Particle Physics – Higgs with CMS at LHC

CERN, Geneva
21 april, 2013

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Outline

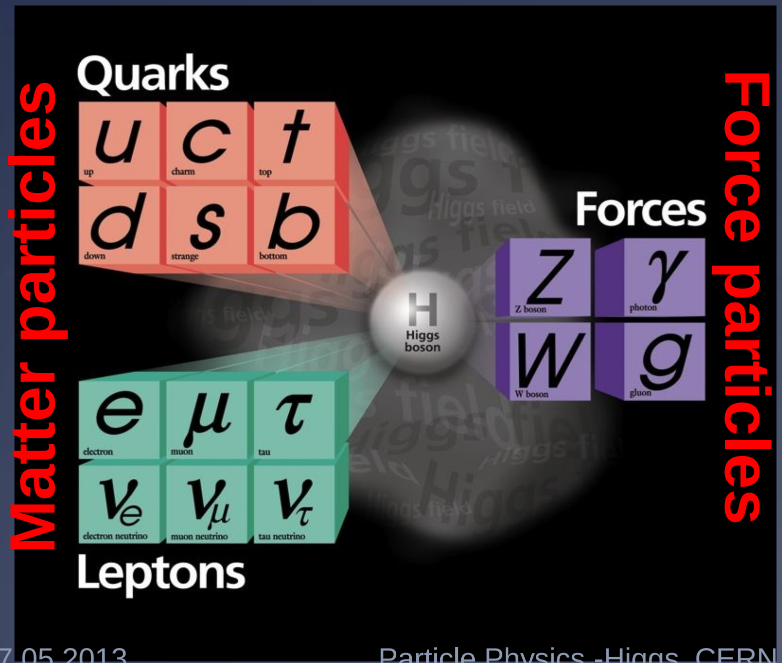
* Particle Physics and Standard Model
* LHC & CMS, Latest Higgs results
* H→γγ analysis update with the full dataset

Particle Physics

Some background and history

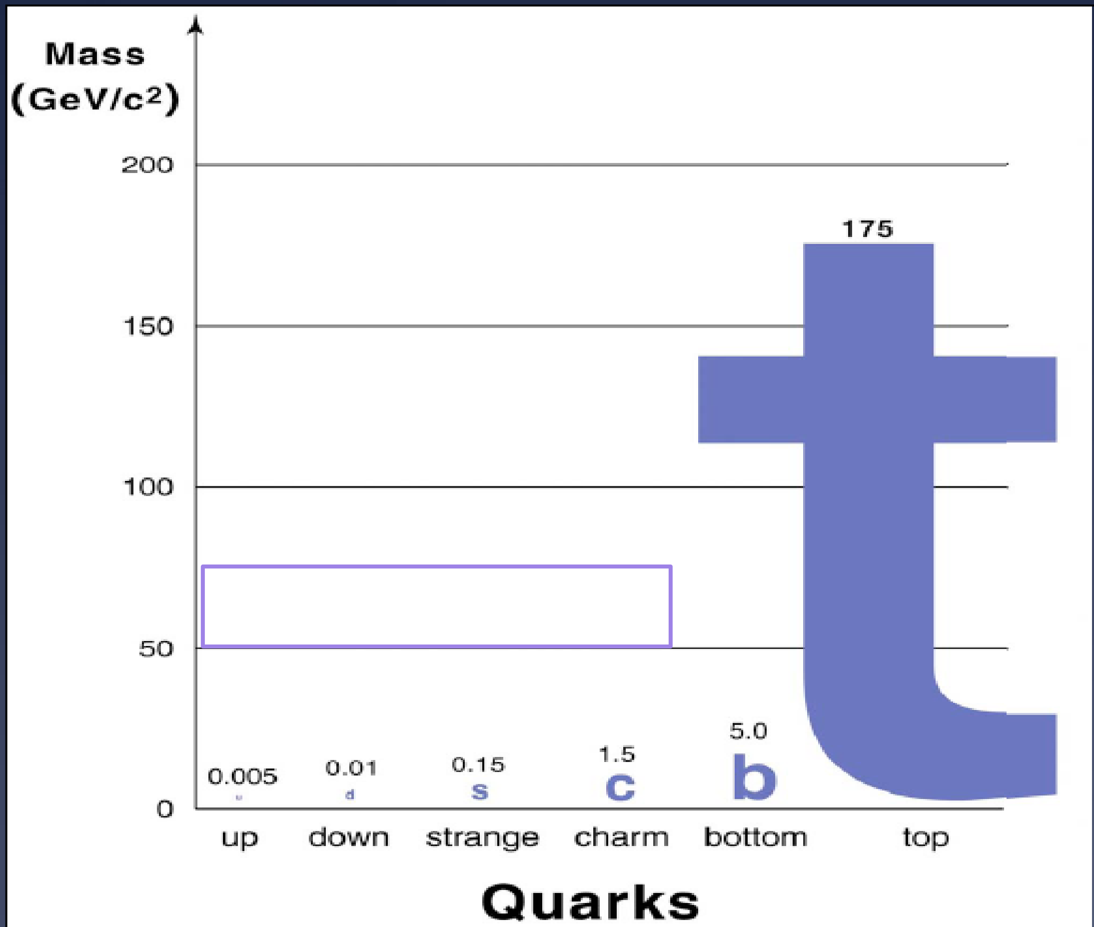
The "Standard Model"

- Over the last ~100 years: The combination of Quantum Field Theory and discovery of many particles has led to
- **The Standard Model of Particle Physics**
  - With a new "Periodic Table" of fundamental elements



One of the greatest achievements of 20th Century Science

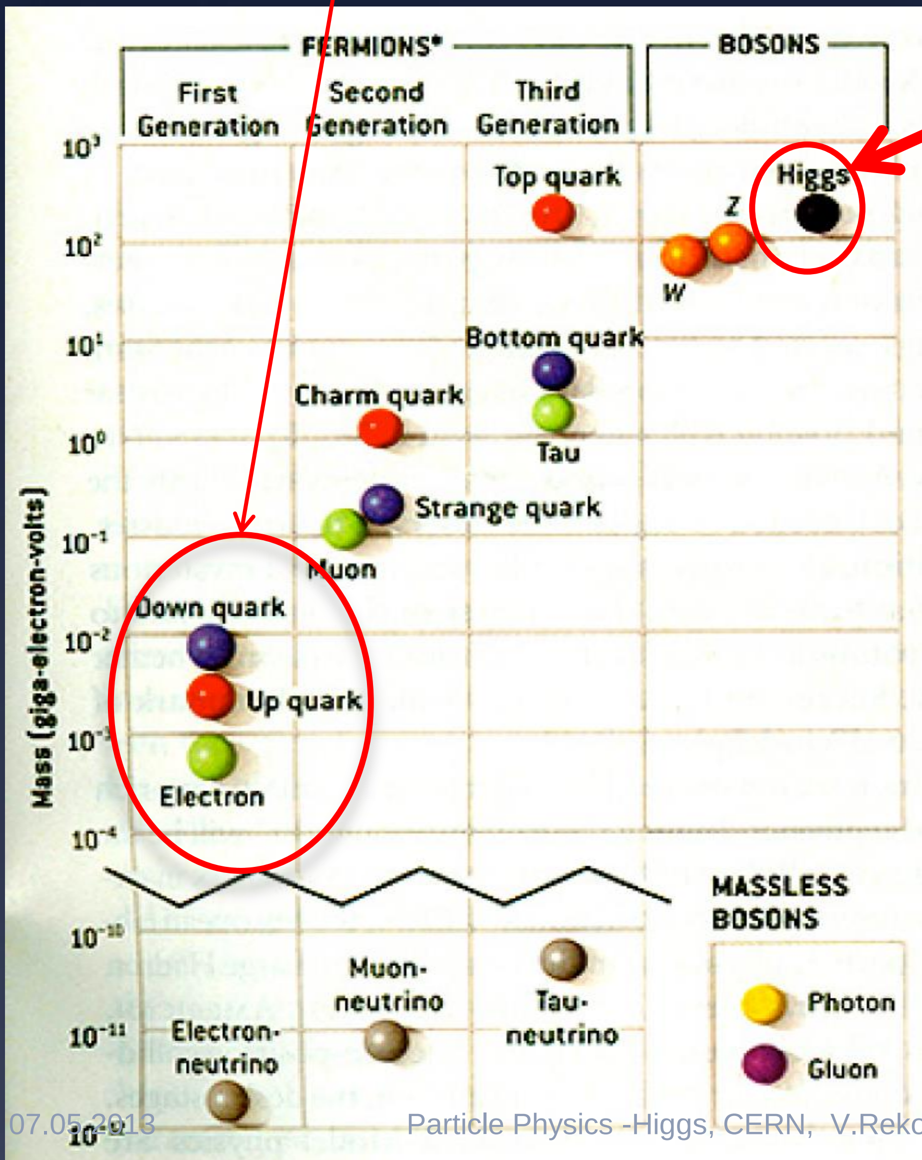
Quark masses

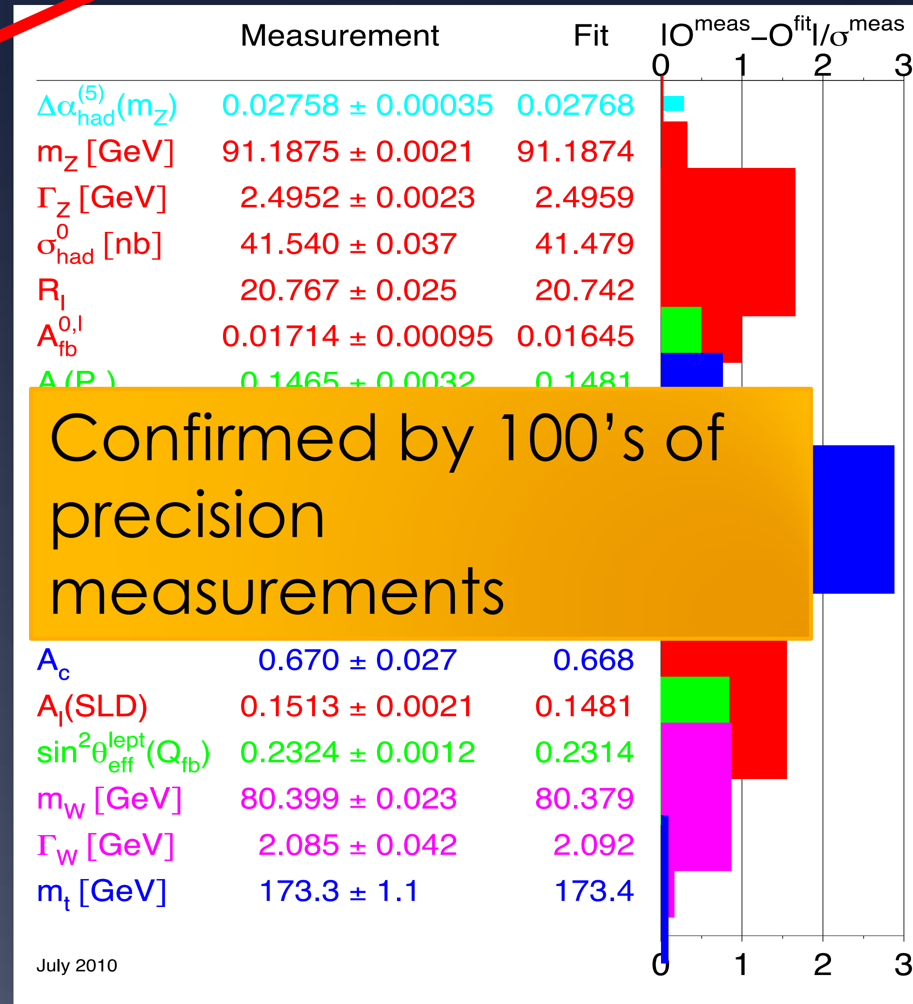


The Standard Model

These are all we "see" around us in everyday life but the others are crucial to defining what we are.

Higgs was missing, now found



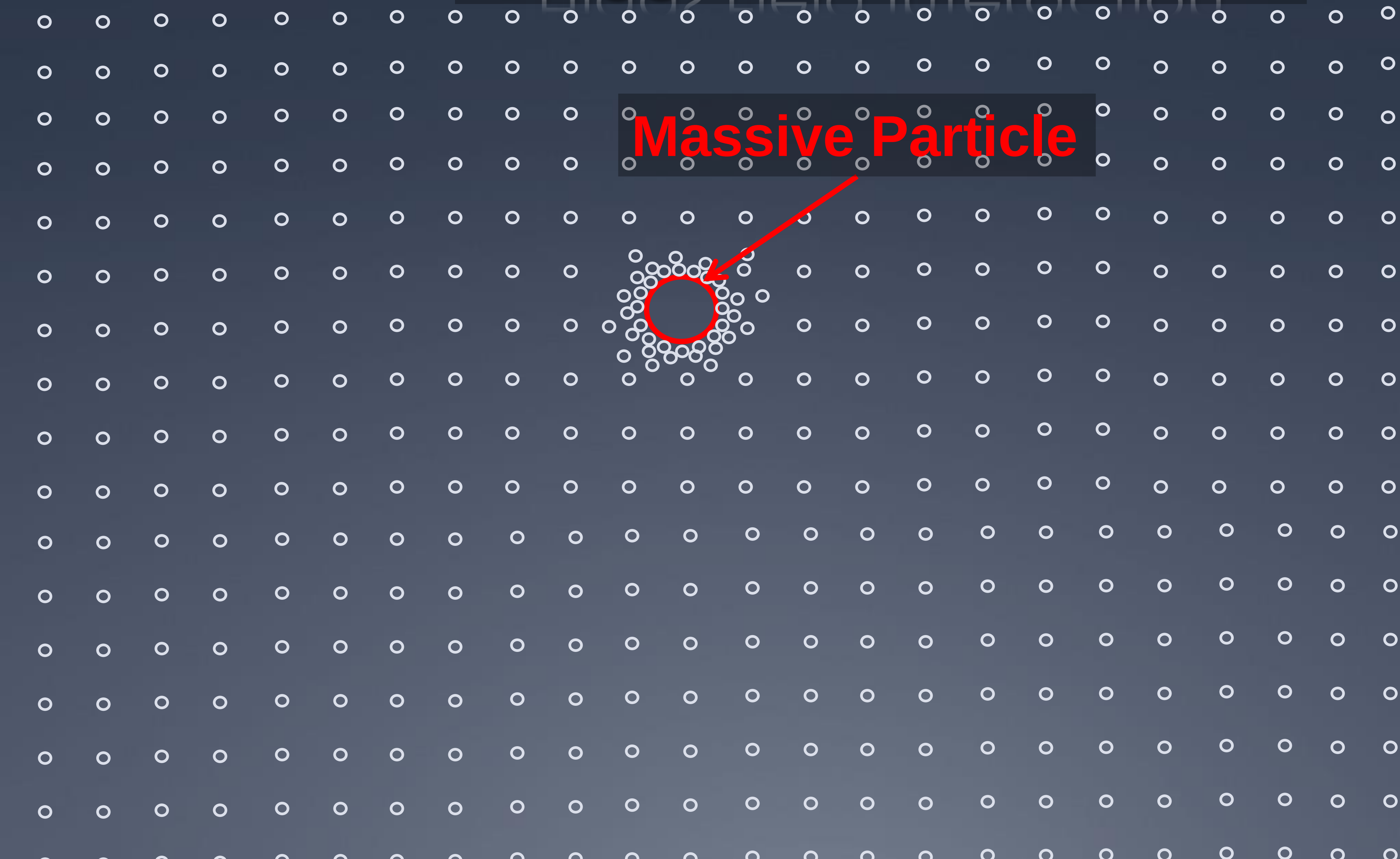


Confirmed by 100's of precision measurements

What is this Higgs particle?

* While developing the modern theory of fundamental forces and interactions, physicists hit a snag
* Particles that carry forces had to be massless but the data seemed to say otherwise!
  * And in fact, why do any particles have mass? What *is* mass?
* Massless particles move at the speed of light
  * Speed of light: c = 300,000 km/second
  * $E=mc^2$ if a particle of mass m is at rest. So $E^2=(mc^2)^2$
  * But if a particle has momentum p then $E^2=(mc^2)^2+(pc)^2$
* So, for a massless particle ($m=0$) you get $E=pc$
  * This is the equation for a particle moving at the speed of light
* An ingenious idea:
* Suppose there is a force field filling the universe that somehow slows particles down to below the speed of light?
  * This would make them have mass !

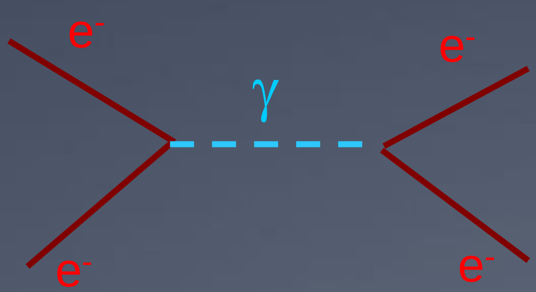
Higgs Field Interaction



Courtesy of Stefan Spanier (UT)

Is it a field or a particle?

- All fields have small packets of energy associated with them that we call "quanta"
  - yes, it's from quantum mechanics
- Field quanta are particles that carry forces
  - Elementary particles interact by exchange of field quanta

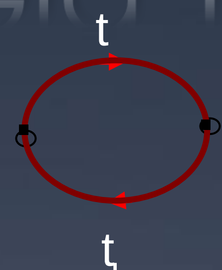


Repulsion of 2 electrons by the exchange of a photon.
The photon is the quantum of the electromagnetic field

- This is not so hard to believe
- But it gets weirder…

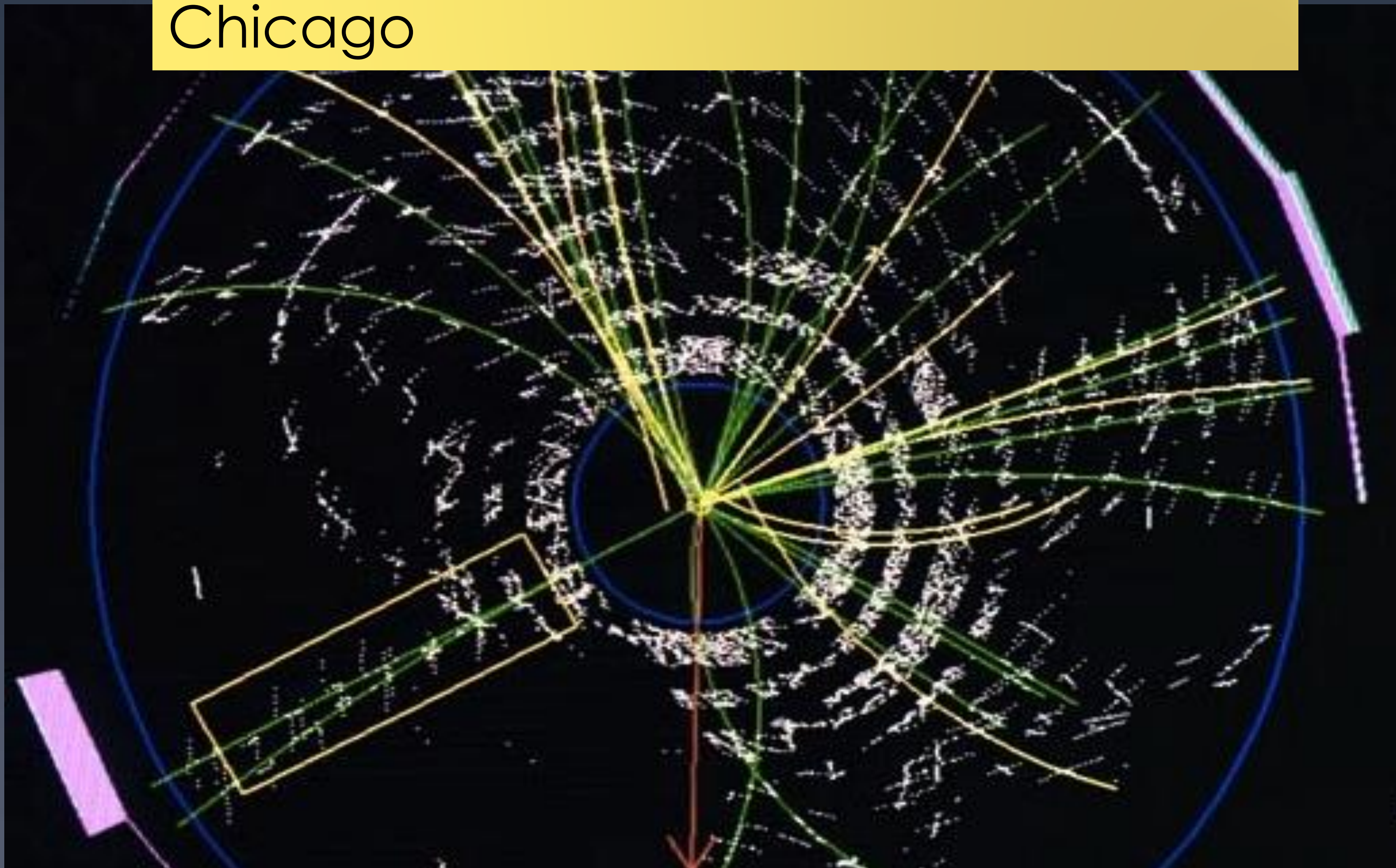
Quantum Field Theory

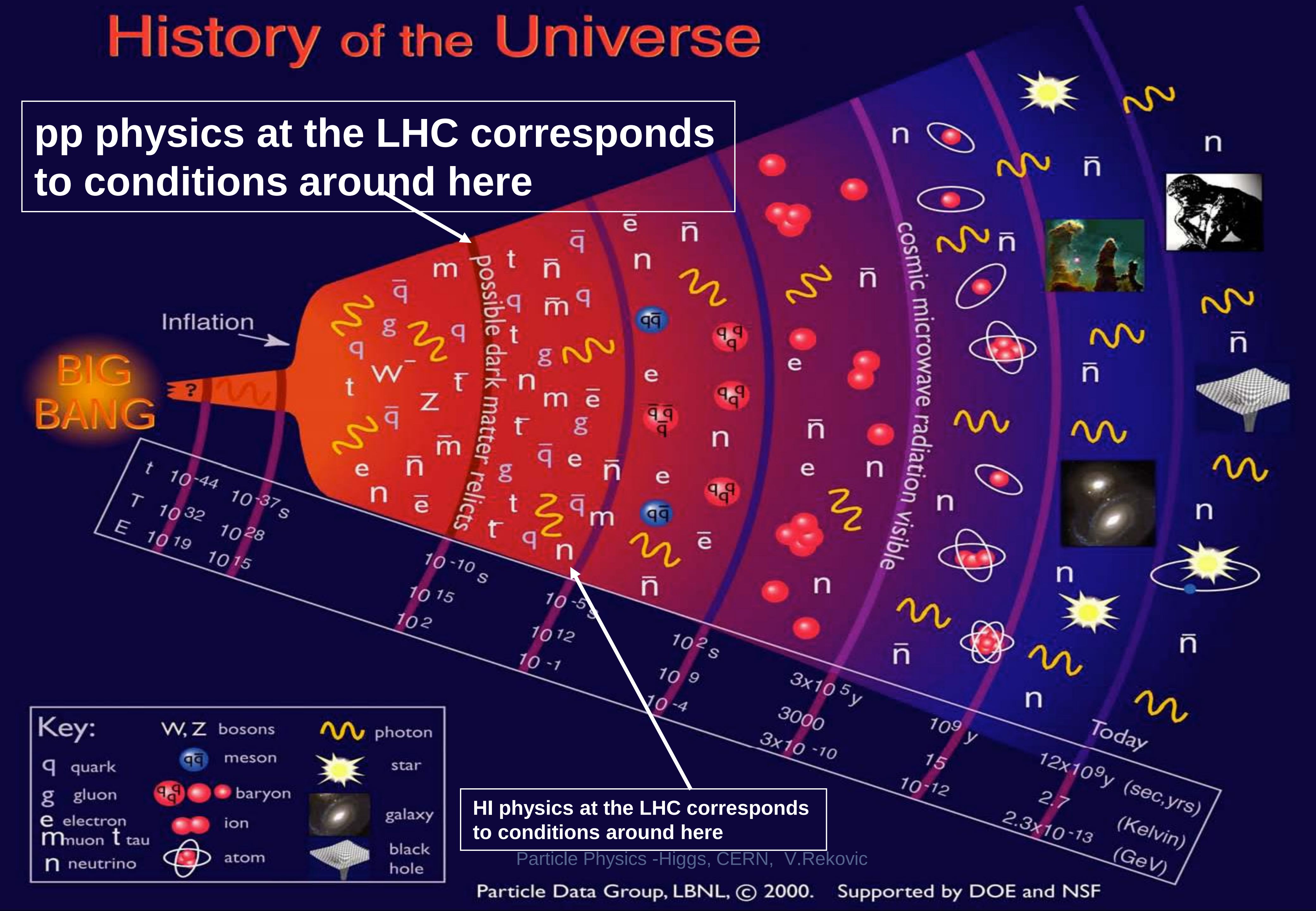
* Energy and matter are equivalent
  * ($E = mc^2$)



* A particle-antiparticle pair can pop out of empty space ("the vacuum")
* And then vanish back into it
  * **These are *Virtual* particles.**
* This has far-reaching consequences
  * The structure of the universe depends on particles that ***don't exist in the usual sense*** **(**but did when the Universe was very young and hot)
* This is the reason we do what we do
* We are searching for the "genetic code" of our universe
  * We do not see these particles in everyday life
  * We must recreate the state of the early hot universe to make them

“Real” top quarks were seen for the first time in the 1990’s at Fermilab near Chicago




History of the Universe
pp physics at the LHC corresponds
to conditions around here
HI physics at the LHC corresponds
to conditions around here
BIG BANG
Inflation
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

What makes us so sure about the Higgs?

* The Higgs theory has predictable consequences
  * It predicts very heavy force particles that carry the weak nuclear force known as the W^+, W^- and Z^o
  * The W^+, W^- should both have a mass of 80.4 GeV
    * Note that the proton has a mass of 1 GeV so these are very heavy fundamental particles!
  * The Z^o should have a mass of 91.1 GeV
* We should be able to find them & measure their masses
  * For instance, the Z^o should decay to two muons. We can measure their momenta and reconstruct the Z^o mass.
  * If we do this for many Z^o particles, a distribution of the mass values we get should have a very predictable shape.

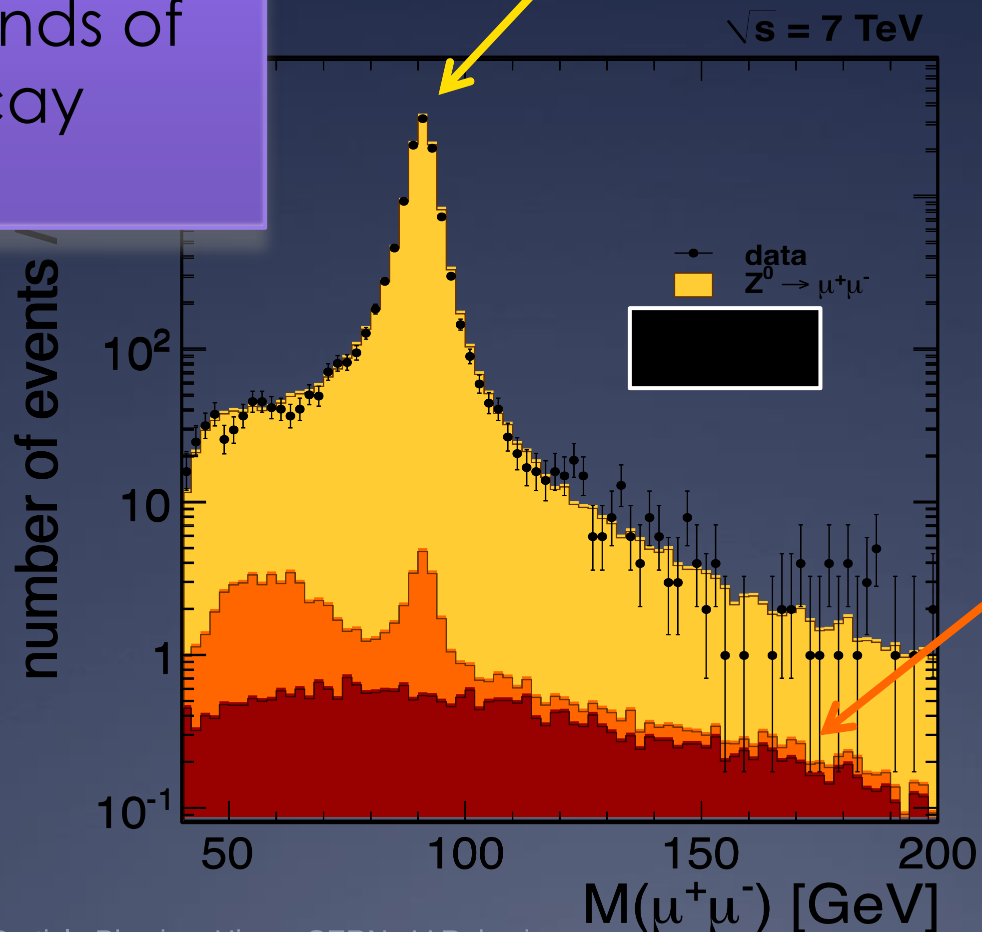
$Z^0 \rightarrow \mu^+\mu^-$

We predict this

This is what we see

up when looking at
many thousands of
$Z^0 \rightarrow \mu^+\mu^-$ decay
events

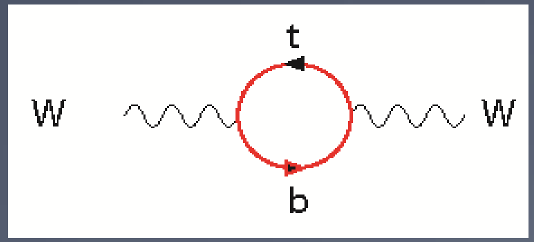
Peak at 91.1 GeV

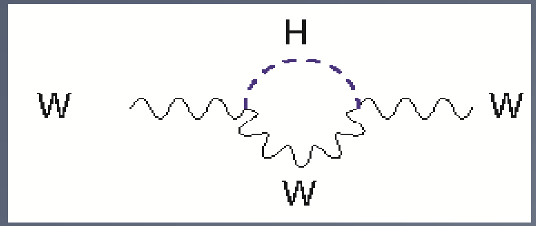


Background events with two muons but not necessarily from simply $Z^0 \rightarrow \mu^+\mu^-$

Fundamental connections

- Fundamental particles have deep connections
  - The mass of the W particle depends a lot on the mass of the top quark and a little on the mass of the Higgs and many other particles
- This is because the identity of a particle is not completely separable from what it can become (or decay into)





This "Feynmann diagram" shows a W particle transforming into a top and a bottom quark and back again to a W.

Here we see a W particle transforming itself into a W + Higgs and then back again to a W.

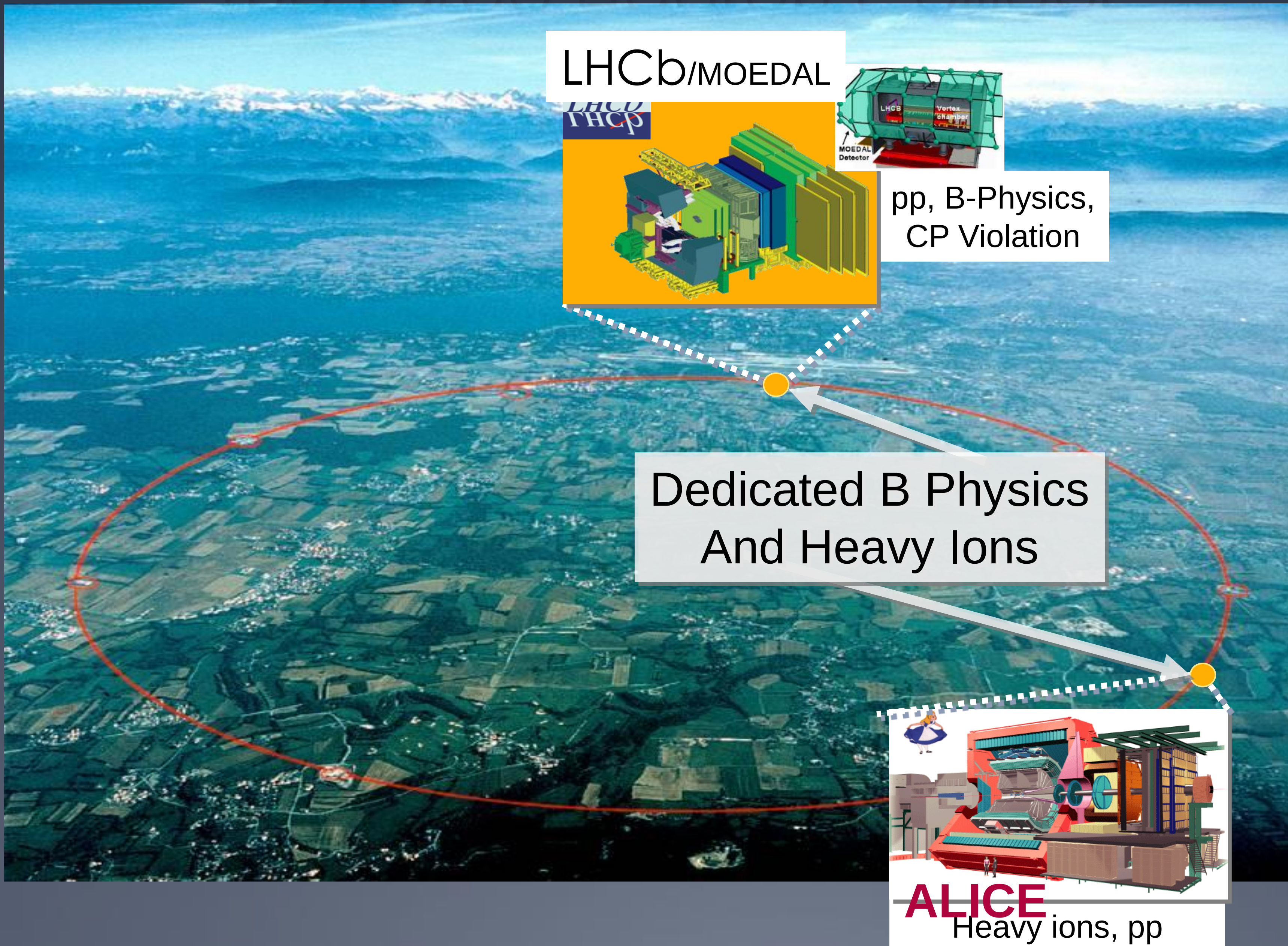
The LHC

Accelerator Complex

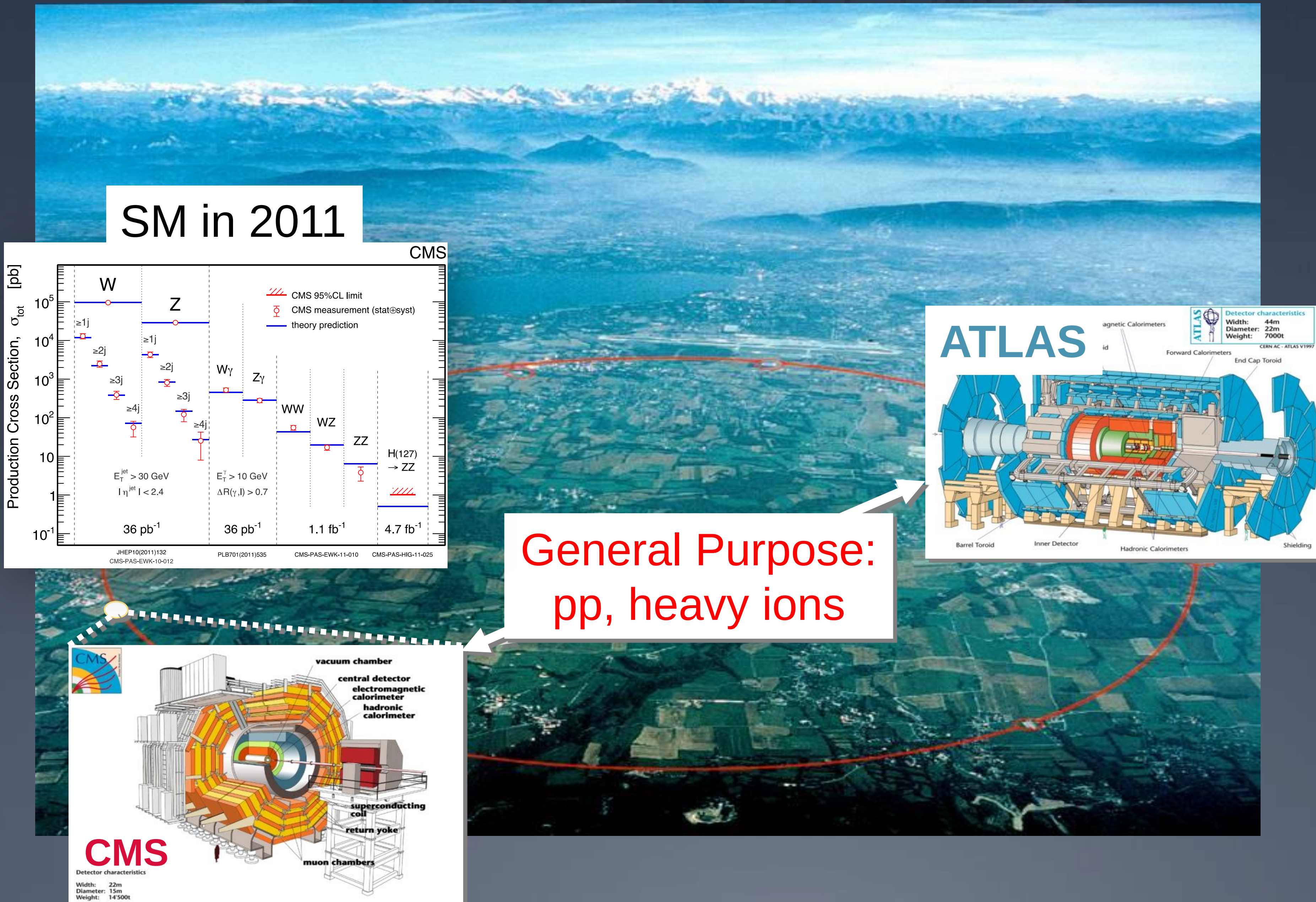
The Large Hadron Collider

The Large Hadron Collider

The Large Hadron Collider



The Large Hadron Collider



Some LHC facts

- Tunnel
  - Diameter 3m, Length 27 km
    - 2 billion pounds excavated
- Beams
  - Made up of bunches
    - 1.2-1.5x10^{11} protons/bunch
    - 1404 (2808) maximum bunches in machine for 50 (25) ns separation
      - 50 ns separation = 15 m
    - At Interaction Point (IP)
      - Bunch length ~ 6 cm
      - Beam radius ~23 μm
    - Bunch collision rates
      - 31.6 MHz (25 ns spacing)
      - 15.8 MHz (50 ns spacing)

- Superconducting dipoles
  - challenge: magnetic field of 8.33 Tesla in total 1232 magnets, each 15 m long operated at 1.9 K
    - That's 523 degrees below room temperature
    - It's colder than space
    - It's emptier than space
  - Largest cryogenic system in the world

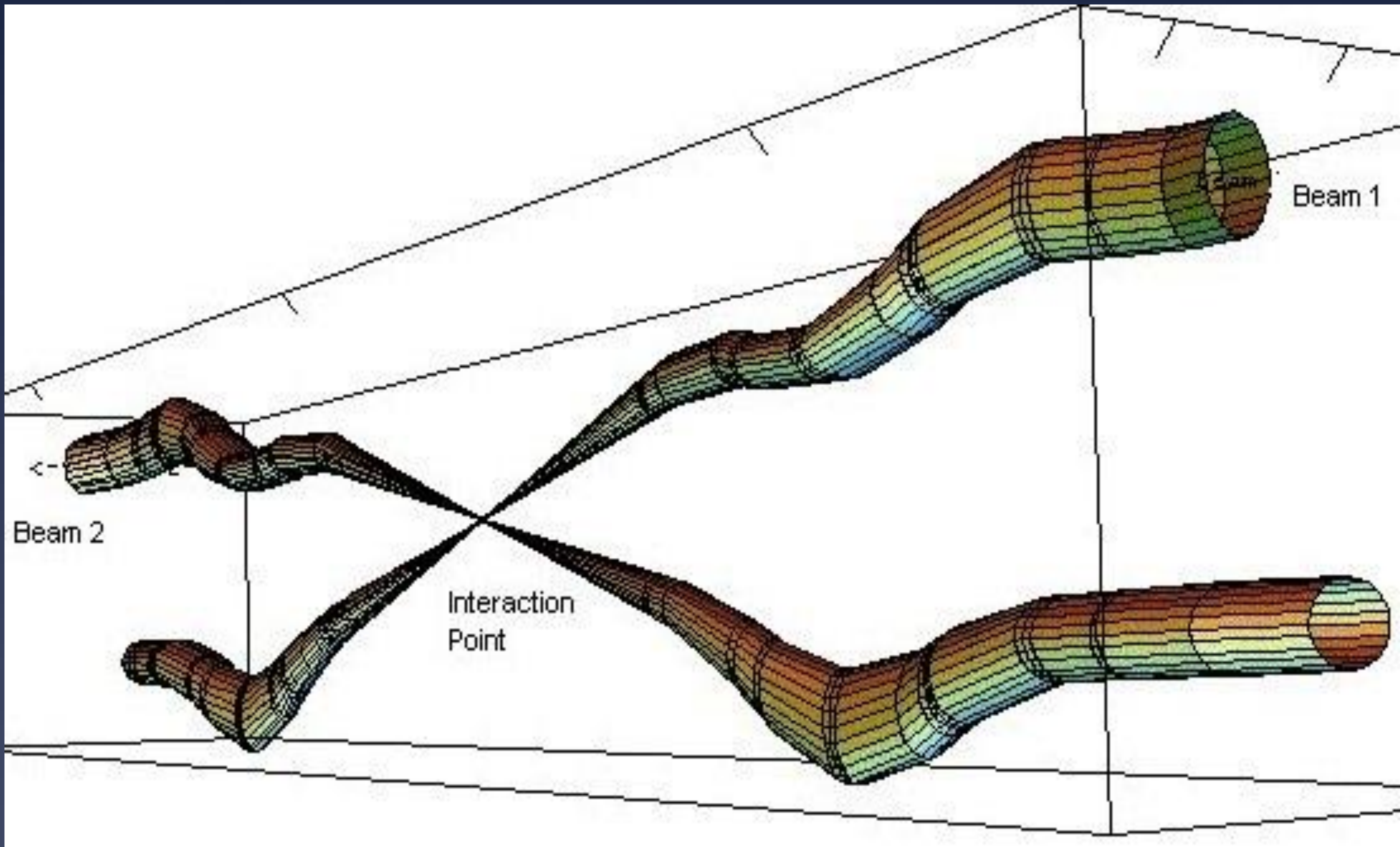
Like Swiss chocolate

- LHC magnets at 14 TeV:
  - 1 dipole magnet E_{stored} = 7 MJ
  - All magnet E_{stored} = 10.4 GJ
- Compared to previous accelerators :
  - A factor 2 in magnetic field
  - A factor 7 in beam energy
  - A factor 200 in stored energy
- Enough to melt 12 tons of Copper!
- The kinetic energy of an A380 at 700 km/hour

- 90 kg of TNT
- 15 kg of chocolate

- Energy stored in LHC beams
  - Kinetic energy of 1 proton bunch:
    - $E_1 = (1.15 \times 10^{11}$ protons$) \times 7$ TeV $= 129$ kJ
  - Kinetic energy of beam = 2808 bunches:
    - $E_{beam} = k \times E_1 = 2808 \times E_1 = 362$ MJ

Squeeze & Collide

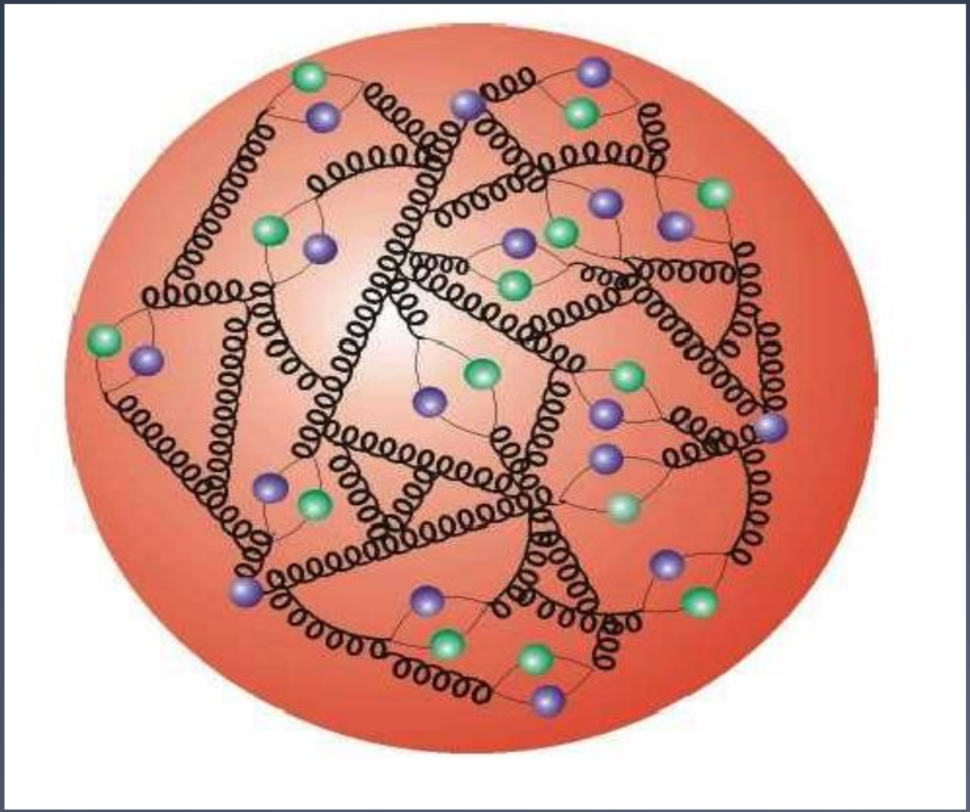


Hadron collider particulars

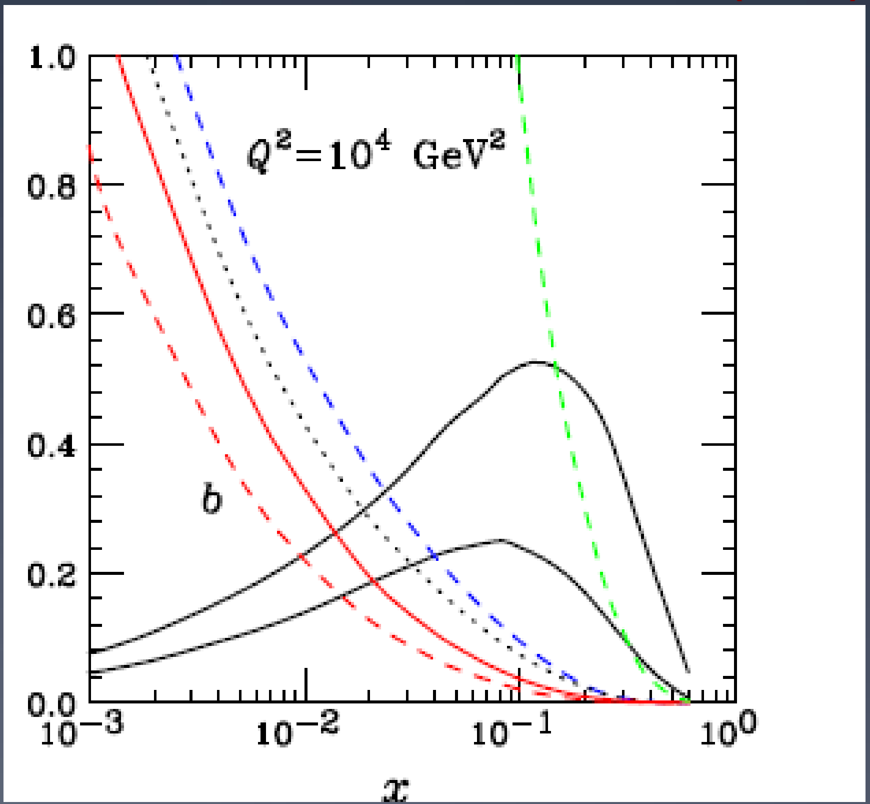
A few important facts

Collide partons (quarks & gluons): qg, qq', gg

Protons have substructure



Parton distribution Functions (PDF)



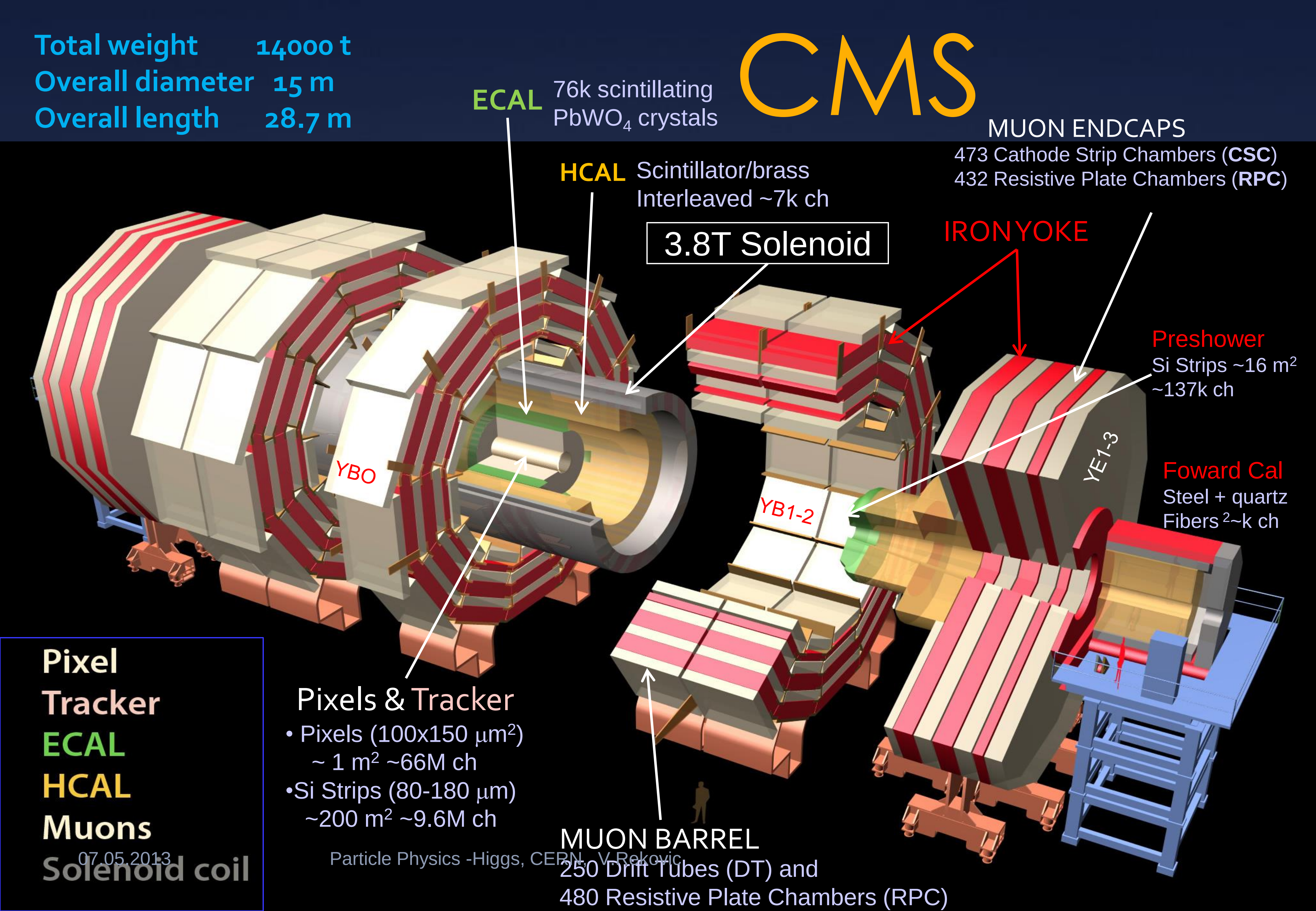
Gluons and quarks (which we collectively call partons) carry fractions x of proton momentum: given by parton distribution functions (PDFs)

To produce a mass of

	LHC	Tevatron
100 GeV:	x ≅ 0.007	0.05
5 TeV:	x ≅ 0.36	--

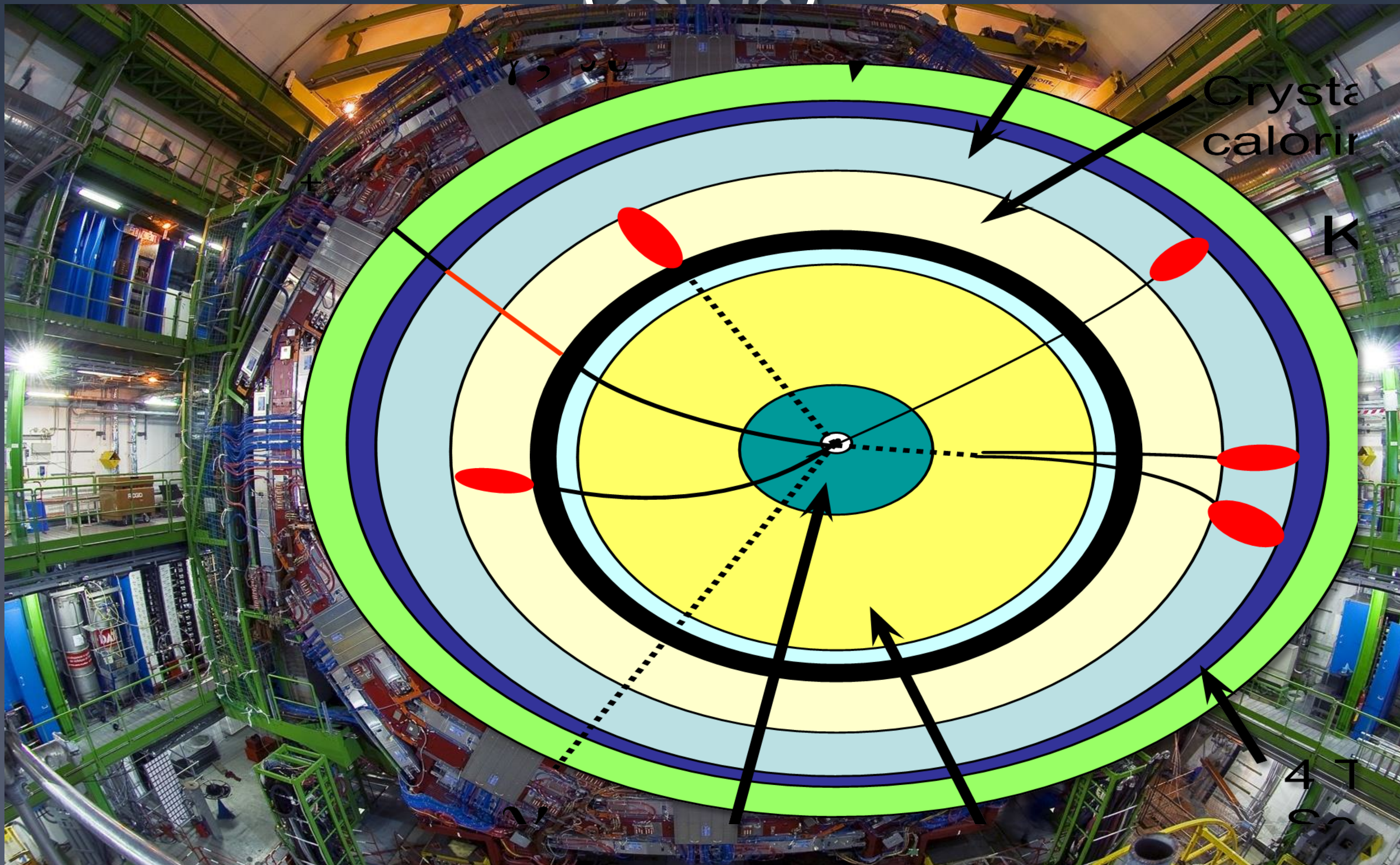
The Compact Muon Solenoid

CMS

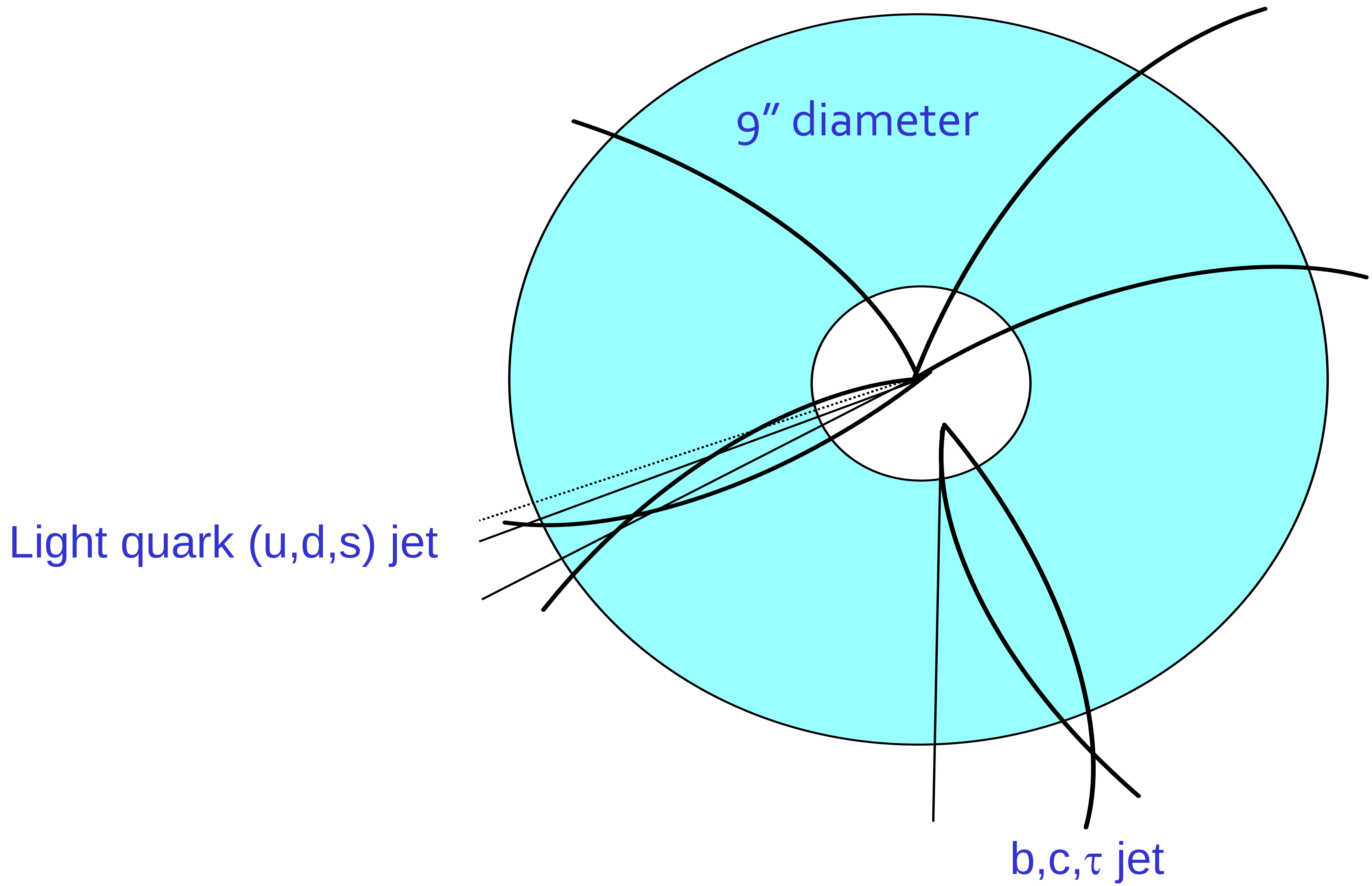

Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
CMS
ECAL
76k scintillating
$PbWO_4$ crystals
HCAL
Scintillator/brass
Interleaved ~7k ch
3.8T Solenoid
MUON ENDCAPS
473 Cathode Strip Chambers (**CSC**)
432 Resistive Plate Chambers (**RPC**)
IRON YOKE
Preshower
Si Strips ~16 m^2
~137k ch
Foward Cal
Steel + quartz
Fibers ^{2}~k ch
YBO
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 ~66M ch
•Si Strips (80-180 μm)
~200 m^2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

So how do we reconstruct what happened in the collision?

Compact Muon Solenoid (CMS)

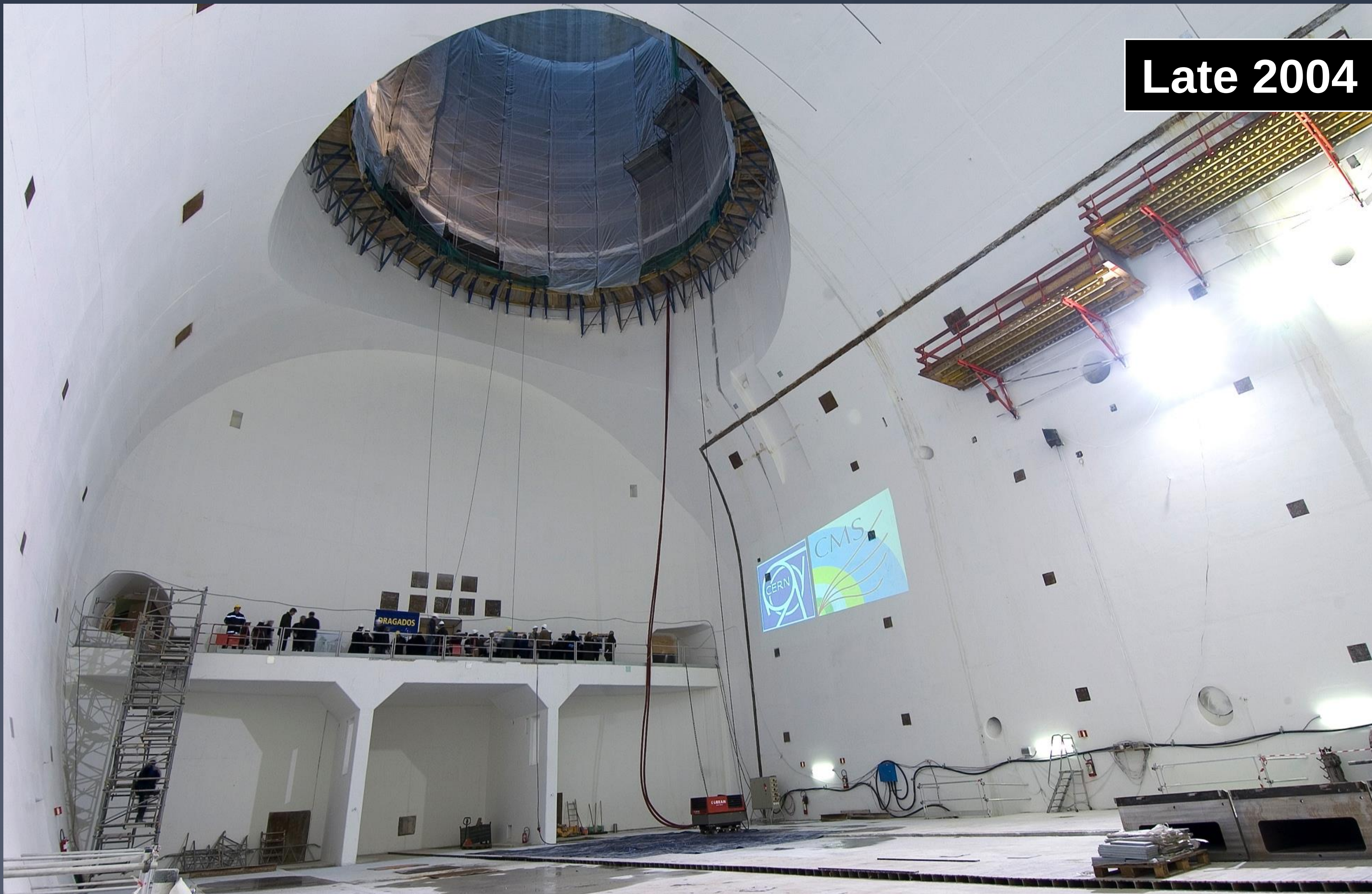


Micro-Vertexing with Pixels

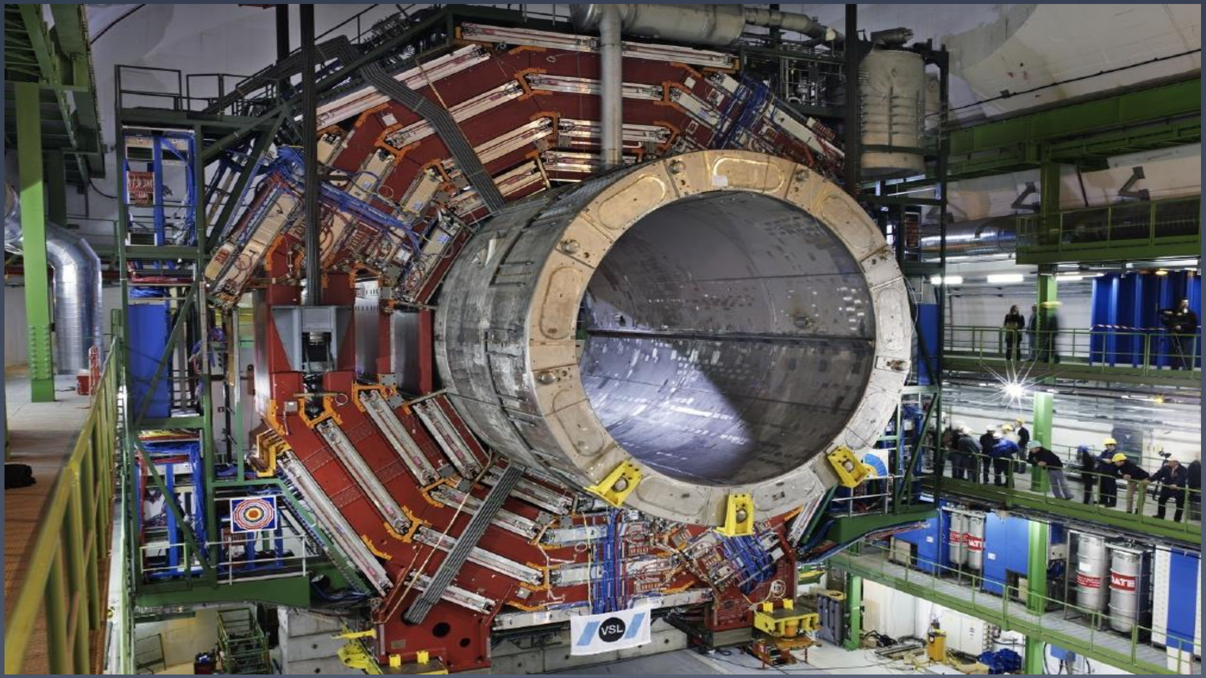


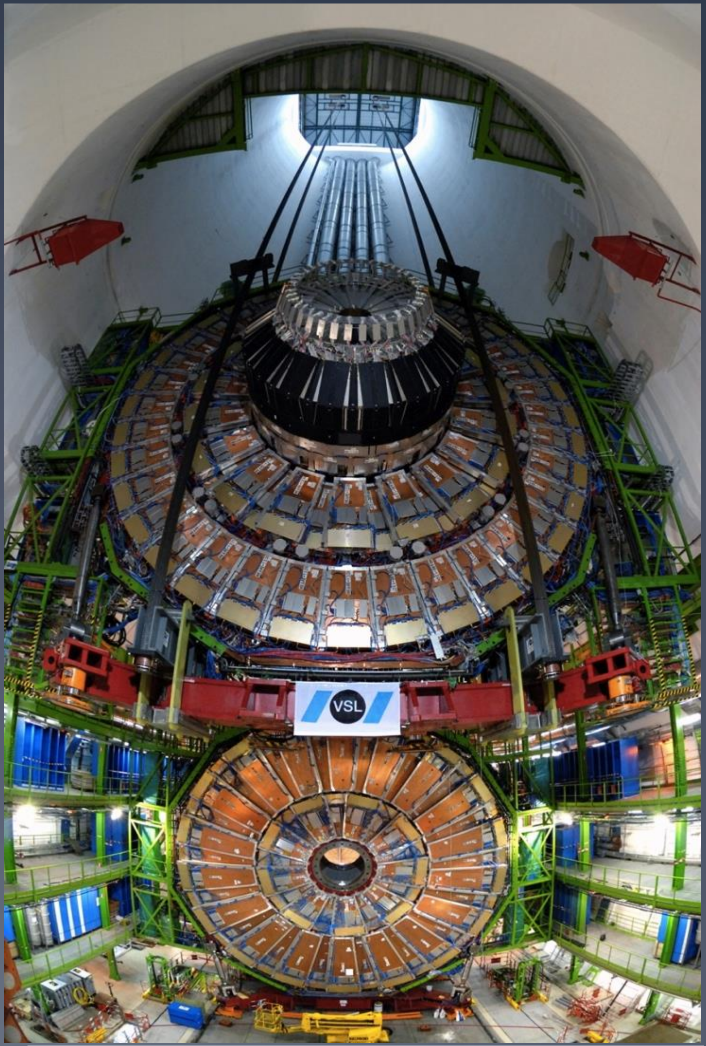
A tour of CMS during construction

Underground Experiment Cavern



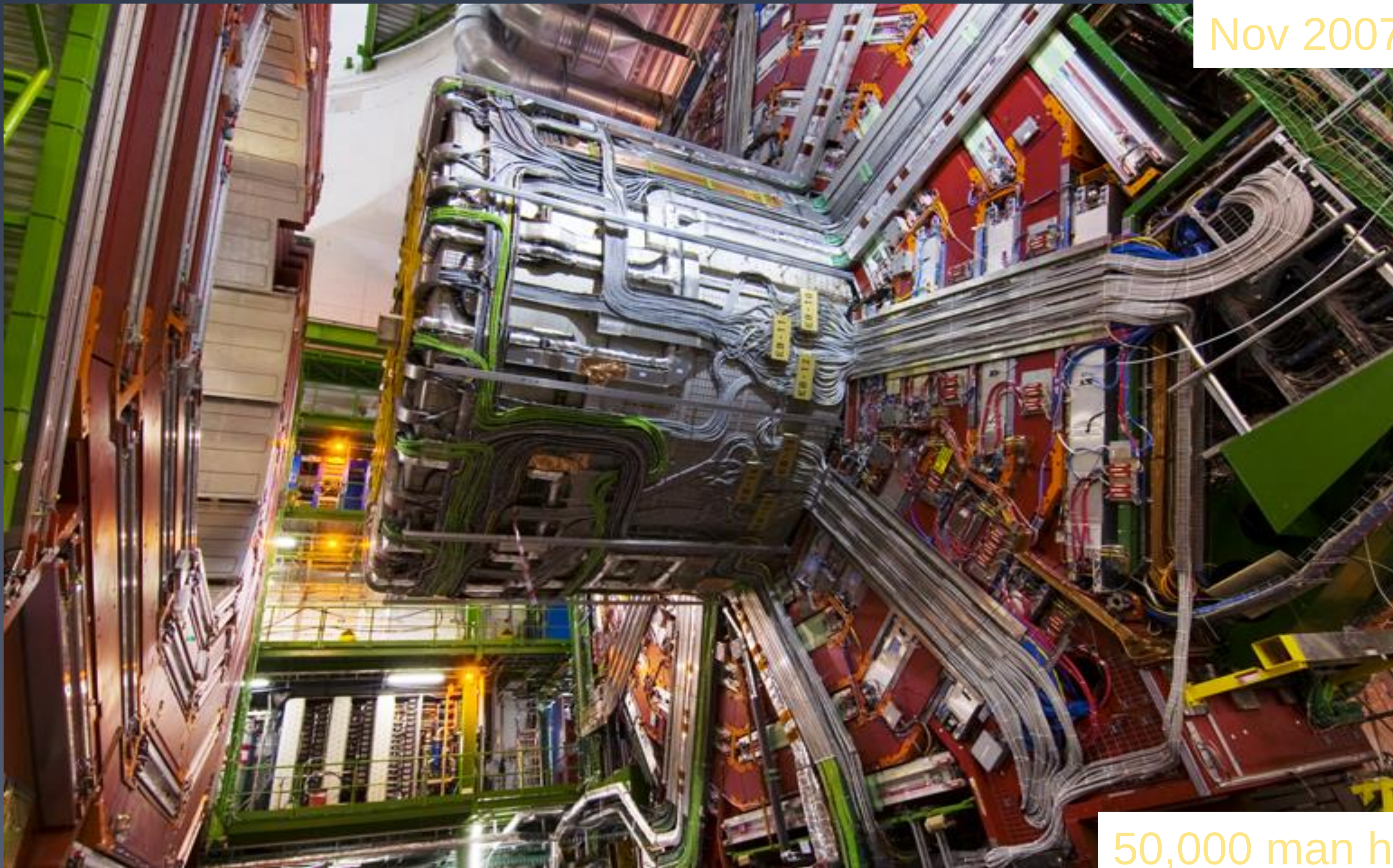
Lowering CMS sections ~30 stories





Lowering YE+1 (Jan'07)

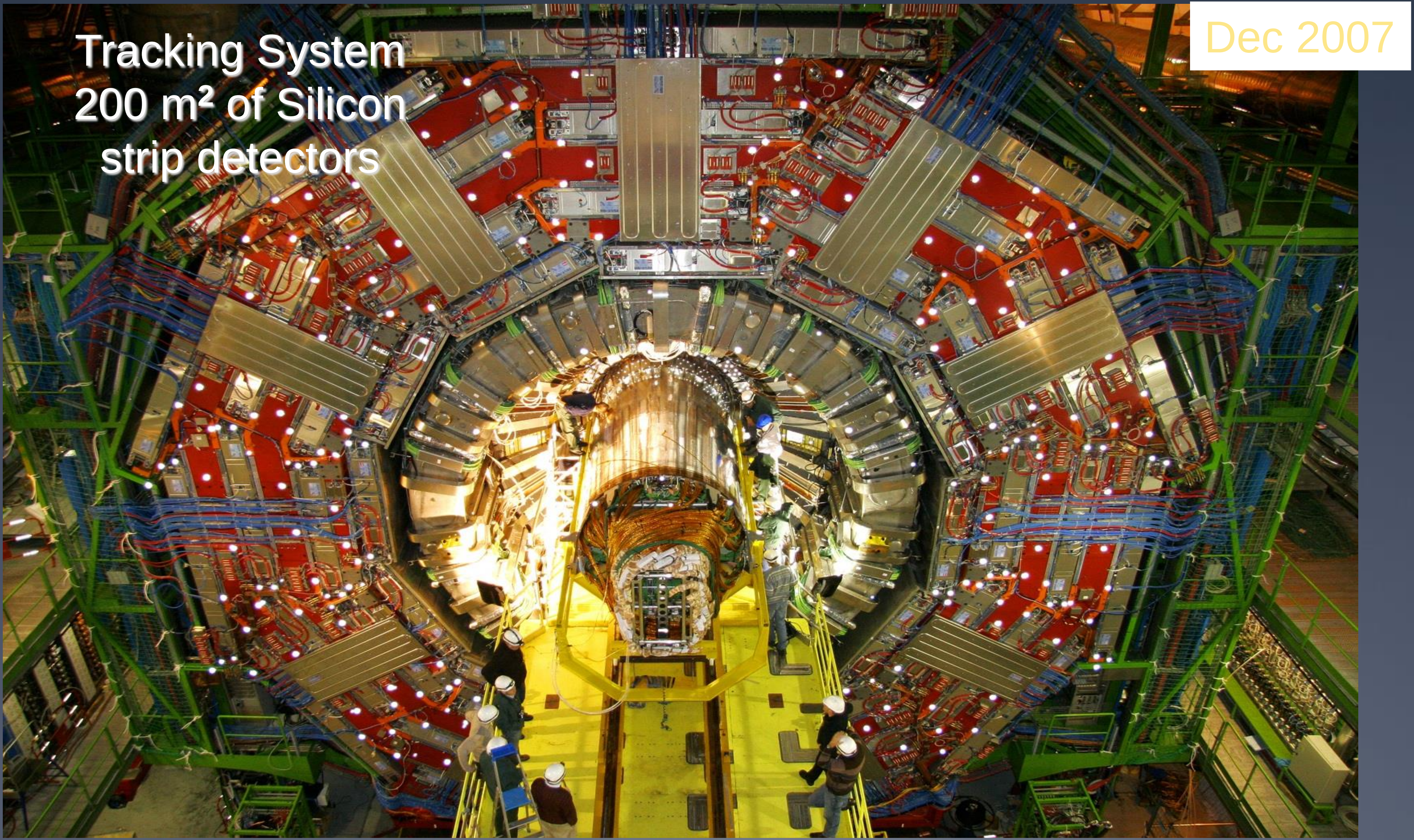
Cables, Pipes and Optical Fibres !



Nov 2007

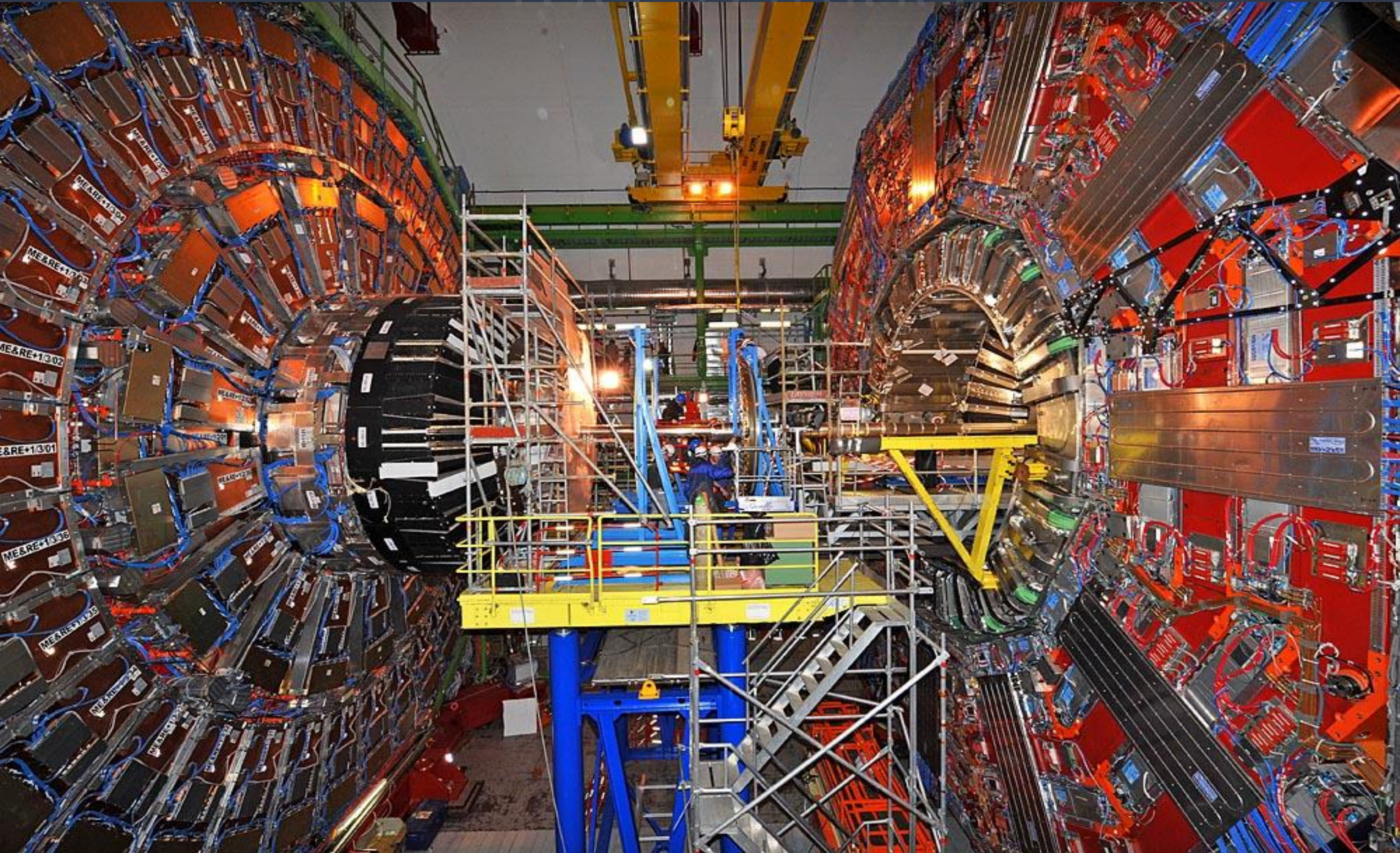
50,000 man hou

Insertion of Innermost Element



Endcap preShower (ES)

The setting



CMS Ready to Close

Quite a camera

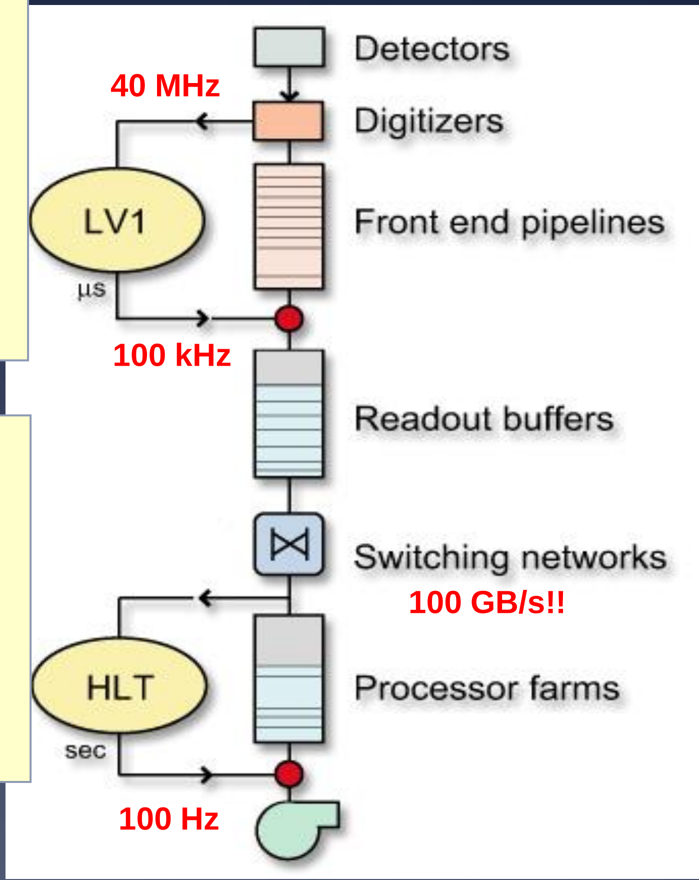
* CMS is like a camera with 80 Million pixels
* But it’s obviously no ordinary camera
  * It can take up to 40 million pictures per second
  * The pictures are 3 dimensional
  * And at 31 million pounds, it’s not very portable
* The problem is that we cannot store all the pictures we can take so we have to choose the good ones fast!

Experimental Challenges

* Collisions are frequent
  * Beams cross ~ 16.5 million times per second at present
  * About 20-30 pairs of protons collide each crossing
* Interesting collisions are rare -
  * less than 1 per 10 billion for some of the most interesting ones
* We can record only about 400 events per second.
* We must pick the good ones and decide fast!
* Decision ('trigger') levels
  * A first analysis is done in a few millionths of a second and temporarily holds 100,000 pictures of the 16,500,000
  * A final analysis takes ~ 0.1 second and we use ~10000 computers
* We still end up with lots of data

Trigger Architecture

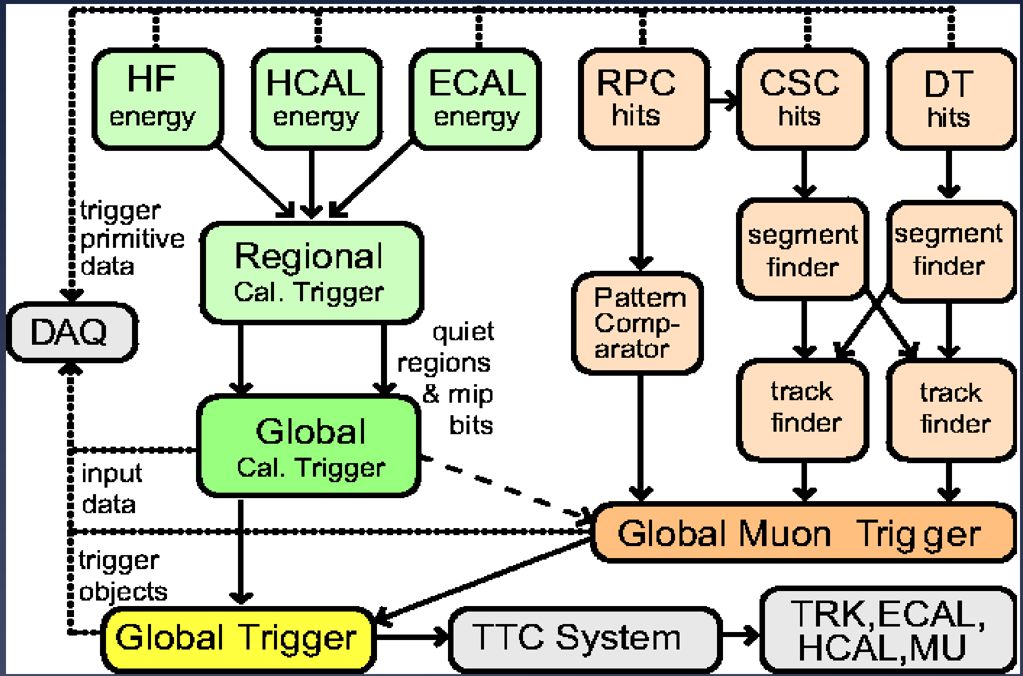
- Start from 40 MHz → Decision every 25 ns
  - Too small even to read raw data
  - Selection in multiple levels, each taking a decision using only part of the available data
- The first level (L1) is only feasible with dedicated, synchronous (clock driven) hardware



- CMS choice: All further selection in a single phisical step (HLT)
  - Build full events and analyze them “as in offline”
  - Invest in networking (rather than in dedicated L2 hardware)

Level-1 Trigger

* Custom programmable processors
  * To minimise latency
* Synchronous decision every 25 ns
  * delayed by 3.2 μs = 128 BX
    (Max depth of pipeline memories)
* Max output ≡ max DAQ input
  * Design: 100 kHz; at startup: 50 kHz
* Only μ detectors and calorimeters
  * e/γ, μ, τ jets, jets, E_T^{miss}, ΣE_T



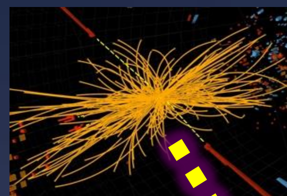
* Selection by the "Global Trigger"
  – 128 simultaneous, programmable algorithms, each allowing:
    * Thresholds on single and multiple objects of different type
    * Correlations, topological conditions
    * Prescaling

HLT

- Run on farm of commercial CPUs: a single processor analyzes one event at a time and comes up with a decision
- Has access to full granularity information
- Freedom to implement sophisticated reconstruction algorithms, complex selection requirements, exclusive triggers…

Constraints:

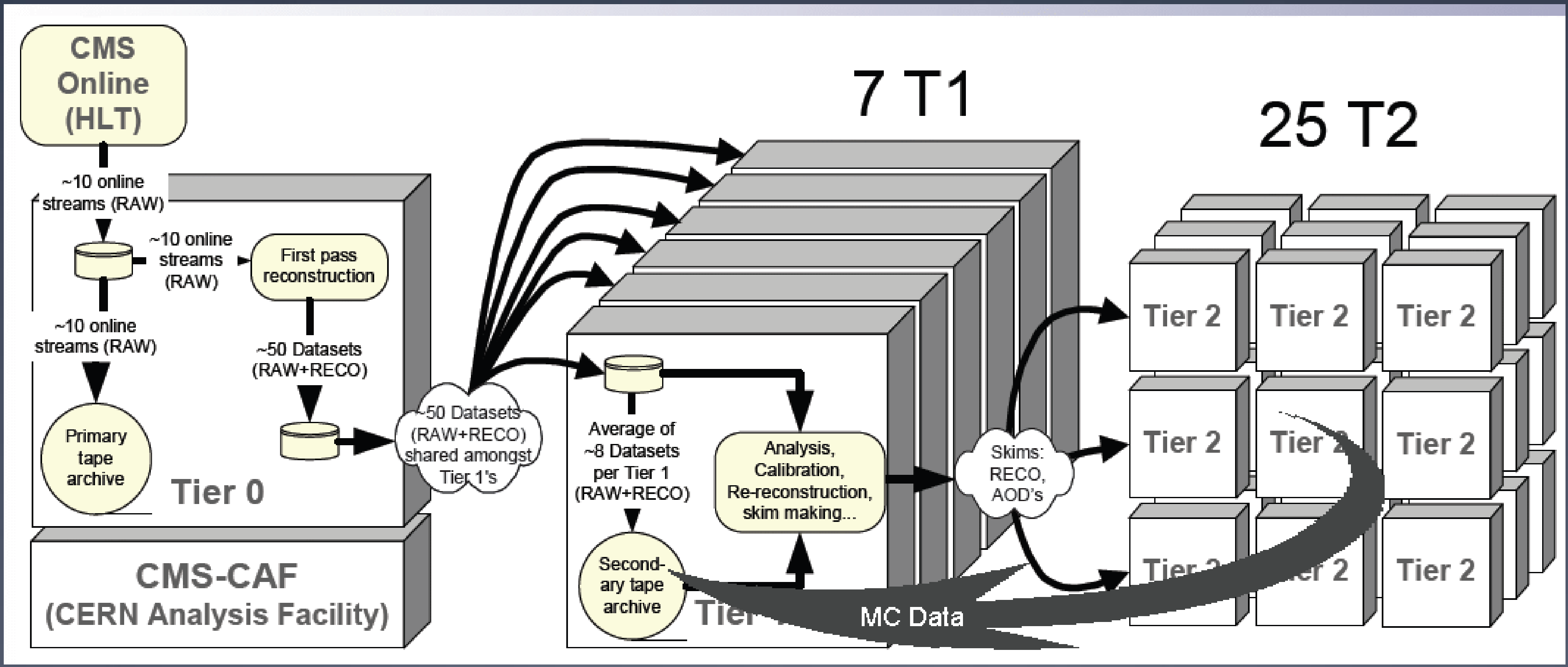
- CPU time (Cost of filter farm)
  - Reject events ASAP: set up internal "logical" selection steps
    - L2: muon+ calorimeter only
    - L3: use full information including tracking
- Must be able to measure efficiency from data
  - Define HLT selection paths from the L1
- Keep output rate limited (400 events/sec with 1MB/event)



Collision event data

- **LHC produces 100 million GigaBytes of data per year (equivalent to > 5 million DVDs)**

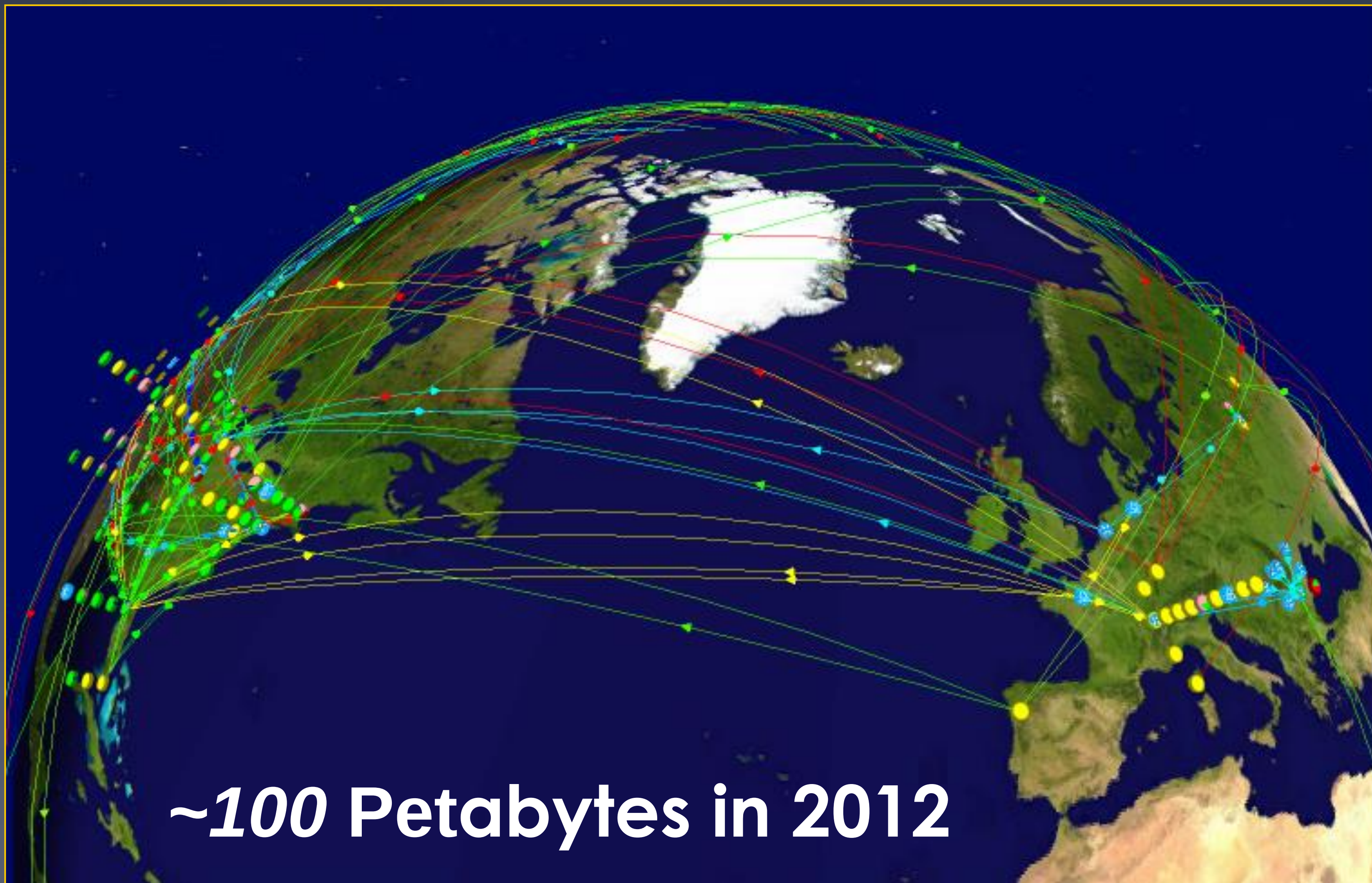
Tier data structure




Map
CERN
Canada
Iceland
Finland
Sweden
Norway
Russia
Ukraine
Mongolia
China
Japan
Korea
North Atlantic Ocean
Algeria
Libya
Egypt
Iraq
Iran
Afghanistan
Saudi Arabia
India
Thailand
Mauritania
Mali
Niger
Chad
Sudan
Nigeria
Ethiopia
Venezuela
Colombia
Brazil
Perú
Bolivia
Chile
DR Congo
Kenya
Tanzania
Angola
Namibia
Botswana
Madagascar
Indian Ocean
Indonesia
Papua New Guinea
Australia
South Atlantic Ocean
South Africa

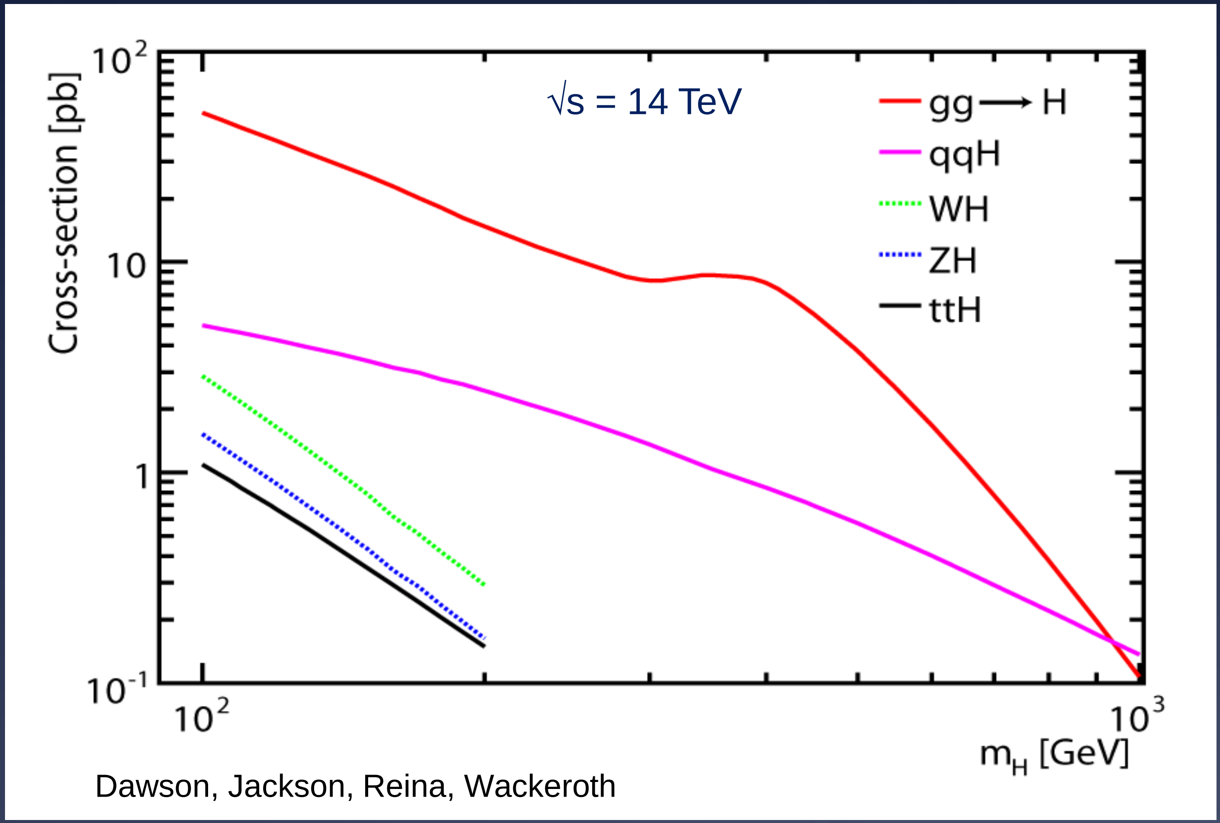
Data distribution

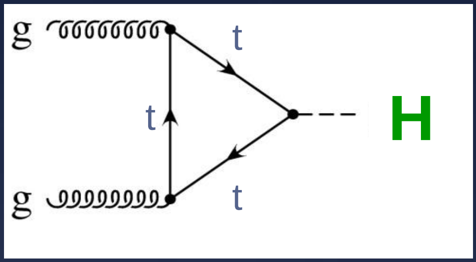
- Grid connects >100,000 processors in 34 countries



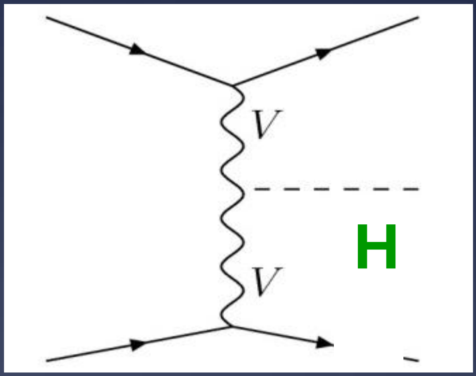
Higgs Searches at LHC

LHC SM Higgs production

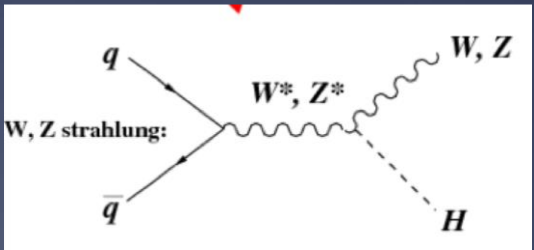




Gluon fusion



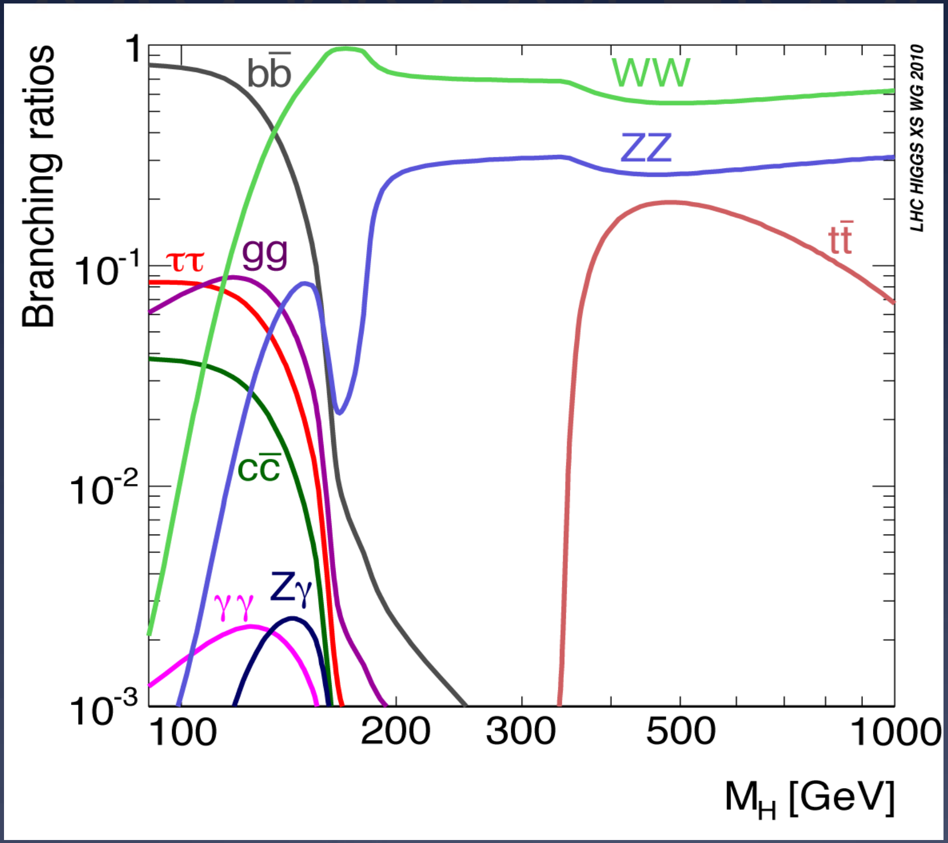
Vector Boson fusion



Associated production

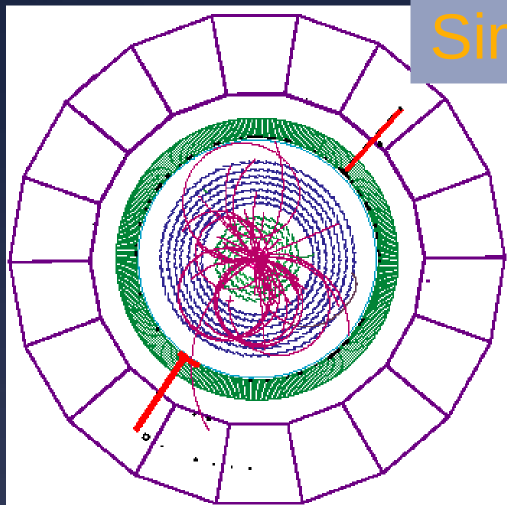
- Two processes
  - Gluon fusion is dominant for the entire m_H range
  - Vector boson fusion is the next most important
- Production rate goes down with higher mass
  - But backgrounds ("noise") also go down so it gets easier in many cases

Standard Model Higgs Decays

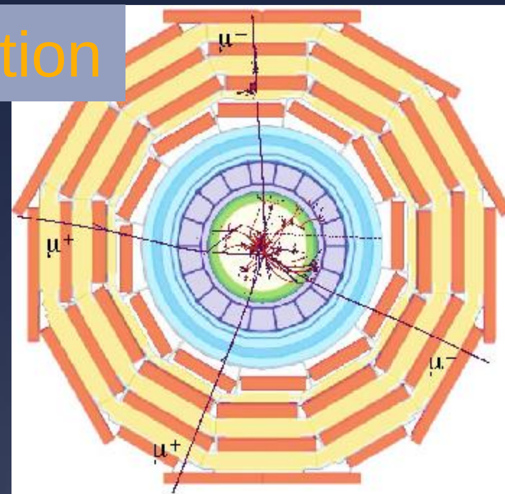


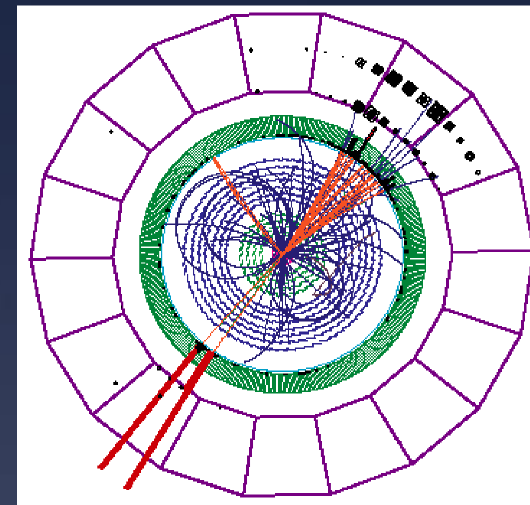
* The SM Higgs is unstable
  * Decays "instantly" in a number of ways with very well known probabilities (called Branching Fractions or Ratios that sum up to 1).
  * Branching ratios change with mass as seen here
  * Some decay modes are more easily seen than others
    * Firstly if they end with electrons, muons, or photons

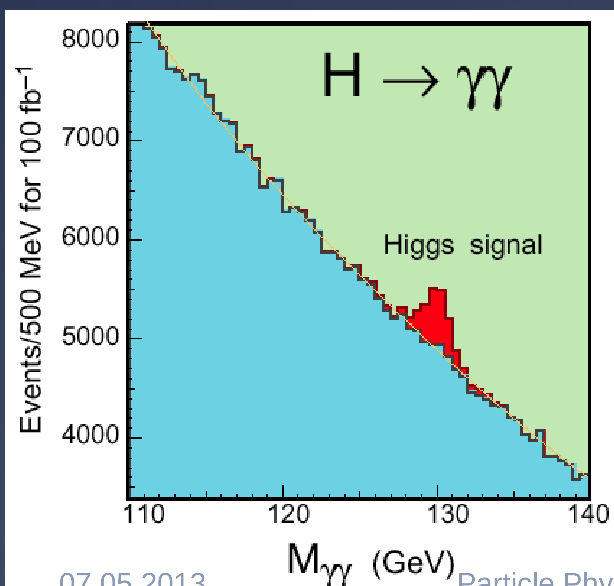
How would we see the Higgs Boson ?

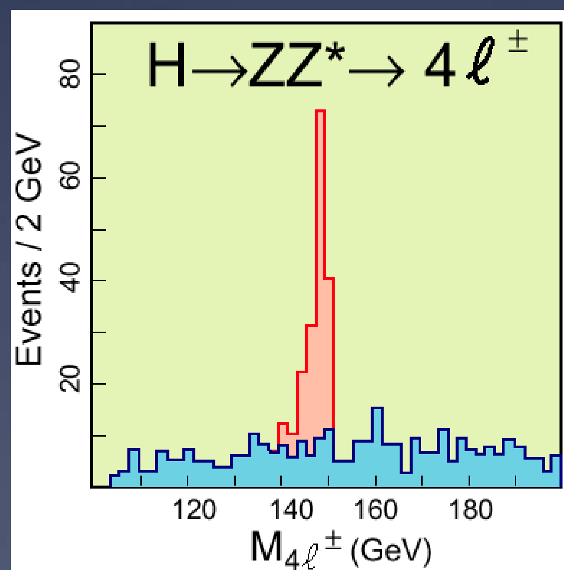


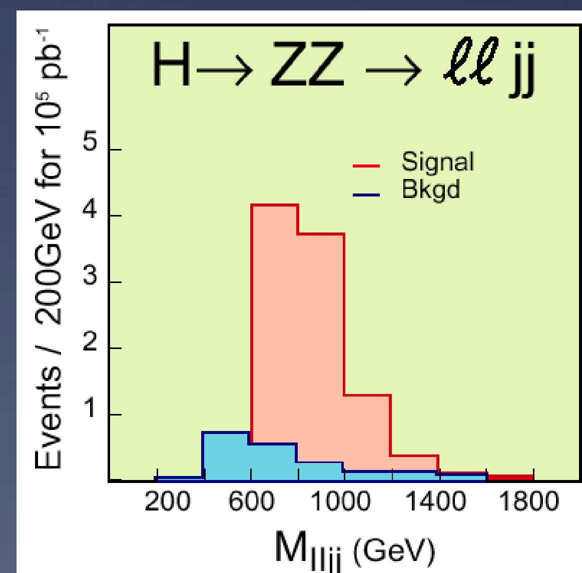
Simulation









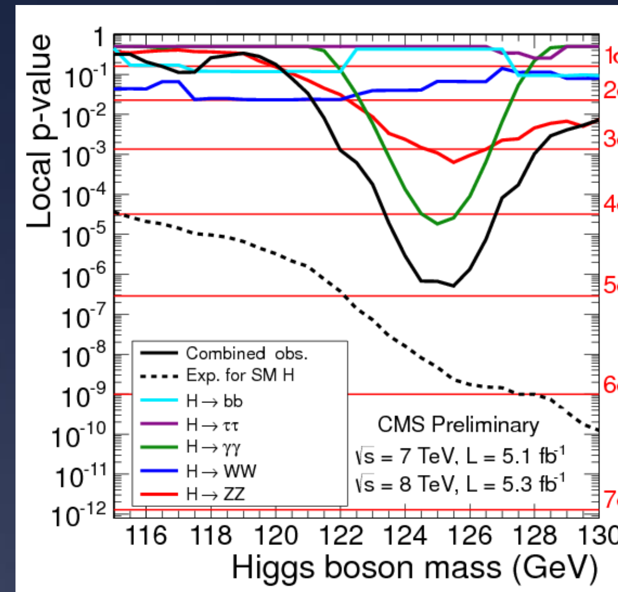


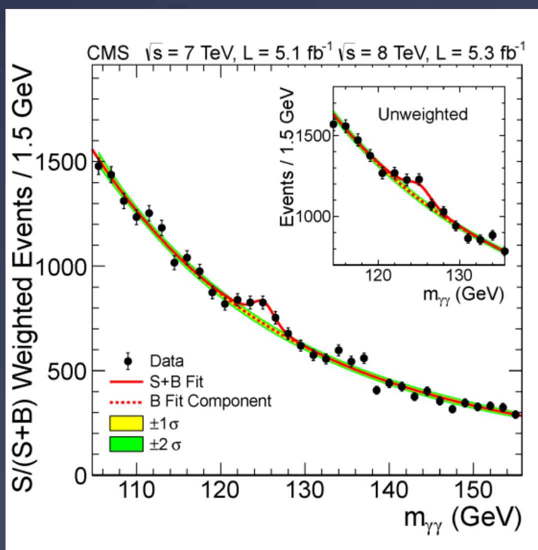
NB: These old plots correspond to ~50 times more sensitivity than we have now (20x more data, 2x the energy)!

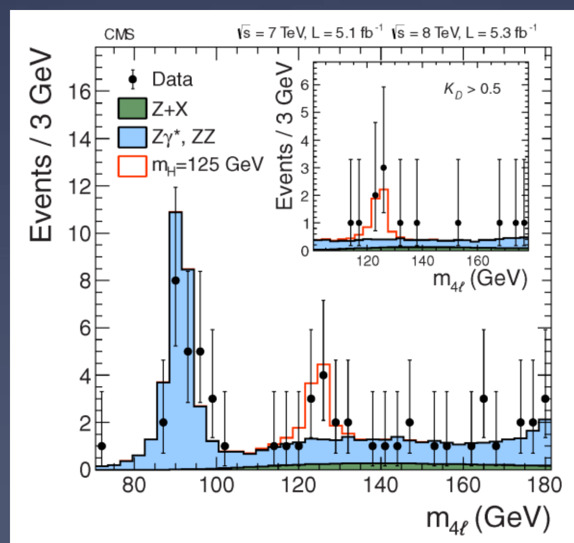
July4th 2012 Higgs-like boson at LHC

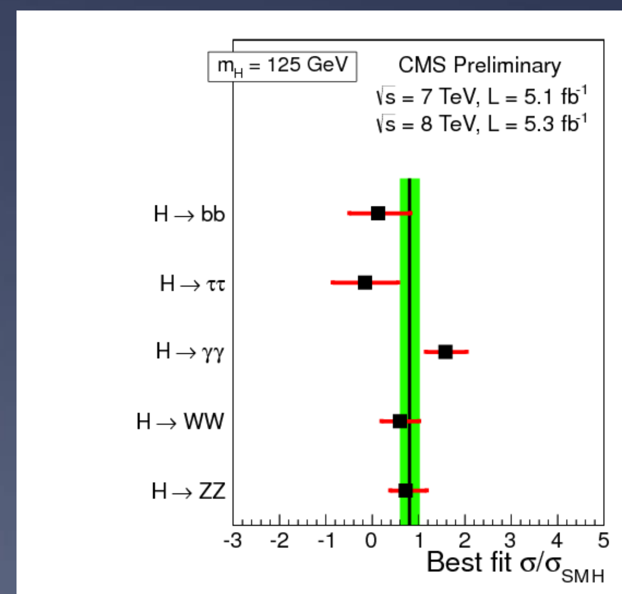
- An excess of events above the expected SM background is observed at mass

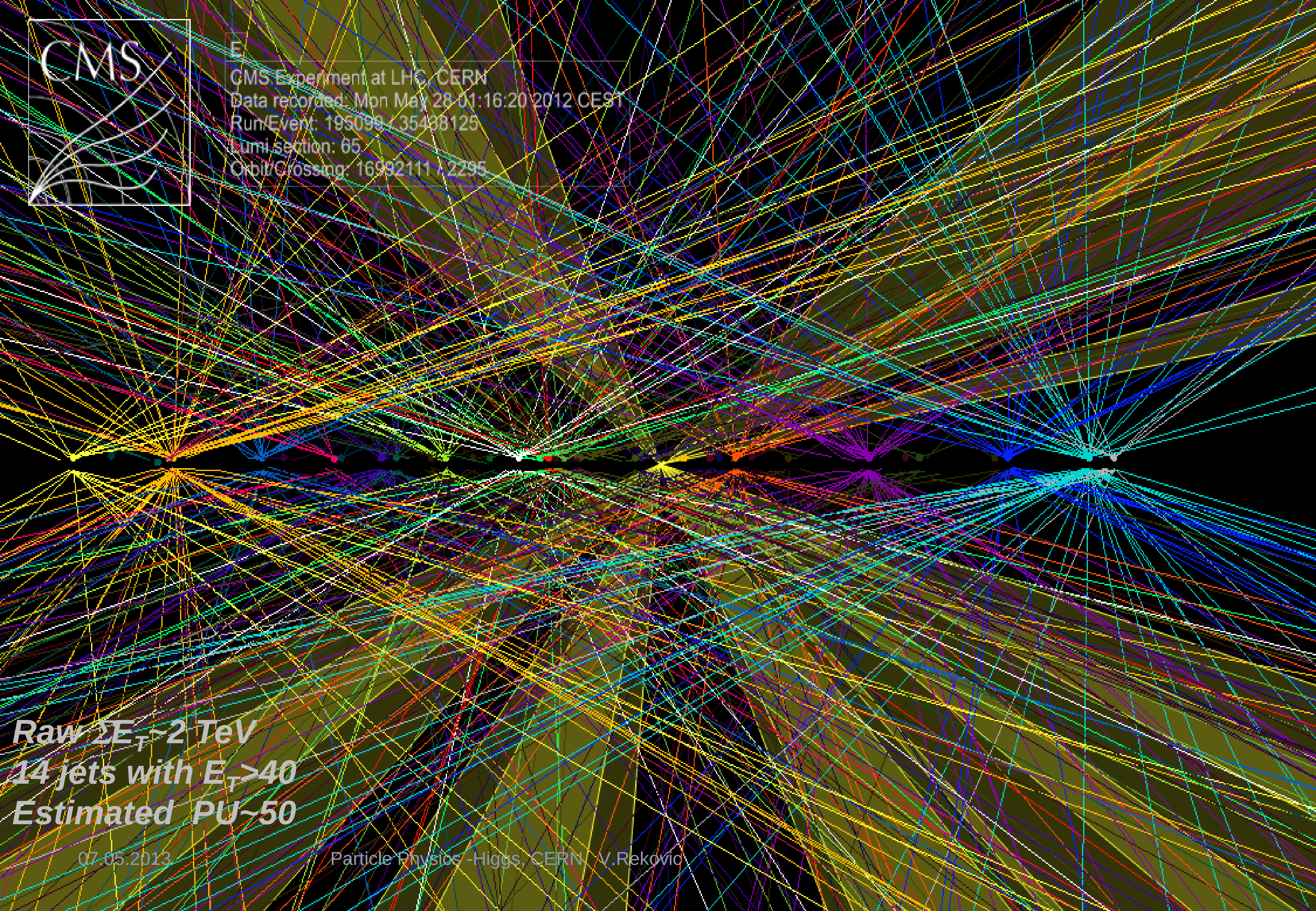
  125.3 ± 0.4 (stat) ± 0.5 (syst) GeV.
- The evidence is strongest in the two final states with the best mass resolution:
  - H→γγ
  - H→ ZZ → 4l
  - Combined with a local significance of 5.1σ









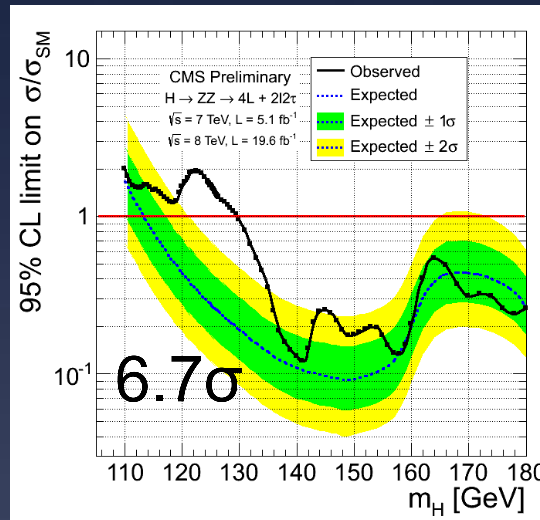

CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
Raw ΣE_T~2 TeV
14 jets with E_T>40
Estimated PU~50

2012/13 was a busy year for Higgs

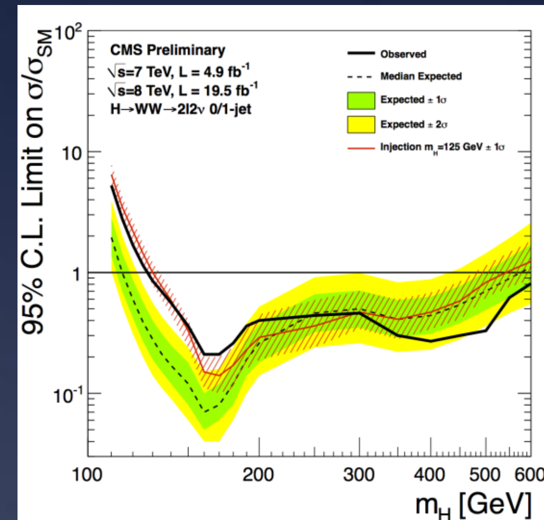
γγ Moriond 13

This talk !

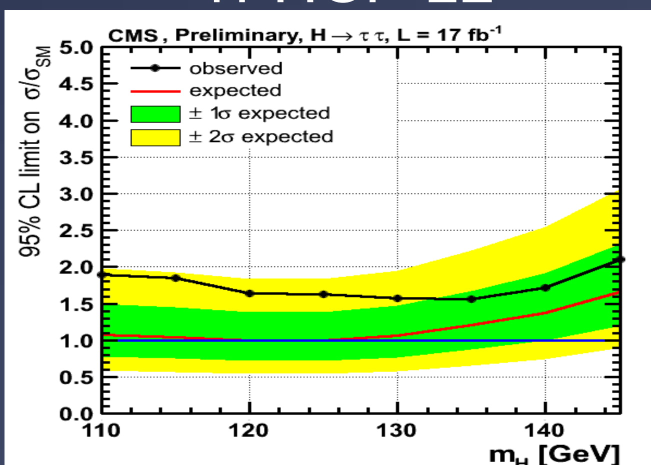
ZZ Moriond 13



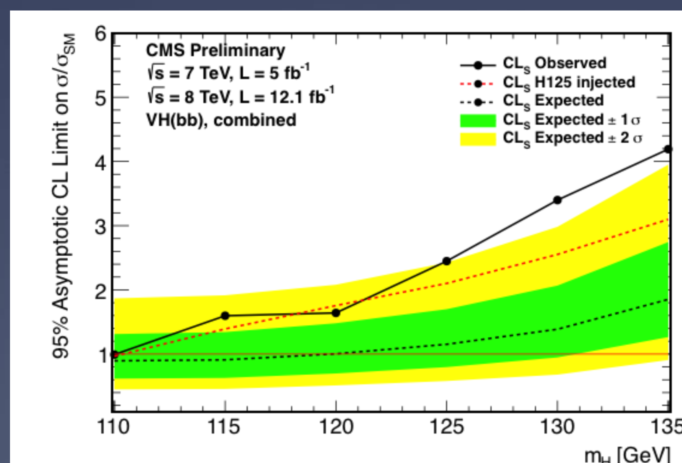
WW Moriond 13



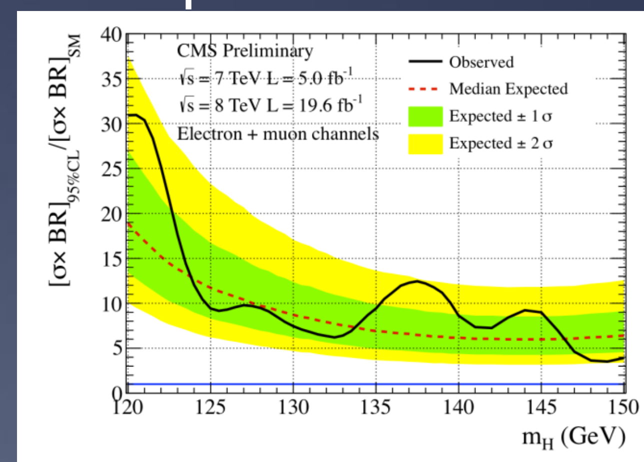
ττ HCP 12



bb HCP 12

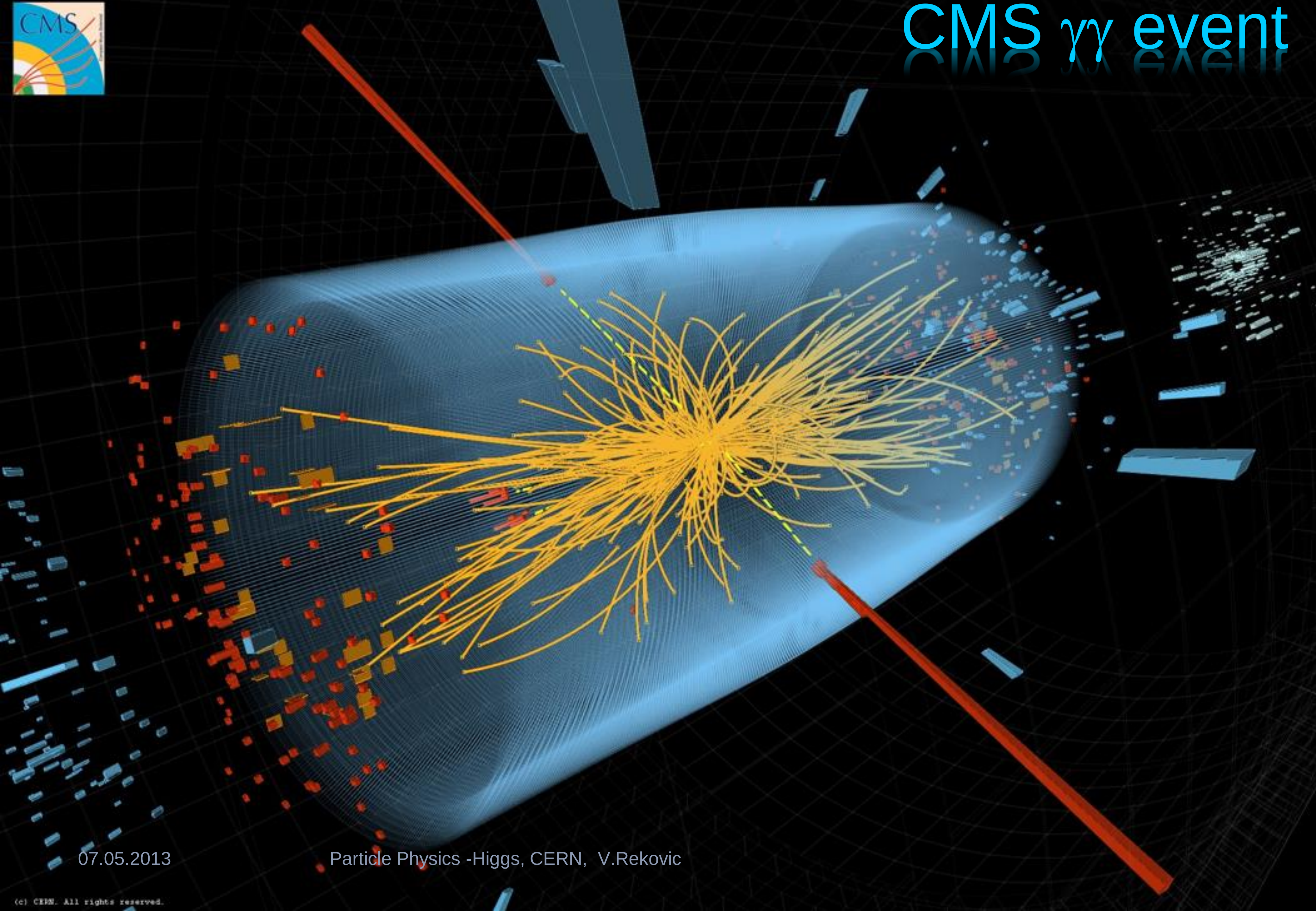


Zγ Moriond 13



H → γγ

CMS $\gamma\gamma$ event



$H \rightarrow \gamma\gamma$ history (I)

7 TeV, 2011, 5.3 fb^{-1}

Re-RECO

2.8σ
March 2012

H→γγ history (II)

7 TeV, 2011, 5.3 fb^{-1} 8 TeV, 2012, 5.1 fb^{-1}

Re-RECO

Run A+B
Prompt RECO

4.2σ
July 2012

H→γγ history (III)

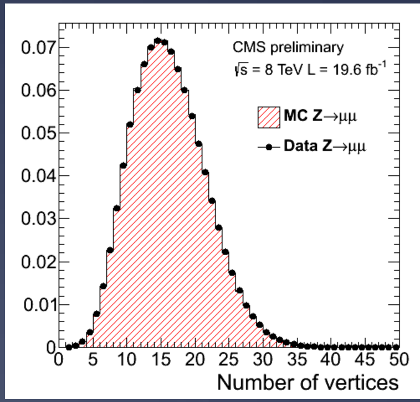
7 TeV, 2011, 5.3 fb^{-1}

8 TeV, 2012, 19.6 fb^{-1}

Re-RECO	Run A+B Re-RECO	Run C Prompt Reco	Run D Prompt Reco

Today: Preliminary results, Moriond 13

* Results with MVA and Cut-in-Categories analysis on 7+8 TeV data. All MC samples re-weighted to the observed pileup distribution in the full 2012 dataset. <NPU>=19.9



* Note: MVA algorithm used not retrained for Run D. Dark current noise in data from irradiated APD's not simulated in MC.

Final results on full 7+8 TeV will be provided later this year w/ final calibrations for Run C+D.

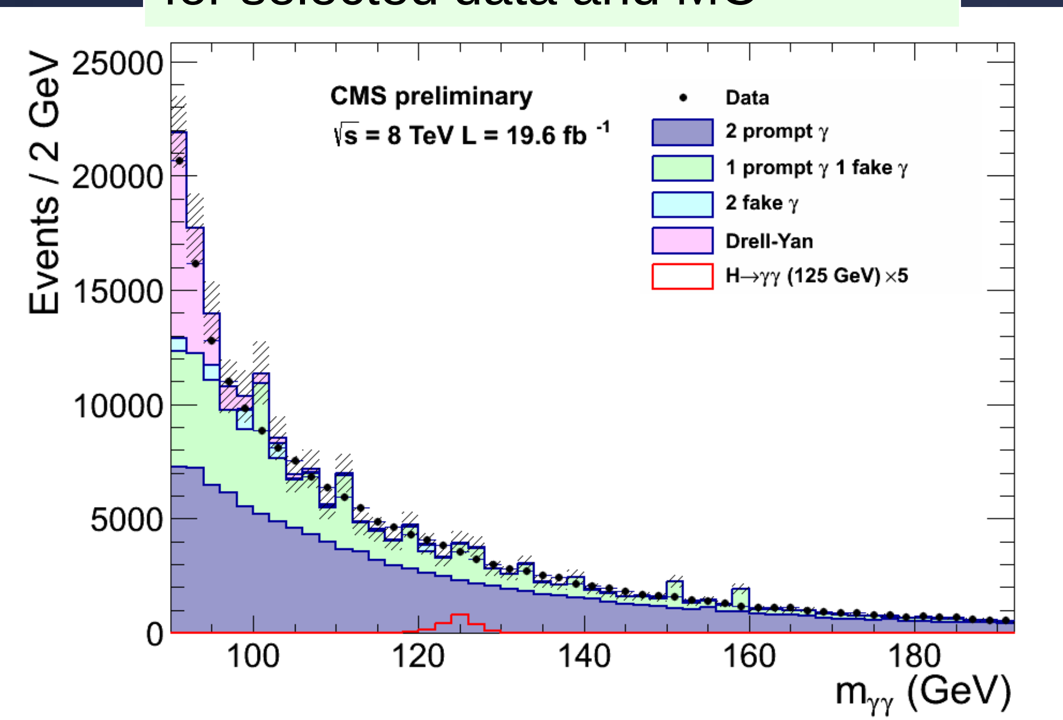
H→γγ search

- Idea: reconstruct di-photon mass and search for a resonance on the smooth background
- Need to measure energy of the two photons and their opening angle
  - Sounds simple. What is the big deal ?!

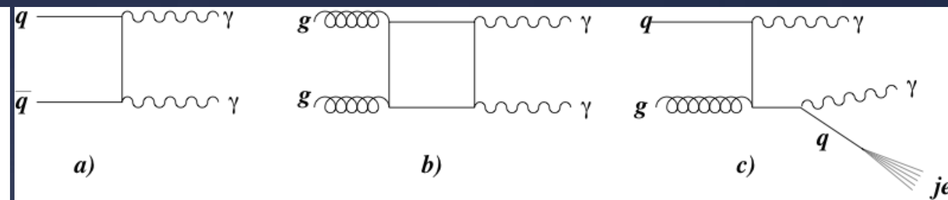
The challenge

* Huge “irreducible” background from QCD di-photon production, plus “reducible” instrumental backgrounds.

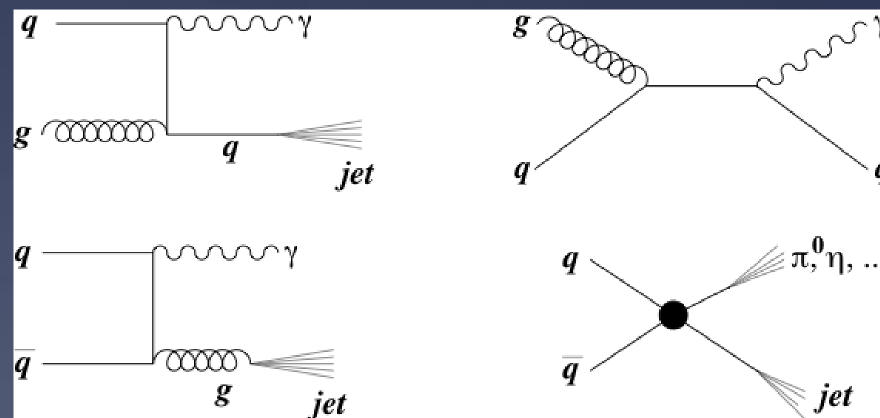
Inclusive inv. mass distribution for selected data and MC



Irreducible



Reducible

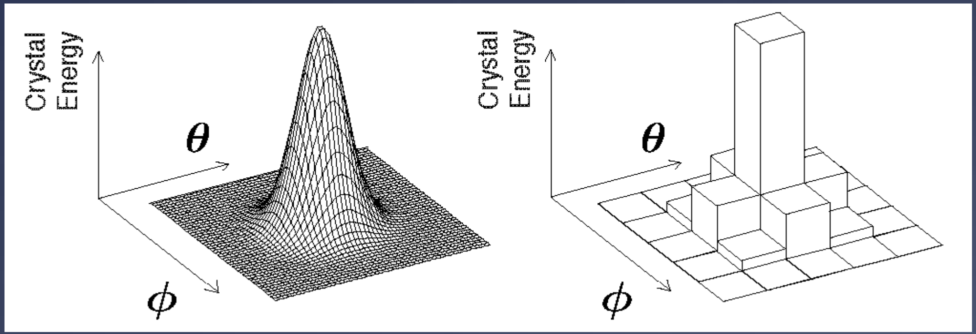


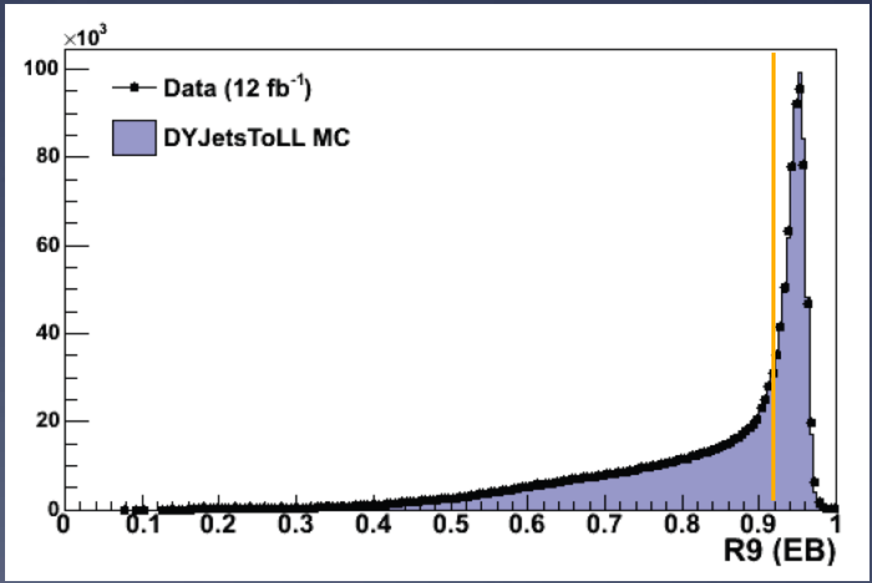
* **Natural thing to do is separate events in categories according to resolution to optimize the sensitivity.**

Photon shower shape, R9

- For some photons, ECAL does a fairly good job at identifying EM clusters on it's own – and does this local to the supercluster
  - These photons are self-selecting + a loose H/E

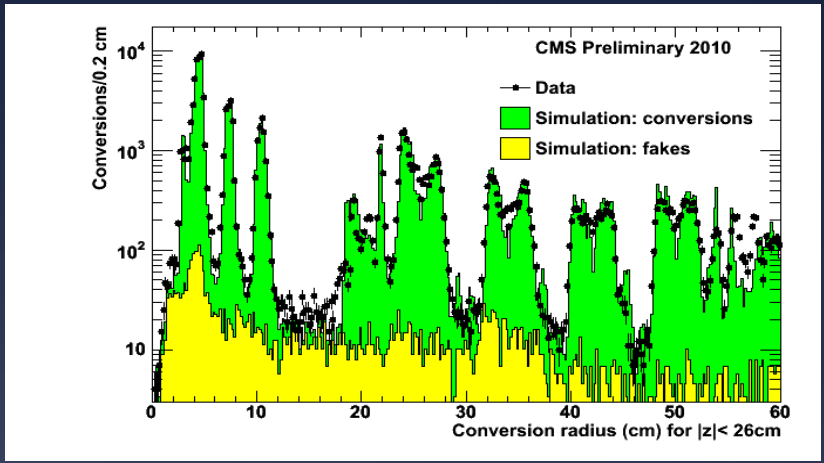
R9 = e3x3/e(supercluster)

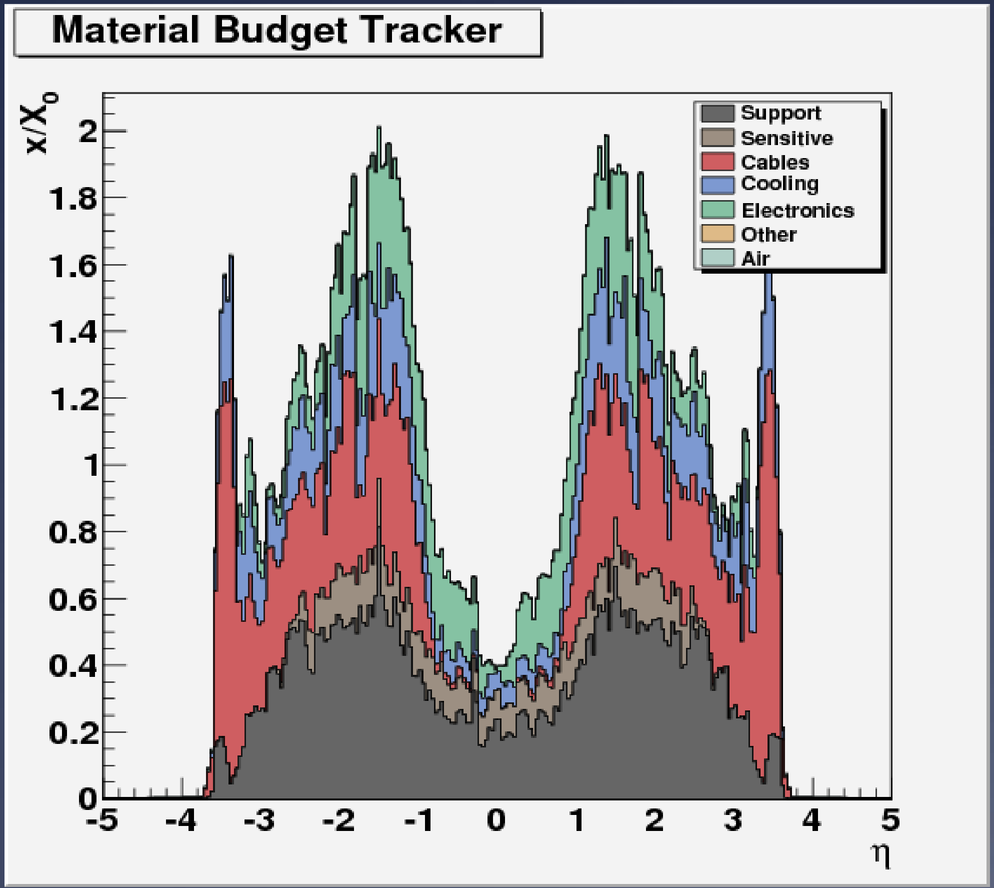


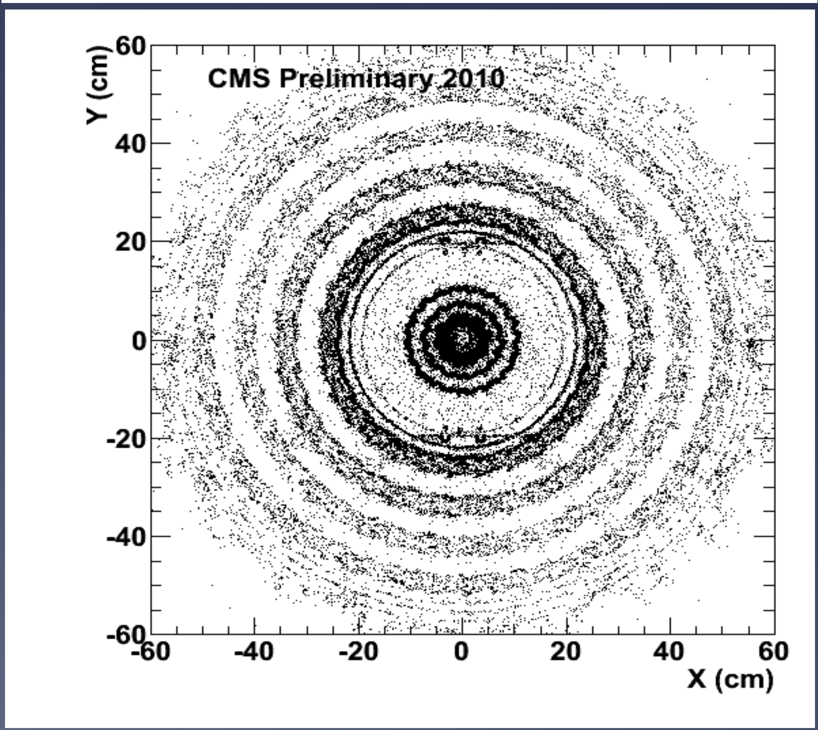


Tracker Material

* Reasonably well described by simulation
* Degrades energy resolution

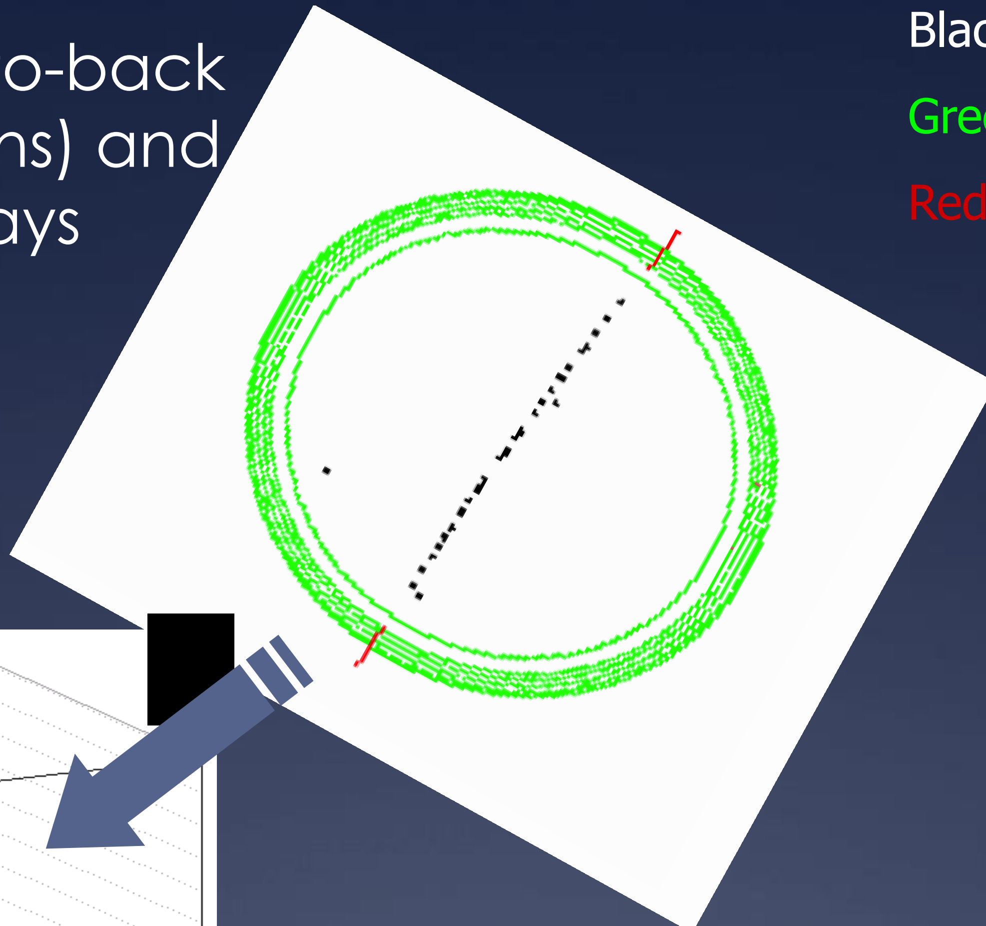






What Material Does to Photons

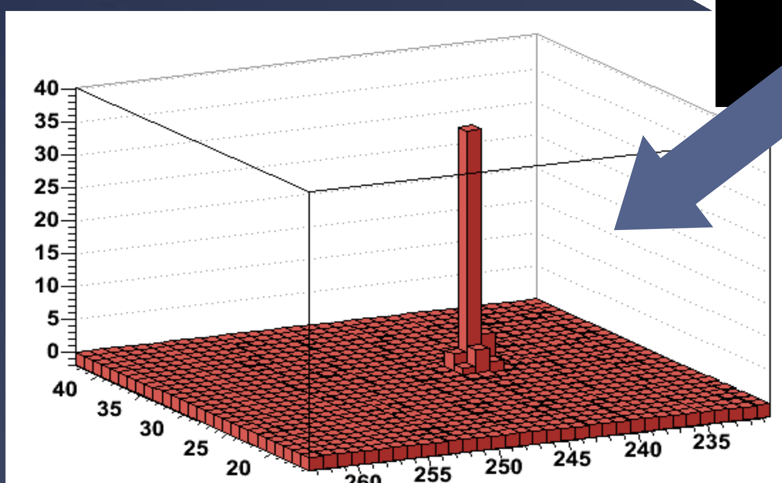
- Generate back-to-back electrons (photons) and scan event displays



Black: hits in tracker

Green: ECAL outline

Red: E_T of ECAL cells



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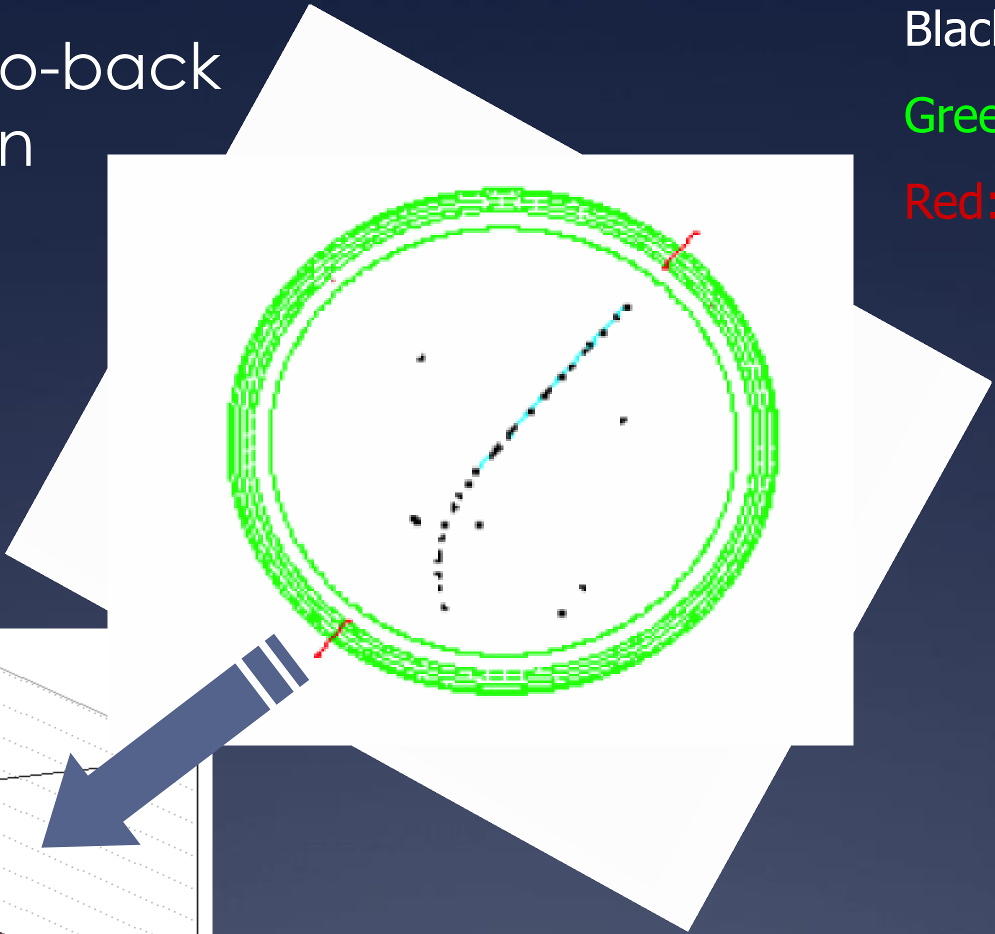

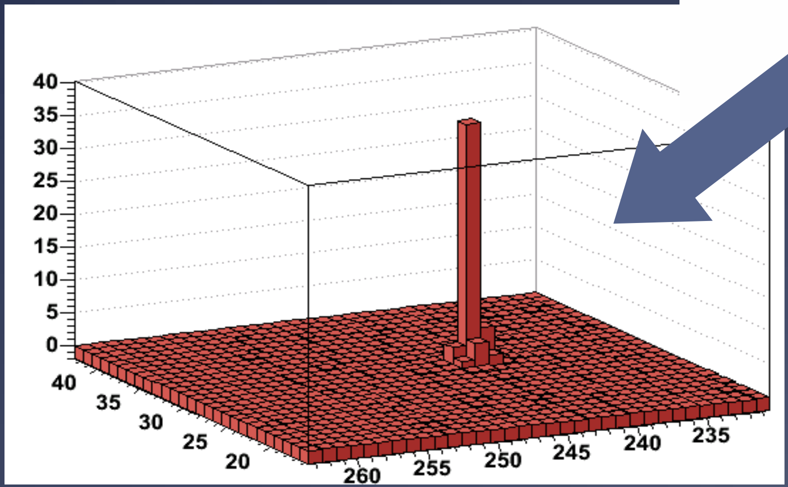

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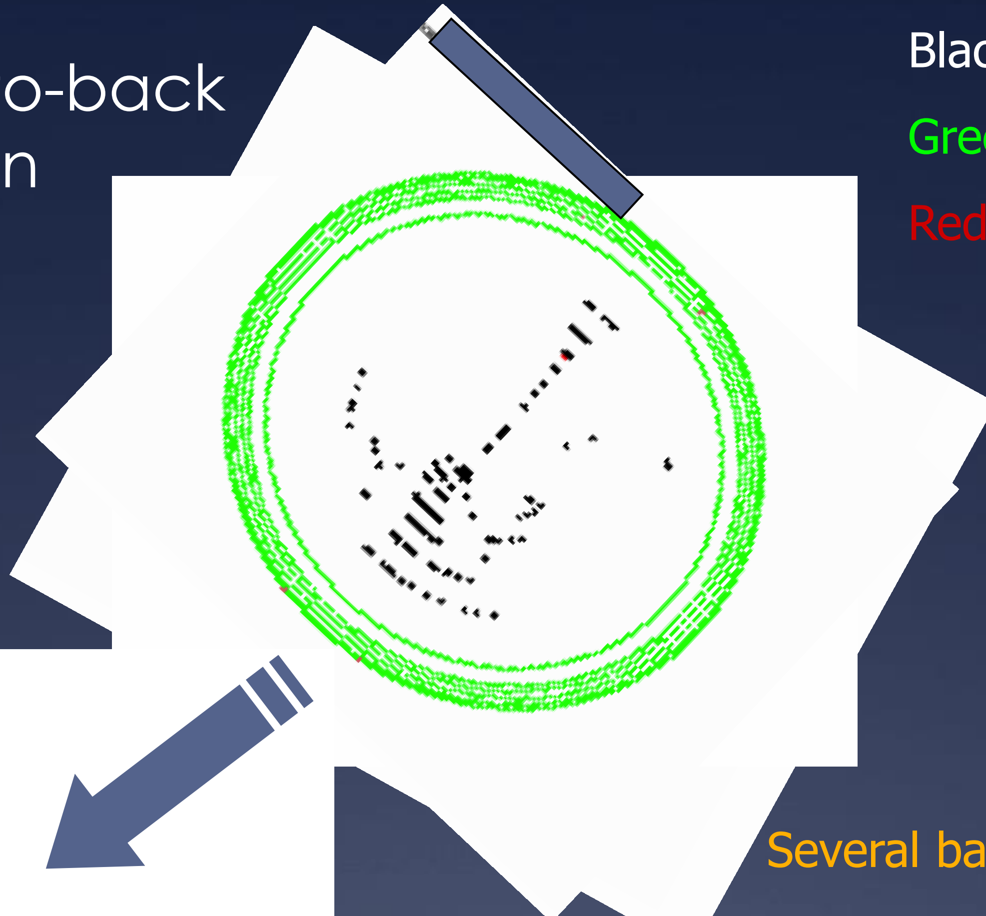

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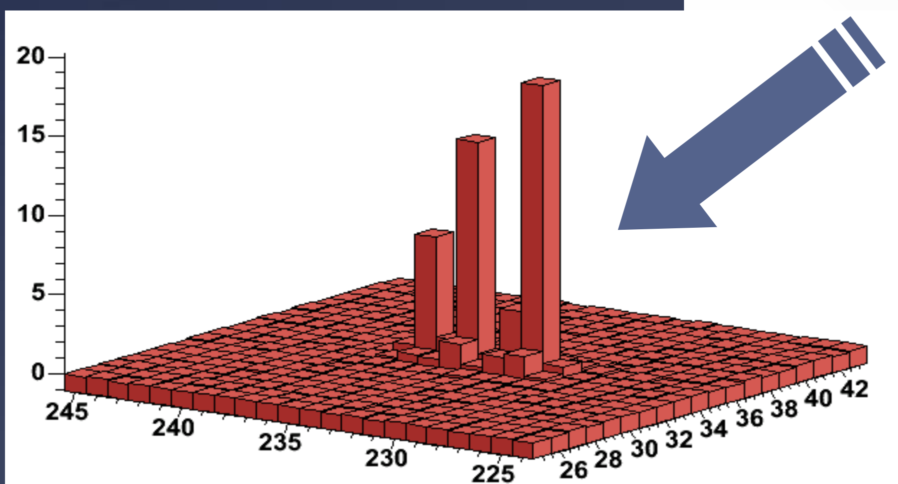


Several bad effects at once:

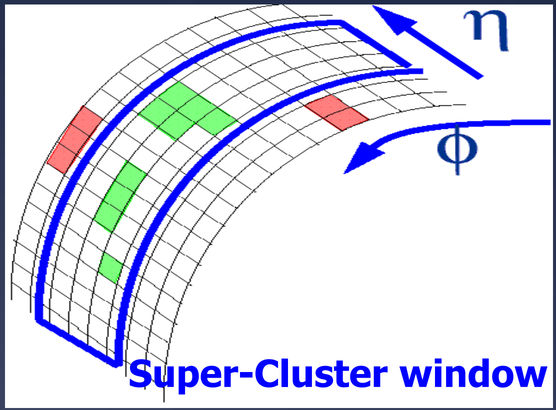
- hard to identify (showers not narrow in azimuth)
- energy resolution has tails due to not clustered energy
- some energy never reaches ECAL (B = 4 Tesla!)

Photon recovery

* Some of the shower can be recovered by making clusters wide in azimuth, but with a cost of picking up energy from UE

→ Q: How to tell which photons have showered and need “recovery”?

→ Q: How to make optimal correction given the detector region and all reconstructed pieces of the photon?



H→γγ search

1) Correct energy (MVA)

1.1) Estimate per photon energy resolution (MVA)

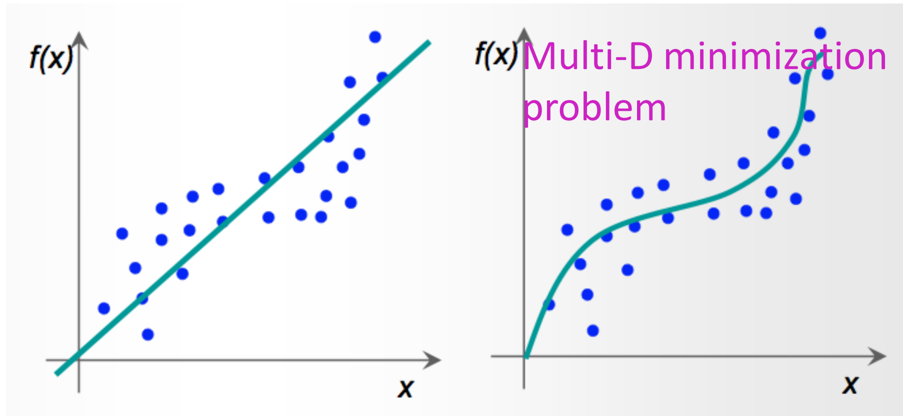
2) Identify vertex (MVA)

2.1) Estimate probability that the correct vertex was identified (MVA)

- **CiC analysis** uses 1) and 2) and categorizes events in **topology (η-R9).**
- **MVA analysis** uses 1) and 2) and
  1.1 + 2.1 + event kinematics are used to build **event MVA** for categorization.

Photon energy corrections

- ECAL cluster energies corrected using an MC trained multivariate regression.
  - Very non-trivial correlations between measured photon properties and the corrections that one needs to apply
  - Inputs
    - Impact point in the calorimeter
    - Whether the photon converted
    - Radius of conversion
    - The amount of material that electrons from conversion have to traverse before impacting calorimeter

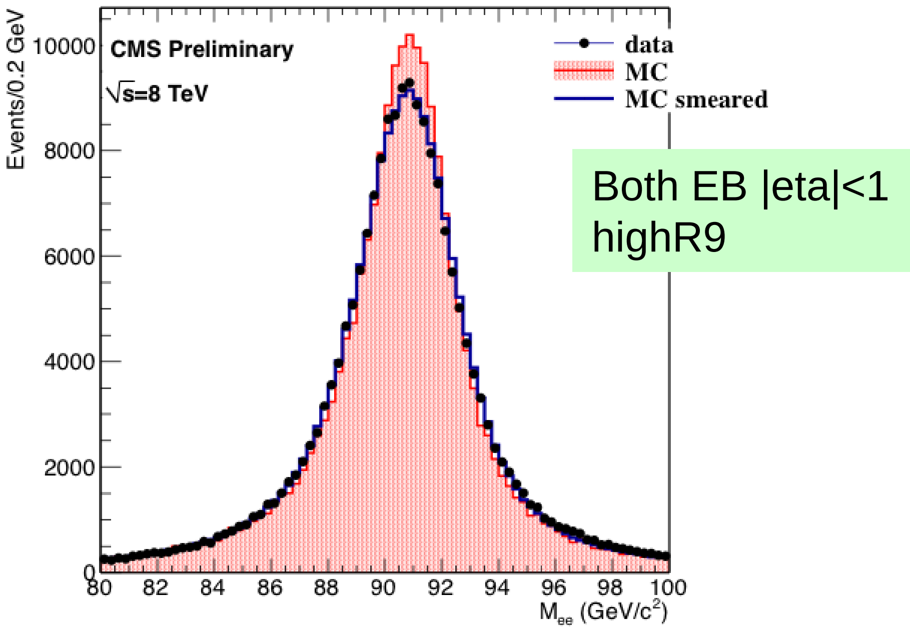


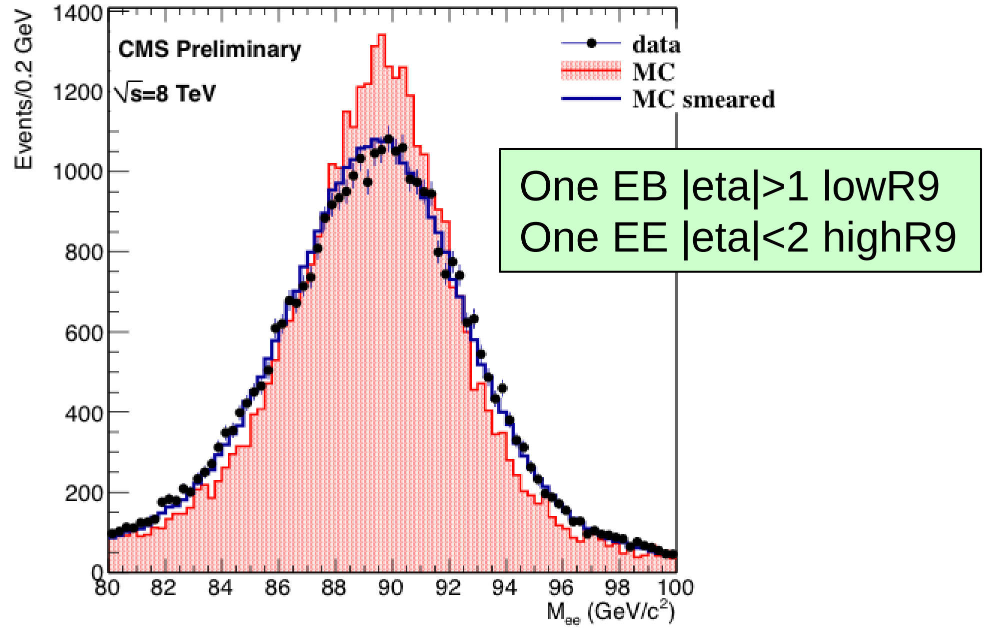
- Energy scale corrections and additional smearings are derived on top of these corrections to resolve the remaining discrepancies between data and MC (next slide)
  - Analytic fit to the Z invariant mass peak performed using a convolution of a Breit-Wigner with a Crystal Ball
- Estimate energy resolution per photon
  - Train BDT to regress to $|(E_{reco}-E_{true)}/E_{true}|$

Energy scale (data) and smearings (MC)

- Use fit to Z invariant mass peak to:
  - Determine scale factor to apply to data in order to match the position of the Z peak in MC
  - Determine amount of additional Gaussian smearing to match the width of the Z peak in data

Category	σ_E/E (%) Pho. regr. (New) No R_9 reweight
EB, $\|\eta\| < 1$, $R9 > 0.94$	$1.11 \pm 0.07 \pm 0.22$
EB, $\|\eta\| < 1$, $R9 < 0.94$	$1.07 \pm 0.06 \pm 0.24$
EB, $\|\eta\| > 1$, $R9 > 0.94$	$1.55 \pm 0.40 \pm 0.60$
EB, $\|\eta\| > 1$, $R9 < 0.94$	$1.94 \pm 0.11 \pm 0.59$
EE, $\|\eta\| < 2$, $R9 > 0.94$	$2.95 \pm 0.25 \pm 0.90$
EE, $\|\eta\| < 2$, $R9 < 0.94$	$2.76 \pm 0.13 \pm 0.30$
EE, $\|\eta\| > 2$, $R9 > 0.94$	$3.70 \pm 0.11 \pm 0.34$
EE, $\|\eta\| > 2$, $R9 < 0.94$	$3.71 \pm 0.16 \pm 0.52$

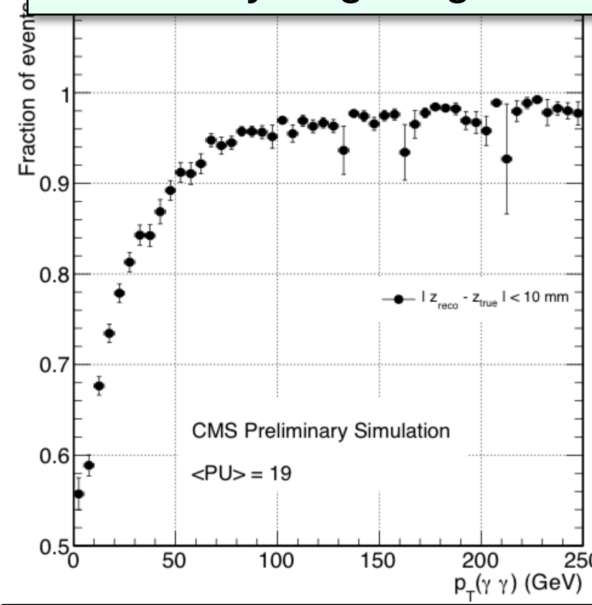




Vertex Identification

- Designed MVA to help identify the right vertex, discriminating hard interaction from pileup vertices.
- MVA evaluated per-vertex for a given photon pair:
  - unconverted photons:
    - Intensity of the vertes Σp_T^2,
    - tracks follow direction of Higgs recoil (p_T balance)
    - Track sum should be similar to Higgs recoil (p_T asymmetry),
  - conversions
    - pull from conversions
- Control samples:
  - Z→□□ (for unconverted)
  - □+jet (for converted photons)
- $p_T(\gamma\gamma)$ is the main discriminant
  - **But can we do better?**

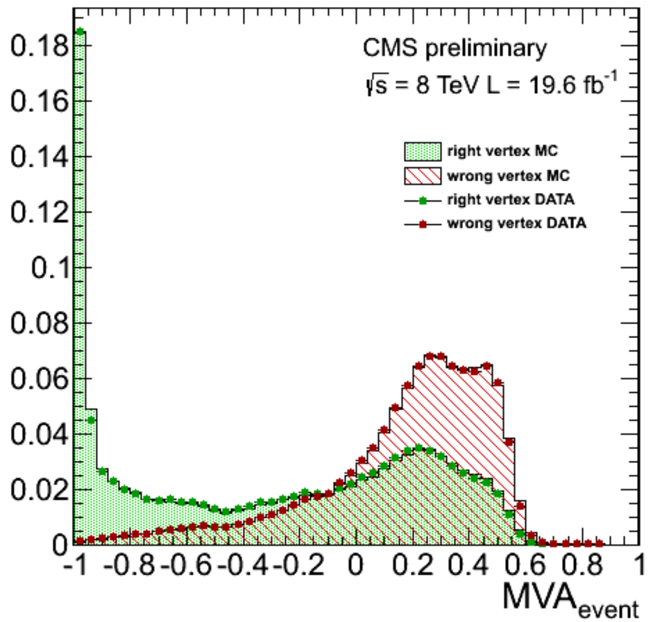
Probability to get right vertex

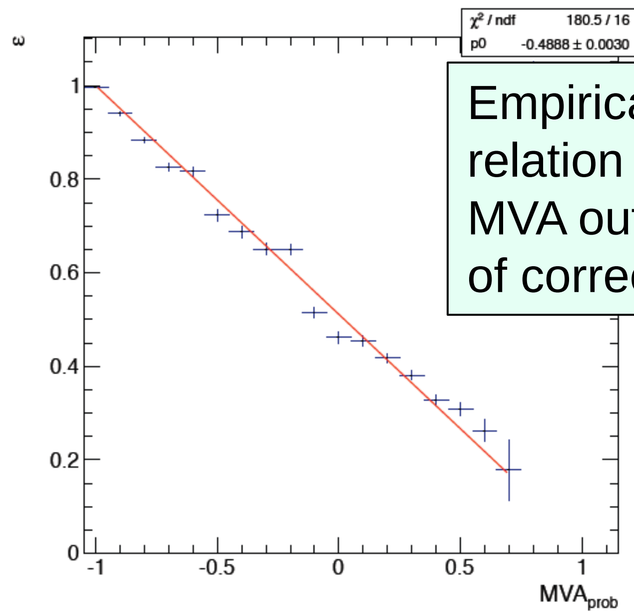


Integrated efficiency 79%

Per-Event Vertex Probability

- The probability that the correct vertex has been identified by the vertex ID MVA is evaluated using a further MVA.
- Inputs: vertex ID MVA output for first 3 vertices, Nvtx, $p_T(\gamma\gamma)$, dZ between vtx0 and vtx1, vtx2, no. of photons with conversion tracks



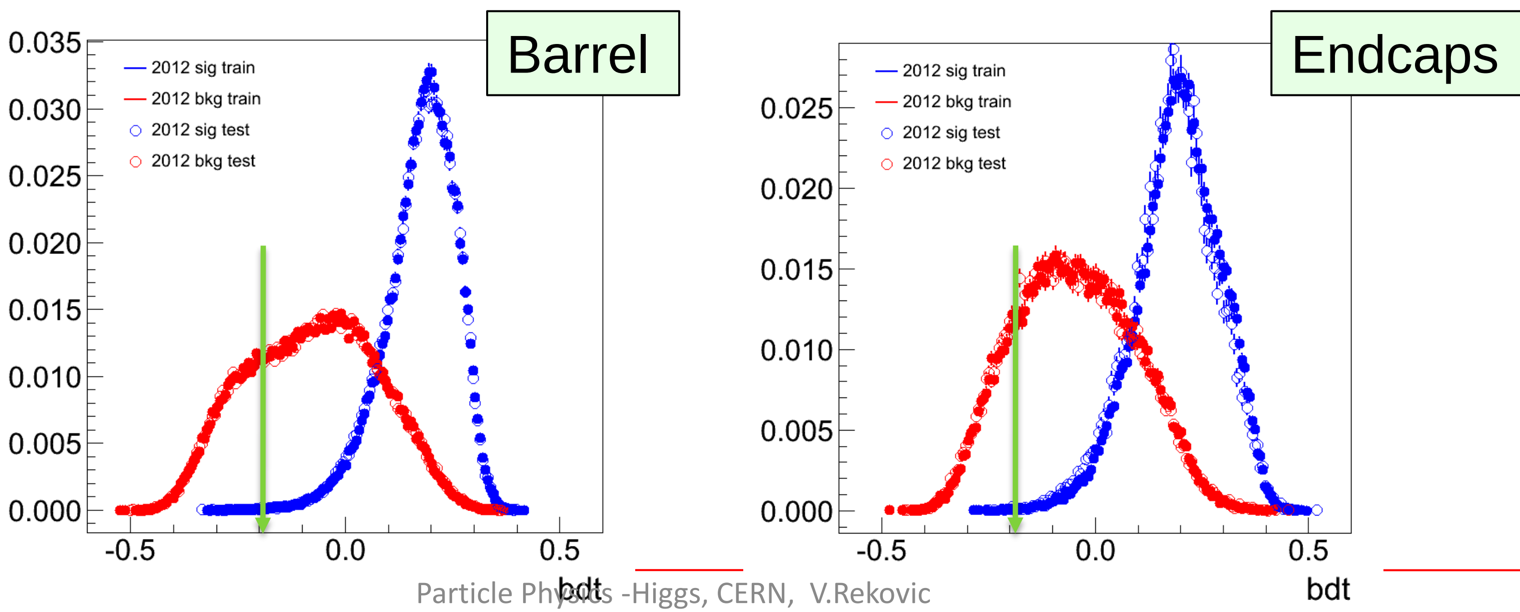


Empirically derived linear relation used to translate MVA output to probability of correct vertex

MVA Analysis

Photon Identification MVA

- Trained using γ+jet MC to distinguish between prompt and non-prompt photons. Validation with Z→ee and Z→μμγ.
- Loose cut applied to the output at -0.2 as part of MVA analysis pre-selection
  - >99% efficiency for signal
  - Efficiency scale factors from Z→ee tag and probe
- Output used as input to diphoton MVA in MVA analysis



MVA analysis: Di-photon Selection

- Require two reconstructed photons satisfying:
  - Photon ID MVA > -0.2
  - η within the ECAL fiducial region
  - $p_T/m_{\gamma\gamma}$>1/3 (lead) and 1/4 (sublead)

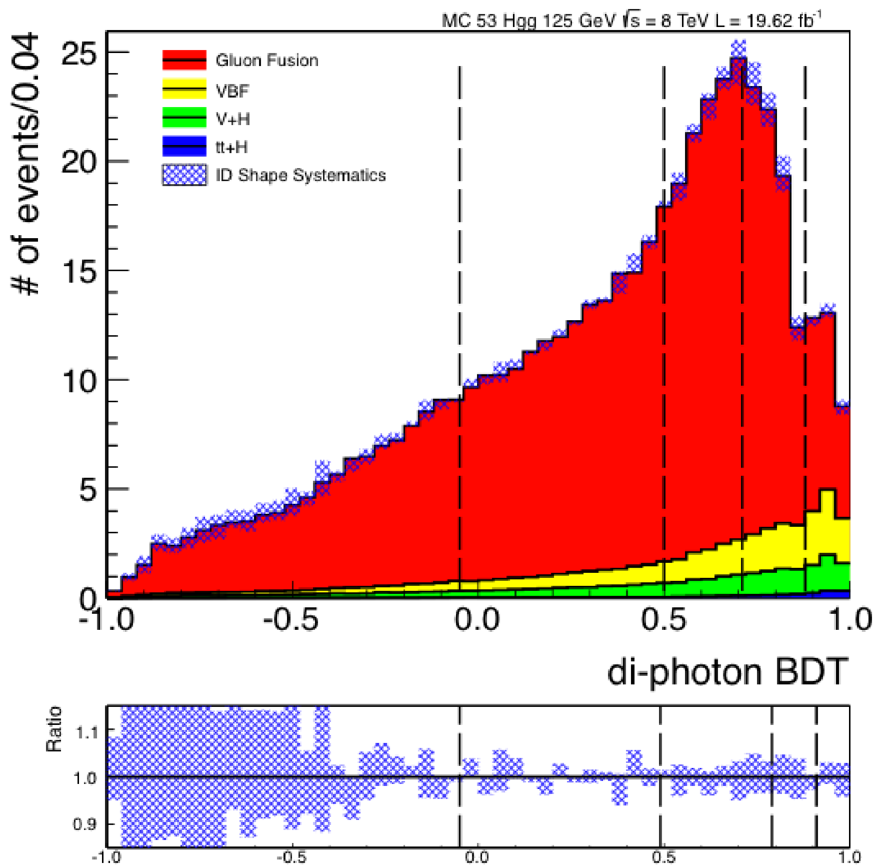
- If more than one pair passes the selection, the pair with highest Σp_T is used.

Diphoton MVA

- Encode all relevant information on signal vs background discrimination (aside from $m_{\gamma\gamma}$ itself) into a single variable
- Use input variables which are to 1st order independent of $m_{\gamma\gamma}$:
  - Kinematics: $p_T/m_{\gamma\gamma}$ and η of each photon, and $\cos\Delta\phi$ between the 2 photons
  - Photon ID MVA output for each photon
  - per-event mass resolution ($\sigma_M/M_{\gamma\gamma}$)
    - Constructed from per-photon energy resolutions (from regression), adding beamspot width contribution for wrong vtx hypothesis
  - Per-event vertex probability
- MVA output is used to define
    - event selection (MVA output>-0.05)
    - event classification – 4 categories

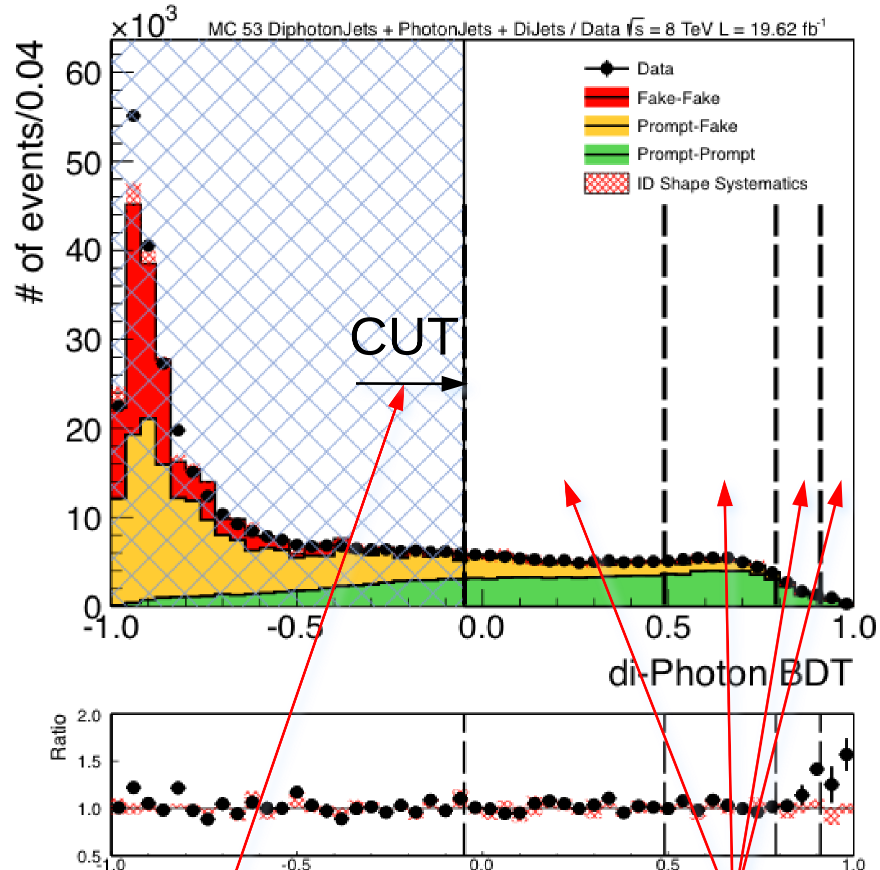
Diphoton MVA output

Signal MC



Blue hashed region:
ID MVA systematic uncertainty

Background MC and data

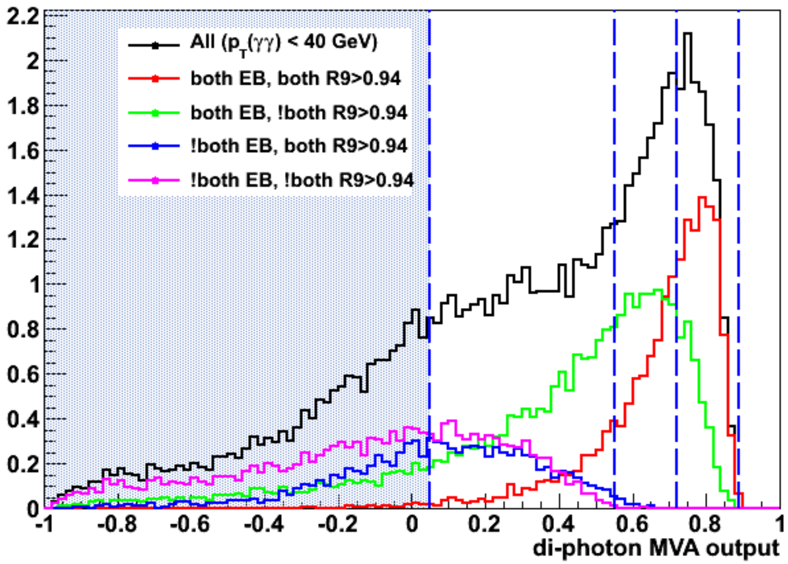


Event selection

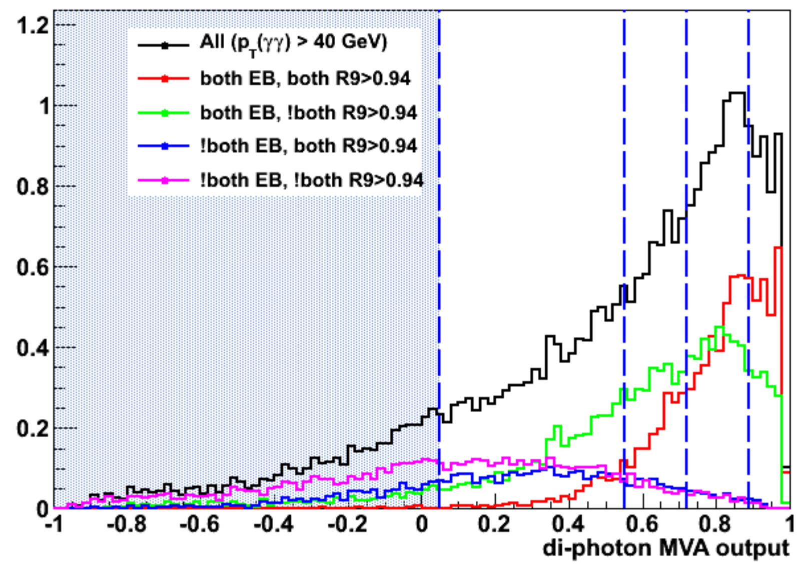
Event classification

Diphoton MVA

Low pT <40 GeV

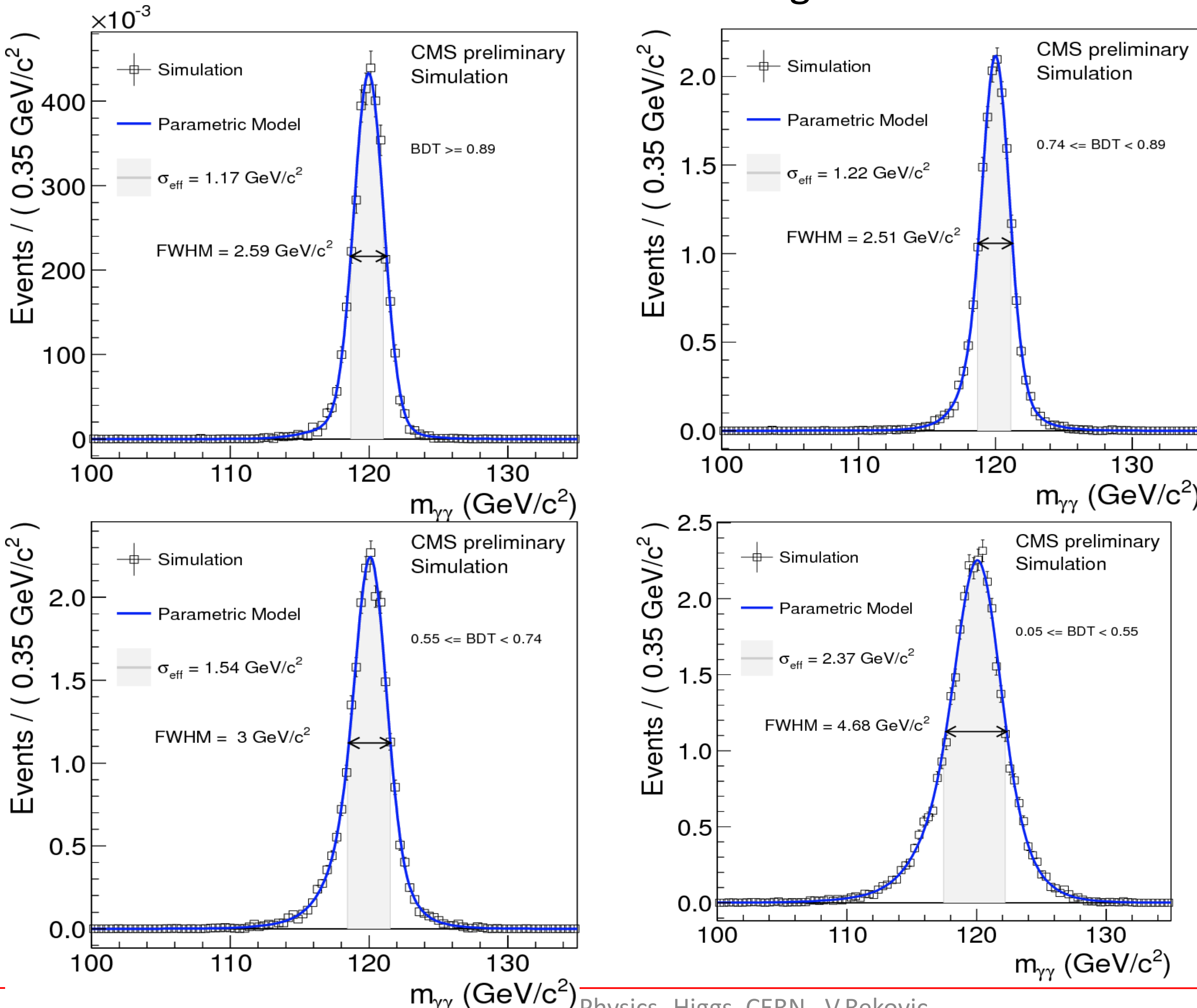


High pT > 40 GeV



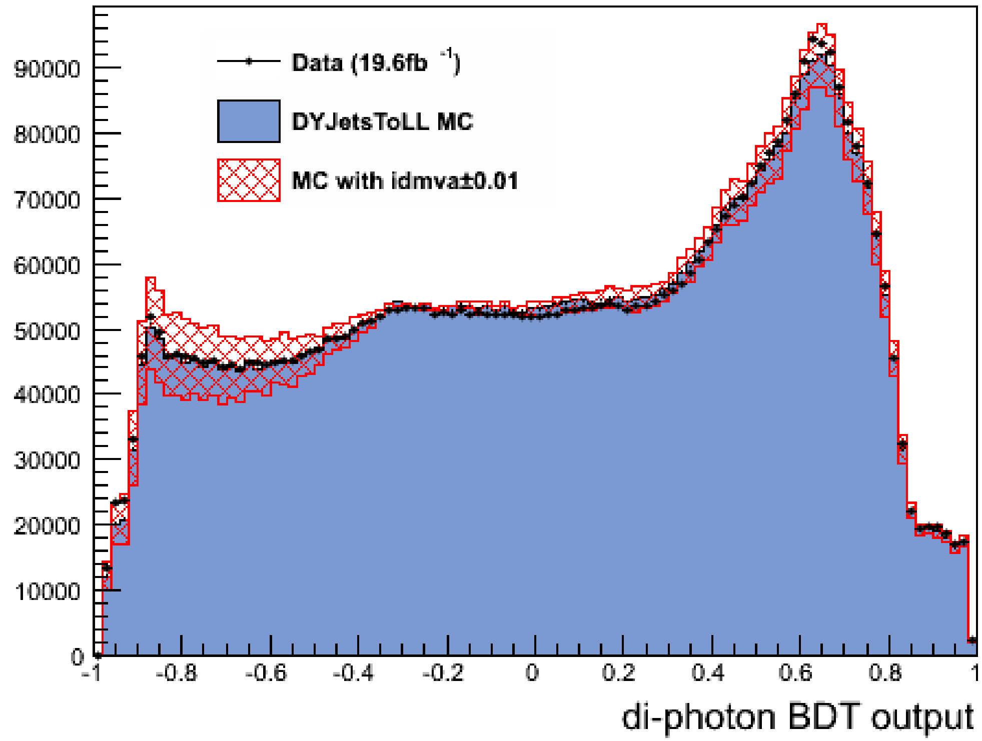
Final Classification

- Demonstration of what final classifier is sensitive to:
  - plot mass resolution for each classifier bin. Signal model is sum of Gaussians.



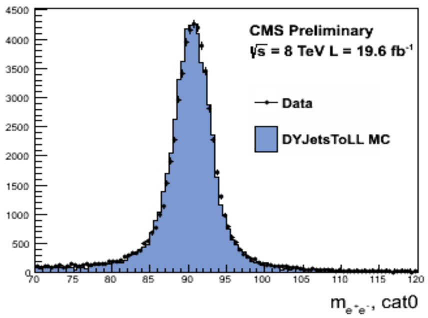
MVA Validation

- Validation of the MVA inputs (photonID, energy resolution) done on Z→ee and Z→μμγ
- **Output of the MVA validated using Z→ee**

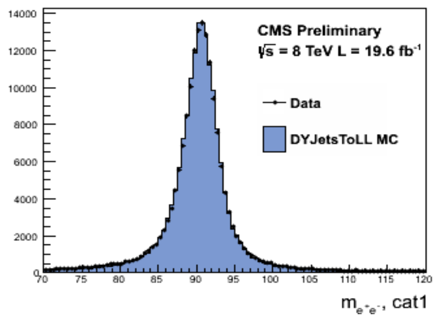


Di-photon MVA validation

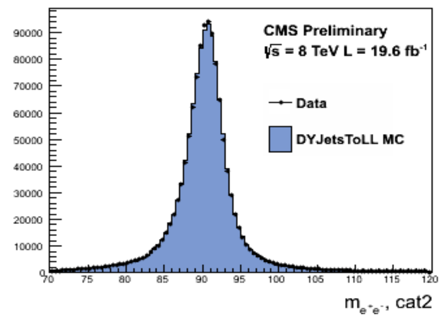
- Z→ee lineshape in MVA untagged categories



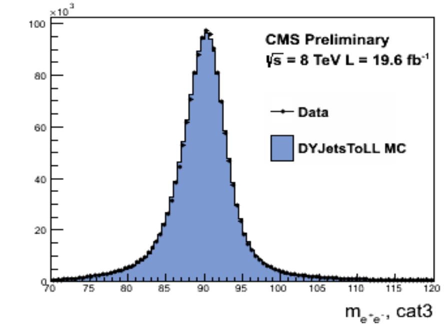
Untag cat0



Untag cat1



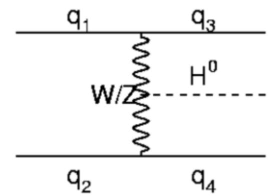
Untag cat2

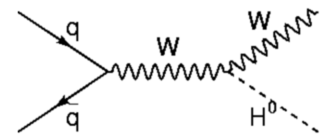


Untag cat3

MVA: Exclusive Categories

- In addition to the four "untagged" event categories defined by the diphoton MVA, five exclusive event categories are defined to enrich the sample in VBF and VH production modes.
  - Differences w.r.t. cut based analysis highlighted





Tagged categories		Requirement	Lead photon p_T	Sublead photon p_T
VBF	Tight di-jet	dijet MVA>0.985	$1/2m_{\gamma\gamma}$	$1/4m_{\gamma\gamma}$
	Loose di-jet	0.93<dijet MVA<0.985		
VH	Muon tag	1 muon $p_T > 20$GeV	$45/120m_{\gamma\gamma}$	$1/4m_{\gamma\gamma}$
	Electron tag	1 electron $p_T > 20$GeV		
	MET tag	MET > 70 GeV		

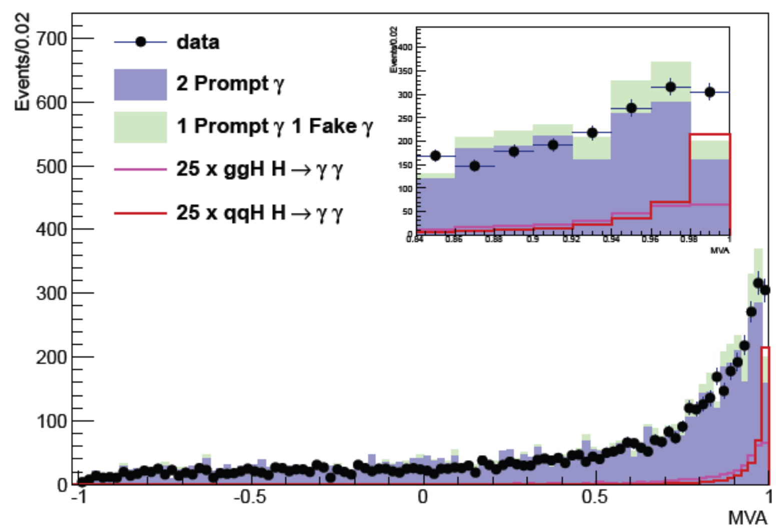
- The categorization proceeds in the following order:

Muon → Electron → Dijet → MET → Untagged

Dijet tag (MVA)

- For MVA analysis, two categories defined from the output of a dijet MVA
- Pre-selection:
  - M_{jj} > 250GeV, p_T^{j1} > 30GeV, p_T^{j2} > 20GeV
- BDT classifier to divide into two categories
  - Input variables include kinematic variables related to the two photons, the two jets and the photon-jet 4-body system
  - Category boundaries optimized to maximize exclusion power
  - Validation using Z→ee

	BDT Boundary	S/B
Tight	0.985	0.50
Loose	0.930	0.16



Lepton and MET tags

- Selection same as in published fermiophobic analysis paper:
  - CMS Collaboration, JHEP 1209 (2012) 11
- Diphoton selection same as untagged selection, except
  - p_T(lead γ)/$M\gamma\gamma$ > 45/120, p_T(sublead γ) > 25GeV, ΔR(lepton,γ) > 1.0
  - For MET tag use EB photons only
- Lepton tag to suppress backgrounds
  - EWK (W/Z +γ like)
- For MET tag, apply topological cuts to enhance S/B and reduce gluon-gluon fusion contamination:
  - $\Delta\phi(\gamma\gamma,\text{MET}) < 2.1$, $\Delta\phi(\text{jet},\text{MET}) < 2.7$, p_T^{jet}>50GeV

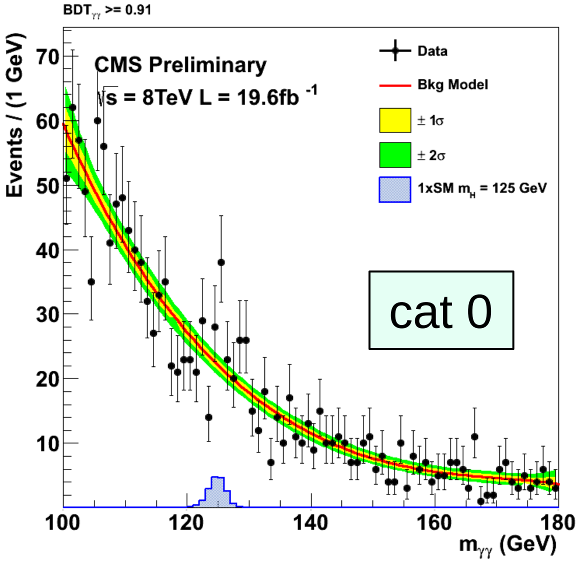
MVA analysis: signal yields

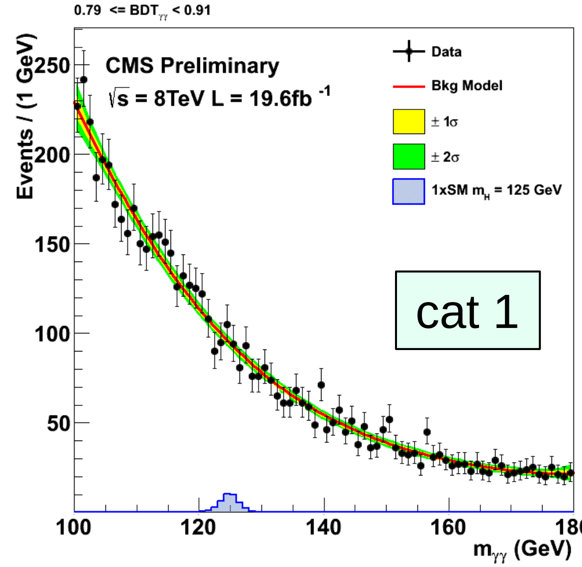
Expected signal

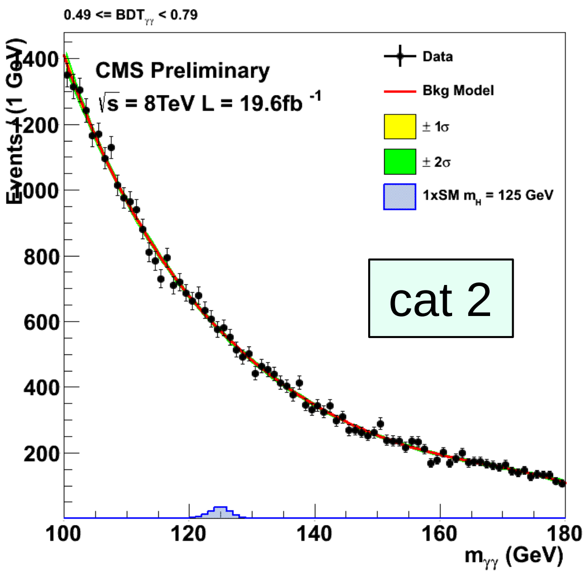
Event classes		SM Higgs boson expected signal (m_H =125 GeV)						
		Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)
8 TeV 19.6 fb^{-1}	Untagged 0	17.5	72.9%	11.6%	13.0%	2.6%	1.38	1.31
	Untagged 1	39.2	83.6%	8.4%	7.1%	1.0%	1.51	1.38
	Untagged 2	154.4	91.7%	4.4%	3.5%	0.4%	1.78	1.52
	Untagged 3	160.3	92.5%	3.9%	3.3%	0.2%	2.63	2.18
	Dijet Loose	9.2	20.7%	78.9%	0.3%	0.1%	1.81	1.43
	Dijet Tight	11.5	46.8%	51.0%	1.7%	0.5%	1.87	1.60
	Muon Tag	1.4	0.0%	0.2%	78.9%	20.9%	1.87	1.55
	Electron Tag	1.0	1.1%	0.4%	78.7%	19.9%	1.92	1.55
	E_T^{miss} Tag	1.7	21.8%	2.6%	63.8%	11.8%	1.81	1.66

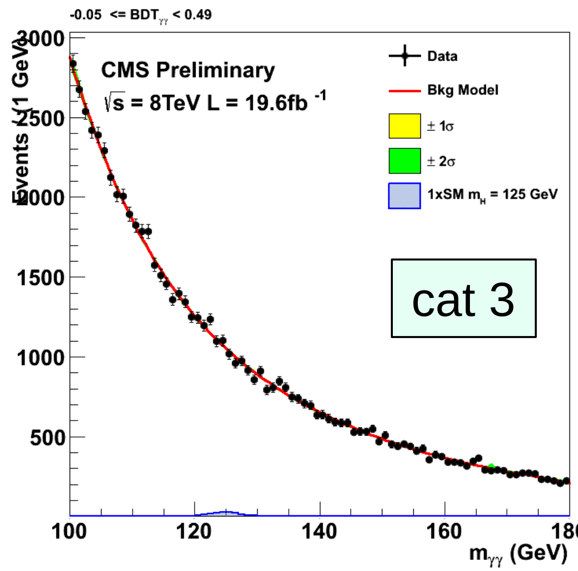
- Signal model is sum of Gaussians fitted to MC

MVA analysis: Background model fits (untagged cats)

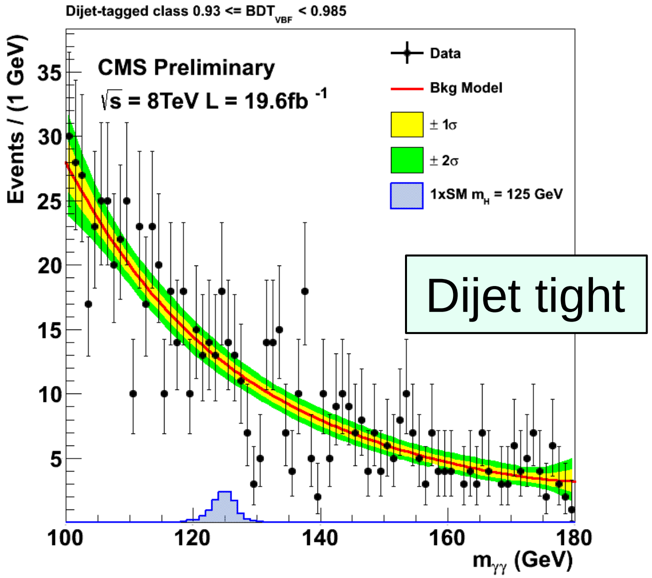


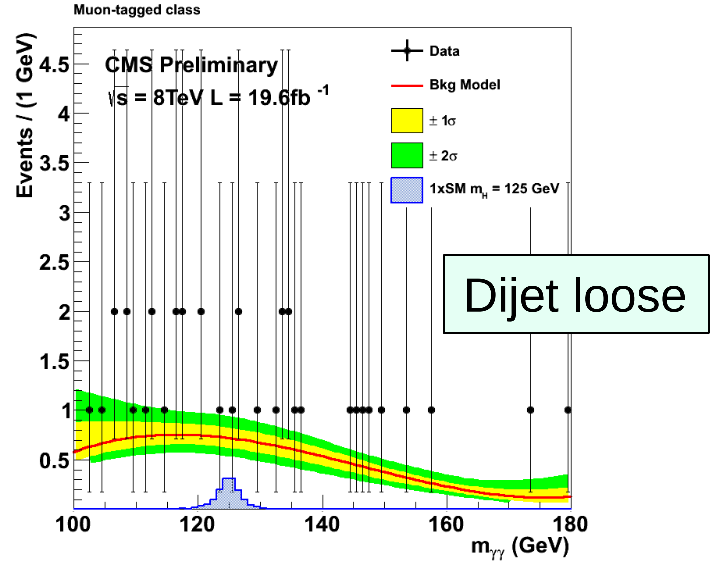


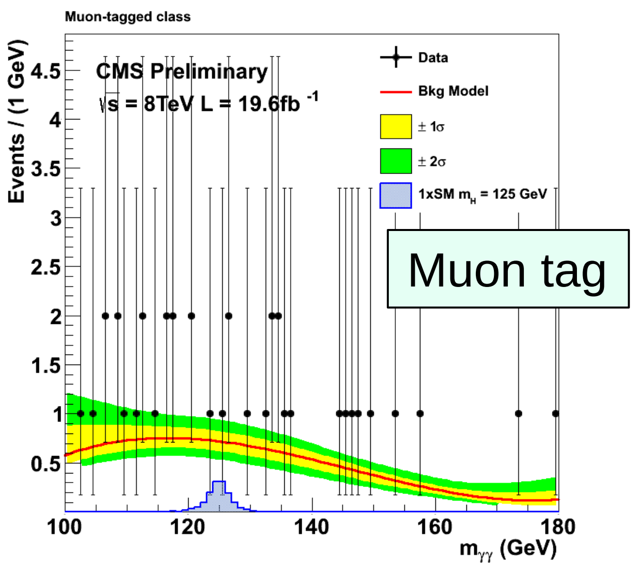


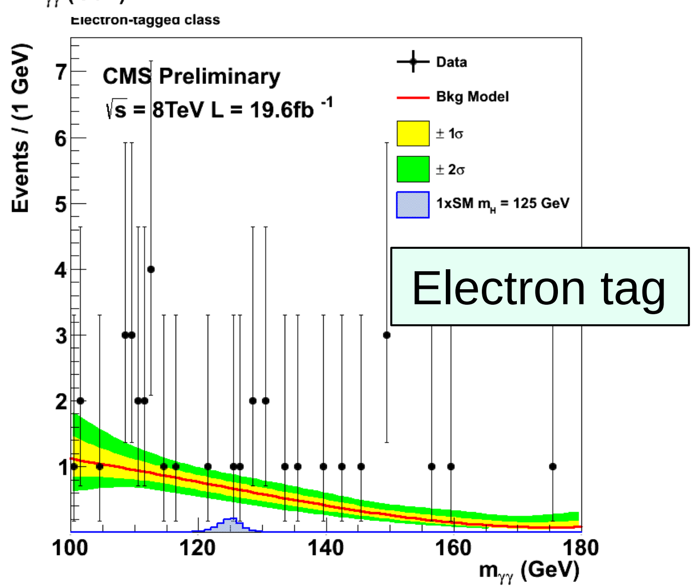


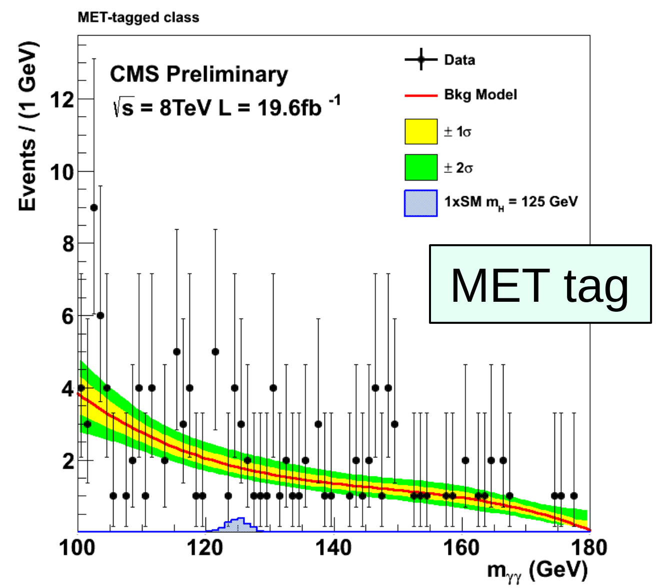
MVA analysis: Background model fits (exclusive cats)











Having signal and background PDF's, construct Likelihood ratio:

$$Q = \frac{P_{Poisson}(Data|s+b)}{P_{Poisson}(Data|b)} = \frac{L(s+b)}{L(b)} = \frac{\exp(-(s_{TOT}+b_{TOT}))}{\exp(-b_{TOT})} \prod_{i=1}^{N_{bins}} \left(\frac{s_i+b_i}{b_i}\right)^{N_i}$$

which can be re-written

$$-2\ln Q(m_H) = 2s_{TOT} - 2\sum_{i=1}^{N_{bins}} N_i \ln\left(1 + \frac{s_i(m_H)}{b_i}\right)$$

Statistical Analysis

Having signal and background PDF's, construct Likelihood ratio:

$$Q = \frac{P_{Poisson}(Data|s+b)}{P_{Poisson}(Data|b)} = \frac{L(s+b)}{L(b)} = \frac{\exp(-(s_{TOT}+b_{TOT}))}{\exp(-b_{TOT})} \prod_{i=1}^{N_{bins}} \left(\frac{s_i+b_i}{b_i}\right)^{N_i}$$

which can be re-written

$$-2\ln Q(m_H) = 2s_{TOT} - 2\sum_{i=1}^{N_{bins}} N_i \ln\left(1 + \frac{s_i(m_H)}{b_i}\right)$$

The higher term, the more sensitive the analysis

Statistical Analysis (Confidence Levels)

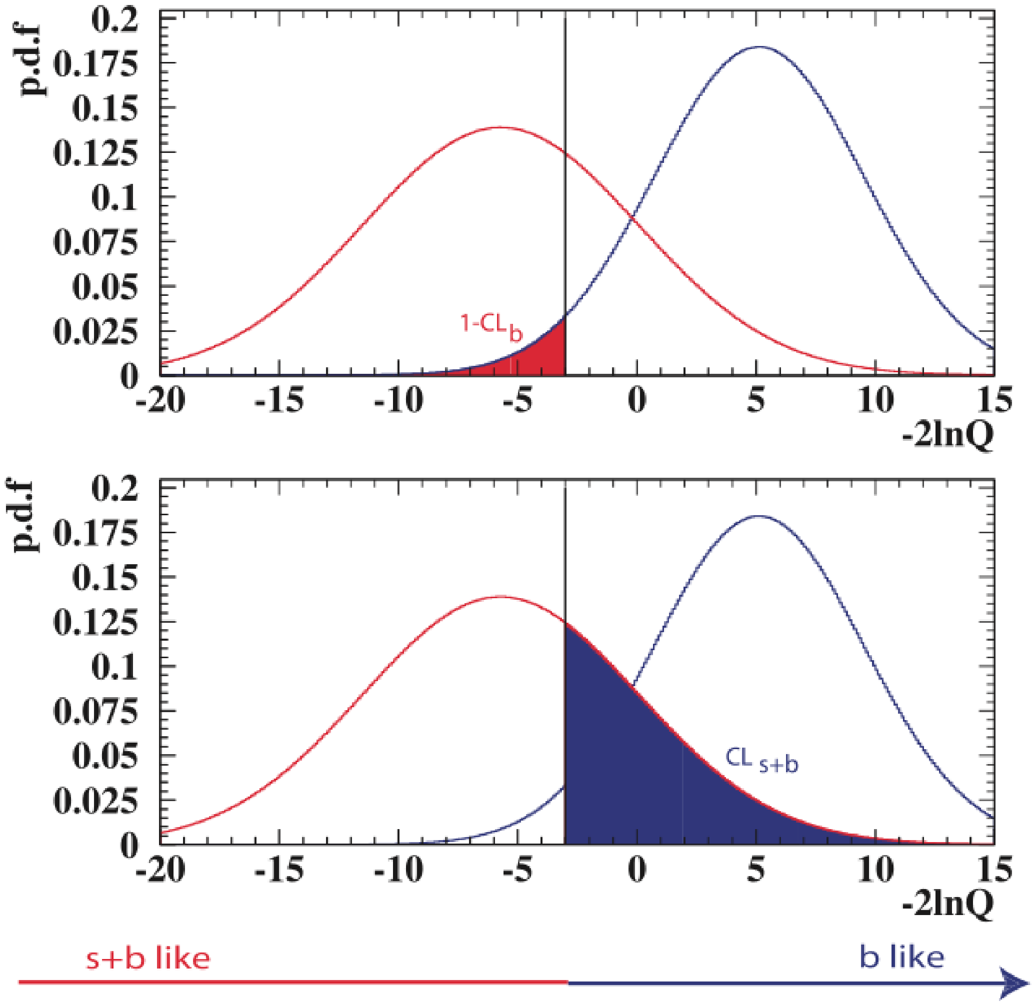
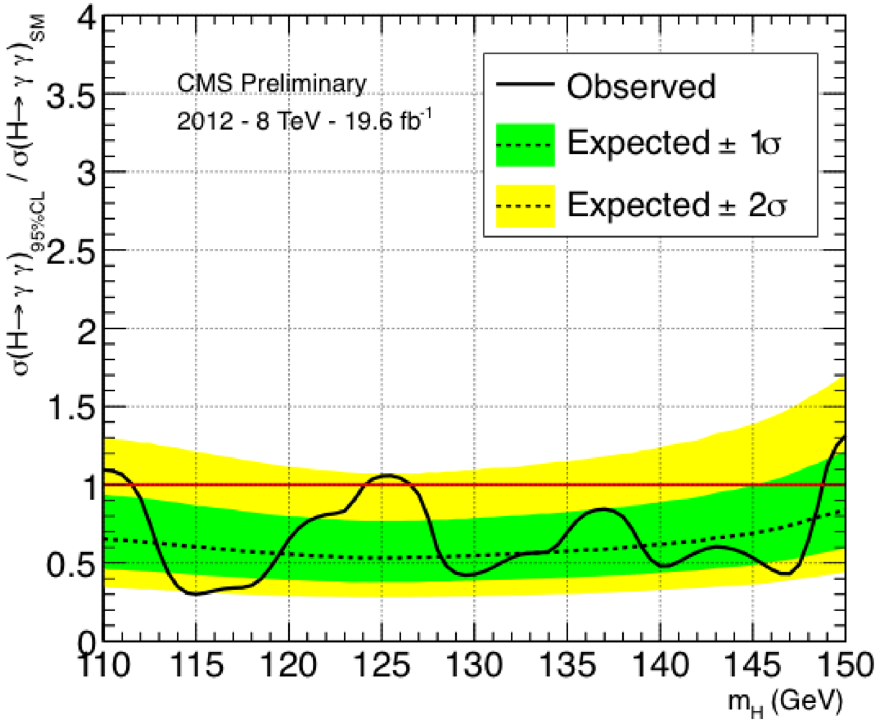
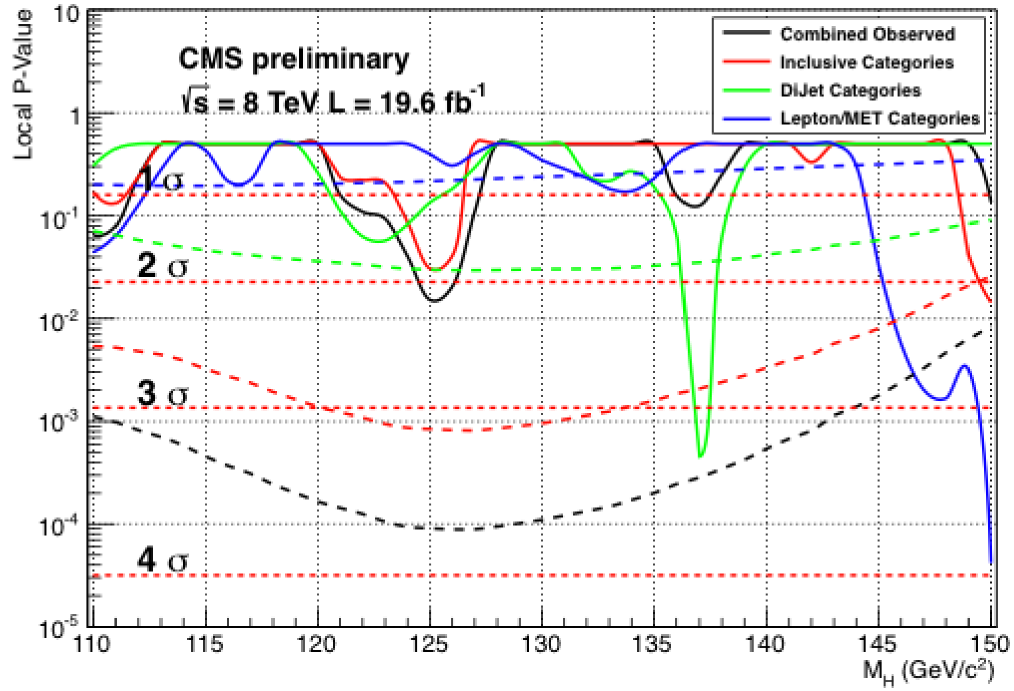


Figure 11: An example of probability density functions (p.d.f's) for background only (solid blue) and signal+background (solid red) experiments. The red shaded area, $1 - CL_b$, measure the compatibility with the background hypothesis while the blue shaded area, CL_{s+b}, the compatibility with the signal+background hypothesis. Detailed explanations are given in the text.

Results (8TeV)

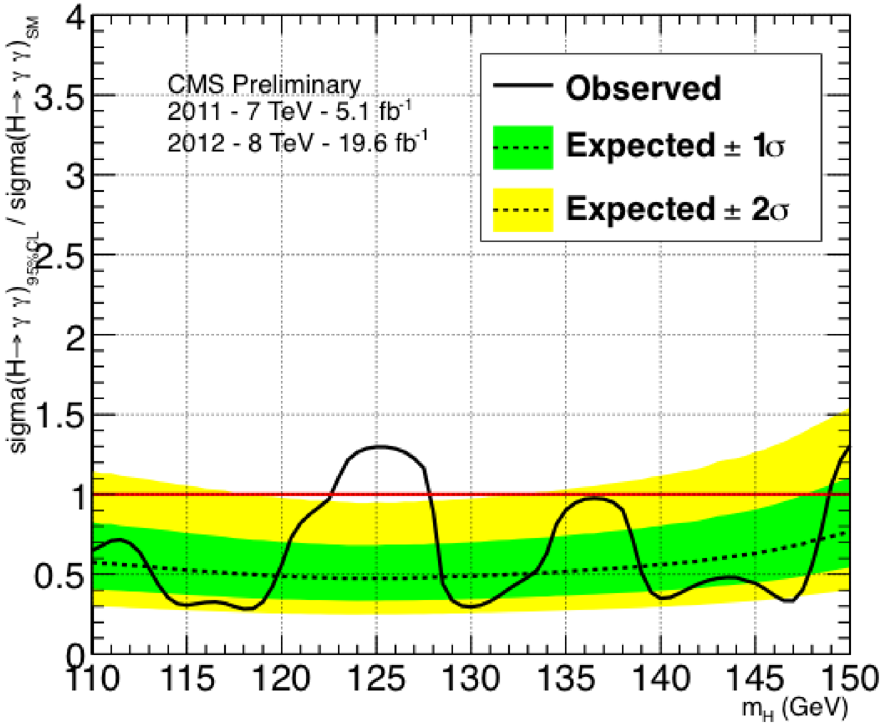


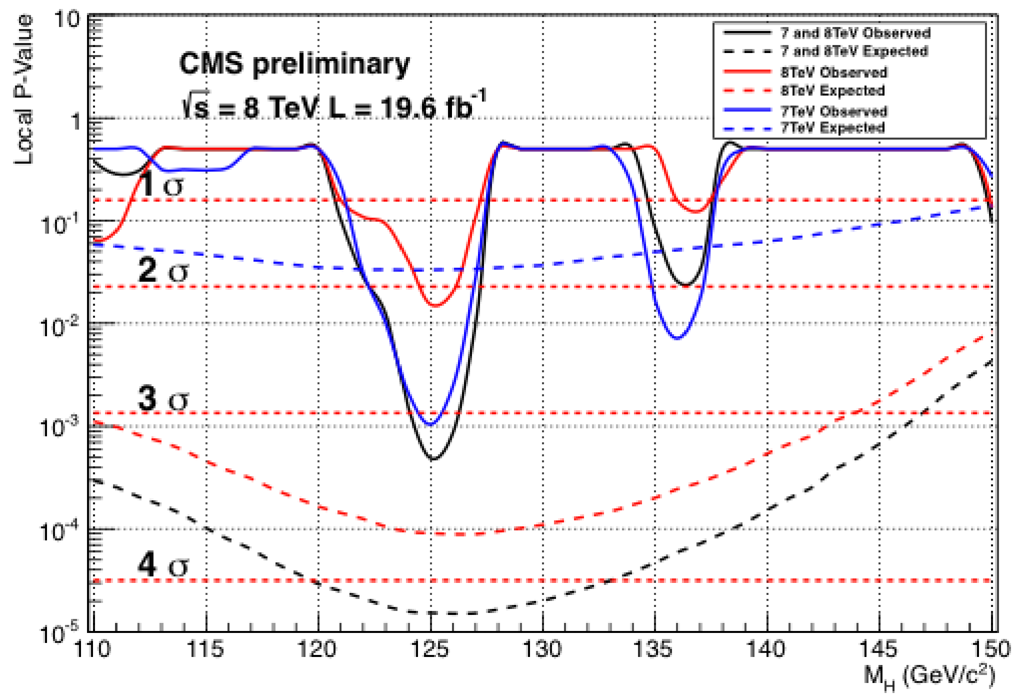


p-value significance at 125.0 GeV: 2.07σ

Results (7+8 TeV)

7TeV MVA + 8TeV MVA

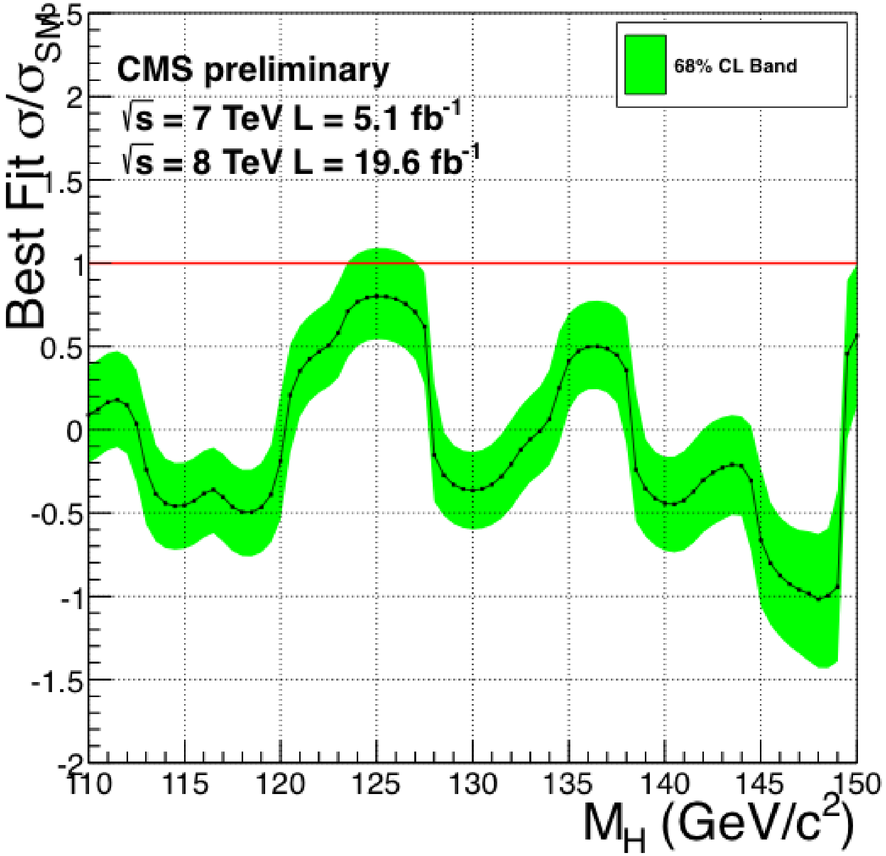


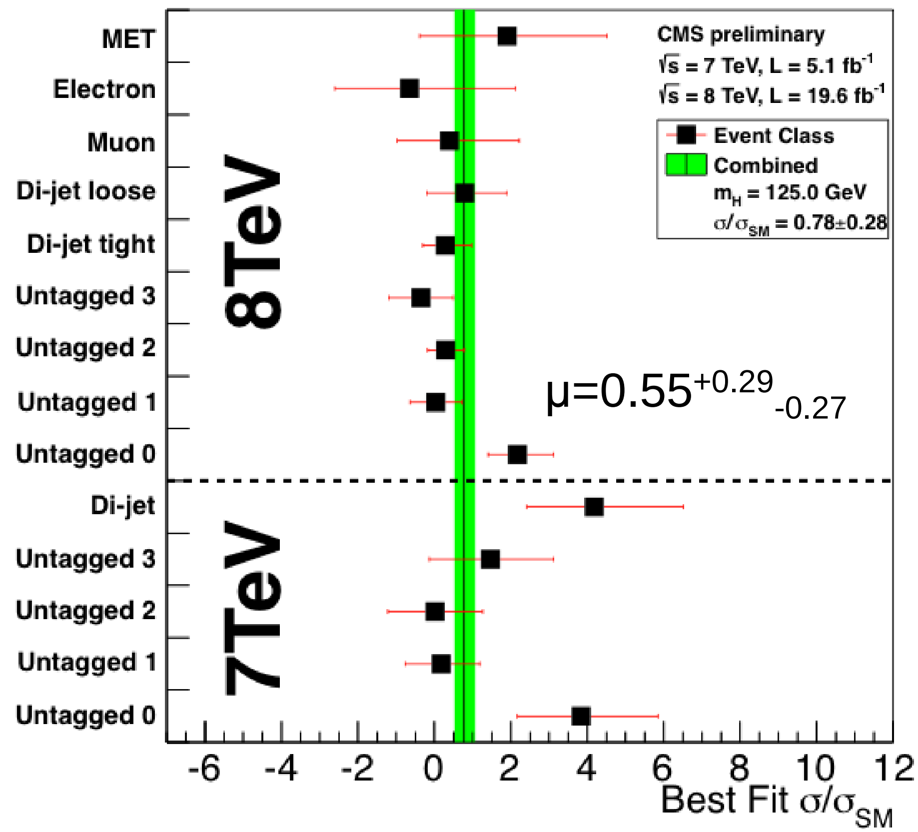


p-value significance at 125 GeV: 3.22σ

Signal Strength (7+8TeV)

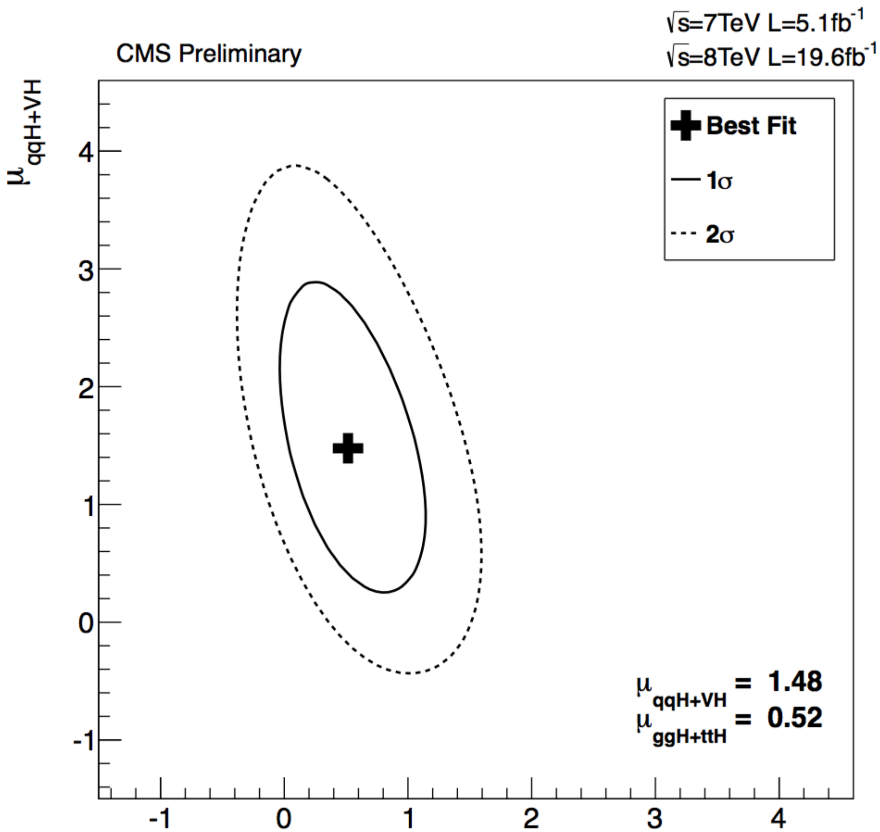
7TeV MVA + 8TeV MVA

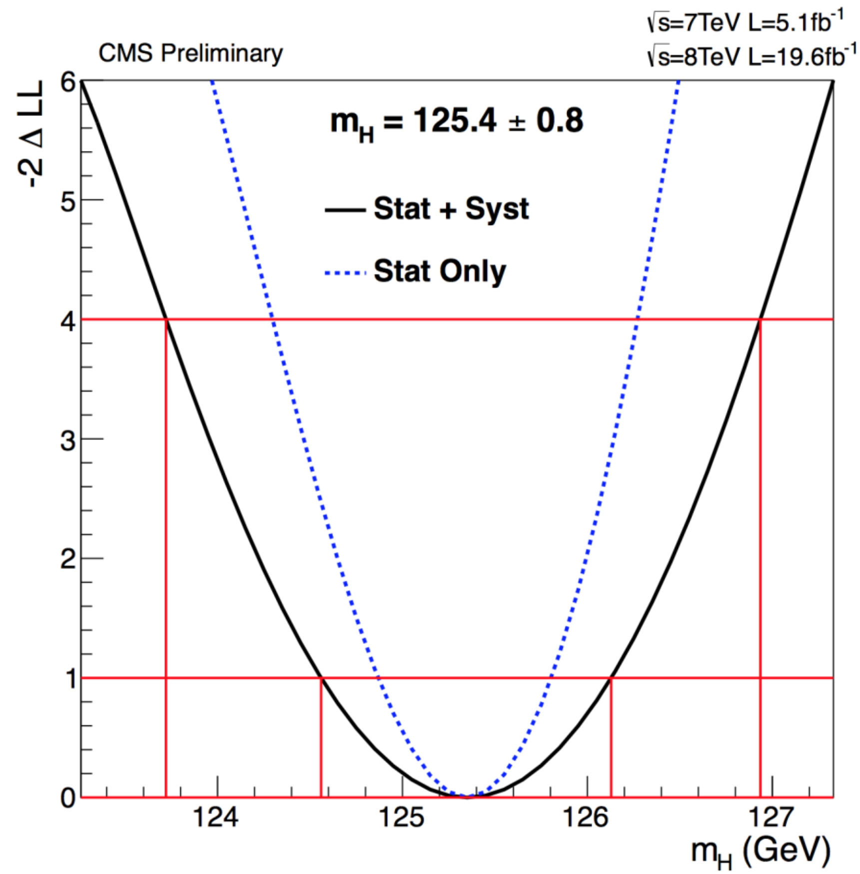




Best fit μ at 125.0 GeV: $0.78^{+0.28}_{-0.26}$

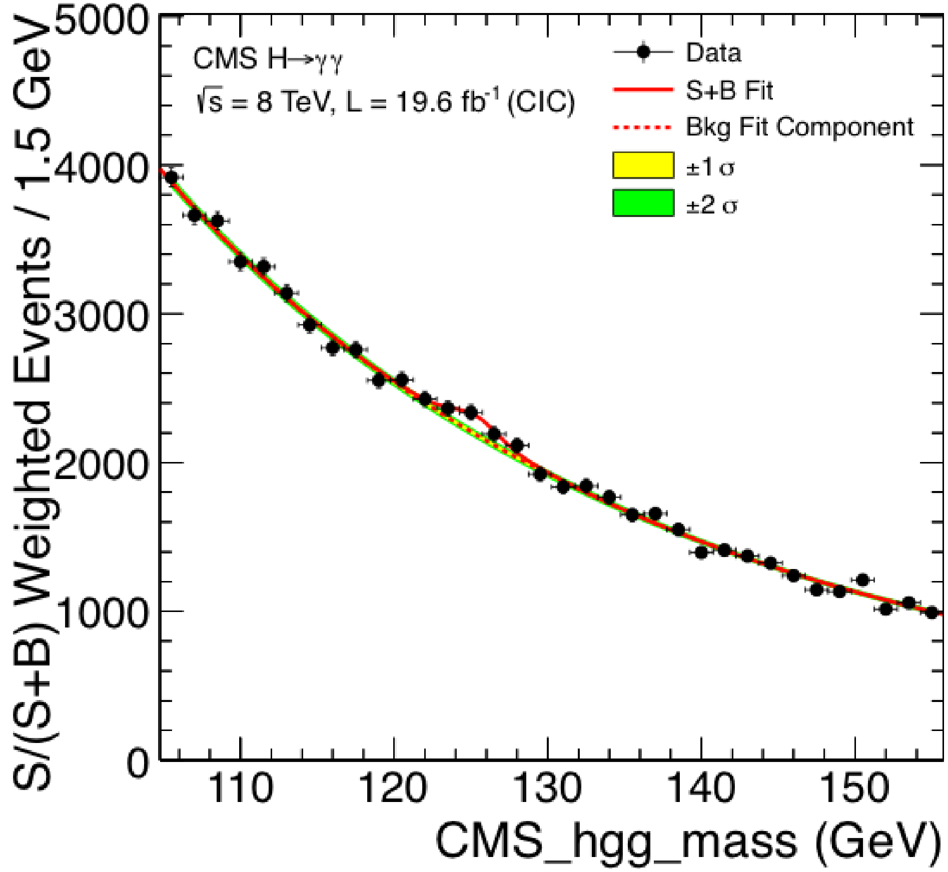
couplings & mass (7+8TeV)





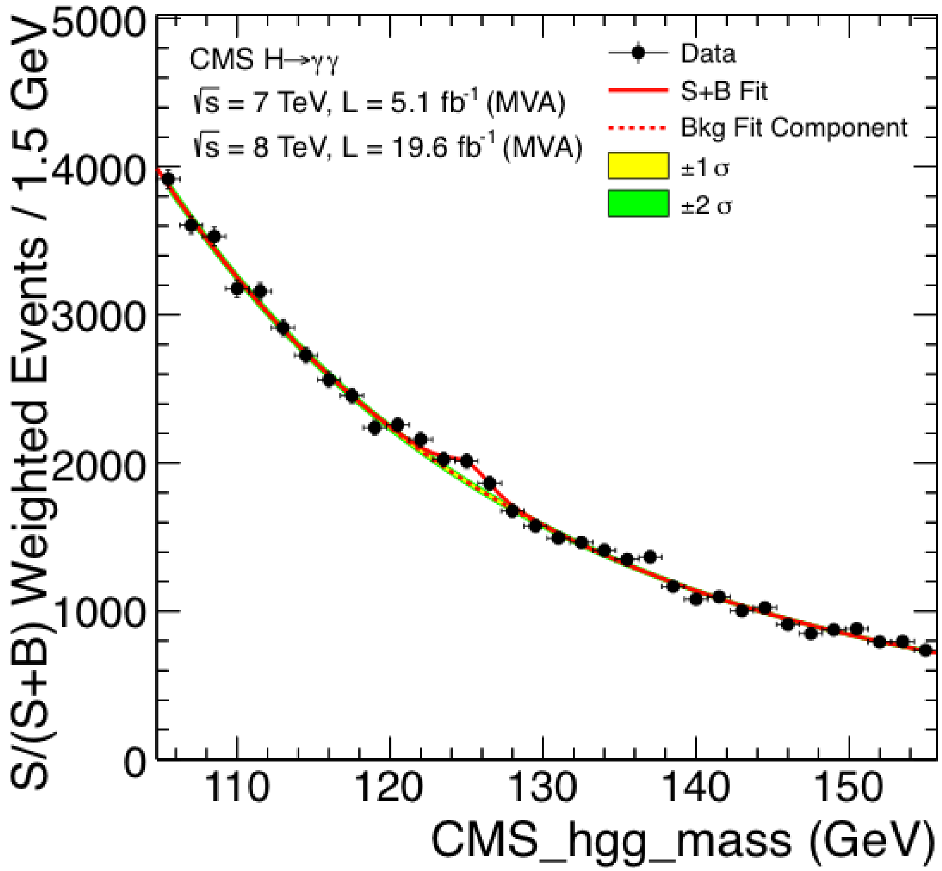
- Mass is measured profiling R_V, R_F and all other nuisances:
  - M_H = 125.4 ± 0.5(stat.) ± 0.6(syst.) GeV
- The systematic uncertainty is dominated by the overall photon energy scale uncertainty (0.47%)

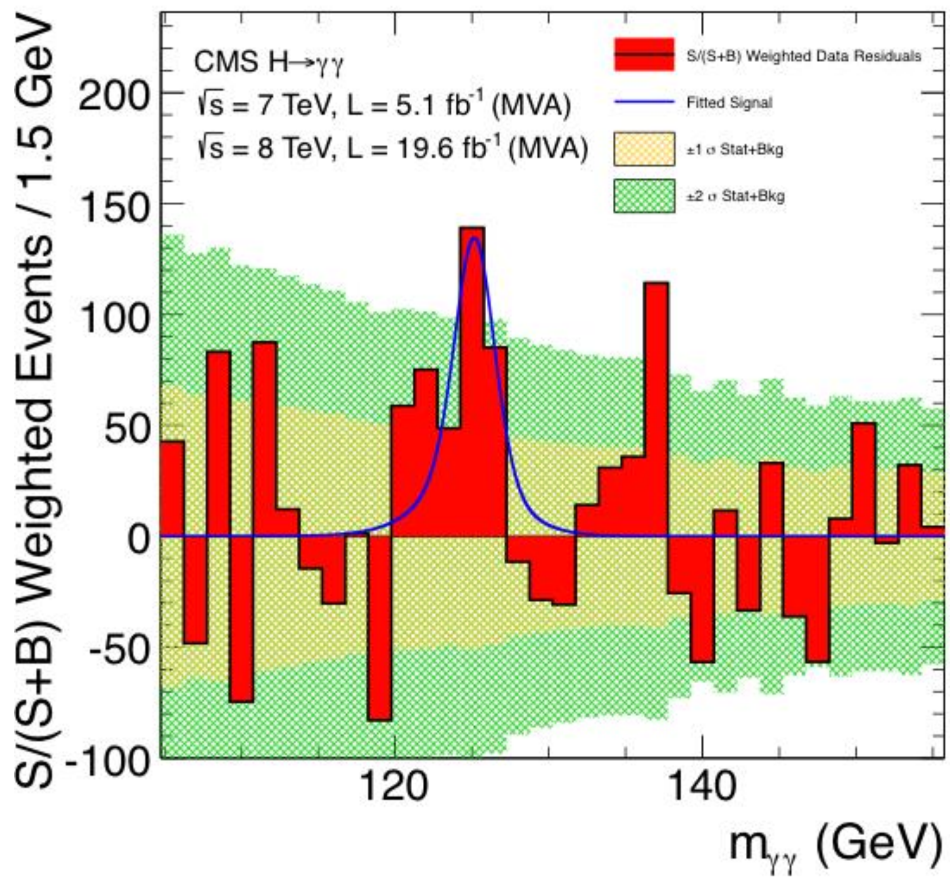
weighted mass plot (8TeV)



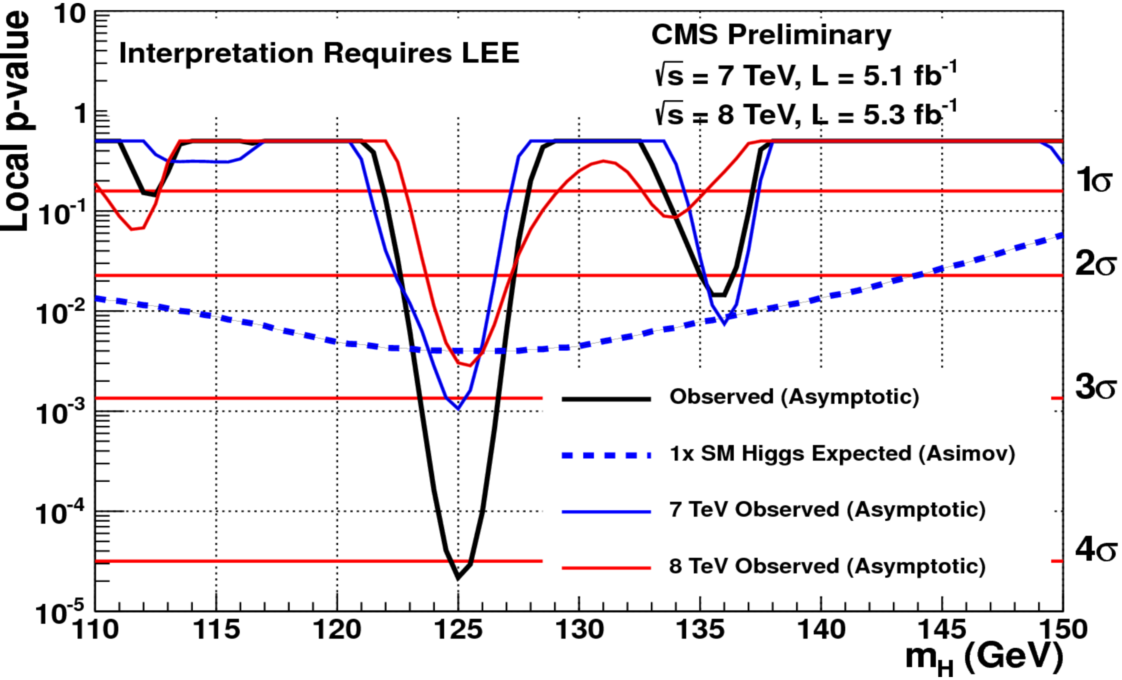
weighted mass plot (7+8TeV)

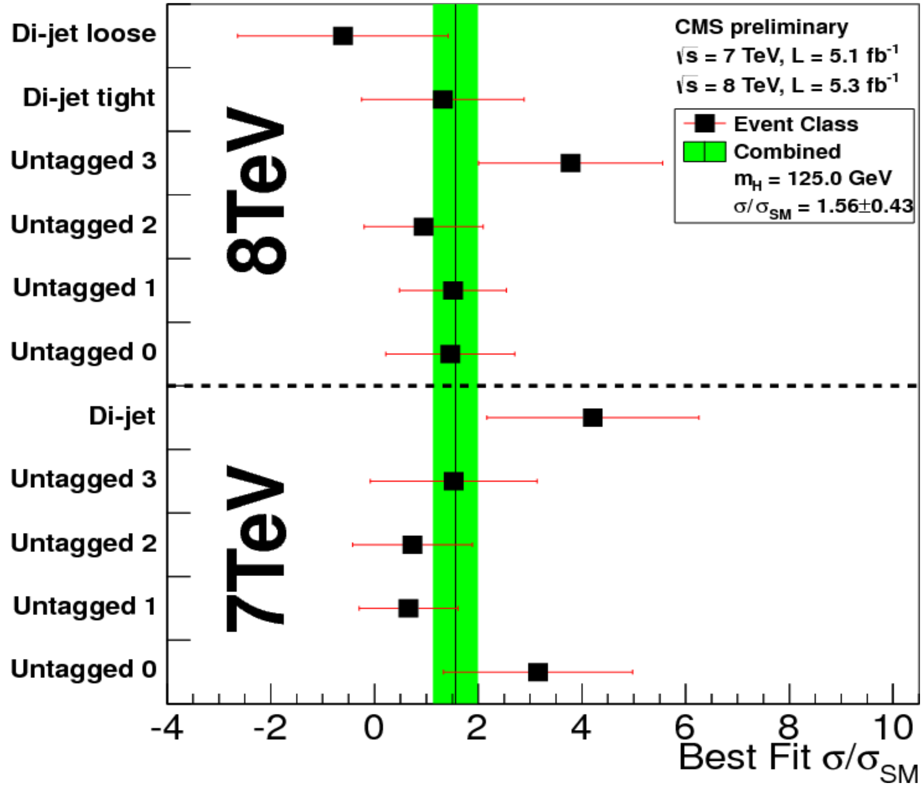
7TeV MVA + 8TeV MVA





What CMS showed in July 2012





Maximum significance 4.1σ at 125.0 GeV

Best fit μ at 125.0 GeV: 1.56 ± 0.43

Compatibility among two analyses (MVA vs CiC)

- 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**

	Signal strength compatibility (including correlation)
MVA vs CiC in full dataset	1.5 σ
MVA vs CiC only in 2012 dataset	1.8 σ

- Signal strength compatibility only in 2012AB (published) :
  - New MVA vs published MVA: 1.6σ
  - Cut-based vs old cut-based (published cross-check): 0.5σ
- A large number of tests have been performed. No source of systematic error was found. Differences appear to be of a statistical nature.

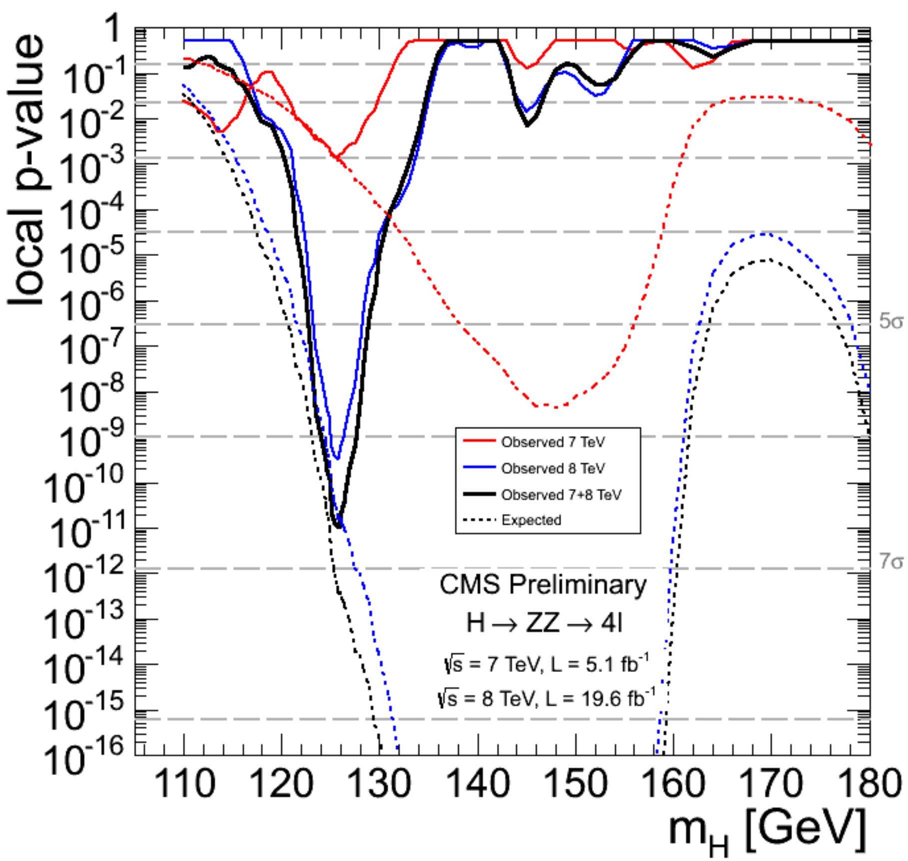
Summary and Conclusions

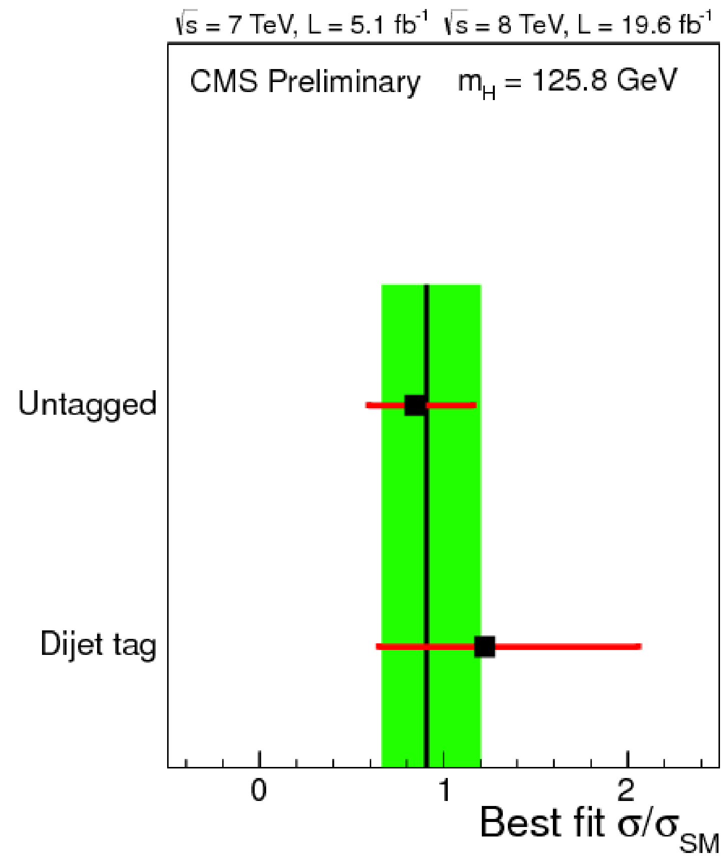
- We analyzed the full 2011+2012 datasets
- The two analyses measure σ/σ_{SM} of
  - MVA: 0.8 ± 0.3
  - CiC: 1.1 ± 0.3
- The difference between cut-based and MVA has triggered numerous cross checks but no hints of problems have been identified
- The measured mass is:
  $125.4 \pm 0.5(\text{stat.}) \pm 0.6(\text{syst.})$ GeV
- Higgs production cross-sections times the γγ BR are found consistent with the SM per production process.
- Final results on the complete 7 and 8 TeV data will be obtained on re-reco data and are expected in the summer.

Thank you.

Backup

3D analysis - m_{4l}, KD, p_T/m_{4l} (VD)

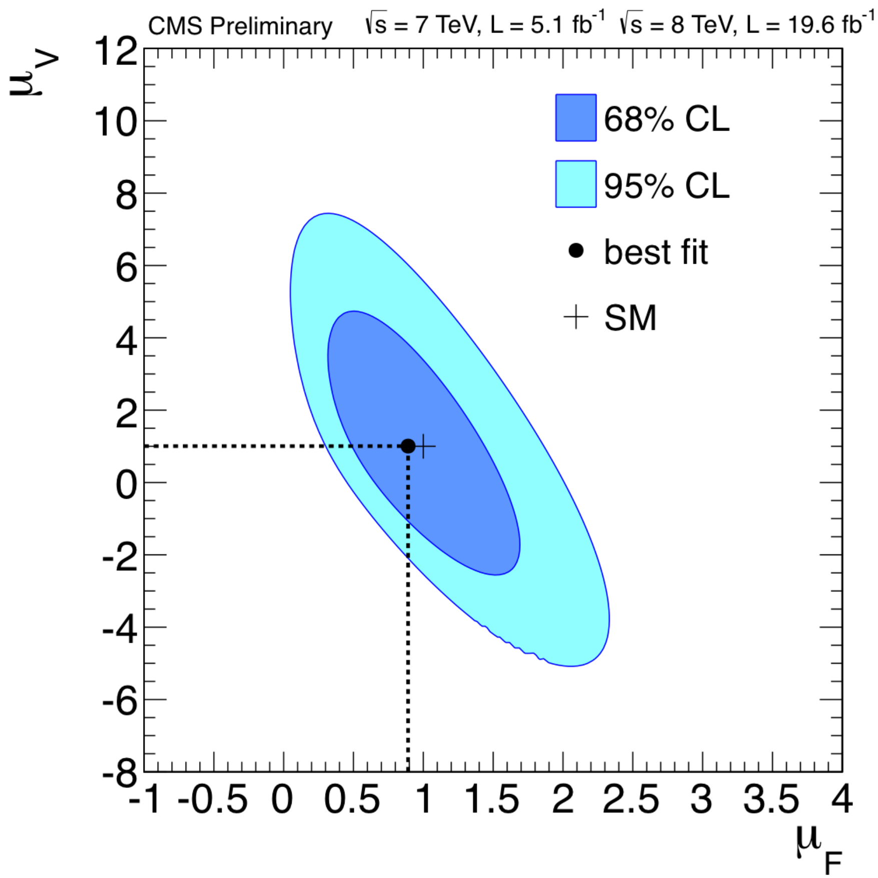


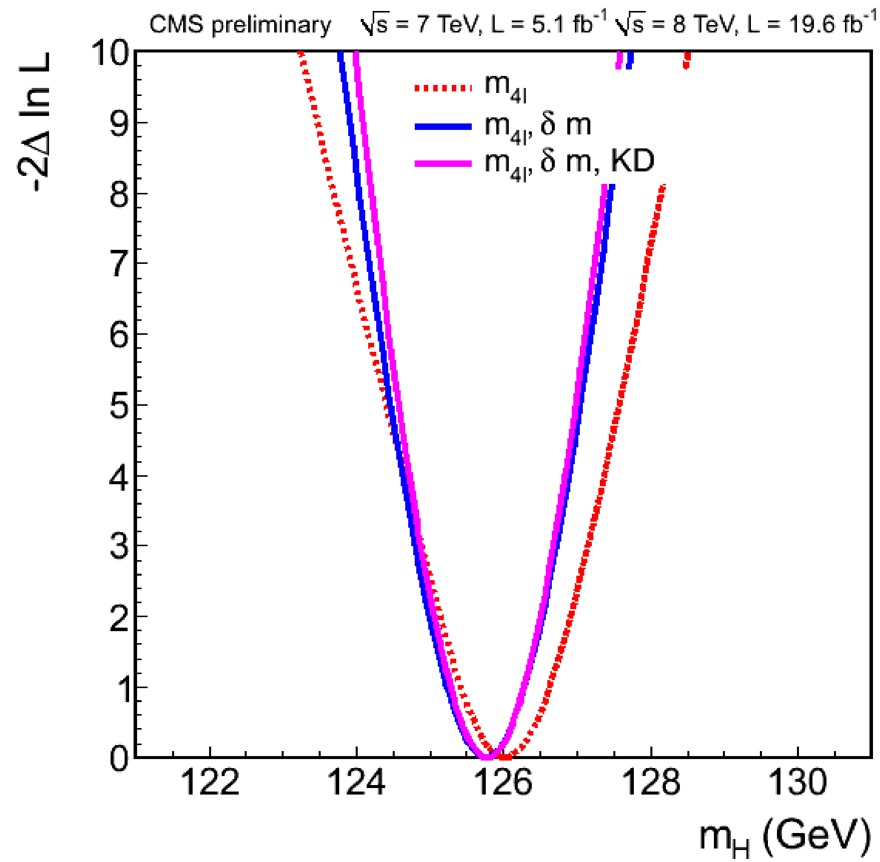


Best fit μ at 125.8 GeV: $0.91^{+0.30}_{-0.24}$

$H \rightarrow ZZ \rightarrow 4l$

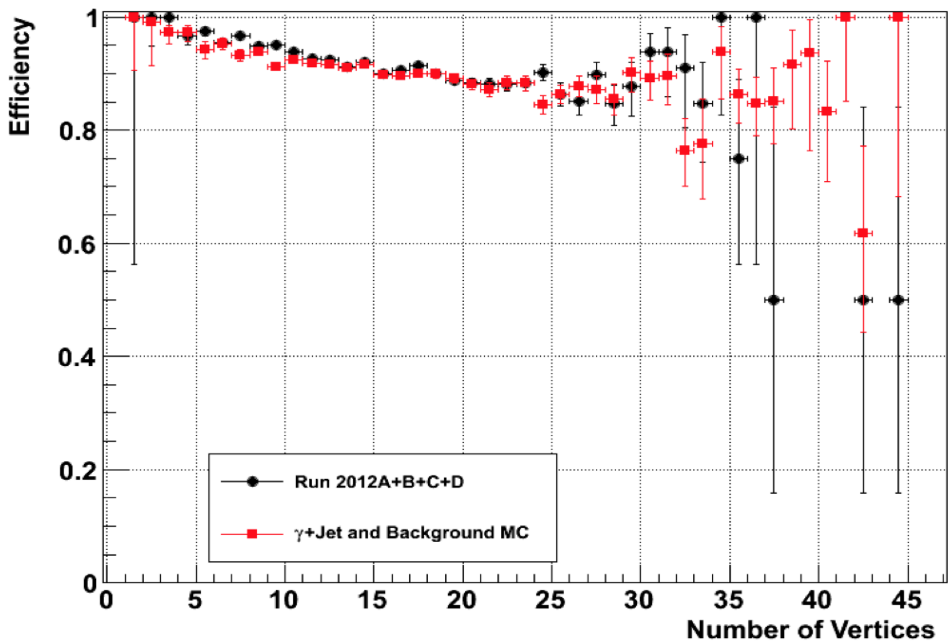
$M_H = 125.8 \pm 0.5(\text{stat.}) \pm 0.2\ (\text{syst.})$ GeV

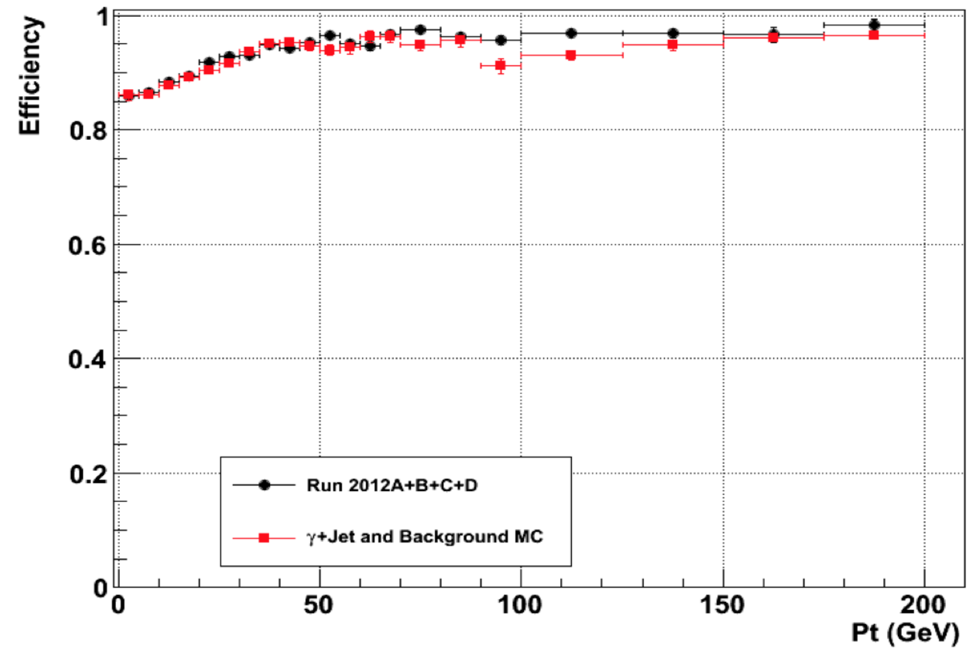




Vertex from converted photons: gam+jet

Vertex pointing from converted photons is validated with γ+jet

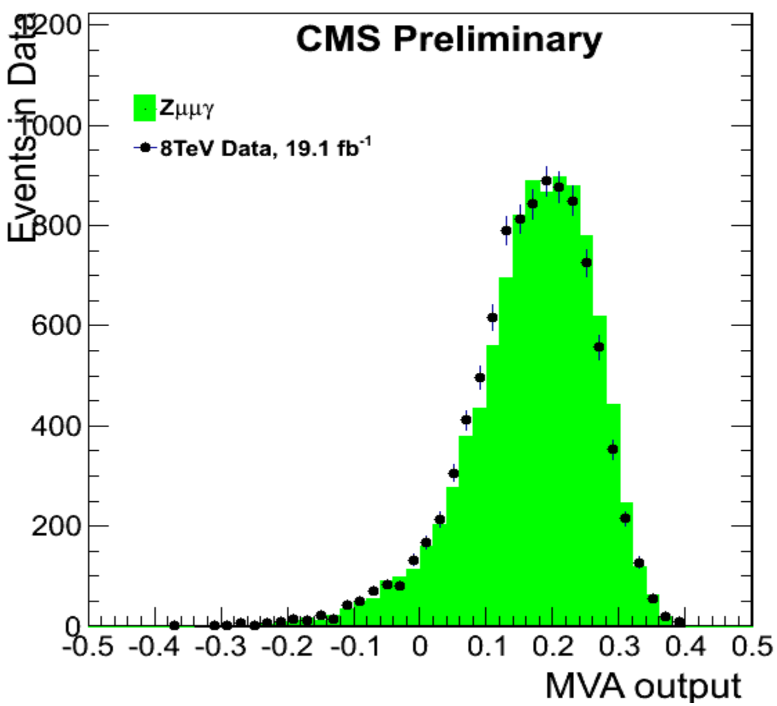




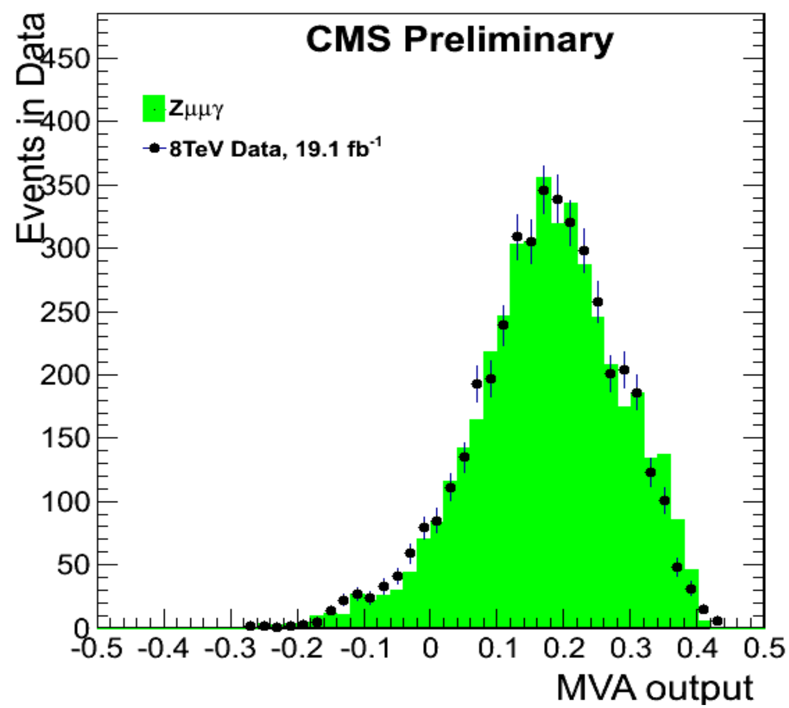
PhotonID MVA

- PhotonID MVA is checked with Z→ee and Z→μμγ

Barrel

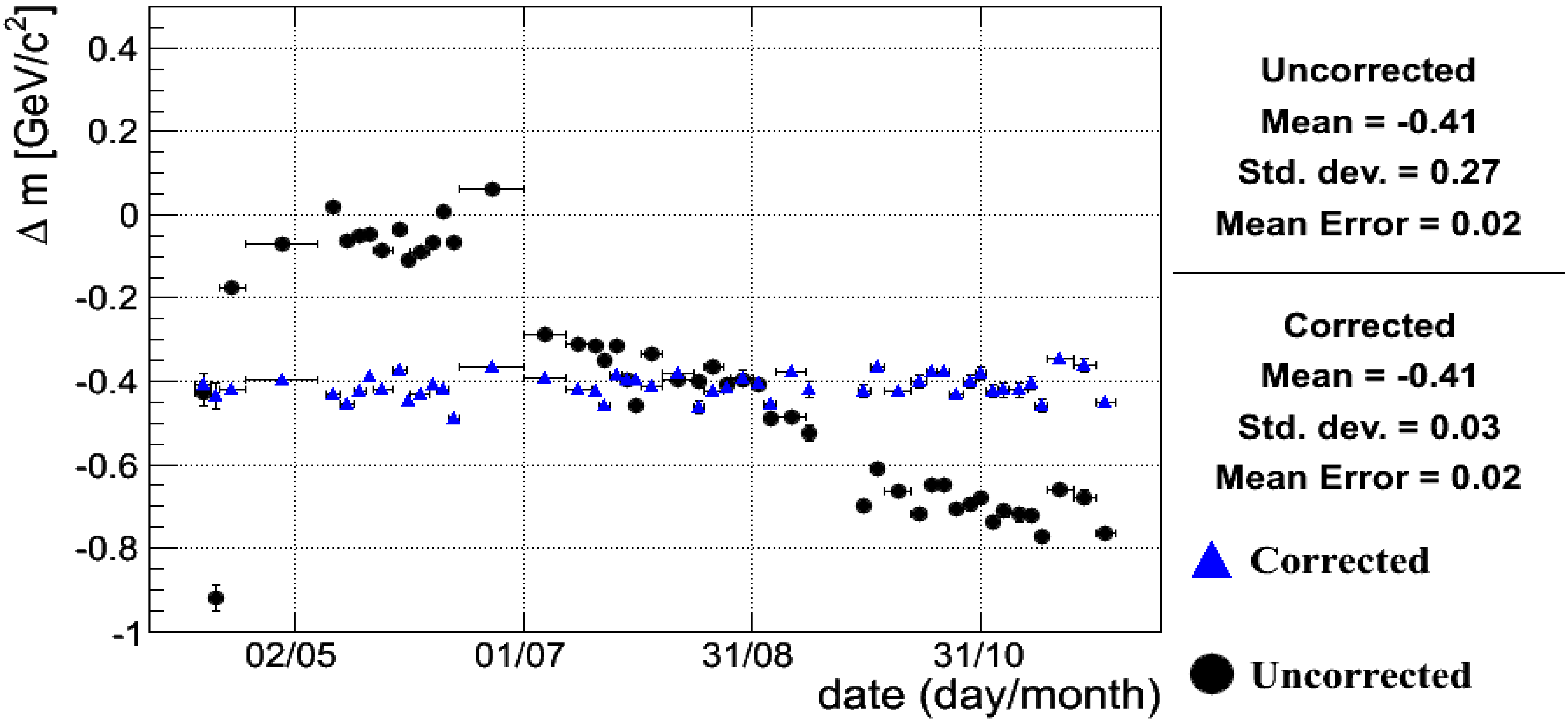


Endcap

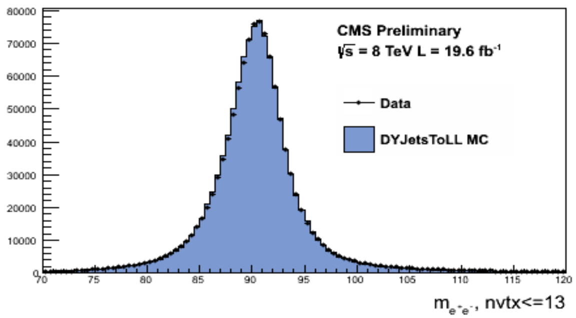


Energy scale vs time

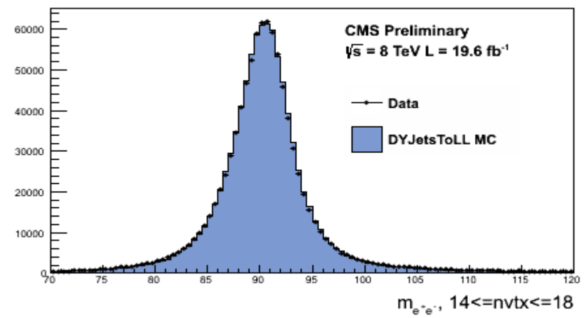
Stability at 0.3% level before application of analysis level corrections with prompt reconstructed data



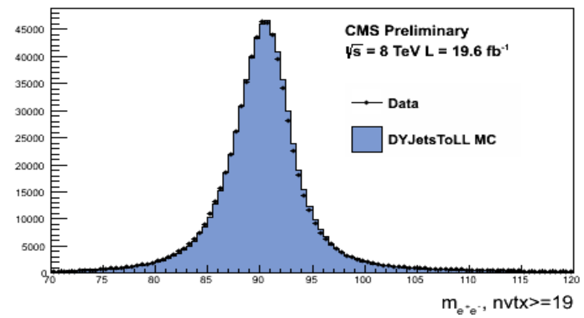
- Data-MC agreement in Z→ee validation maintained across nvtx bins:



nvtx<=13



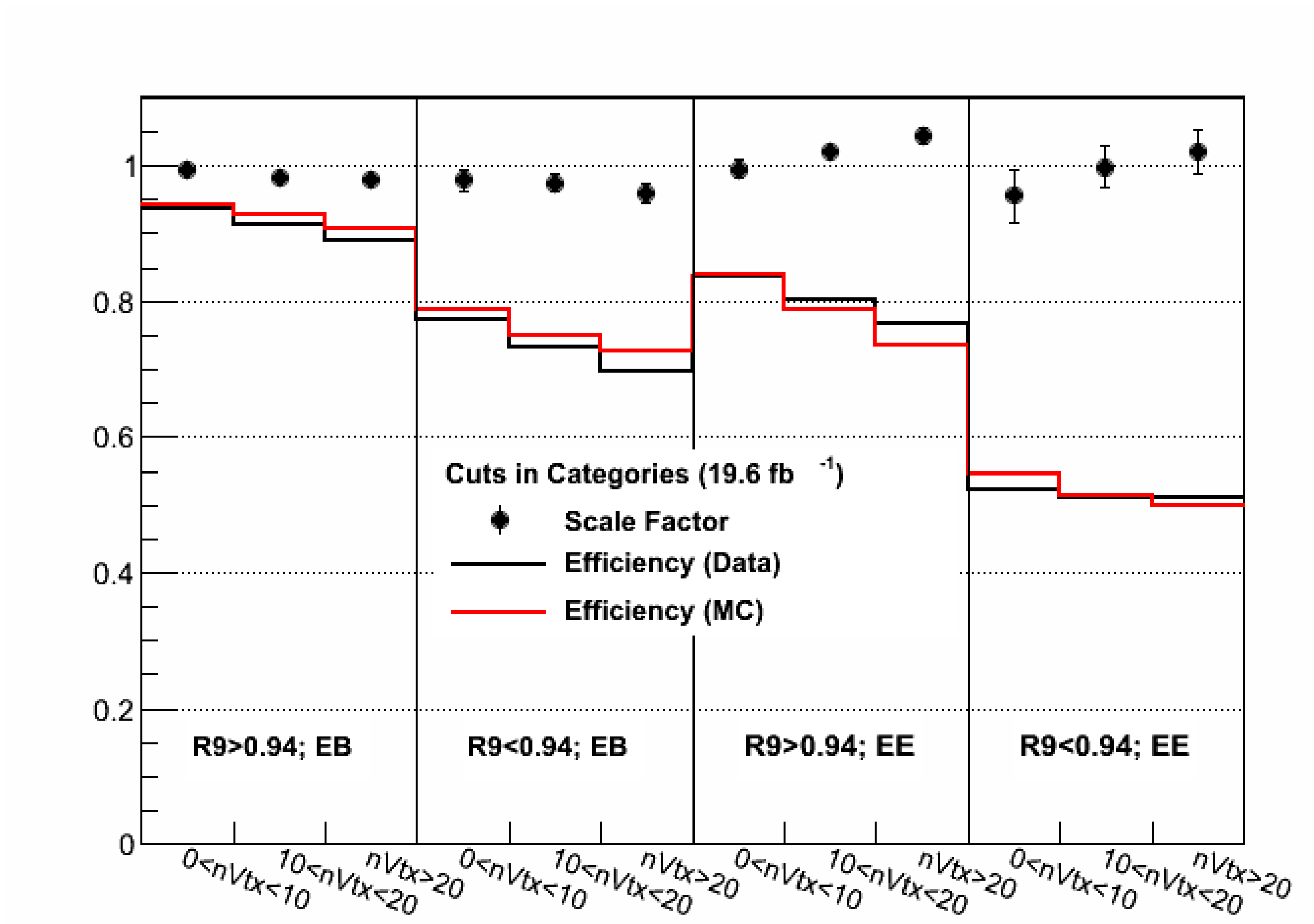
14<=nvtx<=18



nvtx>=19

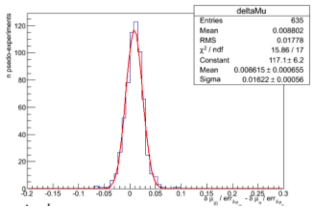
Pileup Robustness: Cut-based ID Efficiency

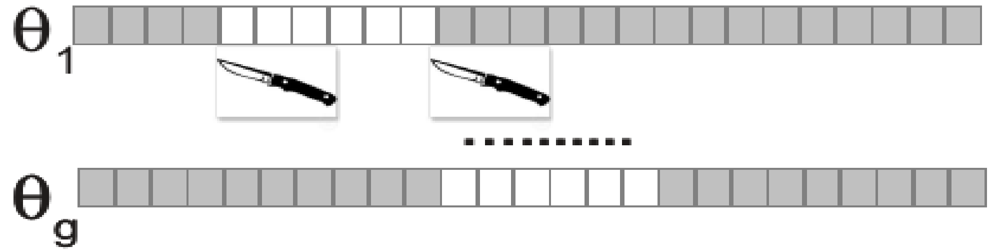
- Cut-based Photon ID efficiency decreases with respect to pileup, well described by MC

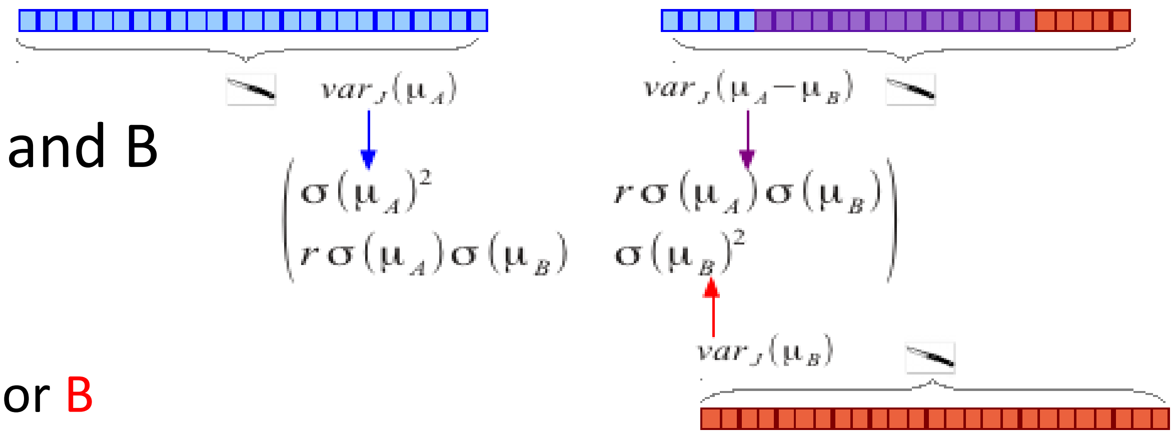


Jacknife resampling

- 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.

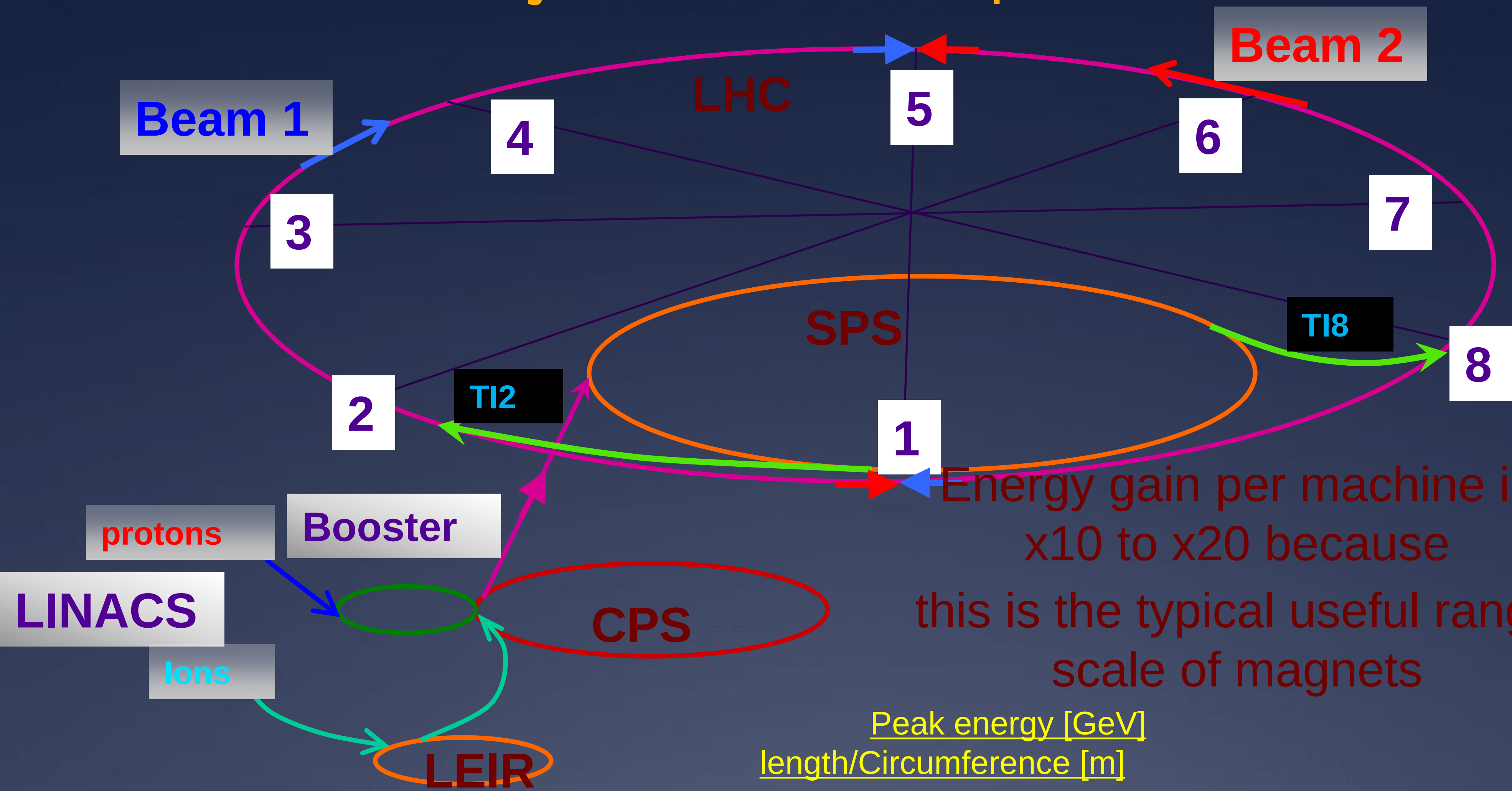






- Cov. matrix given analyses A and B
  - Sample selected by analysis A
  - Sample selected by analysis B
  - Sample selected by analysis A or B
- Estimate the variance of μ_A, μ_B, and μ_A-μ_B applying the jackknife resampling to the events selected. For the latter use events selected by either analysis.

The LHC injector complex



Energy gain per machine is x10 to x20 because
this is the typical useful range scale of magnets

Peak energy [GeV]
length/Circumference [m]

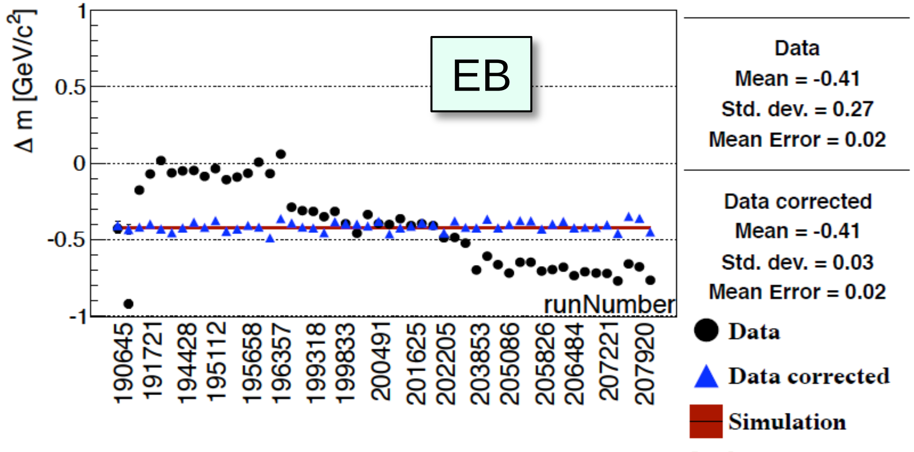
Linac 0.12 30
PSB 1.4 157
CPS 26
628 = 4 PSB
SPS 450
6'911 = 11 x PS

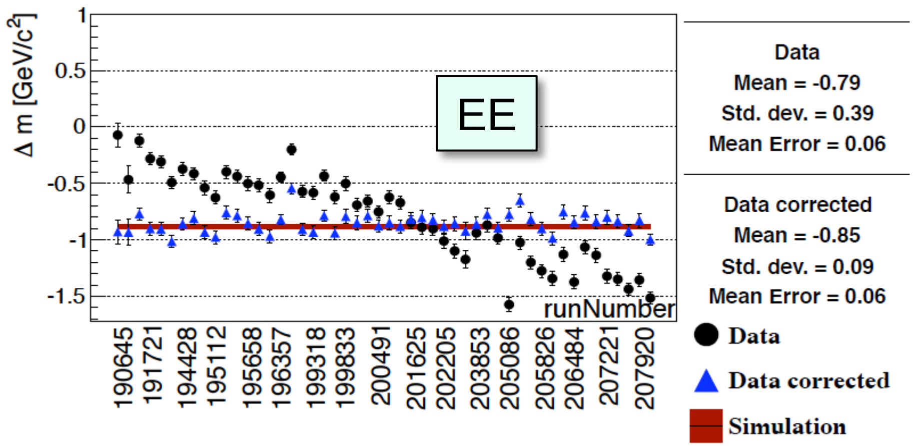
Limit stored energy ⇒ 8 power sectors.
~1 GJ/sector

Sector = 2.9 km, 154 dipoles + 50 quads

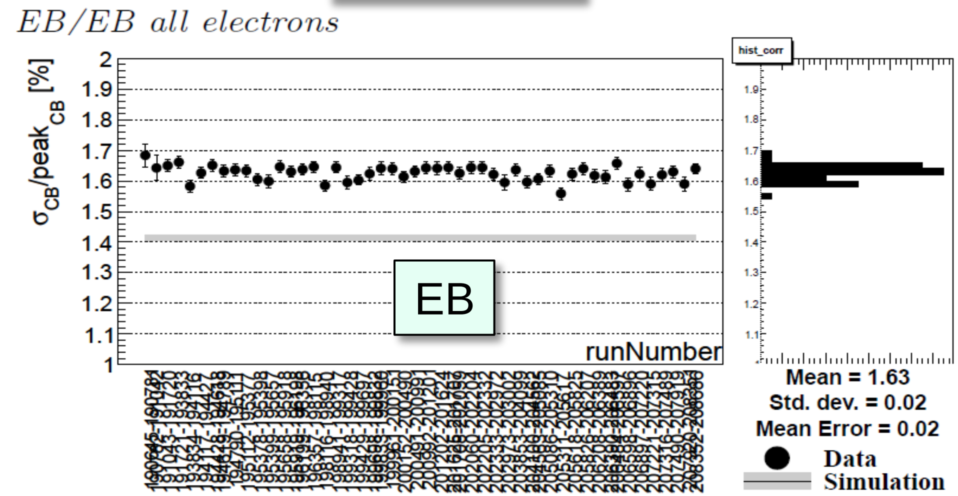
Energy scale and resolution vs run rumber

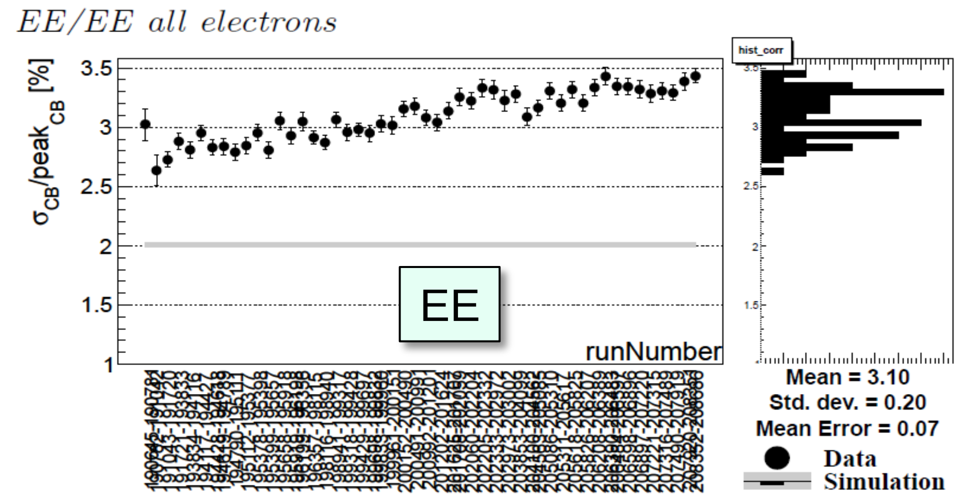
Scale





Resolution

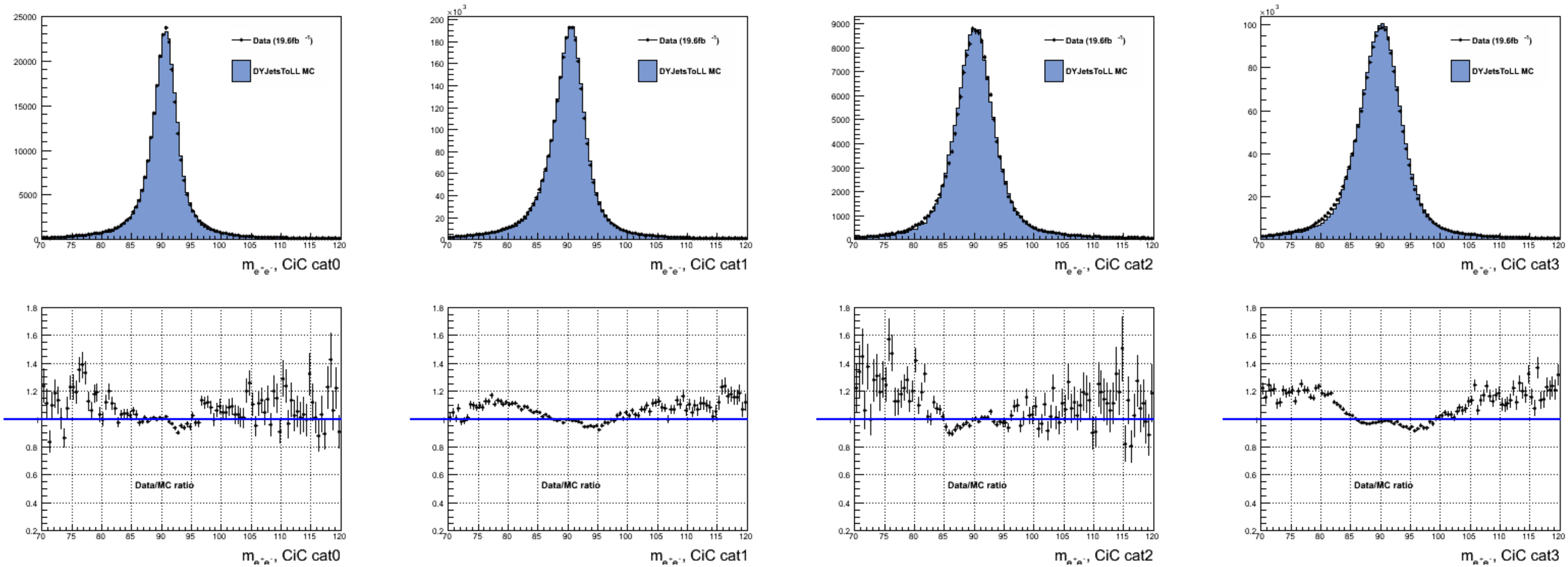




Validation of energy scale and smearing

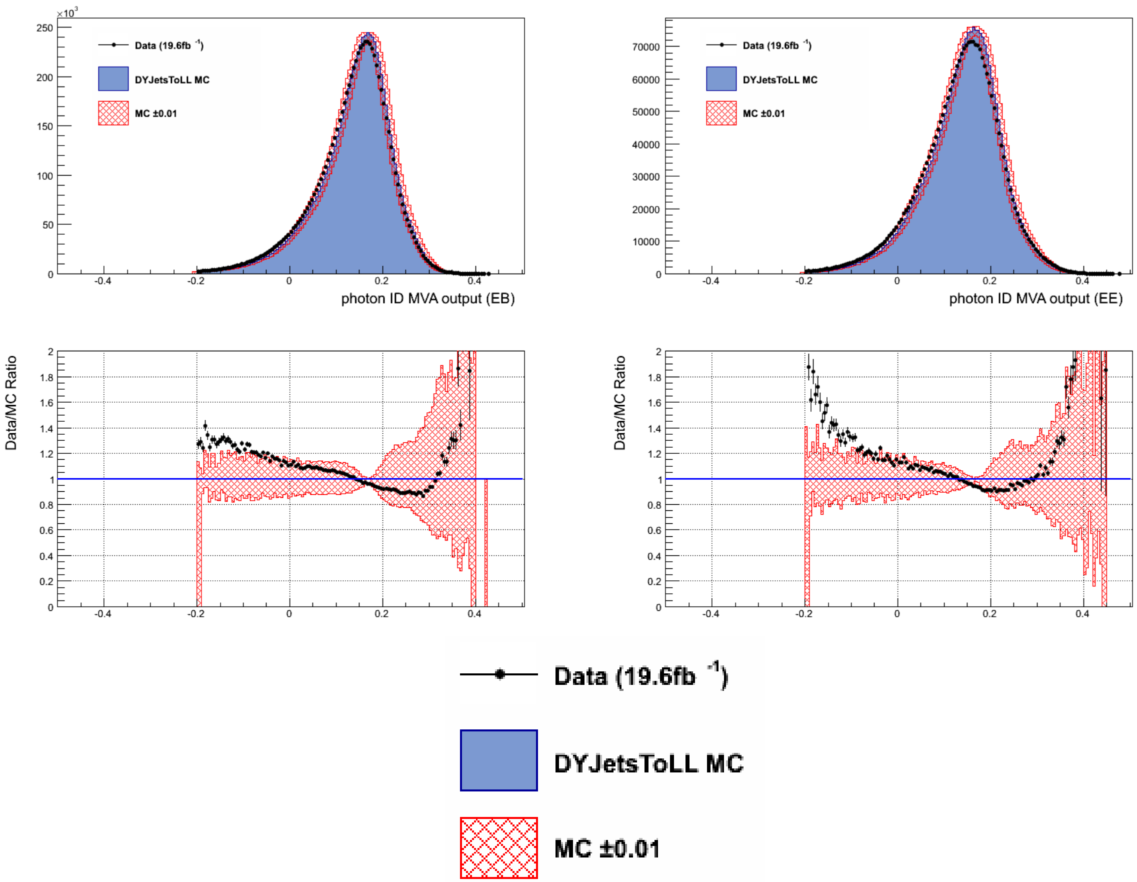
- Validation using electrons reconstructed as photons in Z→ee events
  - Apply H→γγ analysis pre-selection with electron veto inverted

Both EB Both high R9	Both EB At least 1 low R9	At least 1 EE Both high R9	At least 1 EE At least 1 low R9

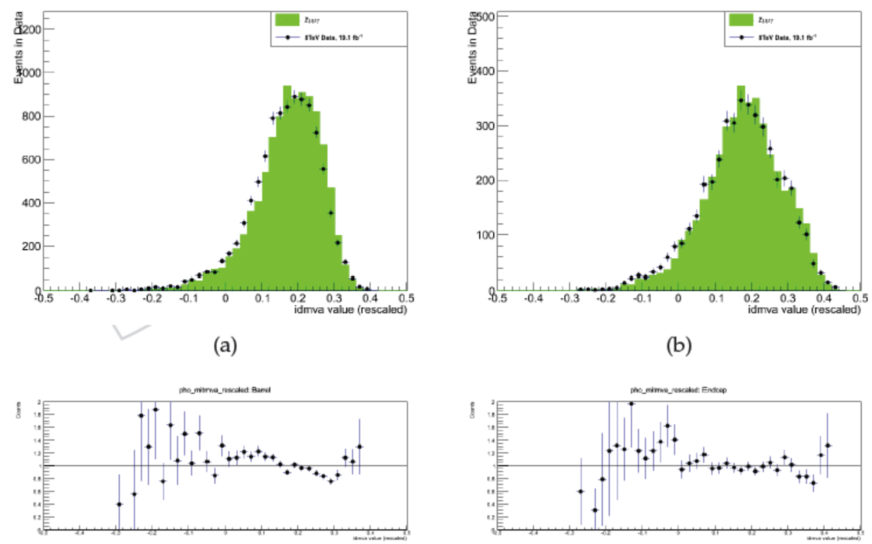


Photon ID MVA: Validation with $Z \to ee$ and $Z \to \mu\mu\gamma$

- Apply photon ID MVA to electrons reconstructed as photons in $Z \to ee$ events (invert electron veto)
  - Some discrepancy observed – discussed later



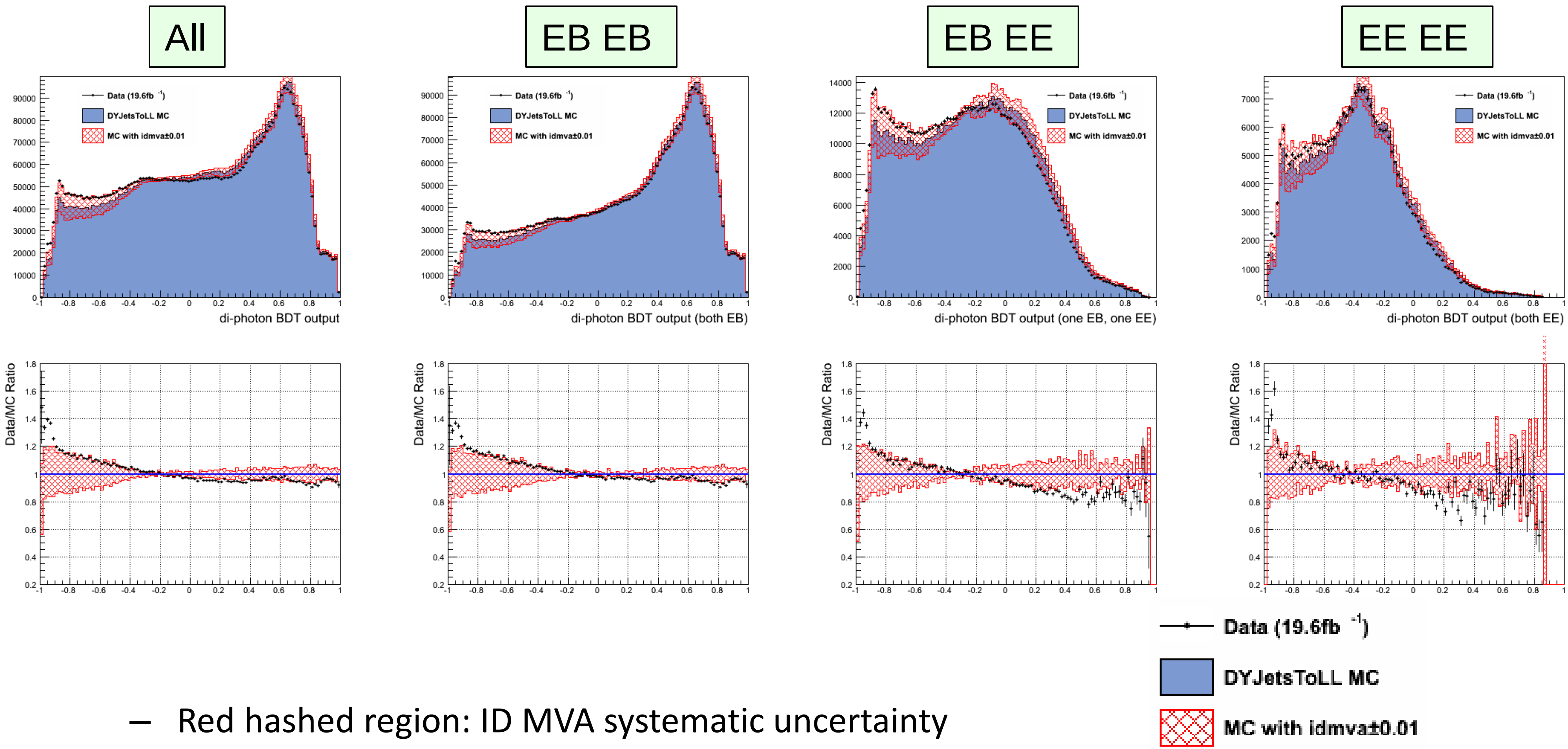
Also validate using $Z \to \mu\mu\gamma$:



(a) (b)

Diphoton MVA output: Validation with Z→ee

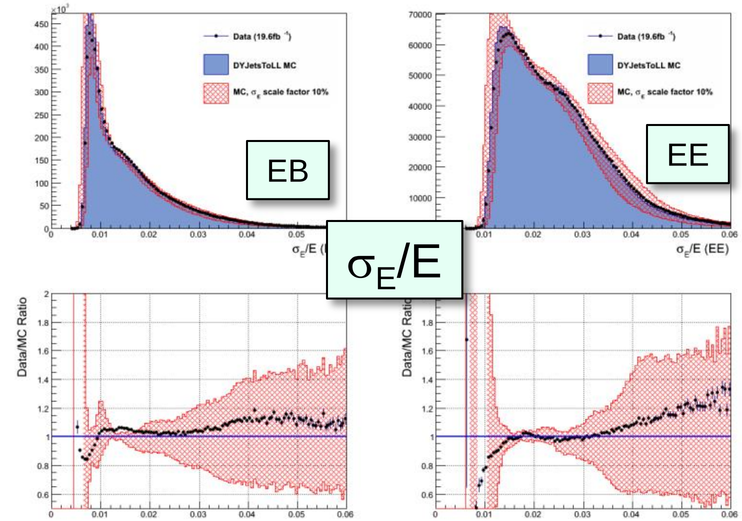
- Validation using electrons reconstructed as photons in Z→ee (electron veto inverted, and p_T reweighted in MC to match data):



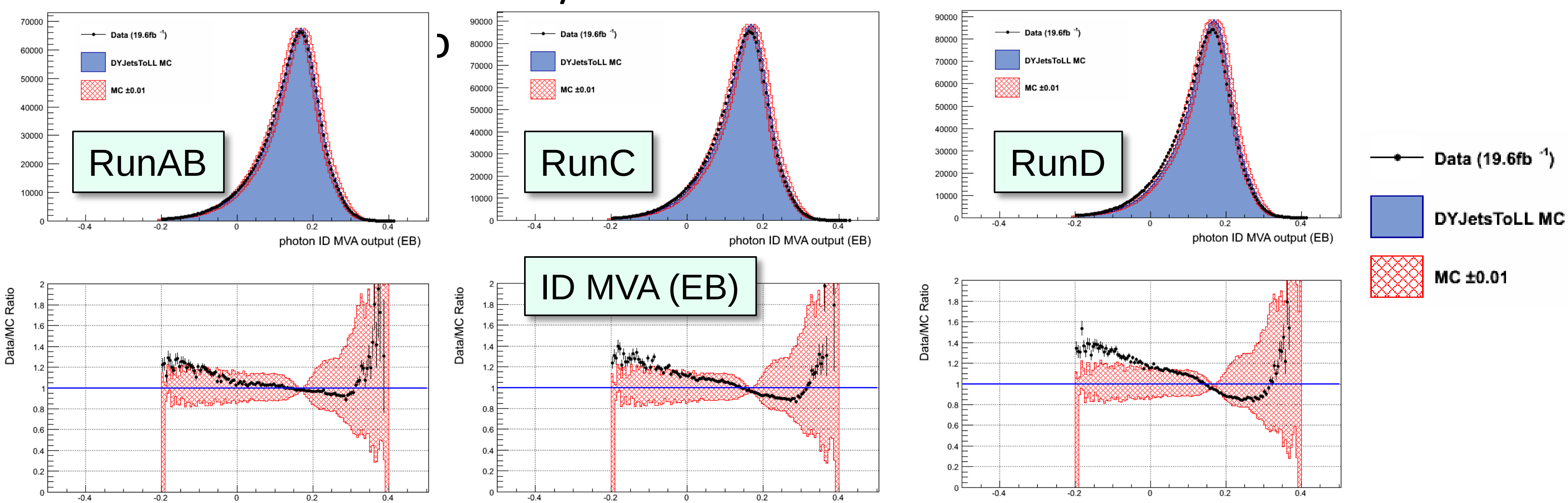
  - Red hashed region: ID MVA systematic uncertainty (±0.01 shift in ID MVA output)

Diphoton MVA output: Validation with Z→ee

- The discrepancy in the diphoton MVA output originates from two of the inputs:
  - The photon identification MVA
  - The per-photon energy resolution estimator.

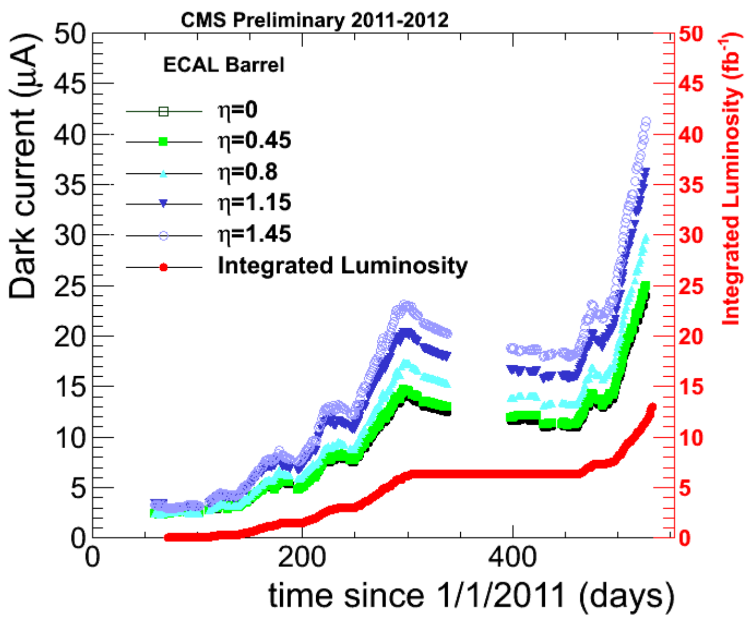


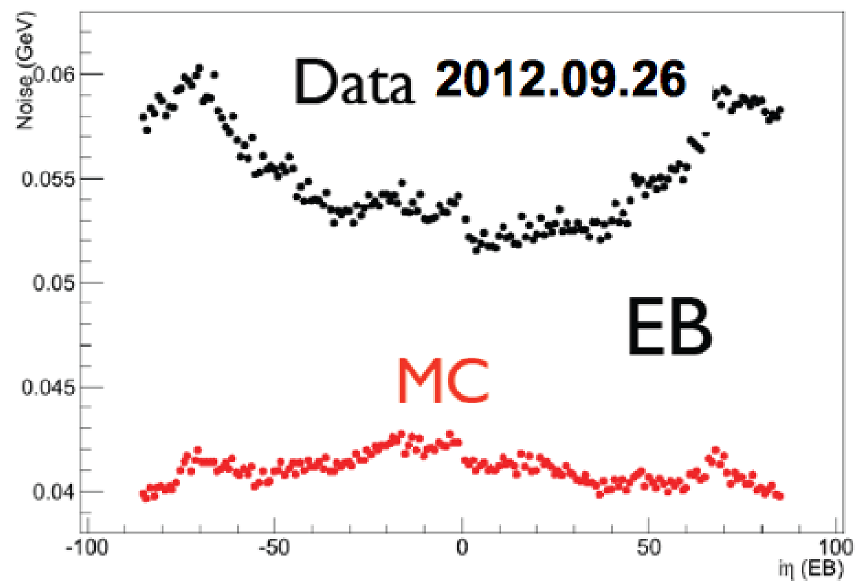
- For the ID MVA the data/MC



The likely cause of the discrepancy

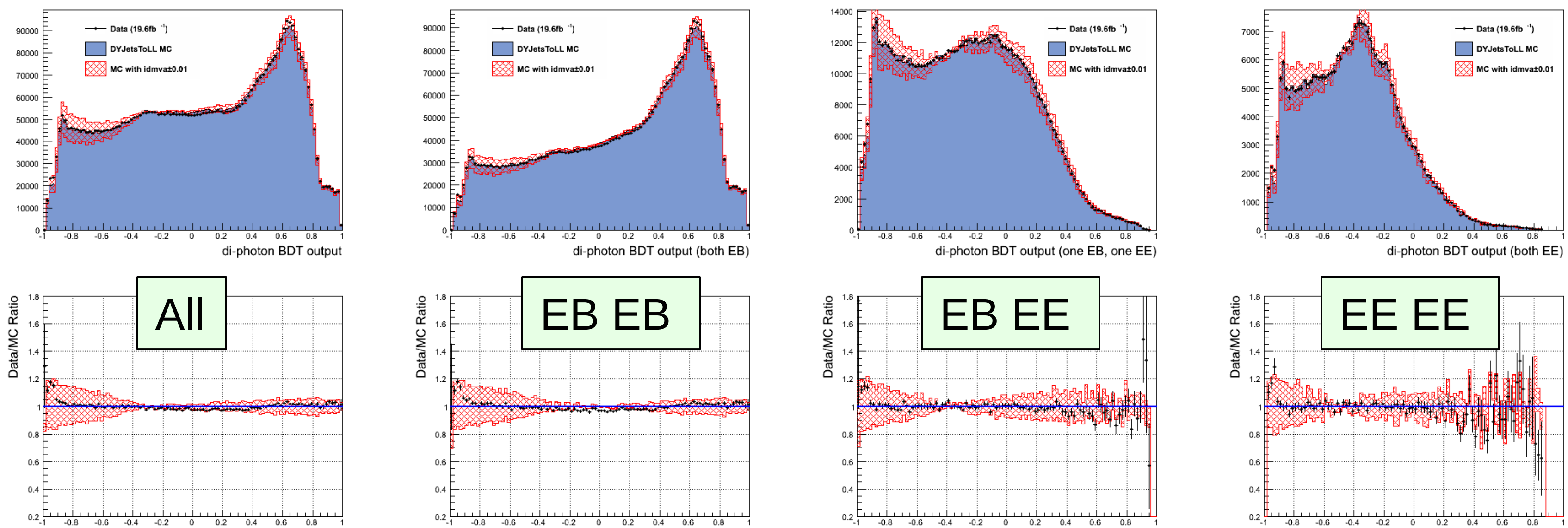
- The source of the discrepancy is believed to be the imperfect simulation of the ECAL noise.
- The worsening with time can be understood in terms of the noise evolution during the run, due to APD irradiation.
- The origin of the photon ID MVA disagreement seems to be linked to the most noise-sensitive cluster shape variables.





Diphoton MVA validation after Corrections

- The data and MC distributions from Zee for the ID MVA and σ_E/E have been used to derive scaling correction functions which can be applied to the MC in order to make the distributions match the data **– validated using Z→μμγ**
  - ID MVA corrections derived separately for R9 >0.94 and for R9 <0.94
  - σ_E/E corrections derived separately for inner ($|\eta|<1.0$) and outer barrel, and for inner ($|\eta|<2.0$) and outer endcaps
- With these corrections applied, data-MC agreement for the diphoton MVA becomes very good. The corrections are applied in the analysis.



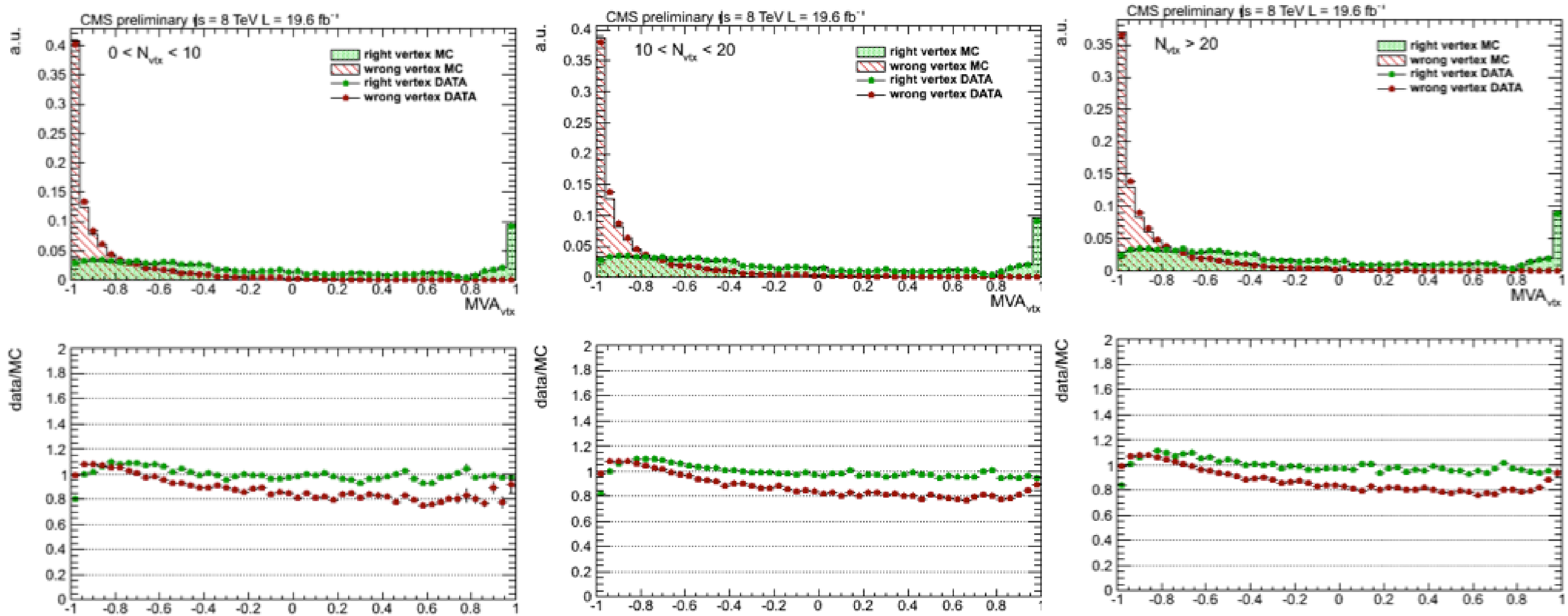
Effect of the corrections on the analysis

- The corrections only affect the analysis through the signal model (background is from data).
- To quantify the size of the effect, signal yields have been calculated with and without the corrections applied
- The difference in category ε x A is small: <2% on the full 2012 dataset. For run D alone the difference increases to 3%.
  - Within the systematic uncertainties assigned for the ID MVA and σ_E/E

RUN ABCD L=19.6 fb-1				
Process	bdt0	bdt1	bdt2	bdt3
ggh	12.799 12.663 -1.1 %	33.128 32.514 -1.9 %	142.567 139.767 -2.0 %	149.226 147.935 -0.9 %
vbf	2.047 2.009 -1.9 %	3.320 3.263 -1.7 %	6.787 6.717 -1.0 %	6.237 6.213 -0.4 %
wzh	2.287 2.255 -1.4 %	2.842 2.794 -1.7 %	5.487 5.400 -1.6 %	5.321 5.299 -0.4 %
tth	0.457 0.447 -2.2 %	0.386 0.381 -1.3 %	0.559 0.553 -1.2 %	0.403 0.405 0.6 %
Total	17.590 17.374 -1.2 %	39.676 38.952 -1.8 %	155.399 152.438 -1.9 %	161.186 159.851 -0.8 %

Vertex ID MVA in nvtx bins

- Binning the comparison according to the number of PV show no hint of mismodelling.
  - MC tracks data very closely in all PU conditions.



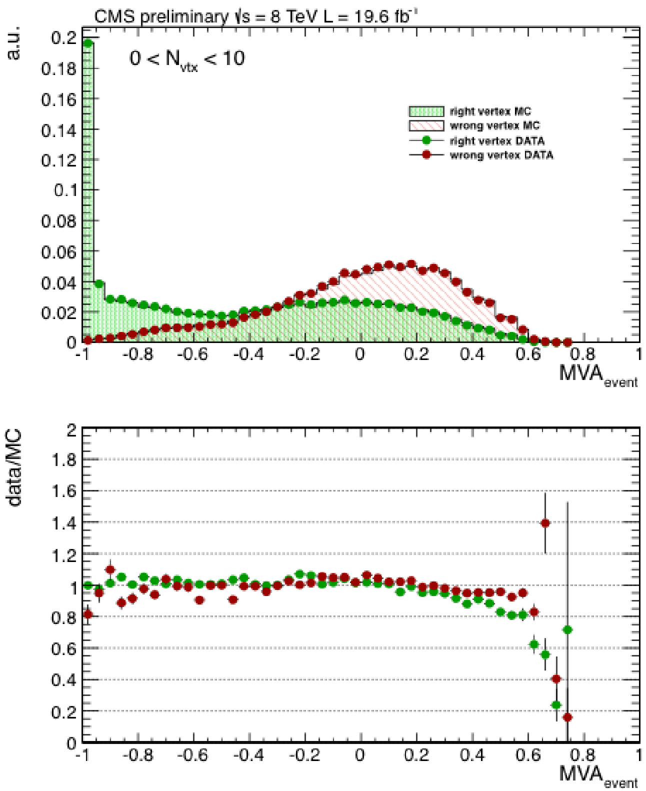
nvtx<=13

14<=nvtx<=18

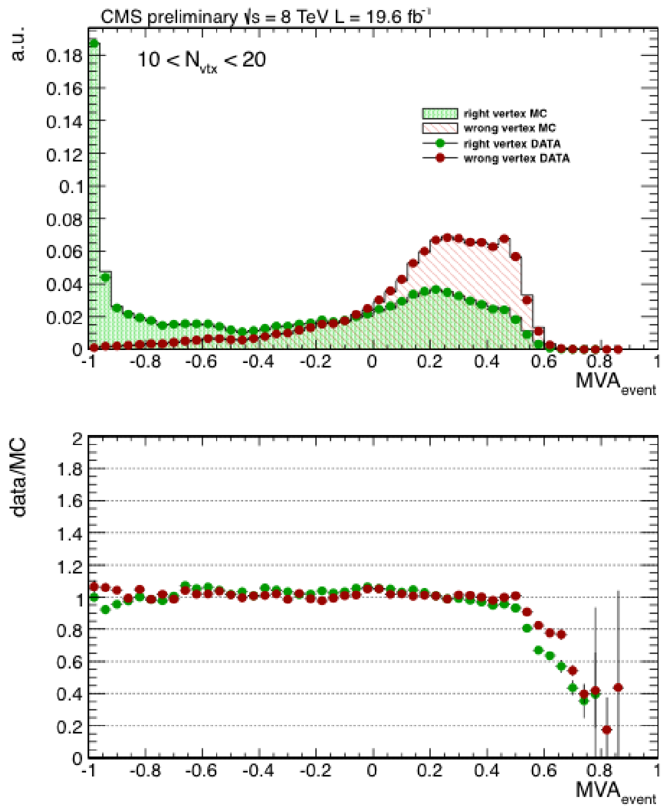
nvtx>=19

Vertex probability MVA in nvtx bins

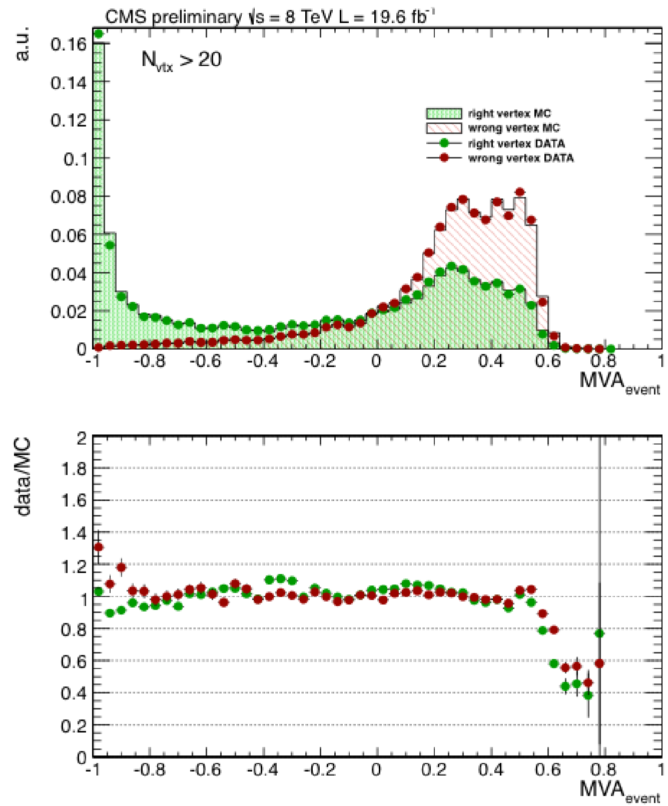
nvtx<=13



14<=nvtx<=18

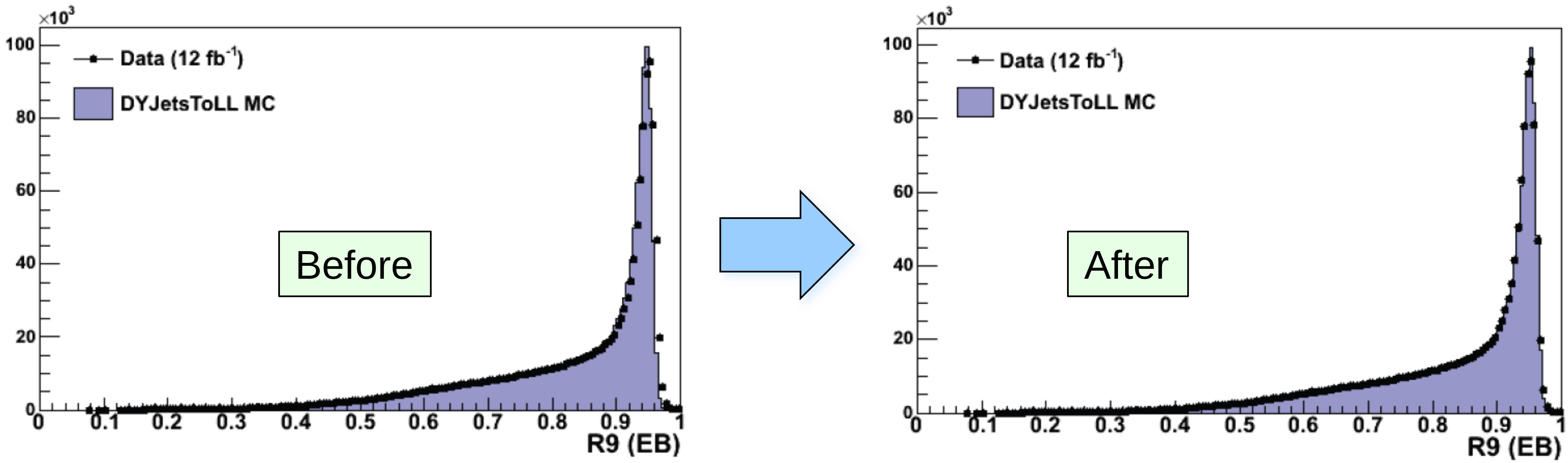


nvtx>=19



Cluster Shape Corrections

- Shower shape variables suffer from known data-MC discrepancies at the level of the Geant EM-shower simulation
- Corrections to shower shape applied to MC :
  - Linear rescaling, derived using probe electrons from Zee tag and probe, applied event-by-event in MC such that the distribution matches the data



Photon pre-selection

- Loose pre-selection designed to be tighter than the trigger selection, as well as the EM enrichment filters in γ+jet and QCD MC
- Change w.r.t. ICHEP/HCP: drop detector based ECAL isolation cut
  - Definition changed in the HLT but not offline; observed to be not well described by the simulation due to the increase of ECAL noise with time
  - Trigger efficiency for photons passing the pre-selection remains >99.5%

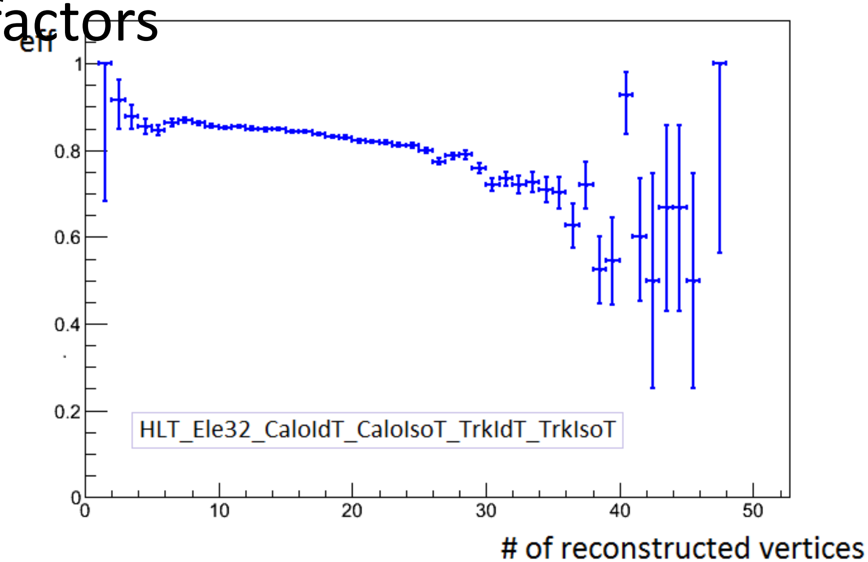
	Barrel		Endcap	
R9	HoE	CovIEtaIEta	HoE	CovIEtaIEta
≤ 0.9	< 0.075	< 0.014	< 0.075	< 0.034
> 0.9	< 0.082	< 0.014	< 0.075	< 0.034
	Both Barrel and Endcap			
R9		EtCorrHcalIso	EtCorrTrkIso	ChargedPFIso
≤ 0.9		< 4 GeV	< 4 GeV	< 4 GeV
> 0.9		< 50 GeV	< 50 GeV	< 4 GeV

- Conversion safe electron veto is applied at this stage
  - Veto if the SC matches a GsfElectron with no missing hits, provided that it does not also match a reconstructed conversion
  - Inverted for signal model validation using $Z\rightarrow ee$
  - Efficiency measured using $Z\rightarrow\mu\mu\gamma$

Photon pre-selection: Efficiency scale factors

- Efficiency measured using tag and probe. In a change w.r.t. ICHEP/HCP, the tag and probe sample is selected using the following trigger only in order to reduce a bias towards low pileup:
  - HLT_Ele32_CaloIdT_CaloIsoT_TrkIdT_TrkIsoT_SC17_Mass50_v*

- Residual bias (even after restricting to the above trigger path) is corrected for by reweighting events in the determination of the scale factors



Pre-Selection Scale Factors	
	Data/MC
EB R9>0.9	0.997± 0.003
EB R9<0.9	0.978 ± 0.006
EE R9>0.9	1.006 ± 0.009
EE R9<0.9	0.990 ± 0.018

MVA analysis: Event classification

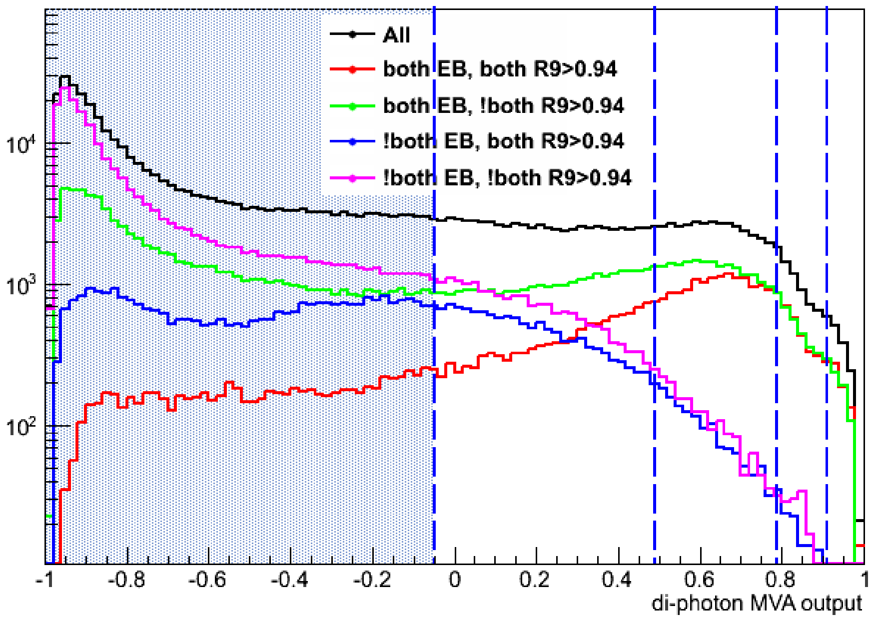
- Event classes are defined from the diphoton MVA output as follows:

Category	Lower boundary	Upper boundary
cat0	0.91	1
cat1	0.79	0.91
cat2	0.49	0.79
cat3	-0.05	0.49

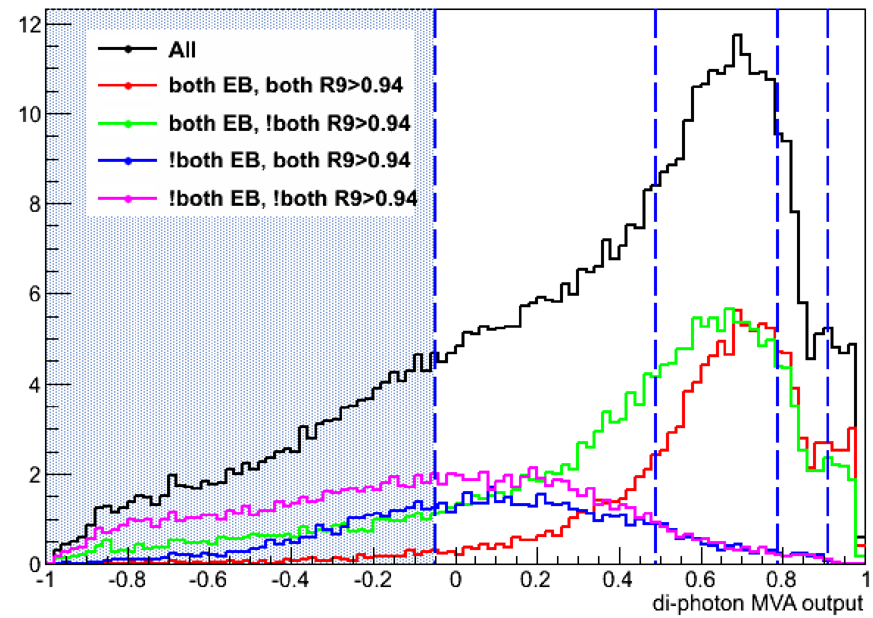
- Events with diphoton MVA output < -0.05 are rejected

Relation between MVA and cut based event classes

Data

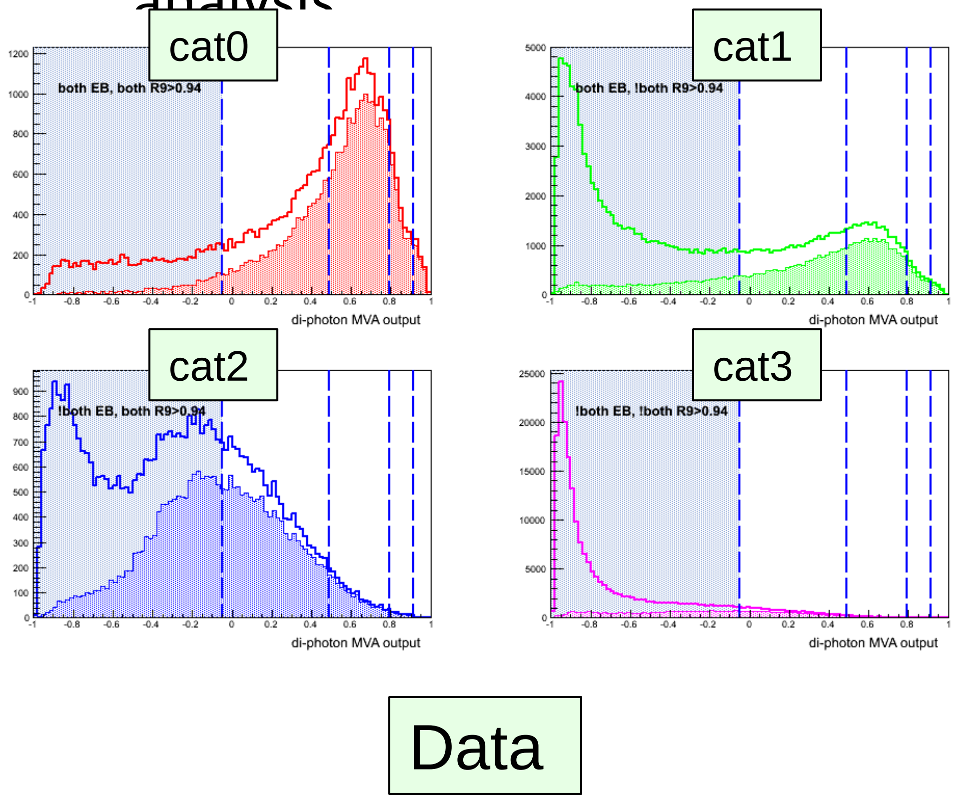


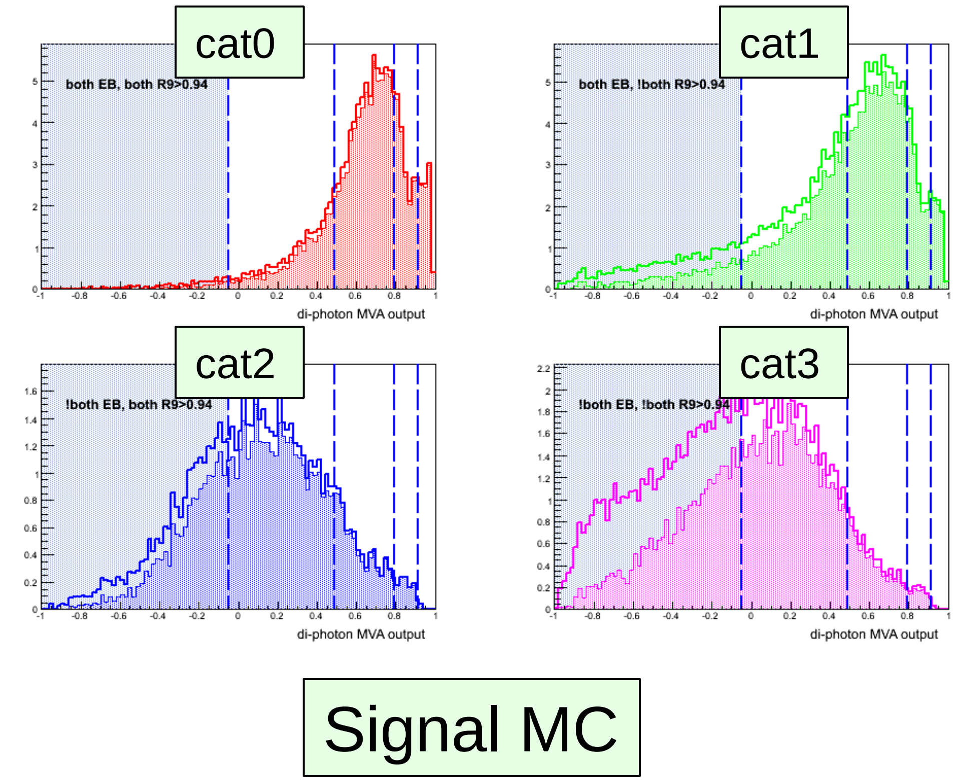
Signal (H→γγ)



Event Overlap - MVA vs CIC

- Diphoton MVA distribution in CiC categories for all pre-selected events (unshaded) and events passing the CiC selection (shaded)
- Region shaded light blue indicates events not selected by the MVA analysis





Event classification for cut based analysis

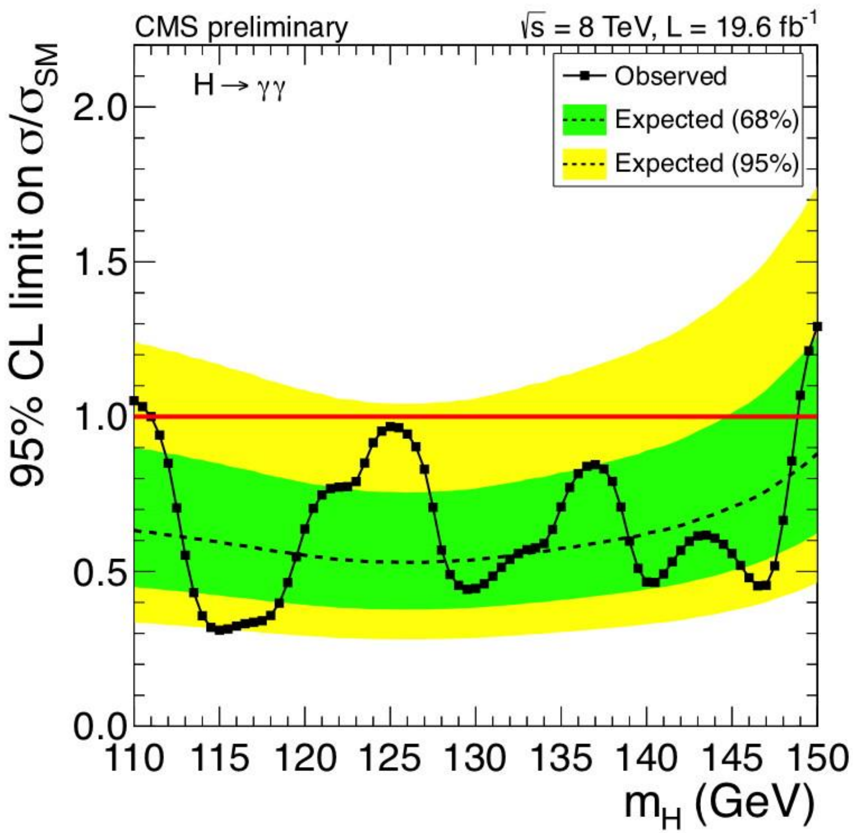
- Events are split into four categories to account for different resolutions and S/B ratios. Analysis performed by fitting $m_{\gamma\gamma}$ spectrum in each c

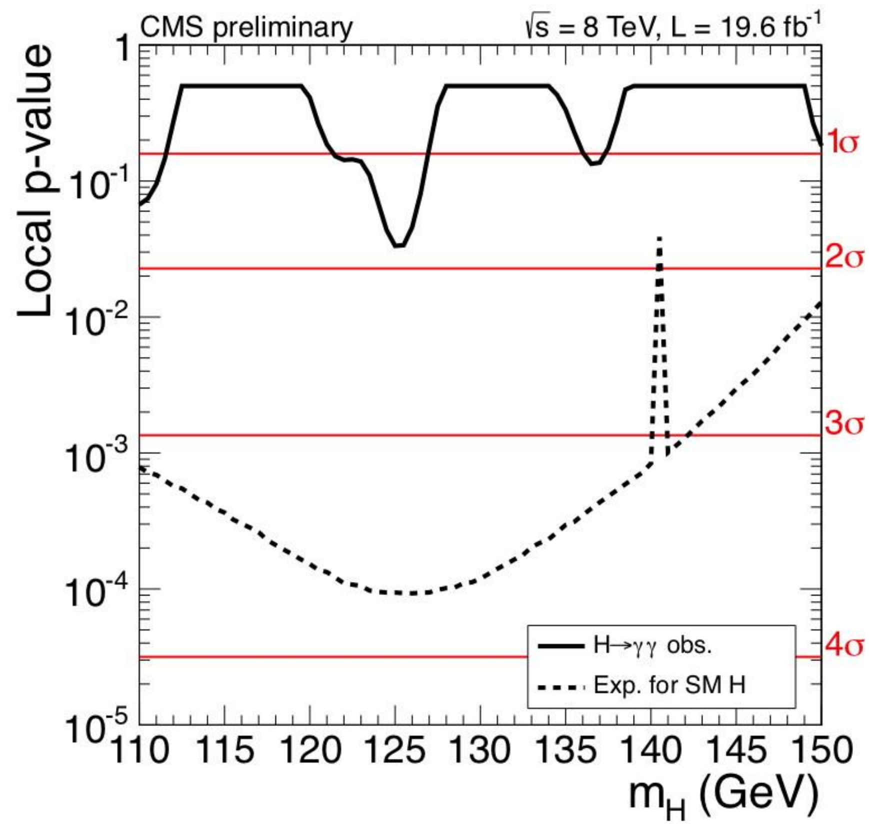
cat0	Both photons in EB	Both photons R_9>0.94
cat1	Both photons in EB	At least one photon with R_9<0.94
cat2	At least one photon in EE	Both photons R_9>0.94
cat3	At least one photon in EE	At least one photon with R_9<0.94

- The modelling of the R_9 categorization for photons have been checked using t ns is well modell

	Data 8TeV 19.6fb^{-1}	MC	Ratio
EB	0.611±0.009	0.619±0.008	0.99±0.02
EE	0.610±0.009	0.635±0.013	0.96±0.02

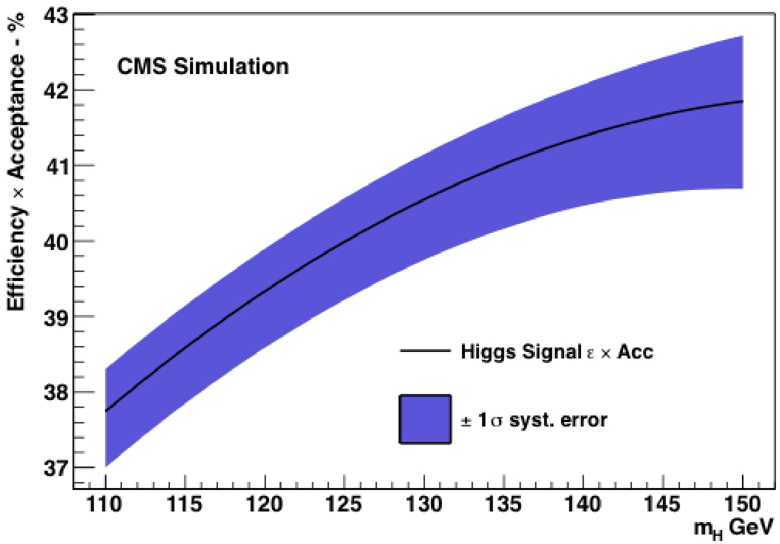
8TeV MVA Results from alternative framework



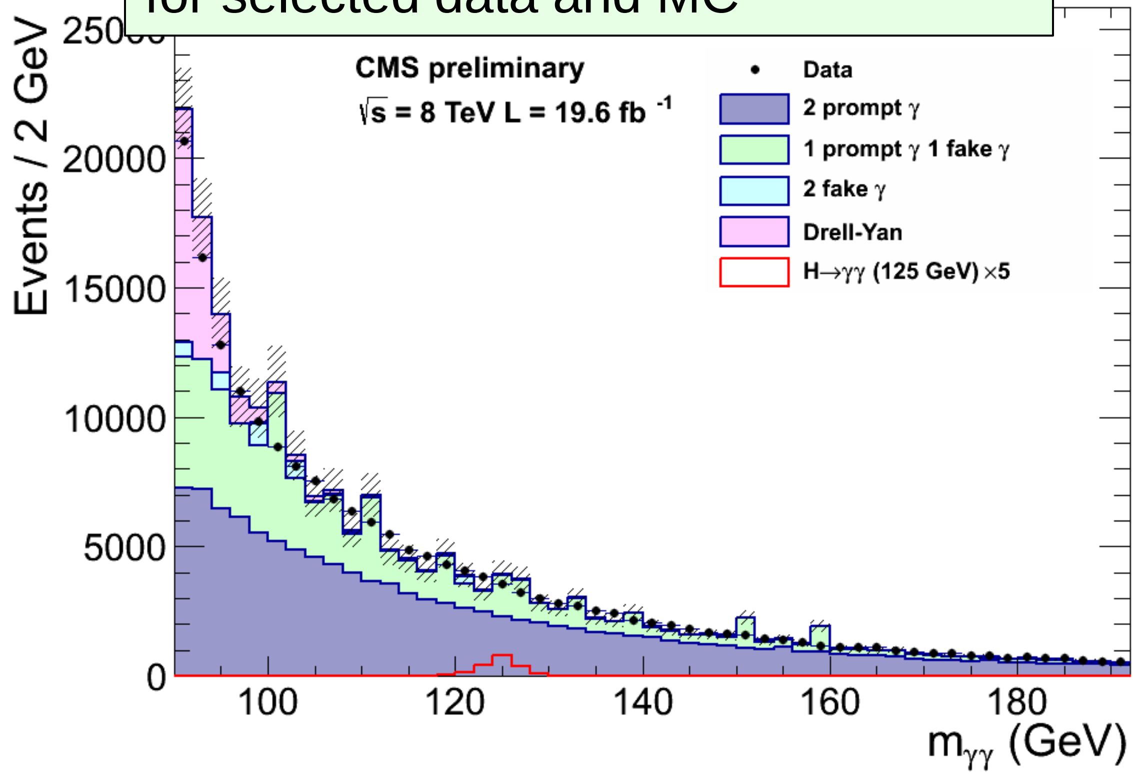


MVA analysis: Selected event sample

Signal Acceptance × Efficiency



Inclusive invariant mass distribution for selected data and MC



Cross-checks

General remarks

- The S/B ratio in the Higgs to gamma gamma analysis is relatively low. As a result, changes in observed results induced by changes in the selection are always dominated by statistical fluctuations in the background.
- Several of the cross-checks requested by the ARC involve calculating the observed μ for different analysis configurations and/or data subsets. Such results are presented with the caveat that it is difficult to draw conclusions from such tests given the dominance of the background statistical uncertainty.

Previous validation of the analysis

- All relevant inputs to both analyses have been validated and/or corrections derived on appropriate control samples ($Z \rightarrow ee$, $Z \rightarrow \mu\mu\gamma$, high mass di-photons, $Z \rightarrow \mu\mu$)
- A comprehensive set of validation and corrections were completed prior to unblinding: analyses believed to be correct at that time, but the surprising results understandably triggered additional tests
- An extensive list of cross-checks were performed between the unblinding and the pre-approval:
  - Many details were checked relating to energy scale, resolution, and modelling of the photon and vertex identification
  - The full list of checks can be found at these links:
    - https://twiki.cern.ch/twiki/bin/viewauth/CMS/H2GMoriondChecks
    - https://twiki.cern.ch/twiki/bin/view/CMS/H2GMoriondARCAnswers

Event Overlap - MVA vs CIC

- Observed signal strength for 8TeV dataset:

Analysis	Observed μ
Mass factorized MVA	$0.54^{+0.31}_{-0.26}$
Cut based	$0.96^{+0.37}_{-0.33}$

- Difference taking into account correlations (jackknife):
  - $\sigma(\delta\mu) = 0.23$ - corresponds to 1.8σ

- Expressed as a correlation coefficient, results are 85% correlated
- Event Overlap in data: 50% overall, 60% for barrel-barrel events
- Event Overlap in signal MC: 81% overall, 86% for barrel-barrel events

Comparison of signal strength for 7 and 8 TeV datasets

- Observed signal strength for MVA analysis for 7 and 8 TeV:

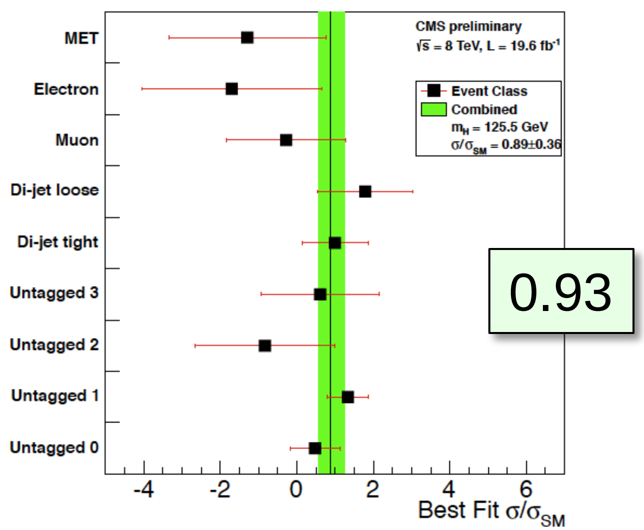
Analysis	Observed μ
8TeV MVA	$0.54^{+0.31}_{-0.26}$
7TeV MVA	$1.69^{+0.65}_{-0.59}$

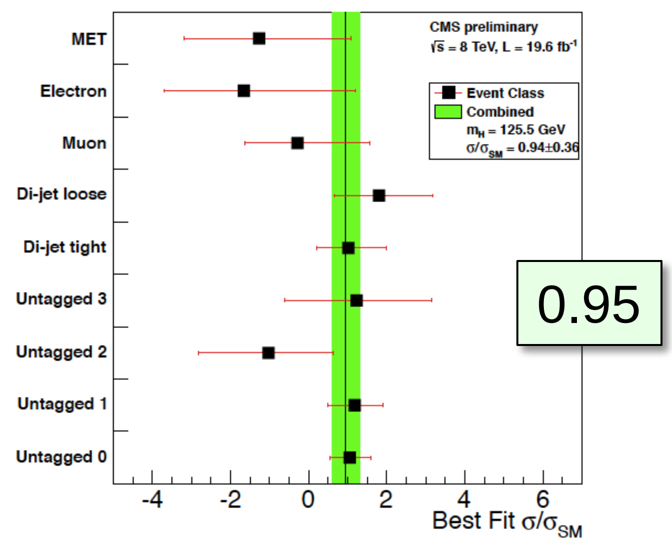
Cut-based Stability vs R9 Boundary

- R9 boundary used for event categorization in CIC analysis varied and μ re-determined:

R9 boundary	μ (m_H=125.5 GeV)
0.93	$0.94^{+0.37}_{-0.33}$
0.94 (nominal)	$0.96^{+0.37}_{-0.33}$
0.95	$0.89^{+0.37}_{-0.33}$

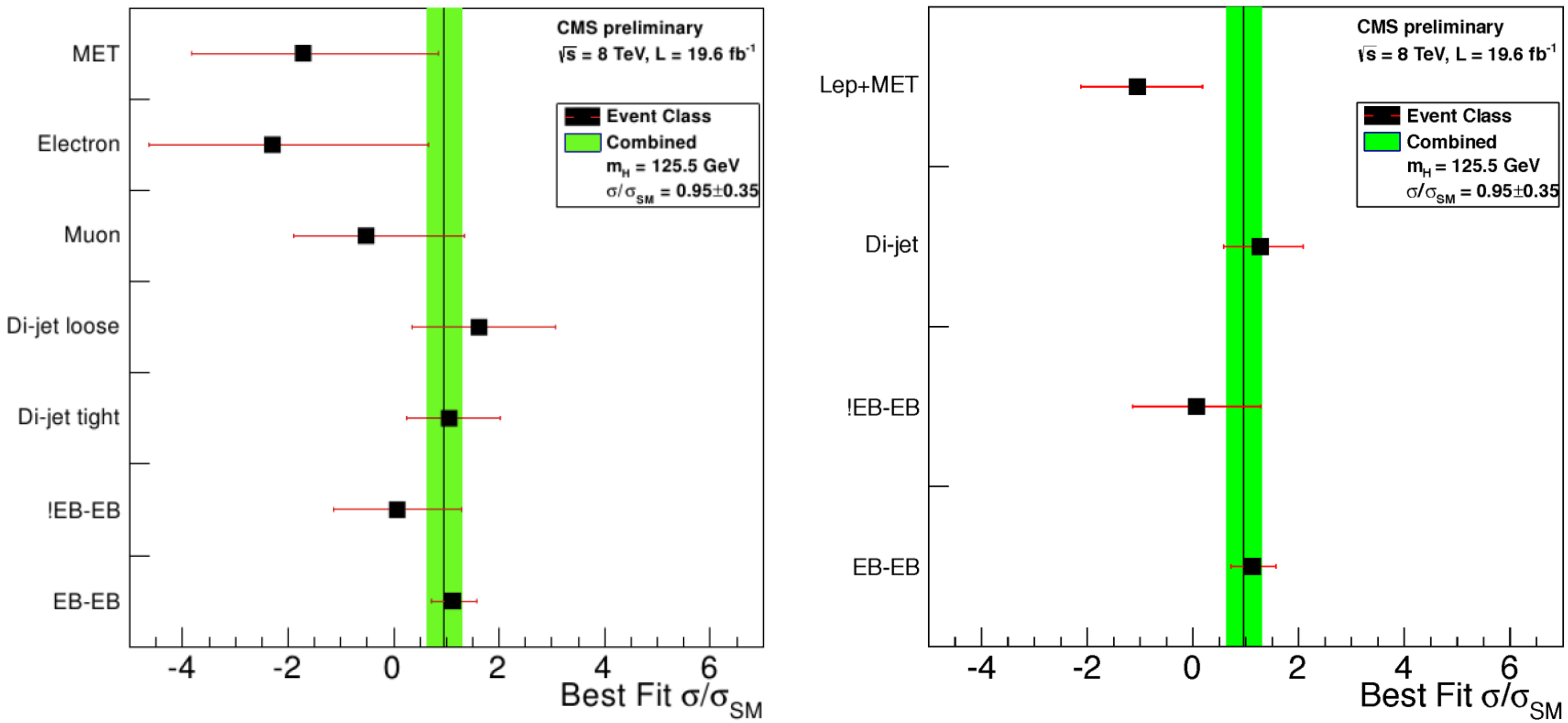
- Moderate shuffling of events between categories, no large changes expecte





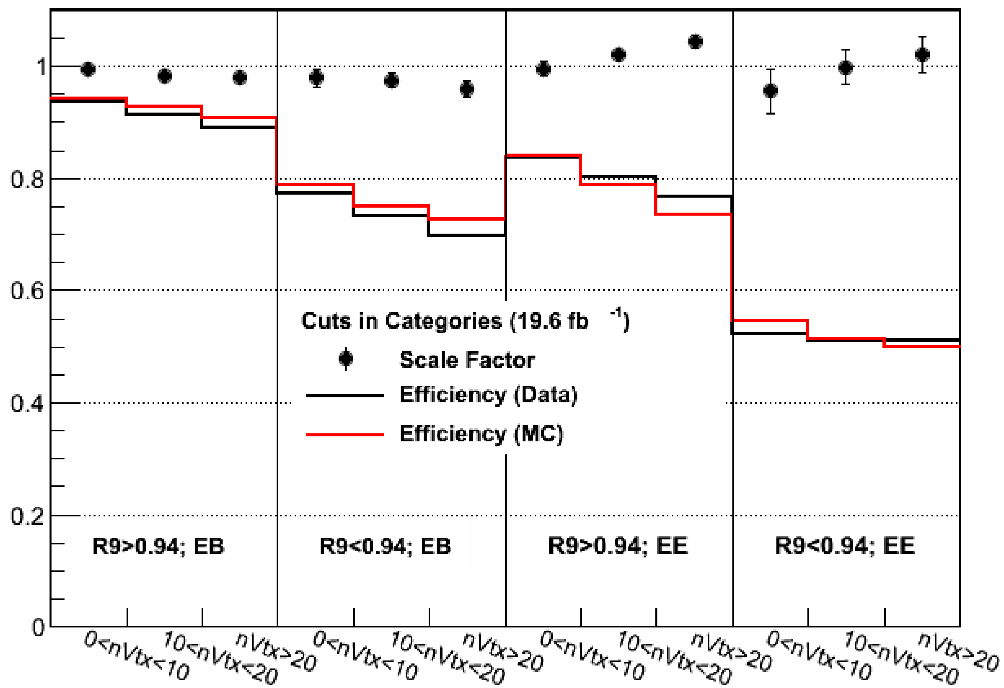
Cut-based Barrel vs Endcap Compatibility

- Endcap categories compatible with barrel-only within the large statistical uncertainties (and contribute relatively less to the overall)

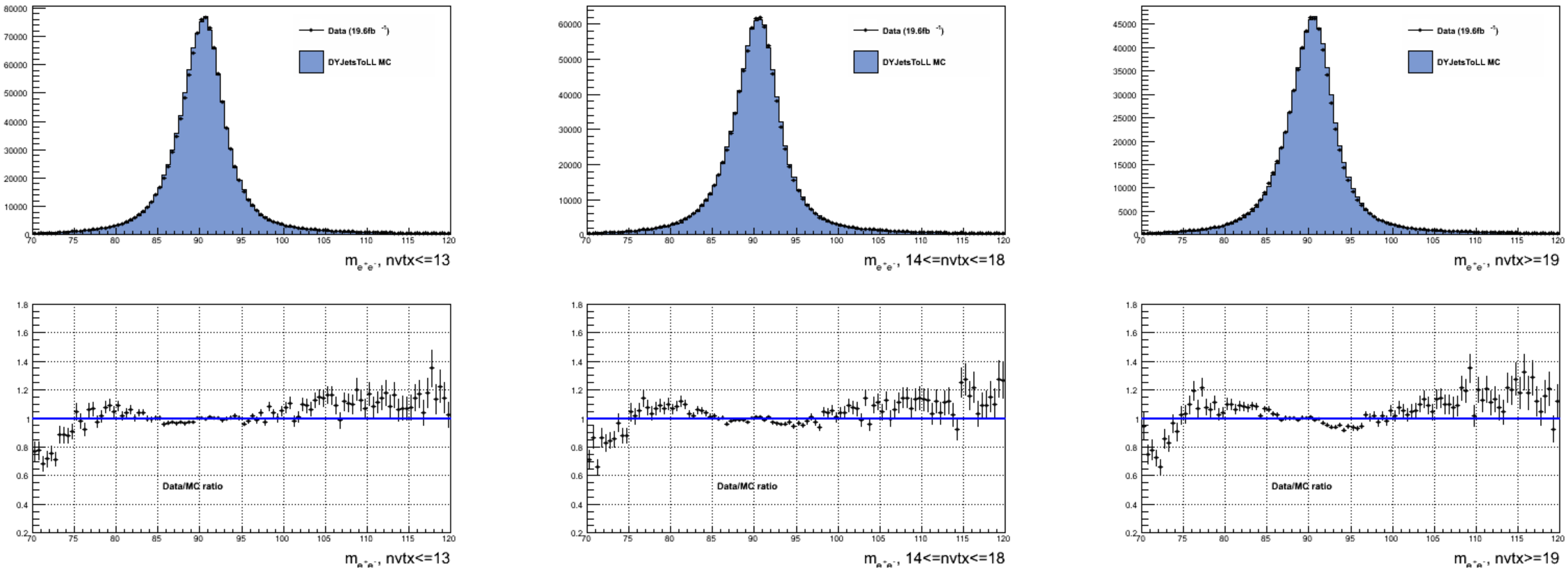


Pileup Robustness: Cut based ID Efficiency

- Cut-based Photon ID efficiency decreases with respect to pileup (isolation quantities intentionally under-corrected to contain fake-rate), but well described by MC
- Scale factors are relatively flat vs pileup. It has been checked that there is no significant change to the result from using scale factors in nvtx bins.



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



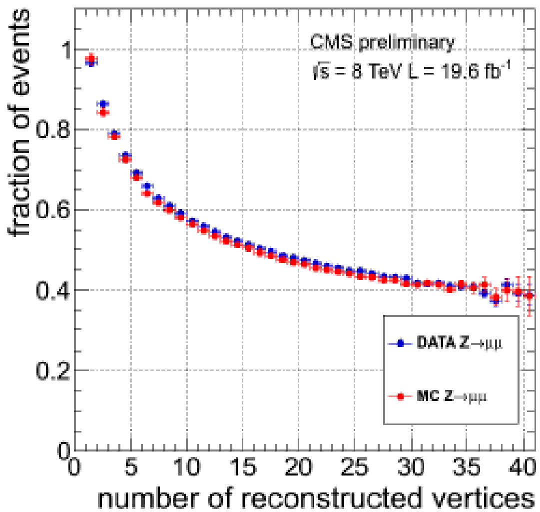
nvtx<=13 | 14<=nvtx<=18 | nvtx>=19

Pileup Robustness - Vertex Efficiency

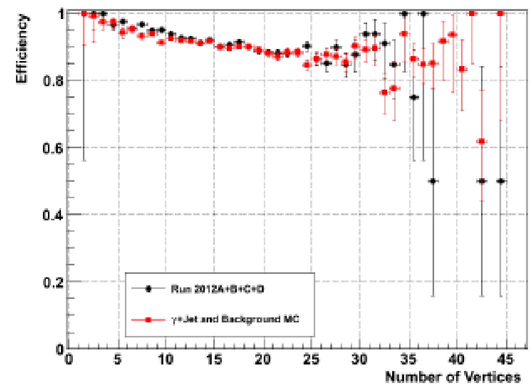
- Vertex ID efficiency vs no. of vertices is well modelled by the MC:

Unconverted photons: validate with $Z \rightarrow \mu\mu$

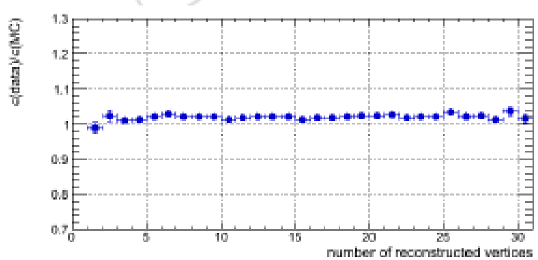
Converted photons: validate with γ+jet

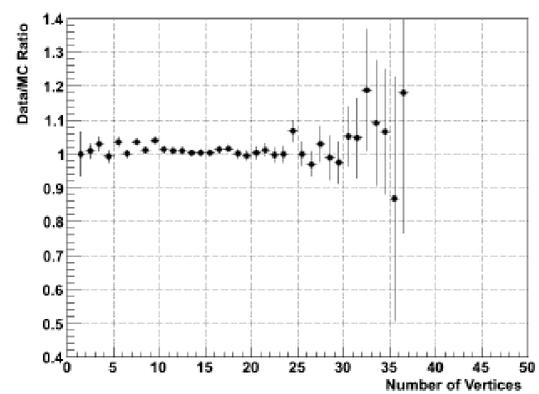


(a)

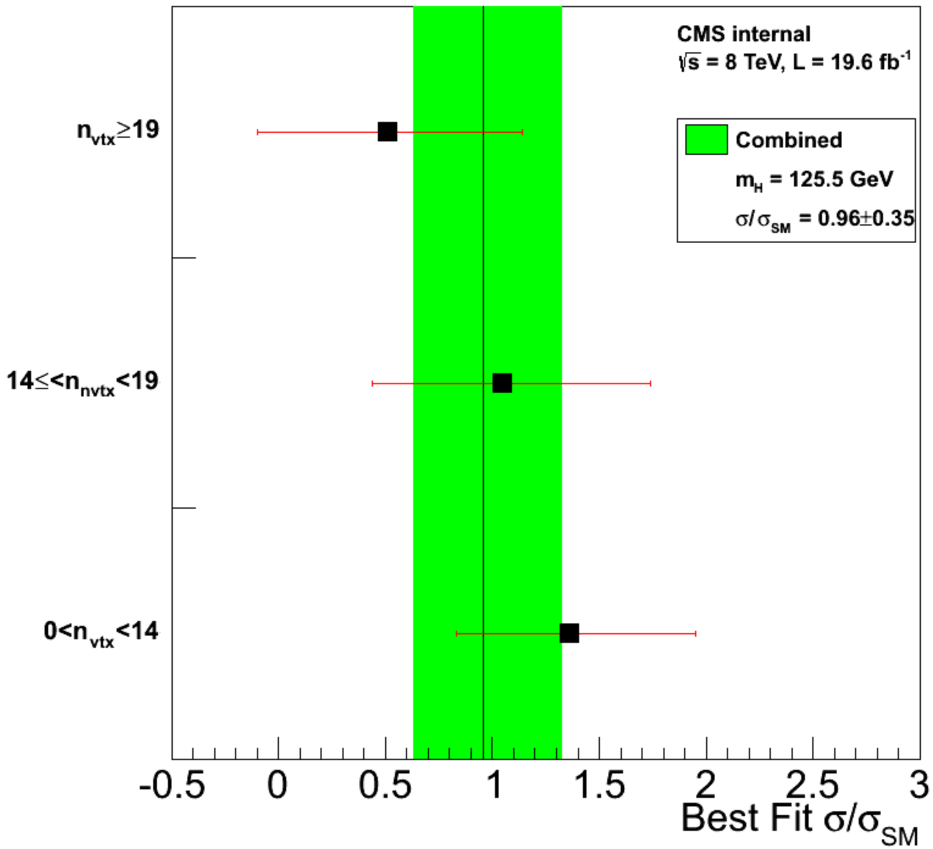


(a)





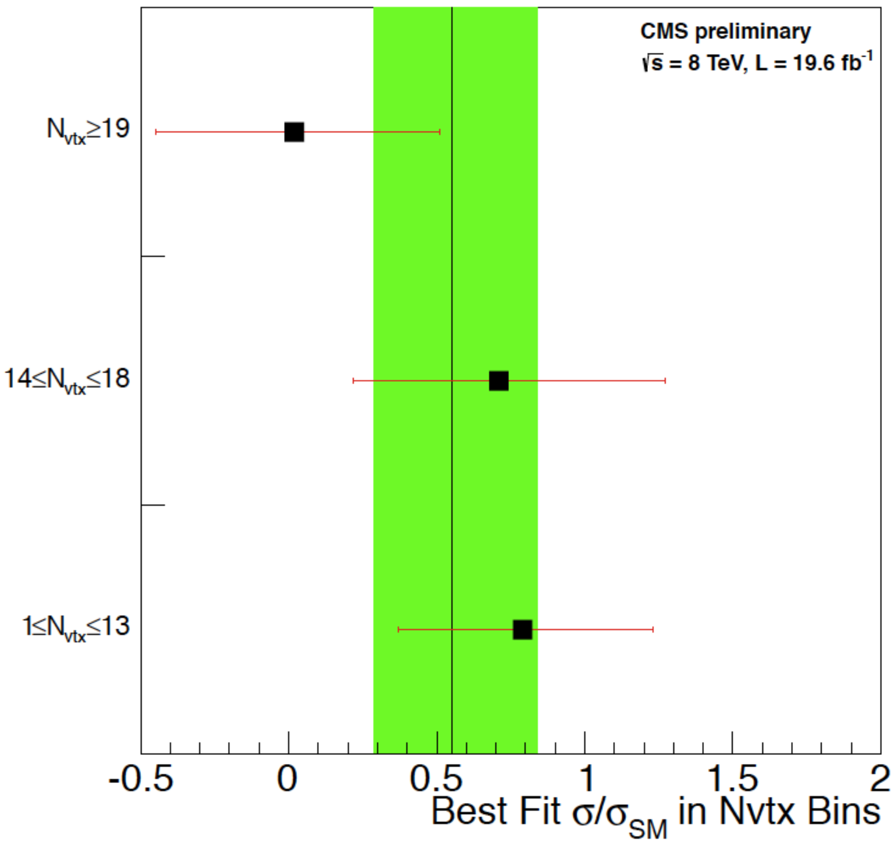
Observed μ vs pileup: Cut based analysis



Nvtx	μ
1-13	$1.36^{+0.53}_{-0.59}$
14-18	$1.05^{+0.61}_{-0.69}$
19+	$0.51^{+0.61}_{-0.63}$
Nominal	$0.96^{+0.33}_{-0.37}$

- Maximum spread 1.0σ
  - Consistent with expectation given 3 measurements

Observed μ vs pileup: MVA analysis



Nvtx	μ
1-13	$0.79^{+0.44}_{-0.42}$
14-18	$0.71^{+0.56}_{-0.49}$
19+	$0.02^{+0.49}_{-0.47}$
Nominal	$0.54^{+0.31}_{-0.26}$

- Maximum spread 1.2σ
- Correlated with the MVA result on the previous slide

Robustness vs Ecal Noise: Cut-based ID

- Cut-based Photon ID efficiency scale factors measured in run periods:

Category	Run Period	Data/MC eff. scale factor	error		Category	Run Period	Data/MC eff. scale factor	error
EB HighR9	AB	0.988	0.003		EE HighR9	AB	1.034	0.008
	C	0.985	0.003			C	1.029	0.008
	D	0.982	0.003			D	1.024	0.008
EB LowR9	AB	0.993	0.011		EE LowR9	AB	1.050	0.025
	C	0.970	0.011			C	1.003	0.025
	D	0.949	0.011			D	0.964	0.025

- Most important effect: drop in efficiency of ~4% for barrel low R9 photons in Run2012D, but taken into account by photon ID scale factors

Robustness vs Ecal Noise: Diphoton MVA

- As already described, observed time dependent discrepancies in the ID MVA and σ_E/E distributions seen in the $Z \rightarrow ee$ validation are likely to be a result of increasing ECAL noise
  - Corrections have been derived using $Z \rightarrow ee$
  - Effect on signal ε x A of applying these corrections calculated to be <2% for the 8TeV dataset and 3% for runD alone

- Effect of the corrections on the observed mu is:
  - $0.53^{+0.28}_{-0.26} \rightarrow 0.54^{+0:29}_{-0.27}$
  - Corresponds to a 2% change in observed μ and a 1% degradation in expected sensitivity

Analysis of events common to MVA and CiC

- Selecting only common events between the MVA and CIC analyses, compute observed μ using two different categorizations (CIC and MVA categorization):

Categorization	Observed μ
MVA categorization	$0.75^{+0.28}_{-0.26}$
CiC categorization	$0.75^{+0.32}_{-0.29}$

- As these two results use exactly the same events, the
- correlation is much higher than some of the other comparisons
  - jackknife $\sigma(\delta\mu)$=0.11

- It can be noted that the errors on the observed μ are smaller. The expected sensitivity is also improved
  - To take into consideration for the next iteration of the analysis

MVA Analysis using CiC categorization

- Using events selected by the nominal MVA analysis, compute observed using two different categorizations (CIC and MVA categorization):

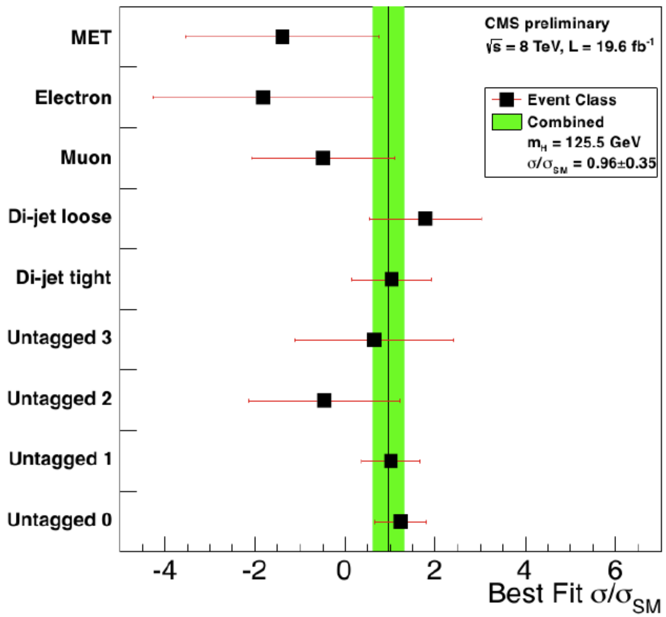
Categorization	Observed μ
MVA categorization	$0.54^{+0.33}_{-0.28}$
CiC categorization	$0.50^{+0.34}_{-0.30}$

- Again, smaller differences expected/observed when using identical events

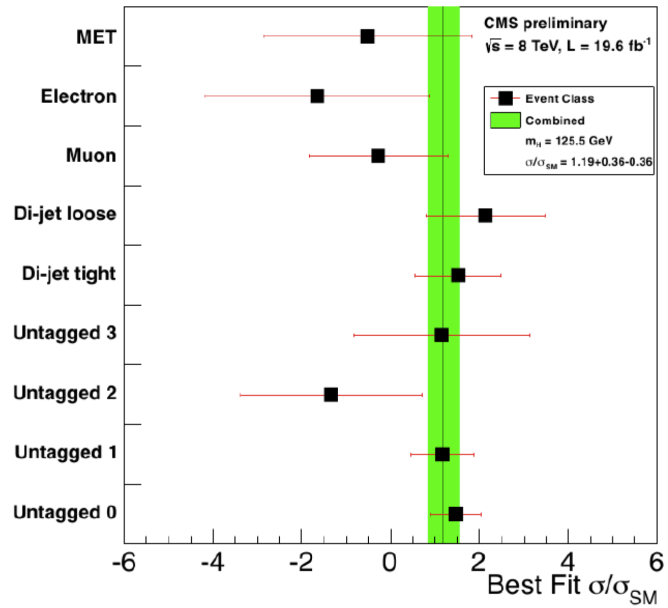
Cut-based Analysis with Σp_T^2 Vertex Selection

- Instead of using vertex ID MVA to identify the correct vertex, select the vertex with highest Σp_T^2 and re-calculate the observed μ

CiC analysis, MVA vertex



CiC analysis, Σp_T^2 vertex

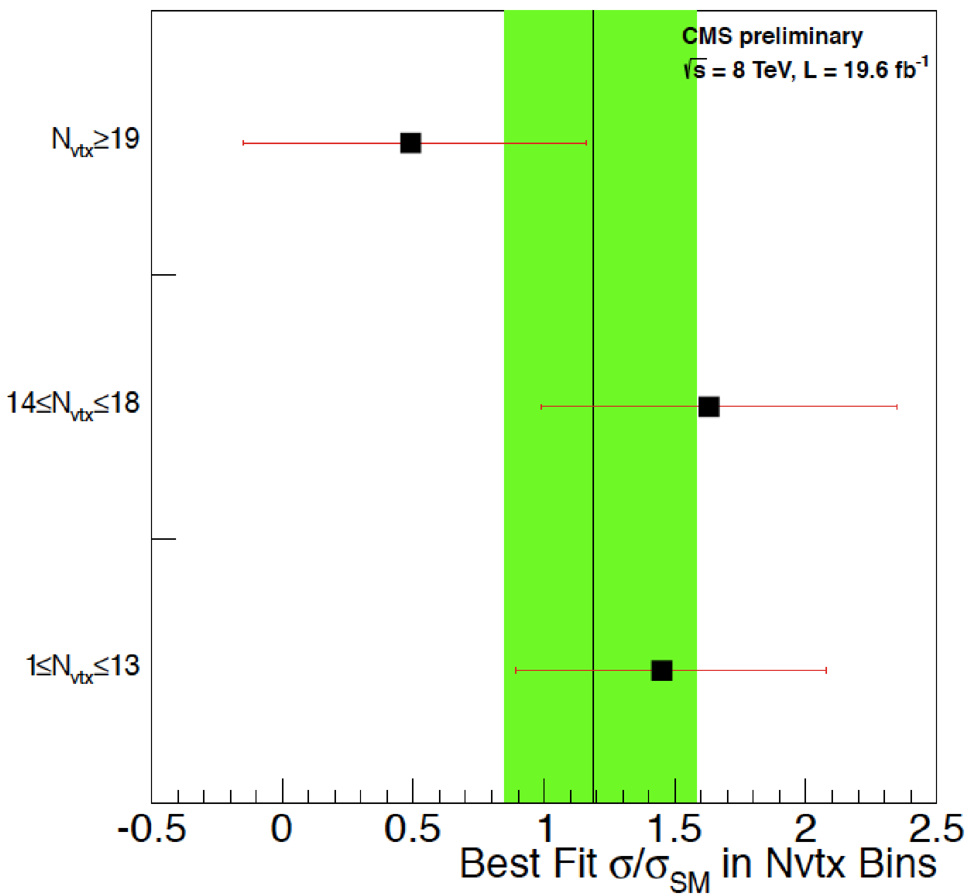


Vertex ID	Observed μ
MVA	0.96 ± 0.35
Σp_T^2	1.19±0.36

- Event overlap: 90%, Jackknife $\sigma(\delta\mu)$ = 0.14, difference is 1.6σ considering correlations
- Analysis with Σp_T^2 vertex ID has about 6% lower expected sensitivity

Observed μ vs pileup:

Cut based analysis using Σp_T^2 Vertex Selection



Nvtx	μ
All	$1.19^{+0.39}_{-0.34}$
1-13	$1.45^{+0.63}_{-0.56}$
14-18	$1.63^{+0.72}_{-0.64}$
19+	$0.49^{+0.67}_{-0.65}$

Compare to (nominal) MVA vertex ID:

Nvtx	μ
All	$0.96^{+0.33}_{-0.37}$
1-13	$1.36^{+0.53}_{-0.59}$
14-18	$1.05^{+0.61}_{-0.69}$
19+	$0.51^{+0.61}_{-0.63}$

Summary

- Updated results for the $H \rightarrow \gamma\gamma$ analysis have been presented for the full 2011+2012 dataset
- There is a difference in the signal strengths observed by the cut based and MVA analyses that has a significance of 1.8σ (evaluated by the jackknife technique).
- An extensive set of cross-checks and tests have been performed for both analyses. No evidence of problems with either analysis has been identified

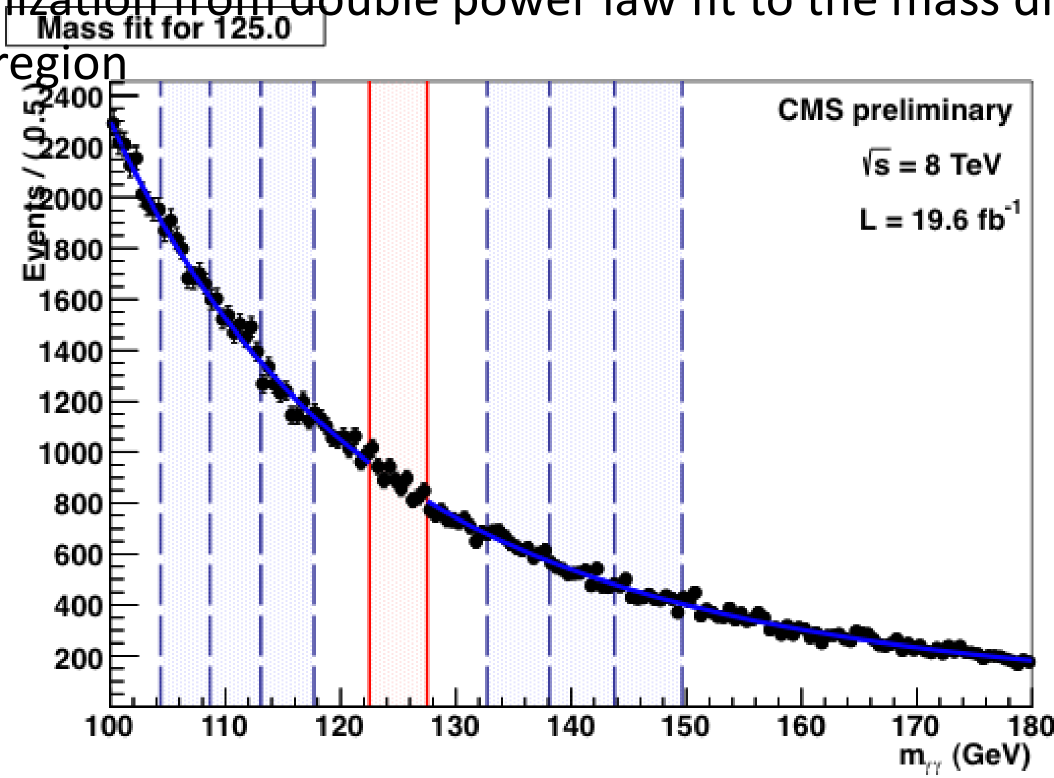
Sideband MVA Analysis

Sideband MVA Analysis

- Cross-check analysis using alternative background model
- All relevant information for extracting the signal is contained in the two variables: diphoton MVA output and $m_{\gamma\gamma}$, (plus exclusive categories)
- Exploit an alternative complementary approach to modeling the signal and background by fitting the output of an BDT constructed from these two input variables
  - Less sensitive to the shape of the $m_{\gamma\gamma}$ distribution
- Includes several features which are not naturally incorporated into mass fits:
  - Sliding window
  - Exclusion of signal region
  - Explicit inclusion of a systematic uncertainty for the possible bias in the background mass fit
- BDT unchanged since HCP
- Results presented are for ID MVA and σ_E/E uncorrected (to be updated

Sideband MVA Analysis

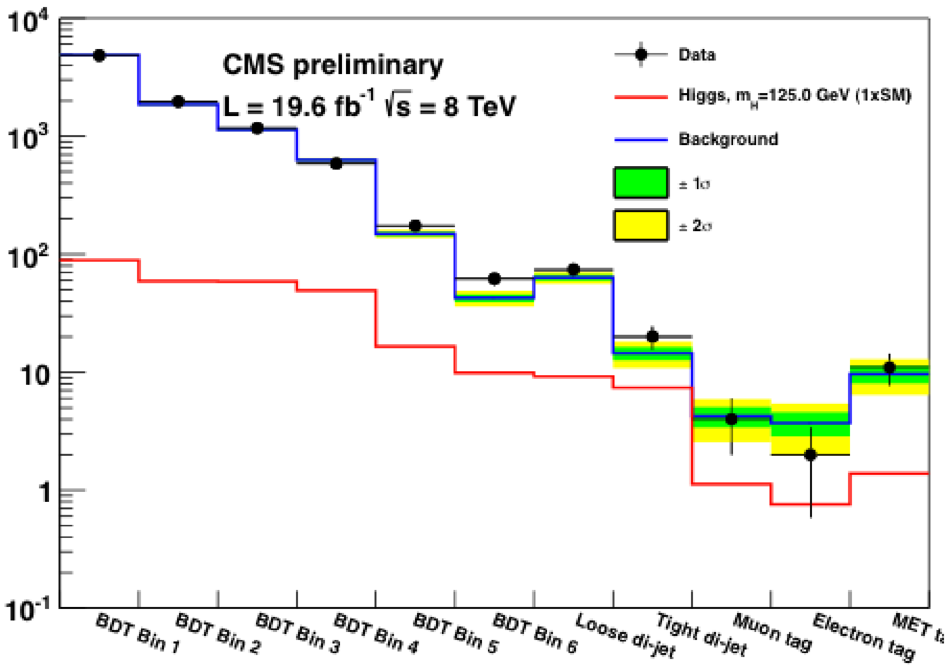
- Signal region is defined as a ±2% window around the signal mass hypothesis
- Background model is constructed from data in the sidebands of the mass distribution
  - Normalization from double power law fit to the mass distribution excluding the signal region

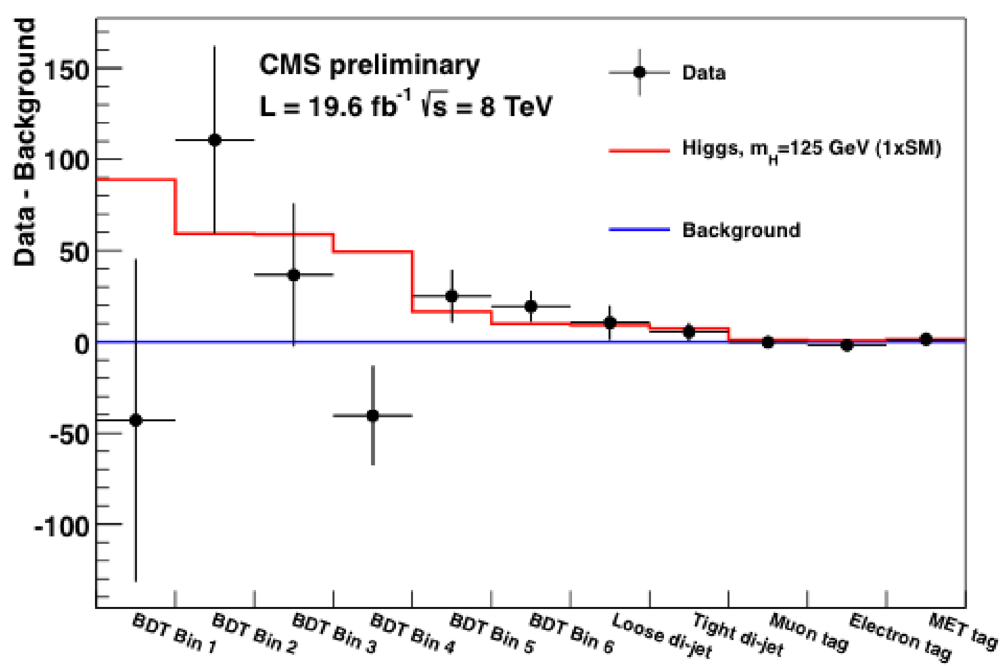


Same event selection as massfit MVA analysis: Diphoton MVA>-0.05

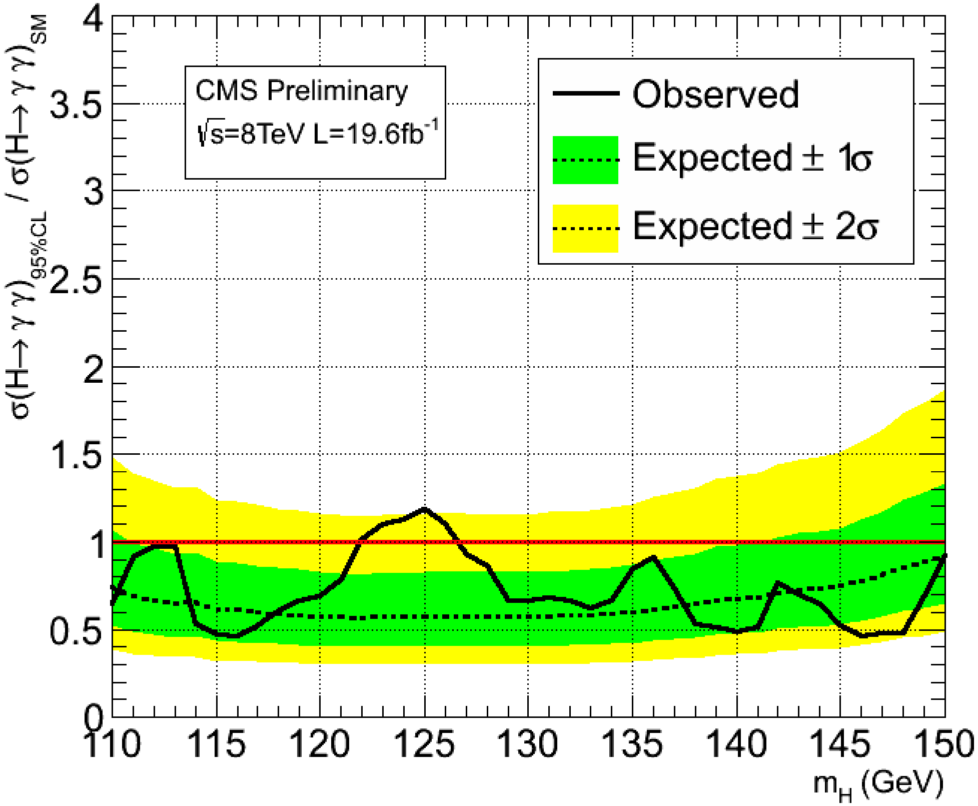
Sideband MVA Analysis

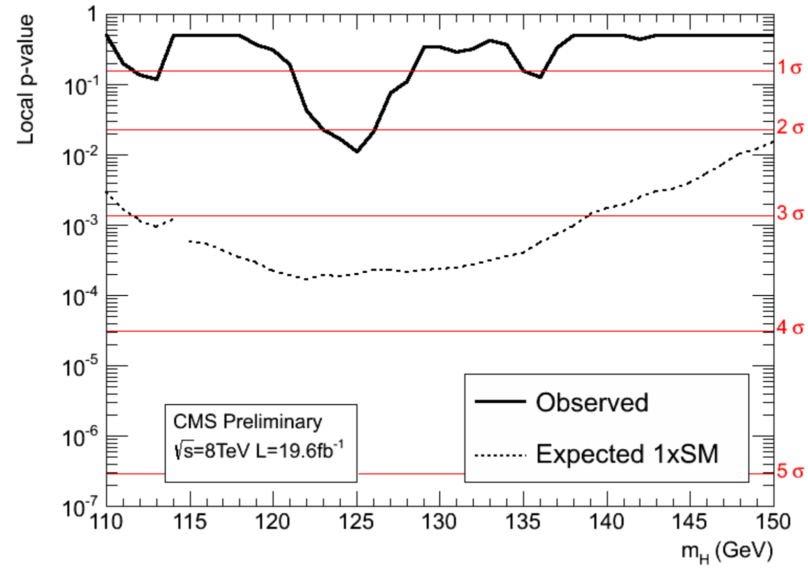
- Event classes are defined by binning the BDT output (bin boundaries optimized to maximize expected significance)
- Exclusive categories treated as additional bins
- Fit results:

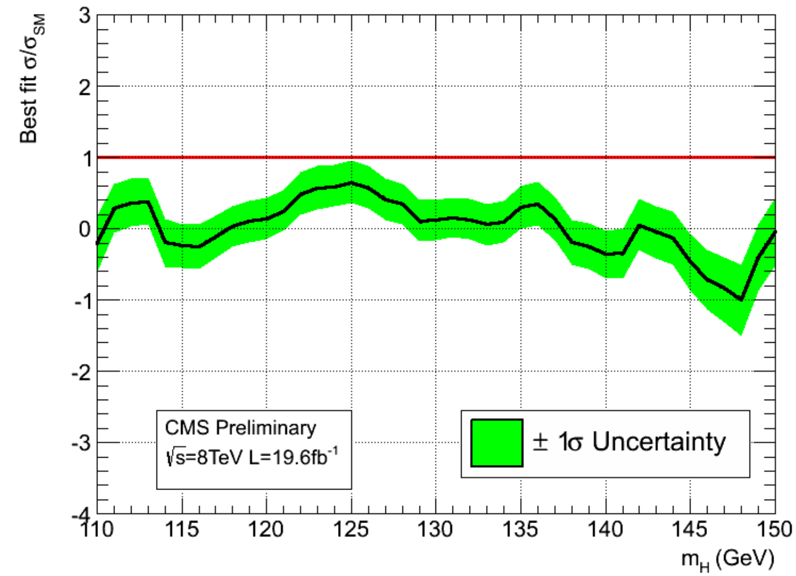




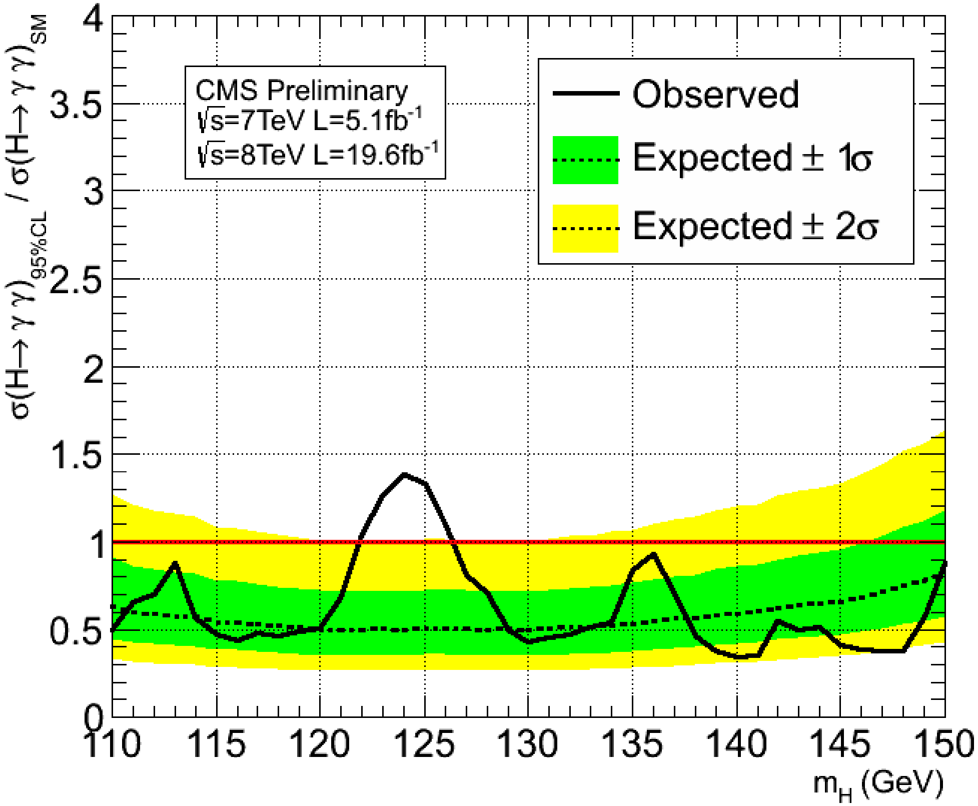
Sideband MVA Results: 8TeV

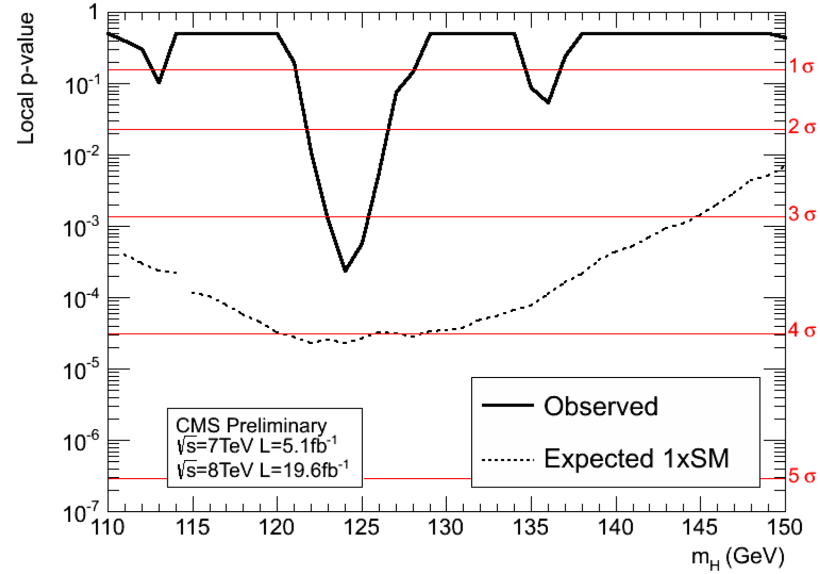


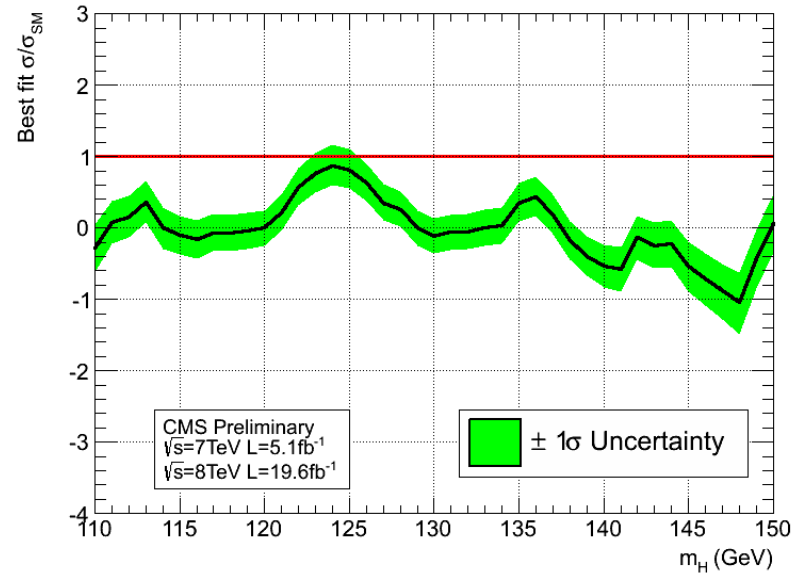




Sideband MVA Results: 8TeV+7TeV



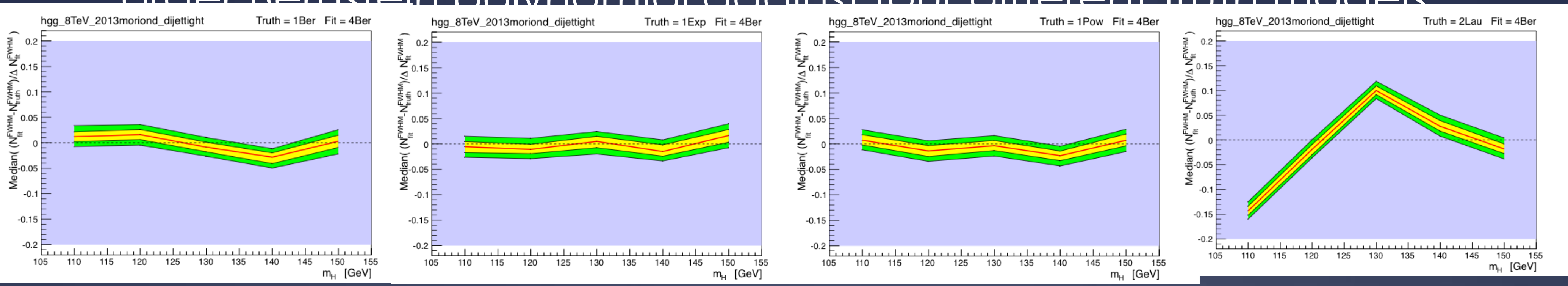




Cut based analysis: Background Model

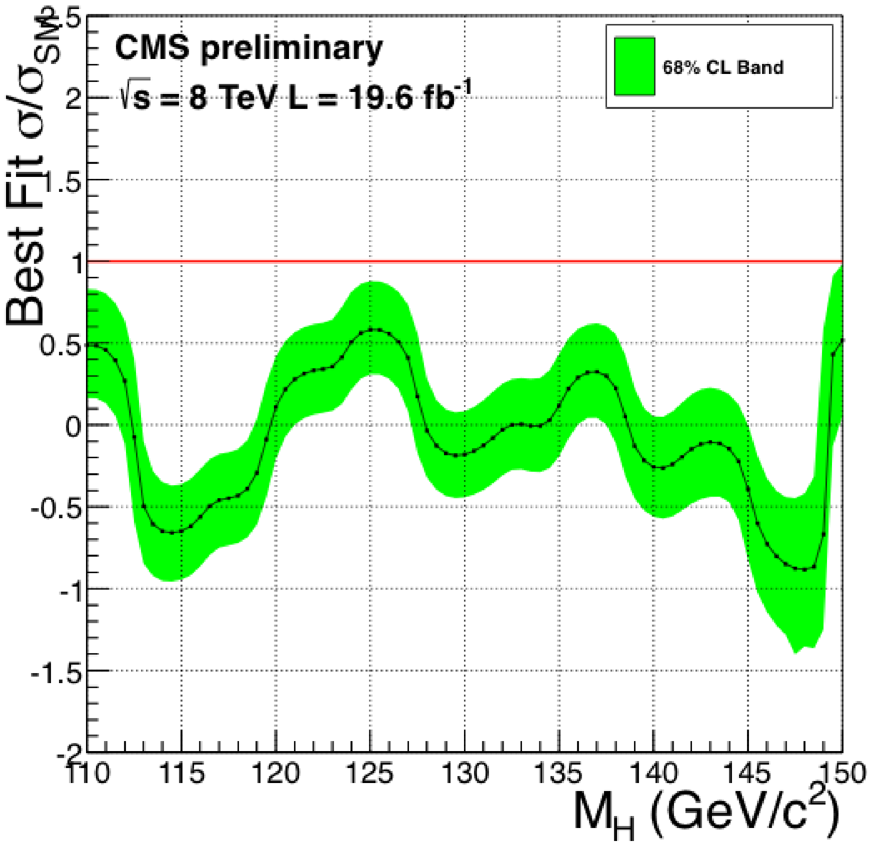
- Bernstein polynomial fits to data invariant mass distribution
  - Order chosen by requiring that the bias is smaller than 1/5 of the statistical uncertainty under all truth hypotheses.
  - Full study made with all 2012 data.

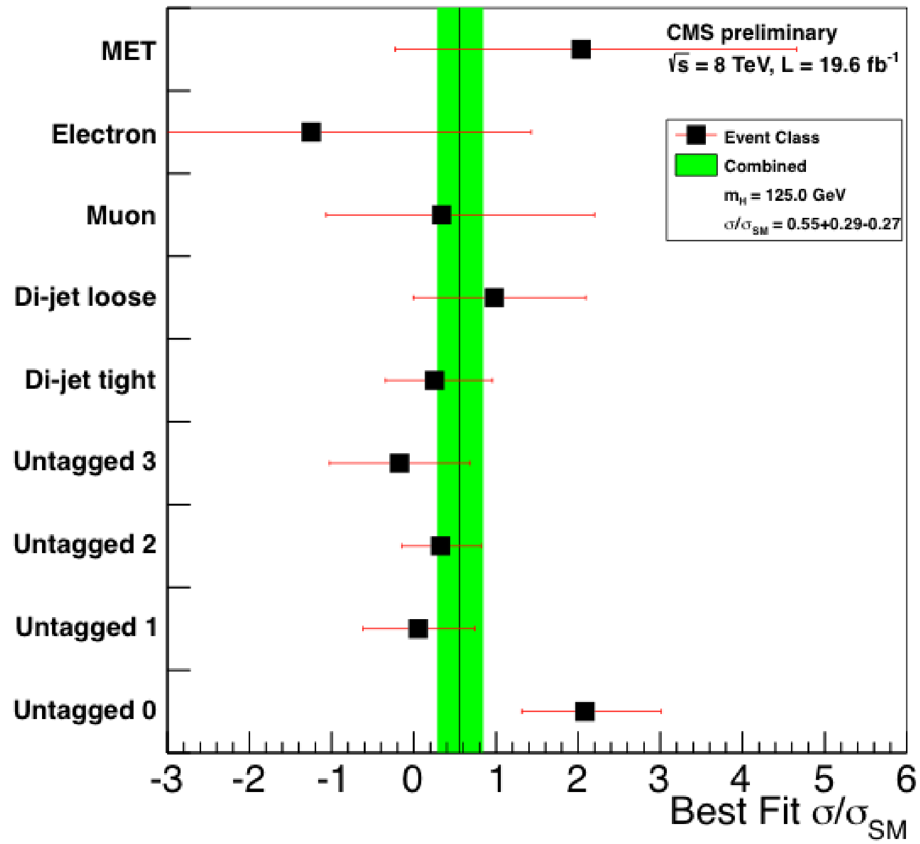
- Example: Toy study results for the tight dijet category testing a 4th order Bernstein polynomial against four different truth models:



category	cat0	cat1	cat2	cat3	DiJet Tight	DiJet Loose	Muon tag	Electron tag	MET tag
Pol order	5	5	5	5	4	4	3	3	3

MVA analysis: Signal Strength (8TeV)



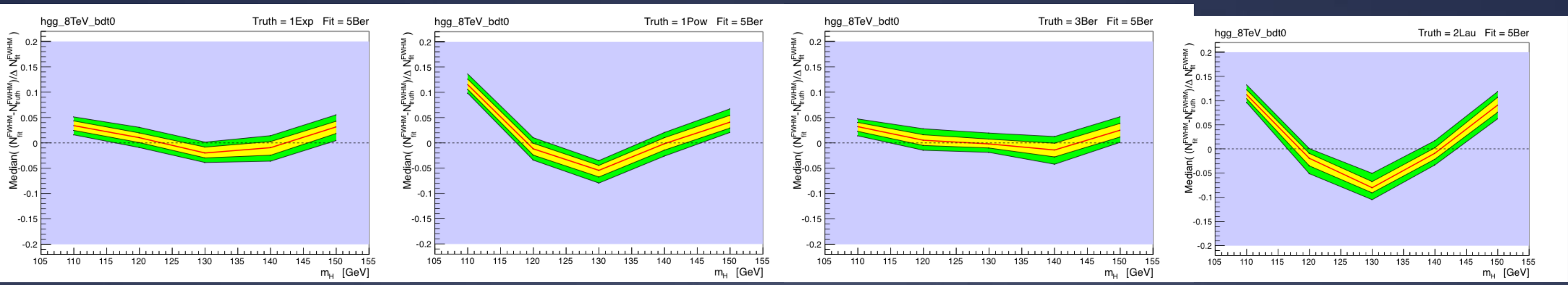


Best fit μ at 125.0 GeV: $0.55^{+0.29}_{-0.27}$

MVA analysis: Background Model

- Bernstein polynomial fits to data invariant mass distribution
  - Find analytical model to minimize bias against hypothetical truth models.

- Example: Toy study results for MVA events category 0 testing a 5^{th} order Bernstein polynomial against four different truth models:



Class	BDT 0	BDT 1	BDT 2	BDT 3	DiJet T	DiJet L	Mu	Ele	MET
Model	5Ber	5Ber	5Ber	5Ber	4Ber	4Ber	3Ber	3Ber	3Ber

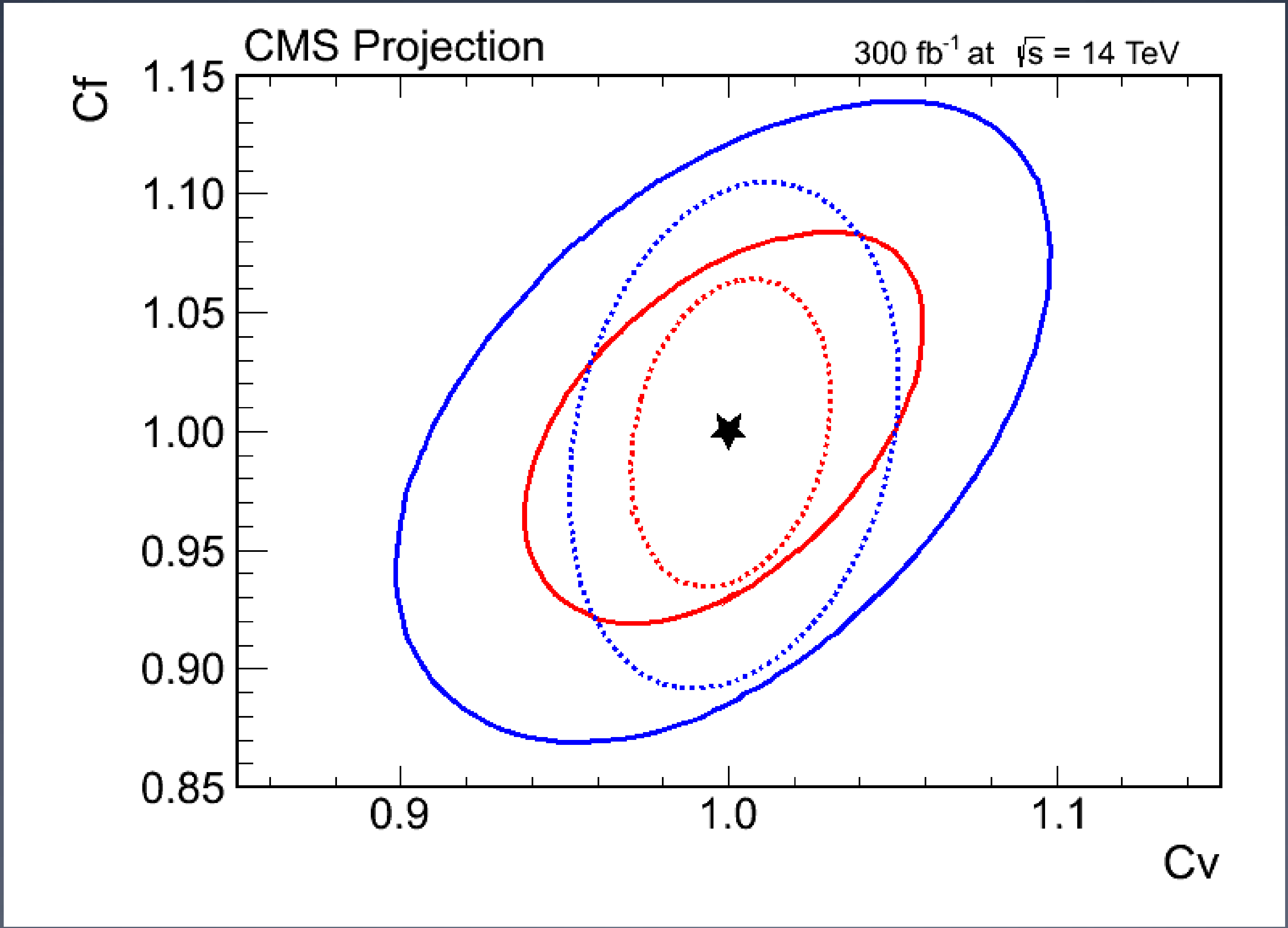
MVA analysis: Systematic

Sources of systematic uncertainty		Uncertainty	
Per photon		Barrel	Endcap
Photon selection efficiency		0.8%	2.2%
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.22%, 0.60%	0.90%, 0.34%
	$R_9 < 0.94$ (low η, high η)	0.24%, 0.59%	0.30%, 0.52%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.19%, 0.71%	0.88%, 0.19%
	$R_9 < 0.94$ (low η, high η)	0.13%, 0.51%	0.18%, 0.28%
Photon identification MVA	(Effect of up to 4.3% event class migration.)	$\pm$0.01 (shape shift)	
Photon energy resolution MVA	(Effect of up to 8.1% event class migration.)	$\pm$10% (shape scaling)	
Per event			
Integrated luminosity		4.4%	
Vertex finding efficiency		0.2%	
Trigger efficiency	One or both photons $R_9 < 0.94$ in endcap	0.4%	
	Other events	0.1%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
	Gluon-gluon fusion process	50%	
Muon selection			
E_T^{miss} cut efficiency	Muon identification efficiency	1.0%	
Electron selection			
E_T^{miss} cut efficiency	Electron identification efficiency	1.0%	
E_T^{miss} selection			
E_T^{miss}	Associated production with W/Z	4%	
	Vector boson fusion	15%	
	Gluon-gluon fusion	15%	
	Associated production with $t\bar{t}$	15%	
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 12.5% event class migration.)	(y, p_T)-differential	

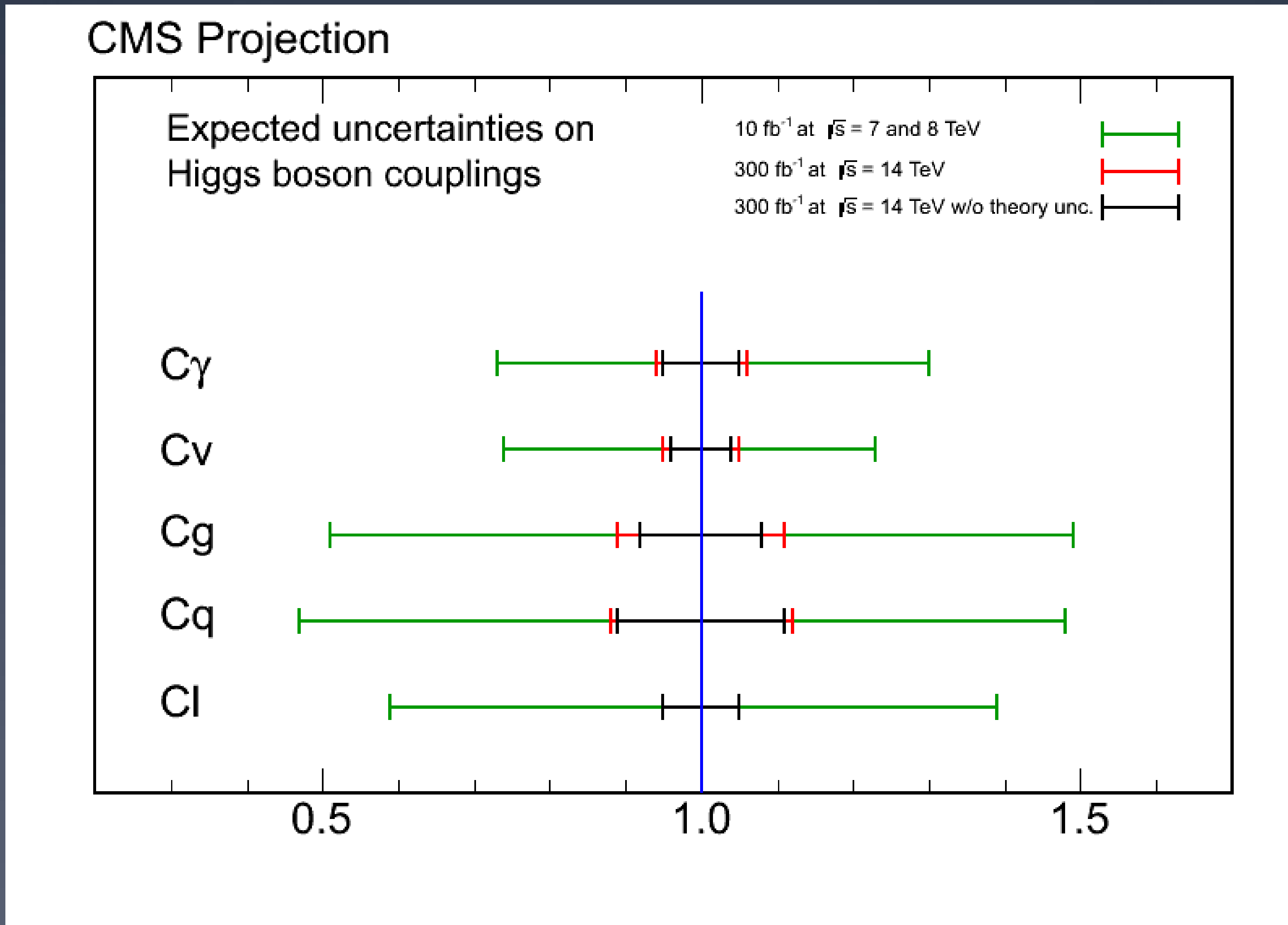
Cut based analysis: Systematic

Sources of systematic uncertainty		Uncertainty	
Per photon		Barrel	Endcap
Photon identification efficiency		1.0%	2.6%
$R_9 > 0.94$ efficiency (results in class migration)		4.0%	6.5%
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.22%, 0.60%	0.90%, 0.34%
	$R_9 < 0.94$ (low η, high η)	0.24%, 0.59%	0.30%, 0.52%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.19%, 0.71%	0.88%, 0.19%
	$R_9 < 0.94$ (low η, high η)	0.13%, 0.51%	0.18%, 0.28%
Per event			
Integrated luminosity		4.4%	
Vertex finding efficiency		0.2%	
Trigger efficiency	One or both photons $R_9 < 0.94$ in endcap	0.4%	
	Other events	0.1%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
	Gluon-gluon fusion process	50%	
Muon selection			
E_T^{miss}	Muon identification efficiency	1.0%	
Electron selection			
E_T^{miss}	Electron identification efficiency	1.0%	
E_T^{miss} selection			
E_T^{miss}	Associated production with W/Z	4%	
	Vector boson fusion	15%	
	Gluon-gluon fusion	15%	
	Associated production with $t\bar{t}$	15%	
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%

Outlook



CMS Projection
300 fb-1 at √s = 14 TeV
Cf
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.9
1.0
1.1
Cv



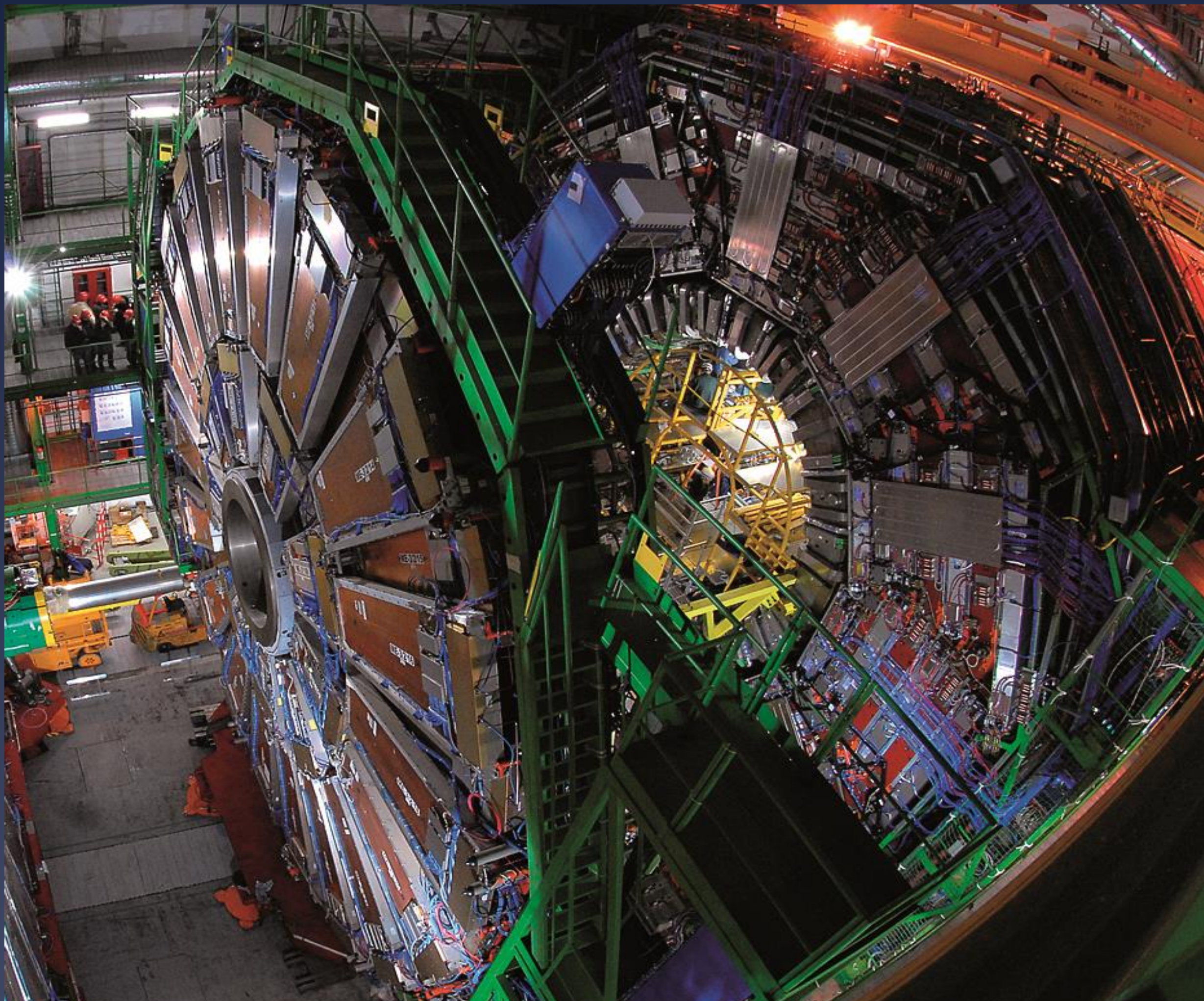
CMS Projection
Expected uncertainties on
Higgs boson couplings
10 fb⁻¹ at √s = 7 and 8 TeV
300 fb⁻¹ at √s = 14 TeV
300 fb⁻¹ at √s = 14 TeV w/o theory unc.
Cγ
Cv
Cg
Cq
Cl
0.5
1.0
1.5

Some LHC facts

* Tunnel
  * Diameter 3m, Length 27 km
    * 1 billion kg excavated
* Beams
  * Made up of bunches
    * 1.2-1.5x10^{11} protons/bunch
    * 1404 (2808) maximum bunches in machine for 50 (25) ns separation
      * 1 ns = 1 billionth of a second
      * 50 ns separation = 15 m
    * At Interaction Point (IP)
      * Bunch length ~ 6 cm
      * Beam radius ~23 μm
    * Bunch collision rates
      * 31.6 MHz (25 ns spacing)
      * 15.8 MHz (50 ns spacing)

* Superconducting dipoles
  * challenge: magnetic field of 8.33 Tesla in total 1232 magnets, each 15 m long operated at 1.9 K
  * Largest cryogenic system in the world

CMS Design Specifications



|η|<2.5 : Tracker

$$s / p_T \approx 10^{-4} p_T \oplus 0.005$$

|η|<4.9 : EM Calorimeter

$$\sigma / E \approx 0.03 / \sqrt{E} + 0.003$$

|η|<4.9 : Had Calorimeter

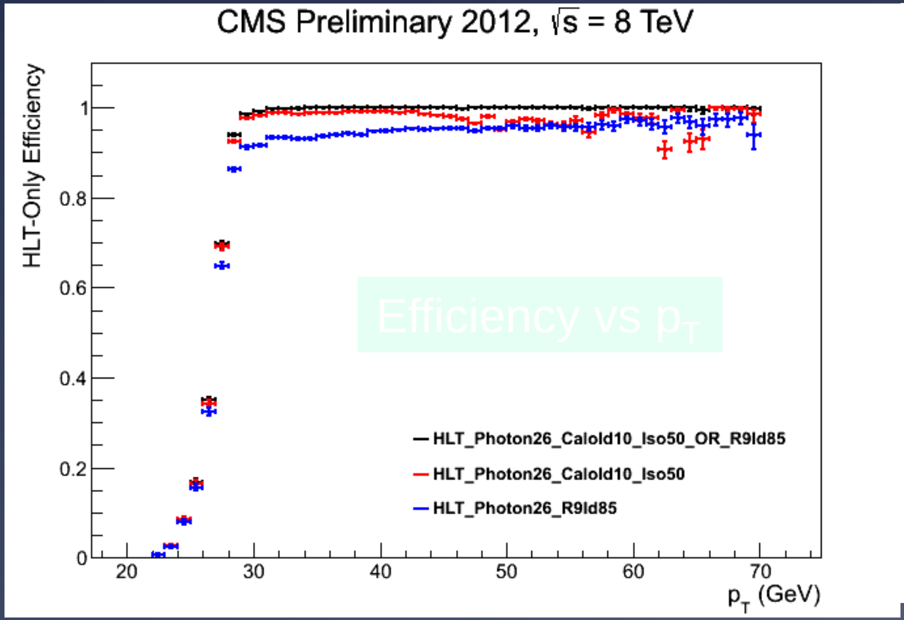
$$\sigma / E \approx 1.0 / \sqrt{E} + 0.05$$

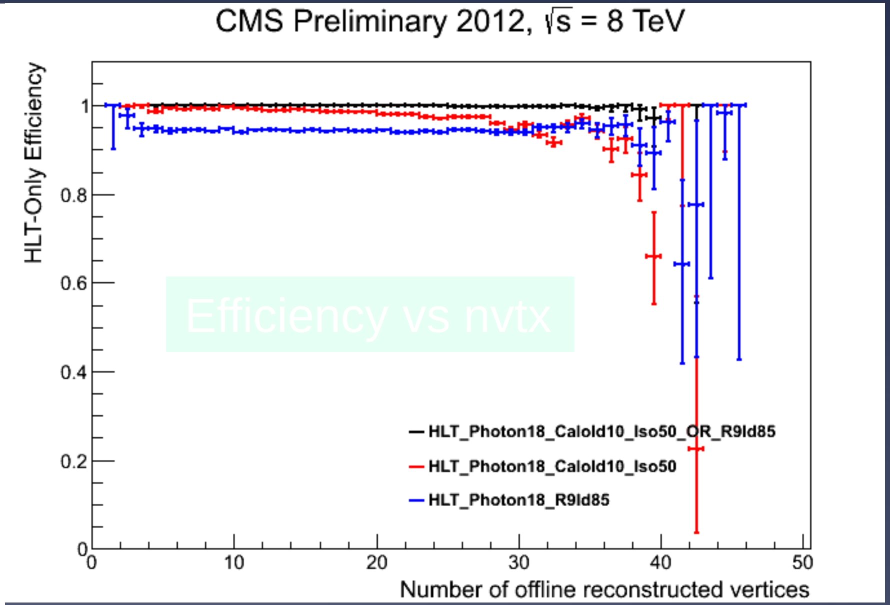
|η|<2.6 : Muon spectrometer

$\sigma / p_T \approx 0.10$ *(1TeV muons)*

Trigger

- General trigger strategy: keep photons passing Iso+CaloId or a cut on shower shape.
- Efficiency > 99.5% across all run periods





Lepton tag – data and bkg MC yields

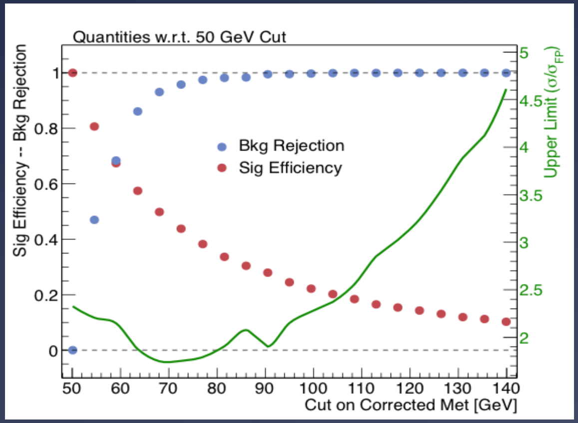
For 100 < m < 160

Bkg. sample	electron-tag	muon-tag
$W(l\nu)\gamma$	0	0.12
$Z\gamma$	4.2	0.12
VV	0.04	0.12
$\gamma\gamma$+jets	0.09	0.03
$W^{\pm}\gamma\gamma$	0.41	0.85
$Z\gamma\gamma$	0.45	0.48
$t\bar{t}\gamma\gamma$	0.026	0.022
Reducible	4.31	0.65
Irreducible	0.89	1.35
Total MC	5.2	2.0
Data	19	8

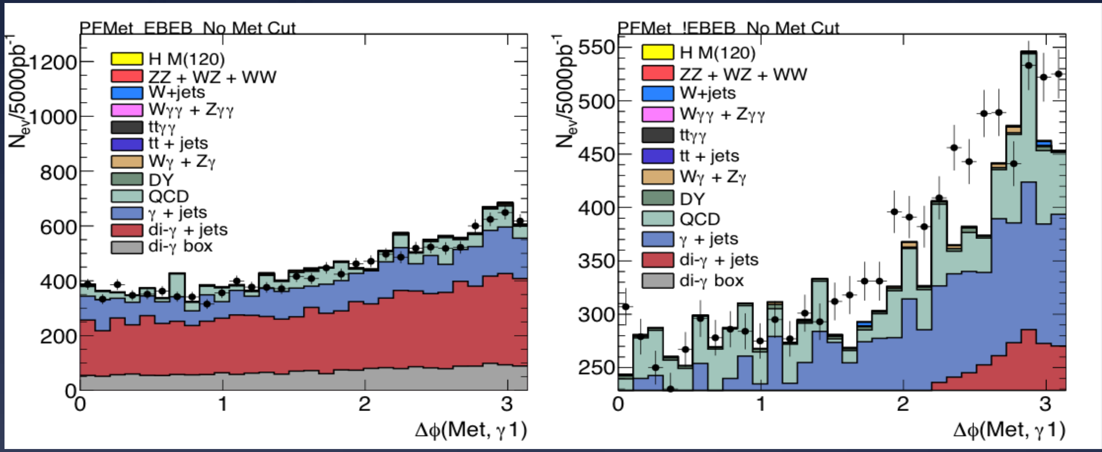
- Model background from data
- Use MC to cross check
  - In 2011 the yields were smaller so we used bkg MC and Control Sample to derive bkg shape, and normalize it to data.
  - In 2012 we derive bkg shape from data from fits of power law function, and normalize to data.

MET tag – event selection

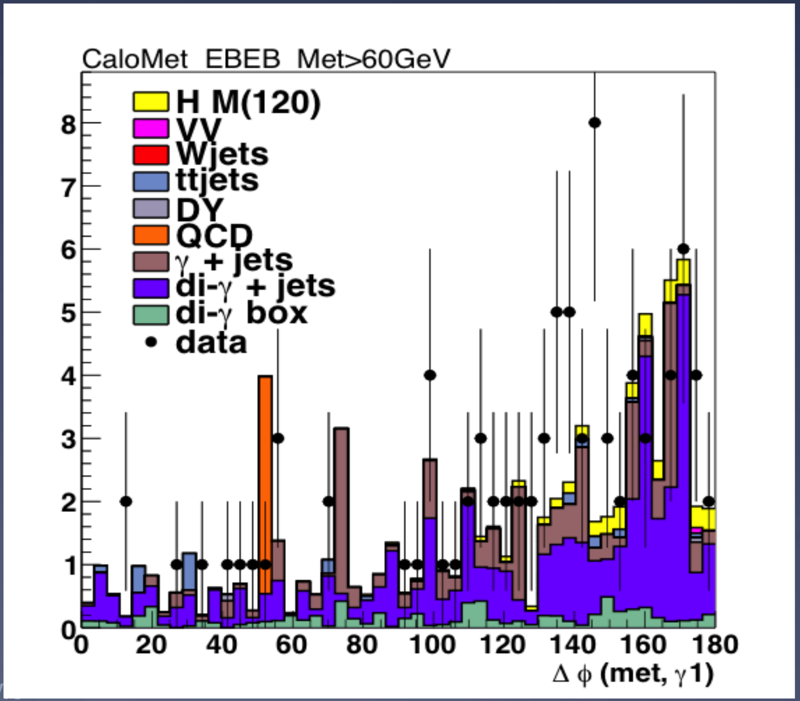
- Two isolated photons + MET
  - $p_T(\gamma_1)/m_{\gamma\gamma} > 45/120$ GeV
    $p_T(\gamma_2) > 25$ GeV
- PFMET>70 GeV



EBEB & MET>0 !EBEB & MET>0



!EBEB & MET>70



Cut Based Analysis

Cut based analysis: Event classification

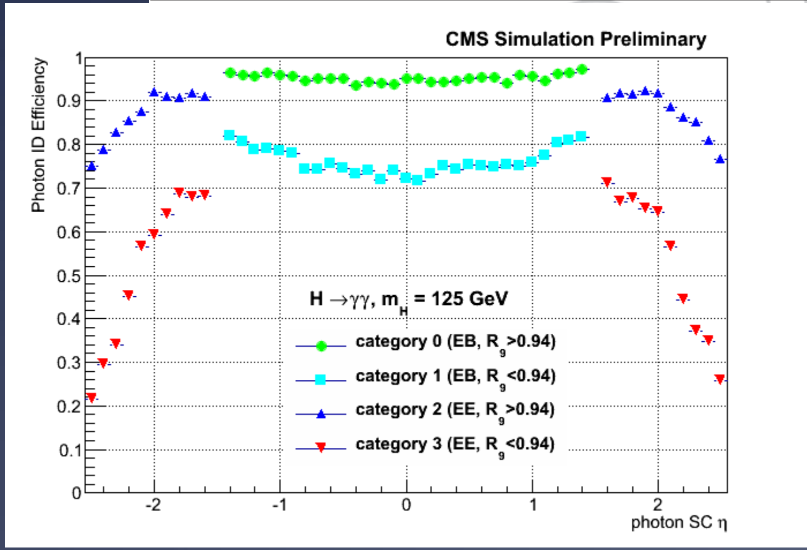
* Events are split into four categories to account for different resolutions and S/B ratios. Analysis performed by fitting $m_{\gamma\gamma}$ spectrum in each category:

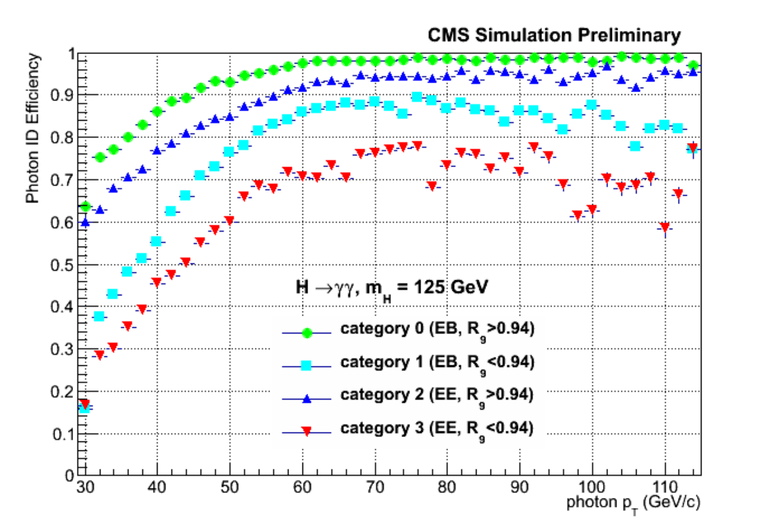
cat0	Both photons in EB	Both photons $R_9 > 0.94$
cat1	Both photons in EB	At least one photon with $R_9 < 0.94$
cat2	At least one photon in EE	Both photons $R_9 > 0.94$
cat3	At least one photon in EE	At least one photon with $R_9 < 0.94$

Cut based photon identification

* Photon ID for cut based analysis consists of cuts on isolation and shower shape, tuned separately for each of four η,R9 catego

	barrel		endcap	
	$R_9 > 0.94$	$R_9 < 0.94$	$R_9 > 0.94$	$R_9 < 0.94$
PF isolation sum, chosen vertex	6	4.7	5.6	3.6
PF isolation sum worst vertex	10	6.5	5.6	4.4
Charged PF isolation sum	3.8	2.5	3.1	2.2
$\sigma_{i\eta i\eta}$	0.0108	0.0102	0.028	0.028
H/E	0.124	0.092	0.142	0.063
R_9	0.94	0.298	0.94	0.24





Cut based analysis: Exclusive Categories

* In addition to the four "untagged" event categories defined by η and R9, five exclusive event categories are defined to enrich the sample in VBF and VH production modes:

Tagged categories		Requirement	Lead photon p_T	Sublead photon p_T
VBF	Tight di-jet	2 jets m_{JJ}>500GeV	$1/2m_{\gamma\gamma}$	25GeV
	Loose di-jet	2 jets m_{JJ}>250GeV		
VH	Muon tag	1 muon p_T > 20GeV	$45/120m_{\gamma\gamma}$	25GeV
	Electron tag	1 electron p_T > 20GeV		
	MET tag	MET > 70 GeV		

Muon → Electron → Dijet → MET → Untagged

Dijet Tag (cut based)

* For the cut based analysis, dijet categories are defined using a cut based selection
  * Unchanged since ICHEP
  * Two categories defined: high and low M_{jj}

Variable	Cut VBF cat1	Cut VBF cat2
$pT_{\gamma 1}/m_{\gamma\gamma}$	>60/120	>60/120
pT_{j1}	> 30 GeV	> 30 GeV
pT_{j2}	**>30 GeV**	**>20 GeV**
$\Delta\eta_{j1j2}$	> 3.0	> 3.0
|Z|	< 2.5	< 2.5
M(j1,j2)	**>500 GeV**	**>250 GeV**
$\Delta\phi(jj,\gamma\gamma)$	> 2.6	> 2.6

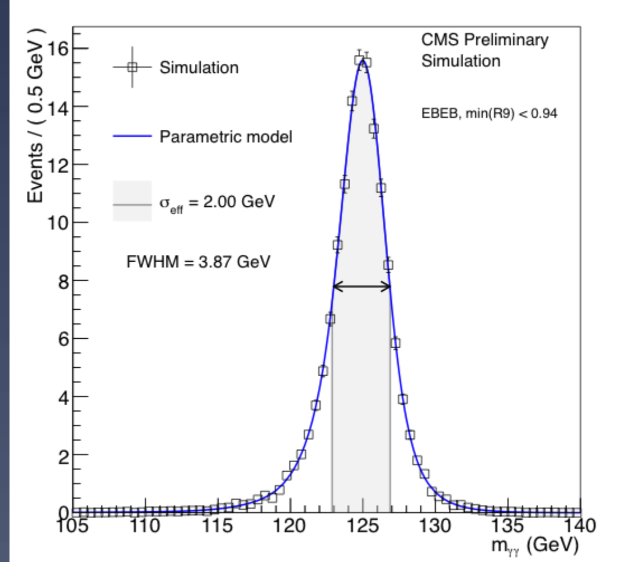
Cut based analysis: Signal Model

- Constructed from MC in each category, applying resolution smearing, shower shape rescaling and efficiency scale factors
- Sum of Gaussians fitted separately to each process per category, then combined for each category

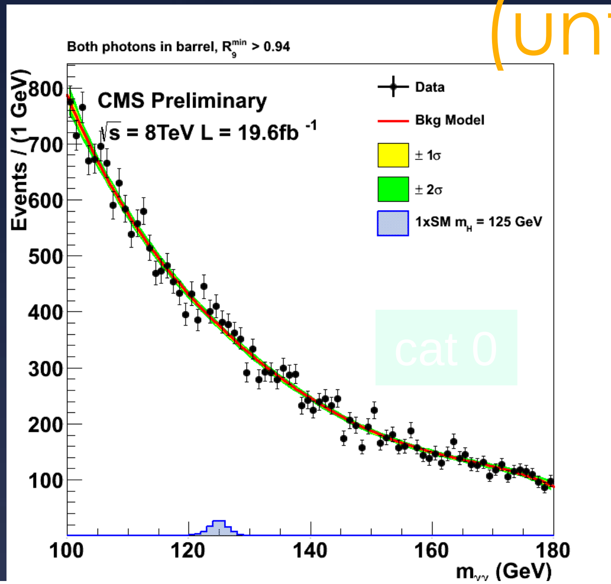
Mass resolution and S/B depend on the category

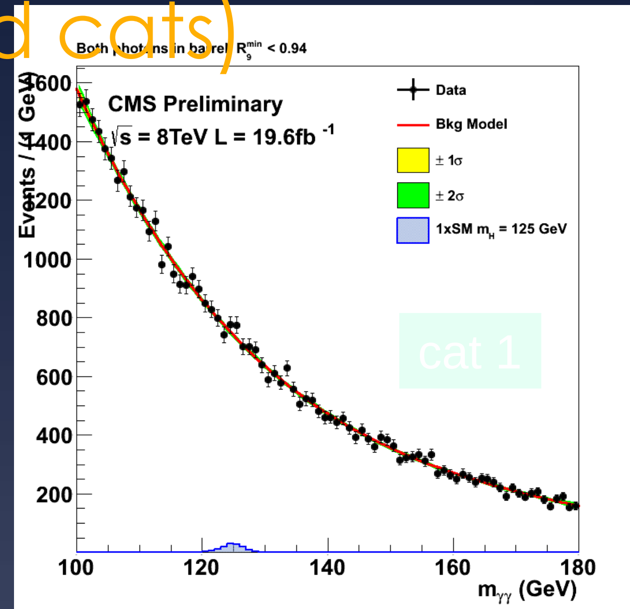
Event classes (8 TeV 19.6 fb^{-1})	SM Higgs boson expected signal (m_H=125 GeV): Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM (GeV)	Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV)
Untagged 0	109.4	91.1%	4.8%	3.6%	0.5%	1.69	3.41	374.7 ± 2.1
Untagged 1	144.6	91.5%	4.7%	3.4%	0.4%	2.01	3.97	739.4 ± 2.9
Untagged 2	55.1	89.3%	5.4%	5.0%	0.3%	3.15	6.82	368.2 ± 2.1
Untagged 3	71.8	90.3%	4.9%	4.6%	0.3%	3.19	6.83	666.9 ± 2.8
Dijet tight	9.4	22.1%	77.3%	0.5%	0.1%	1.94	3.86	5.3 ± 0.2
Dijet loose	10.8	52.2%	46.2%	1.6%	0.0%	1.95	3.92	14.9 ± 0.4
Muon tag	1.4	0.0%	0.2%	81.3%	18.5%	1.96	3.63	0.7 ± 0.1
Electron tag	0.9	1.1%	0.5%	80.2%	18.1%	1.93	3.48	0.8 ± 0.1
E_T^{miss} tag	1.6	22.6%	3.0%	63.8%	10.5%	1.79	3.65	1.7 ± 0.1

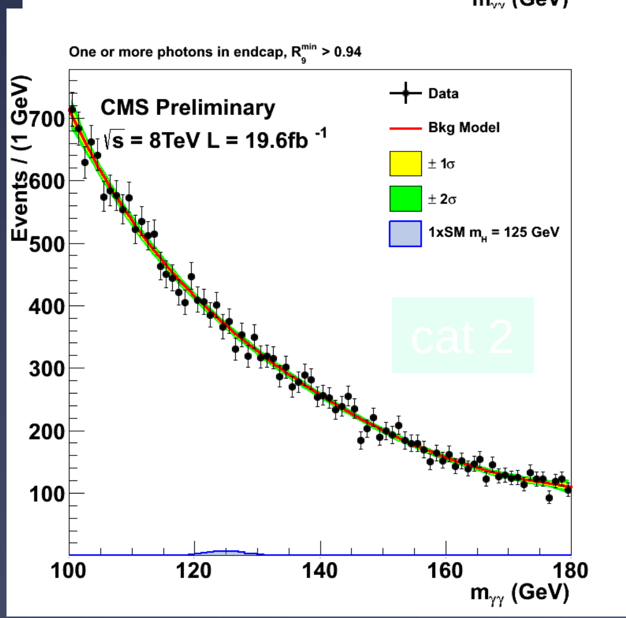
Signal model for untagged cat 1

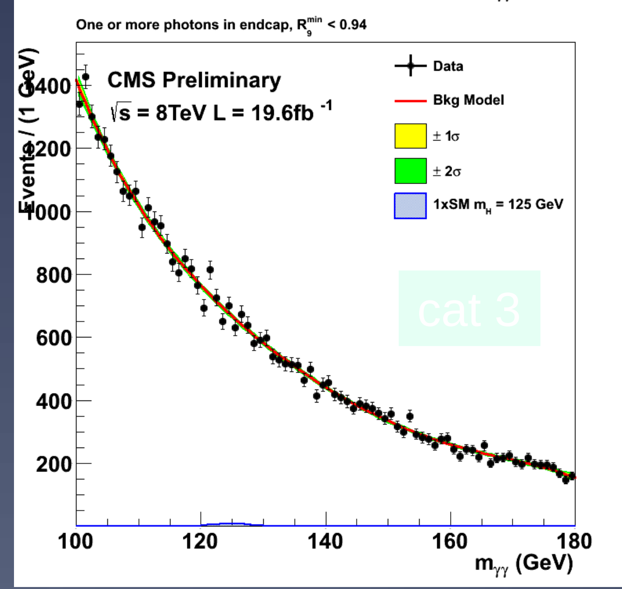


Cut based analysis: Background model fits (untagged cats)

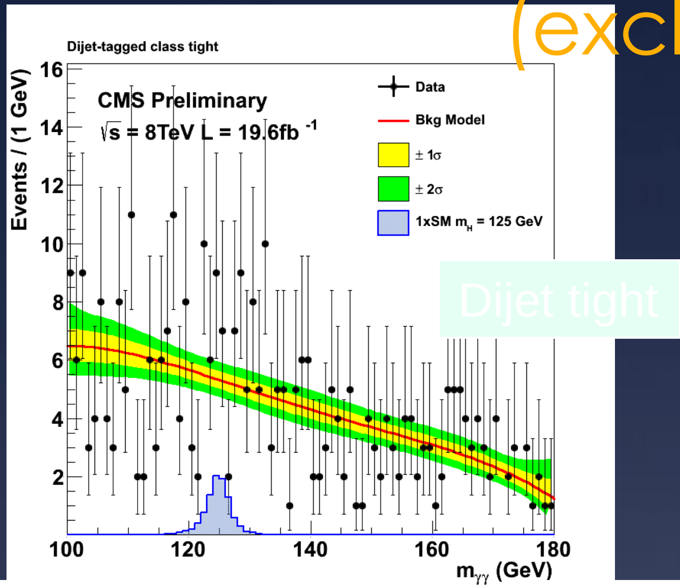


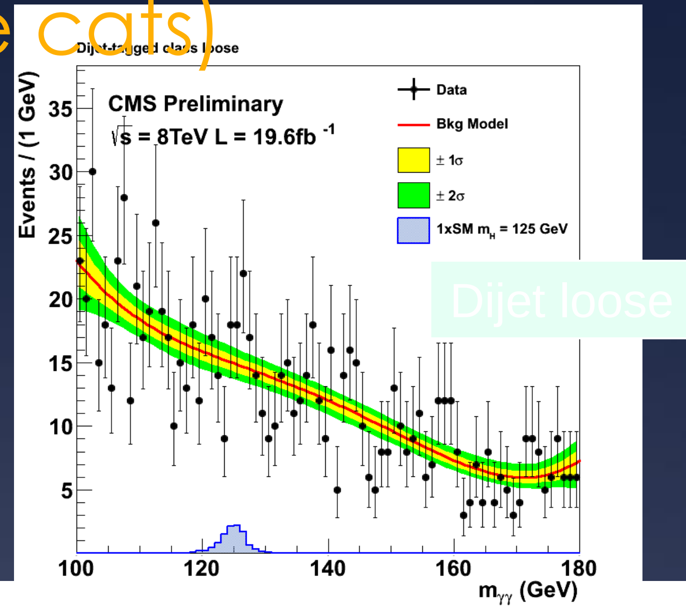


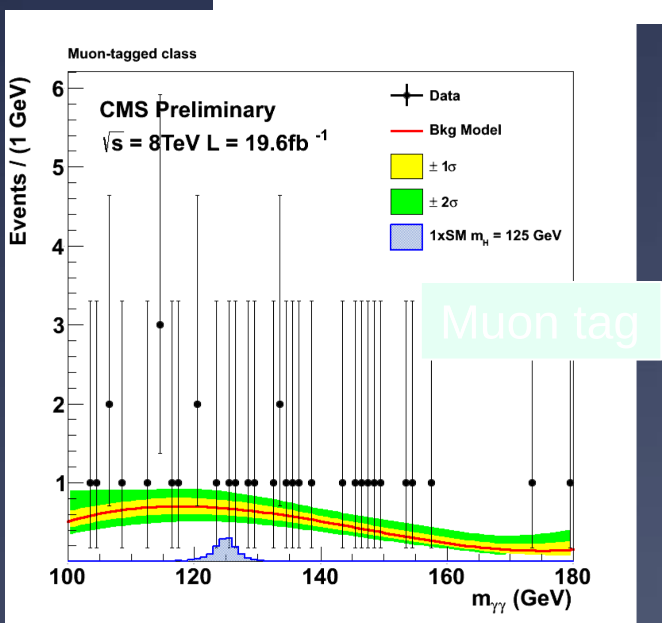


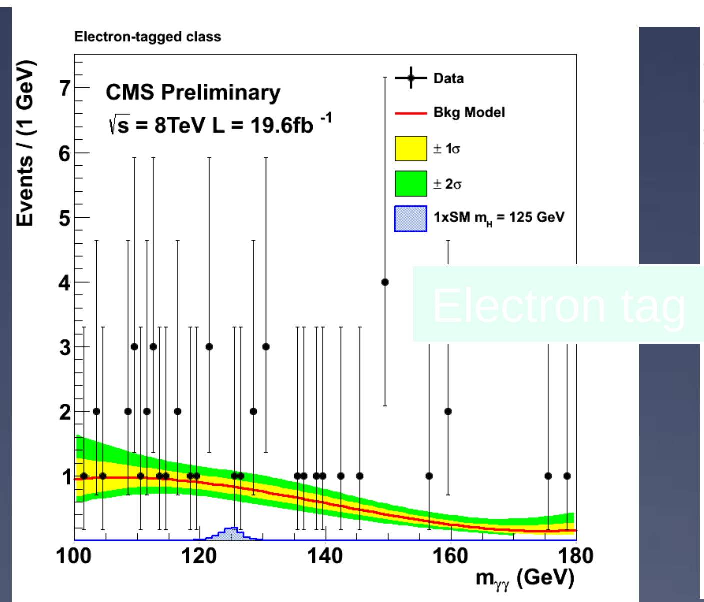


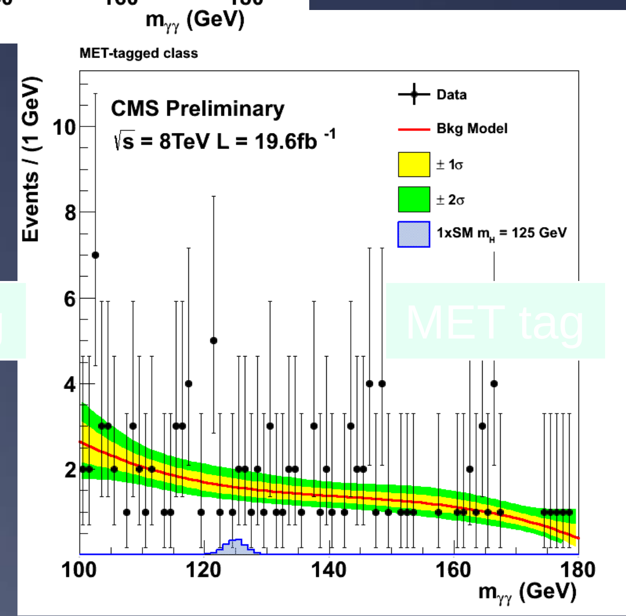
Cut based analysis: Background model fits (exclusive cats)



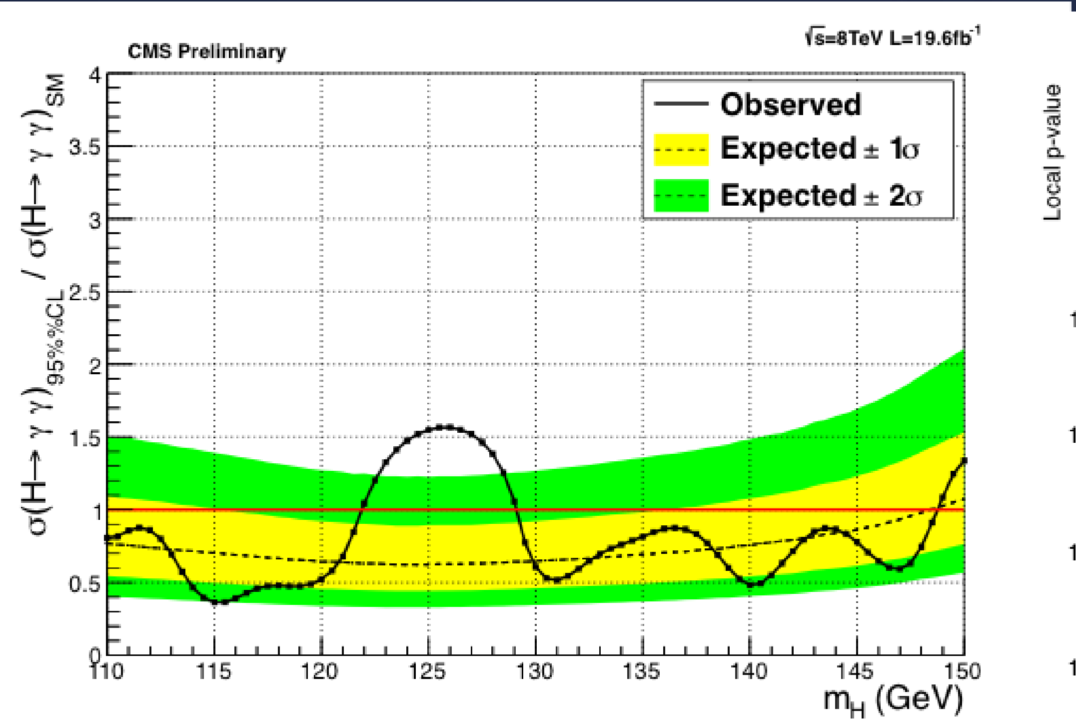


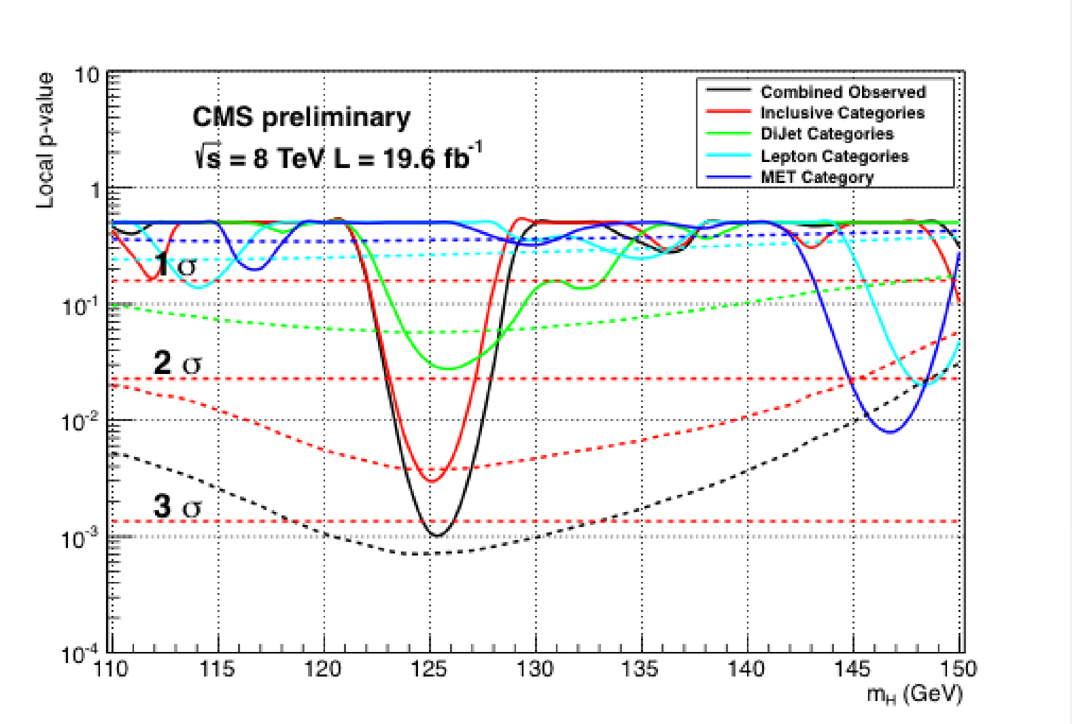






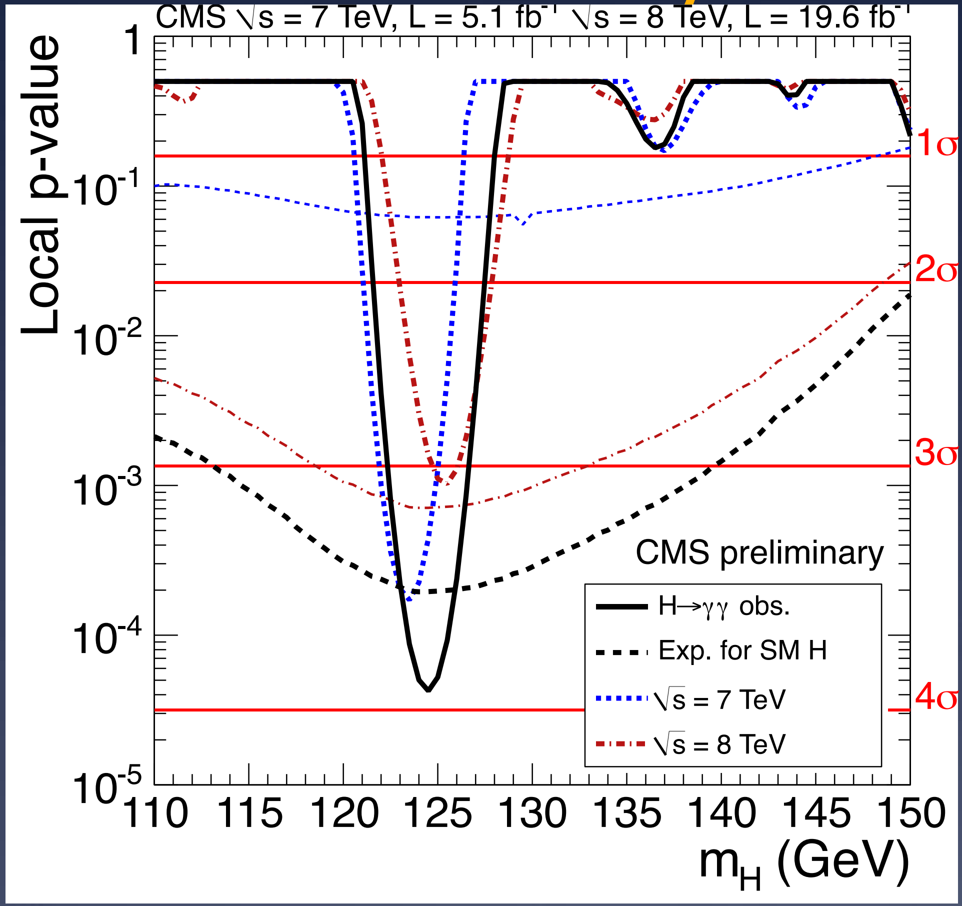
Cut based analysis: Results (8TeV)





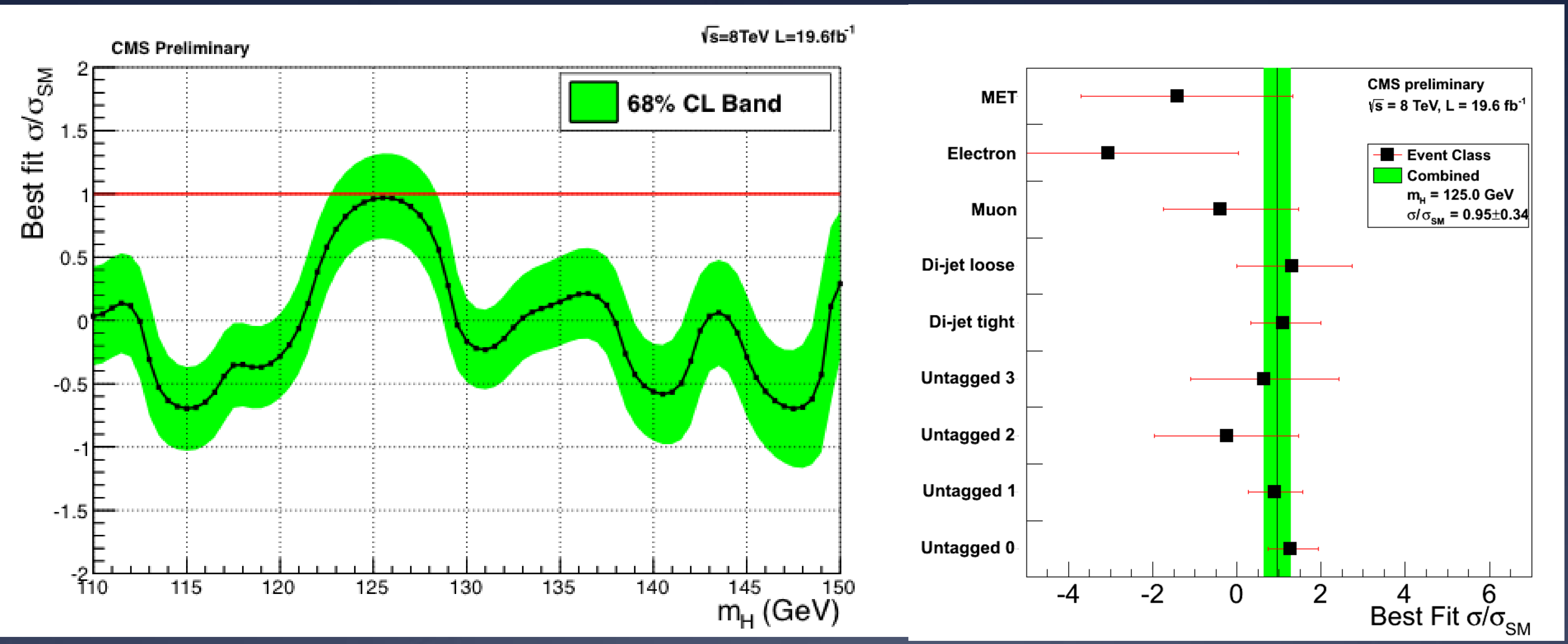
p-value significance
at 125.0 GeV: 3.06σ

Cut based analysis: Results (7+8 TeV)



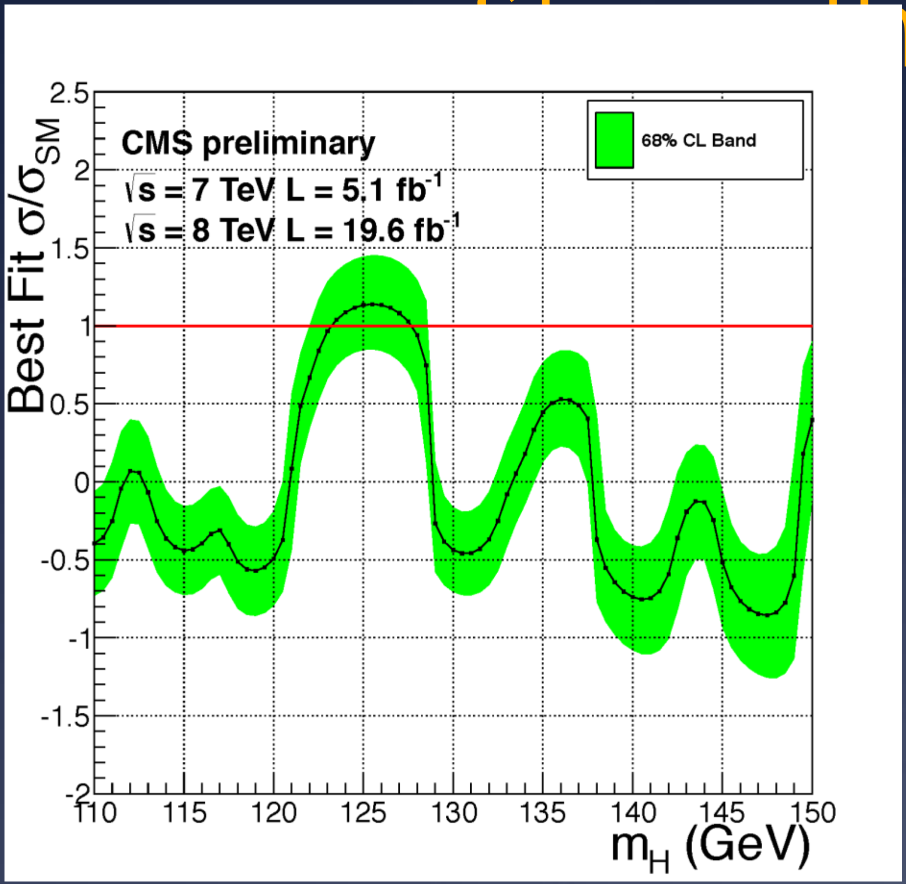
p-value significance at 124.5 GeV: 3.9σ expected 3.5σ

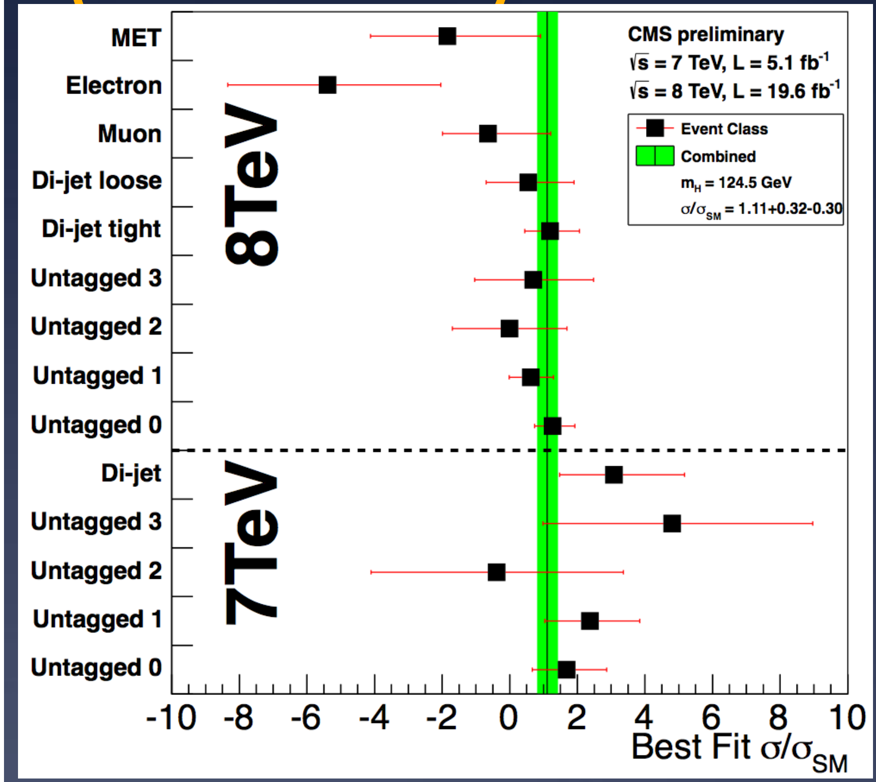
Cut based analysis: Signal Strength (8TeV)



Best fit μ at 125.0 GeV: 0.95^{+34}_{-32}

Cut based analysis: Signal … h (7+8TeV)





Best fit μ at 125.0 GeV: $1.14^{+0.31}_{-0.29}$