CMS Measurements of the Higgs-like Boson in the $\gamma\gamma$ Channel

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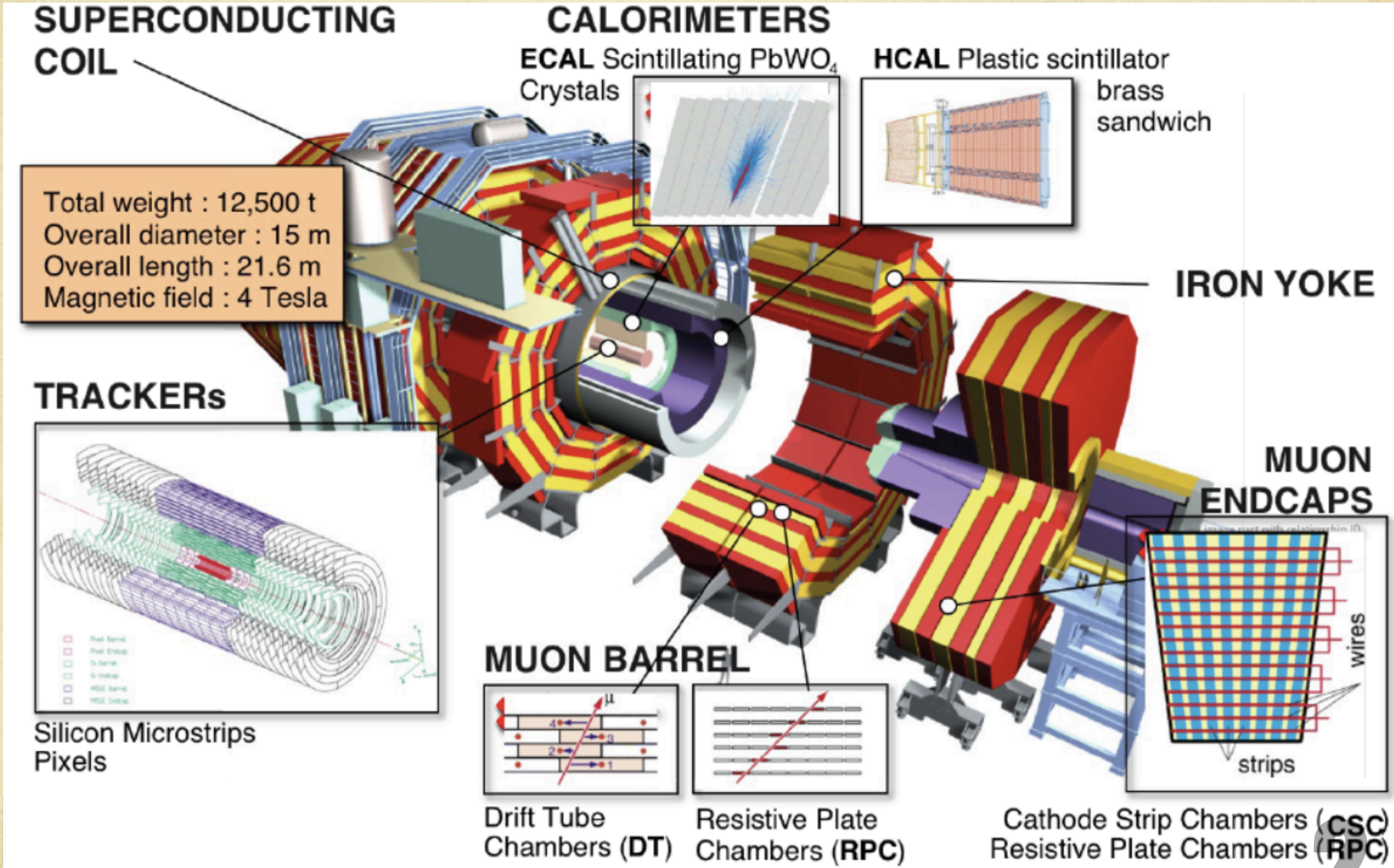
On Behalf of the CMS Collaboration

LISHEP 2013, Rio de Janeiro

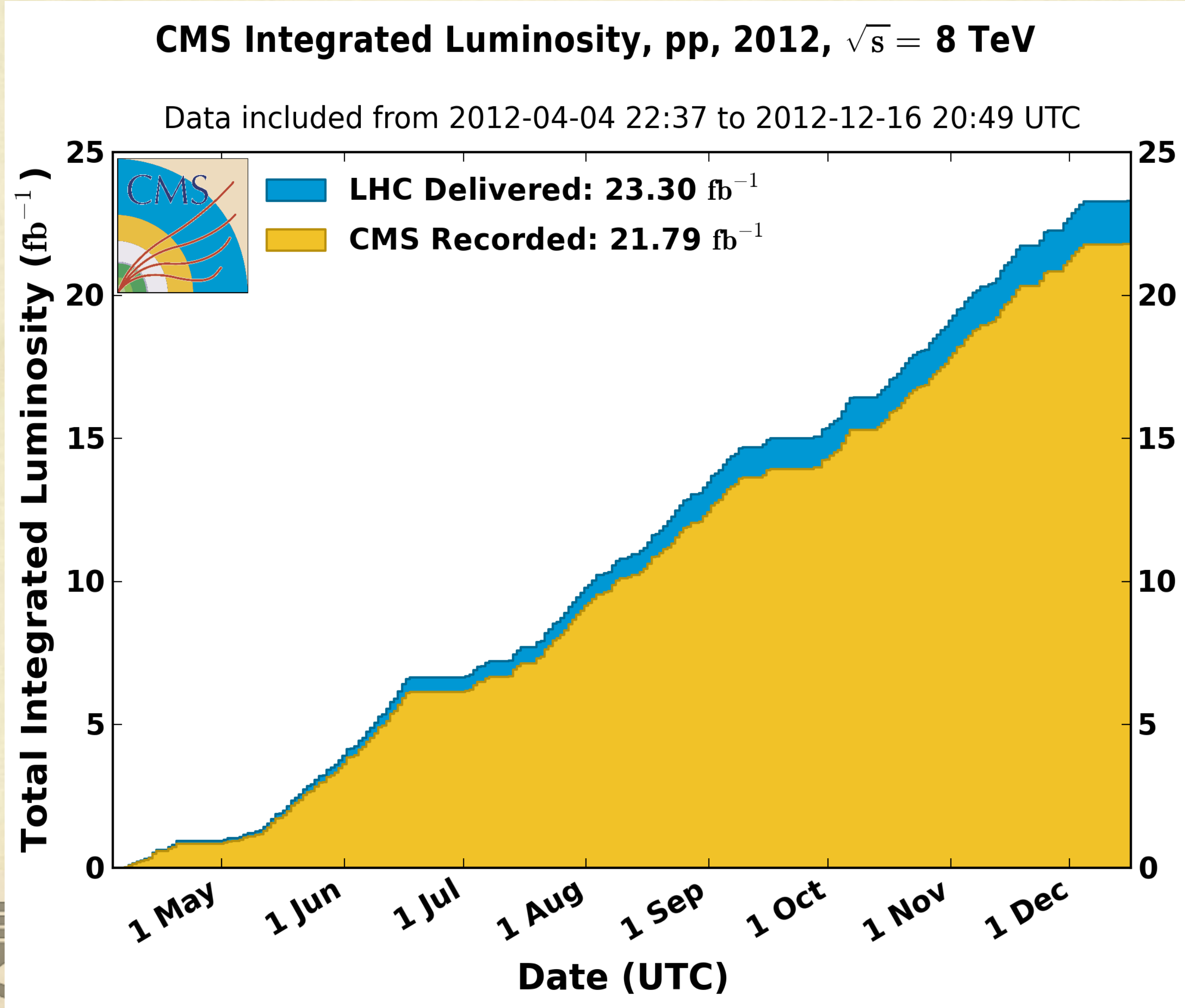
CMS Detector



Dataset

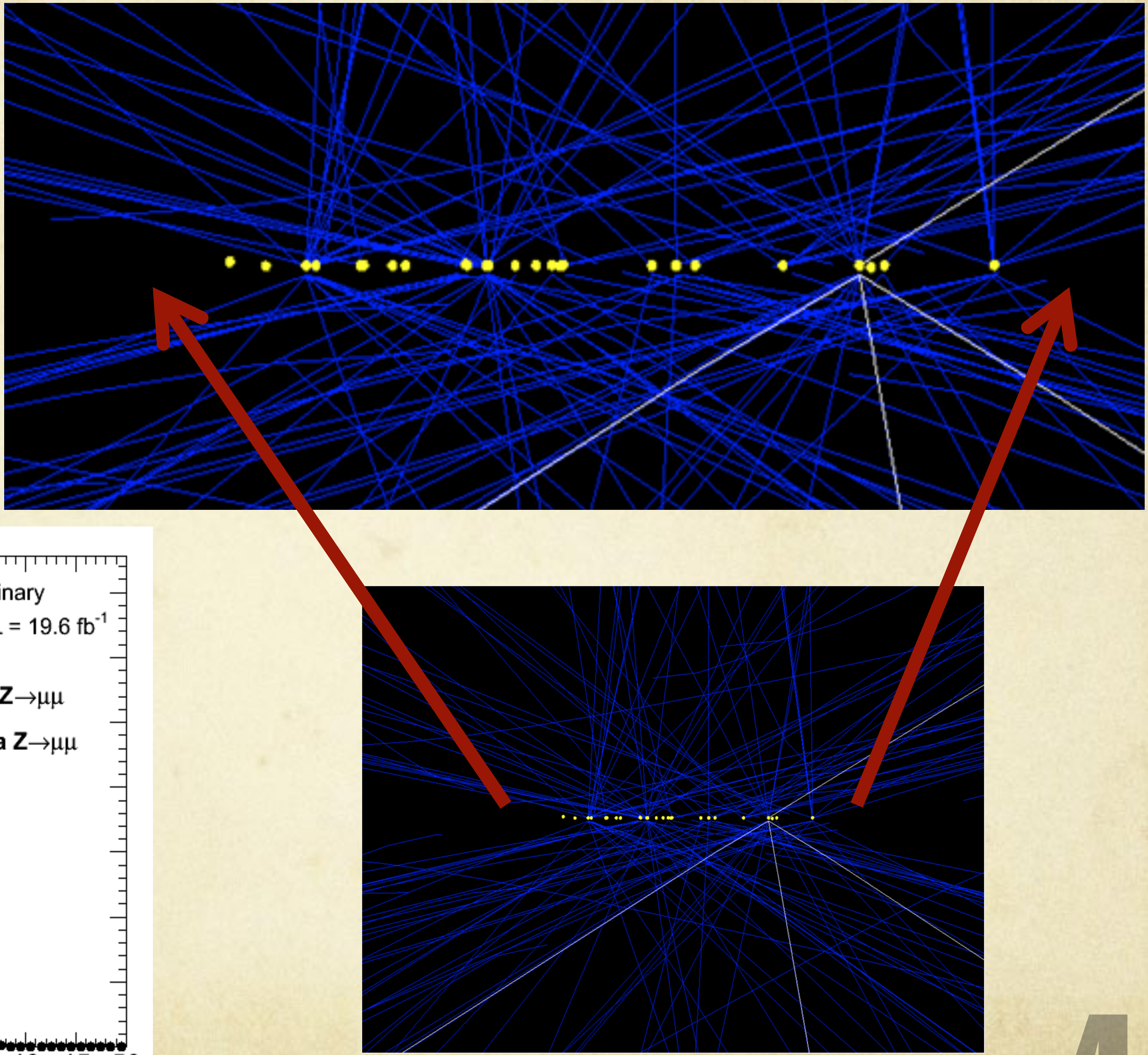
- Thanks to excellent collision delivery from LHC (>29 fb^{-1}) and great data collection from CMS (efficiency > 90%)

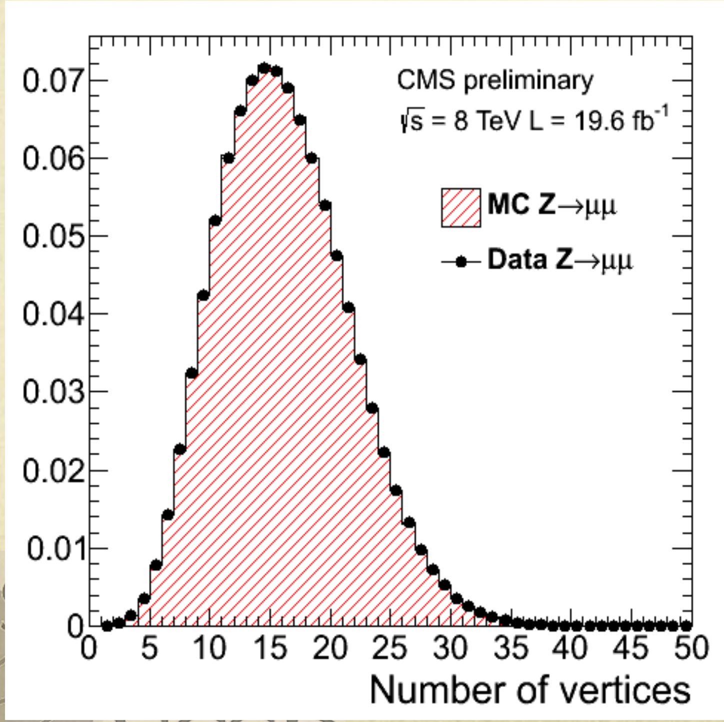
- 2011 dataset – 5.1 fb^{-1}
- 2012 dataset – 19.6 fb^{-1}



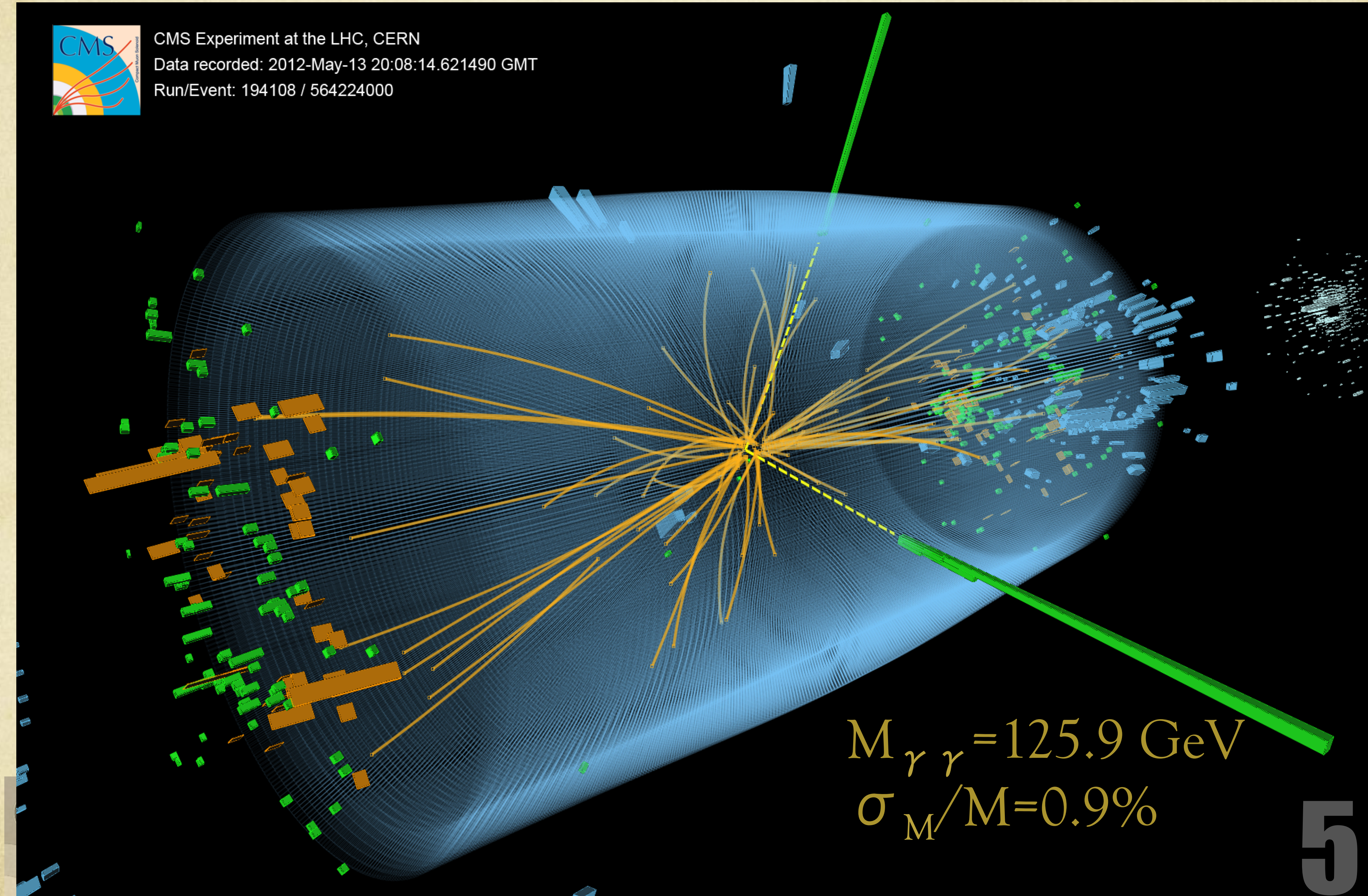
Pile Up (PU)

- Beam conditions yield multiple collisions in recorded events
  - <PU>$_{2012}$ = 20



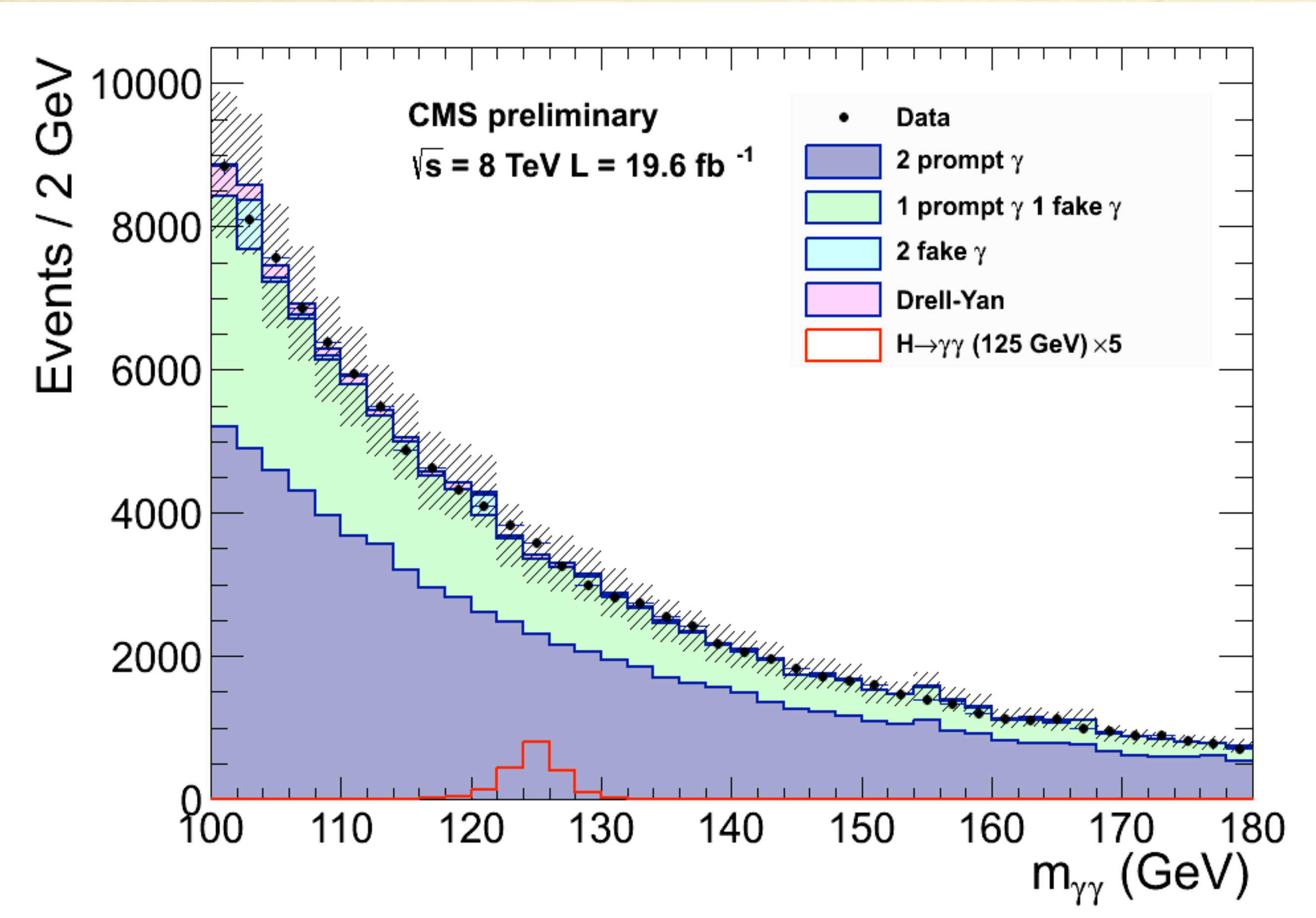


Di-photon Candidate



Updated analysis on the full dataset

- Added more exclusive channels in 2012 analysis
- Added MVA in dijet selection for the MVA analysis in 2012 analysis
- 2011 data analysis is the same as in published discovery paper
- Strategy is kept as in previous analysis:
  - Look for narrow peak on a smoothly falling continuous background



MC background **not used for the BKG estimation** but only for analysis optimization

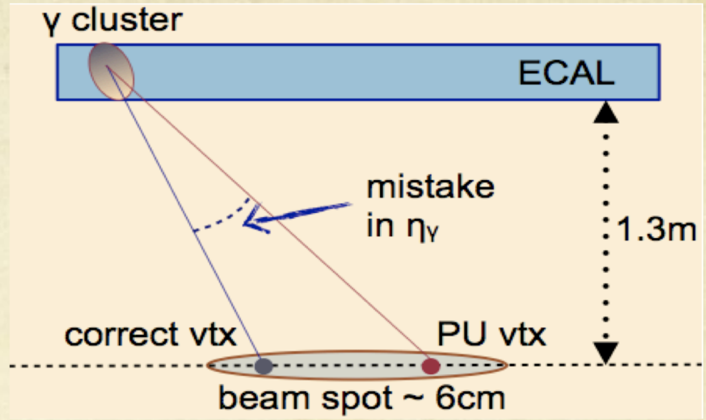
Analysis described in PAS HIG-13-001

Analysis Strategy

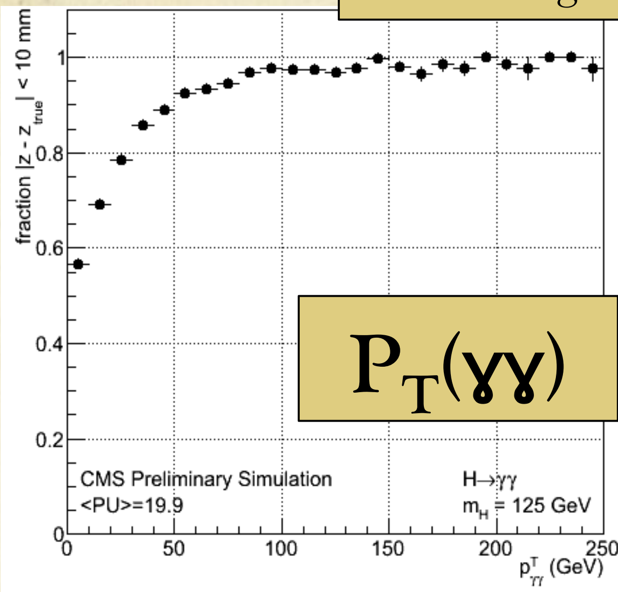
- Select events with two high E_T, well-isolated photons
- Events are separated in exclusive categories with different S/B and resolution.
- Special “tagged” categories enriched in VBF and VH signal production.
  - Improve the sensitivity of the analysis for the coupling measurements.
- Background directly estimated from data
  - Fit the $\gamma\gamma$ invariant mass in categories using polynomials (3rd-5th order)
- Two different analysis
  - Multivariate (MVA): select and categorize events using a BDT
  - Cut-based (CiC): cut-based photon identification; categorized by shower shape and detector region
- **Baseline result: MVA approach** (about 15% better expected sensitivity)

Vertex Selection

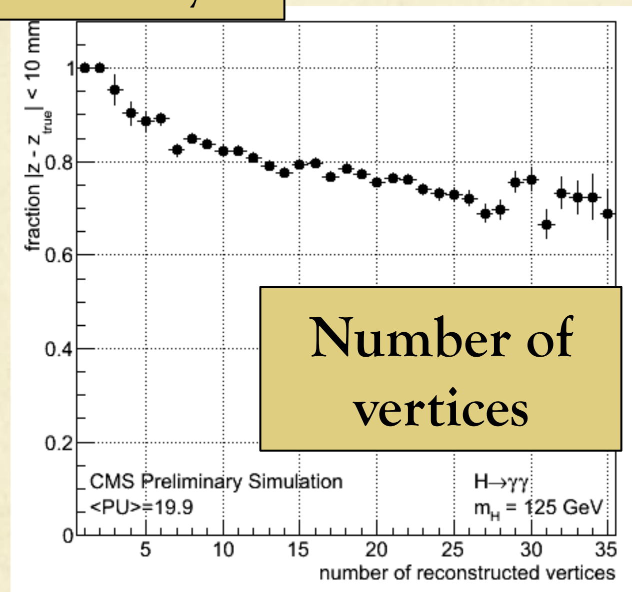
- Higgs production vertex is selected using a Boosted Decision Tree (BDT)
- Σp_T^2 of vertex tracks
- Vertex recoil wrt diphoton system
- Pointing from converted photons.



MC Signal Efficiency



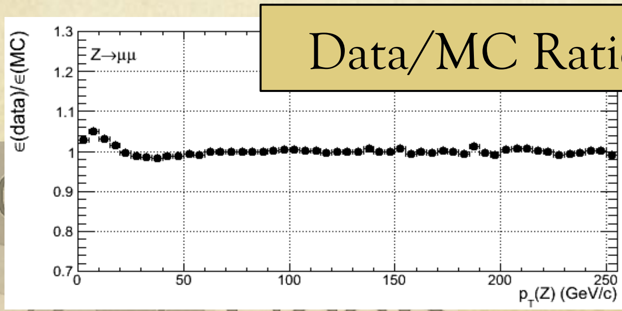
$P_T(\gamma\gamma)$

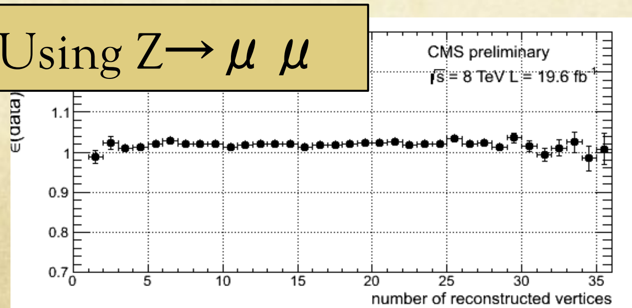


Number of vertices

- Control samples are used for BDT validation
- $Z\rightarrow\mu\mu$ for unconverted photons
- γ +jets for converted photons

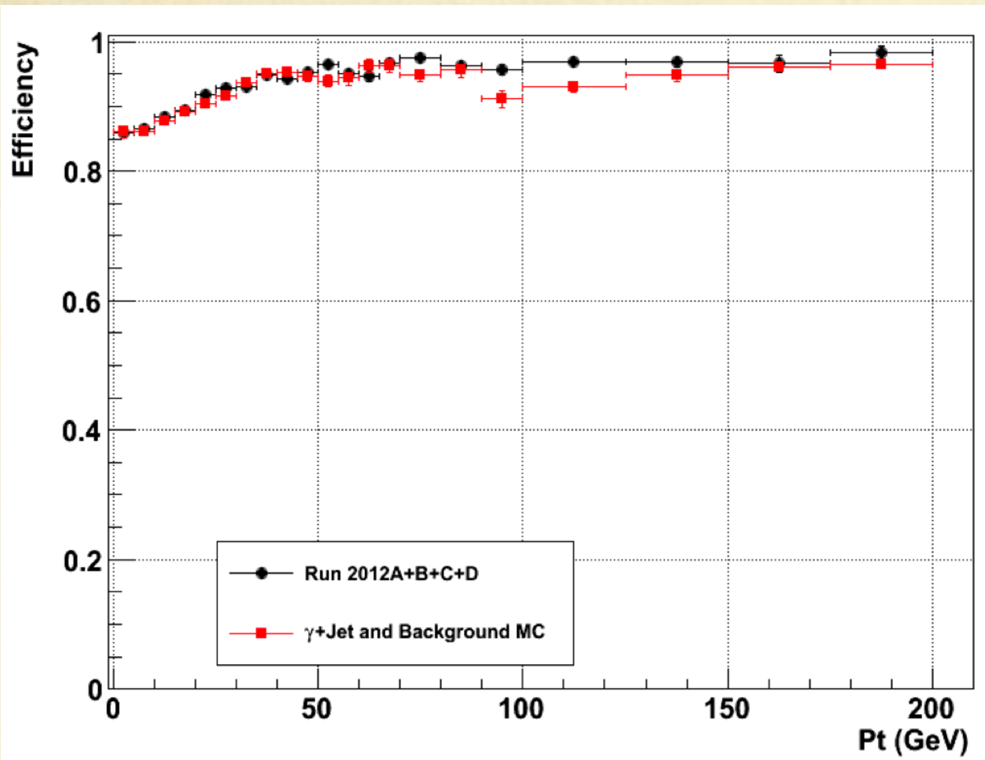
Data/MC Ratio Using $Z\rightarrow\mu\mu$

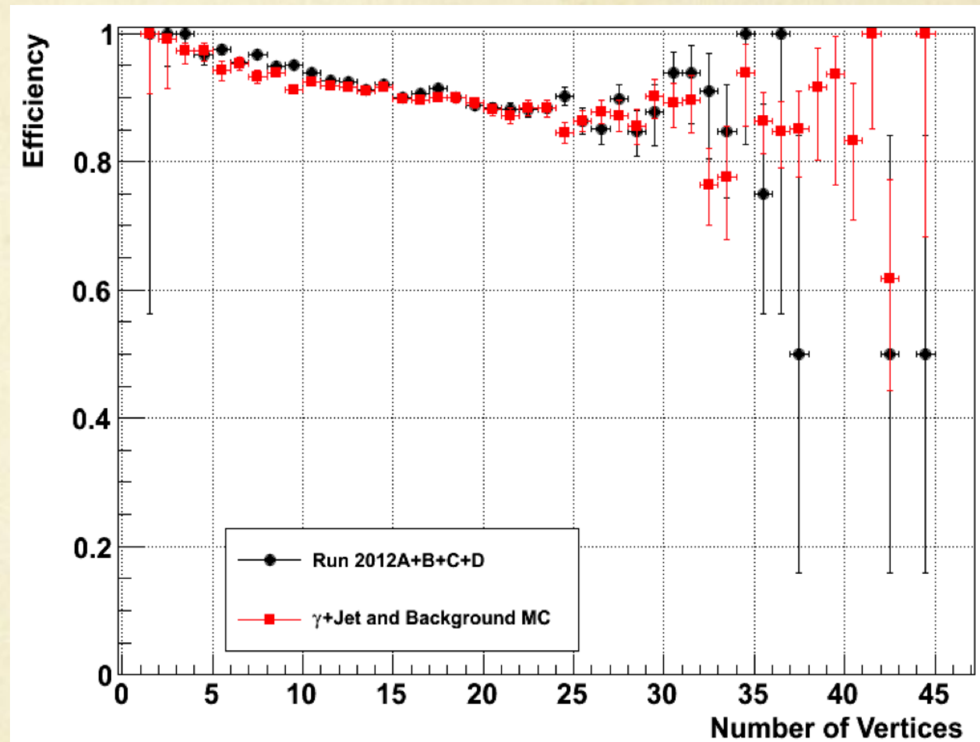




Vertex from Converted Photons in γ +jet Events

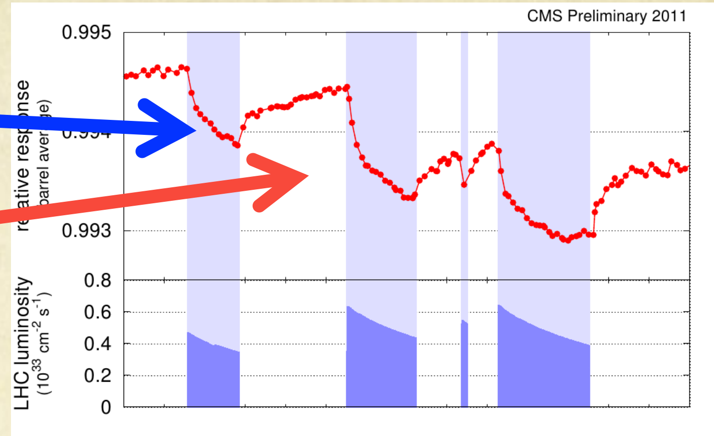
Vertex pointing from reconstructed conversions from photons is validated with γ +jet



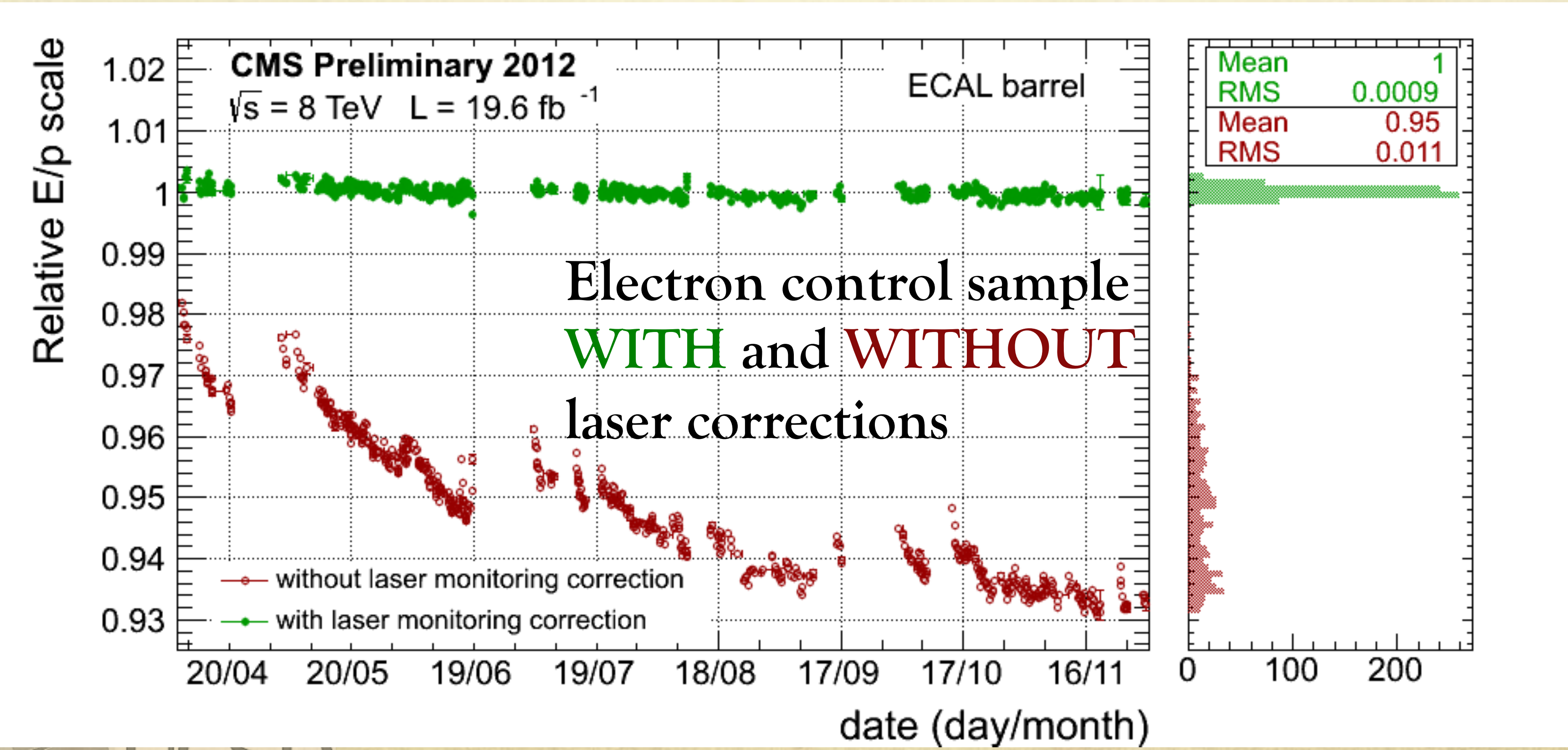


ECAL Transparency Loss/Recovery

- During collisions Electromagnetic CALorimeter (ECAL) losses transparency
  - This is expected and measured with laser monitoring
  - Some transparency is recovered during downtime
- ECAL measurements are calibrated using this data

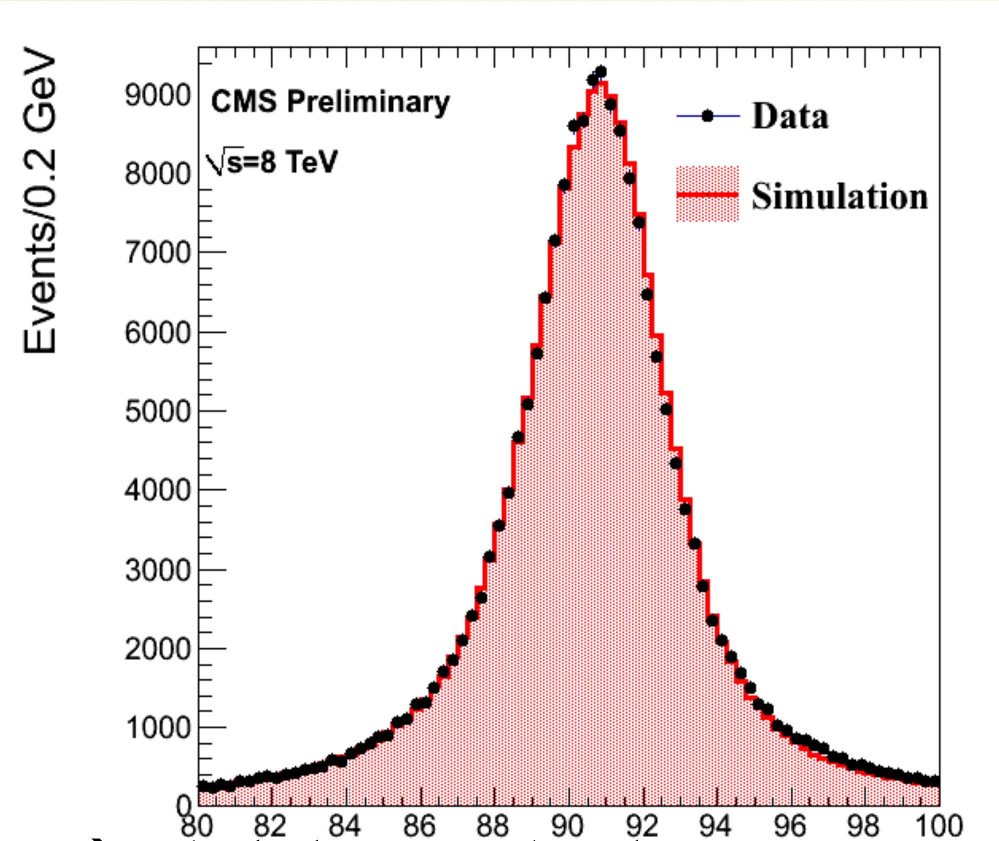


Laser response vs time



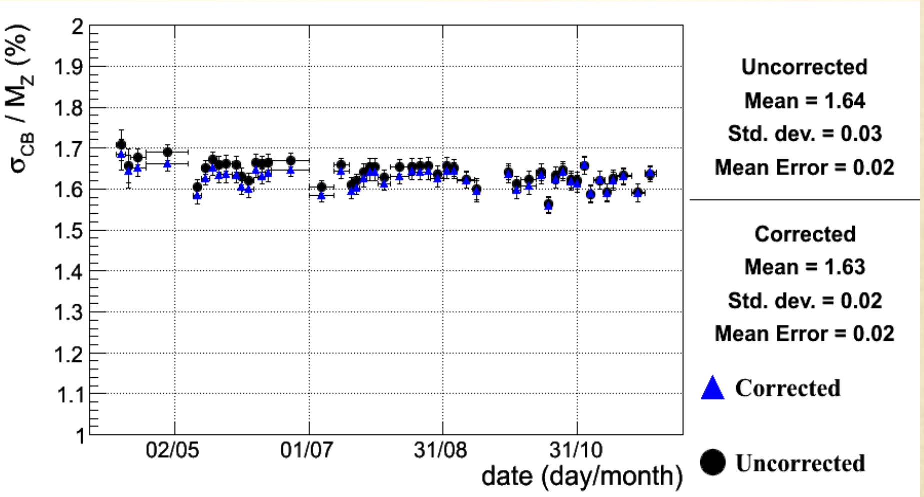
ECAL Performance

- Very good ECAL performance in 2012
- Z→ee mass resolution better than 1.2% for electrons with low bremsstrahlung in the barrel.
- Stable performance already using promptly reconstructed data

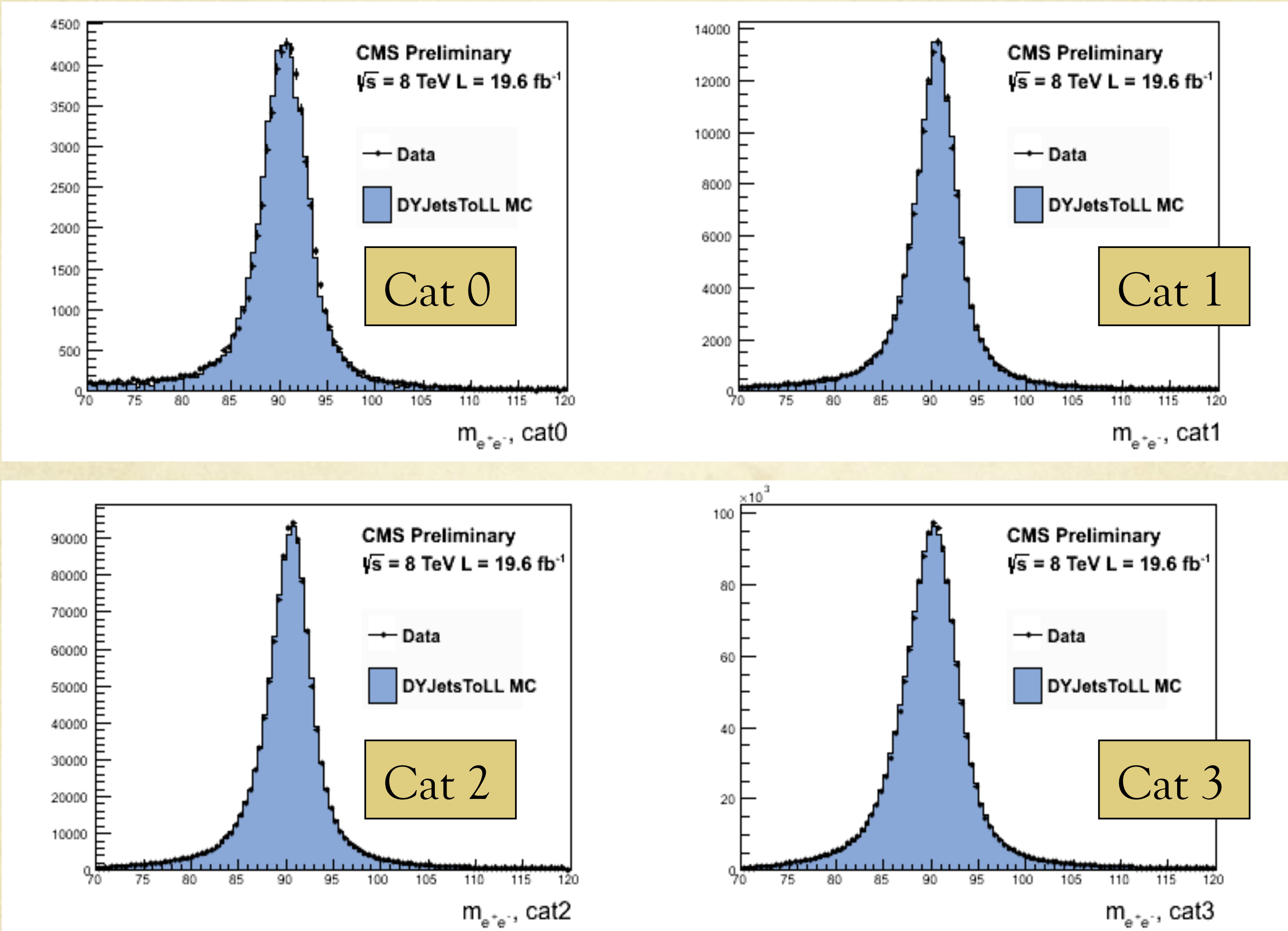


Z→ee; both electrons in barrel with low bremsstrahlung

Z mass resolution as a function of time after application of analysis level corrections

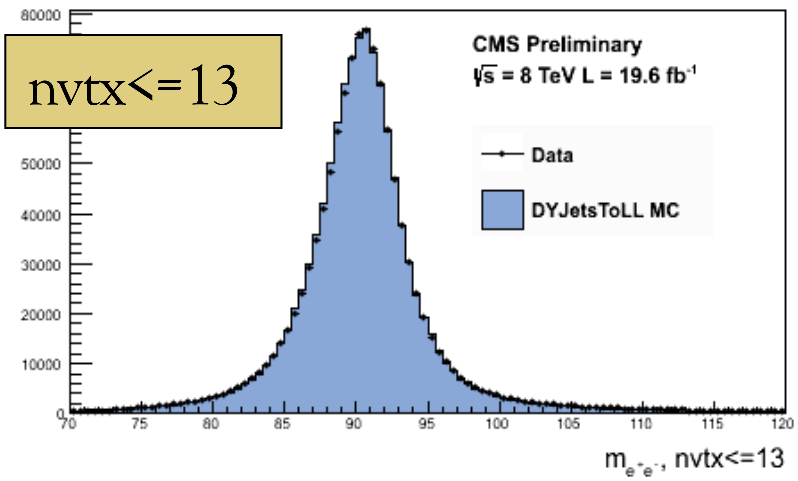


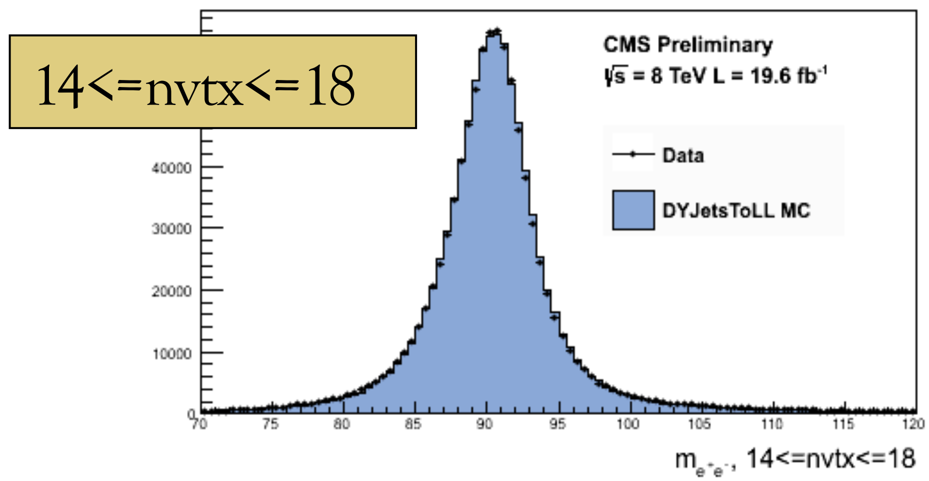
Energy Scale in MVA Categories with Z→ee Events

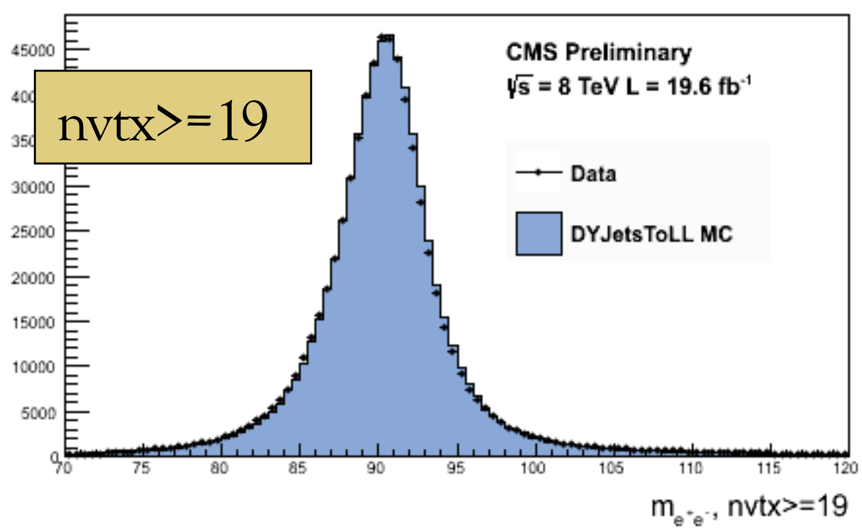


Electrons are treated as photons

Pile-Up Robustness - Energy Scale/Resolution





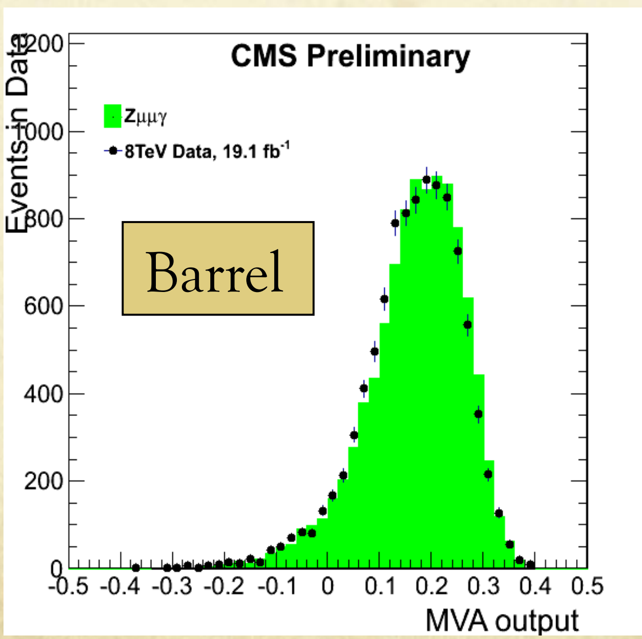


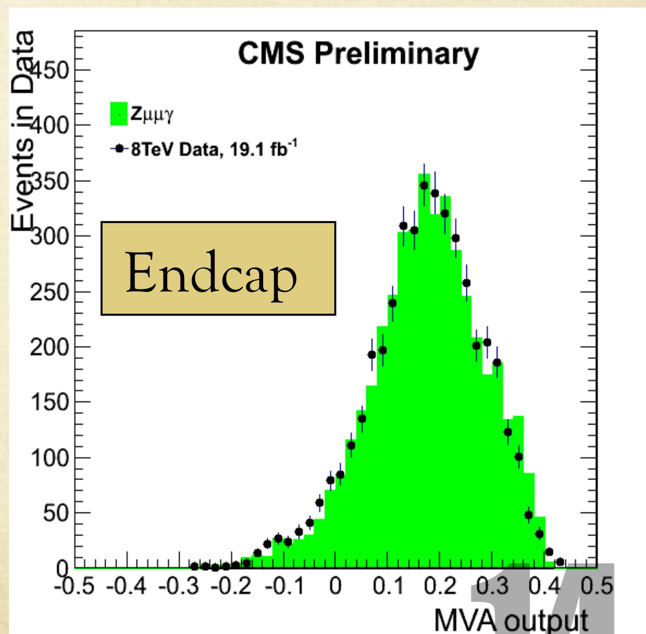
Data-MC agreement in Z→ee validation maintained across nvtx bins

Photon ID MVA

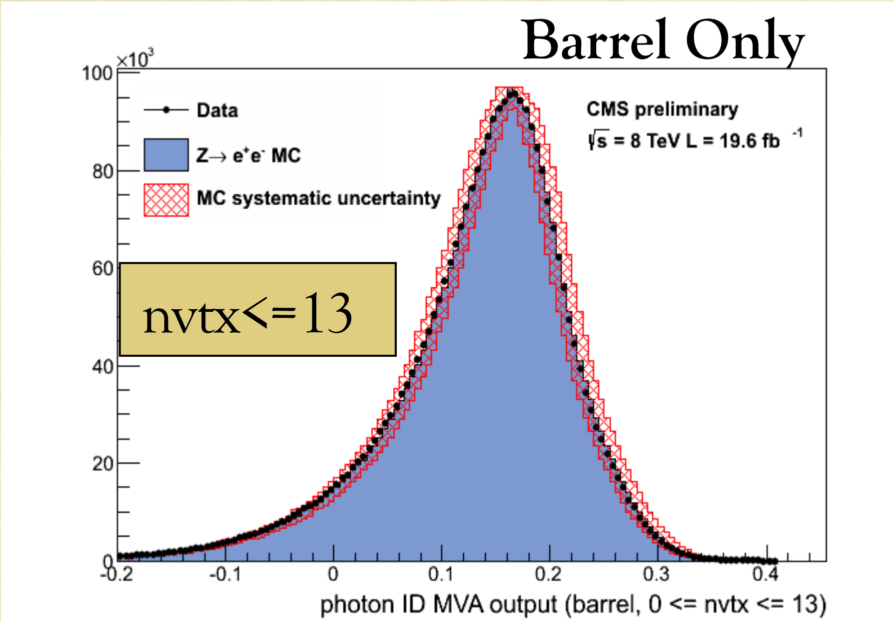
- Inputs
  - Several shower shape variables (MC corrected to match data shape)
  - Isolation
    - Energy from other particles close to photons
  - Average energy density
    - Correlated to PU
  - Detector region (η)
- Output
  - Validated with Z→ee and Z→ $\mu \mu \gamma$
  - Shape corrections derived with Z→ee
    - Applied before used as input to di-photon MVA

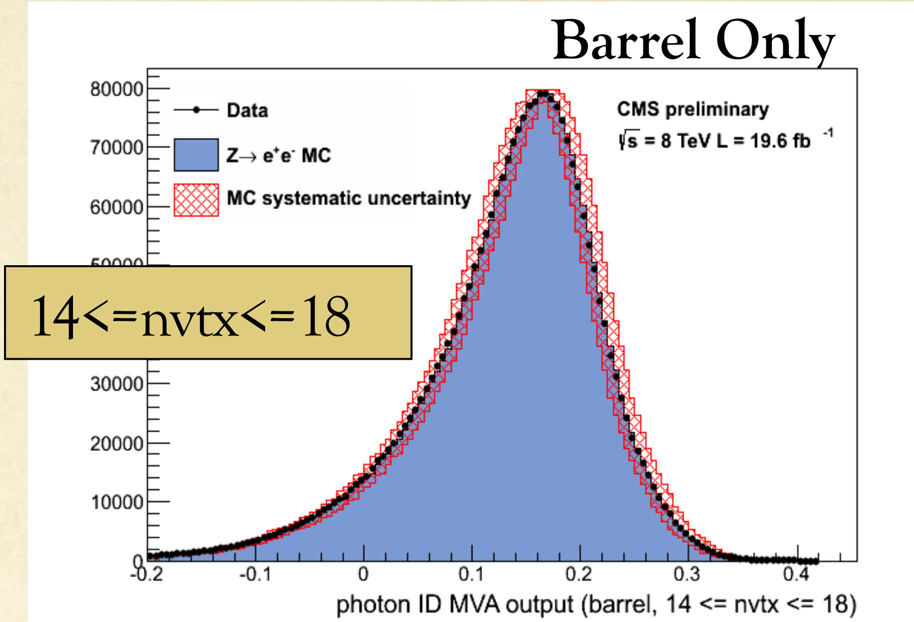
Z→ $\mu \mu \gamma$ Validation

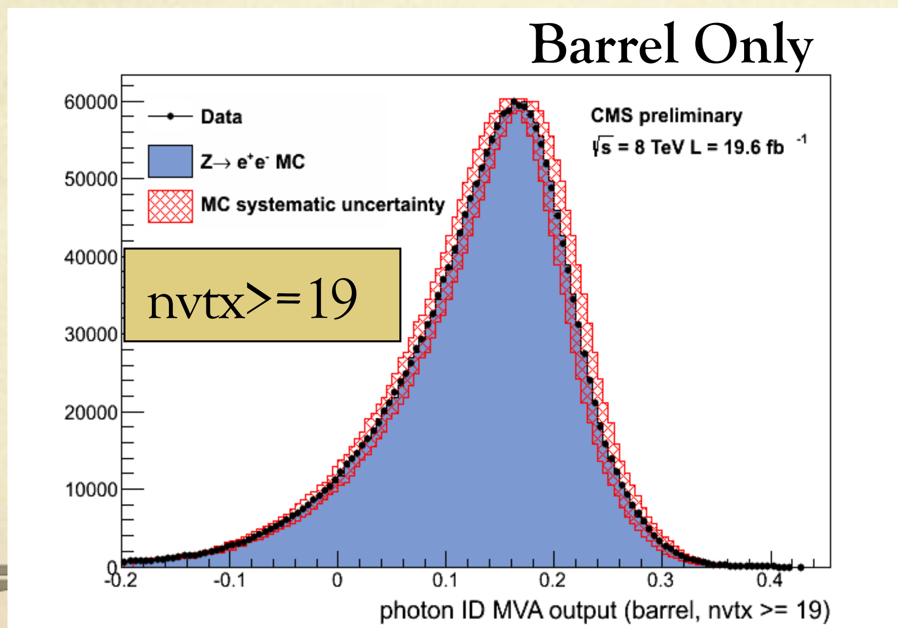




Photon ID MVA – PU Bins



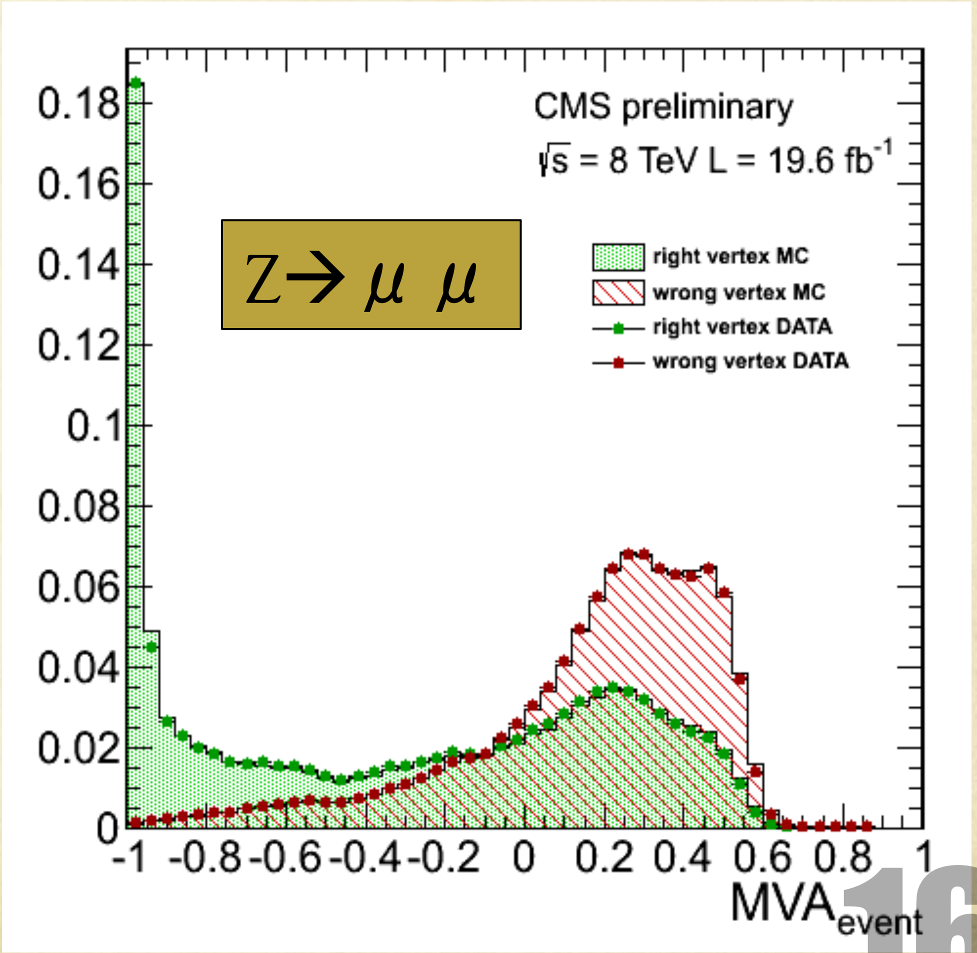




Data-MC agreement in Z→ee validation maintained across nvtx bins

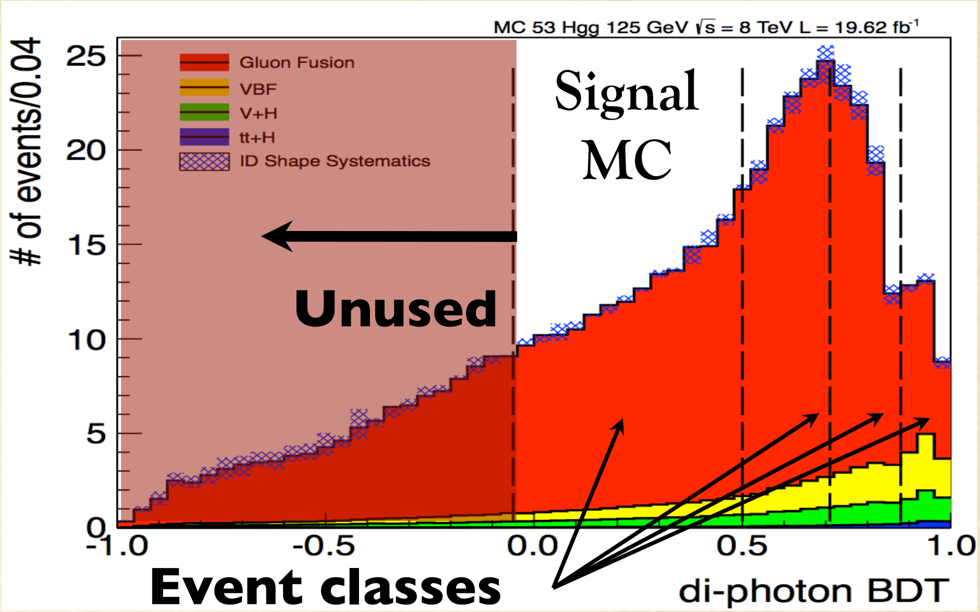
Vertex Probability

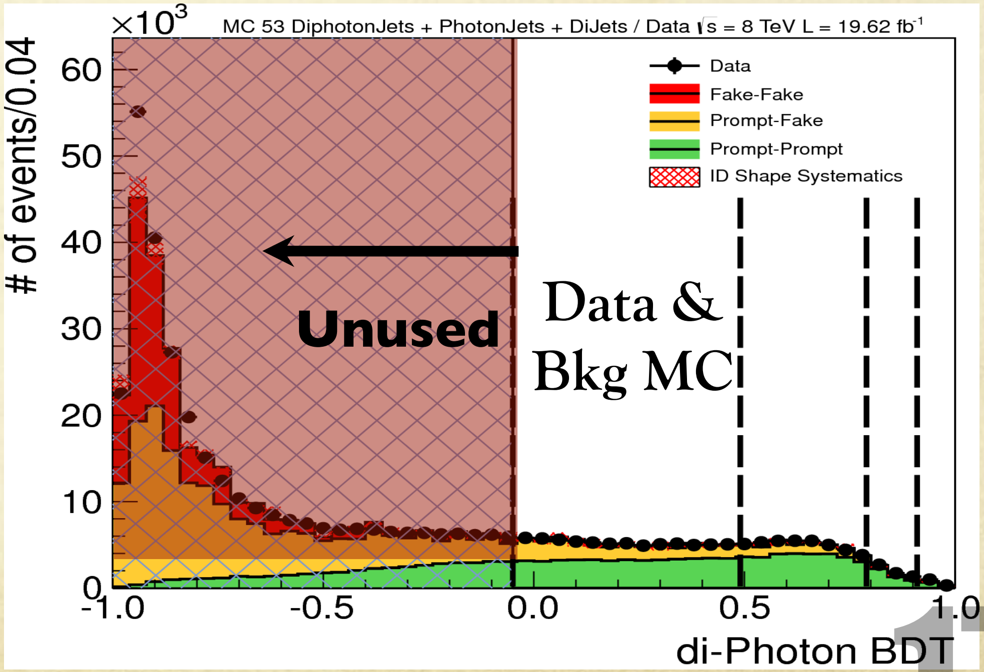
- Selecting the right vertex is important for resolution
- Knowing the vertex is right helps to sort events in resolution categories
- Inputs
  - Number of vertices
  - $P_{T,\gamma\gamma}$
  - Per vertex MVA values of top 3 vertices
  - ΔZ between 1st vertex and 2nd (3rd) vertex
  - Number of conversions associated to photons
- Validated on $Z \rightarrow \mu\mu$
- Linear transformation converts MVA to probability



Di-photon MVA

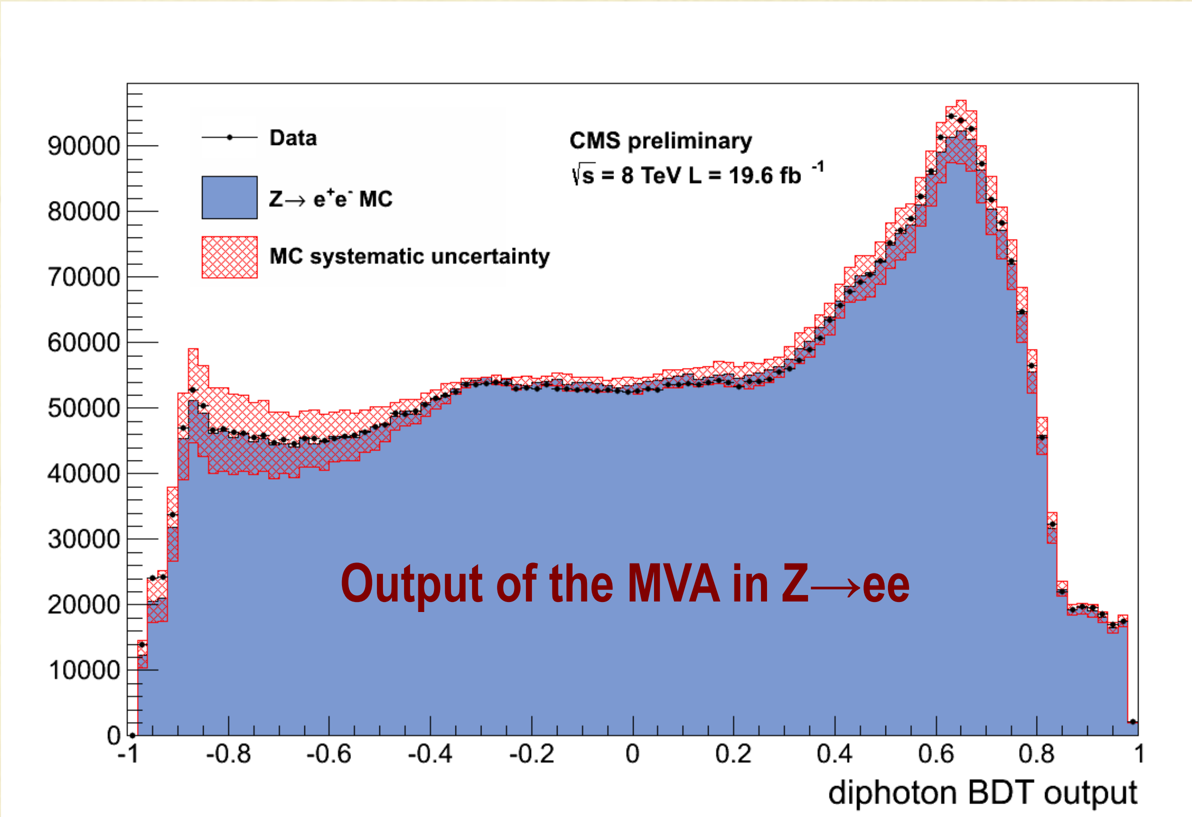
- A single discriminant (BDT) trained on MC signal and background using
  - Photon kinematics
  - Vertex probability
  - Photon ID MVA (shape corrected)
  - Di-photon mass resolution estimates (shape corrected)
- 4 untagged categories are defined on the output of the di-photon BDT





Di-photon MVA Validation

- Inputs to this BDT are validated on
  - Z→ee events (where the electrons are treated as photons)
  - $Z \to \mu \mu \gamma$ events
- Empirical corrections are derived from Drell-Yan data/MC **for inputs** (mass resolution and photon ID) and applied to MC
- After inputs are corrected, data/MC match very well within systematic errors.



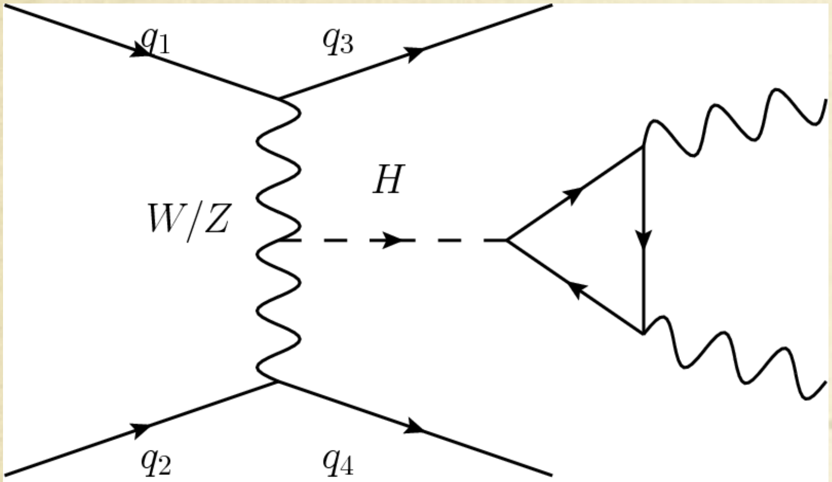
Cut Based Analysis

- Cut-based photon identification – Cuts in Categories (CiC)
- Categories define by
  - Shower shape – narrow showers/not narrow (roughly unconverted/converted)
  - Detector region of photons – ECAL barral/ ECAL endcaps
- Efficiency corrections are derived from Z→ee events in data/MC

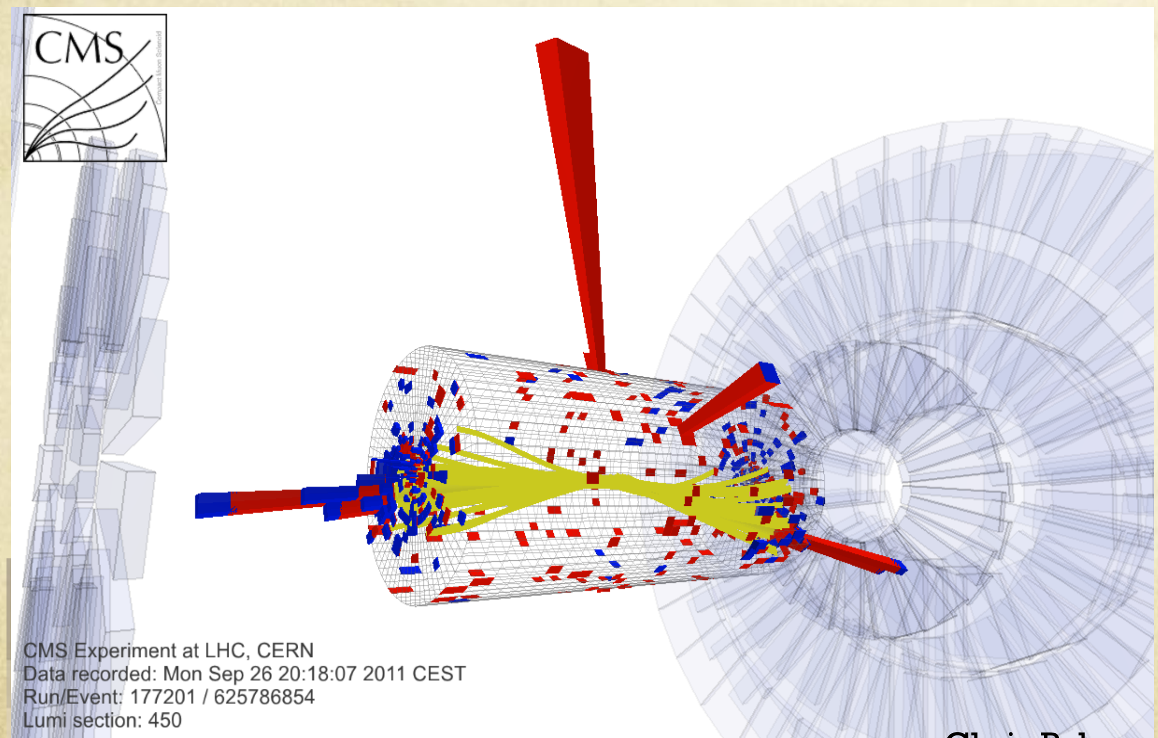
Cat 0	Both photons in barrel	Both photons narrow shower shape
Cat 1	Both photons in barrel	At least one photon not narrow
Cat 2	At least one photon in endcaps	Both photons narrow shower shape
Cat 3	At least one photon in endcaps	At least one photon not narrow

VBF Signature Channels

Two forward, high-momentum jets



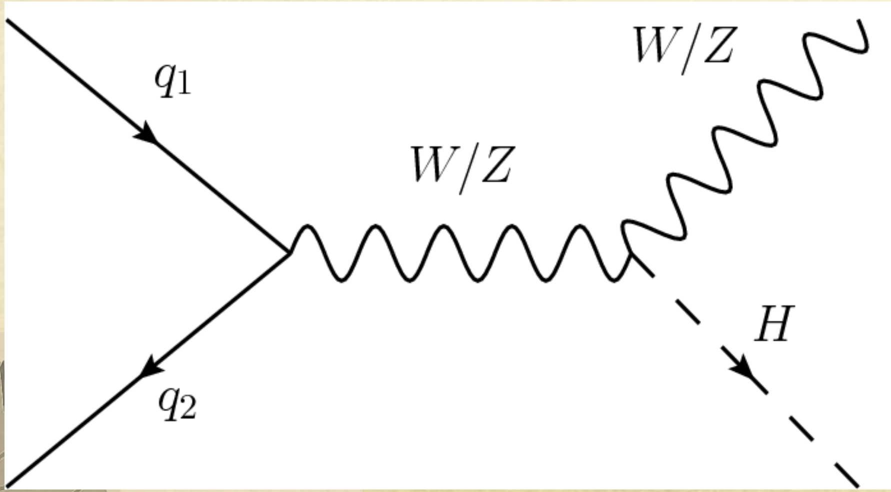
- 2011 – Single, loose, cut-based tag
- 2012
  - 2 categories (loose/tight) with increasing VBF purity
  - PU id rejects jets from PU
  - MVA analysis uses a di-jet BDT-based selection (validated using Z+jets events)
  - CiC analysis uses 2 cut-based dijet categories as in the paper



	Signal Yield	Gluon Fusion	S/B (in $\pm 2\sigma_{Eff}$)
2011	2.9	27%	0.3
2012 – Tight	9.2	21%	0.4
2012 – Loose	11.5	47%	0.1

VH Signature Channels

- When Higgs are produced via Higgsstrahlung the associated vector boson's (VB) decay products can be tagged
  - Leptonic decays of the VB are exploited here.
  - S/B high but yield is low
  - Main addition to the analysis is in reducing the error on coupling measurements (not in significance)
- Only in 2012
- Same in tags MVA and CiC



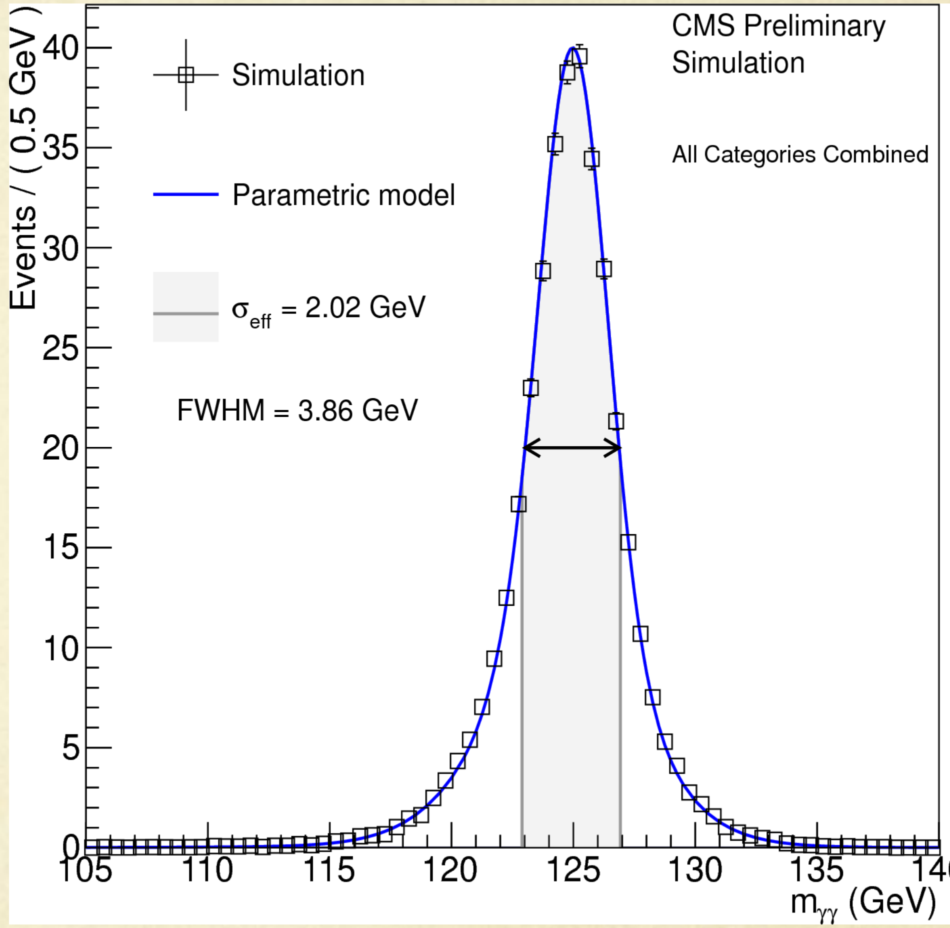
- Additional leptons
  - Electron or muon
  - P_T>20 GeV)
  - Well isolated
- MET (>70 GeV)

	Signal Yield	Gluon Fusion	S/B (in $\pm 2\sigma_{Eff}$)
Muon	1.4	0%	0.3
Electron	0.9	1.1%	0.2
MET	1.7	22%	0.1

Signal Resolution in Categories

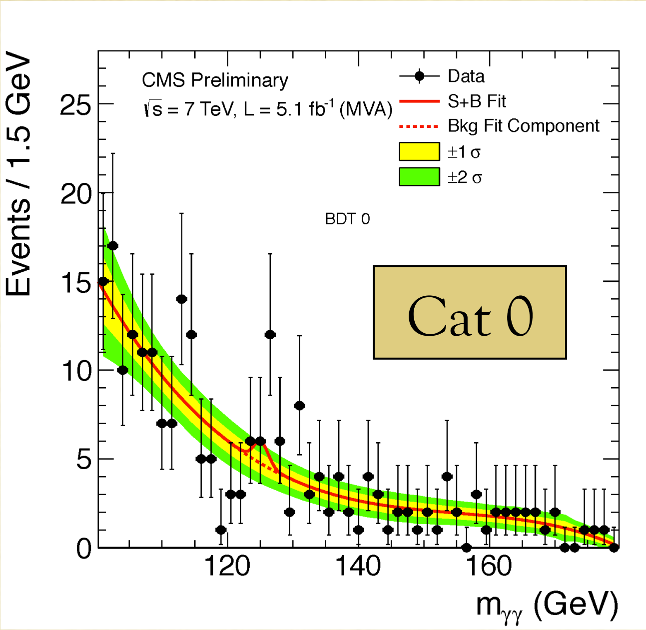
Event classes		σ_{eff} (GeV)	FWHM/2.35 (GeV)
7 TeV 5.1 fb^{-1}	Untagged 0	1.21	1.14
	Untagged 1	1.26	1.08
	Untagged 2	1.59	1.32
	Untagged 3	2.47	2.07
	Dijet tag	1.73	1.37
8 TeV 19.6 fb^{-1}	Untagged 0	1.36	1.27
	Untagged 1	1.50	1.39
	Untagged 2	1.77	1.54
	Untagged 3	2.61	2.14
	Dijet tight	1.79	1.50
	Dijet loose	1.87	1.60
	Muon tag	1.85	1.52
	Electron tag	1.88	1.54
	$E_{\mathrm{T}}^{\mathrm{miss}}$ tag	1.79	1.64

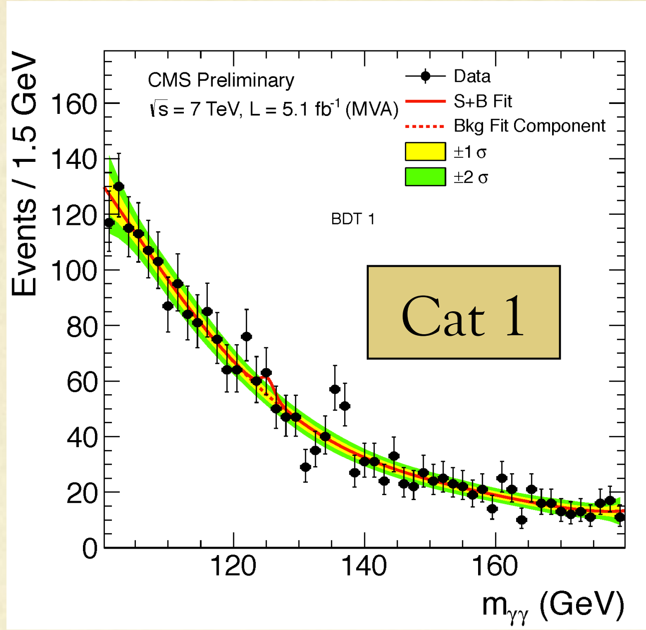
8TeV: All categories combined

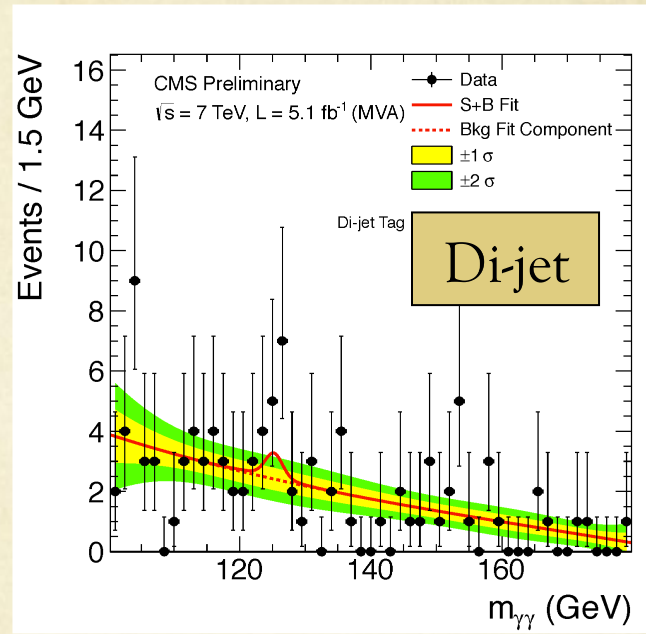


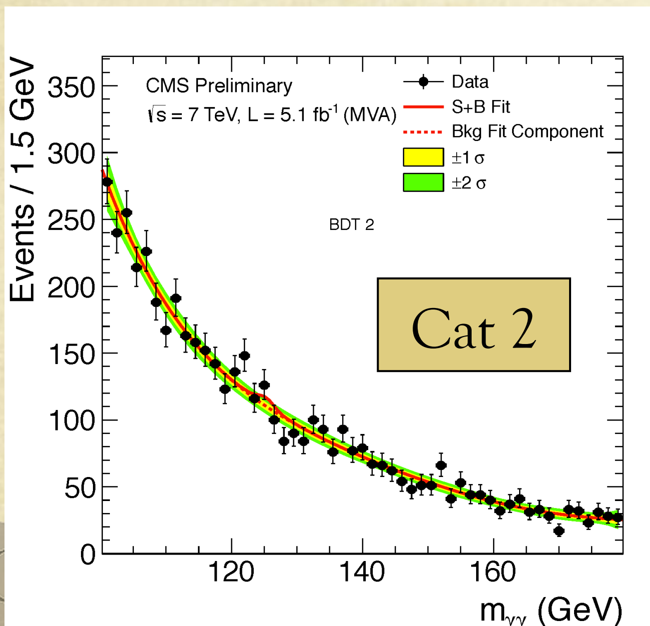
Resolution improves as function of BDT/category

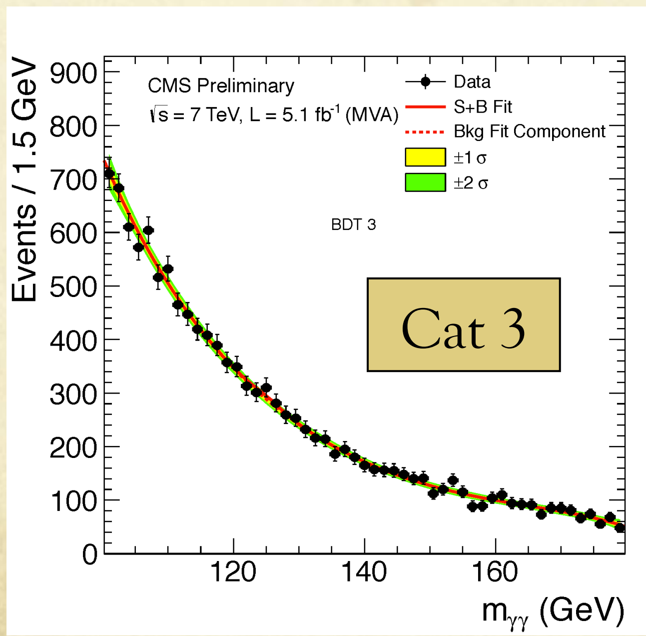
MVA Mass Spectra – 2011



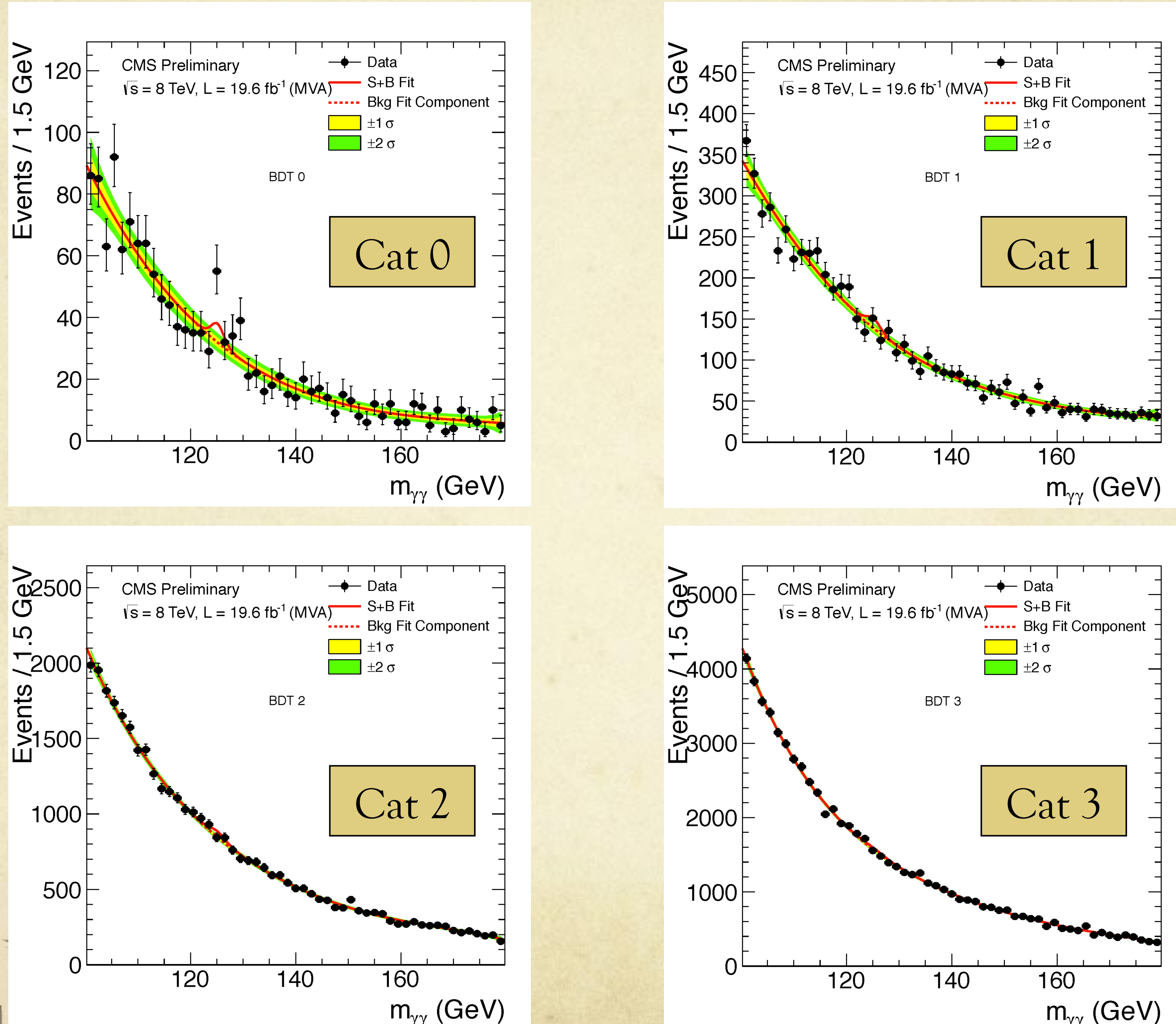




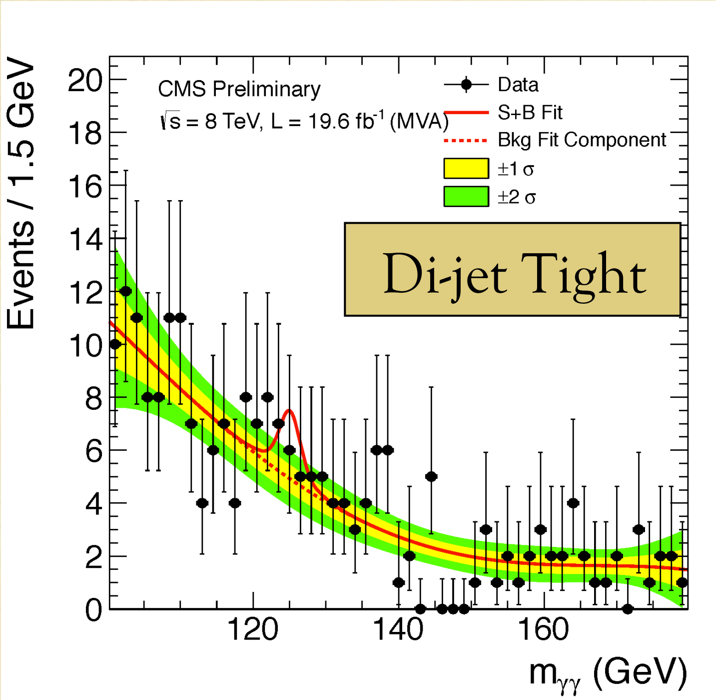


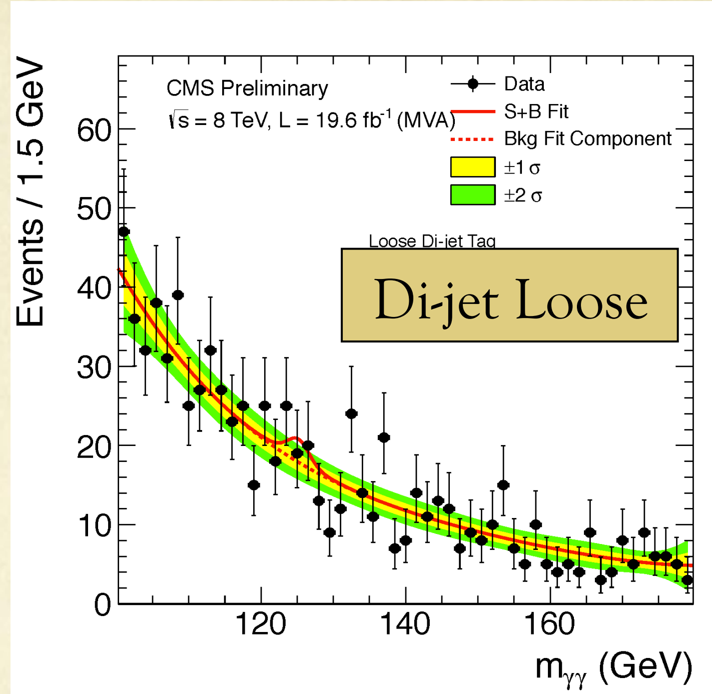


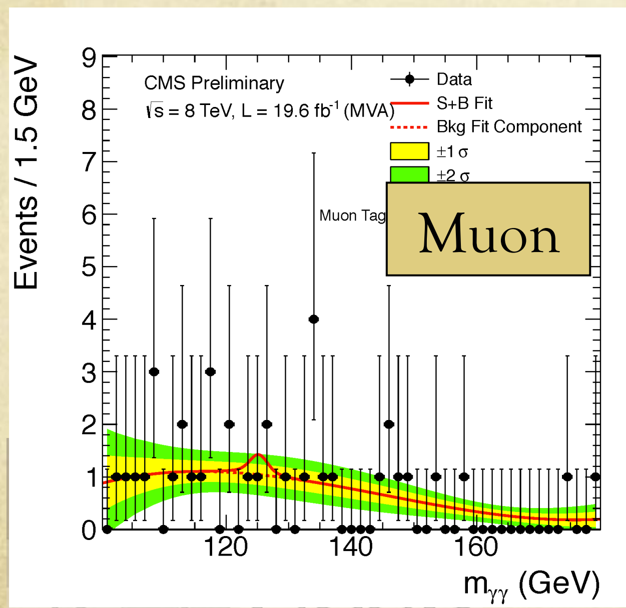
MVA Mass Spectra – 2012 – I/II

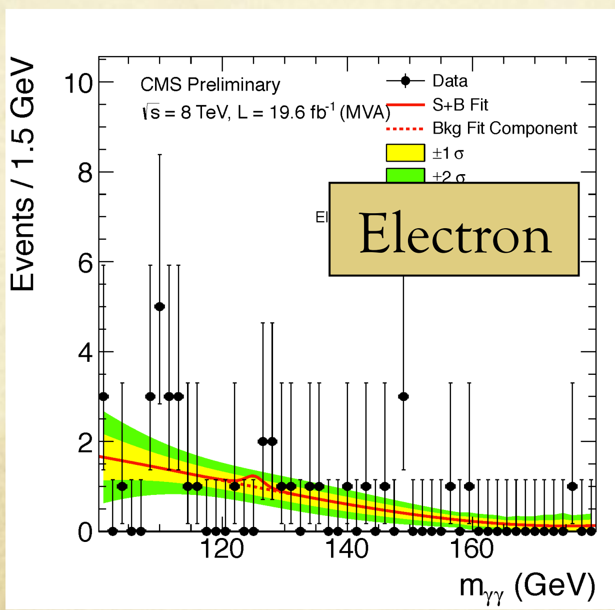


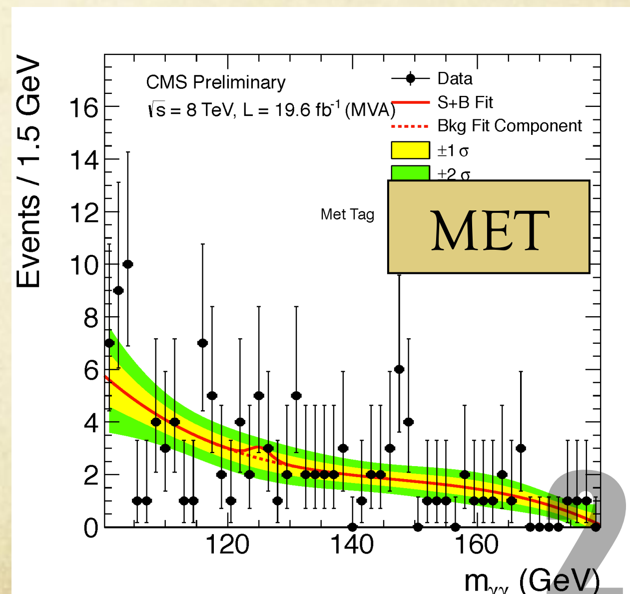
MVA Mass Spectra – 2012 – II/II





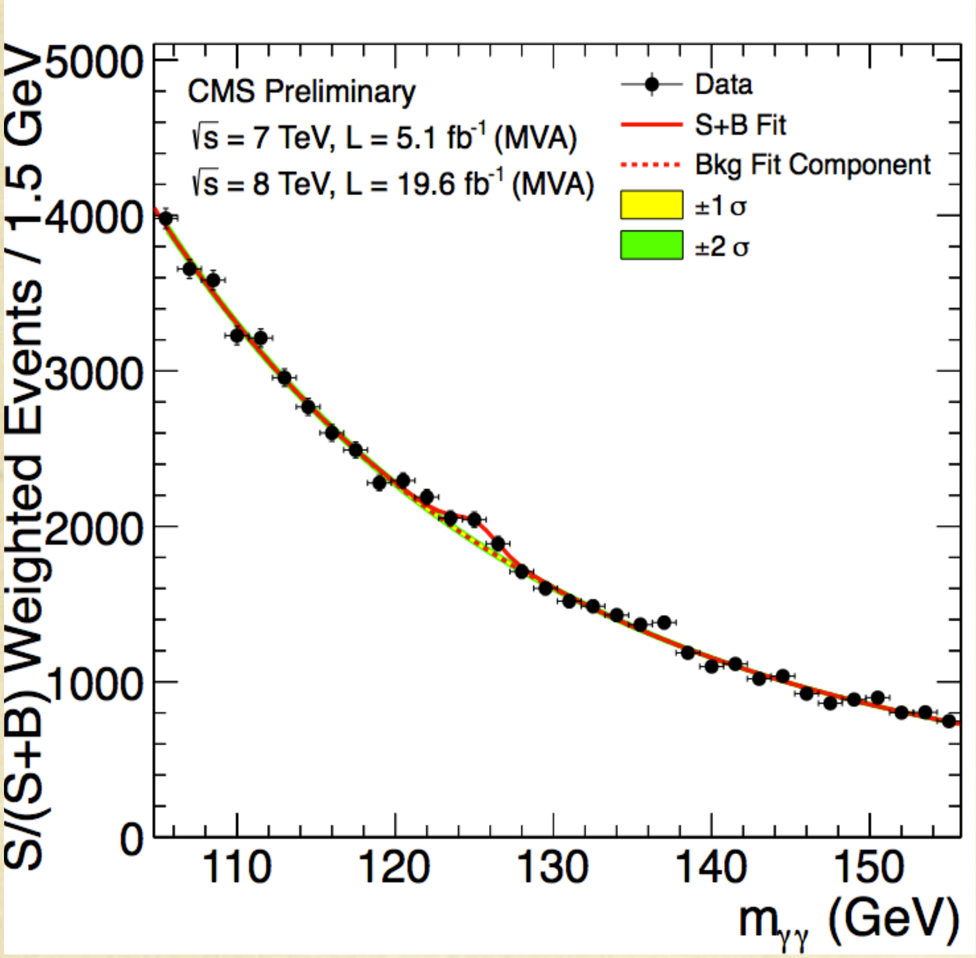




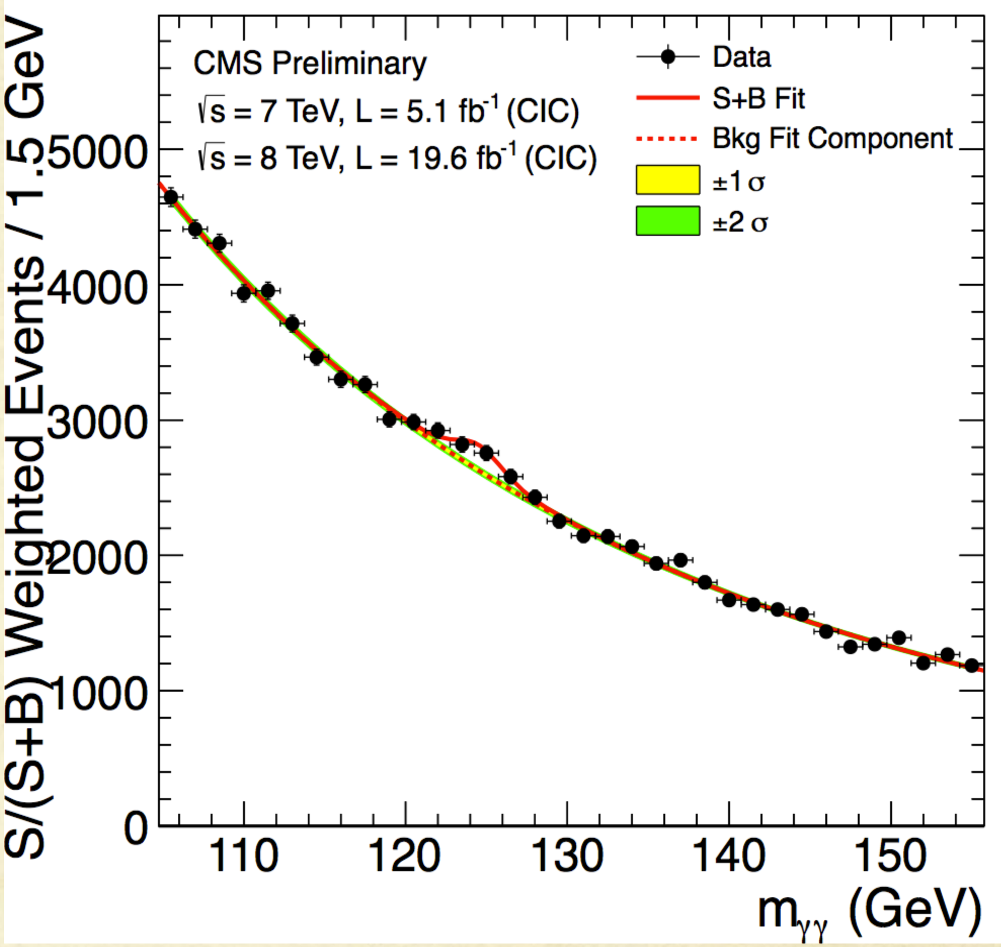


Combined Mass 7TeV + 8TeV

MVA



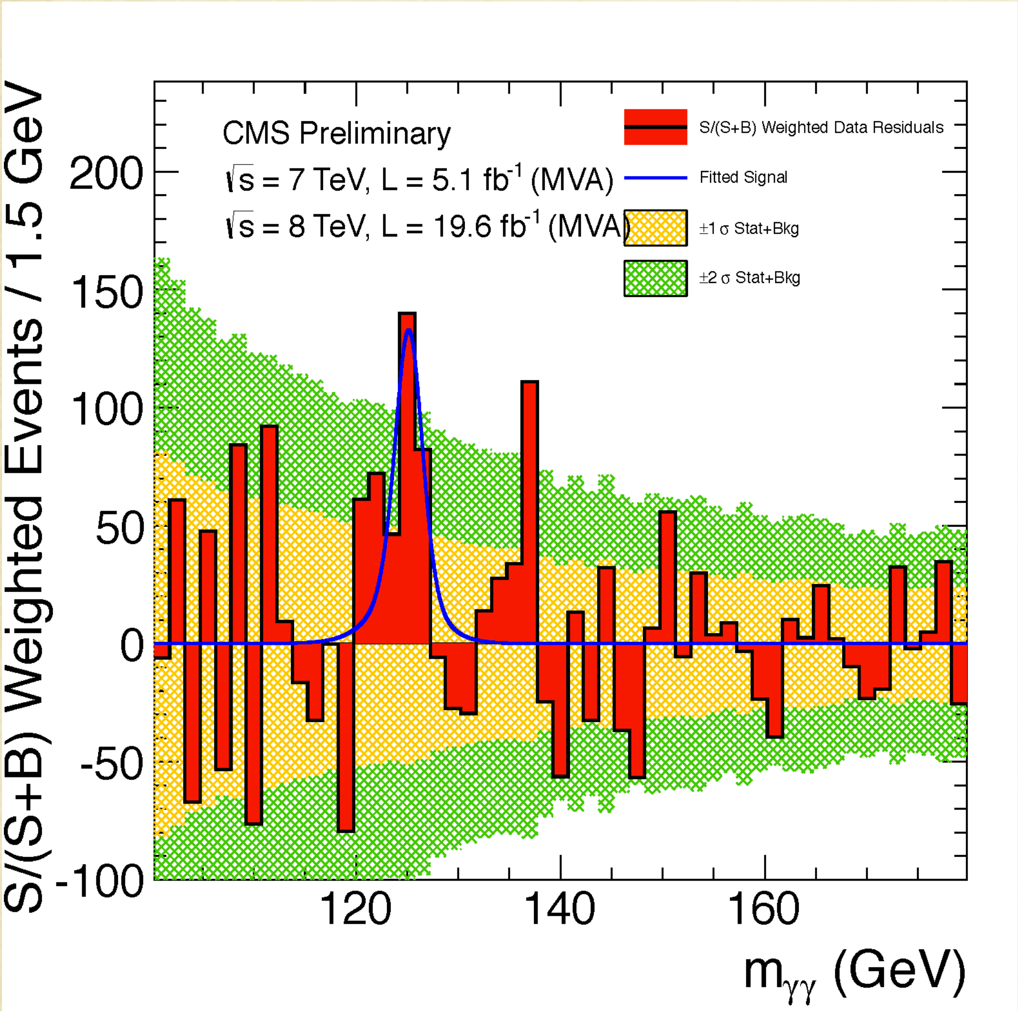
Cut-based



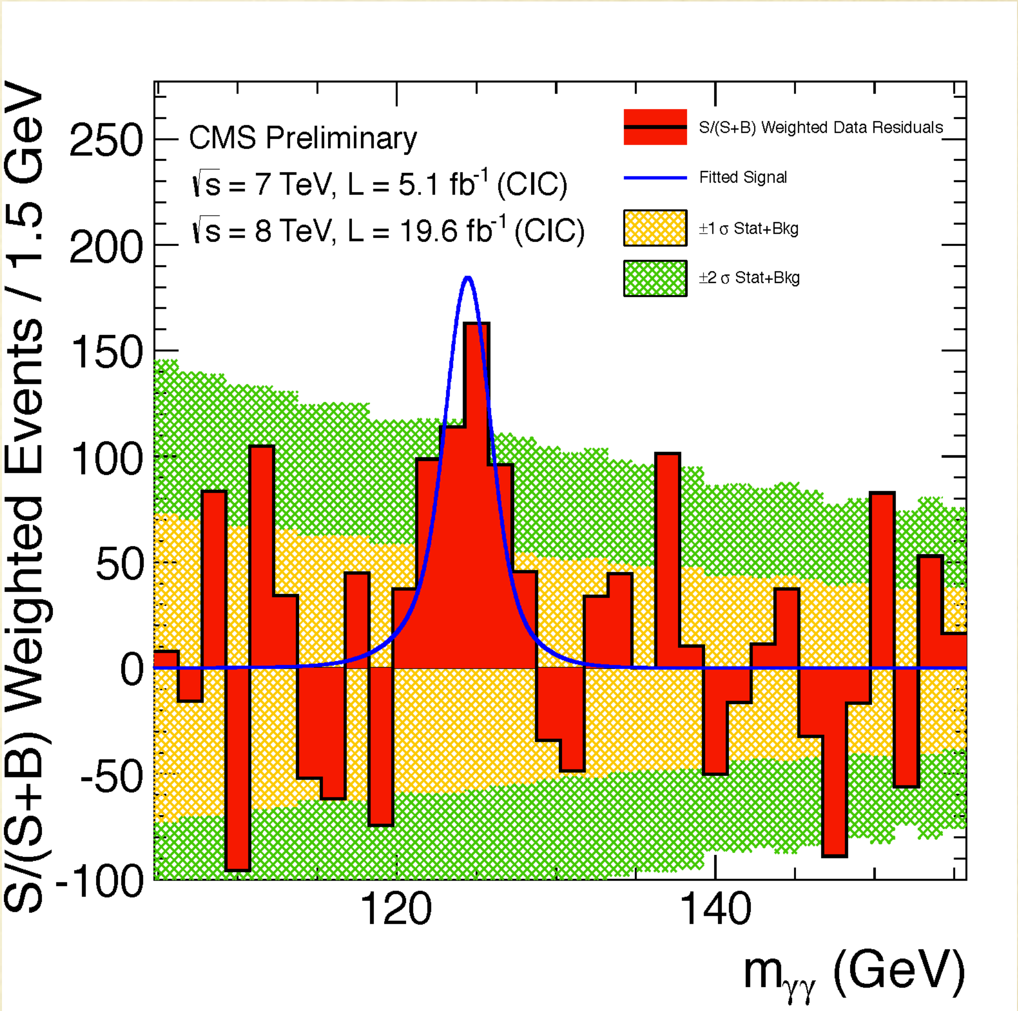
Weighted with S/(S+B)
Normalized such that S is as measured

Background Subtracted Mass

MVA



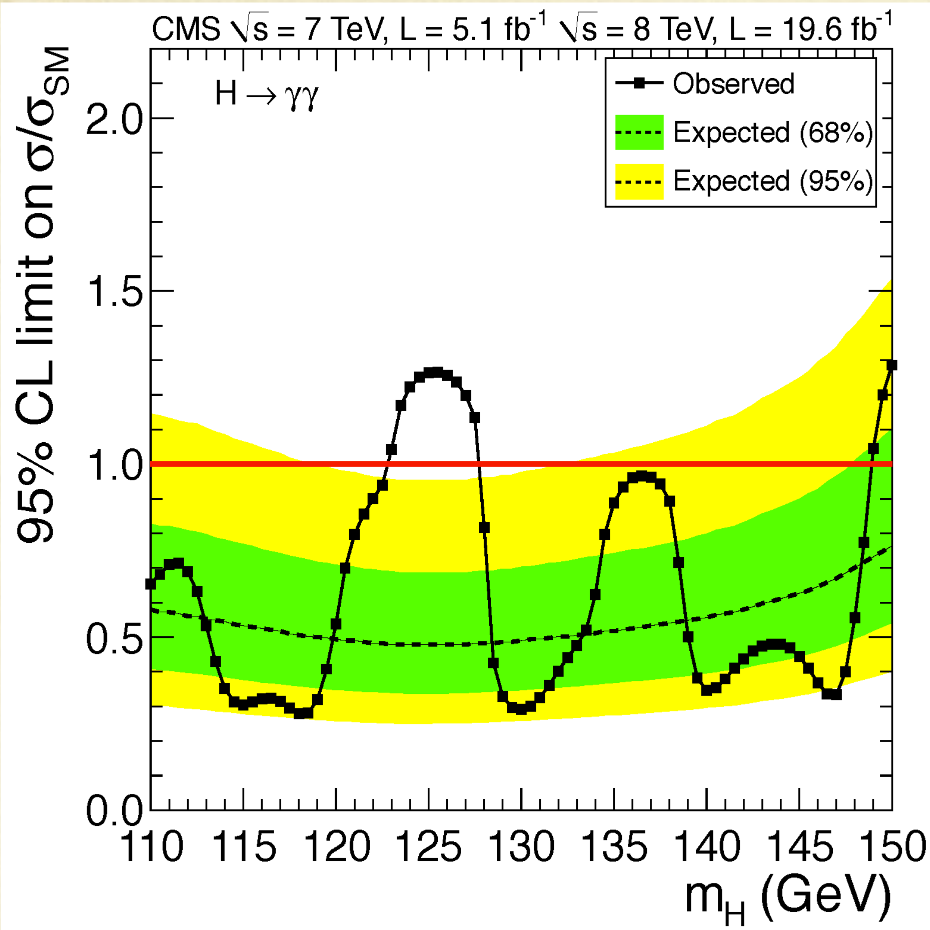
Cut-based



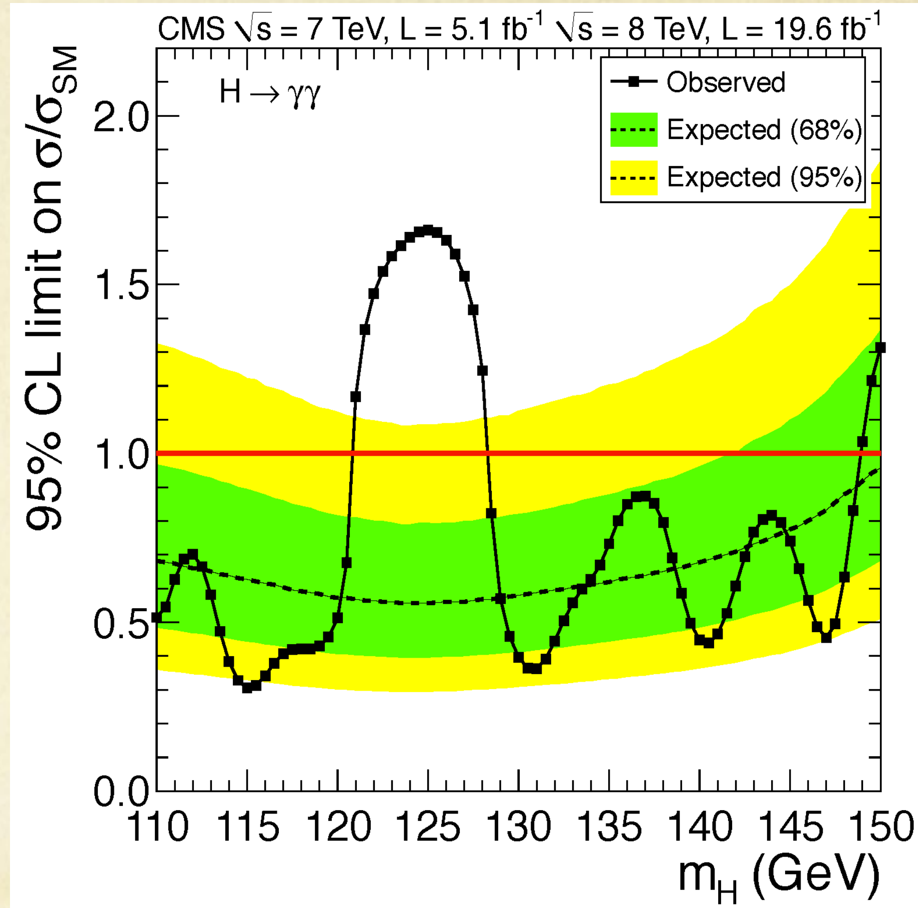
Weighted with S/(S+B)
Normalized such that S is as measured

Results: Exclusion Limits

MVA



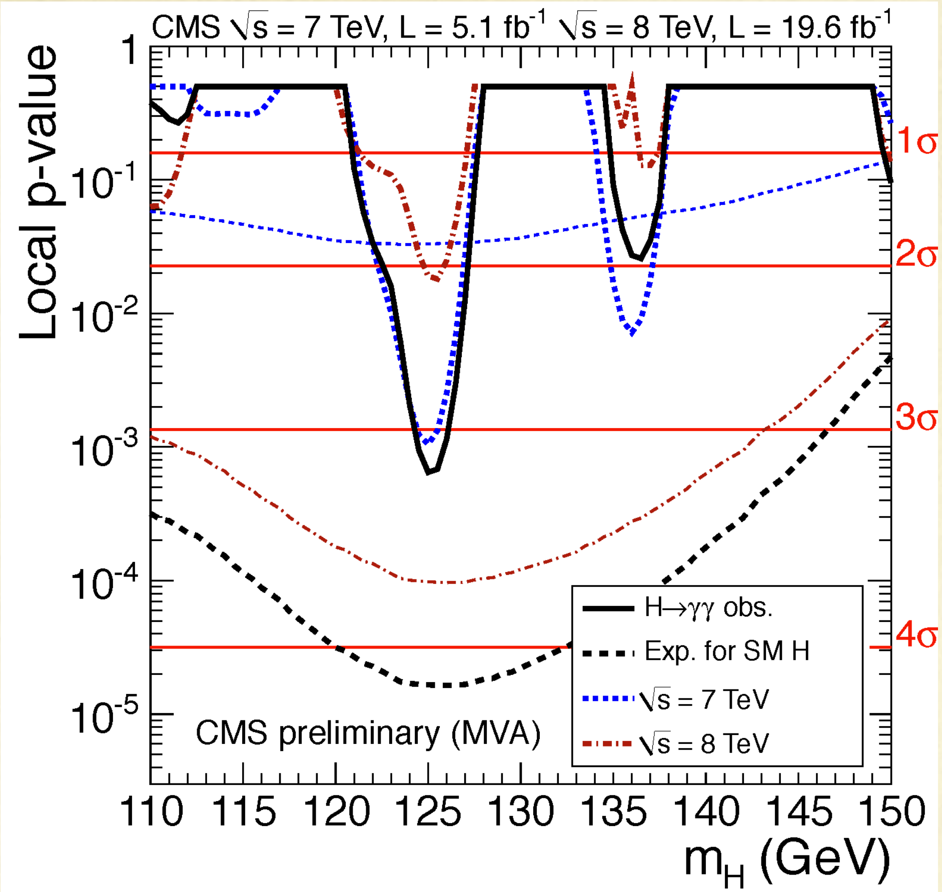
Cut-based



Almost the full mass range except the region around 125 GeV is excluded at 95% CL

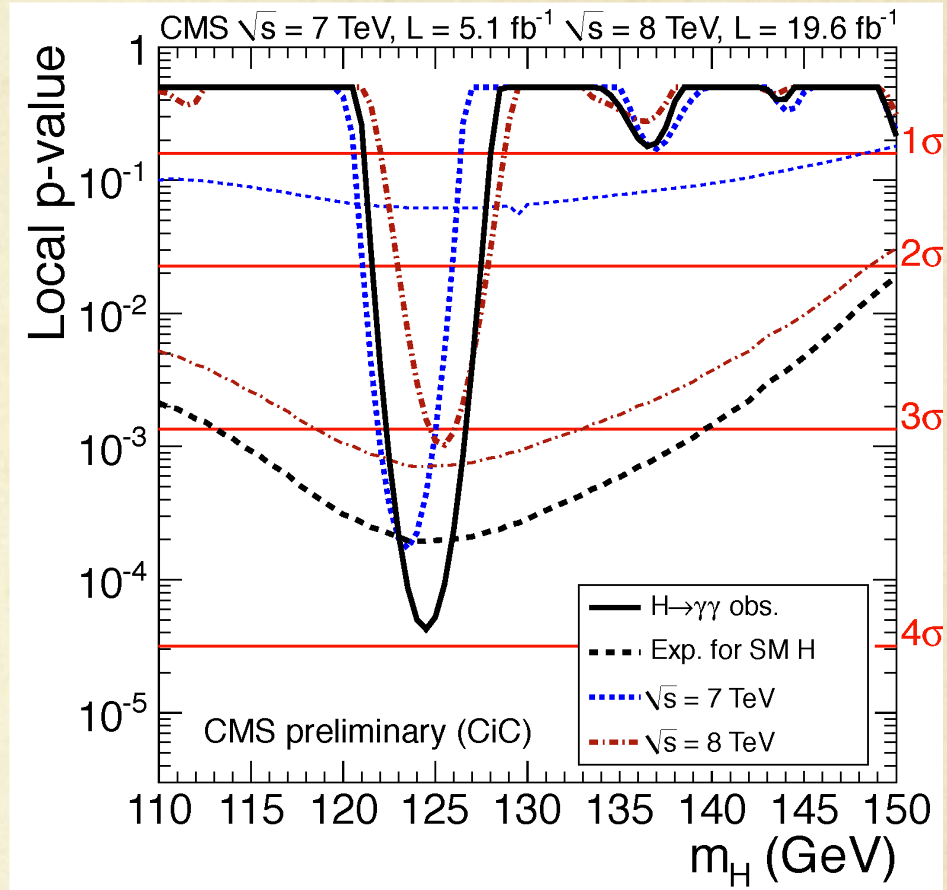
Results: P-values

MVA



Significance @ 125.0 GeV: 3.2 σ (4.2 σ exp.)

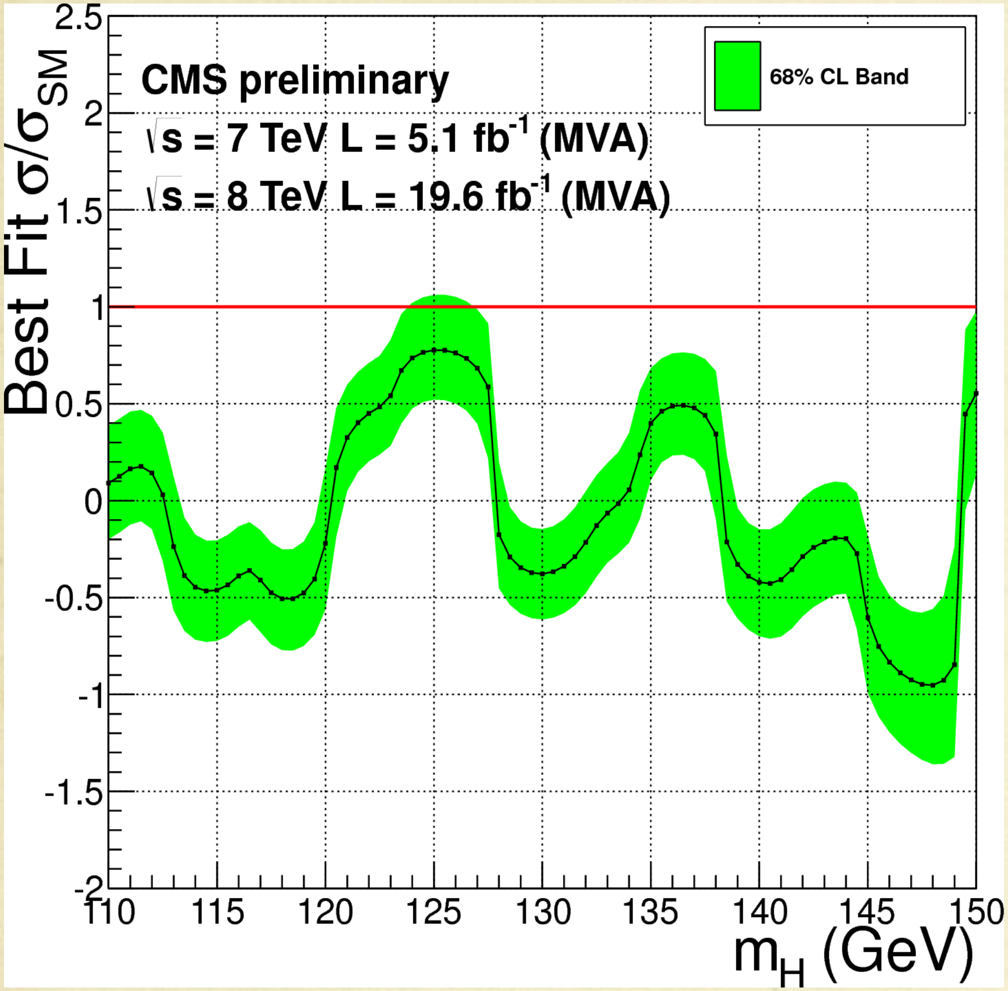
Cut-based

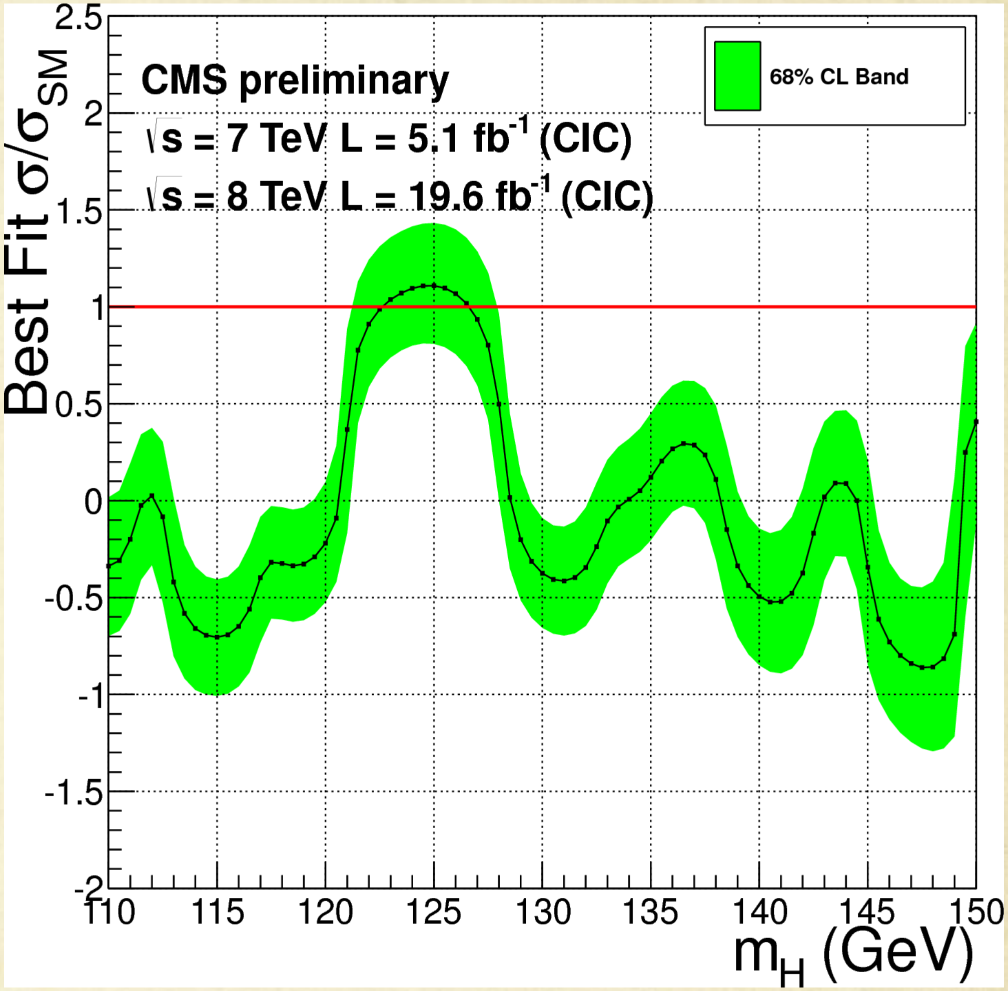


Significance @ 124.5 GeV: 3.9 σ (3.5 σ exp.)

Results: Signal Strength

MVA | **Cut-based**

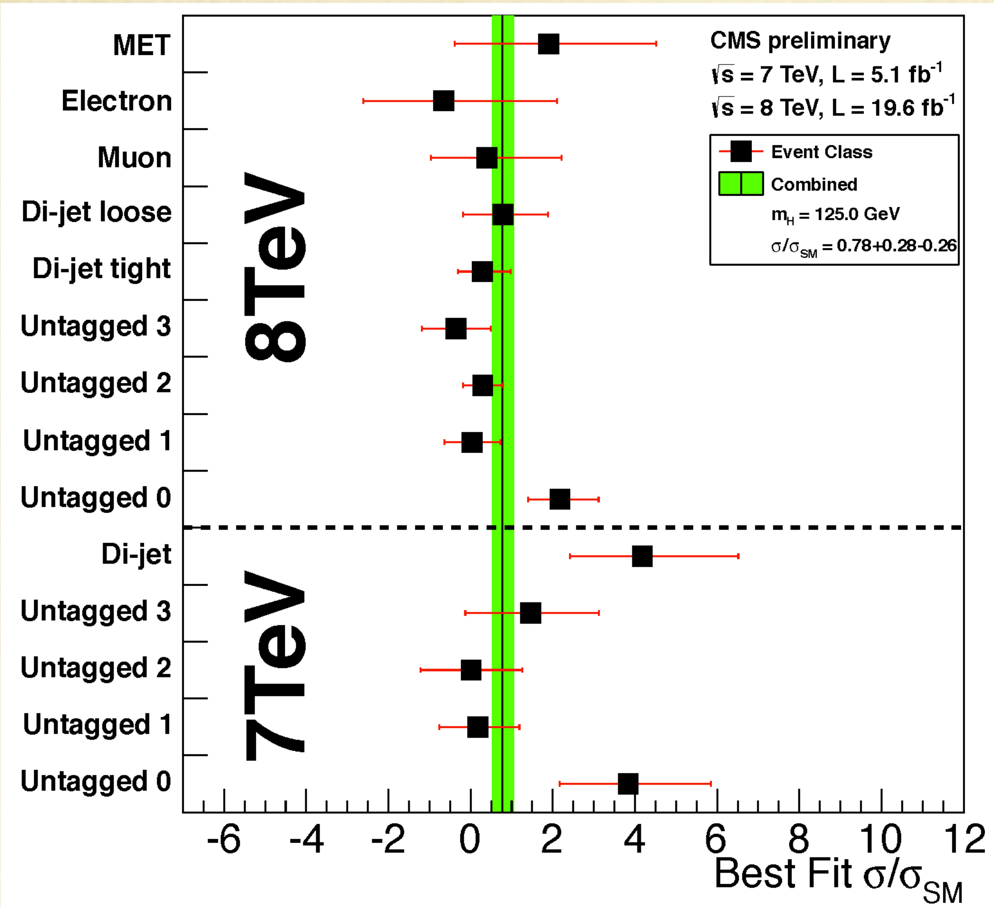




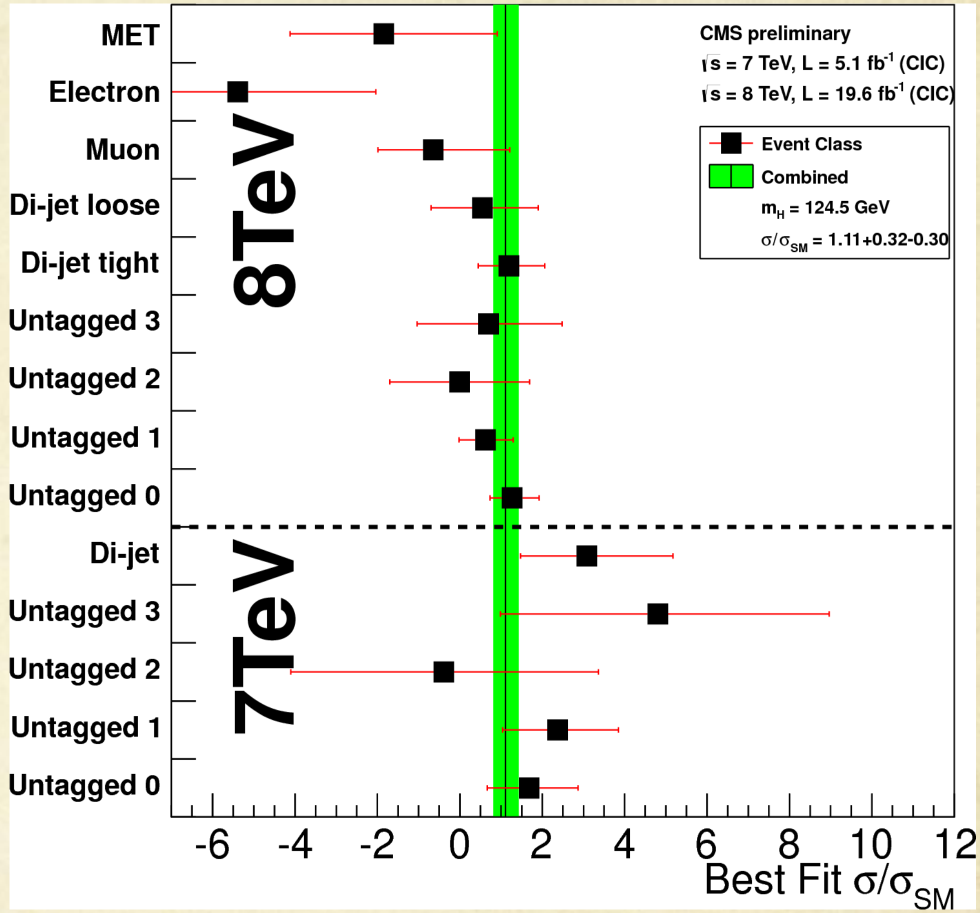
Compared to the published results, the measured mu value decreased with the re-analysis of early 8 TeV data and the addition new data.

Results: Channel Compatibility

MVA



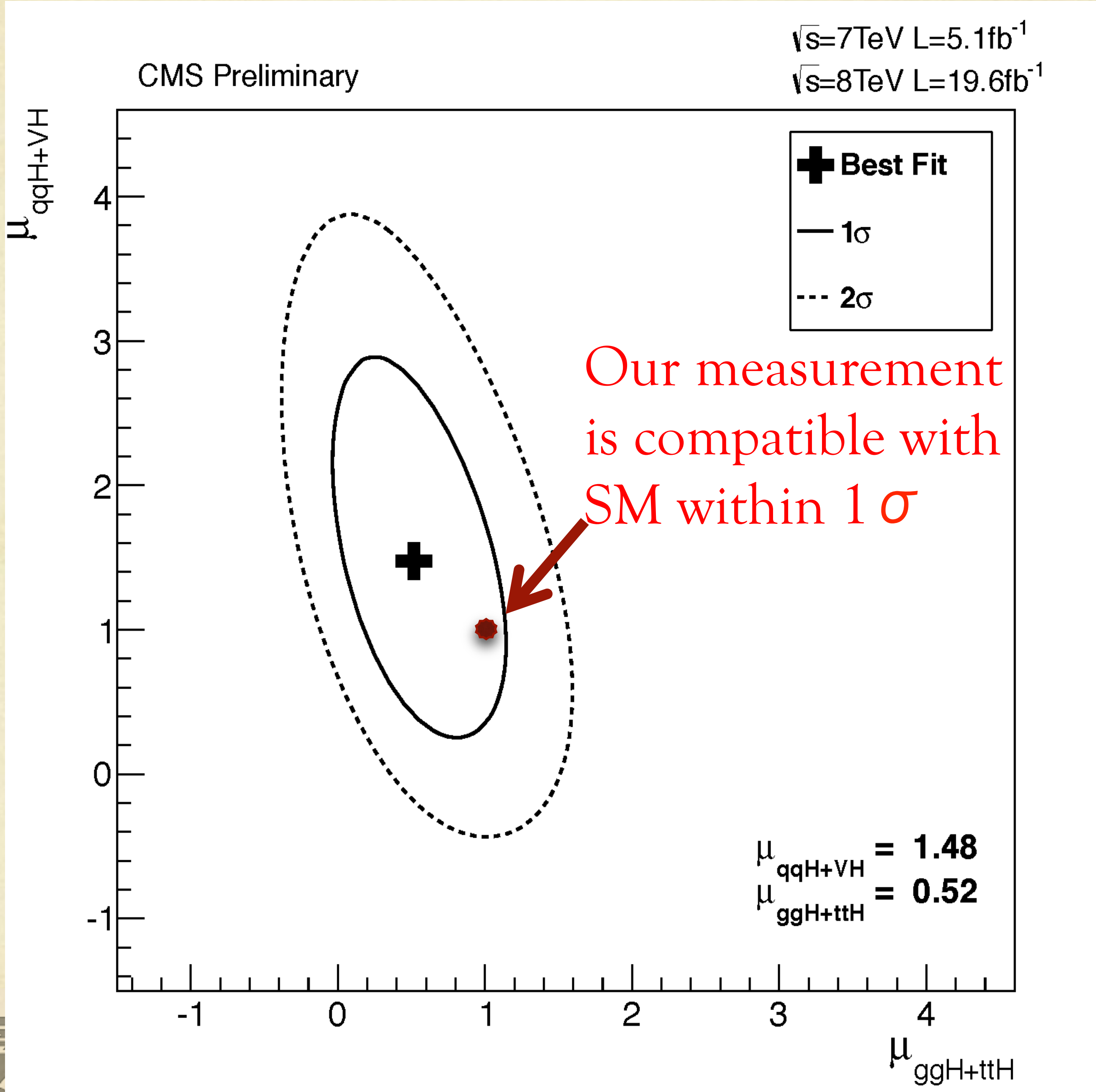
Cut-based



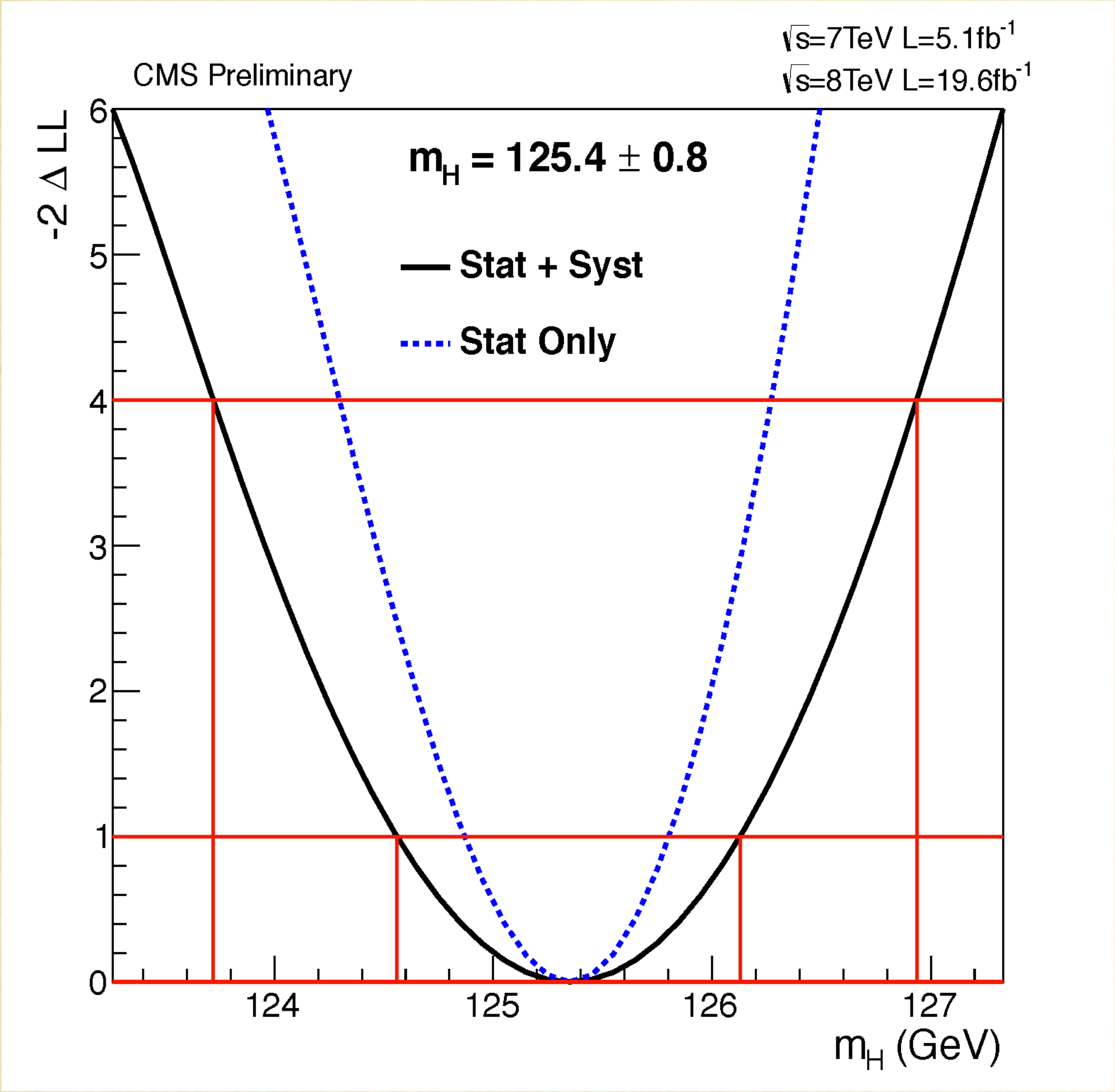
7+8 TeV: σ / σ_{SM} @ 125.0 GeV = $0.78^{+0.28}_{-0.26}$

7+8 TeV: σ / σ_{SM} @ 124.5 GeV = $1.11^{+0.32}_{-0.30}$

Production Mechanism



Mass Measurement



- For further model independence μ_{qqH+VH} and $\mu_{ggH+ttH}$ profiled instead of single μ.
- Systematic errors dominated by overall photon energy scale: 0.47%
  - Extrapolation from Z→H energy scales
  - Electron/photon differences

m_H = 125.4 ± 0.5 (stat.) ± 0.6 (syst.)

Conclusions

- The CMS higgs to two photons search analysis has been updated to include the entire 2011 and 2012 datasets with 5.1 fb^{-1} and 19.6 fb^{-1}, respectively.
- The analysis on the full dataset has yielded a 3.2 σ (4.2 σ expected) significance excess near 125 GeV.
- Our 2 dimensional fit in $\mu_{ggH+ttH}$, μ_{qqH+VH} is compatible at the 1 σ level to the SM.
- We have determined the mass of the excess to be 125.4 ± 0.8 GeV.
- MVA signal strength at 125.0 GeV $\sigma/\sigma_{SM} = 0.78^{+0.28}_{-0.26}$
- Cut based signal strength at 124.5 GeV $\sigma/\sigma_{SM} = 1.11^{+0.32}_{-0.30}$

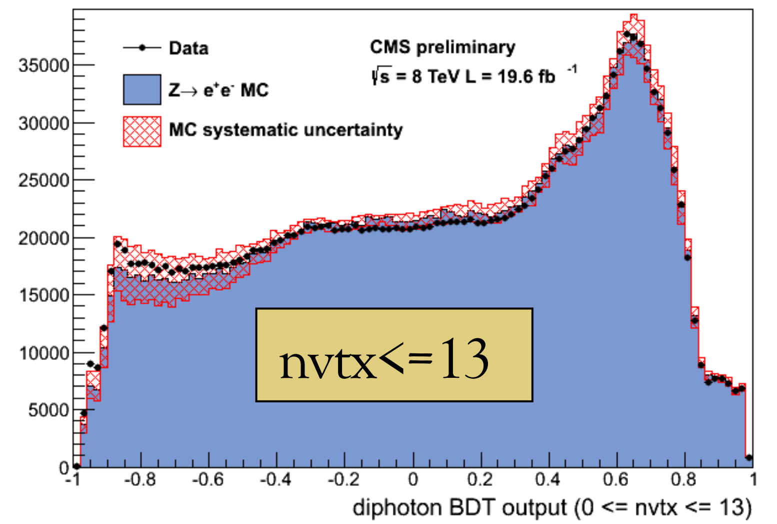
Thank you for your patience!

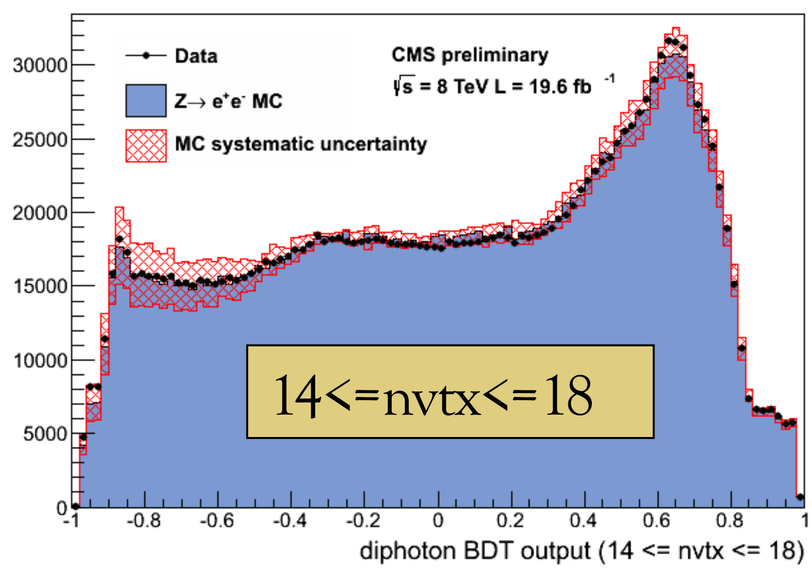
Any questions?

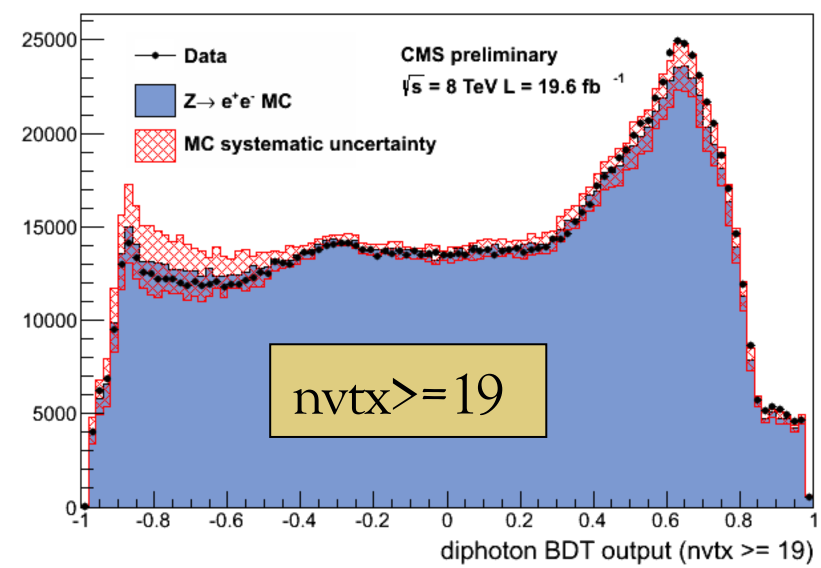
BACK UP

Di-photon MVA Validation

- Inputs to this BDT are validated on Z→ee events (where the electrons are treated as photons)
  - In bins of number of vertices







MVA Data and Expected Signal Yields in Categories

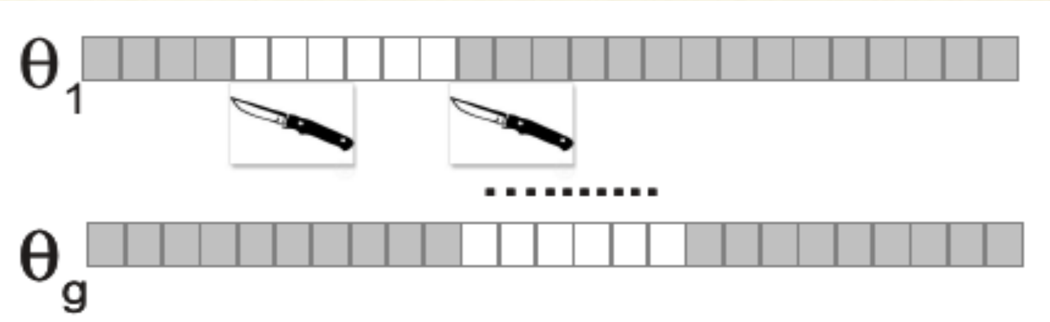
Expected signal and estimated background

Event classes		SM Higgs boson expected signal (m_H=125 GeV)							Background $m_{\gamma\gamma} = 125$ GeV (ev./GeV)
		Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	26.8%	72.5%	0.6%	–	1.73	1.37	1.7 ± 0.2
8 TeV 19.6 fb^{-1}	Untagged 0	17.0	72.9%	11.6%	12.9%	2.6%	1.36	1.27	22.1 ± 0.5
	Untagged 1	37.8	83.5%	8.4%	7.1%	1.0%	1.50	1.39	94.3 ± 1.0
	Untagged 2	150.2	91.6%	4.5%	3.6%	0.4%	1.77	1.54	570.5 ± 2.6
	Untagged 3	159.9	92.5%	3.9%	3.3%	0.3%	2.61	2.14	1060.9 ± 3.5
	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%	1.79	1.50	3.4 ± 0.2
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%	1.87	1.60	12.4 ± 0.4
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%	1.85	1.52	0.7 ± 0.1
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%	1.88	1.54	0.7 ± 0.1
	E_T^{miss} tag	1.7	22.0%	2.6%	63.7%	11.7%	1.79	1.64	1.8 ± 0.1

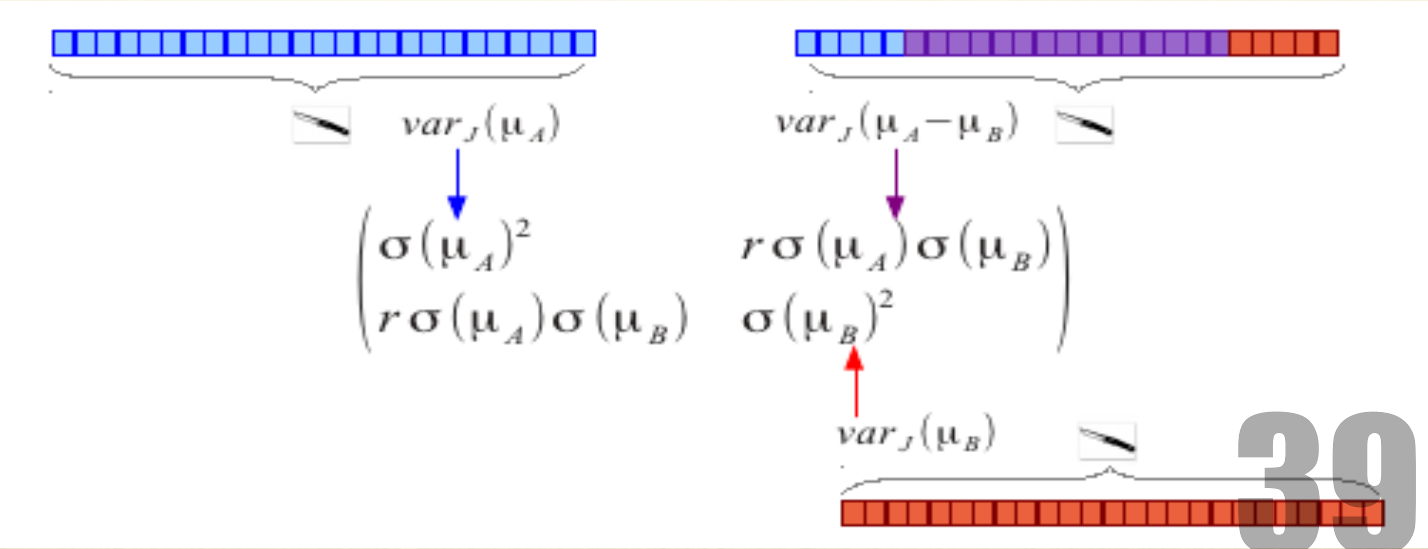
Resolution improves as function of BDT/category

Jackknife Re-sampling

- Jackknife re-sampling can be used to estimate the variance of stat. estimators in a non parametric way.
  - Achieved evaluating the estimator on subsets of the stat. sample.



- Given analyses A and B, used to estimate the variance of of m_A-m_B applying the jackknife resampling to the events selected by either analysis.



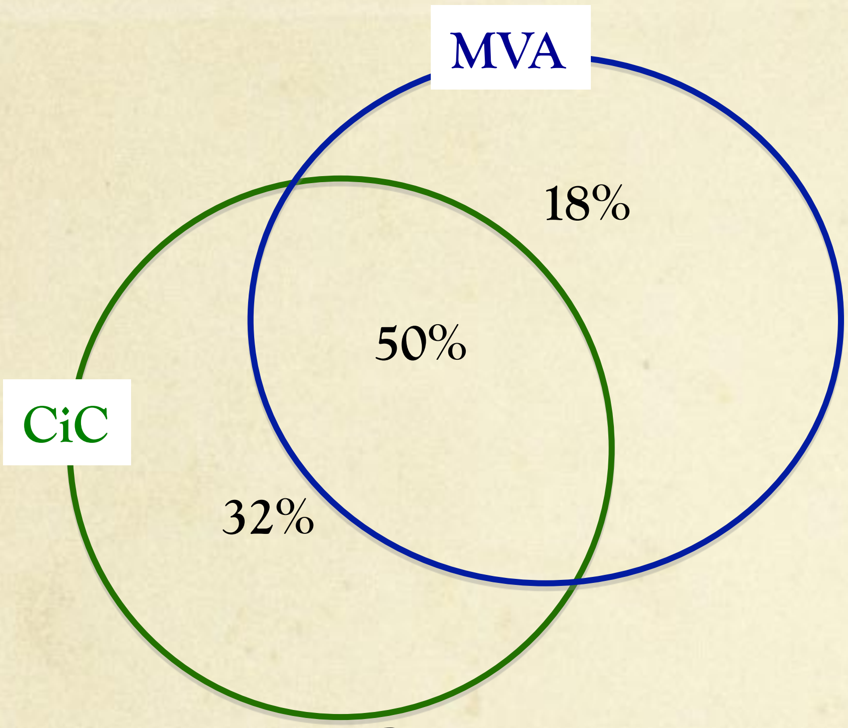
Compatibility of Main Result with Cut Based Cross Check

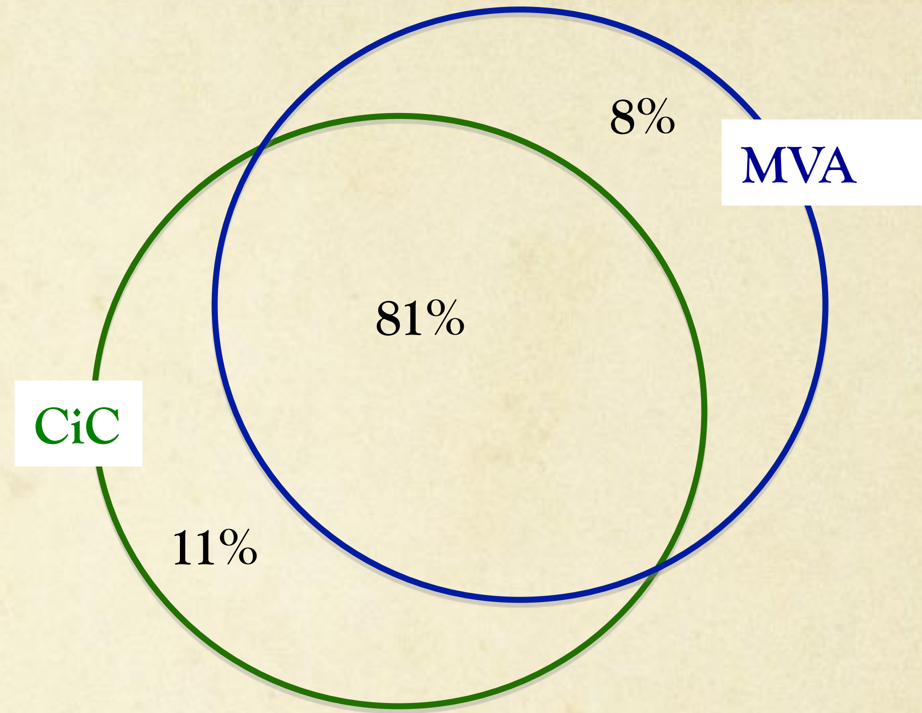
- We estimate the correlation between the two analyses using the resampling jackknife technique (Quenouille M (1949), Tukey JW (1958)
- The correlation coefficient between the two measurements is found to be r=0.76.

	Dataset	**Signal strength compatibility (including correlation)**
MVA vs CiC	Full dataset	1.5 σ
MVA vs CiC	2012 dataset	1.8 σ

A large number of tests have been performed. No source of systematic error has been found. All observed differences are statistically compatible at less than 2σ.

Overlap of Selected Events





Data
(Background MC agrees)

Signal MC

Results by Year

MVA mass-factorized

7+8 TeV: σ / σ_{SM} @ 125.0 GeV = $0.78^{+0.28}_{-0.26}$

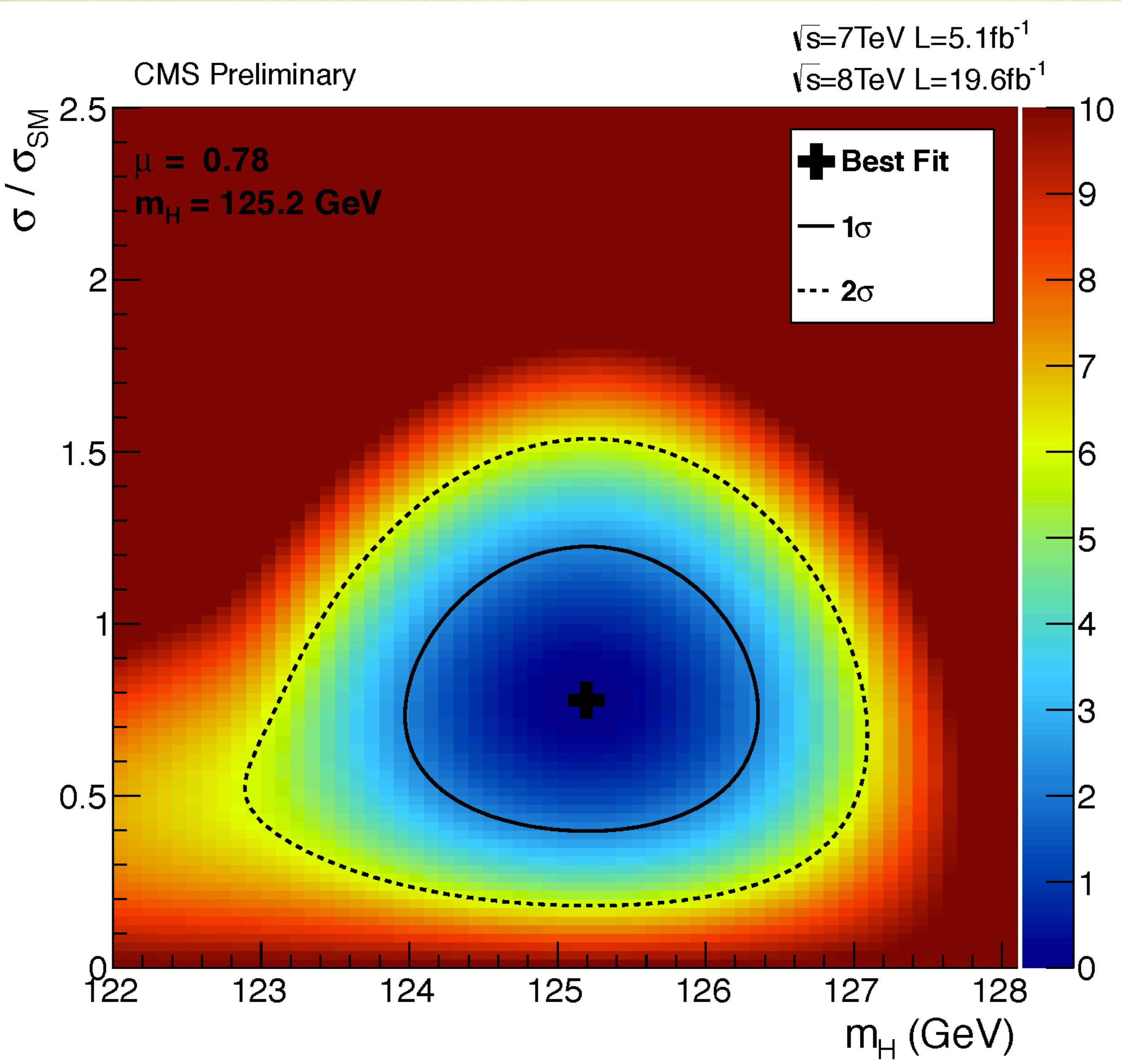
7 TeV: σ / σ_{SM} @ 125.0 GeV = $1.69^{+0.65}_{-0.59}$
8 TeV: σ / σ_{SM} @ 125.0 GeV = $0.55^{+0.29}_{-0.27}$

Cut-based

7+8 TeV: σ / σ_{SM} @ 124.5 GeV = $1.11^{+0.32}_{-0.30}$

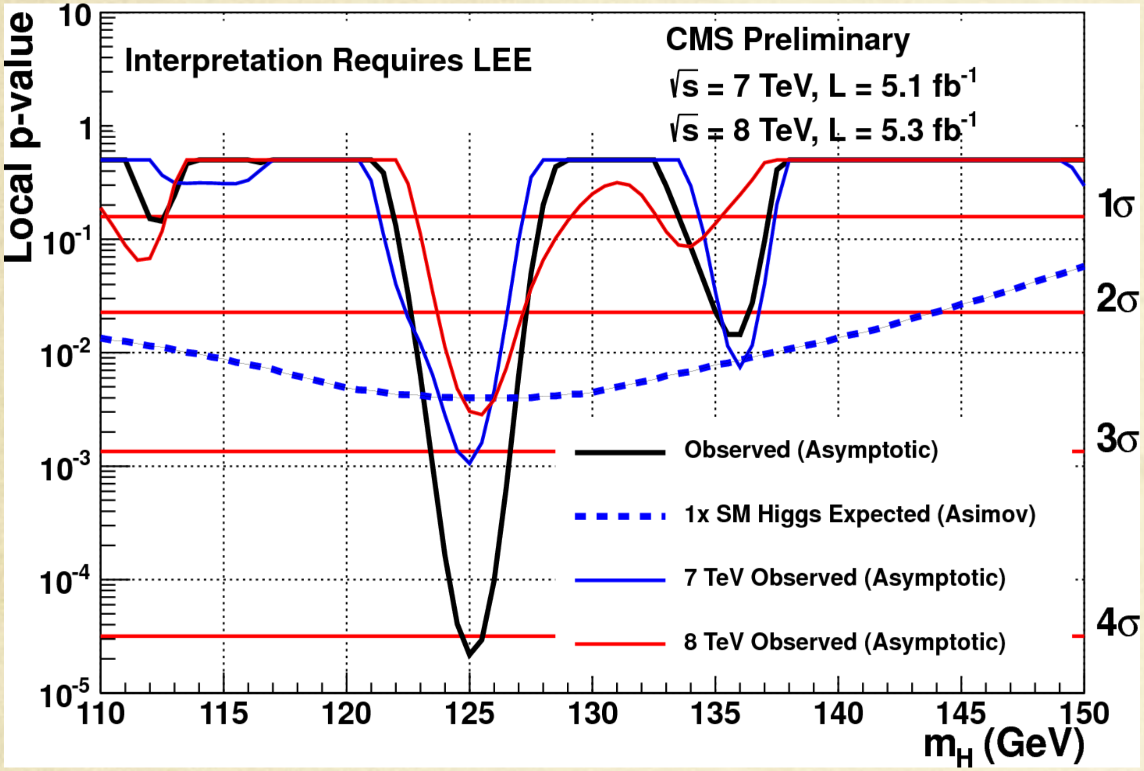
7 TeV: σ / σ_{SM} @ 124.5 GeV = $2.27^{+0.80}_{-0.74}$
8 TeV: σ / σ_{SM} @ 124.5 GeV = $0.93^{+0.34}_{-0.32}$

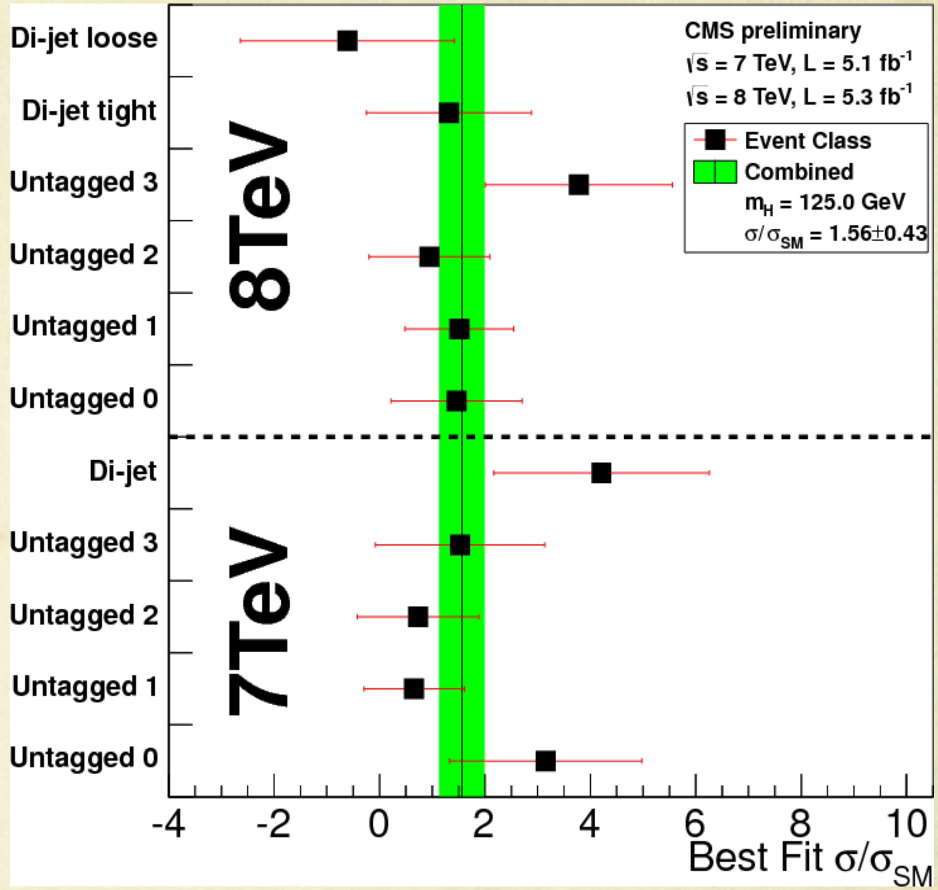
Signal Strength vs Mass Profile



- Profiling single μ

Published Result

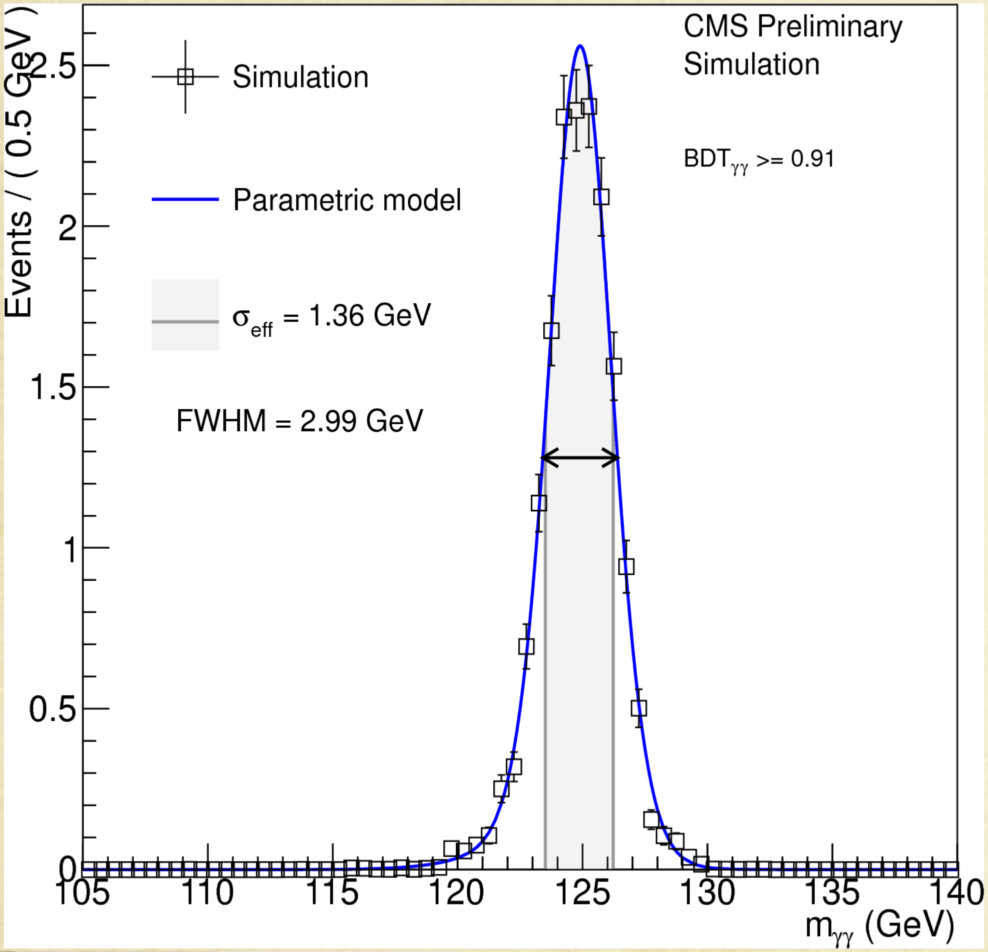




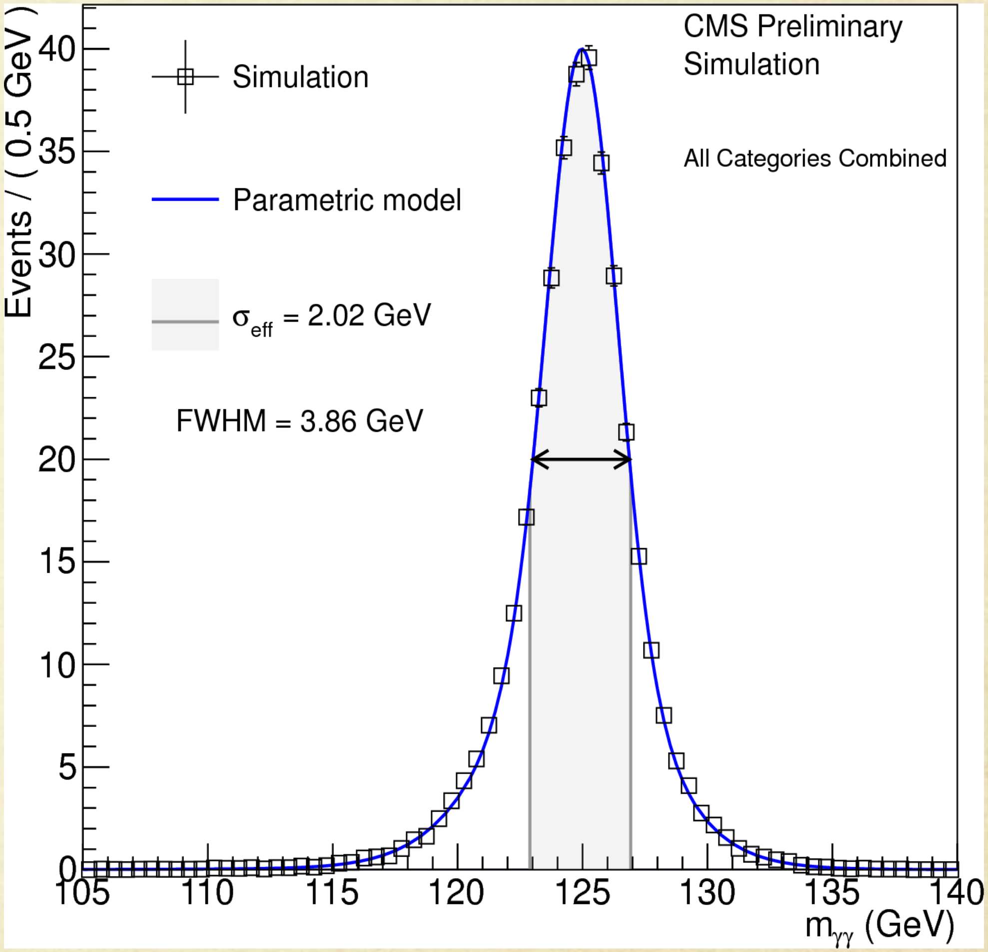
- Maximum significance 4.1 σ at 125 GeV

Signal Models: MVA Categories

8TeV Untagged cat 0



8TeV: All categories combined



Systematic Errors

Sources of systematic uncertainty		Uncertainty	
Per photon		Barrel	Endcap
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.23%, 0.72%	0.93%, 0.36%
	$R_9 < 0.94$ (low η, high η)	0.25%, 0.60%	0.33%, 0.54%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.20%, 0.71%	0.88%, 0.12%
	$R_9 < 0.94$ (low η, high η)	0.20%, 0.51%	0.18%, 0.12%
Cut-based			
Photon identification efficiency		1.0%	2.6%
$R_9 > 0.94$ efficiency (results in class migration)		4.0%	6.5%
Mass-fit and mass-sidebands			
Photon identification BDT		±0.01 (shape shift)	
	(Effect of up to 4.3% event class migration.)		
Photon energy resolution BDT		±10% (shape scaling)	
	(Effect of up to 8.1% event class migration.)		
Per event			
Integrated luminosity		4.4%	
Vertex finding efficiency		0.2%	
Trigger efficiency		1.0%	
Global energy scale		0.5%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
	Gluon-gluon fusion process	28%	
	(Effect of up to 15% event migration among dijet classes.)		
Muon selection			
Muon identification efficiency		1.0%	
Electron selection			
Electron identification efficiency		1.0%	
E_T^{miss} selection			
E_T^{miss} cut efficiency	Gluon-gluon fusion	15%	
	Vector boson fusion	15%	
	Associated production with W/Z	4%	
	Associated production with $t\bar{t}$	4%	
Production cross sections		Scale	PDF
Gluon-gluon fusion		+7.6% -8.2%	+7.6% -7.0%
Vector boson fusion		+0.3% -0.8%	+2.6% -2.8%
Associated production with W/Z		+2.1% -1.8%	4.2%
Associated production with $t\bar{t}$		+4.1% -9.4%	8.0%

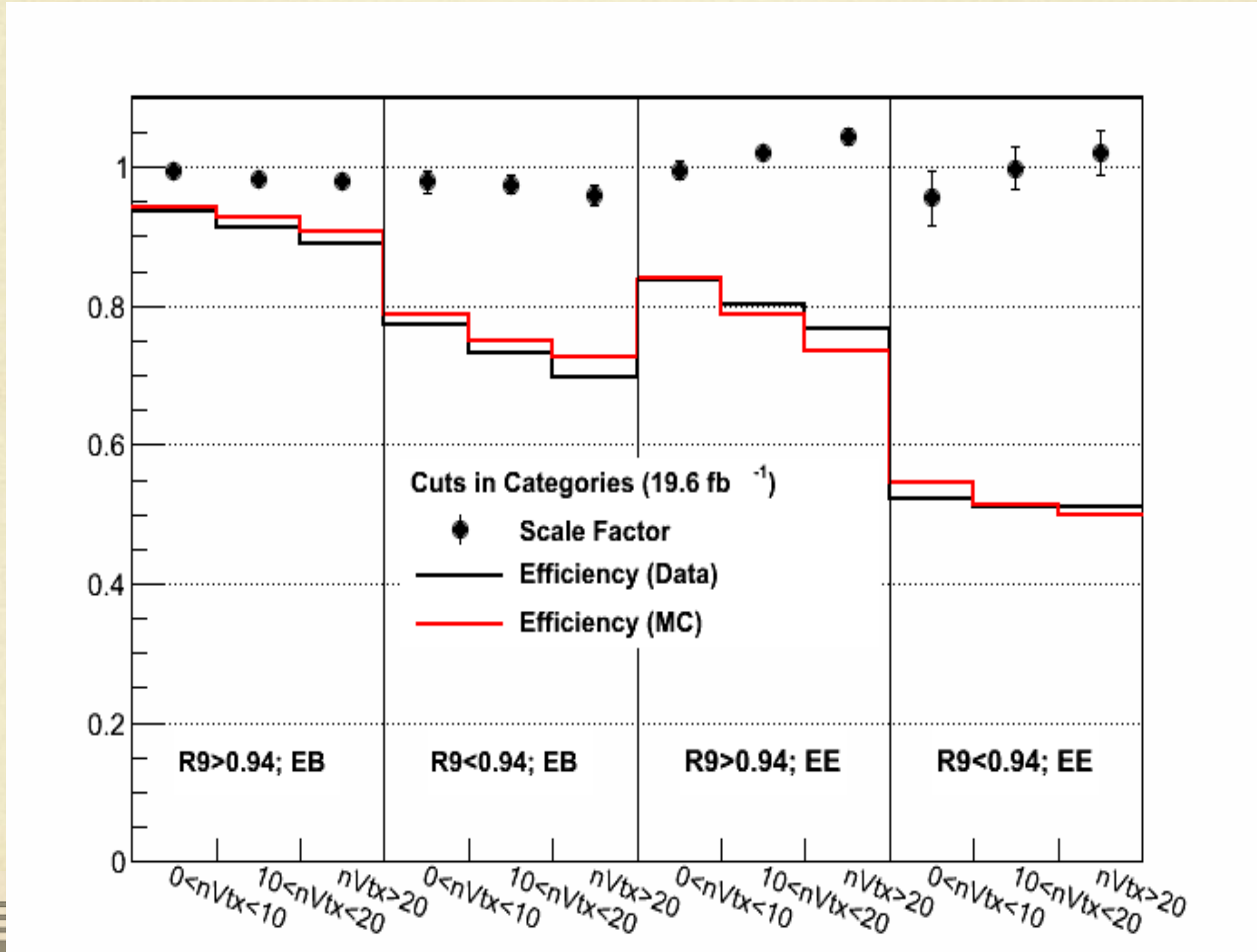
Production Signature Channels

- In addition to the untagged categories, high S/B categories are defined using additional objects in the event
  - Improve significantly the reach to measure Higgs couplings

Categorization Priority (via S/B)

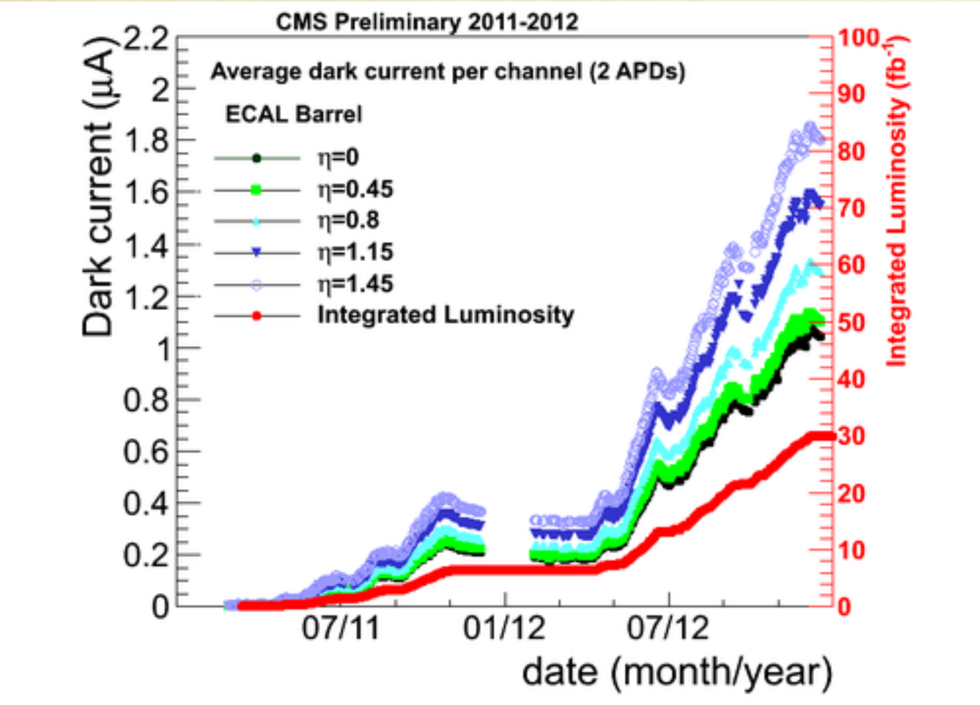
Pileup Robustness: Cut-based ID Efficiency

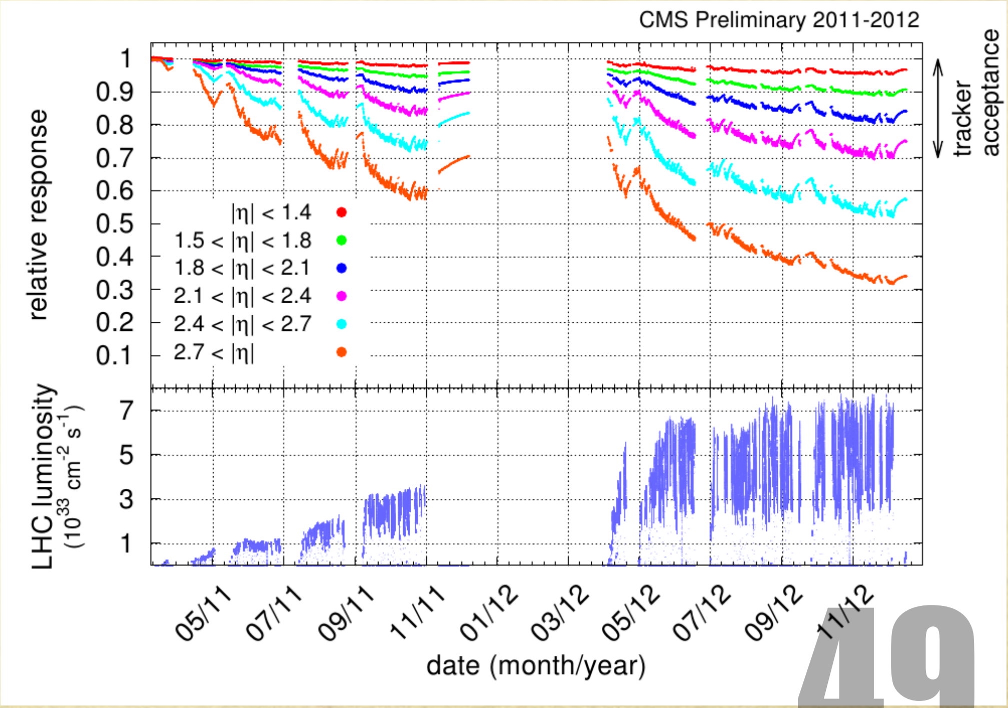
- Cut-based Photon ID efficiency decreases with respect to pileup, well described by MC



Dark Current in ECAL

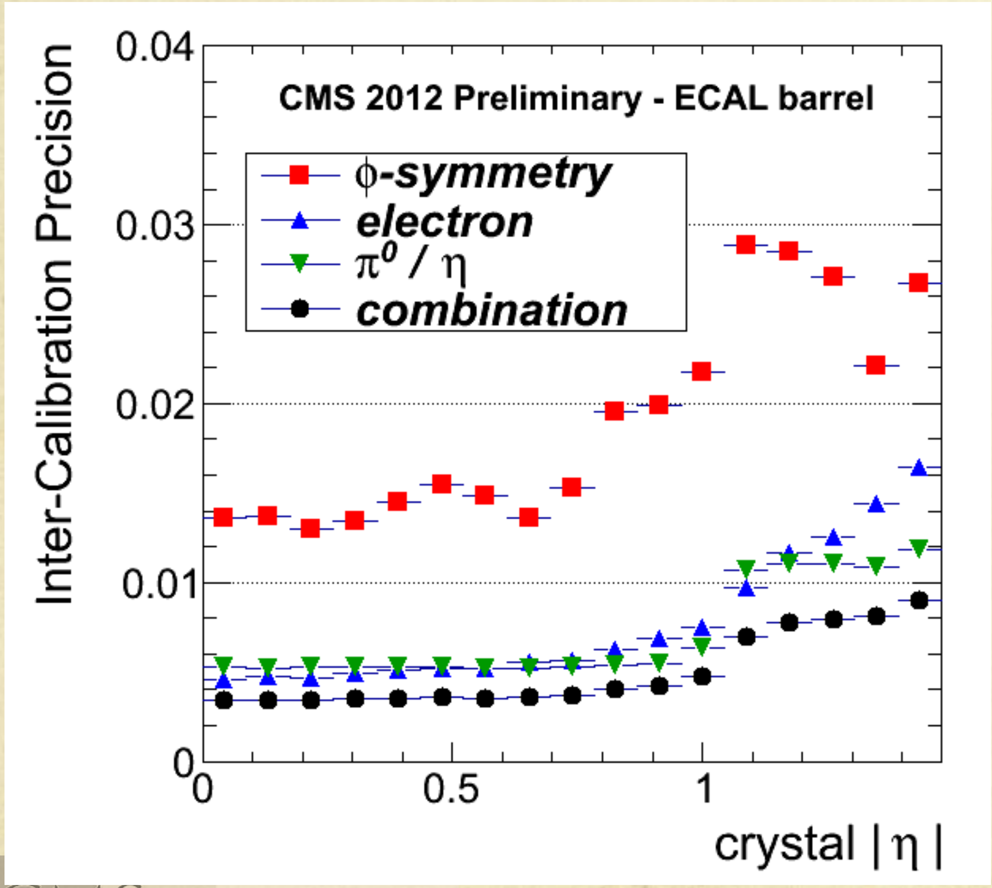
- Avalanche Photo Diodes (APD) have increasing, random noise from radiation damage over time
- This analysis is not dependent on variables that are directly dependent on this noise
- Energy scale in electrons is very well corrected/understood over time despite the dark current

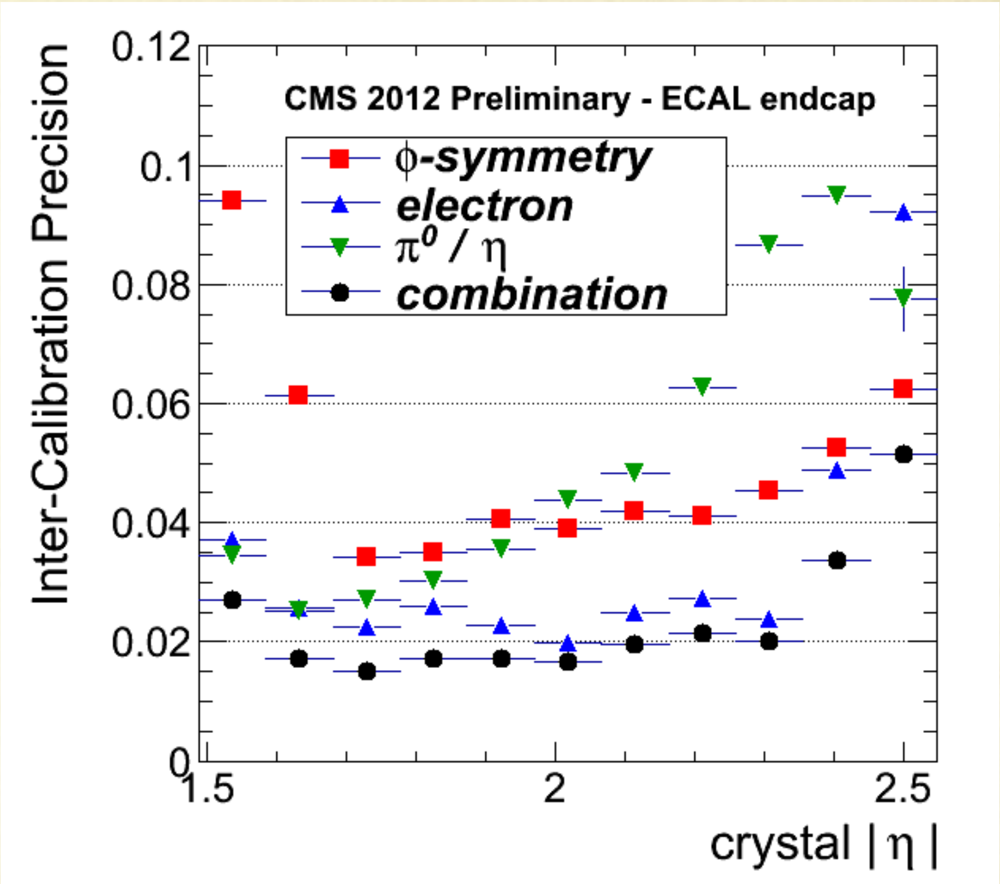




ECAL Inter-Calibration Precision

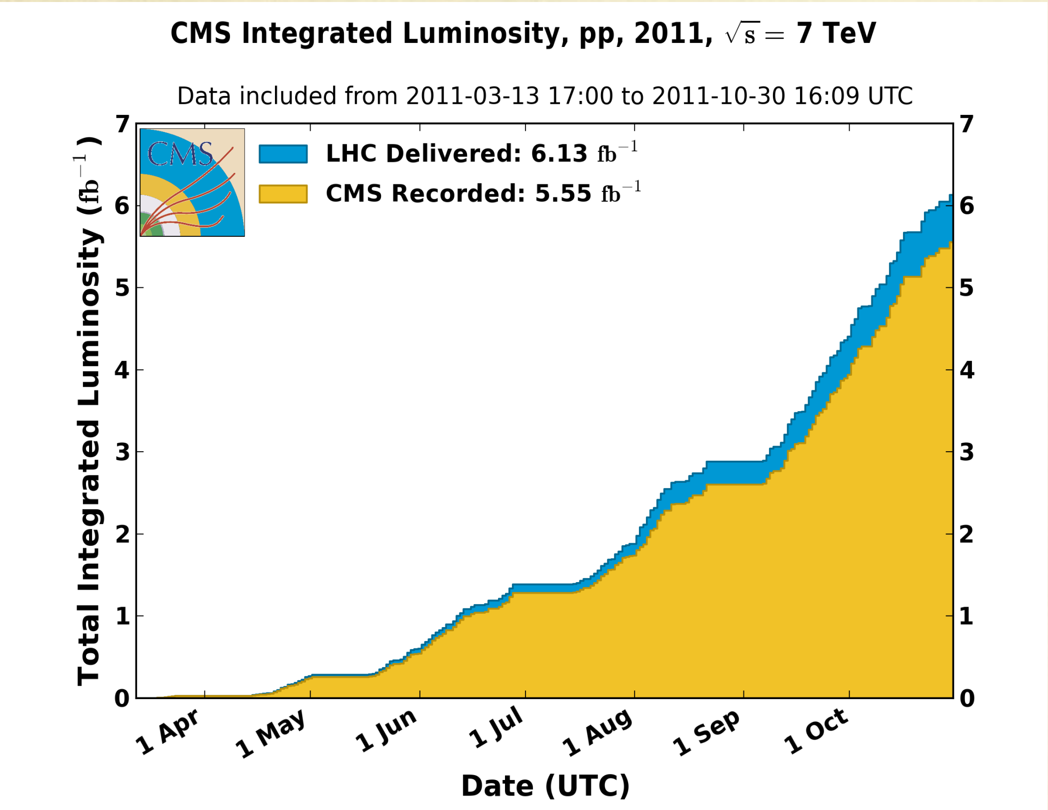
- The overall error on the inter-calibration (not energy scale) is less than 0.005 (0.02) in the barrel (endcaps).





Integrated Luminosity

2011



2012