A SEARCH FOR THE HIGGS BOSON IN THE CHANNEL $H \rightarrow \gamma\gamma$ WITH CMS

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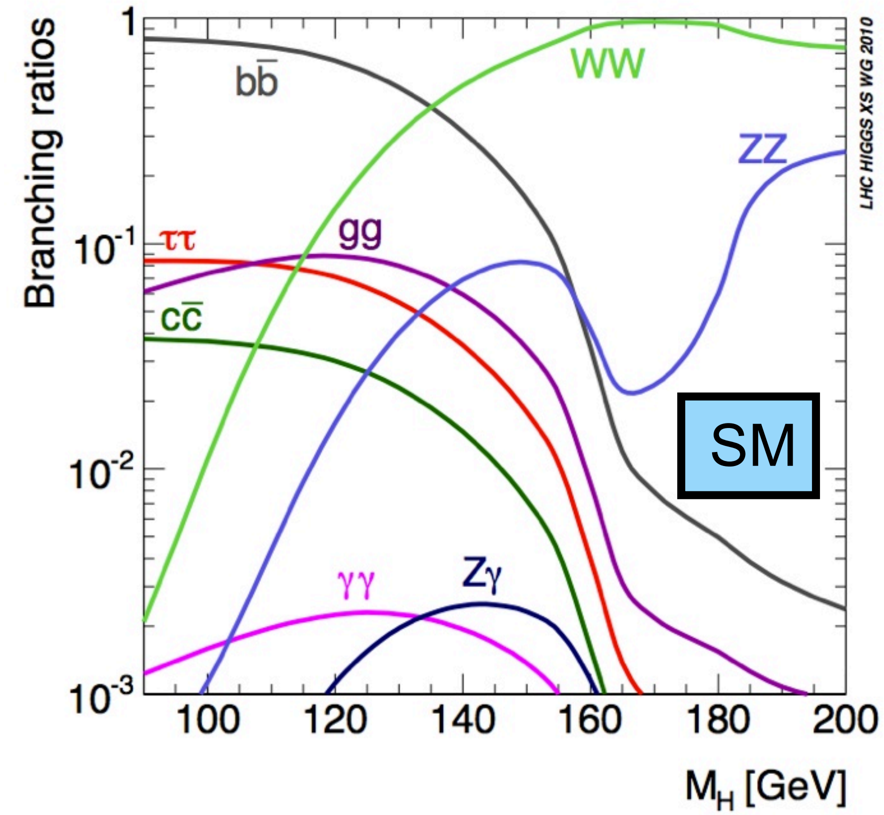
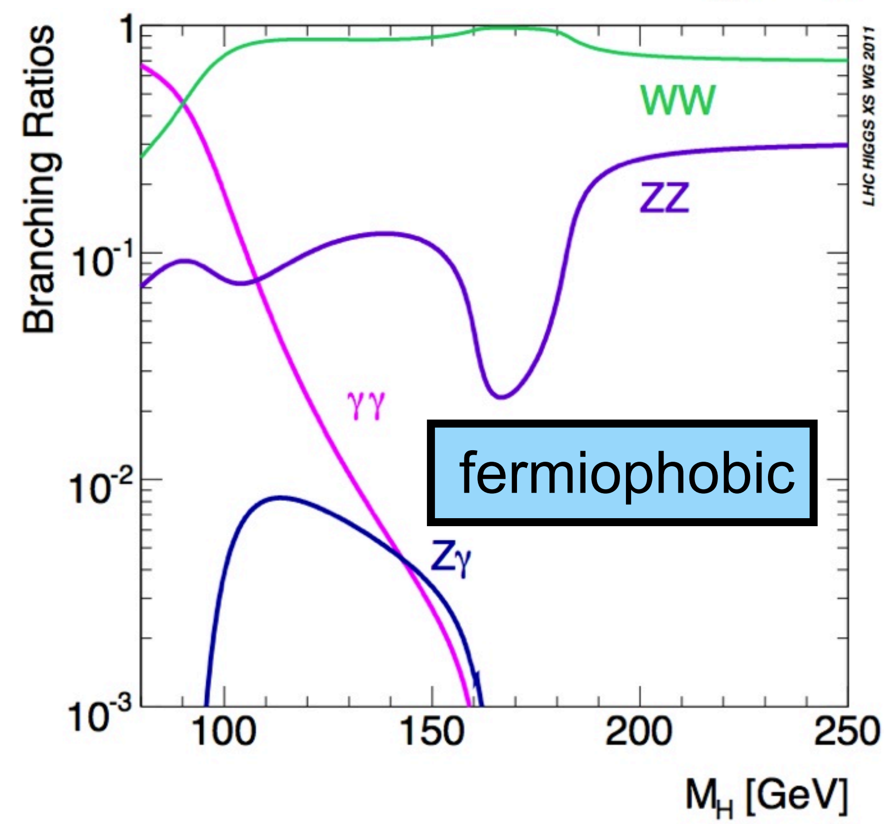
H → γγ

- **light Higgs favored** by precision electroweak tests

- **H→γγ one of the most sensitive** channels at low masses despite the small branching ratio
  - **striking signature** (two photons, peak in invariant mass)

- **very interesting channel** in models where Higgs is **fermiophobic**
  - high branching ratio for di-photon decay
  - exclusion/discovery with O(fb^{-1})





Electromagnetic Calorimeter (ECAL)

- **discovery potential dependent on** di-photon **invariant mass resolution**

  ➪ **excellent** performance of **em crystal calorimeter (ECAL)** needed

- **design energy resolution** of ECAL ~**0.5% for E(γ) >100GeV** (for unconverted γ in barrel)

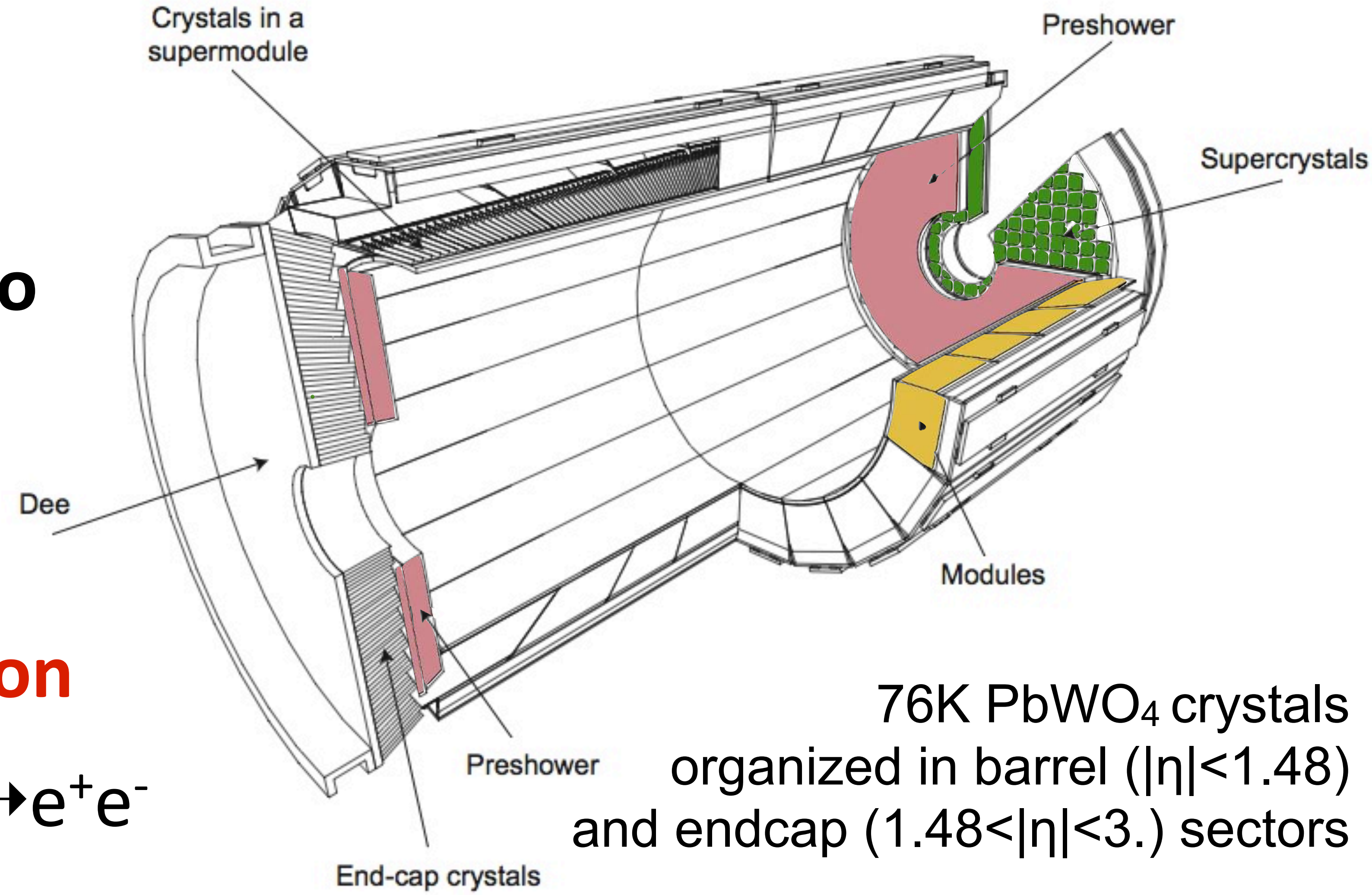
- critical issues:

  ➪ **transparency loss due to radiation damage**

  use of laser monitoring

  ➪ **on-site energy calibration**

  use of $\pi^0 \to \gamma\gamma$, E_e/p_e, $Z \to e^+e^-$



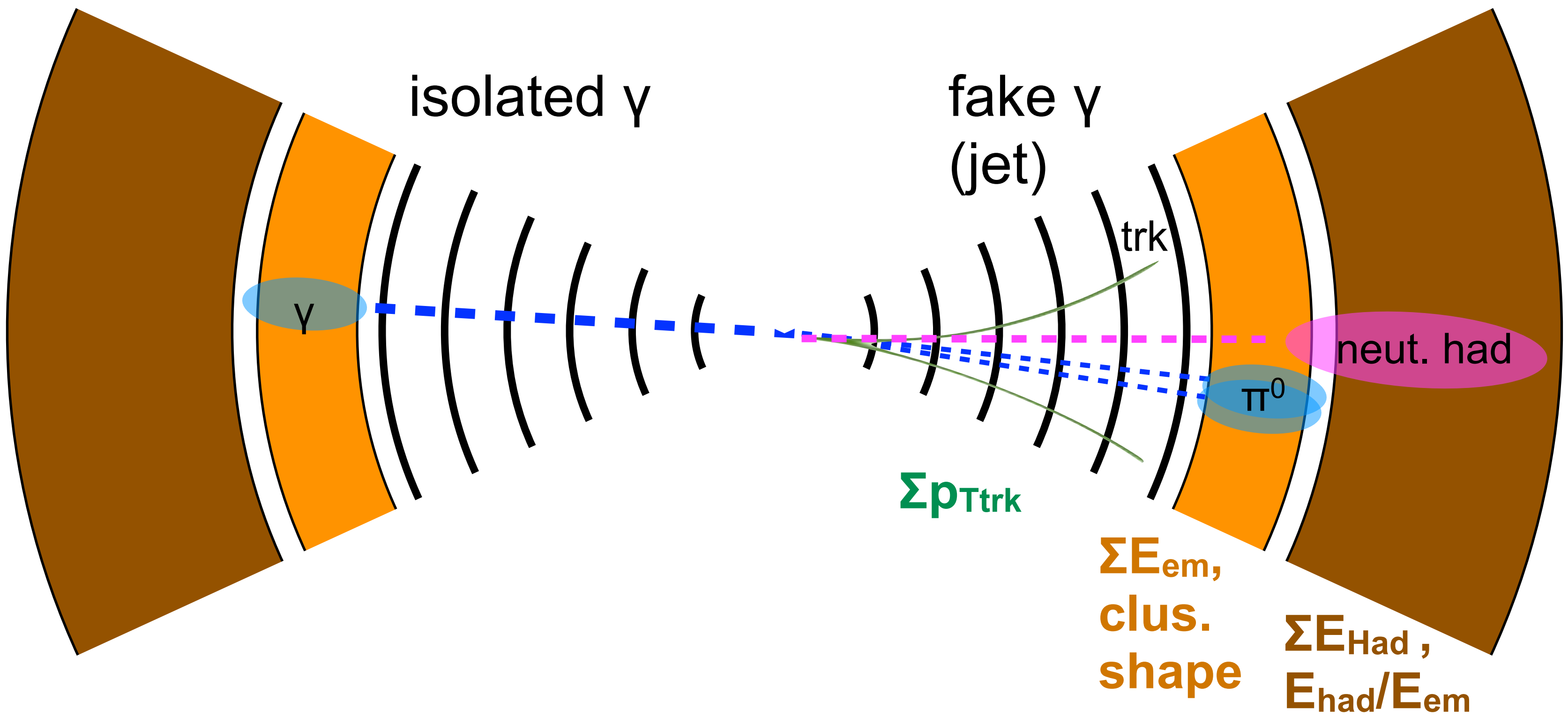
76K $PbWO_4$ crystals organized in barrel (|η|<1.48) and endcap (1.48<|η|<3.) sectors

Analysis Strategy

STEP	CRITICAL ISSUES
1) two isolated photons with large transverse momentum $p_T(1\gamma)>40GeV$, $p_T(2\gamma)>30GeV$ $\|\eta\|<1.444$ || $1.566<\|\eta\|<2.5$	• tight isolation to reject γ+jet and QCD background • determine efficiency from data
2) di-photon mass reconstruction	• vertex determination in presence of pile-up (PU) • energy scale and resolution calibration
3) signal extraction	• event categories to maximize sensitivity • background shape

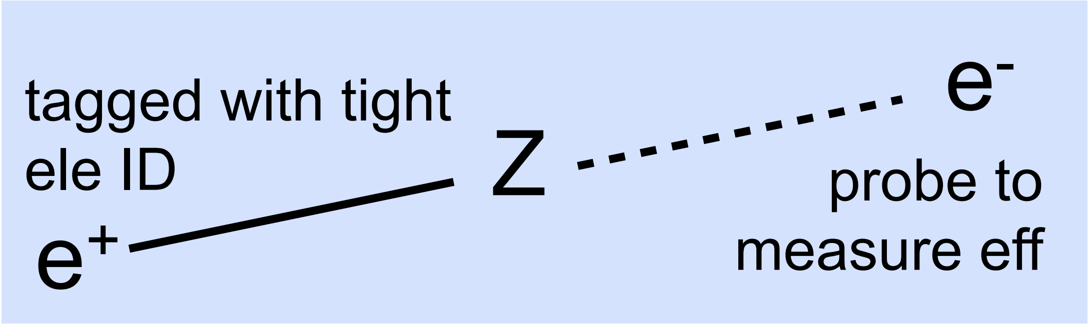
BACKGROUND REJECTION

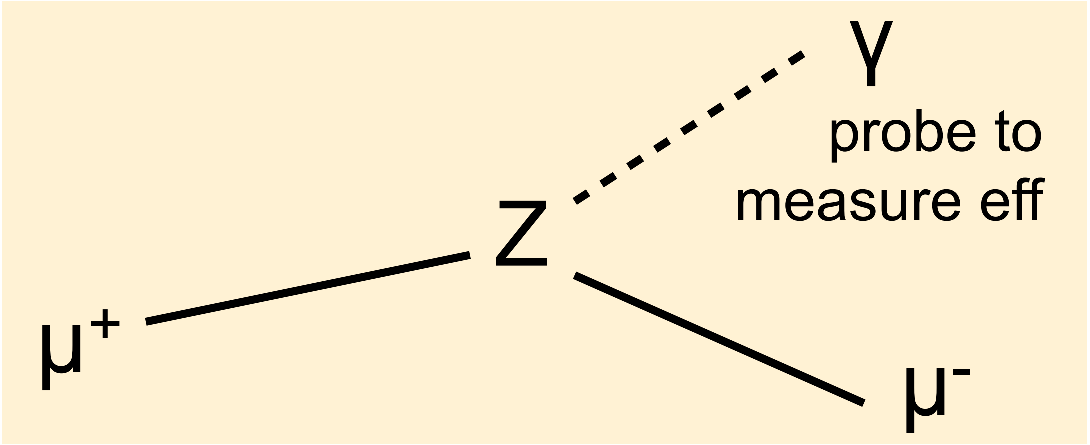
- **photon isolation** variables evaluated within a cone of $\sqrt{\Delta\eta^2+\Delta\phi^2}=0.3\text{-}0.4$ to reject γ+jet and QCD background
  - based on **Σp_{Ttrk}, energy deposited in em and hadronic calorimeters. Corrected for PU** via subtraction of PU energy density
- **lepton veto**
- **cluster shape** in ECAL to reject $\pi^0\rightarrow\gamma\gamma$ (using spread along η) and conversions (use of R9 = $E_{3x3crys}/E_{cluster}$)
- all above combined **in barrel/endcap and large/small R9 classes**



Selection Efficiency

photon ID and trigger efficiency is determined from **data control samples**





1) **$Z \to e^+e^-$ with tag and probe**:

- one electron selected with tight ele-ID (tag), other used to measure trigger and offline selection efficiency (probe)
- cannot be used to measure ele. veto

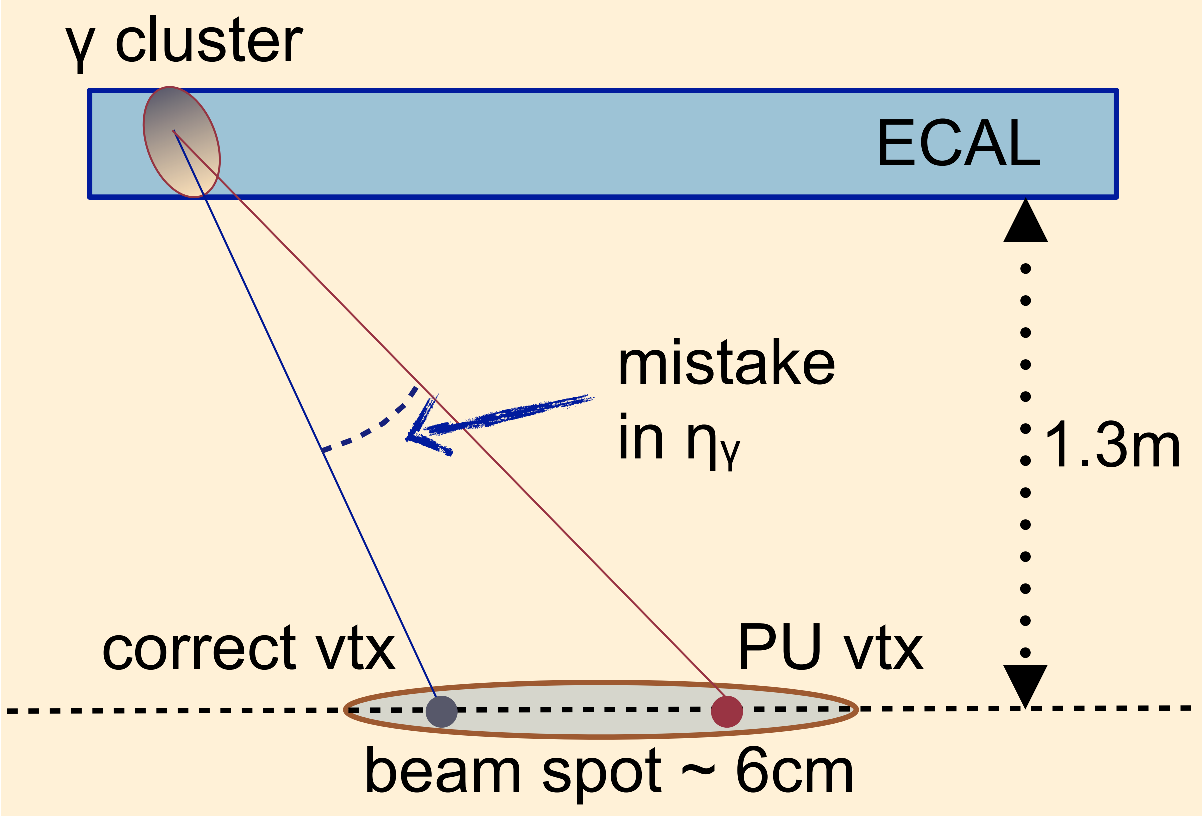
2) **$Z \to \mu^+\mu^-\gamma$**:

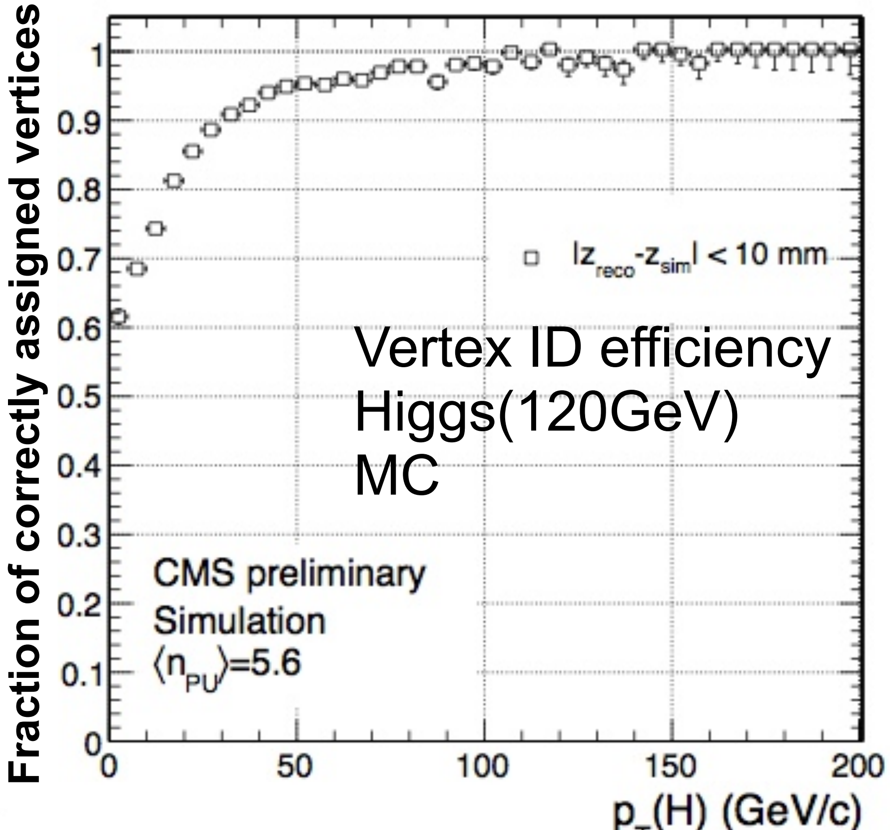
- select muons and photon (w/o electron veto) to make Z mass
- use γ to derive electron veto efficiency

Category	ε_{data}(%)	ε_{MC}(%)	$\varepsilon_{data}/\varepsilon_{MC}$
All cuts except electron rejection (from $Z \to ee$)			
barrel, R9>0.94	91.77±0.14	92.43±0.07	0.993±0.002
barrel, R9<0.94	72.67±0.43	71.89±0.08	1.011±0.007
endcap, R9>0.94	80.33±0.47	80.04±0.18	1.004±0.008
endcap, R9<0.94	57.80±1.26	55.09±0.15	1.049±0.025
Electron rejection cut (from $Z \to \mu\mu$)			
barrel, R9>0.94	$99.78^{+0.13}_{-0.16}$	$99.59^{+0.13}_{-0.17}$	$1.002^{+0.002}_{-0.002}$
barrel, R9<0.94	$98.77^{+0.59}_{-0.73}$	$97.70^{+0.32}_{-0.37}$	$1.011^{+0.007}_{-0.008}$
endcap, R9>0.94	$99.32^{+0.51}_{-1.02}$	$99.29^{+0.30}_{-0.42}$	$1.000^{+0.006}_{-0.011}$
endcap, R9<0.94	$93.0^{+2.1}_{-2.3}$	$93.34^{+0.79}_{-0.86}$	$0.996^{+0.024}_{-0.027}$

Vertex Determination

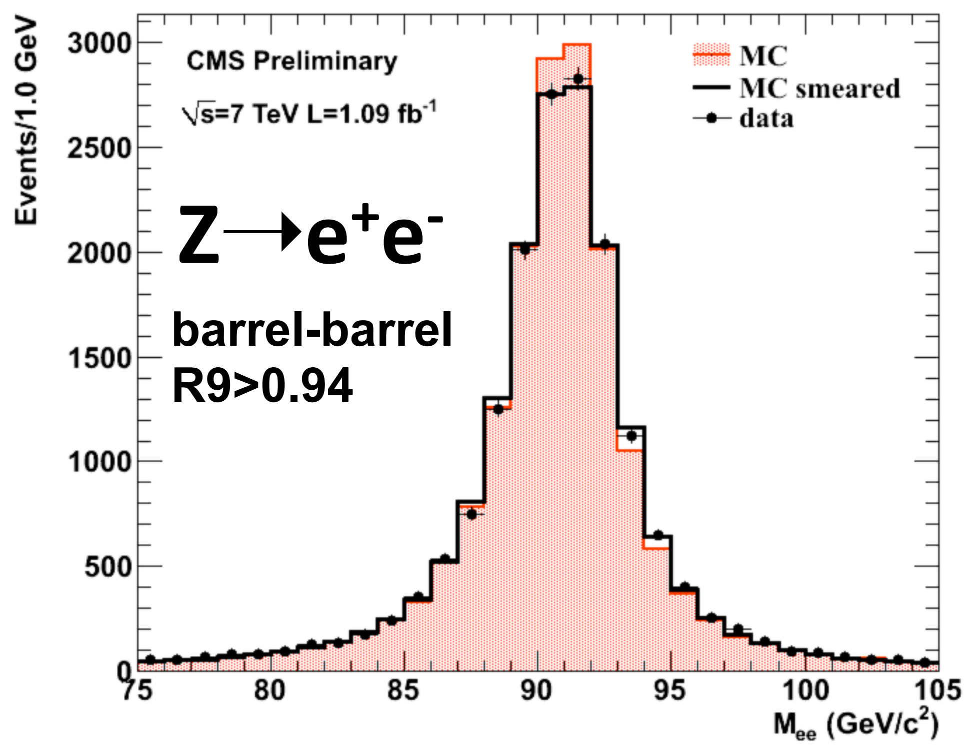
- **“large” pile-up conditions**
  - ➪ $\langle N_{PU} \rangle \sim 5.6$
- di-photon invariant **mass resolution affected by vertex** choice
- **vextex determination** based on
  - **tracks belonging to vertex** combined **with di-photon kinematics**
    - use of $\Sigma p_T{}^2{}_{trk}$ and p_T balancing
  - **conversion-track** finding and projection on beam spot
- performance **cross-checked using $Z \rightarrow \mu^+\mu^-$** after removing muon tracks

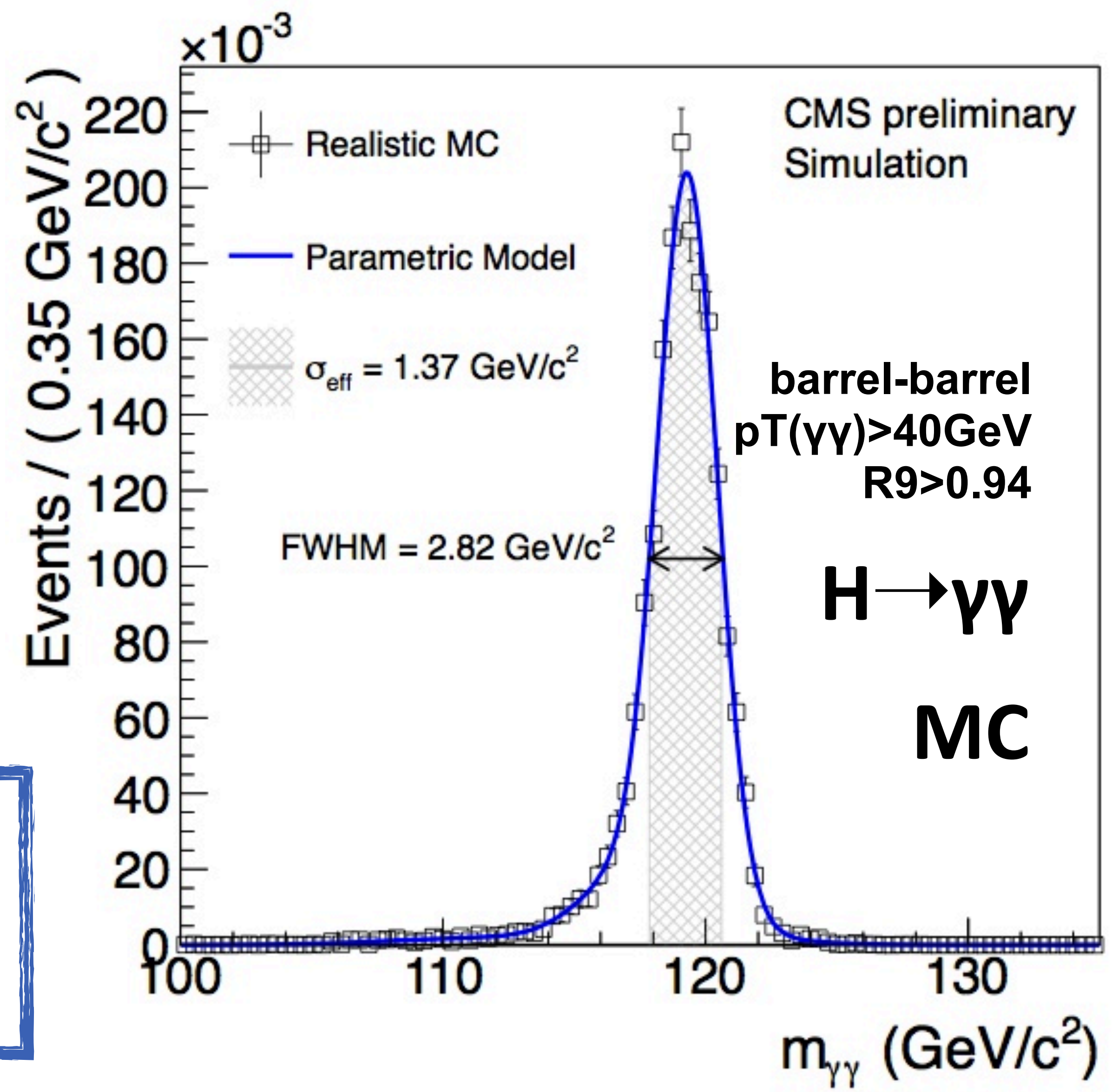




Photon Energy Scale and Resolution

- **$Z \to e^+e^-$ invariant mass** to determine **energy scale and resolution**
  - done in each different photon categories (barrel/endcap, large/small R9)
  - maximum likelihood analysis performed while modifying energy
- **photon energy smeared** on MC to match data





- Resolution degraded by sub-optimal corrections for transparency loss and material budget
- Still room for improvement

Categories and Limit Extraction

- **event categories** to:
  - maximize statistical power
  - exploit differences in kinematics between signal and backgrounds
- **8 categories**:

2 p_T categories		2 η categories		2 R9 categories
(1) $p_T(\gamma\gamma)$<40GeV (2) $p_T(\gamma\gamma)$>40GeV	⊗	(1)1γ,2γ in barrel (2) remainder	⊗	(1) R9(1γ,2γ)>0.94 (2) remainder

- limit is extracted with two methods giving consistent results
  - **modified frequentist approach (CLs)** using profile likelihood
  - **bayesian approach** with flat prior
- **signal from MC** after energy smearing (see previous slide)
- **bkg is fitted** with 2^{nd} order Bernstein poly. (100GeV<$M_{\gamma\gamma}$<150GeV)

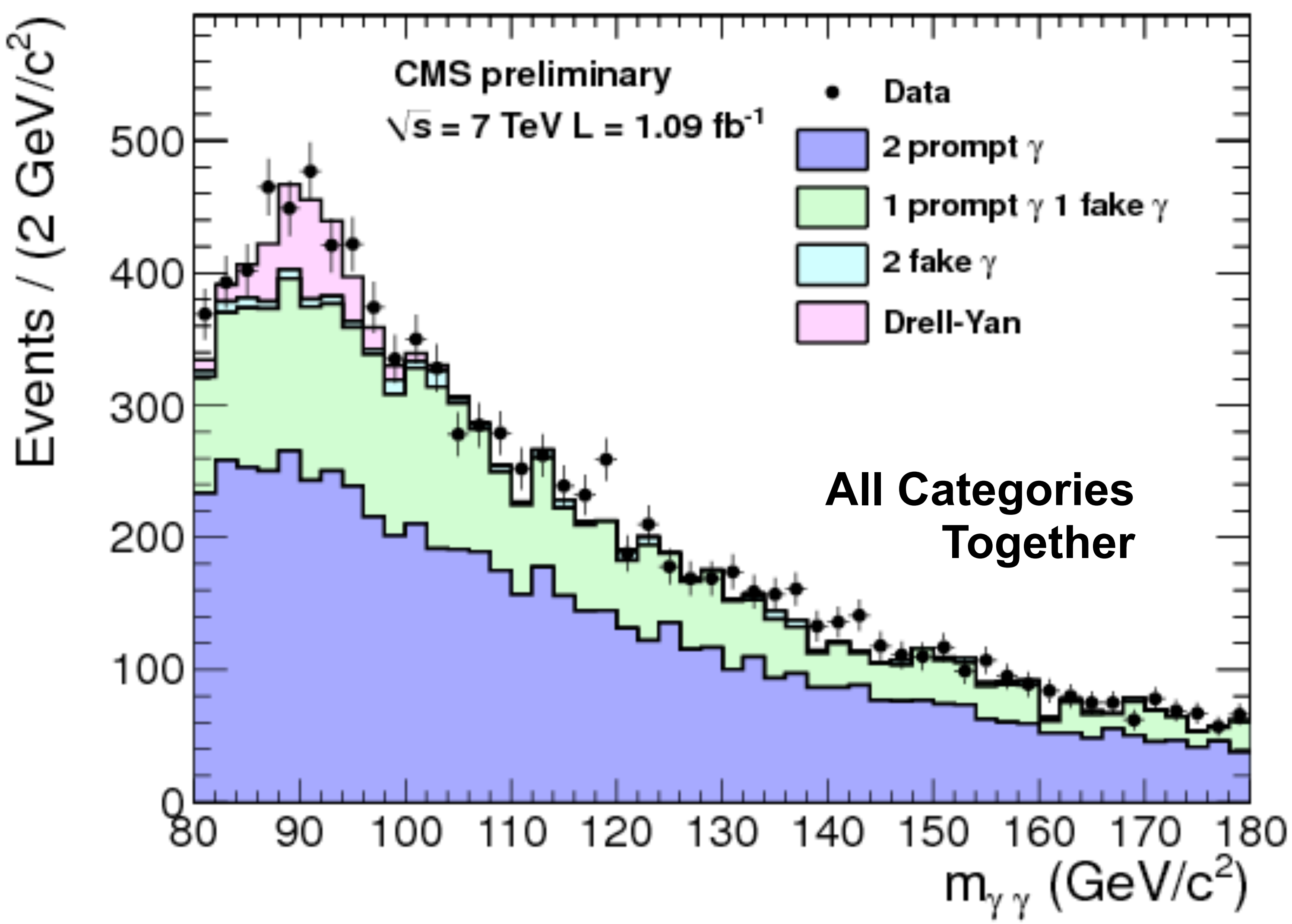
SYSTEMATICS

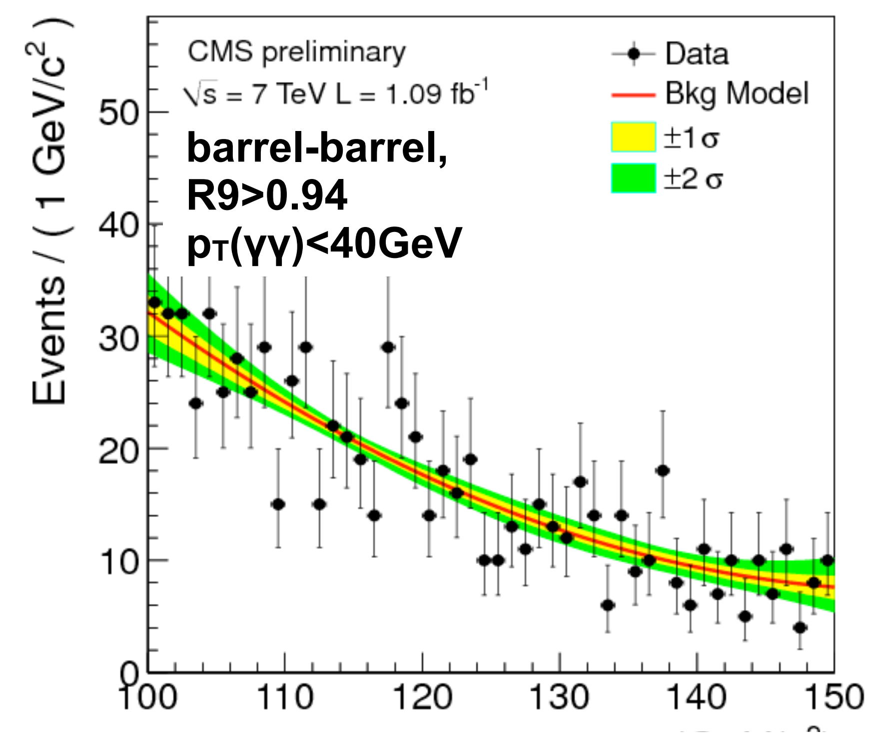
Source	Systematics
applicable to individual photons	
Photon identification efficiency	1.0% ÷ 4.0%
R9 cut efficiency	4.0% ÷ 6.5%
Energy resolution	0.2% ÷ 0.5%
Energy scale	0.05% ÷ 0.34%
applicable to di-photons	
Integrated luminosity	6.0%
Trigger efficiency	1.0%
Vertex finding efficiency	0.5%
pT>40GeV cut efficiency	6.0%
cross sections and branching ratios	
Gluon-gluon cross section	12.5%(scale) 7.9%(PDF)
Fermiophobic: scale	0.5%(VBF) 0.8%(WH) 1.6%(ZH)
Fermiophobic: PDF	3.1%
Fermiophobic: BR	5.0%

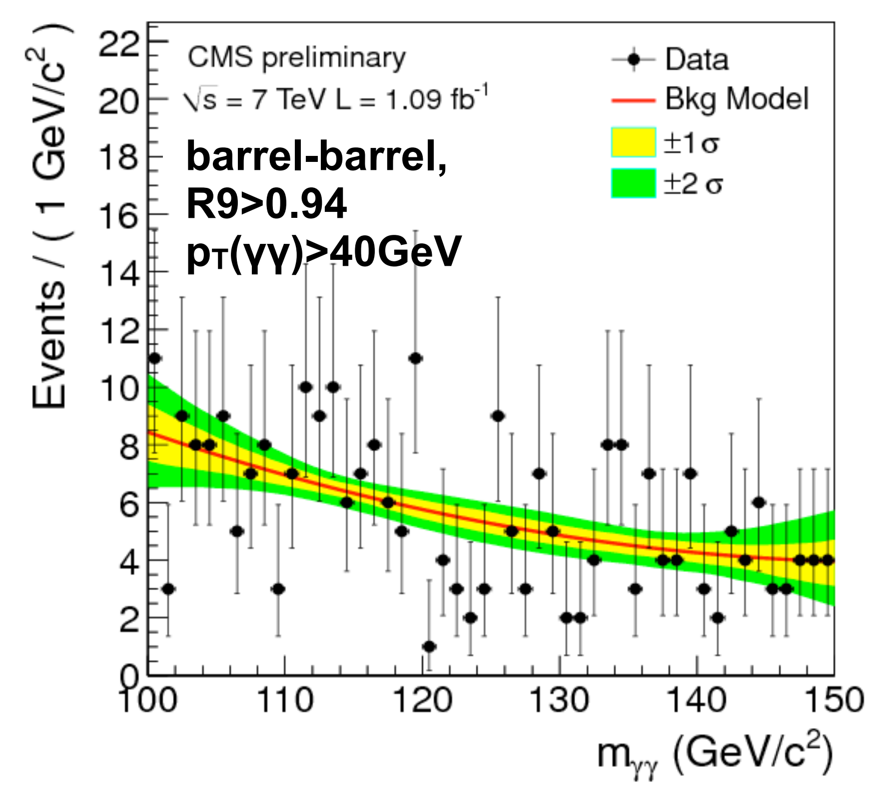
$M_{\gamma\gamma}$ SPECTRUM

- **with 1.09fb^{-1}** **no striking structure** seen
- **good agreement** with expected MC background **shape and normalization**

Examples of bkg fit in categories



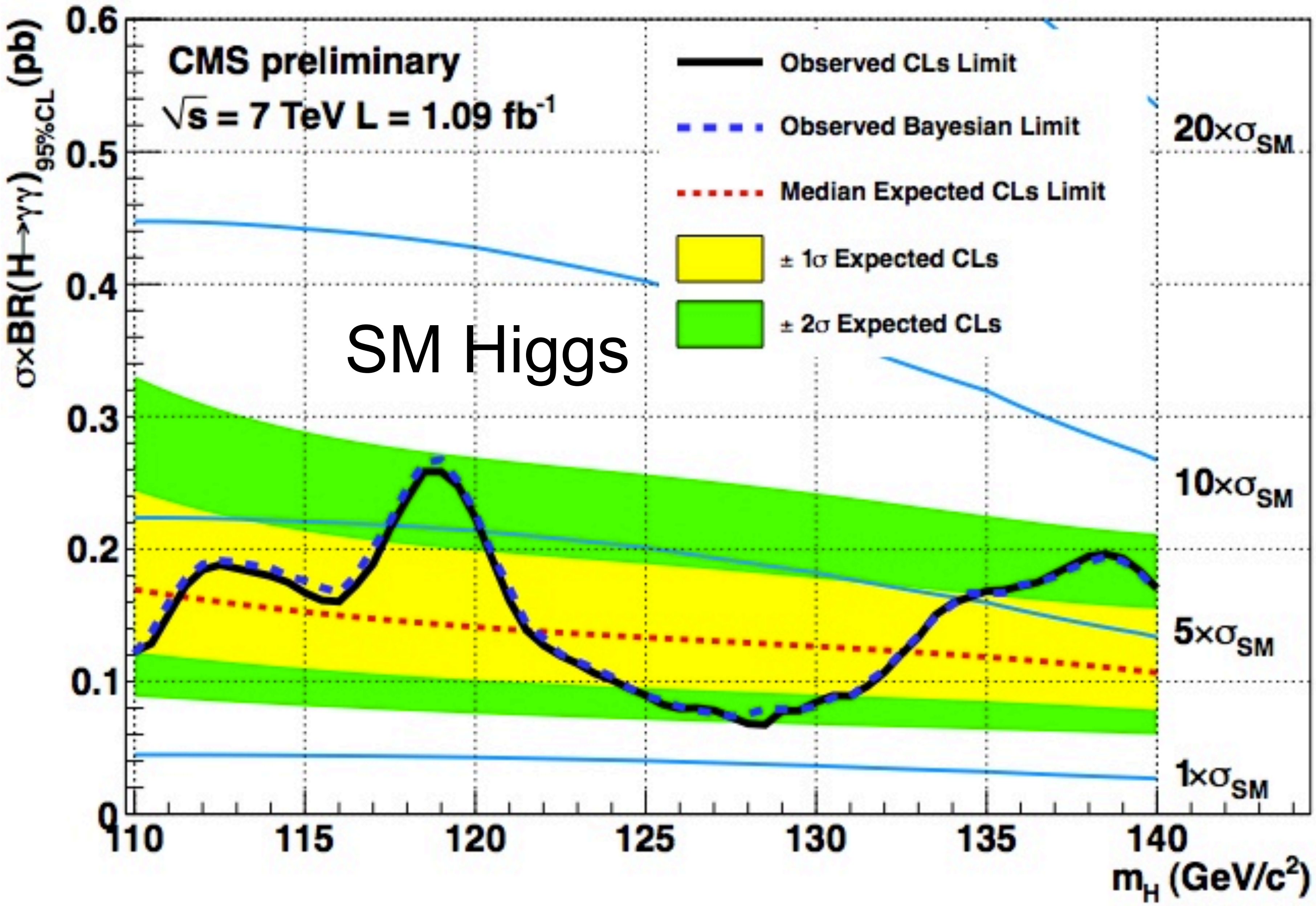




Exclusion Plots: SM Higgs

Exclusion (@95% CL) 0.06 pb < σ×BR < 0.26 pb

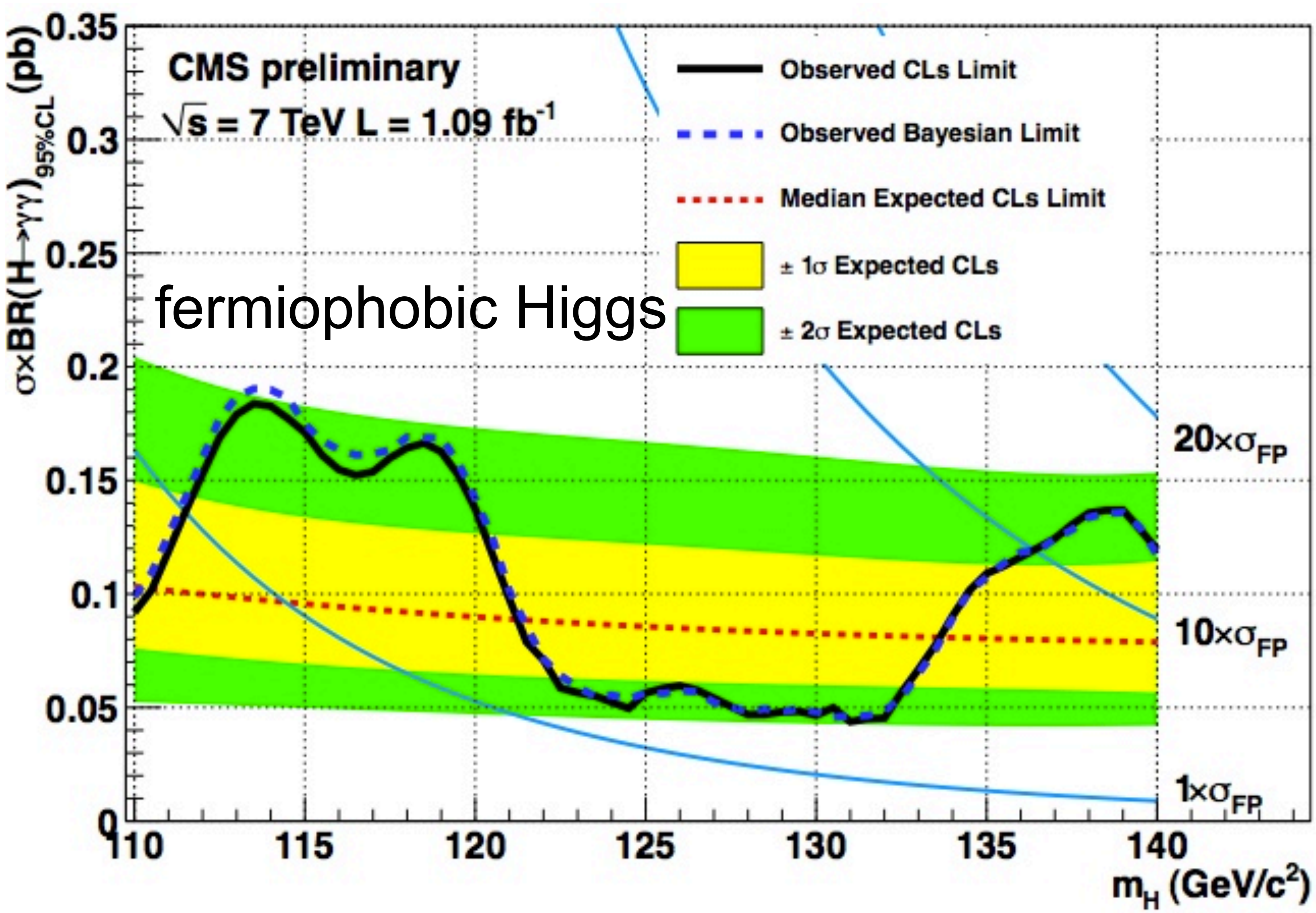
- **×2 ÷ ×6 SM** for **110 GeV < m(H) < 135 GeV**
- observed limit within 2σ from expected value



EXCLUSION PLOTS: FERMIOPHOBIC

Exclusion (@95% CL) 0.04 pb < σ×BR < 0.18 pb

- **m(H) > 111 GeV** constraint for **fermiophobic Higgs**
- observed limit within 2σ from expected value



CONCLUSIONS

- **Search for $H \rightarrow \gamma\gamma$** performed **with 1.09fb^{-1}:**
  - stringent **photon isolation** criteria corrected for PU energy
  - **vertex determination** based on topology and conversions
  - photon **energy scale and resolution** determined from data
  - **event categories** according to mass resolution and S/B to maximize sensitivity

- Exclusion limits (@95% CL):
  - **$\sigma\times$BR between $\times 2$ and $\times 6$ SM for 110 GeV < m(H) < 135 GeV**
  - **m(H) > 111 GeV** constraint for **fermiophobic Higgs**

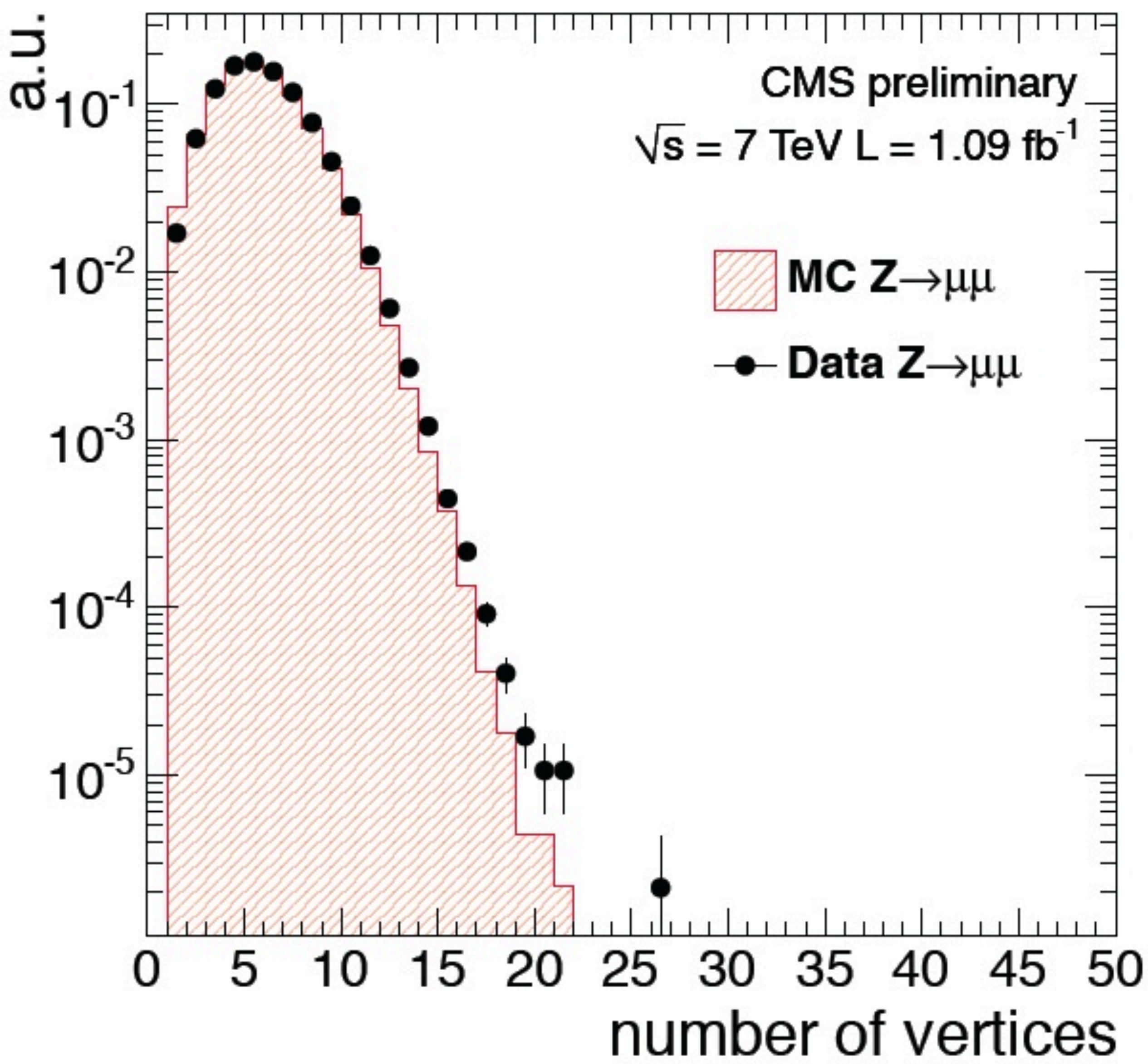
- Perspectives:
  - **improve energy calibration** to fully exploit ECAL potential and increase Higgs discovery reach

CMS PAS HIG-11-010

BACKUP

PILEUP RE-WEIGHTING

- **re-weighting** applied on the number of in-time PU events according to the number of expected number of interactions in data
- consistently applied when deriving efficiencies and resolutions
- average PU conditions:
  - $\langle N_{PU} \rangle = 5.6$ σ_Z=5.8cm

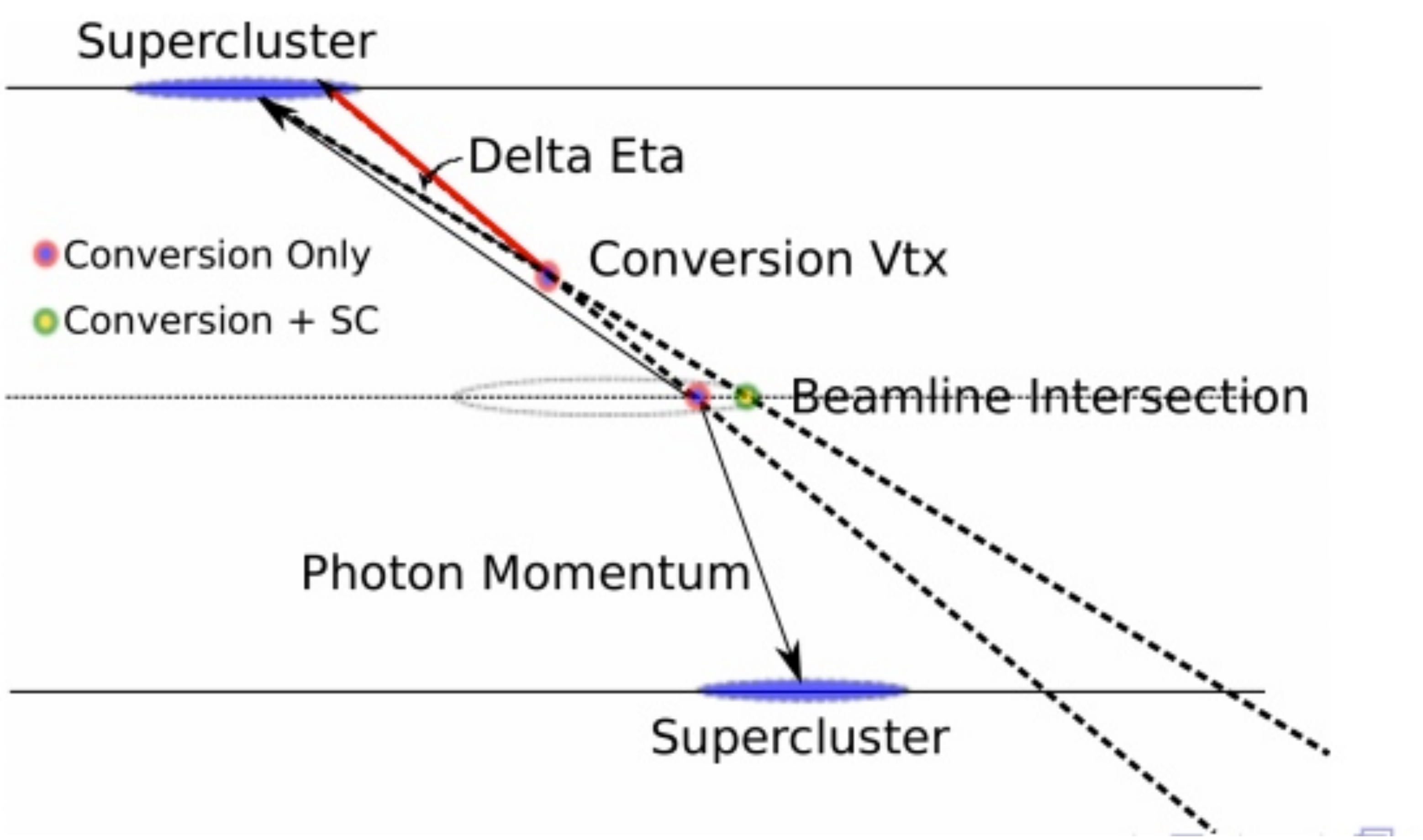


Vertex ID: Variables

- **Sum p_T^2 =** $\sum_{tracks} p_T^2$
- **p_T^{asym} =** $\left(\sum_{tracks} p_T - p_T^{\gamma\gamma}\right) / \left(\sum_{tracks} p_T + p_T^{\gamma\gamma}\right)$
- **p_T^{bal} =** $-\sum_{tracks}\left(\bar{p}_T^{track} \cdot \frac{\bar{p}_T^{\gamma\gamma}}{\left|\bar{p}_T^{\gamma\gamma}\right|}\right)$

VERTEX ID: CONVERSIONS

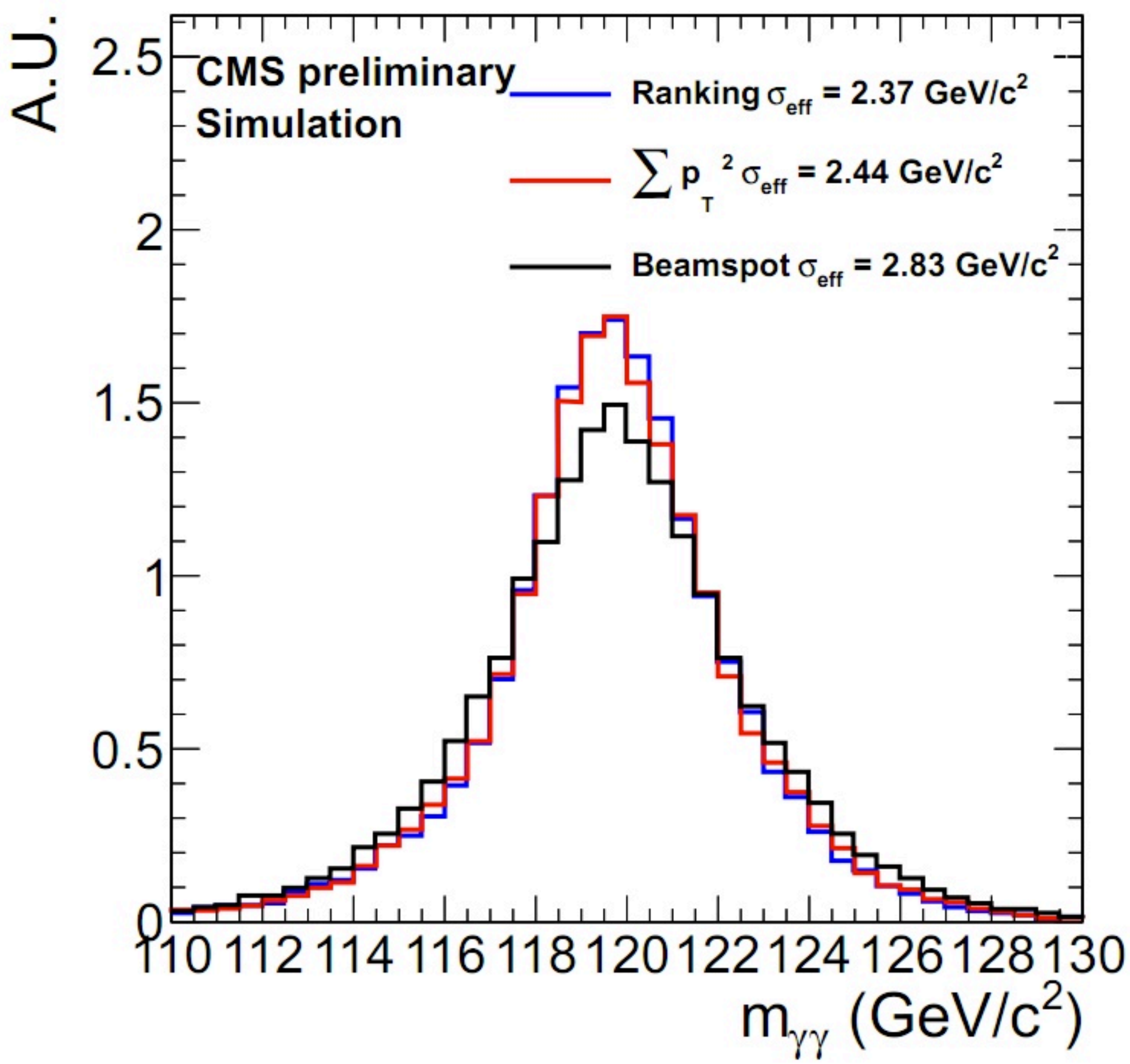
- about **40% of photons converts** in Tracker Volume
- measure photon direction using c**onversion vertex position and cluster barycenter**



VERTEX ID: PERFORMANCE

Overall performance integrated over Higgs P_T spectrum (from data):

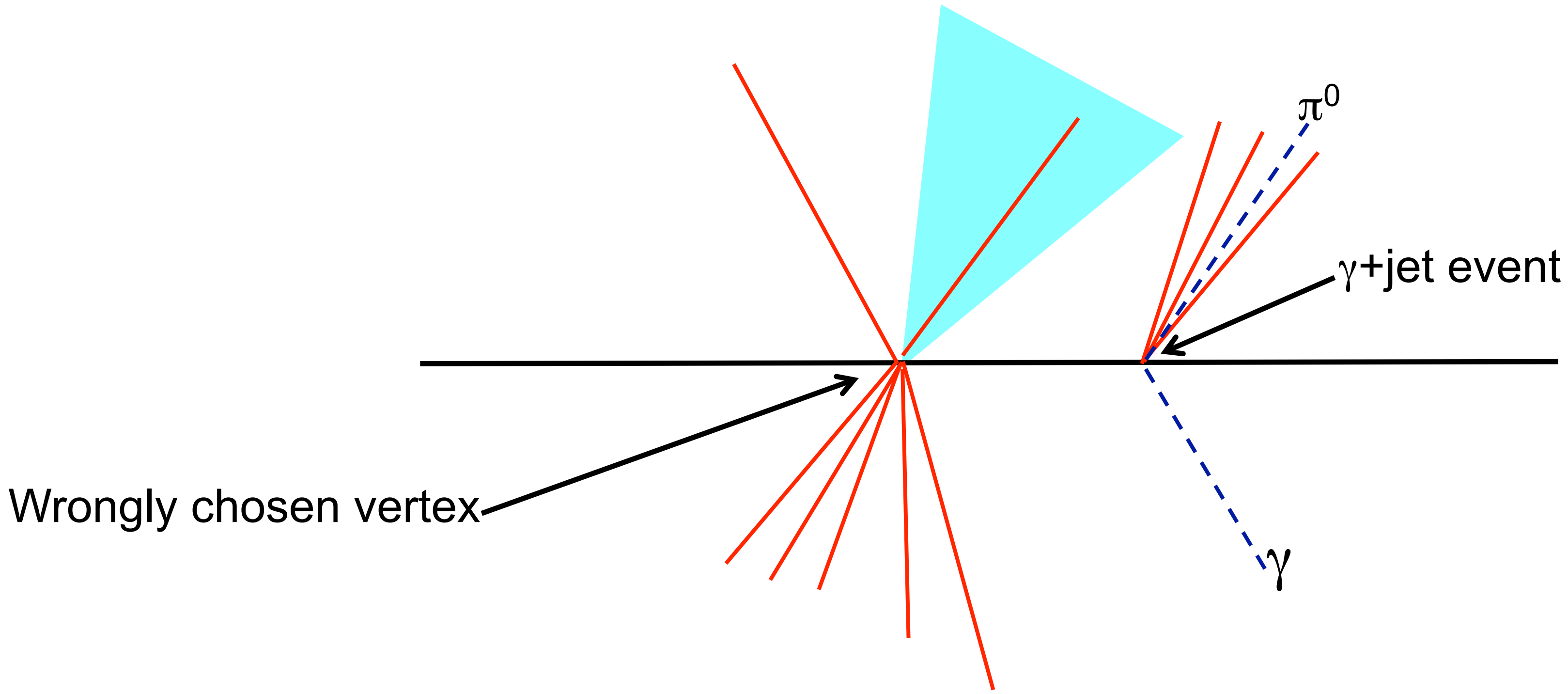
$$83.1\% \pm 0.2\%(\text{stat}) \pm 0.5\%(\text{syst})$$



PHOTON ISOLATION AND PU

Multiple interactions pose additional challenges in this area:

- **additional energy in isolation cones (ECAL and HCAL)**
  - addressed using **FastJet** ρ subtraction
- **for track isolation cut on Δz to reject PU tracks**, but need to protect against incorrect vertex assignment
  - additional cut on track isolation computed wrt vertex giving highest track isolation sum for a given photon



ISOLATION VARIABLES

- Three seperate isolation quantities are cut on:
  1. **Relative Track Isolation wrt Selected Vertex:** Track isolation with $|\Delta z| < 1.0$ cm, $|d_{xy}| < 0.1$ cm wrt selected vertex. Annulus $0.02 < \Delta R < 0.3$. $Iso_{TRKRel} = \frac{\sum p_T^{track}}{p_T^{\gamma}/50\text{GeV}}$
  2. **Combined Relative Isolation wrt Selected Vertex:**
     - Track isolation as above
     - Ecal isolation with 0.3 cone-size with Jurassic veto region, ρ correction with $A_{eff} = 0.17$
     - HCal isolation with 0.4 cone-size and 0.15 inner veto cone, ρ correction with $A_{eff} = 0.17$
     - $Iso_{Rel} = \frac{Iso_{Trk} + Iso_{Ecal} + Iso_{Hcal}}{p_T^{\gamma}/50\text{GeV}}$
  3. **Combined Relative Isolation wrt Largest Iso Vertex:**
     - Relative isolation as above, except track isolation Δz cut computed with respect to the vertex giving the highest isolation sum
     - Cone size of 0.4 for all iso sums (to be more sensitive to choosing the vertex where a jet originated)
     - A_{eff} for Ecal and Hcal iso of 0.52 (due to larger Ecal cone size)

Photon ID In Categories

- different cuts are applied for different photon categories based on η x R_9

Category	Photon requirement	Common name
1	$\lvert\eta\rvert$ <1.4442, R_9 >0.94	Barrel, high R_9
2	$\lvert\eta\rvert$ <1.4442, R_9 <0.94	Barrel, low R_9
3	1.566< $\lvert\eta\rvert$ <2.5, R_9 >0.94	Endcap, high R_9
4	1.566< $\lvert\eta\rvert$ <2.5, R_9 <0.94	Endcap, low R_9

- cuts are optimized such that given for a given purity value (S/B) efficiency is optimized across the photon categories

Variable	Cut value			
	Category 1	Category 2	Category 3	Category 4
Rel. comb. iso. (selected vertex)	3.8	2.2	1.77	1.29
Rel. comb. iso. (worst vertex)	11.7	3.4	3.9	1.84
Rel. track iso. (selected vertex)	3.5	2.2	2.3	1.45
$\sigma_{i\eta i\eta}$	0.0106	0.0097	0.028	0.027
H/E	0.082	0.062	0.065	0.048
R_9	0.94	0.36	0.94	0.32
ΔR to electron track	-	0.062	-	-

Table 6: Photon ID selection cut values. The cuts are applied to both the leading and sub-leading photons.

BACKGROUND NORMALIZATION

- **DiPhoton bkg** divided in different categories defined by experimental origin: **k-factors** derived x category as product of $(K_{NLO}/K_{LO})*(K_{DATA}/K_{NLO})$

prompt-prompt 1.3±0.2 CMS QCD-10-035
prompt-fake 1.3±0.25 CMS gamma-jet QCD-10-037
fake-fake 1±0.5
DY: CMS measurements in EWK-10-005

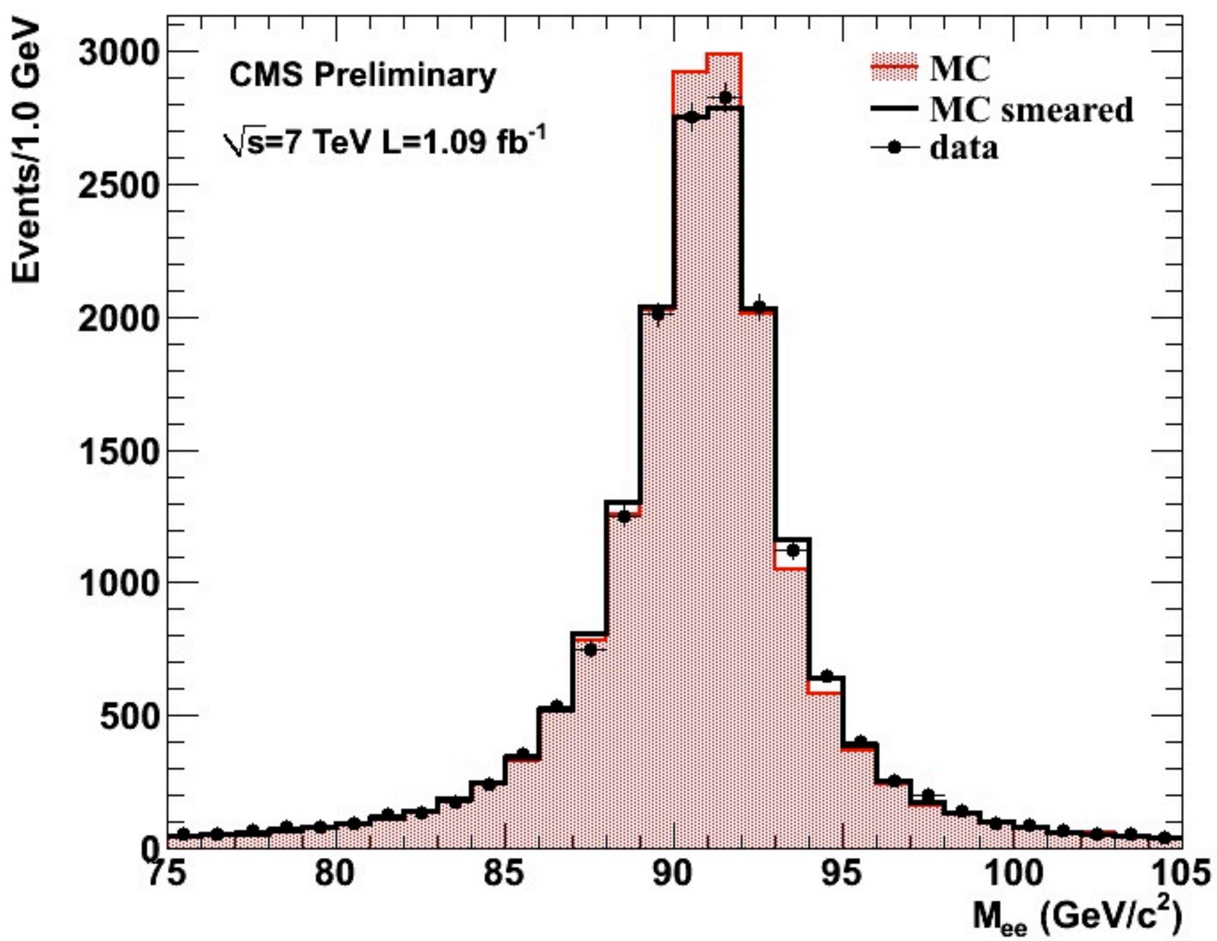
PHOTON ENERGY SCALE AND RESOLUTION

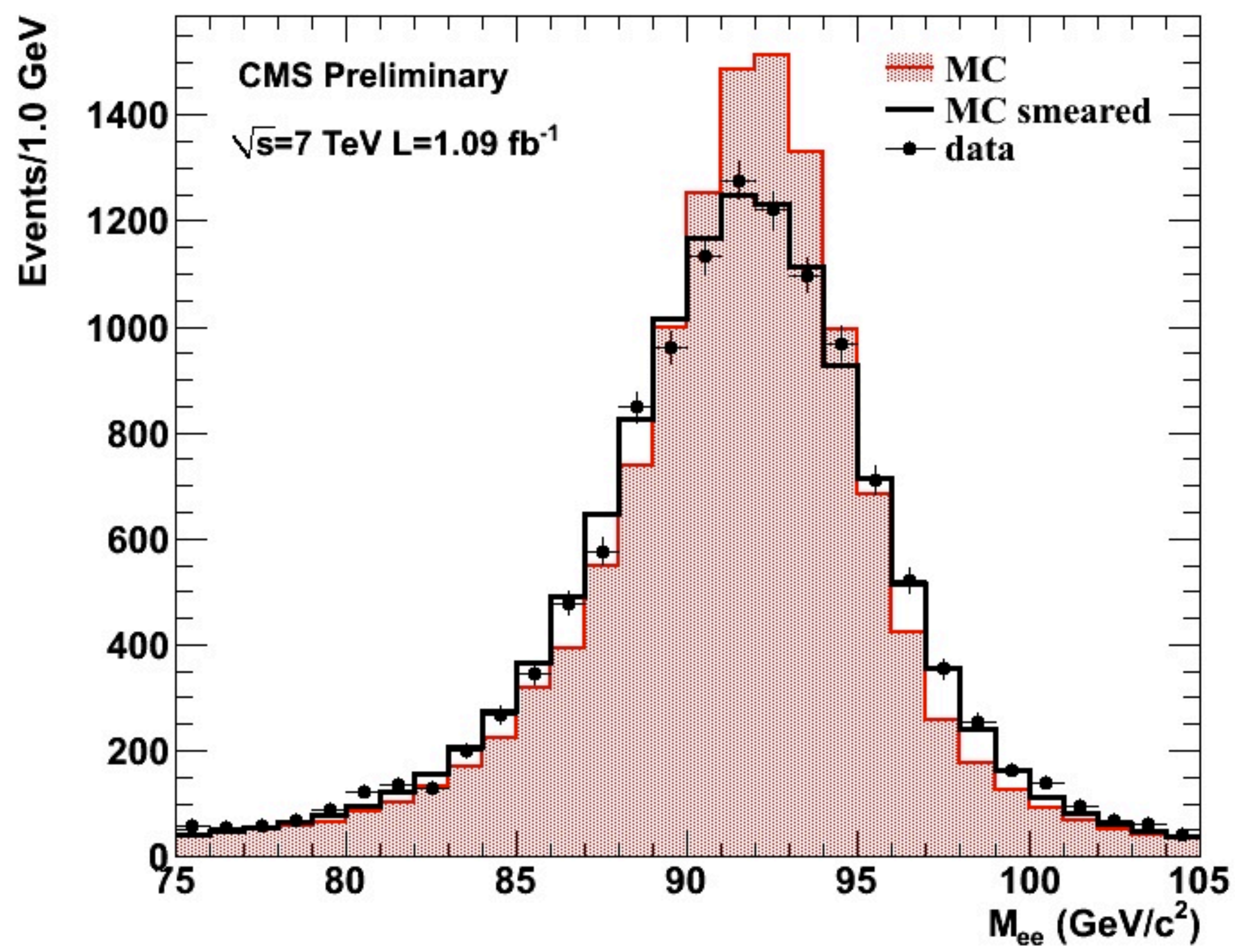
- energy scale and resolution corrections **measured from Z→ee** per photon category (2 η x 2 R_9)
- values obtained by

  1) **smearing** electron energies in the MC

  2) find the **values** (bias and smearing) that **maximize the likelihood** between the invariant mass distributions in data and smeared MC
- electrons divided in categories (same categories as photons)
- results cross-checked with fit to the Z line shape using Breit-Wigner ⊗ Crystal ball (with larger uncertainties)

Z → EE AFTER SMEARING





Both electrons in Barrel High R_9 category

One electron in Barrel High R_9 category, One electron in Endcap Low R_9 category

Event Classes

- For signal/background modeling (and limit/signal extraction) **divide events in 8 classes (2η x 2R_9 x 2 $p_{T\gamma\gamma}$)** exploiting differences in mass resolution and S/B
- **$p_{T\gamma\gamma}$ classification particularly sensitive to Fermiophobic higgs scenarios** (production mechanism restricted only to VBF and VH)

m_H=120 GeV/c^2

	Both photons in barrel		One or more in endcap	
	$min(R_9)$ >0.94	$min(R_9)$ <0.94	$min(R_9)$ >0.94	$min(R_9)$ <0.94
$p_T^{\gamma\gamma}$ <40 GeV/c				
Signal	20.9%	27.1%	9.4%	11.6%
Background	16.7%	26.3%	12.9%	20.3%
Signal σ_{eff} (GeV/c^2)	1.58	2.33	3.14	3.60
$p_T^{\gamma\gamma}$ >40 GeV/c				
Signal	10.2%	12.2%	3.5%	5.1%
Background	4.3%	7.9%	4.3%	7.4%
Signal σ_{eff} (GeV/c^2)	1.37	2.12	2.95	3.26

σ_{eff} = half width of narrowest window containing 68.3%
(Used because of non-Gaussian tails: both fitted σ, and FWHM are too optimistic; RMS is too pessimistic)

Signal Modeling

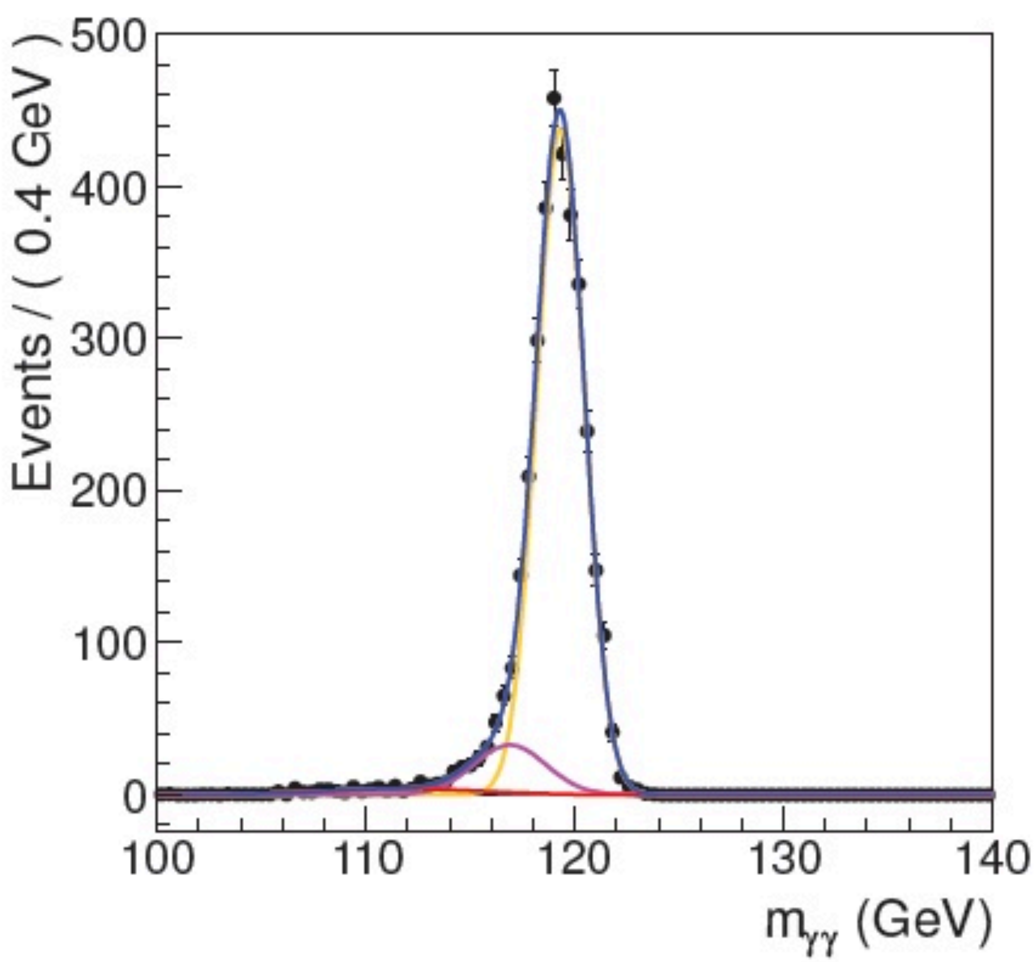
Two approaches pursued for limit setting:

- **parametric model**
  - fit smeared/corrected MC invariant mass distributions with a parametric model
  - systematics are parametrized as shape variations
- **binned/template morphing**
  - Nominal shape obtained from histograms of smeared/corrected MC
  - Systematics incorporated as alternate histograms (+/- 1σ) and using template morphing

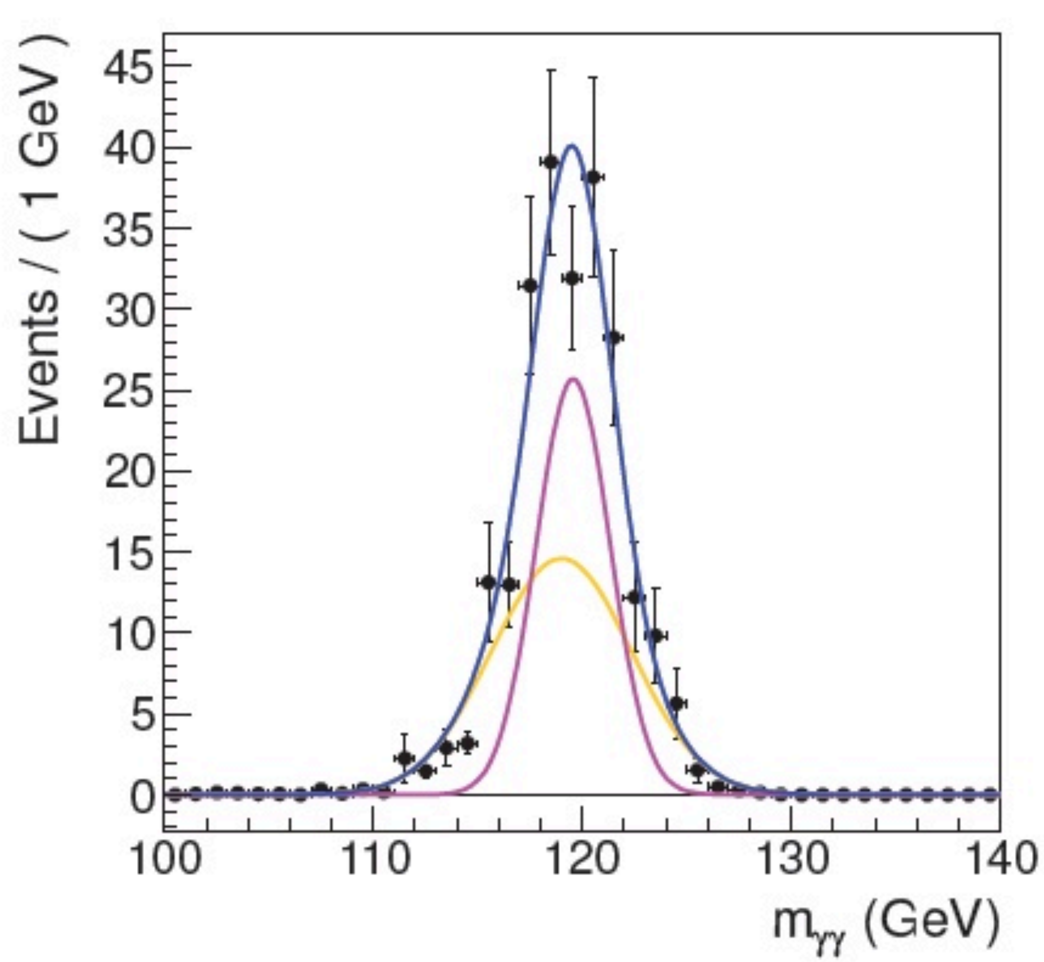
Parametric Signal Modeling

- fit separately correct and incorrect vertex selected events in each of the 8 event classes using **sum of gaussians** (up to 3 needed. Gaussian used because numerically convenient)
- **interpolation** between available MC mass points to derive the model as a function of Higgs mass

Correct Vtx

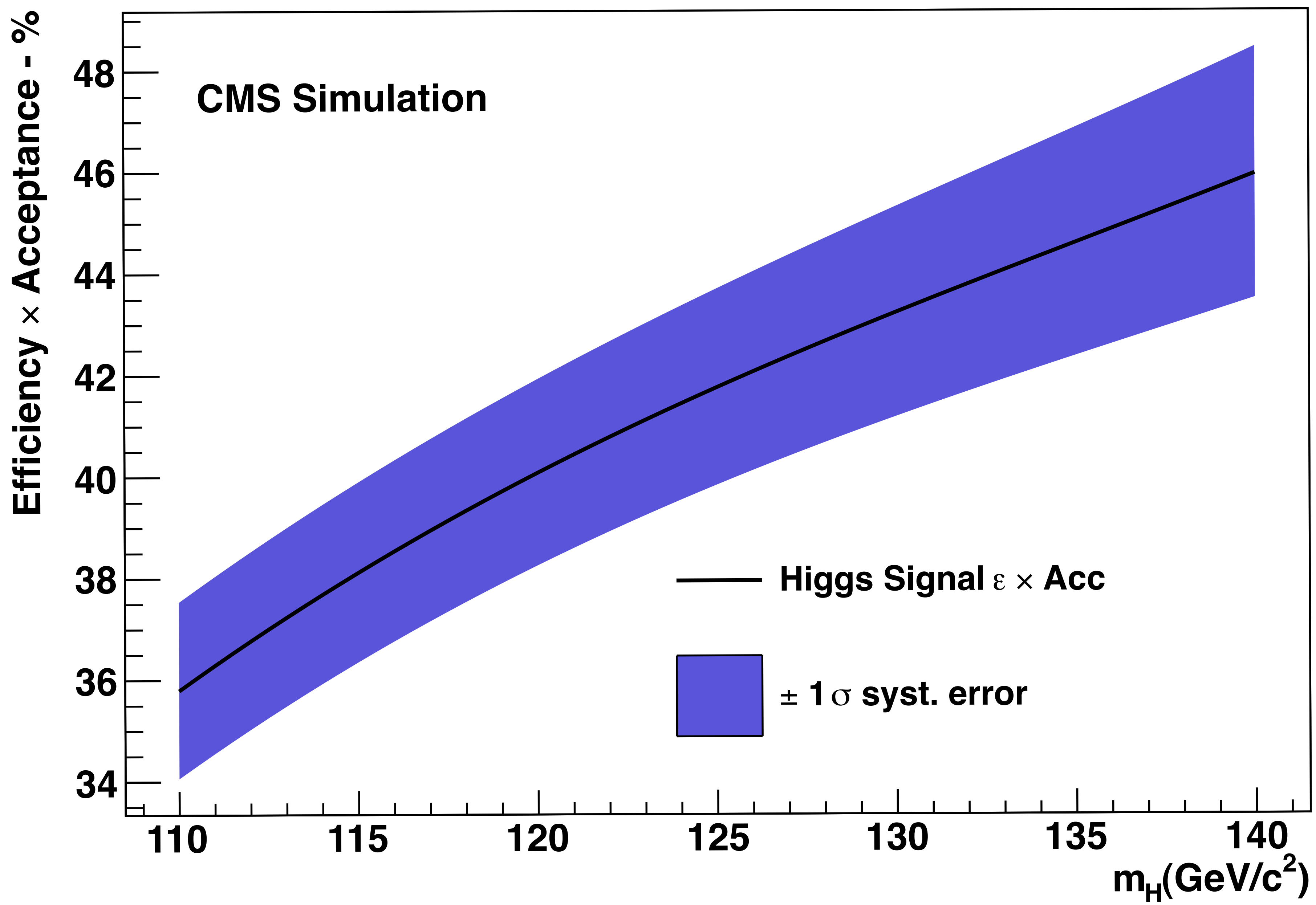


Incorrect Vtx

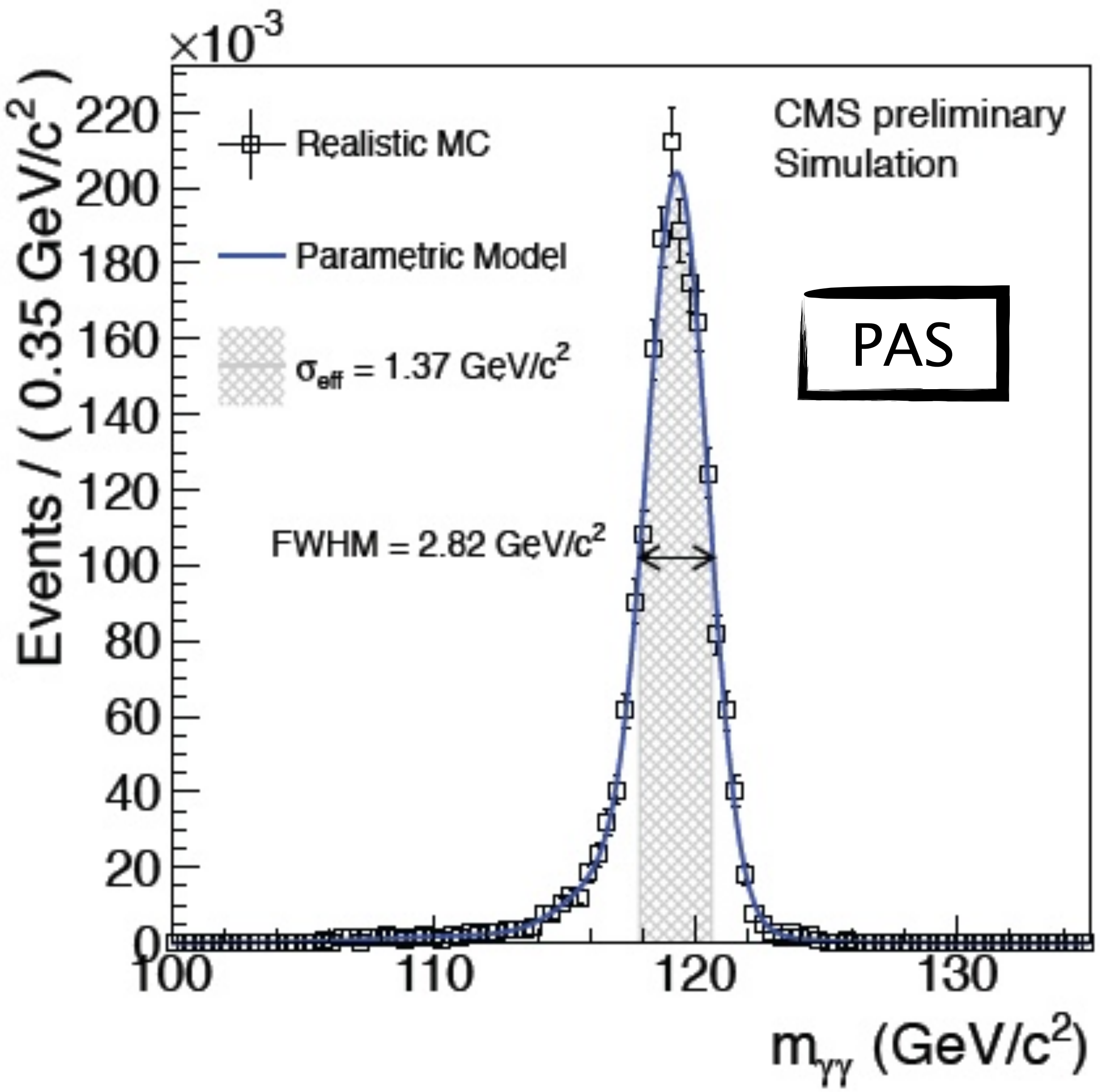


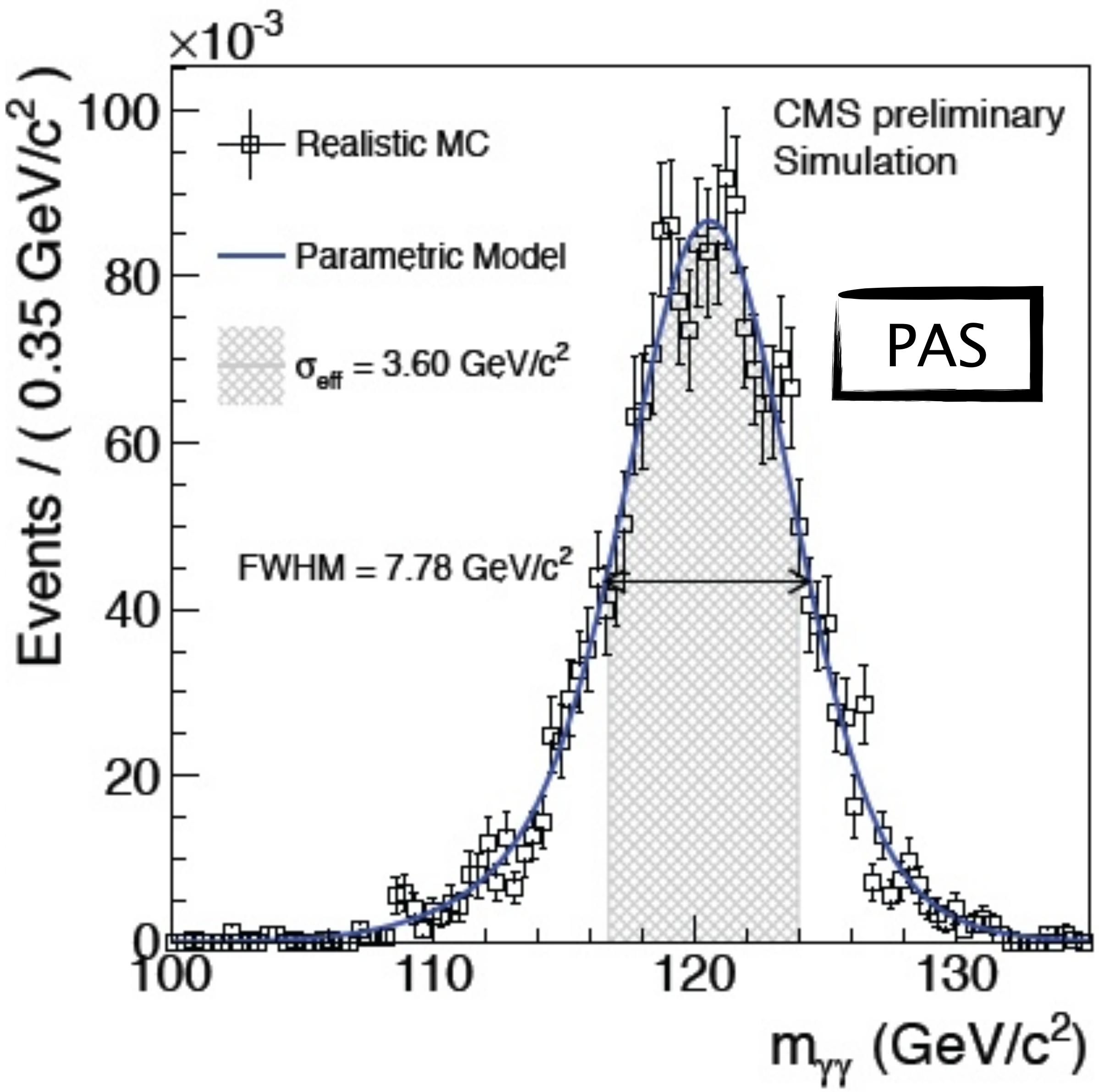
EFF X ACC VS HIGGS MASS

Eff x Acc goes from ~36% to ~46% from 110 to 140 Higgs mass: mostly due to fixed 40,30 p_T cuts and to the p_T dependence of the photon identification



MASS RESOLUTION: BEST AND WORST CLASS





Both photons in Barrel and High R_9, P_T>40 GeV

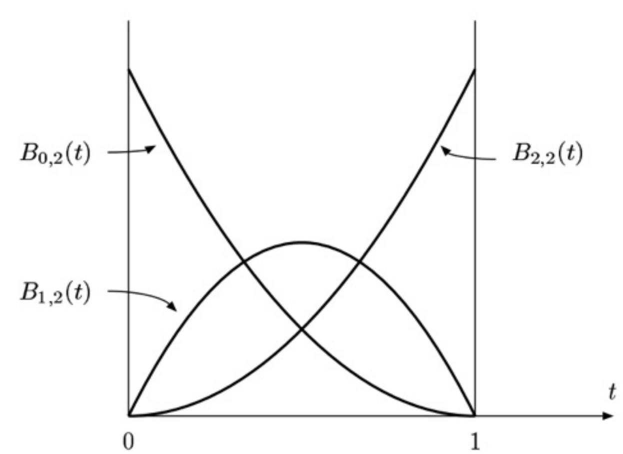
At least one photon in endcap, min(R_9)<0.94, P_T<40 GeV

Background Modeling

- **Background** modeled by a **fit to data in each event class from 100 to 150 GeV**
  - limit extracted in region 110-140 to allow enough sidebands
- **Fitting using 2nd order polynomials** to allow for kinematic turn-on in high p_T categories and to have enough parametric freedom to reasonably cover systematics
- **Bernstein polynomials basis chosen** (physically equivalent to a simple 2nd order polynomial function) in order to avoid fit to become negative (used as pdf in limit extraction)

http://www.idav.ucdavis.edu/education/CAGDNotes/Bernstein-Polynomials.pdf

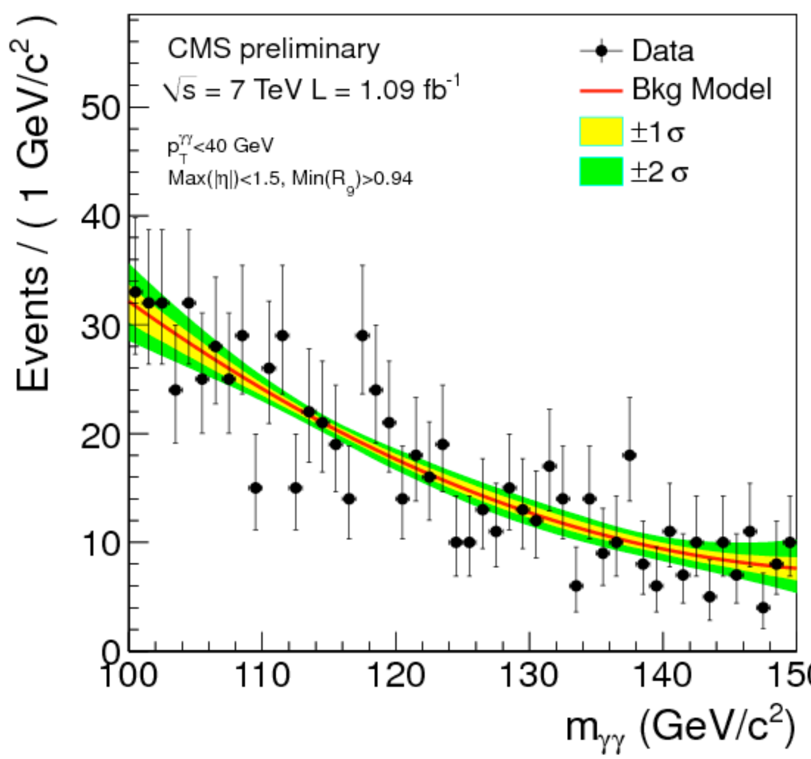
$$
\boxed{
\begin{aligned}
B_{0,2}(t) &= (1-t)^2 \\
B_{1,2}(t) &= 2t(1-t) \\
B_{2,2}(t) &= t^2
\end{aligned}
}
$$

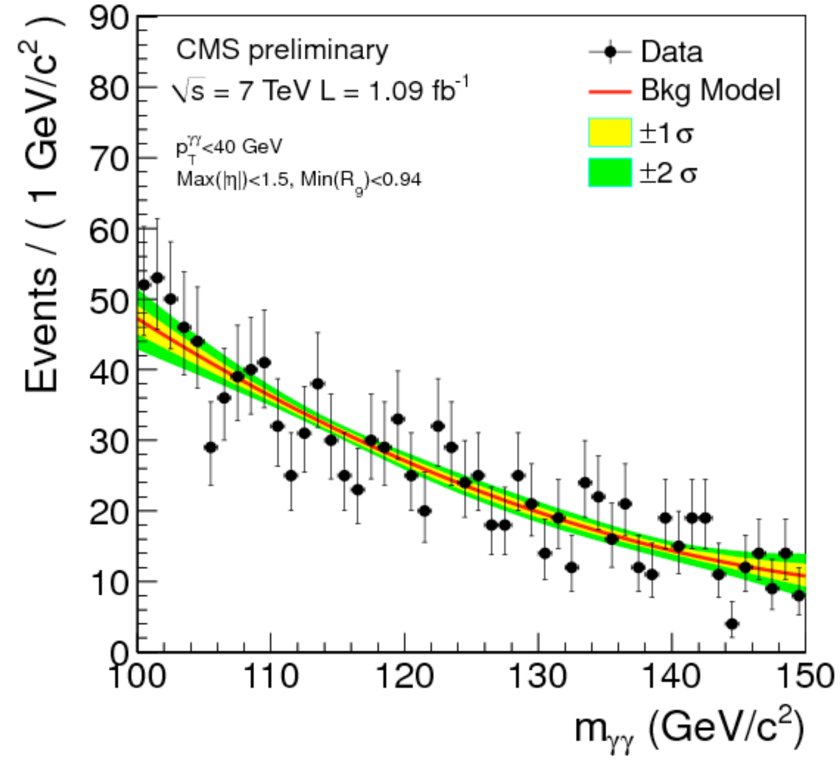


BACKGROUND FITS: LOW PT(<40) CLASSES

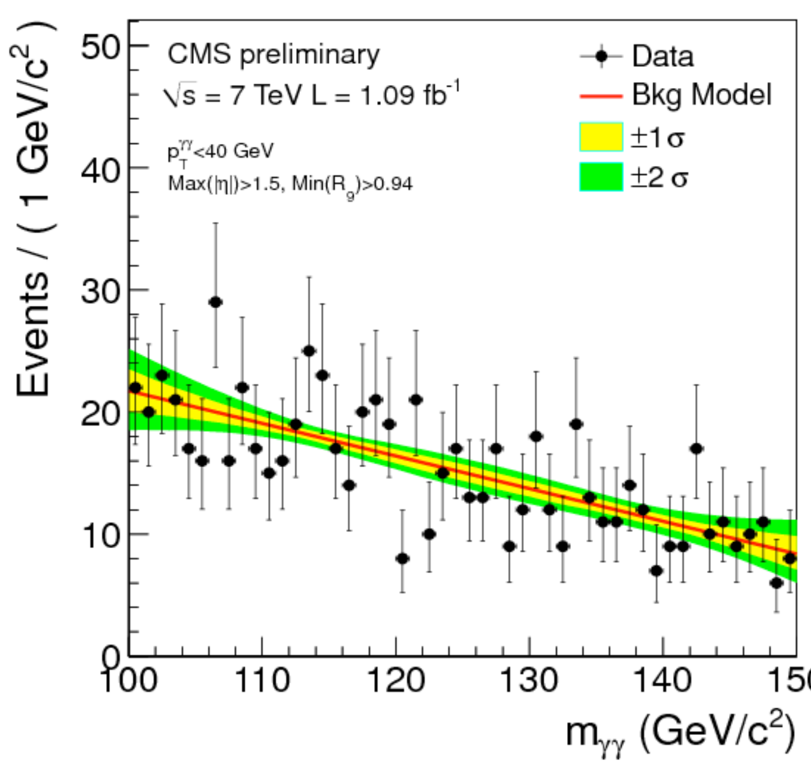
min(R_9)>0.94 | **min(R_9)<0.94**

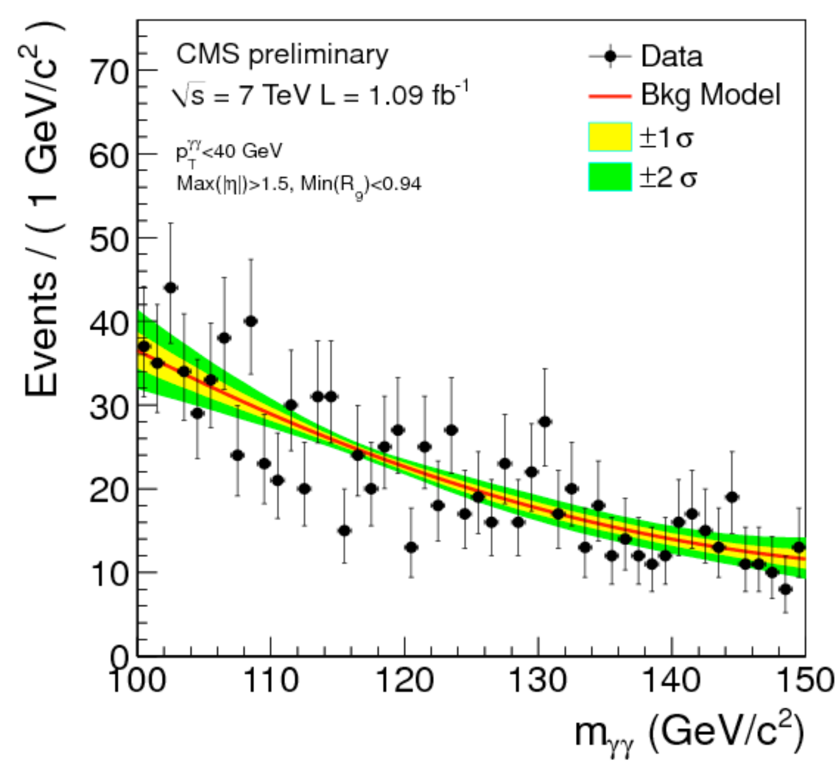
Both EB





At least one in EE



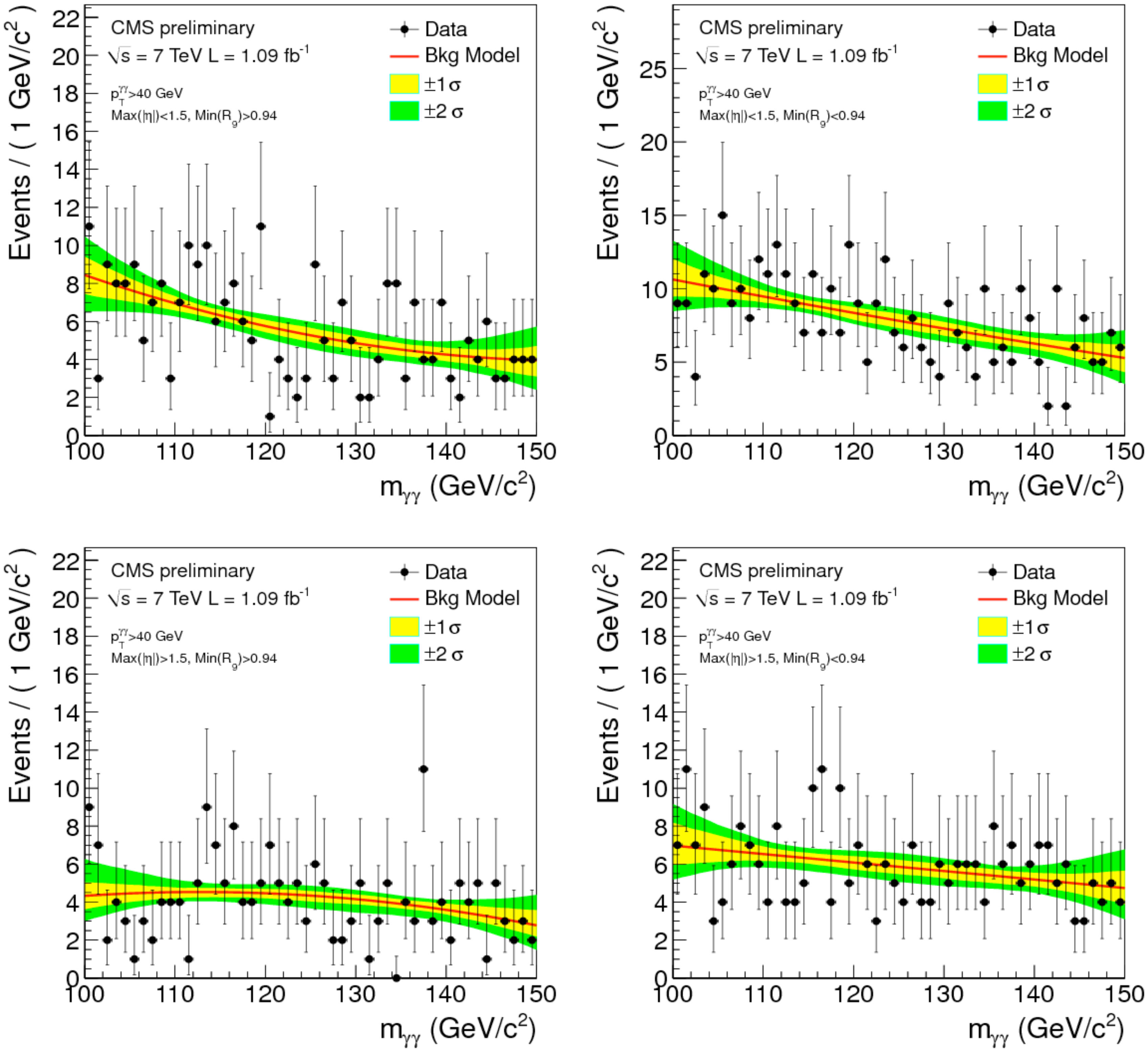


Background Fits: High Pt(>40) Classes

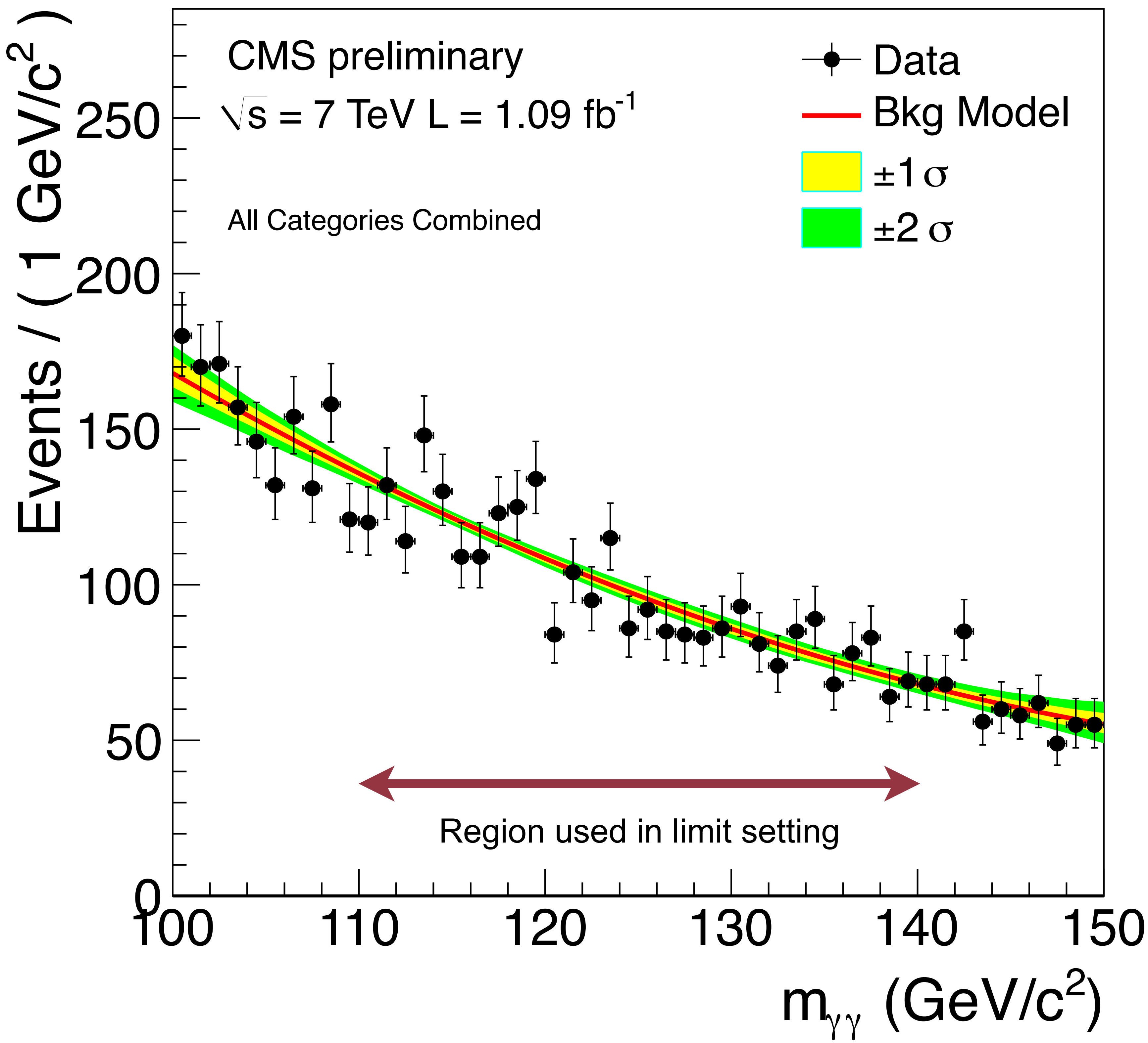
min(R9)>0.94 | min(R9)<0.94

Both EB

At least one in EE



BACKGROUND FIT: ALL CATEGORIES COMB.



SETTING LIMITS

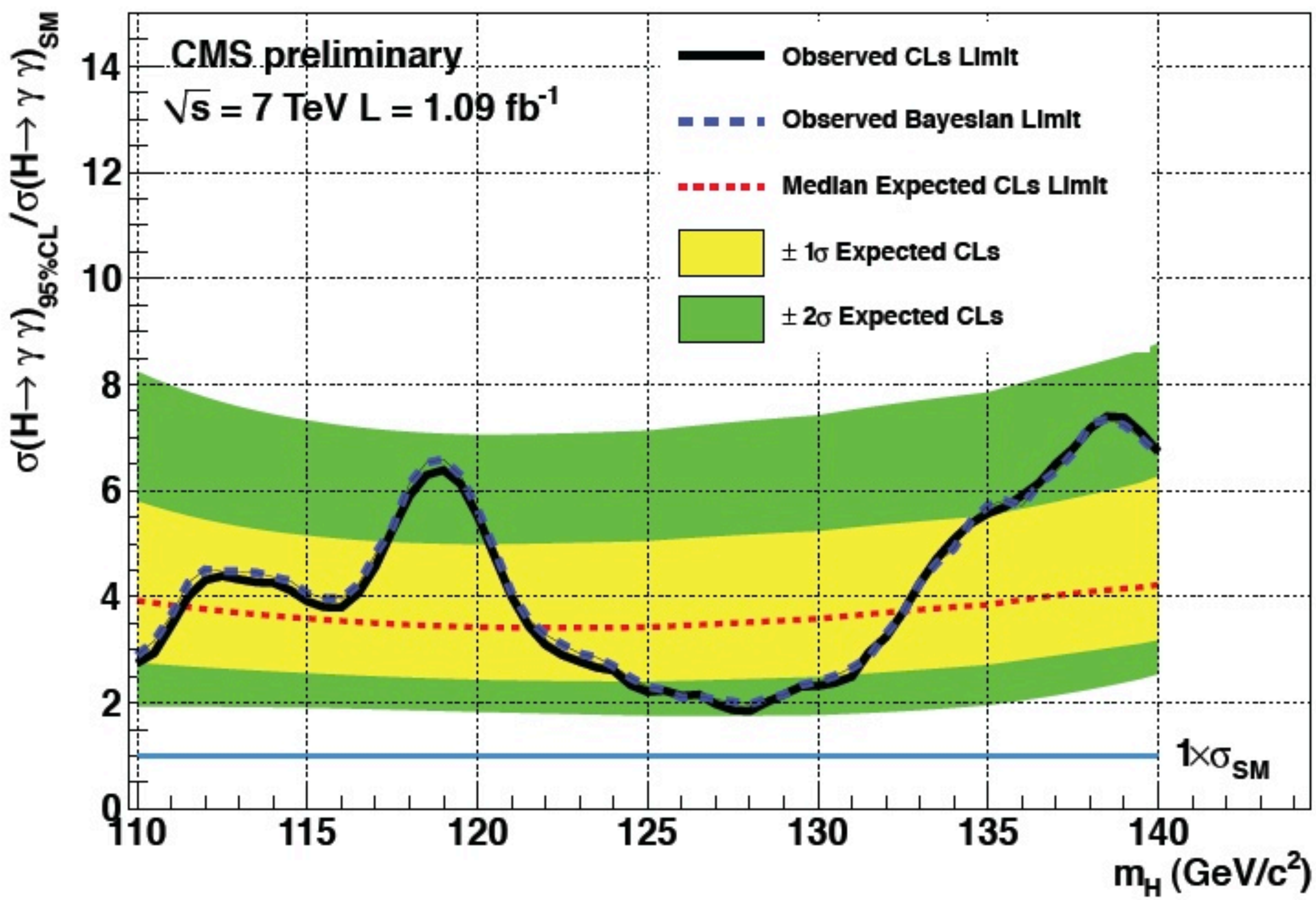
- CL_s Frequentist method is used with "LHC-type" test statistics

CLs "LHC-type" test statistic: $Q = -\ln \frac{\mathcal{L}(data|b(\hat{\theta}_b)+\mu s(\hat{\theta}_s))}{\mathcal{L}(data|b(\hat{\theta}_b)+\hat{\mu} s(\hat{\theta}_s))}$
(constrain $0 \leq \hat{\mu} \leq \mu$, and add external constraints for signal nuisances)

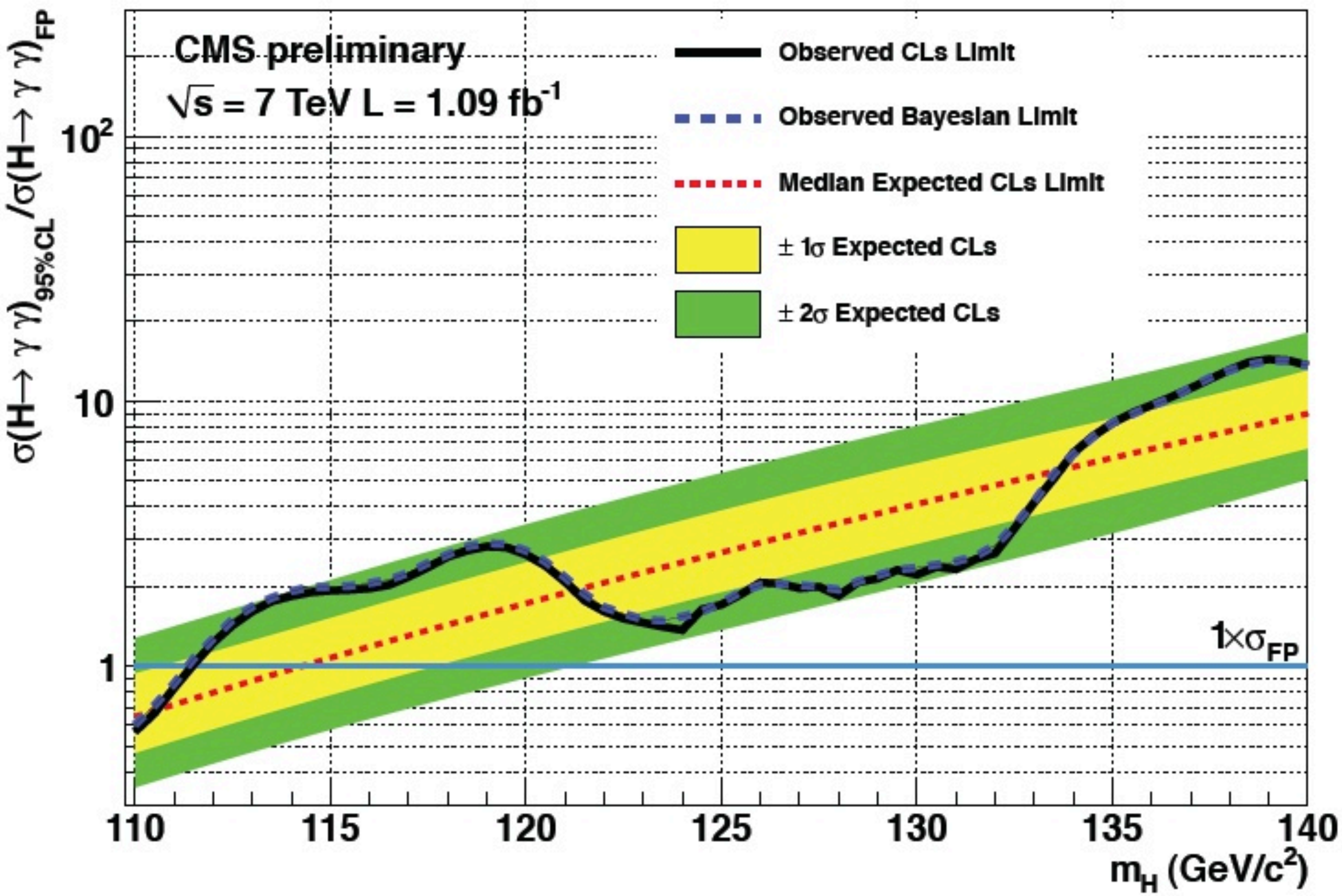
- Limits are given in Higgs mass range 110-140 in 0.5 GeV/c^2 mass steps

- Bayesian limit is compared with CL_s results

LIMIT FOR SM HIGGS (RELATIVE)



LIMIT FOR FERMIOPHOBIC (RELATIVE)



CMS Excluded region between 110-111 GeV (expected 110-114)

Latest Tevatron results:

•D0 8.2 fb^{-1}: <112 GeV (exp. 112)

•CDF 7.0 fb^{-1}: <114 GeV (exp. 111)

UL: Classes and Systematics

Computed on expected limit @ 120 GeV

Table 23: Within the PL approximation, effect of different changes on the expected limit.

	Expected (95% CL, pb)	Ratio to nominal
Standard Model		
Nominal (8 classes)	0.139	1.00
No signal syst. (8 classes)	0.138	0.99
EB only (4 classes)	0.146	1.05
No $p_T^{\gamma\gamma}$ class. (4 classes)	0.142	1.02
No classes	0.169	1.21
No MC smearing (8 classes)	0.117	0.84
Fermiophobic		
Nominal (8 classes)	0.0885	1.00
No signal syst. (8 classes)	0.0876	0.99
EB only (4 classes)	0.0931	1.05
$p_T^{\gamma\gamma} > 40\,\mathrm{GeV}/c$ only (4 classes)	0.0896	1.01
No $p_T^{\gamma\gamma}$ class. (4 classes)	0.1406	1.59
No classes	0.1678	1.90

UL: Classes and Systematics

Computed on expected limit @ 120 GeV

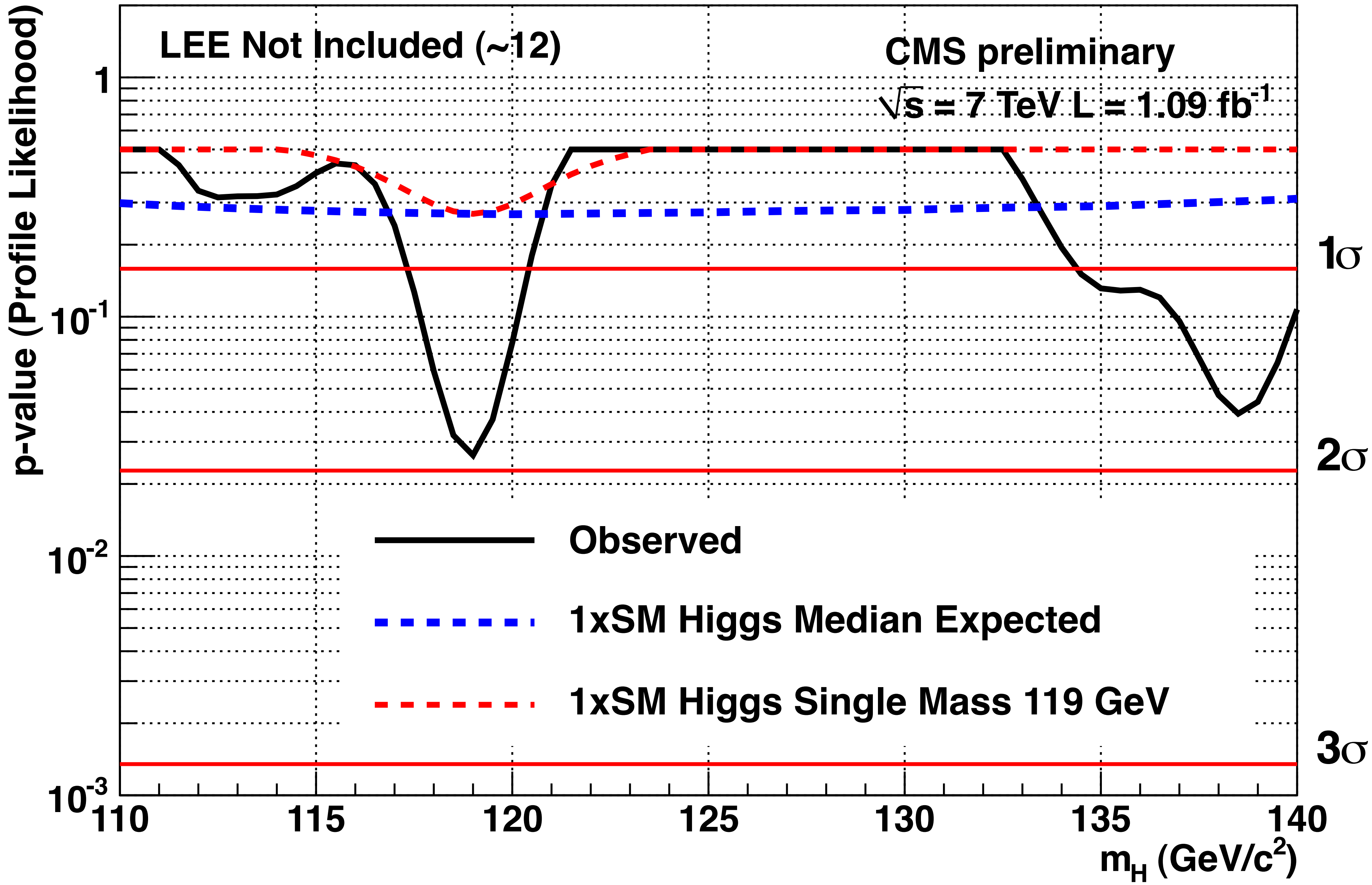
Table 21: Standard Model: expected limits (95% CL, PL, in pb) for $m_H = 120\,\mathrm{GeV}/c^2$ for each individual event class.

	Both photons in barrel		One or more in endcap	
	$min(R_9) > 0.94$	$min(R_9) < 0.94$	$min(R_9) > 0.94$	$min(R_9) < 0.94$
$p_T^{\gamma\gamma} < 40\,\mathrm{GeV}/c$	0.27	0.31	0.90	0.93
$p_T^{\gamma\gamma} > 40\,\mathrm{GeV}/c$	0.30	0.38	1.22	1.07

Table 22: Fermiophobic Model: expected limits (95% CL, PL, in pb) for $m_H = 120\,\mathrm{GeV}/c^2$ for each individual event class.

	Both photons in barrel		One or more in endcap	
	$min(R_9) > 0.94$	$min(R_9) < 0.94$	$min(R_9) > 0.94$	$min(R_9) < 0.94$
$p_T^{\gamma\gamma} < 40\,\mathrm{GeV}/c$	0.88	1.02	2.58	2.68
$p_T^{\gamma\gamma} > 40\,\mathrm{GeV}/c$	0.12	0.16	0.45	0.46

P-VALUES (SM)



Values extracted from asymptotic behavior of ProfileLikelihood test statistics. Look elsewhere effect not included (~12)

P-VALUES (FERMIOPHOBIC)