



Search for the Higgs Boson decaying in two photons with CMS and ATLAS

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$H \rightarrow \gamma\gamma$

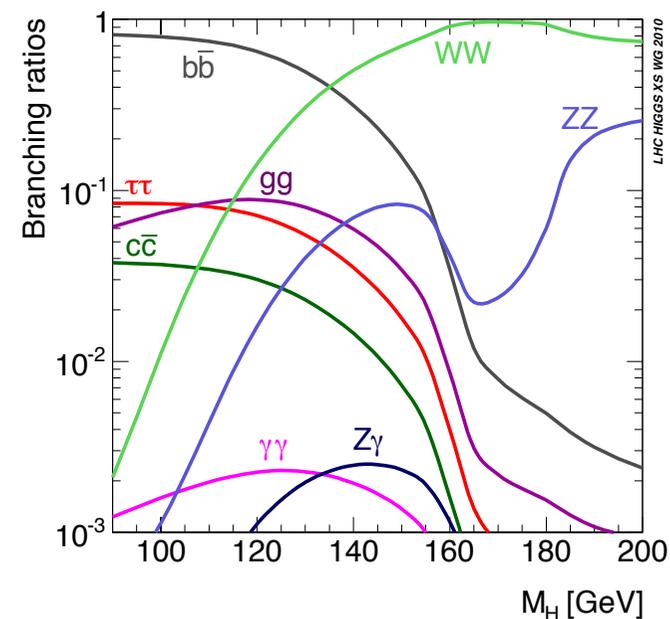
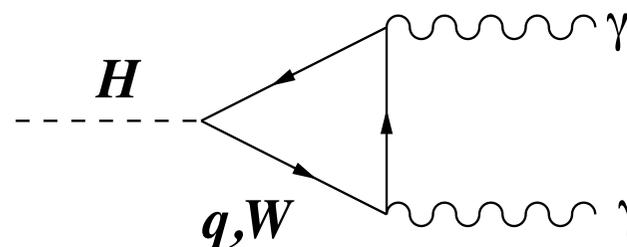
- $H \rightarrow \gamma\gamma$ is a discovery channel for low mass SM Higgs, between LEP limit (114.4 GeV) and LHC exclusion (145 GeV)

- low signal rate with $B \sim 10^{-3}$
- decay involves q, W loops;
- clean signature (contrarily to $H \rightarrow \bar{b}b$);

- CMS performs searches for two models

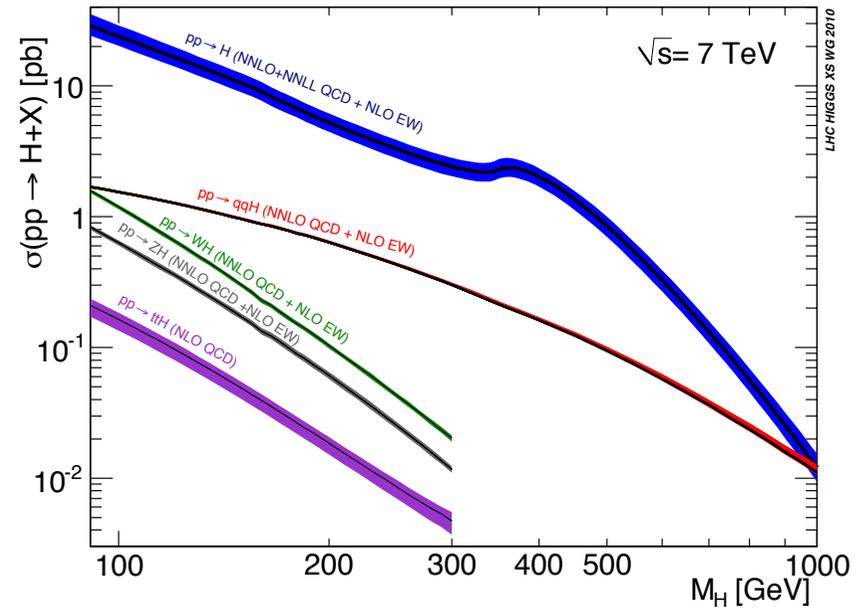
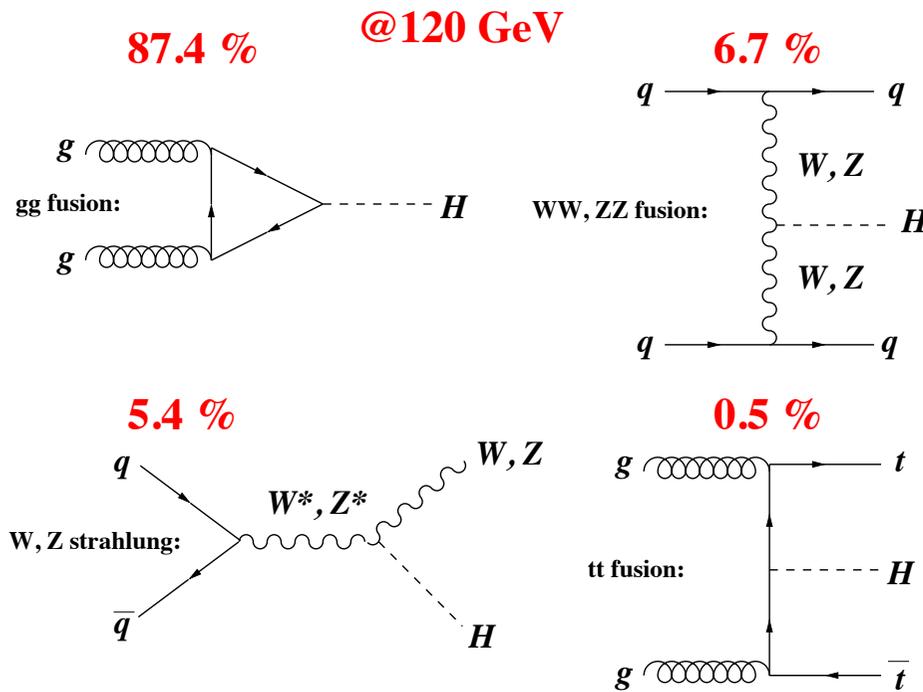
- **Standard Model (SM) $h \rightarrow \gamma\gamma$**
 - most likely scenario after first LHC results

- **Fermiophobic (FP) $h_f \rightarrow \gamma\gamma$**
 - has particular interest for beyond the SM scenario of EWSB (2 HDM)
 - sensitive to new physics effects
 - no fermion couplings \Rightarrow enhance $B(h_f \rightarrow \gamma\gamma)$
 - already measures couplings





Rates and Cross Sections for SM Higgs



- ggH is the dominant production mechanism for SM Higgs at LHC.
 - associated jets produced in soft gluon radiation (NLO)
 - high k-factor (~ 2)
 - large theoretical uncertainties

NNLO cross sections and branching ratios (SM)

M_h (GeV)	110	115	120	130	140	150
σ ggH (pb)	19.8	18.1	16.6	14.1	12.1	10.5
σ VBF (pb)	1.40	1.33	1.27	1.15	1.05	0.96
σ WH (pb)	0.88	0.75	0.66	0.50	0.39	0.30
σ ZH (pb)	0.47	0.41	0.36	0.28	0.22	0.17
σ $t\bar{t}H$ (pb)	0.13	0.11	0.10	0.08	0.06	0.05
Total σ (pb)	22.7	20.7	19.0	16.1	13.8	12.0
$\mathcal{B}(h \rightarrow \gamma\gamma)$, %	0.20	0.21	0.23	0.23	0.19	0.14
$\sigma \times \mathcal{B}$ (fb)	44.7	43.5	43.7	37.0	26.2	16.8

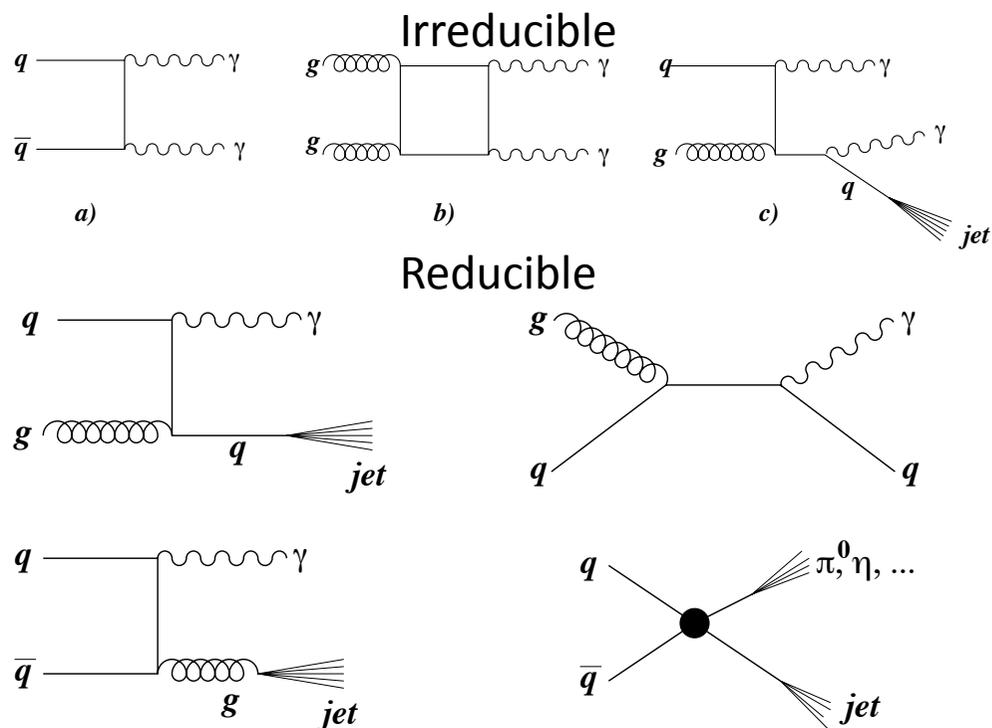
Backgrounds

- Irreducible backgrounds:
 - Born (a), Box (b), and isolated bremsstrahlung (c).
- Reducible backgrounds:
 - QCD with hard jets, where neutral hadrons (π^0, η) fake photons.
 - Need jet suppression at 10^4 level.
- Differential rates of irreducible backgrounds

$d\sigma/dm_{\gamma\gamma} \sim 100 \text{ fb}/\text{GeV}/c^2$

 drive need for mass resolution

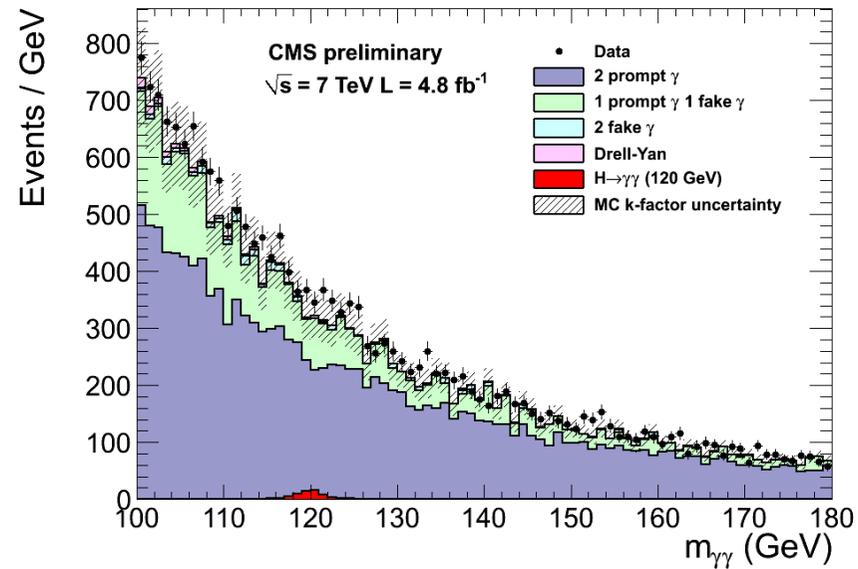
$\Delta M_{\gamma\gamma} \sim 1 \text{ GeV}/c^2$
- Search for a narrow resonance in a diphoton continuum.



Process	p_T (GeV/c)	σ_{LO} (pb)
$H \rightarrow \gamma\gamma$ ($120 \text{ GeV}/c^2$)	–	0.044 (NNLO)
$pp \rightarrow \gamma\gamma$ (Born)	> 25	22.4
$pp \rightarrow \gamma\gamma$ (Box)	> 25	12.4
$pp \rightarrow \gamma + \text{jet}$	> 30	2.0×10^4
$pp \rightarrow \text{jets}$	> 30	6.0×10^7
Drell Yan ee	–	3×10^3



Data vs Background MC in CMS



MC is simulated with Madgraph, using k-factors from existing QCD measurements. MC is used only to optimize selection cuts.



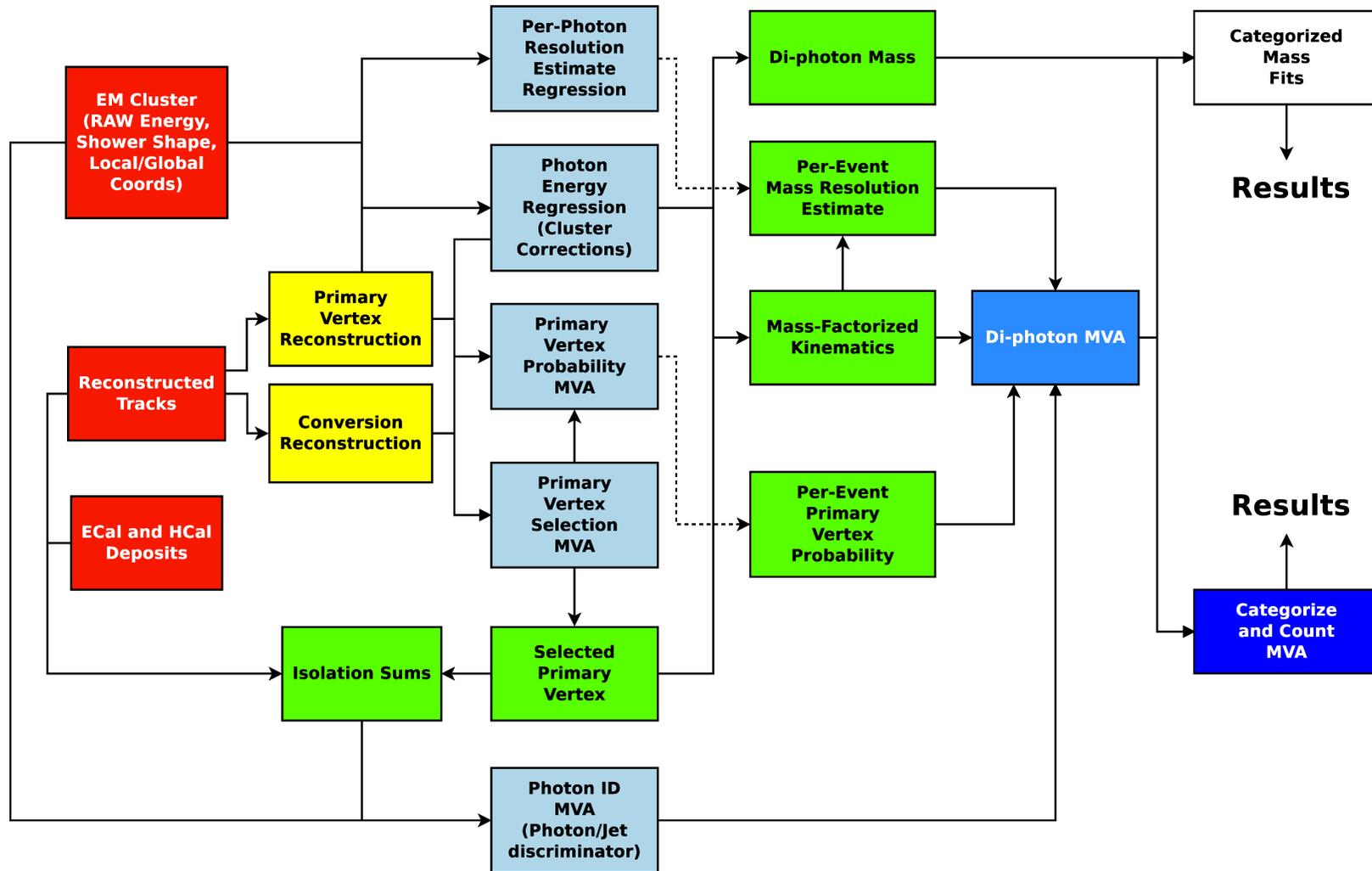
Analysis Strategy is Simple

Basic idea is simple, but the methods used can be quite advanced

- Reduce background:
 - CMS: Vertex ID **MVA**, Photon ID **MVA** (Photon/Jet discriminator)
 - ATLAS: Vertex ID, Photon ID
- Separate events in categories to maximize the sensitivity
 - CMS: Moved from Converted/unconverted $\times \eta$ (HIG-11-033) to diphoton **MVA** (HIG-12-001) which is mass independent. Additional exclusive category – dijet tag optimized for VBF.
 - ATLAS: Converted/unconverted $\times \eta \times p_T^{\gamma\gamma}$ (9 categories) and no exclusive ch.
- Model signal , background
 - CMS: Sum of Gaussians or Crystall Ball + Gaussian, Polynomial
 - ATLAS: Crystall Ball + Gaussian), Exponential
- Search for a peak using likelihood
 - Test statistic is profile likelihood ratio



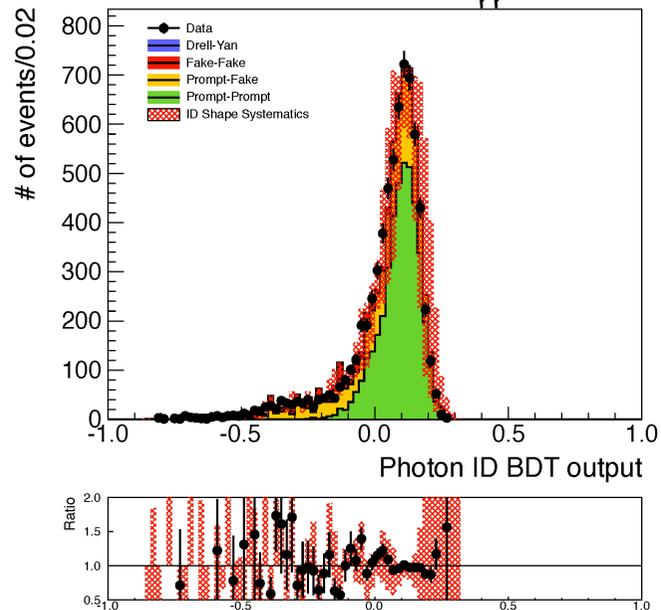
Analysis Strategy in CMS



Analysis Strategy is Simple

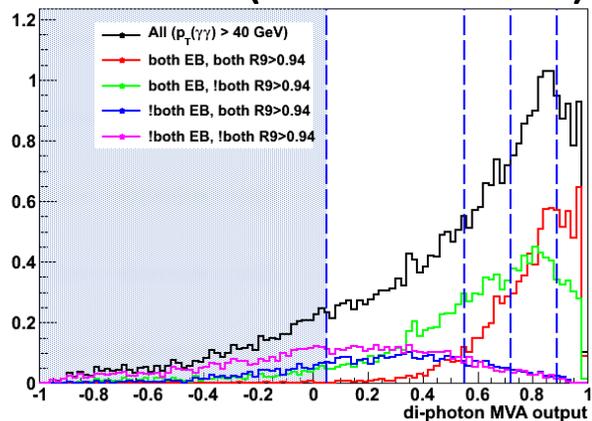
- Photon ID **MVA**

γ ID MVA Validation for $m_{\gamma\gamma} > 160$ GeV

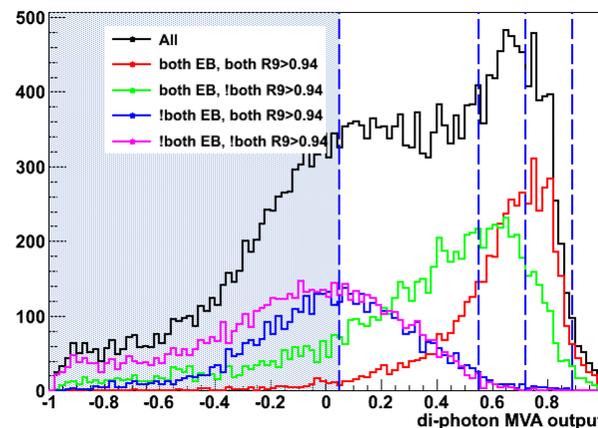


- Moved from even categorization Converted/unconverted $\times \eta$ (HIG-11-033) to diphoton **MVA** (HIG-12-001) which is mass independent.

MC



Data



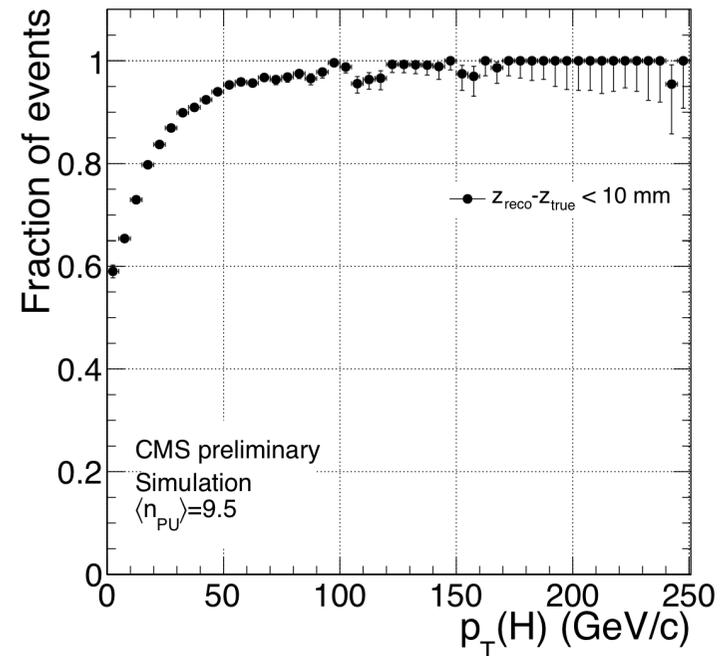


Mass Resolution and Vertex Identification

- Energy scale (ΔE) and mass resolution (σ_m) are dominant systematics
 - mass scale is equivalent to energy scale: $\Delta m \equiv \Delta E$
 $m^2 = 2E_1E_2(1 - \cos \theta)$
 - σ_m depends on energy (σ_E) and angular (σ_θ) resolutions

$$\frac{\sigma_m}{m} = \frac{1}{2} \left(\frac{\sigma_{E_1}}{E_1} \oplus \frac{\sigma_{E_2}}{E_2} \oplus \frac{\sigma_\theta}{\tan \theta/2} \right)$$

- Higgs is produced in association with tracks from:
 - underlying event
 - initial state gluon radiation
 - associative particles qqH, VH
 - photon conversion

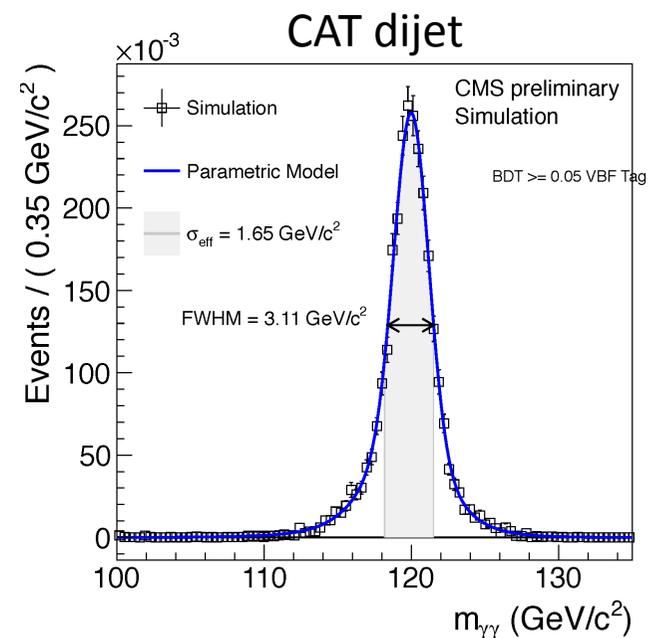
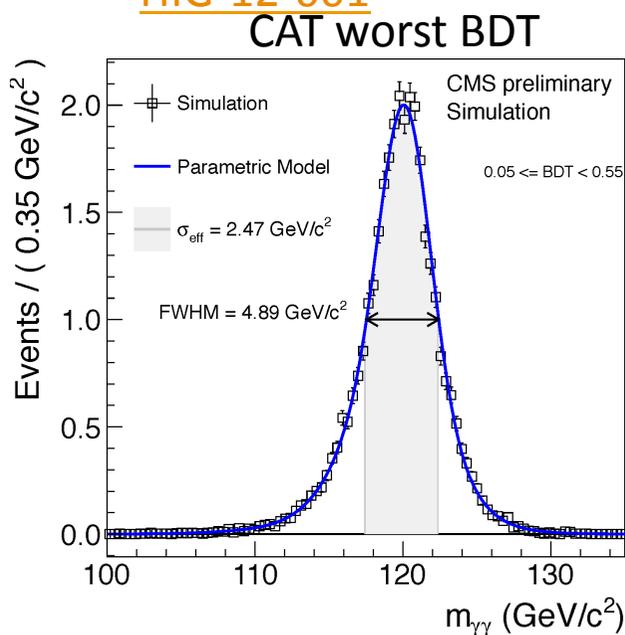
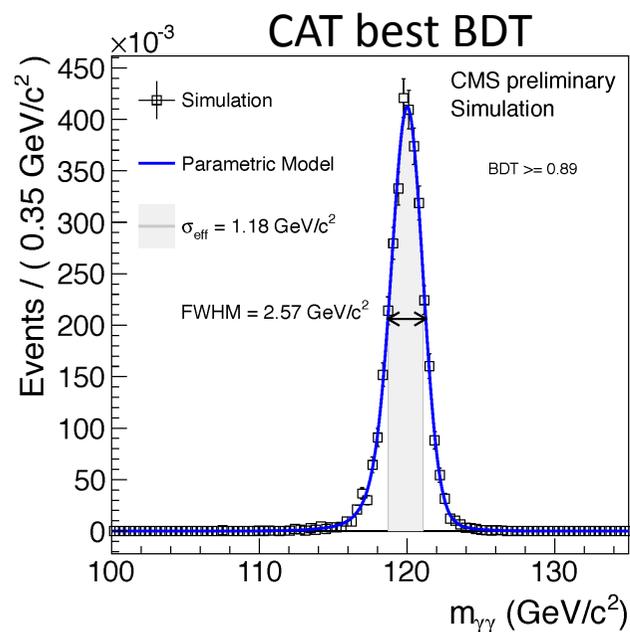


CMS Built MVA (BDT) using tracks from primary vertices and any conversions in the event. Improvement w.r.t. previously used ranking of these variables is $\sim 5\%$ at low p_T .



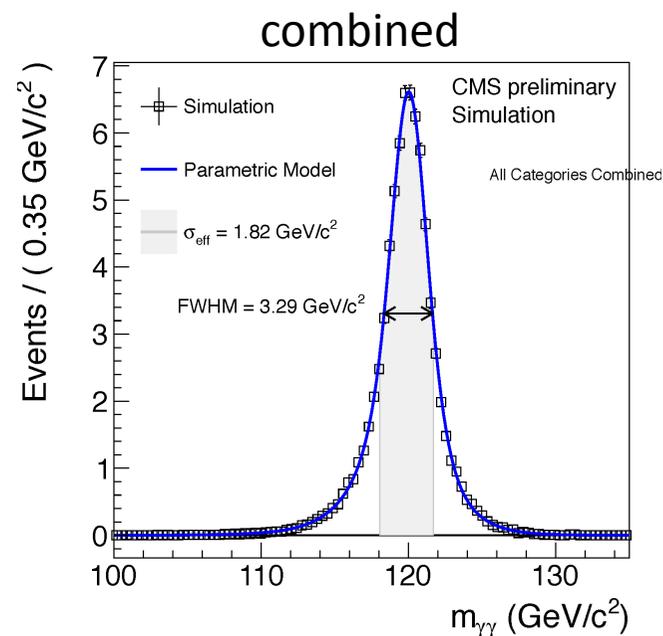
Resolution Model in CMS

HIG-12-001



Higgs signal model is derived from MC applying corrections for photon identification/ isolation. Regression used to correct ECAL cluster energies, to improve energy scale and resolution. Efficiencies and energy resolution extrapolated from data using $Z \rightarrow e^+e^-$.

Since Moriond 2012, CMS has improved the calibration and reconstructed data with new constants. Improved energy resolution in EB and EC by 5-10%.



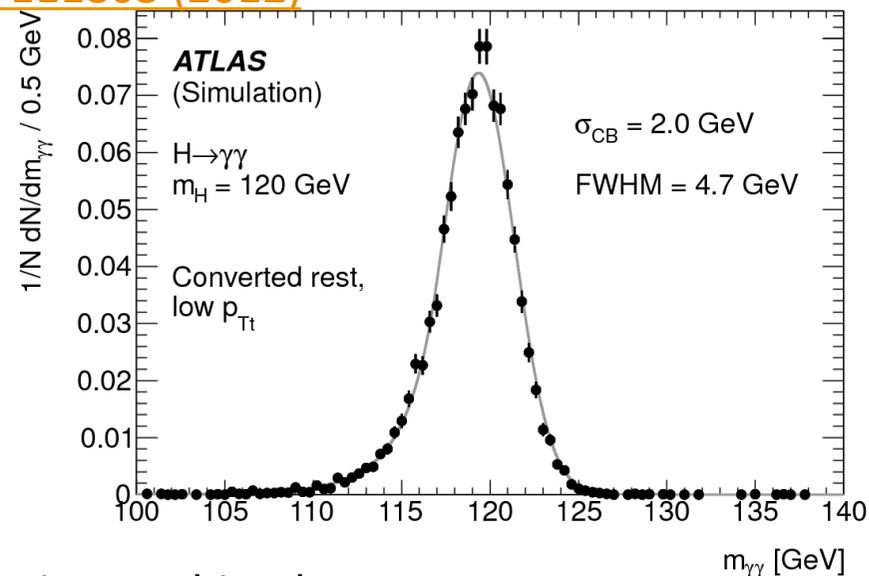
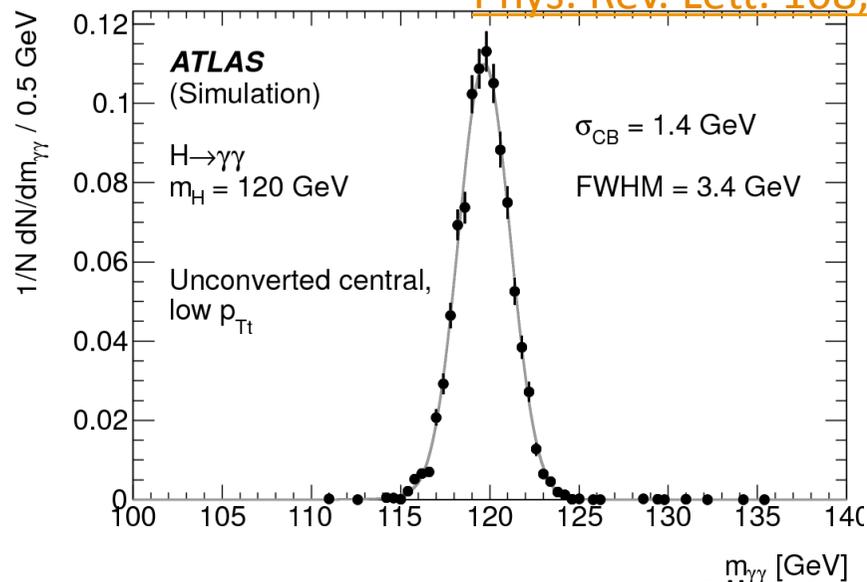


Resolution Model in ATLAS

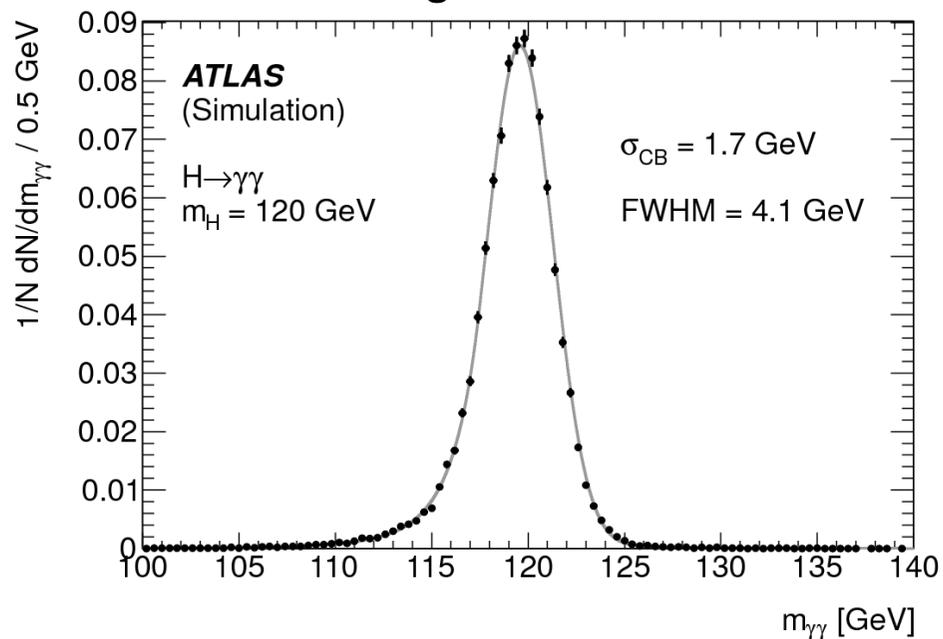
Central nonconverted low pT

Rest converted low pT

[Phys. Rev. Lett. 108, 111803 \(2012\)](#)

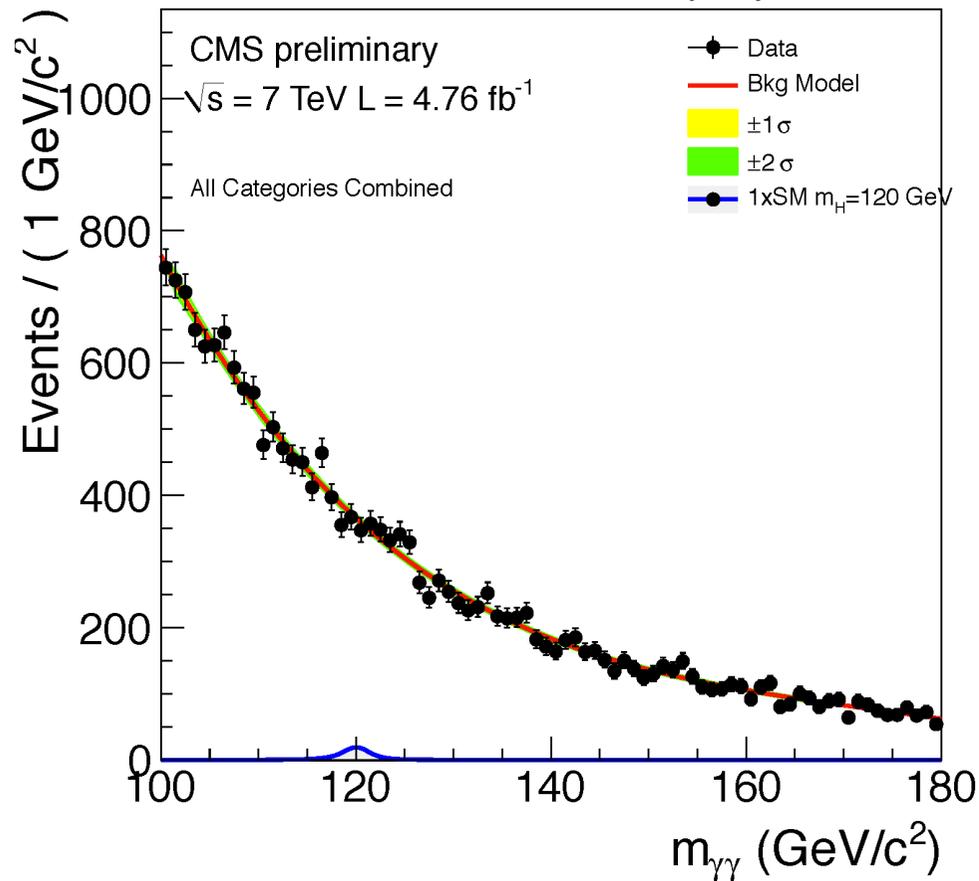


All categories combined

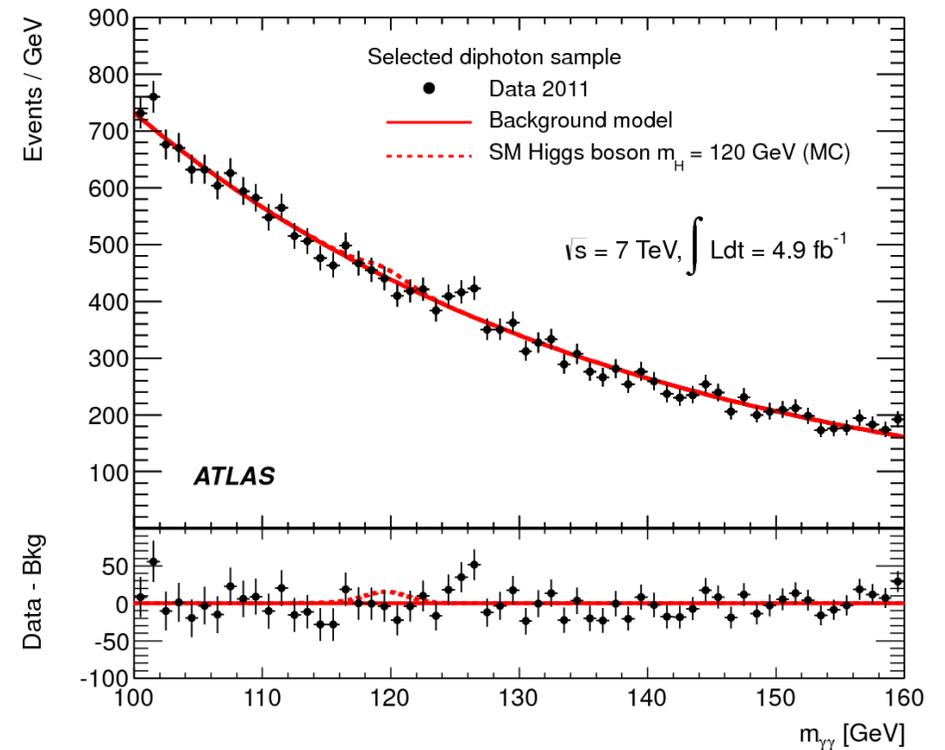


Background model is derived directly from data.

CMS: Fit with a 3rd-5th order polynomial



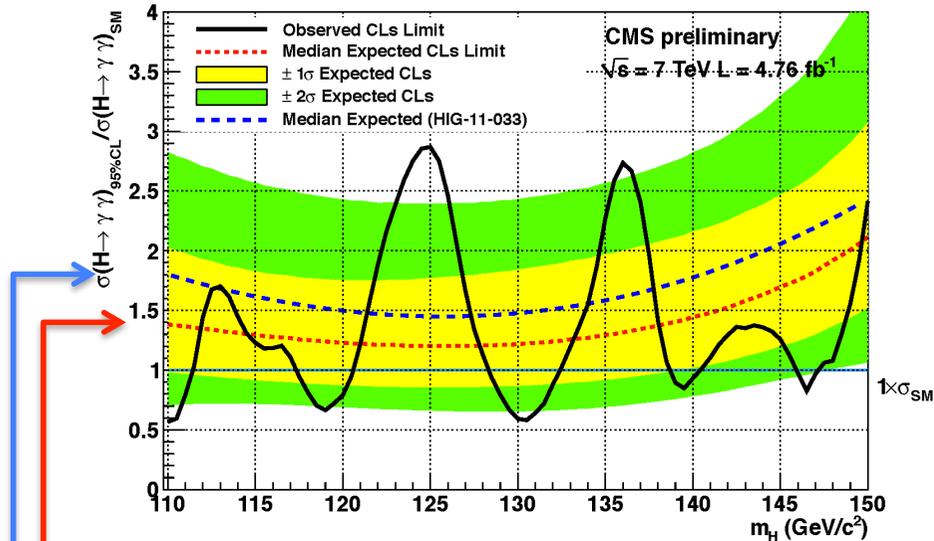
CMS: Fit with an exponential



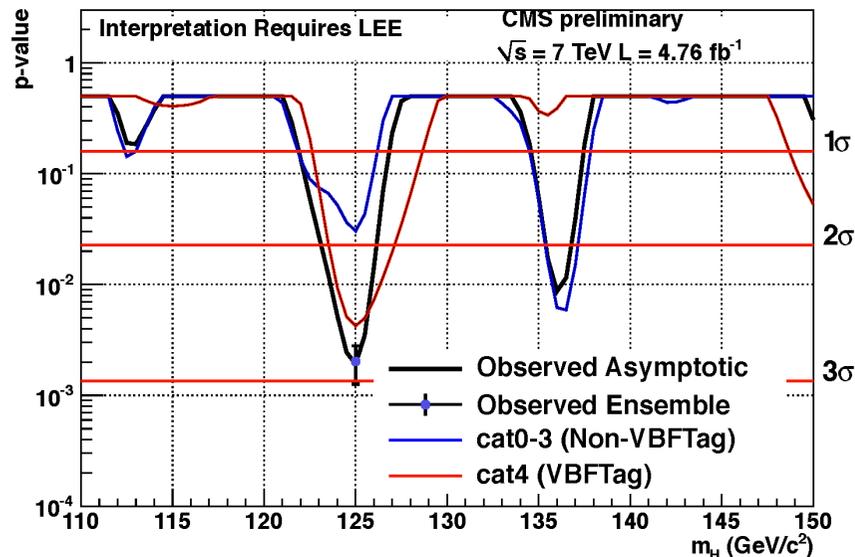


SM Limits and Local p-values

HIG-12-001

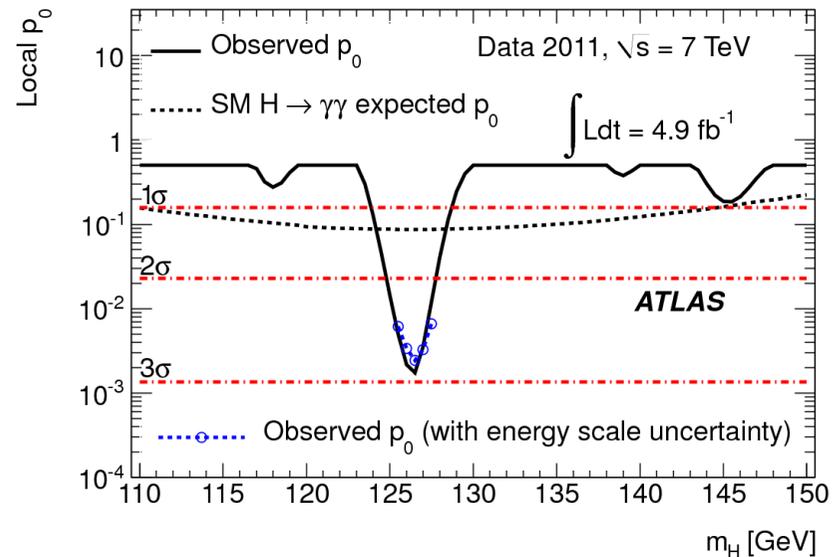
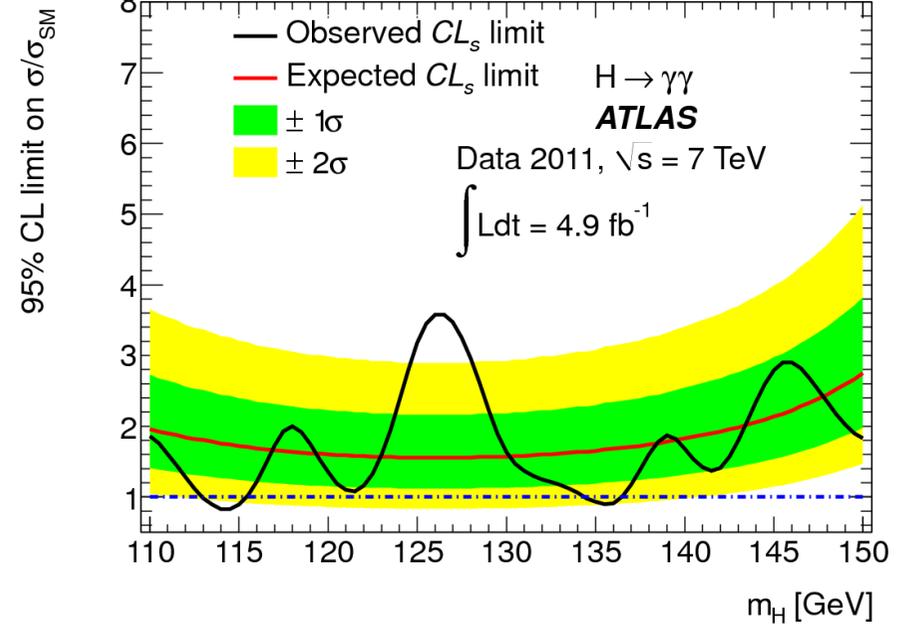


Limit Improved by ~10% due to DiJet – tag.
 Additional ~15% improvement due to MVA.



Global (local) significance 2.9σ (1.6σ)

ATLAS-CONF-2012-013

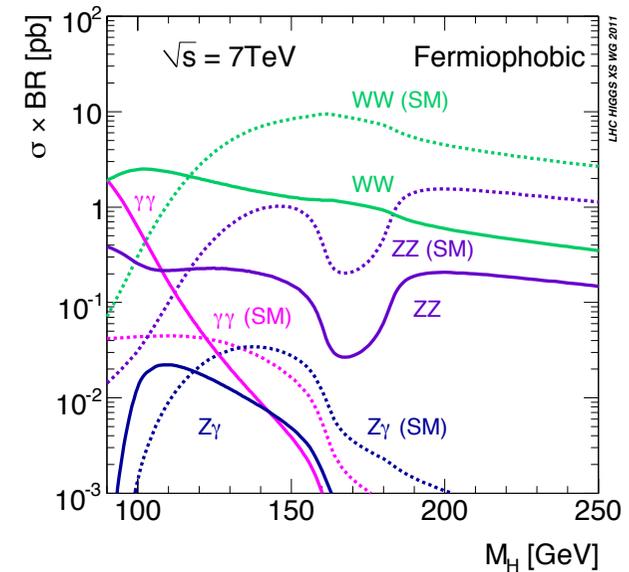
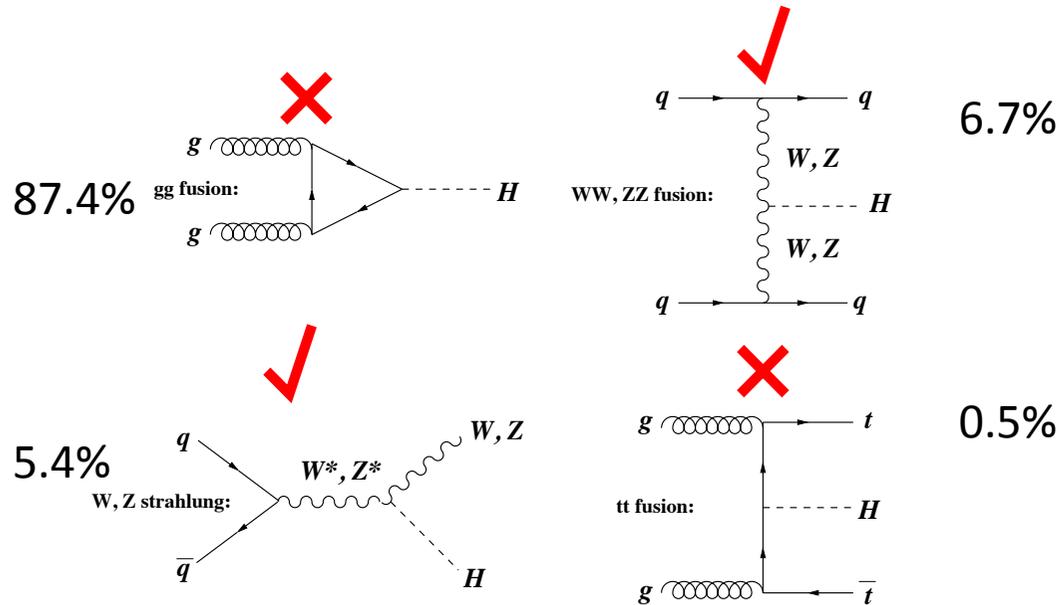


Global (local) significance 2.8σ (1.5σ)



FERMIOPHOBIC HIGGS (FP)

Production of Fermiophobic Higgs



- An extreme model, important part of Higgs program that measures couplings.
- No coupling to fermions, so driven by VBF and VH
 - Signal yields from FP become comparable to SM Higgs at 125 GeV, due to increased BR to two photons.
- Jets (VBF) and leptons (VH) produced at LO.
 - low k-factor (~ 1), small theoretical uncertainties.
 - Higgs is boosted
 - Additional signatures (dijet, lepton)

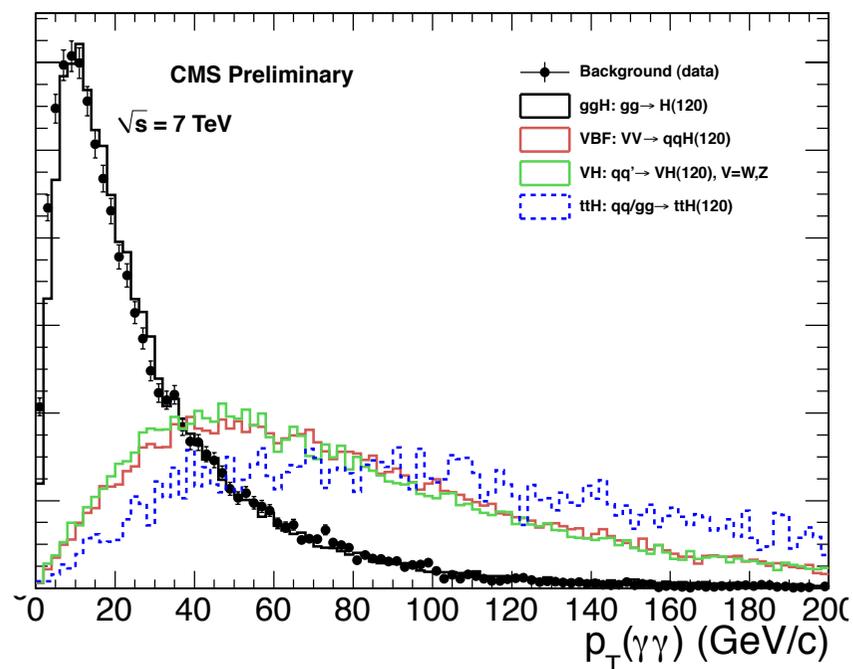
NNLO cross sections and branching ratios (FP)

M_{h_f} (GeV)	90	100	110	120	130	140	150
σ VBF (pb)	1.71	1.55	1.40	1.27	1.15	1.05	0.96
σ WH (pb)	1.64	1.19	0.88	0.66	0.50	0.39	0.30
σ ZH (pb)	0.86	0.63	0.47	0.36	0.28	0.22	0.17
Total σ (pb)	4.21	3.37	2.75	2.29	1.93	1.66	1.43
$\mathcal{B}(h_f \rightarrow \gamma\gamma)$, %	41.0	18.0	6.2	2.8	1.9	0.61	0.20
$\sigma \times \mathcal{B}$ (fb)	1726	607	170.5	64.1	36.7	10.1	2.9

Interesting for LHC

Tevatron excludes $M_{FP} < 119$ GeV [arXiv:1109.0576v1](https://arxiv.org/abs/1109.0576v1)

- Difference in the signal and background kinematics have been used both in CMS and ATLAS.
- CMS
 - include recoil objects in signature
 - dijet tag for VBF (SM and FP),
 - lepton tag (FP)
 - exploit Higgs kinematical properties
 - 2D analysis with (mass, $p_T(\gamma\gamma)$)
- ATLAS:
 - Use two $p_T(\gamma\gamma)$ categories: $<(>) 40$ GeV
 - $p_T(\gamma\gamma) > 40$ GeV enhances VBF and VH for FP scenario



ggH spectrum is reweighted using NNLO/NLO corrections (HqT)



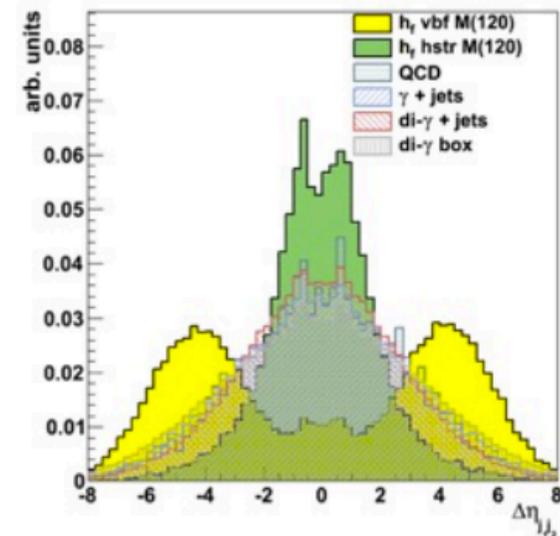
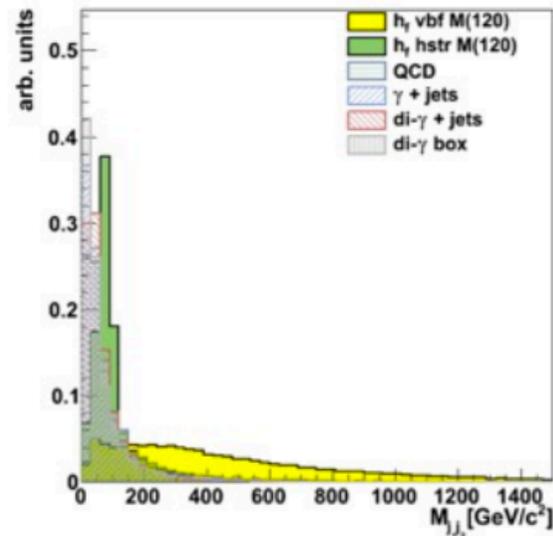
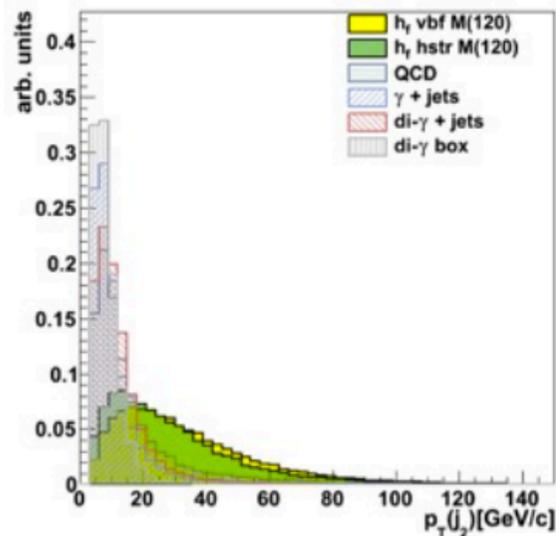
VBF di-jet Tag: Summary of Selection

Variable	cut VBF
$p_T^{\gamma 1} / m_{\gamma\gamma}$	$> 55/120 \text{ GeV}$
$p_T^{\gamma 2}$	$> 25 \text{ GeV}$
p_T^{j1}	$> 30 \text{ GeV}$
p_T^{j2}	$> 20 \text{ GeV}$
$ \Delta\eta_{j1j2} $	> 3.5
$ Z $	< 2.5
M_{j1j2}	$> 350 \text{ GeV}$
$ \Delta\phi(jj, \gamma\gamma) $	> 2.6

Eff(H(120 GeV) – VBF) ~ 15%

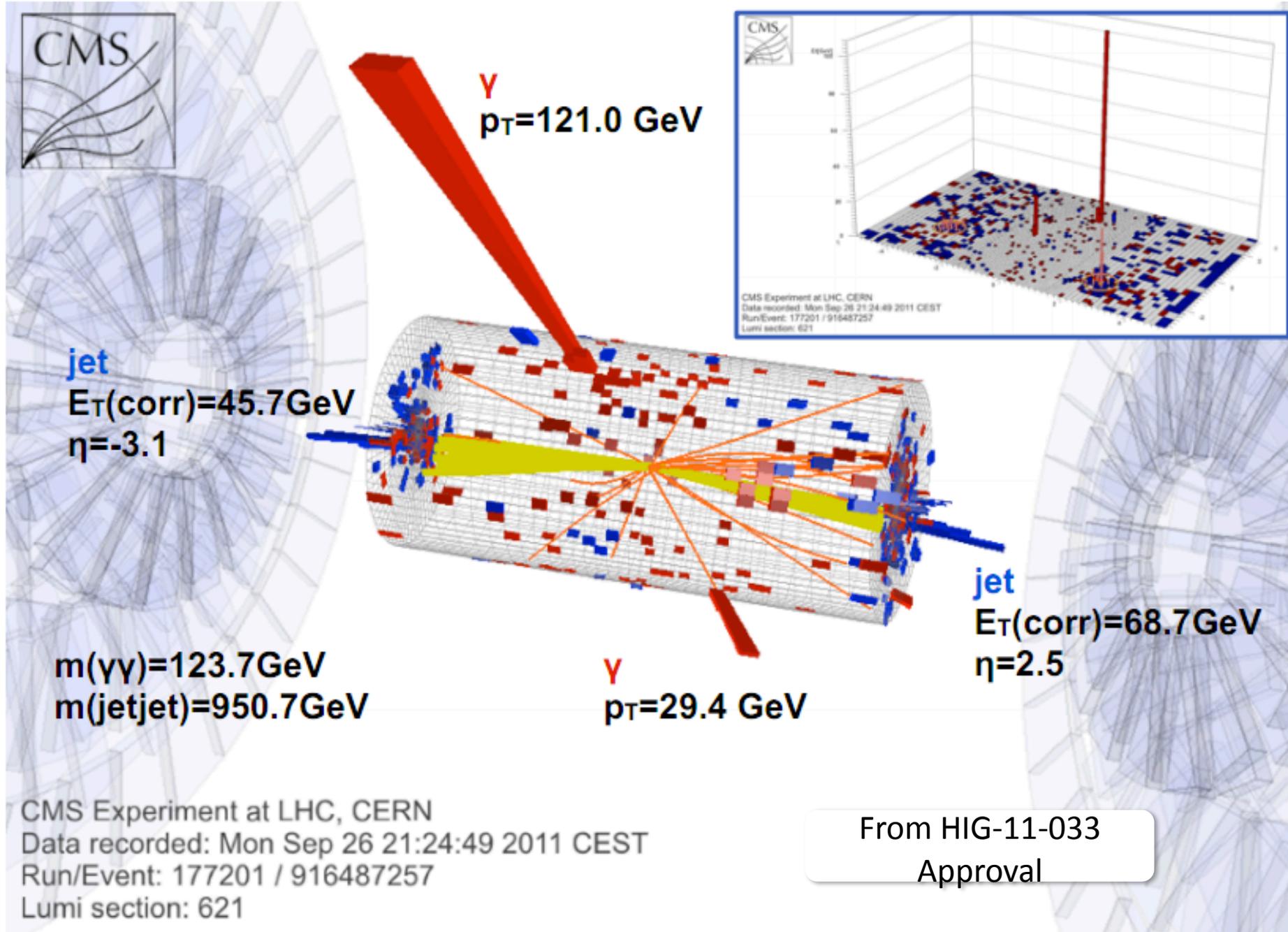
Expected S/B = O(1)

$$Z = \eta(\gamma\gamma) - \frac{\eta(\text{jet1} + \text{jet2})}{2}$$





Dijet Event Display



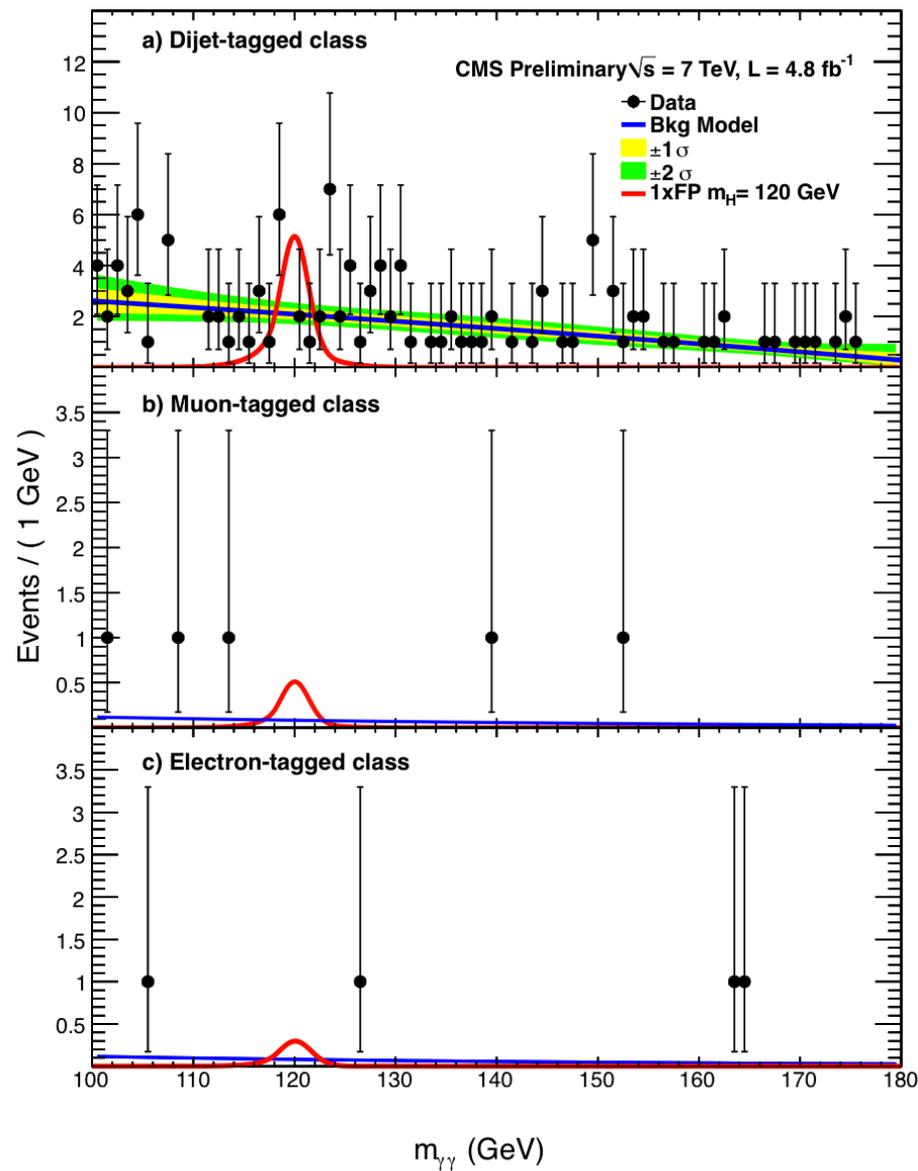


CMS FP Letpon Tag Channels for VH

- Lepton (muon, electron) Tag -VH
 - Same $\gamma\gamma$ event selection as in inclusive, but with $p_{T,1} > 45$ m/120, $p_{T,2} > 25$ GeV
 - Further reduce BKG by requiring
 - ID isolated lepton (muon or electron) with $p_T > 20$ GeV
 - minimal dR separation of lepton from each photon
 - minimal separation of $M_{e\gamma}$ to M_Z (in case of electron tag)
 - Presence of isolated lepton suppresses background from QCD, Predominant BKG is from EWK process with Z/W leptonic decays plus one γ .

Expected S/B > O(1)

CMS Mass in the tagging channel



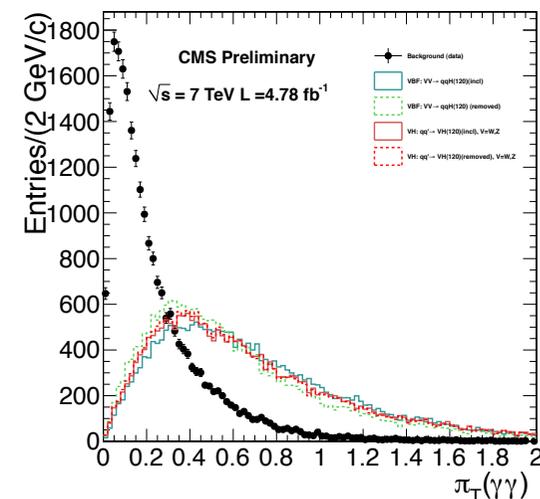


CMS FP 2D for VBF and VH

- Complement events from dijet-tag and lepton-tag channels, by the untagged events that pass the inclusive selection

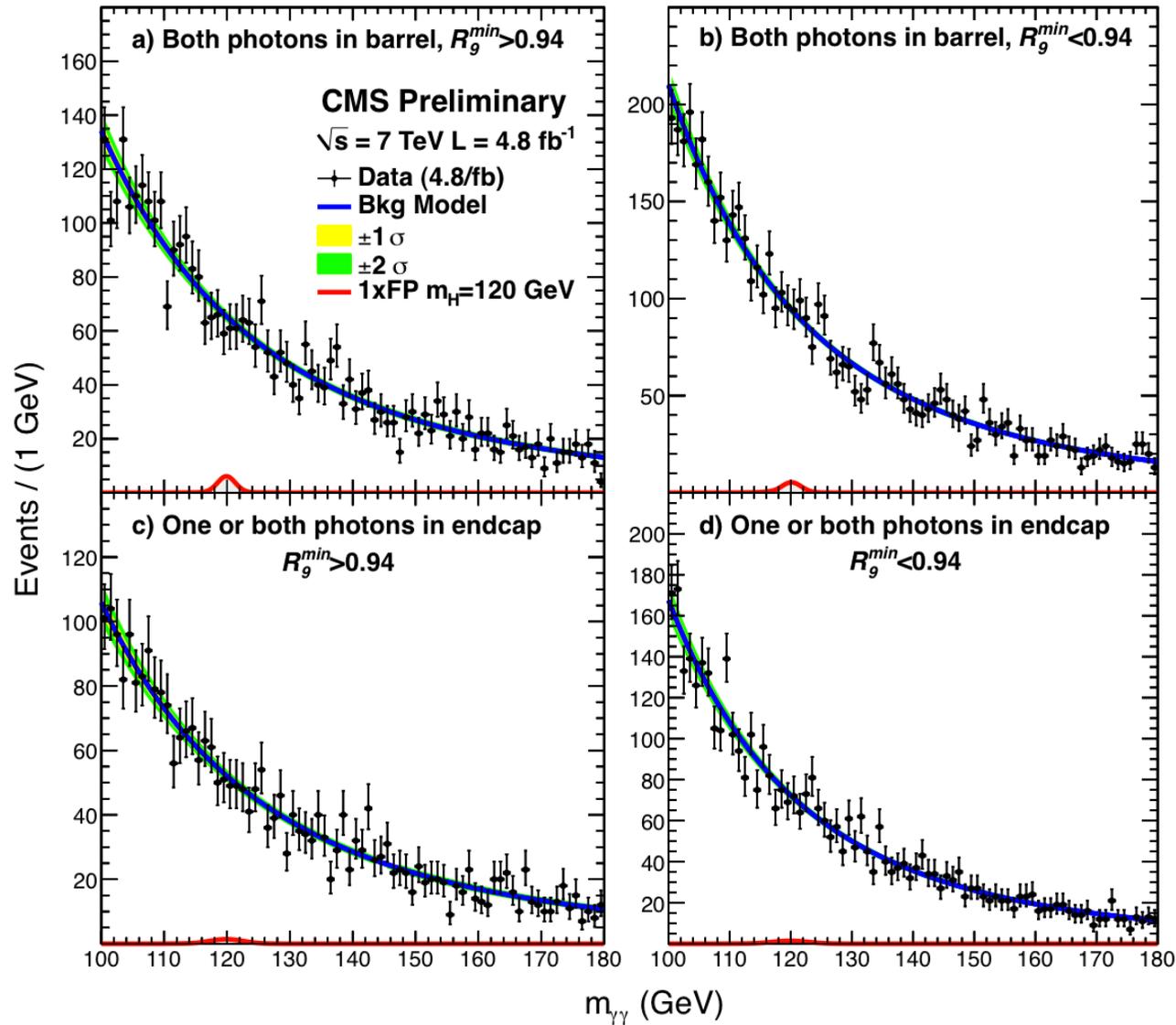
	All	EB high R_9 (0)	EB low R_9 (1)	non EB high R_9 (2)	non EB low R_9 (3)
MC Signal					
Di-jet tag	0.79	0.74	0.77	0.85	0.85
Lepton tag	0.74	0.70	0.73	0.80	0.81
Data					
Di-jet tag	0.995	0.992	0.994	0.998	0.996
Lepton tag	0.994	0.991	0.993	0.997	0.996

- π_T shown for VBF and VH signal at $M=120$ before (solid line) and after (dashed) exclusive-tagged events are removed. Each normalized to data (dots).
- Discrimination power of observable π_T does not change significantly after exclusively-tagged events are removed.

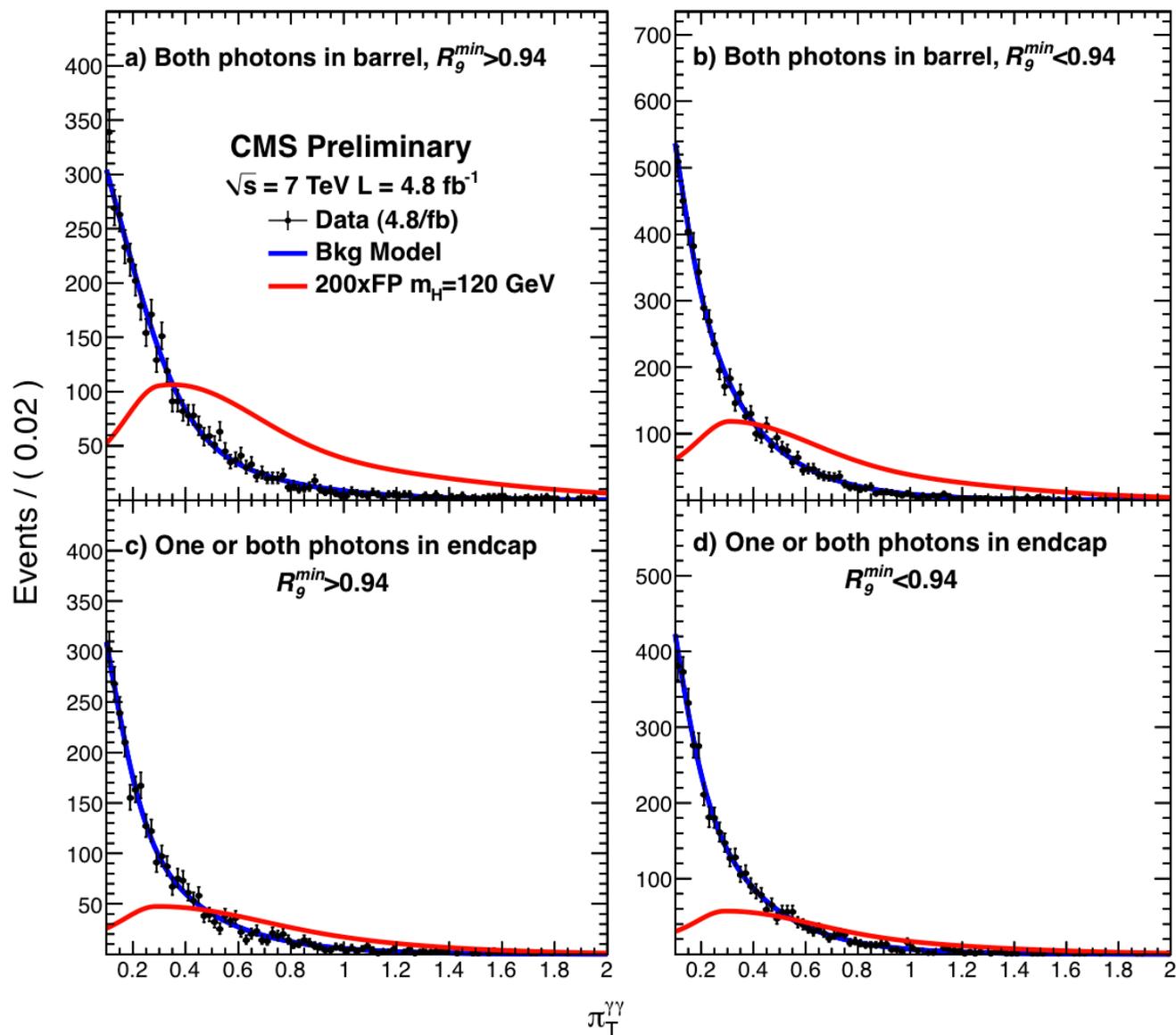


Model with power law including linear correlation with π_T

$$M_b^i(m_{\gamma\gamma}, \pi_T^{\gamma\gamma} | a_0, a_1) = m^{a_0 + a_1 \pi_T}$$

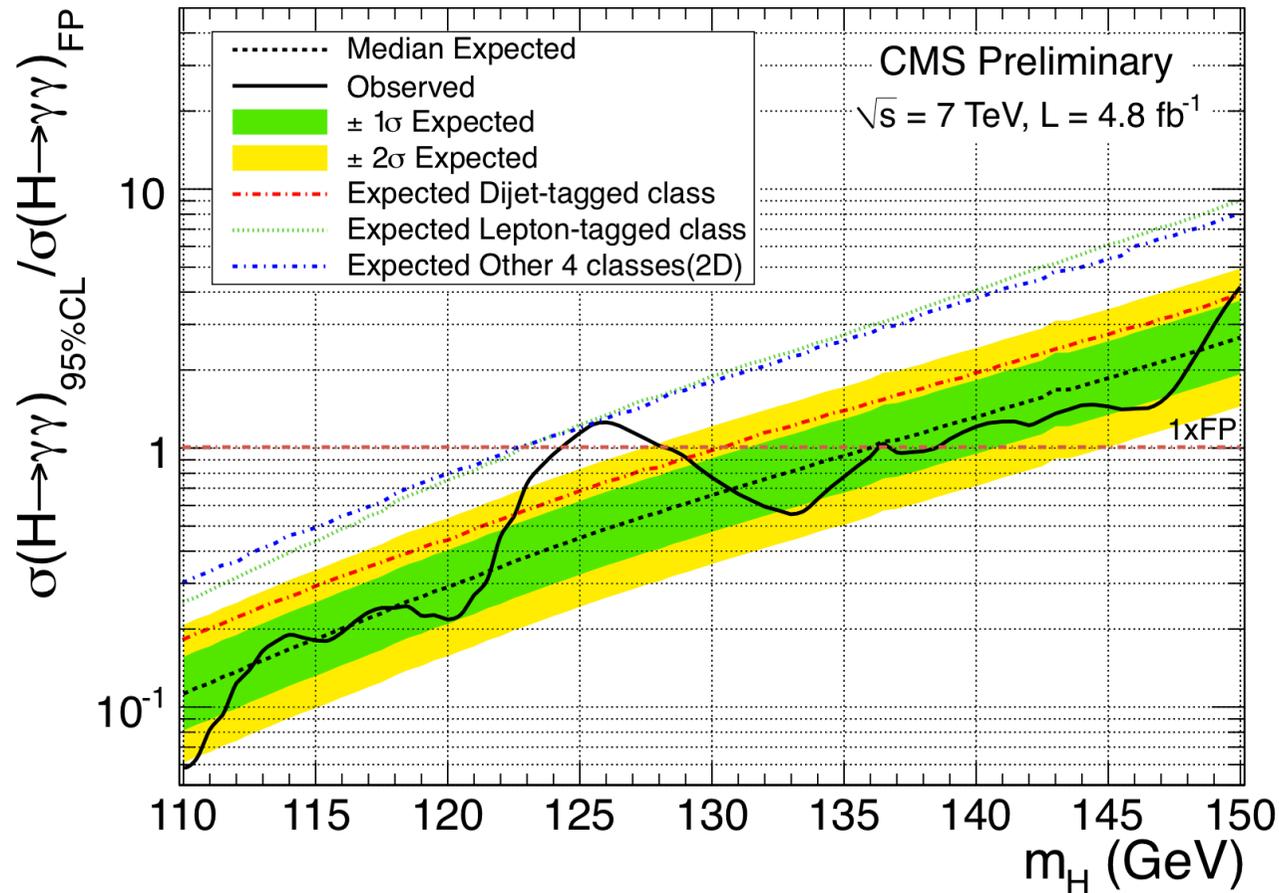


Model with Gaussian centered at zero plus Exp (3 parameters)





CMS FP Channels Combined – FP Limit



Expected combined limit at 135 GeV:

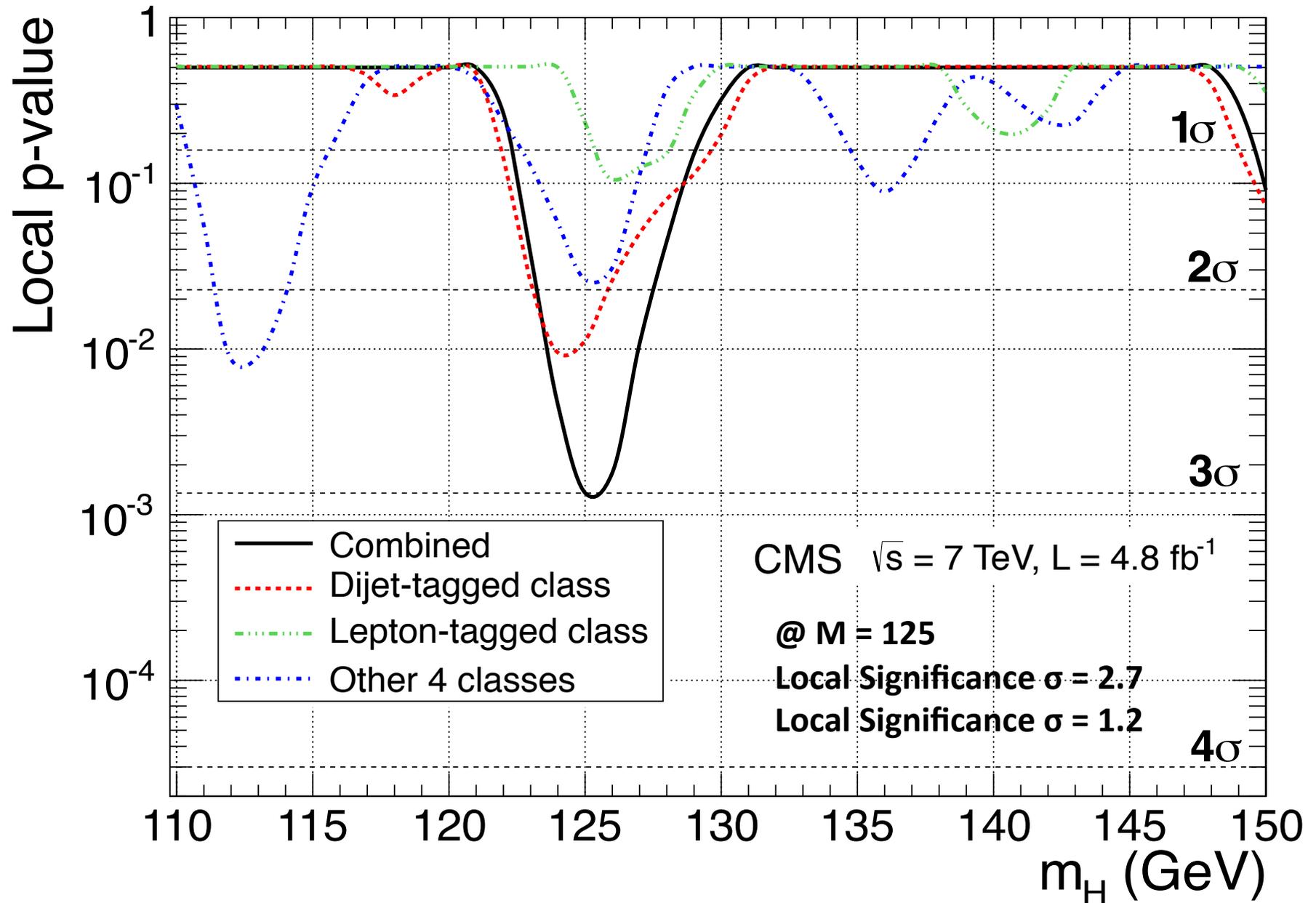
Dijet (130), Lepton (119), Inclusive w/o common events (122).

Improvements made to Dijet channel with Lepton (15%), 2D (20%).

Observed exclusion limit 110-123 and 128-135 GeV.

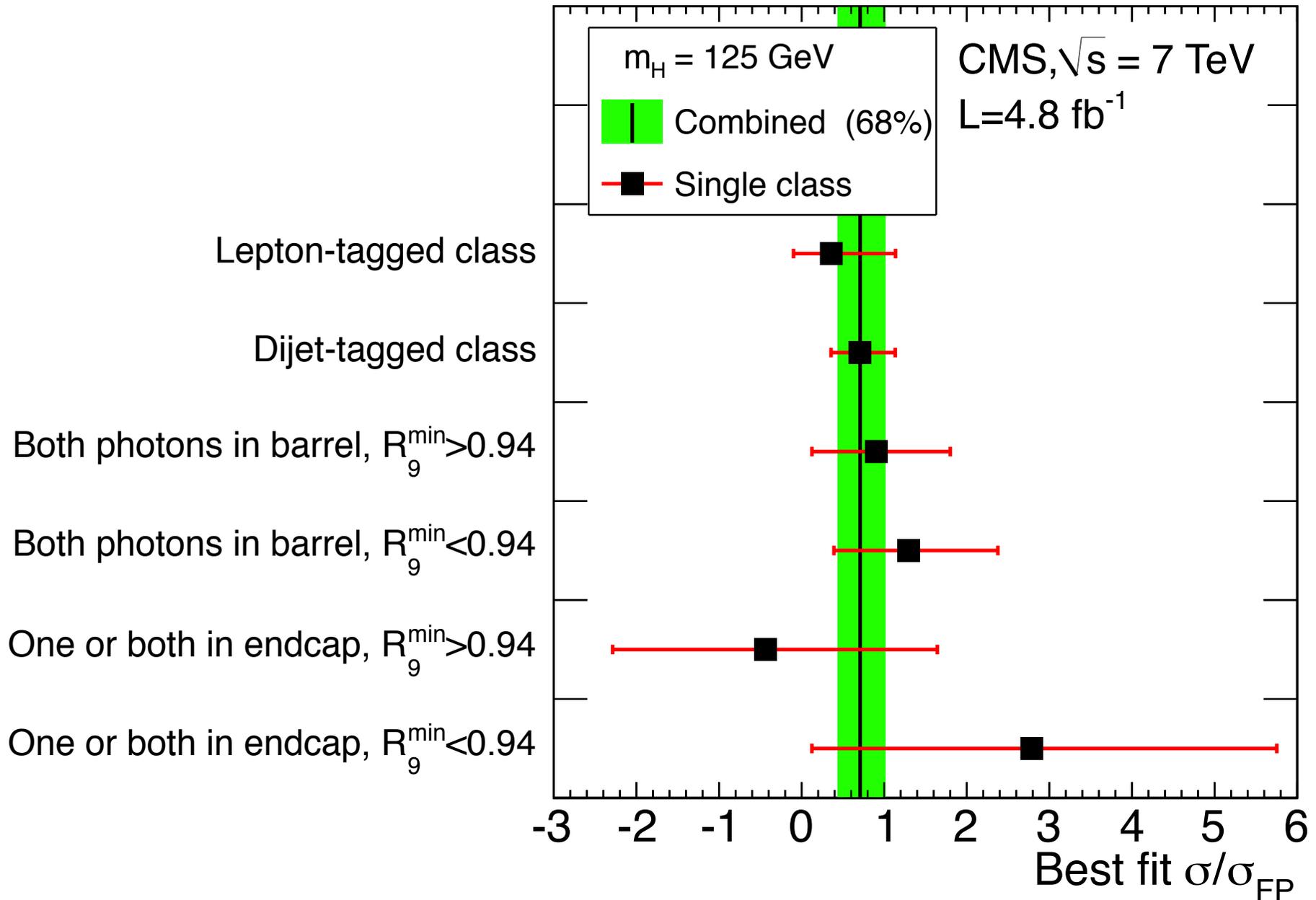


Combined Channels p-value





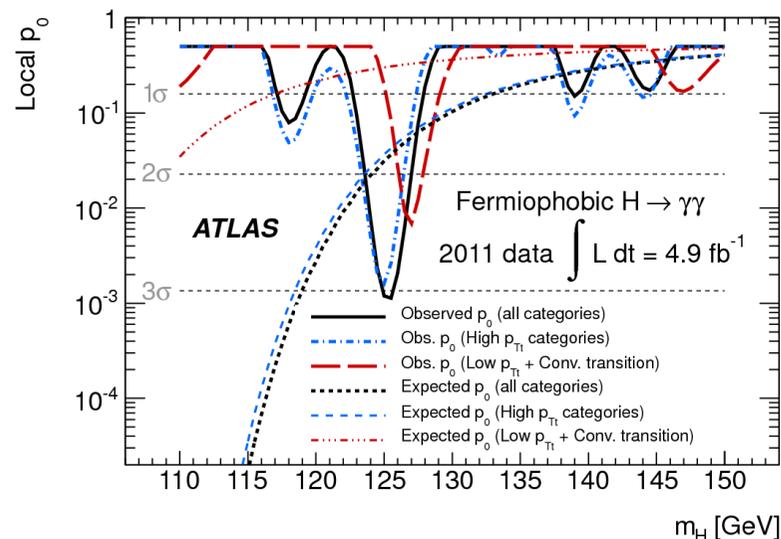
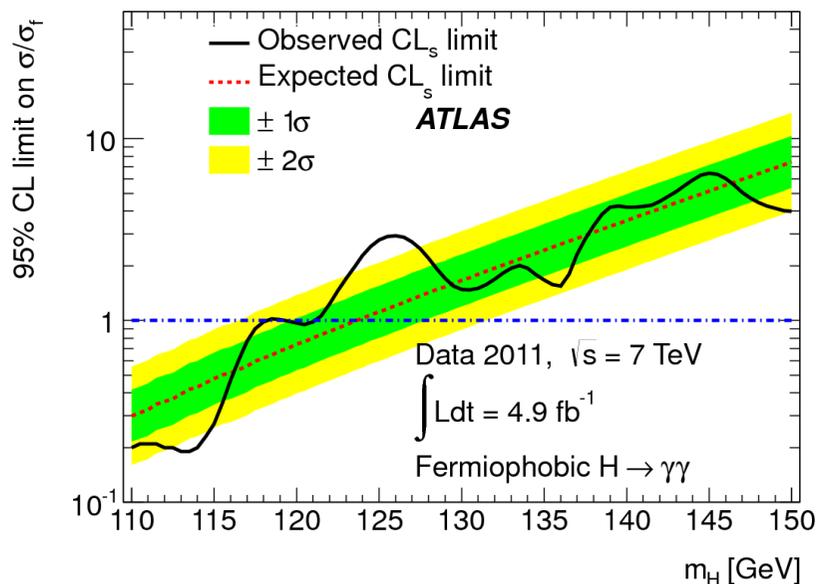
CMS FP - Signal Strength Best Fit





ATLAS FP Limit – Interpretation of SM Analysis

arXiv:1205.0701, came out yesterday, May3



Expected combined limit at 135 GeV:

Dijet (130), Lepton (119), Inclusive w/o common events (122).

Improvements made to Dijet channel with Lepton (15%), 2D (20%).

Observed exclusion limit 110-123 and 128-135 GeV.



Conclusions

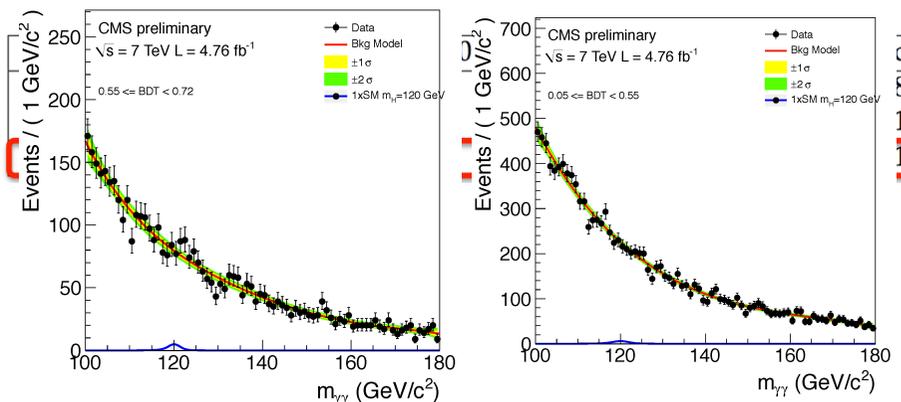
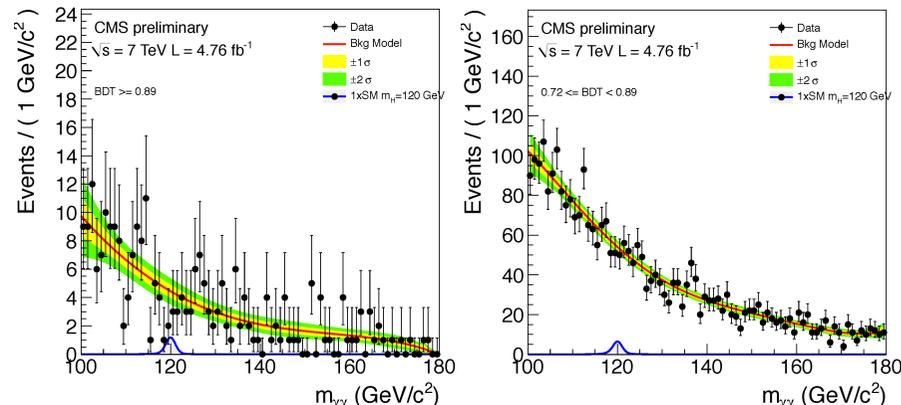
- Both CMS and ATLAS performed a search for a SM Higgs,
 - Excluding $m(H)$ observing excess over expected limit around 125.
 - CMS: ~ 125 GeV with local (global) significance 2.9σ (1.8σ)
 - ATLAS: ~ 126 GeV with local (global) significance 2.8σ (1.5σ)
- Both ATLAS and CMS performed a search for FP Higgs
 - CMS: Dedicated analysis Excluding FP Higgs 110-137 GeV (except for 124-128 GeV)
 - ATLAS: Interpretation of SM analysis. Excluding FP Higgs 110-121 GeV (except for 118-119.5 GeV)
 - Both observe excess over expected limit around 125 GeV
 - In case of CMS, the data could suggest that the signal strength could be slightly weak to be FP.



BACKUP

HIG-12-001

- 4 non-VBF event classes split based on the diphoton BDT classifier output
- BG is estimated by fitting to a polynomial in the full mass range (3rd to 5th order)
 - Possible BG bias is always less than 20% of the statistical error



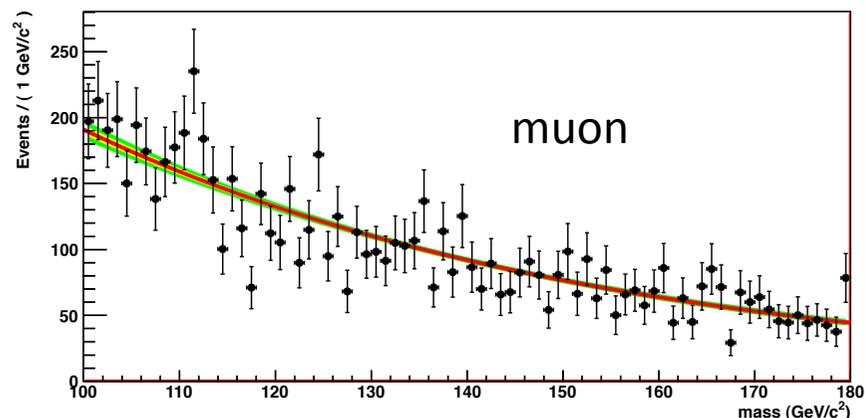
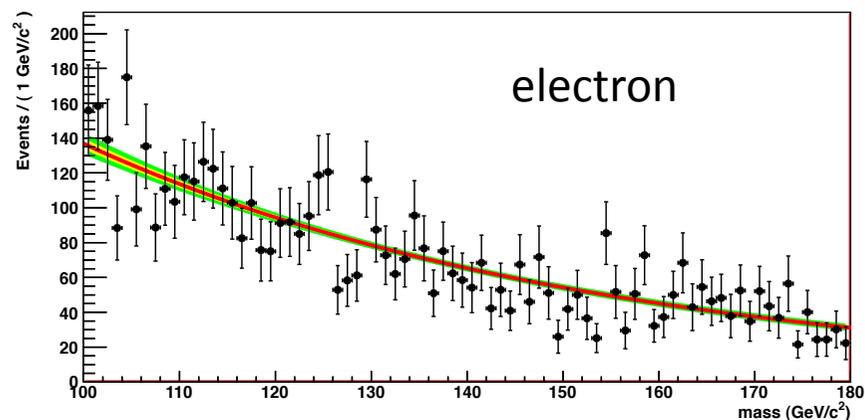
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Lepton Tag – Background Estimation

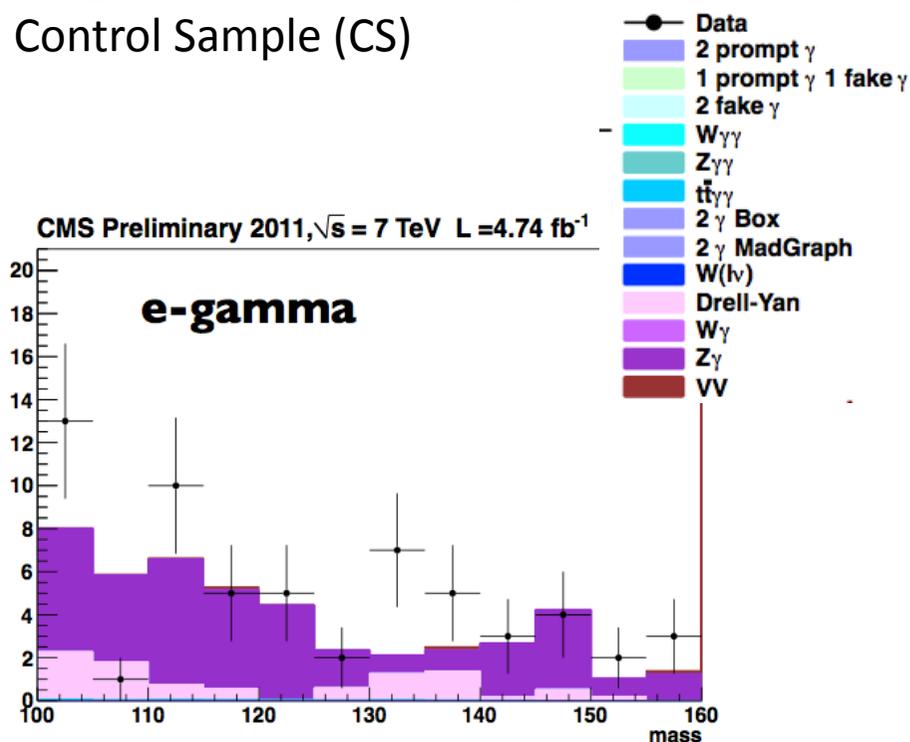
Background shape is obtained from MC irreducible background.
Use single Exponential function.

Irreducible background from MC:



For electron tag: reducible background from data CS by inverting track veto on one photon.
weighted sum of fit to e-gamma

Control Sample (CS)





CMS- FP Summary of Systematic Uncertainties

Source		Uncertainty	
Photon identification efficiency:	barrel	1.0%	
	endcap	2.6%	
$R_9 > 0.94$ efficiency (results in class migration)	barrel	4%	
	endcap	6.5%	
Energy resolution ($\Delta\sigma/E_{MC}$):	barrel low η , high η	$R_9 > 0.94$	$R_9 < 0.94$
	endcap low η , high η	0.22%, 0.61%	0.24%, 0.59%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	barrel low η , high η	0.91%, 0.34%	0.30%, 0.53%
	endcap low η , high η	0.19%, 0.71%	0.13%, 0.51%
Integrated luminosity	barrel low η , high η	0.88%, 0.19%	0.18%, 0.28%
	endcap low η , high η	4.5%	
Trigger efficiency: One or more photons $R_9 < 0.94$ in endcap	Other events	0.4%	
		0.1%	
Vertex finding efficiency		0.4%	
Dijet tagging efficiency (VBF process)		10%	
Charged lepton identification efficiency:		1.0%	

Vector boson fusion process cross section (scale)	+0.5% -0.3%
Vector boson fusion process cross section (PDF)	+2.7% -2.1%
Associated production with W/Z cross section (scale)	+1.8% -1.8%
Associated production with W/Z cross section (PDF)	+4.2% -4.2%
BR in the FP model	5%

$$-\log \mathcal{L} - \log g(\theta_s) = NLL_0 + NLL_P$$

← Put into likelihood via penalty term