

# Recent Results from CMS

**Suvadeep Bose**

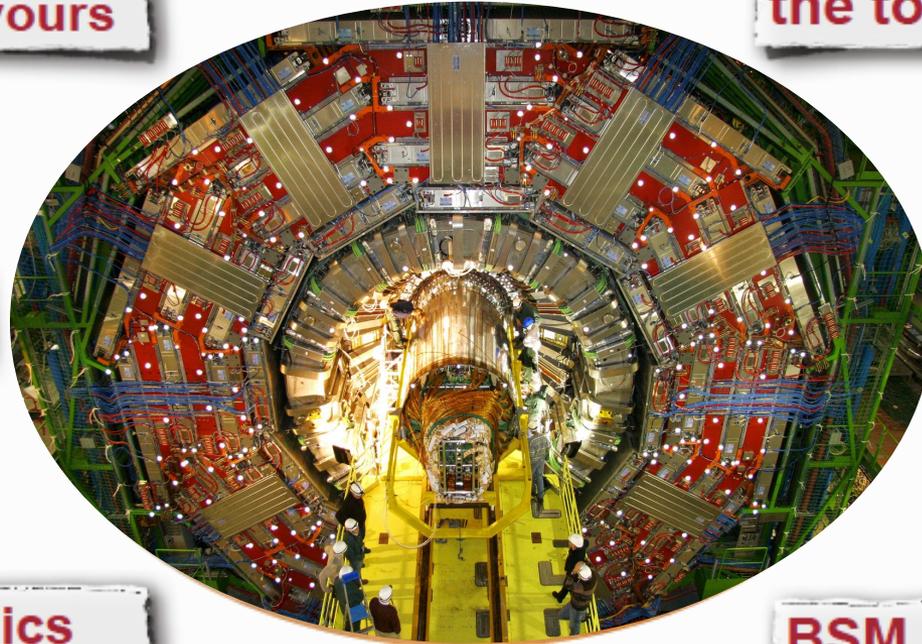
University of Nebraska Lincoln

*(On behalf of CMS collaboration)*

Heavy Flavours

the top

probing QCD



Higgs searches

EWK physics

BSM searches

*What to expect:*

- a selection only, with focus on most recent results
- will focus on pp physics only
- see all the specialized talks at this conference for much more details by [Yuriy Pakhotin](#), [Norbert Neumeister](#), [Rocio Vilar Cortabitarte](#)

# CMS: the detector

Total weight  
14000 t  
Diameter 15 m  
Length 28.7 m

**ECAL** 76k scintillating  
PbWO<sub>4</sub> crystals

**HCAL** Scintillator/brass  
Interleaved ~7k ch

**MUON  
ENDCAPS**  
473 Cathode Strip Chambers (CSC)  
432 Resistive Plate Chambers (RPC)

**3.8T Solenoid**

**IRON YOKE**



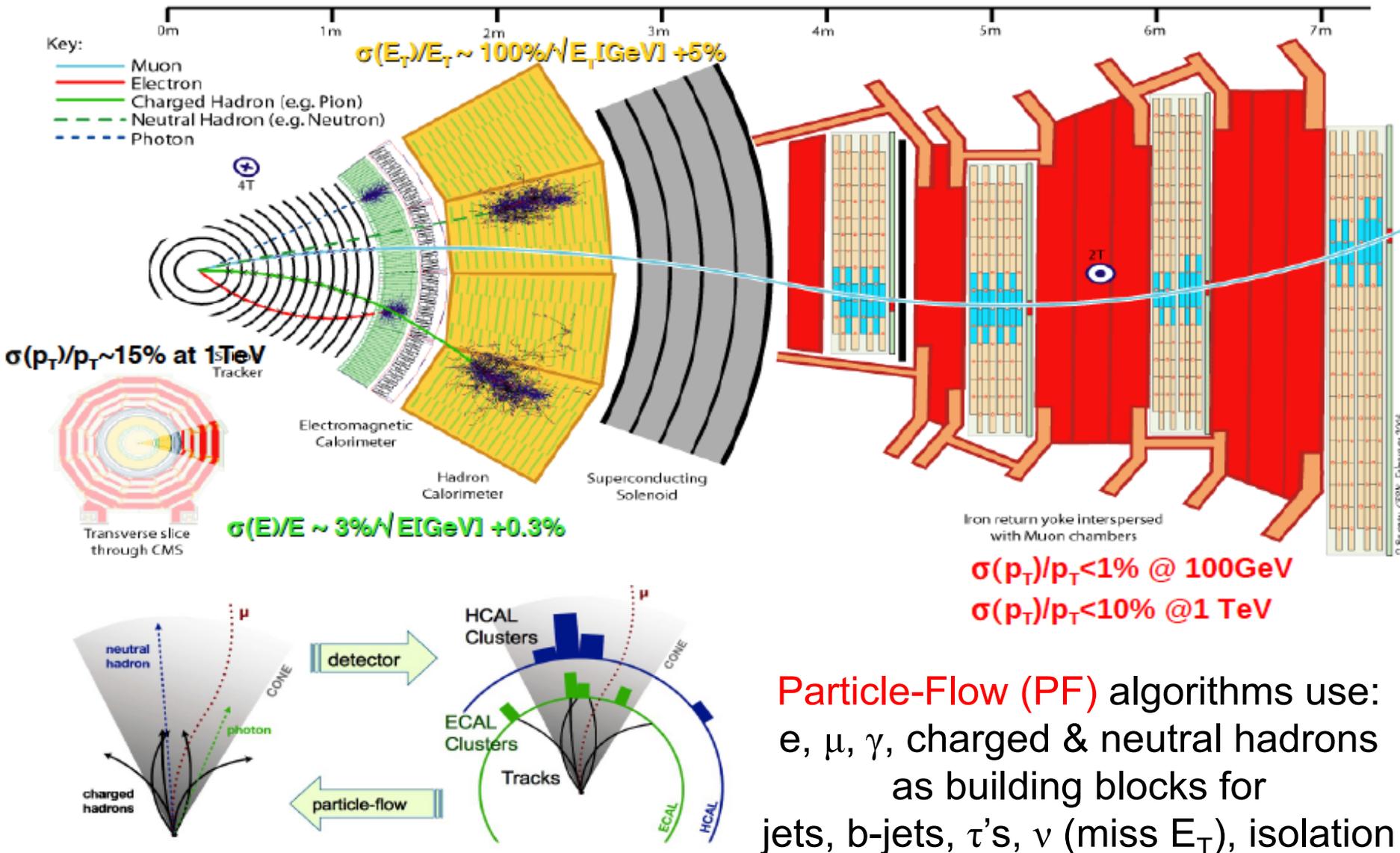
**Preshower**  
Si Strips ~16 m<sup>2</sup>  
~137k ch

**Foward Cal**  
Steel + quartz  
Fibers ~2k ch

**Pixel  
Tracker  
ECAL  
HCAL  
Muons  
Solenoid coil**

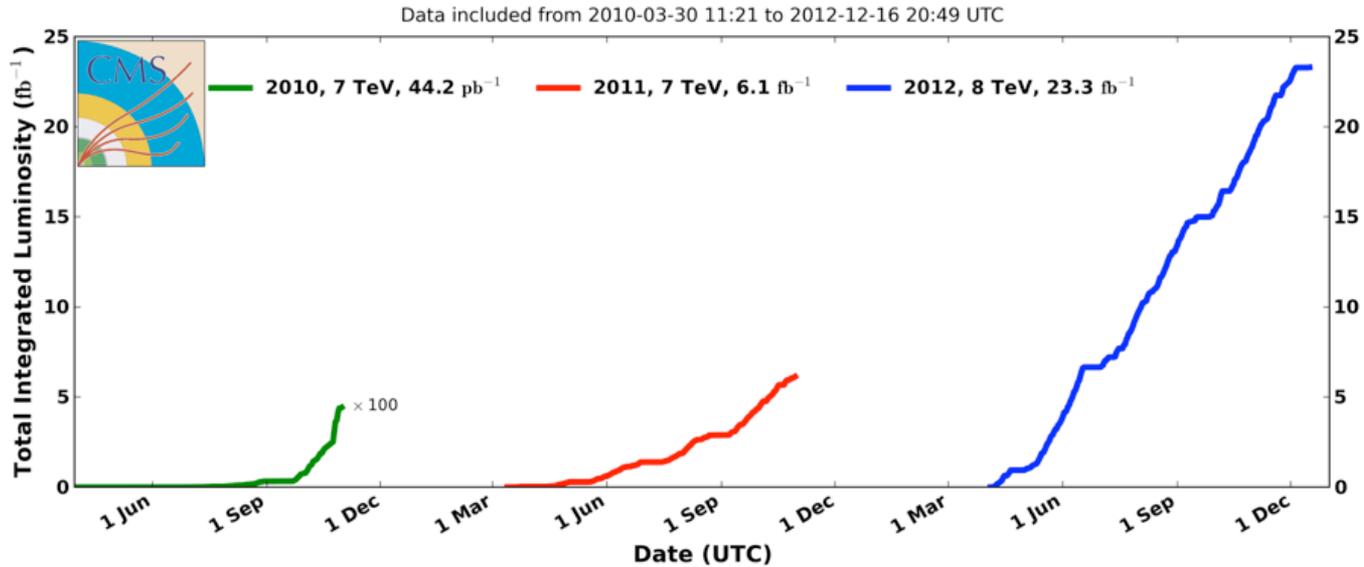
**Pixels & Tracker**  
• Pixels (100x150 μm<sup>2</sup>)  
~ 1 m<sup>2</sup> ~66M ch  
• Si Strips (80-180 μm)  
~200 m<sup>2</sup> ~9.6M ch

**MUON BARREL**  
250 Drift Tubes (DT) and  
480 Resistive Plate Chambers (RPC)

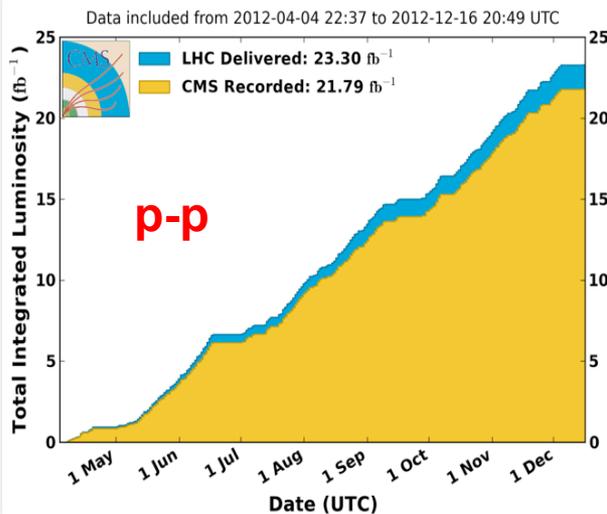


# Thanks LHC for Fantastic 3 years!

CMS Integrated Luminosity, pp

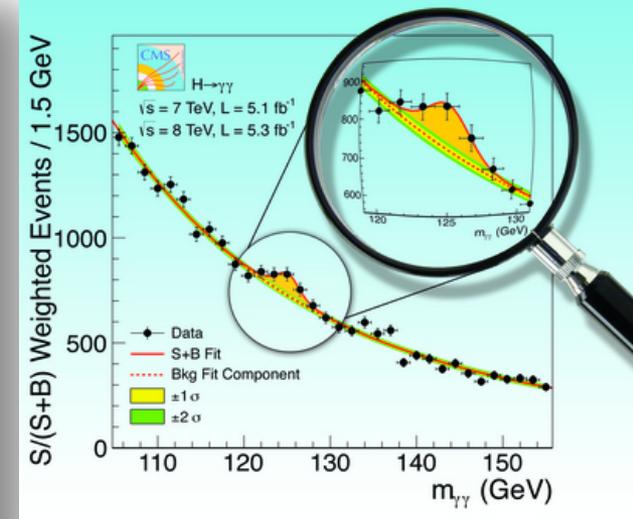
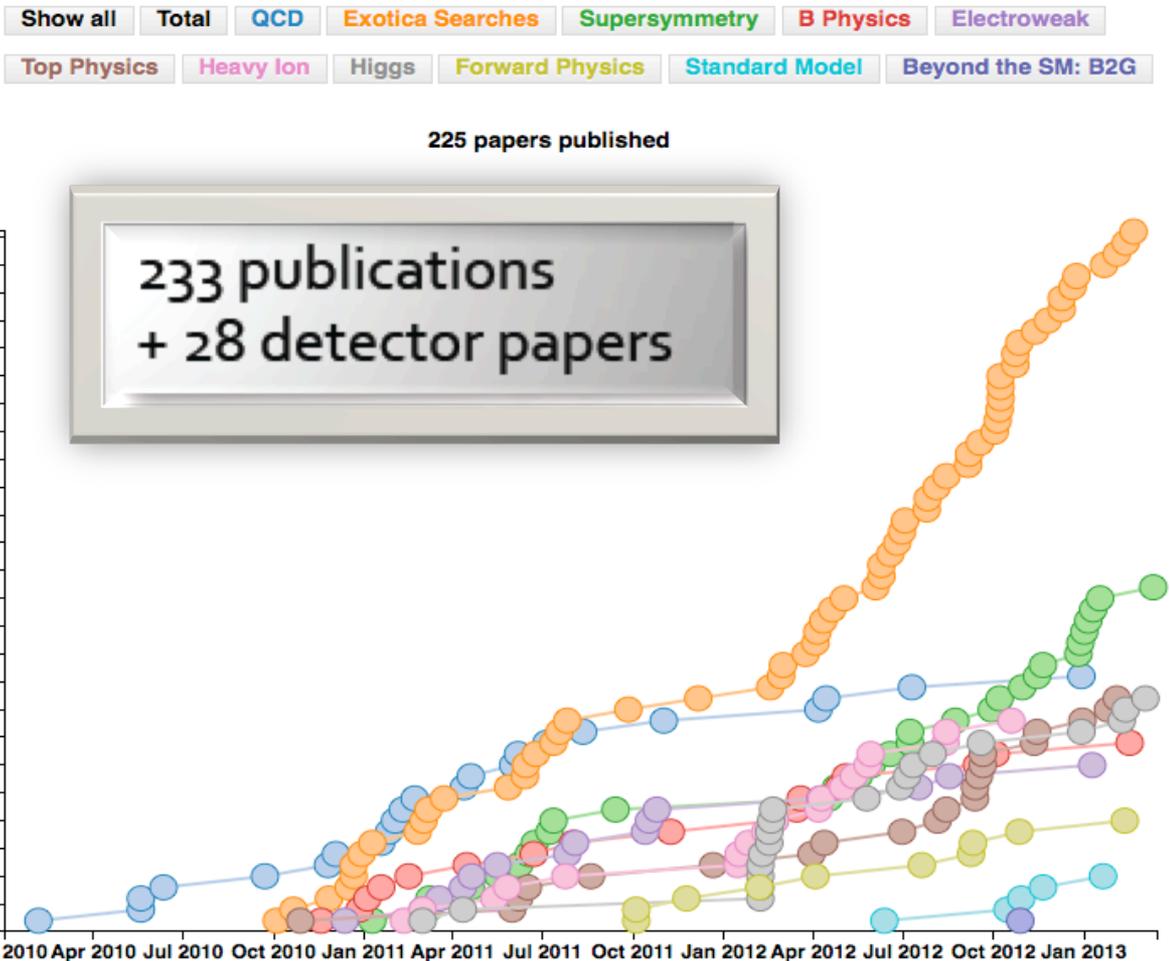


CMS Integrated Luminosity, pp, 2012,  $\sqrt{s} = 8$  TeV

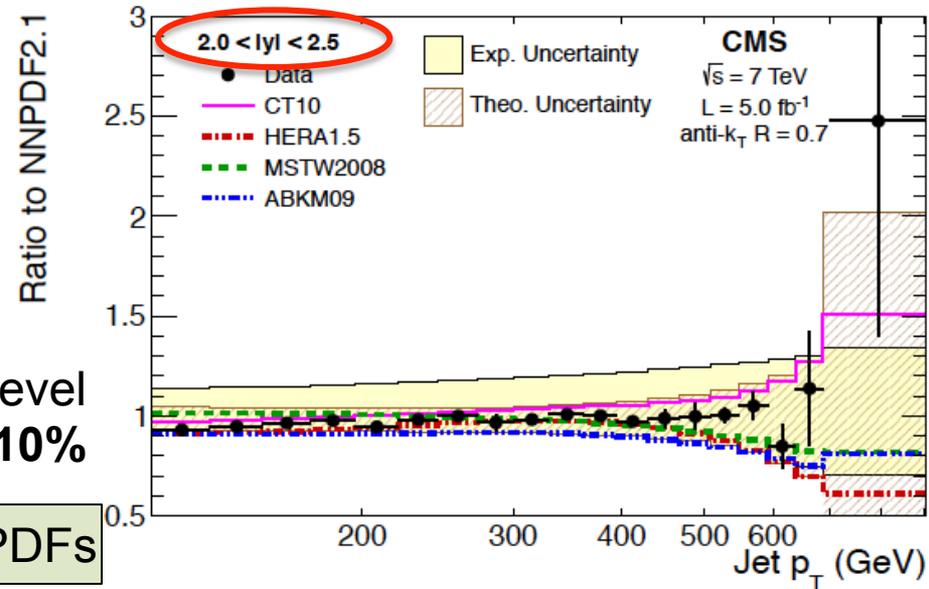
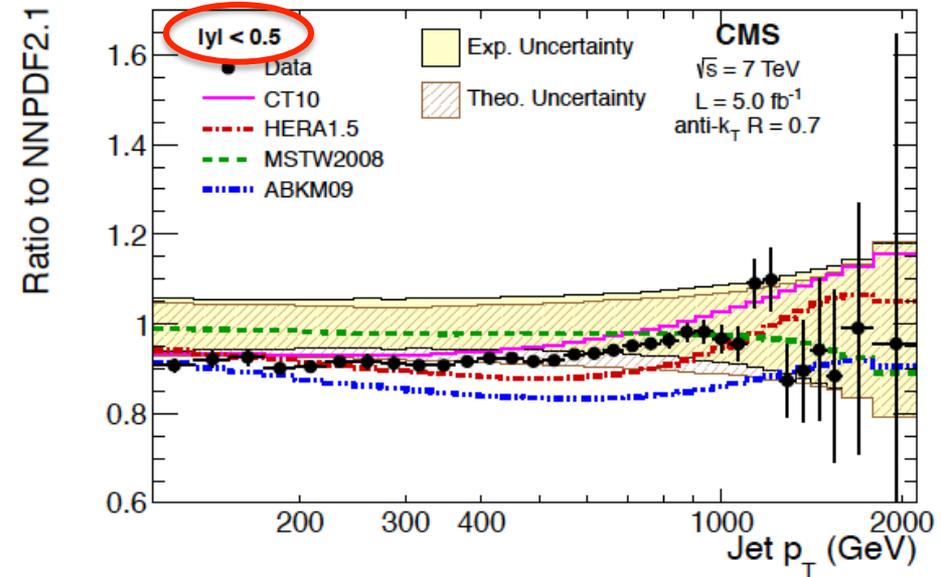
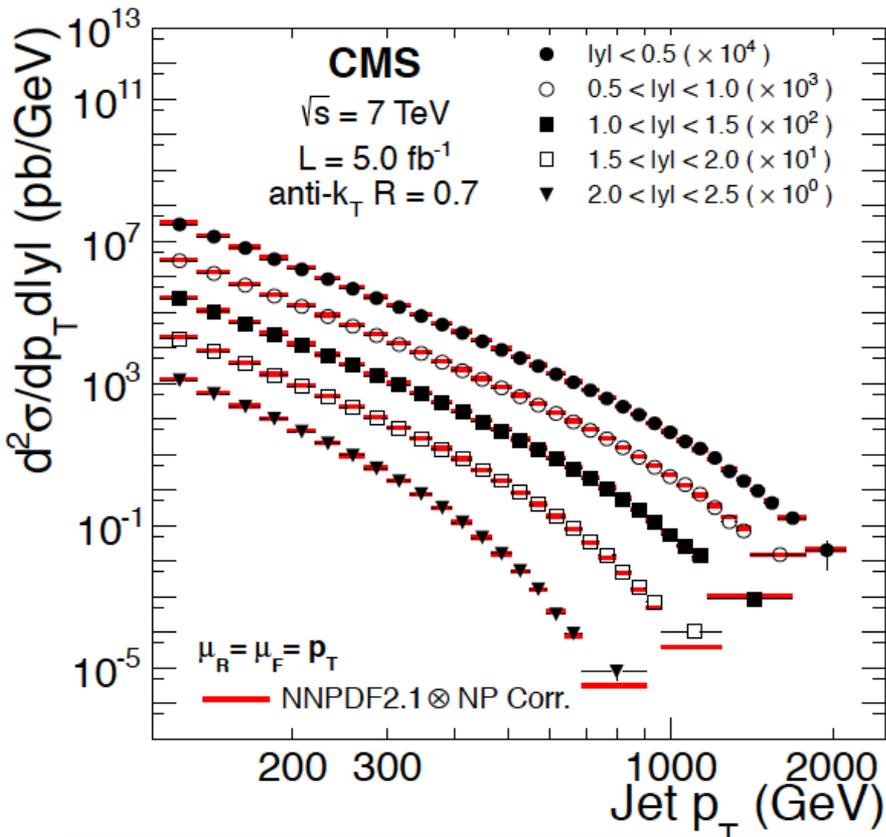


- Public physics results are available at:

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults>



# Probing QCD

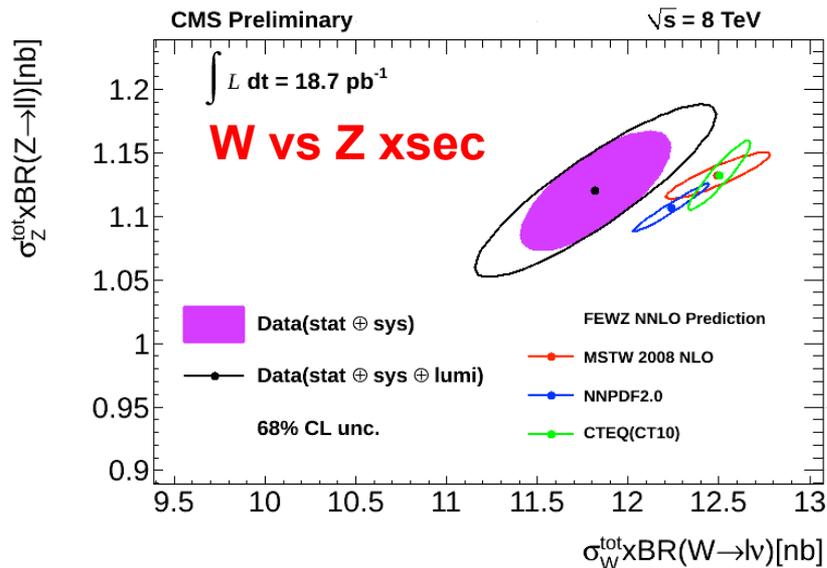
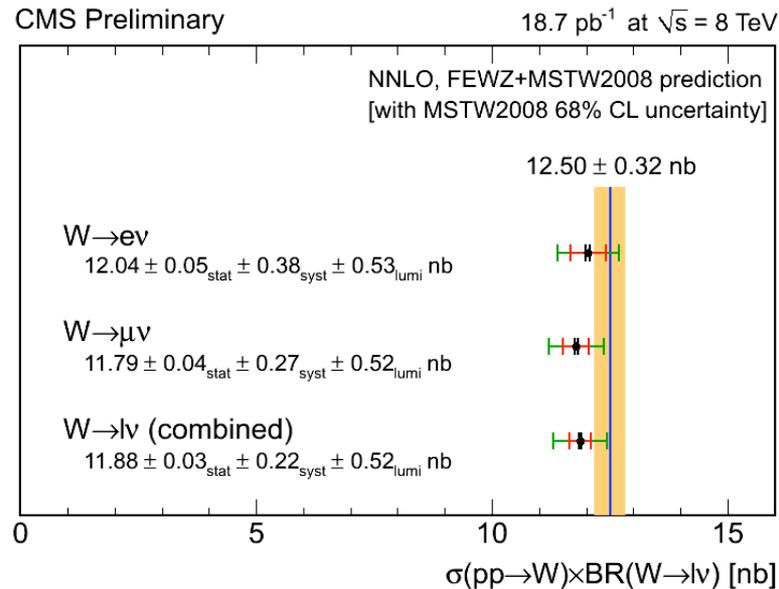
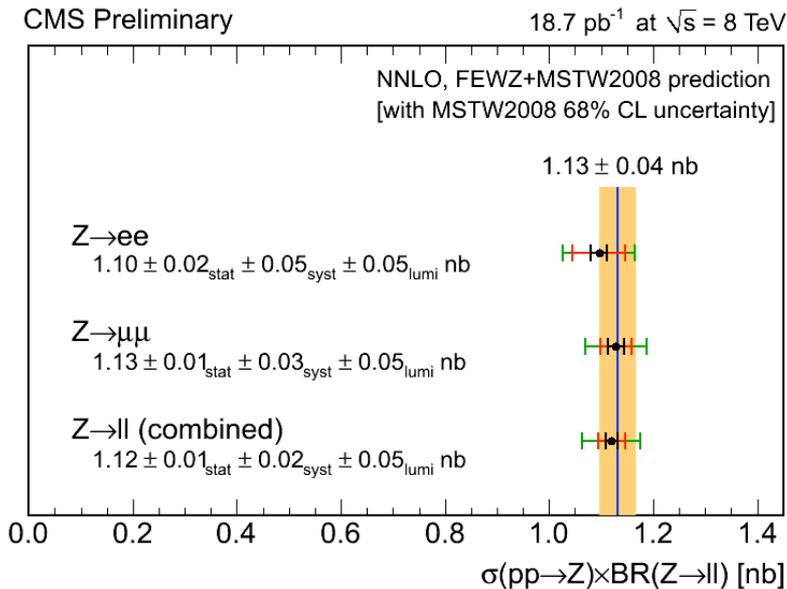


□ NLO QCD describes data over  
 ~ 9 orders of magnitude

- Jet energy scale uncertainties at the **1-2%** level
- For central  $|y|$ : exp. / theo. uncertainties, **5-10%**

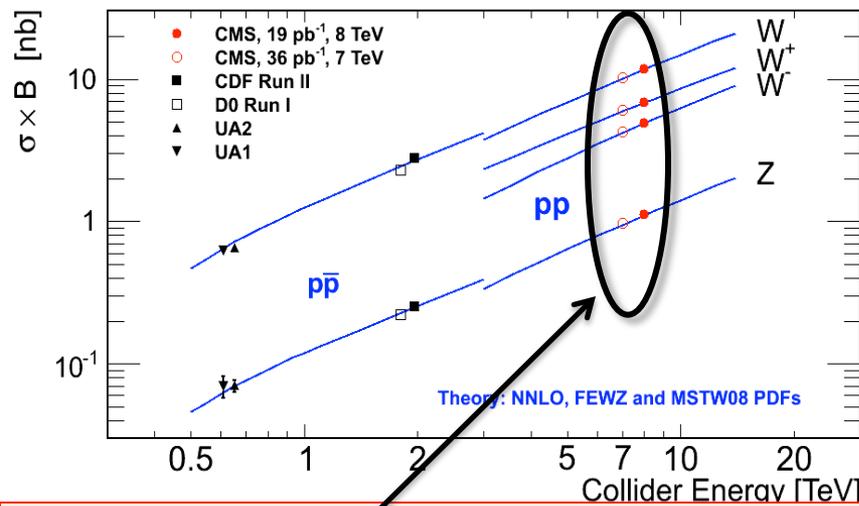
Inclusive jet: Important tool for constraining PDFs

# EWK Physics

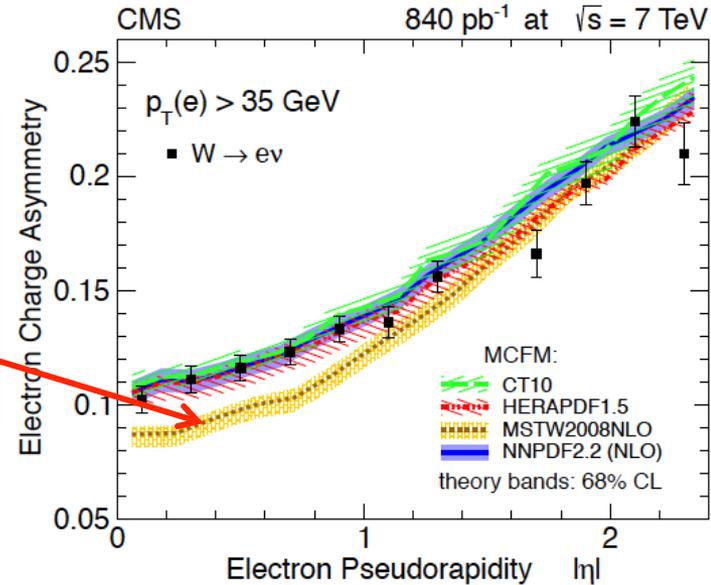


## Inclusive cross sections:

- At 7 TeV: experimental precision had reached the 1% level, especially for ratio-observables
- New 8 TeV results from dedicated low-pile up run early in 2012
- Total uncertainty: 2-5 % (4.4 % lumi, 2-3% acceptance, 1.1-1.7% exp)

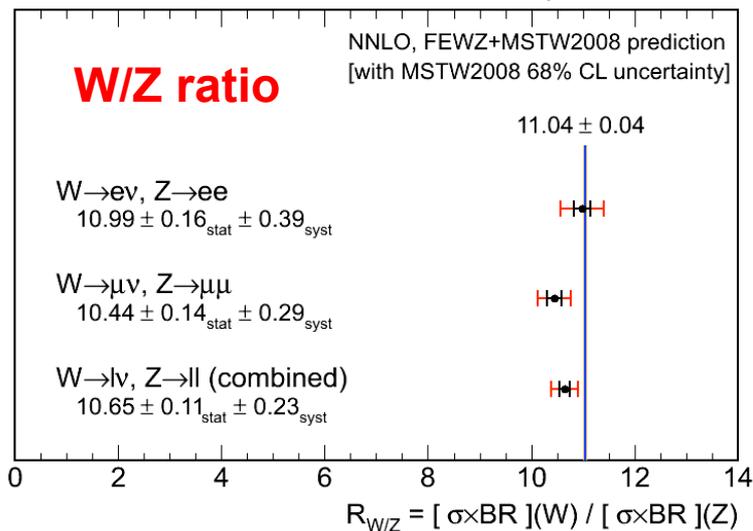


MSTW08 too low for the lepton asymmetry at 7 TeV

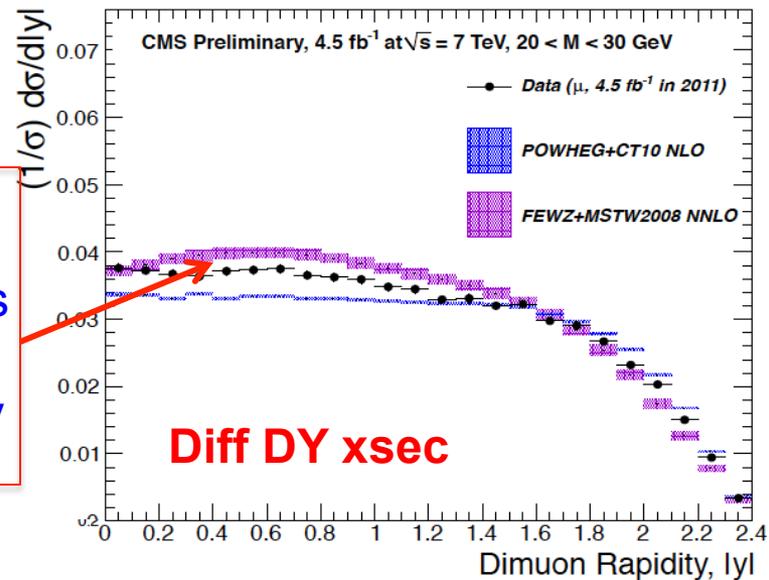


Good agreement with NNLO QCD, both @ 7, 8 TeV

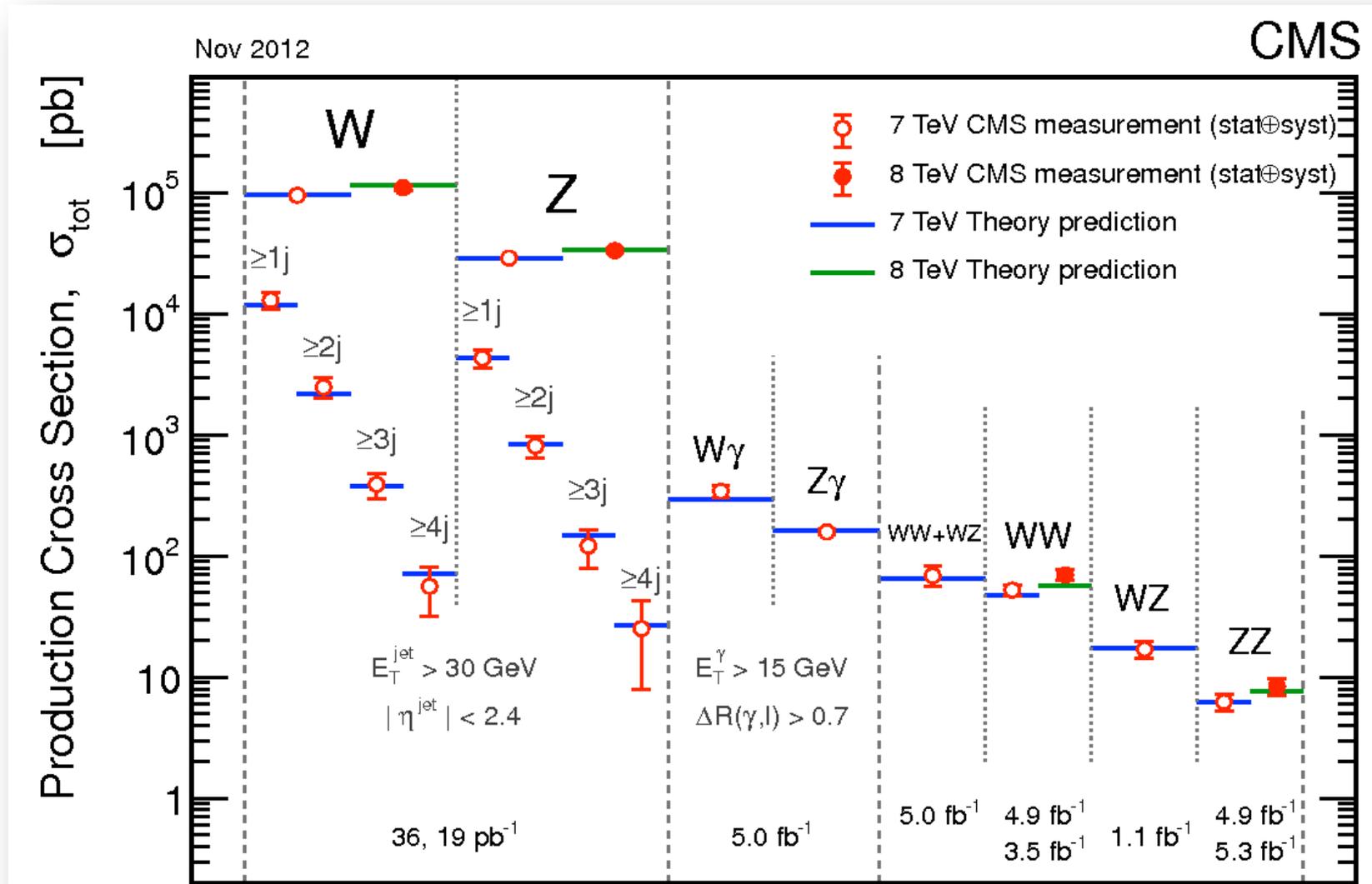
CMS Preliminary 18.7 pb<sup>-1</sup> at  $\sqrt{s} = 8$  TeV



Low-mass Drell-Yan gives interesting PDF sensitivity

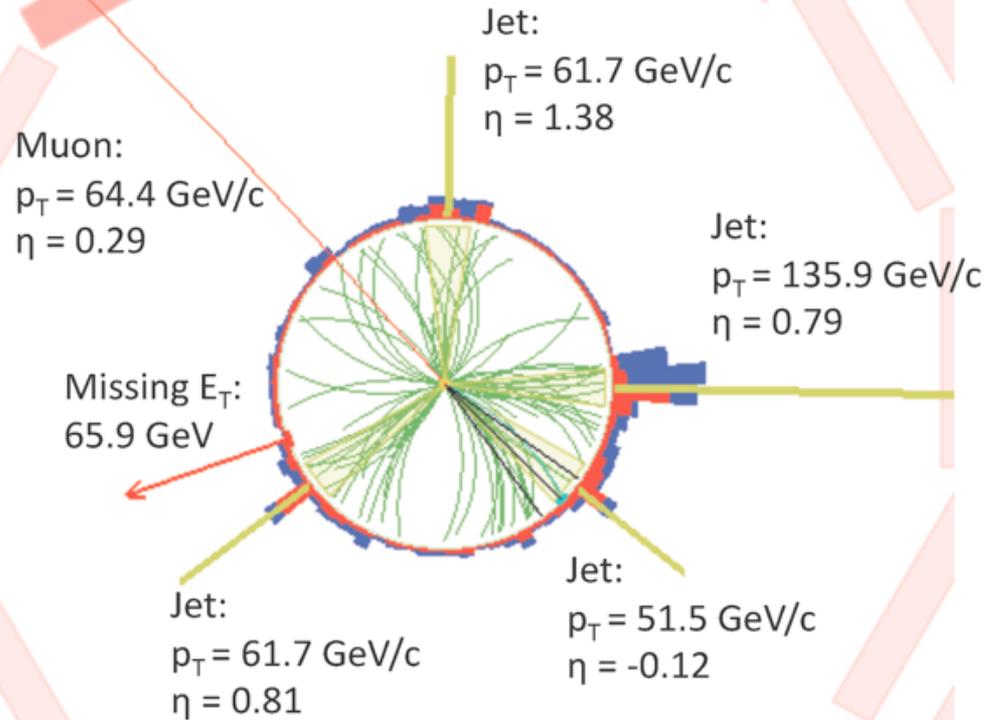


❖ W/Z ratio at 8 TeV: 1.5 σ difference with MSTW08



Overall, the SM works at 7 and 8 TeV centre-of-mass energy...

# Top physics

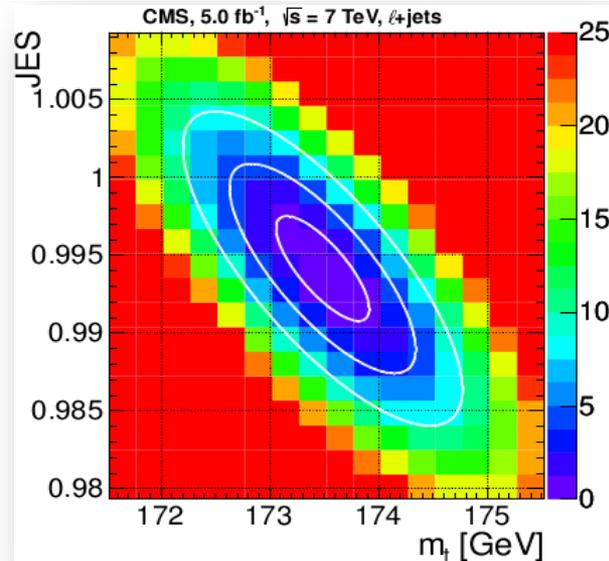


Run: 163480  
 Event: 81224410

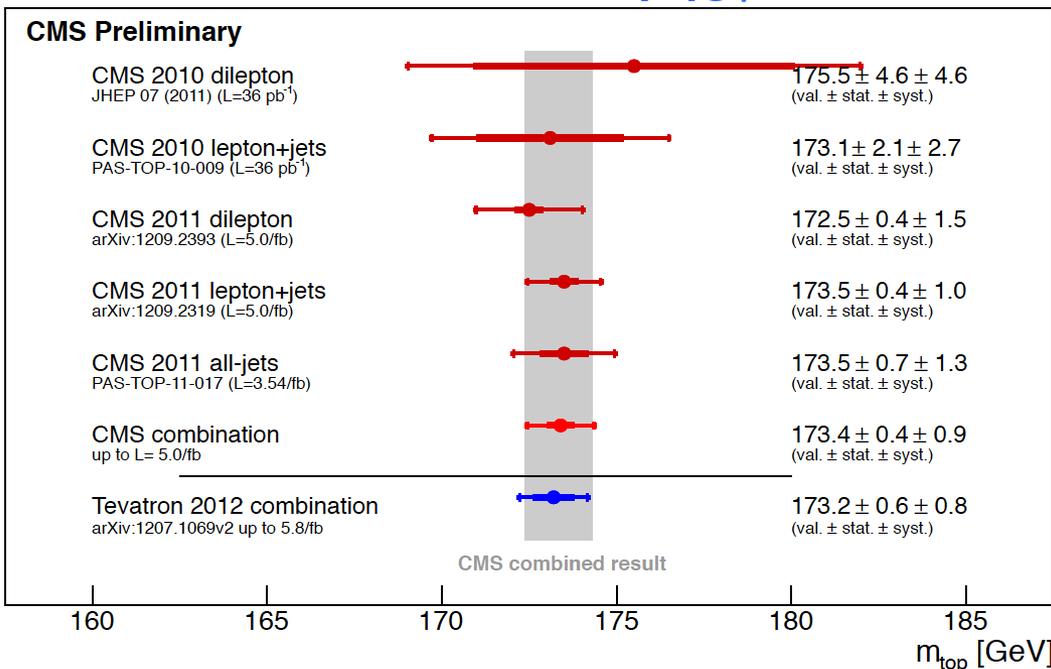
## ☐ Ideogram Method:

- Reconstruct  $m_{t\text{-fitted}}$  via a kinematic fit
- Event by event likelihood for fit results to be consistent with a given  $m_t$
- Based on the  $p(m_t | m_{t\text{-fitted}})$  given signal (different  $m_t$ ) and background, accounts all different combinations weighted by the likelihood of the fit

7 TeV



7 TeV



☐ Good consistency among all measurements

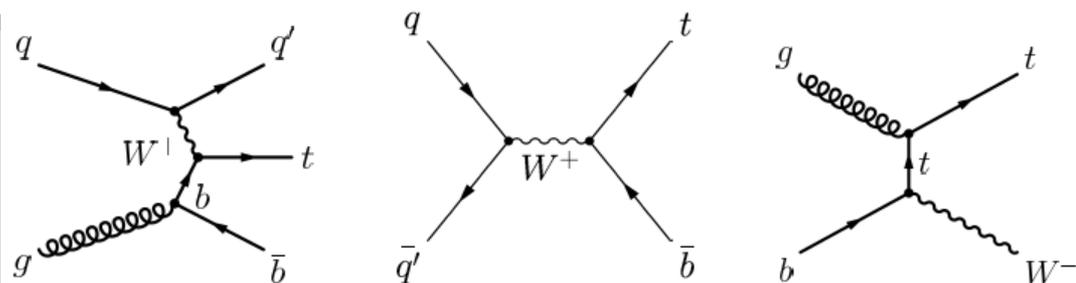
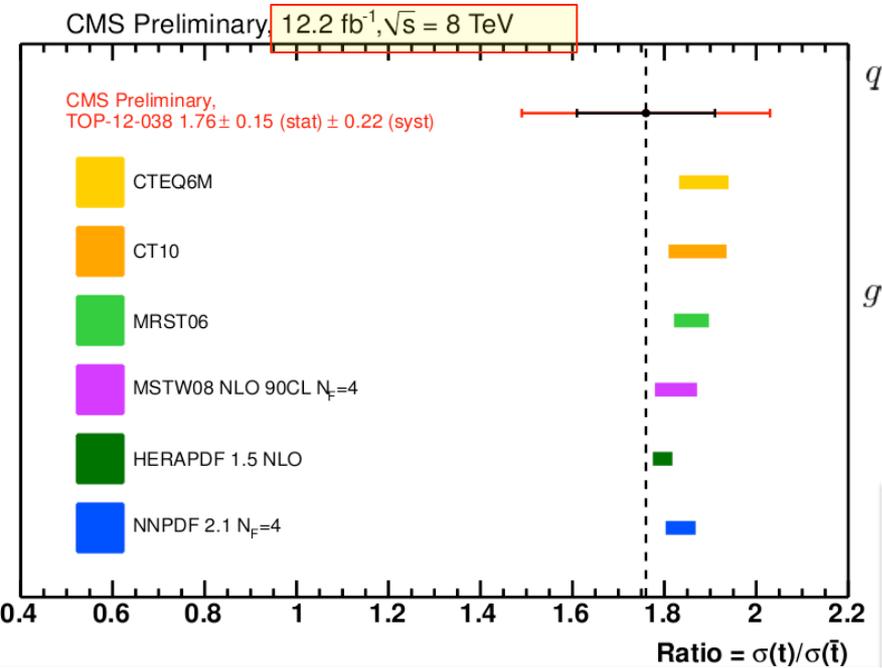
**Top mass (GeV):**

CMS (combination):

$173.36 \pm 0.38(\text{stat}) \pm 0.91(\text{syst})$

Tevatron (combination):

$173.18 \pm 0.56(\text{stat}) \pm 0.75(\text{syst})$



Cross section ratio  $t/\bar{t}$  in t-channel  
 $R_t = 1.76 \pm 0.14(\text{stat}) \pm 0.21(\text{syst})$

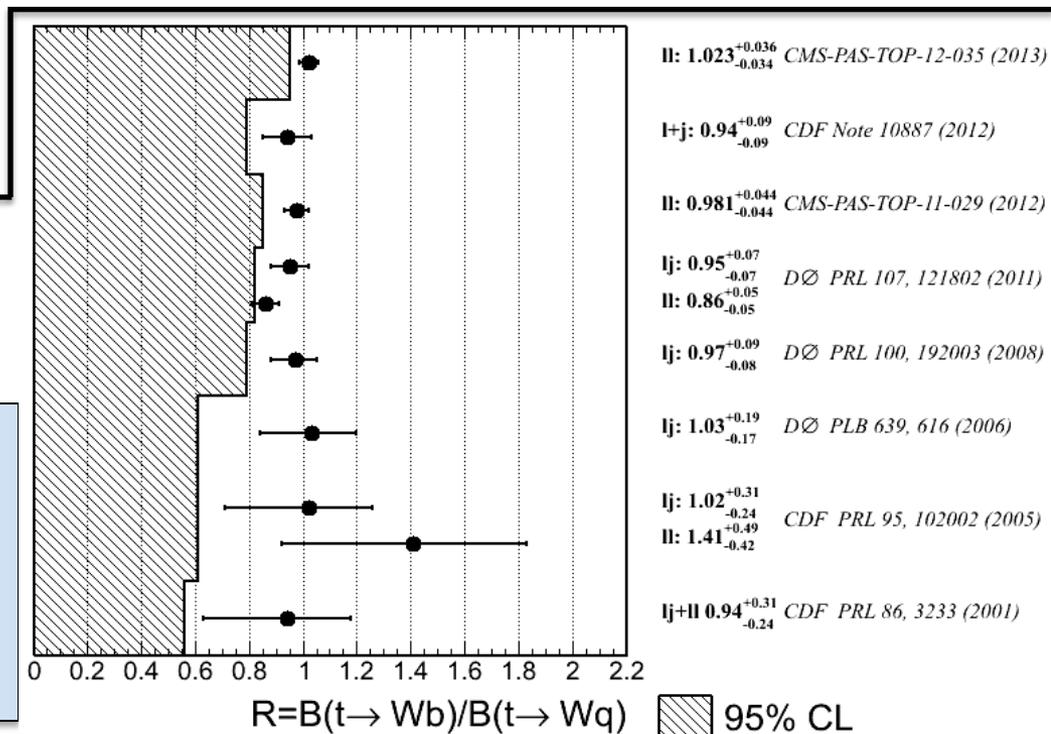
## Top decay:

$$R = \text{BR}(t \rightarrow Wb) / \text{BR}(t \rightarrow Wq)$$

$$= 1.023^{+0.036}_{-0.034}$$

Good agreement with SM

**World most precise measurement**



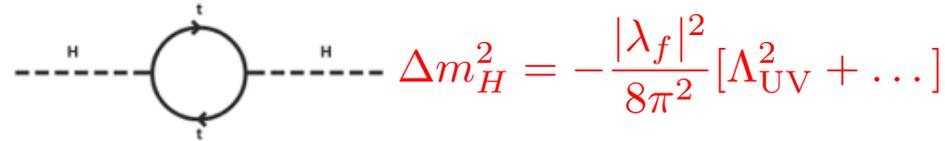
# Beyond Standard Model (BSM) Physics

□ What, if anything, makes the Higgs mass light?

• QFT:  $m_H^2 = m_H^2{}^{tree} + \Delta m_H^2{}^{top} + \Delta m_H^2{}^{W,Z} + \Delta m_H^2{}^{self} \sim \mathcal{O}(125)\text{GeV}$

• Corrections diverge quadratically  $\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} [\Lambda_{UV}^2 + \dots]$

• Either we live in a fine-tuned Universe or QFT is wrong, or there must be some new physics to take care of divergences



□ 3 general theoretical solutions:

(1) **Supersymmetry - SUSY:**

• Extra “svirtual” contributions stabilize Higgs potential.

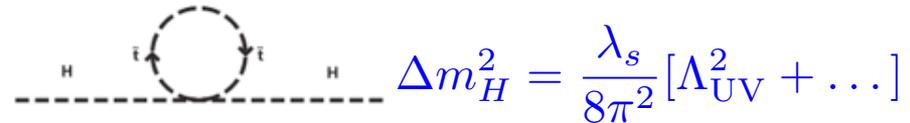
(2) **Higgs not elementary** (Goldstone boson of new gauge group):

• Technicolor, composite-Higgs, ..., (little-Higgs), ...

(3) **Quantum gravity** sets in at  $\sim \text{TeV}$ :

• Effects from hidden dims (0.1 mm to 10<sup>-19</sup> m). → KK-towers, radion, mini-BH, ...

➤ **All solutions imply new particles at TeV scale !**



- ❑ Light stops, sbottoms: final states include multiple jets + leptons + MET
- ❑ (b)jets + MET ☑ Use 176 mutual exclusive categories

### Event sample legend

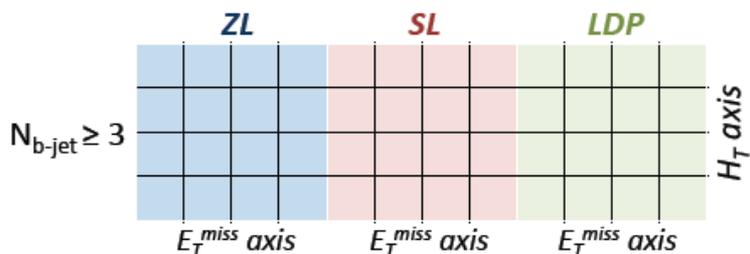
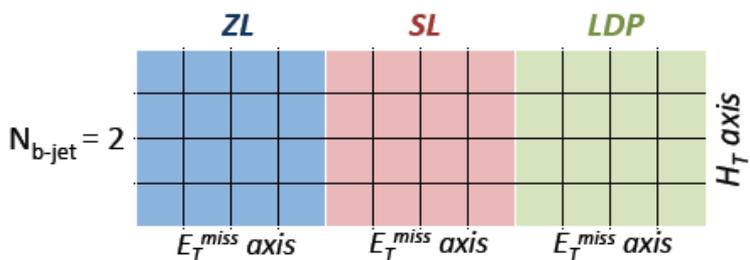
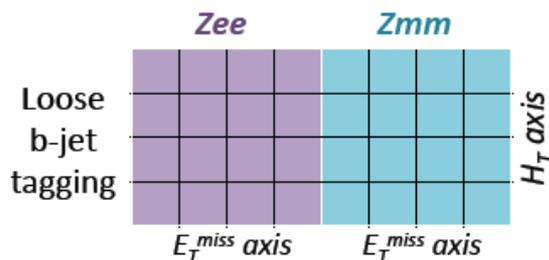
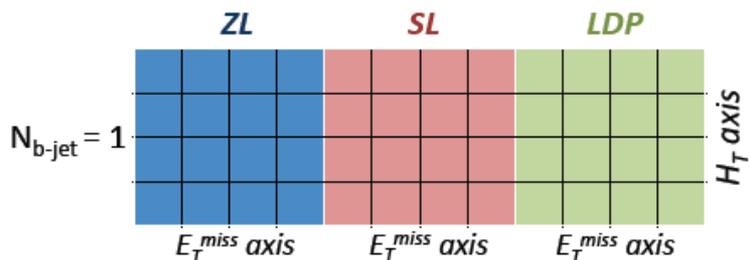
**ZL** = Zero Lepton;  
signal sample

**SL** = Single Lepton;  
top & W+jets control  
sample

**LDP** = low  $\Delta\hat{\phi}_{\min}$ ;  
QCD control  
sample

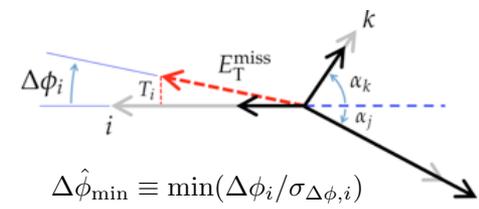
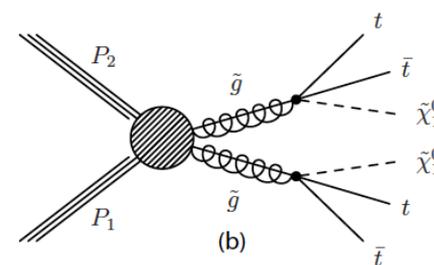
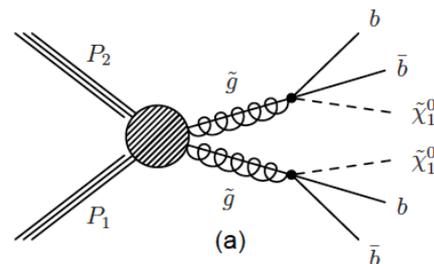
**Zee** =  $Z \rightarrow e^+e^-$ ;  
Z to  $\nu\bar{\nu}$  control  
sample

**Zmm** =  $Z \rightarrow \mu^+\mu^-$ ;  
Z to  $\nu\bar{\nu}$  control  
sample



Bin	$H_T$ (GeV)	$E_T^{\text{miss}}$ (GeV)
1	400 – 500 (HT1)	125 – 150 (MET1)
2	500 – 800 (HT2)	150 – 250 (MET2)
3	800 – 1000 (HT3)	250 – 350 (MET3)
4	> 1000 (HT4)	> 350 (MET4)

gluino mediated bottom and top-squark production:



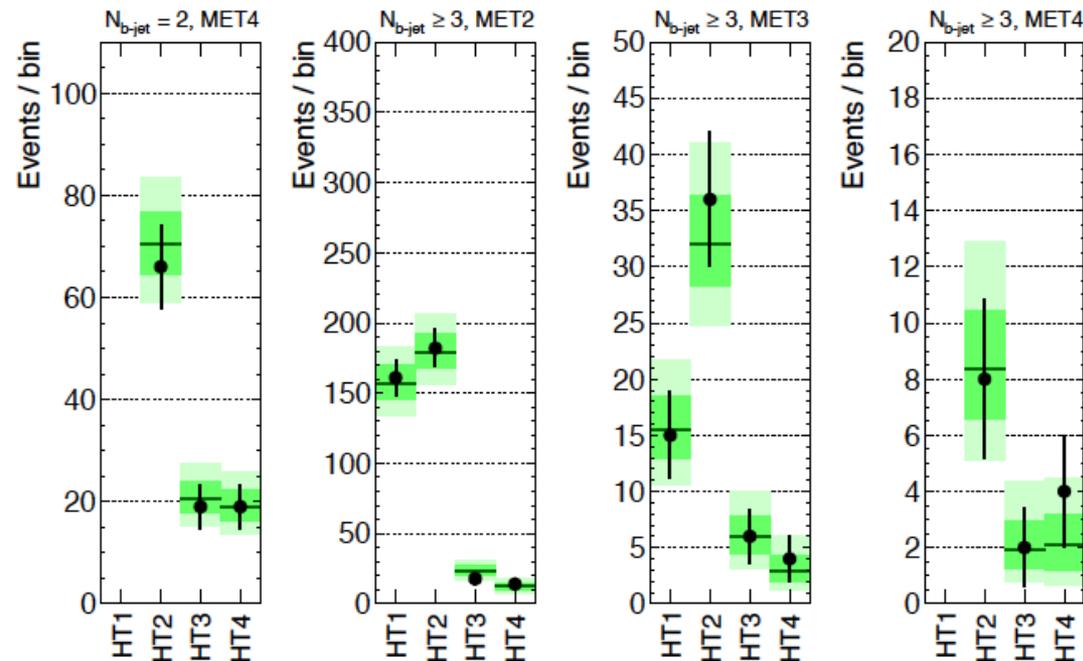
$$\Delta\hat{\phi}_{\min} \equiv \min(\Delta\phi_i/\sigma_{\Delta\phi,i})$$

$$\sigma_{\Delta\phi,i} = \arcsin(\sigma_{T_i}/\text{MET})$$

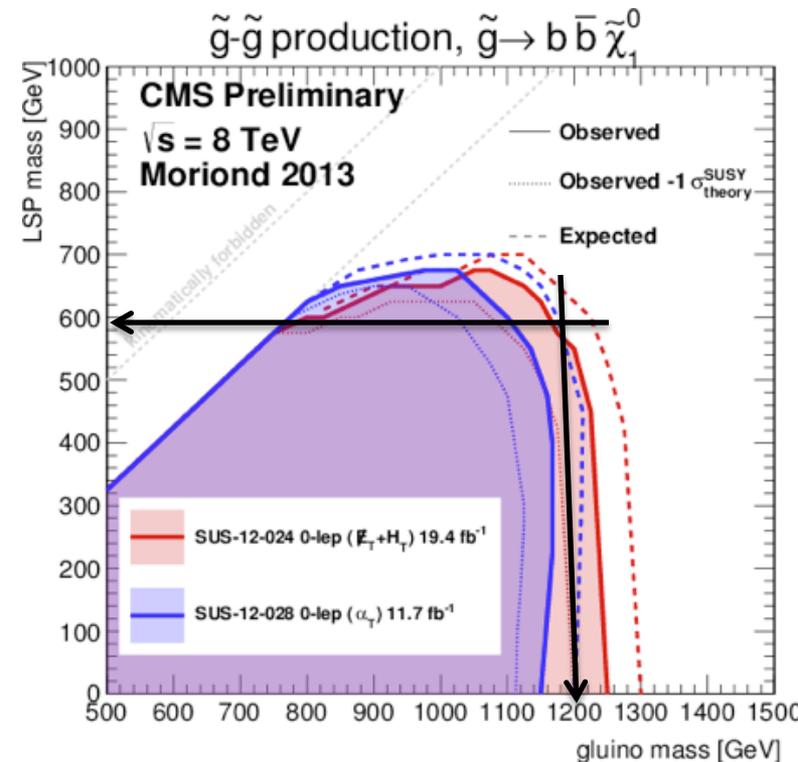
- Use global fit to extract contributions from different backgrounds and compare predictions to data in bins most sensitive to signal

CMS Preliminary,  $L_{\text{int}} = 19.4 \text{ fb}^{-1}$ ,  $\sqrt{s} = 8 \text{ TeV}$

■ Full fit    ● Data

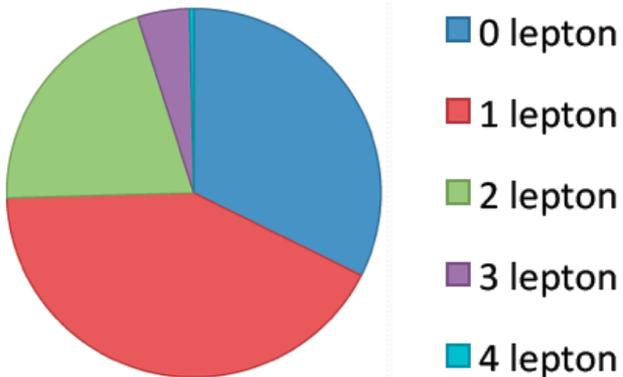
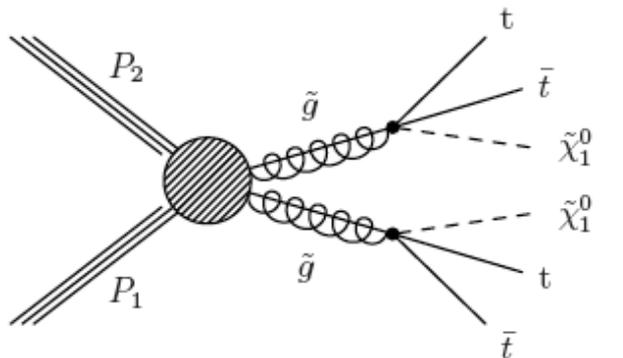


Prediction and observation



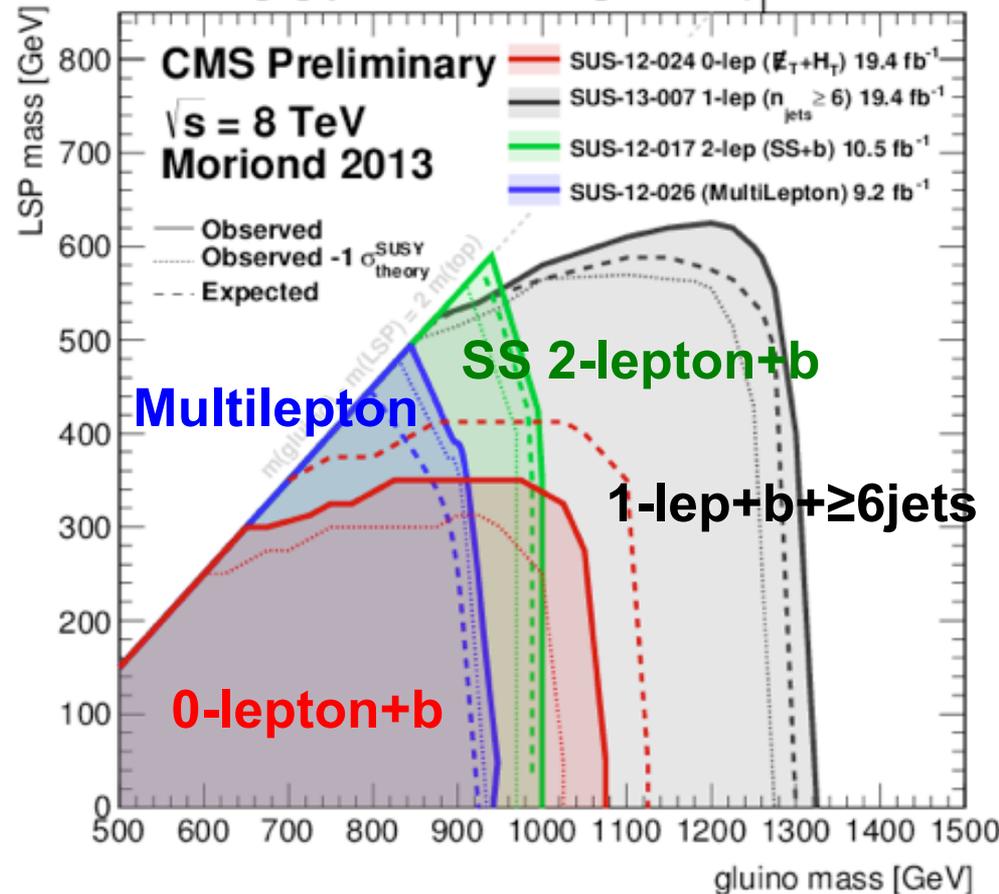
- No evidence for signal
- Excluded Gluino masses of **1.2 TeV** for LSP masses upto **600 GeV**

Two LSPs ( $\tilde{\chi}^0_1$ ) : Large MET



- Searches performed in the final states categorized into 0, 1, SS/OS 2-leptons, multileptons

$\tilde{g}\text{-}\tilde{g}$  production,  $\tilde{g} \rightarrow t \bar{t} \tilde{\chi}^0_1$

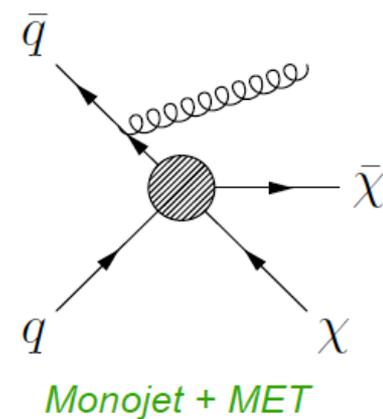
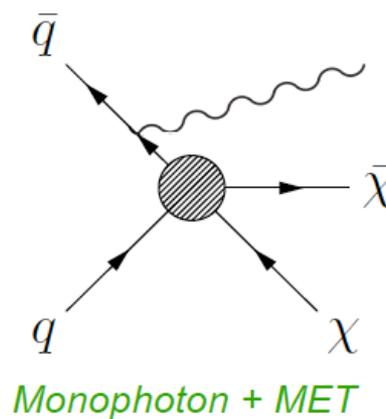
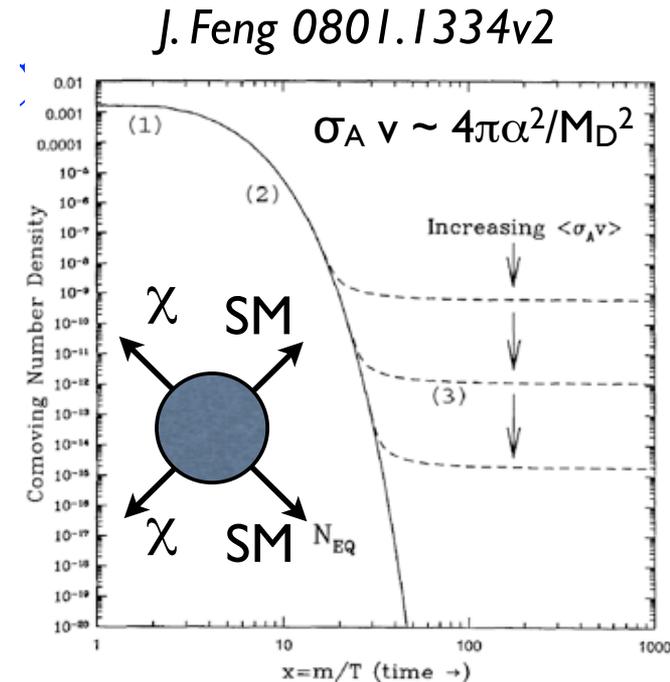


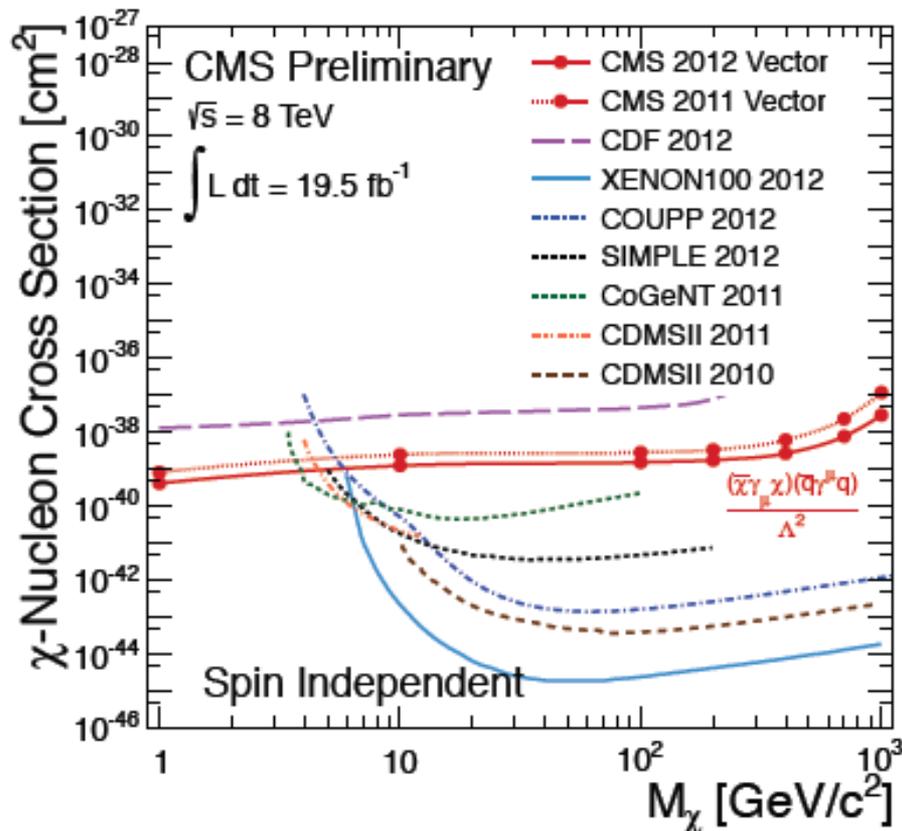
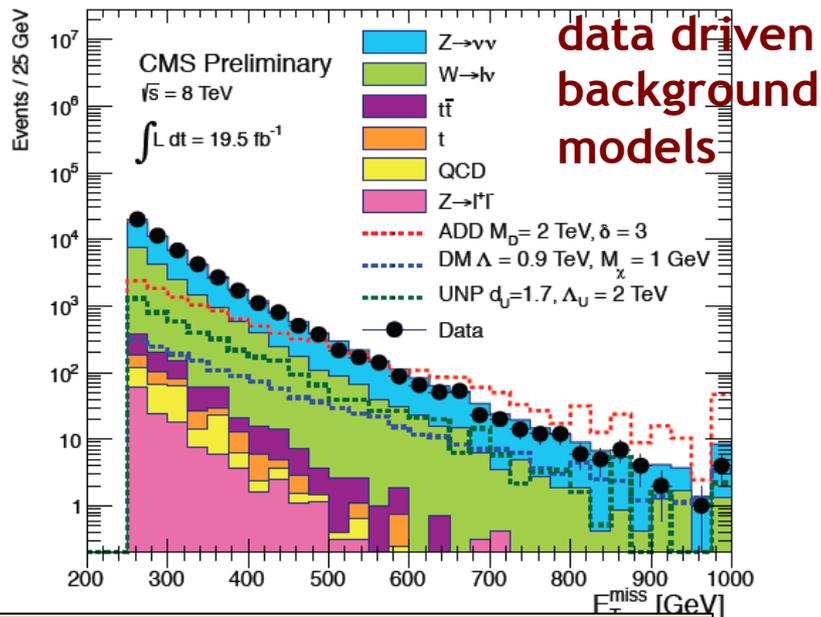
$m_{\text{LSP}} > 0.6 \text{ TeV}$   
 $m_{\text{gluino}} > 1.2 \text{ TeV}$

- ❑ Dark matter can be searched for LHC
  - Probably produced in pairs
  - WIMP “miracle”
    - $M_D \sim 10 - 1000 \text{ GeV}$  to get  $\Omega_{DM}$  right

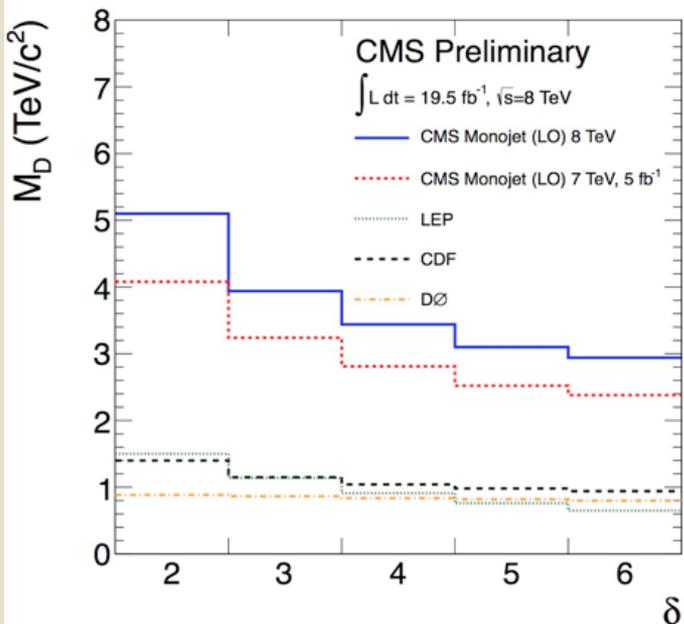
- ❑ If it is produced at LHC in pairs one must find the trigger
  - Initial state radiation:  $\gamma$ +MET and jet+MET

- ❑ Same final state can be used to search for a number of interesting phenomena
  - ADD Large Extra Dimensions
  - Unparticle models
  - Light Stop
  - Anomalous TGCs ( $\gamma$ +MET)





90% CL upper limits for Dark matter mass

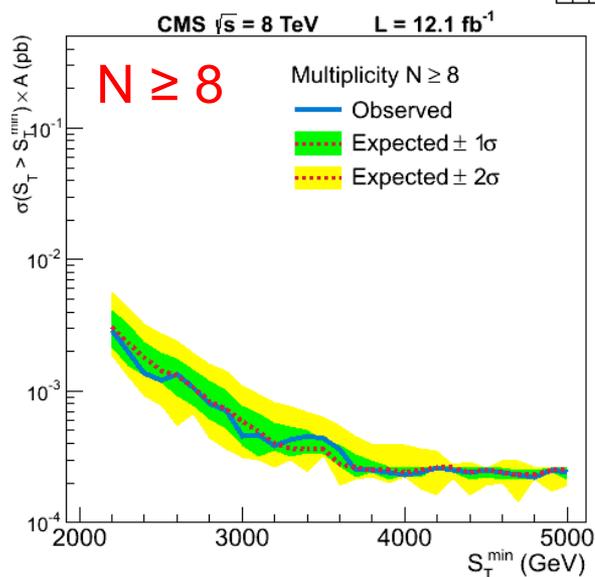
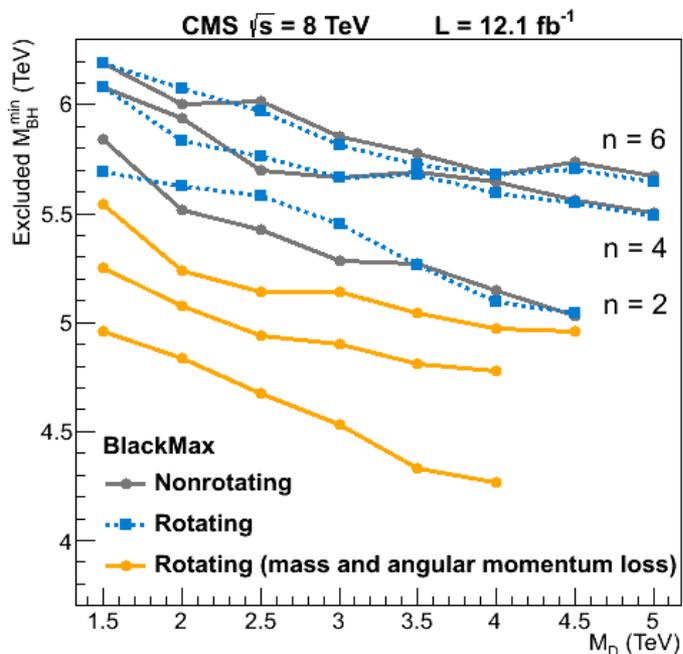
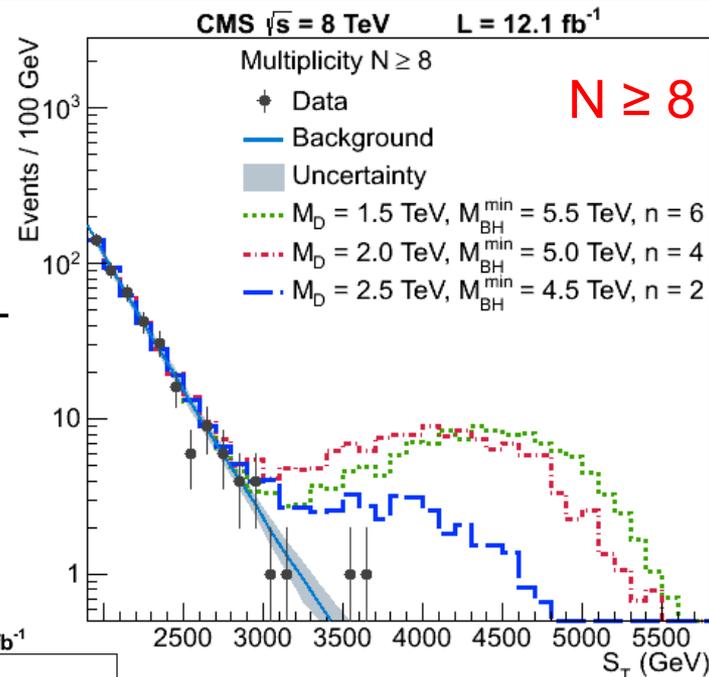


$$M_{Pl}^2 \approx M_D^{\delta+2} R^\delta$$

$M_D < 5 \text{ TeV}$  excluded for ADD  $n=2$

$M_D < 2.9 \text{ TeV}$  excluded for ADD  $n=6$

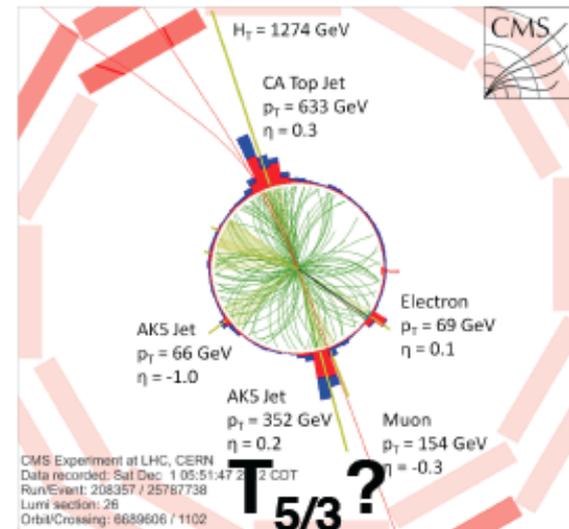
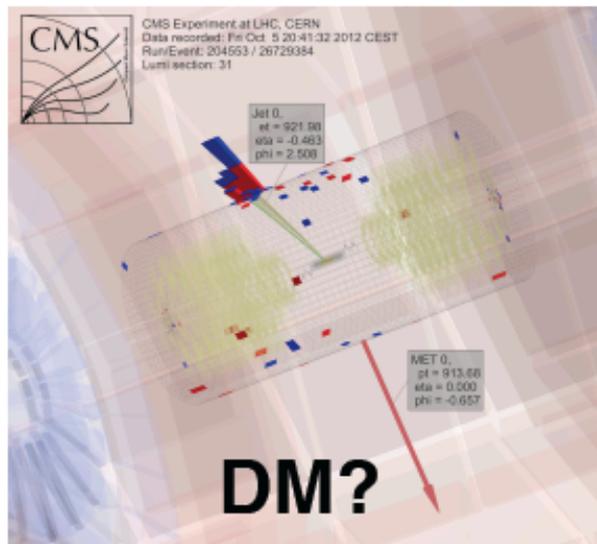
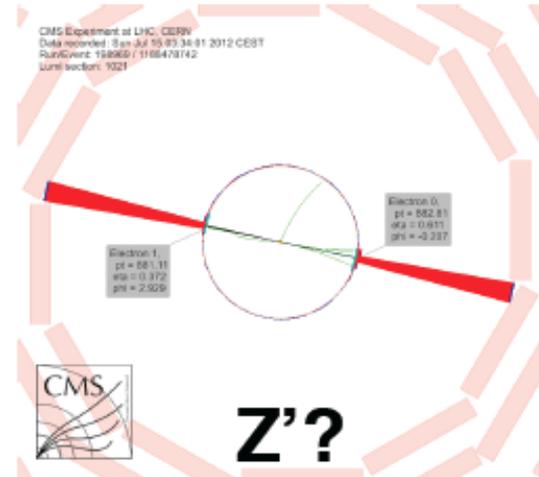
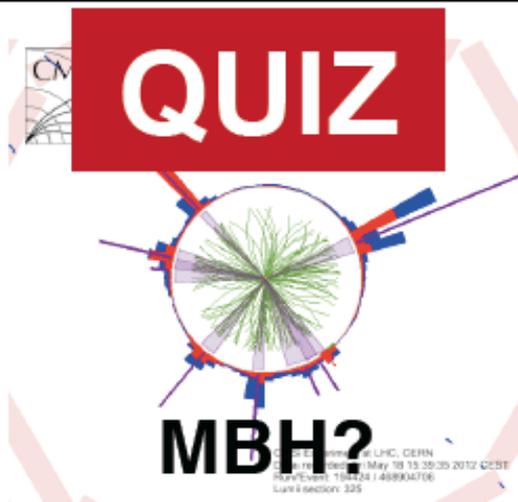
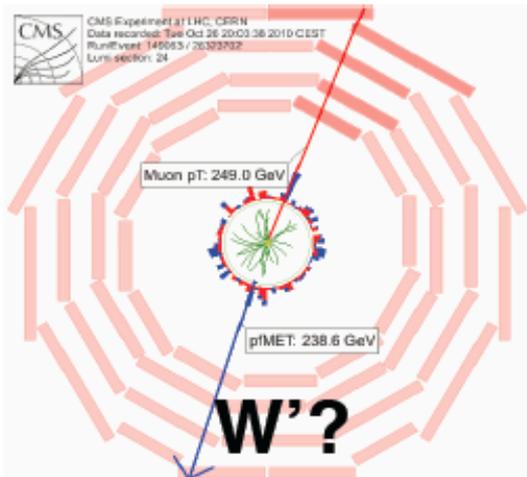
- Smoking gun signature of TeV scale quantum gravity
- BH produce large number of energetic objects
- **Search for deviation in  $ST$  distribution in bins of object multiplicity** ( $N$  at least  $> 2$ )
- $S_T$  = scalar sum of all objects with  $p_T > 50$  GeV+MET
- Use  $ST$  spectrum from  $N=2$  to predict QCD background at  $N \geq 3, 4, 5, 6, 7, 8, 9, 10$  where signal would be present



- No excess observed in data
- Set model independent upper limit on the minimum BH mass of 4.3 – 6.2 TeV



## Looking forward to see more of these events...



Slide Courtesy: S Lee



# Higgs Results

$$(\mathcal{D}_\mu \phi)^\dagger \mathcal{D}^\mu \phi - \mathcal{V}(\phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

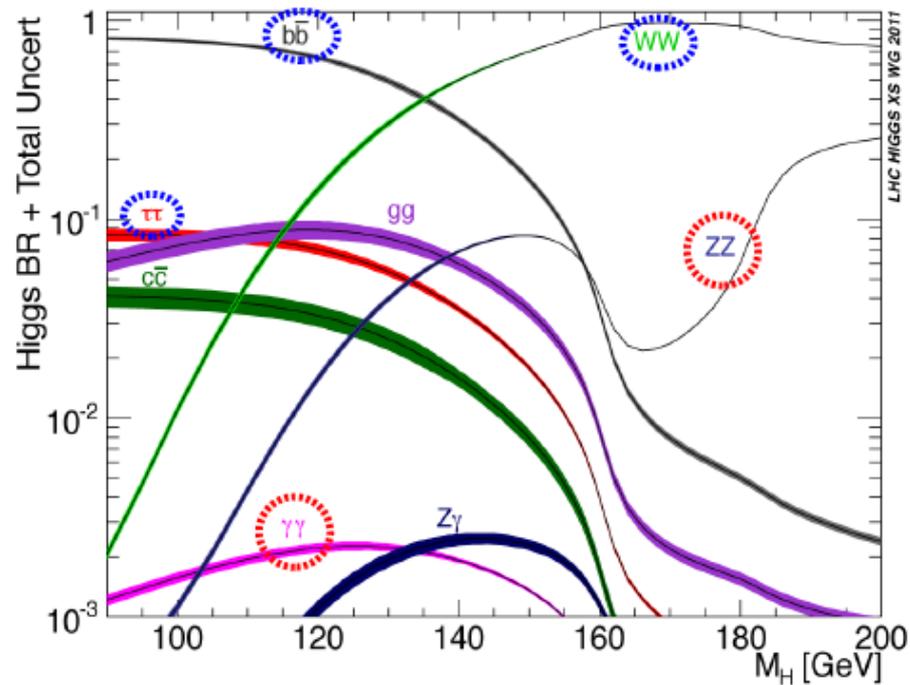
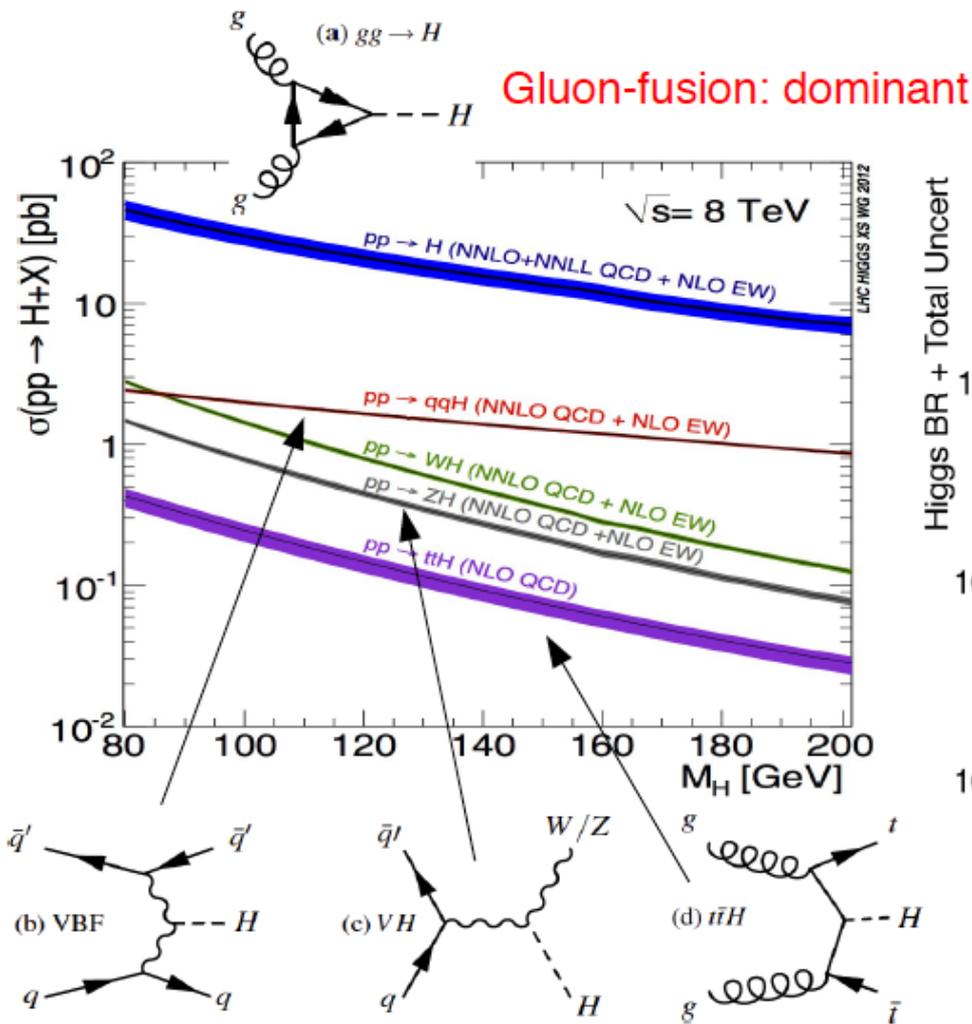
$$\mathcal{D}_\mu \phi = \partial_\mu \phi - i e A_\mu \phi$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\mathcal{V}(\phi) = \alpha \phi^\dagger \phi + \beta (\phi^\dagger \phi)^2$$

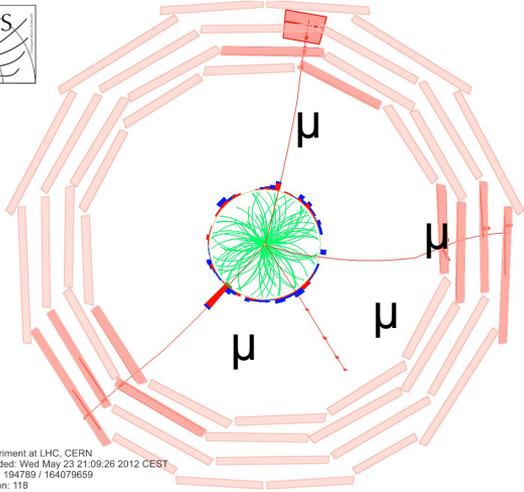
$$\alpha < 0, \quad \beta \geq 0$$



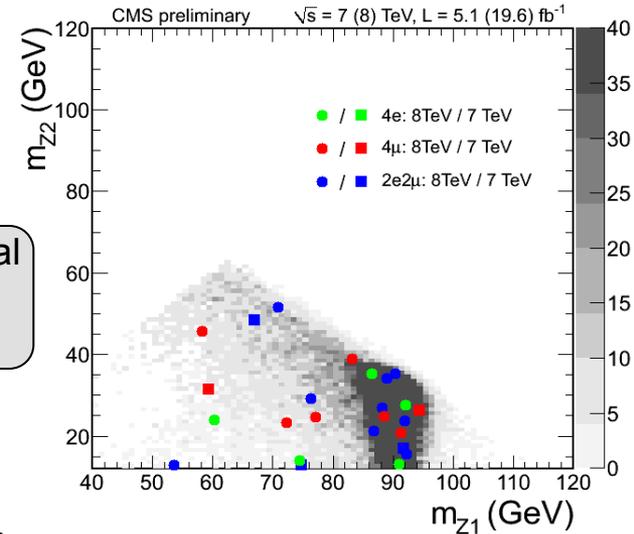
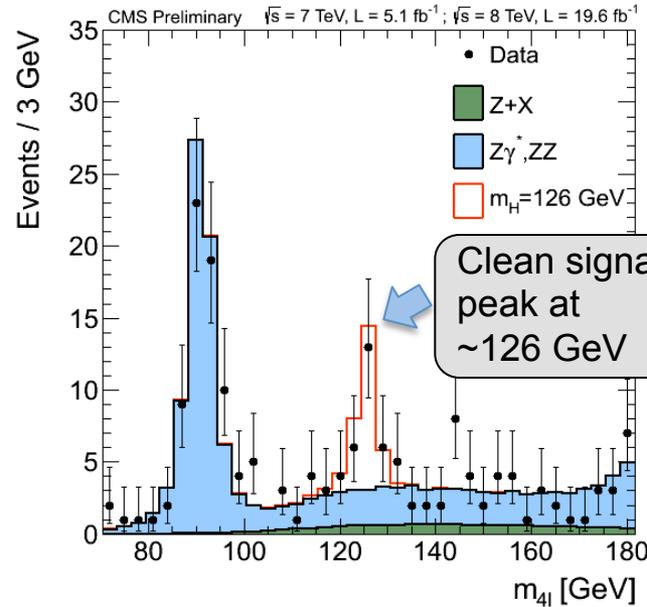


«Cleanest» channels:  $H \rightarrow \gamma$ 's, leptons  
 Large x-section channels:  $H \rightarrow WW, \tau\tau, bb$

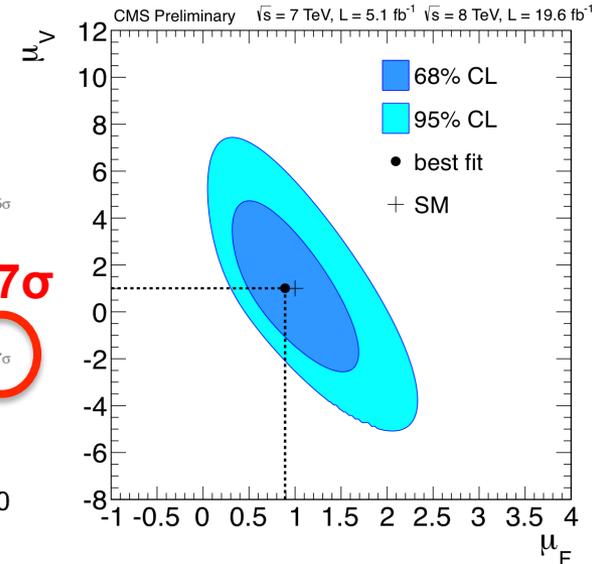
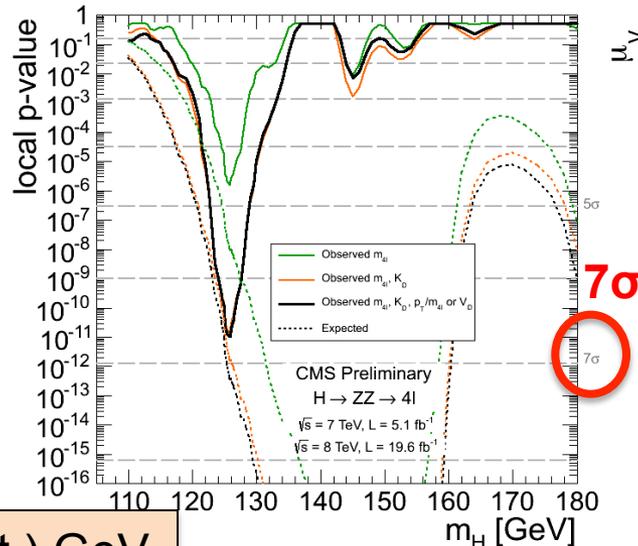
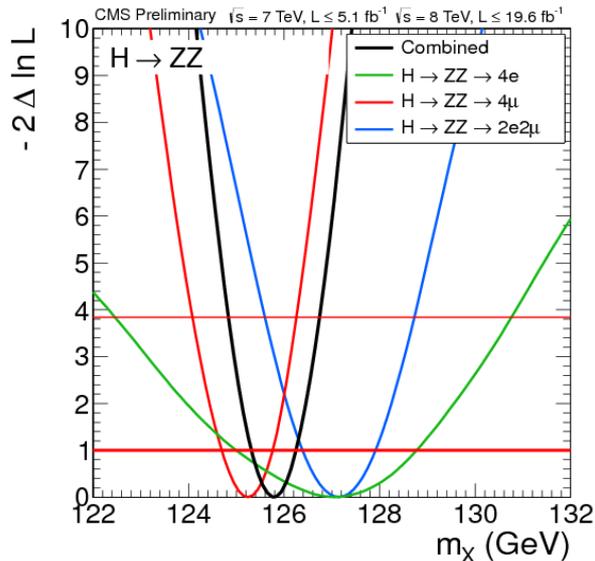
@ 125GeV	signature	S/B	Mass Resol.	N events in 20fb <sup>-1</sup>	Good For
<b>H → bb</b>	two b-jets, Z or W, bb inv. mass	low O(0.1)	10%	~10 <sup>5</sup> ~50 (sel)	couplings to fermions
<b>H → ττ</b>	had tau, leptons, MET	low O(0.1)	15%	~10 <sup>4</sup> ~40 (sel)	couplings to fermions
<b>H → WW</b>	two leptons with opposite charge MET	medium O(1)	-	~10 <sup>3</sup> ~120 (sel)	cross section, BR, couplings to V
<b>H → γγ</b>	two photons peak in inv. mass	low O(0.1)	2%	800 ~400 (sel)	H mass, couplings K <sub>V</sub> K <sub>F</sub> , discovery
<b>H → ZZ</b>	four leptons with right charge peaks in inv. mass (Z <sub>1</sub> and Higgs)	high >1	1-2%	40 ~12 (sel)	H mass, discovery



## Higgs Mass

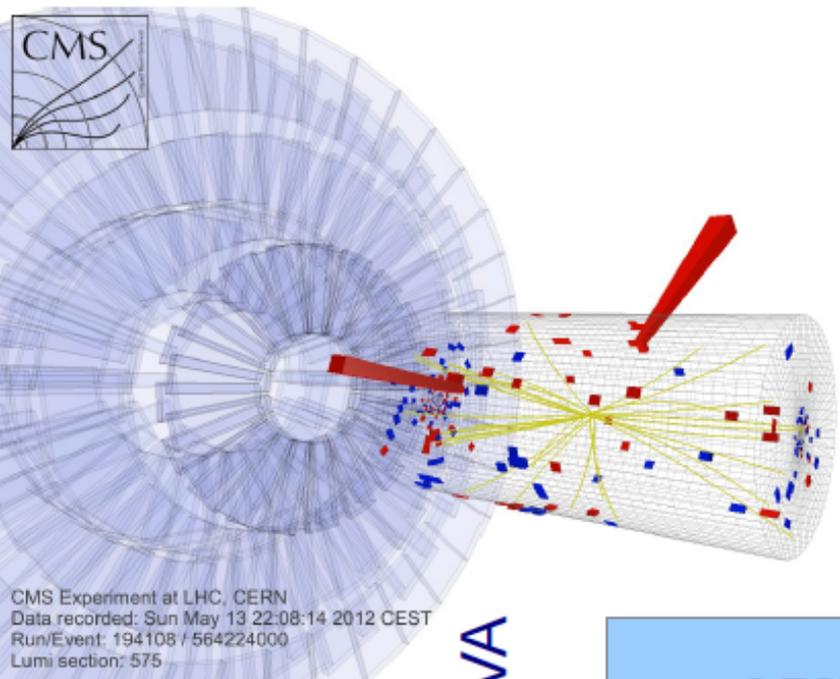


## Signal strength



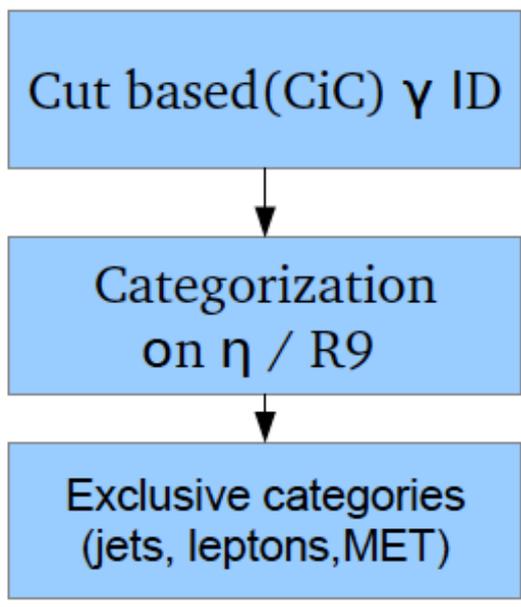
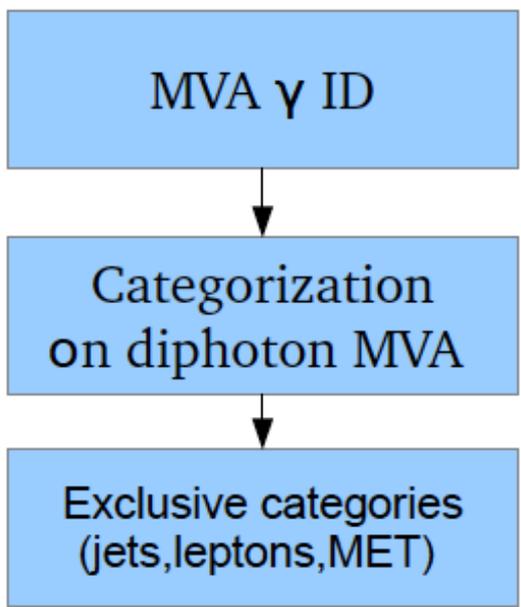
**m = 125.8 ± 0.5(stat.) ± 0.2(syst.) GeV**

- Two energetic isolated photons
- Very good mass resolution
- Backgrounds
  - Direct  $\gamma\gamma$  production
  - Fake photons
- Two independent analyses public with full data



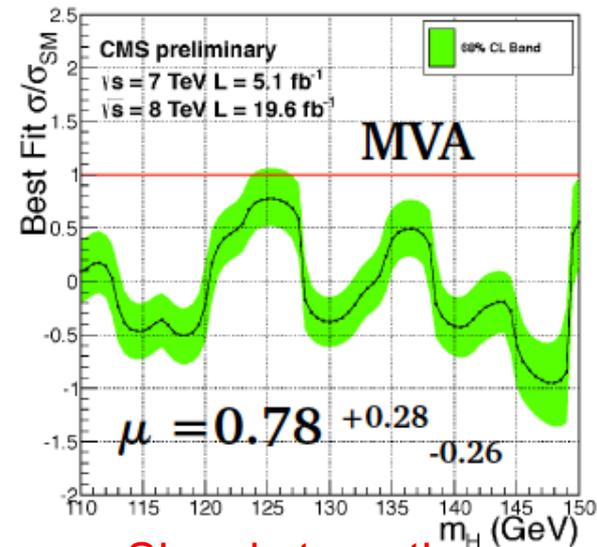
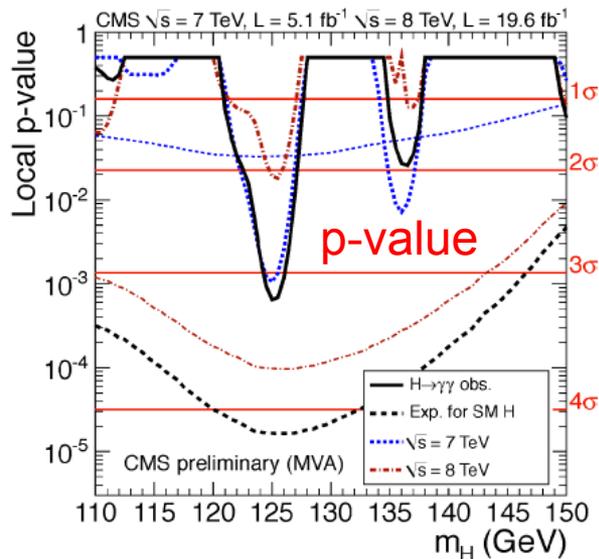
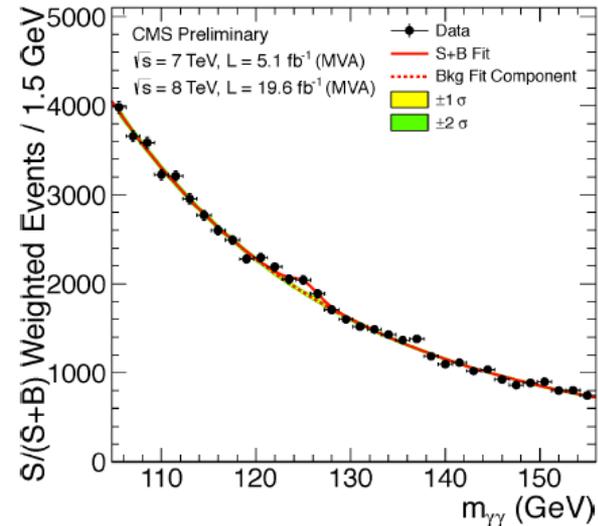
CMS Experiment at LHC, CERN  
 Data recorded: Sun May 13 22:08:14 2012 CEST  
 Run/Event: 194108 / 564224000  
 Lumi section: 575

Mass factorized MVA  
(main analysis)



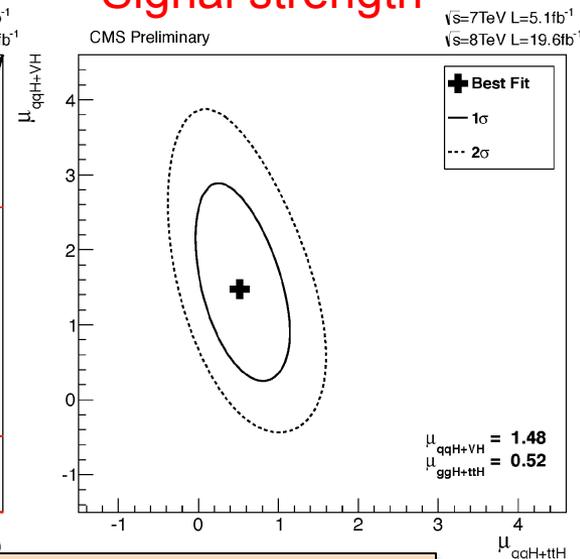
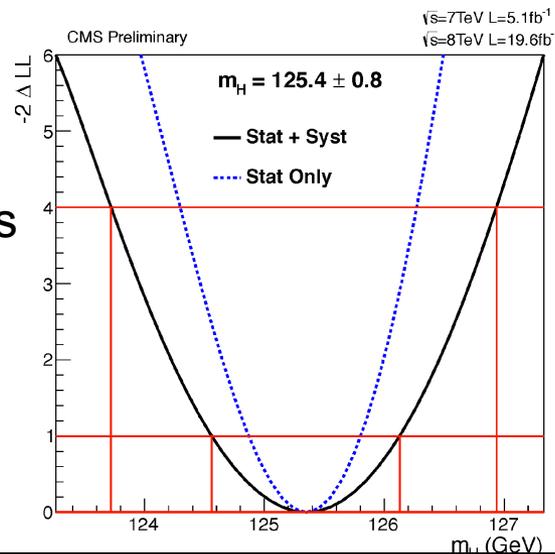
Cut based(CiC)

# H $\rightarrow$ $\gamma\gamma$



Peak visible @  $\sim 125 \text{ GeV}$   
 Expected 4.2  $\sigma$ , Observed 3.2  $\sigma$

- Difference between the analyses
- Due to fluctuations of the large background
- Signal strength compatibility estimated with Jackknife resampling within 1.5 $\sigma$  (for both 7+8 TeV)

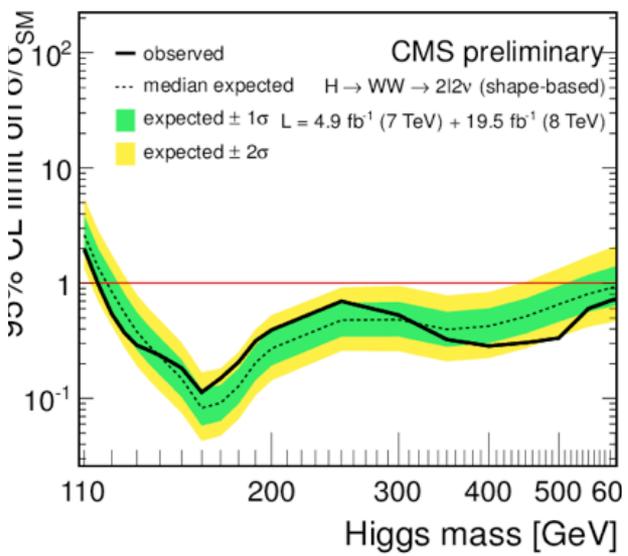
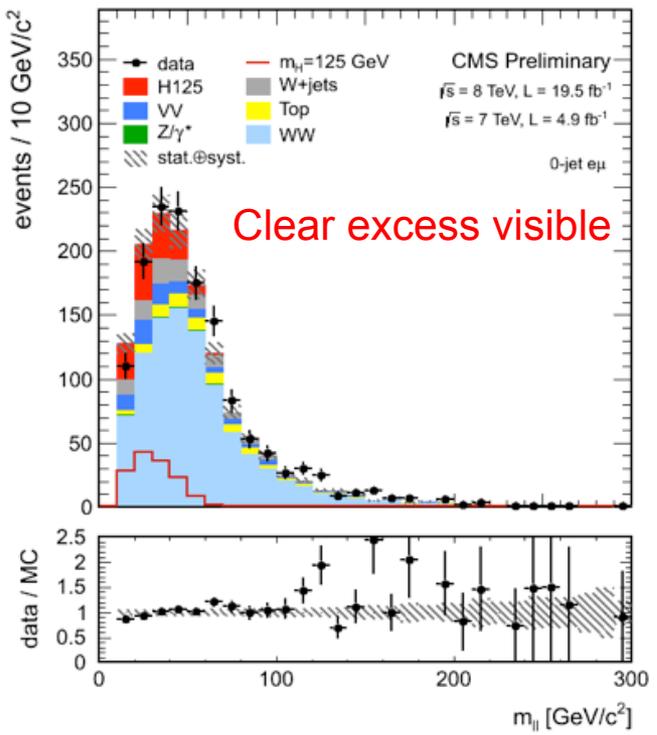
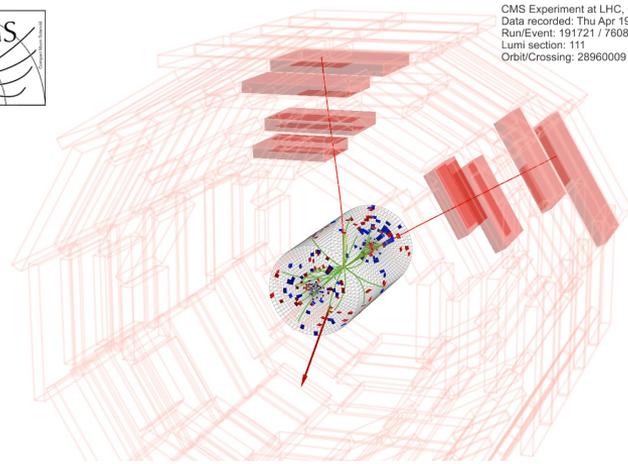


Mass = 125.4  $\pm$  0.5(stat.)  $\pm$  0.6(syst.) GeV (MVA)

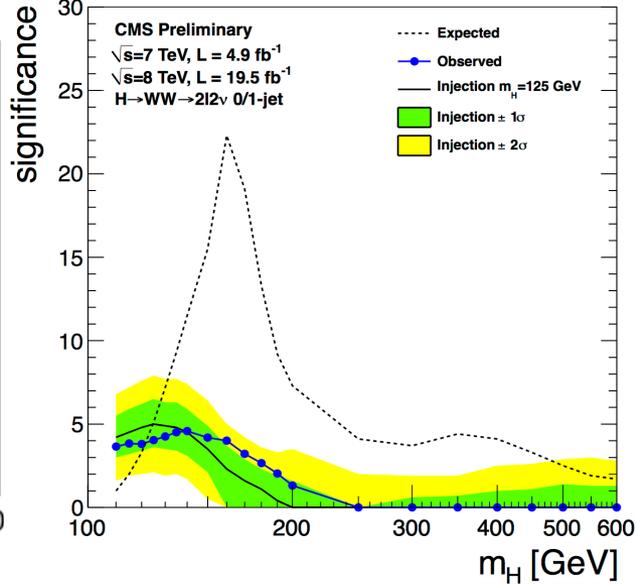
# H → WW → 2l2ν

CMS Experiment at LHC, CERN  
 Data recorded: Thu Apr 19 09:14:14 2012 CEST  
 Run/Event: 191721 / 78089774  
 Lumi section: 111  
 Orbit/Crossing: 28960009 / 815

- Two high- $p_T$  isolated leptons and moderate MET
  - Split data into two categories
    - Different-Flavor (DF), Same-Flavor (SF)
    - No jet, 1-jet (VBF is not updated for Moriond)
  - Two approaches: cut-based and shape-based
- Use 2D ( $M_{\ell\ell} - M_T$ ) to separate signal from background for DF shape-based analyses, counting method for the rest;  $M_T = \sqrt{2p_T^{\ell\ell} \text{MET} \cos\Delta\phi_{\ell\ell-\text{MET}}}$

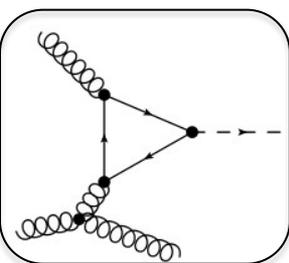


**Exclude 128-600 GeV at 95% C.L**

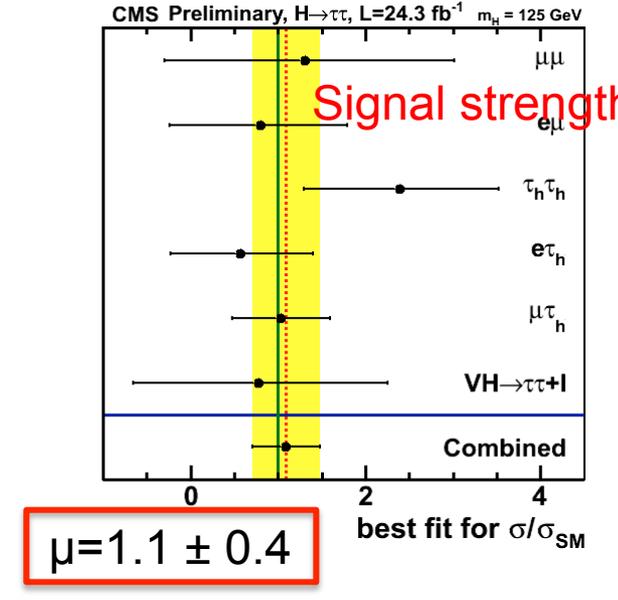
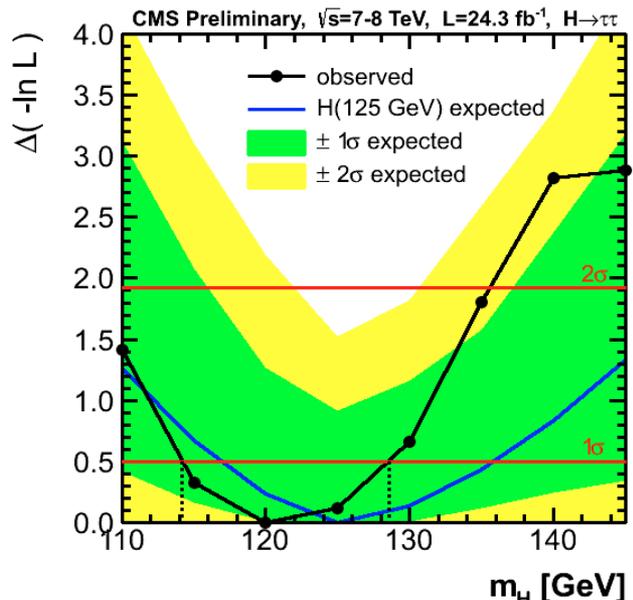
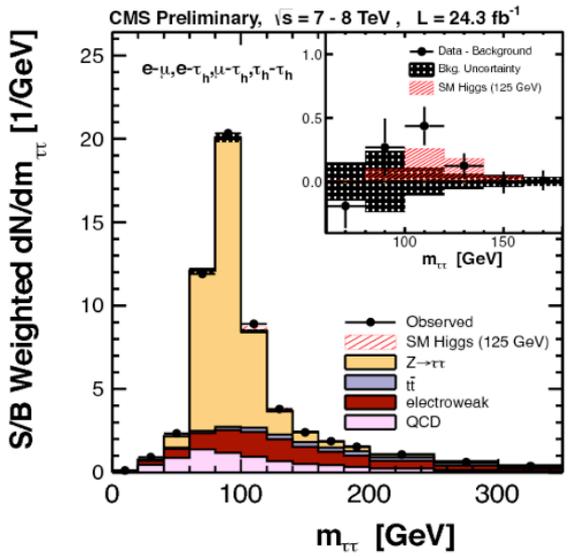
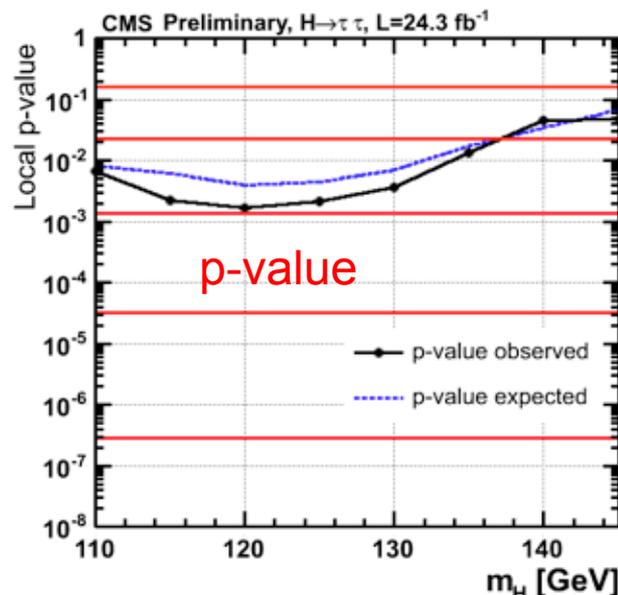
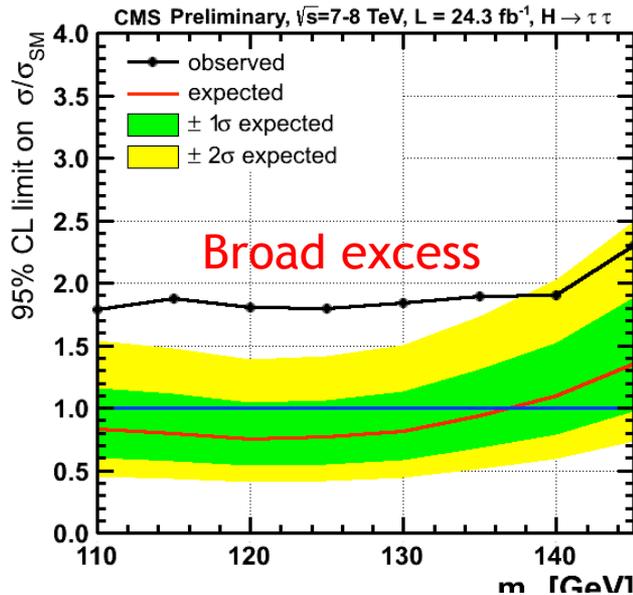
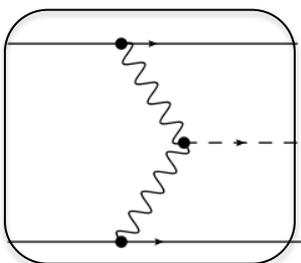


**5.0 σ expected , 4.1 σ observed  
 Second most sensitive final state!**

**Inclusive**

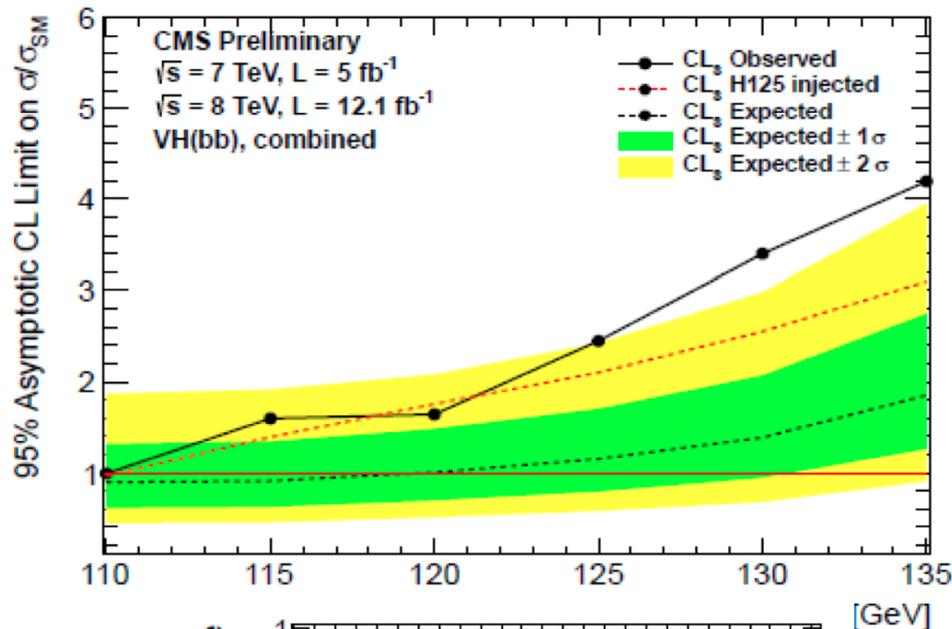
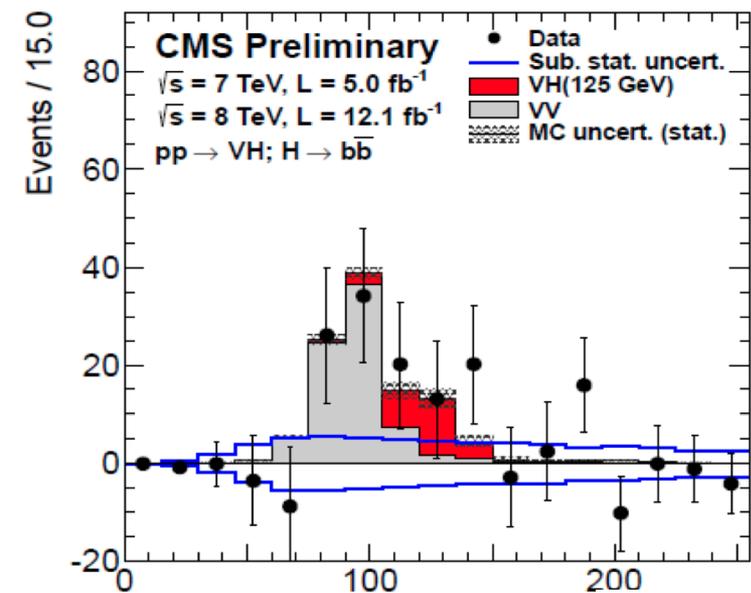


**VH**



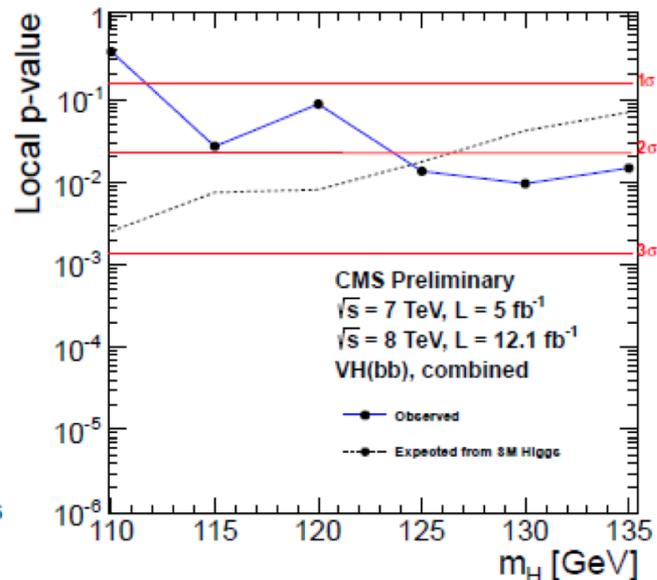
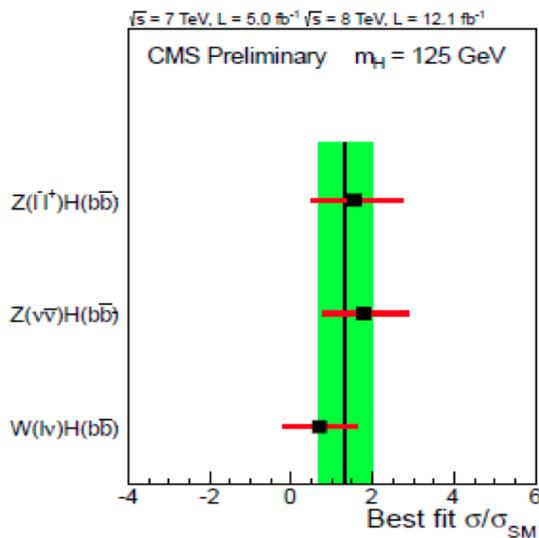
$m_H = 120^{+9}_{-7}$  (stat+syst) GeV

$\mu = 1.1 \pm 0.4$



at 125 GeV  
 $\text{sig} = 2.2\sigma$   
 $\mu = 1.3^{+0.7}_{-0.67}$

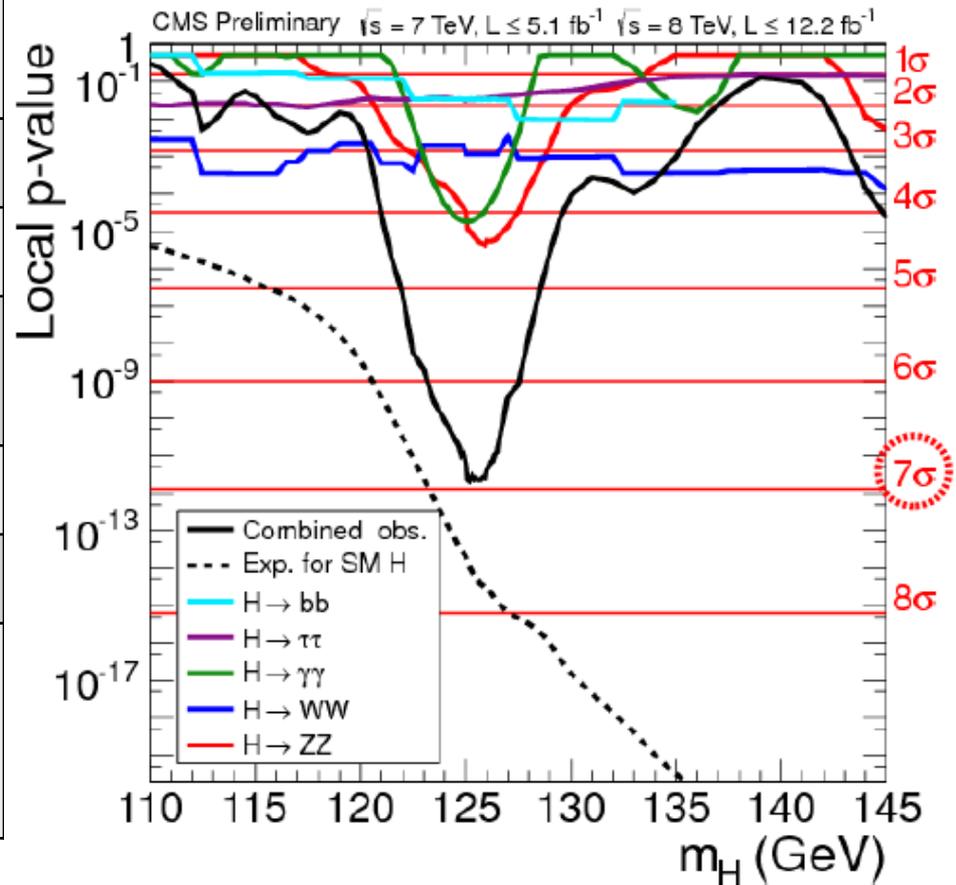
Soon will be updated  
 with full statistics



Decay	Expected	Observed
$H \rightarrow ZZ$	$7.1 \sigma$	$6.7 \sigma$
$H \rightarrow \gamma\gamma$	$3.9 \sigma$	$3.2 \sigma$
$H \rightarrow WW$	$5.3 \sigma$	$3.9 \sigma$
$H \rightarrow bb \star$	$2.2 \sigma$	$2.0 \sigma$
$H \rightarrow \tau\tau$	$2.6 \sigma$	$2.8 \sigma$
$H \rightarrow \tau\tau$ and $H \rightarrow bb$	$3.4 \sigma$	$3.4 \sigma$

$\star$  will be updated by LHCP

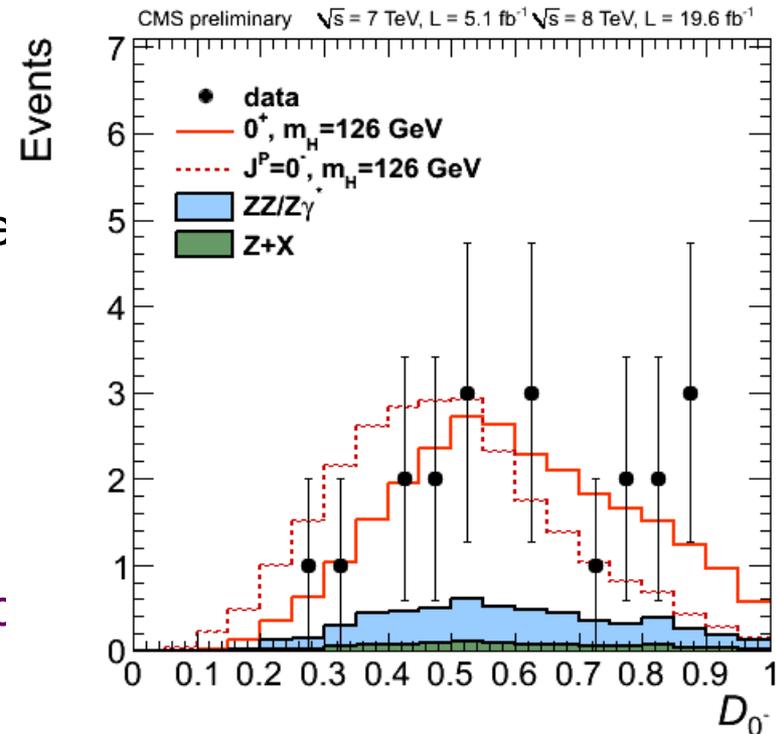
Combined significance (local p-value):



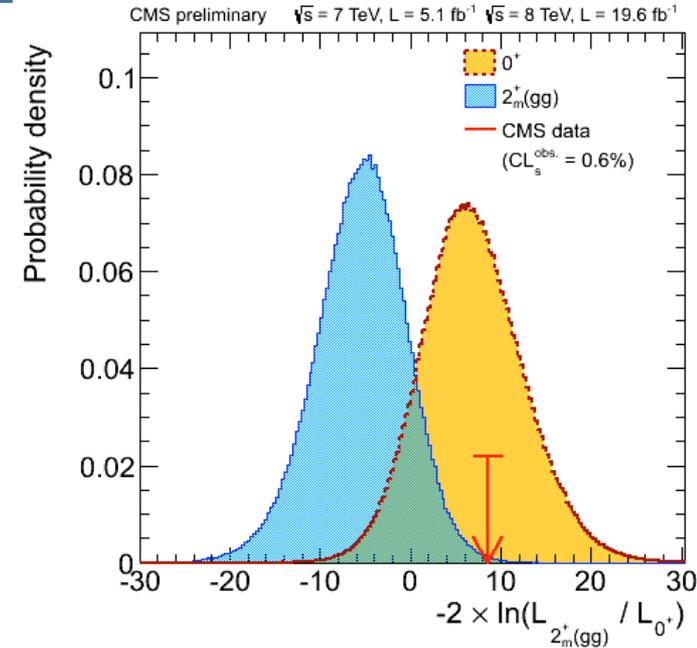
- So far we know the observed particle (assuming just one particle)
  - X is a boson (decays to  $\gamma\gamma$ ,  $4l$  etc)
  - X can not be spin 1 (decays to  $\gamma\gamma$  + Landau-Yang theorem)
  - X can not be 100%  $0^-$  (from  $4l$  correlations) [[PRL 110, 081803 \(2013\)](#)]

□ Further tests in  $ZZ(4l)$  and  $WW(l\nu l\nu)$  channels with full data on a few reasonably well motivated  $J^P$  hypothesis (“pure” states only) w.r.t. SM Higgs

- Using kinematic distributions to distinguish different signal models
  - Probe different amplitude structures
- Test compatibility of data with distinct mode (*Neyman-Pearson hypothesis testing*)
  - Null Hypothesis always SM Higgs
- Discriminator  $D_{JP}$  to separate SM Higgs hypothesis from alternative hypothesis
- Discriminator  $D_{bkg}$  to separate SM Higgs from backgrounds



$J^P$	production	comment
$0^-$	$gg \rightarrow X$	pseudoscalar
$0_h^+$	$gg \rightarrow X$	higher dim operators
$2_{m}^+$	$gg \rightarrow X$	minimal couplings
$2_{mq\bar{q}}^+$	$q\bar{q} \rightarrow X$	minimal couplings
$1^-$	$q\bar{q} \rightarrow X$	exotic vector
$1^+$	$q\bar{q} \rightarrow X$	exotic pseudovector



❑ Expected results with  $\mu=1$ "

ZZ	WW	Comb	<i>obs. value weaker than exp. for WW due to best fit <math>\mu &lt; 1</math></i>
6.8%	1.4%	0.2%	

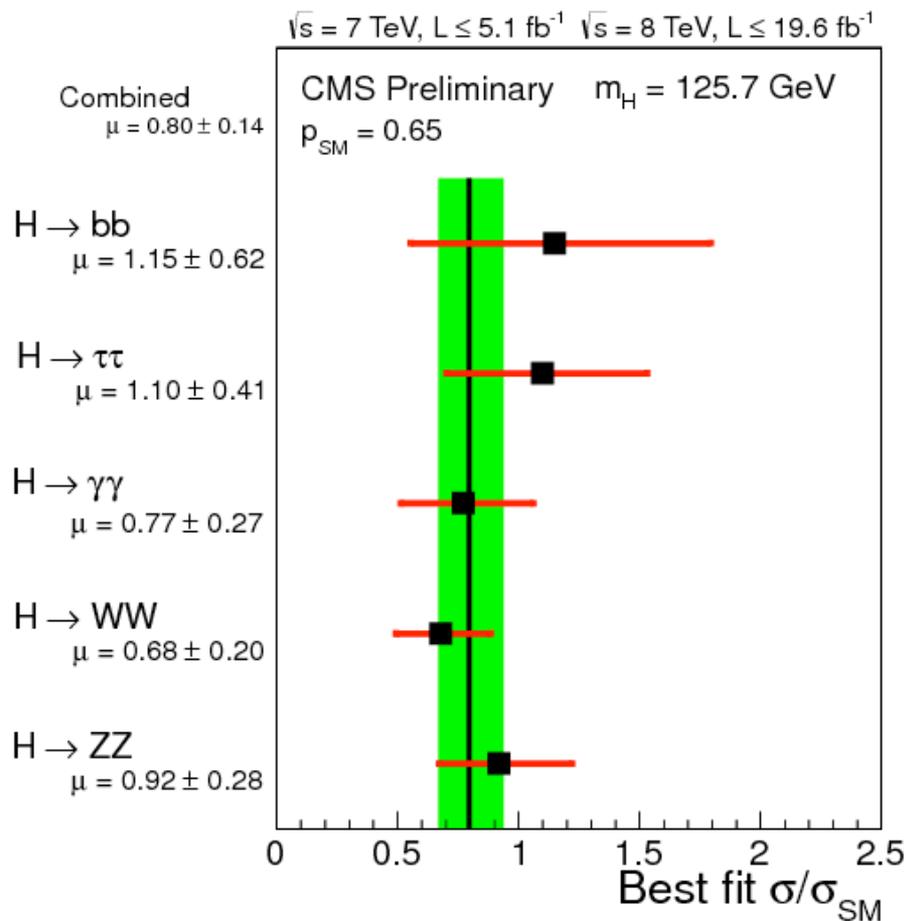
❑ Observed results at measured  $\mu$

ZZ	WW	Comb	<i>obs. value better than exp. for ZZ due to a fluctuation</i>
1.4%	14%	0.6%	

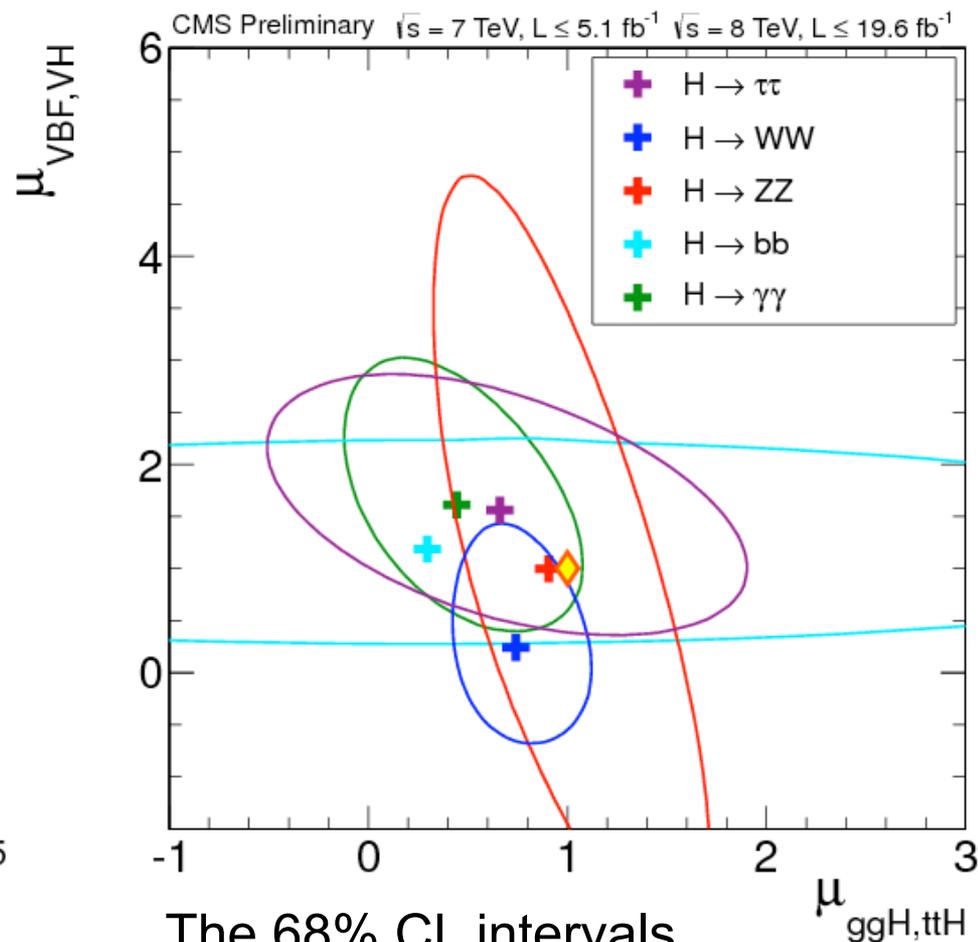
☑ **The observation is well compatible with SM Higgs expectations ( $0^+$ )**

❑ **Data disfavors the  $2_m^+$  (gg) hypothesis with a  $CL_s$  value of 0.6%**

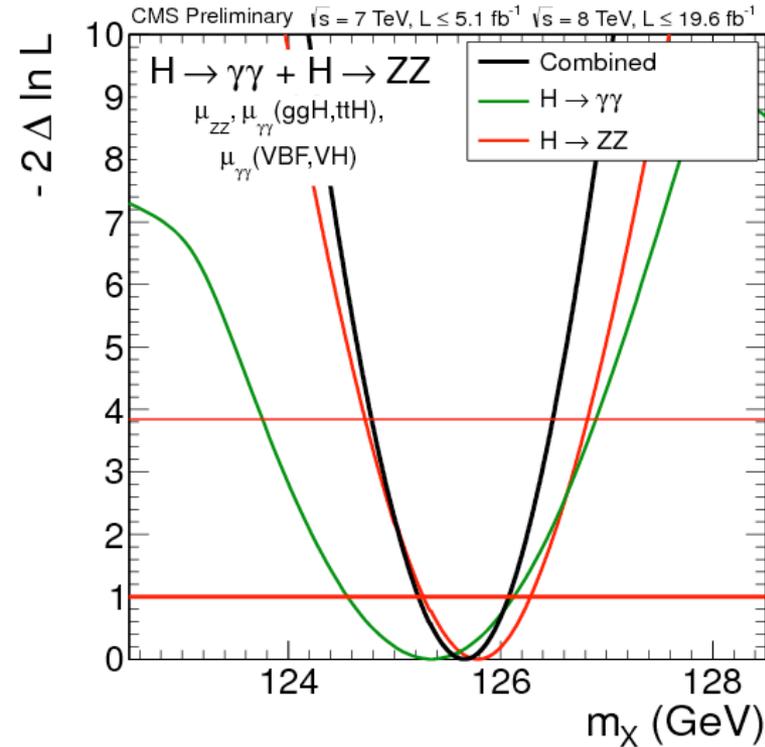
□ Signal strengths are consistent with SM prediction



**$\mu = 0.80 \pm 0.14$**



The 68% CL intervals for signal strength



## H → ZZ → 4l:

Very small systematics due to the very good control of the leptons scale and resolution:

$$m_H = 125.8 \pm 0.5 \text{ (stat.)} \pm 0.2 \text{ (syst.) GeV}$$

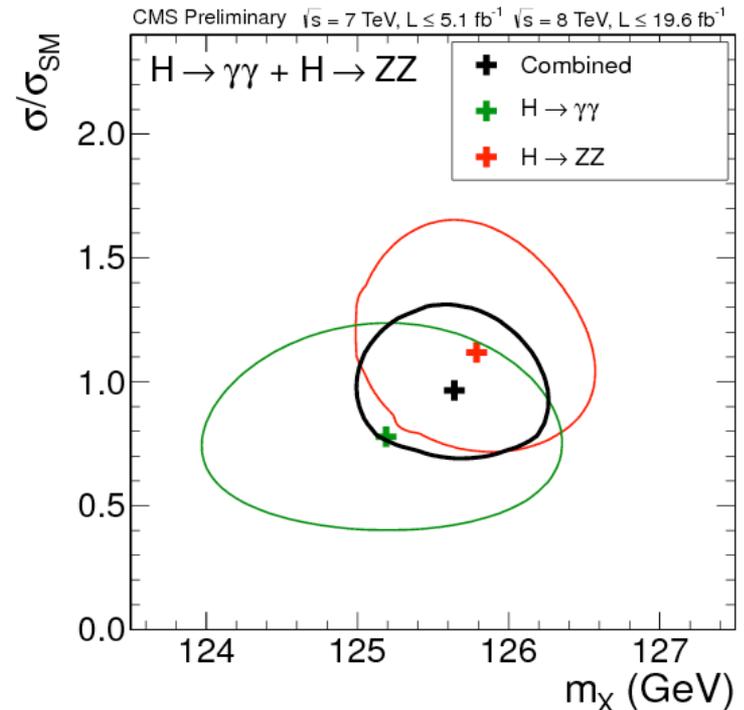
## H → γγ:

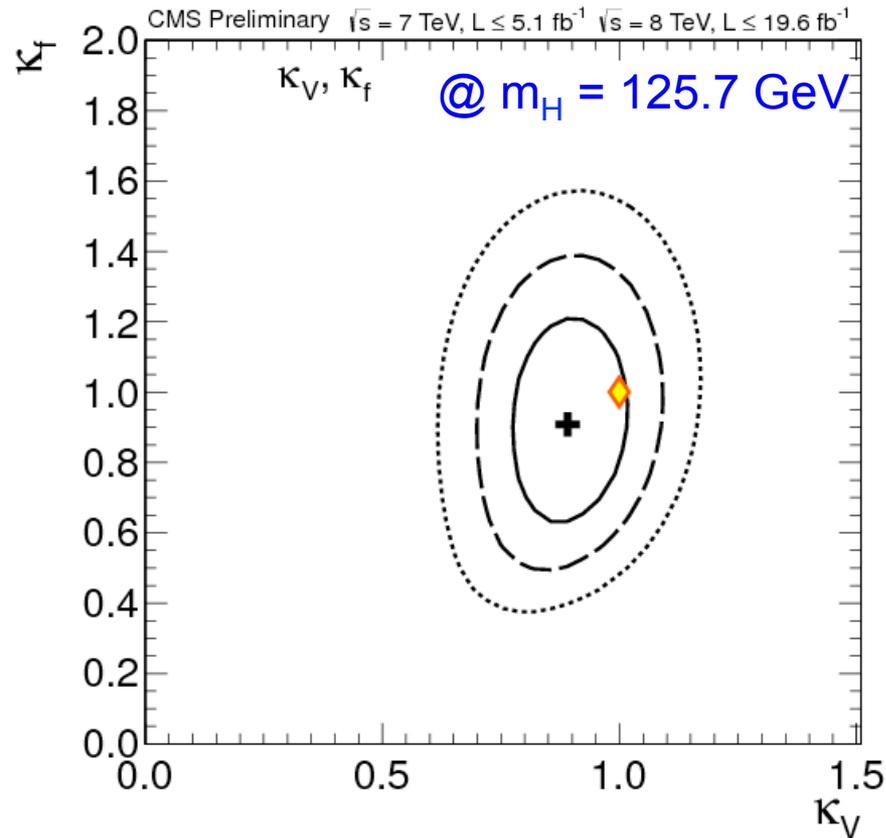
Systematics on the extrapolation from the Z → ee to H → γγ (0.25% (e to γ), 0.4% (Z to H))

$$m_H = 125.4 \pm 0.5 \text{ (stat.)} \pm 0.6 \text{ (syst.) GeV}$$

$$m_x = 125.7 \pm 0.3 \text{ (stat)} \pm 0.3 \text{ (syst) GeV}$$

$$= 125.7 \pm 0.4 \text{ GeV}$$

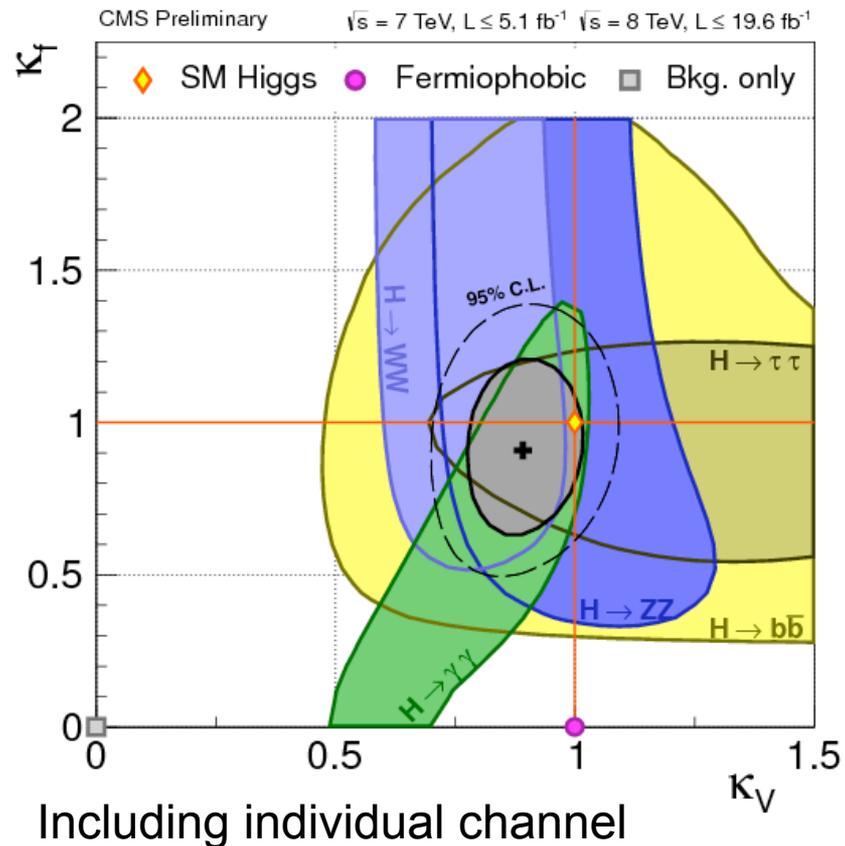




$$\Gamma(H \rightarrow \gamma\gamma) \sim |\alpha \kappa_V + \beta \kappa_f|^2$$

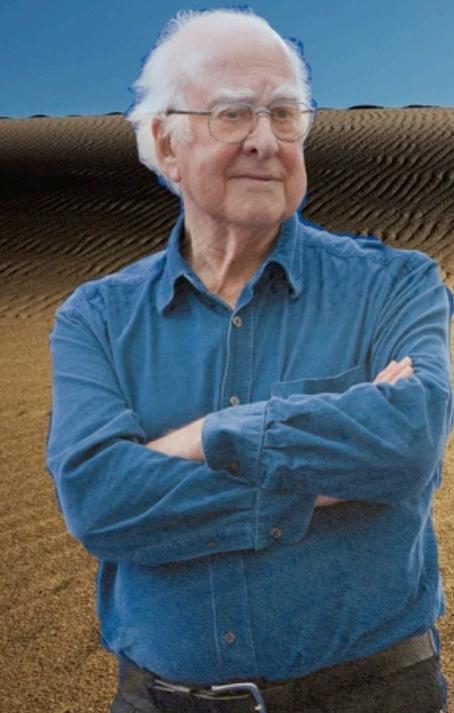
$$\alpha/\beta = -0.2$$

$$\Gamma_{\text{BSM}} = 0$$



□ Consistent with SM prediction

- CMS has contributed in a significant manner **to probing nature at the TeV scale**
- CMS have given extensive proof of being able to deliver, at high quality and over short time scales
  - this promises well also for the coming years
- **CMS discovered the first fundamental scalar field**
- **Spin-parity results are consistent with the SM Higgs** and disfavor other considered scenarios; **signal strengths are consistent with the SM prediction** as well.
- **Mass of the new boson is  $125.7 \pm 0.4$  GeV**
- *More results to follow later this summer*
- A lot of experience with data analyses at Run 1
- Rather complex searches, pushing capabilities of the hardware to its fullest (but still a lot of things can be improved for Run 2!)
- **No evidence for physics beyond the SM so far** – searches will continue
- Is new physics that control the Higgs mass is right around the corner? Or do we live in a very unnatural Universe?



*Thank You!*

Channel	ATLAS Lumi [1/fb]	CMS Lumi [1/fb]	Specialty	Inclusive signature	$\sigma$ Obs. (Exp.)	mass [GeV]	Signal Strength $\mu$	Spin/Parity
H $\rightarrow$ ZZ $\rightarrow$ 4l	4.6+20.7	5.1+19.6	mass, <b>discovery</b> , spin/parity	4 leptons	6.6 (4.4)	124.3 $\pm$ 0.6 (stat) $\pm$ 0.5 (sys)	1.5 $\pm$ 0.4	✓
					6.7 (7.2)	125.8 $\pm$ 0.5 (stat) $\pm$ 0.2 (sys)	0.91+0.30-0.24	✓
H $\rightarrow$ WW $\rightarrow$ 2l2v	4.6+20.7	4.9+19.5	cross section, coupling	2 leptons, MET	3.8 (3.7)	consistent	1.01 $\pm$ 0.31	✓
					4.0 (5.1)	consistent	0.76 $\pm$ 0.21	✓
H $\rightarrow$ $\gamma\gamma$	4.8+20.7	5.1+19.6	mass, <b>discovery</b> , couplings	two photons	7.4 (4.1)	126.8 $\pm$ 0.2 (stat) $\pm$ 0.7 (sys)	1.6 $\pm$ 0.3	✓
					3.2 (4.2)	125.4 $\pm$ 0.5 (stat) $\pm$ 0.6 (sys)	0.78+0.28-0.26	-
H $\rightarrow$ bb	4.7+13.0	5.0+12.1	coupling to fermions	two b-jets	-	consistent	-0.4 $\pm$ 1.0	-
					2.2 (2.1)	consistent	1.3+0.7-0.6	-
H $\rightarrow$ $\tau\tau$	4.6+13.0	4.9+19.4	couplings to leptons	hadronic taus, leptons, MET	1.1 (1.7)	consistent	0.8 $\pm$ 0.7	-
					2.9 (2.6)	120+9-7	1.1 $\pm$ 0.4	-

CMS

ATLAS