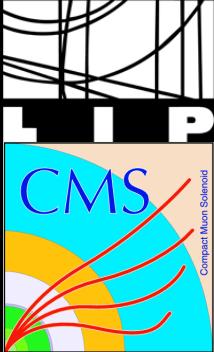


Search for the SM Higgs boson decaying in di-photons

[CMS-PAS-HIG-12-001]



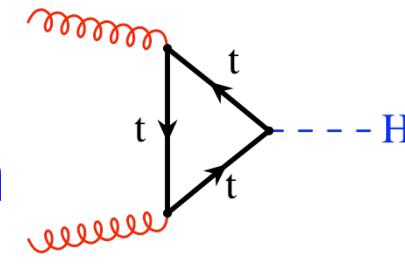
Search for the SM Higgs boson decaying in di-photons

[CMS-PAS-HIG-12-001]

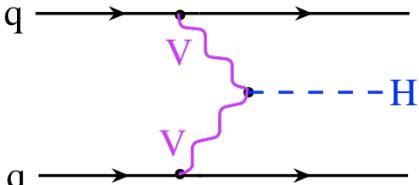
made with ZIP

How the SM Higgs is produced

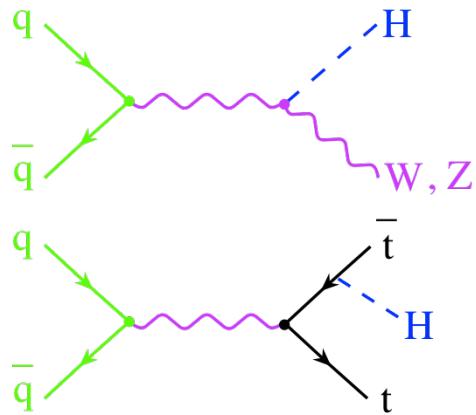
1. Gluon fusion



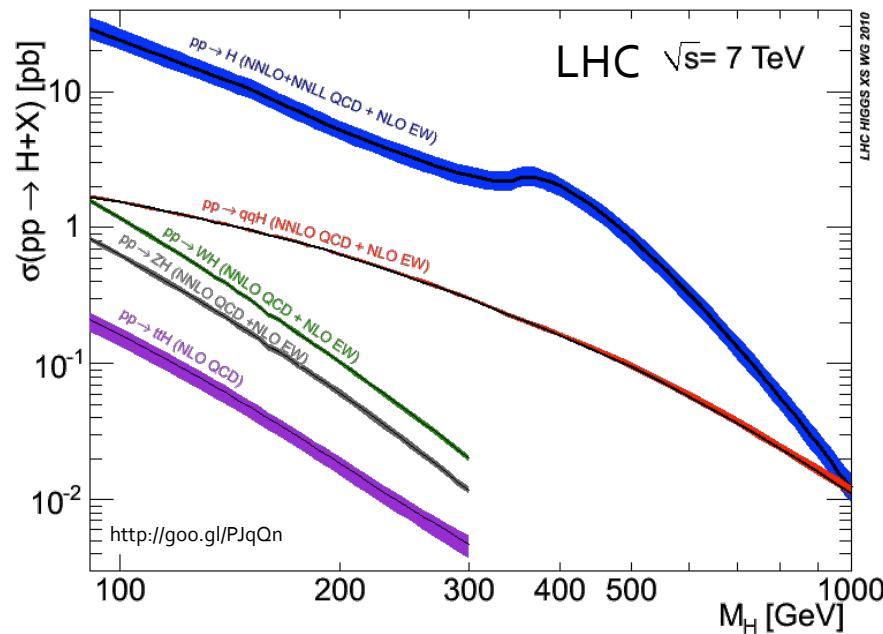
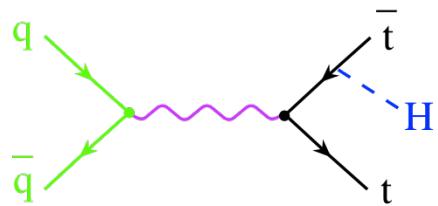
2. VBF



3. VH



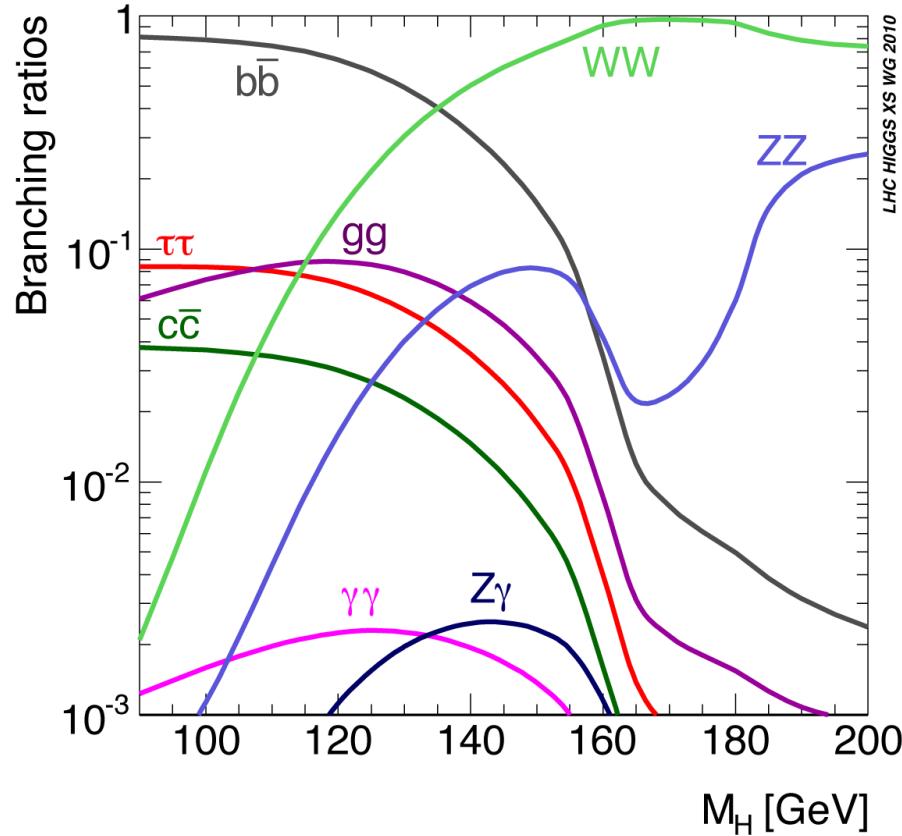
4. ttH



How the SM Higgs decays

<http://goo.gl/uiWwA>

- Direct decay via:
 - Gauge coupling.
(WW , ZZ)
 - Yukawa coupling.
(bb , $\tau\tau$)
- Decay through loops.
($\gamma\gamma$, $Z\gamma$)
 - Heavily suppressed BR.
- *Decay to cc and gg undetectable at the LHC.*



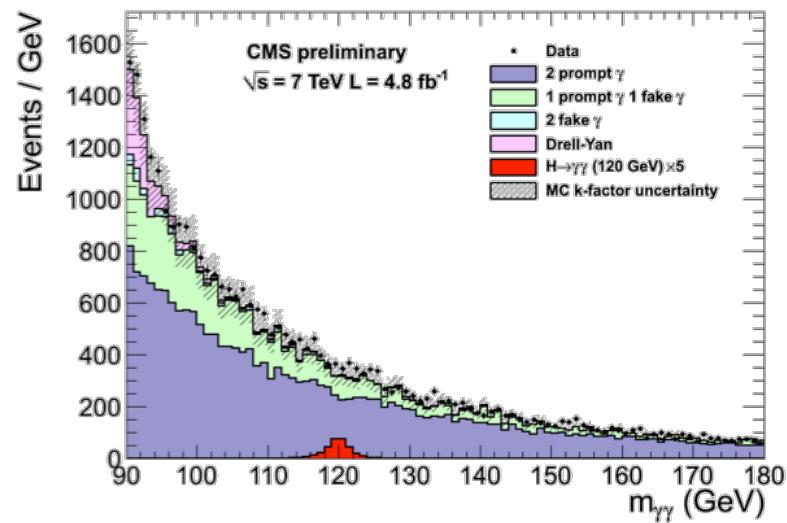
The di-photon channel at the LHC...

- ...is the most sensitive for $m_H < 125$ GeV.
 - Where electroweak measurements point to.
- ... has excellent mass resolution.
 - Unlike $b\bar{b}$, $\tau\tau$, or WW .
- ... has some background.
 - Allows to gauge sensitivity.
 - Unlike the golden decay: $ZZ \rightarrow 4l$.



The di-photon channel in CMS

- $H \rightarrow \gamma\gamma$ one of the most sensitive channels in $110 < m_H < 150$ GeV
 - Clean final state:
two high p_T isolated photons
 - Narrow mass peak
- $H \rightarrow \gamma\gamma$ sensitivity driven by mass resolution and S/B
 - Mass resolution
 - * Photon energy
 - * Di-photon opening angle
 - Major Backgrounds
 - * $pp \rightarrow \text{jet} + \text{jet}$, $pp \rightarrow \gamma + \text{jet}$ with jet faking photon (mainly π^0)
 - * $pp \rightarrow \gamma\gamma$
- Multivariate analysis (MVA) techniques used to improve $H \rightarrow \gamma\gamma$ search sensitivity
 - provides more optimal event classification
- The analysis uses $\int L dt = 4.76 \text{ fb}^{-1}$ of CMS data

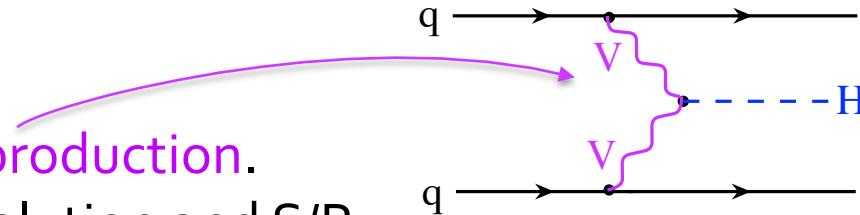


Analysis strategy evolution

■ Cut-based analysis.

[PLB 710 (2012) 403-425]

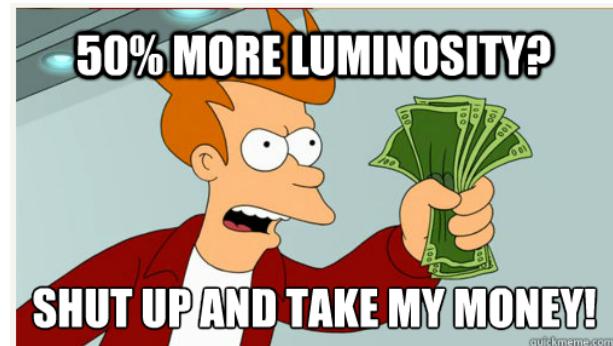
1. Di-jet tagged events for VBF production.
2. Remaining events split by resolution and S/B:
 - Photon pseudorapidity (barrel / endcap).
 - Photon shower shape (unconverted / converted / π^0).



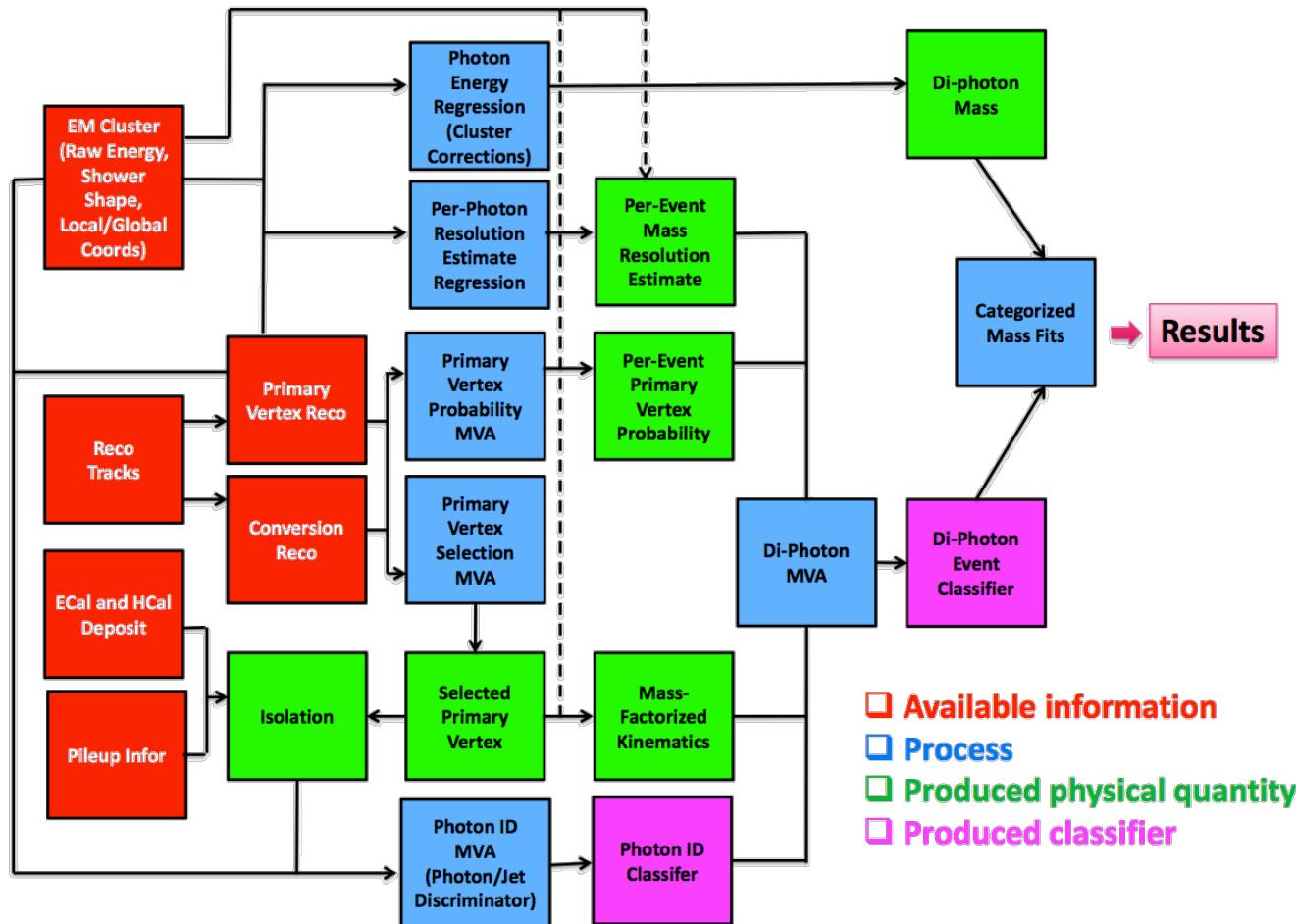
■ Multivariate (MVA) analysis.

[CMS-PAS-HIG-12-001]

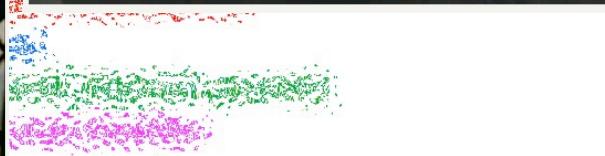
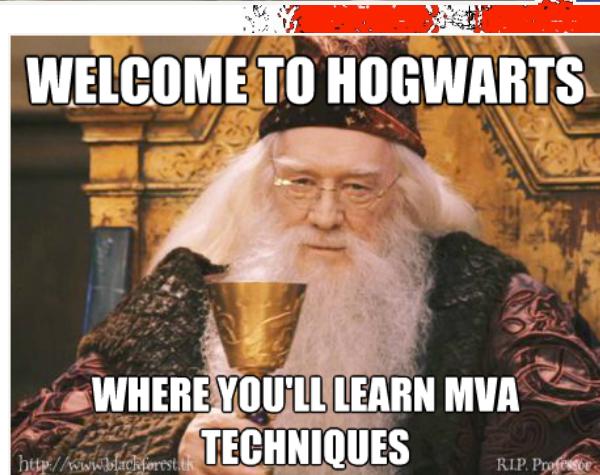
- Event-by-event boosted decision tree (BDT) classifier.
 - Details in the coming slides.
- Sensitivity improvement equivalent to ~ 50% more integrated luminosity.



Anatomy of the analysis



Anatomy of the analysis



Mass resolution deconstructed

$$M_{\gamma\gamma}^2 = 2E_{\gamma 1}E_{\gamma 2}(1 - \cos(\alpha))$$

Photon
energies

Di-photon
opening
angle

$$\frac{\delta M}{M} = \frac{1}{2} \left(\frac{\delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\delta \alpha}{\tan(\alpha / 2)} \right)$$

Photon energy resolution

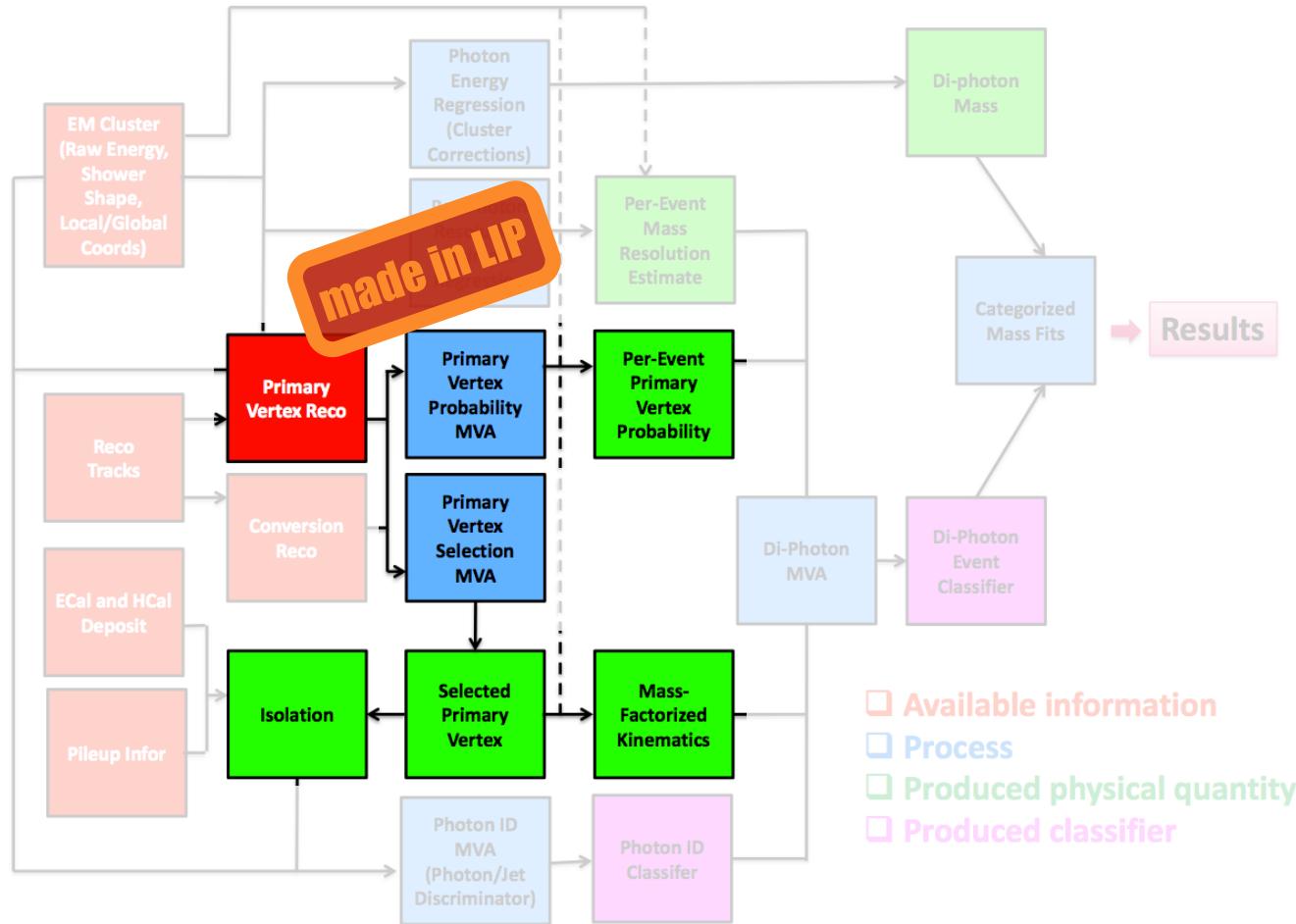
Angular resolution

Angular resolution

- Unconverted photons have no tracks.
- CMS ECAL is homogeneous, optimized for energy resolution, no pointing ability.

- So, either:
 - you get the right vertex with the right angle...
 - ...or you don't.

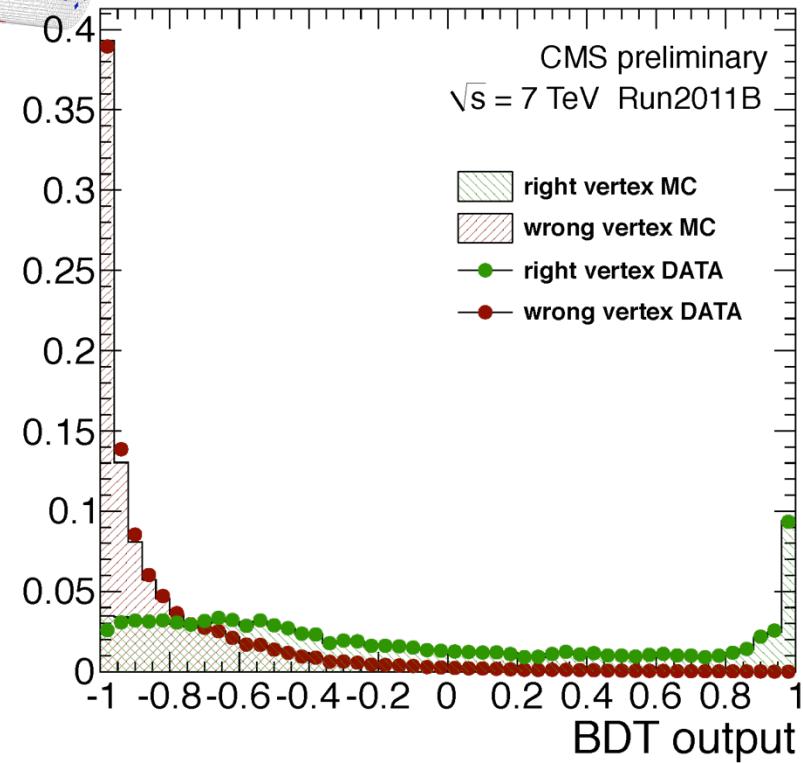
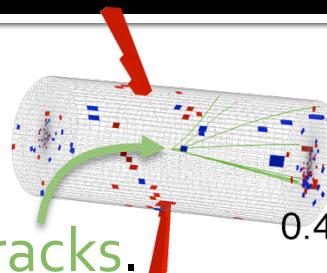
Anatomy of the analysis



Choosing the best vertex

- Main handles:
 - Di-photon recoil **tracks**.
 - Good at high p_T .
 - Validated with $Z \rightarrow \mu\mu$ events. →
 - Photon conversion tracks.
 - Validated with γ -jet events.

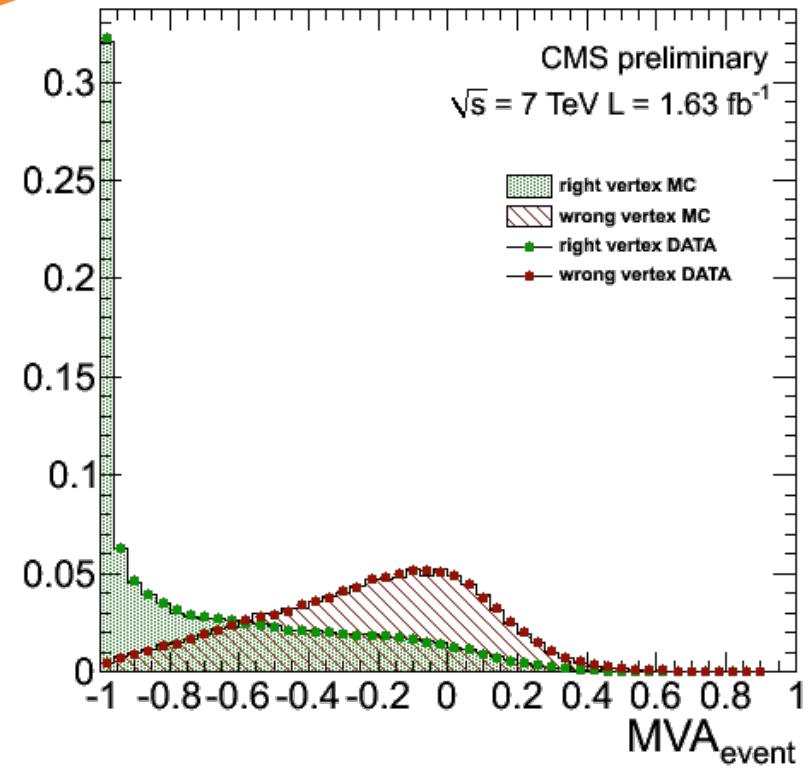
made in LIP



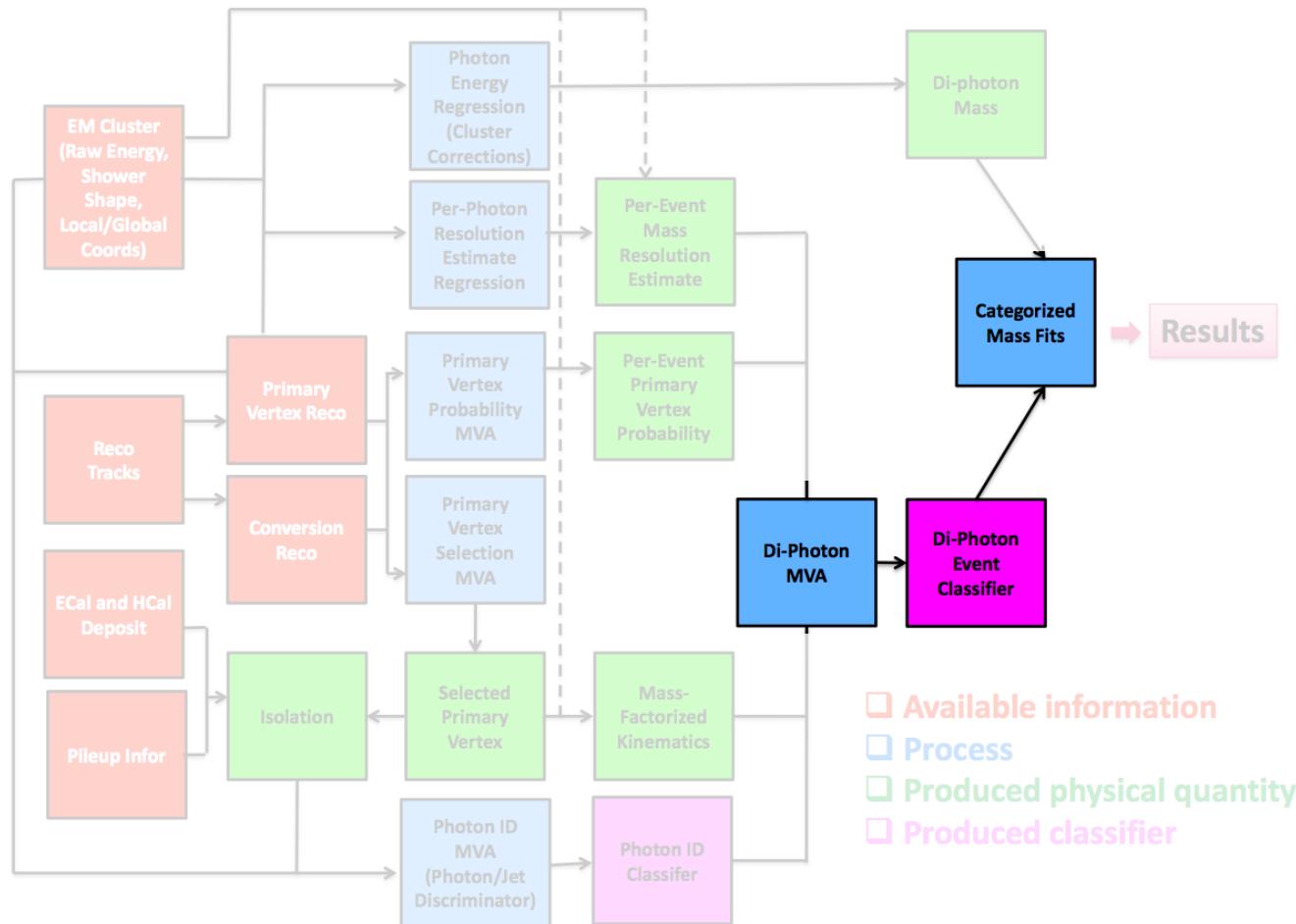
Is the best vertex the right one for this event?

- Make use of several event quantities:
 - Total number of vertices.
 - For each vertex:
 - MVA score.
 - Distance to best vertex.
 - Di-photon p_T .
 - Number of identified conversions.
- Validation in $Z \rightarrow \mu\mu$ events. →

made in LIP

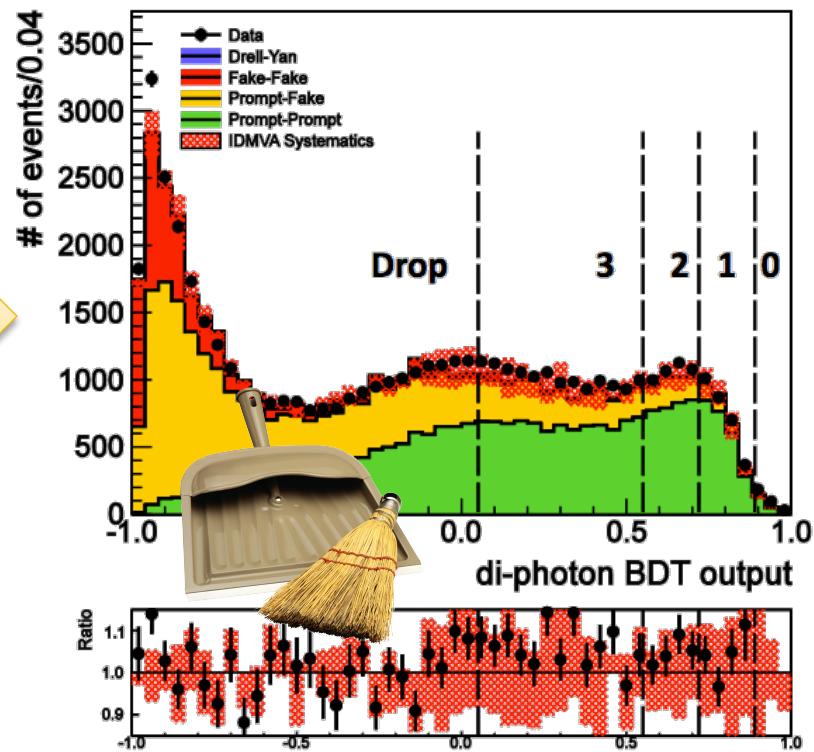


Anatomy of the analysis

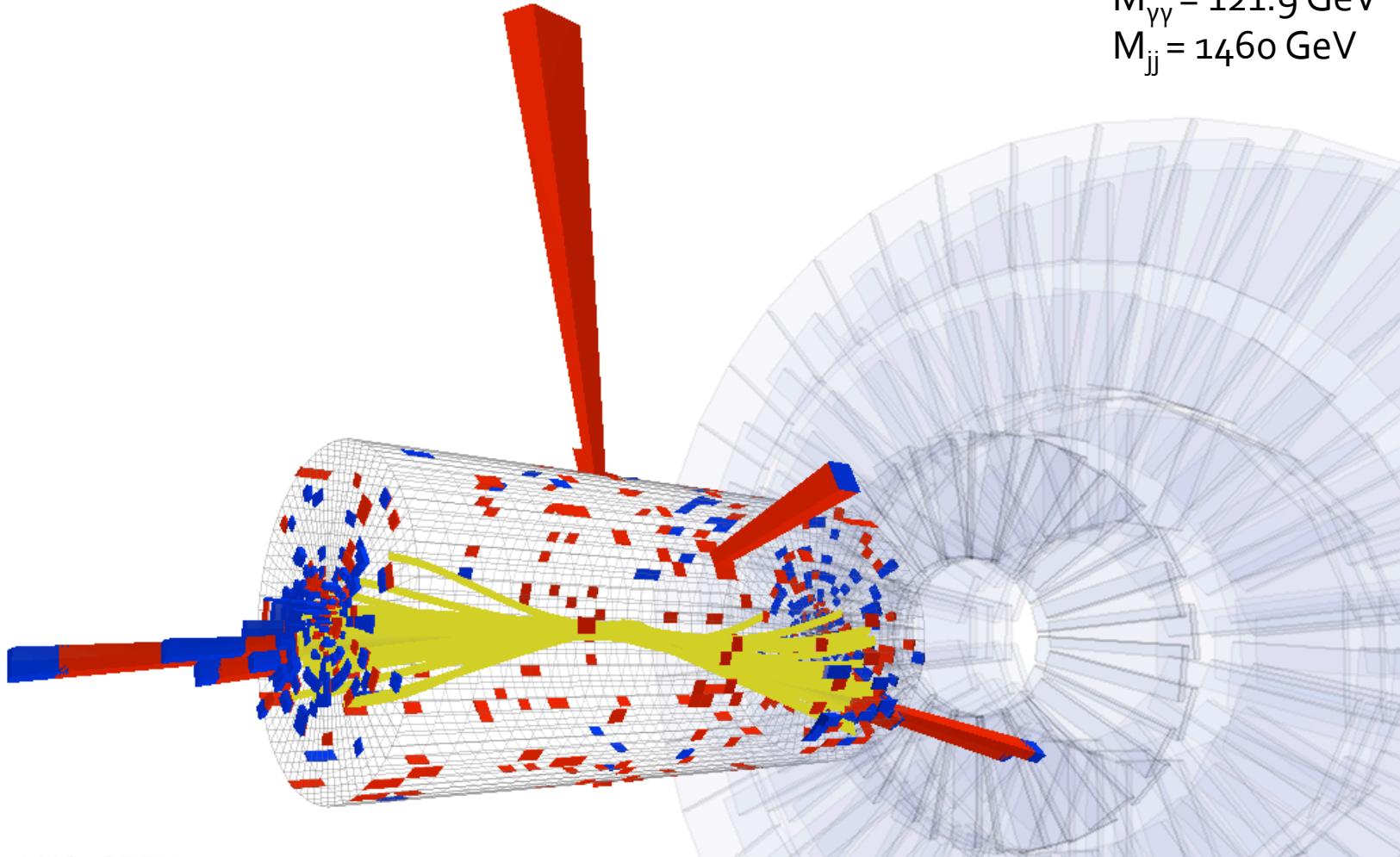
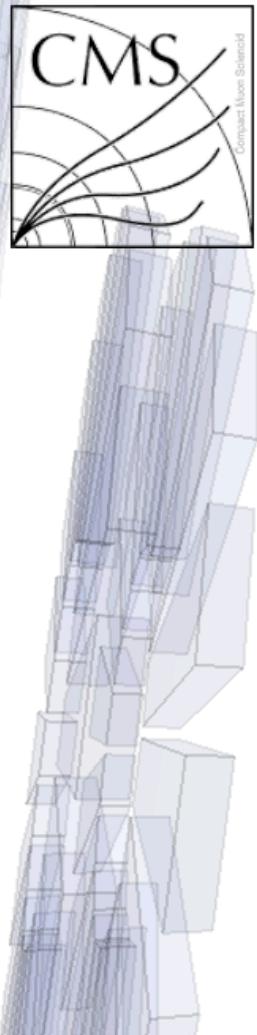


Di-photon classification

- Uses BDT method on MC background and Higgs boson signal events ($m_H=123\text{GeV}$)
- Training variables include photon ID, kinematics, right vertex probability and estimate mass resolution
- Keep Di-photon mass factorized
- Introduce good resolution as a desired feature by weighting signal events by $1/\text{estimate mass resolution}$
- MVA output used to make **5 categories** with different S/B
- Separate di-jet tagged category to select VBF Higgs production
- Signal event category migration systematics
 - Up to 11% due to photon ID
 - Up to 8% due to estimate mass resolution



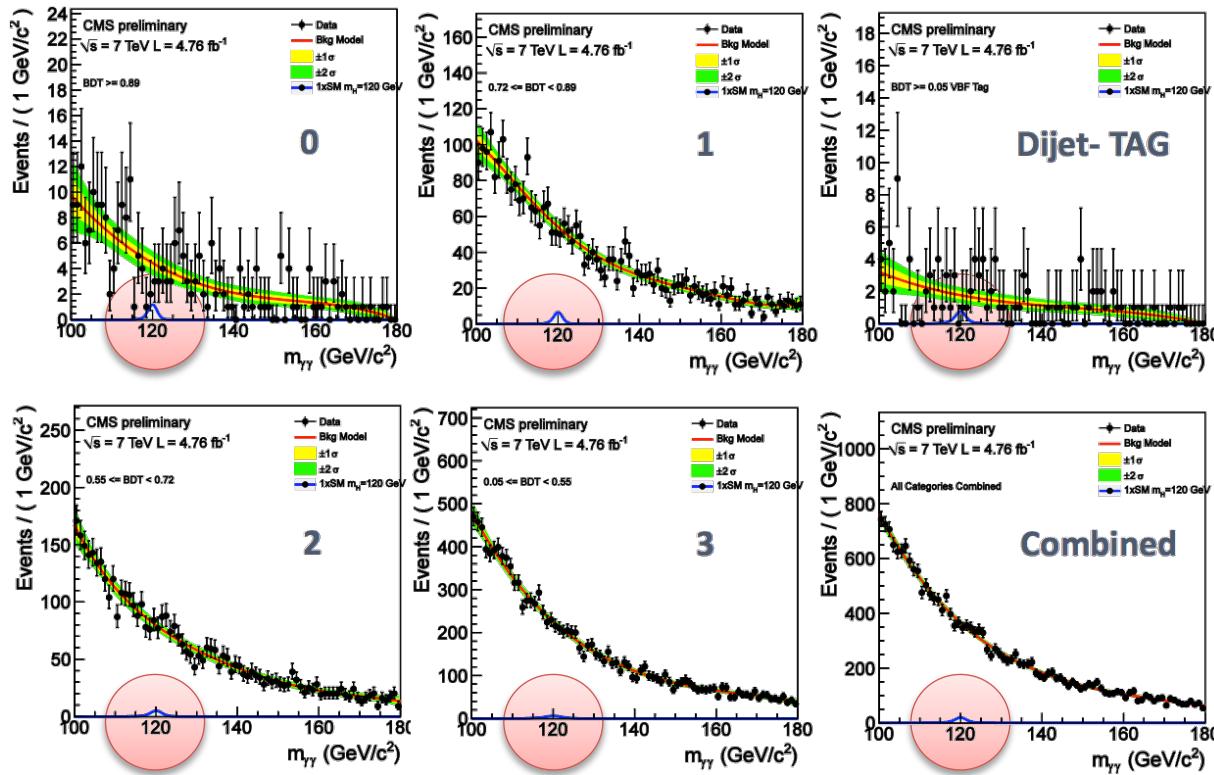
Di-jet tagged event



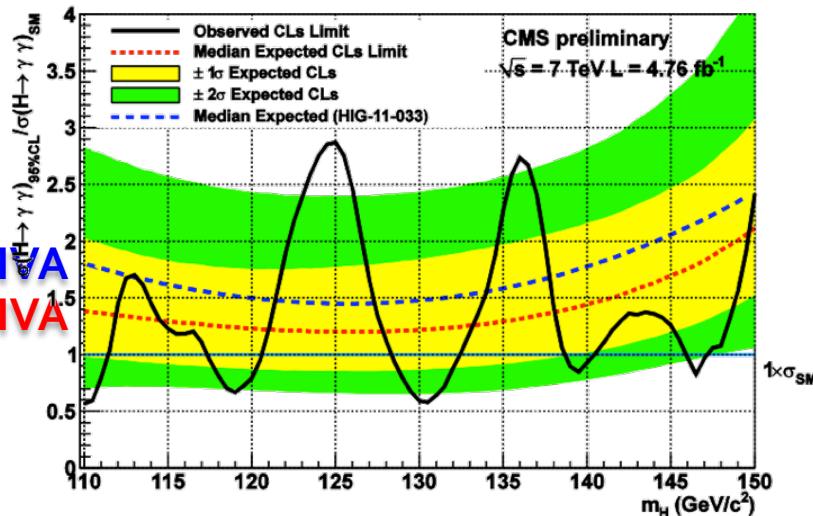
Signal and background modeling

- Higgs mass modeled using MC with energy scale and resolution correction from $Z \rightarrow ee$
- Background mass spectrum modeled by polynomial fit
 - Polynomial order between 3 and 5 depending on event category statistics

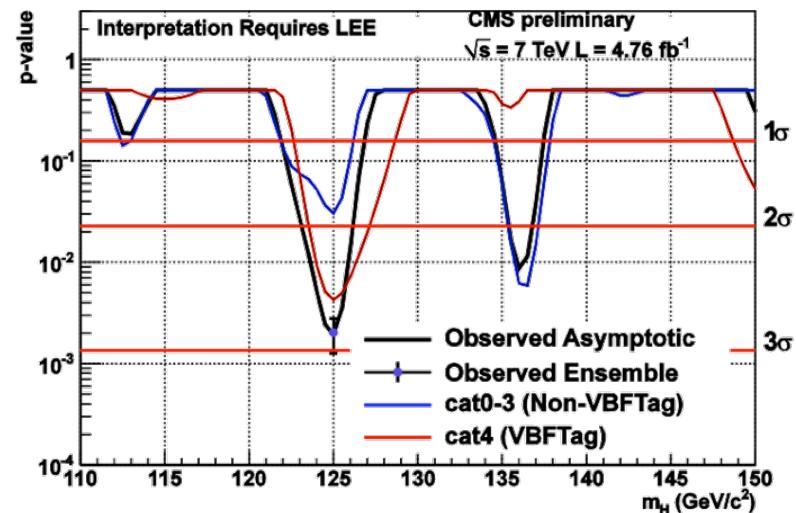
$m_H = 120 \text{ GeV}$
 $1 \times \text{SM}$



Results



- Expected and observed exclusion limit at 95% CL

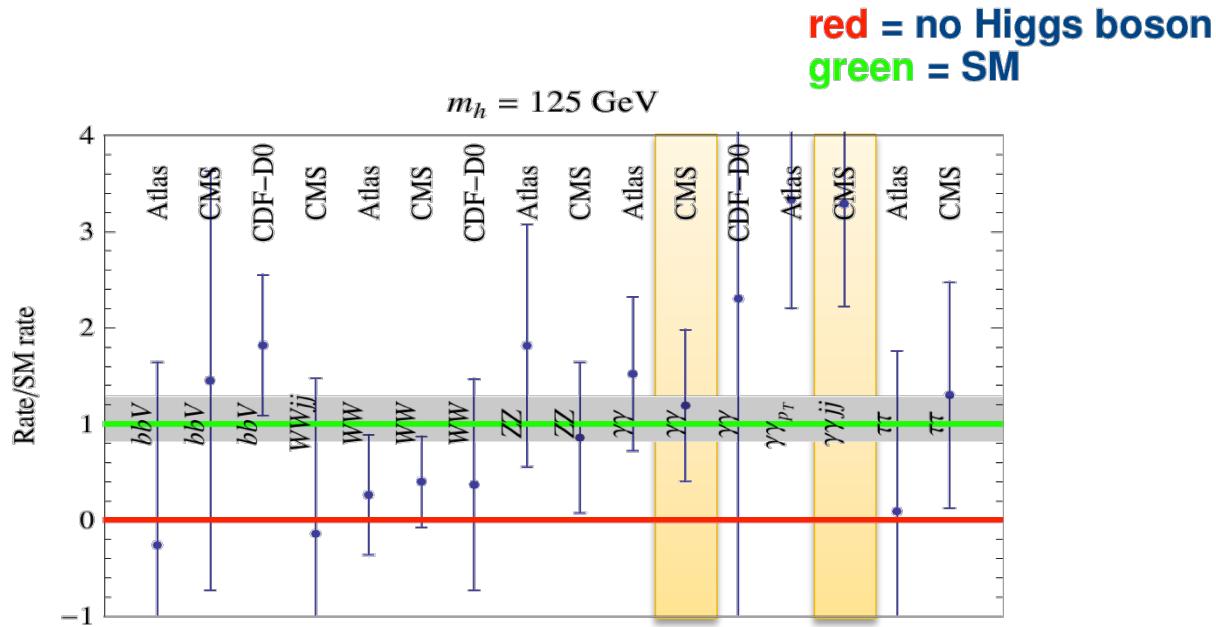


- Largest excess observed around 125 GeV with local significance 2.9σ and global significance 1.6σ

And the data were made public

<http://goo.gl/CVm6s>

- After Moriond 2012, new fits disfavor the SM and motivate for New Physics



P. Giardino, K. Kannike, M. Raidal, A. Strumia, [1203.4254](https://arxiv.org/abs/1203.4254)

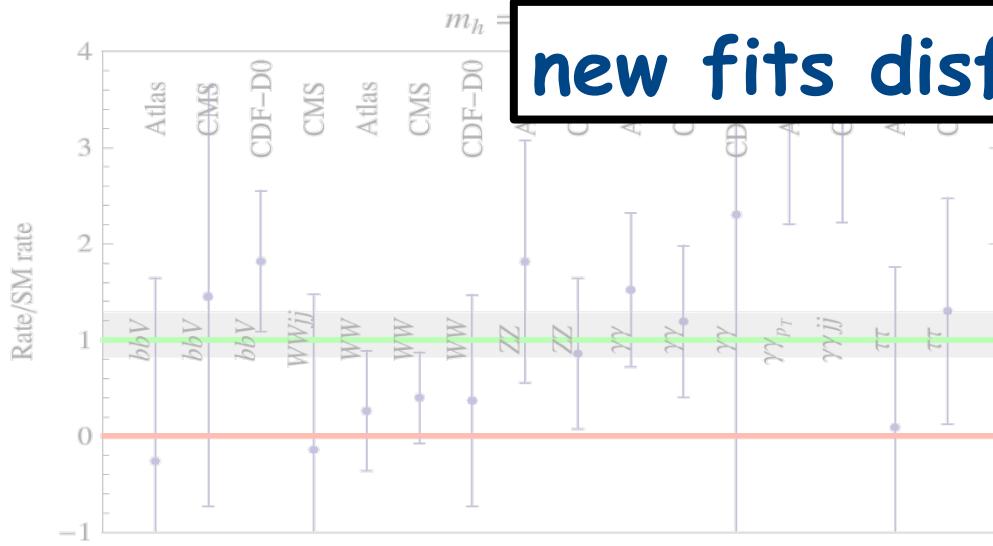
And the data were made public

<http://goo.gl/CVm6s>

■ After Moriond 2012, new fits disfavor the SM and motivate for New Physics

new fits disfavor the SM on
green = SM

new fits disfavor the SM



P. Giardino, K. Kannike, M. Raidal, A. Strumia, [1203.4254](https://arxiv.org/abs/1203.4254)

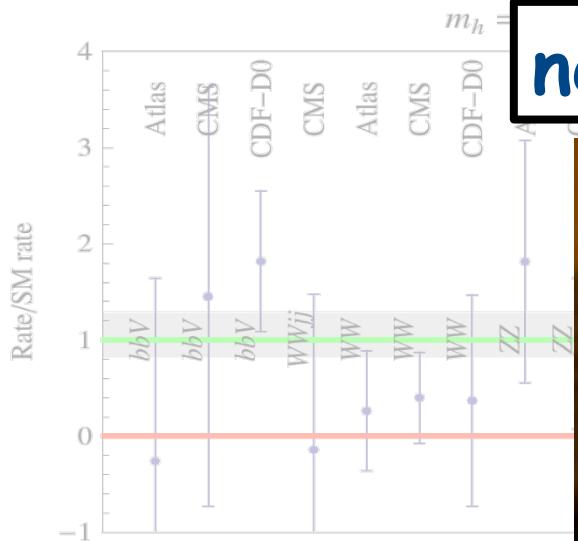
And the data were made public

<http://goo.gl/CVm6s>

■ After Moriond 2012, new fits disfavor the SM and motivate for New Physics

new fits disfavor the SM on
green = SM

new fits disfavor the SM

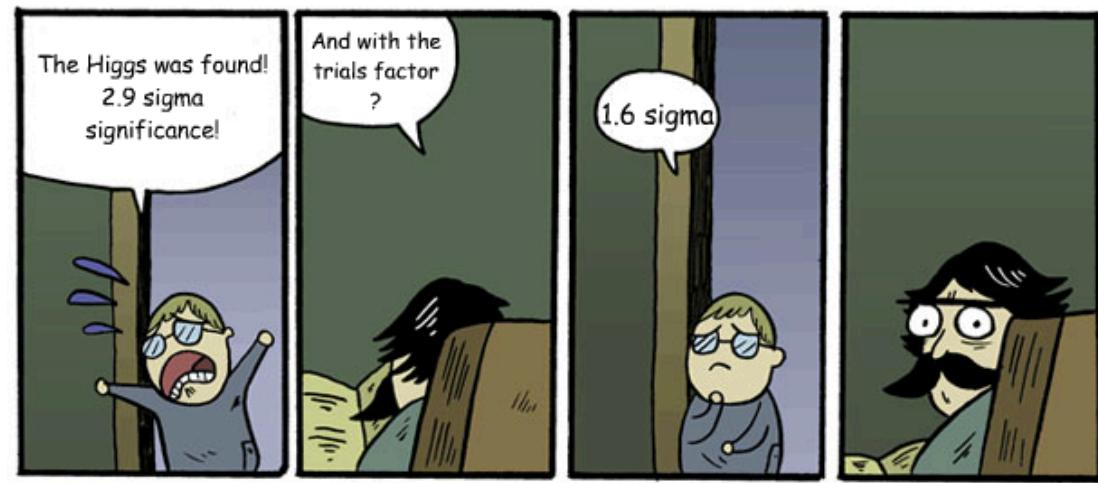


P. Giardino, K. Kannike, M. Ra



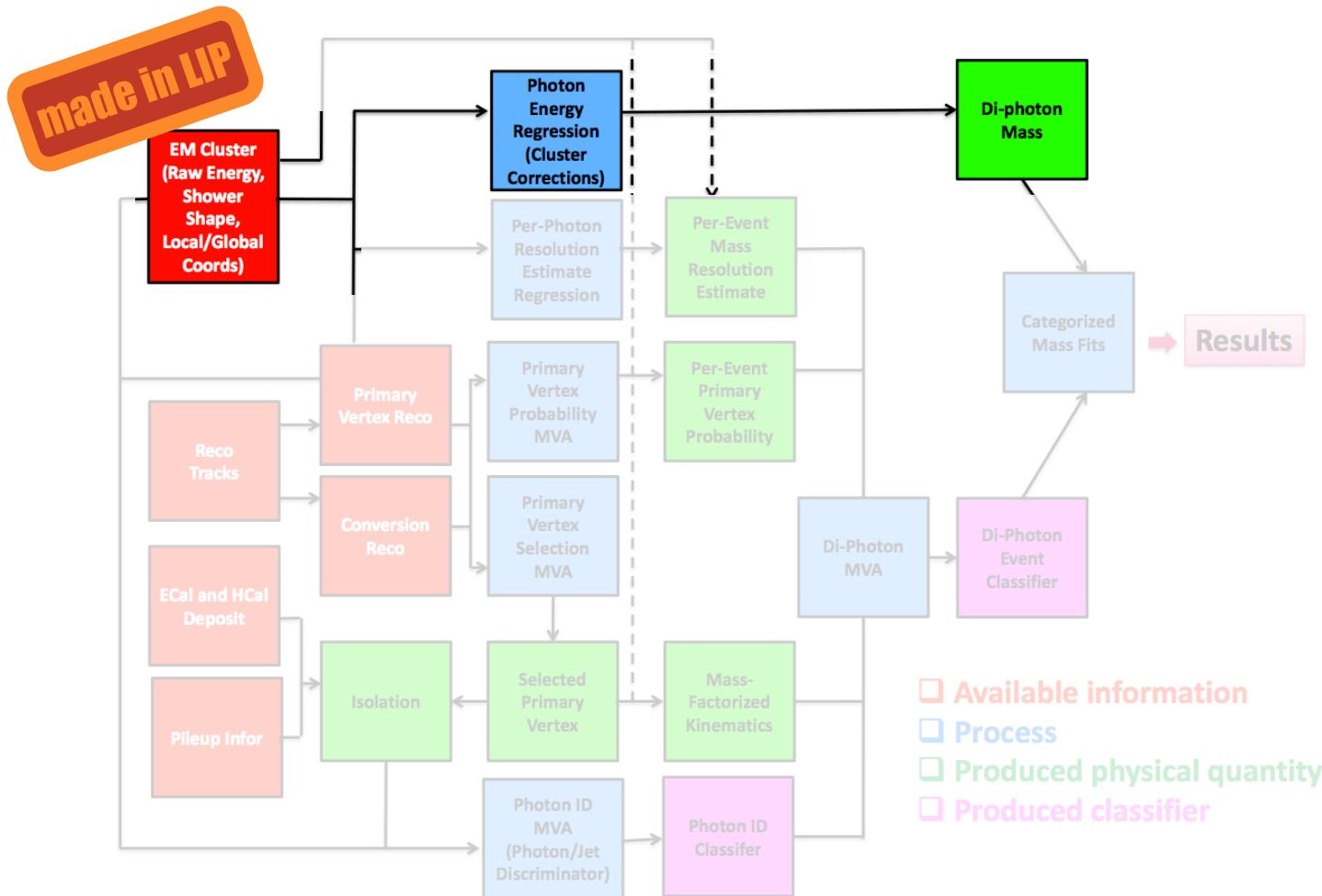
Experimentalist's conclusions

- **ECAL energy resolution performance ~1%.**
 - First year performance close to ultimate.
- **Vertex determination without pointing calorimeter.**
 - ...despite 10 pileup interactions on average.
- **Di-jet tag providing insight into VBF production.**
 - Heavily exploited by phenomenologists.
- **In 110—150 GeV, 1.6σ for $m_H=125$ GeV.**
 - *"More data required to understand the nature of the excess."*
 - 2012 data has more than double the pileup...

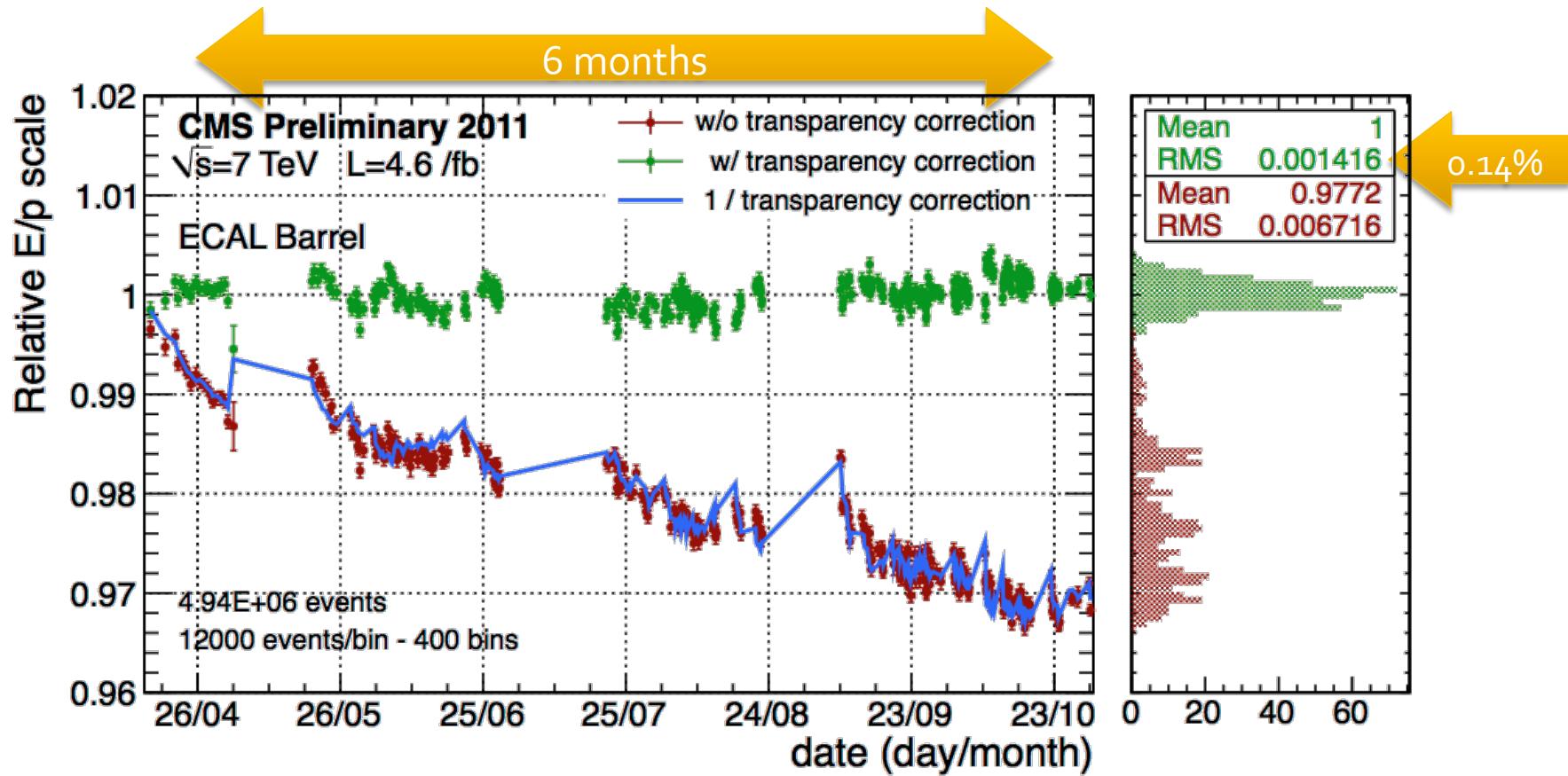


For discussion

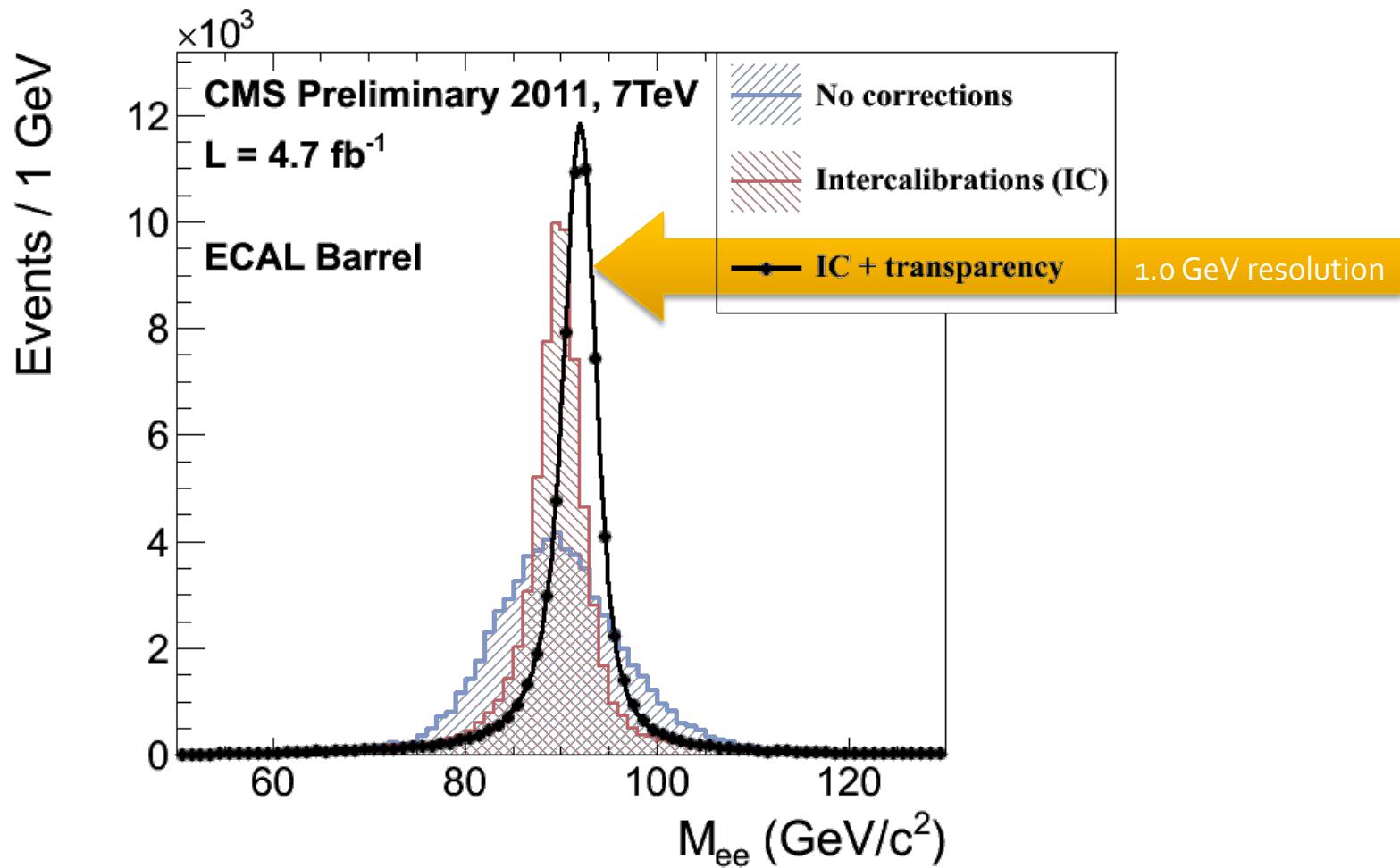
Anatomy of the analysis



ECAL calibration: isolated electrons

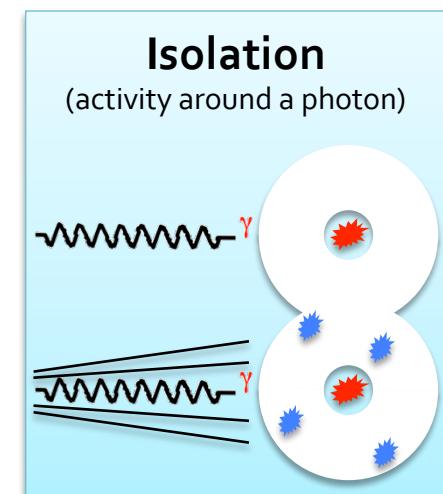
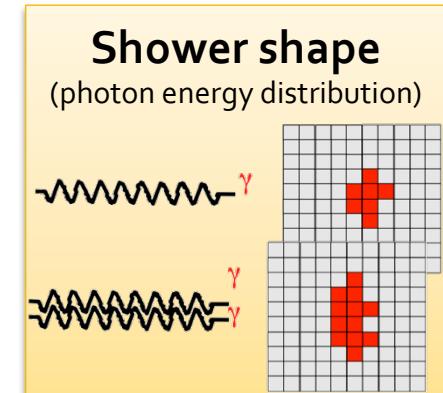
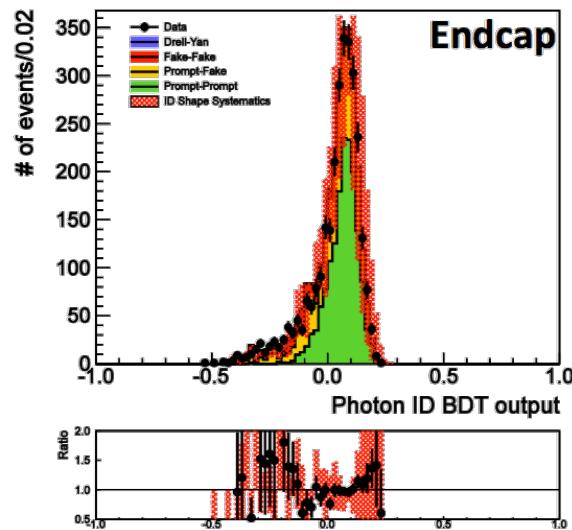
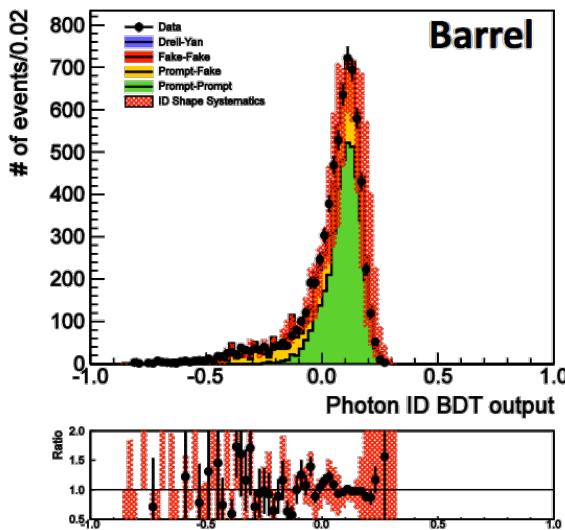


ECAL calibration: $Z \rightarrow ee$ peak

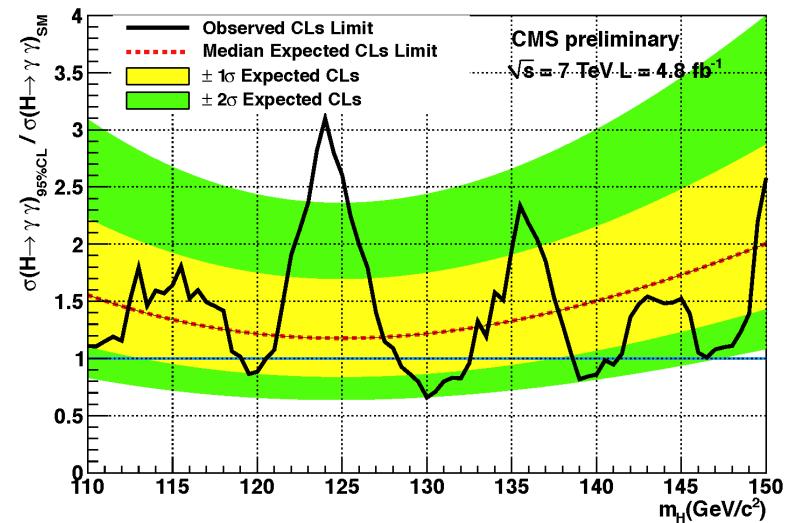
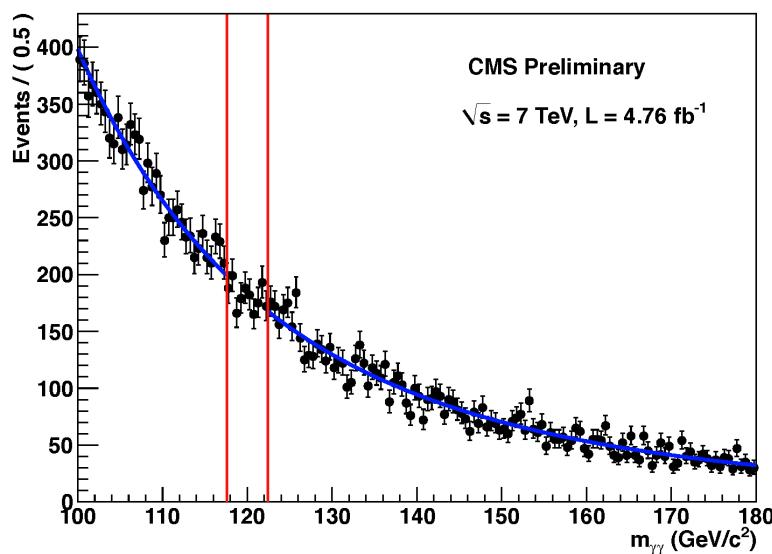


Photon identification

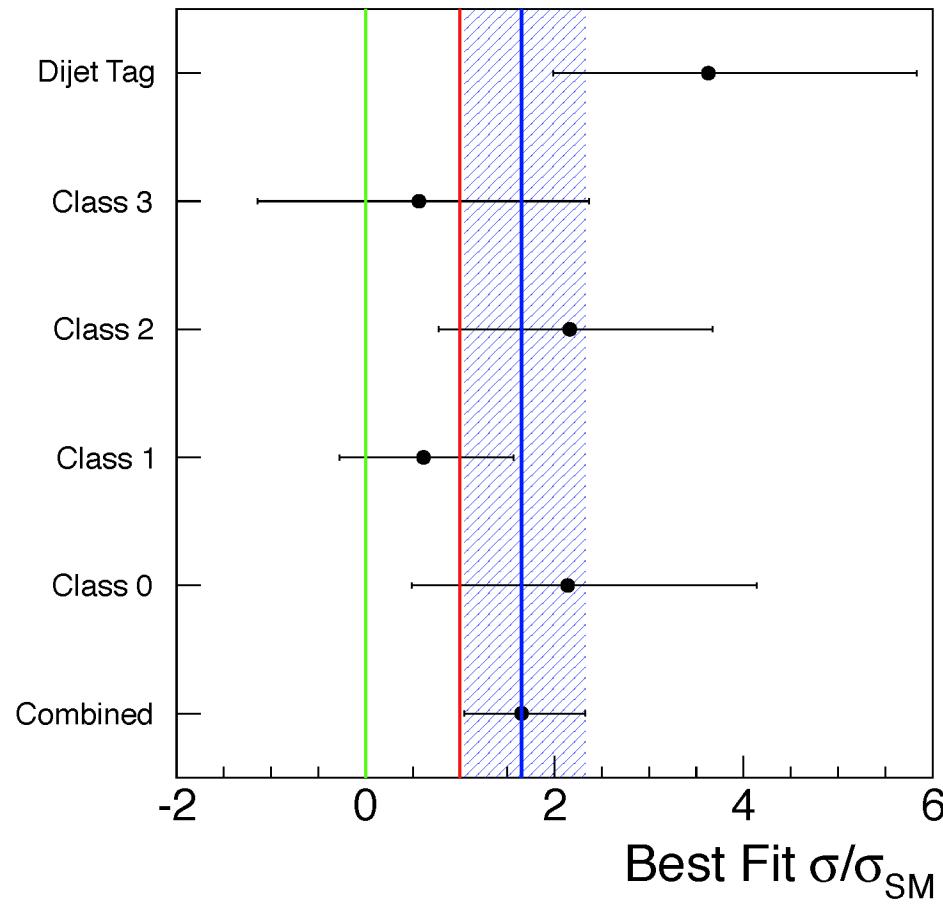
- Photon ID MVA discriminates prompt photon from jet faking photon using a boosted decision tree (BDT) trained on MC simulation events
 - Signal sample: prompt photons from $H \rightarrow \gamma\gamma$
 - Background sample: jets from $pp \rightarrow \gamma + \text{jet}$
- MVA trained separately for Barrel and Endcap
- Uses variables related to **shower shape** and **isolation**
- MVA output gives a classifier variable discriminating prompt photons from fakes
- Photon ID MVA output for the leading photon in preselected di-photon events with $m_{\gamma\gamma} > 160$ GeV is compared between data and MC



Side-band background treatment



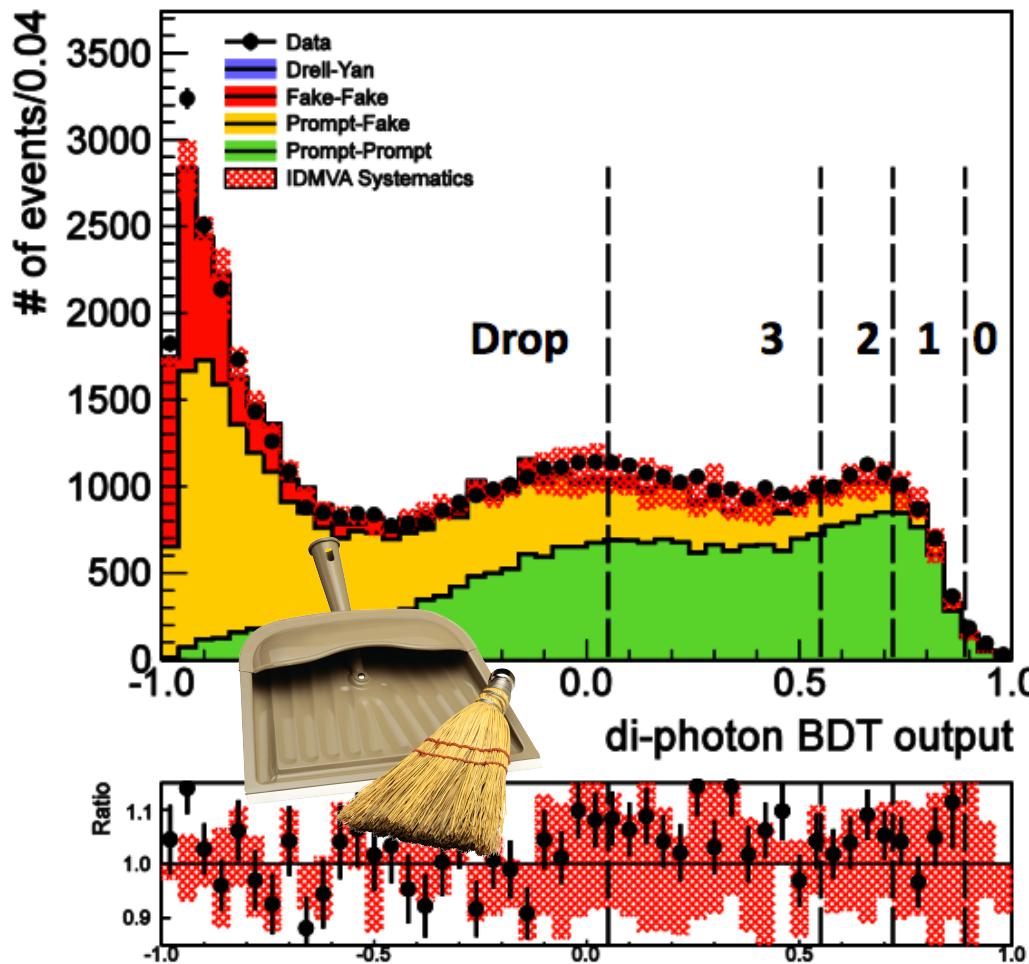
Best-fit strength breakdown



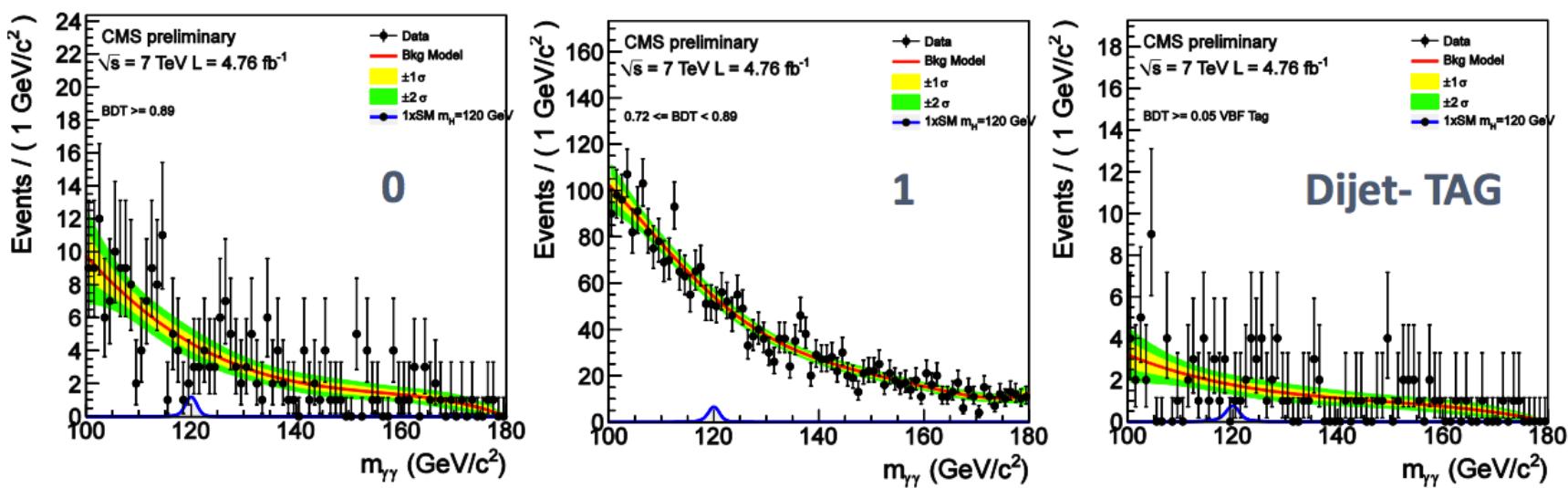
Details on the event classes

	0	1	2	3	Dijet tag
SM signal expected	3.4 (4.4%)	19.3 (25.0%)	18.7 (24.2%)	33.0 (42.8%)	2.8 (3.6%)
Data (events/GeV)	4.5 (1.2%)	55.1 (14.8%)	81.3 (21.8%)	229.1 (61.6%)	2.1 (0.6%)
σ_{eff} (GeV)	1.18	1.25	1.64	2.47	1.65
FWHM/2.35 (GeV)	1.09	1.09	1.43	2.08	1.32

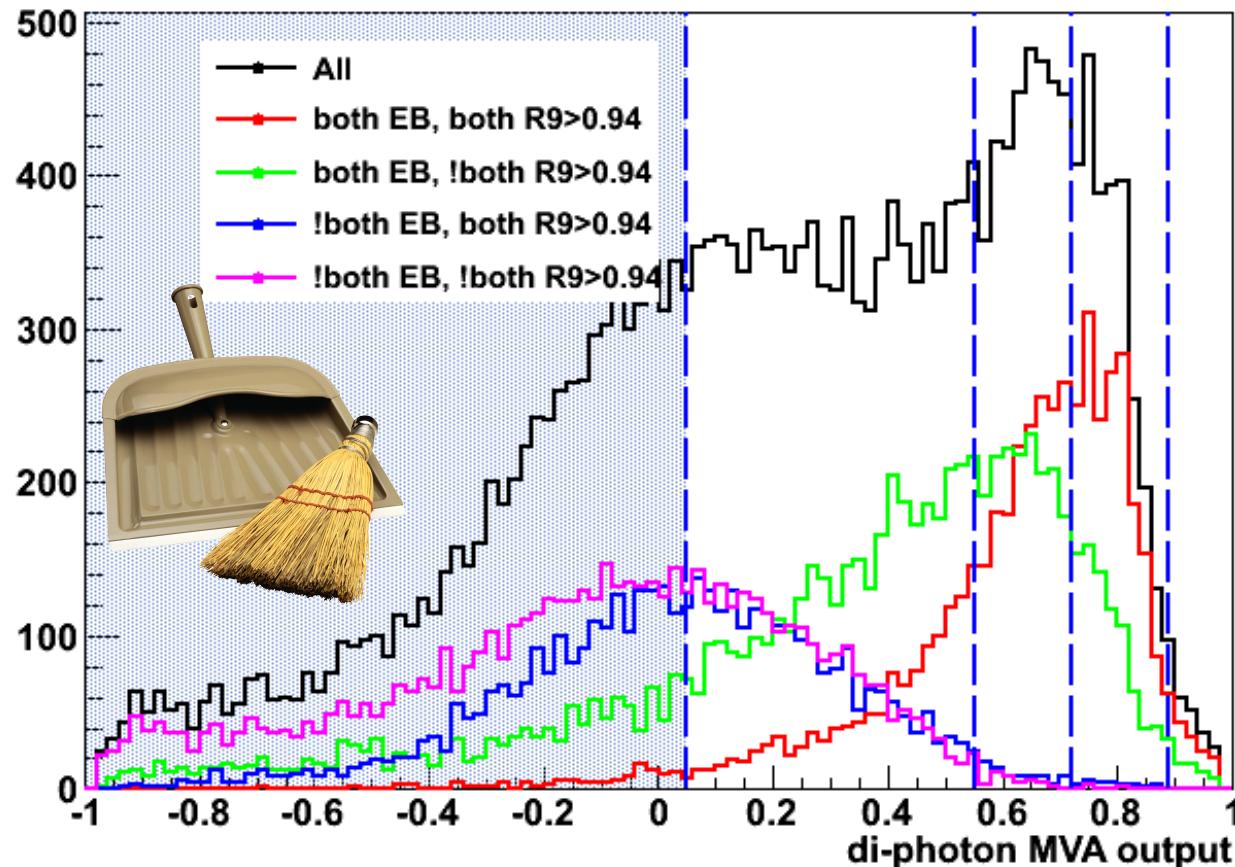
Zoom on the di-photon MVA output



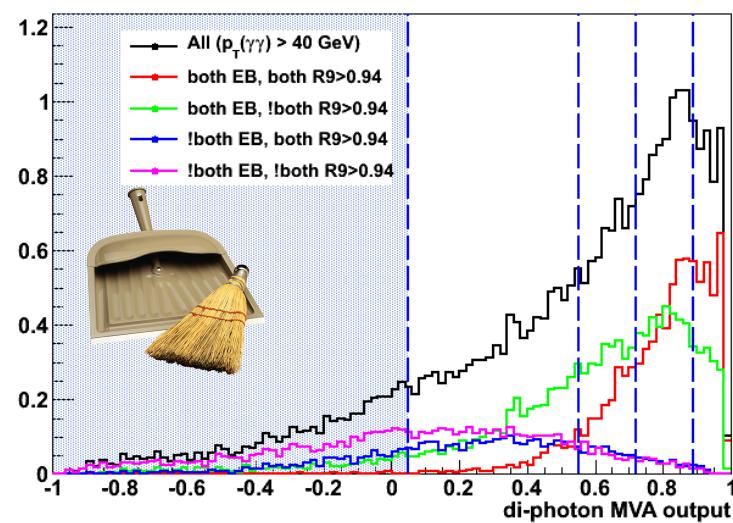
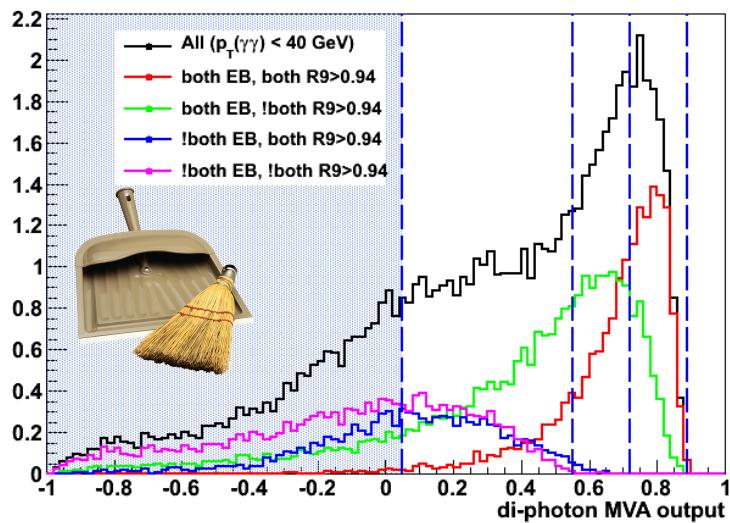
Zoom on the best event classes



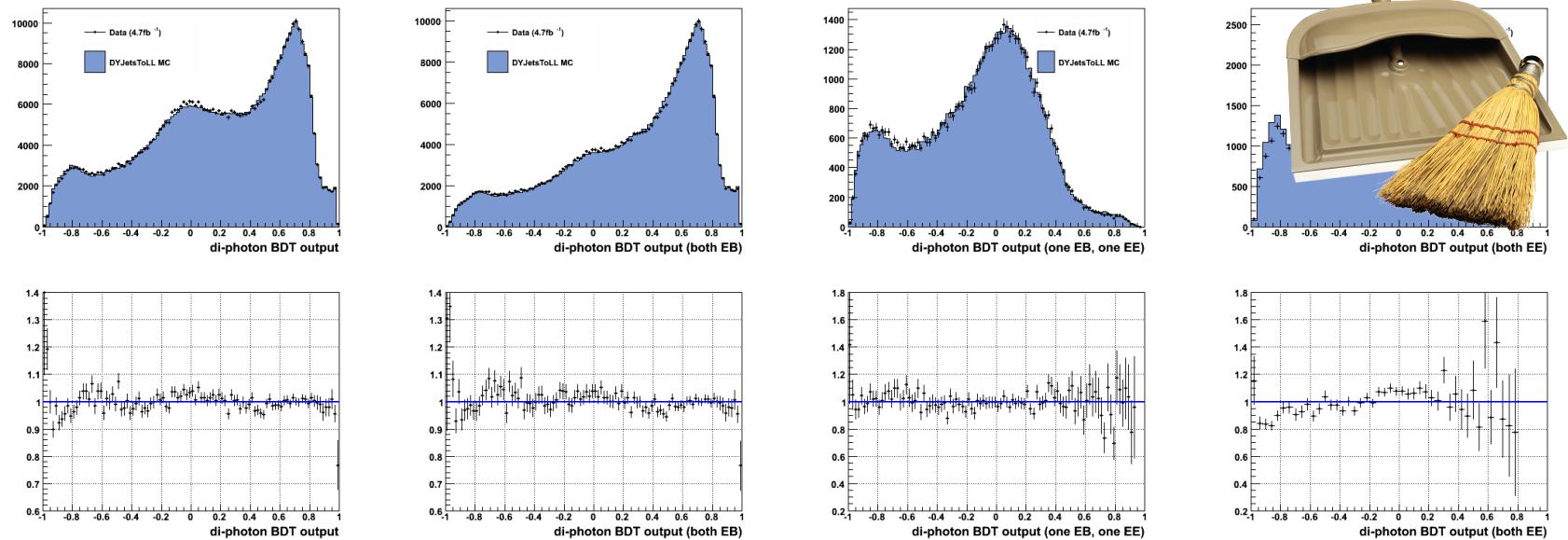
MVA in terms of simple classification



MVA in $p_T(\gamma\gamma)$ bins



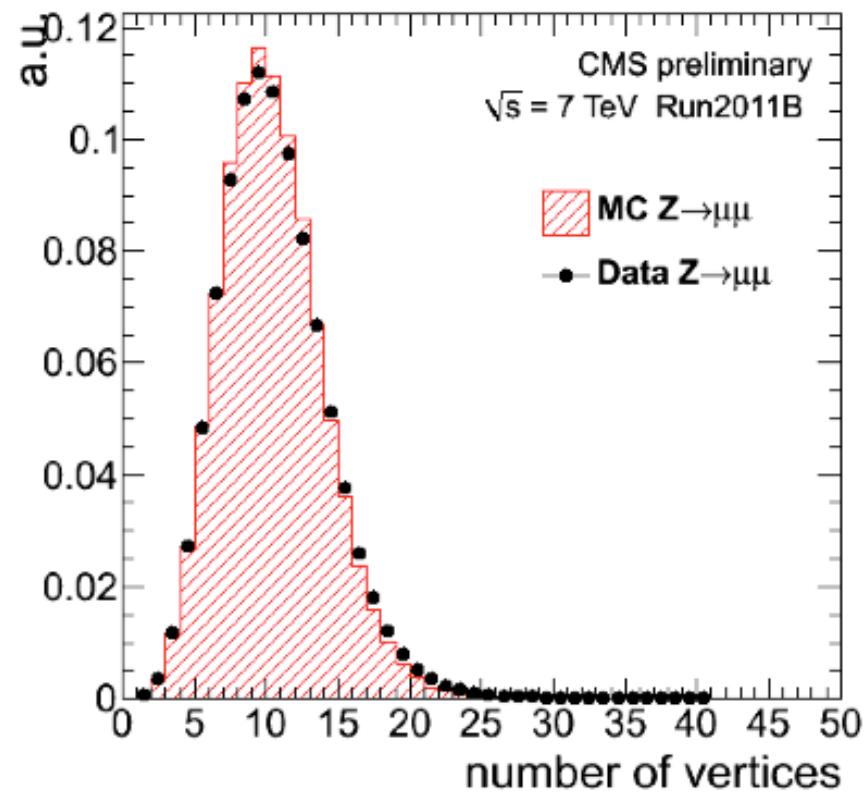
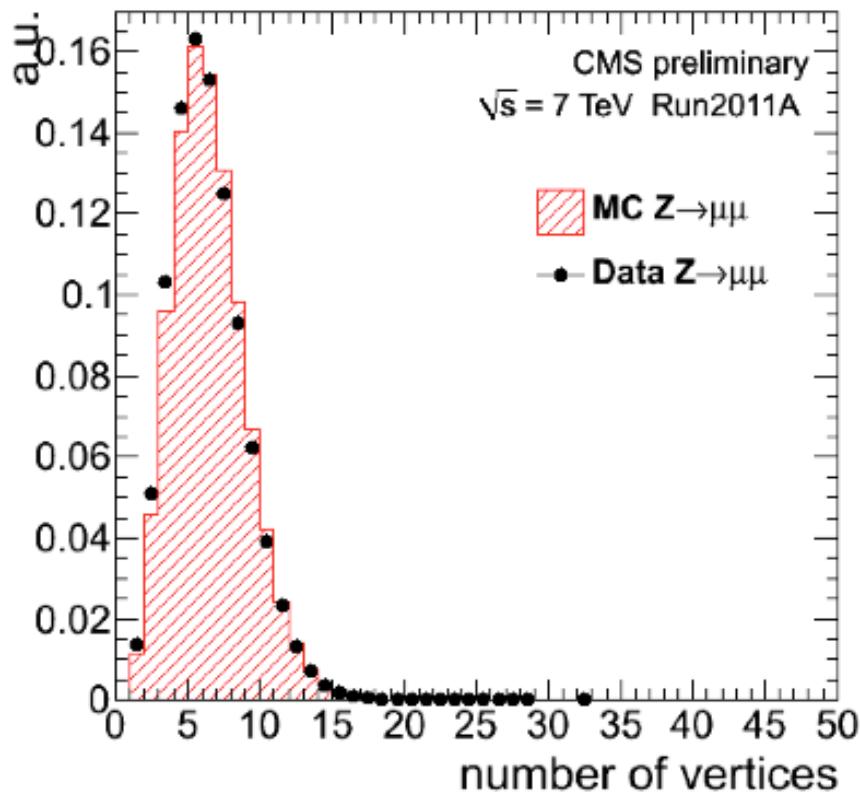
MVA validation on $Z \rightarrow ee$



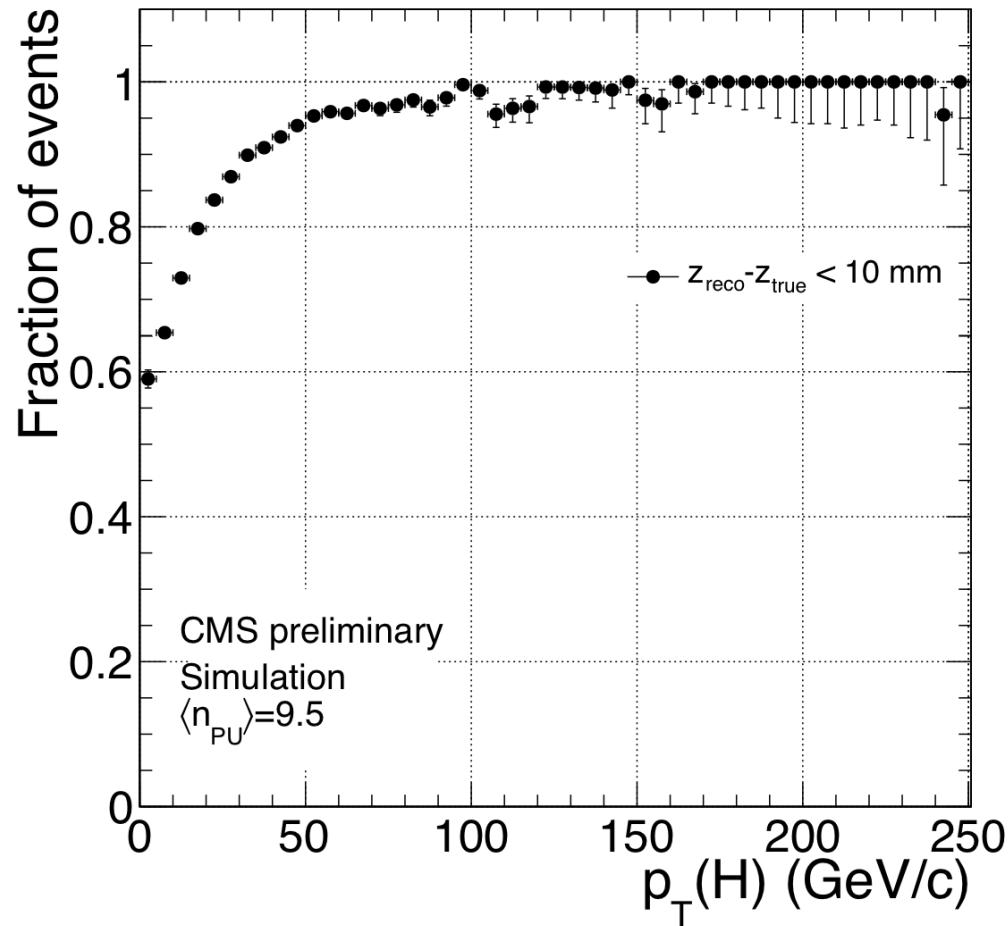
Systematic uncertainties

Sources of systematic uncertainty	Uncertainty	
Per photon	Barrel	Endcap
Photon identification efficiency	1.0%	2.6%
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η , high η) $R_9 < 0.94$ (low η , high η)	0.22%, 0.61% 0.24%, 0.59%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η , high η) $R_9 < 0.94$ (low η , high η)	0.19%, 0.71% 0.13%, 0.51%
Photon identification BDT (Effect of up to 11% event class migration.)	± 0.025 (shape shift)	
Photon energy resolution BDT (Effect of up to 8% event class migration.)	$\pm 10\%$ (shape scaling)	
Per event		
Integrated luminosity	4.5%	
Vertex finding efficiency	0.4%	
Trigger efficiency	One or both photons $R_9 < 0.94$ in endcap Other events	0.4% 0.1%
Dijet selection		
Dijet-tagging efficiency	VBF process Gluon-gluon fusion process	10% 70%
Production cross sections	Scale	PDF
Gluon-gluon fusion	+12.5% -8.2%	+7.9% -7.7%
Vector boson fusion	+0.5% -0.3%	+2.7% -2.1%
Associated production with W/Z	1.8%	4.2%
Associated production with $t\bar{t}$	+3.6% -9.5%	8.5%
Scale and PDF uncertainties (Effect of up to 16% event class migration.)	(y, p_T) -differential	

2011 dataset pileup

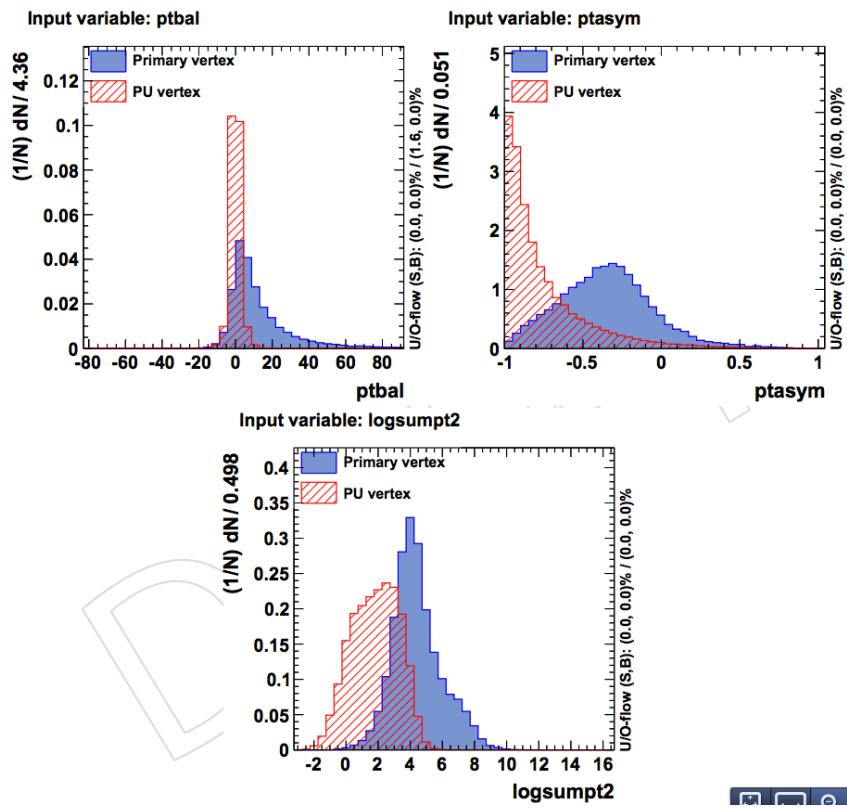


Vertex choice efficiency



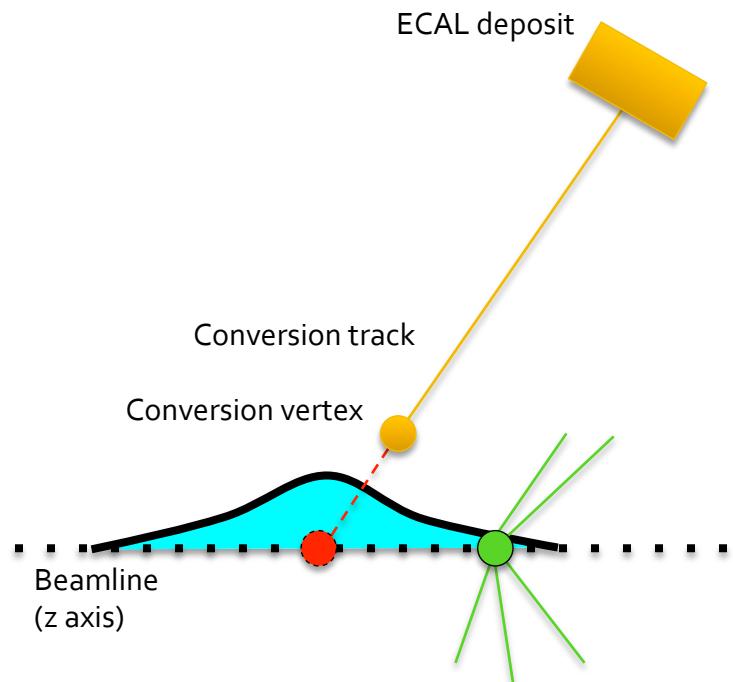
Vertex recoil variables

- $sumpt2: \sum_i |\vec{p}_T^i|^2.$
- $ptbal: -\sum_i (\vec{p}_T^i \cdot \frac{\vec{p}_T^{\gamma\gamma}}{|\vec{p}_T^{\gamma\gamma}|}).$
- $ptasym: (|\sum_i \vec{p}_T^i| - p_T^{\gamma\gamma}) / (|\sum_i \vec{p}_T^i| + p_T^{\gamma\gamma}).$



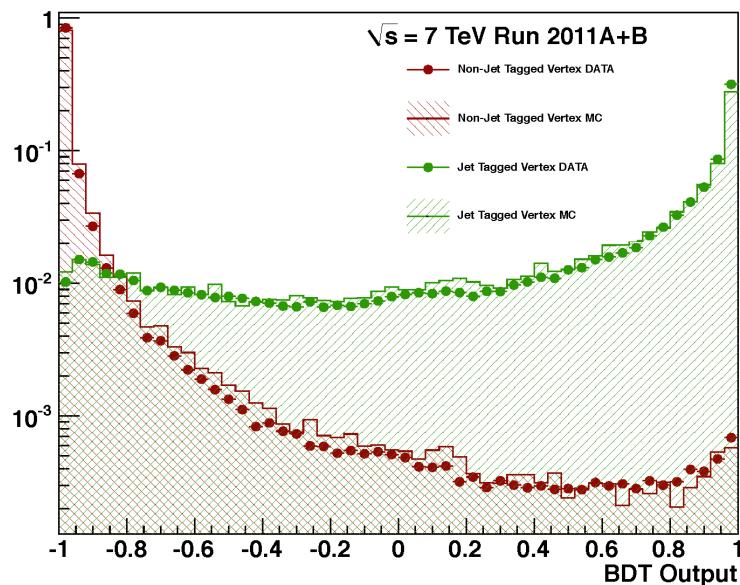
Converted photon vertexing

$$pull_{conv} = |z_{conversion} - z_{vertex}| / \sigma_{conversion}.$$

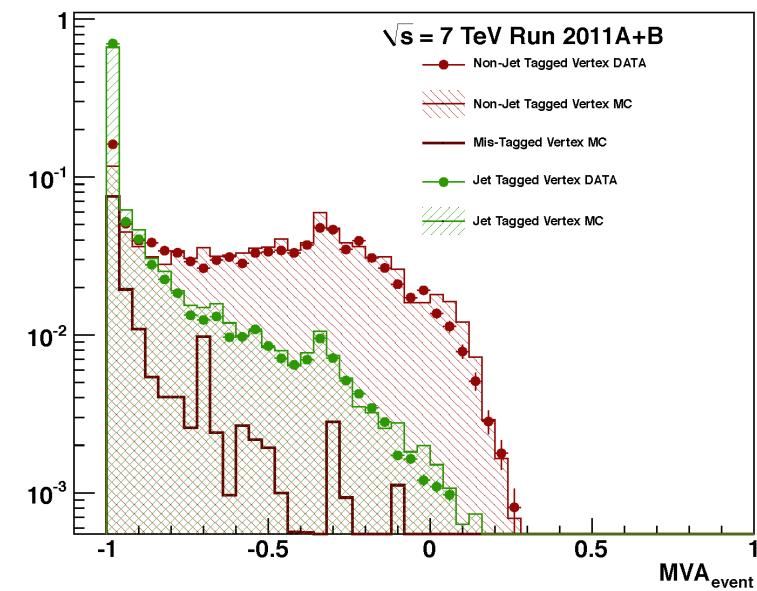


Photon-jet vertex MVA validation

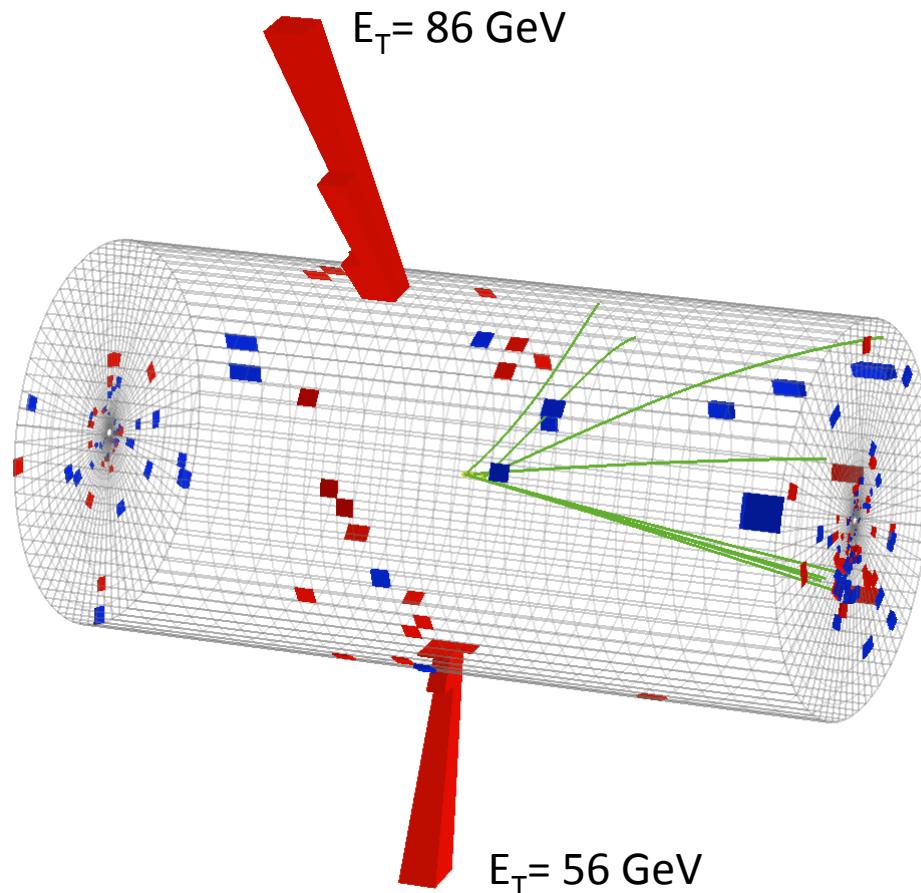
PER VERTEX MVA



PER EVENT MVA



The cover event

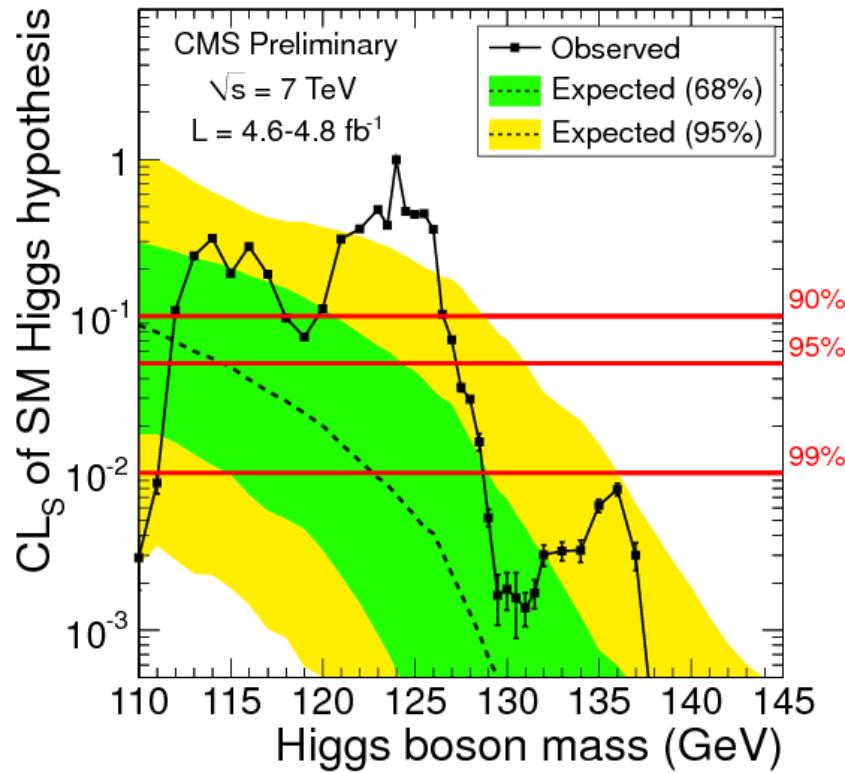
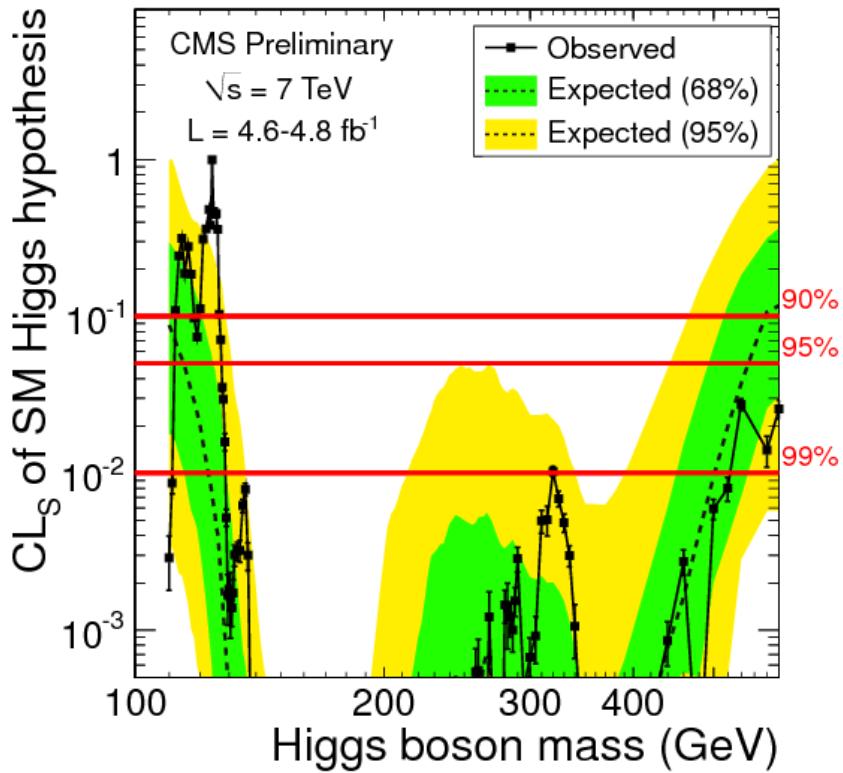


CMS combination

[CMS-PAS-HIG-12-008]

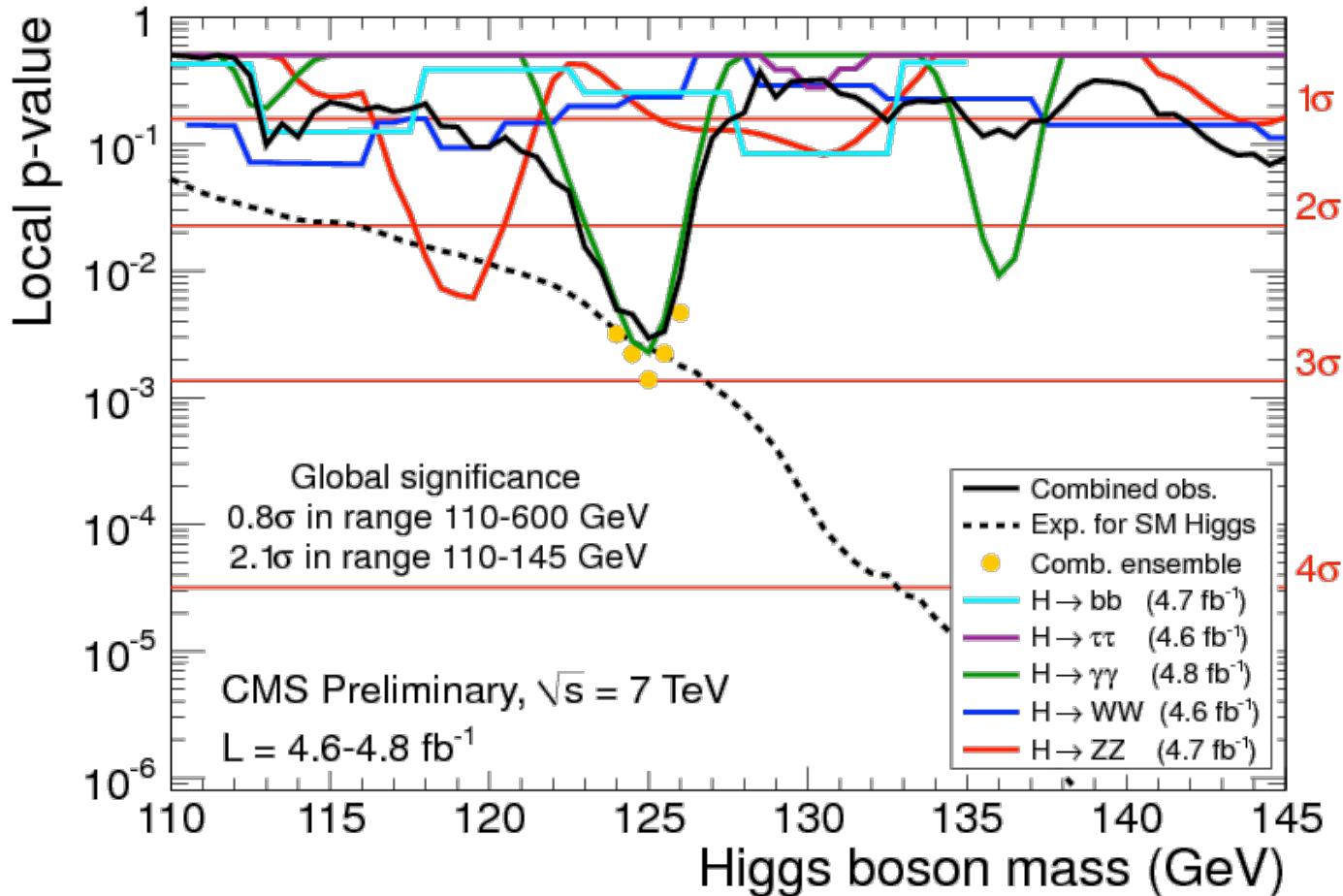
CMS combination

[CMS-PAS-HIG-12-008]



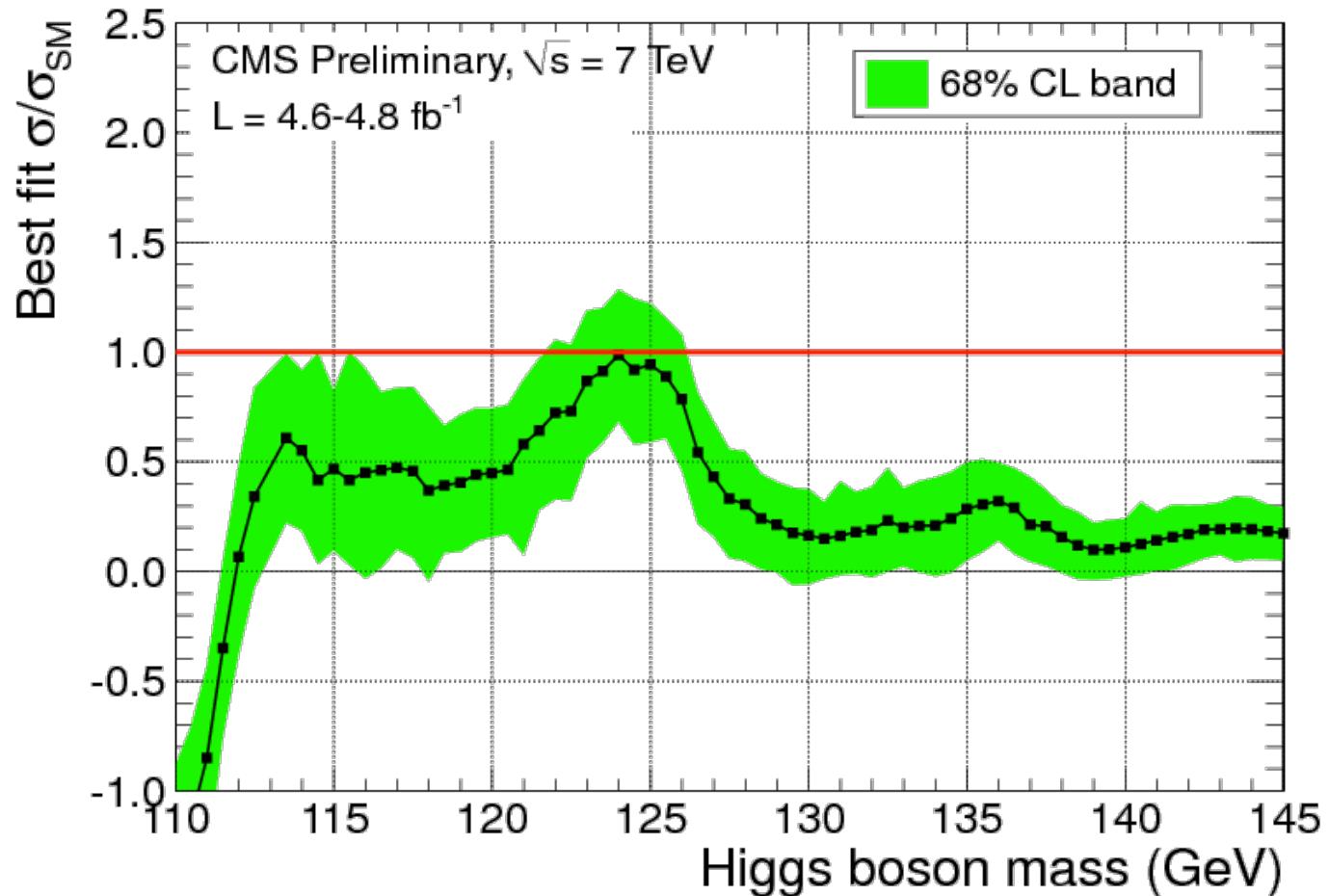
CMS combination

[CMS-PAS-HIG-12-008]



CMS combination

[CMS-PAS-HIG-12-008]



CMS combination

[CMS-PAS-HIG-12-008]

