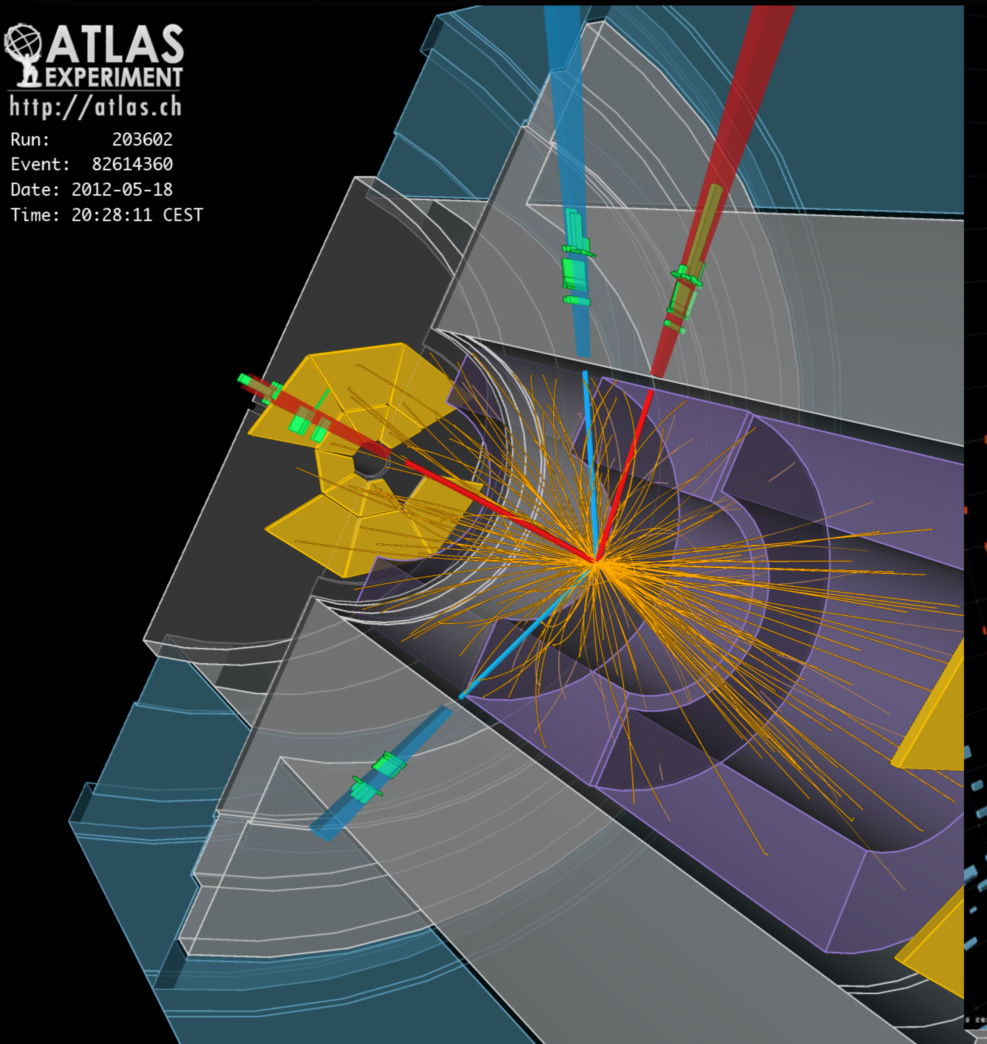
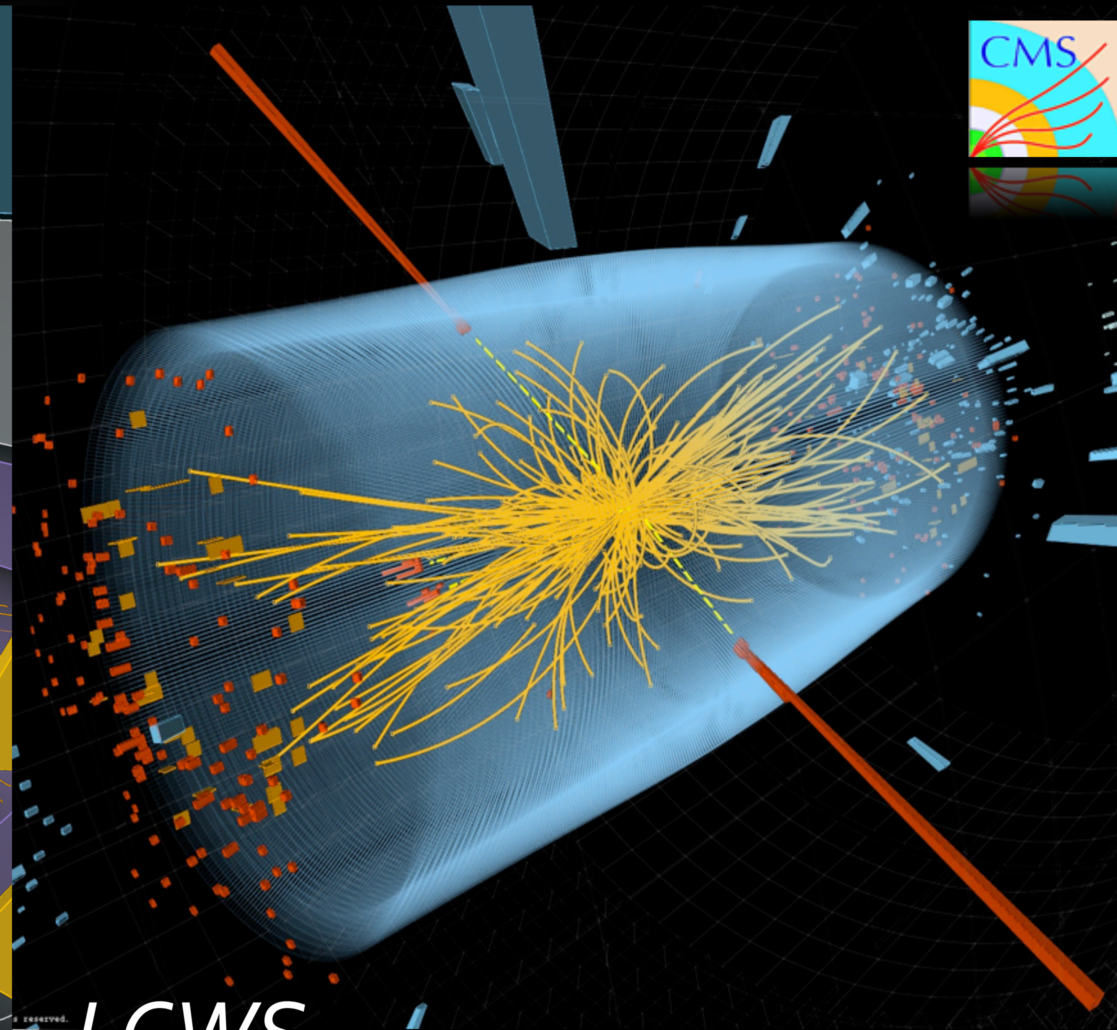
LHC Higgs: Results and Projections

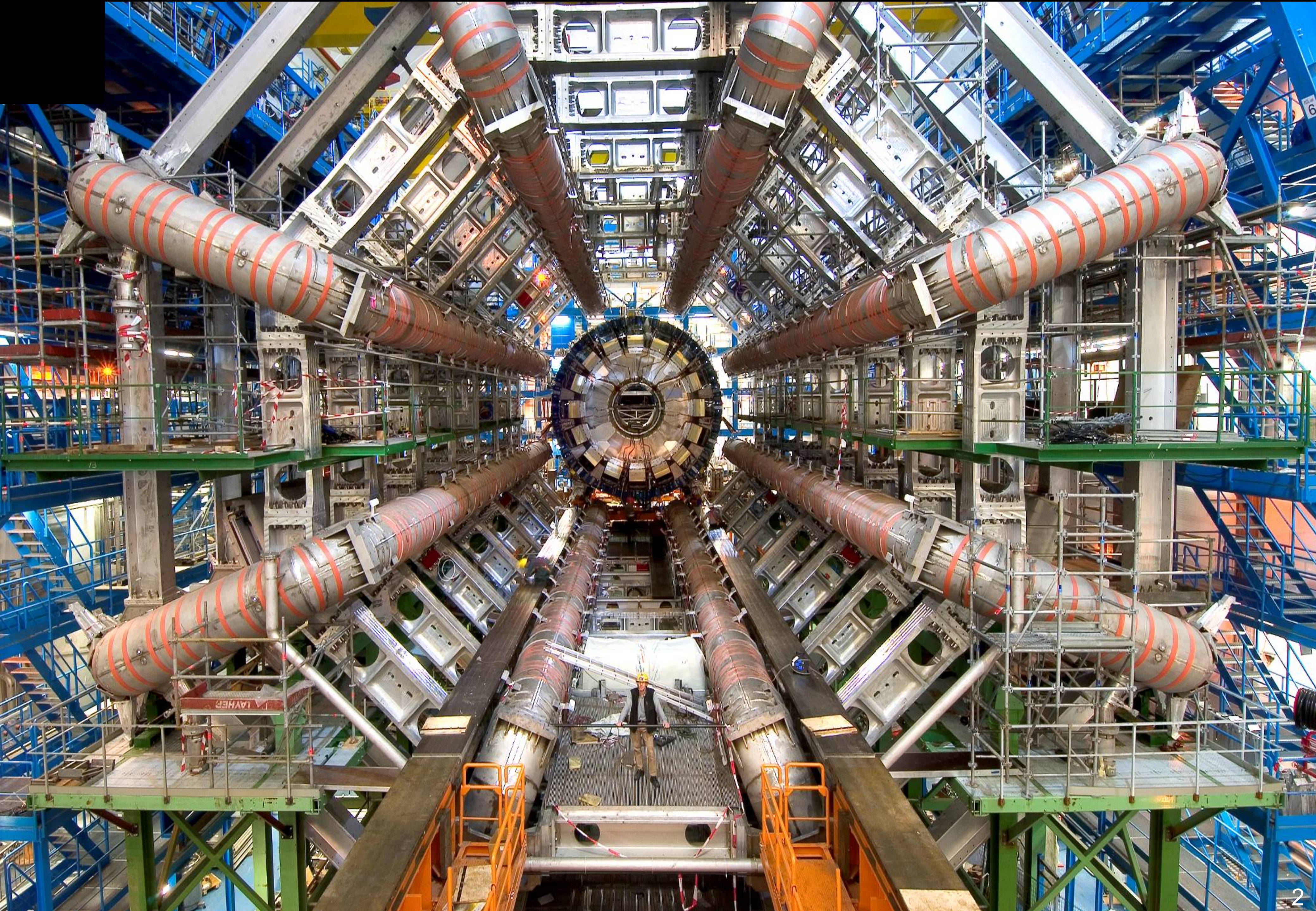




LCWS

Arlington, TX
October 24, 2012

Joe Incandela
UCSB/CERN



On behalf of ATLAS and…

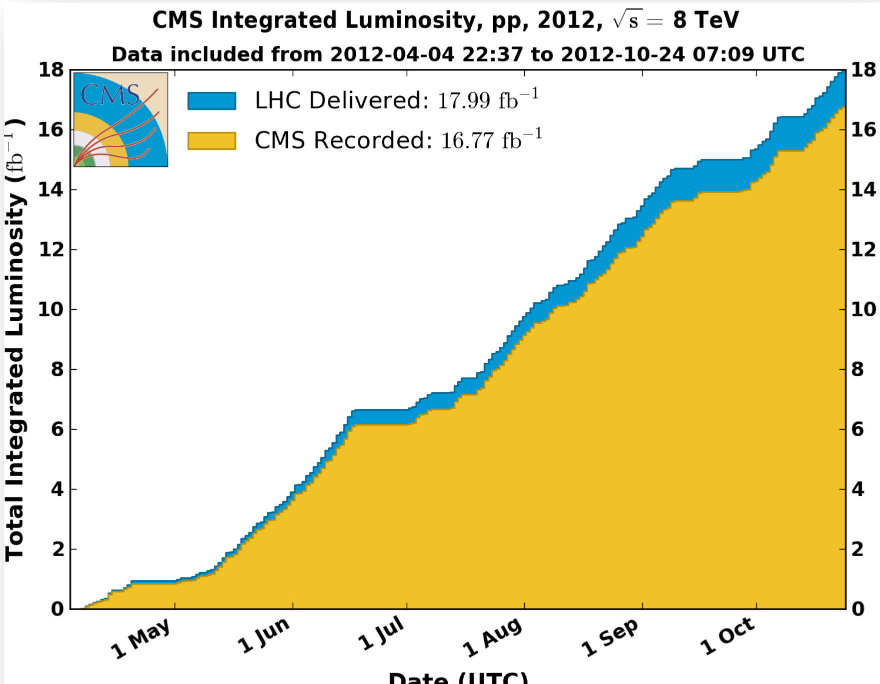
Most ATLAS material in this talk is Courtesy F. Gianotti

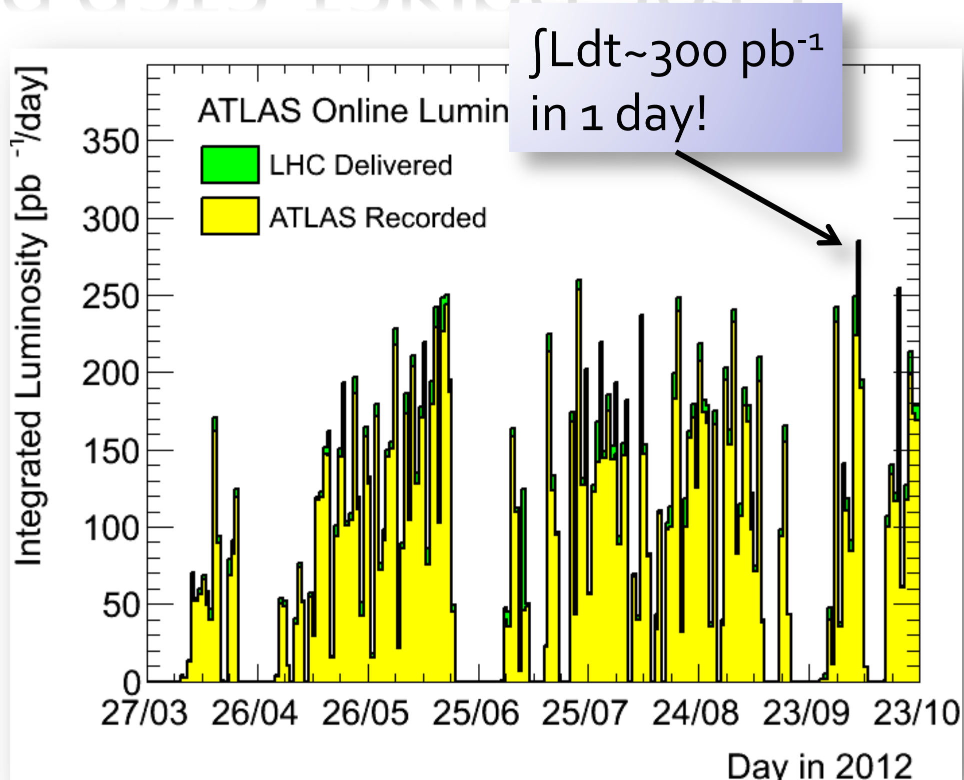
- 38 Countries, 176 Institutions, 2988 Scientific Authors total, 1807 with a Ph.D, 886 Graduate Students

CMS

41 Countries and 179 institutes ~3000 Authors including ~2200 PhD's and ~800 PhD students

LHC and data-taking 2012



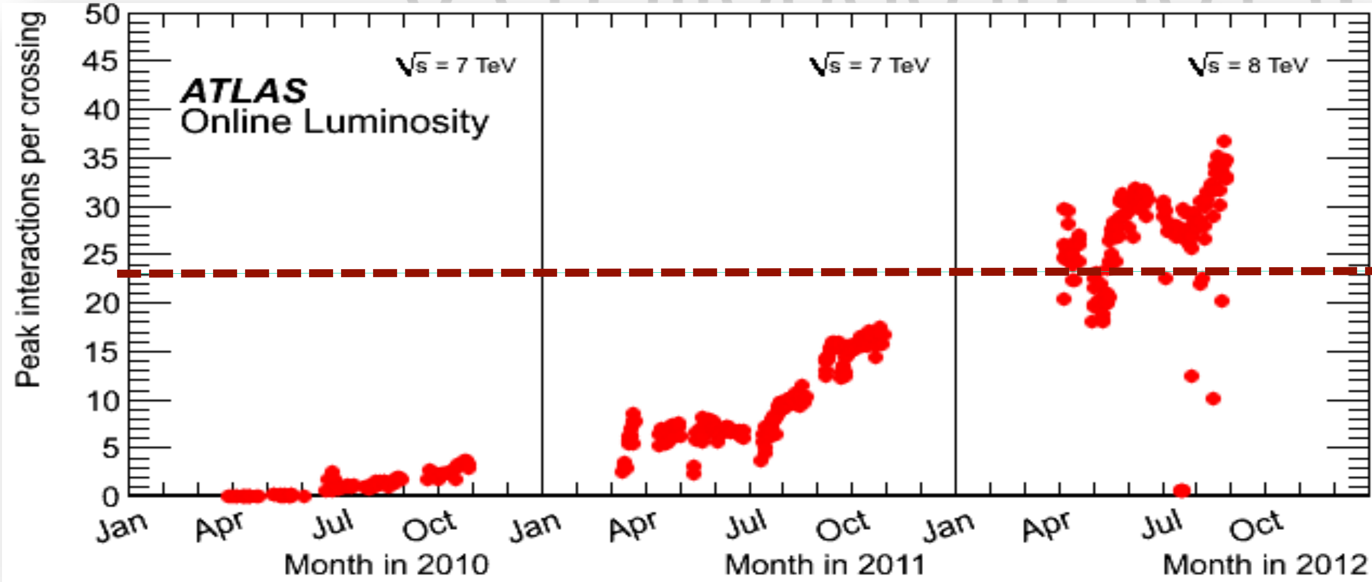


CMS	Deliv fb^{-1}	Record fb^{-1}	Eff.	Down time	Dead time
April-June	6.78	6.26	92.3%	5.9%	1.8%
July-21Aug**	4.97	4.73	95.1%	3.8%	1%
22Aug-16 Sep	2.99	2.74	94.4%	4.1%	1.5%
26 Sept-7Oct	1.44	1.37	95.1%	3.4%	1.5%

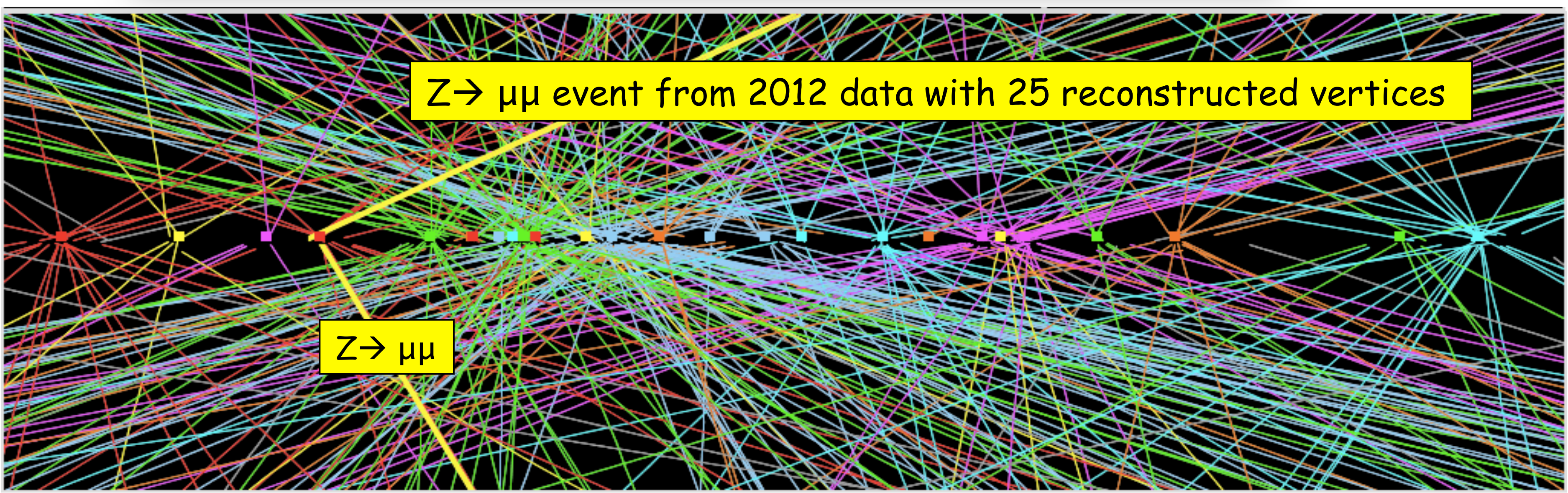
Data-taking performance	ATLAS	CMS
Non-functioning channels	‰ to 4%	‰ to 4.5%
$\varepsilon_{Recorded} \times \varepsilon_{Good}$	94% x 93%	94% x 94%

Efficiency Improving but in CMS, infrastructure incidents cost > 0.5 fb^{-1}

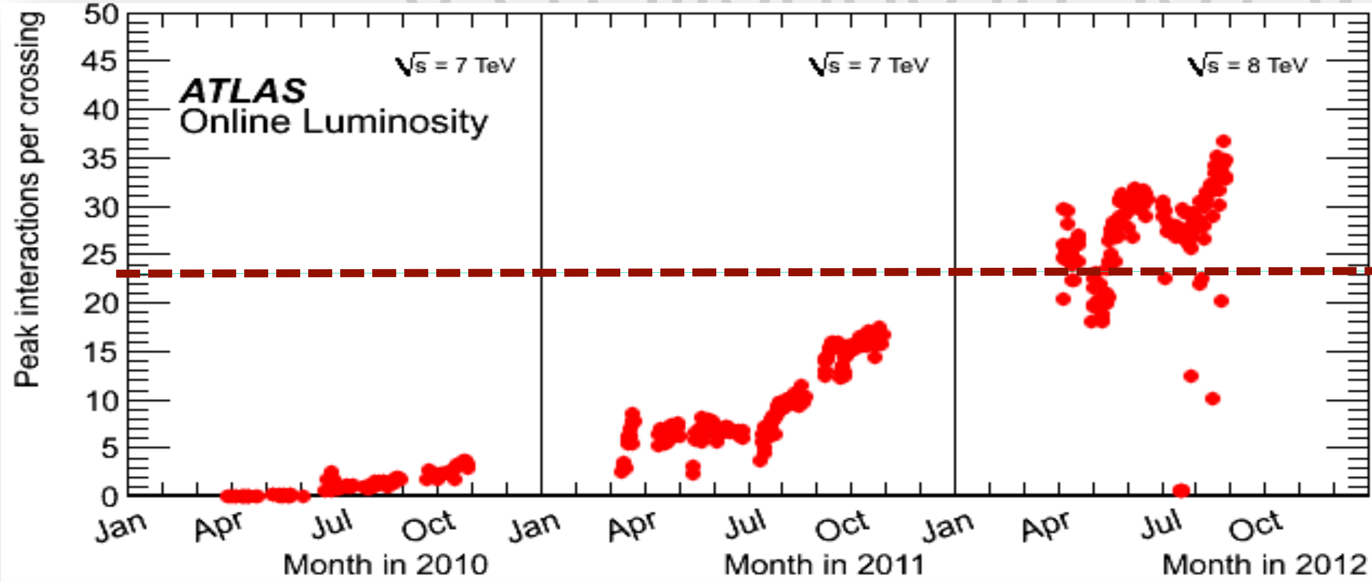
A challenge in 2012: Pile-up



~Design value
(L=10^{34} , 25ns)



A challenge in 2012: Pile-up



~Design value
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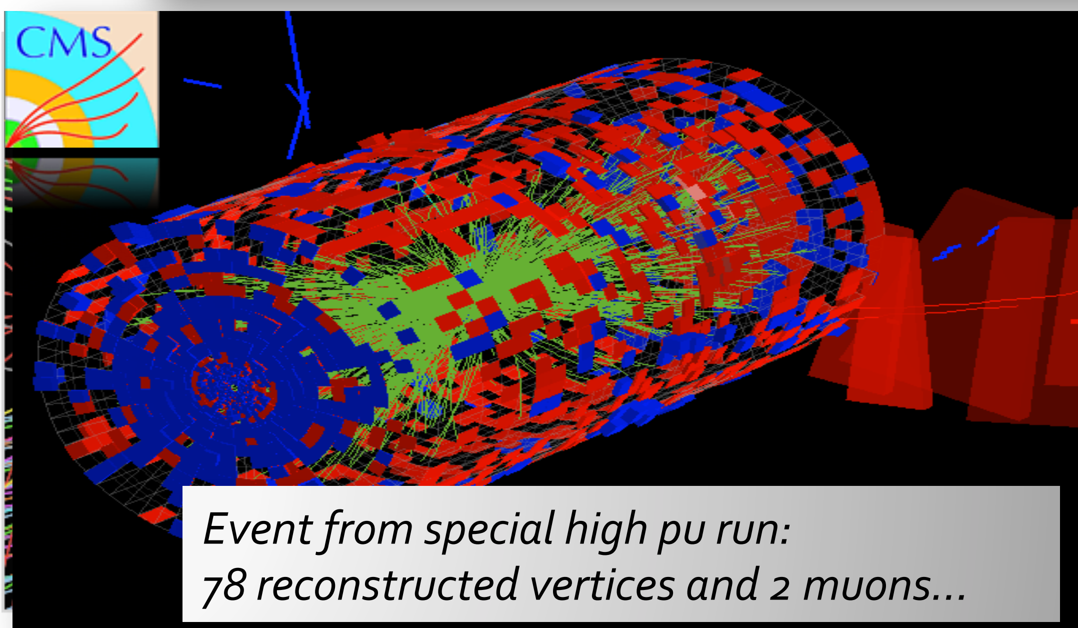
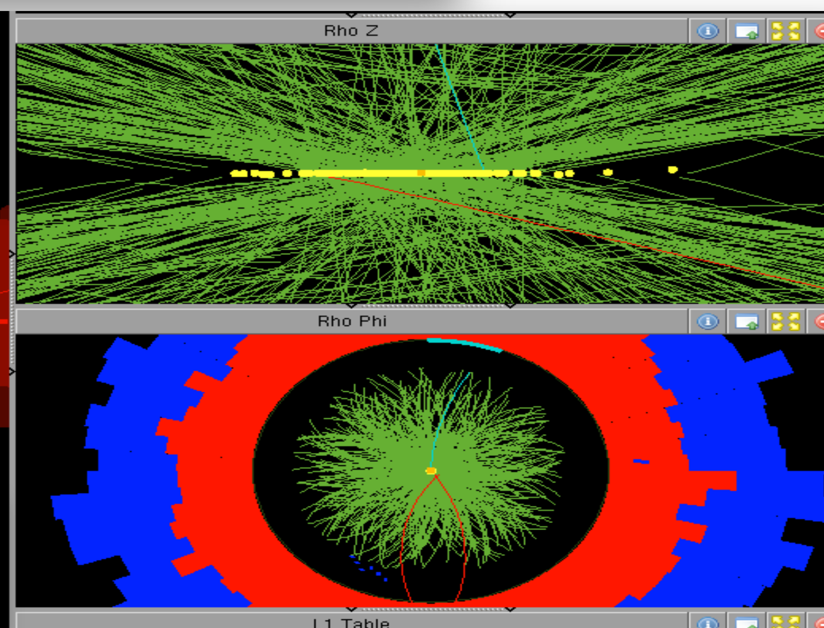
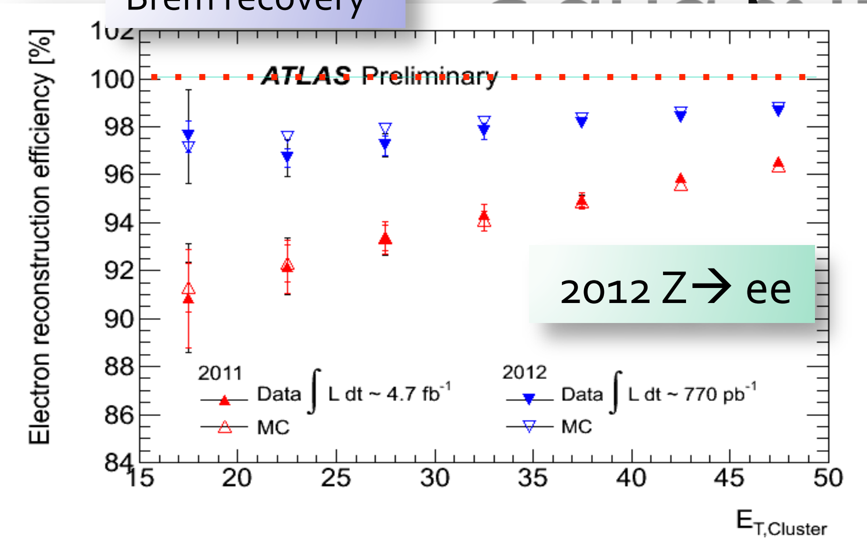




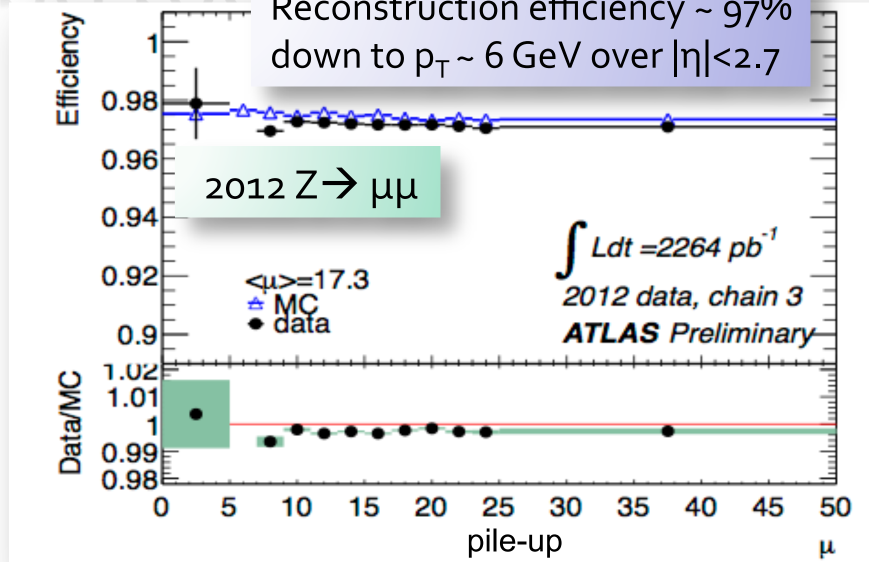
Event from special high pu run:
78 reconstructed vertices and 2 muons…

e and μ ID and reconstruction

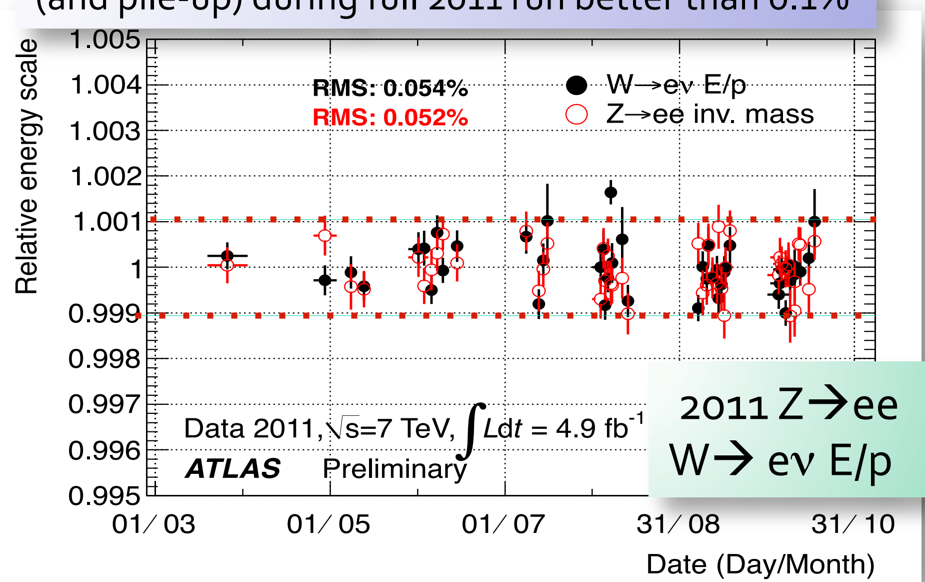
Brem recovery



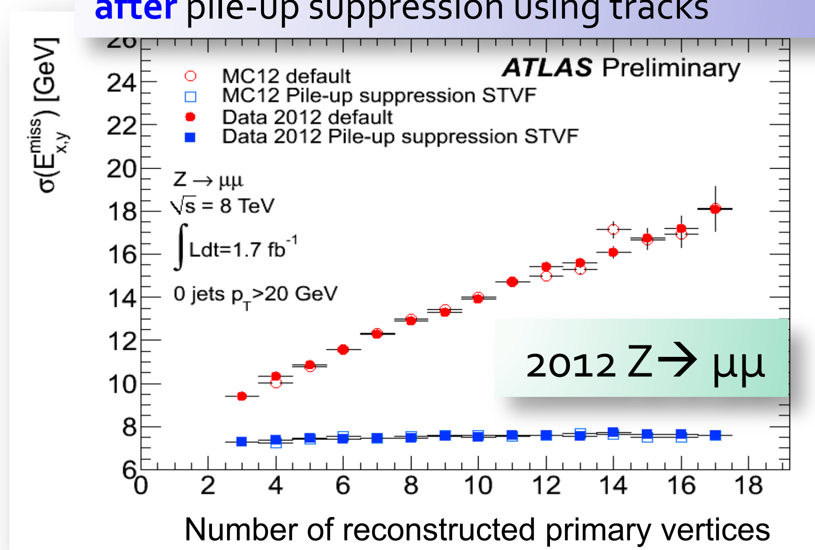
Reconstruction efficiency ~ 97% down to p_T ~ 6 GeV over $|\eta|<2.7$



Stability of EM calorimeter response vs time (and pile-up) during full 2011 run better than 0.1%



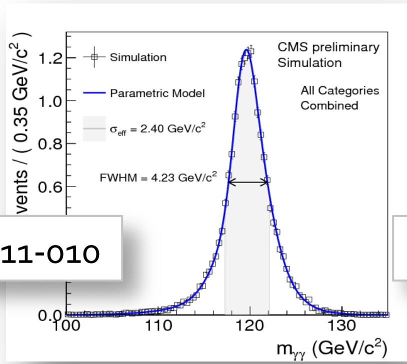
E_T^{miss} resolution vs pile-up **before** and **after** pile-up suppression using tracks



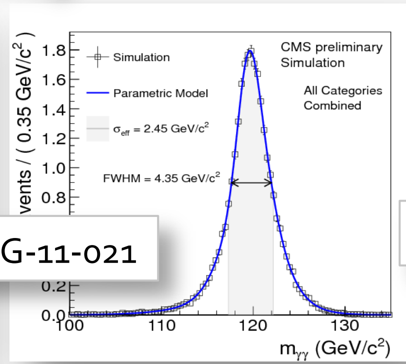
ECAL response and m(γγ) resolution

7 TeV: 25% improvement over one year

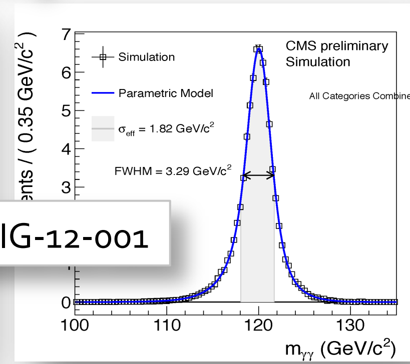
EPS – Jul 2011	LP – Aug 2011	Moriond – Feb 2012	ICHEP – Jul 2012
FWHM = **4.23 () GeV** →	**4.35 GeV** →	**3.29 GeV** →	**3.2 GeV (σ~1.3 GeV)** →



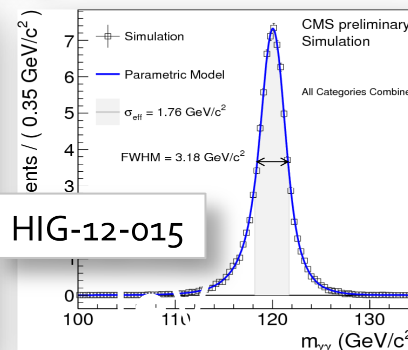
HIG-11-010



HIG-11-021

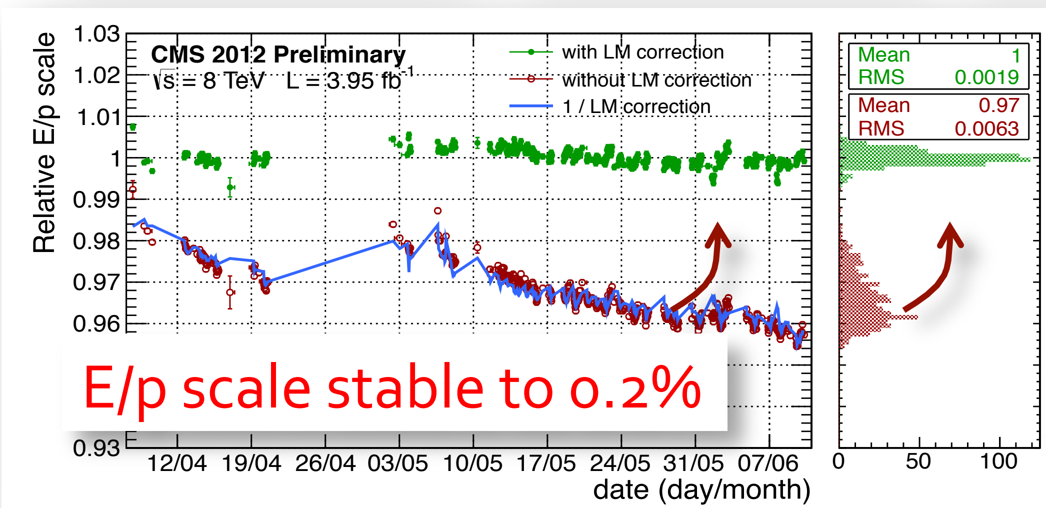


HIG-12-001



HIG-12-015

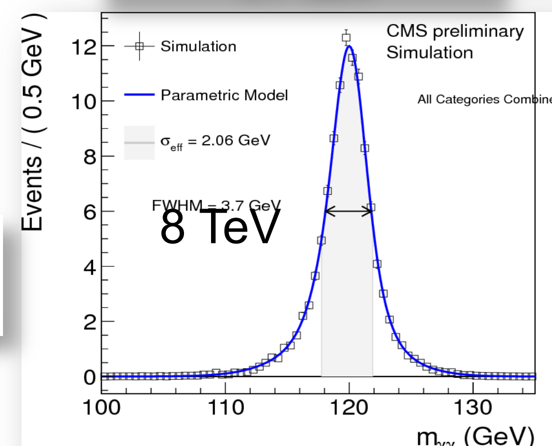
Even better performance



E/p scale stable to 0.2%

CMS-DP-2012-015

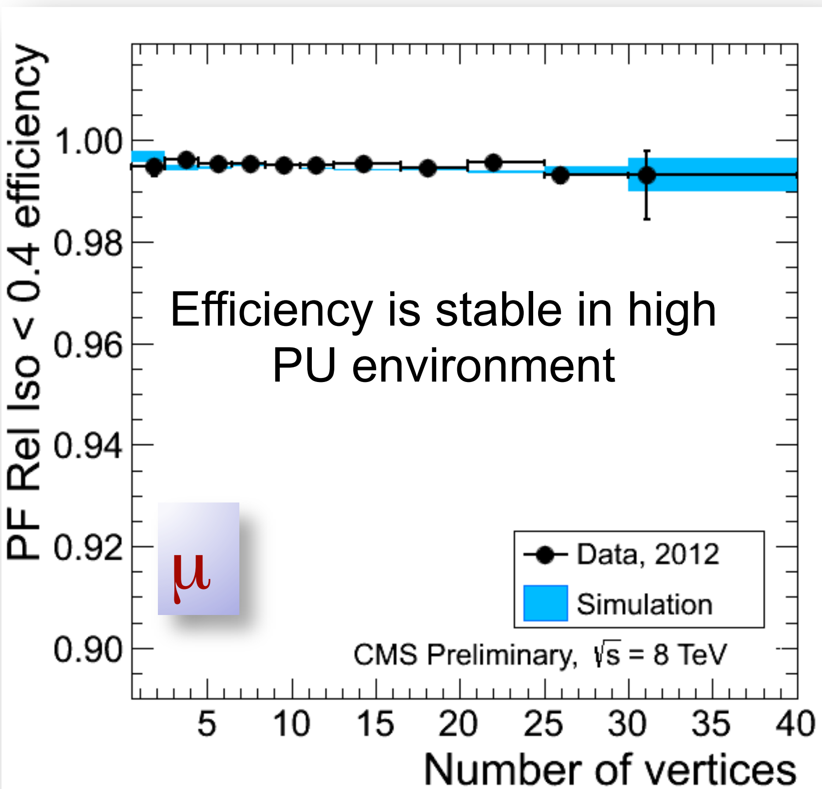
3.7 GeV →

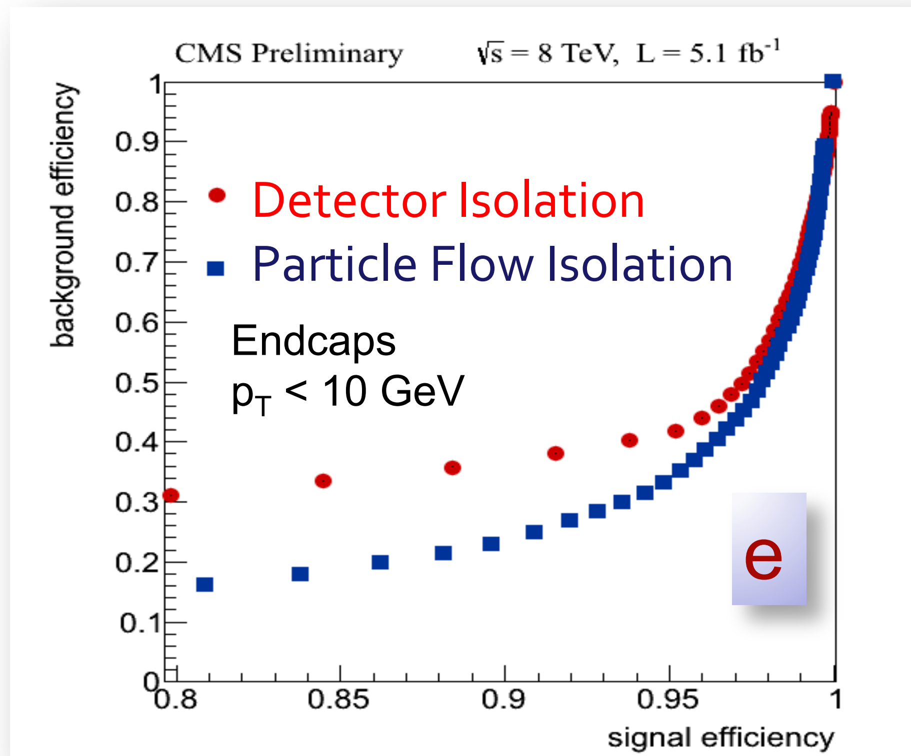


Laser calibration: Automated 48-hour calib. loop.

Pileup and Particle Flow

- Particle flow isolation is less sensitive to pileup
  - Propagated into trigger, it reduces tau, jet, MET trigger rates and improves efficiency
- Pile-up contribution:
  - Negligible for charged hadrons (vertexing)
  - Neutrals corrected w/global energy density (ρ)



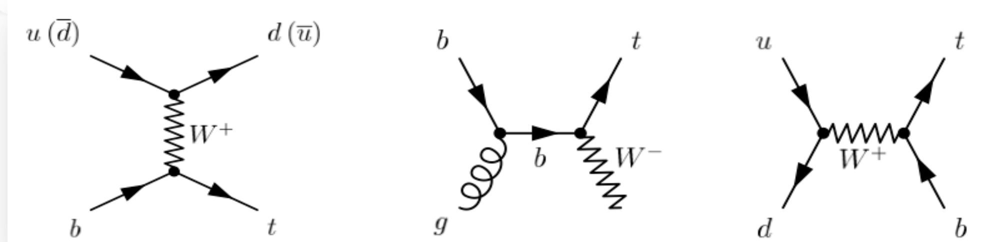


Detector vs Particle Flow

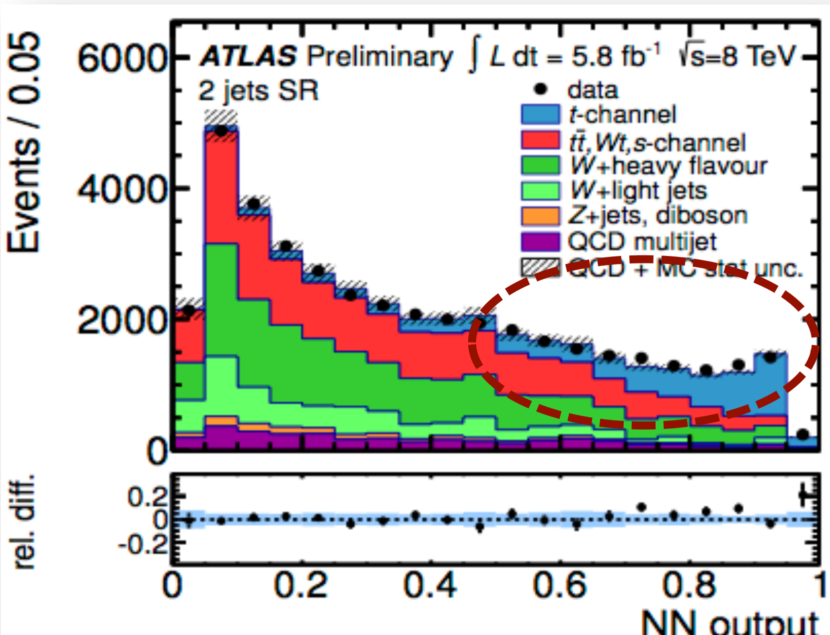
Some recent results

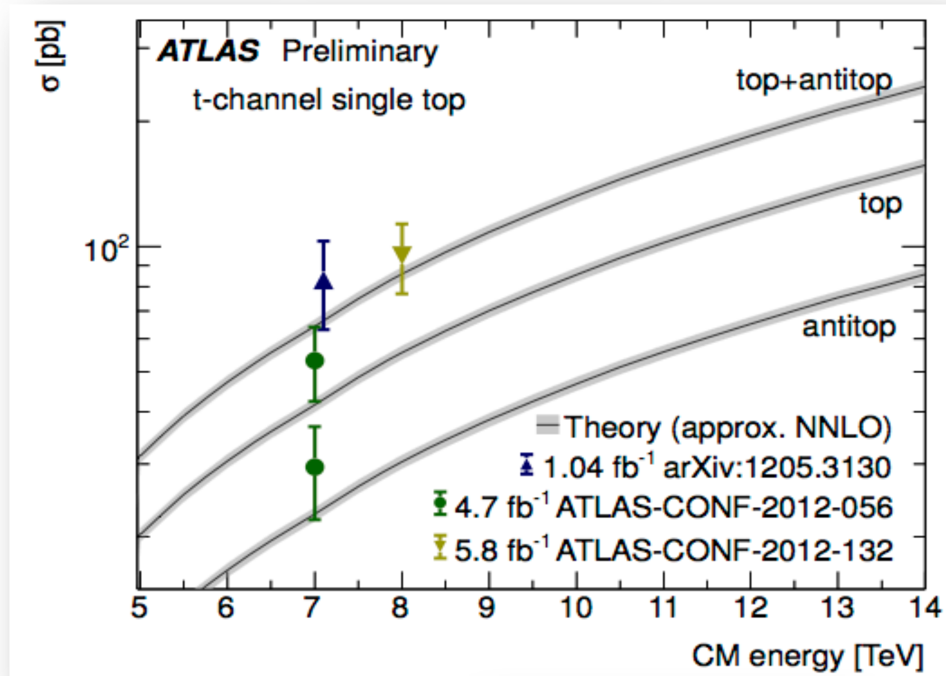
Single top production

- All main physics objects in final state:
  - leptons, jets, b-jets, E_T^{miss}
- Background to Higgs and other searches
- Difficult to extract from tt and W+jets
  - backgrounds → requires “advanced”
  - analysis techniques (NN)



t-channel	Wt-channel	s-channel
$\sigma_t = 87.8^{+3.4}_{-1.9}$ pb	$\sigma_{Wt} = 22.4 \pm 2.4$ pb	$\sigma_s = 5.6 \pm 0.2$ pb



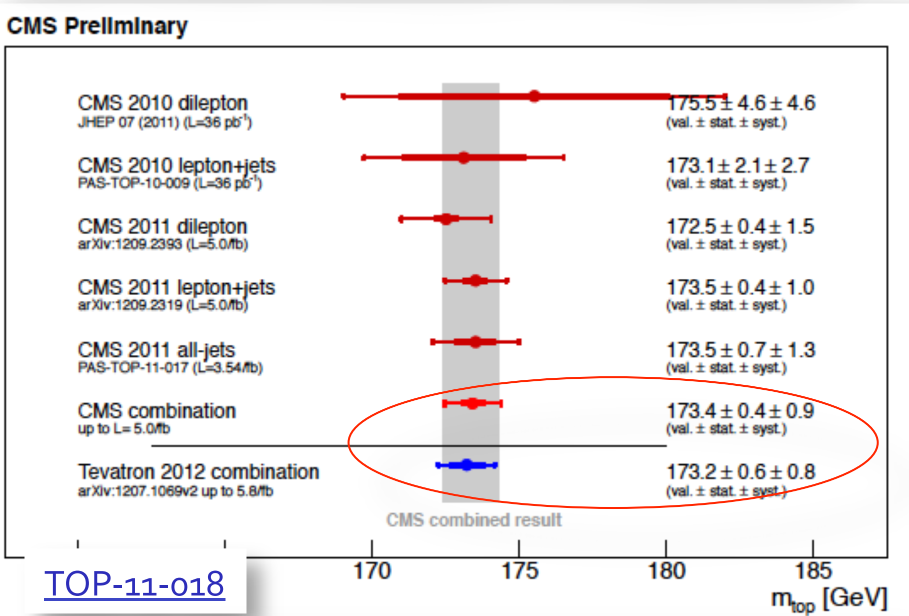


σ_t (7 TeV) = 83 ± 20 pb σ_t (8 TeV) = 95 ± 18 pb
σ_{Wt} (7 TeV) = 17 ± 6 pb σ_s (7 TeV) < 26 pb

$$|V_{tb}| = 1.04^{+0.10}_{-0.11}$$

Top Highlights: Properties

$m_t = 173.36 \pm 0.38\,(\text{stat.}) \pm 0.91\,(\text{syst.})\,\text{GeV}$



TOP-11-018

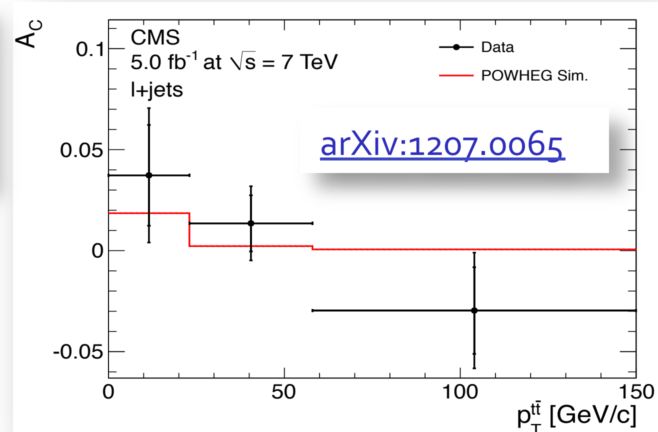
Table 2: Correlation coefficients between the input measurements

	Di-lepton 2010	Lepton+jets 2010	Di-lepton 2011	Lepton+jets 2011	All-jets 2011
Di-lepton 2010	1.00				
Lepton+jets 2010	0.30	1.00			
Di-lepton 2011	0.35	0.67	1.00		
Lepton+jets 2011	0.26	0.44	0.64	1.00	
All-jets 2011	0.36	0.59	0.71	0.56	1.00

FCNC top decay: arXiv:1208.0957

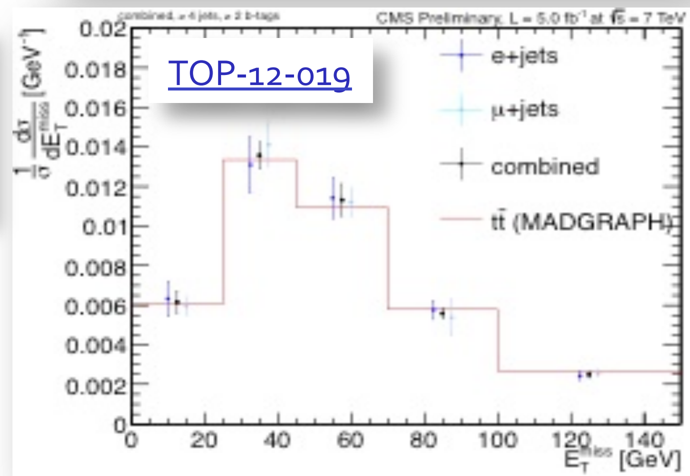
B(t → Zq) < 0.24% @ 95% CL

- $t\bar{t}$ differential measurements:
  - e.g. Q asymmetry



arXiv:1207.0065

Associated production $t\bar{t}$+ME$_T$

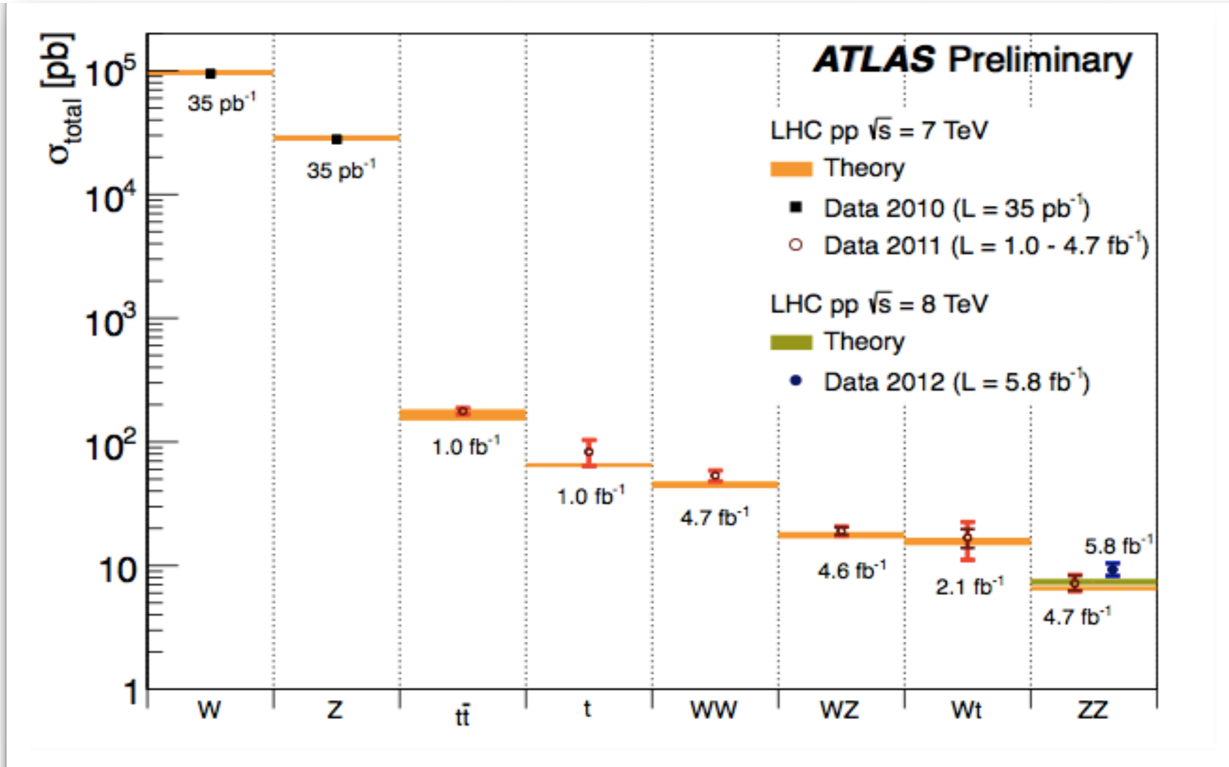


TOP-12-019

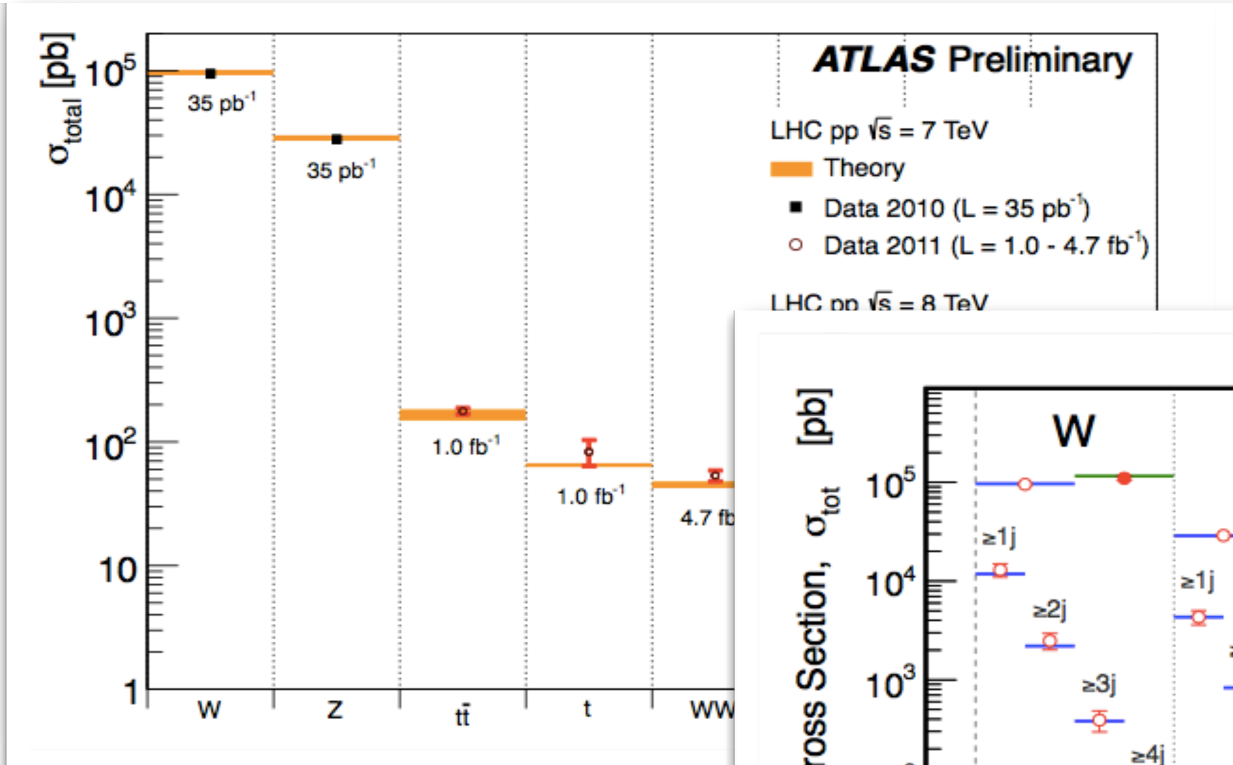
Associated production $t\bar{t}b\bar{b}$

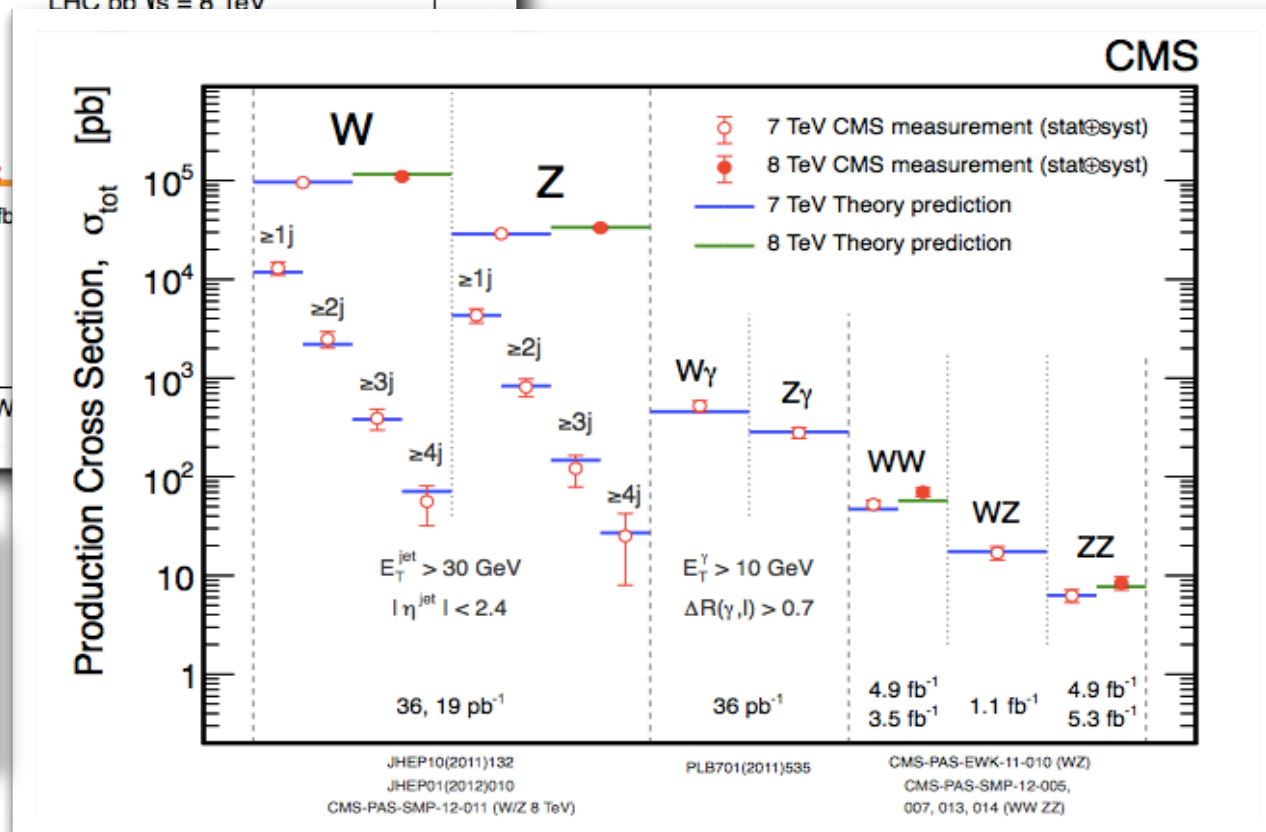
$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 3.6 \pm 1.1(stat.) \pm 0.9(sys.)\%$$

Standard Model Background Processes



Standard Model Background Processes



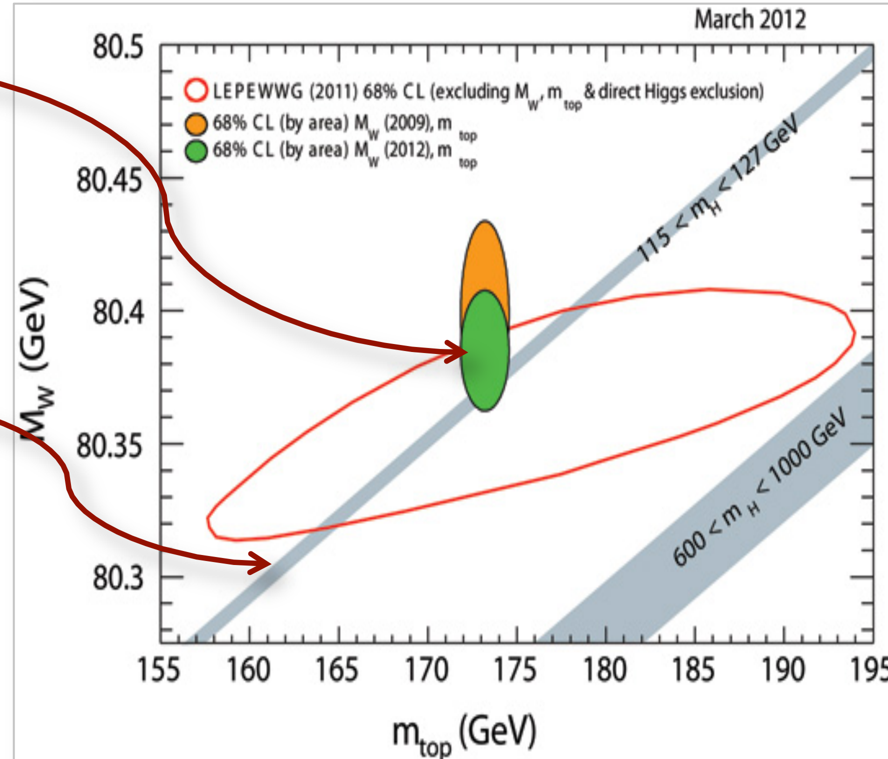


Fabulous understanding of the Standard Model at 7,8 TeV

…so, onto the Higgs…

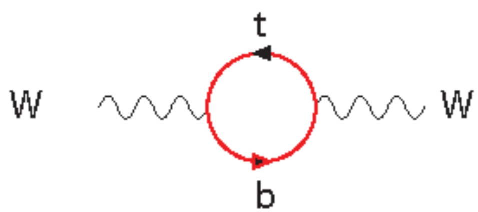
Higgs

- M_{top} vs. M_W
  - Tevatron M_W *Tour de Force!!*
    - m_W = 80385 ± 15 MeV (World Ave – Mar 2012)
  - Shifts for SM Higgs expectation

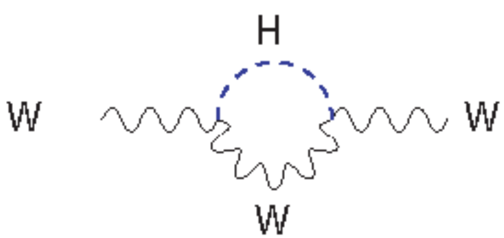


- LHC eliminated ~450 GeV of the mass range in ~ 1 year leaving only a sliver at lo mass

(Tevatron killed ~20 GeV even earlier)

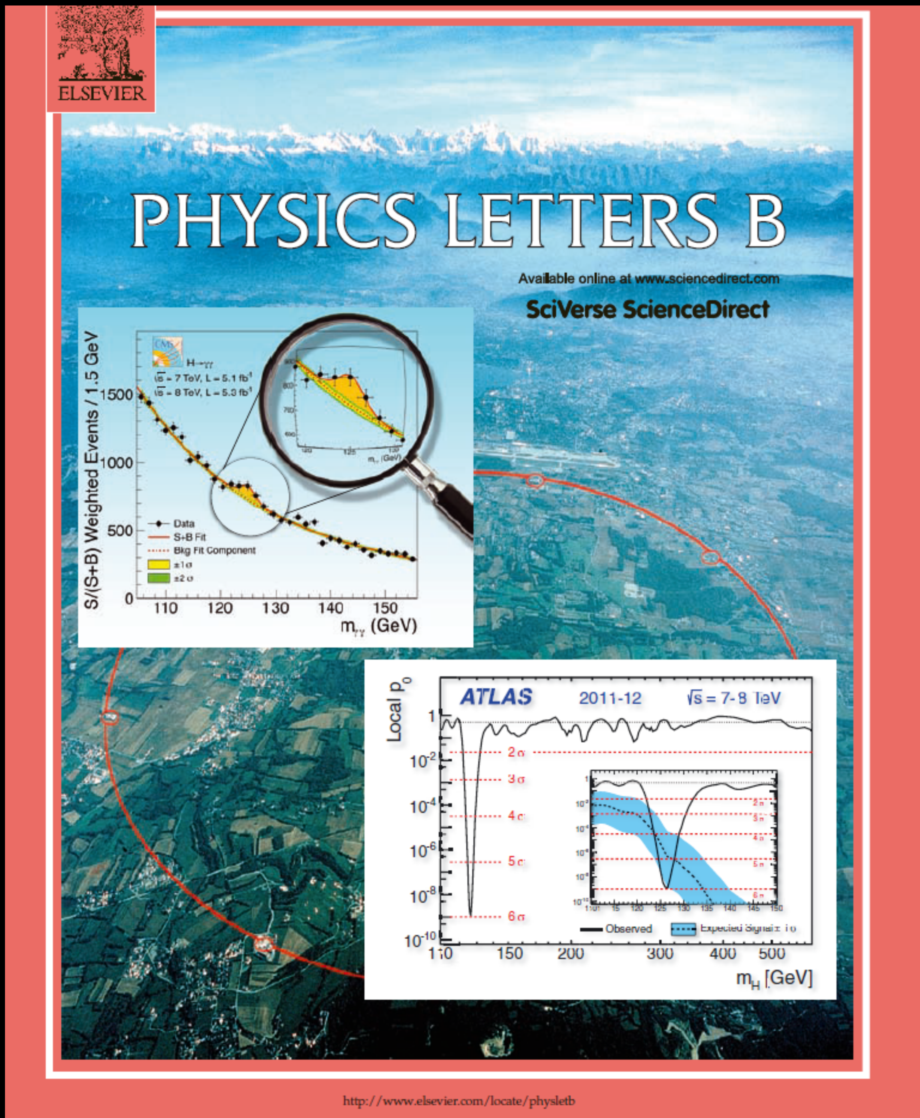


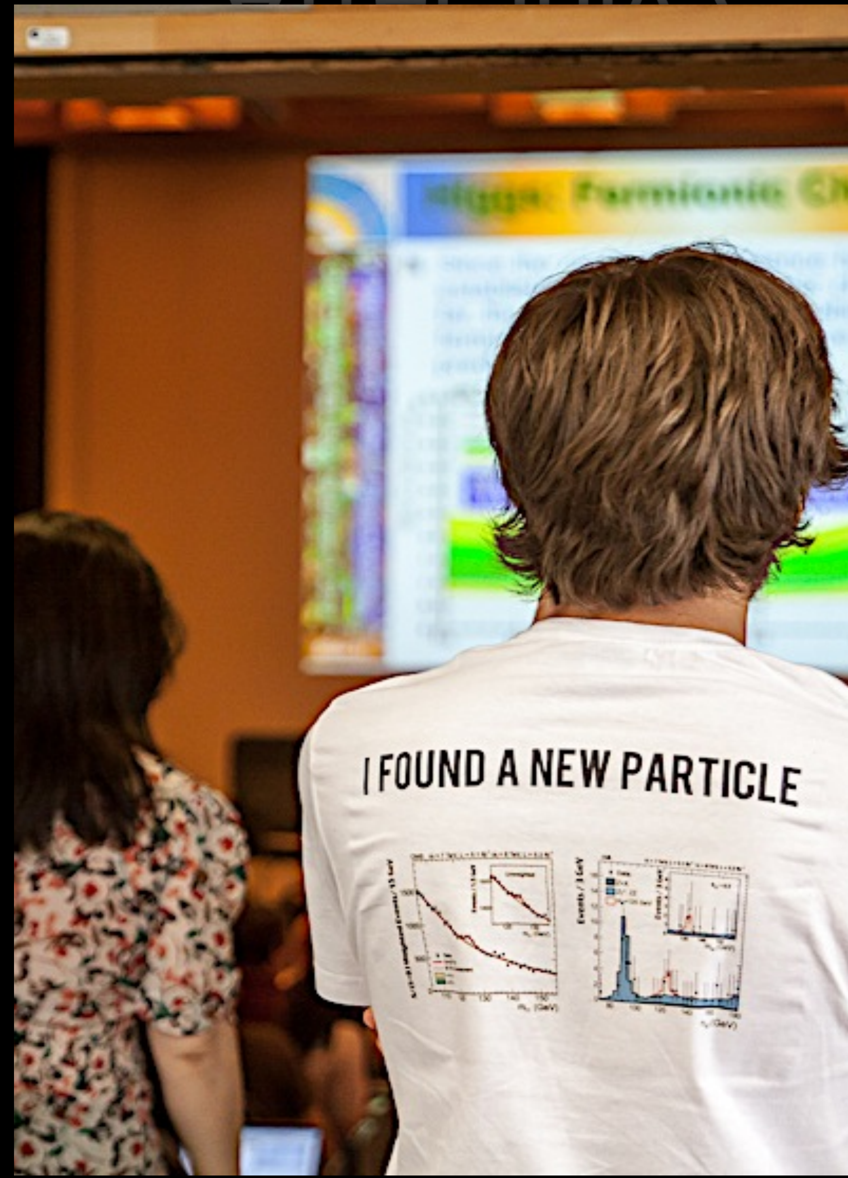
$\sim M_t^2$



$\sim \ln(m_H)$

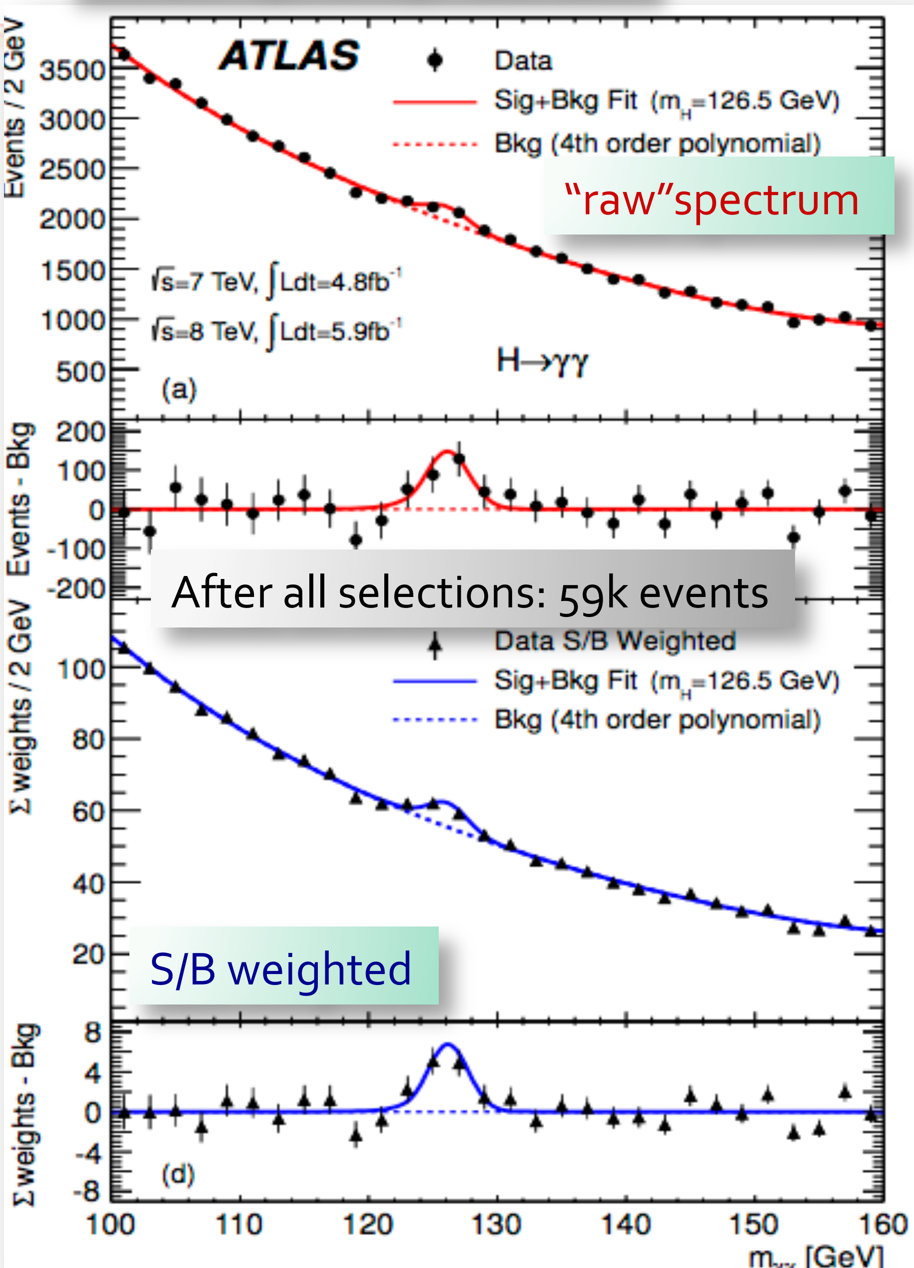
After July 4th





ATLAS γγ

σ x BR ~ 50 fb m_H ~ 126 GeV



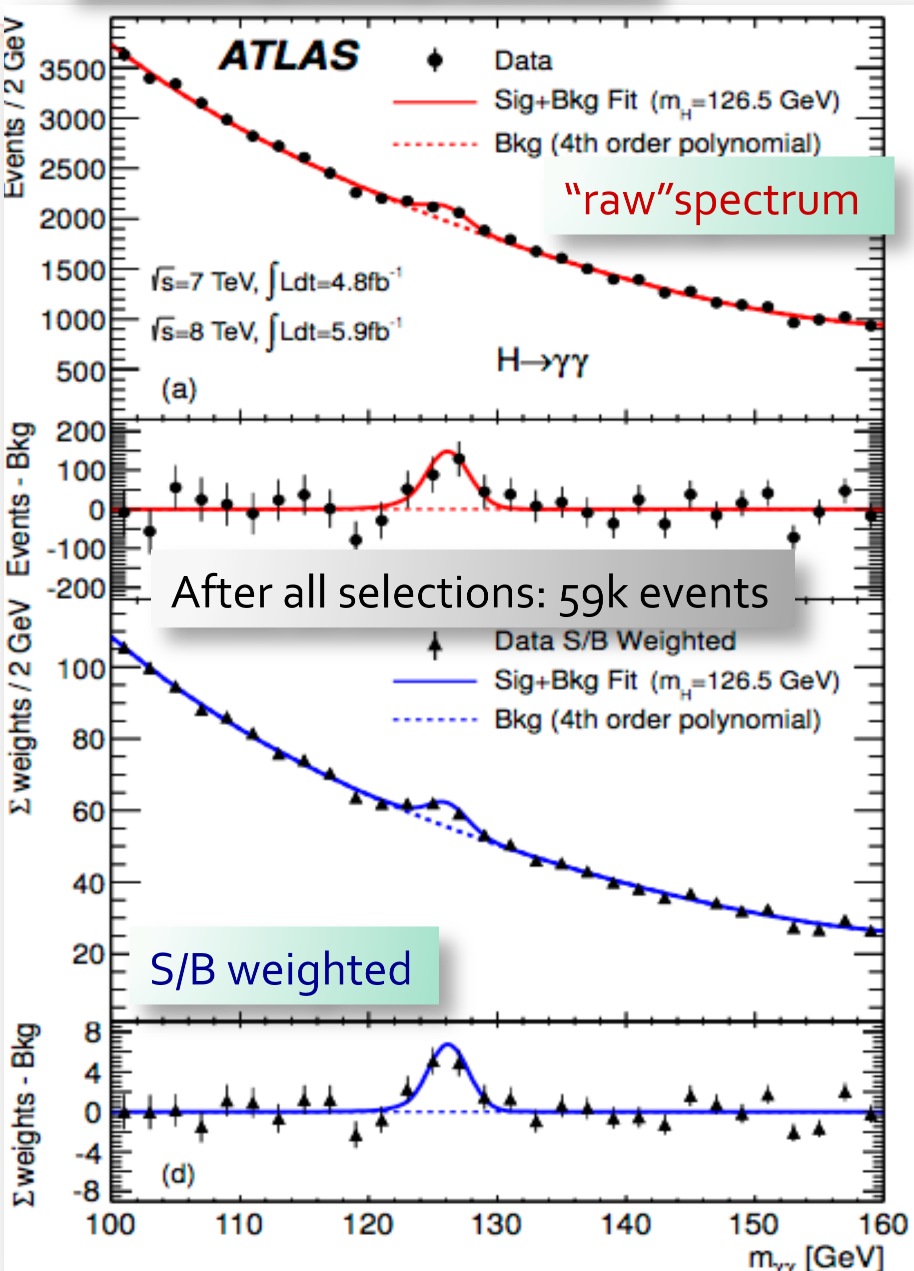
10 categories based on
- γ rapidity
- converted/unconverted
- p_{Tt} ($p_T^{\gamma\gamma}$ ⊥ to γγ thrust axis)
- 2 forward jets (VBF)

Expect (for 10.7 fb^{-1}, m_H~ 126 GeV)

→ S/B ~ 3% inclusive (~ 20% 2jet category)
- ~ 170 signal events
- ~ 6340 background events in mass window

ATLAS γγ

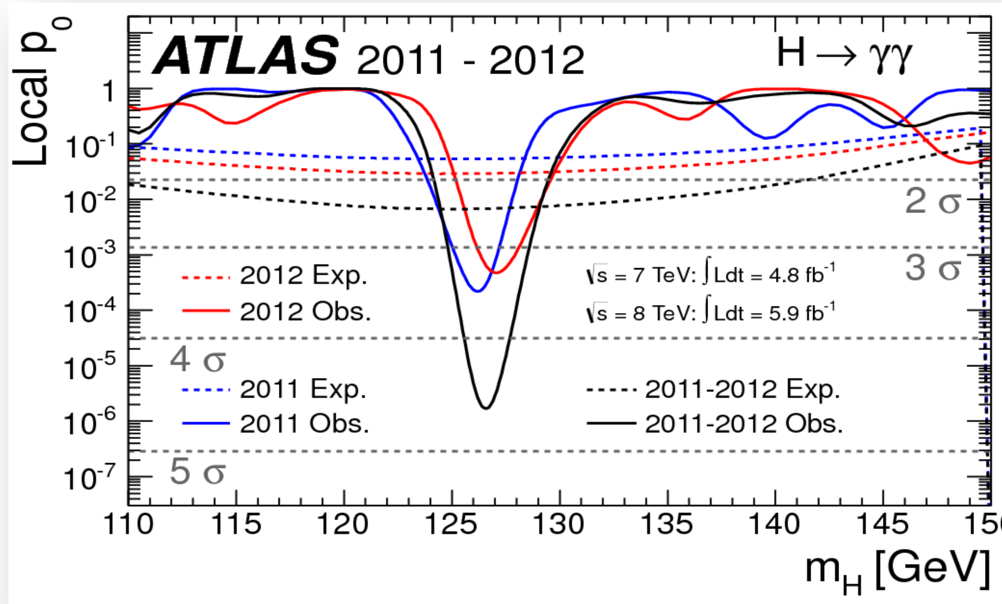
σ x BR ~ 50 fb m_H ~ 126 GeV



"raw" spectrum

After all selections: 59k events

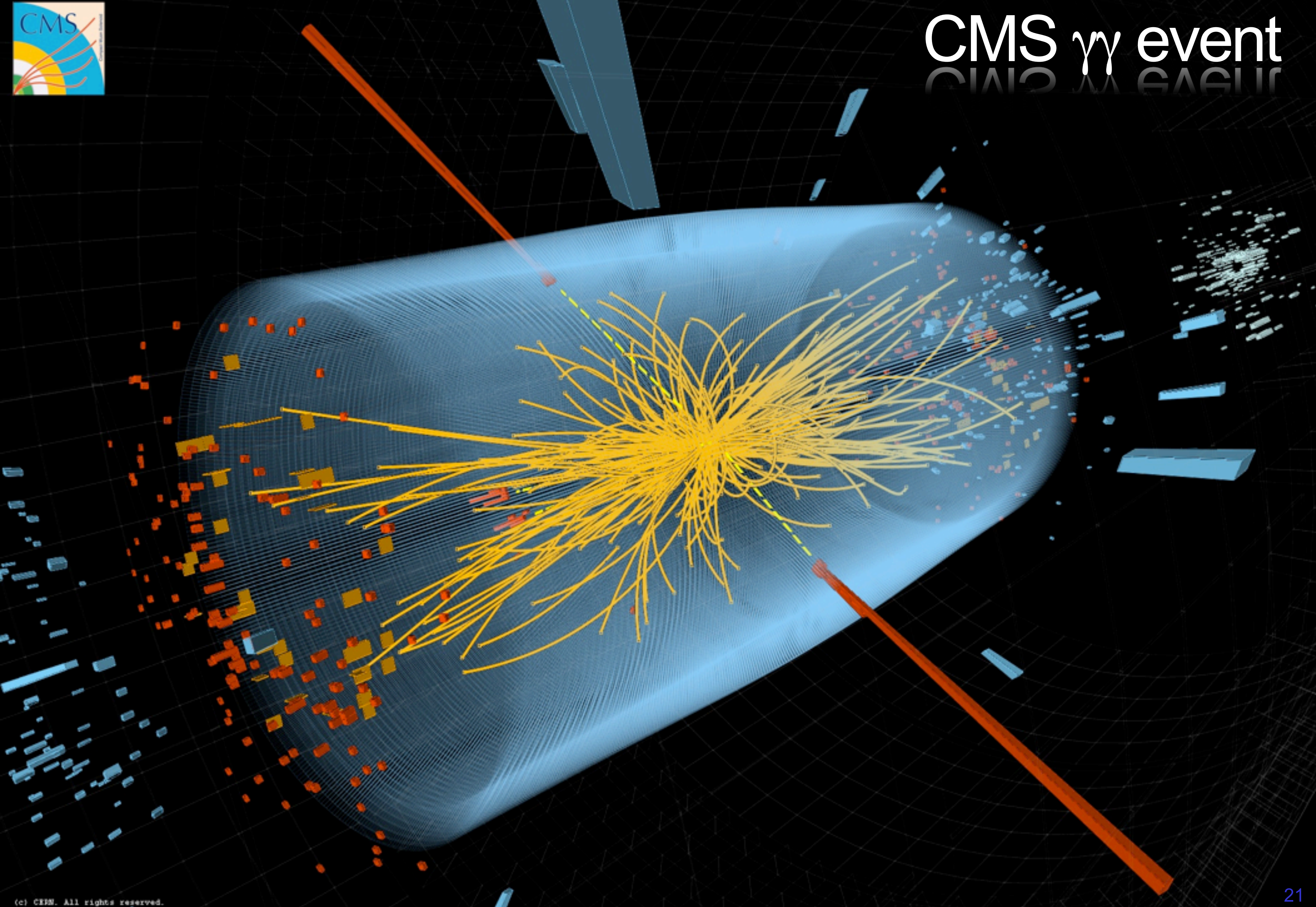
S/B weighted



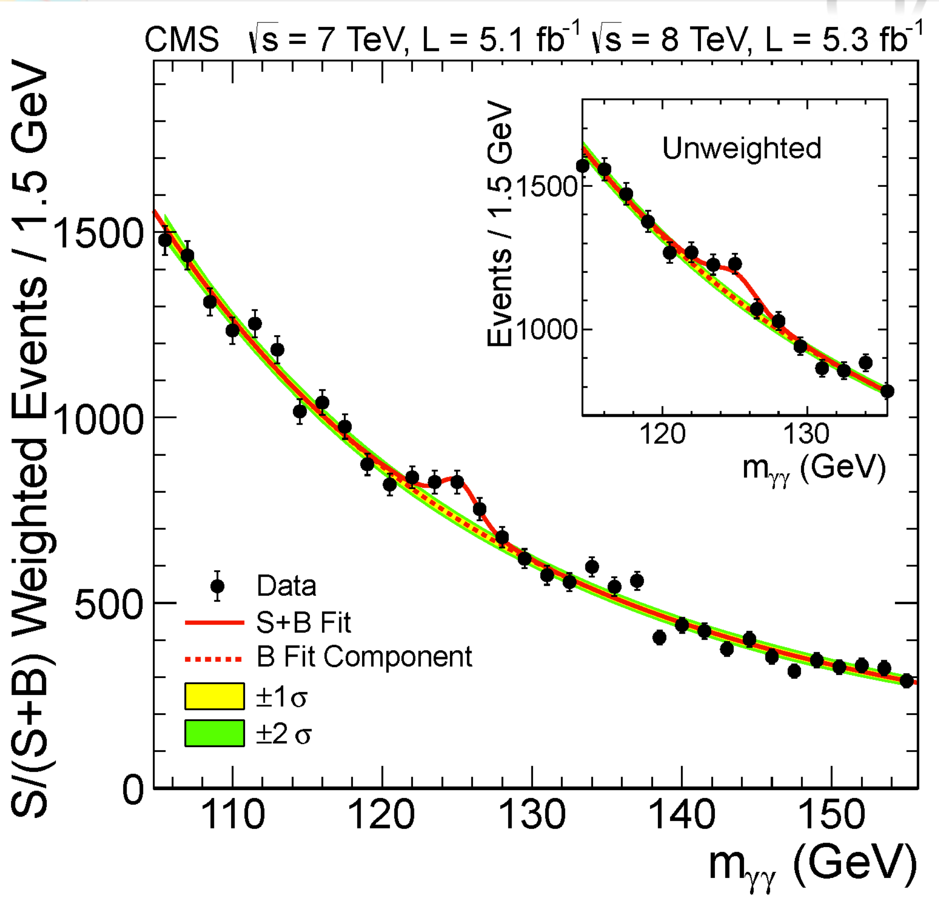
p-value: consistency of data with background-only expectation

Data sample	m_H of max significance	local significance obs. (exp. SM H)
2011	126 GeV	3.4 σ (1.6)
2012	127 GeV	3.2 σ (1.9)
2011+2012	126.5 GeV	4.5 σ (2.5)

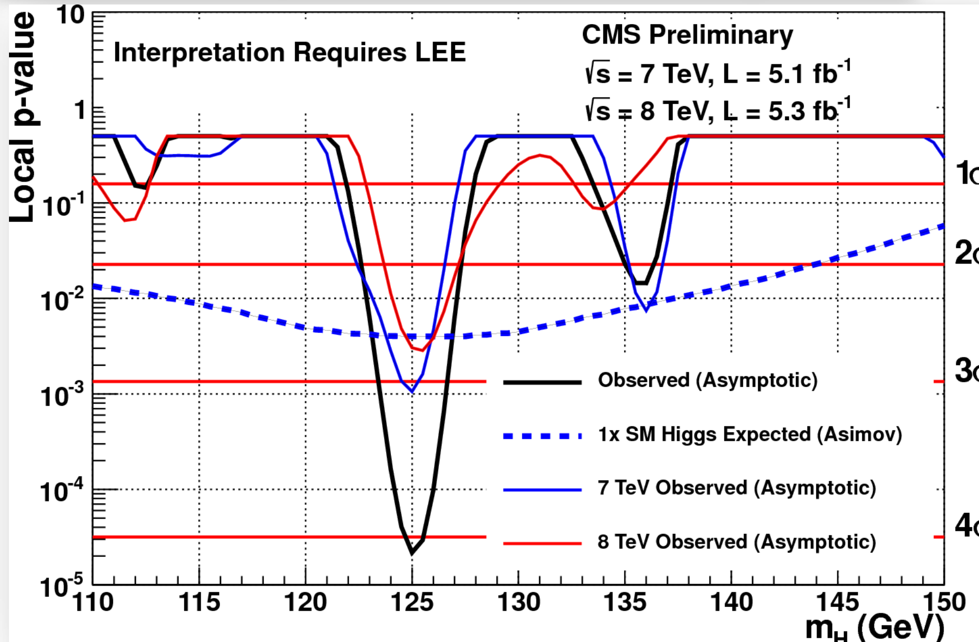
CMS $\gamma\gamma$ event



CMS γγ

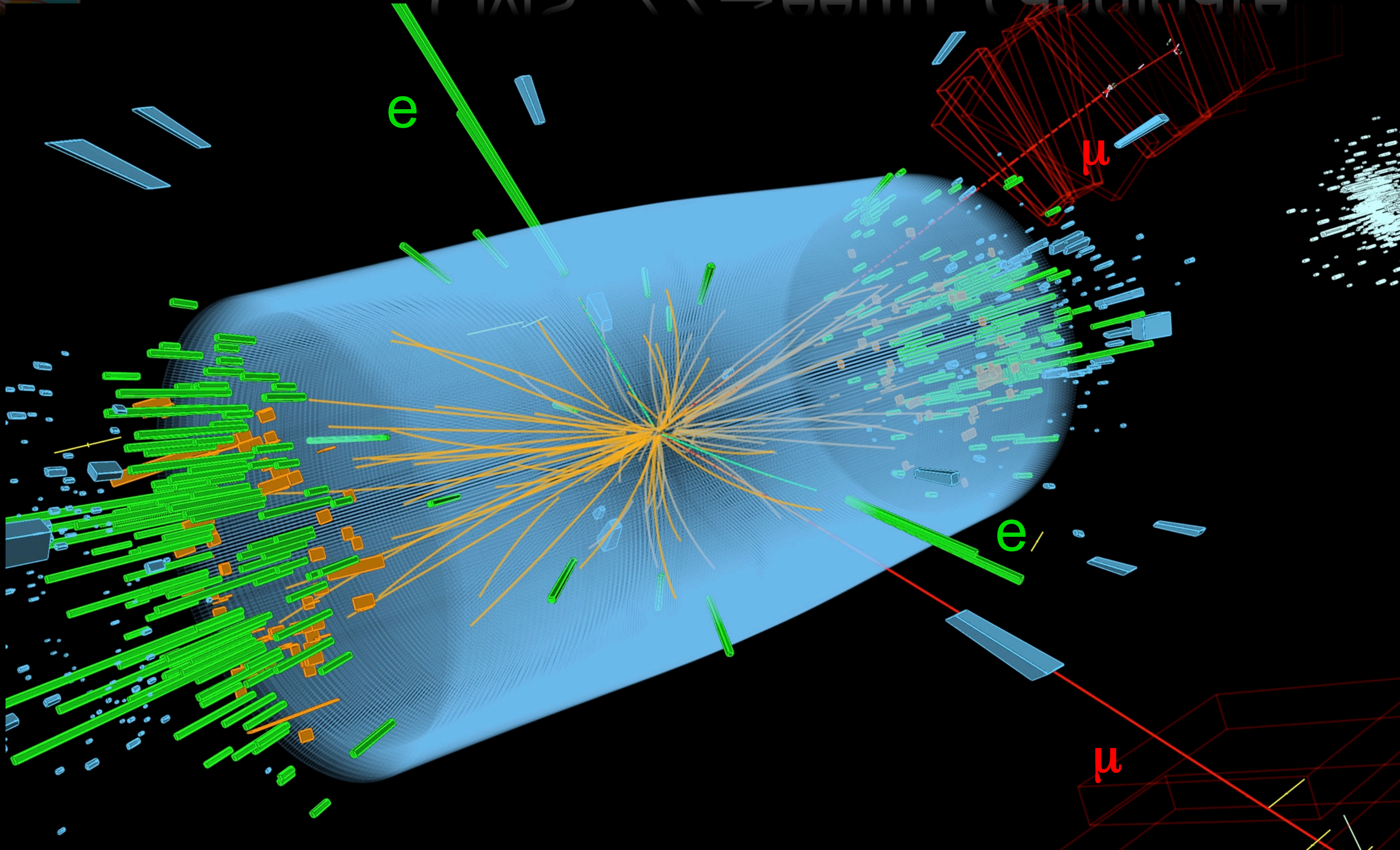


- 11 Categories (5+6, 2011+12)
  - Includes VBF selection
  - BDT: optimize γ id, and categories



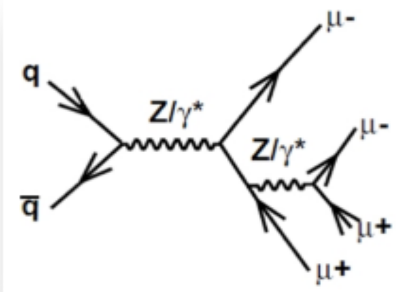
- Minimum local p-value at 125 GeV with a local significance of 4.1 σ
  - Similar excesses in 2011 and 2012
  - Independent analyses give similar results (3.5 and 4.6 σ)

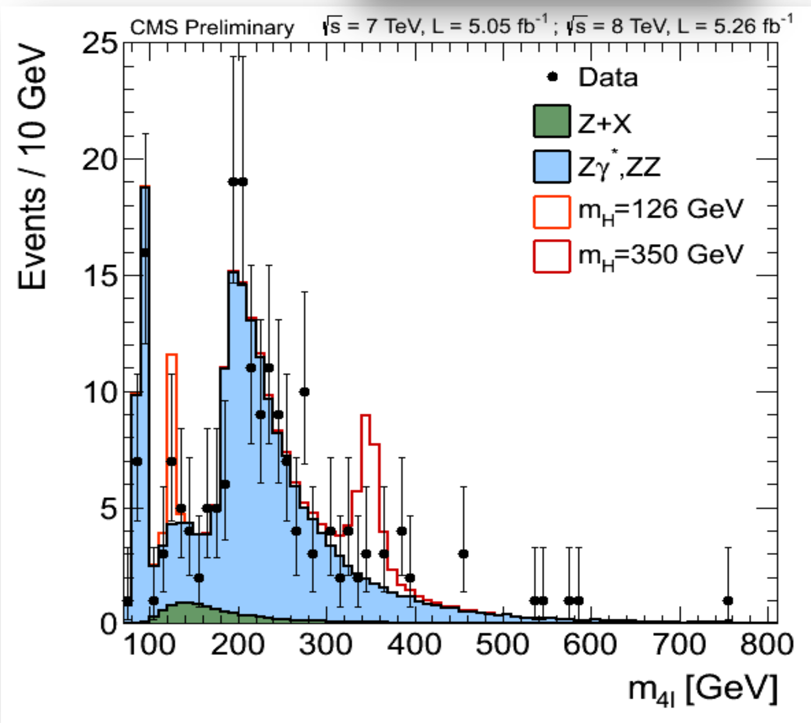
CMS ZZ→eeμμ candidate

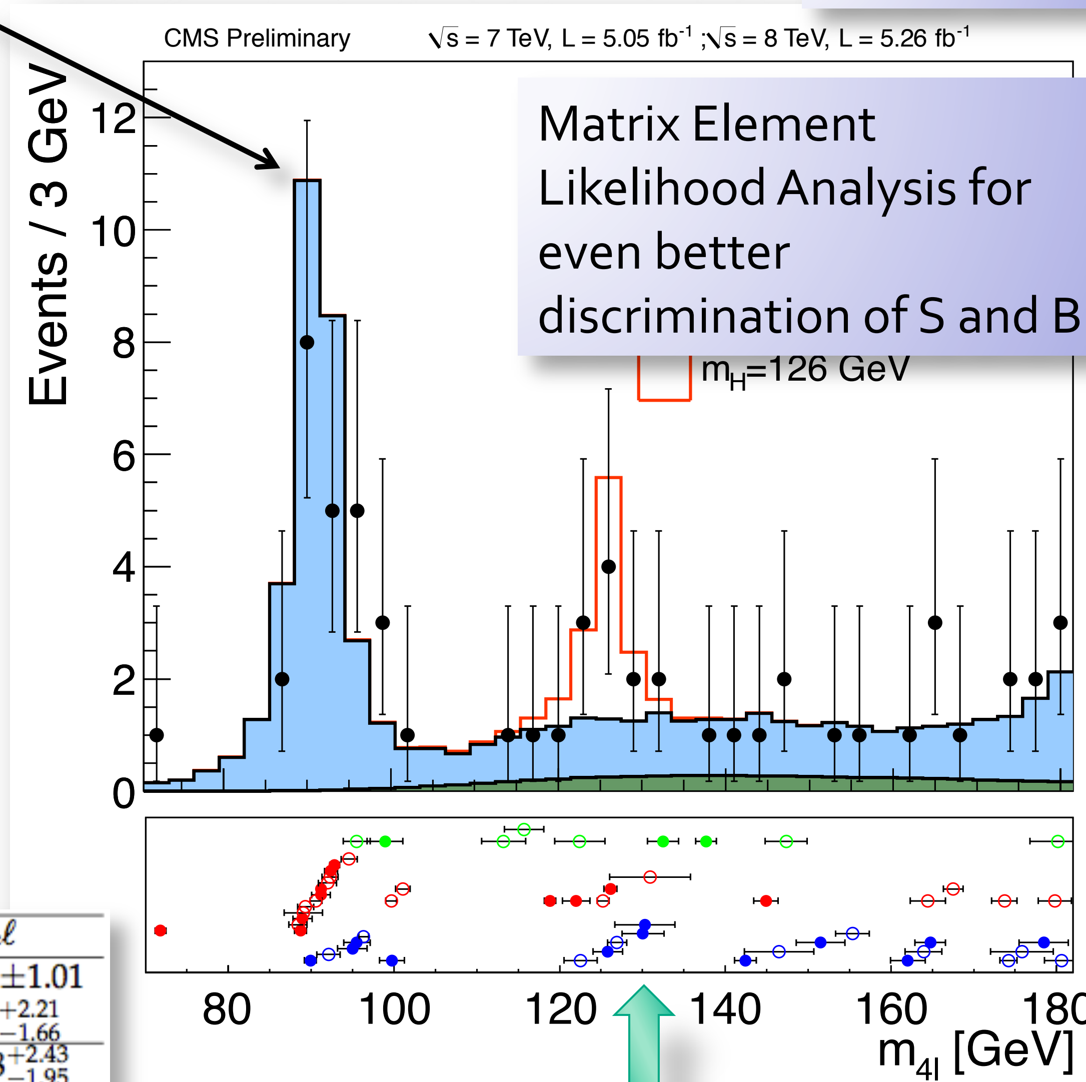


CMS ZZ* m_{4l} spectrum

2011+2012







Matrix Element Likelihood Analysis for even better discrimination of S and B

Event-by-event errors

Yields for m(4l)=110..160 GeV

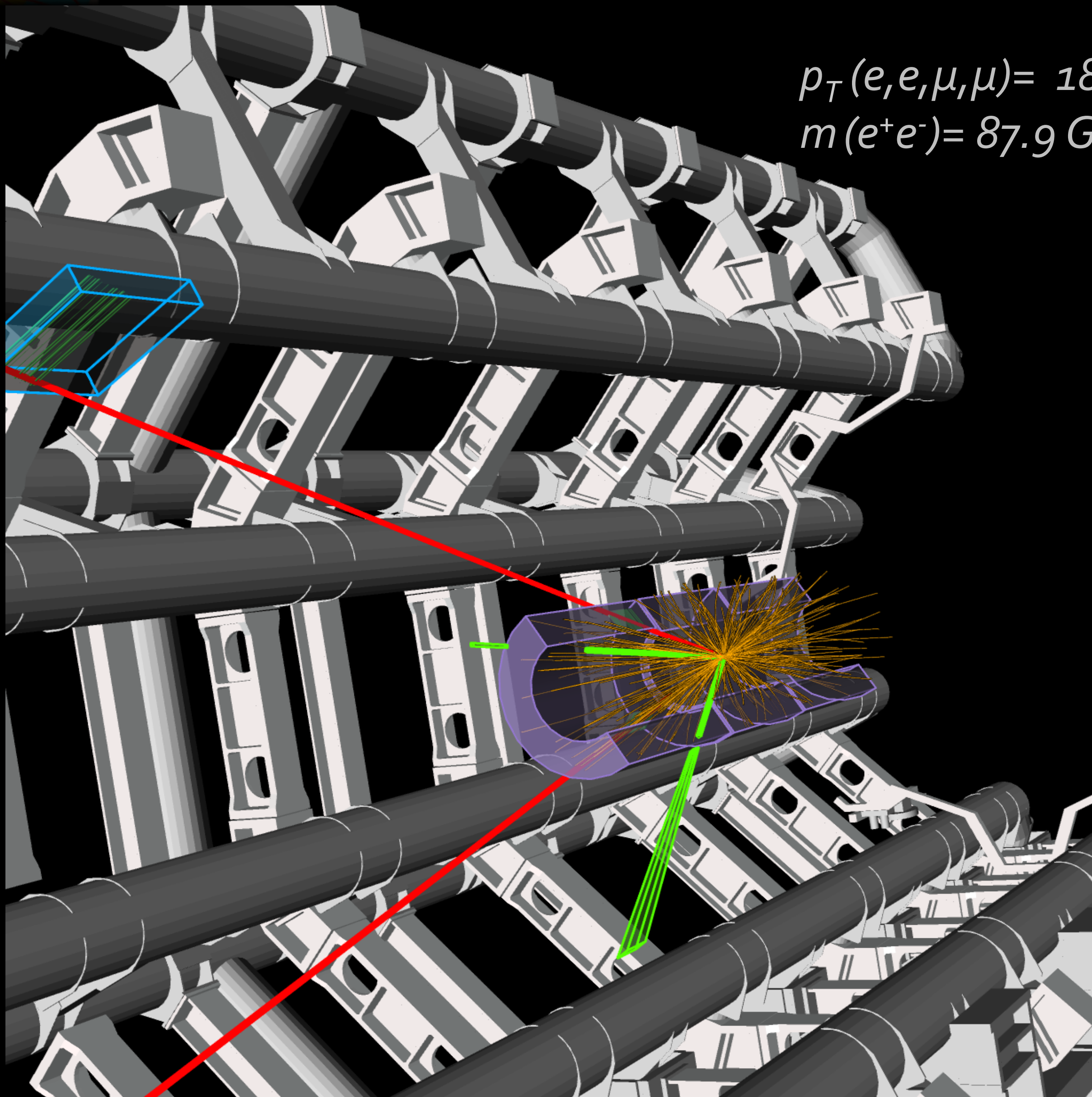
Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 ±0.31	5.65 ±0.59	7.17 ±0.76	15.48 ±1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
m_H = 126 GeV	1.51 ±0.48	2.99 ±0.60	3.81 ±0.89	8.31 ±1.18

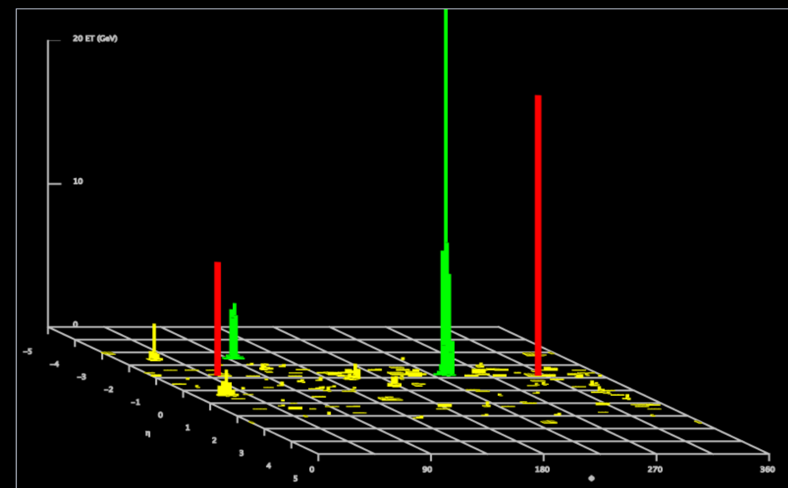
164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

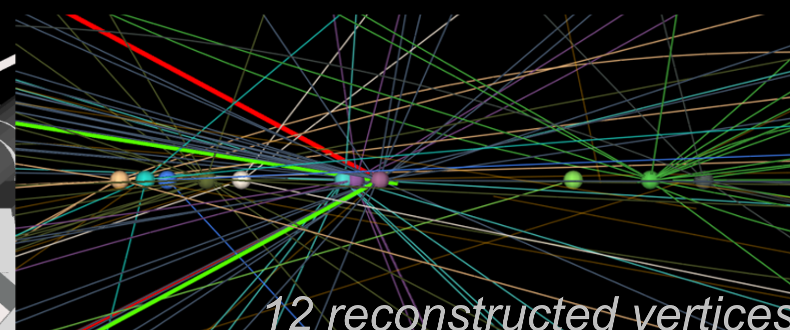
ATLAS: $M_{2e2\mu}$= 123.9 GeV

p_T (e,e,μ,μ)= 18.7, 76, 19.6, 7.9 GeV,
m (e^+e^-)= 87.9 GeV, m($\mu^+\mu^-$) =19.6 GeV

http://atlas.ch
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST

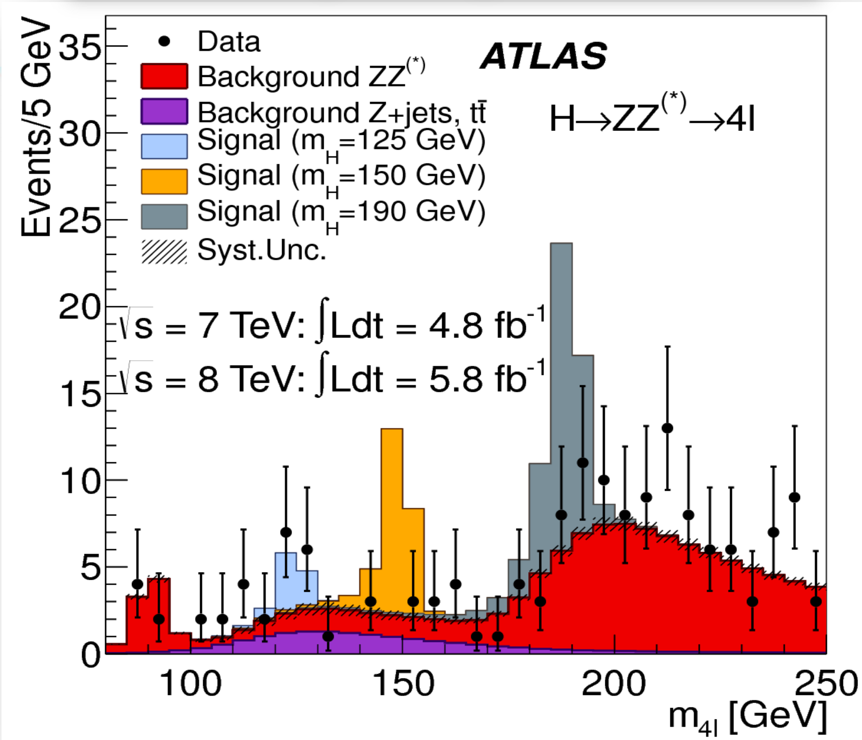






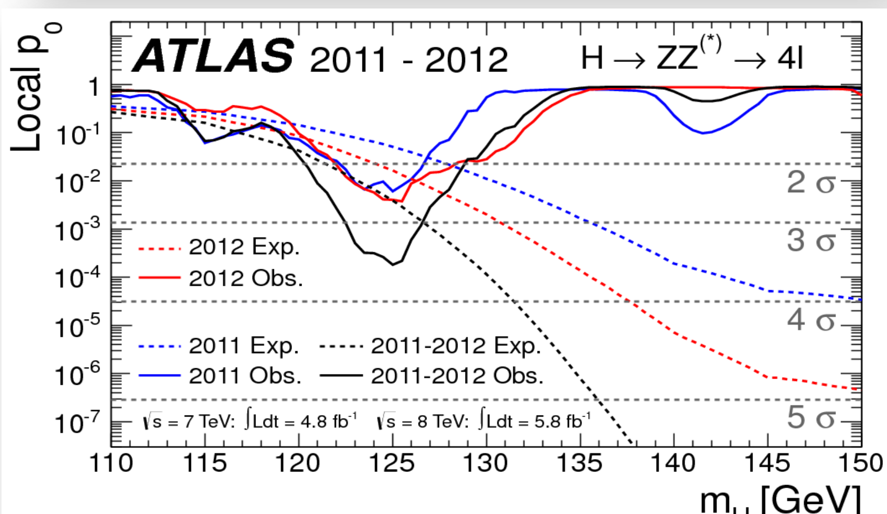
ATLAS ZZ*

σ x BR ~ 2.5 fb m_H ~ 126 GeV



In the region 125 ± 5 GeV	
Observed	13 events
Expected from background only	4.9 ± 1
Expected from Higgs signal	5.3 ± .8

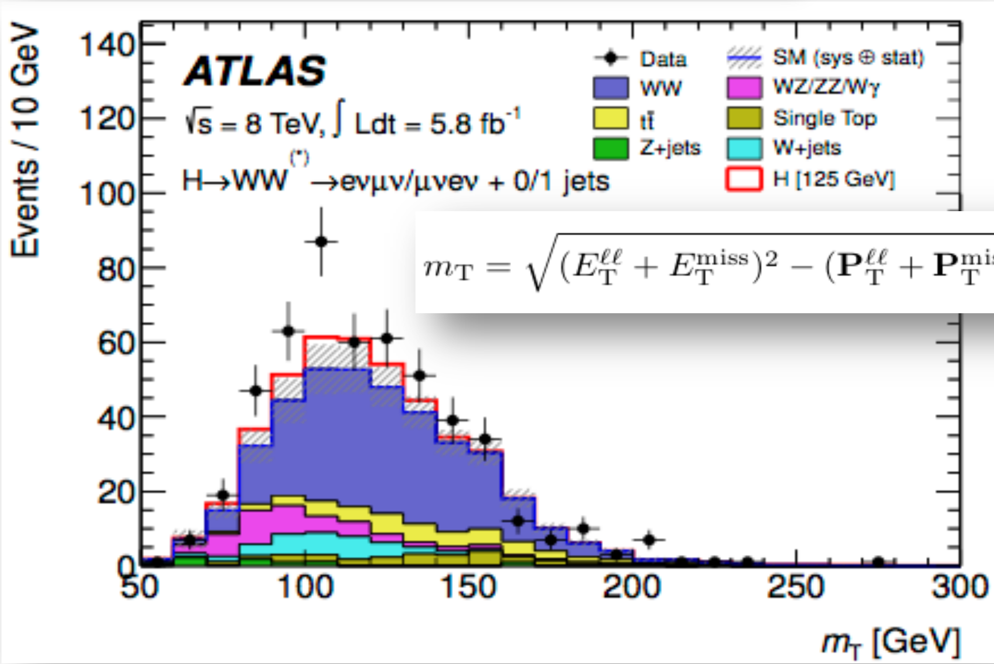
	4μ	2e2μ	4e
Data	6	5	2
Expected S/B	1.6	1.1	0.6
Reducible/total B	10%	60%	70%



Data sample	m_H of max significance	local significance obs. (exp. SM H)
2011	125 GeV	2.5 σ (1.6)
2012	125.5 GeV	2.6 σ (2.1)
2011+2012	125 GeV	3.6 σ (2.7)

σ x BR ~ 200 fb for m_H~ 125 GeV

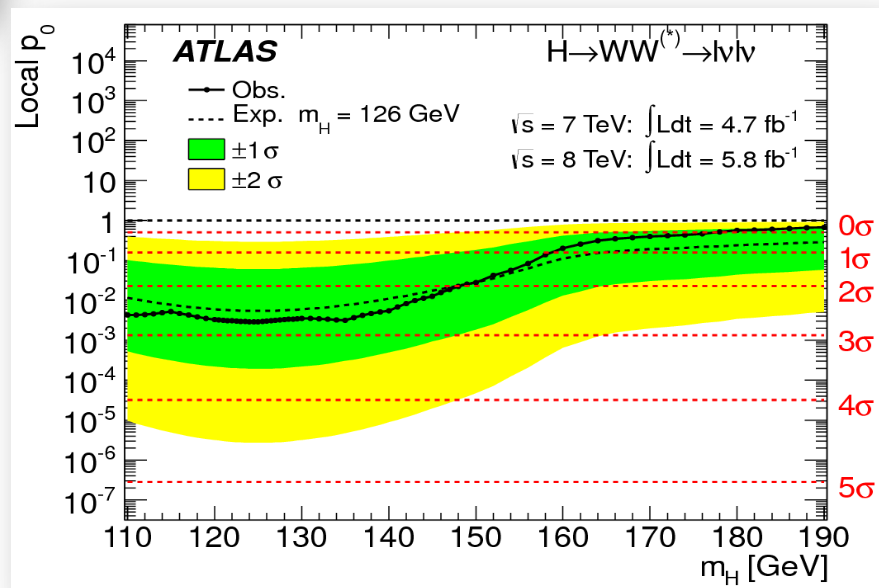
ATLAS lνl'ν'



$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$

Observed:	223 events
expected from background only	168 ± 20
expected from Higgs m_H=126 GeV	25 ± 5

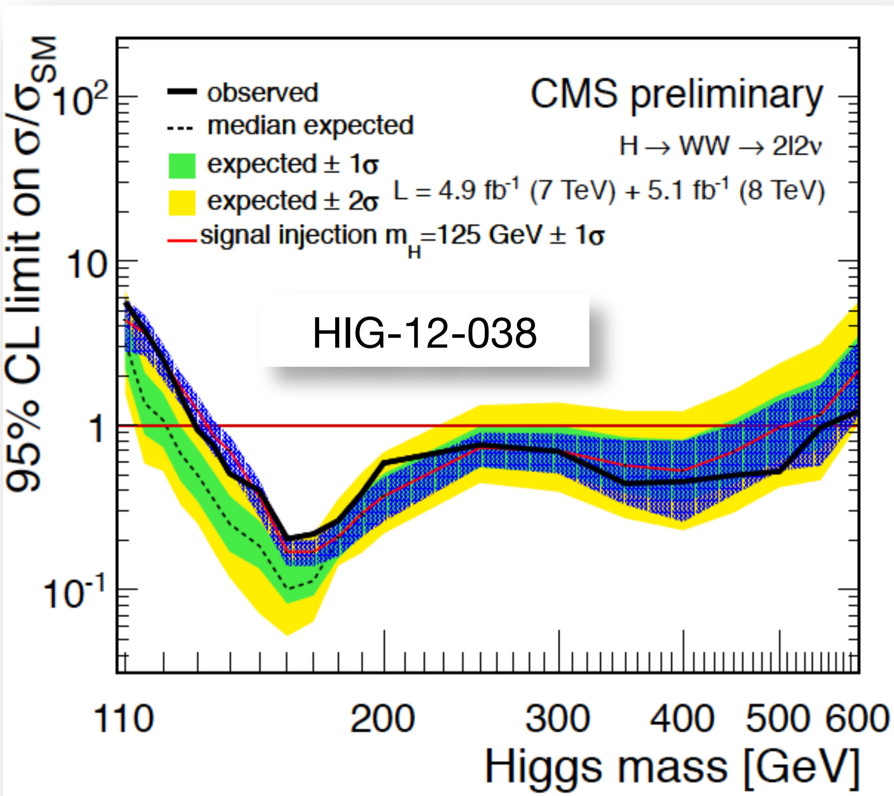
Data sample	m_H of max significance	local significance obs. (exp. SM H)
2011	135 GeV	1.1 σ (3.4)
2012	120 GeV	3.3 σ (1.0)
2011+2012	125 GeV	2.8 σ (2.3)



Broad excess, extending over > 50 GeV in mass, due to poor mass resolution

New CMS H→WW Shape-Based Analysis

- PLB: SF (ee, μμ) and DF (eμ) cut-based analysis
  - SF background dominated by DY+MET is very non-trivial in the presence of large PU (sensitivity is marginal)
- Shape-based DF analysis shown here
  - 4th July combo with other channels: 5 σ → 5.2 σ

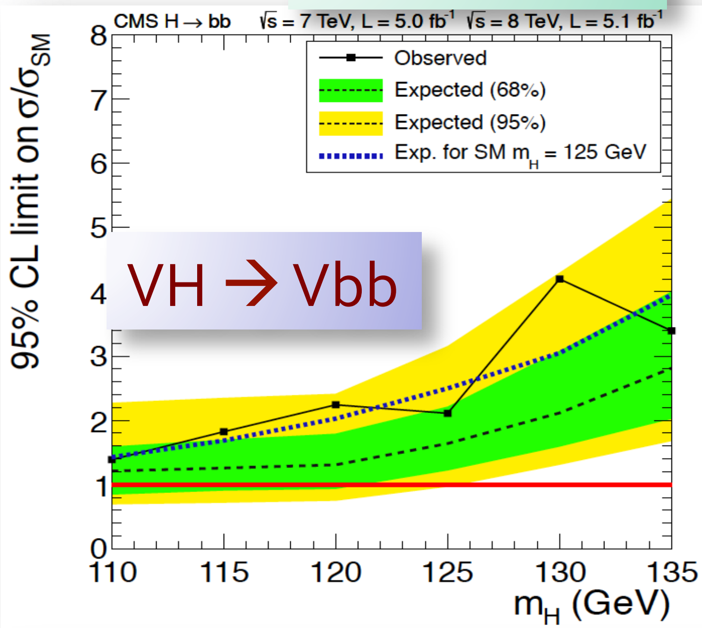


7 TeV published
+ 8 TeV DF shape and
SF cut-based

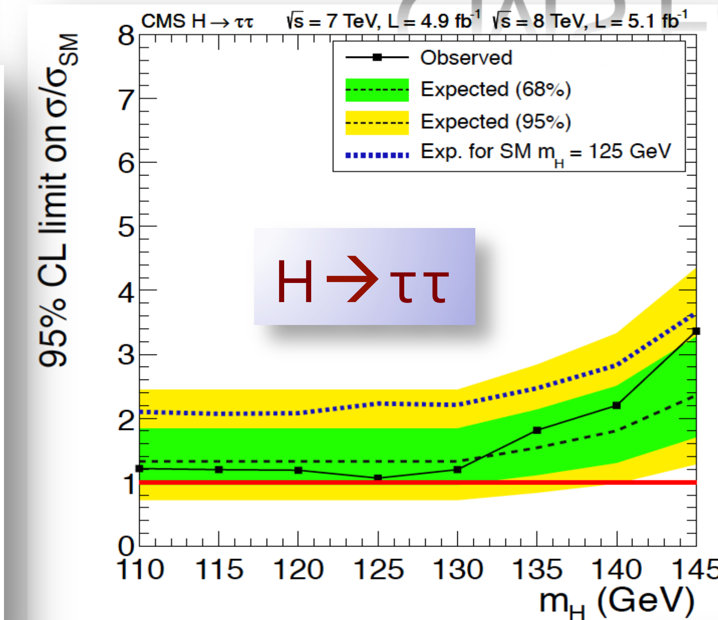
CMS Fermions

Compatible with background or S+B for 125 GeV Higgs

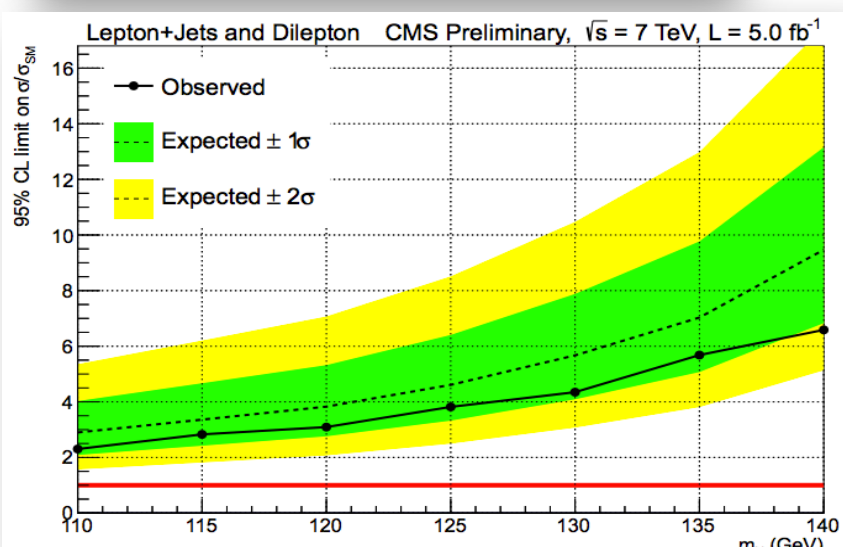
VH → Vbb



H → ττ

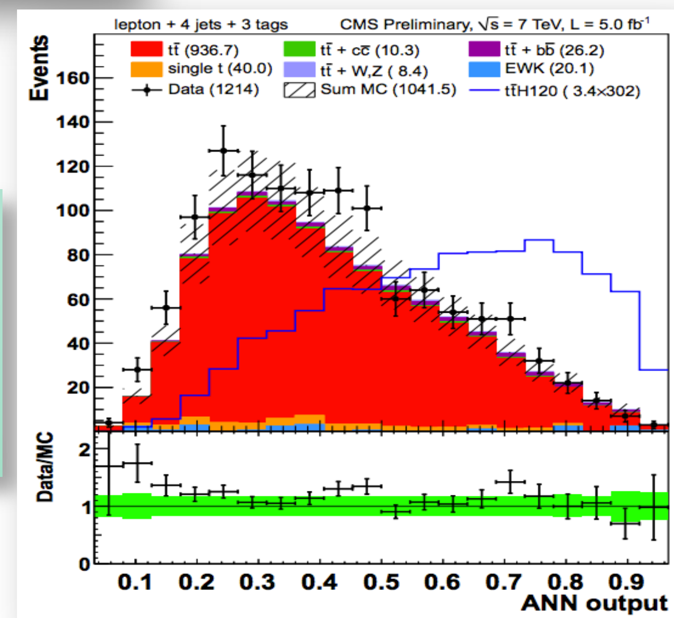


No significant departure from SM background-only expectation



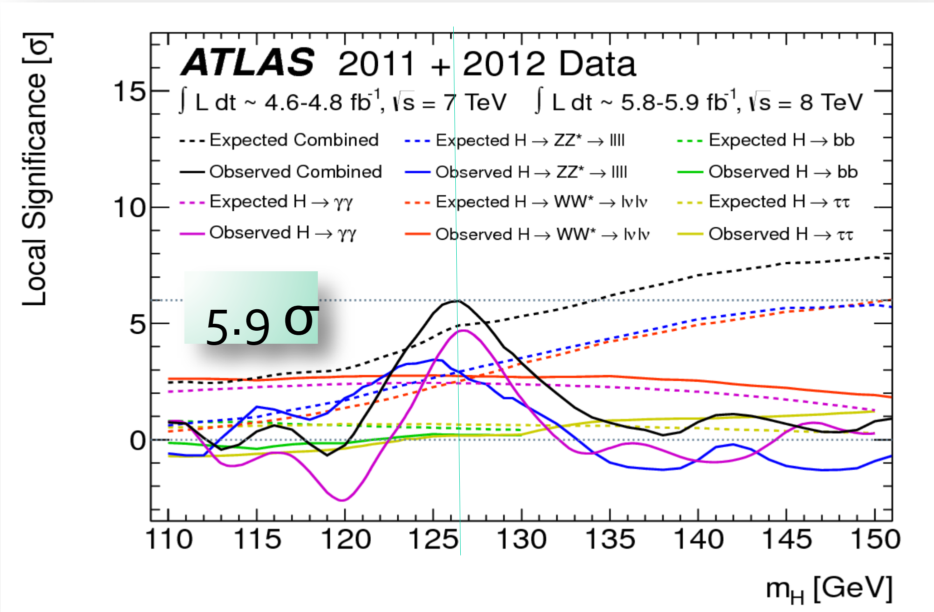
- $t\bar{t}$ H
  - $t\bar{t}$ (lepton+jets and dileptons)
    - Count b-tags
    - Shape analysis

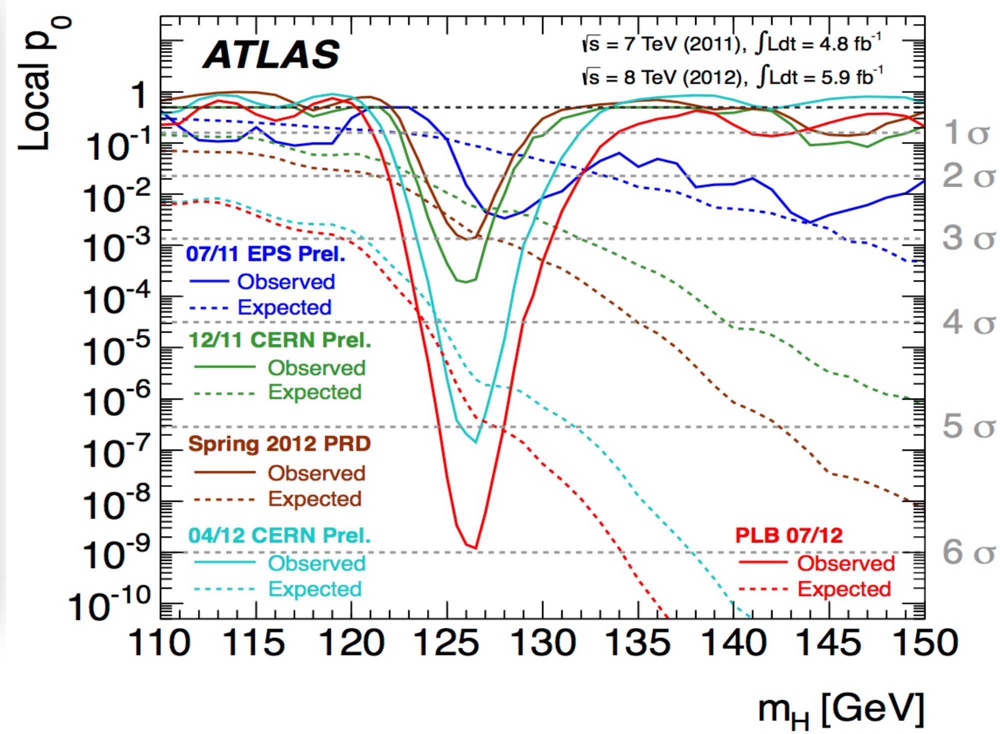
[HIG-12-025]



Higgs combinations and properties

ATLAS Combination





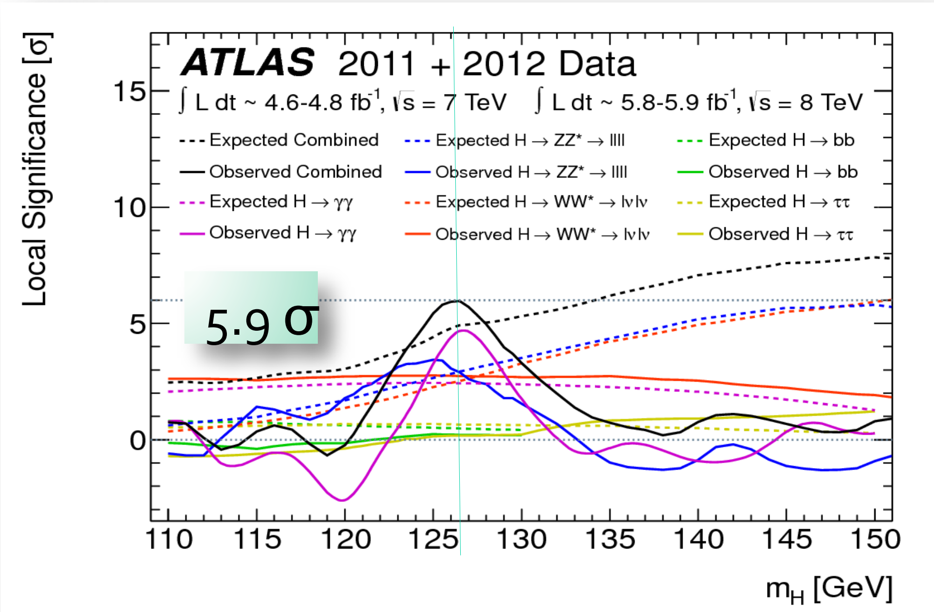
Breakdown by channel

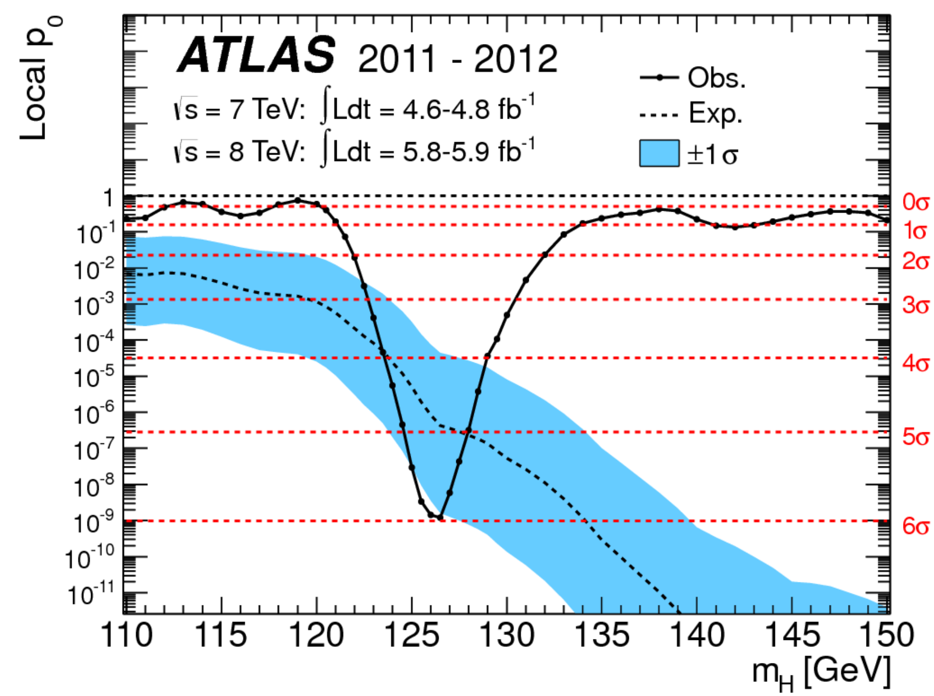
Channel	m_H of max significance	local significance obs. (exp. SM H)
H→ γγ	126.5 GeV	4.5 σ (2.5)
H→ 4l	125 GeV	3.6 σ (2.7)
H→ lνlν	125 GeV	2.8 σ (2.3)
Combined	126.5 GeV	5.9 σ (4.9)

Significance increase from 4th July: 2012 data for H→ WW* search

H→ ττ and W/ZH → W/Zbb: ~ no sensitivity (~3xSM cross-section)

ATLAS Combination





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Significance increase from 4th July: 2012 data for H→ WW* search

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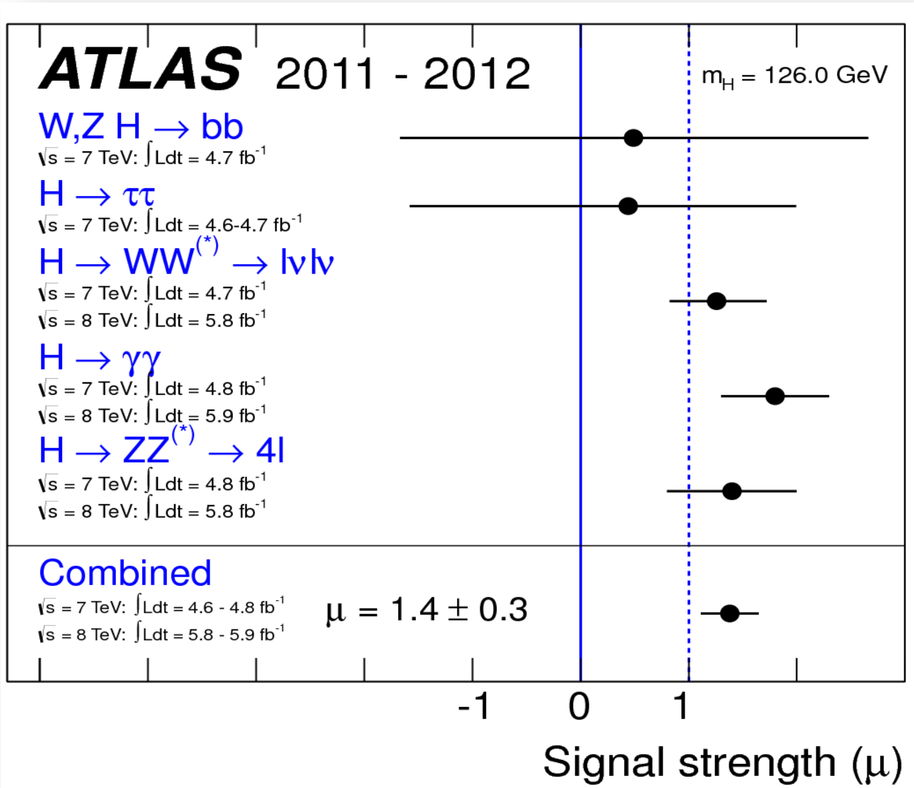
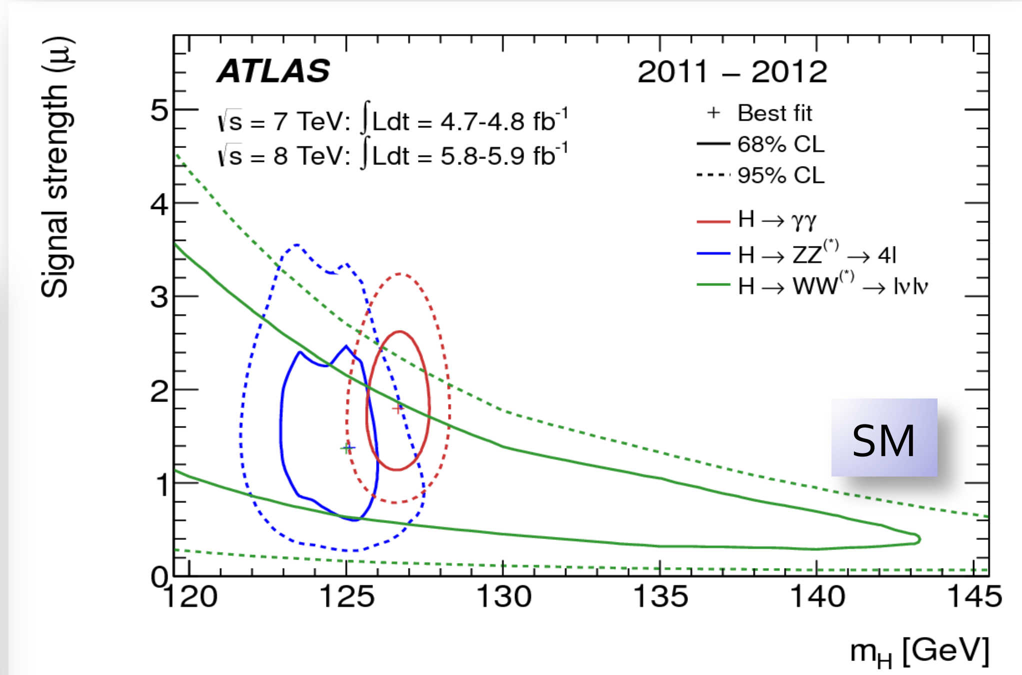
ATLAS Mass and signal strength

Estimated mass:
m_H = 126 ± 0.4 (stat) ± 0.4 (syst) GeV

μ = signal strength normalized to the SM Higgs expectation at m_H = 126 GeV

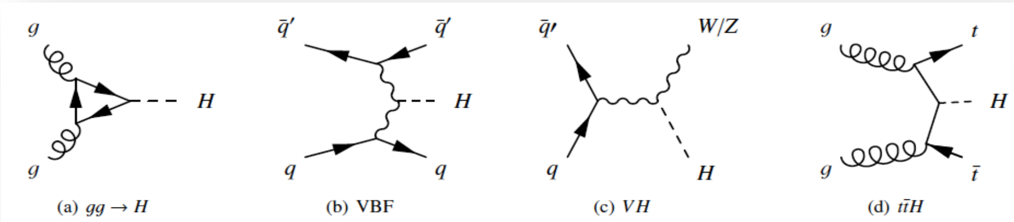


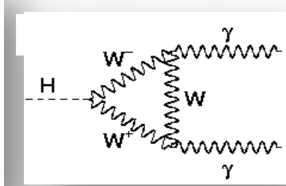
2D likelihood fit to signal mass and strength

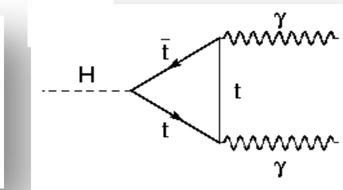


Best-fit value at 126 GeV
μ = 1.4 ± 0.3

ATLAS couplings

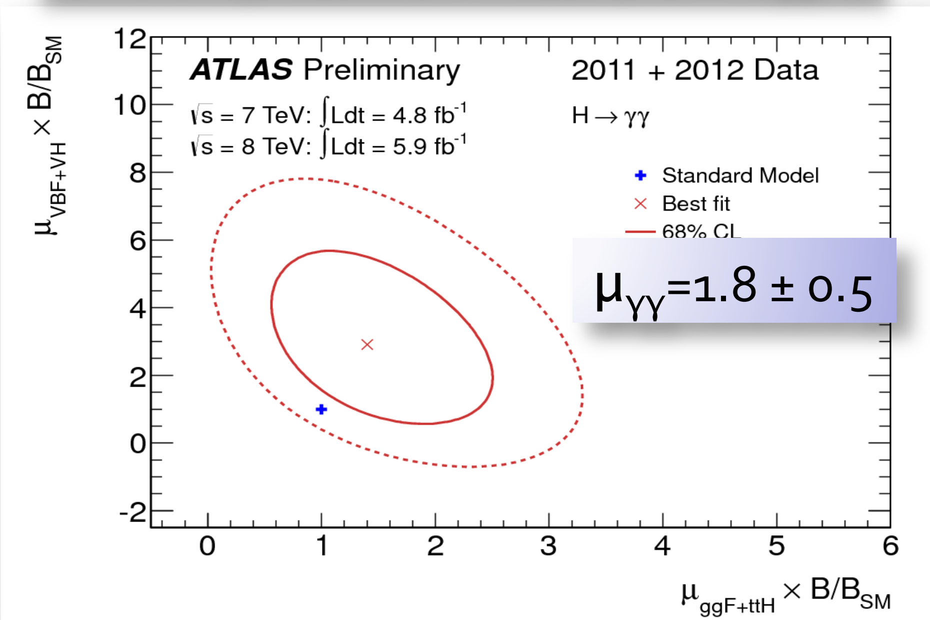




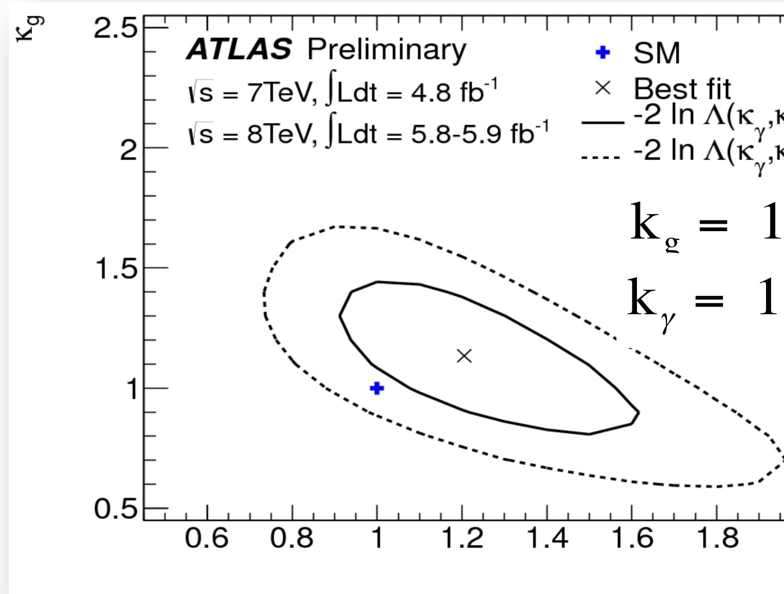


Explore tension SM-data from $H \to \gamma\gamma$ different production modes (VBF vs ggF)

New particles in the gg → H and $H \to \gamma\gamma$ loops ?



$\mu_{\gamma\gamma}=1.8 \pm 0.5$



$$k_g = 1.1^{+0.2}_{-0.3}$$

$$k_\gamma = 1.2^{+0.3}_{-0.2}$$

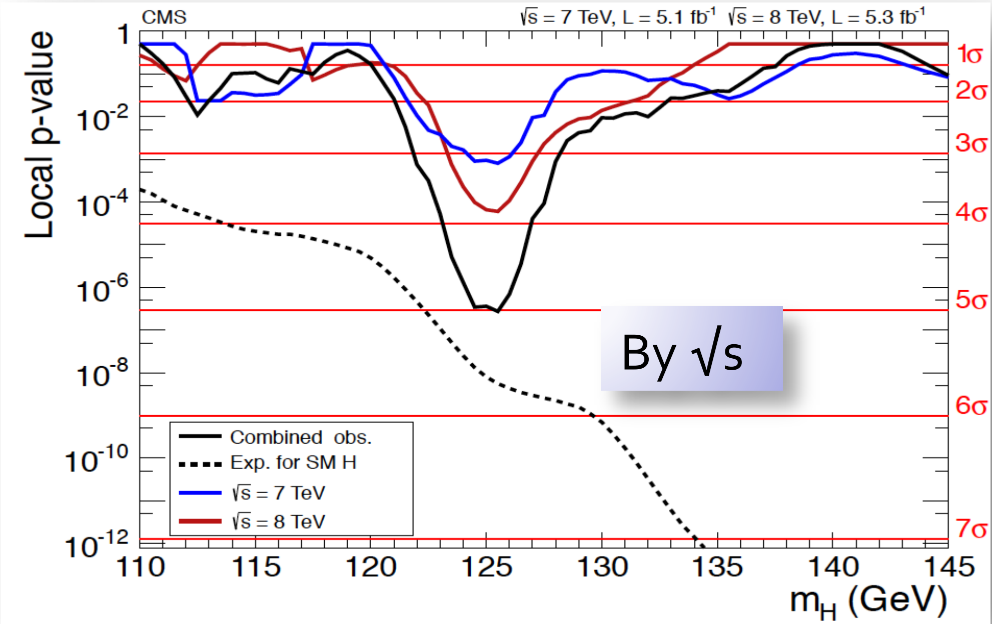
$$k_i^2 = \frac{\Gamma_i^{data}}{\Gamma_i^{SM}}$$

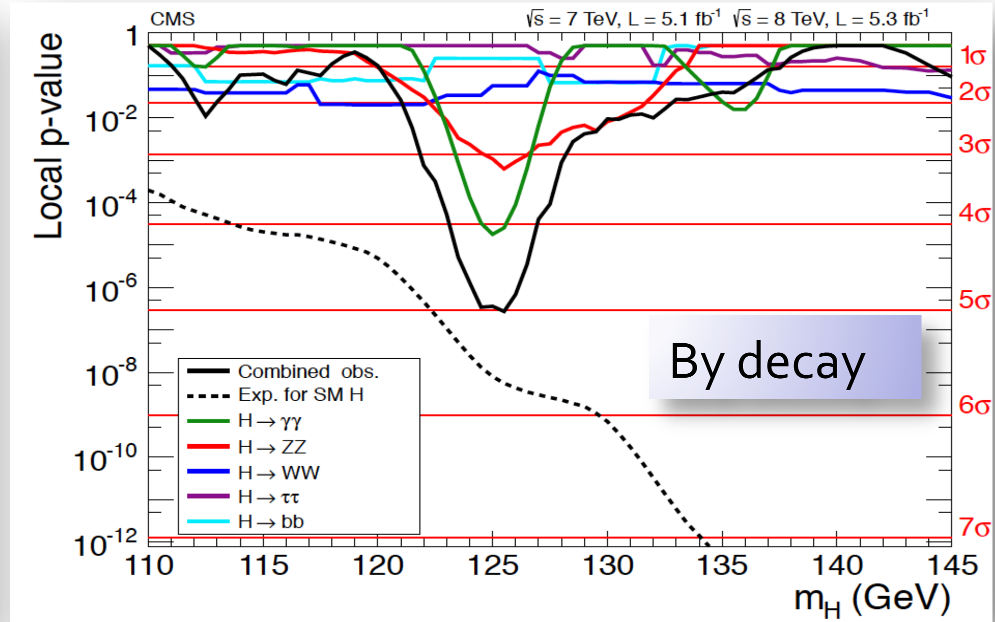
$$\frac{k_W}{k_Z} = 1.07^{+0.35}_{-0.27}$$

B(H→ invisible/undetected) < 0.84 (95%CL)

Couplings to fermions k_F weakly constrained by direct $H \to \tau\tau$, bb; indirect constraints from ggF (tt loop) indicate it's non-vanishing

CMS: Combined results





Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.6	3.1
$\tau\tau$ + bb	2.4	0.4
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

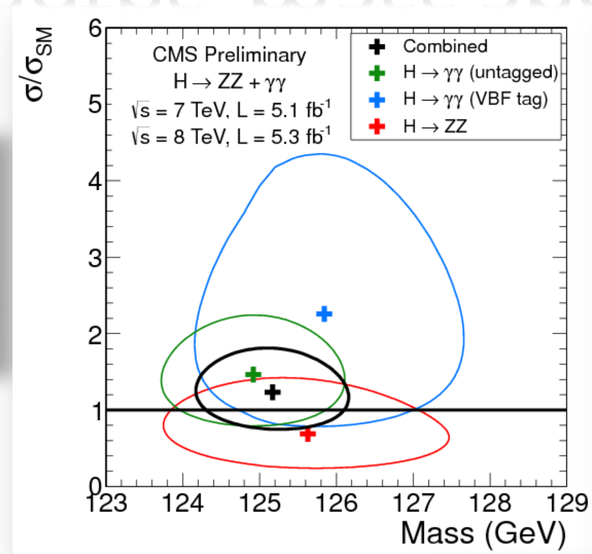
5.0σ versus
5.8σ expected

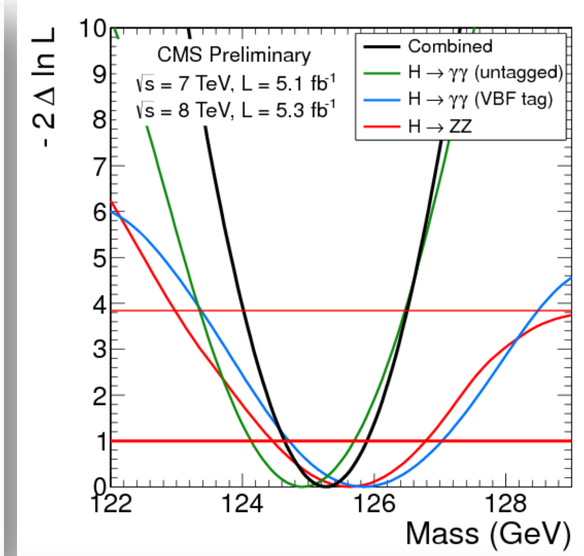
Signal strengths, mass and couplings

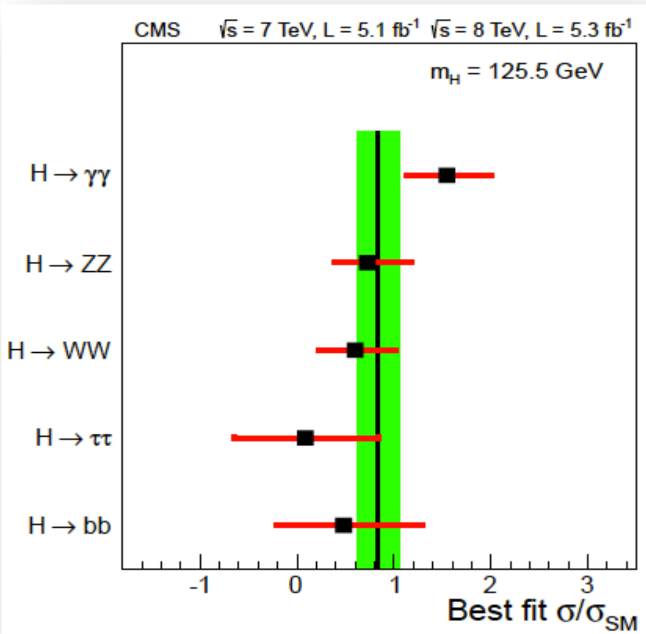
- 2D Likelihood scan in 3 channels

m = 125.3 ± 0.4 (stat) ± 0.5 (syst)

- Ultimate precision: $\sigma_m < 100$ MeV

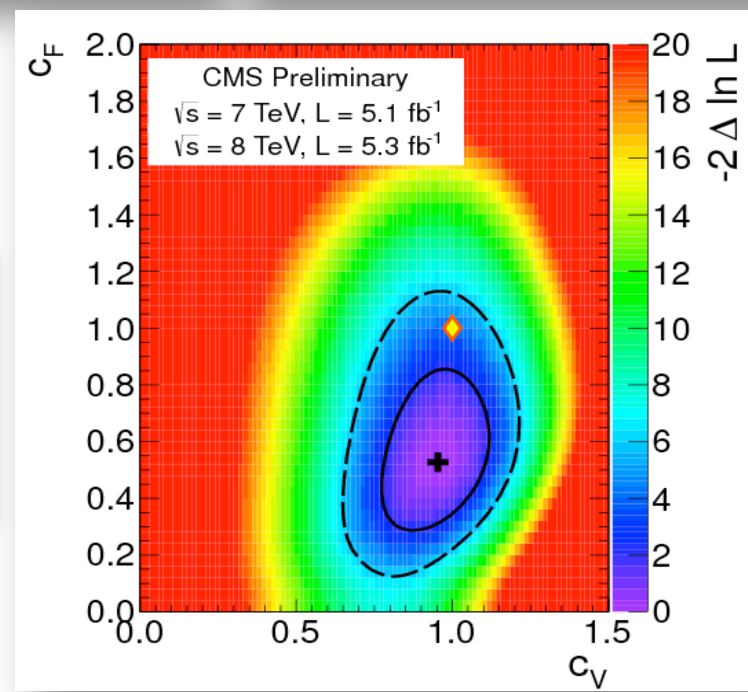






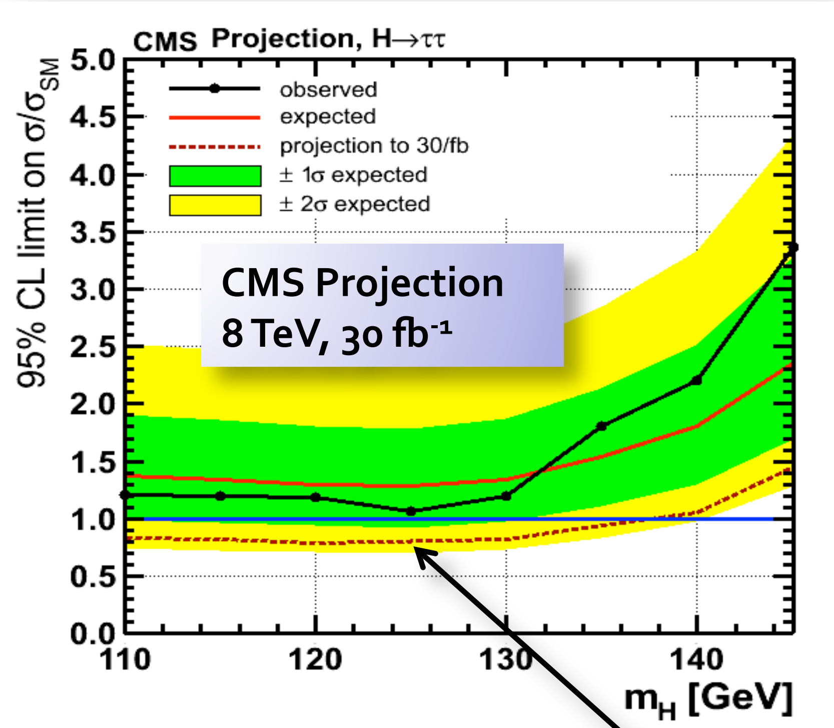
$$\frac{\sigma}{\sigma_{SM}} = 0.87 \pm 0.23$$

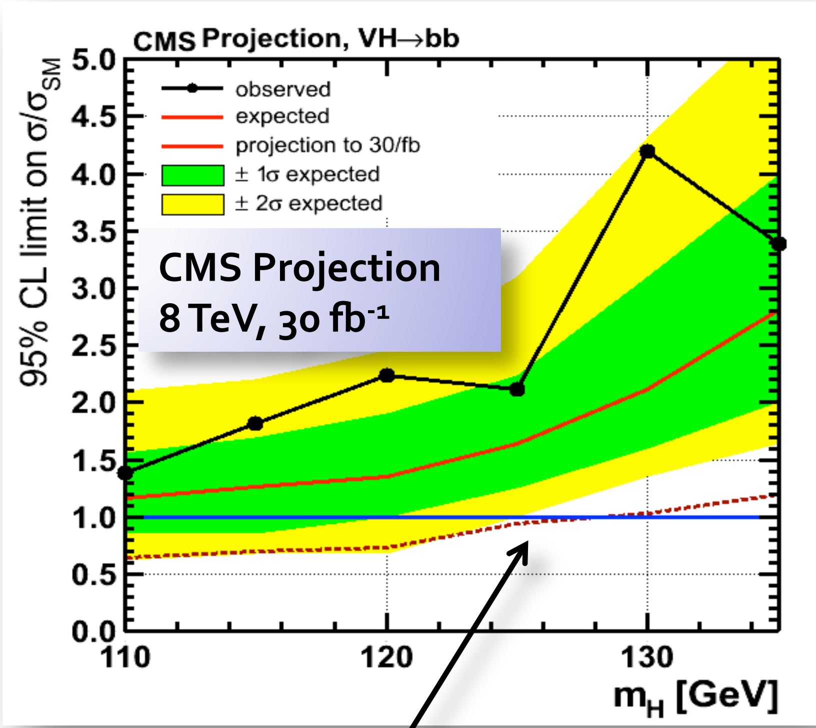
Fit to C_V and C_F (couplings to Vector bosons and fermions)



Some Projections

CMS: Fermionic Channels





SM sensitivity is reached or exceeded (dashed red lines)

Spin-Parity: H->ZZ, WW, γγ

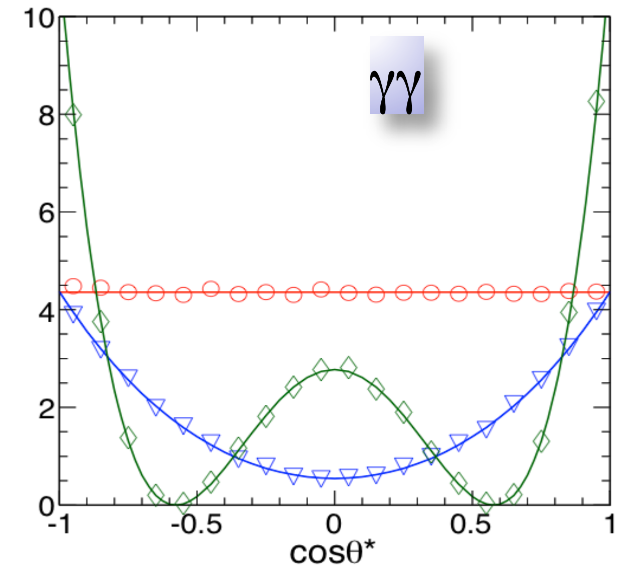
- Follow-up study
  - S.Bolognesi et al., arXiv:1208.4018
  - WW feature: angle between decay planes
  - γγ: production angle

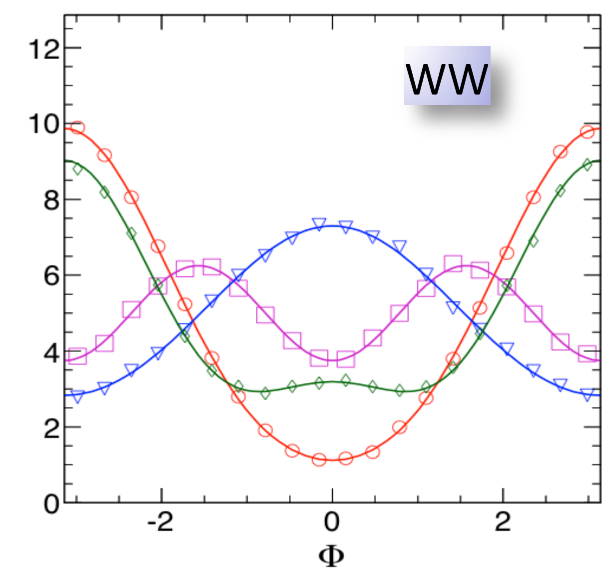
scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0^+_m vs bkg	7.1	4.5	5.2	9.9
0^+_m vs 0^-	4.1	1.1	0.0	4.2
0^+_m vs 2^+_m	1.6	2.5	2.5	3.9

spin-2, minimal, 35/fb

spin-0, parity-odd, 35/fb

- Close to 4σ separation possible (certainly true for ATLAS+CMS)
  - For both odd parity and spin-2
    - More scenarios are possible…

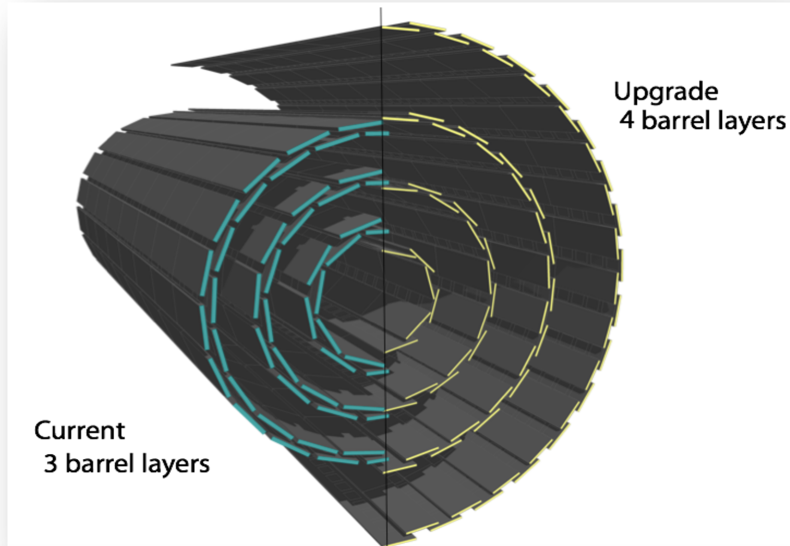




CMS Pixel and HCAL Upgrades

- Both CMS and ATLAS will upgrade their detectors.
- Very few full simulation results are available for upgrade detector designs.

- Upgraded Pixel Detector
  - Less material, better radial distribution
    - *New ROC & extra layer recovers tracking efficiency, reduces fakes*
- Upgraded HCAL
  - Improve background rejection
  - Improve MET resolution
  - Improve Particle Flow
    - *via improved S/N photodetectors*
  - Identify depth of shower max
    - *via longitudinal segmentation, timing*



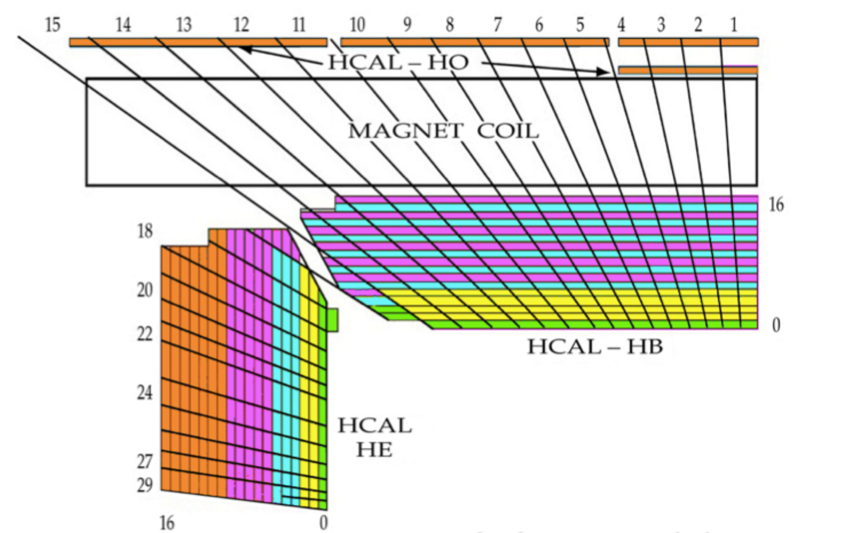
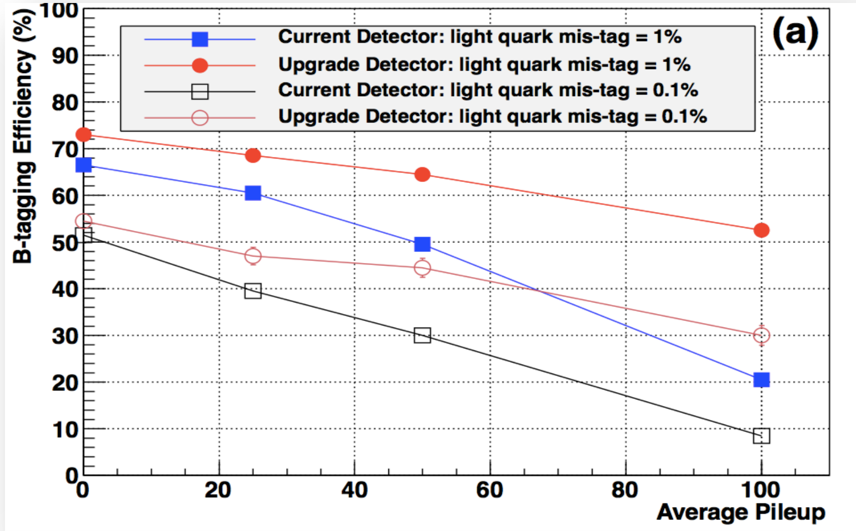


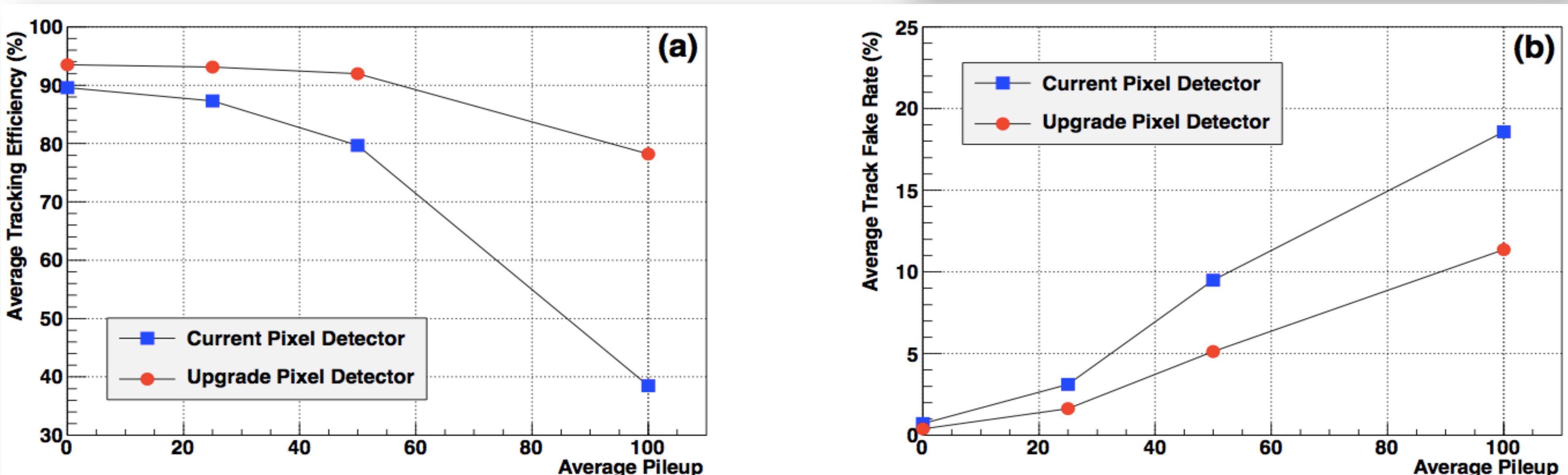
Figure 3.1: Current proposed depth segmentation structure for the HB and HE calorimeters, made possible by the use of SiPM photodetectors.

Improved Tracking & Btagging

- CMS Full simulation $t\bar{t}$ comparisons vs PU
  - B-tag performance (Top-Right)
  - Tracking performance (Bottom)
    - Efficiency (Left) and Fake rate (Right)



- Very powerful even without optimization!
  - B tagging, tracking efficiency at 65-70 PU equal to current detector at 25 PU
  - Fakes not quite as big improvement



Upgrades: Impact on Higgs Physics

H → ZZ → 4l

- *Key channel very sensitive to efficiency*
  - *50% improved*

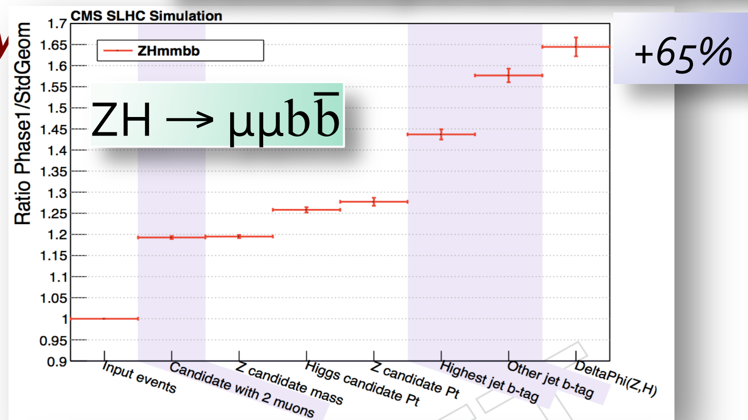
ZH → μμbb̄

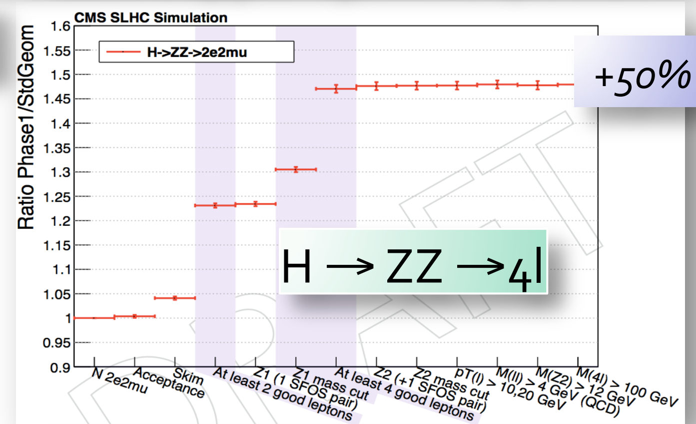
- *High muon ID efficiency high b-tagging efficiency good dijet mass resolution.*
  - *65% improved*

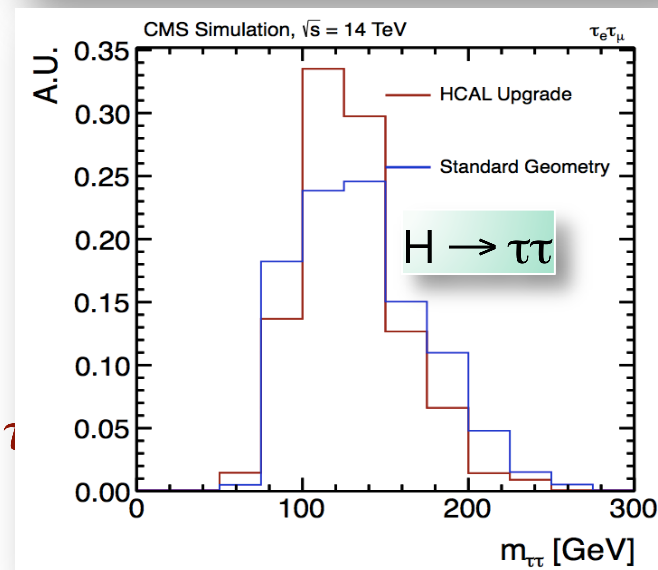
H → ττ (VBF)

- *MET resolution, forward jet tagging, τ Identification*
  - *Better mass resolution*

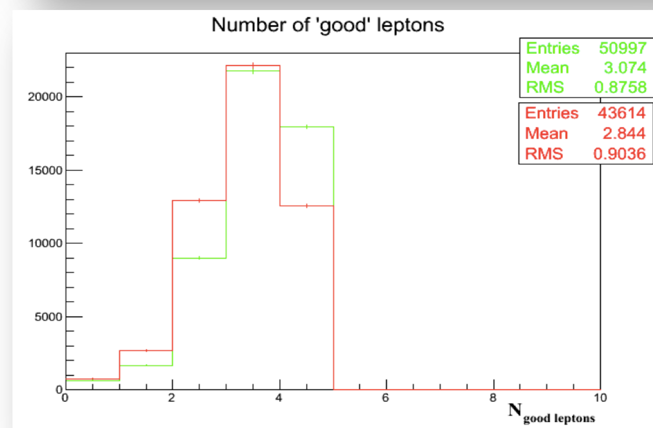
Improved signal yield (relative to current detector):
shaded regions indicate cuts with biggest gains expected





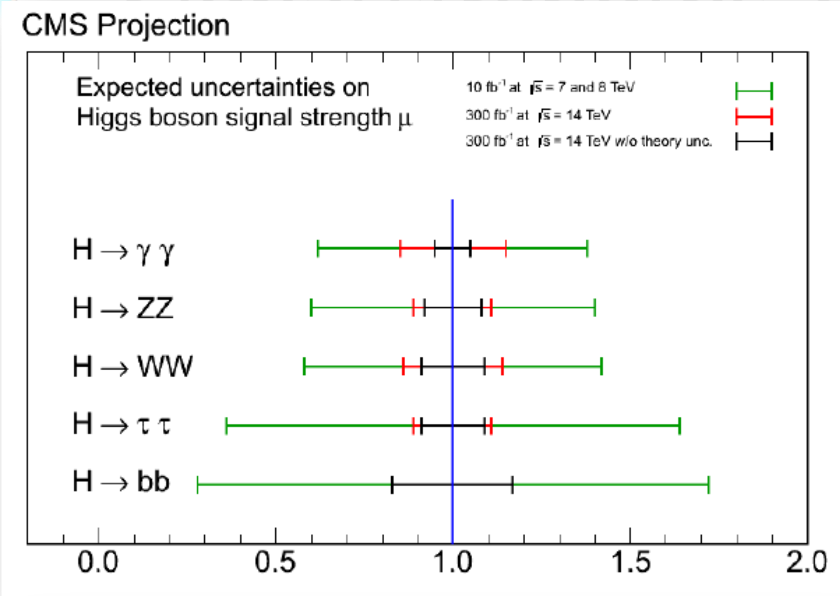


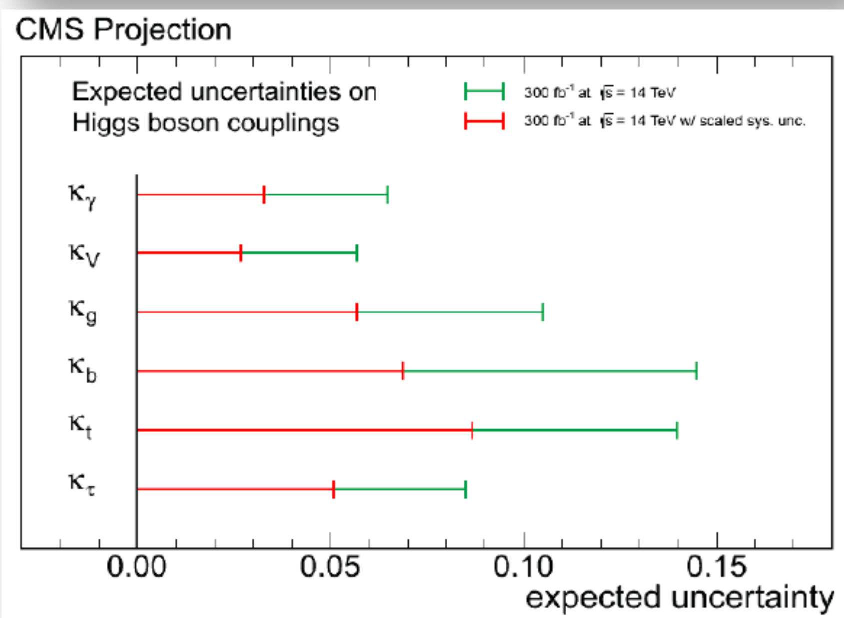
- Improved $m_{\tau\tau}$ resolution



- More good leptons
better tracking & isolation

Signal strengths, couplings: 300,3000 fb^{-1}





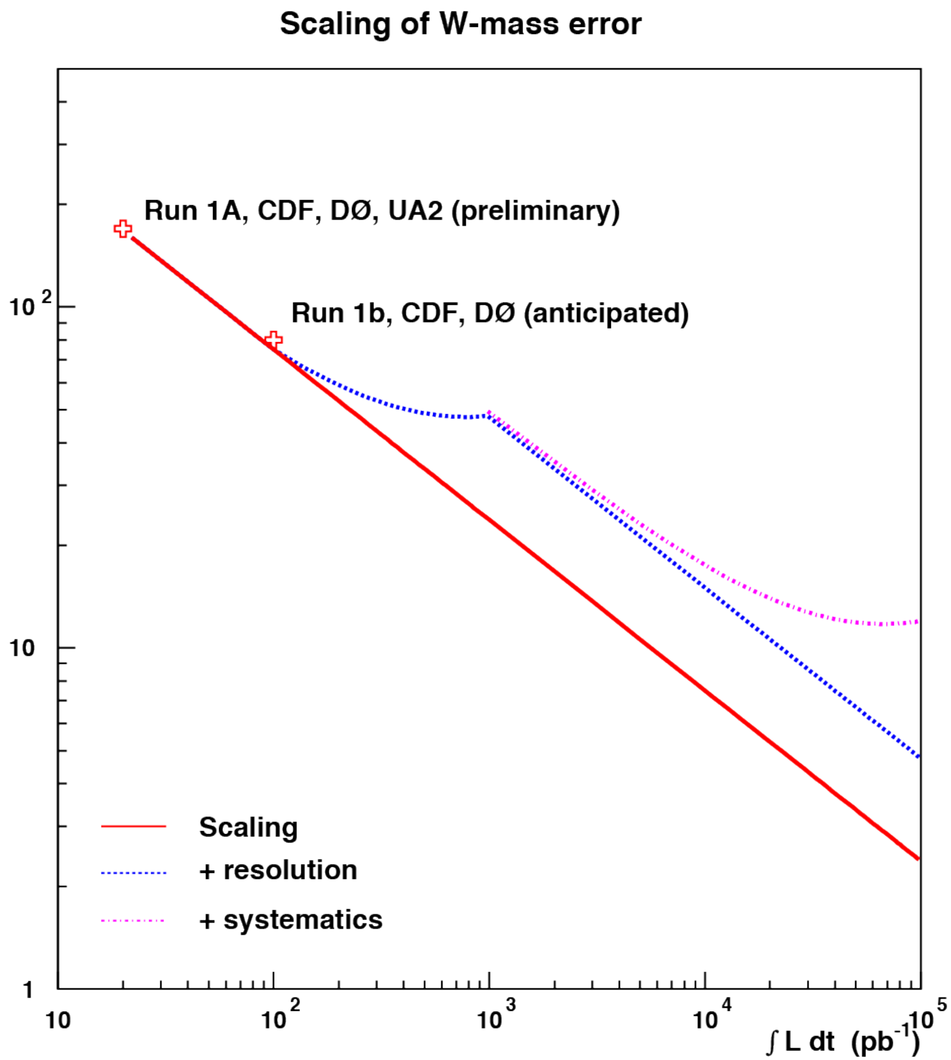
- Signal Strengths: ~10-15%
  - Present (Green). Present systematics at 300 /fb 14 TeV (Red). Setting theoretical uncertainties to zero (Black).

	Uncertainty (%)			
Coupling	300 fb^{-1}		3000 fb^{-1}	
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Simple scenarios for couplings

1. Systematics unchanged
2. Theory uncertainties reduced ½, all other systematics ~ $1/\sqrt{(\int L dt)}$

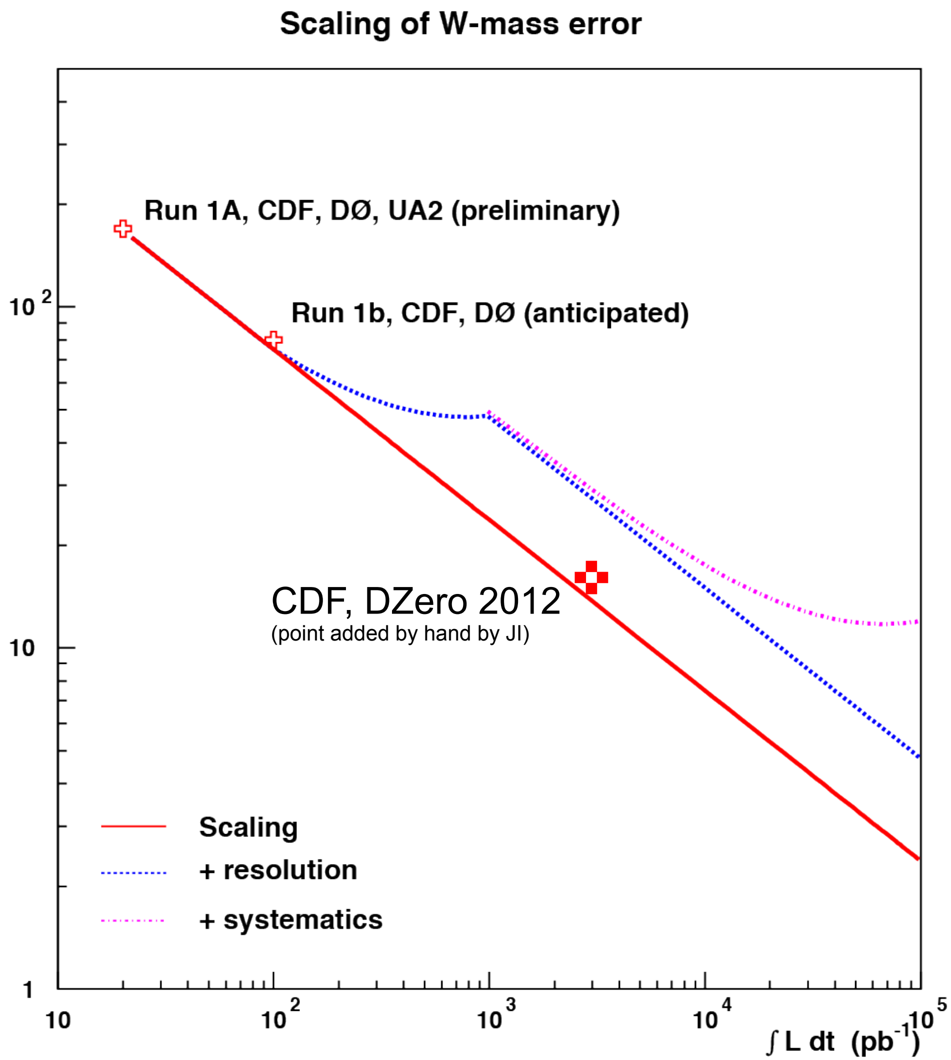
Tevatron M_W projections from 1995



- From TeV2000 report Ch.4
  - http://theory.fnal.gov/TeV2000/chapter4_IVB.ps
  - Attempted to project from 20 /pb per experiment to 100 /fb
  - In addition to simple scaling 1/√N included several models Concluded that with 10/fb per experiment could reach ±30MeV on combination
- Moriond 2012

  1) CDF Talk on 2.2 /fb
  2) DZero Talk on 4.4 /fb
  - Uncertainty achieved ±15 MeV
- Compared to the 1985 projections?

Tevatron M_W projections from 1995



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  2) DZero Talk on 4.4 /fb

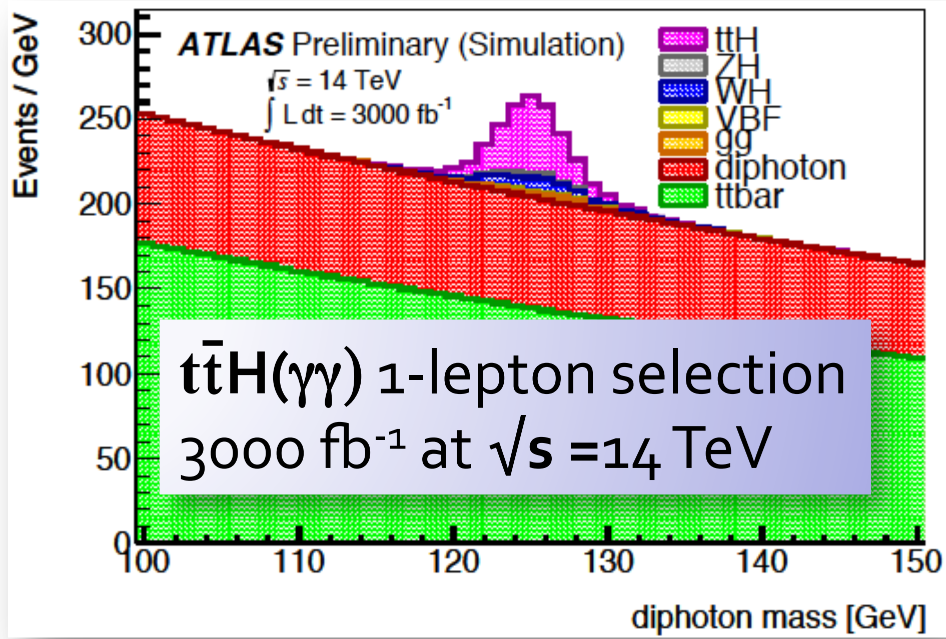
  - Uncertainty achieved ±15 MeV
- Compared to the 1985 projections?

ATLAS Projections: Higgs boson couplings

- $H \rightarrow \gamma\gamma$
  - 0-jet and 2-jet final state (VBF)
- $H \rightarrow ZZ \rightarrow 4l$
- $H \rightarrow WW \rightarrow l\nu l'\nu'$
  - 0- and 2-jet (VBF)

- *Above analyses carried out analogously to PLB methods*

- $H \rightarrow \tau\tau$
  - 2-jet final state VBF selection*



- $WH \rightarrow ZH(b\bar{b})$ and $t\bar{t}H(\gamma\gamma)$
  - Low signal rate at the LHC, but expect to observe > 100 signal events with the HL-LHC
  - Measurement of the square of the top-Yukawa coupling

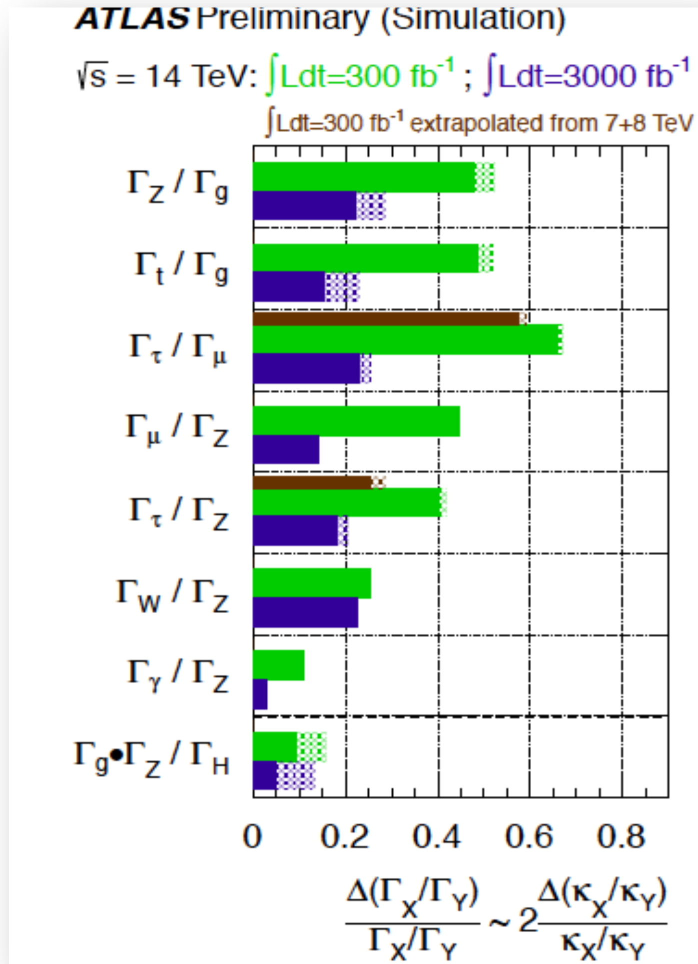
* http://arxiv.org/abs/1206.5971

ATLAS Projections

. The coupling fit parameters are chosen as the ratios

$$\frac{\Gamma_W}{\Gamma_Z}, \frac{\Gamma_\gamma}{\Gamma_Z}, \frac{\Gamma_\tau}{\Gamma_Z}, \frac{\Gamma_\mu}{\Gamma_Z}, \frac{\Gamma_t}{\Gamma_g}, \frac{\Gamma_Z}{\Gamma_g} \text{ and } \frac{\Gamma_g \cdot \Gamma_Z}{\Gamma_H} .$$

- γγ and ZZ final states
  - profit most from the high ∫Ldt
    - stat and syst uncertainties (dominated by events sideband) reduced considerably.
  - γγ especially important
    - All initial states and associated couplings accessible to the LHC
- ττ VBF production
  - $H \to \tau_{lep}\tau_{lep}$ and $H \to \tau_{lep}\tau_{had}$
  - Scale current 5+10 fb^{-1} to 300 fb^{-1} at 14 TeV



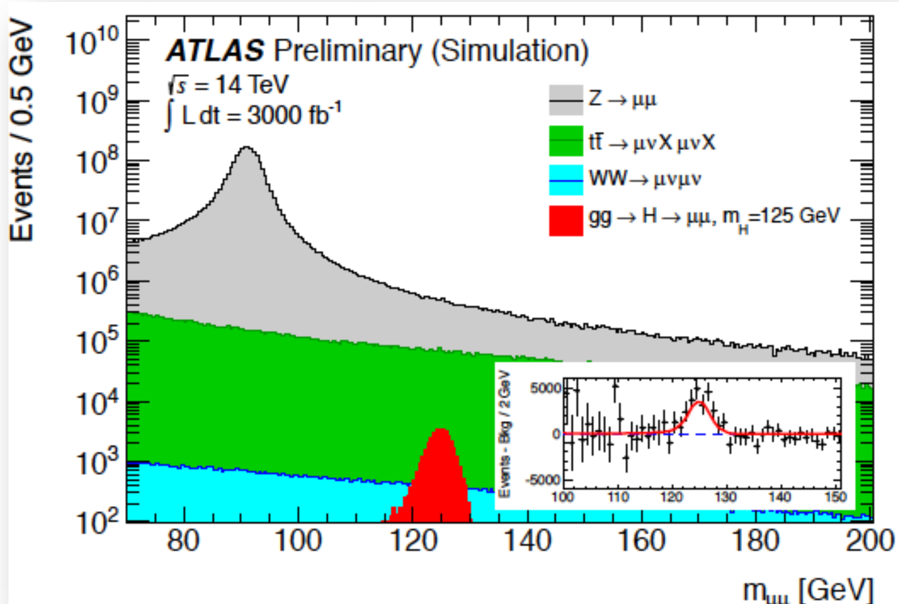
	$300\,fb^{-1}$	$3000\,fb^{-1}$
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)

- Minimal coupling fit, 2 independent scale factors for vector and fermion couplings
  - No BSM contributions in loops or total width

ATLAS Projections: Rare Processes

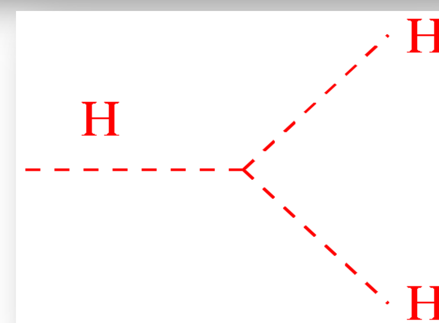
- $H \rightarrow \mu\mu$
  - Low rate and S/B only 0.2%

    > 6σ with 3000 fb^{-1}



- $t\bar{t}H$, $H \rightarrow \mu\mu$
  - ~ 30 events at 3000 fb^{-1}
    - *S/B >1 can be achieved*

      ⇒ top- and μ-Yukawa couplings with a precision on total signal strength of 25%



~ λv

$m_H^2 = 2\,\lambda\,v^2$

- Higgs self-couplings: ~ 3σ from
  - HH → bbγγ channel with 3000 fb^{-1}
  - HH→ bbττ also promising
  - 30% measurement of λ/λ_{SM} may be achieved
- Results are very preliminary and conservative
  - *NB: Physics potential of HL-LHC is much more than Higgs!*

Conclusions

- Major Discovery
  - A new boson with mass of ~125-126 GeV
- LHC, ATLAS, CMS performing extremely well
  - In 3rd year of first run!
- Major battle with pile-up has been won
  - But tougher in future, upgrades will be crucial
- Acquiring lots of great data
  - HCP will involved more than 50% increase in statistics
  - Moriond will be almost 3x the statistics of July 4th
- Beginning to understand how well we can do
  - With high luminosity and higher energy LHC