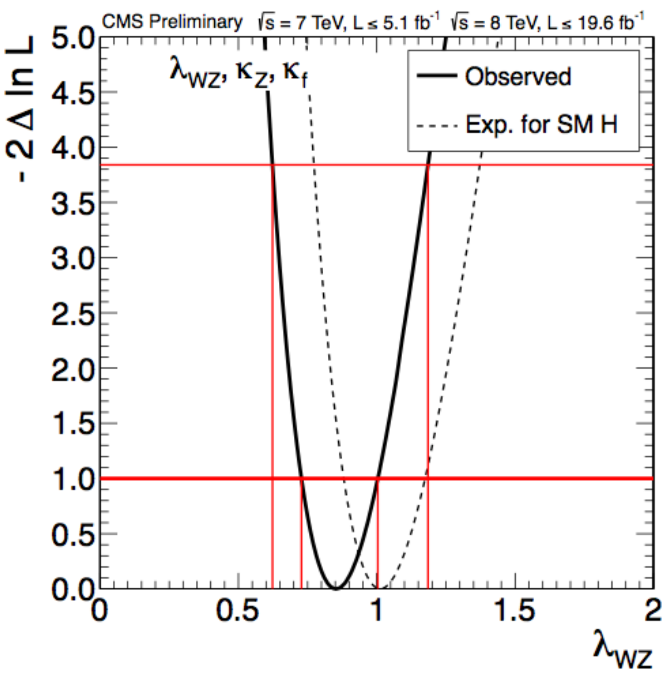
Main results II : Probing the W to Z ratio (custodial symmetry)





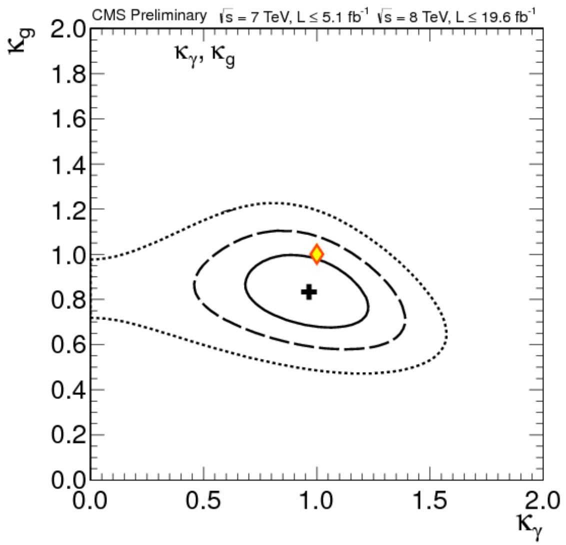


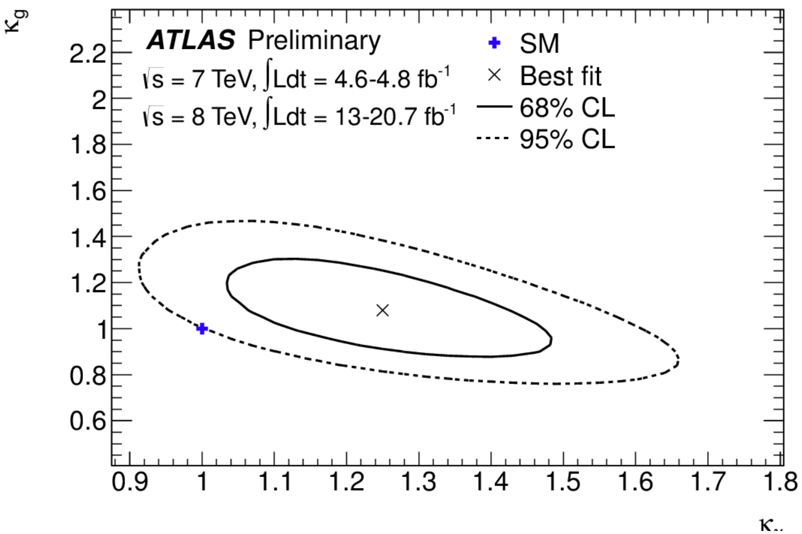


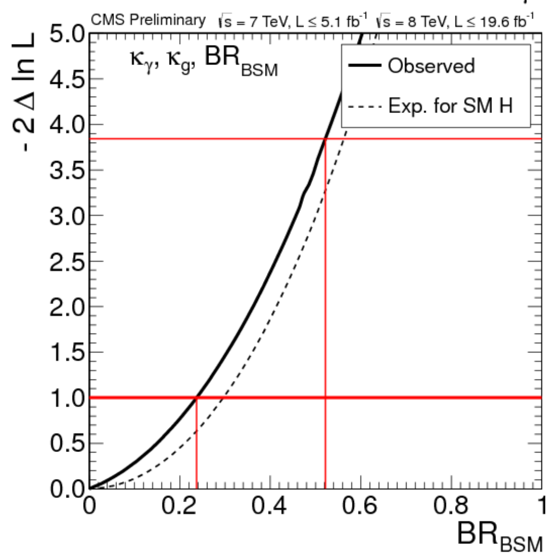


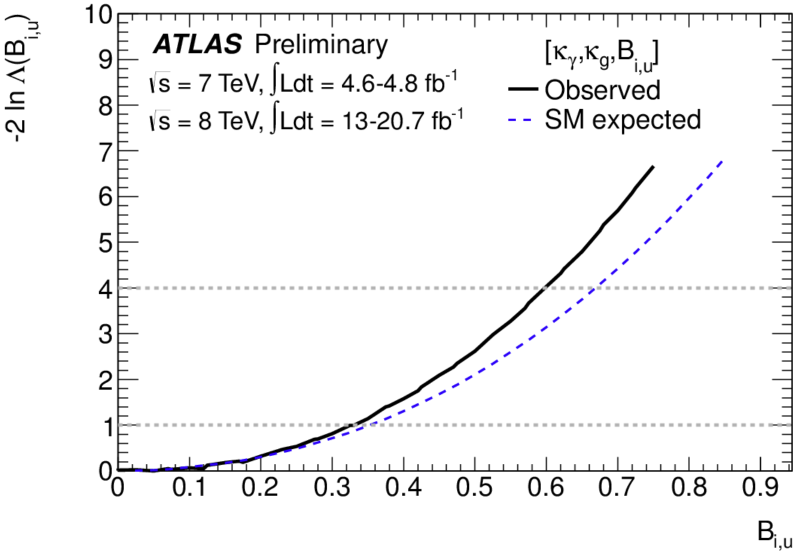
Main results III : Probing physics beyond the Standard Model

(In the decays and/or in the loops)









Limit @95% CL :

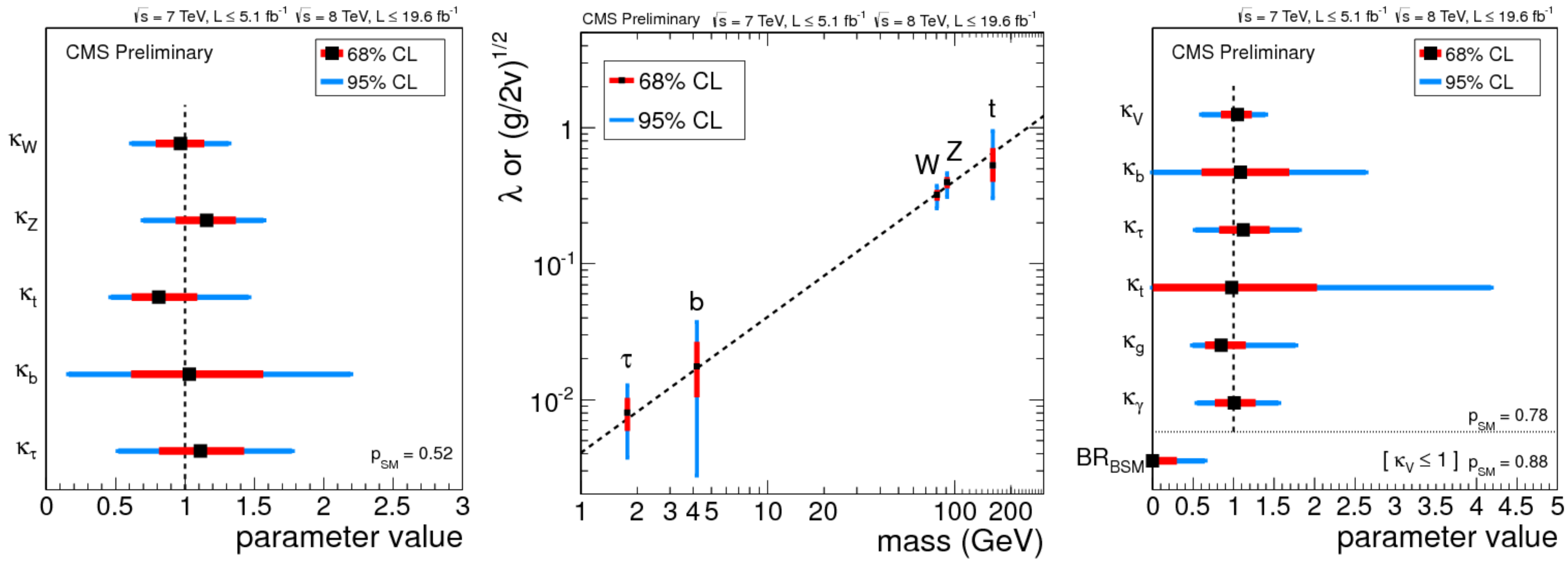
CMS : $Br_{inv,und}$ <64%

ATLAS : $Br_{inv,und}$ < 60%

Total width in terms of:

- Invisible
- undetected

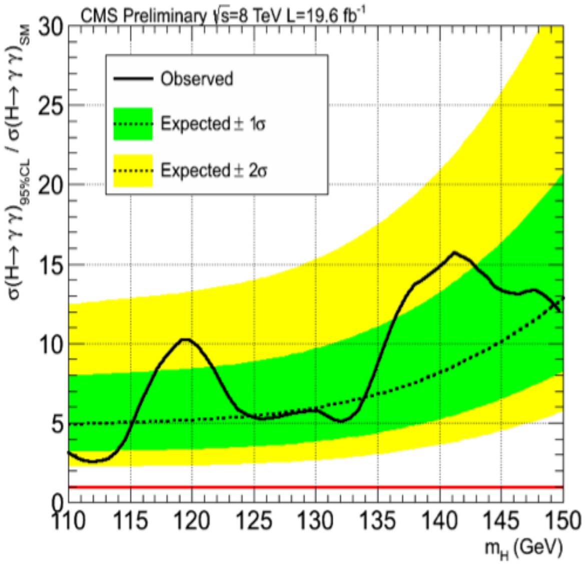
Main results IV : Other Relevant Models



- Test of the predicted Yukawa structure of the couplings
- 3 coupling strength parameter fits κu, κd and κV for MSSM and 2HDM limits

ttH

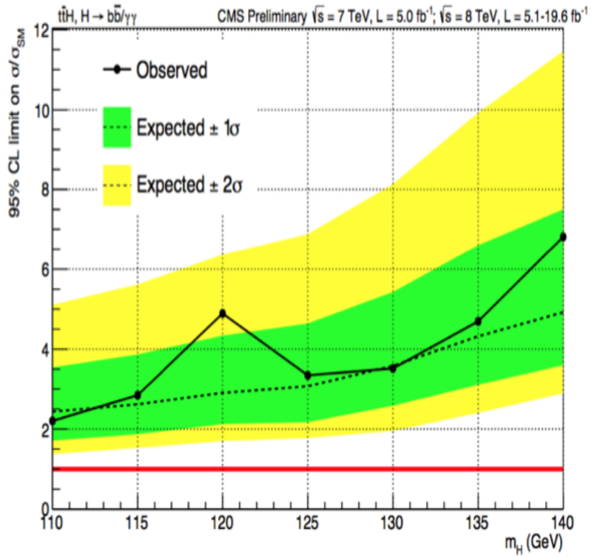
$H \to \gamma\gamma$



Key Features:

- Robust channel
- Will require (very) large statistics

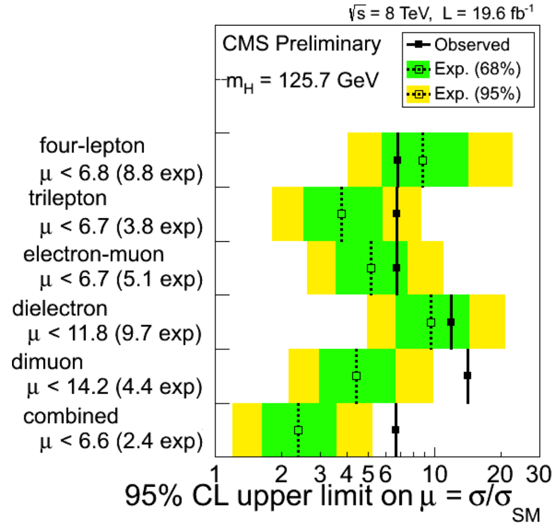
$H \to bb$



Key Features:

- Will it ever be possible be sensitive?
- Relies on the control of the tt+HF background

$H \to WW, \tau\tau$

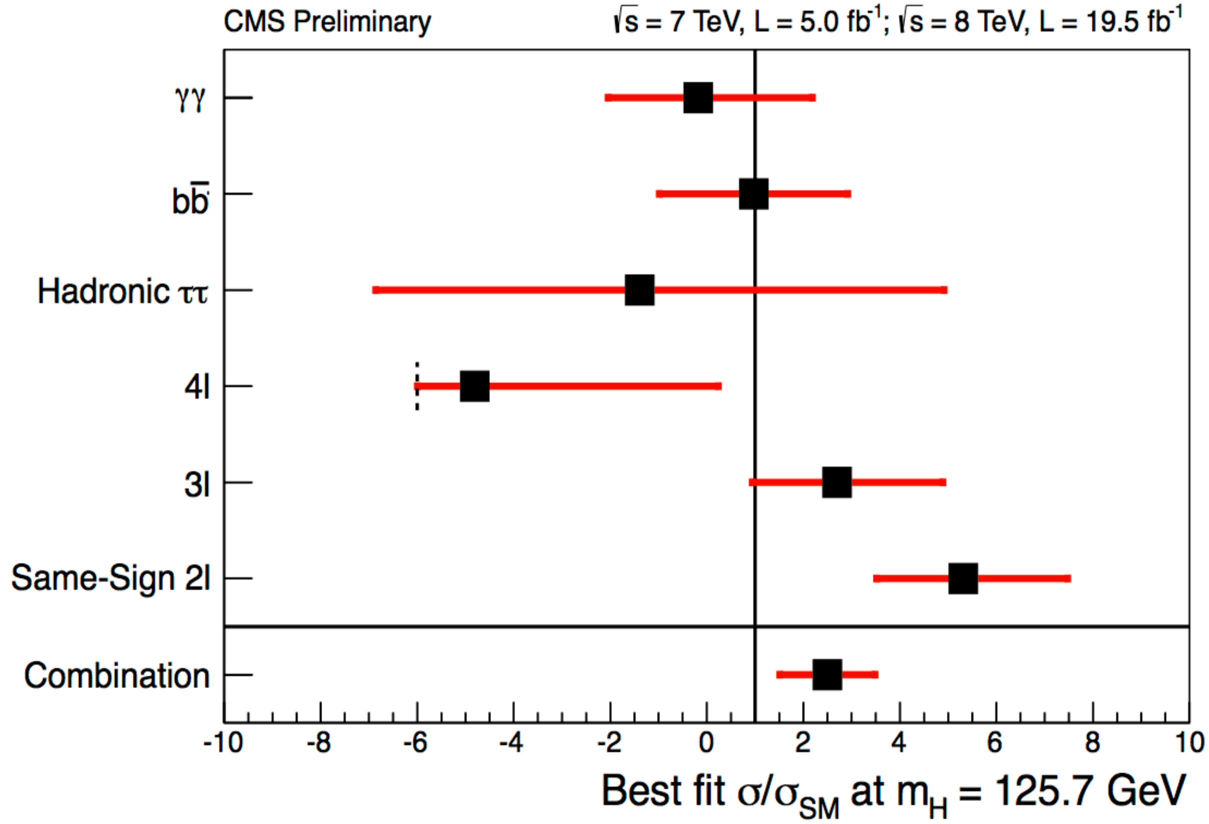


Key Features:

Inclusive multi-signatures

ttH

Summary and combination :



Beyond any reasonable doubt…

The consistency of rates of the three discovery channels and the supporting evidence from the additional channels leaves little doubt about the nature of the particle.

For it NOT to be a Higgs boson would require a very savvy conspiring impostor

- Observation in the diphoton channel implies C = 1 (assuming C conservation)
- Observation in the diphoton channel (Landau-Yang theorem) implies $J \neq 1$
- Observation in WW channel favors J=0
- Observation in the ZZ and WW channels disfavors P=-1

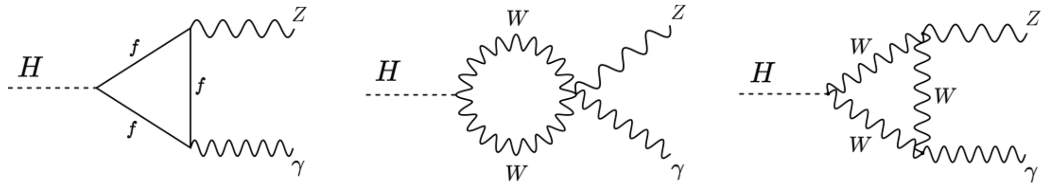
This being said we still perform analyses to test the main quantum numbers directly from model independent observables.

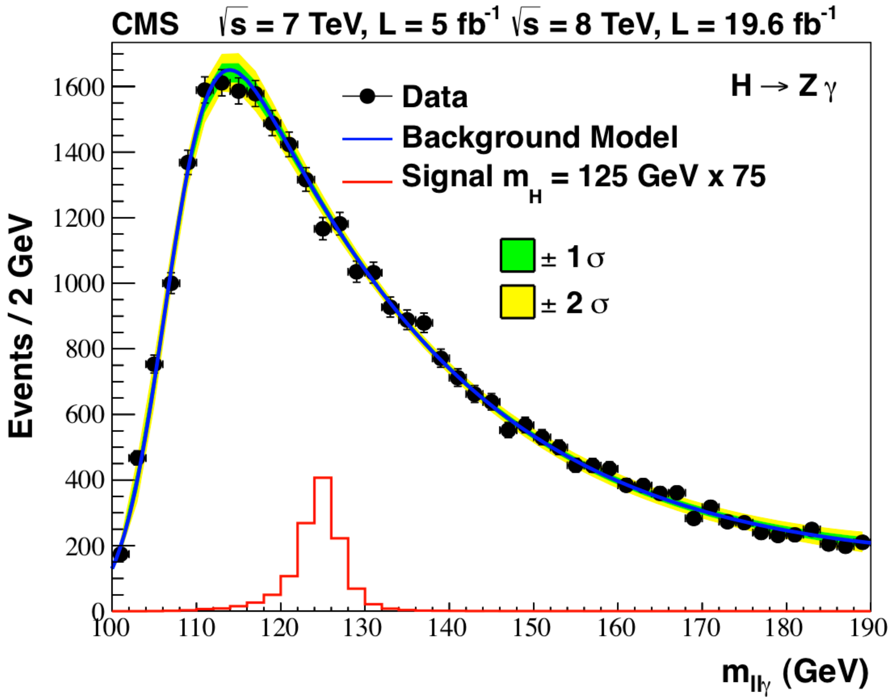
Invisible and rare decays

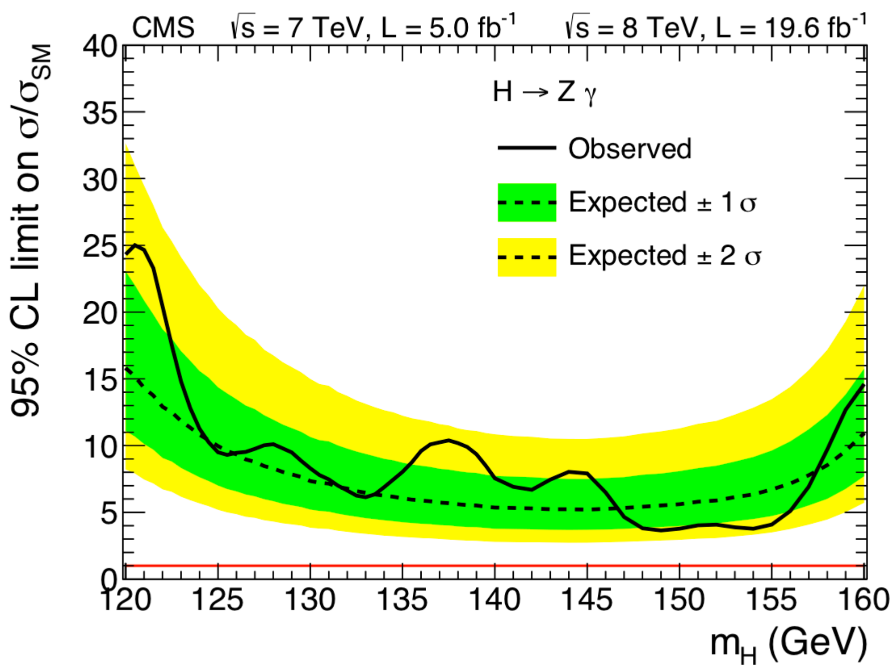
Channel categories	ATLAS				CMS				TeVatron	
	ggF	VBF	VH	ttH	ggF	VBF	VH	ttH	VH	ggF
γγ	✓	✓	✓	✓	✓	✓	✓	✓	(inclusive) ✓	
ZZ (llll)	✓	✓			✓	✓			✓	
WW (lνlν)	✓	✓	✓		✓	✓	✓		✓	✓
ττ	✓	✓	✓		✓	✓	✓	✓	✓	
H (bb)			✓	✓		✓	✓	✓	✓	
Zγ	(inclusive) ✓				✓	✓				
μμ	(inclusive) ✓									
Invisible	(✓)		✓			✓	✓			

Rare decays I

Search for the Higgs boson decaying to $Z\gamma$

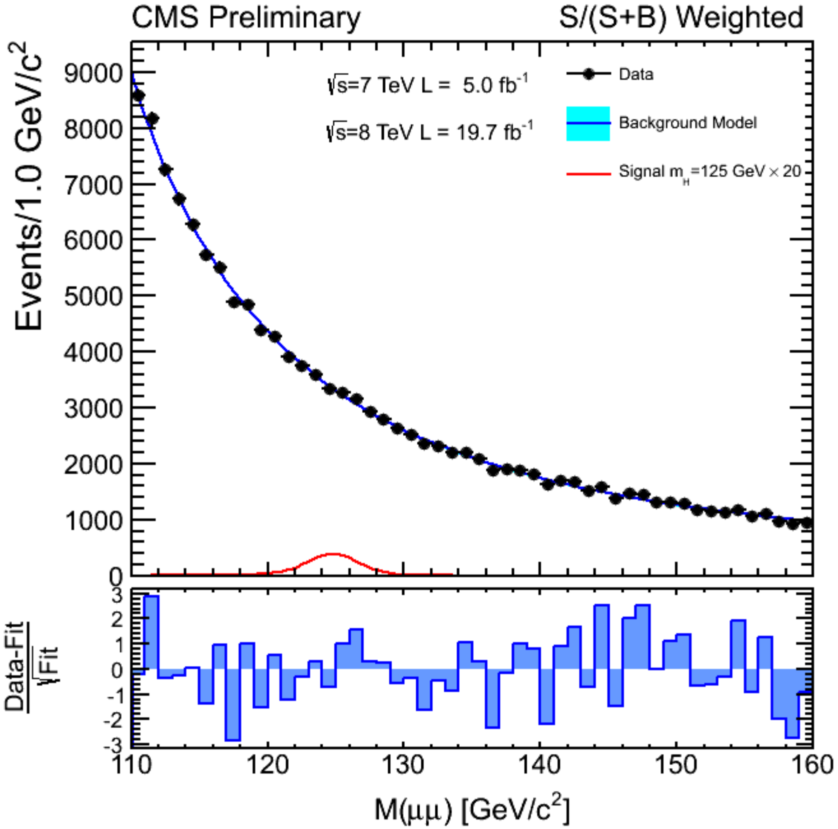


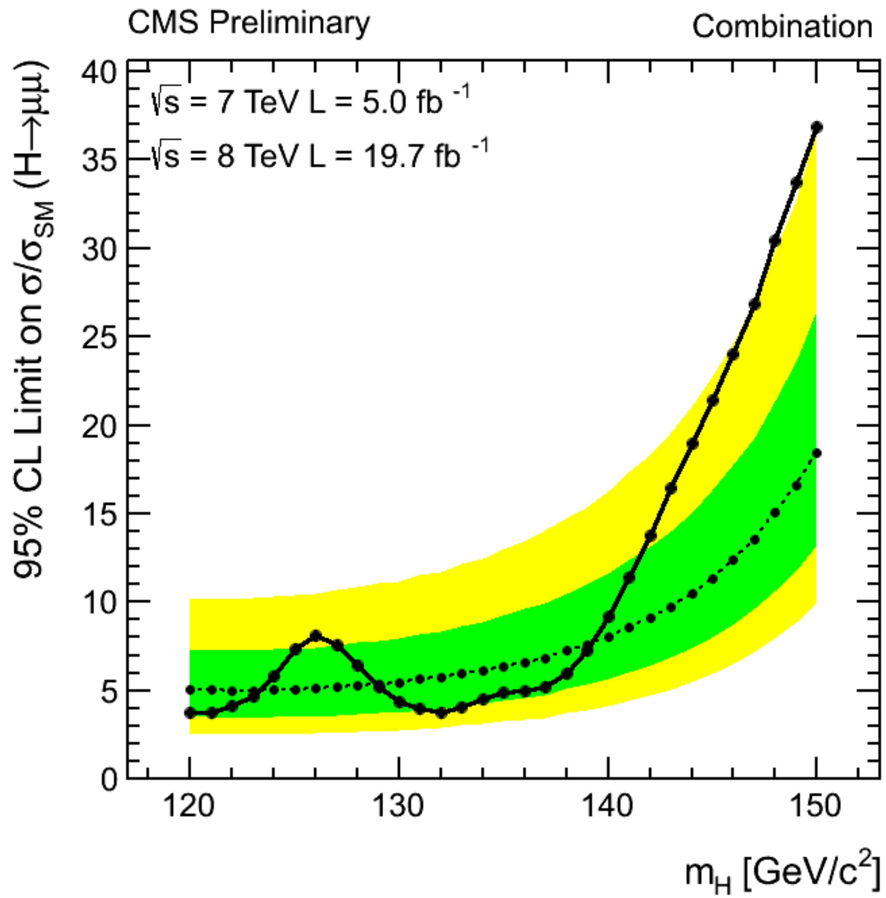




Rare decays II

Search for the Higgs boson decaying to a di-muon pair

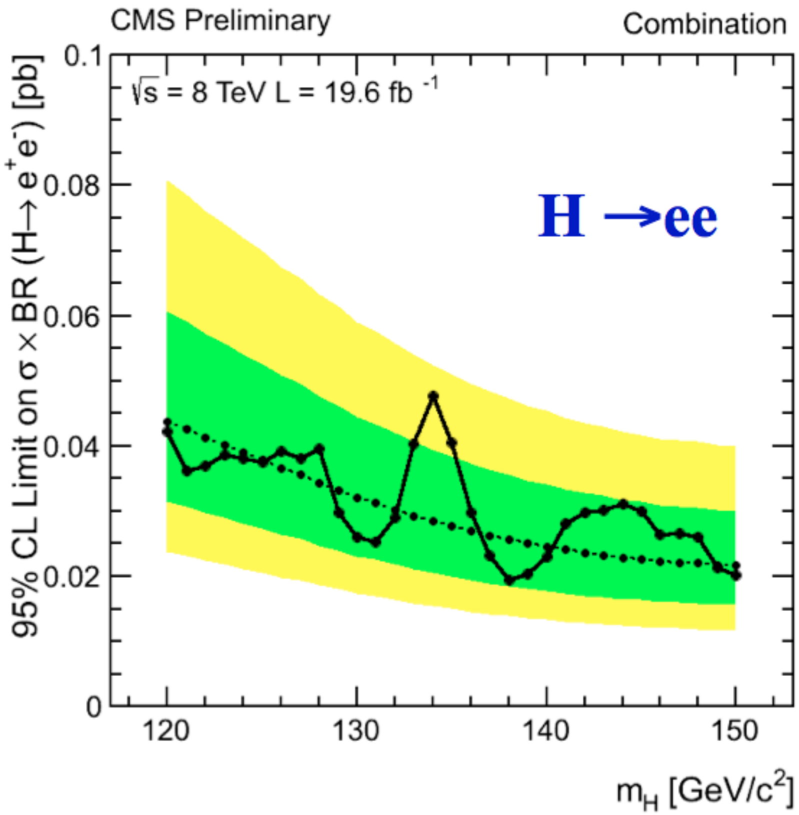


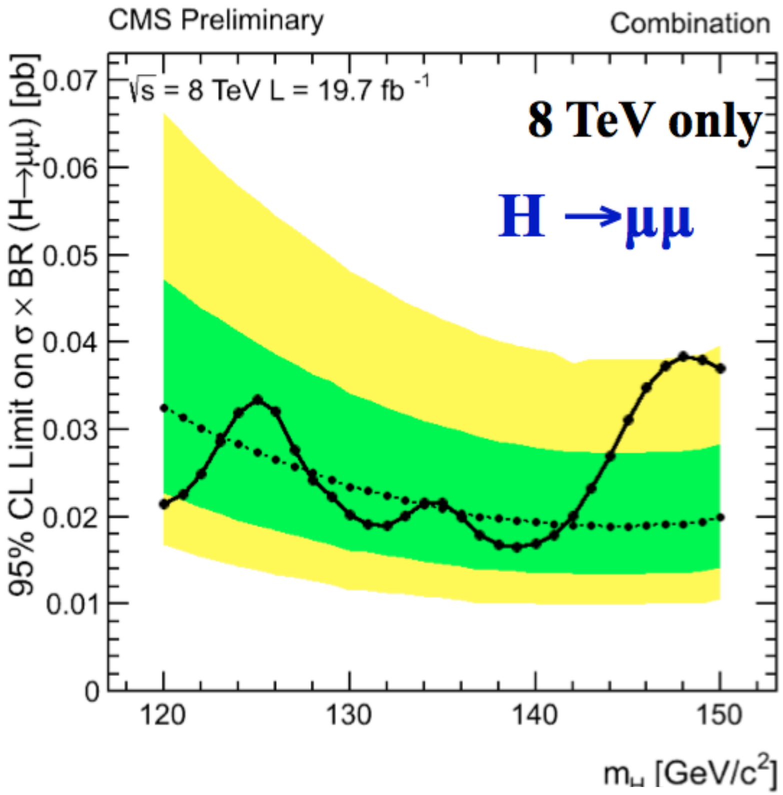


Di tau ~ 280 x Dimuon : Flavour non universality !

Rare decays III

Search for the Higgs boson decaying to a di-electron pair





95% CL observed upper limit σ*BR at m_H= 125 GeV:

Dielectron	~ 0.038 pb
Di muon	~ 0.034 pb

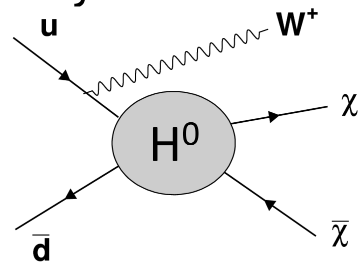
Dimuon ~ 5 10^4 x Dielectron : Flavour non universality !

Invisible Higgs Channels I

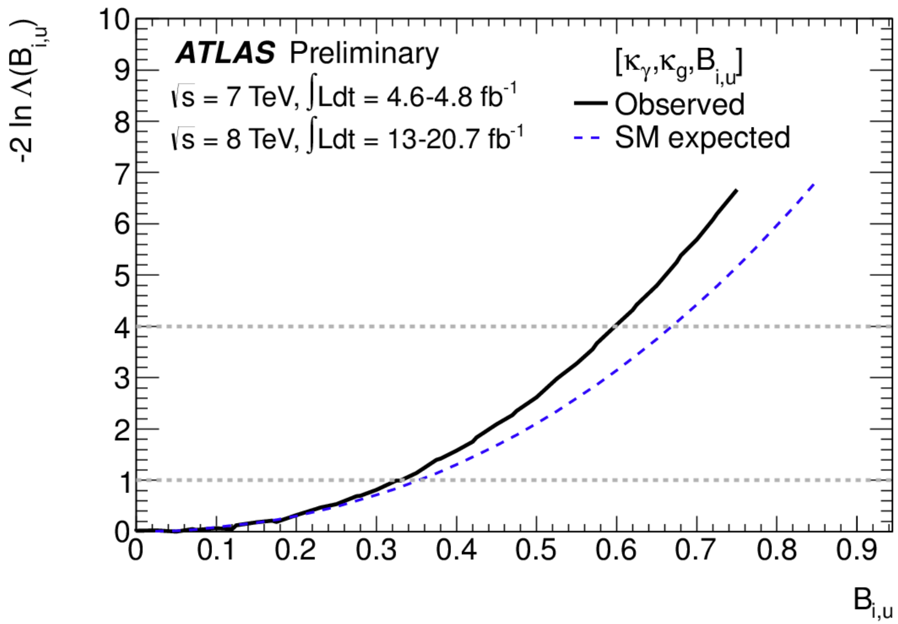
- Indirect constraints on the invisible and undetected Branching

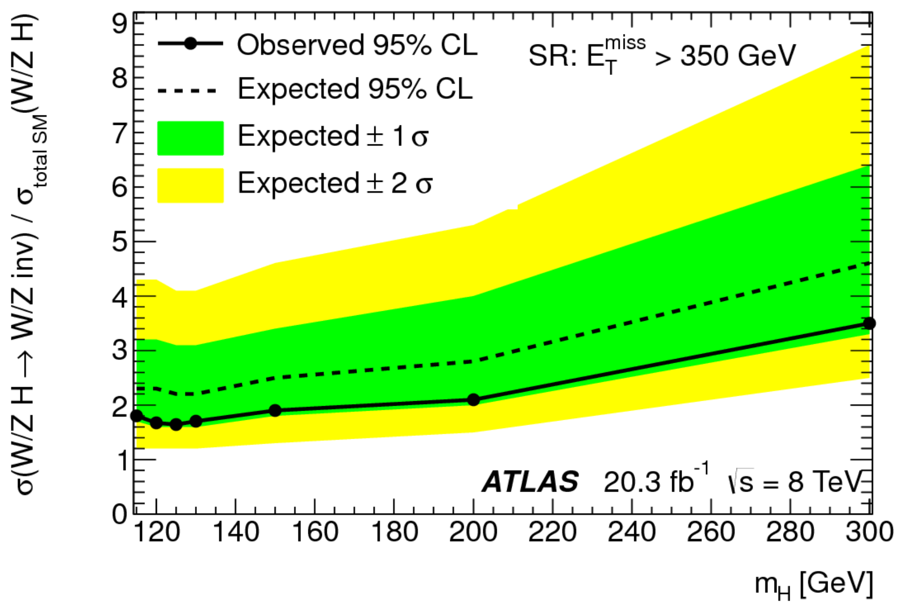
  (*a fortiori* on the invisible branching)

- Re-interpretation of mono-jet and mono-W or Z analyses



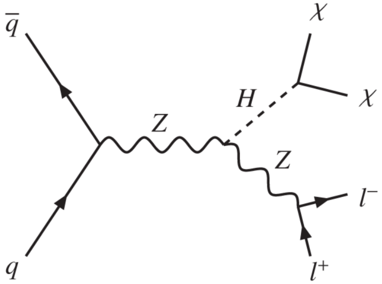
$$\kappa_g, \kappa_\gamma, Br_{\text{inv,undet}}$$



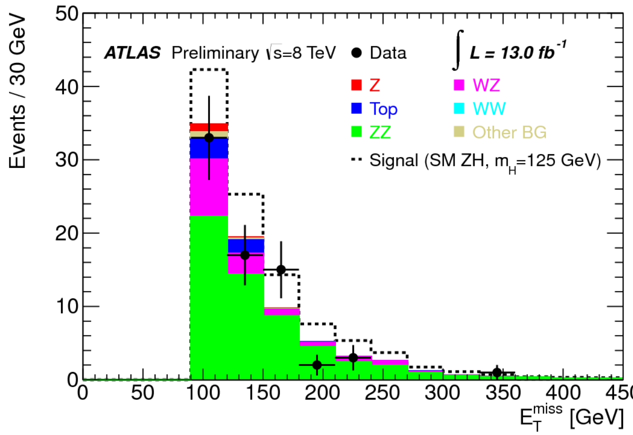


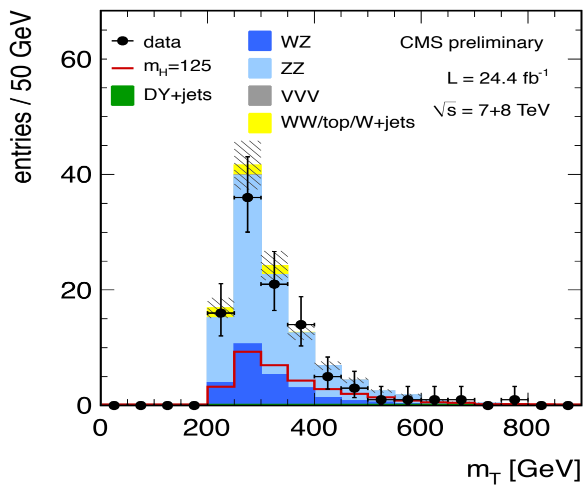
For a 125 GeV Higgs: $\sigma Br_{inv}/\sigma_{SM} < 1.6$ at 95%CL (obs)

Invisible Higgs Channels II



- Search for a dilepton pair compatible with a Z and missing transverse energy
- Analyses using fits to MET (ATLAS) or MT (CMS)





For a 125 GeV Higgs:

- ATLAS

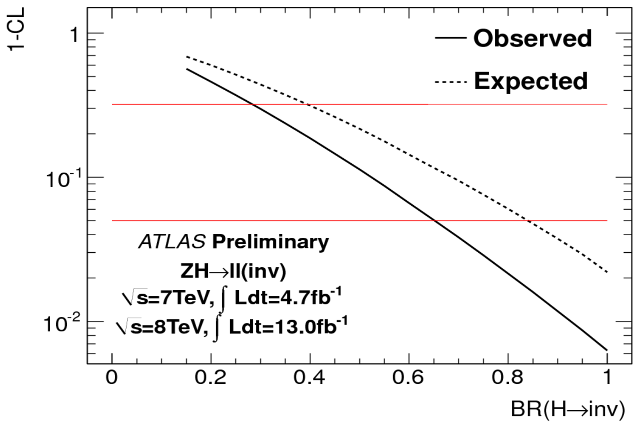
  Br_{inv} < 65% at 95%CL (obs)

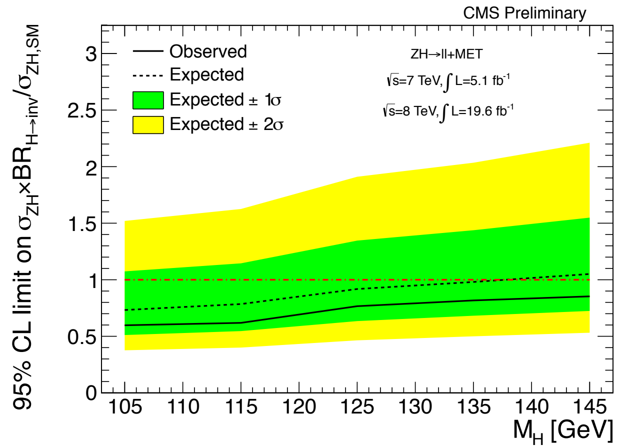
  Br_{inv} < 84% at 95%CL (exp)

- CMS

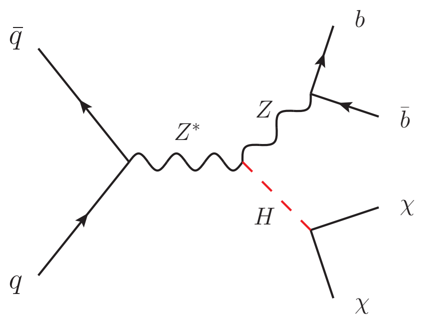
  Br_{inv} < 75% at 95%CL (obs)

  Br_{inv} < 91% at 95%CL (exp)

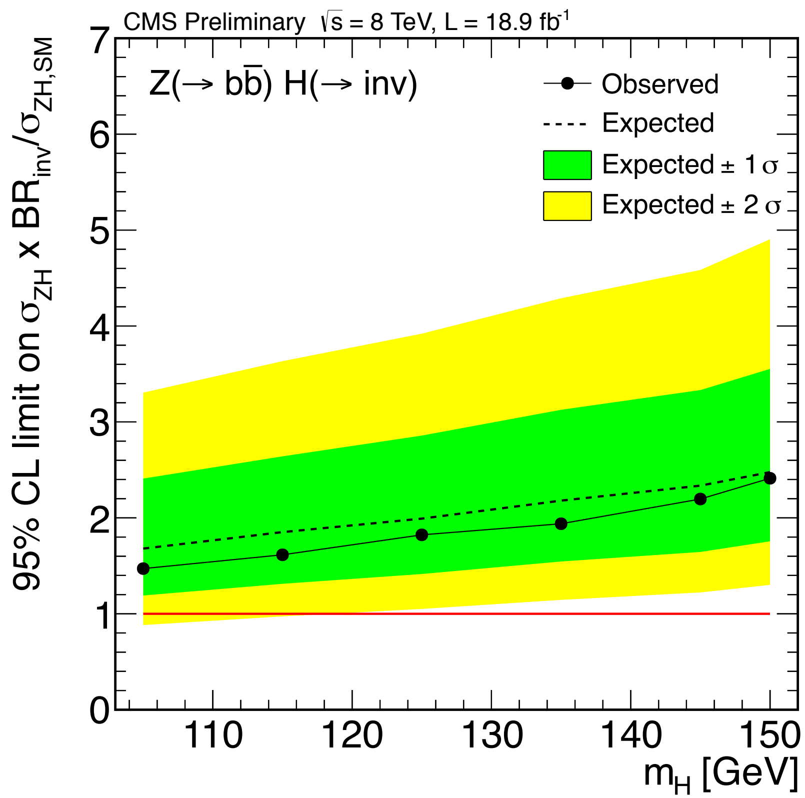


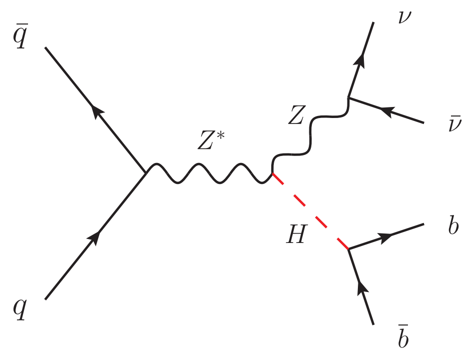


Invisible Higgs Channels III



- Associated production with a Z in bb (CMS only)
- Search following closely VH(bb)
- Contribution from VH(bb) has very little impact





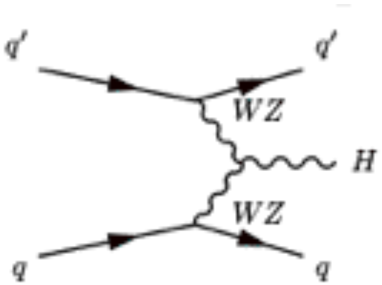
For a 125 GeV Higgs:

$\sigma Br_{inv}/\sigma_{SM}$ < 1.8 at 95%CL (obs)

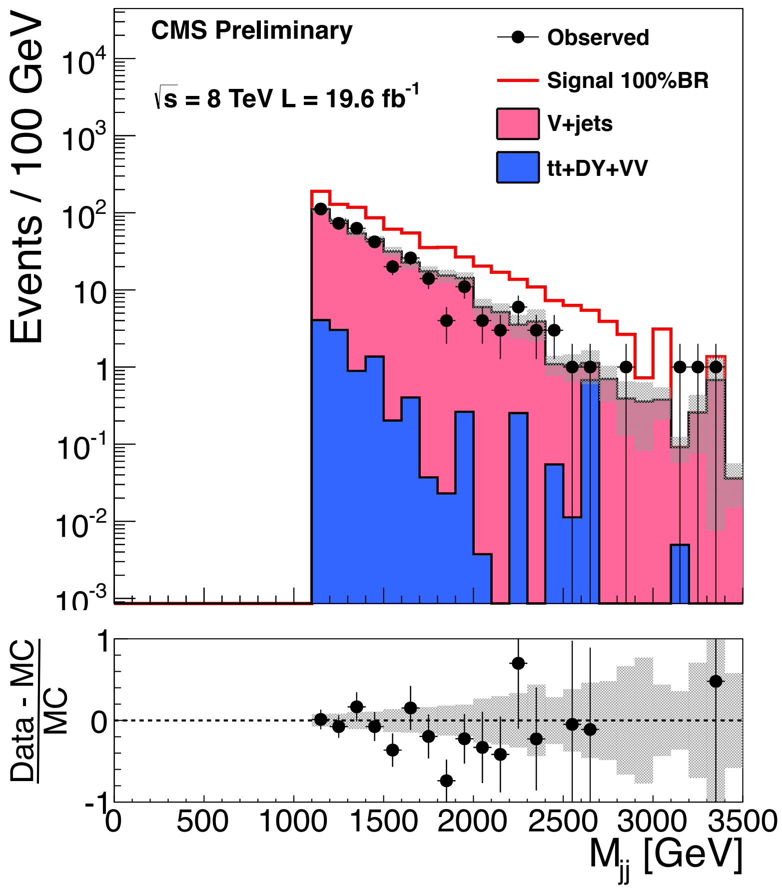
$\sigma Br_{inv}/\sigma_{SM}$ < 2.0 at 95%CL (exp)

CMS-PAS-HIG-13-028

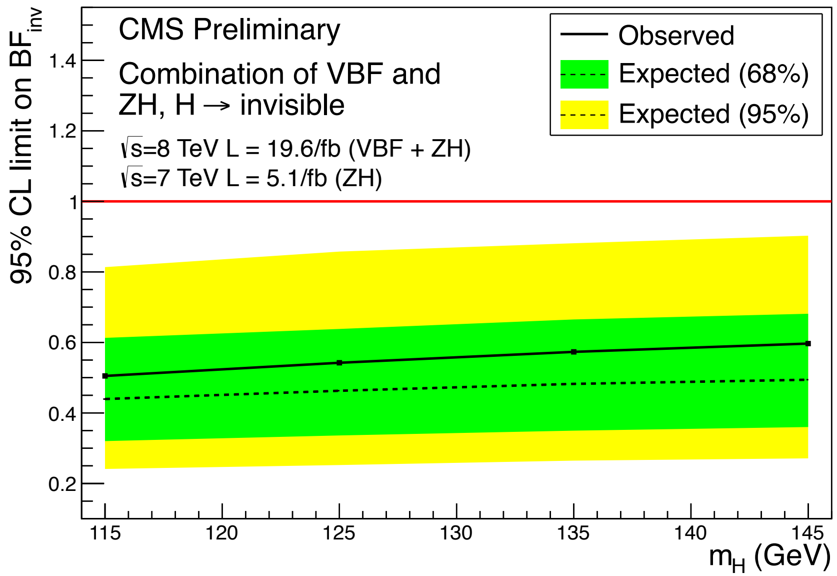
Invisible Higgs Channels IV



- Search in the VBF production mode
- Main selection on M_{jj}, $\Delta\eta_{jj}$, and large MET



CMS-PAS-HIG-13-013



For a 125 GeV Higgs:

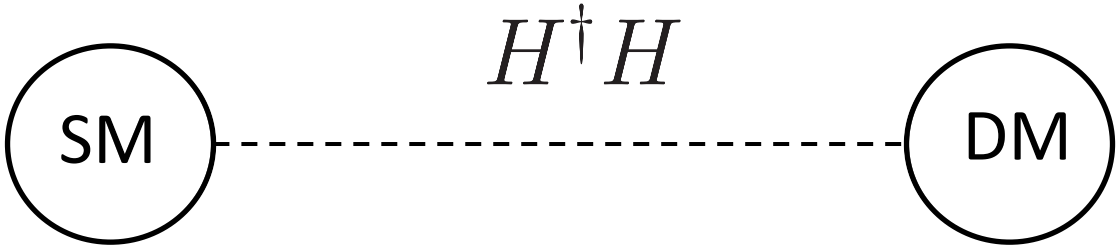
- CMS

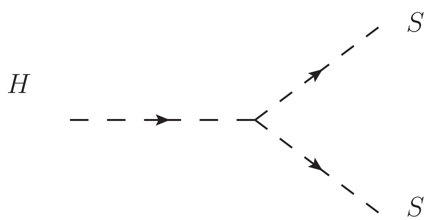
  Br_{inv} < 69% at 95%CL (obs)

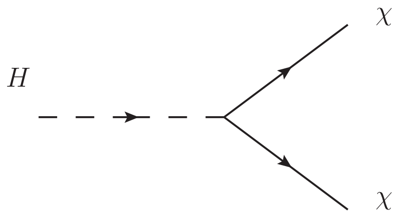
  Br_{inv} < 53% at 95%CL (exp)

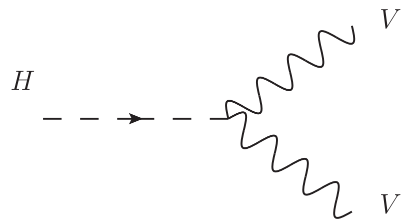
Interpretation in Higgs Portal to DM

Djouadi, Falkowski, Mambrini, Quevillon









$\mathcal{L}_S \supset -\frac{1}{2} m_S S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2$

$\mathcal{L} \supset -\frac{1}{2} m_f \overline{\chi}\chi - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H \overline{\chi}\chi$

$\mathcal{L} \supset \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu$

Spin Independent (SI) DM-nucleon elastic cross section

$$\sigma^{SI}_{S-N} = \frac{\lambda^2_{hSS}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_S + m_N)^2} ,$$

$$\sigma^{SI}_{V-N} = \frac{\lambda^2_{hVV}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_V + m_N)^2} ,$$

$$\sigma^{SI}_{f-N} = \frac{\lambda^2_{hff}}{4\pi \Lambda^2 m_h^4} \frac{m_N^4 M_f^2 f_N^2}{(M_f + m_N)^2}$$

$$\Gamma^{\rm inv}_{h\to SS} = \frac{\lambda^2_{hSS} v^2 \beta_S}{64\pi m_h} ,$$

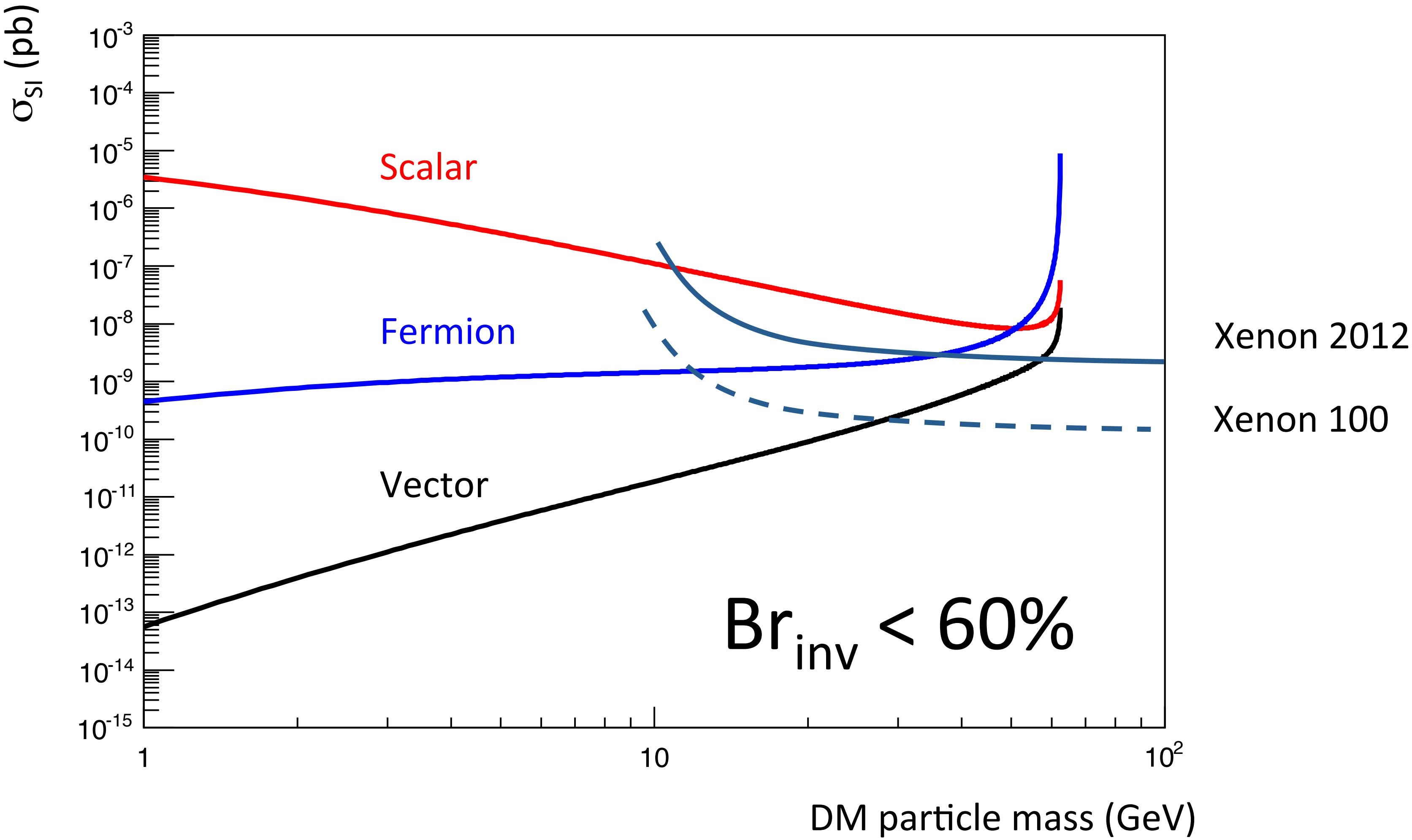
$$\Gamma^{\rm inv}_{h\to VV} = \frac{\lambda^2_{hVV} v^2 m_h^3 \beta_V}{256\pi M_V^4} \left(1 - 4\frac{M_V^2}{m_h^2} + 12\frac{M_V^4}{m_h^4}\right) ,$$

$$\Gamma^{\rm inv}_{h\to\chi\chi} = \frac{\lambda^2_{hff} v^2 m_h \beta_f^3}{32\pi\Lambda^2} ,$$

$$\beta_X = \sqrt{1 - 4M_X^2/m_h^2}$$

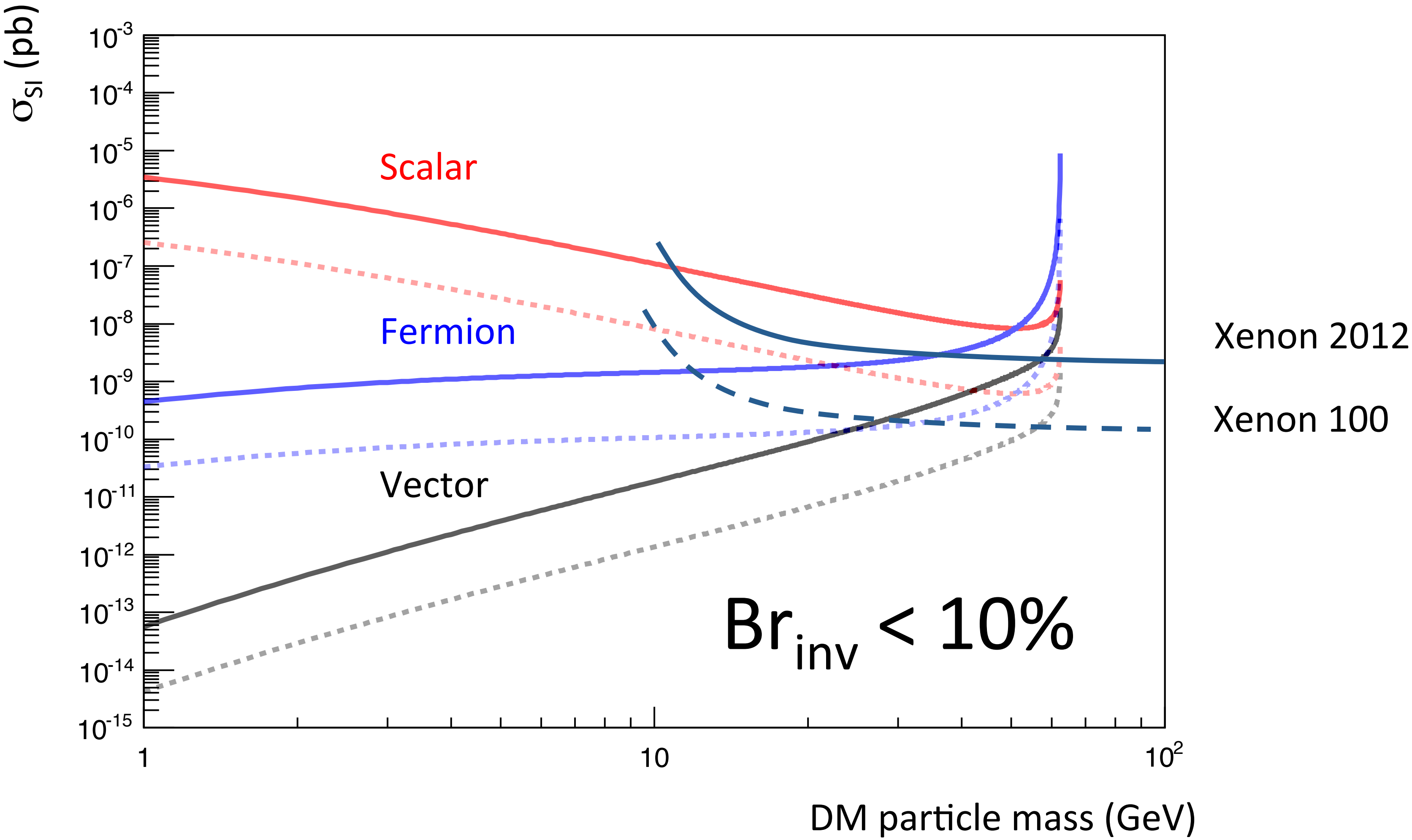
Interpretation in Higgs Portal to DM

Spin Independent (SI) DM-nucleon elastic cross section



Interpretation in Higgs Portal to DM

Spin Independent (SI) DM-nucleon elastic cross section



Higgs width determination

- Direct measurement will only be possible at future collider… what can be done at the LHC?

- Direct measurement at LHC from the Higgs lineshape in diphoton and 4l will be limited by systematics and in particular the modeling of the resolution systematic uncertainties (See CMS result)

- Direct measurement through decay length in the 4l channel has also very limited sensitivity.

- Very indirect estimates through coupling fit (with various assumptions)

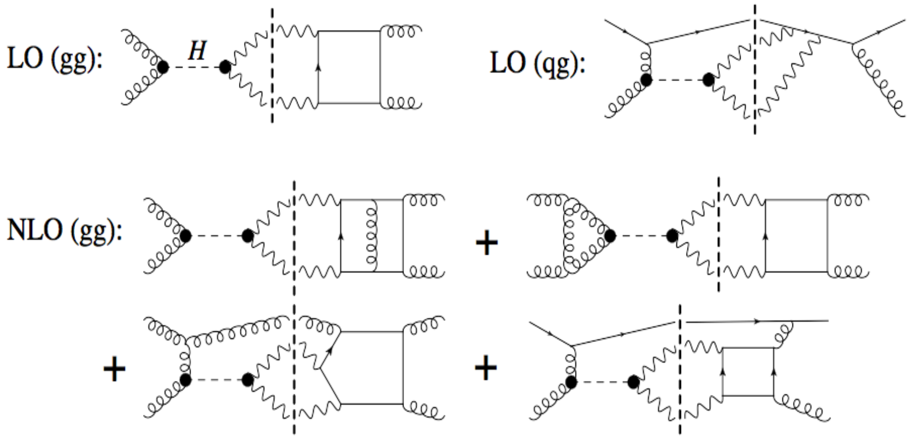
- Using unitarity constraints

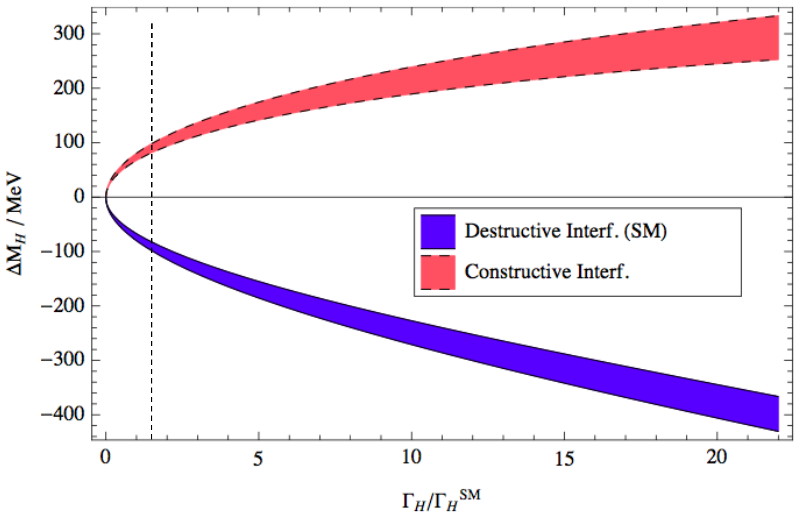
- New trends in trying to constrain the Higgs width (still indirect, but little to no assumptions):

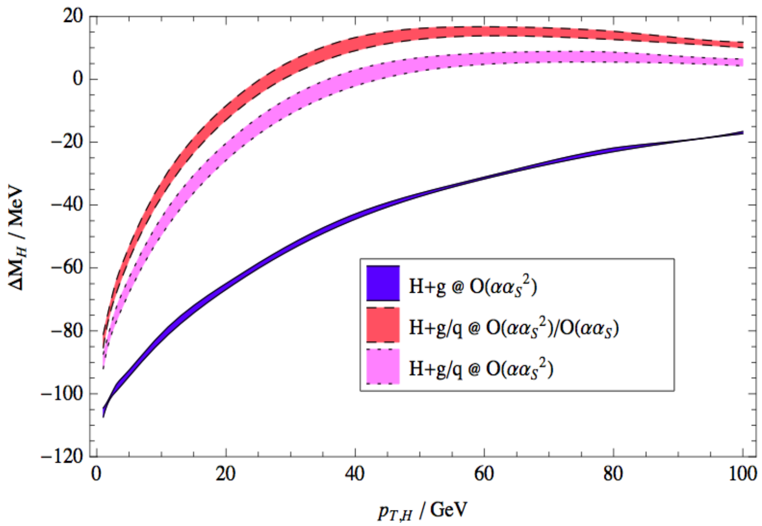
    - Width through mass differences
    - Width through precise high mass VV cross section measurements

Interferometry and mass shift

- Adding detector resolution effects, mass shift induced: ~70 MeV at NLO
- Interference dependent on Γ_H → measure of the shift could allow to bound the width.
- Measurement of the shift can be done:
  - by comparing the masses in H→ZZ and H→γγ
  - by exploiting dependence with Higgs boson pT





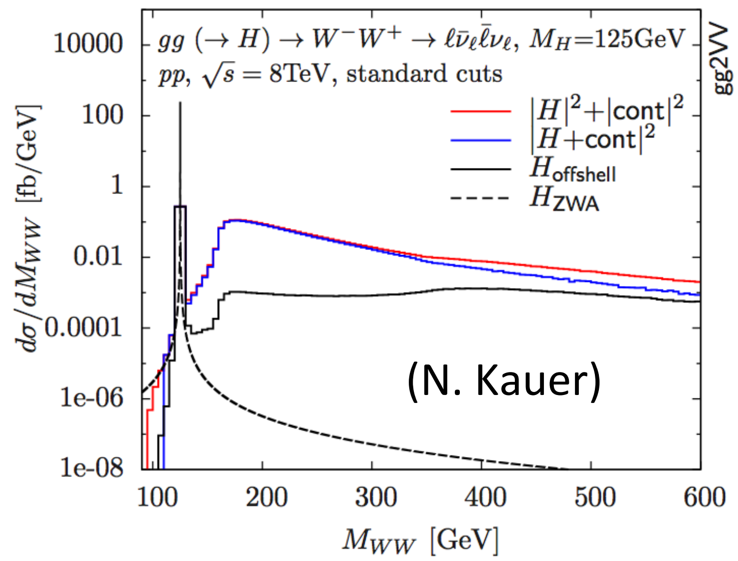


Lance J. Dixon and Ye Li.. Submitted to Phys. Rev. Lett., 2013

ZZ High Mass cross section

- Off shell
- Interference in the high mass range

$gg \to H \to WW \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$



Standard cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $\not{p}_T > 30$ GeV, $M_{\ell\ell} > 12$ GeV

First study by Fabrizio Caola, Kirill Melnikov (arXiv:1307.4935) for $M_H = 126$ GeV using CMS data (LHC7: 5.1fb^{-1}, LHC8: 19.6fb^{-1}) and gg2VV (NK)

Signal process: $pp \to H \to ZZ \to 2e2\mu, 4e, 4\mu$

resonance contribution to signal cross section ("on-peak")): $M_{ZZ} < 130$ GeV
off-resonance contribution to signal cross section ("off-peak"): $M_{ZZ} > 130$ GeV

Energy	$\sigma^{\mathrm{H}}_{\mathrm{on-peak}}$	$\sigma^{H}_{\mathrm{off-peak}}$	$\sigma^{\mathrm{interference}}_{\mathrm{off-peak}}$
7 TeV	0.203	0.044 (21%)	−0.108
8 TeV	0.255	0.061 (24%)	−0.166
$N^{\mathrm{SM}}_{2e2\mu}$	9.8 (CMS)	1.73	−4.6
$N^{\mathrm{SM}}_{2e2\mu+4e+4\mu}$	21.1 (CMS)	3.72	−9.91

ZZ High Mass cross section

(From N. Kauer)

rescale Higgs couplings and Higgs width keeping σ_{peak} fixed to SM

$$N_{4l}^{\text{off}} = 3.72 \times \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} - 9.91 \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}}$$

CMS in $pp \to ZZ \to 4\ell$: 451 evts observed, 432 ± 31 evts expected (on-peak only/ZWA)

expected total number of events with rescaled Higgs couplings/width:

$$N_{\text{exp}} = 432 + 3.72 \times \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} - 9.91 \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}} \pm 31$$

95% CL (2σ) upper limit: $\Gamma_H \leq 38.8\,\Gamma_H^{\text{SM}} \approx 163$ MeV

(Caola and Melnikov)

Ultimately (assuming 3% uncertainty) the limit ~20-40 MeV

Future Prospects

The LHC timeline

LS1 Machine Consolidation

LS2 Machine upgrades for high Luminosity

- Collimation
- Cryogenics
- Injector upgrade for high intensity (lower emittance)
- Phase I for ATLAS : Pixel upgrade, FTK, and new small wheel

LS3 Machine upgrades for high Luminosity

- Upgrade interaction region
- Crab cavities?
- Phase II: full replacement of tracker, new trigger scheme (add L0), readout electronics.

European Strategy Update

Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.

LHC timeline

2009 Start of LHC

Run 1, 7+8 TeV, ~25 fb^{-1} int. lumi

2013/14 Prepare LHC for design *E* & lumi **LS1**

Collect ~30 fb^{-1} per year at 13/14 TeV

2018 Phase-1 upgrade ultimate lumi **LS2**

Twice nominal lumi at 14 TeV, ~100 fb^{-1} per year

~2022 Phase-2 upgrade to HL-LHC **LS3**

~300 fb^{-1} per year, run up to > 3 ab^{-1} collected

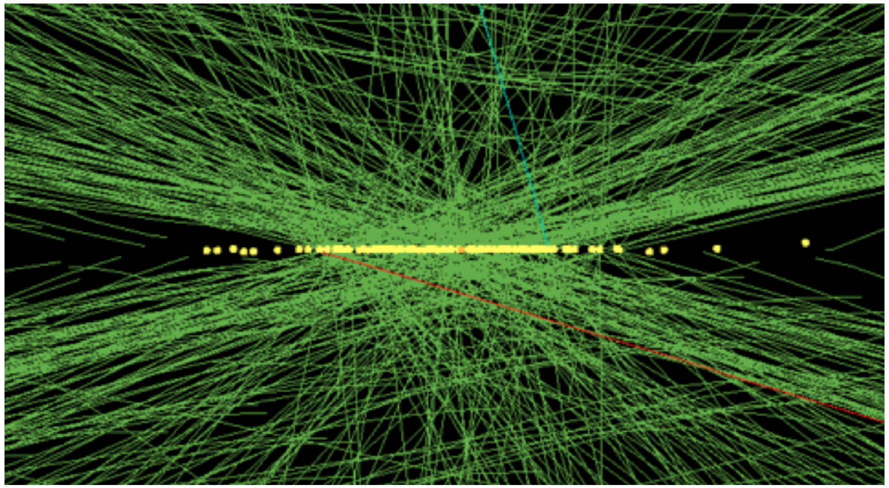
~2030

HL-LHC Beam Parameters

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Two HL-LHC scenarios

Parameter	2012	Nominal	HL-LHC (25 ns)	HL-LHC (50 ns)
C.O.M Energy	8 TeV	13-14 TeV	14 TeV	14 TeV
N_p	$1.2\ 10^{11}$	$1.15\ 10^{11}$	$2.0\ 10^{11}$	$3.3\ 10^{11}$
Bunch spacing / k	50 ns /1380	25 ns /2808	25 ns /2808	50ns /1404
ε (mm rad)	2.5	3.75	2.5	3.0
β* (m)	0.6	0.55	0.15	0.15
L ($cm^{-2}s^{-1}$)	~7×10^{33}	10^{34}	$7.4\ 10^{34}$	$8.4\ 10^{34}$
Pile up	~25	~20	~140	~260

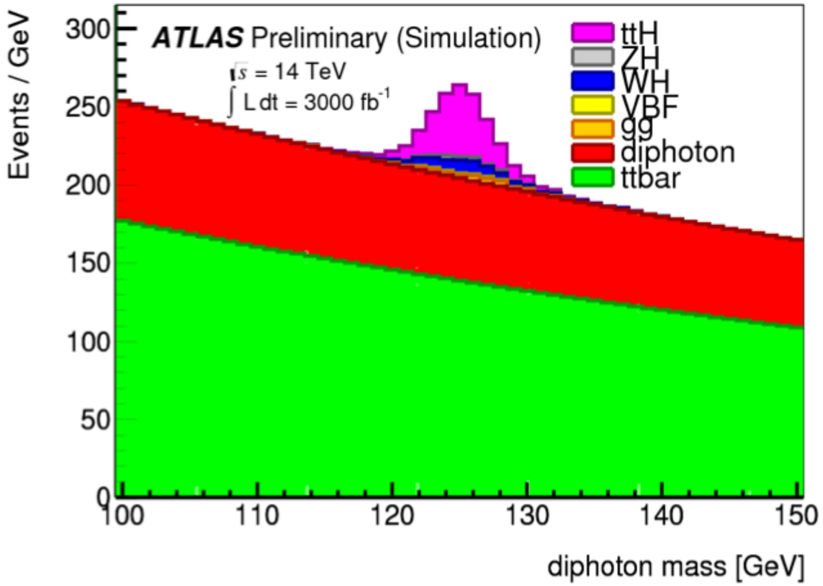


Pile up is a crucial issue!

CMS event with 78 reconstructed vertices

Reaching ttH Production in (robust) rare modes

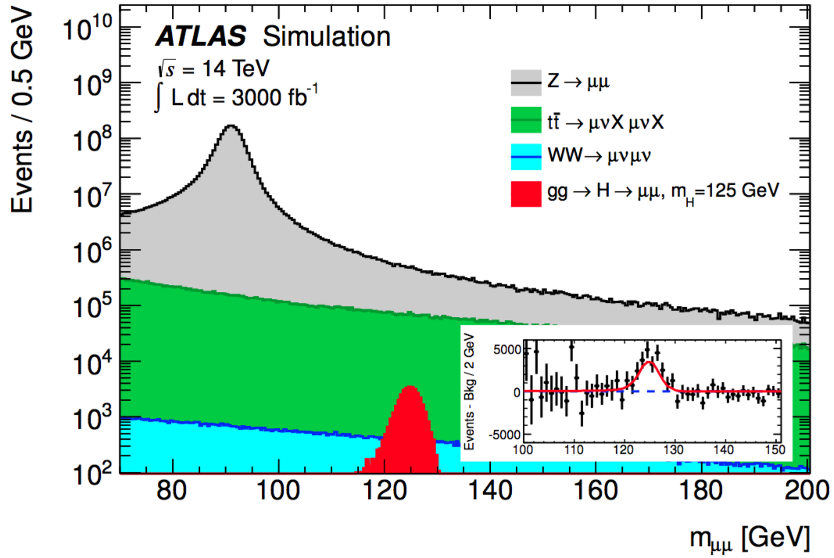
Analyses not relying on more intricate decay channels (bb, tt and WW)



- $\gamma\gamma$ channel: more than 100 Events expected with s/b~1/5
- $\mu\mu$ channel: approximately 30 Events expected with s/b~1

Analyses (rather) robust to PU

$\mu\mu$ decay mode should reach more than 5 standard deviation

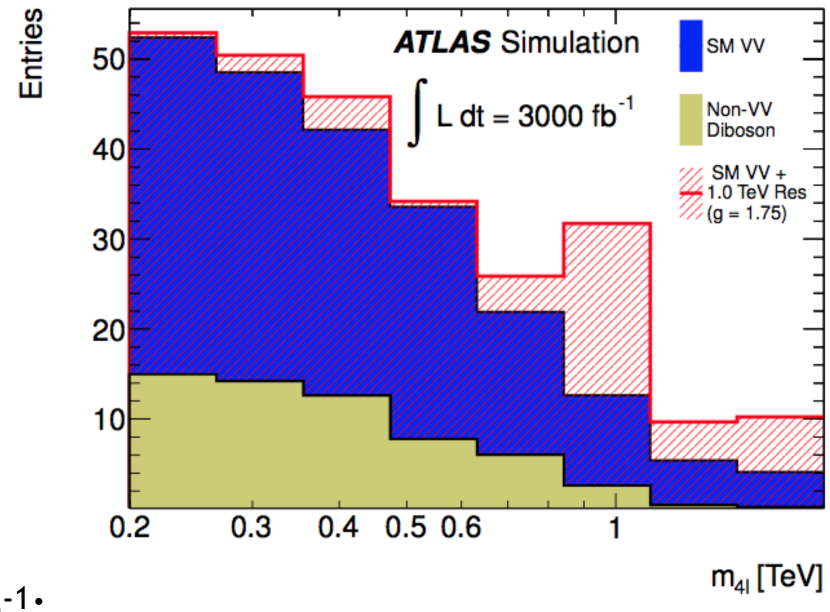


Completing the Picture WBS

Weak Boson Scattering

Only taking into account the cleanest signals : ZZjj in the 4 leptons final state

Very clean signature for a TeV resonance (in anomalous WBS models)

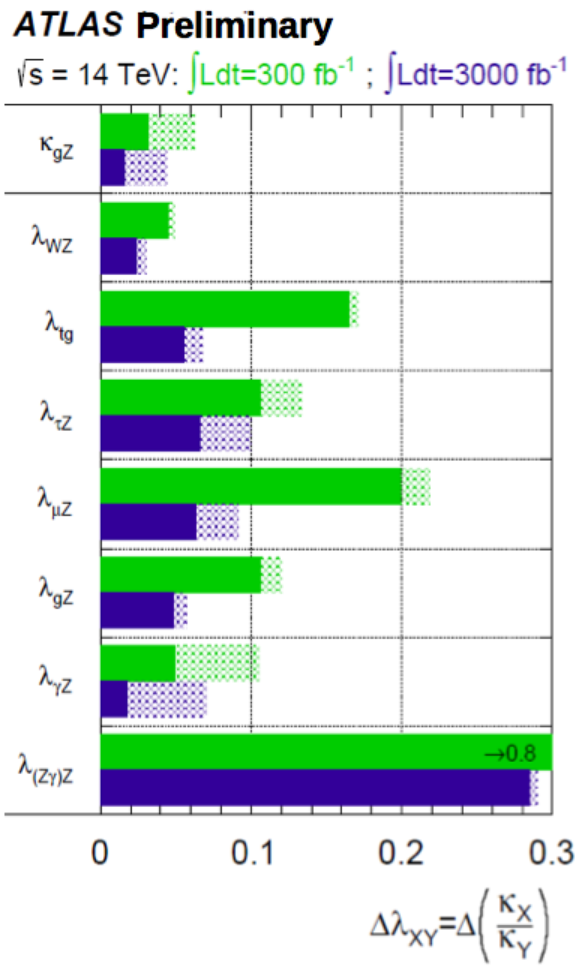


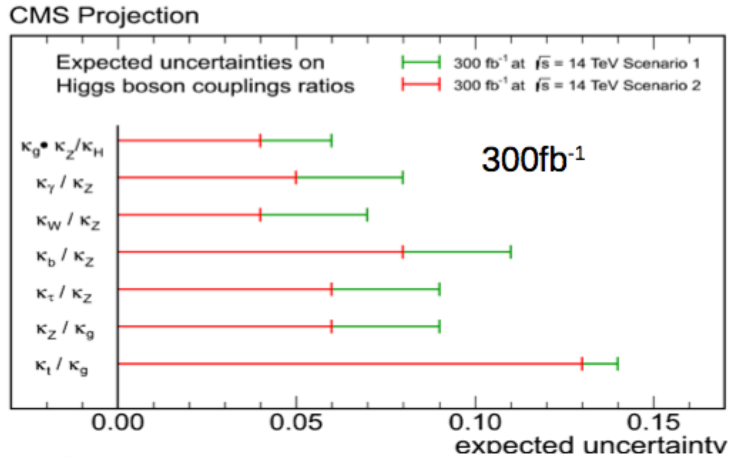
Sensitivities for 300 fb^{-1} and 3 ab^{-1}:

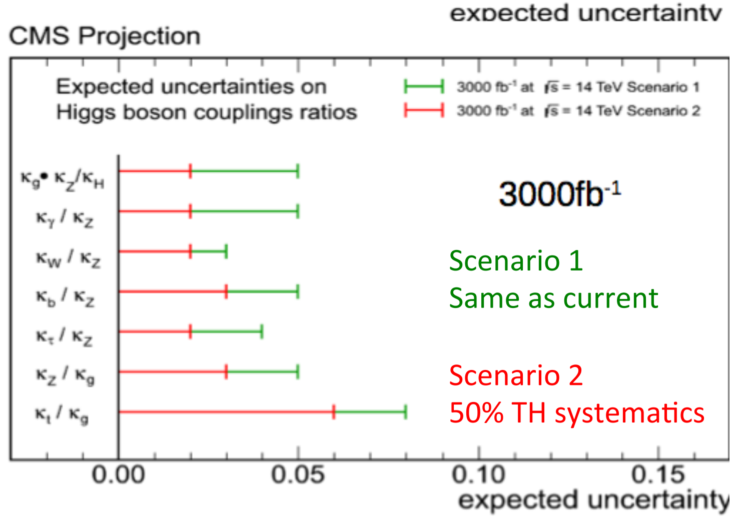
Model (anomalous WBS)	300 fb^{-1}	3 ab^{-1}
500 GeV and g=1	2.4 σ	7.5 σ
1 TeV and g=1.75	1.7 σ	5.5 σ
1 TeV and g=2.5	3.0 σ	9.4 σ

LHC Higgs Physics Program: Main Couplings

Couplings Projections recently reappraised with a sample of analyses







Only indirect (however not negligible) constraint on the total width

Necessary to use assumptions or measure ratios: Precision down to ~5% level

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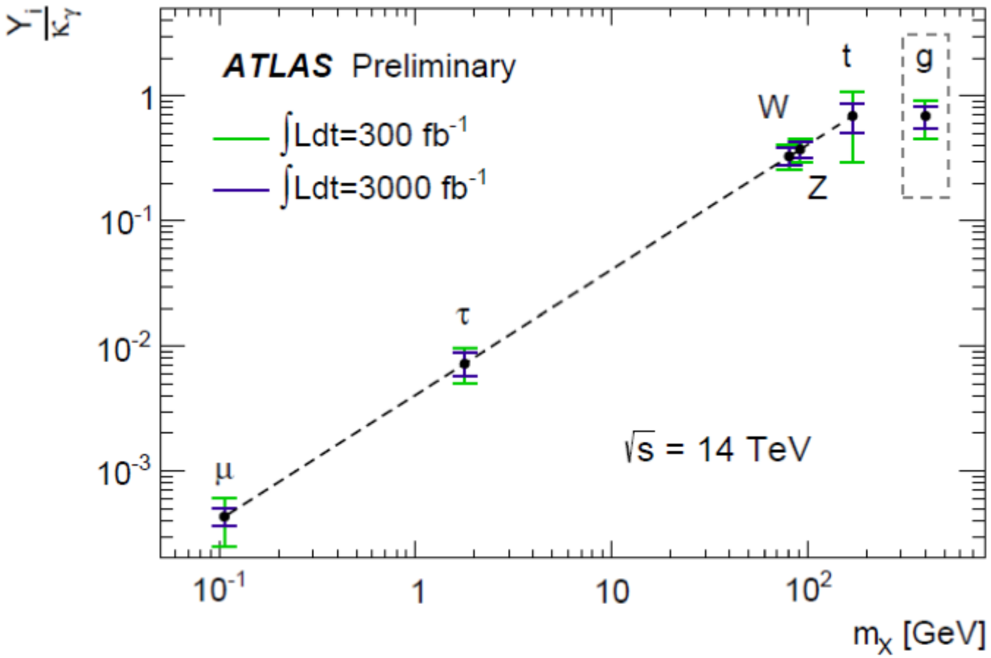

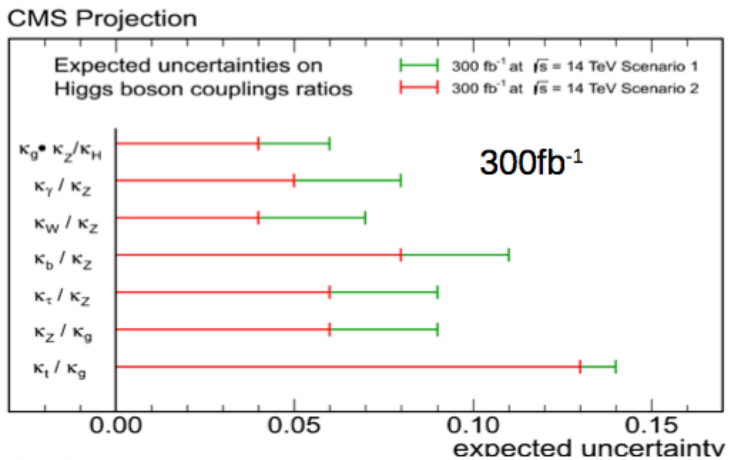

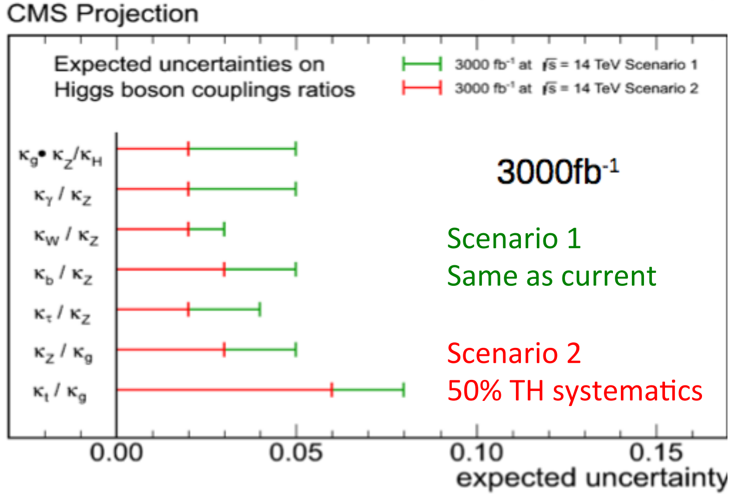

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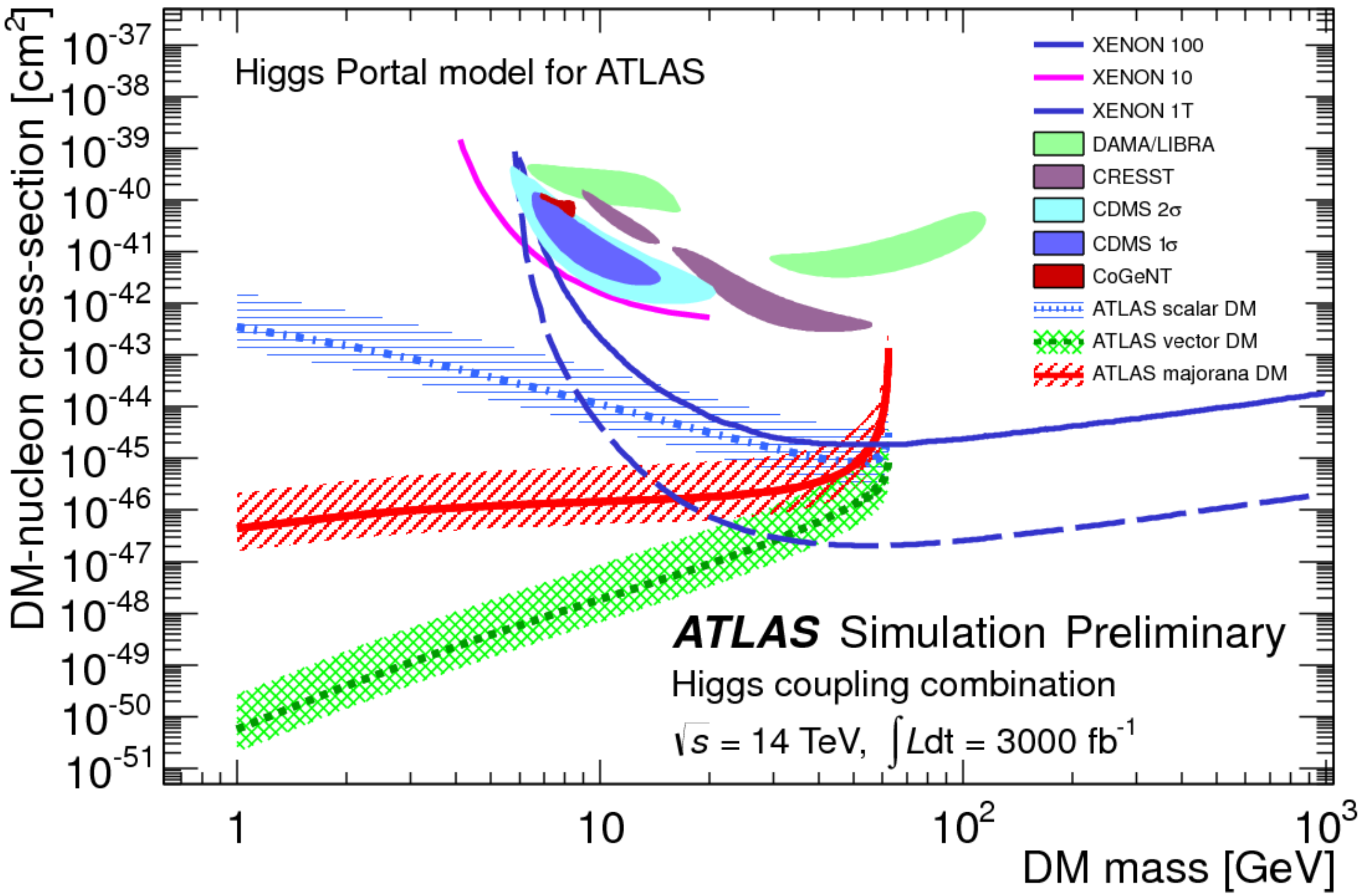


Invisible branching ~25% for 300 fb^{-1} and 15% for 3000fb^{-1}

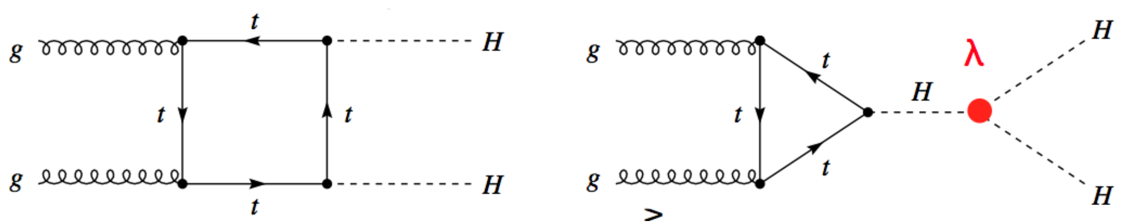
Self Couplings

Determination of the scalar potential, essential missing ingredient : **self couplings !**

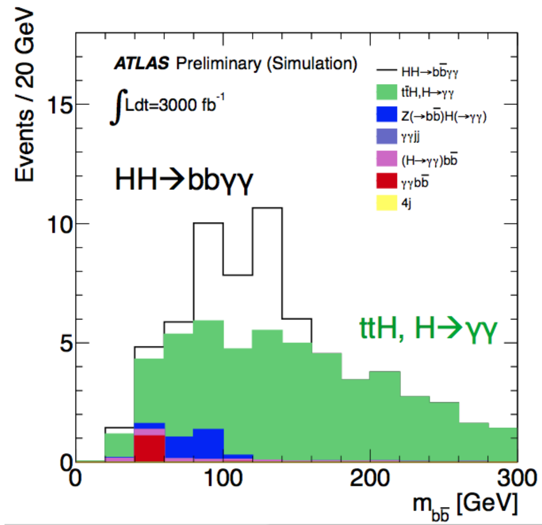
Are they as predicted : $\lambda_3 \sim m_H^2/(2v)$, $\lambda_4 \sim m_H^2/(8v^2)$

λ_4 : hopeless in any planed experiment (?)

λ_3 : very very hard in particular due to the double H production, which also interferes with the signal…

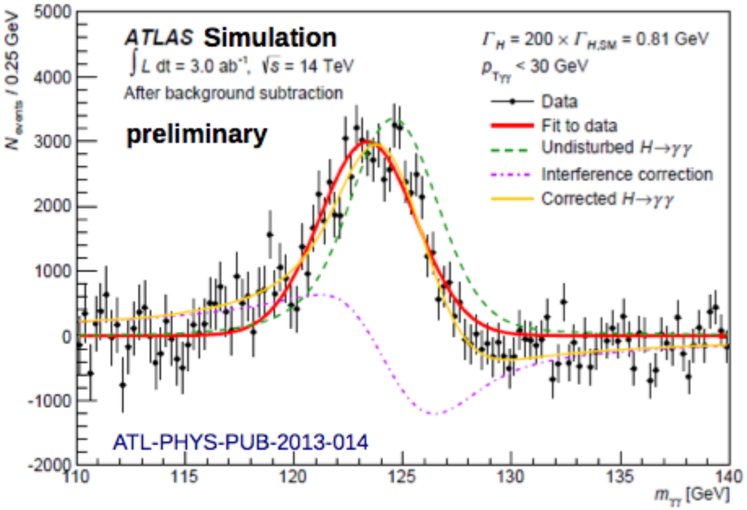


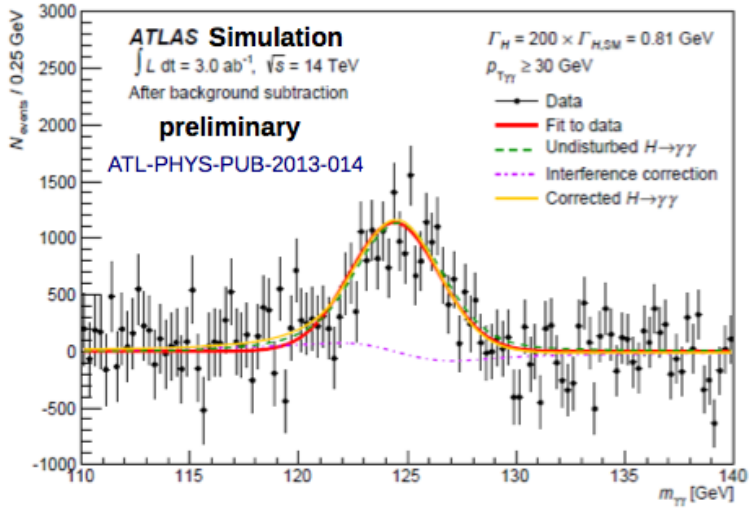
… but some hope, in (rather) robust
pp → HH → $bb\gamma\gamma$
(S ~ 15, B ~ 21 for 3 ab^{-1} and some faith…) $bb\tau^+\tau^-$
(under study)



New Trends

Interferometry !

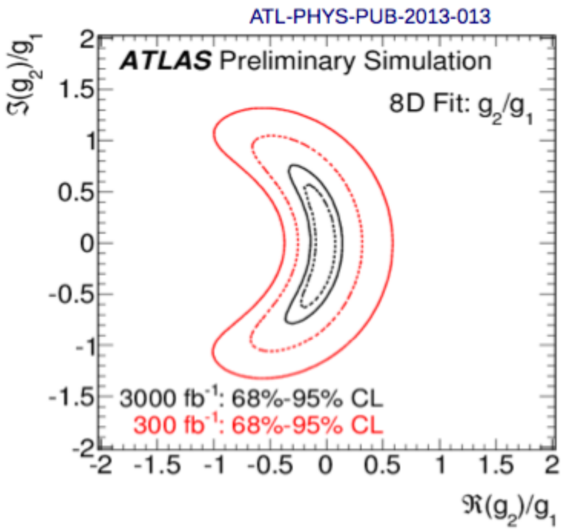


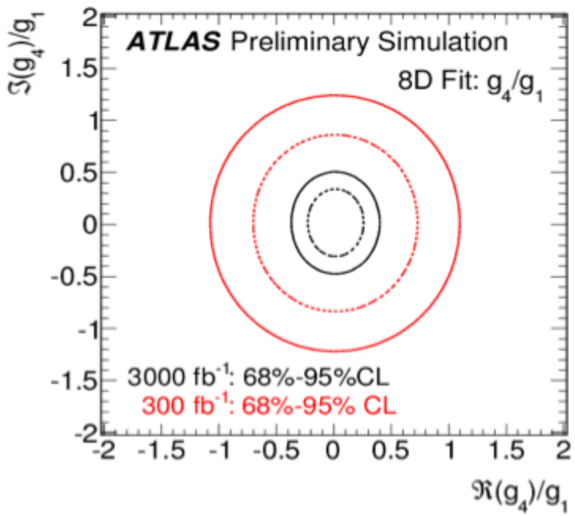


Limits at 3 ab^{-1} around 200 MeV on total width

CP properties

Exploring the complexe structure of couplings





Beyond LHC Programs

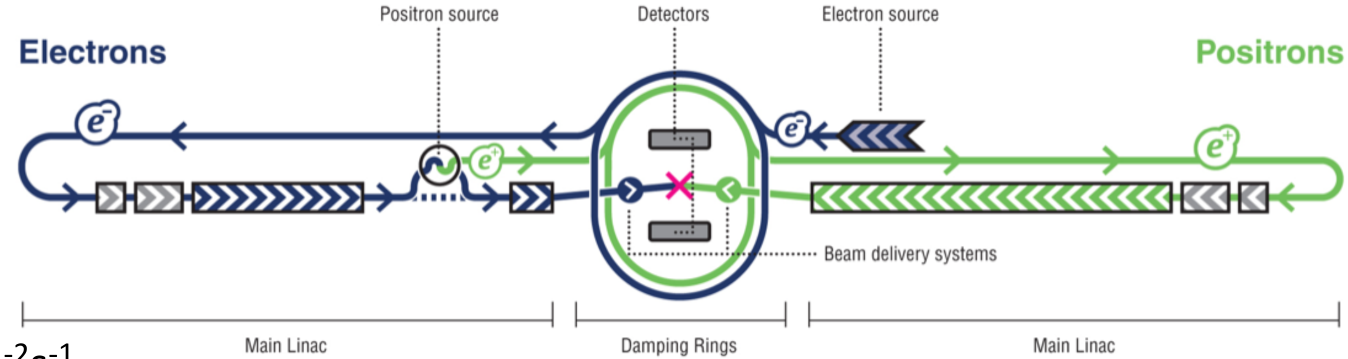
e^+e^- colliders

ILC

Three scenarios

- 250 GeV
- 500 GeV
- 1000 GeV

Lumi 0.7 to 5 10^{34} $cm^{-2}s^{-1}$

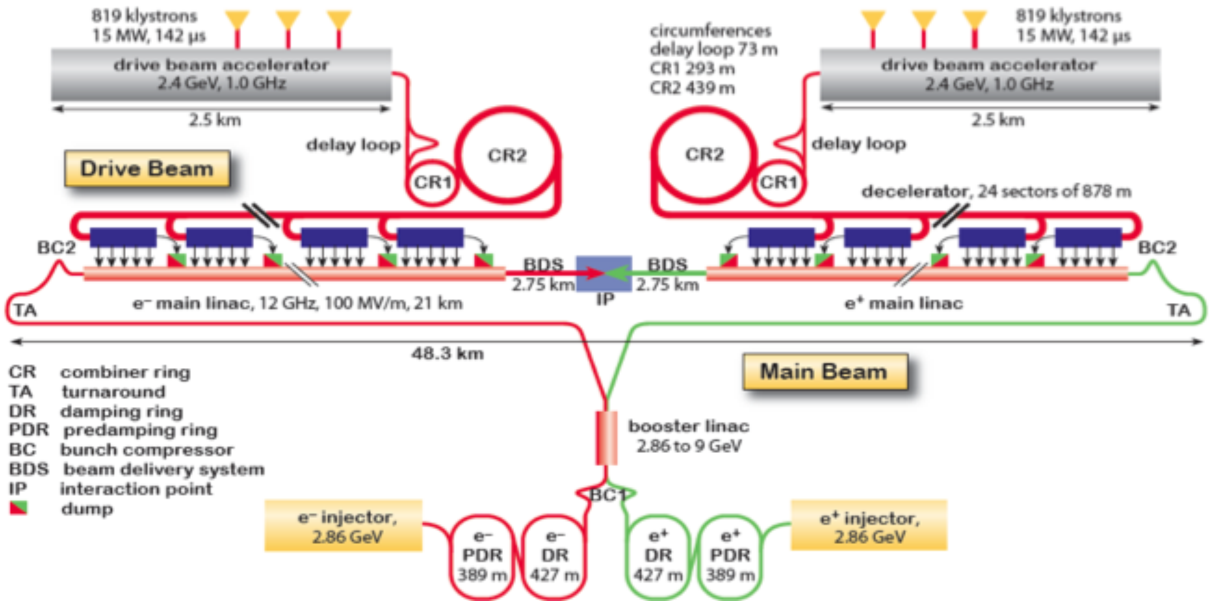


CLIC

Three scenarios

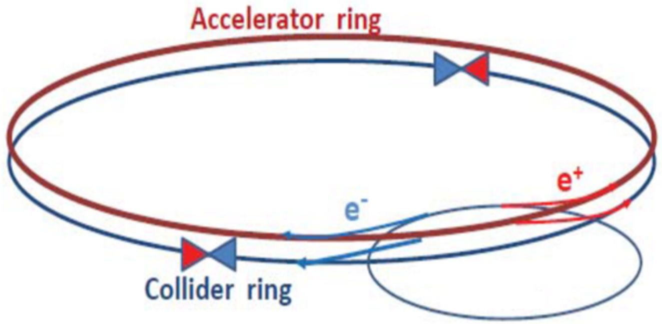
- 500 GeV
- 1500 GeV
- 3000 GeV

Lumi 1.3 to 6 10^{34} $cm^{-2}s^{-1}$



Beyond LHC Programs

Future circular collider VHE-LHC including e^+e^- collider

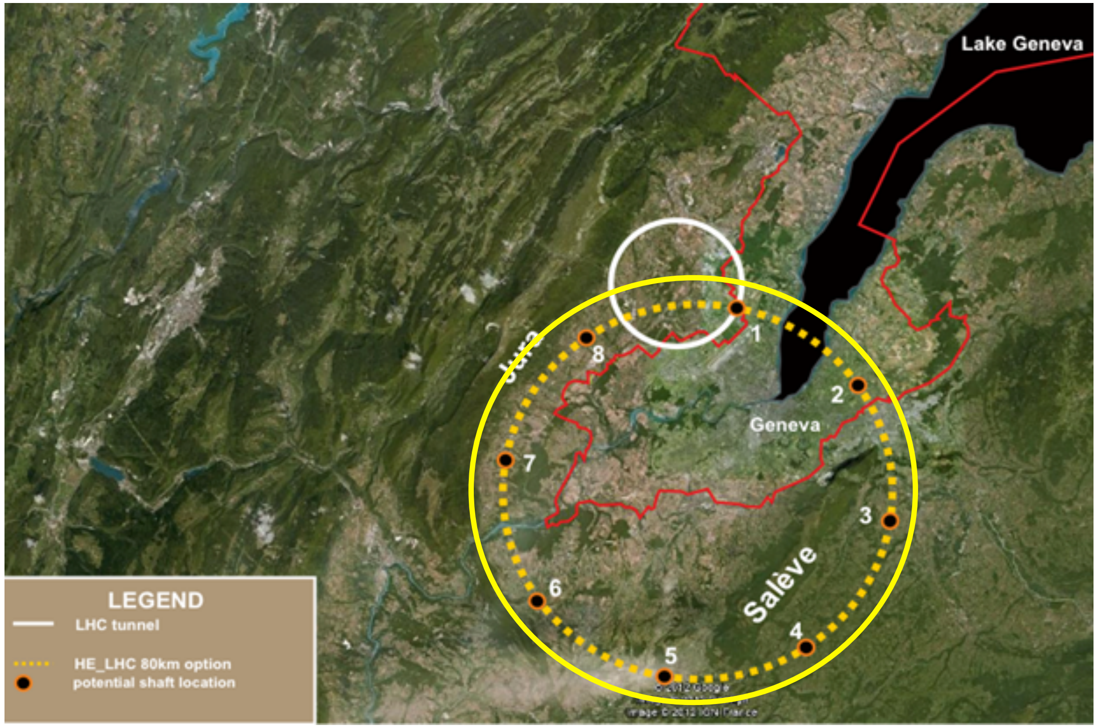


TLEP

Two scenarios

- 240GeV
- 350GeV

Lumi 5 to 7 $cm^{-2}s^{-1}$
(but 4 IPs)



VHE-LHC

100 TeV Collider
(~20T magnets)

Beyond LHC Programs

e^+e^- colliders

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

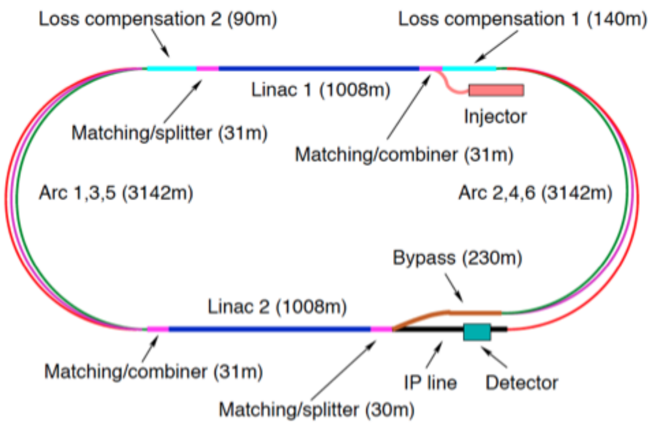
C. Grojean

- Reaching few permil to percent level precision on the couplings
- Direct measurement of branching fractions

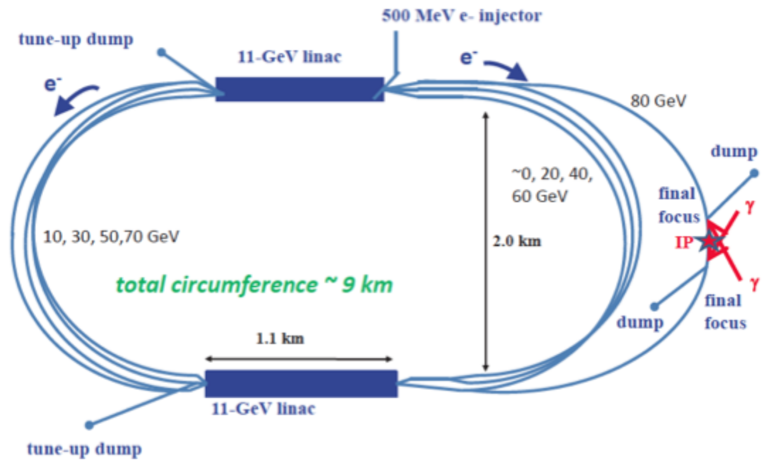
Beyond LHC Programs

Further Programs

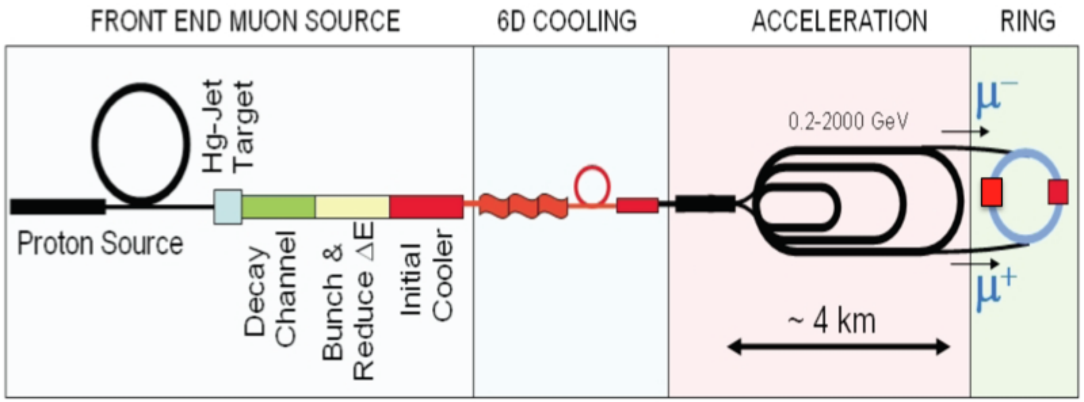
ep Collider



γγ Collider



Ultimate Higgs factory
μμ Collider



Conclusions and Outlook

From the theory point of view

See A. Masiero's talk

New era in experimental particle physics

- New horizons and measurements possible involving the Higgs boson
    - Precision in measuring coupling and spin/CP properties!
    - New trends to measure natural width
    - Rare decay modes (charm, J/Psi γ, WD, etc…)
    - Using the Higgs particle to probe FCNCs
    - Decays to exotic particles (hidden valley pions, dark Zs, etc…)
    - Exciting new analysis techniques (jet substructure)

- Searches for new physics involving the Higgs particle

- Focal point for the future large scale projects