SEARCH FOR A RESONANT SM HIGGS BOSON IN CMS USING DIPHOTON DECAYS

April 2014

Case study of a Higgs search.

Outline

SM and the minimal SM (mSM)

mSM Higgs boson

CMS's Electromagnetic Calorimeter

Search for H decaying in gamma gamma

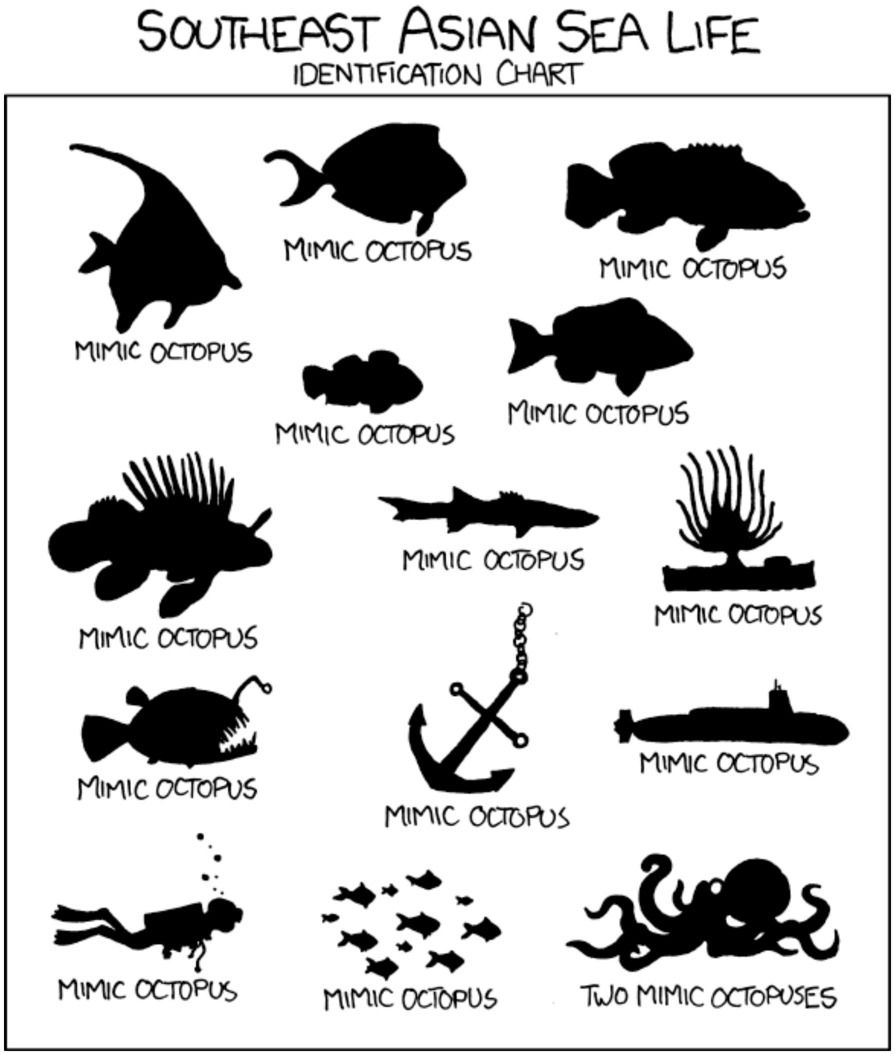
(with and without multivariate methods)

Looking elsewhere

Combining it all

Higgsoctopuses and the Southeast Model

- Different people may mean different things when they say:
  - Standard Model.
  - Higgs.



The least assumptions

http://goo.gl/kZhbw

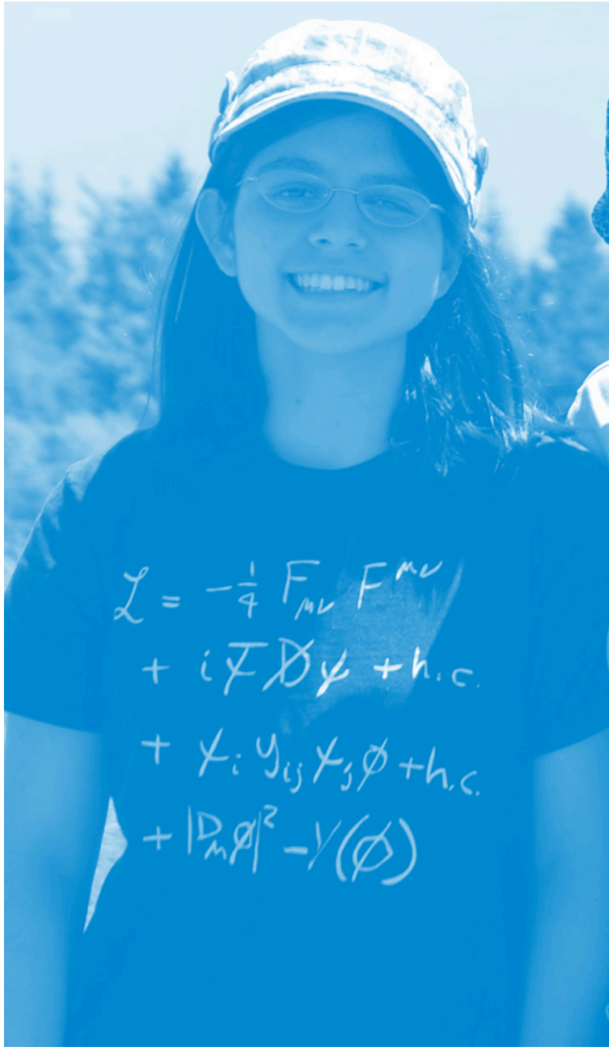
- Basic things:
  - Since massive vector bosons exist
    - → a Higgs field exists.
  - Given EW precision data
    - → the field is light.
  - If QFT is right
    - → the Higgs field has a Kallen-Lehmann spectral density.

- Add-ons:
  - A single Higgs boson is just the simplest realization
    - → minimal SM.

What most people mean by SM

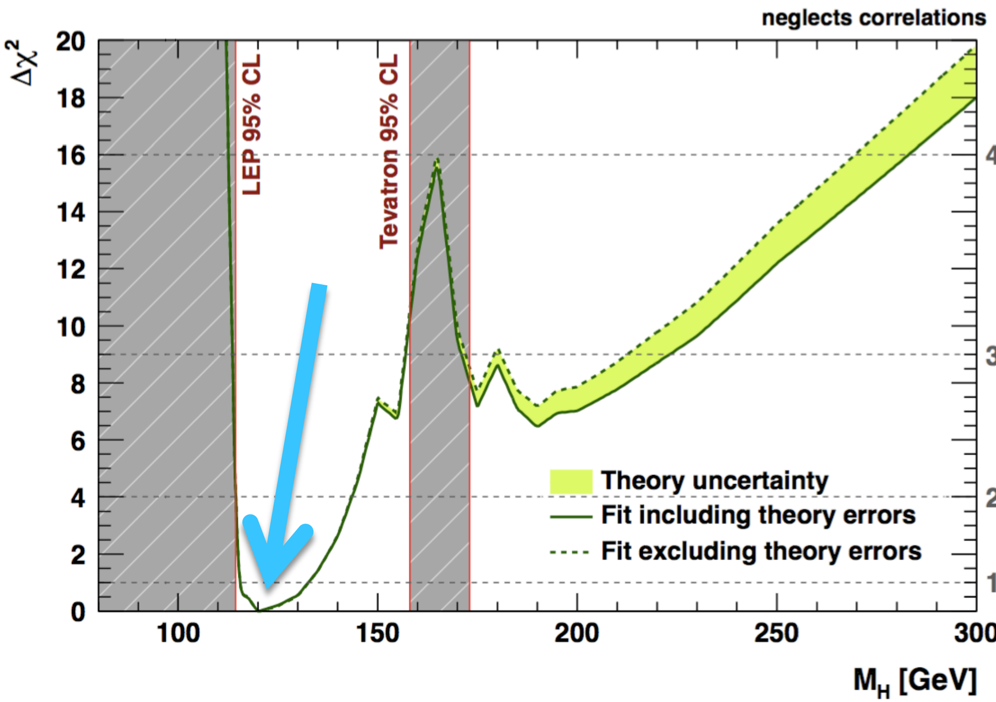
- The SM with one Higgs doublet is the most extensively studied SM model.
  - It is also the simplest.

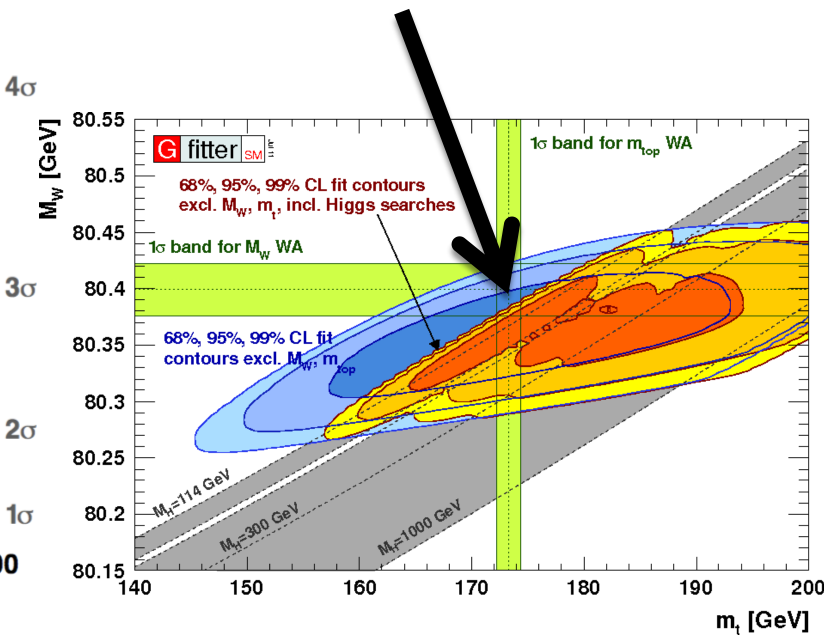
- **Let me call this particular SM, the minimal SM (mSM).**
  - Yes, there are more possible SMs.
- It should be the first to rule out experimentally.



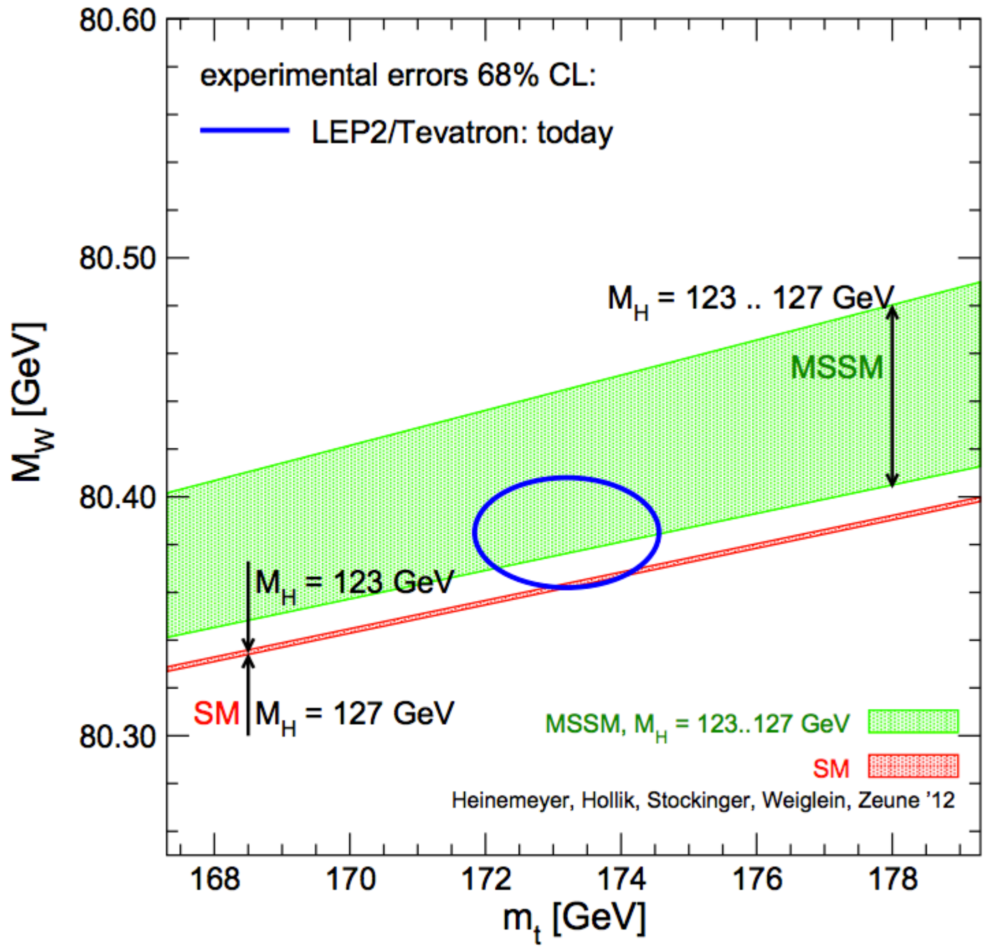
Constraints on the mSM

- Electroweak precision data is a powerful lighthouse.
  - A light resonance is **preferred**.
    - Still the case after LHC data.
    - LEP direct searches truncate the lower mass range.
  - Some **tension** with m_W and m_t.



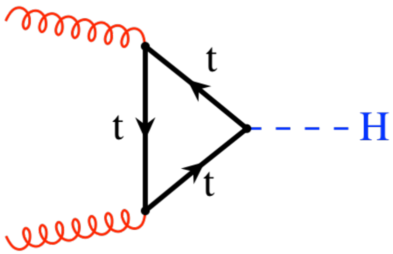


Latest m_W from the Tevatron

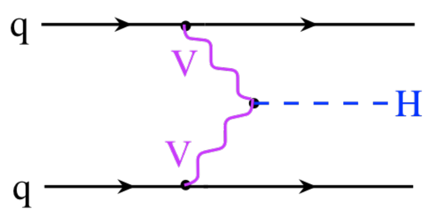


How the SM Higgs is produced

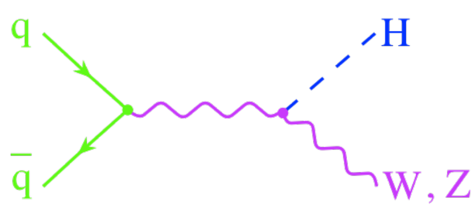
1. **Gluon fusion**



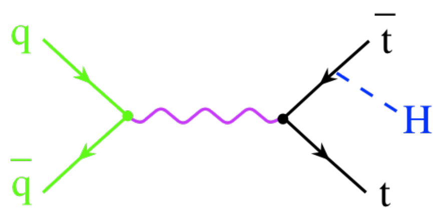
2. **VBF**

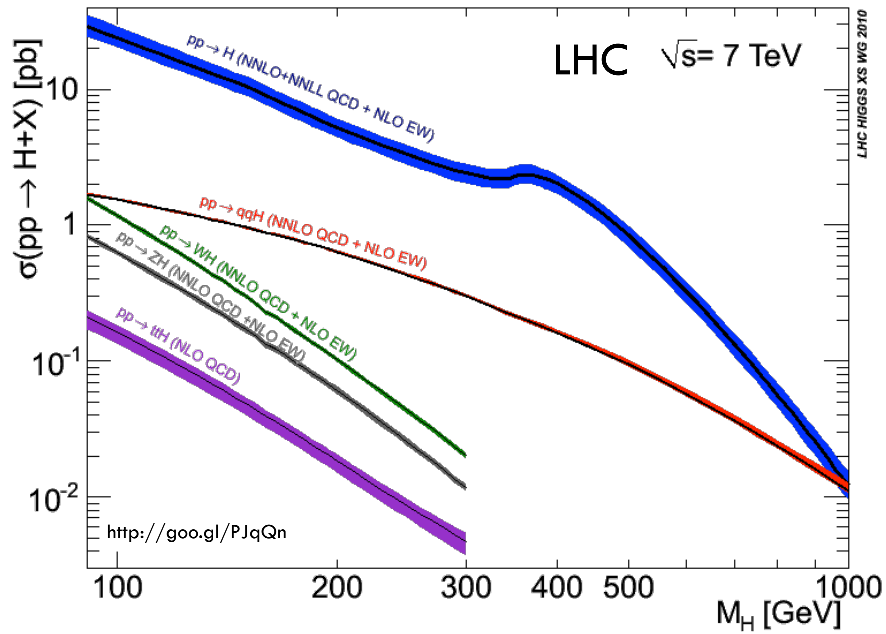


3. **VH**



4. **ttH**

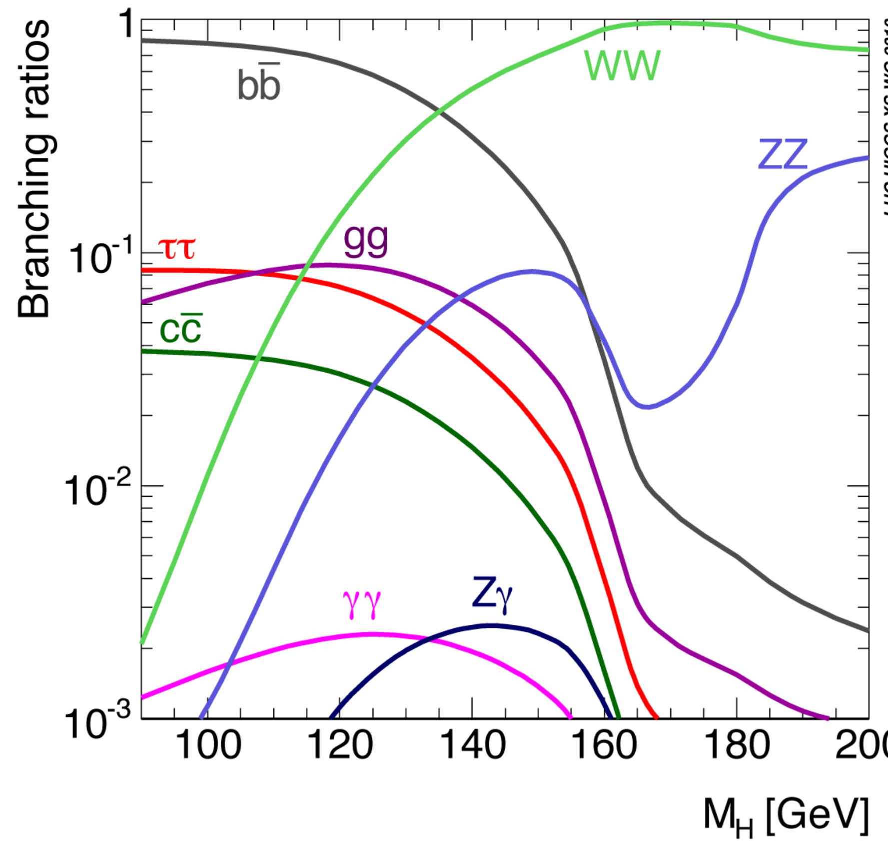




How the SM Higgs decays

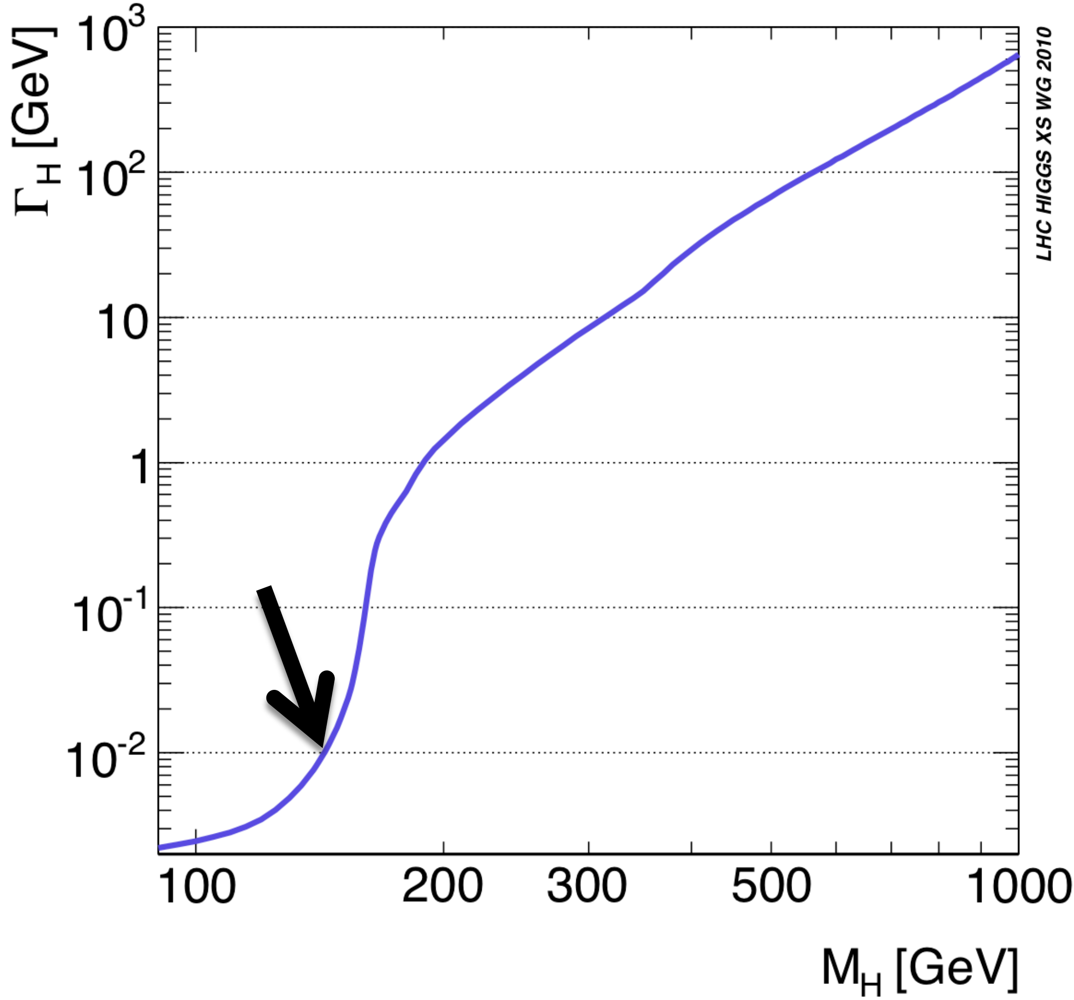
http://goo.gl/uiWwA

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



The width of mSM Higgses

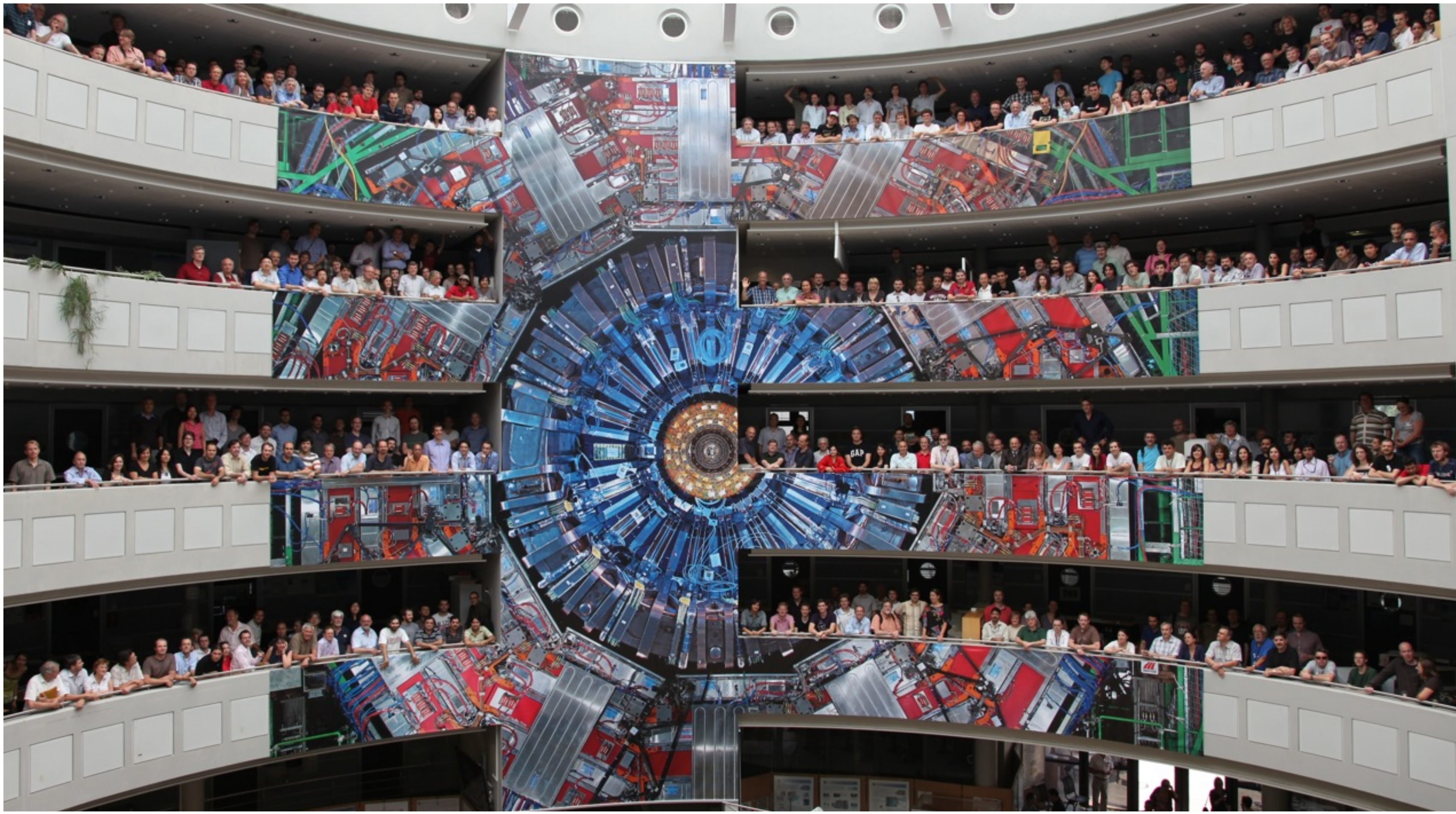
- Extremely narrow for low masses:
  - $\Gamma_H < 100$ MeV for $m_H < 140$ GeV.



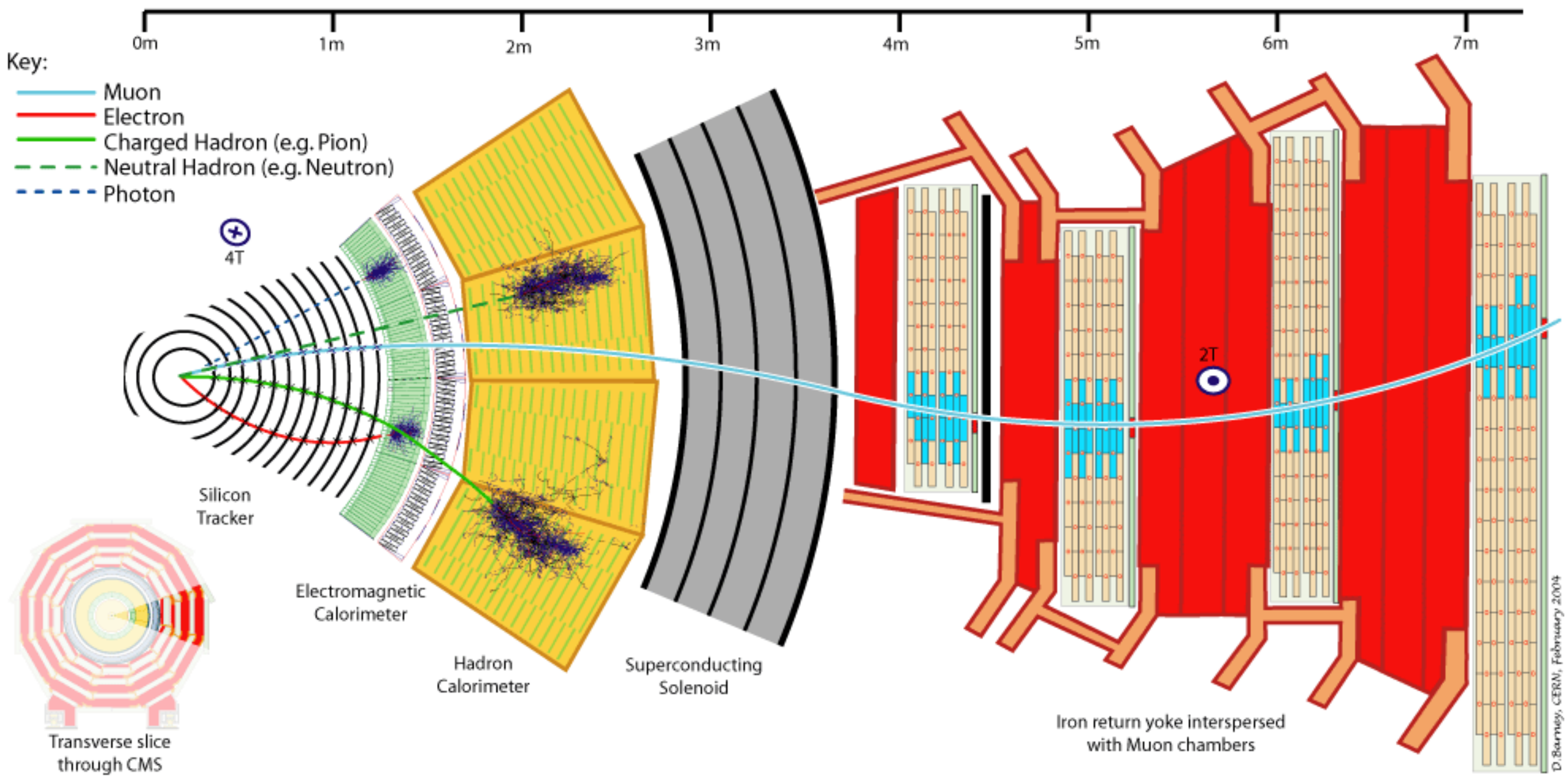
The di-photon channel at the LHC…

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

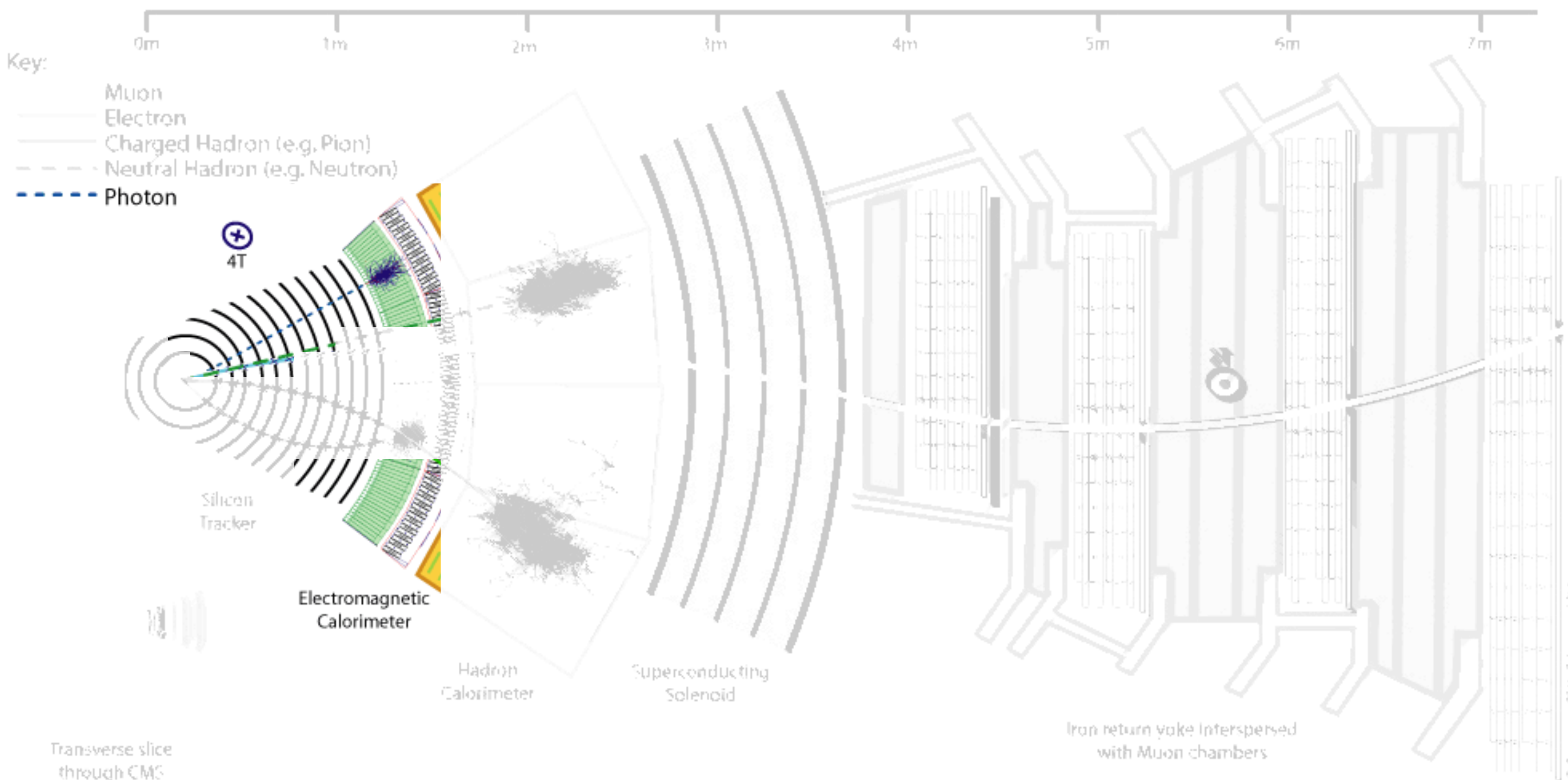
Collaborations are formed



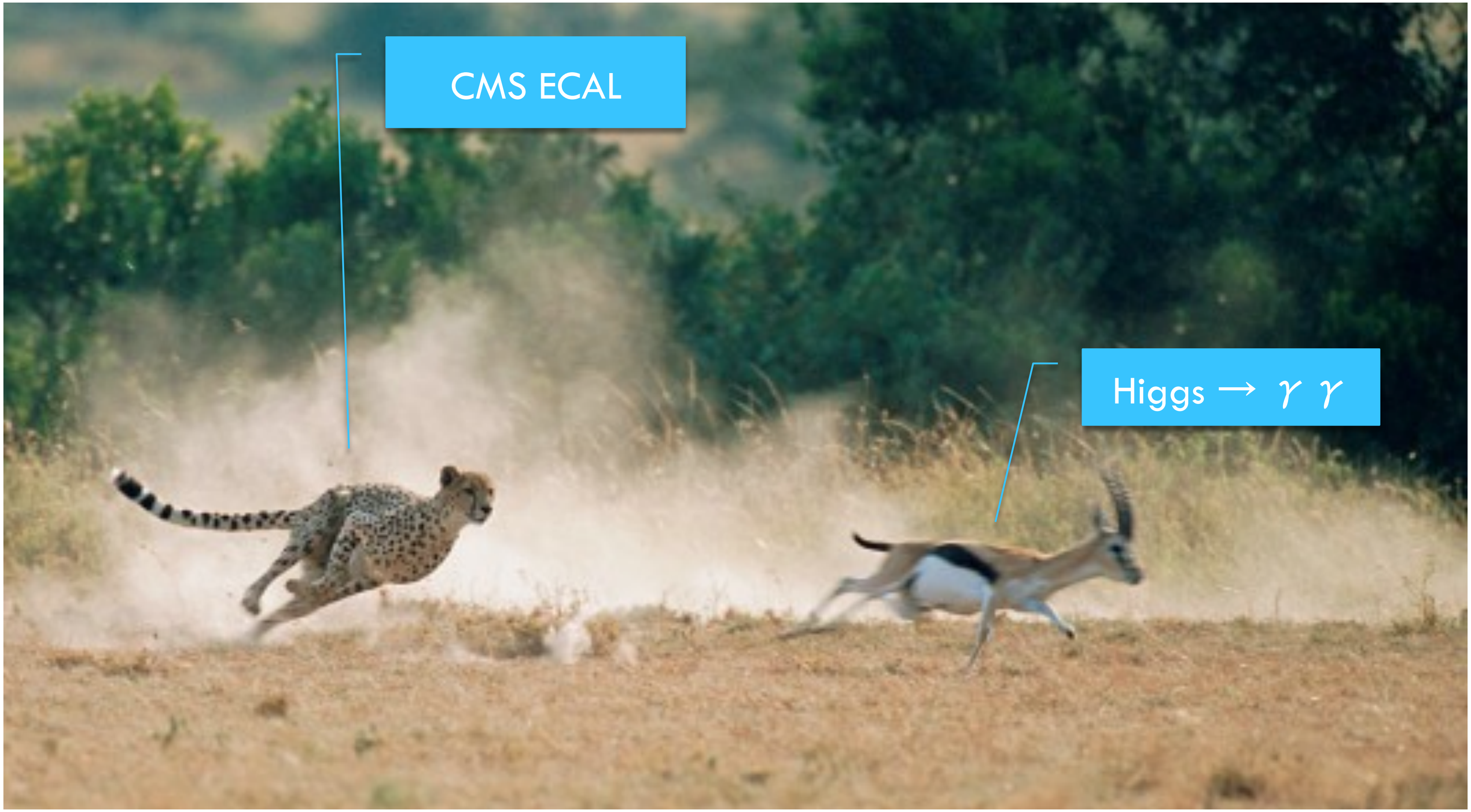
The CMS detector



Photons in CMS

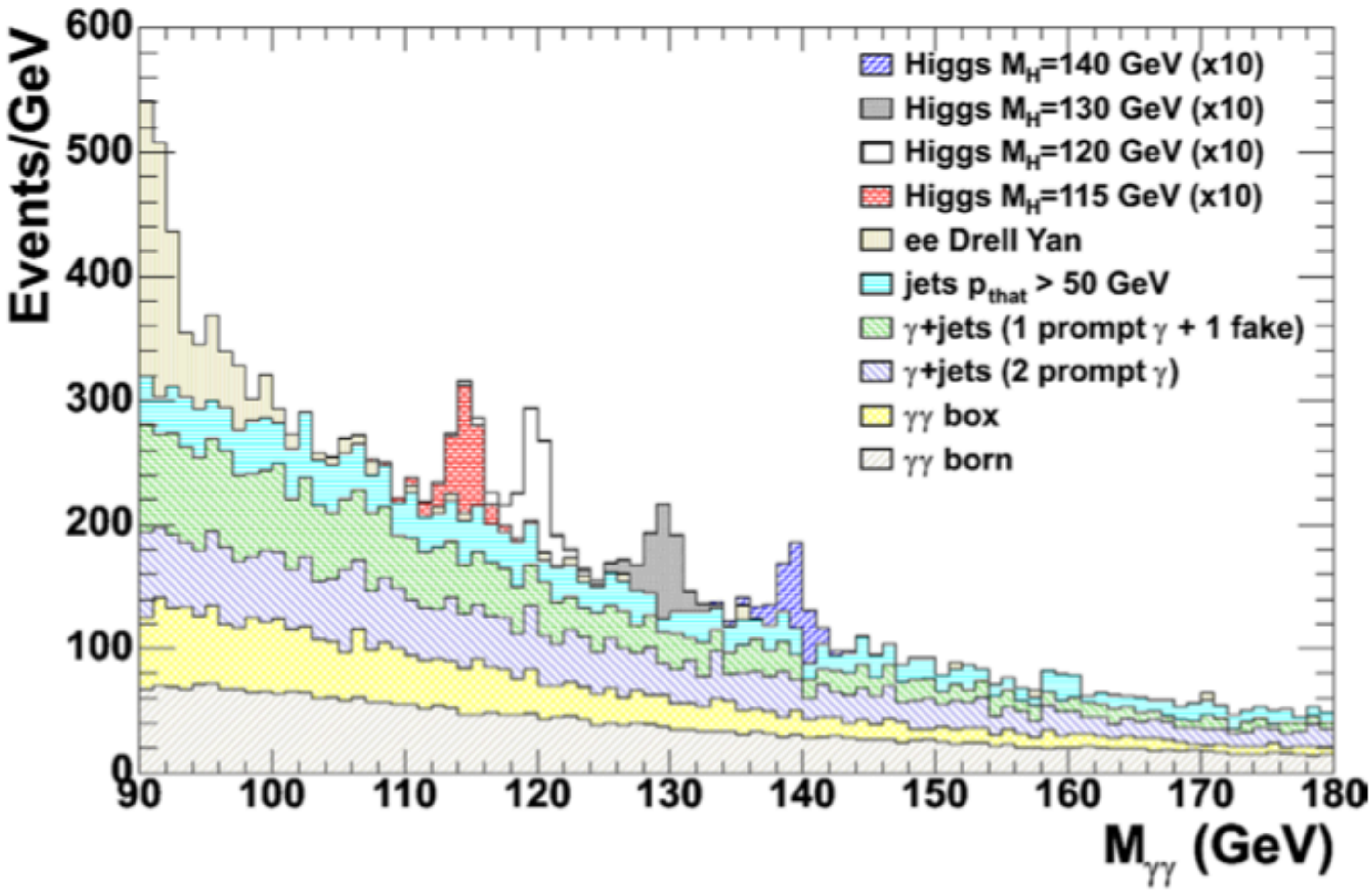


The hunt

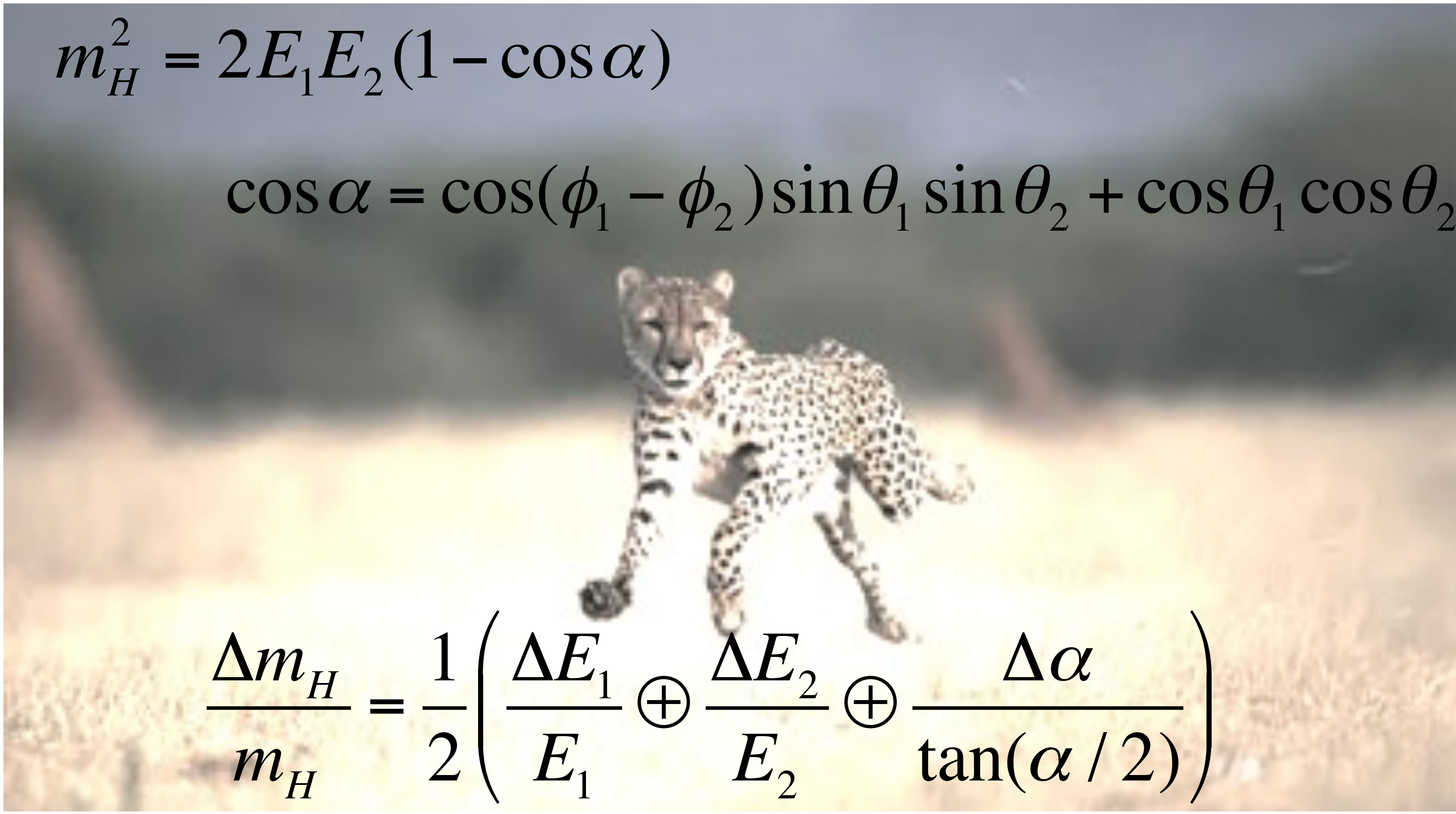


It's all about mass resolution

2007 J. Phys. G: Nucl. Part. Phys. 34 995



Anatomy of di-photon mass resolution



$$m_H^2 = 2E_1E_2(1-\cos\alpha)$$

$$\cos\alpha = \cos(\phi_1-\phi_2)\sin\theta_1\sin\theta_2 + \cos\theta_1\cos\theta_2$$

$$\frac{\Delta m_H}{m_H} = \frac{1}{2}\left(\frac{\Delta E_1}{E_1}\oplus\frac{\Delta E_2}{E_2}\oplus\frac{\Delta\alpha}{\tan(\alpha/2)}\right)$$

Energy and angular resolution

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a, **stochastic term** – photoemission/sampling fluctuations.
b, **"noise term"** – electronics and pileup energy.
c, **"constant term"** – non-uniformities, shower containment etc.

Energy resolution

- Each term should be ~the same at relevant energies ($E=m_H/2$ ~ 60 GeV).
- An homogeneous ECAL has the potential to achieve a stochastic term of ~2%/√E – but quite difficult to control the systematics that build-up the constant term.

Angular resolution

- Primary vertex position along beam axis + photon incidence positions on ECAL → α .
- At high $\mathcal{L}$ need to use hard tracks associated to Higgs production to define the correct vertex (there may be ~20 vertices spread over ~20 cm along the beam axis).

goal → *a* ~ 2.5%
b < 200 MeV
c ~ 0.5%

and an angular resolution
σ_α ~ 50 mrad/√E

Early chronology

- 1990: HEP meeting in Aix-la-Chapelle.
  - LHC and possible future experiments presented.
- 1990: Creation of a CERN R&D programme (DRDC).
- 1991: Creation of the Crystal Clear collaboration(RD18).
  - R&D on scintillating inorganic crystals for the LHC.
- 1992: 1st conference on inorganic scintillators organized by Crystal Clear.
  - Chamonix Crystal 2000.

HEP crystal favorites

	NaI(Tl)	BaF_2	CsI(Tl)	CeF_3	BGO $Bi_4Ge_3O_{12}$	PWO $PbWO_4$
Xo [cm]	2.59 ☹	2.03 ☹	1.86 😐	1.66 😐	1.12 🙂	0.92 🙂
ρ [g/cm^3]	3.67 ☹	4.89 ☹	4.53 ☹	6.16 🙂	7.13 🙂	8.2 🙂
τ [ns]	230 ☹	0.6 🙂 620 ☹	1050 ☹	30 🙂	340 😐	15 🙂
λ [nm]	415 🙂	230 🙂 310 😐	550 🙂	310 😐 340 😐	480 🙂	420 😐
n@λ_{max}	1.85 😐	1.56 🙂	1.80 😐	1.68 🙂	2.15 ☹	2.3 ☹
LY [%NaI]	100 🙂	5 ☹ 16 ☹	85 🙂	5 😐	10 🙂	0.5 ☹

$PbWO_4$

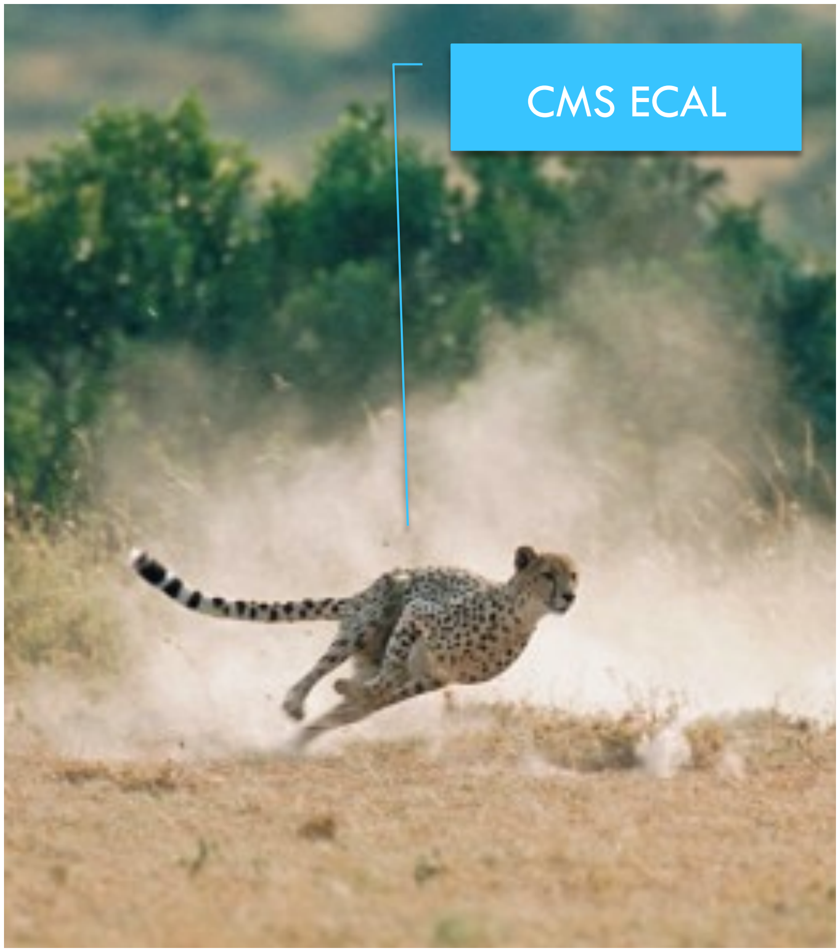
- CMS chose to construct an homogeneous ECAL based on lead-tungstate ($PbWO_4$) crystals:

Reason for $PbWO_4$ crystals	***Challenges***
• Potential to achieve 2% stochastic term.	• Relatively low light yield – need photodetectors with gain.
• Very compact - $26X_0$ in <25cm (X_0 = 0.89cm) – able to place entire calorimeter inside 4T solenoid of CMS.	• Uniformity of light production and collection is important.
• Small Molière radius (~2.2cm) – excellent granularity possible – for isolation efficiency, pileup rejection and spatial precision.	• Light yield is temperature dependant – need to stabilize xtal temperature to 0.1°C (see later).
• Fast light emission (average ~25ns).	• Some low-level radiation damage – need to monitor the xtal transparency using lasers (see later).
• Radiation hard.	• Test and assembly of ~75000 crystals.

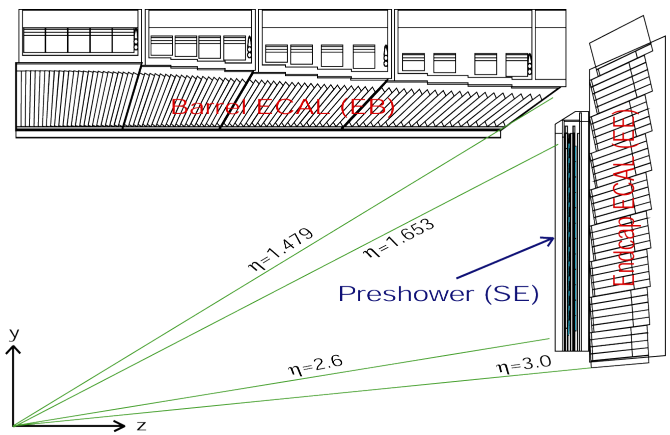
15+ years of work with crystals

- 1990-1993: Several candidate technologies on the table.
  - Liquid Xe, CeF, Shashlik.
- 1993/4: Lead tungstate (PWO) chosen for CMS ECAL.
- 1994-1998: intense R&D on PWO.
- 1998-2000: pre-production of 6000 crystals in Russia.
  - Increase production rate.
  - Improve homogeneity of production quality.
- 2001: start of production in Russia.
- 2005: start of production in China.
- 2007: last barrel crystal produced.
- 2008: last endcap crystal produced.

The making of the hunter



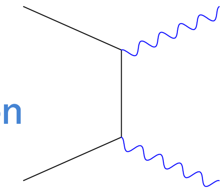
- 75000 $PbWO_4$ crystals
- Si-preshower in the endcaps



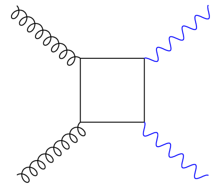
The endcap reducible difficulty

Irreducible	**Reducible**
Quark annihilation; Gluon fusion	Higher orders (mainly brem.); **Jets – γ faked by π^0**

Quark annihilation

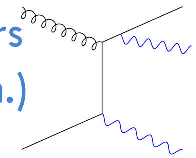


Gluon fusion

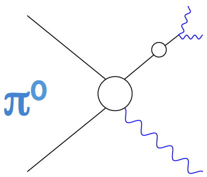


Isolation

Higher orders (mainly brem.)



Jets – γ faked by π^0



Isolation

π^0 rejection

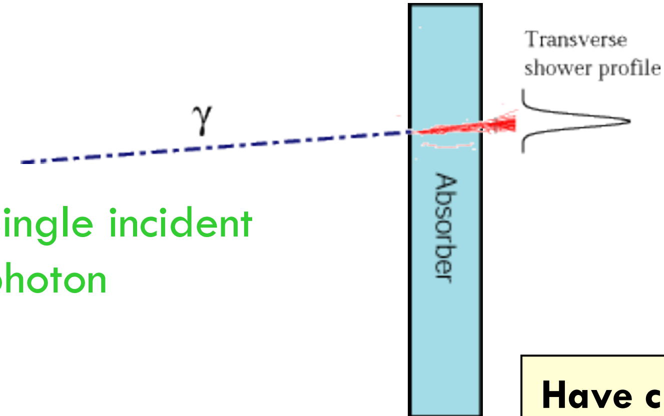
Both isolation and π^0 rejection require high granularity detectors.

A π^0 with p_T~60 GeV will produce 2 photons separated by a small distance in CMS:

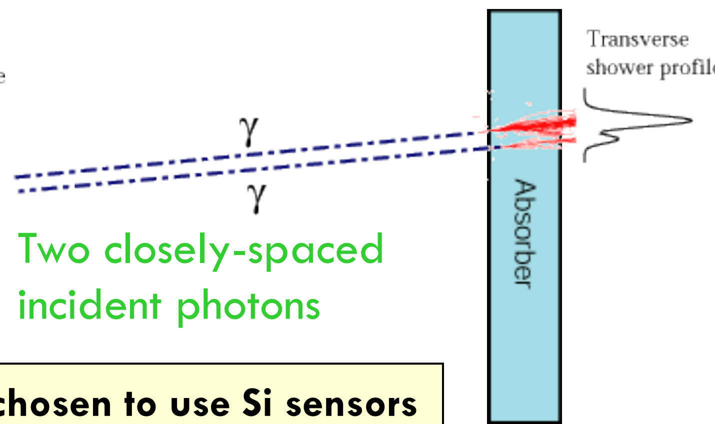
~ 1cm in the barrel after travelling ~1-3m

~ few mm in the endcaps after travelling > 3m

Idea of Preshower:



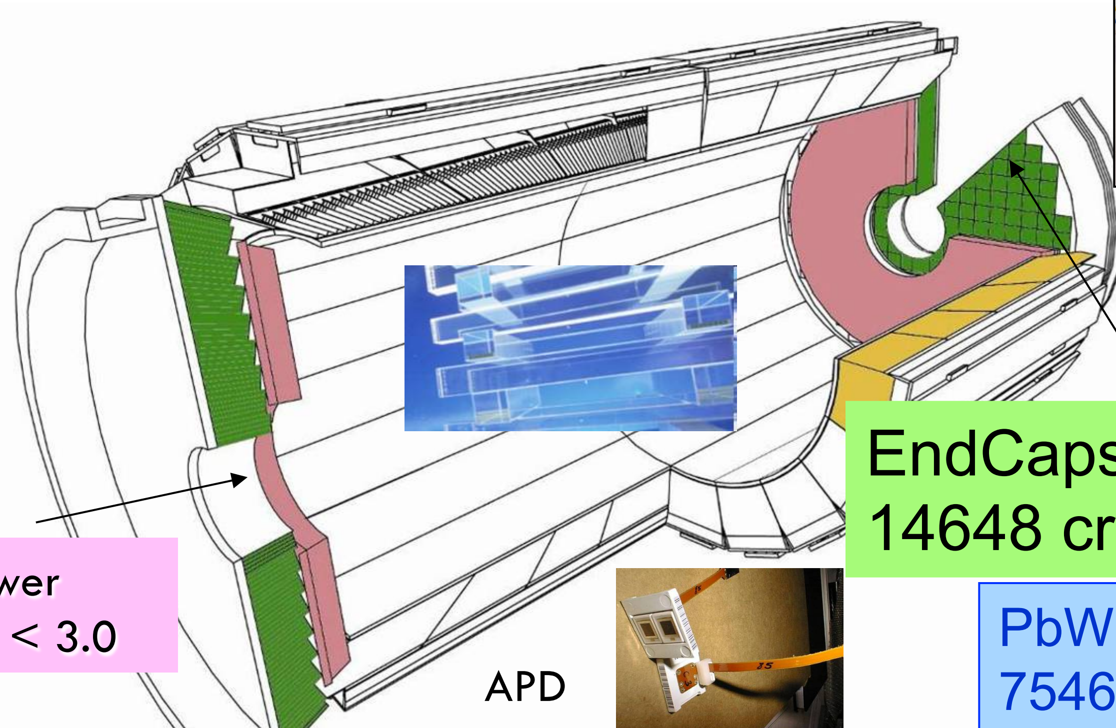
Single incident photon

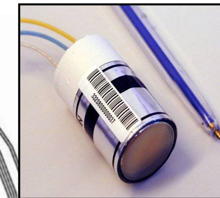


Two closely-spaced incident photons

Have chosen to use Si sensors

CMS electromagnetic calorimeter





VPT

EndCaps: 1.48 < |η| < 3.0
14648 crystals (3x3x22cm³)

Pb/Si preshower
1.65 < | η | < 3.0

APD

PbWO$_4$
75468 crystals
produced in China (SIC) and Russia
X_0 0.89 cm
LY~100 pe/MeV (PMT)

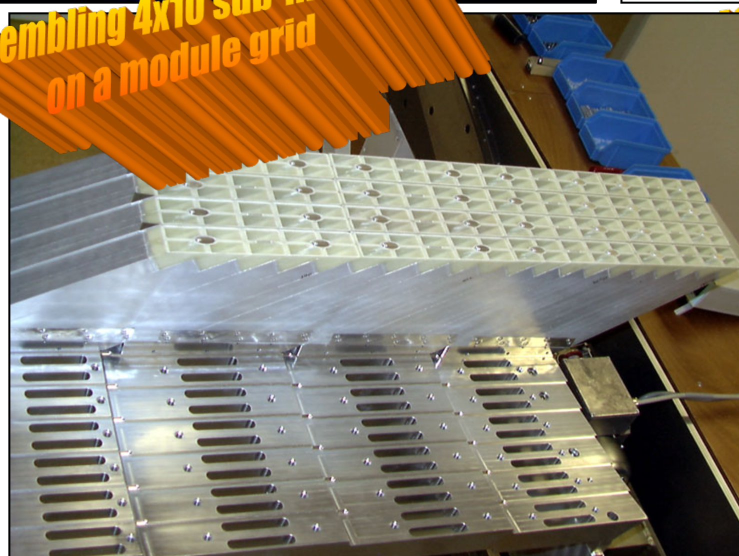
Barrel: |η| < 1.48
61200 crystals (2x2x23cm³)

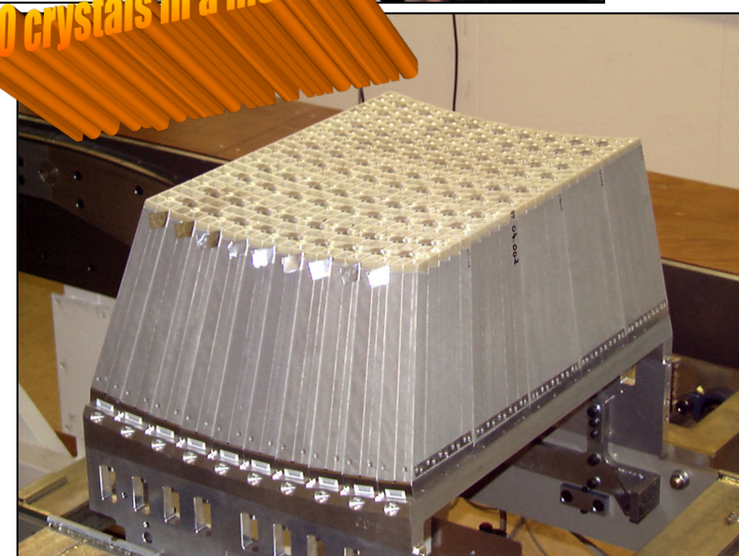
DESIGN ENERGY RESOLUTION (BARREL)

$$\frac{\sigma(E)}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.55\% \oplus \frac{155MeV}{E}$$

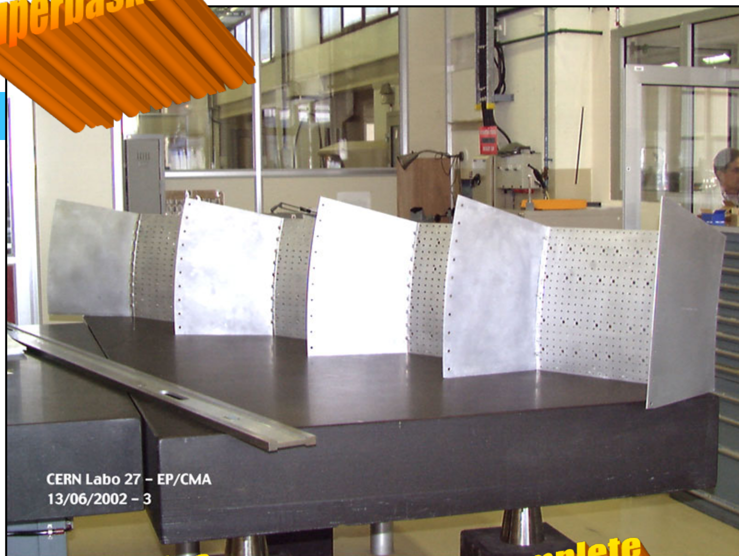
Granularity Barrel
ΔηxΔϕ=0.0174x0.0174

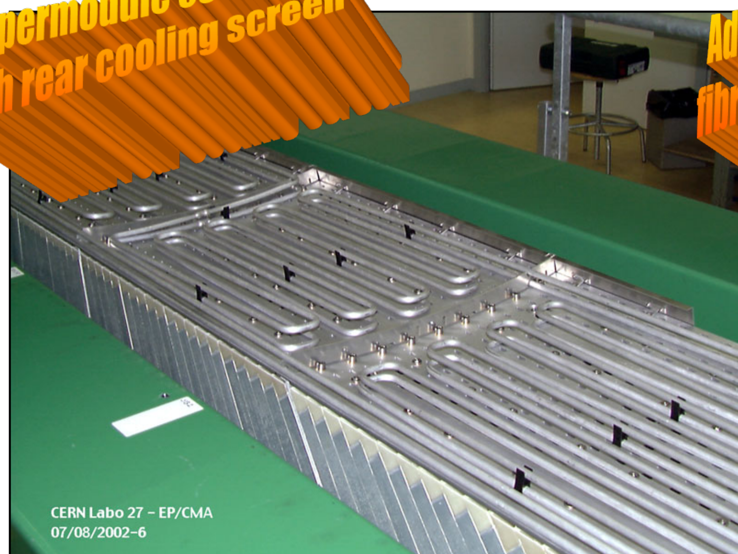
Barrel Module Assembly

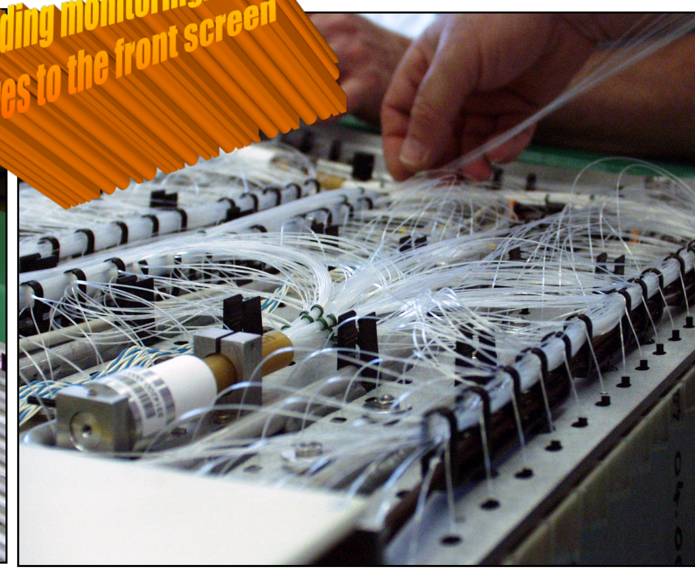




Supermodule Assembly





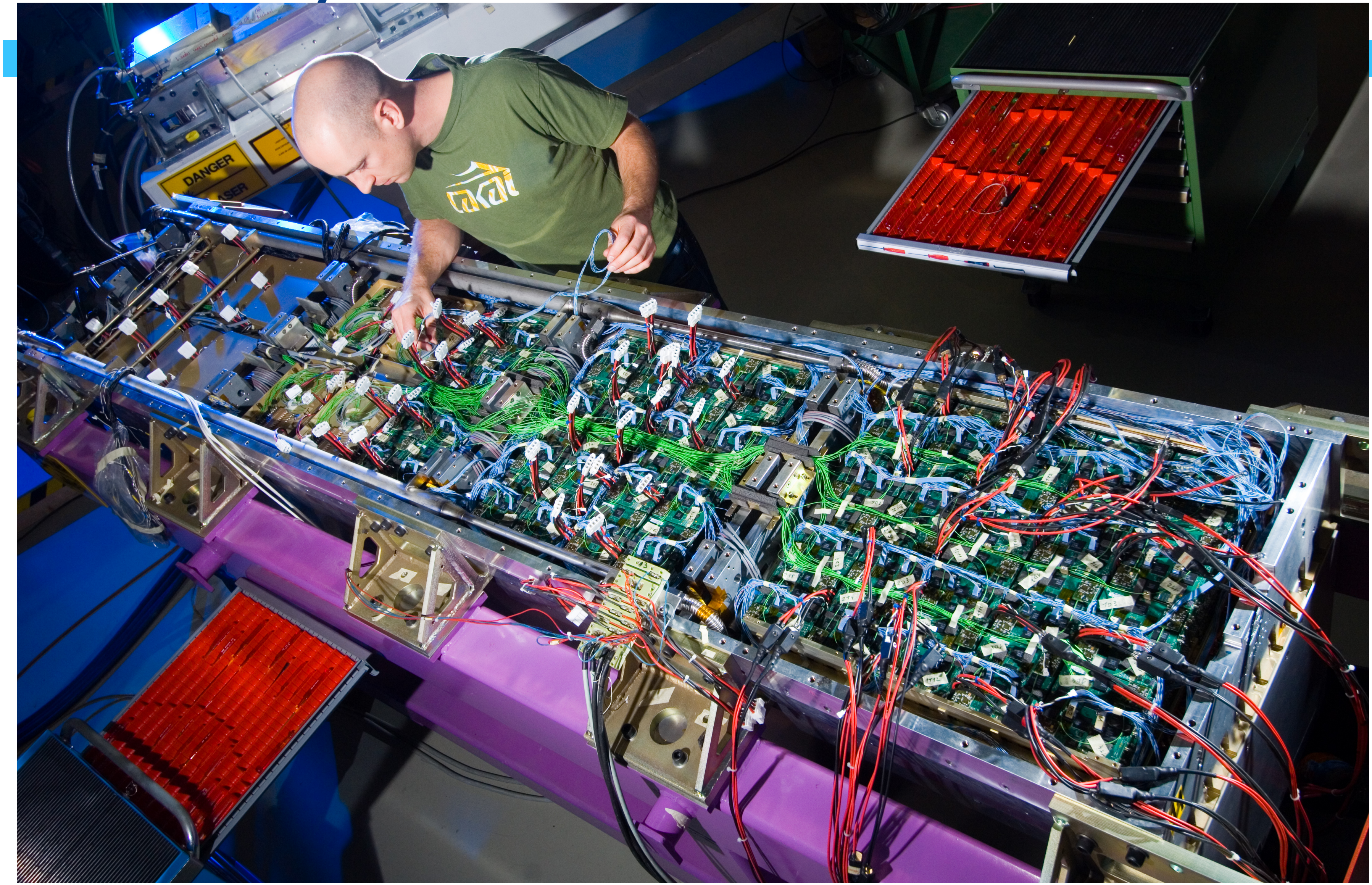


Supermodule Assembly

Then the electronics need to be added!

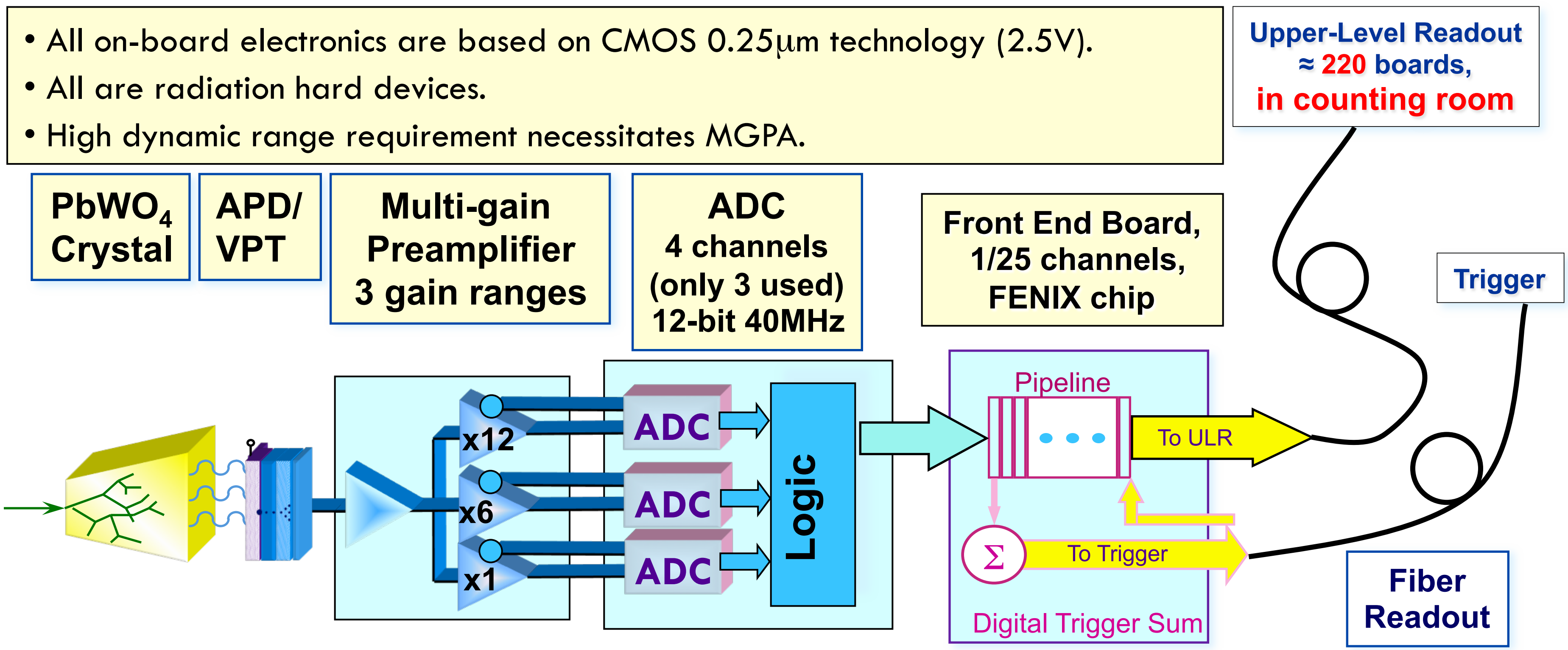
36+1 supermodules assembled at CERN between 2003 and 2007.

Assembly of front-end electronics



ECAL front-end electronics

- All on-board electronics are based on CMOS 0.25μm technology (2.5V).
- All are radiation hard devices.
- High dynamic range requirement necessitates MGPA.

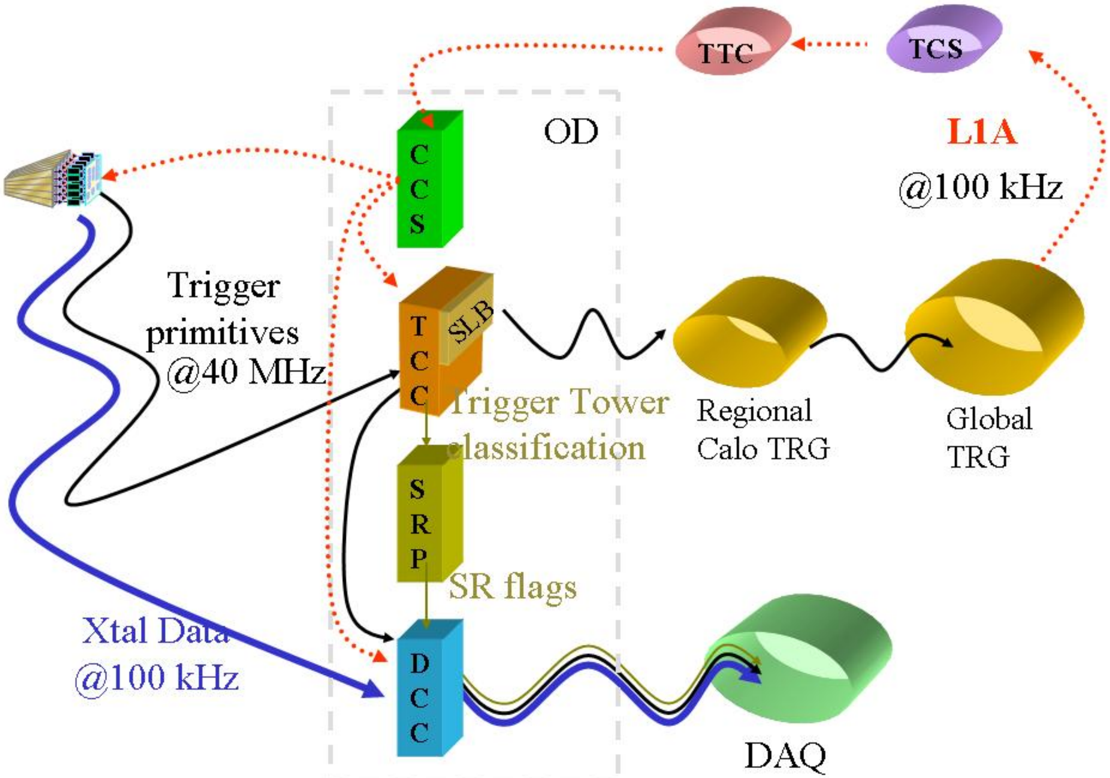


three optical links per Trigger Tower
25 xtals
800 Mbit/s

Light-to-light readout system

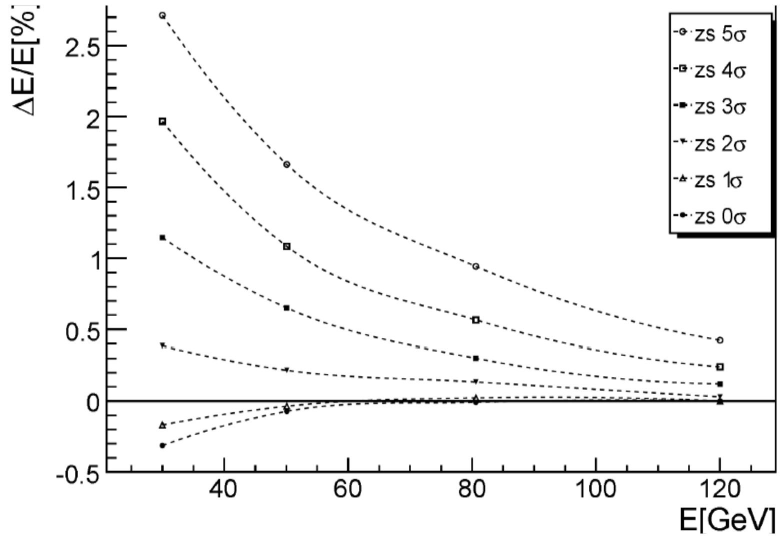
ECAL off-detector electronics

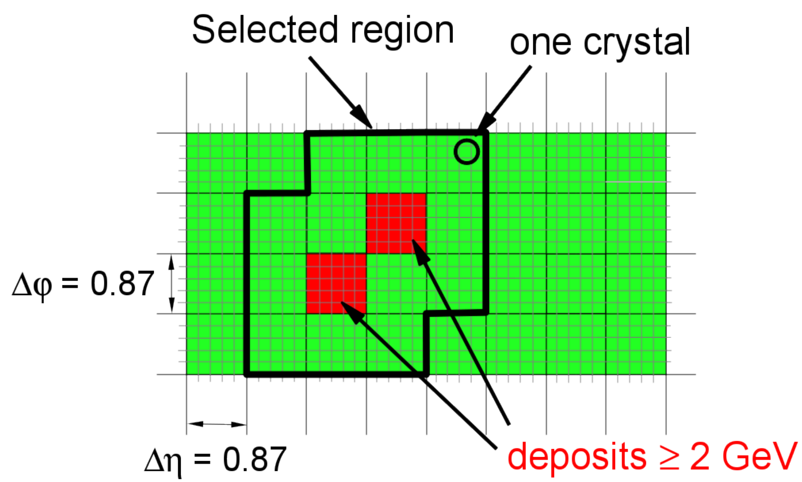
- Part of the CMS Level 1 trigger.
- Readout of 10 time samples at 100 kHz.
- Data reduction of factor 20 needed:
  - Selective Readout Processor to preserve energy resolution.



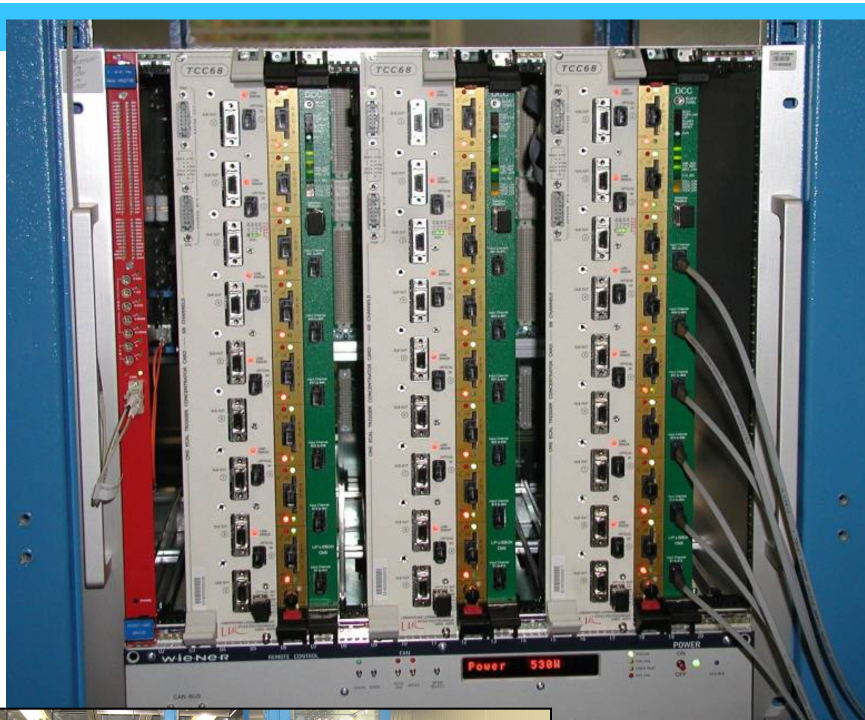
Selective readout

- Factor 20 reduction in data size needed to fit within CMS event budget.
- **Simple zero suppression spoils energy resolution. ➔**
- Perform selective readout of zones neighboring large deposits:
  - Drop, strong ZS, weak ZS, and full readout.

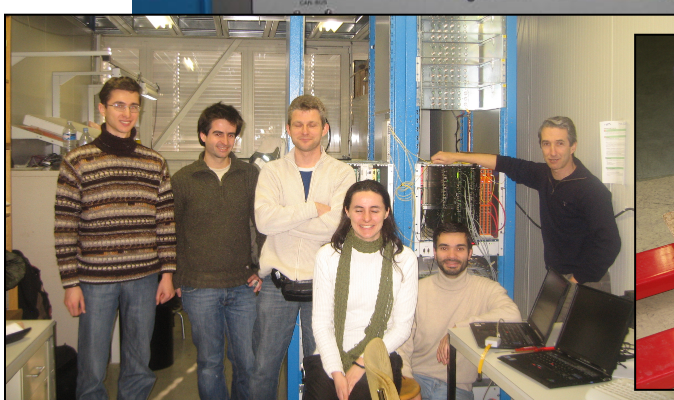
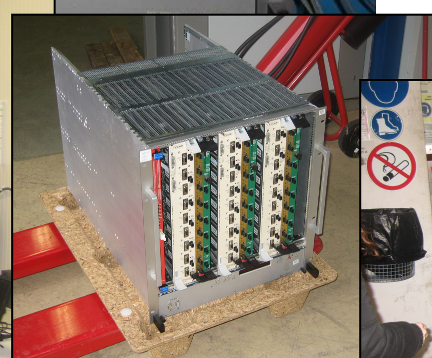




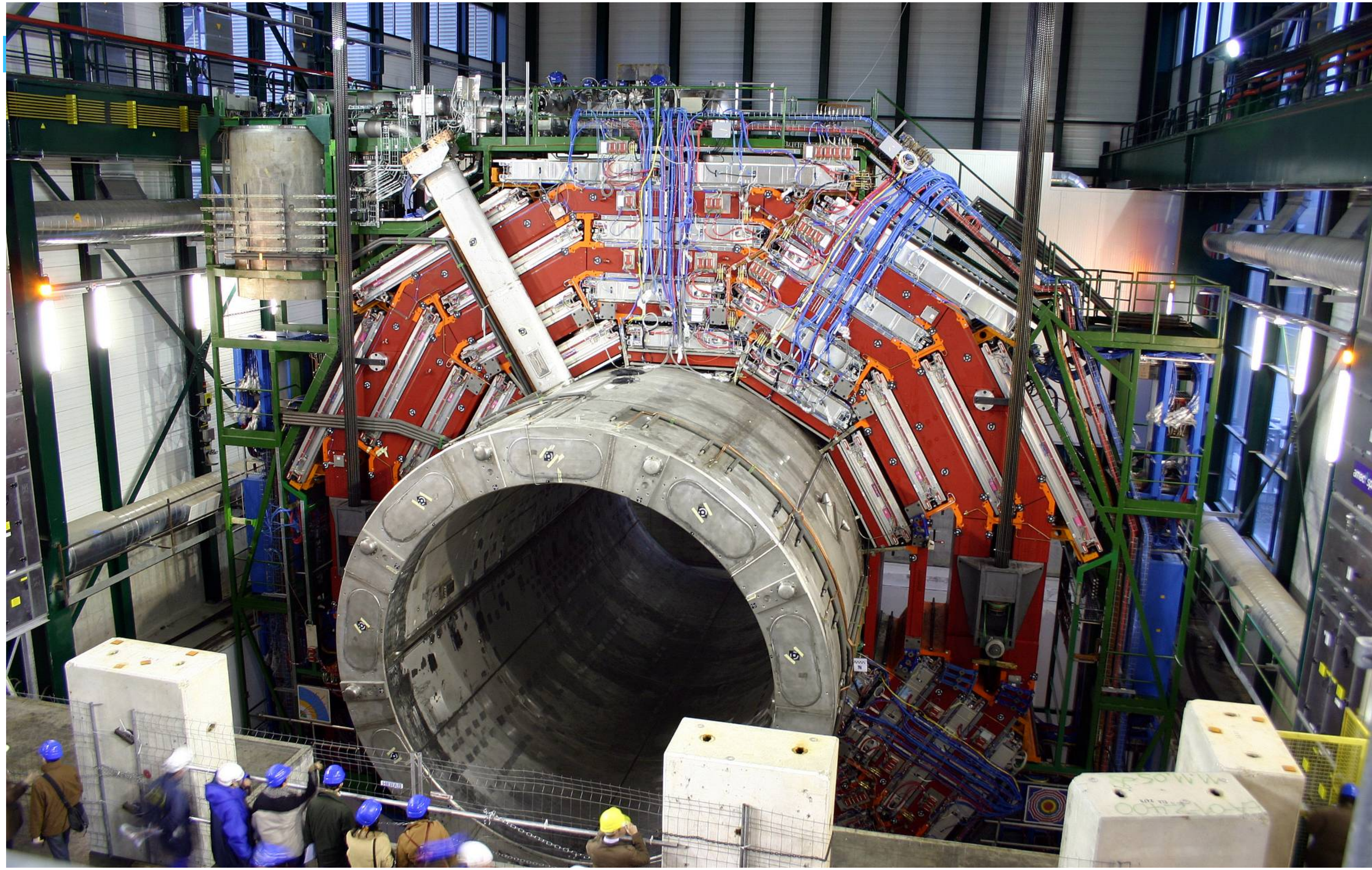
April 2007: ECAL electronics integration



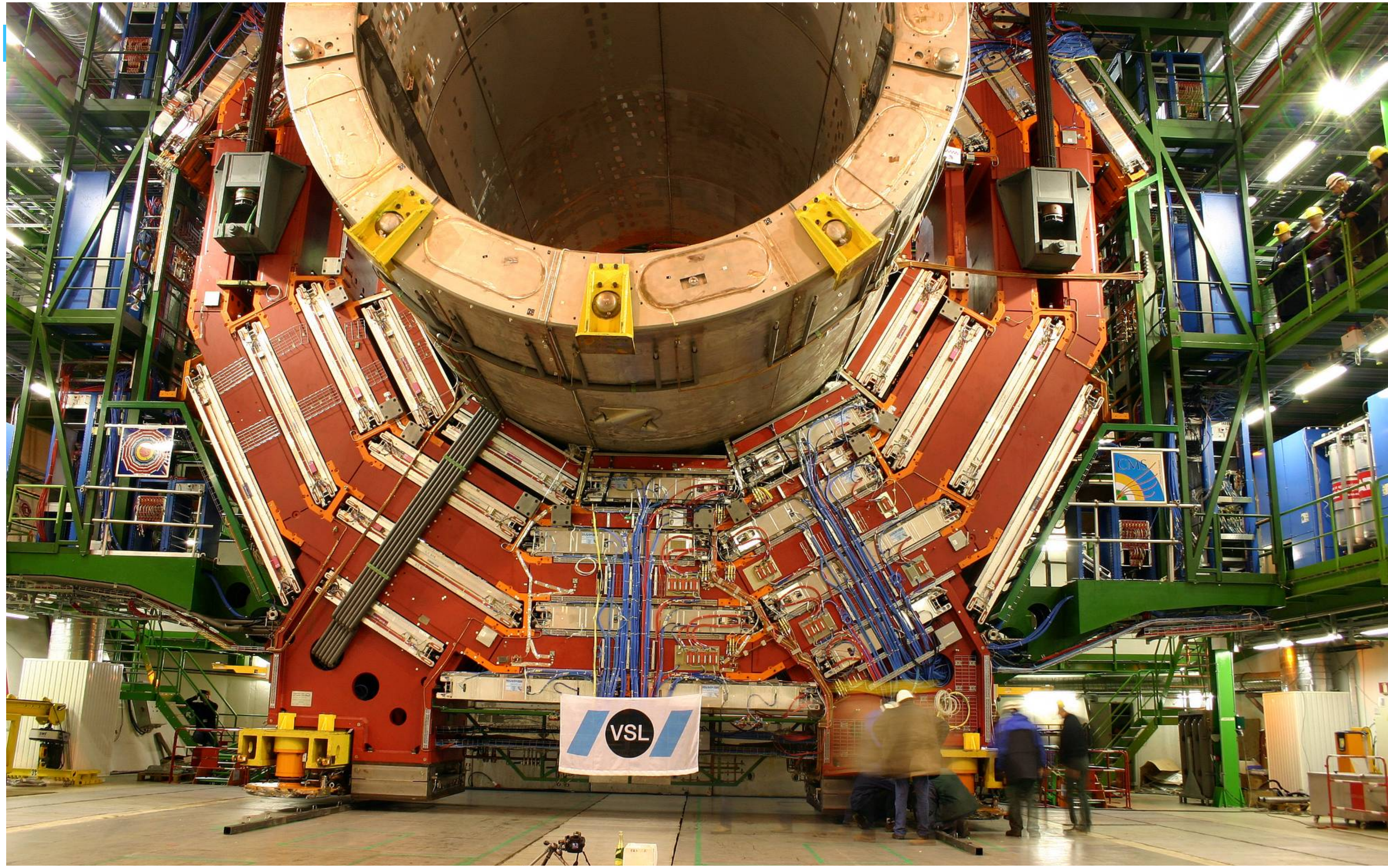
- **Integrated tests** of Data, Trigger and Control cards prior to installation.
- 12 crates with **110 cards** intensively tested.
- **>10 hours of continuous testing** per crate.

2007: lowering of the central barrel

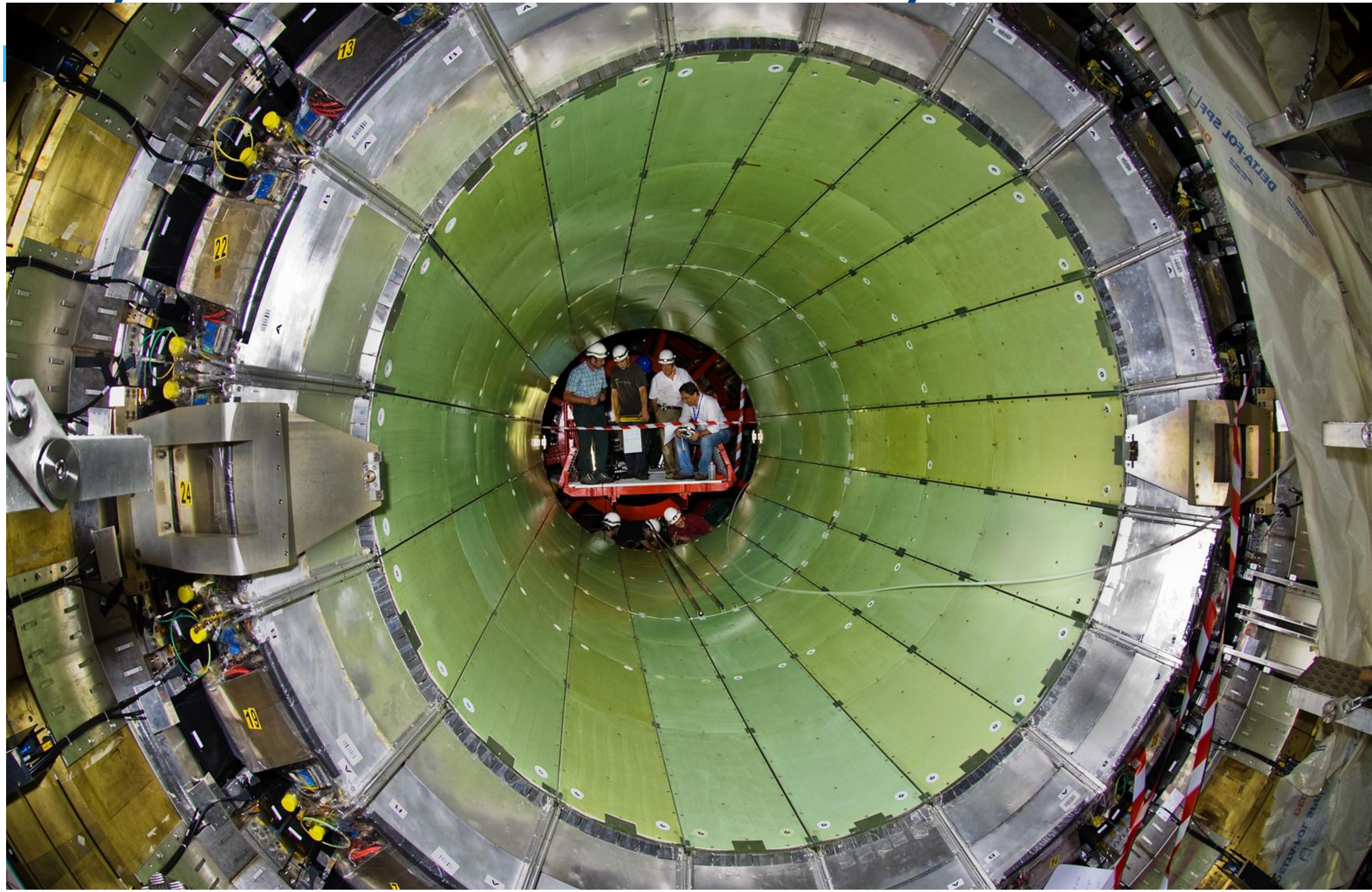


Touch down !

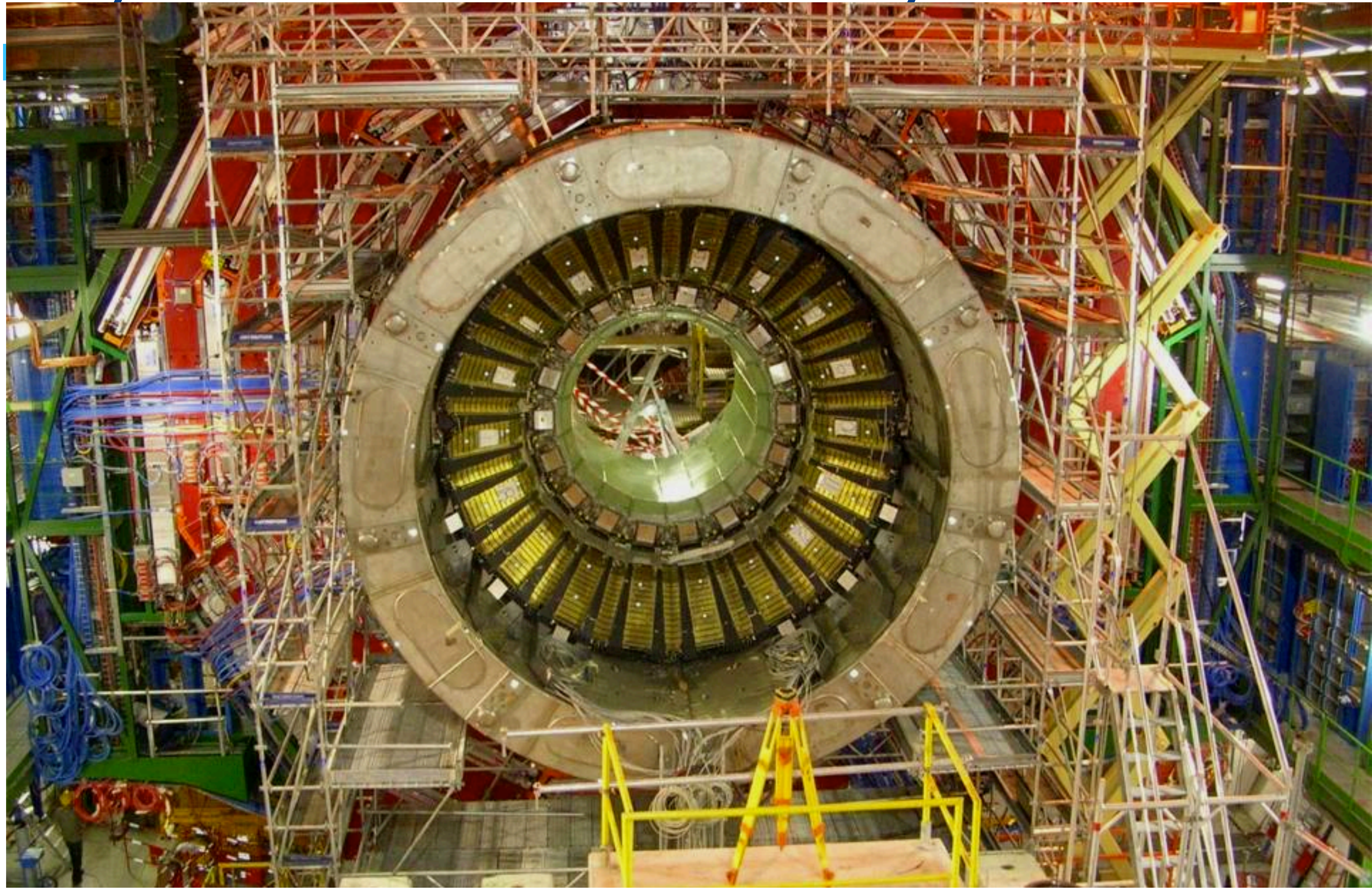


May 2007: ECAL barrel installation

July 2007: ECAL barrel fully installed

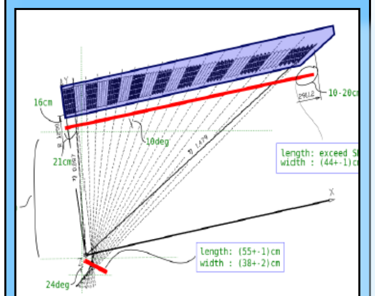


July 2007: ECAL barrel fully installed



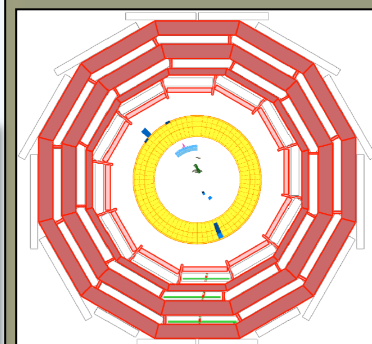
Highlights from the CMS ECAL Timeline

2006-2007
Commissioning & calibration of each SM with cosmics on surface.

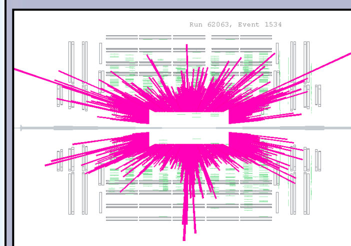


2006
H4 Test Beam: 9 SM calibrated; H2 Combined Test Beam: ECAL+HCAL.

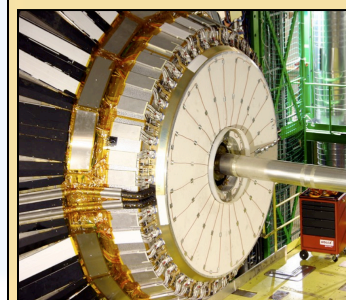
2006
2 SM tested with B-field on surface (MTCC).



2008
Endcap Installation. Commissioning with cosmics and first beam in-situ.



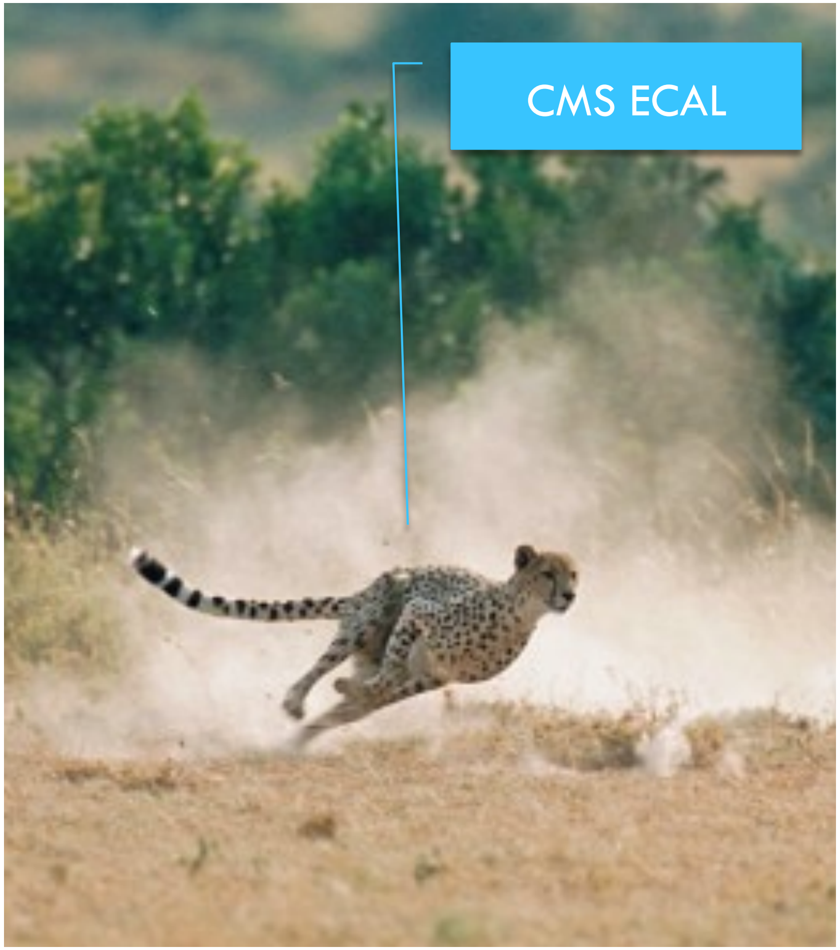
2009
Installation of preshower. Commissioning of Endcap trigger.



2007
H4 EE Test Beam; Individual signoff of each SM during installation.

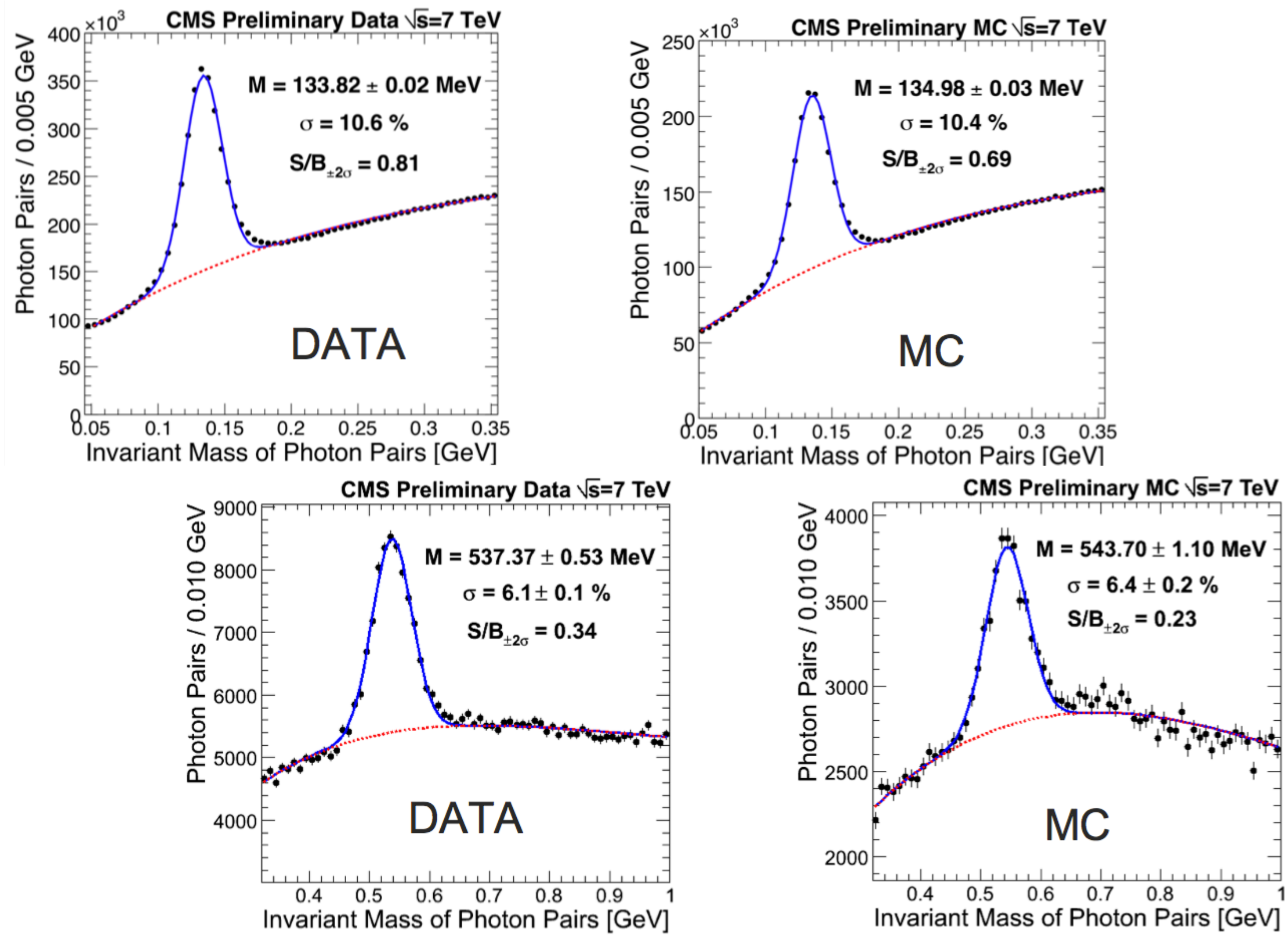
2006 — 2007 — 2008 — 2009

The hunter



- High-granularity in >75000 crystals.
- Light yield monitoring to better than 0.2%.
- APD HV stability better than 10 mV.
- Temperature stability better than 0.05 C.
- Selective full readout.

2010: η and π^0 reconstruction/calibration



Start off with single photons

One comes before two.

Isolated photons – first step

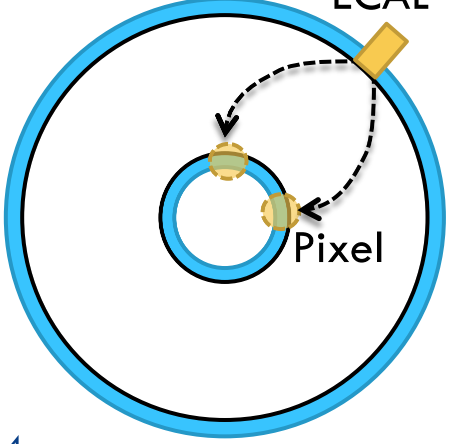
- Studied experimentally since 30 years.
  - Large contamination from the decay of energetic neutral mesons.
  - Experimentally accessible objects: **isolated photons.**
  - Main handles:
    - track and calorimeter sums,
    - shower shapes.

Photon candidate ID

- Robust start-up selection →
  - Small set of variables
    - $Iso_{TRK} = \Sigma_{R<0.4}$ track p_T
    - $Iso_{ECAL} = \Sigma_{R<0.4} E_{T\ ECAL}$
    - $Iso_{HCAL} = \Sigma_{R<0.4} E_{T\ HCAL}$
    - $H/E = \Sigma_{R<0.15} E_{HCAL}/E_{ECAL}$
    - Pixel seed veto →
- Criteria away from simulation details

Variable	Selection
Track Isolation (Iso_{TRK})	$<$ **2.0** GeV + 0.001 E_T
ECAL Isolation (Iso_{ECAL})	$<$ **4.2** GeV + 0.003 E_T
HCAL Isolation (Iso_{HCAL})	$<$ **2.2** GeV + 0.001 E_T
H/E	$<$ 0.05

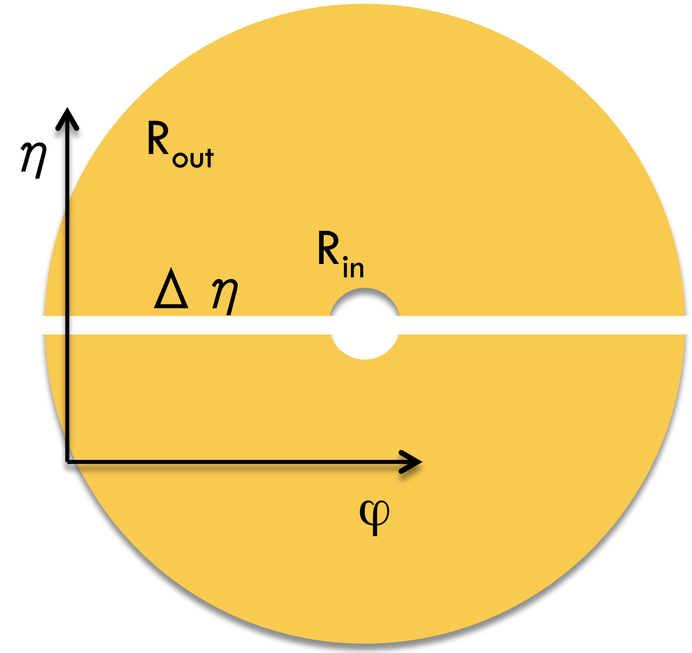
(veto events with pixel seeds compatible with electron tracks) ↓



Photon candidate ID: isolation

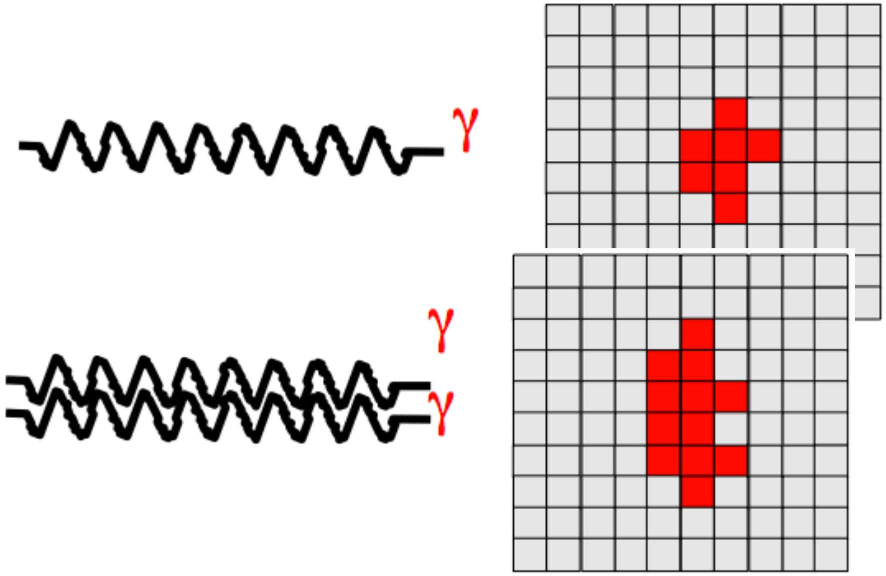
- **Hollow cone removing central η strip.**
- Allows the use of (Z) electron control samples:
  - Fully data-driven corrections.
  - Insufficient prompt-photon control sample in 2/pb.

Variable	R_{out}	R_{in}	$\Delta\eta$
Iso_{TRK}	0.4	0.040	0.015
Iso_{ECAL}	0.4	0.06	0.04
Iso_{HCAL}	0.4	0.15	-



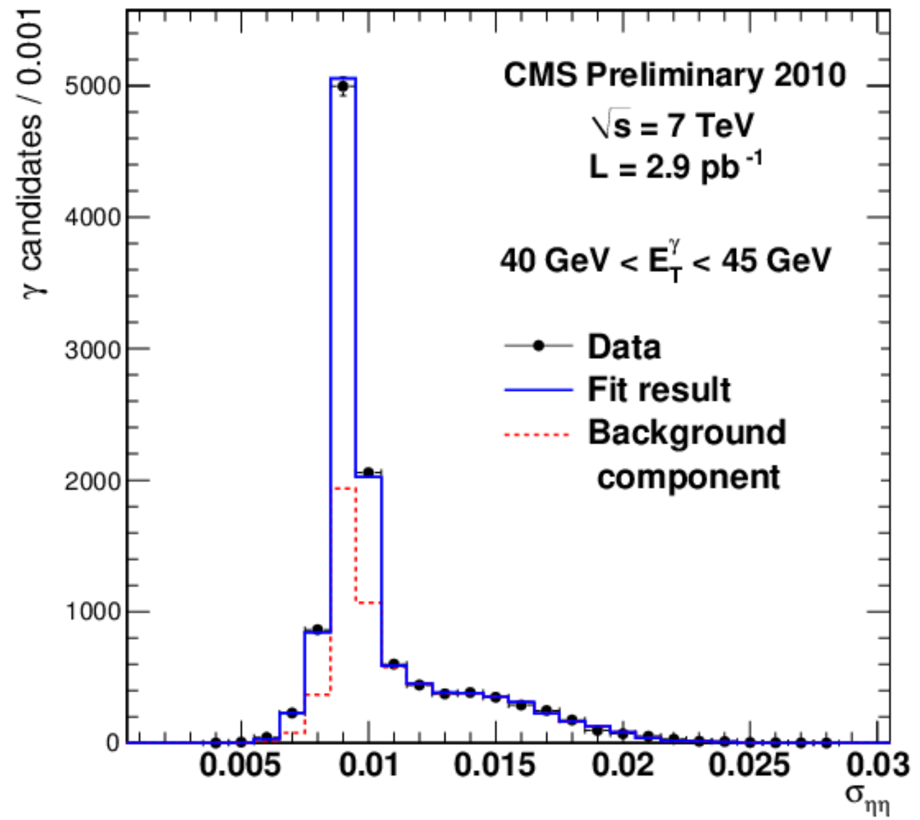
Handles for photon signal yield extraction

- Main background for isolated photons are neutral mesons decaying into 2γ.
- Two main tools to disentangle:
  - Candidate isolation in Tracker, ECAL, HCAL.
  - Shower shape in ECAL. ➘



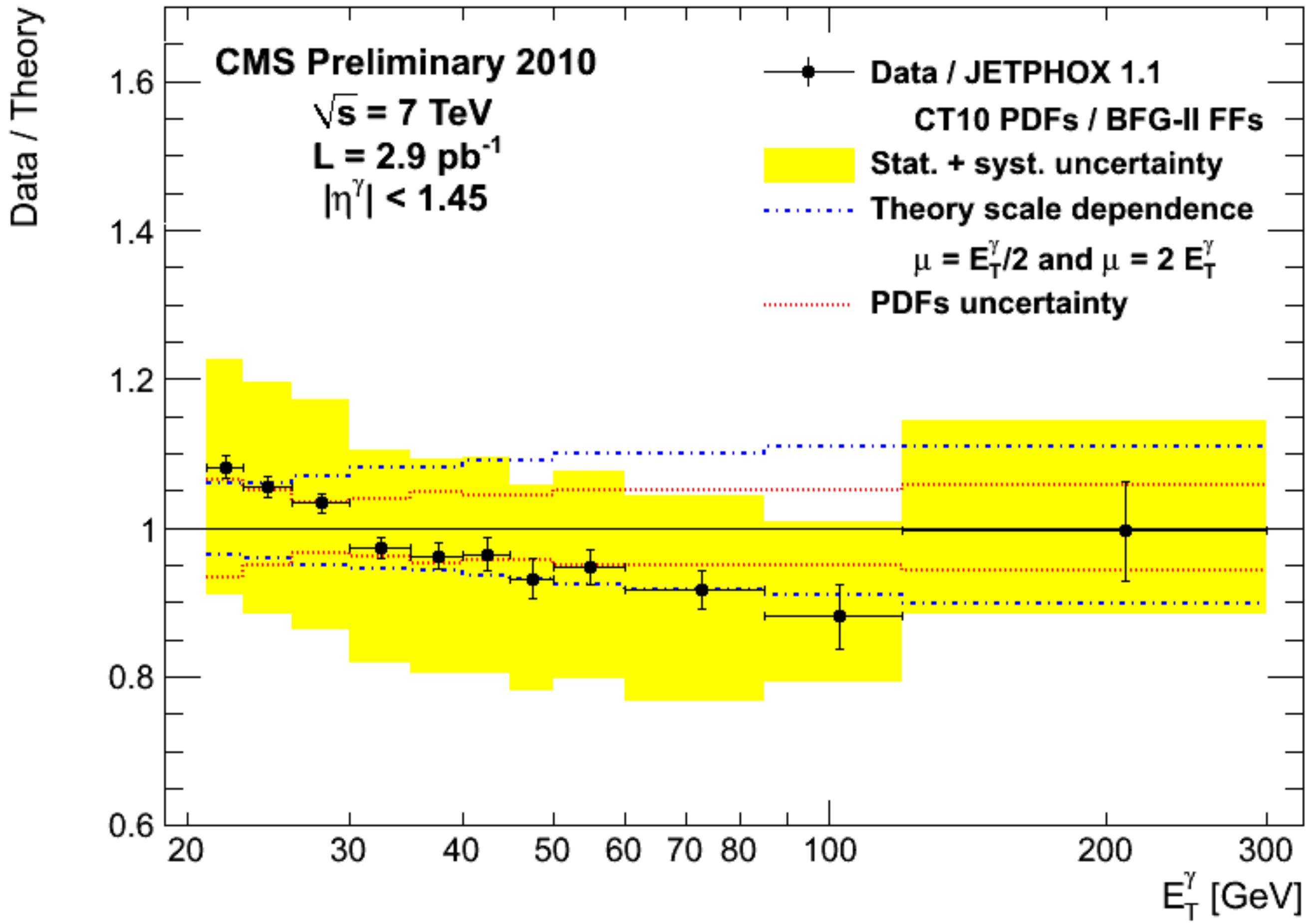
Two-component fit to the data

- Good **fit** to the **data.**
  - Signal shape from MC:
    - Corrected by Z-electron data.
    - Not enough $Z\gamma$ events
  - Background from data in isolation sideband.



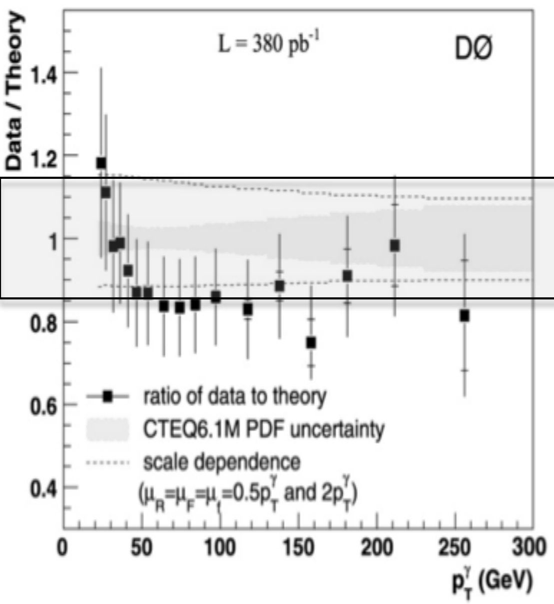
Comparison between theory and data

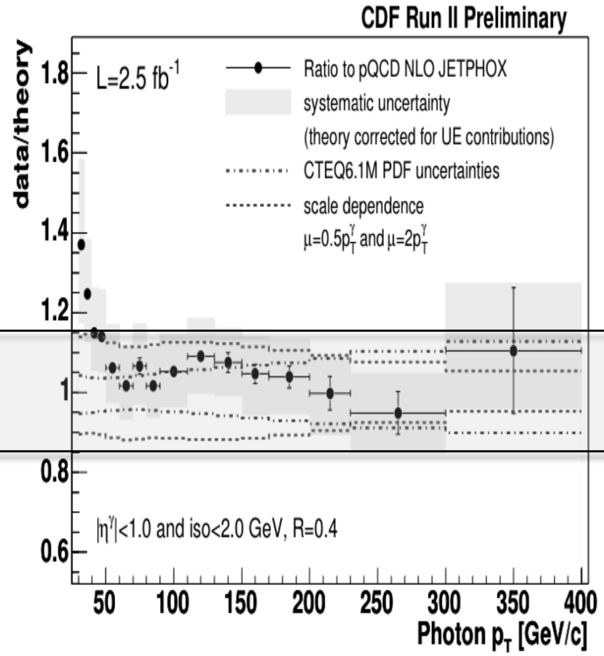
- 11% lumi uncertainty not included.

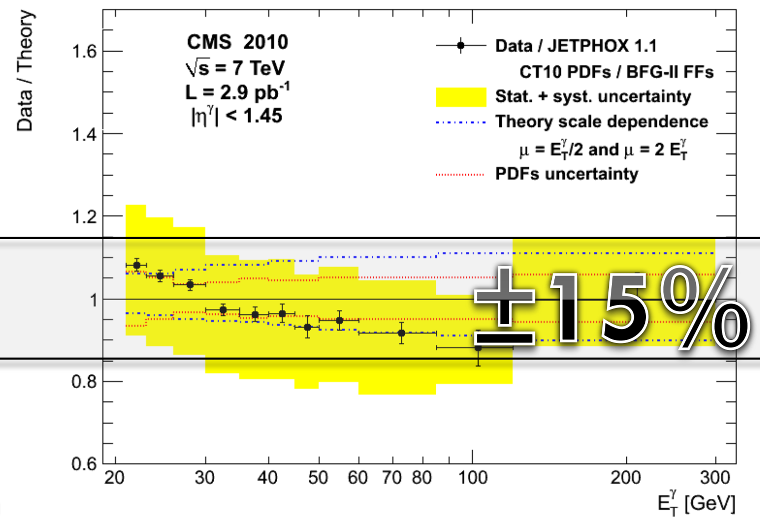


Excellent first step

PRL 106:082001 (2011)





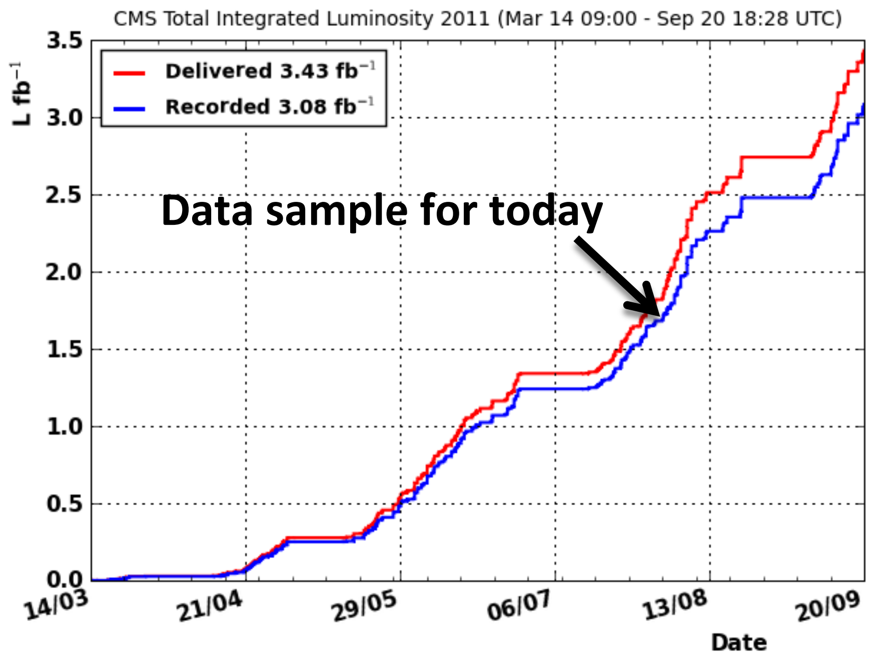


Episode One: simple cuts.

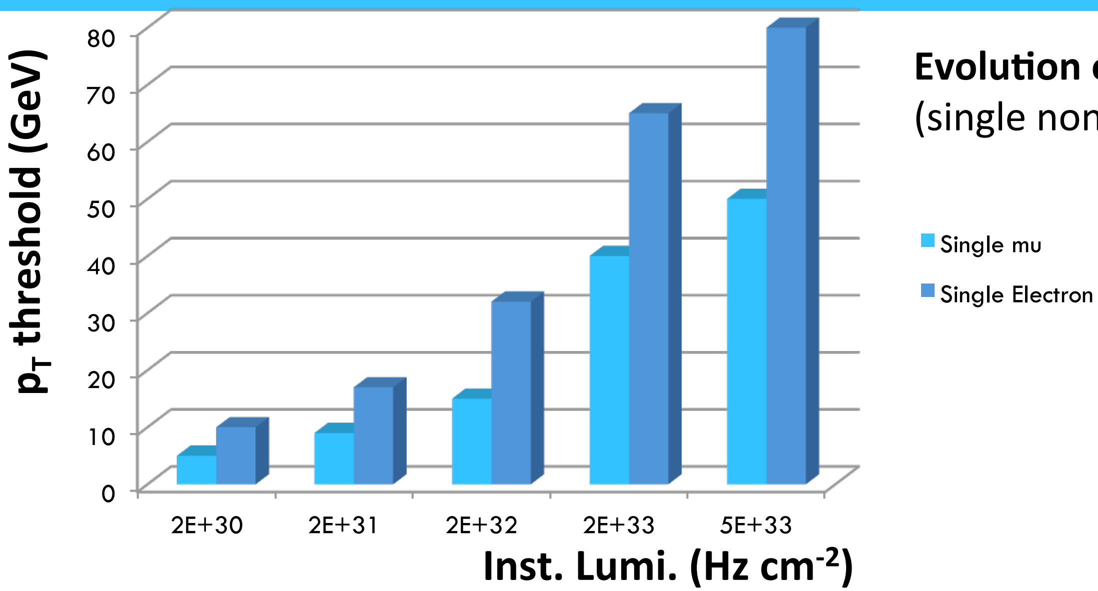
[CMS-PAS-HIG-11-021] described here.
Later published as [PLB 710 (2012) 403-425]
(simplified and with more data)

2011: breaking all expectations

- Results shown for a total luminosity of **1.66/fb.**
- Highest instantaneous luminosity **$2x10^{33}$ cm^{-2} s^{-1}.** (in the sample analyzed up to now)
- LHC already delivered **3x** the 2011 integrated luminosity target.



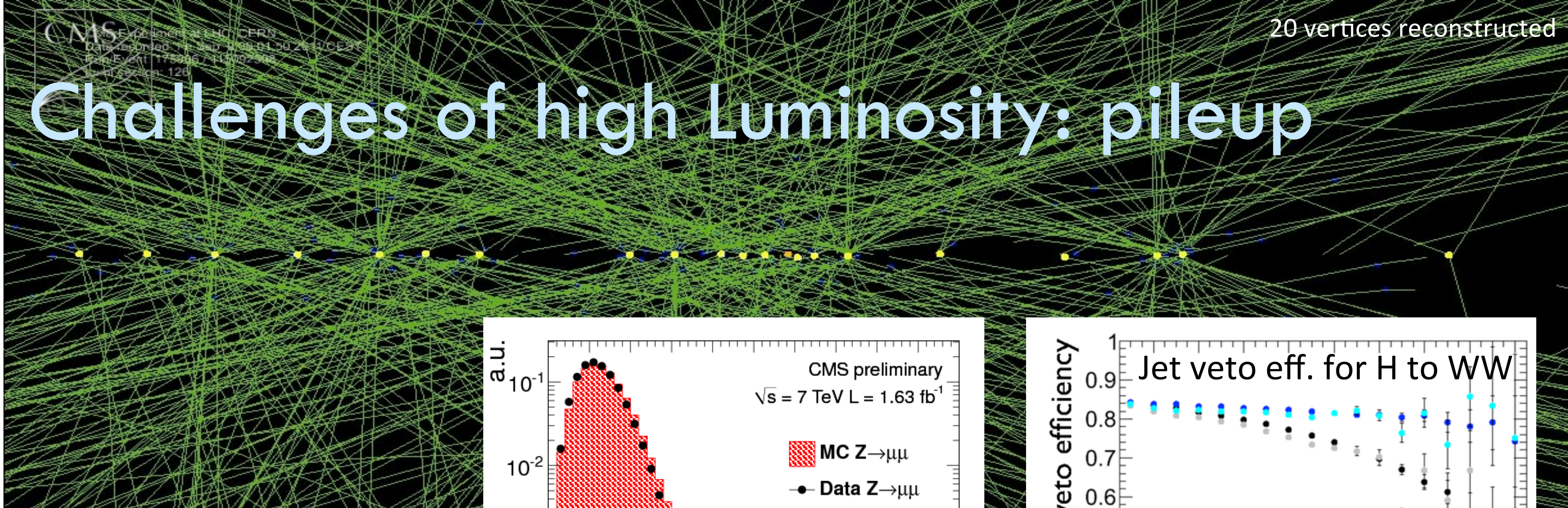
Challenges of high Luminosity: trigger

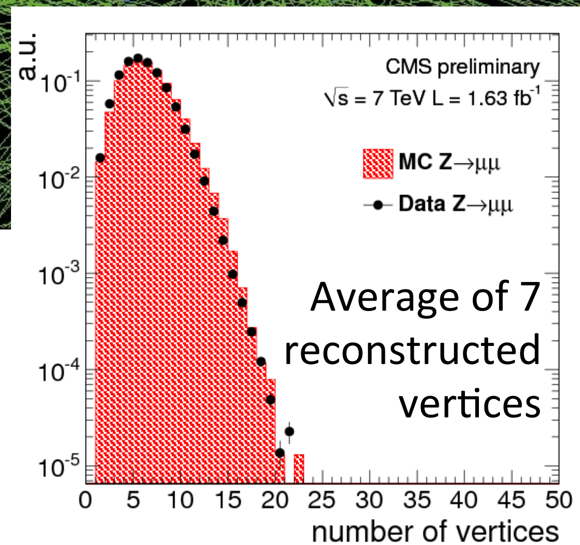


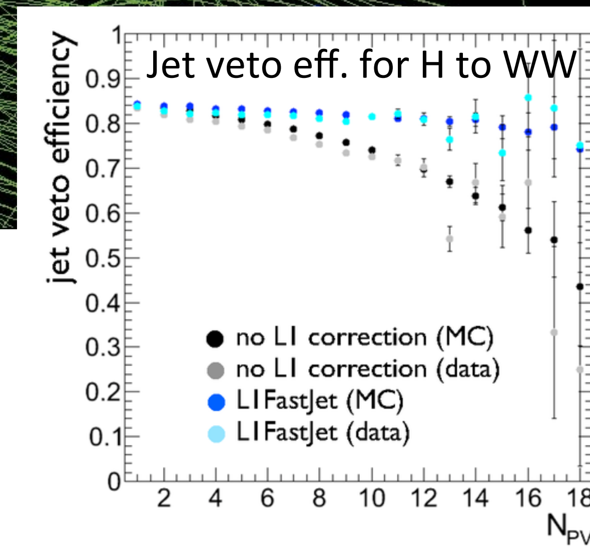
Evolution of trigger thresholds
(single non-isolated leptons)

- Inclusive triggers must have high thresholds.
- Each analysis developed dedicated trigger strategies:
  - H→WW: Double mu and double electron thresholds at [17, 8] GeV.
  - **H→γγ : Double photon [36, 18] GeV.**
- Challenging for the low mass Higgs searches.

Challenges of high Luminosity: pileup



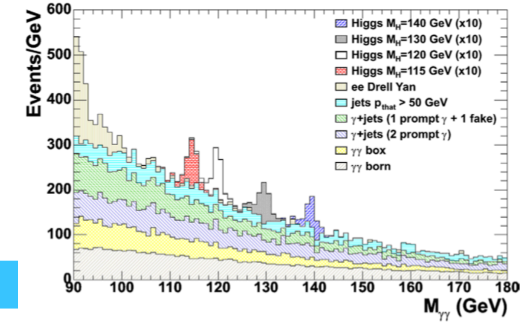




- Additional pile-up (PU) interactions substantially affect:
  - ME_T resolution, jet energy scale/resolution and multiplicity, lepton isolation, **primary vertex identification.**
- Several techniques have been developed to address the PU effects:
  - FastJet corrections for jets and lepton isolation, track-based ME_T, etc.

H→γγ search – CMS

http://goo.gl/mHpMN



- **Search for a narrow di-photon mass peak over a smoothly falling background.**
- Main ingredients:
  - 2 high-p_T isolated photons: $p_T > 40, 30$ GeV/c.
  - Pile-up mitigation: selection of di-photon vertex and isolation (also) with respect to worst vertex.
  - Isolation+ID cuts in 4 photon categories $[2\,\eta \times 2R_9]$ following ECAL performance.
    - $R_9 = E_{3\times3}/E_{cluster}$ (converted vs unconverted photons).
  - Correct MC (di-)photon efficiencies using Data/MC scale factors.

Photon categories and photon ID

Category	Photon requirement
1	$\|\eta\|$ <1.4442, R_9 >0.94
2	$\|\eta\|$ <1.4442, R_9 <0.94
3	1.566< $\|\eta\|$ <2.5, R_9 >0.94
4	1.566< $\|\eta\|$ <2.5, R_9 <0.94

1. combined isolation using selected event vertex: the isolation sum is calculated as:

$$\sum Iso = Iso^{tracker} + Iso^{ECAL} + Iso^{HCAL},$$

   where $Iso^{tracker}$ is the sum of the transverse momenta of tracks within a hollow cone of size $\Delta R = 0.3$ (excluding an inner cone $\Delta R = 0.02$) consistent with the chosen photon primary vertex (within ± 10 mm in the beam direction), Iso^{ECAL} is computed as the transverse energy sum of ECAL energy deposits located within a radius $\Delta R = 0.3$ excluding an inner veto region of $\Delta R = 3.5$ crystals and an eta-slice of $\Delta\eta = 2.5$ crystals (a barrel crystal subtends 0.0174 in η and ϕ), and Iso^{HCAL} is summed using HCAL towers with centres between radii of $\Delta R = 0.4$ and ΔR= 0.15 from the supercluster; this sum is corrected for pileup as described above,

2. combined isolation using the vertex choice hypothesis which gives the largest sum: this is computed with an outer cone size of ΔR= 0.4 for all 3 subdetectors; this sum is corrected for pileup as described above,

3. tracker isolation: the same tracker isolation sum as is used in the combined isolation using selected event vertex, but used on its own,

4. H/E: the ratio of hadronic energy to electromagnetic energy, calculated from the sum of HCAL tower energies within a cone of size $\Delta R < 0.15$ centred on the ECAL supercluster position, and the energy of the super-cluster,

5. $\sigma_{i\eta i\eta}$: the transverse width of the electromagnetic shower, computed as an RMS with logarithmic energy weighting,

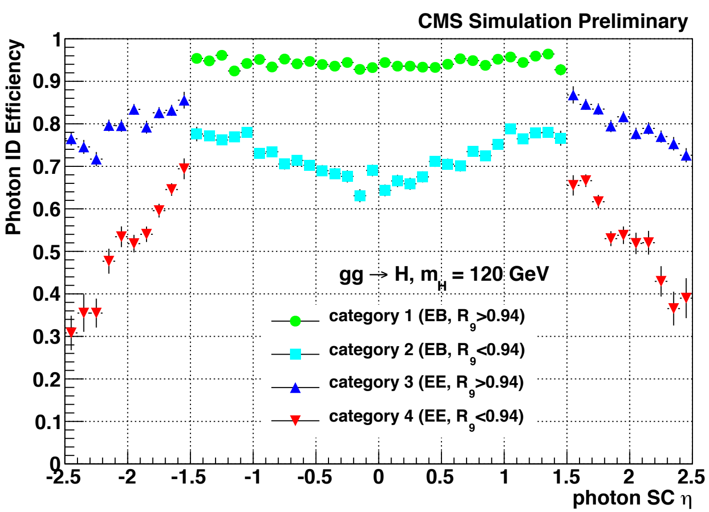
6. R_9: a minimum threshold is applied to R_9,

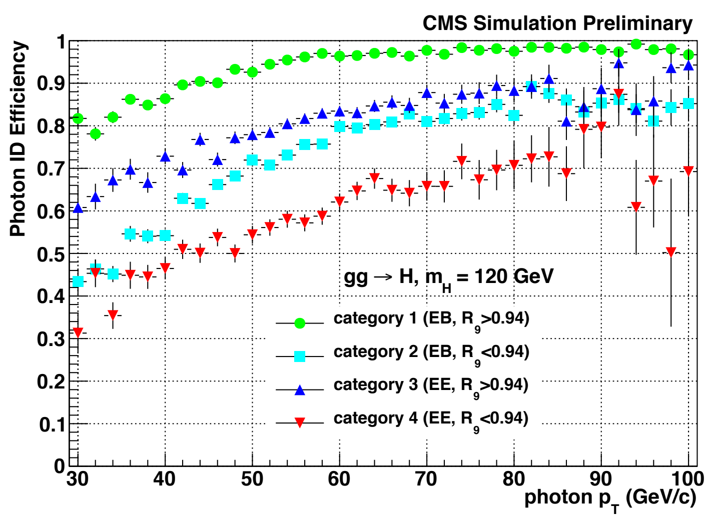
7. ΔR to electron track: there is an electron veto: if a reconstructed electron having a track with no missing hits in the first layers of the tracker is matched to the supercluster then the photon is rejected; the ΔR cut places an additional constraint on the vetoing electron: the angle at the vertex between the electron track and the trajectory which would track to the supercluster, is required to be less than the cut value.

Photon ID efficiency

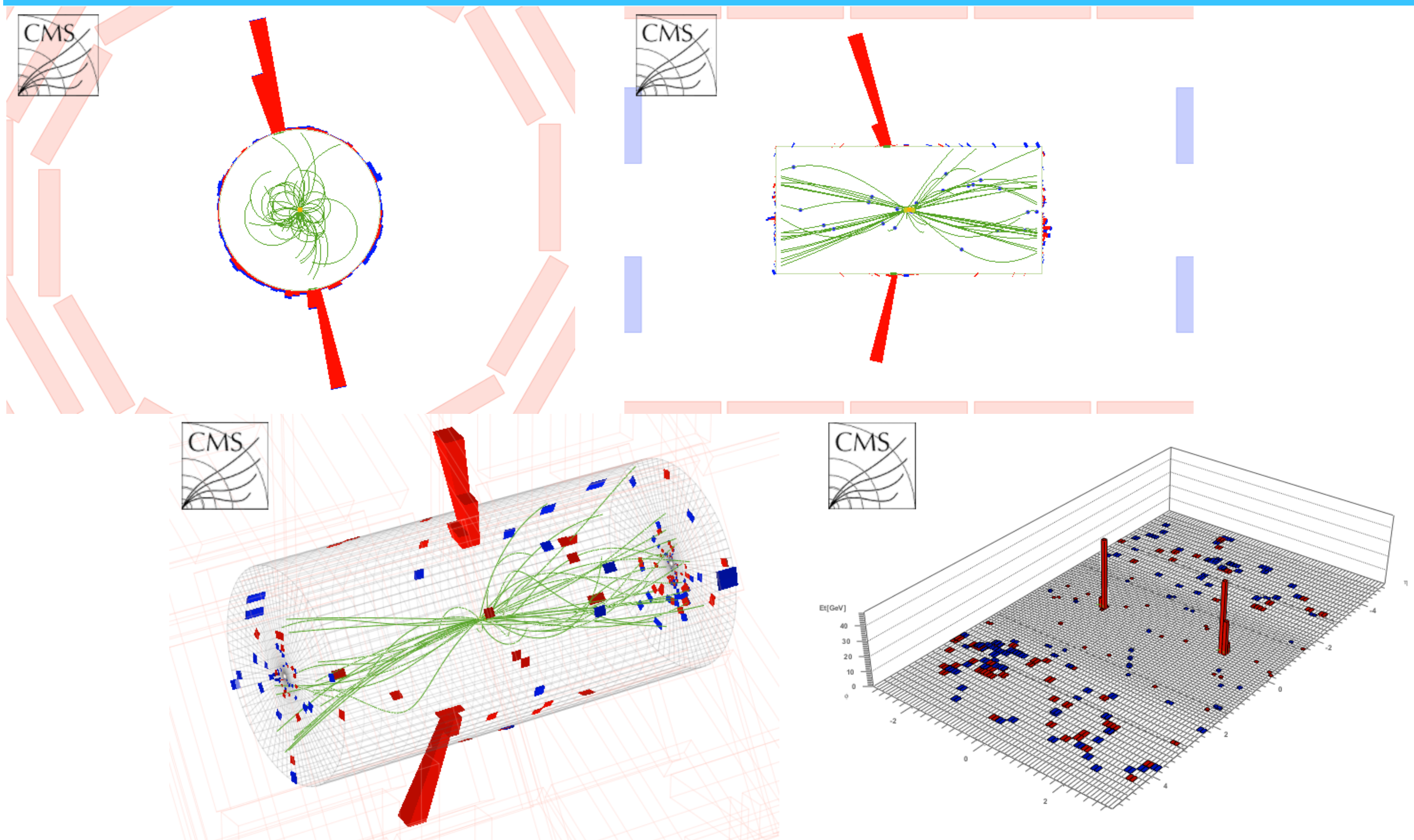
- Estimated from
  - Higgs MC, and
  - Z decay data/MC ratios. ➔
- Good description of PU effects in MC.

Category	ϵ_{data} (%)	ϵ_{MC} (%)	$\epsilon_{data}/\epsilon_{MC}$
All cuts except electron rejection (from $Z \to ee$)			
1	91.77 ± 0.14	92.43 ± 0.07	0.993 ± 0.002
2	72.67 ± 0.43	71.89 ± 0.08	1.011 ± 0.007
3	80.33 ± 0.47	80.04 ± 0.18	1.004 ± 0.008
4	57.80 ± 1.26	55.09 ± 0.15	1.049 ± 0.025
Electron rejection cut (from $Z \to \mu\mu\gamma$)			
1	$99.78^{+0.13}_{-0.16}$	$99.59^{+0.13}_{-0.17}$	$1.002^{+0.002}_{-0.002}$
2	$98.77^{+0.59}_{-0.73}$	$97.70^{+0.32}_{-0.37}$	$1.011^{+0.007}_{-0.008}$
3	$99.32^{+0.51}_{-1.02}$	$99.29^{+0.30}_{-0.42}$	$1.000^{+0.006}_{-0.011}$
4	$93.0^{+2.1}_{-2.3}$	$93.34^{+0.79}_{-0.86}$	$0.996^{+0.024}_{-0.027}$





Main ingredients: 2 isolated photons



H→γγ search – CMS

http://goo.gl/mHpMN

- Di-photon invariant mass resolution:
  - Di-photon vertex chosen using tracks, di-photon recoil, and conversion information.
  - ECAL energy scale and resolution determined from Z→ee.
    - Data corrected for measured scale variations.
    - Higgs signal MC smeared to match observed resolution.

Vertex ranking variables

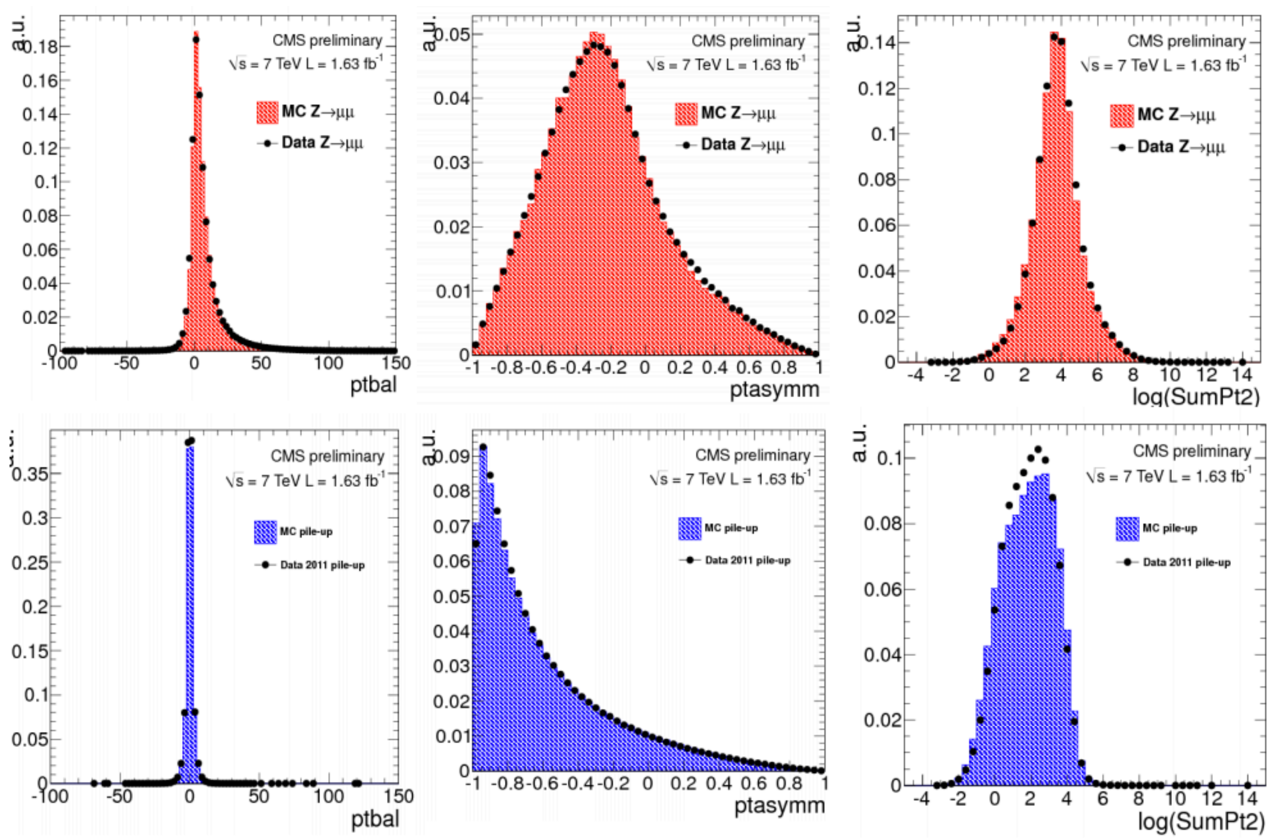
- Exploit correlations of recoil and diphoton.
- Simple ranking algorithm (no MVA).

- Complement with pointing from converted photon tracks.

$$p_T^{bal} = -\sum_{tracks}\left(\vec{p}_T^{\,track}\cdot\frac{\vec{p}_T^{\gamma\gamma}}{|\vec{p}_T^{\gamma\gamma}|}\right)$$

$$p_T^{asym} = \left(\sum_{tracks} p_T - p_T^{\gamma\gamma}\right)\Big/\left(\sum_{tracks} p_T + p_T^{\gamma\gamma}\right)$$

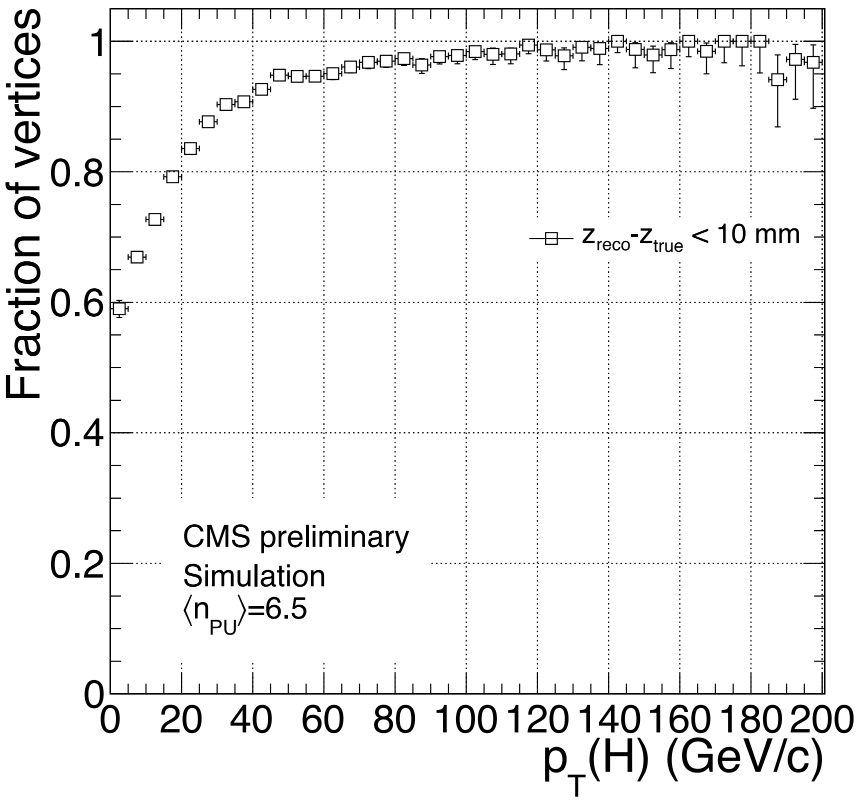
$$\text{Sum } p_T^2 = \sum_{tracks} p_T^2$$



Vertex assignment

- Estimated from:
  - $H \rightarrow \gamma\gamma$ MC,
  - $Z \rightarrow \mu\mu$ Data/MC ratio.
- Evolution with pile-up as expected.

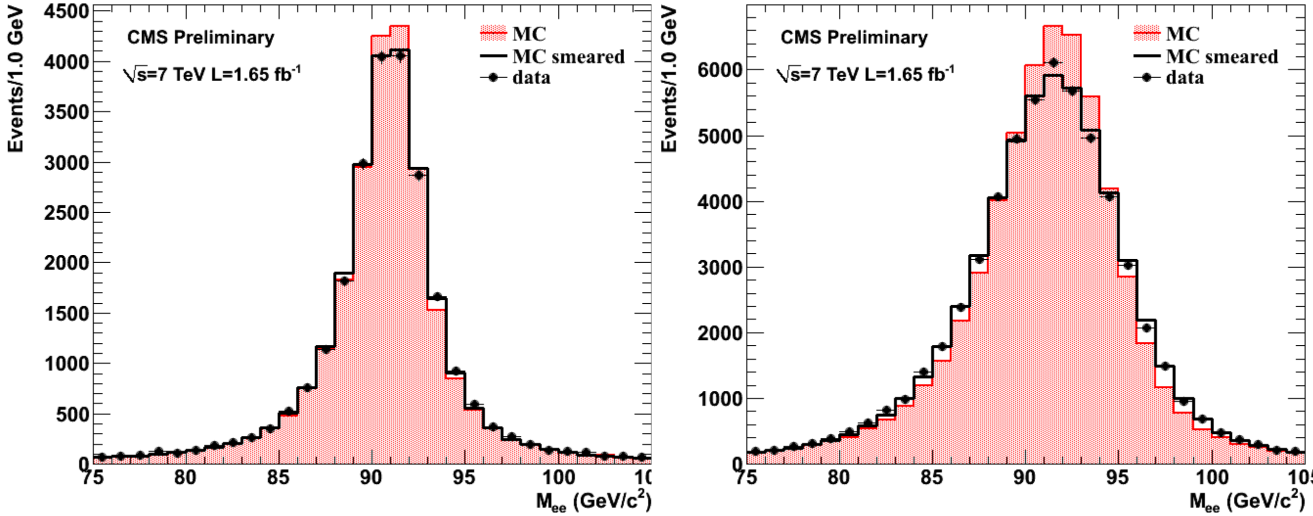
Eff. [%]	σ_{stat}	σ_{syst}
82.8	0.2	0.5



Calibration, calibration, calibration

- Compensate for residual mis-calibration:
  - Measure energy scale in run periods.
    - Correct Data.
  - Determine smearing that matches resolution of MC to that of the corrected Data. ➔
    - Apply smearing to MC.
- Smearing in best and worst photon categories for Z→ee (data and MC). ➘

	$R_9>0.94$	$R_9<0.94$
barrel	$1.00^{+0.05}_{-0.05}\pm0.23\%$	$1.69^{+0.03}_{-0.03}\pm0.42\%$
endcap	$3.03^{+0.05}_{-0.06}\pm0.51\%$	$2.96^{+0.05}_{-0.05}\pm0.38\%$

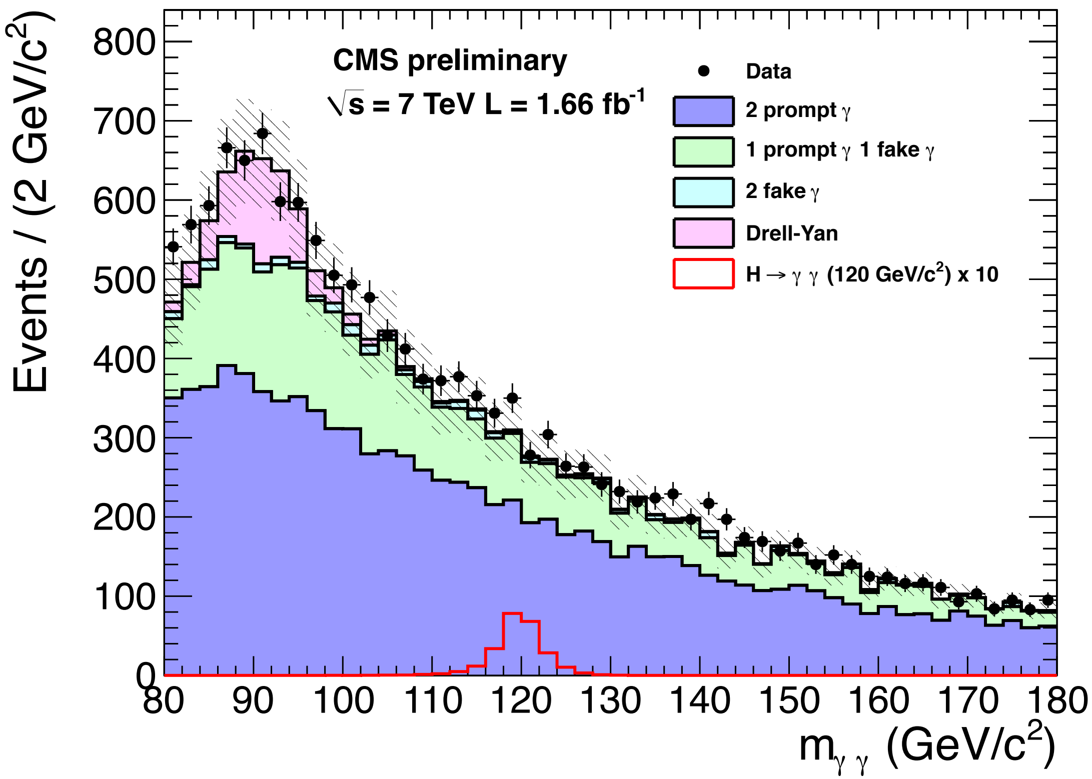


H→γγ search – CMS

- Signal model from MC:
  - Cross-sections, branching ratios, and theoretical uncertainties from LHC XS WG.
    - PowHeg p_T distributions reweighted to NLO+NNLL HqT.
- Background MC (**not used in the limits)**
  - Madgraph: di-photon+jets, DY+jets.
  - Pythia: di-photon Box, photon+jets, QCD.
  - K-factors using CMS Data/Theory.
- Background model
  - Follow the data: 2^{nd}-order polynomial fit.

Comparison of Data and MC

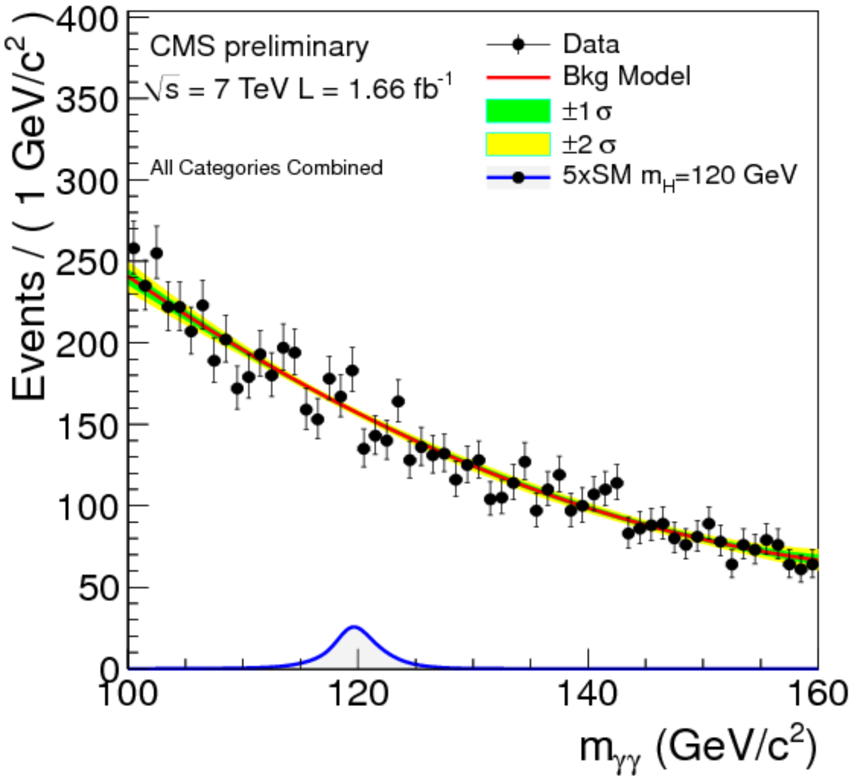
- Shape ok. Good purity.
- Just a sanity check, **not used for setting limits.**



H→γγ search – CMS

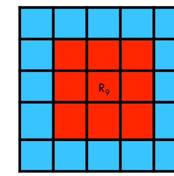
http://goo.gl/mHpMN

- Narrow peak on smooth continuum.
  - Signal modeled by parametric shape.
  - Background from fitting data.
- 8 sub-channels following mass resolution and S/B.
  - Sum of all sub-channels. ➘



Sub-channels

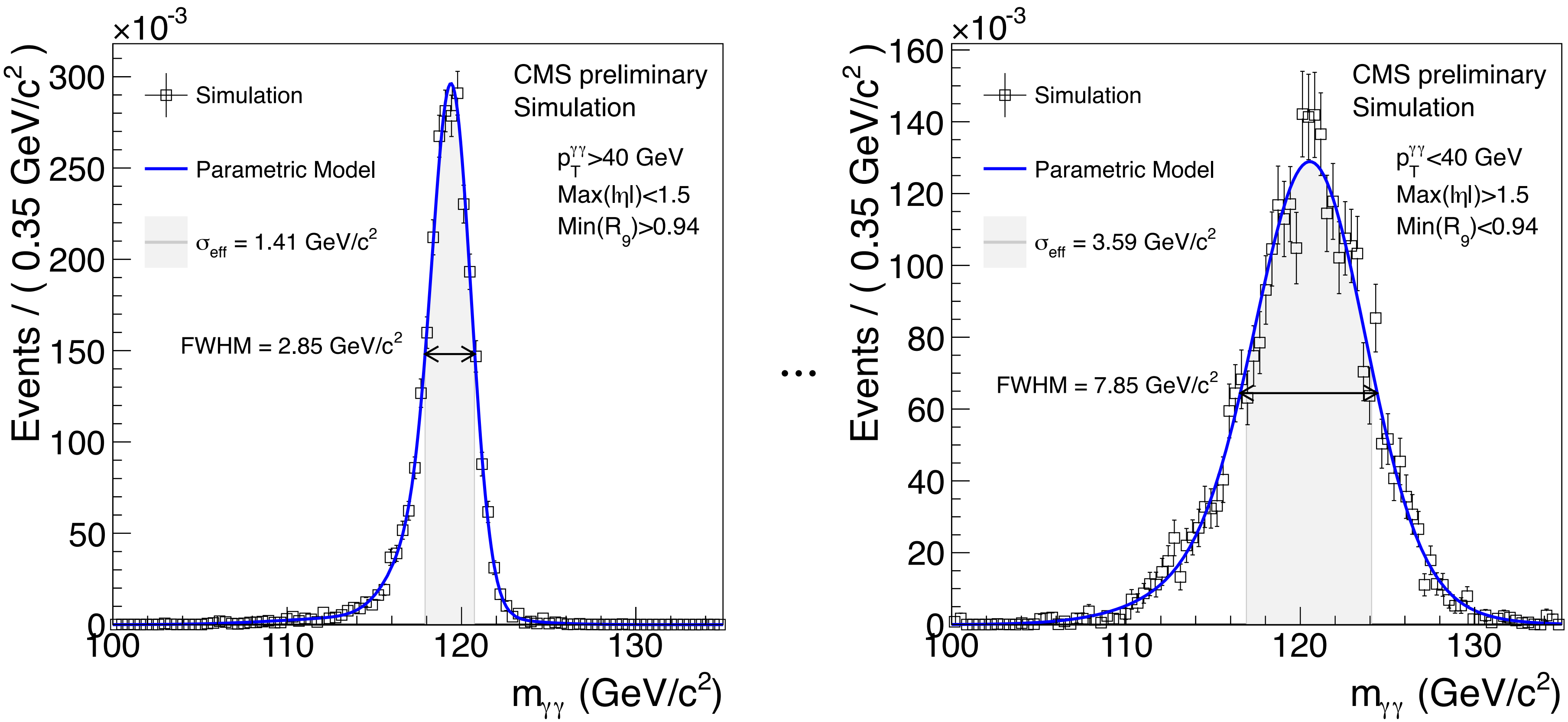
- 8 sub-channels following S/B and mass resolution:
  - η (barrel-barrel vs endcap-any).
  - $R_9 = E_{3\times3}/E_{cluster}$ (converted vs unconverted photons).
  - $p_T(\gamma\gamma)$ (S/B and fermiophobic search).
- Treated as individual channels when setting limits.



	Both photons in barrel		One or more in endcap	
	$min(R_9) > 0.94$	$min(R_9) < 0.94$	$min(R_9) > 0.94$	$min(R_9) < 0.94$
$p_T^{\gamma\gamma} < 40$ GeV/c				
Signal	20.9%	27.1%	9.4%	11.6%
Background	16.7%	26.3%	12.9%	20.3%
Signal σ_{eff} (GeV/c^2)	1.64	2.43	3.16	3.59
$p_T^{\gamma\gamma} > 40$ GeV/c				
Signal	10.2%	12.2%	3.5%	5.1%
Background	4.3%	7.9%	4.3%	7.4%
Signal σ_{eff} (GeV/c^2)	1.41	2.10	2.96	3.41

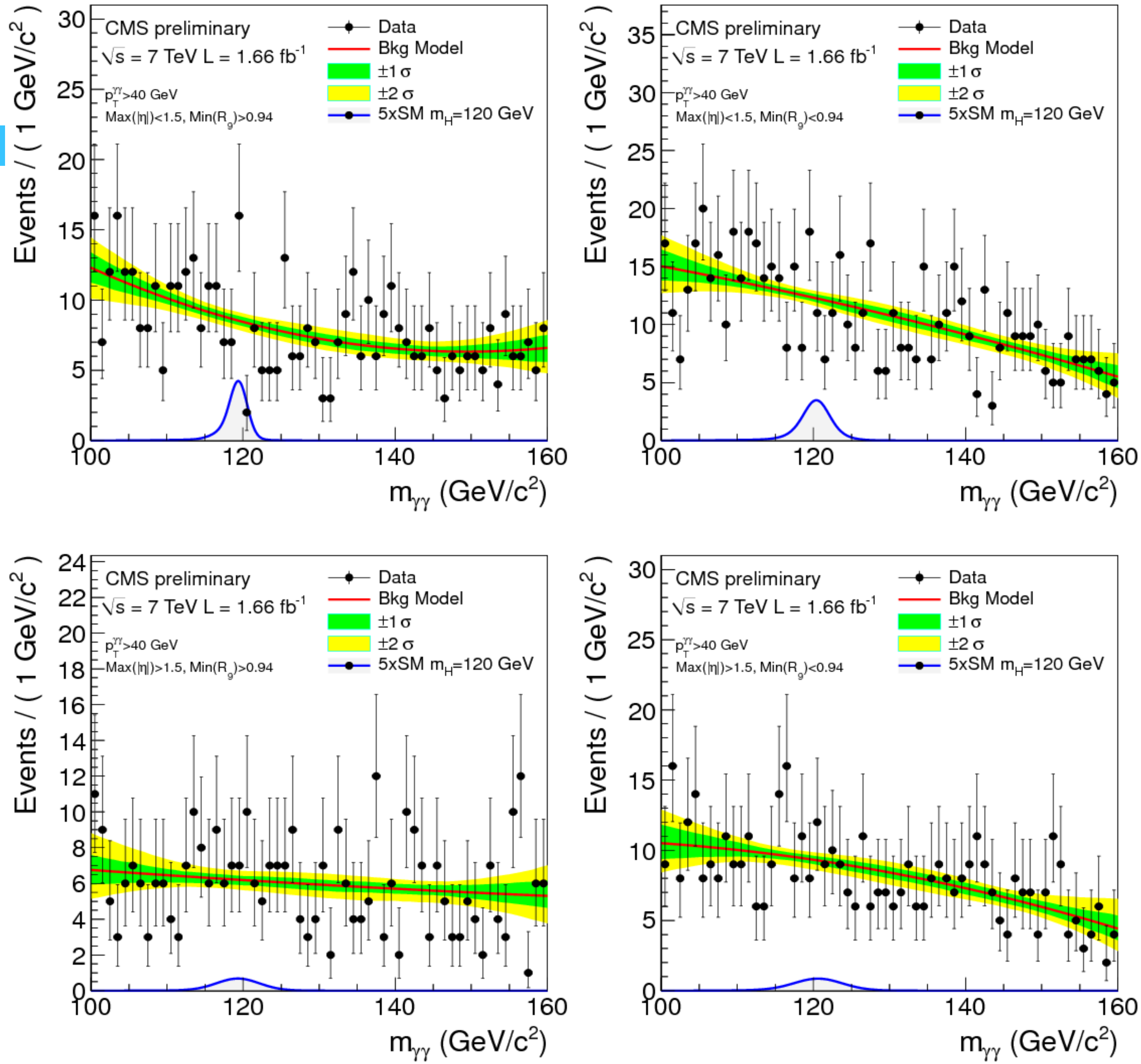
Signal model: mass resolution

- Modeled with sum of gaussians (computational convenience).
- Best and worst sub-channels. ➔



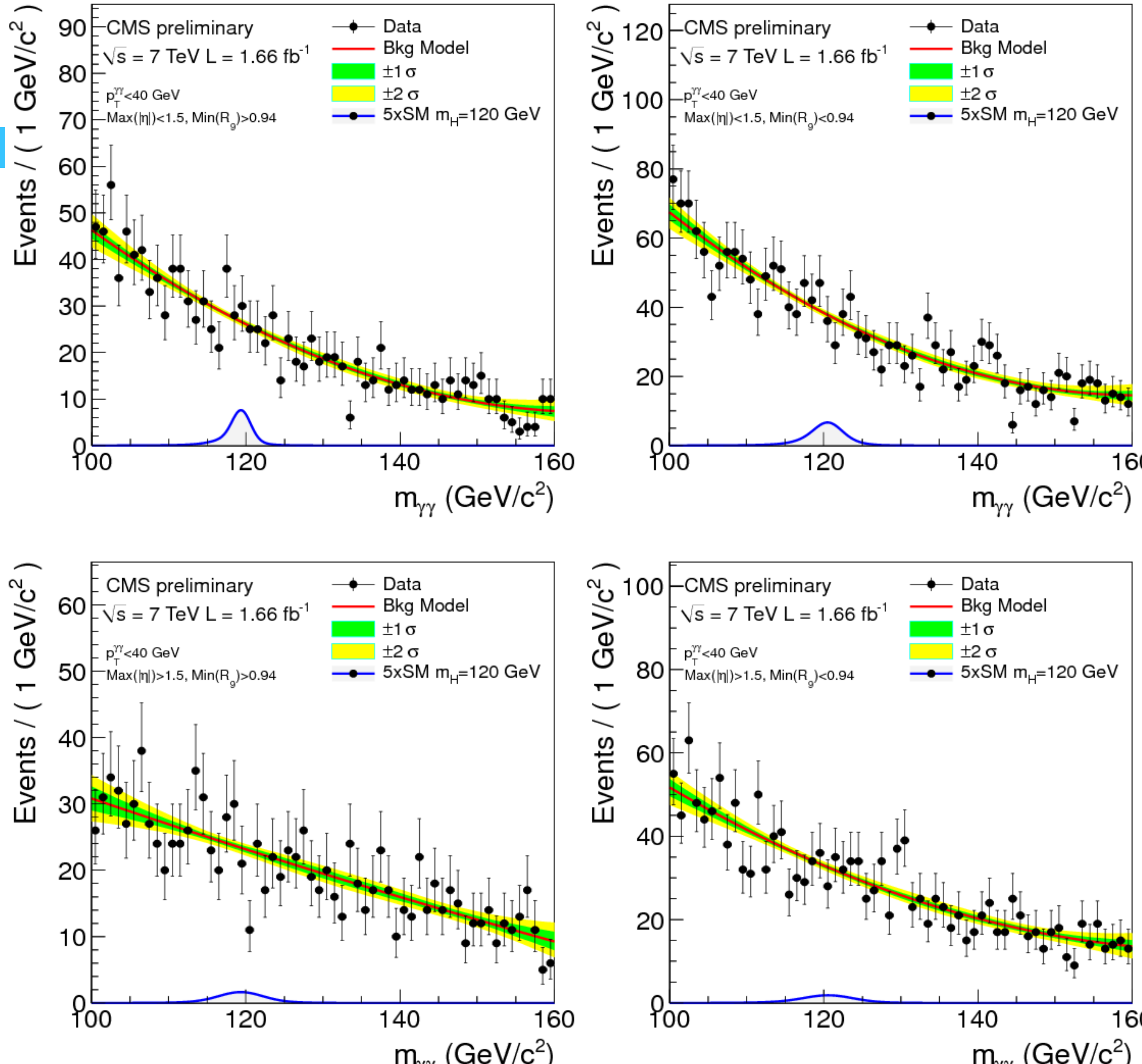
S&B

- $p_T(\gamma\gamma) > 40$ GeV



S&B

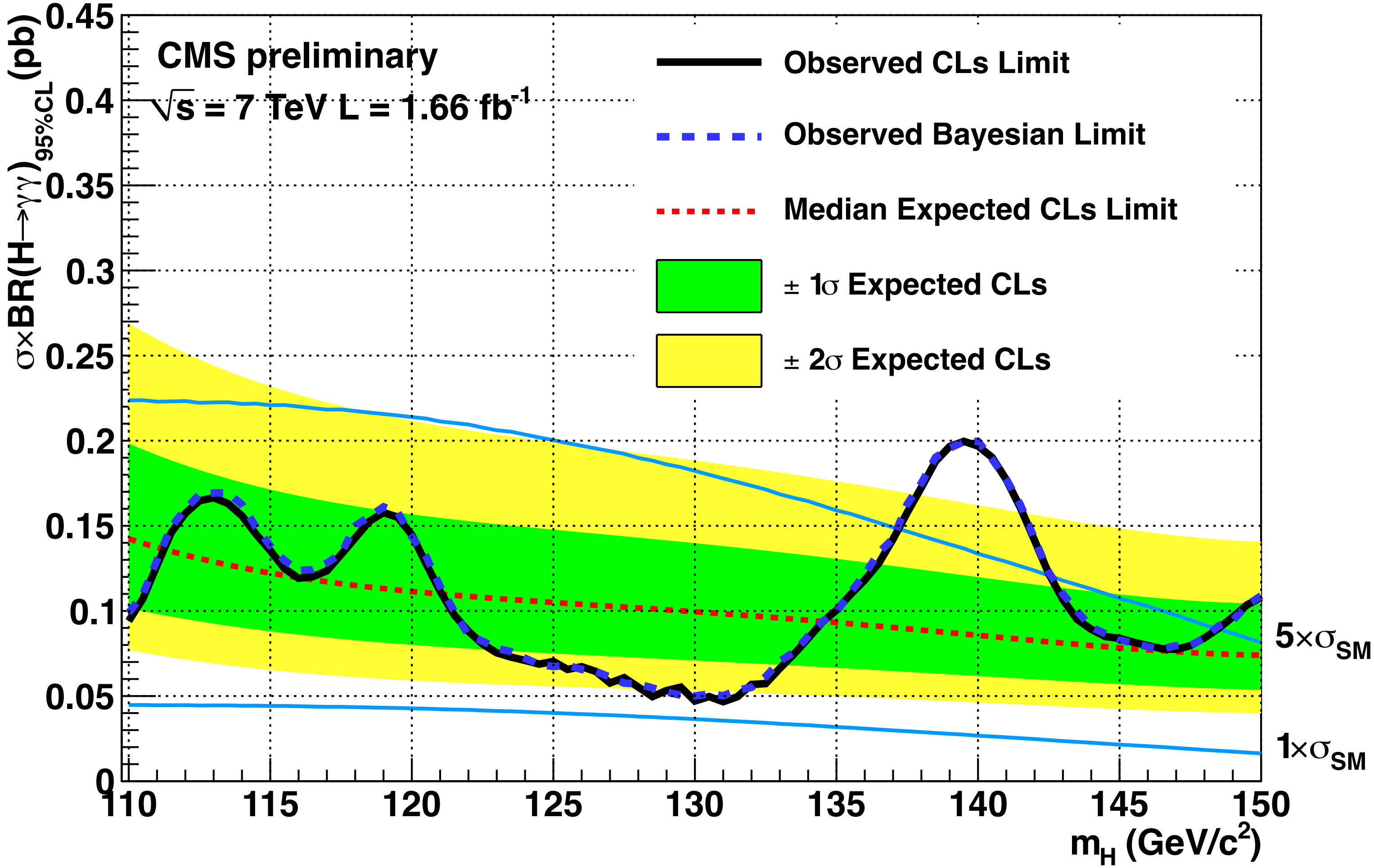
- $p_T(\gamma\gamma)$ < 40 GeV



H→γγ search – CMS

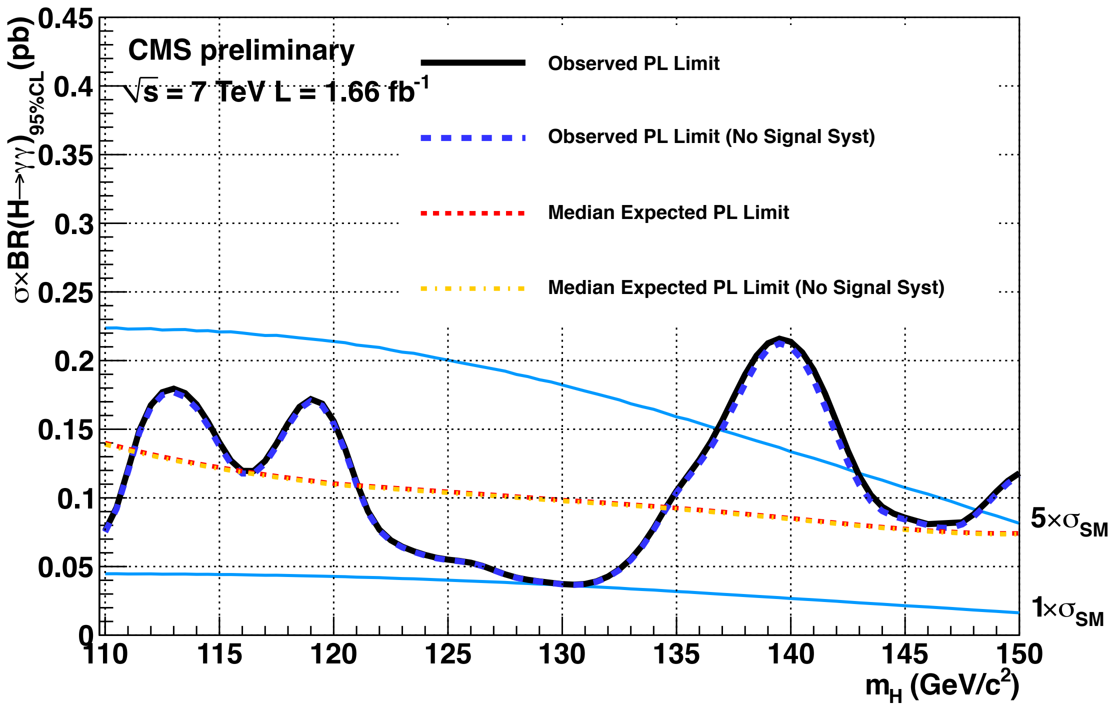
- Statistical analysis
  - CLs with LHC test-statistic (and Bayesian with flat prior).
  - Systematics and mass-point interpolations:
    - Unbinned method: smooth interpolation of fit parameters.
    - Binned method: histogram interpolation with per-photon systematics.
  - Test mSM and fermiophobic (FP) hypotheses.
  - Check effects on the limits using Profile Likelihood Approximation (PLA).

Standard Model limits

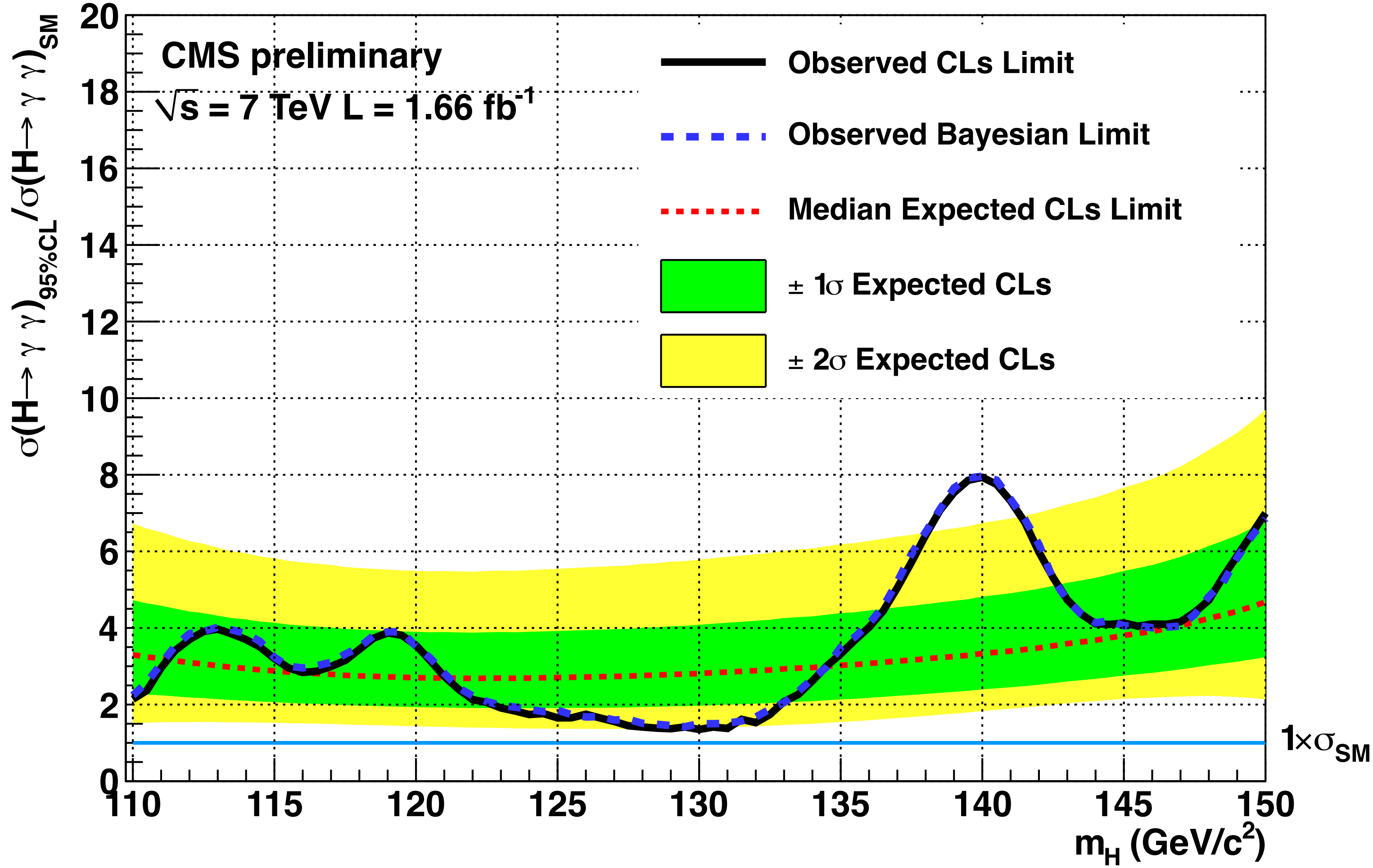


Systematic uncertainties

- Single photon:
  - ID efficiency.
  - Shower shape (class migration).
  - Energy scale.
  - Energy smearing.
- Per event:
  - Integrated luminosity.
  - Trigger efficiency.
  - Diphoton p_T (class migration).
  - Vertex finding.
- **No effect !**



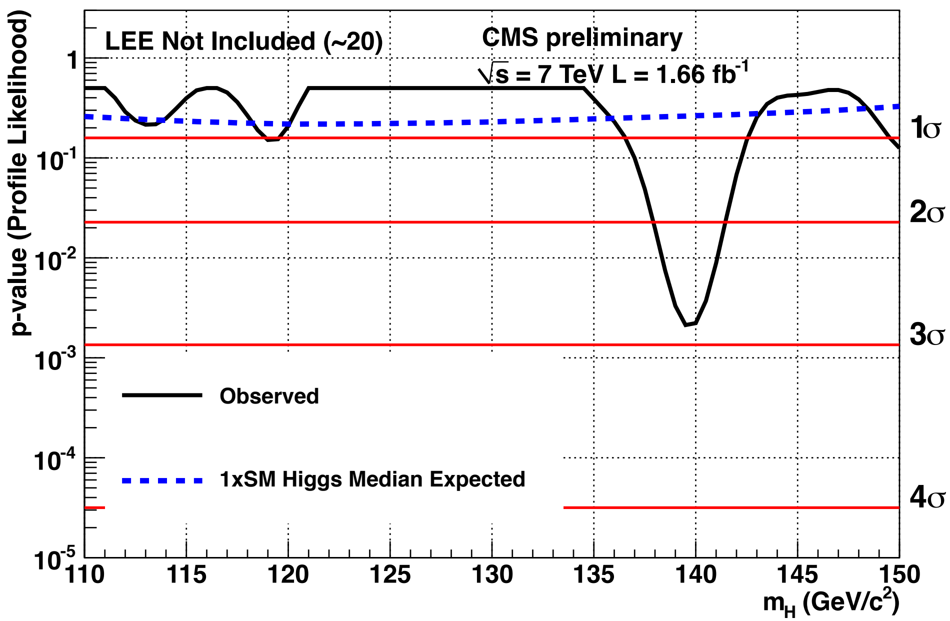
Standard Model limits



So, how many sigma is that?

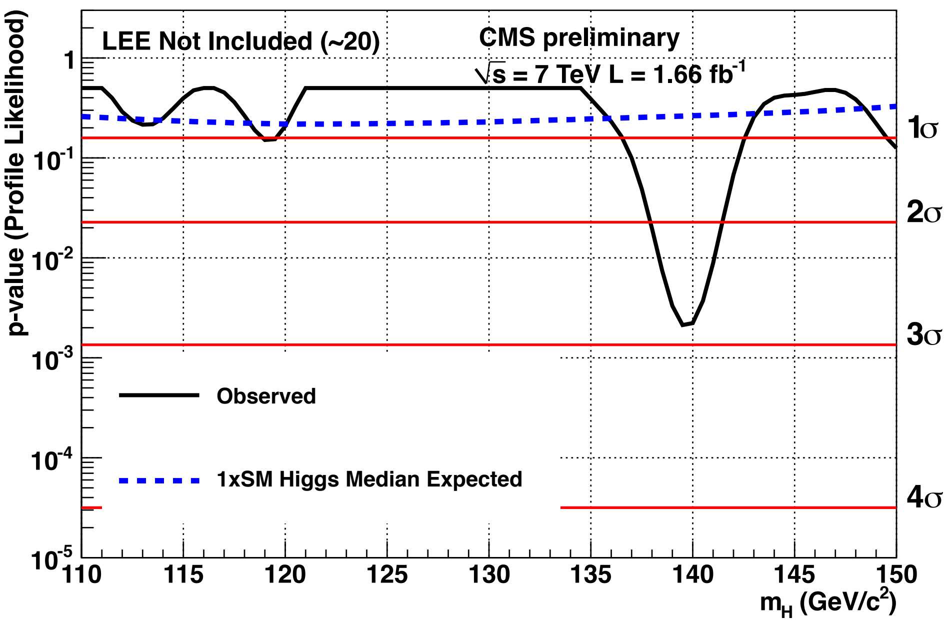
- Hypothesis being tested: mSM with **free** cross-section.
- Framework:
  - CLs LHC-type test statistic.
  - Fully parameterized BG and signal models.

- Smallest local p-value searched by throwing toys in 0.5 GeV mass steps.
  - Minimum at 139.5 GeV.
  - **Local p-value $(2.5 \pm 0.3) \times 10^{-3}$ ($2.8\,\sigma$).**



So, how many sigma is that?

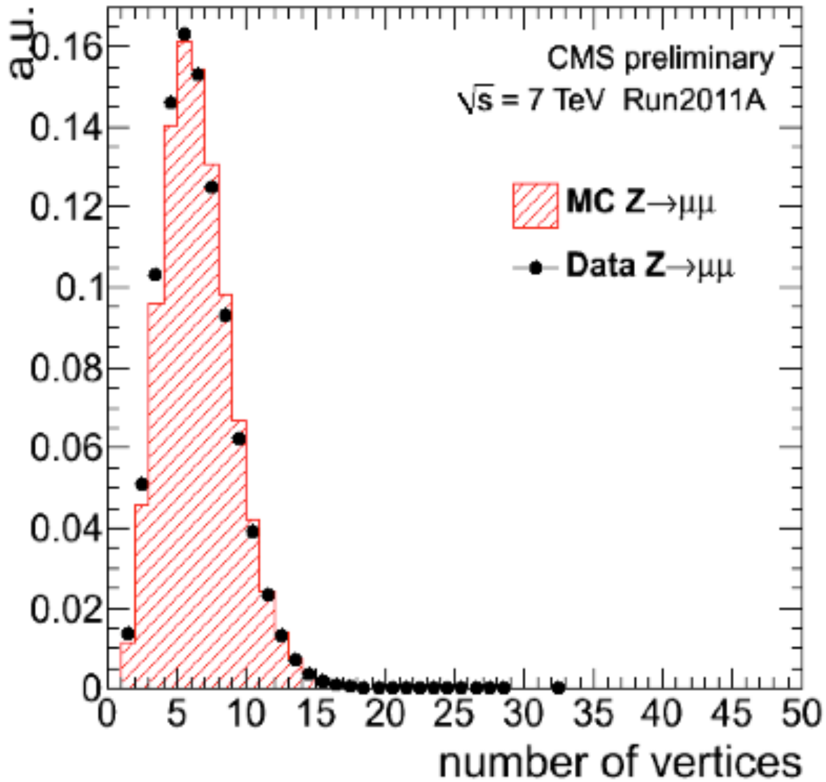
- Global p-value evaluation:
  - Throw BG-only toys.
  - Fit with Sig+BG and let mass free.
  - Make distribution of smallest p-value in each toy.
  - **Global p-value for the excess at 139.5 GeV: $(5.0\pm0.5)\times10^{-2}$ ($1.6\,\sigma$)**
- Trials factor = 20±3.
- Best fit parameters:
  - $\sigma / \sigma_{SM} = 4.5^{+1.9}_{-1.7}$
  - m_H = 139.7±0.8 GeV.

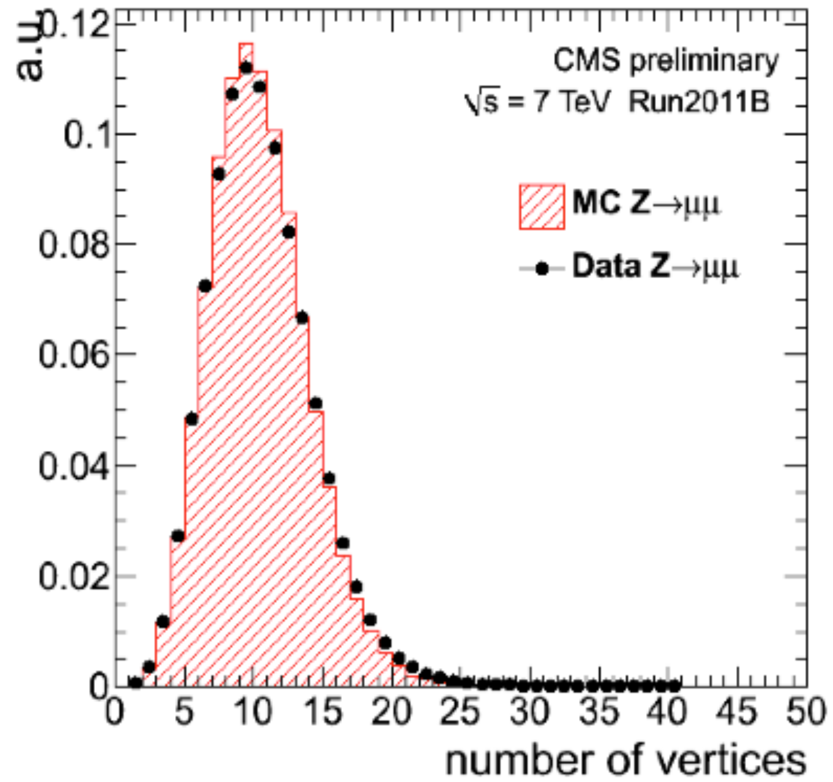


Episode Two: multivariate.

[CMS-PAS-HIG-12-001] described next.

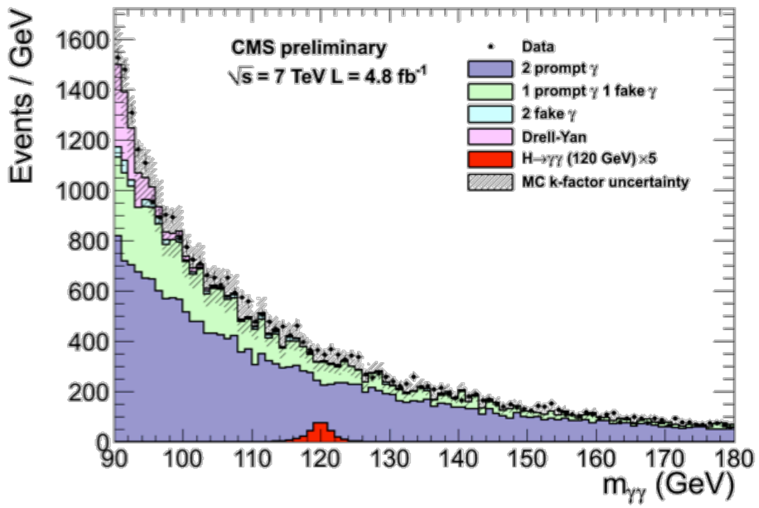
Full 2011 dataset: pileup





The di-photon channel in CMS

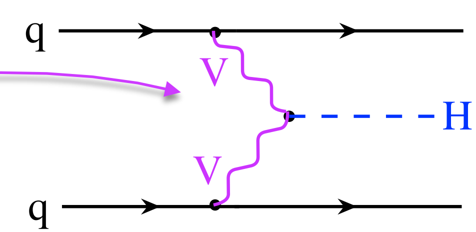
- H → $\gamma\gamma$ one of the most sensitive channels in 110 < m_H < 150 GeV
  - Clean final state: two high p_T isolated photons
  - Narrow mass peak
- H → $\gamma\gamma$ sensitivity driven by mass resolution and S/B
  - Mass resolution
    * Photon energy
    * Di-photon opening angle
  - Major Backgrounds
    * pp → jet + jet , pp → γ + jet with jet faking photon (mainly π^0)
    * pp → $\gamma\gamma$



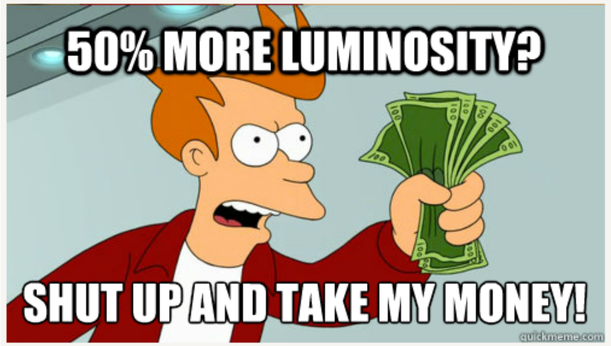
- Multivariate analysis (MVA) techniques used to improve H → $\gamma\gamma$ search sensitivity
  - provides more optimal event classification
- The analysis uses $\int L\,dt$ = 4.76 fb^{-1} of CMS data

Analysis strategy evolution

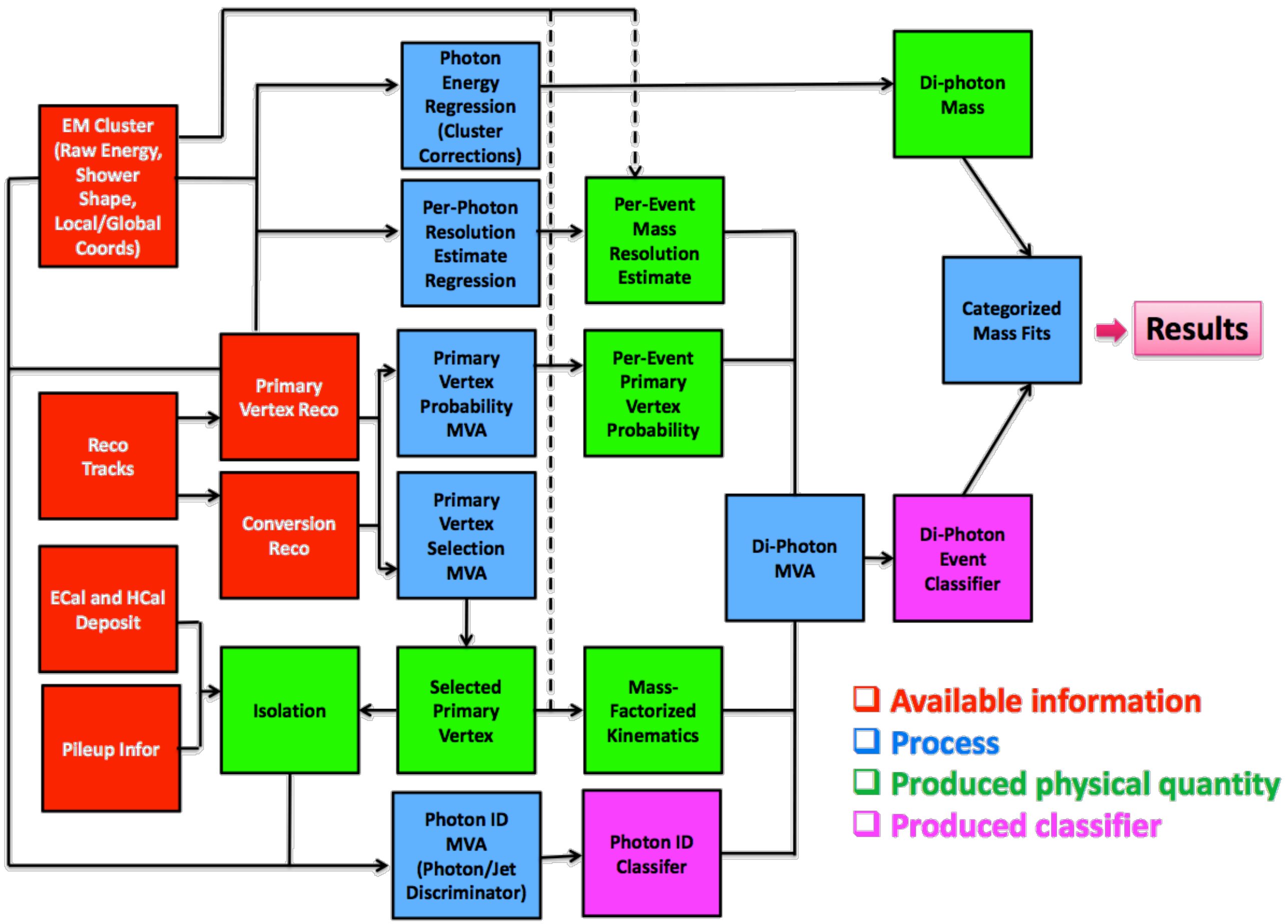
- **Cut-based analysis.**
  [PLB 710 (2012) 403-425]
  1. Di-jet tagged events for VBF production.
  2. Remaining events split by resolution and S/B:
     - Photon pseudorapidity (barrel / endcap).
     - Photon shower shape (unconverted / converted / π^0).



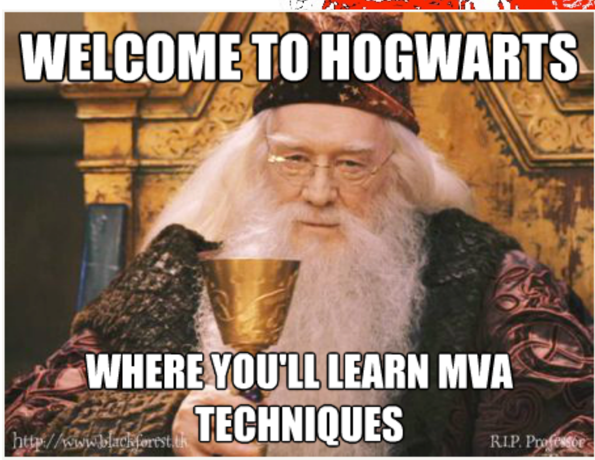
- **Multivariate (MVA) analysis.**
  [CMS-PAS-HIG-12-001]
  - Event-by-event boosted decision tree (BDT) classifier.
  - Sensitivity improvement equivalent to ~ 50% more integrated luminosity.

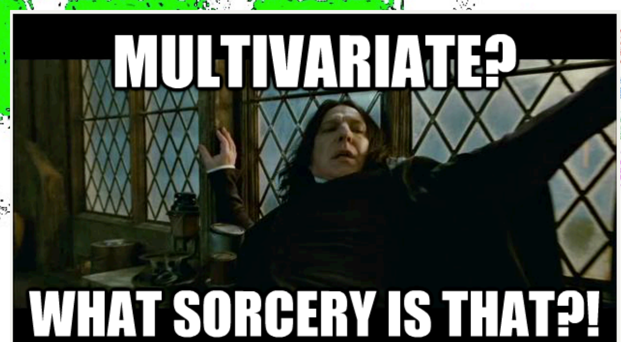


Anatomy of the analysis



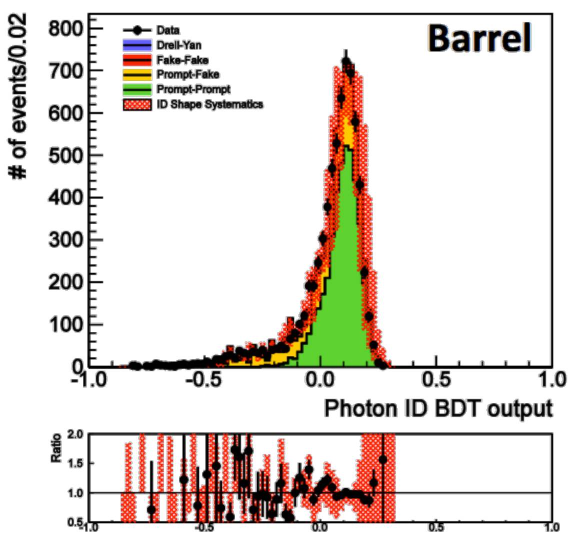
Anatomy of the analysis

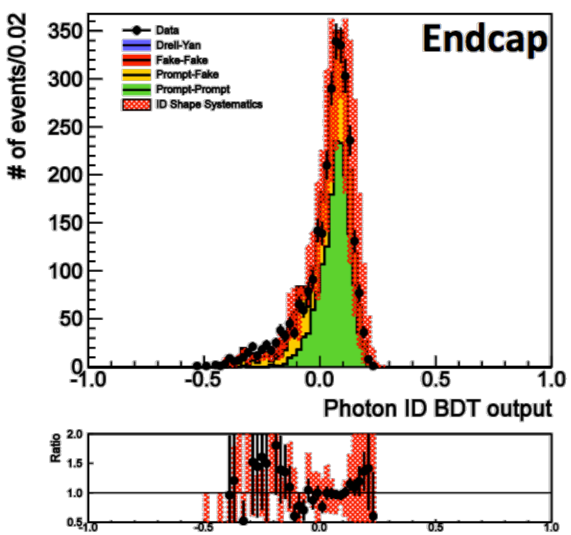


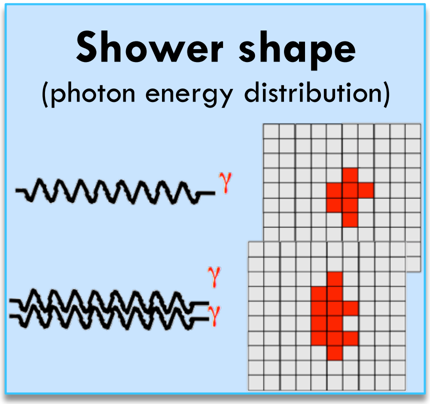


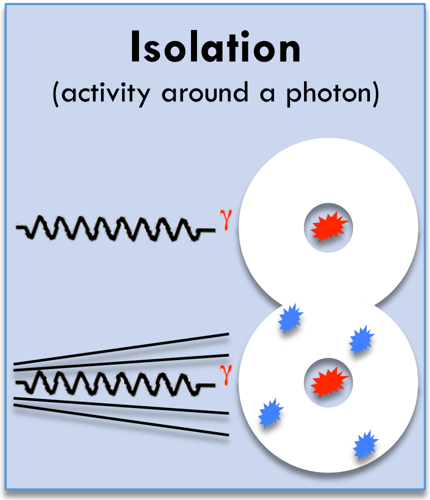
Photon identification

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









Mass resolution deconstructed

Photon energies

Di-photon opening angle

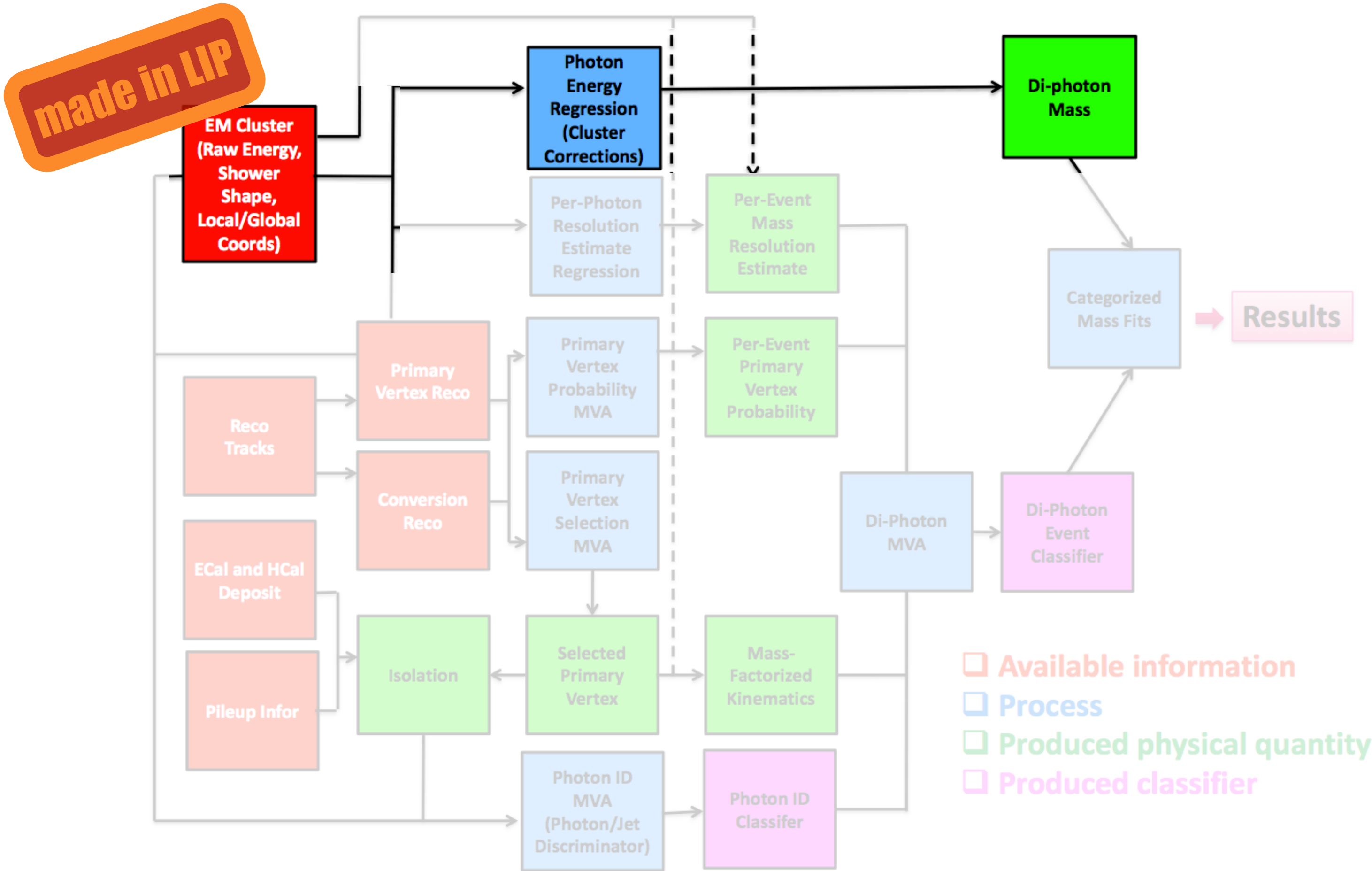
$$M_{\gamma\gamma}^2 = 2E_{\gamma 1}E_{\gamma 2}\left(1-\cos(\alpha)\right)$$

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

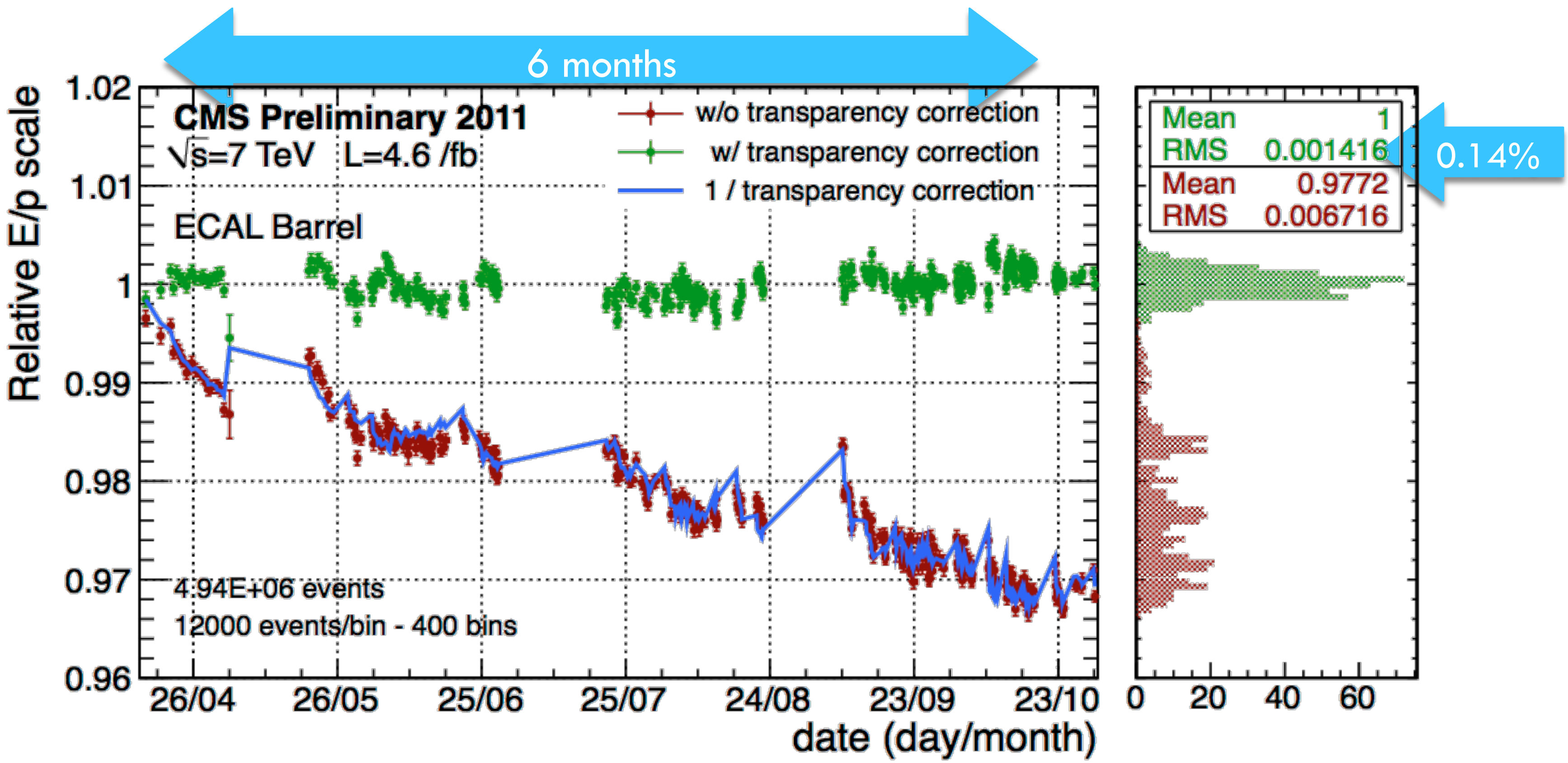
Photon energy resolution

Angular resolution

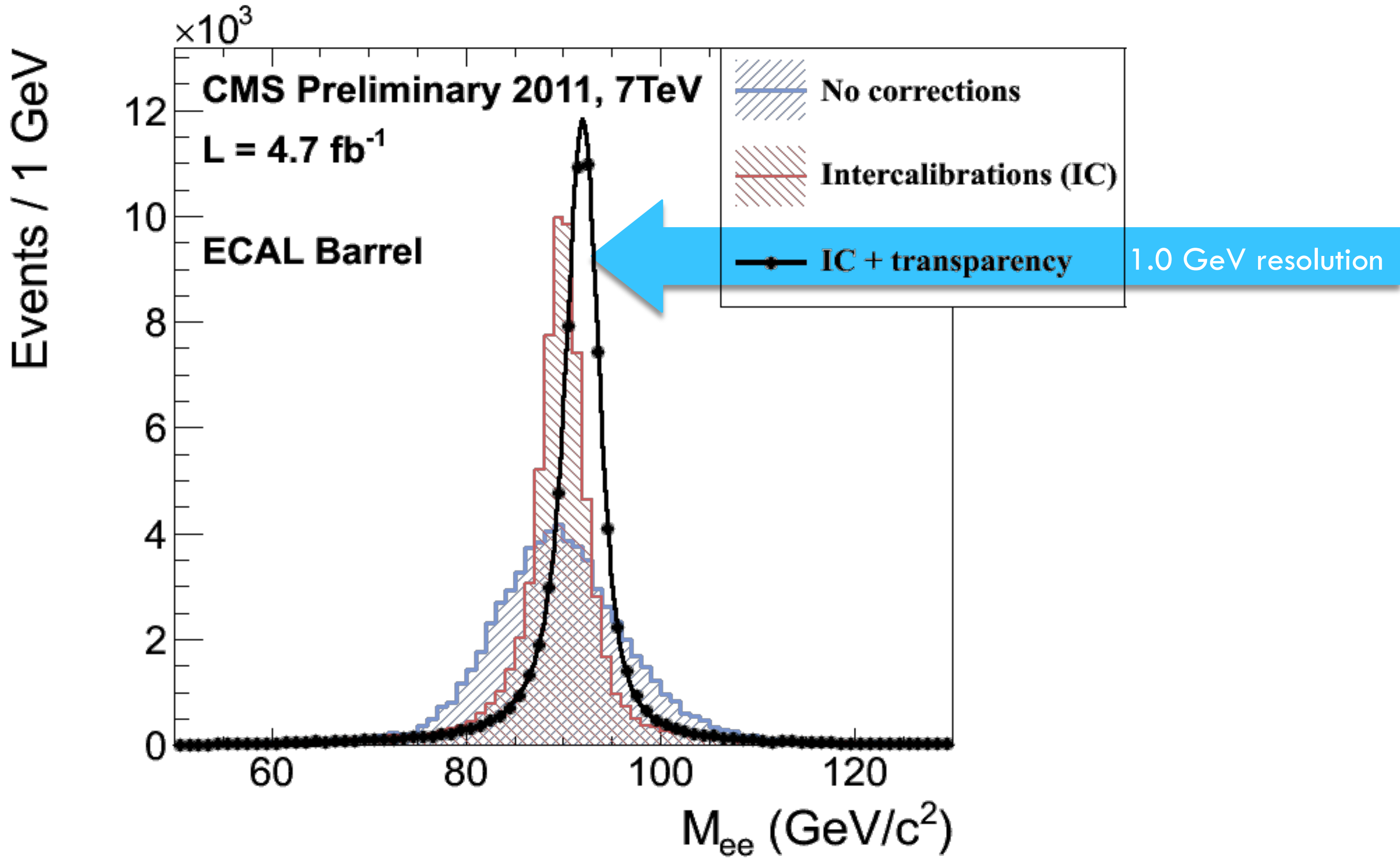
Anatomy of the analysis



ECAL calibration: isolated electrons

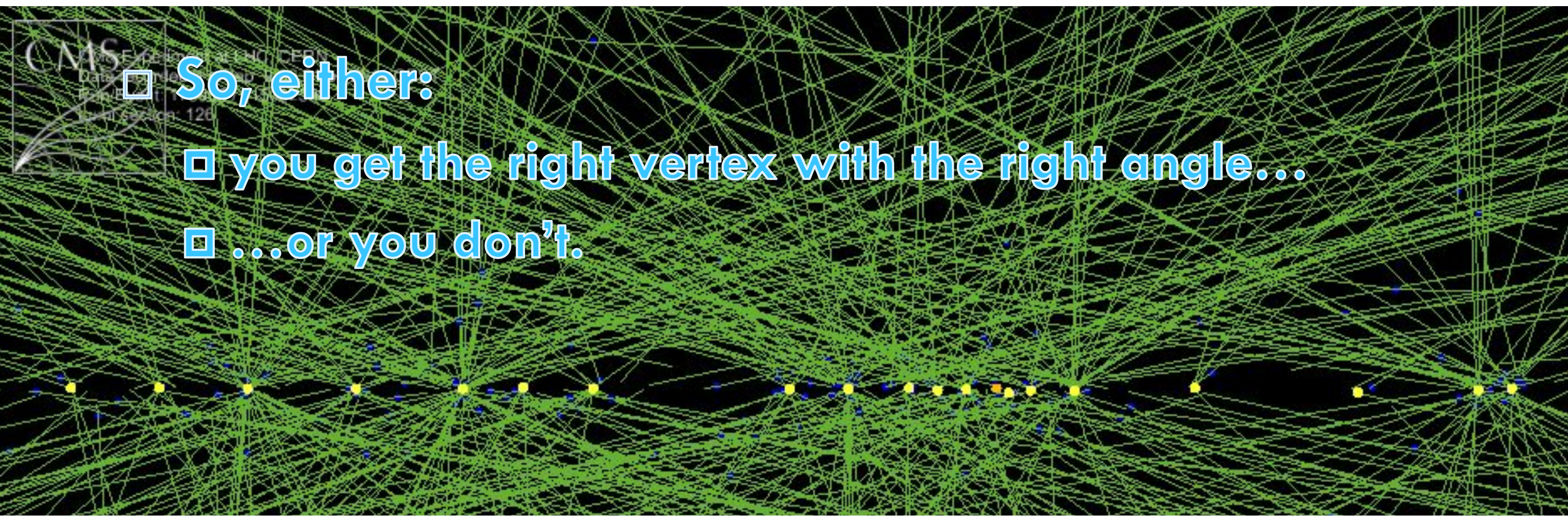


ECAL calibration: Z→ee peak



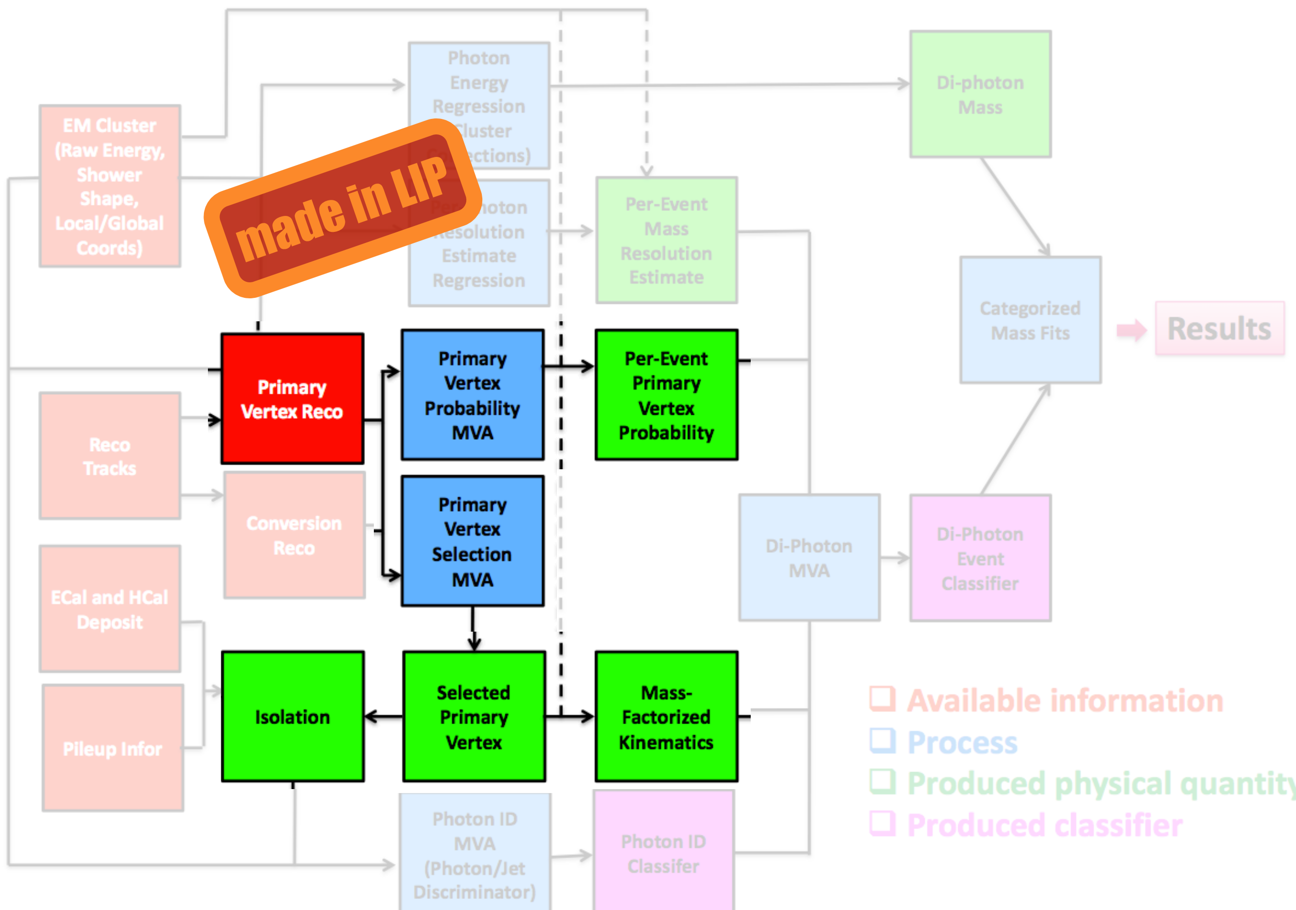
Angular resolution

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

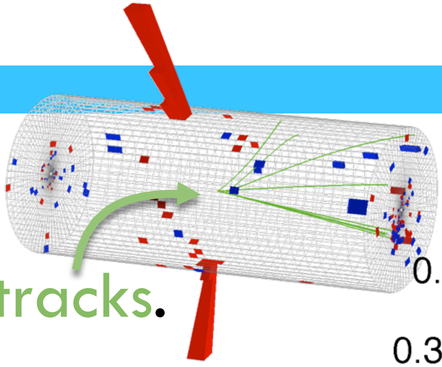


- So, either:
  - you get the right vertex with the right angle…
  - …or you don't.

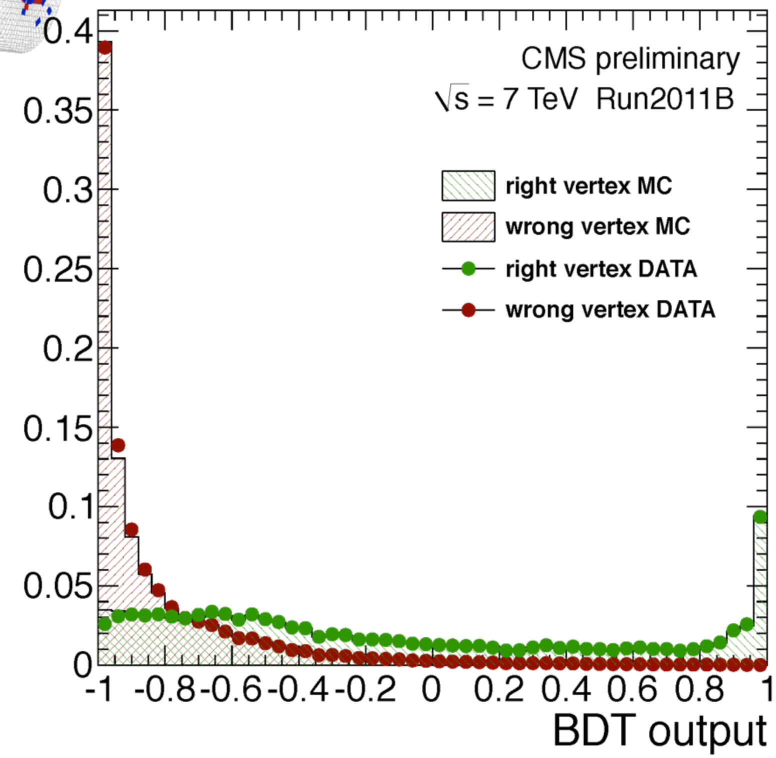
Anatomy of the analysis



Choosing the best vertex

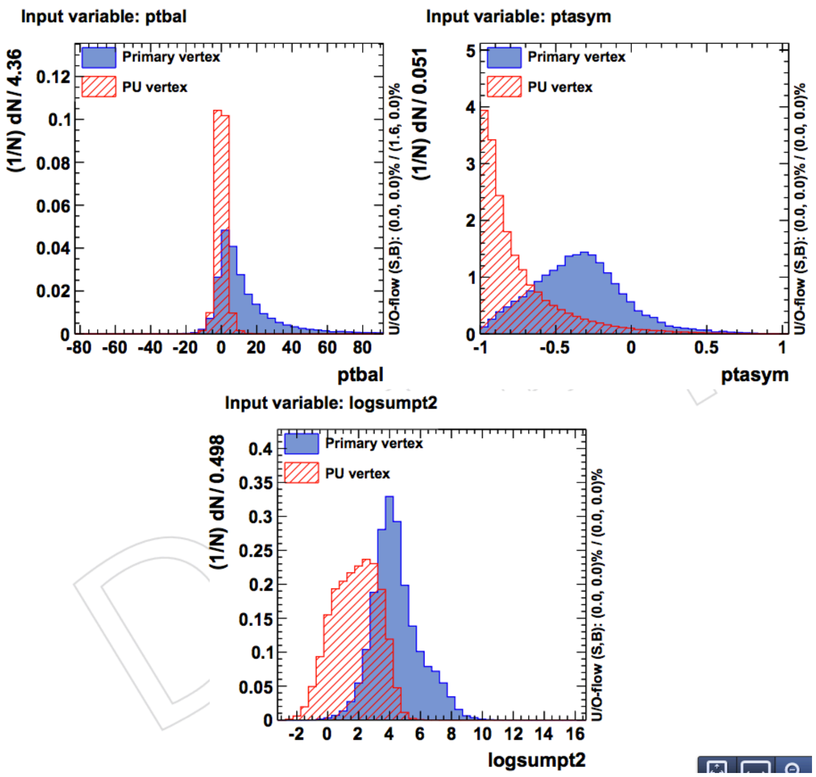


- Main handles:
  - Di-photon recoil tracks.
    - Good at high p_T.
    - Validated with $Z \to \mu\ \mu$ events. ➔
  - Photon conversion tracks.
    - Validated with γ -jet events.



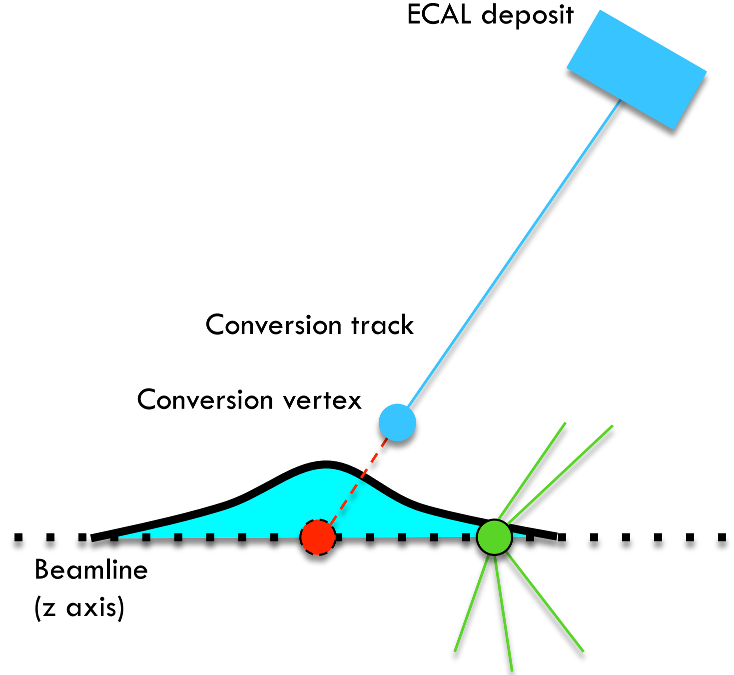
Vertex recoil variables

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

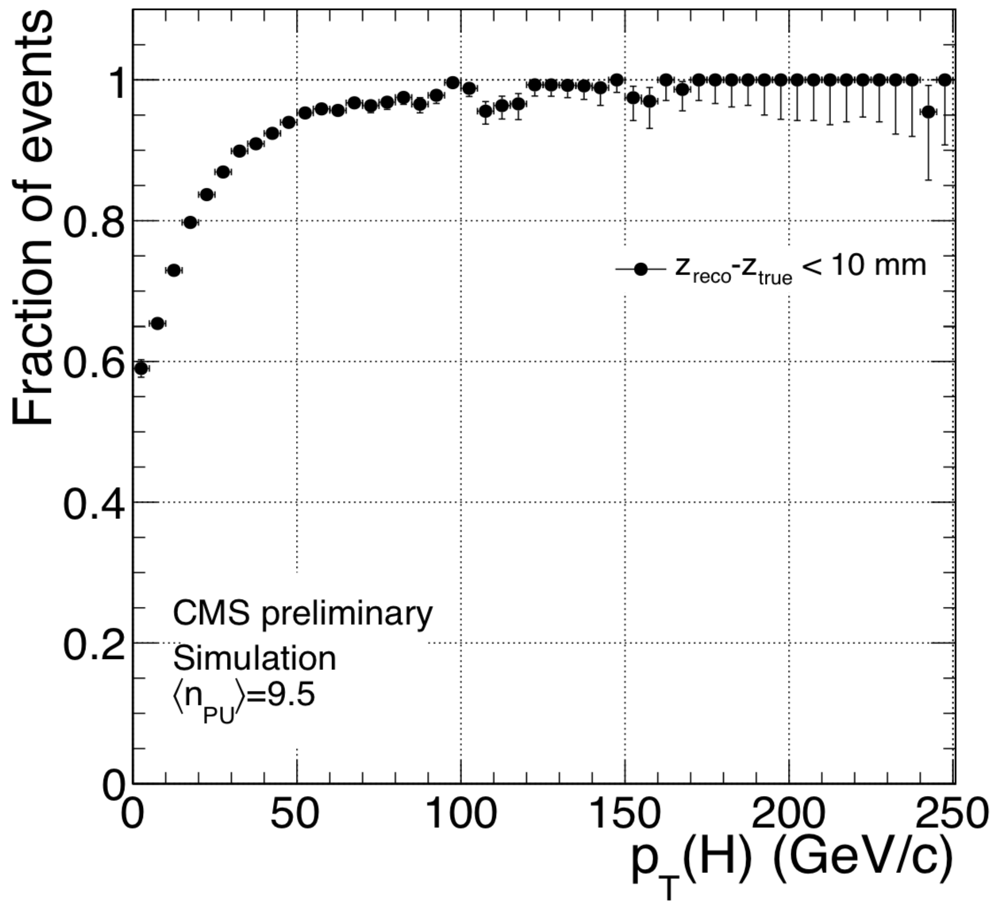


Converted photon vertexing

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



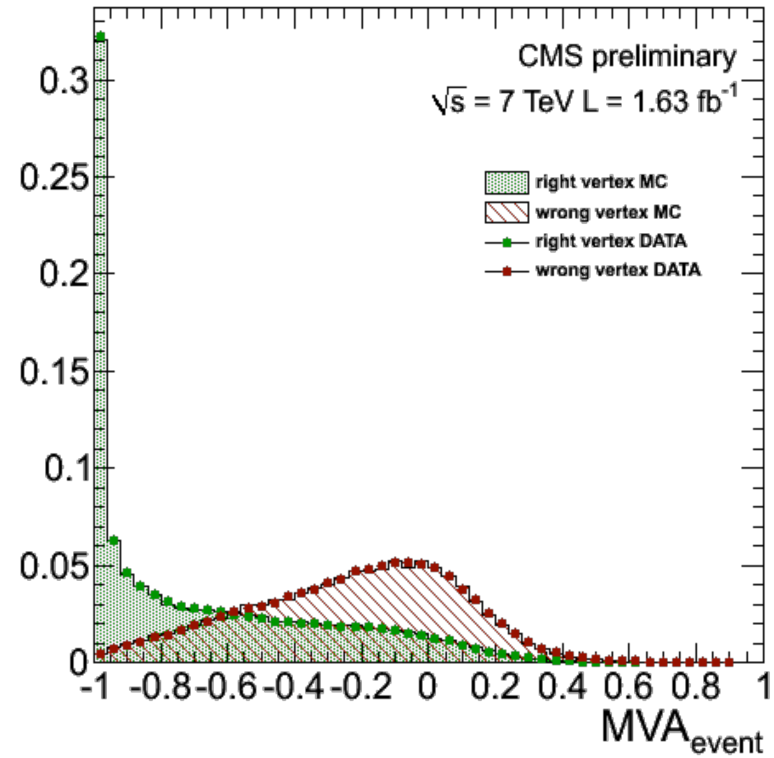
Vertex choice efficiency



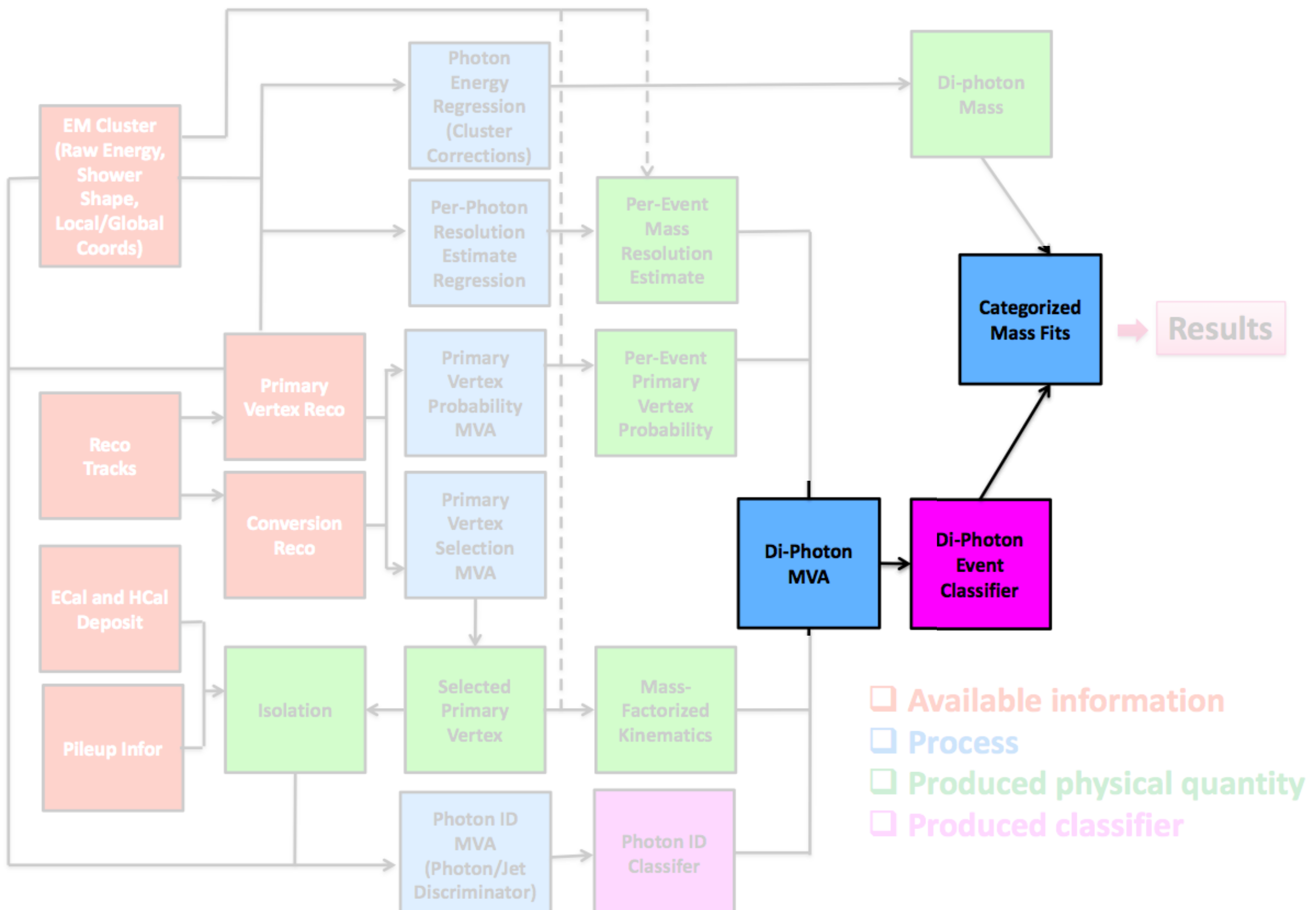
Is the best vertex the right one for this event?

made in LIP

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

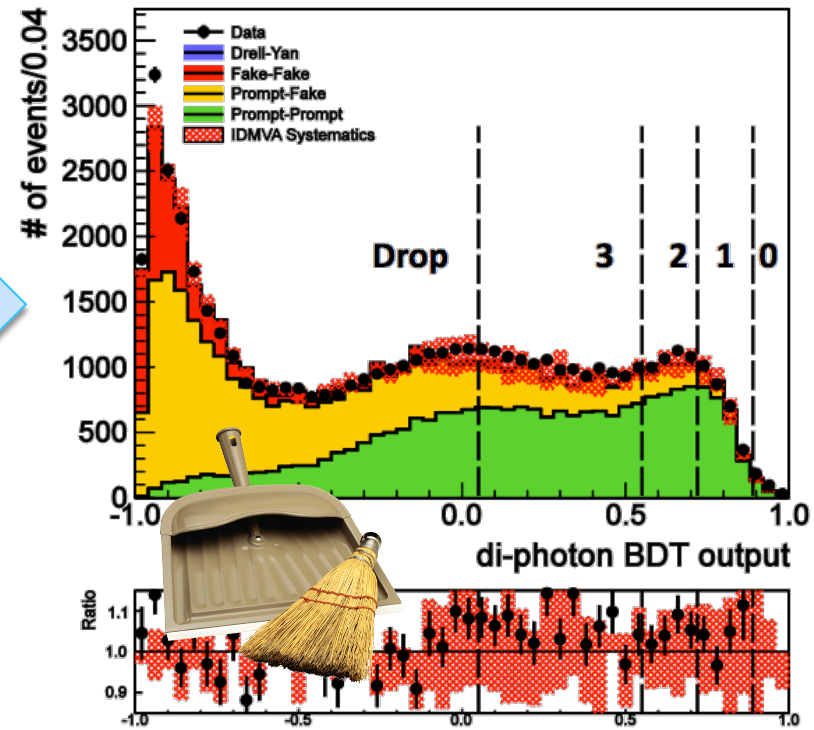


Anatomy of the analysis

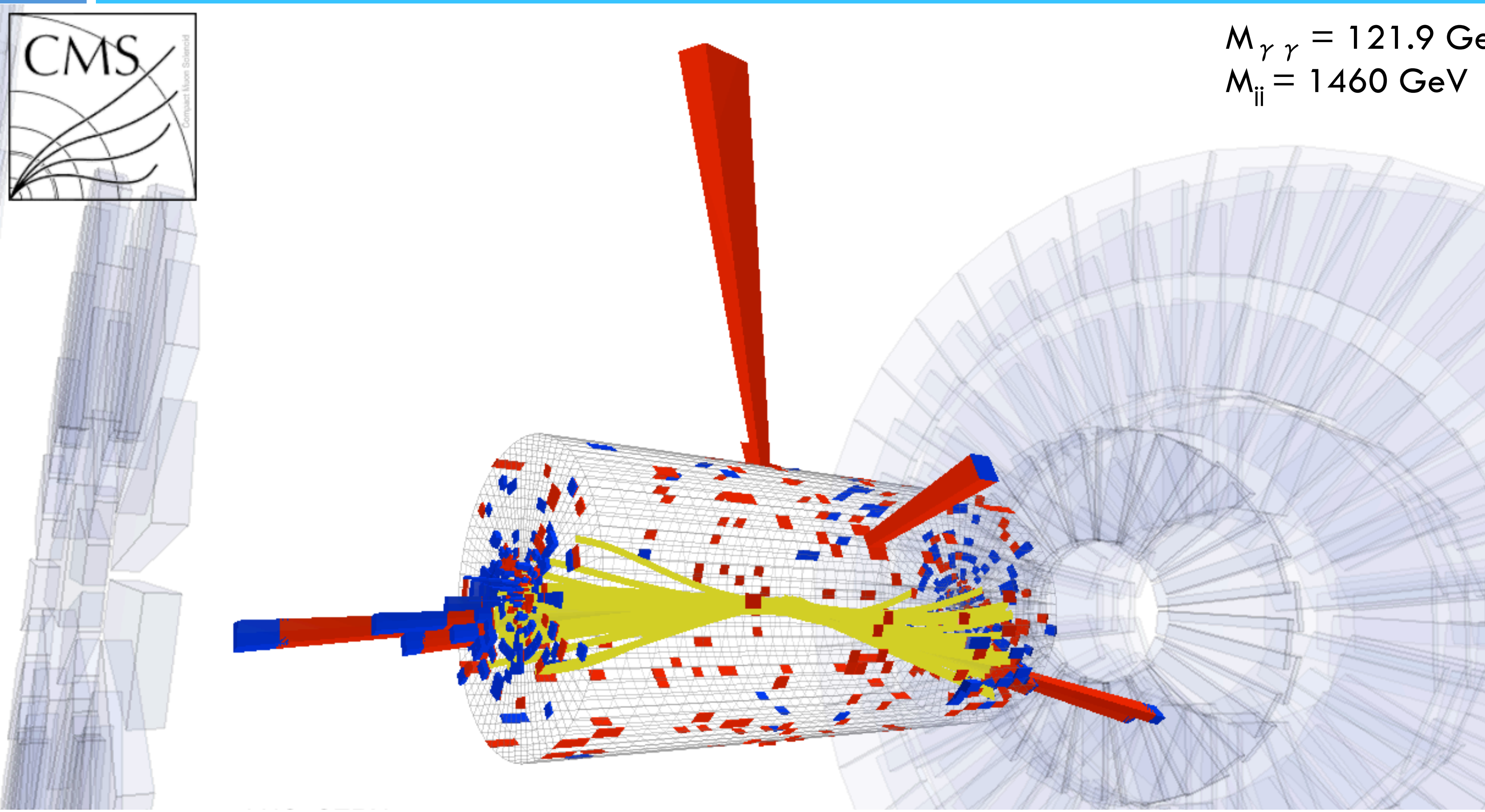


Di-photon classification

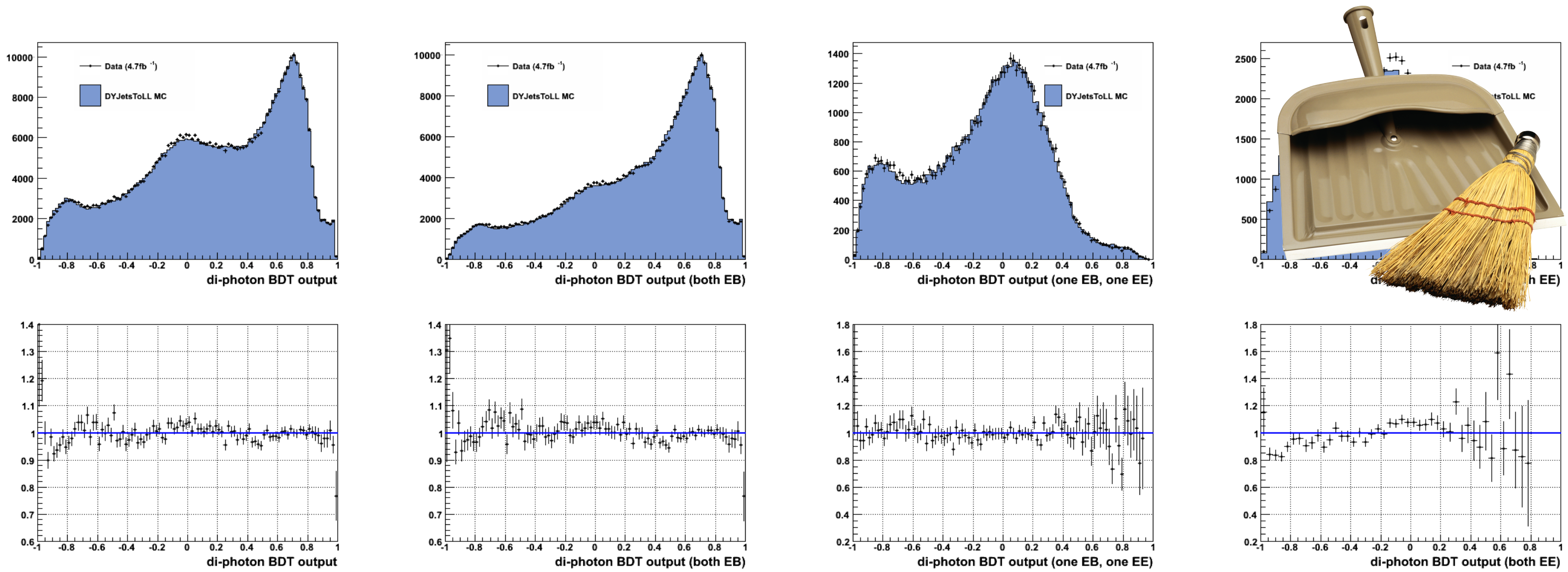
- Uses BDT method on MC background and Higgs boson signal events (m_H=123GeV)
- Training variables include photon ID, kinematics, right vertex probability and estimate mass resolution
- Keep Di-photon mass factorized
- Introduce good resolution as a desired feature by weighting signal events by 1/estimate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



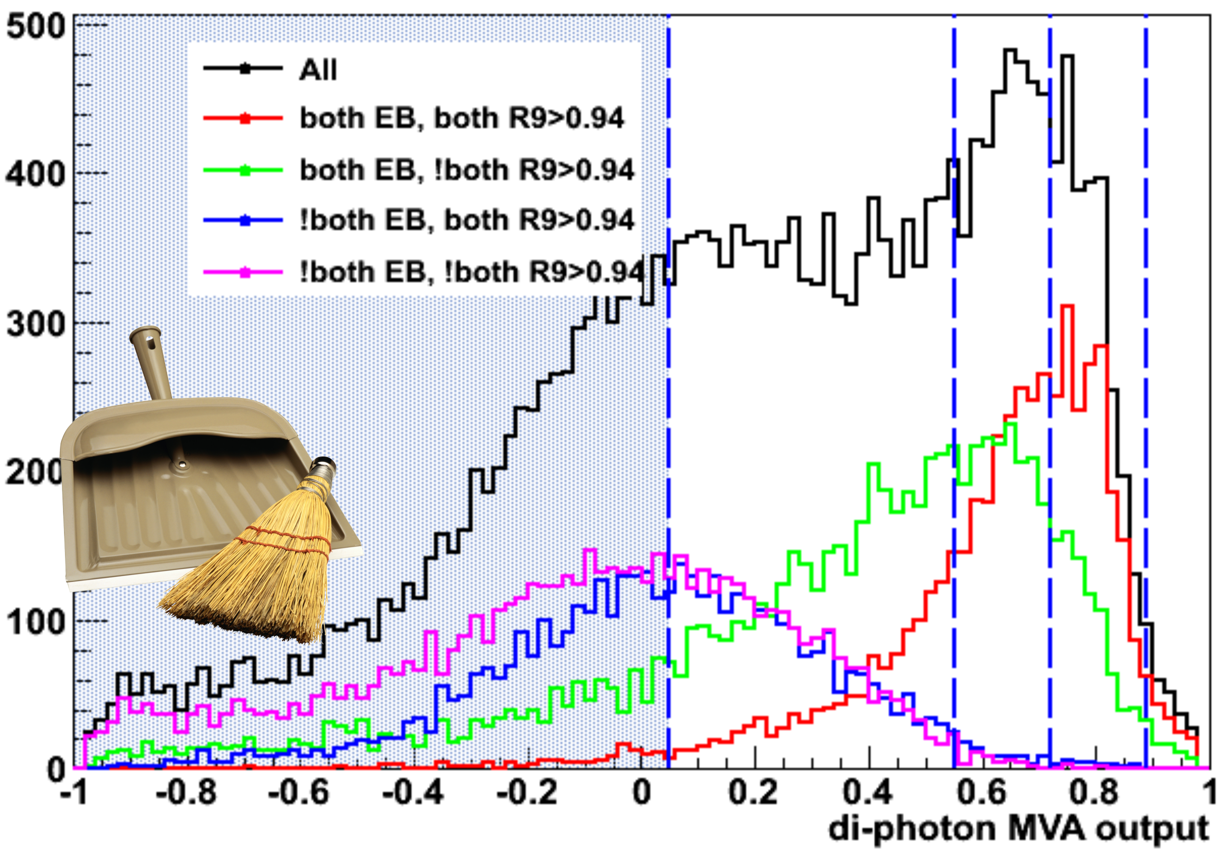
Di-jet tagged event



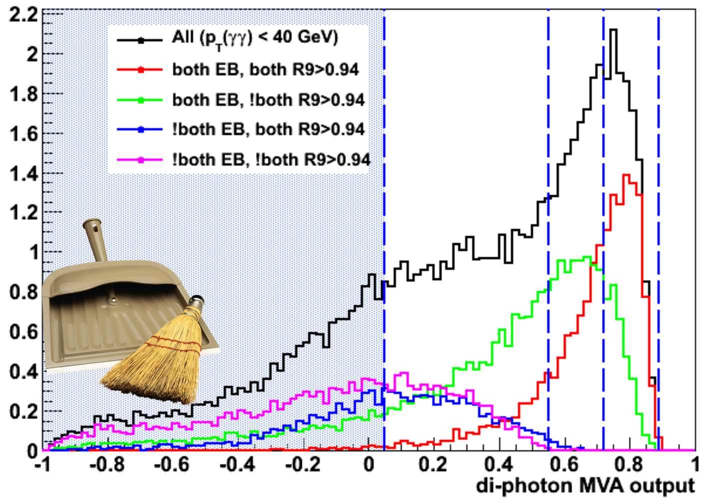
MVA validation on Z→ee

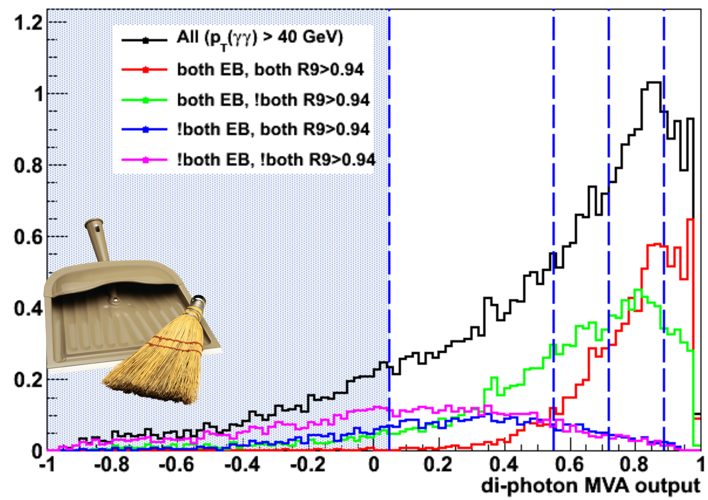


MVA in terms of simple classification



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

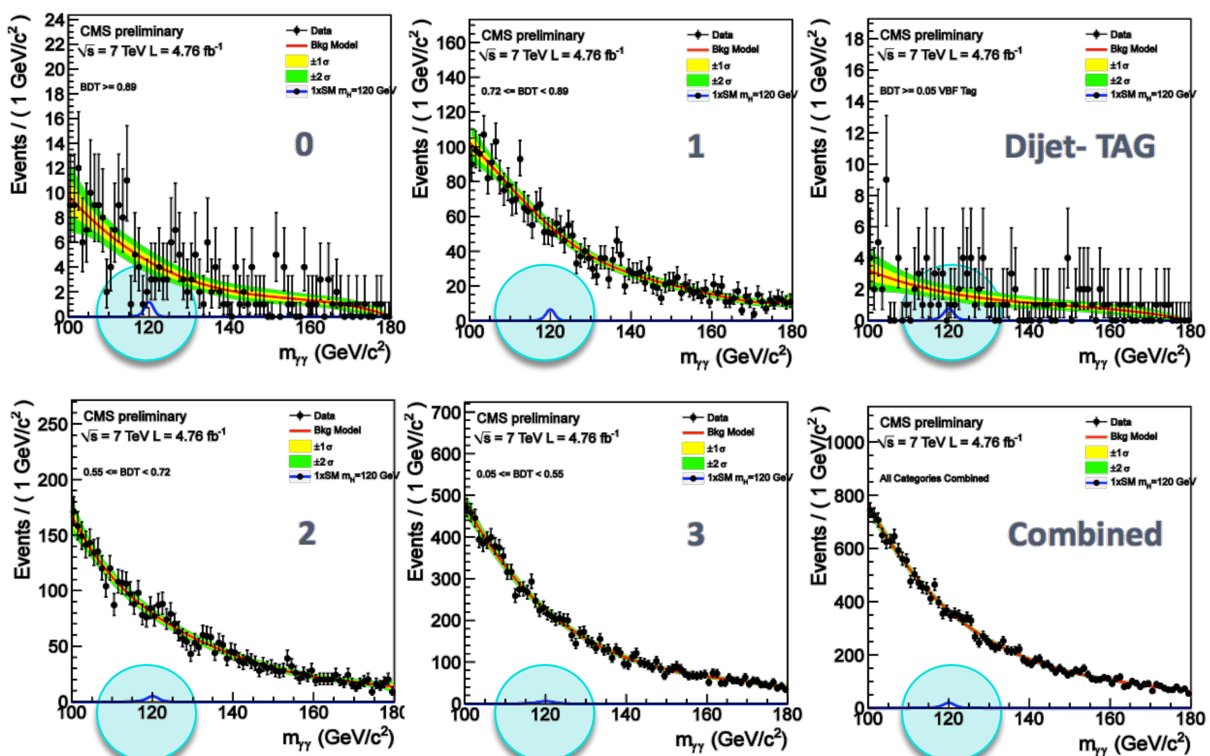




Signal and background modeling

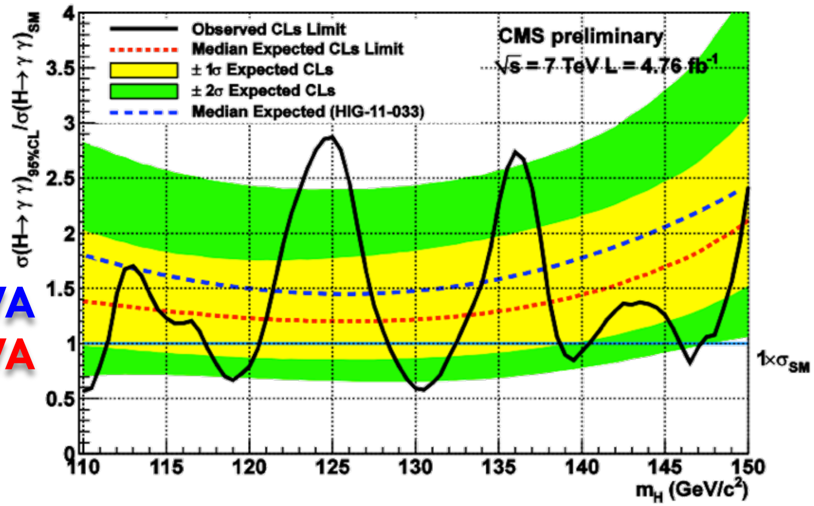
- Higgs mass modeled using MC with energy scale and resolution correction from $Z \rightarrow ee$
- Background mass spectrum modeled by polynomial fit
  - Polynomial order between 3 and 5 depending on event category statistics

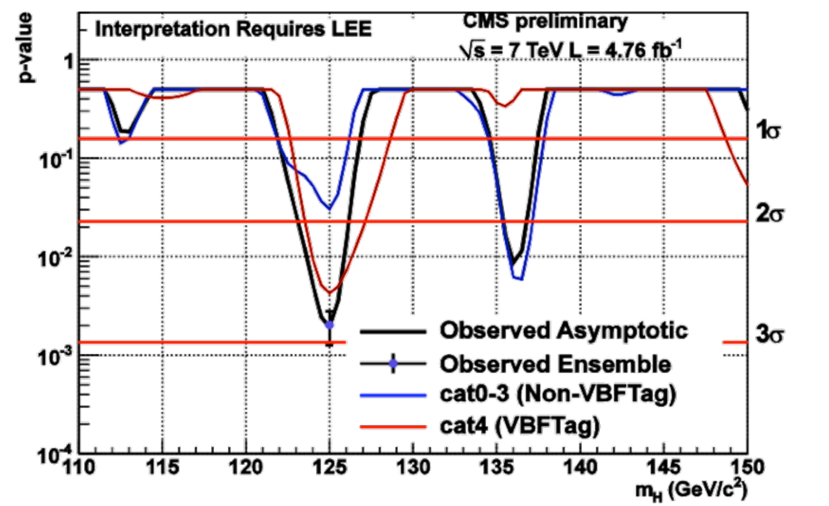
$m_H = 120$ GeV
$1 \times$ SM



Results

No MVA
MVA





- Expected and observed exclusion limit at 95% CL
- Largest excess observed around 125 GeV with local significance 2.9 σ and global significance 1.6 σ

And the data were made public…

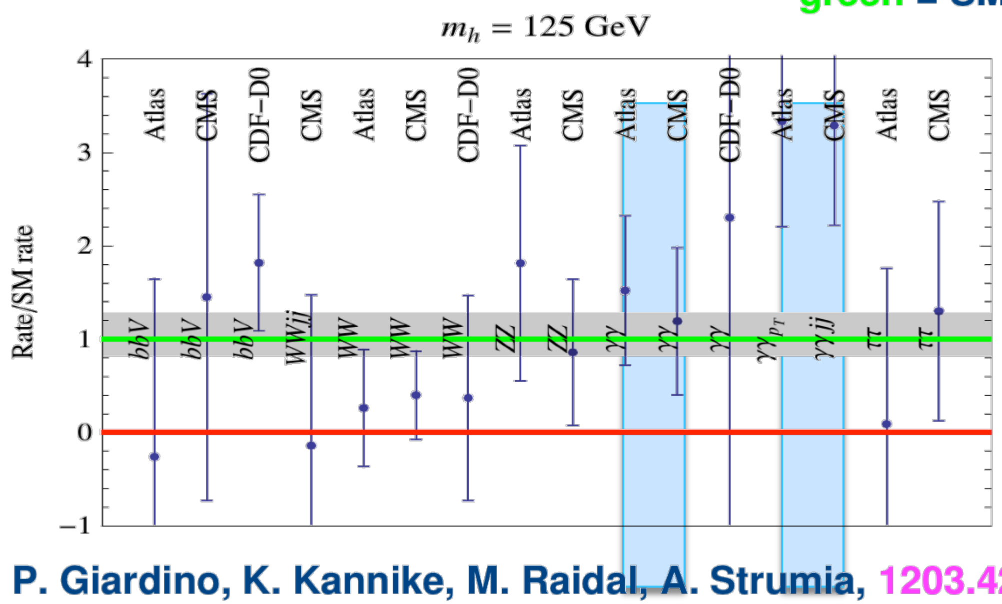
Some theorists…

…go so deep into error bars…

http://goo.gl/CVm6s

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

red = no Higgs boson
green = SM



P. Giardino, K. Kannike, M. Raidal, A. Strumia, 1203.4254

...and draw conclusions...

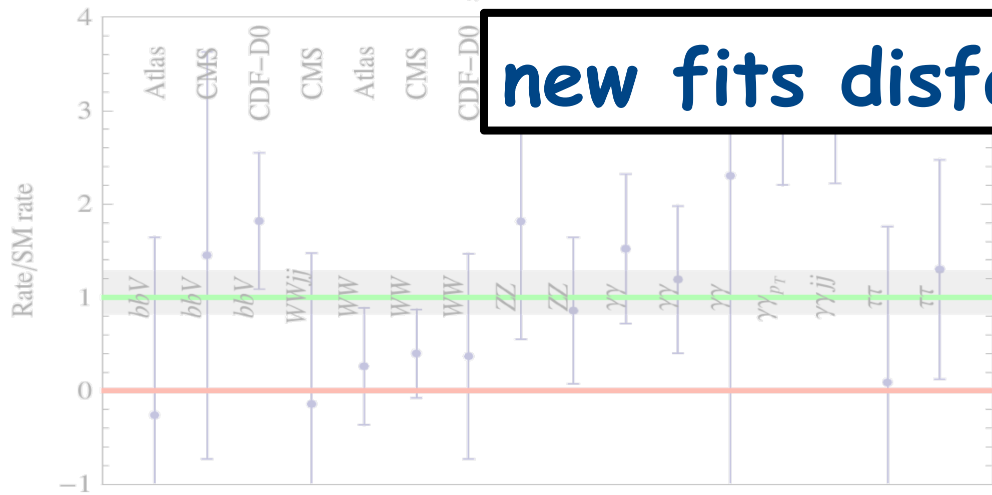
http://goo.gl/CVm6s

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

new fits disfavor the SM

new fits disfavor the SM

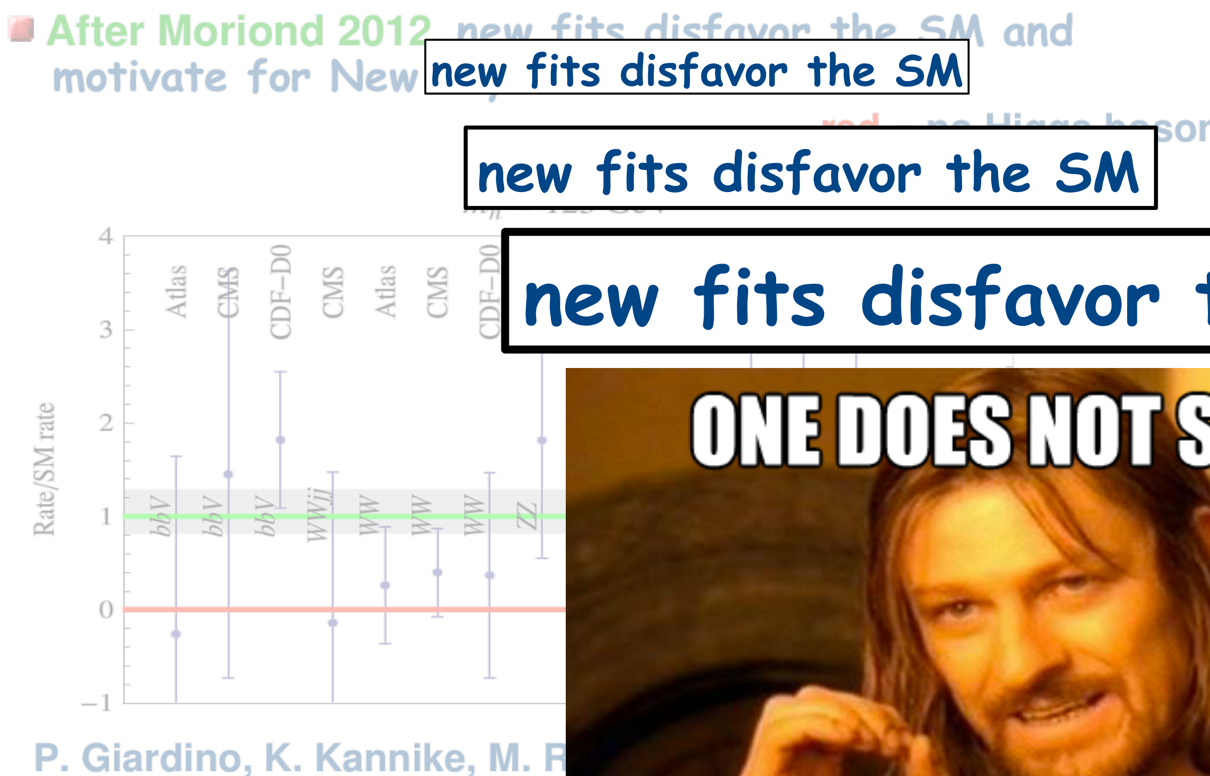
new fits disfavor the SM



P. Giardino, K. Kannike, M. Raidal, A. Strumia, 1203.4254

…and draw conclusions…

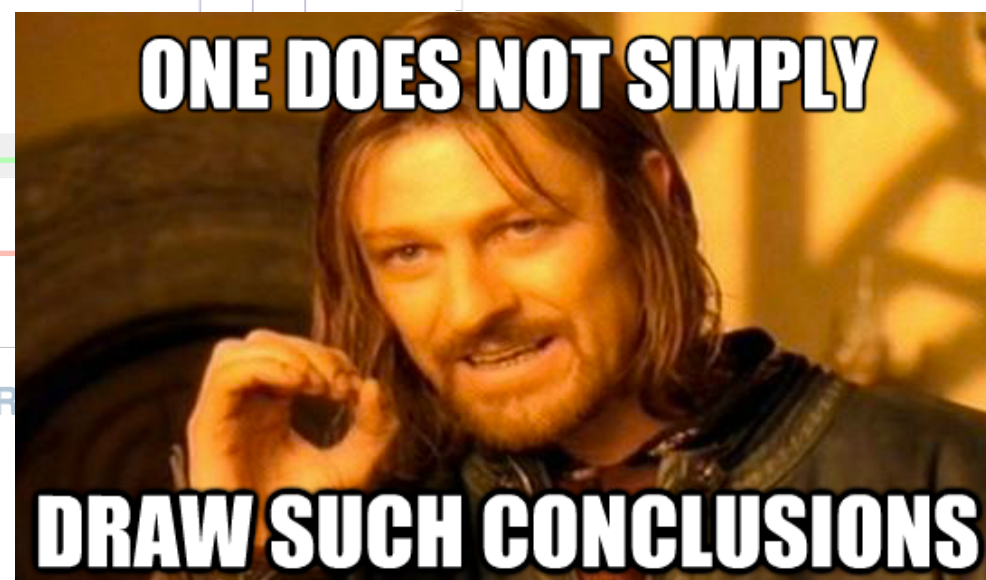
http://goo.gl/CVm6s



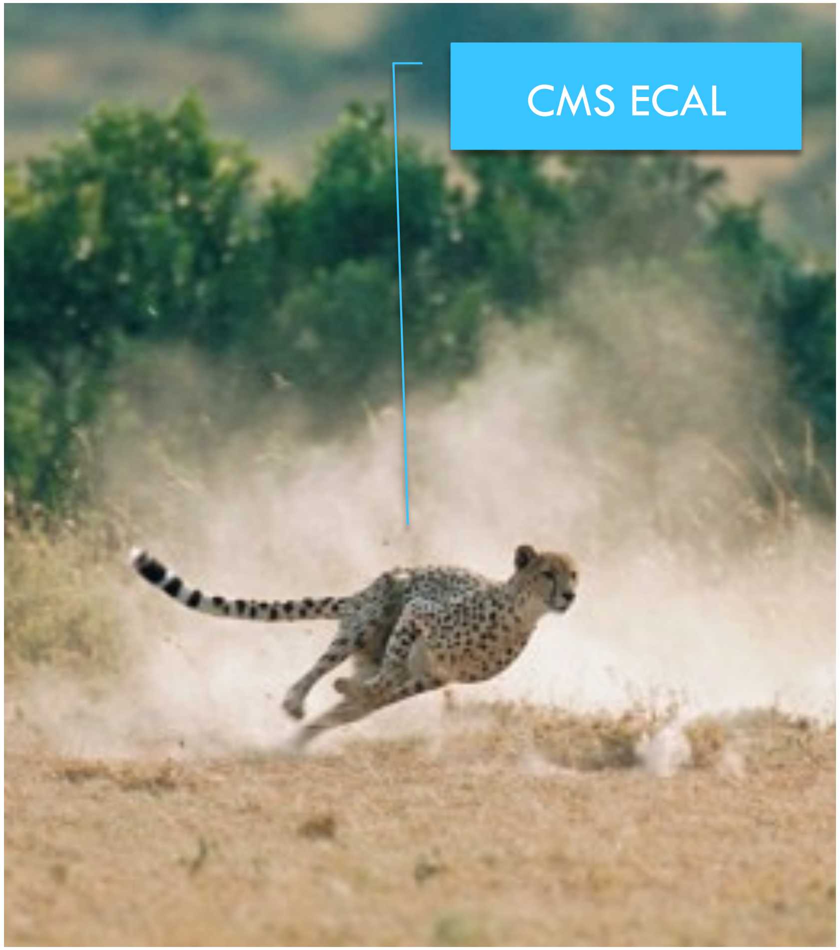
new fits disfavor the SM

new fits disfavor the SM

new fits disfavor the SM

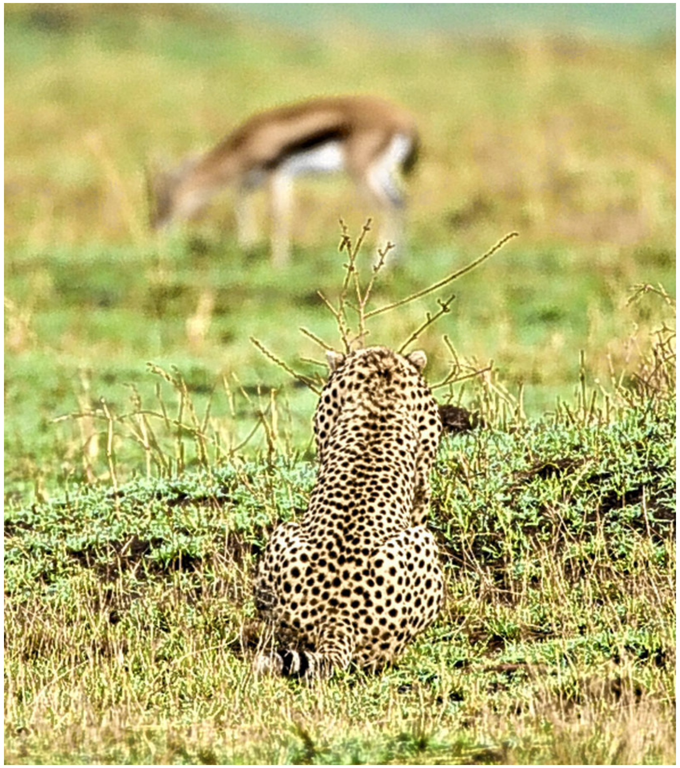


Conclusions – CMS ECAL



- A long way since the 1990s.
- CMS ECAL has an exquisite resolution.
  - Excellent performance around 1% already in 2011.
- Calibration, calibration, calibration…

Conclusions – Higgs analysis



Higgs field, we're watching you.

- The mSM has very clear predictions.
  - That have proven hard to disprove until now.
- Simple cuts are easy to understand.
- Complex MVAs are powerful for analyses.
- Do not lose sight of the big picture by over-optimising details.

Christmas 2012

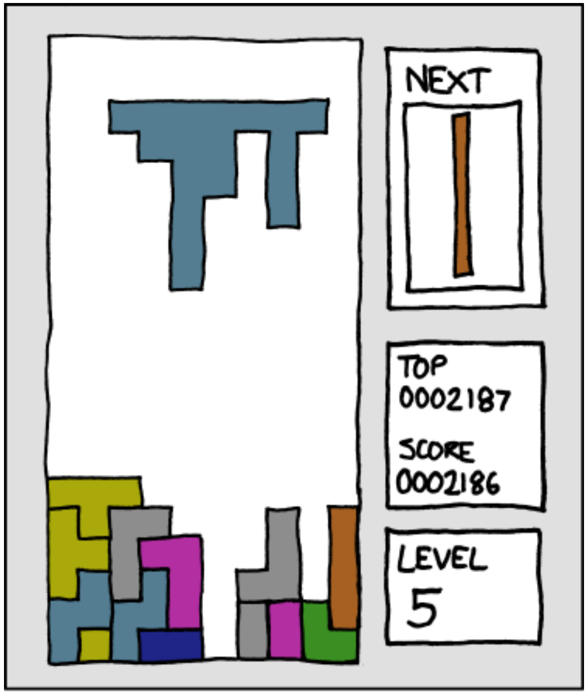
For discussion

CMS combination

[CMS-PAS-HIG-12-008]

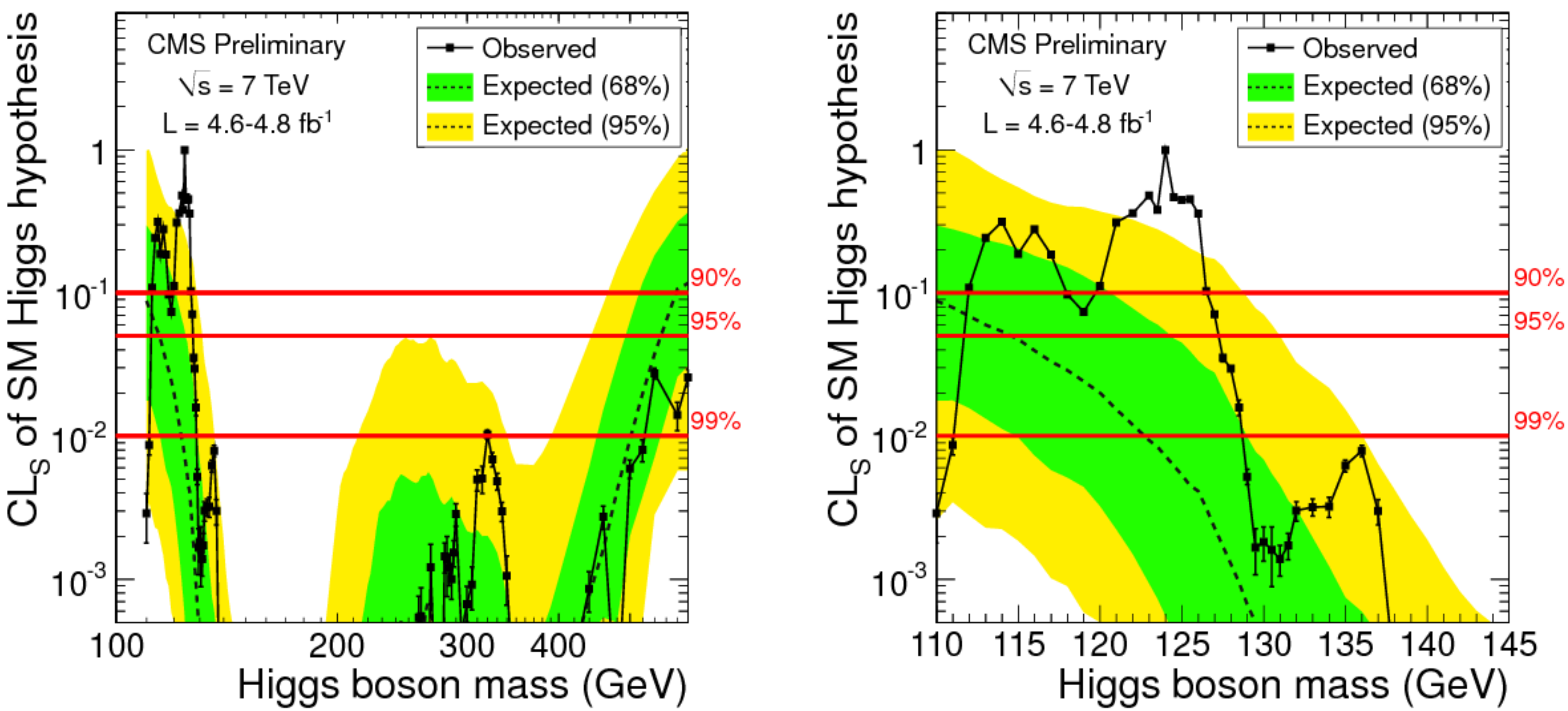
LHC Higgs working groups

- Joining ATLAS, CMS, LHCb, and theory:
  - Cross sections and branching fractions WG:
    - 7 TeV, 8 TeV, 14 TeV.
    - SM, SM4, Fermiophobic.
  - Statistical methods and combinations WG.
- Selecting the best pieces for a common puzzle. ➔



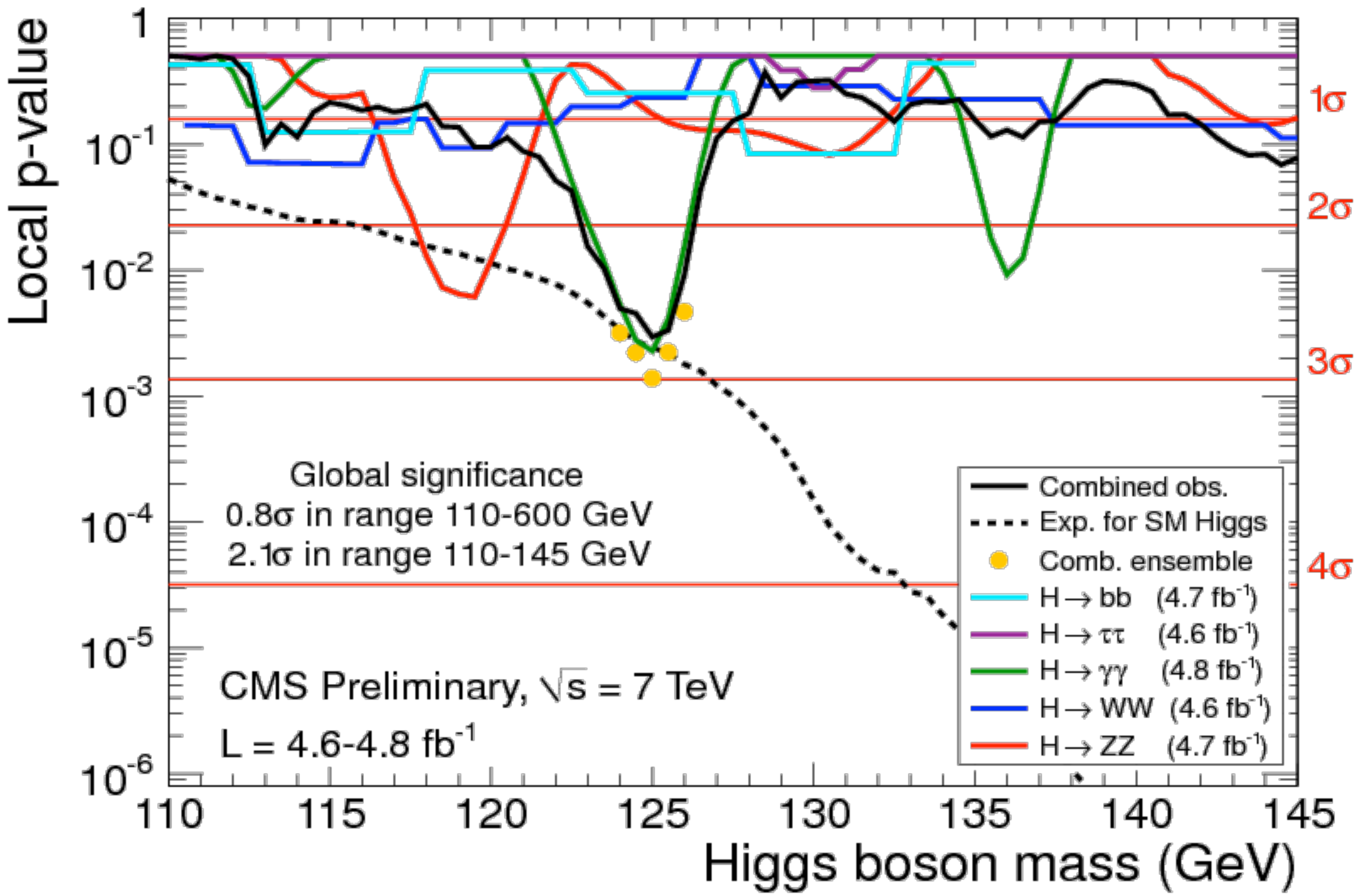
HEAVEN

CMS combination [CMS-PAS-HIG-12-008]

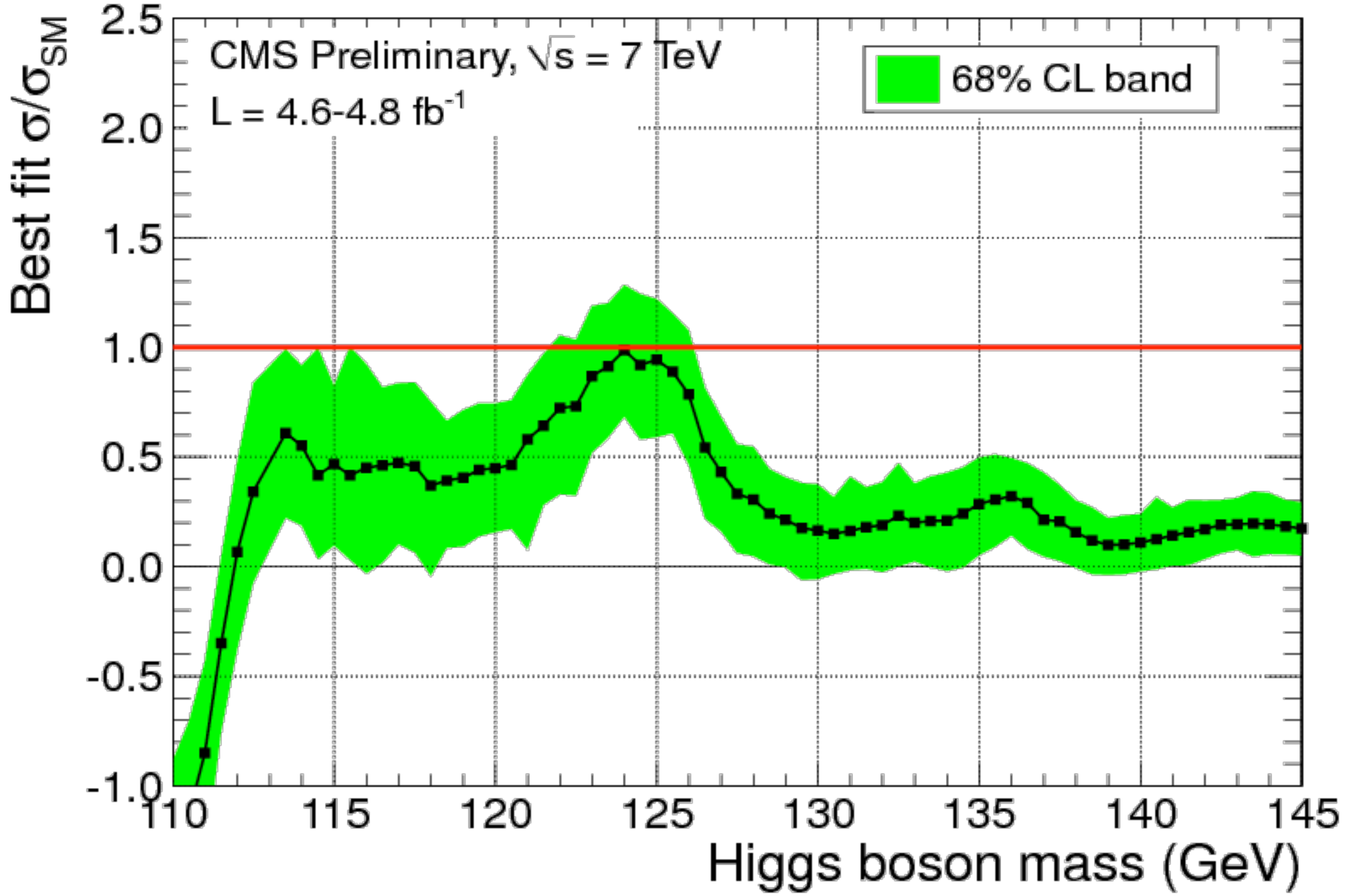


a.david@cern.ch - #CERNPhil2014

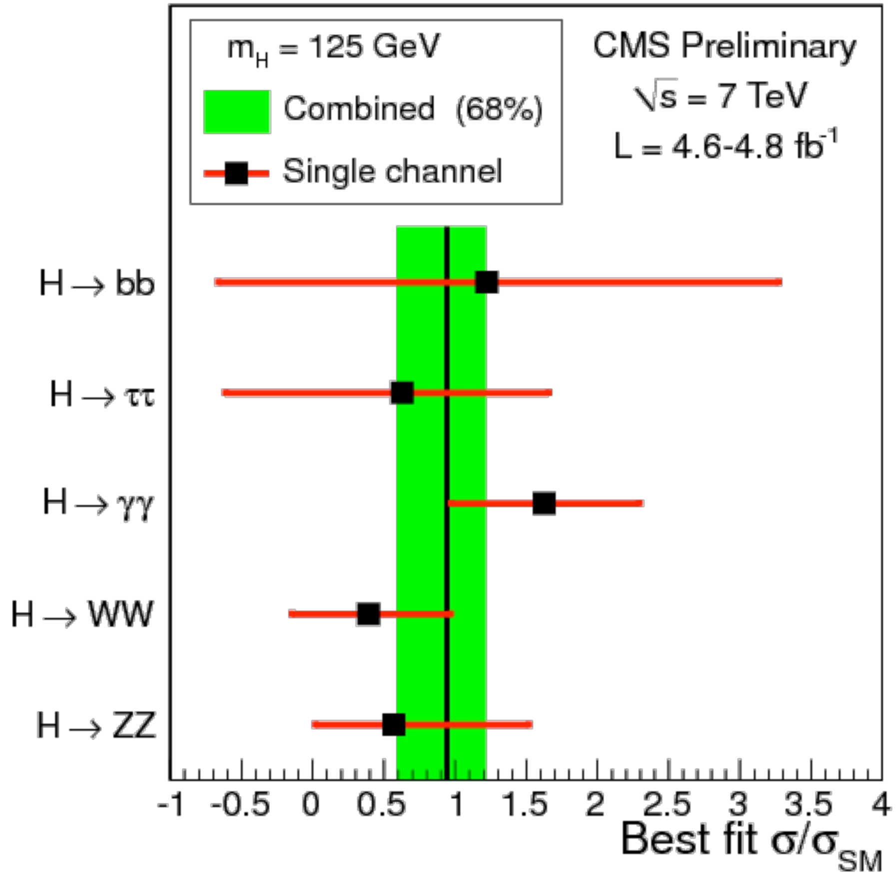
CMS combination [CMS-PAS-HIG-12-008]



CMS combination [CMS-PAS-HIG-12-008]



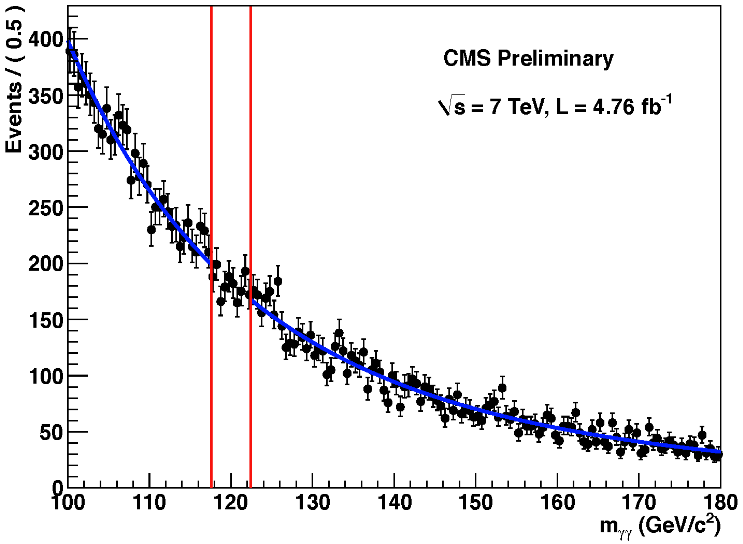
CMS combination [CMS-PAS-HIG-12-008]

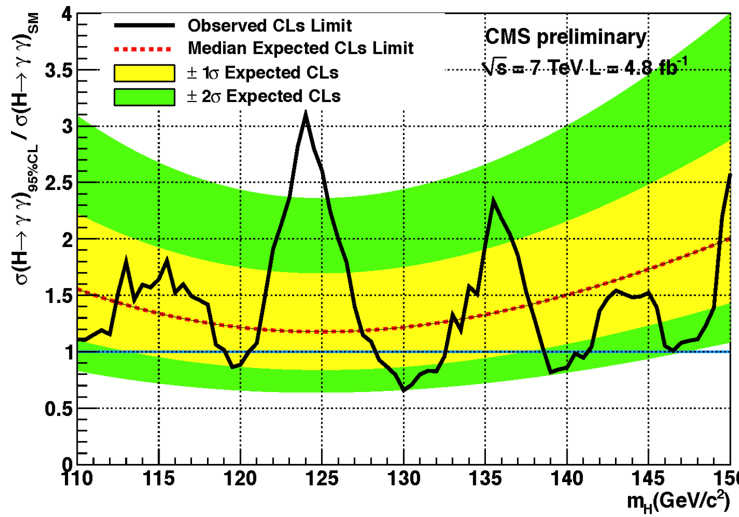


More details

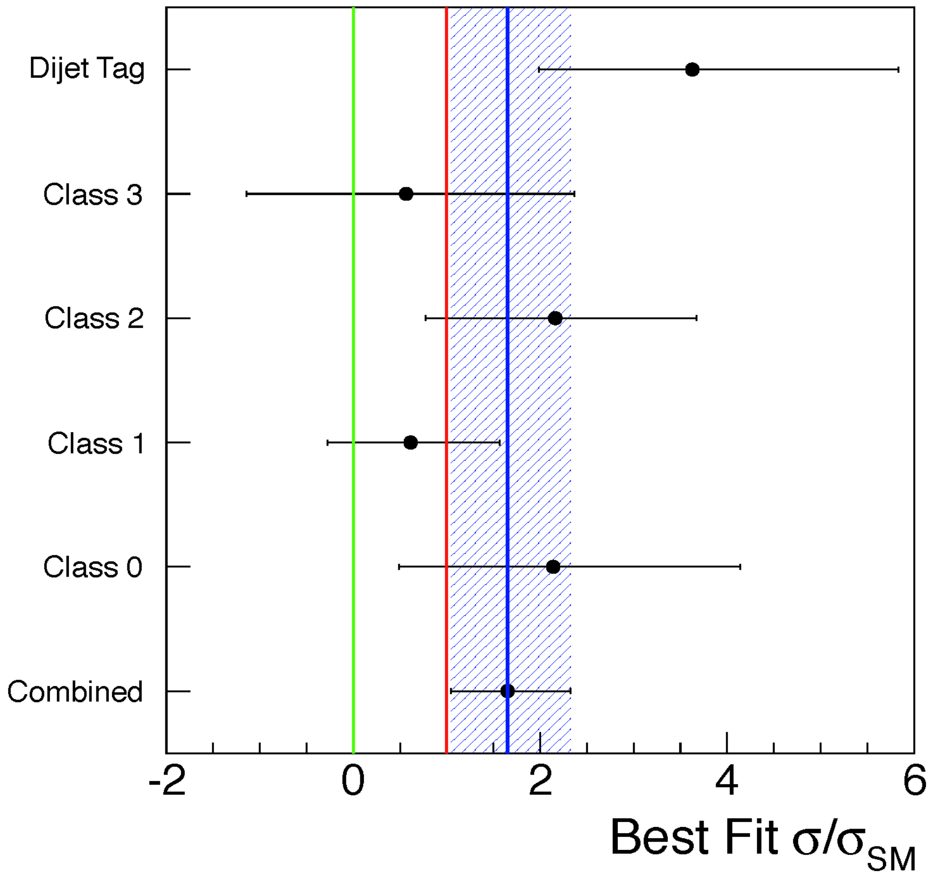
[CMS-PAS-HIG-12-001]

Side-band background treatment





Best-fit strength breakdown



Details on the event classes

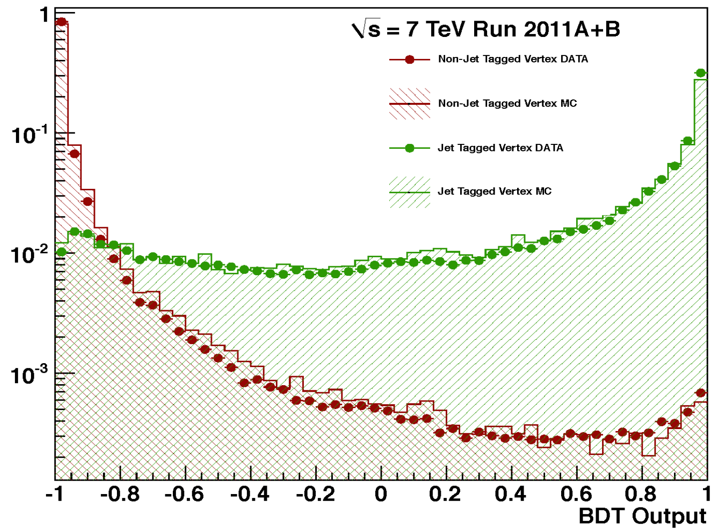
	0	1	2	3	Dijet tag
SM signal expected	3.4 (4.4%)	19.3 (25.0%)	18.7 (24.2%)	33.0 (42.8%)	2.8 (3.6%)
Data (events/GeV)	4.5 (1.2%)	55.1 (14.8%)	81.3 (21.8%)	229.1 (61.6%)	2.1 (0.6%)
σ_{eff} (GeV)	1.18	1.25	1.64	2.47	1.65
FWHM/2.35 (GeV)	1.09	1.09	1.43	2.08	1.32

Systematic uncertainties

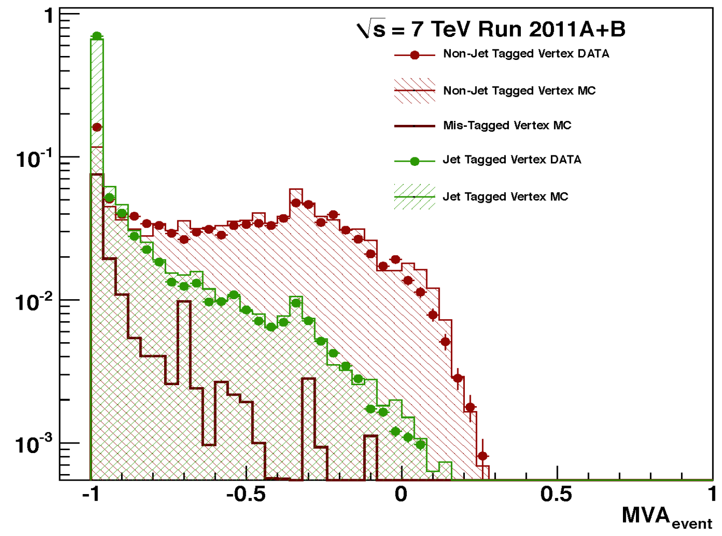
Sources of systematic uncertainty		Uncertainty	
Per photon		Barrel	Endcap
Photon identification efficiency		1.0%	2.6%
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.22%, 0.61%	0.91%, 0.34%
	$R_9 < 0.94$ (low η, high η)	0.24%, 0.59%	0.30%, 0.53%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (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 BDT	(Effect of up to 11% event class migration.)	$\pm$0.025 (shape shift)	
Photon energy resolution BDT	(Effect of up to 8% event class migration.)	$\pm$10% (shape scaling)	
Per event			
Integrated luminosity		4.5%	
Vertex finding efficiency		0.4%	
Trigger efficiency	One or both photons $R_9 < 0.94$ in endcap	0.4%	
	Other events	0.1%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
	Gluon-gluon fusion process	70%	
Production cross sections		Scale	PDF
Gluon-gluon fusion		+12.5% -8.2%	+7.9% -7.7%
Vector boson fusion		+0.5% -0.3%	+2.7% -2.1%
Associated production with W/Z		1.8%	4.2%
Associated production with $t\bar{t}$		+3.6% -9.5%	8.5%
Scale and PDF uncertainties	(Effect of up to 16% event class migration.)	(y, p_T)-differential	

Photon-jet vertex MVA validation

Per Vertex MVA



Per Event MVA



More details

[CMS-PAS-HIG-11-021]

Variations on a limit theme

	Expected (95% CL, PLA, pb)	Ratio to nominal
Standard Model, $m_H = 120\,\mathrm{GeV}/c^2$		
Nominal (8 classes)	0.1104	1.000
No signal systematics (8 classes)	0.1097	0.993
EB only (4 classes)	0.1163	1.053
Merge $p_T^{\gamma\gamma}$ classes (4 classes)	0.1130	1.023
Merge all classes	0.1318	1.193
Fermiophobic, $m_H = 120\,\mathrm{GeV}/c^2$		
Nominal (8 classes)	0.0696	1.000
No signal systematics (8 classes)	0.0691	0.993
EB only (4 classes)	0.0734	1.055
Merge $p_T^{\gamma\gamma}$ classes (4 classes)	0.1107	1.591
Merge all classes	0.1303	1.872
$p_T^{\gamma\gamma} > 40\,\mathrm{GeV}/c$ only (4 classes)	0.0704	1.012

Limits per event class

Table 19: Standard Model: median expected limits (95% CL, PLA, pb) for $m_H = 120\,\mathrm{GeV}/c^2$ for each individual event class (4 best individual classes highlighted).

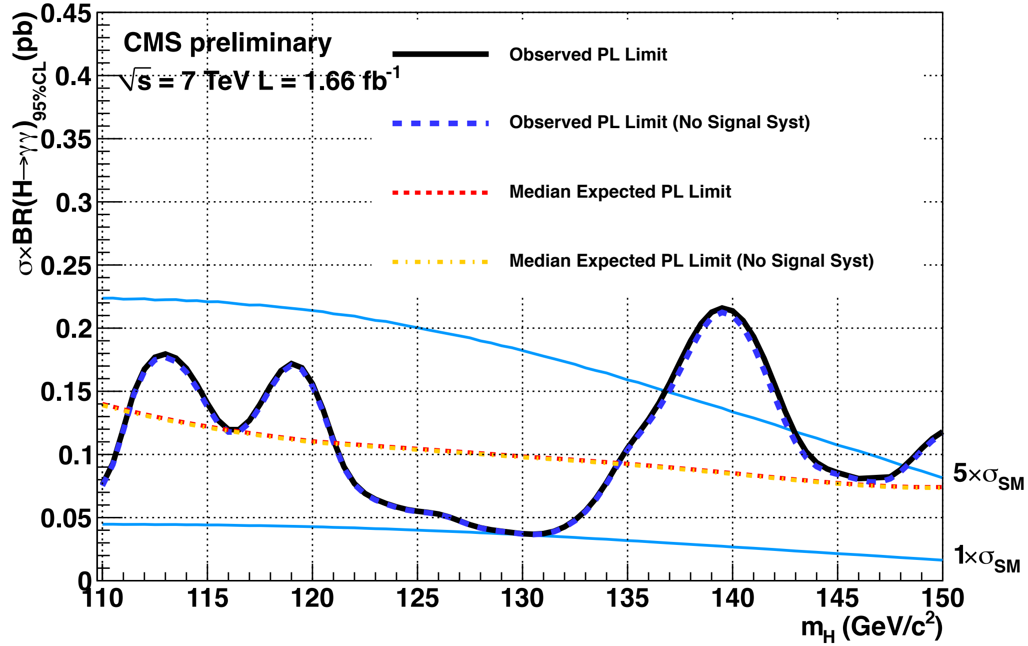
	Both photons in barrel		One or more in endcap	
	$min(R_9) > 0.94$	$min(R_9) < 0.94$	$min(R_9) > 0.94$	$min(R_9) < 0.94$
$p_T^{\gamma\gamma} < 40\,\mathrm{GeV}/c$	***0.22***	***0.24***	0.69	0.69
$p_T^{\gamma\gamma} > 40\,\mathrm{GeV}/c$	***0.24***	***0.29***	0.91	0.82

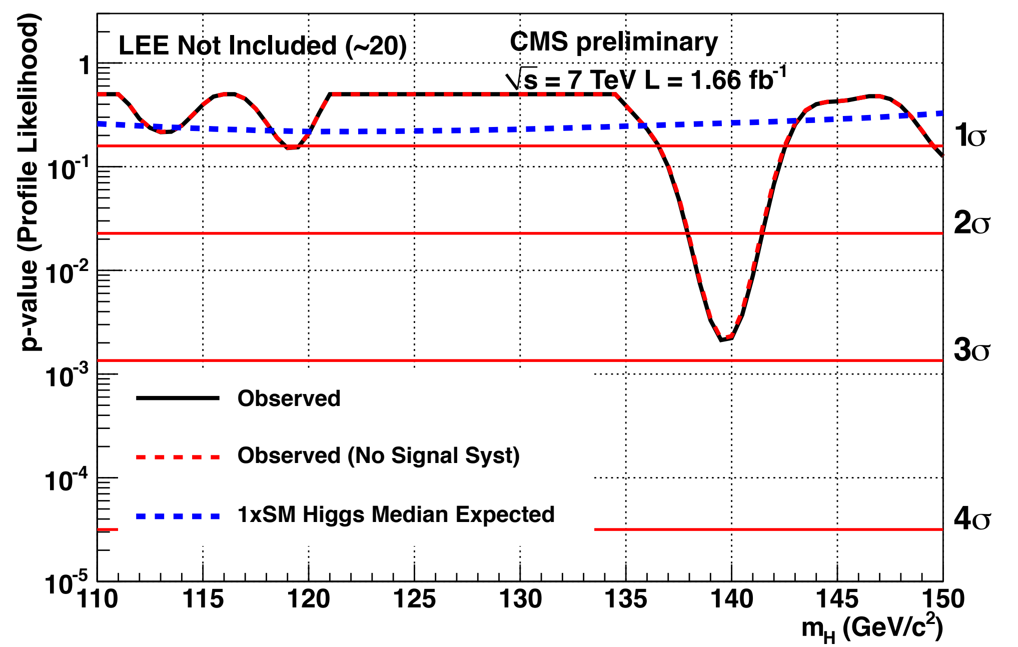
Table 20: Fermiophobic Model: median expected limit (95% CL, PLA, pb) for $m_H = 120\,\mathrm{GeV}/c^2$ for each individual event class (4 best individual classes highlighted).

	Both photons in barrel		One or more in endcap	
	$min(R_9) > 0.94$	$min(R_9) < 0.94$	$min(R_9) > 0.94$	$min(R_9) < 0.94$
$p_T^{\gamma\gamma} < 40\,\mathrm{GeV}/c$	0.70	0.79	2.00	1.87
$p_T^{\gamma\gamma} > 40\,\mathrm{GeV}/c$	***0.10***	***0.12***	***0.34***	***0.35***

Systematics

- Systematic uncertainties:
  - Single photon:
    - ID efficiency.
    - Shower shape (class migration).
    - Energy scale.
    - Energy smearing.
  - Per event:
    - Integrated luminosity.
    - Trigger efficiency.
    - Diphoton p_T (class migration).
    - Vertex finding.
- **No effect !**





Systematic uncertainties: per photon

- Small differences from EPS.
  - Changes driven by multi-period energy scale corrections.

Source		Uncertainty	
Photon identification efficiency			
	barrel	1.0%	
	endcap	2.5%	
$R_9 > 0.94$ efficiency			
(results in class migration)	barrel	4%	
	endcap	6.5%	
		$R_9 > 0.94$	$R_9 < 0.94$
Energy resolution ($\Delta\sigma / E_{MC}$)			
	barrel	0.2%	0.4%
	endcap	0.5%	0.4%
Energy scale ($(E_{data} - E_{MC}) / E_{MC}$)			
	barrel	0.1%	0.4%
	endcap	0.3%	0.4%

Systematic uncertainties

- Per event uncertainties.

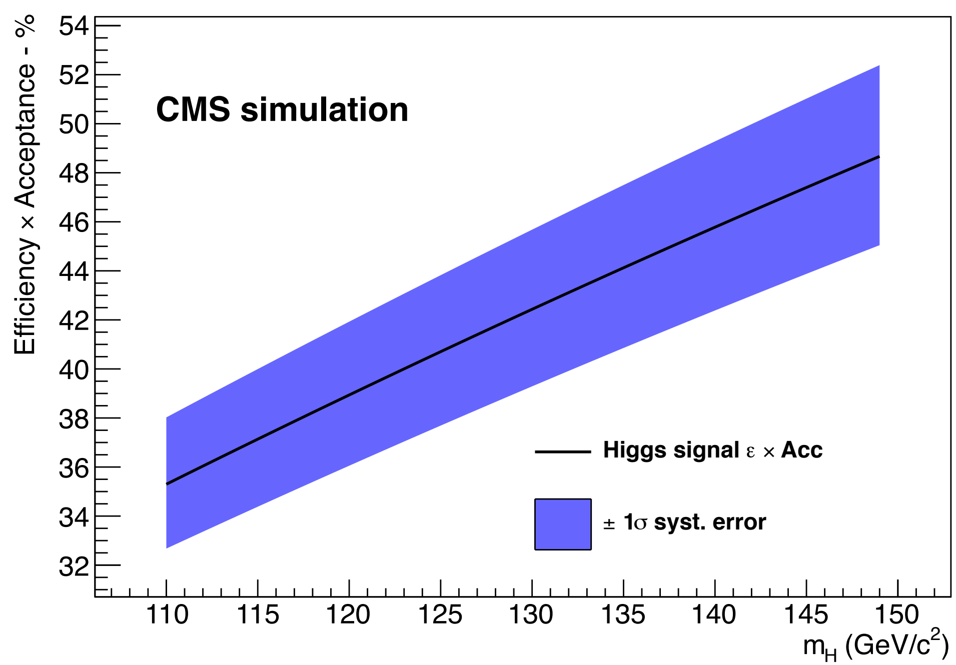
Source	Uncertainty
Integrated luminosity	4.5%
Trigger efficiency	
both photons in barrel	1.0%
one or more photon in endcap	1.0%
Vertex finding efficiency	0.5%
p_T^H >40 GeV/c in gluon fusion (class migration)	6%

- Theoretical uncertainties.

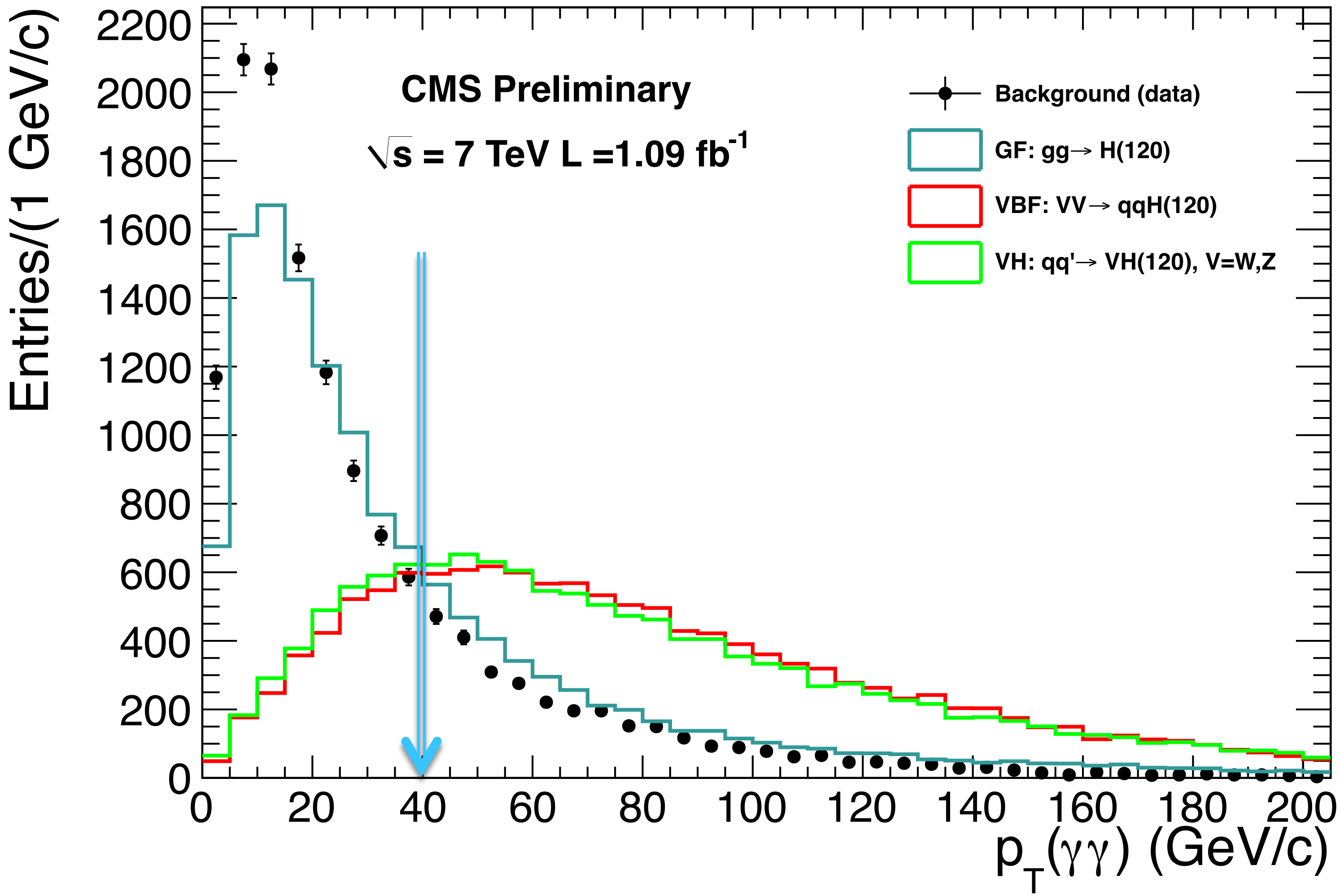
	Source	Uncertainty
Standard Model	gg cross section (scale)	12.5%
	gg cross section (PDF)	7.9%
fermiophobic model	VBF cross section (scale)	0.5%
	WH cross section (scale)	0.8%
	ZH cross section (scale)	1.6%
	VBF + VH cross section (PDF)	3.1%
	fermiophobic H $\rightarrow \gamma\gamma$ BR	5%

Signal model: A× ε

- 35% to 48% for m_H from 110 to 150 GeV.
- Mass dependence from:
  - Fixed 40, 30 p_T cuts.
  - p_T-dependence of photon ID cuts.



Event classes in $p_T(\gamma\gamma)$



Trigger efficiency

- Dedicated triggers, very high efficiency:

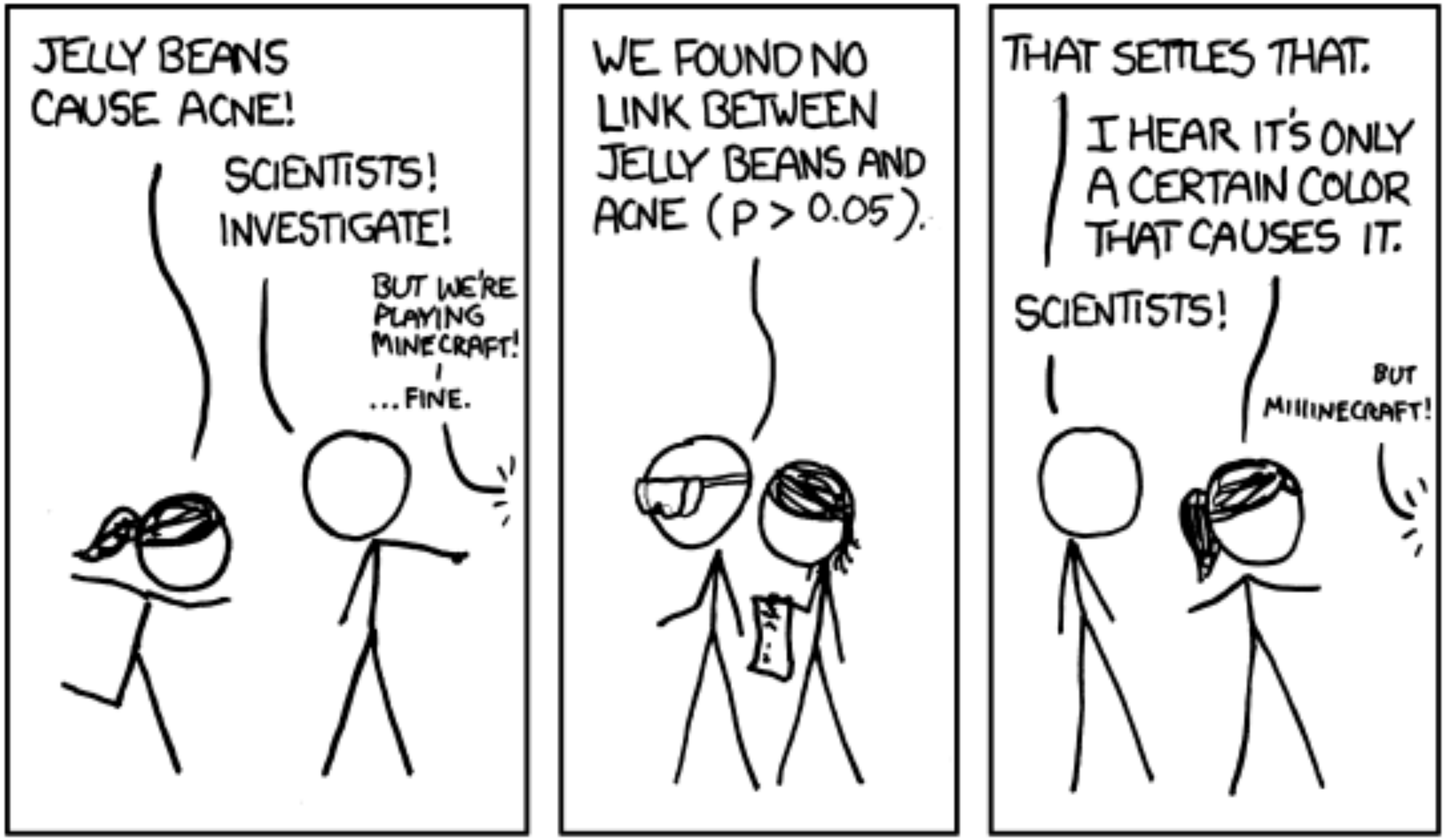
Both photons in barrel		One or more in endcap	
$min(R_9) > 0.94$	$min(R_9) < 0.94$	$min(R_9) > 0.94$	$min(R_9) < 0.94$
$100.00^{+0.00}_{-0.01}\%$	$99.53 \pm 0.04\%$	$100.00^{+0.00}_{-0.02}\%$	$98.86 \pm 0.07\%$

More on smearing

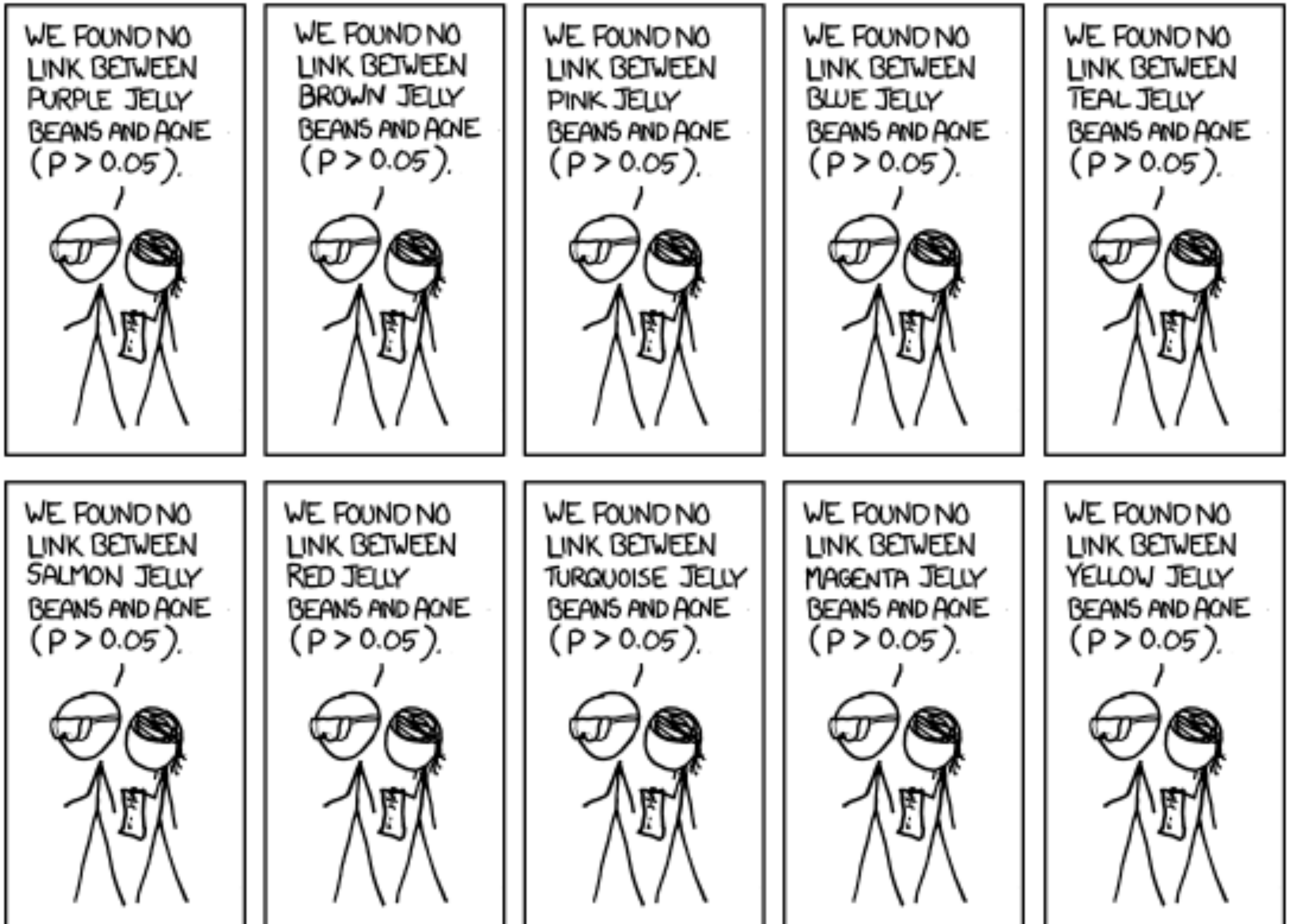
- Systematic uncertainties account for:
  - Extraction method (fit vs. MC smearing)
  - category (different set of non-diagonal categories)
  - p_T threshold
  - R_9 reweighting

About significance…

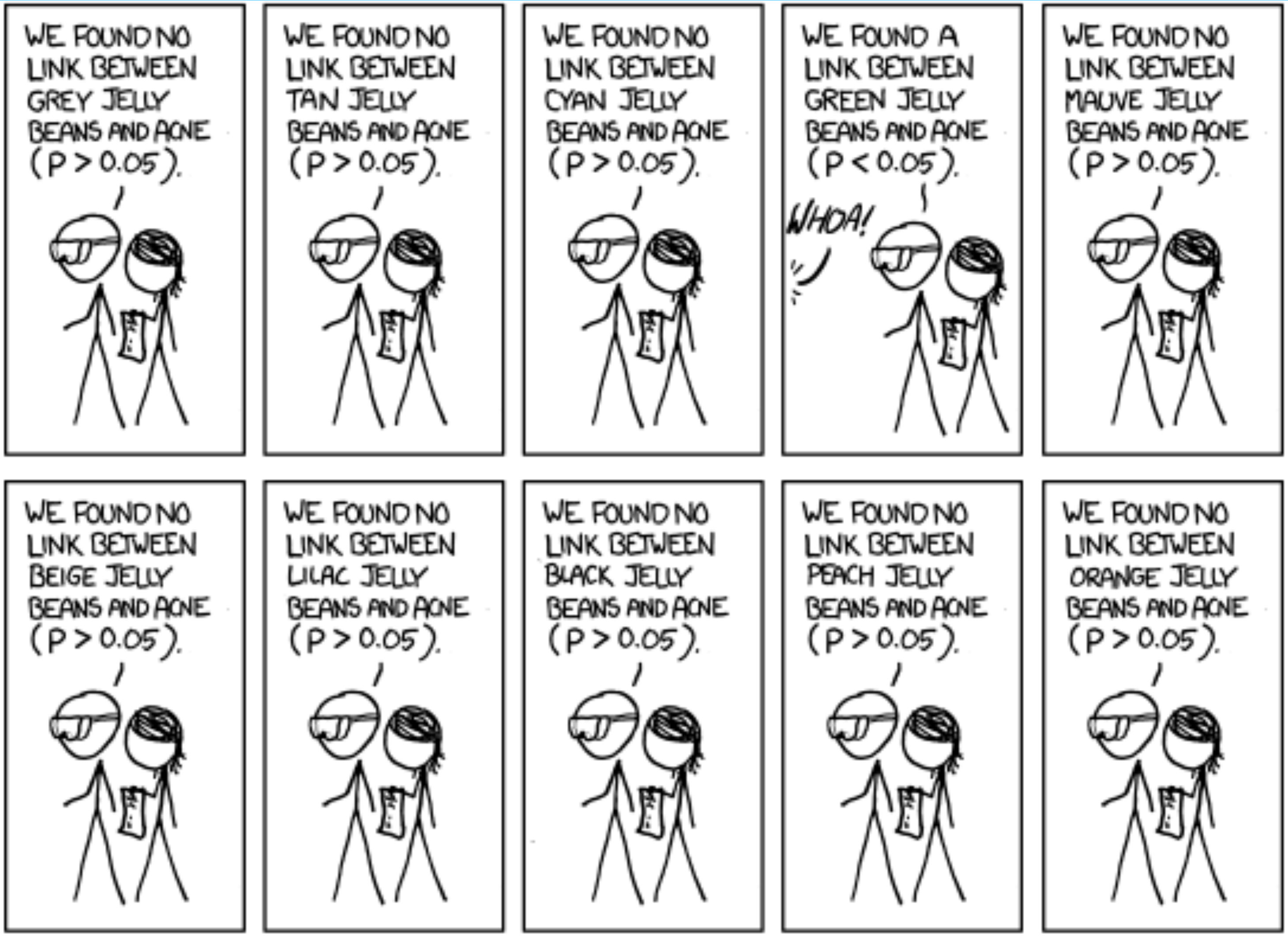
Significant – xkcd.com/882



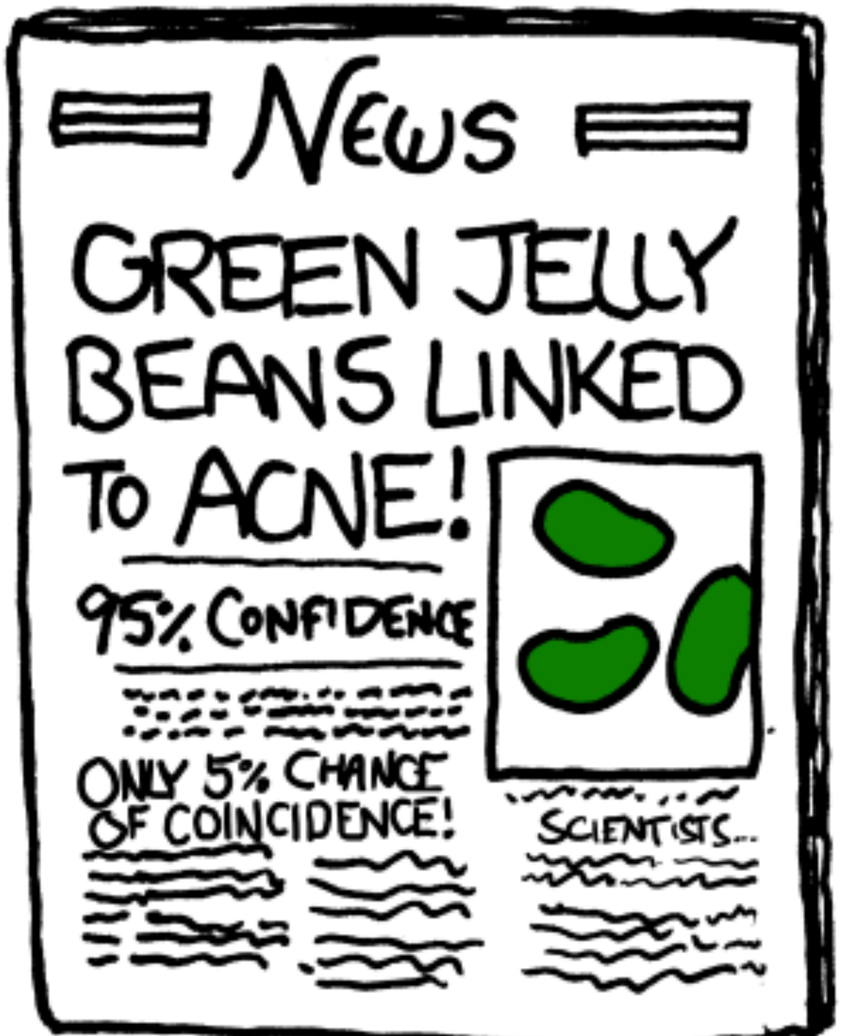
Significant – xkcd.com/882



Significant – xkcd.com/882



Significant – xkcd.com/882



nmSM

Next to minimal SM alternatives

Fermiophobic Higgs – FP

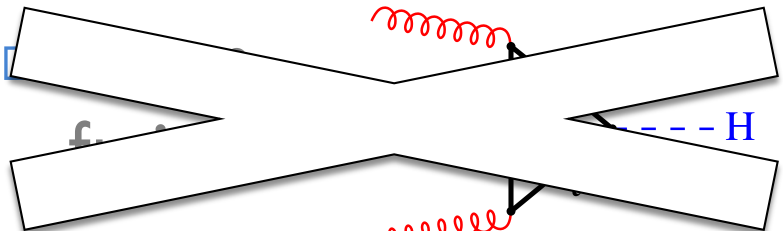
Why?

- Minimal extension of the SM Higgs sector.
- One of the 2HDM.
- Discovery would disfavor MSSM.

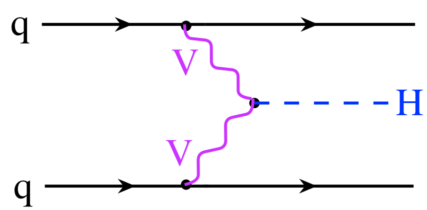
What?

- No gluon fusion:
  - Levels the luminosity play field for Tevatron.
  - Harder Higgs p_T, better S/B.
- BR($\gamma\gamma$) 20×SM for M_H=110 GeV.

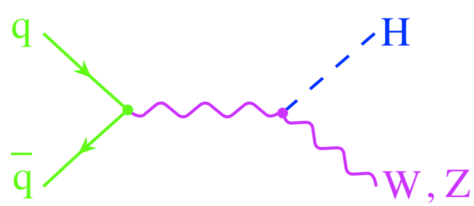
How Higgses are born – FP

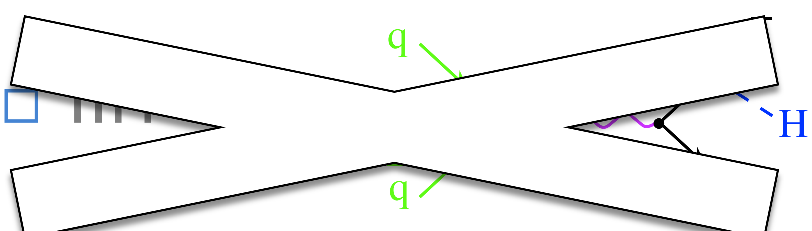


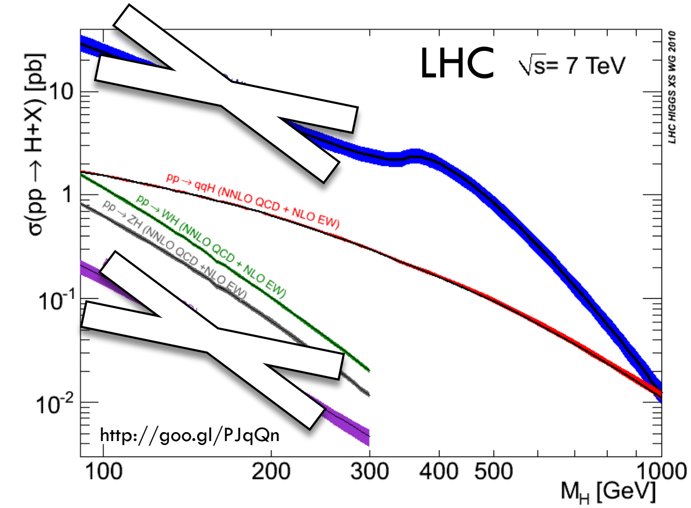
- **VBF**

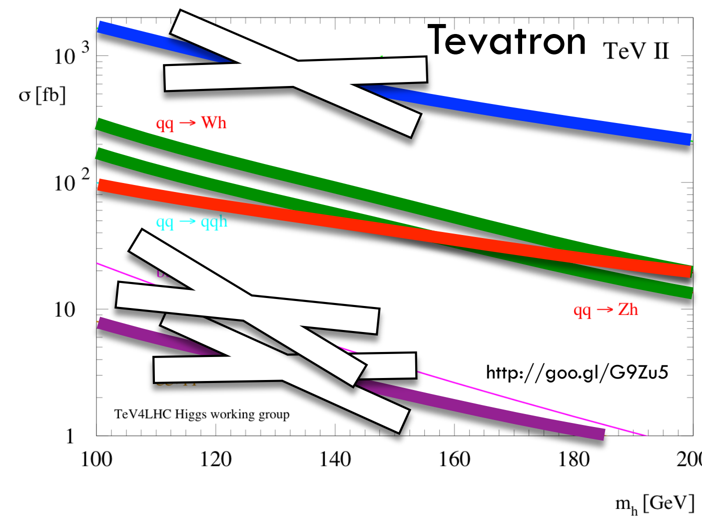


- **VH**





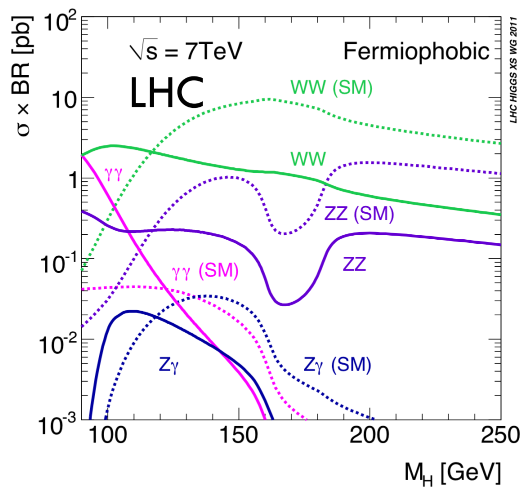


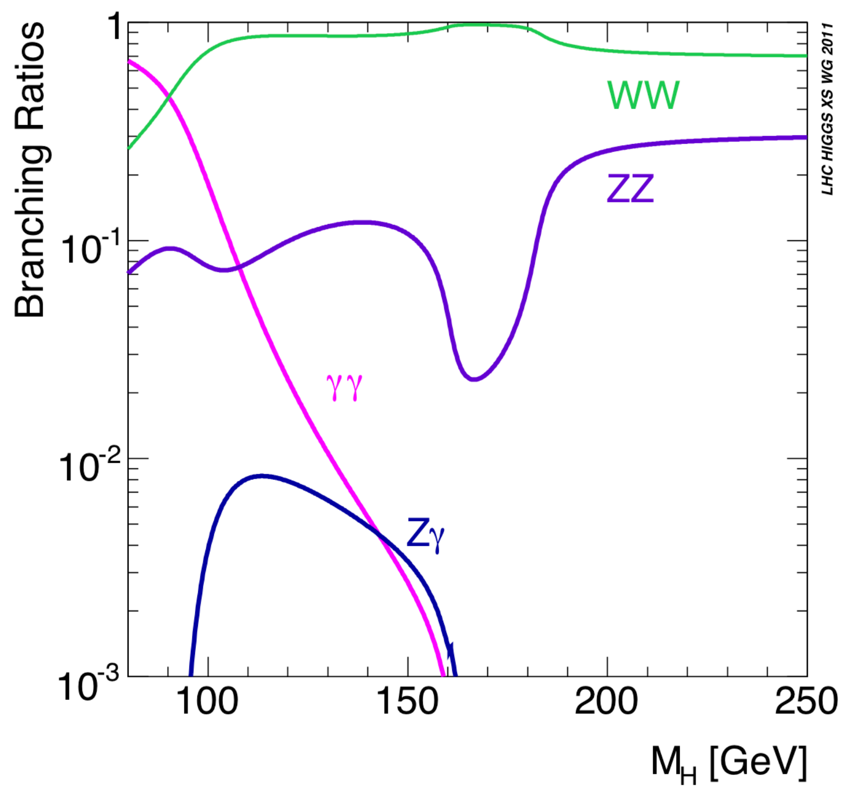


How Higgses decay – FP

http://goo.gl/tRZl7

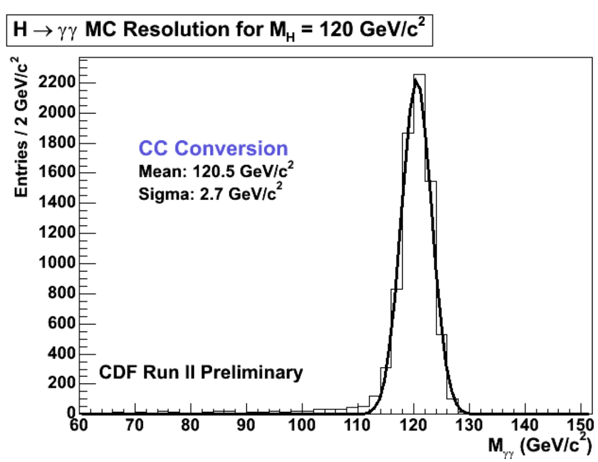
- Very large enhancement for $\gamma\gamma$: FP experimental workhorse.
- LHC using 5% BR uncertainty for unknown electroweak corrections.

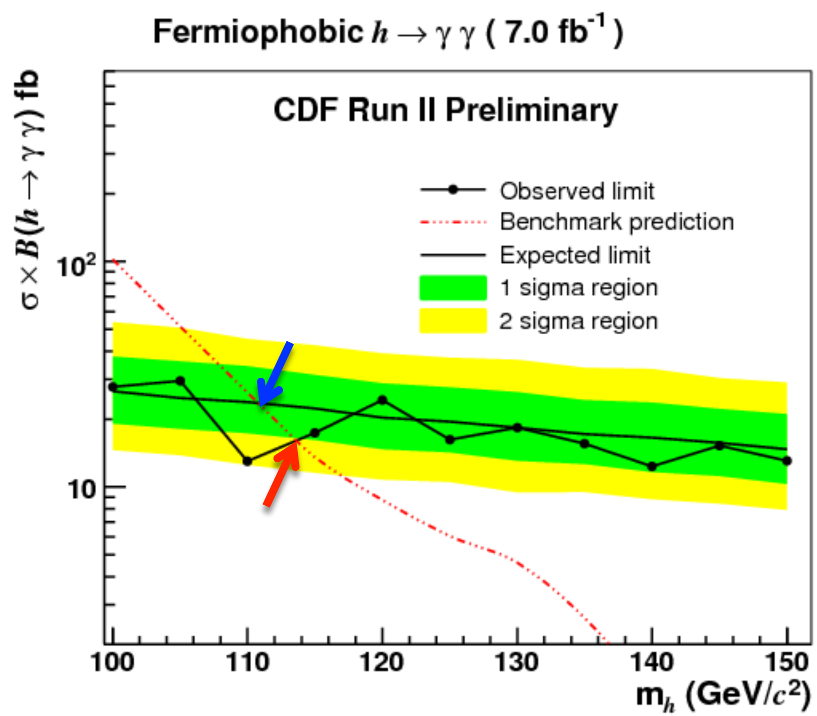




FP Higgs – CDF

- $M_{\gamma\gamma}$ distribution.
  - σ_M < 3.0 GeV (best below); 12 (?) sub-channels.
- Preliminary result from May 2011 using 7.0/fb.
  - FP exclusion: (100) – 114; expected (100) – 111.

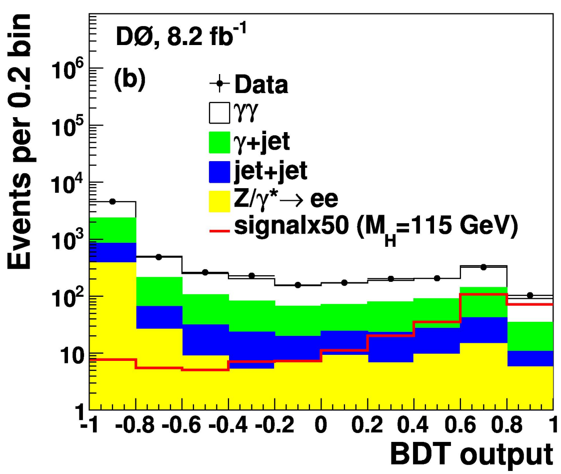


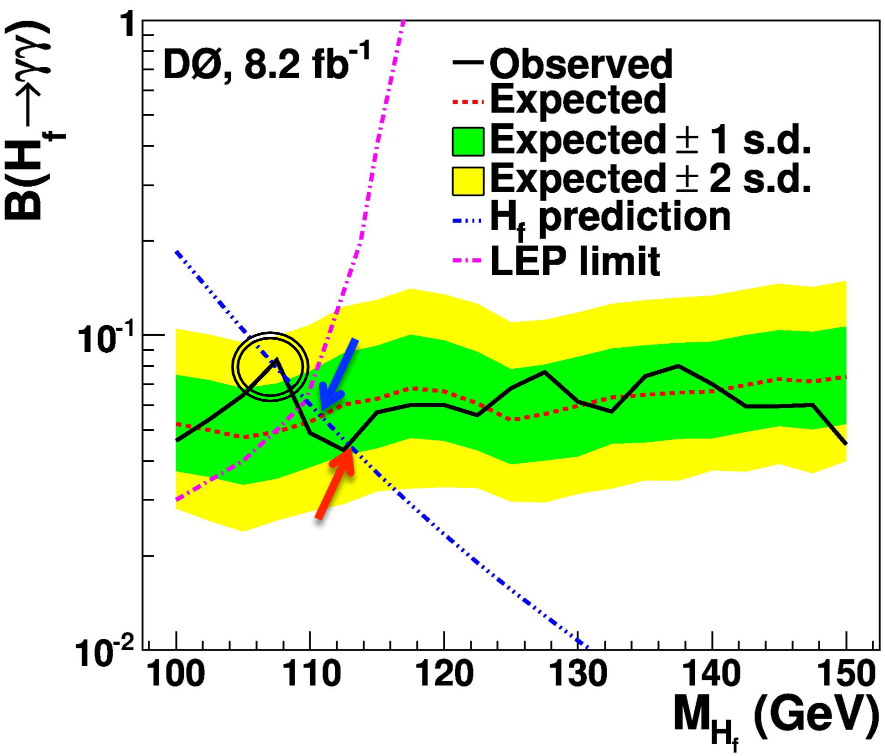


FP Higgs – DØ

[arxiv:1107.4587]

- BDT ($M_{\gamma\gamma}$, $\Delta\phi_{\gamma\gamma}$, $p_T^{\gamma\gamma}$, $p_T^{\gamma 1}$, $p_T^{\gamma 2}$)
- Result from July 2011 using 8.2/fb.
  - FP exclusion: (100) – 112.9; expected (100) – 110.5.

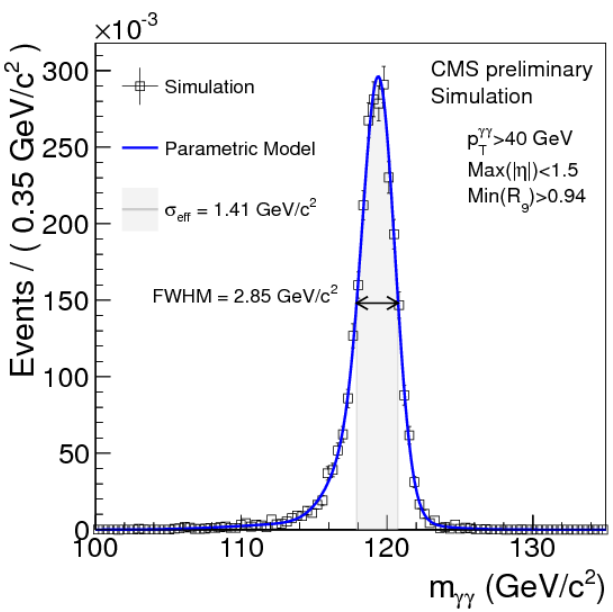


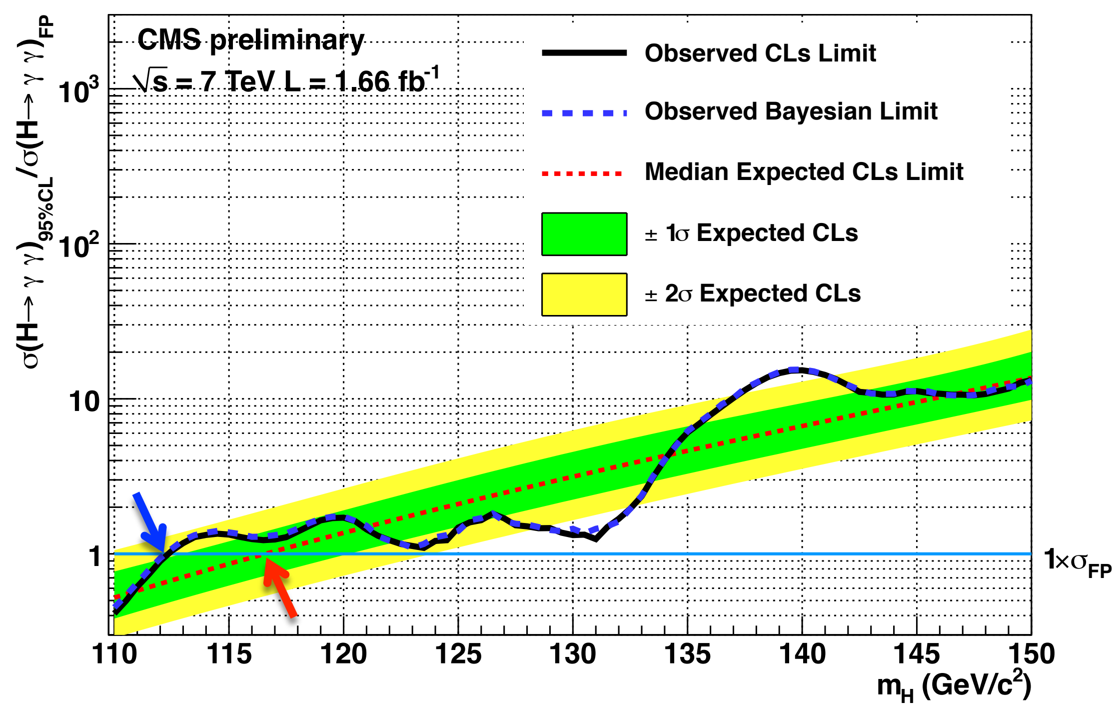


FP Higgs – CMS

http://goo.gl/mHpMN

- $M_{\gamma\gamma}$ distribution.
  - σ_M < 3.6 GeV (best below); 8 sub-channels.
- Update for LP2011 with 1.7/fb.
  - FP exclusion: (110) – 112; expected (110) – 116.5.





SM with 4 fermion families – SM4

Why?

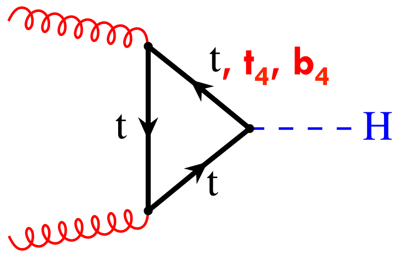
- If $M(\nu_4) > M_Z/2$ there could easily be U_4, D_4 quarks.
- SM-like couplings, simply new/more matter to couple to.
- Starting point: NNLO SM cross-section calculations.

- SM4 means different things at Tevatron and LHC
  - Different choices of $M_{\nu 4}$, M_{L4}, M_{U4}, M_{D4}.
  - Not up to speed with theoretical advances in NLO electroweak corrections.

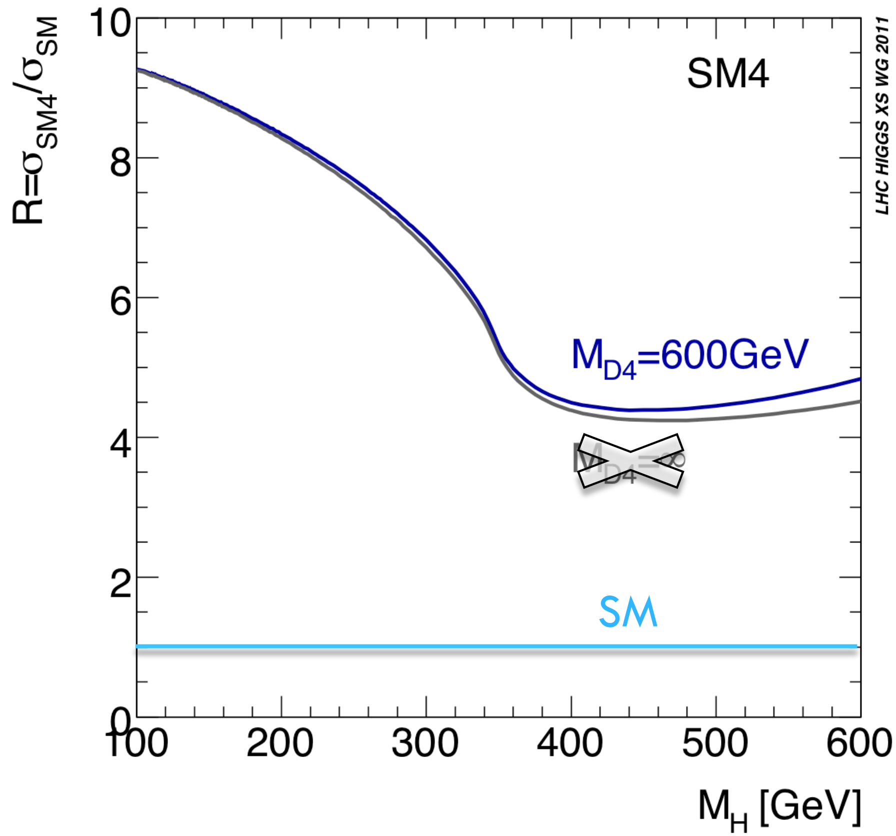
How Higgses are born – SM4

http://goo.gl/sbf53

- **Gluon fusion**



More fermions in the loop, much larger ggH cross-section. ⬇



- VBF
- VH
- ttH

Tevatron's SM4 – TEVNPHWG

[arXiv:1108.3331]

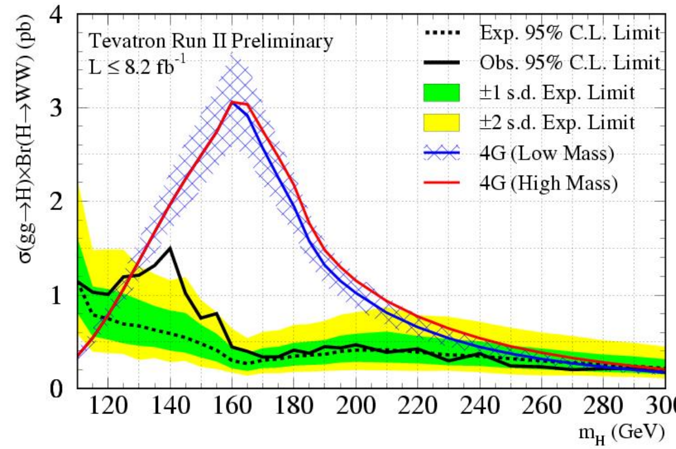
- "4G low mass"
  - $M_{\nu 4} = 80$ GeV.
  - $M_{L4} = 100$ GeV.
  - $M_{D4} = 400$ GeV.
  - $M_{U4} = M_{D4} + 50 \text{ GeV} + 10 \times \ln(M_H/115)$.

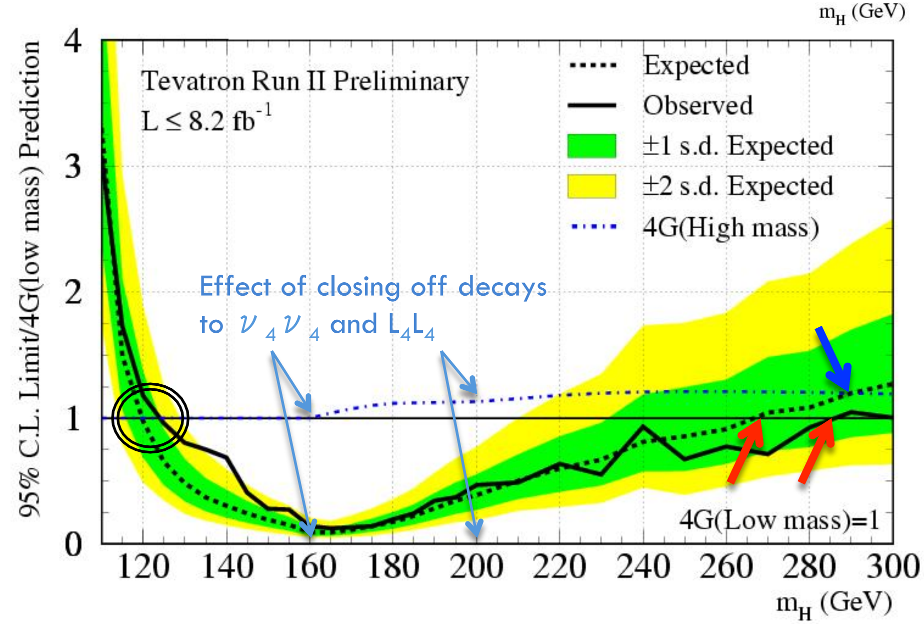
- "4G high mass"
  - Ditto, but $M_{\nu 4} = M_{L4} = 1$ TeV.

SM4 Higgs – CDF+DØ

http://goo.gl/DdGXs

- Combination of WW and ZZ searches from August 2011.
- Exclusion:
  - "4G low mass"
    - Expected: 120 – 267
    - Observed: 124 – 286
  - "4G high mass"
    - Expected: 120 – 290
    - Observed: 124 – (300)





LHC's SM4 – LHC Higgs XSWG

http://goo.gl/sbf53

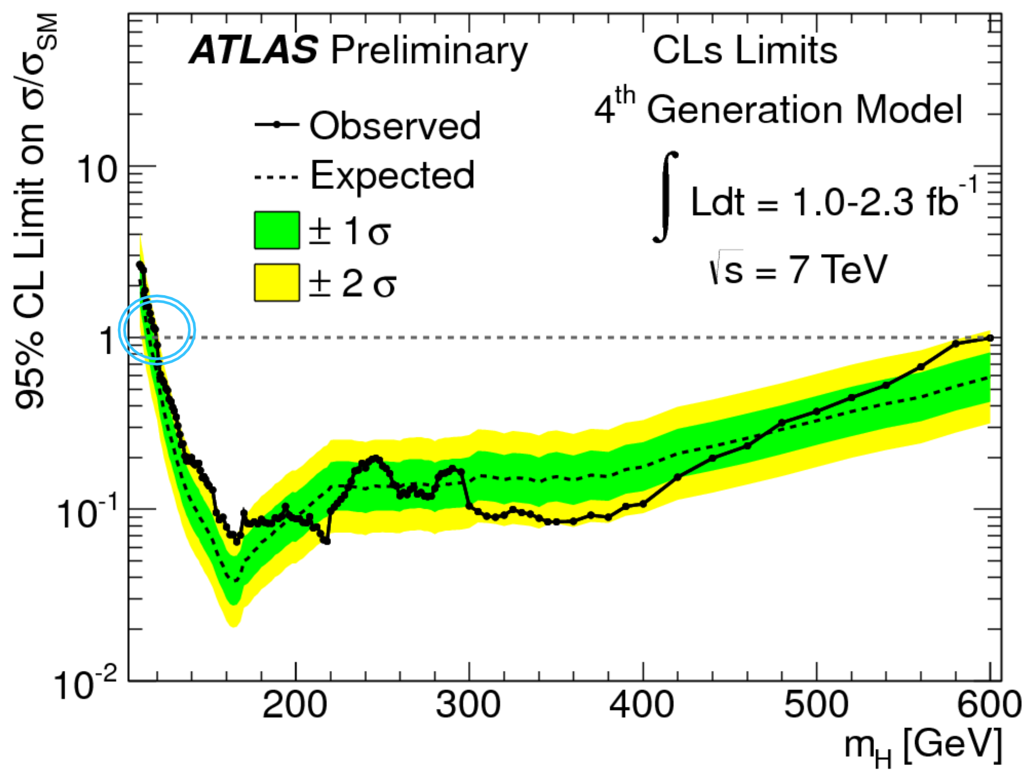
- "SM4"
  - $M_{\nu 4} = M_{L4} = M_{D4} = 600$ GeV.
  - $M_{U4} = M_{D4} + 50 \text{ GeV} + 10 \times \ln(M_H/115)$.
    - Heavier than Tevatron SM4 (ν_4 ~7.5×, L_4 ~6×, U_4/D_4 ~1.5×).
    - Trying to be conservative in limits given lower expected cross-sections.
  - Not yet up-to-speed with recent NLO EW radiative corrections.
    - σ(ggH): +12% for $M_H = 120$ GeV (-13% at 600 GeV) [arxiv:1108.2025].
    - Γ(WW/ZZ): -70% for $M_H < 200$ GeV (-25% at 600 GeV) [Prophecy4fv2].

- "SM4∞"
  - Ditto, but $M_{\nu 4} = M_{L4} = M_{D4} = 10$ TeV.
  - Idea: try and be even more conservative.
  - Duly killed by a theoretical reality: **Yukawa couplings diverge.**
  - **Not used.**

SM4 Higgs – ATLAS

http://goo.gl/XOd62

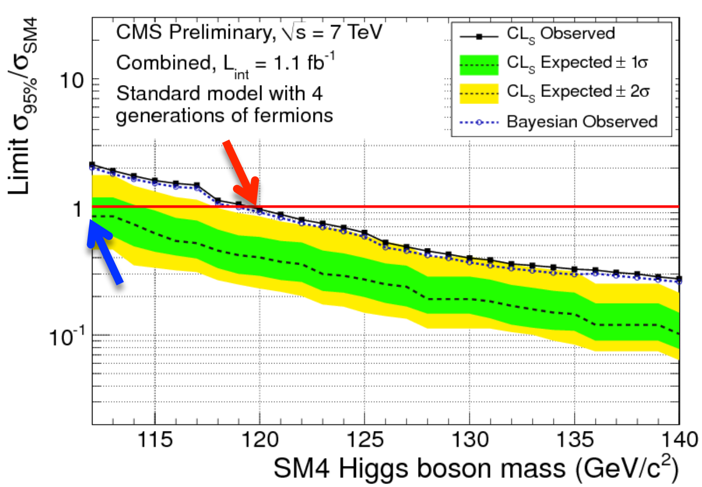
- All channels as in SM search updated for LP2011.
- "SM4" exclusion: 120 – (600); expected: 116 – (600).

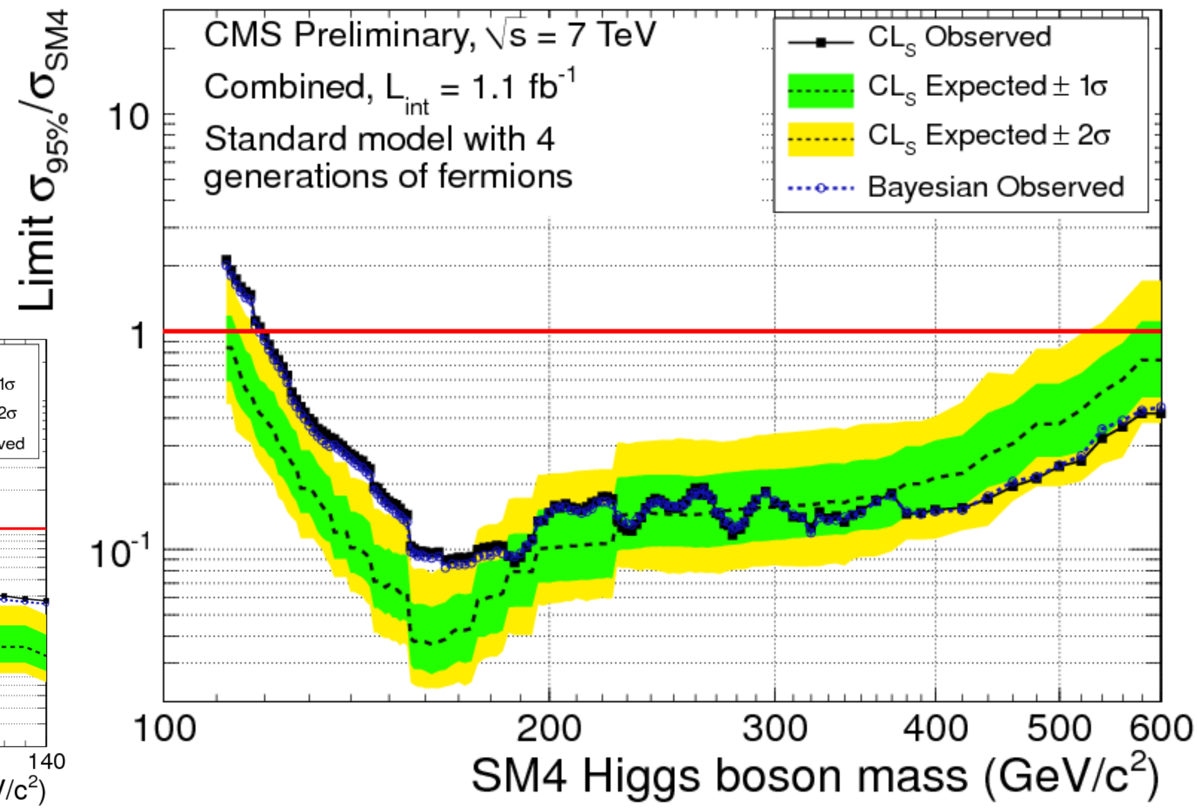


SM4 Higgs – CMS

http://goo.gl/Uifxv

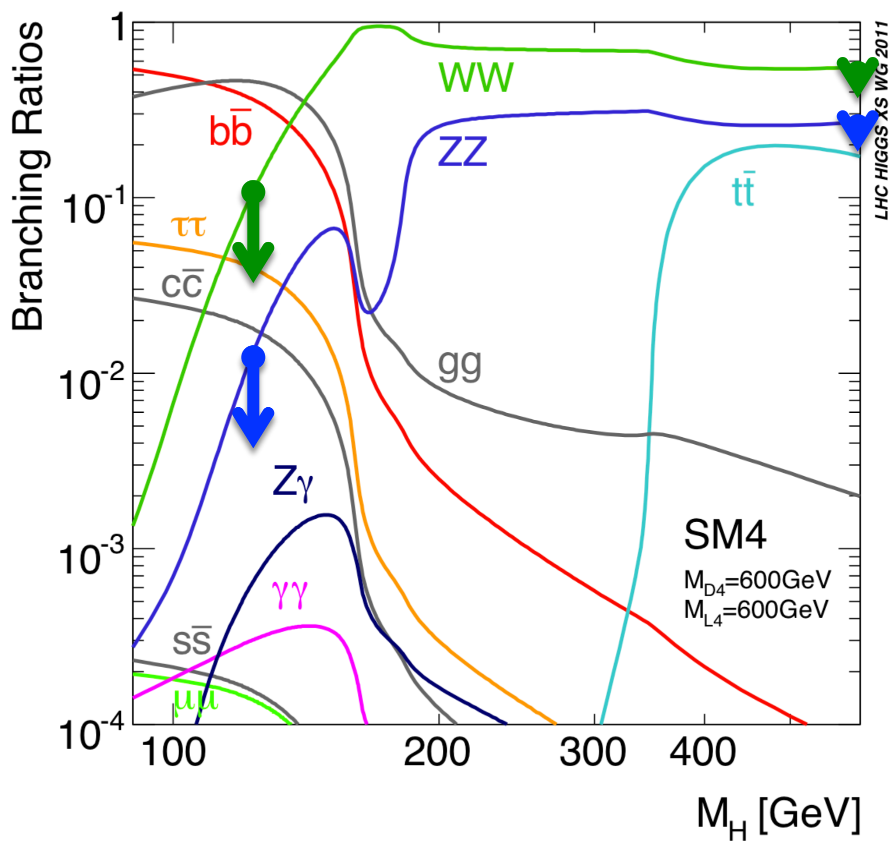
- All channels as in SM search updated for EPS2011.
- "SM4" exclusion: 120 – (600); expected: (112) – (600).





SM4 – go heavier, correct more.

- At M_H = 120 GeV:
  - SM4:
    - BR($\gamma\gamma$) ~1/8 of SM (W loops losing to fermion loops).
    - BR(WW) ~1/2 of SM.
  - **SM4+NLO EW:**
    - **BR($\gamma\gamma$, $\tau\tau$, bb) ~ same.**
    - **BR(WW, ZZ) ~1/3 of current SM4.**
  - Observed exclusion very steep, effect <10 GeV.
- At M_H = 600 GeV:
  - **SM4+NLO EW:**
    - **BR(WW,ZZ) ~3/4 of current SM4.**
  - Possibly ~30 GeV effect on ATLAS exclusion.



CMS ECAL performance drivers

Requirements for the EM calorimeters

	CMS	ATLAS
•Large acceptance •Extremely good energy and position resolution for high energy EM showers up to |η| <2.5	• Excellent energy resolution	•Good energy resolution
•Fast •compact •granular	•Fast •compact • High granularity	•Fast • High granularity • Longitudinally segmented
•radiation tolerant •Large dynamic range (from 200 MeV to ~2 TeV) •linear •Particle identification (e/jet and γ/π^0 separation)	• Radiation resistance •E range MIP → TeV •Homogeneous calorimeter made of 75000 $PbW0_4$ scintillating crystals + PS FW	• Radiation resistance • E range MIP → TeV •Sampling LAr-Pb, 3 Longitudinal layers + PS

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Energy resolution: stocastic term *a*

- photostatistics contribution, including
  - Light Yield
  - light collection efficiency
  - geometrical efficiency of the photodetector
  - photocatode quantum efficiency

  N_{pe}/GeV = 4000 for 0.5 cm^2 APD → 1.6%

- electron current multiplication in APD, contributing a square root of excess noise factor, F = 2

  1.6×1.4 = 2.25%

- Lateral containment (5×5 matrix) → 1.5%

Total stochastic term **a = 2.7 %**

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Energy resolution: noise term *b*

40 ns shaping time, summed over 5x5 channels

- Serial noise (p.d. capacitance) ∝ $1/\sqrt{t}$
  - 150 MeV
- Parallel noise (dark current) ∝ $\sqrt{t}$, mostly radiation induced
  - 100 MeV after one year at high luminosity
- Physics pile-up (simulated, with big uncertainties)
  - high luminosity 100 MeV

Total contribution

- **high luminosity 210 MeV**

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Energy resolution: constant term c

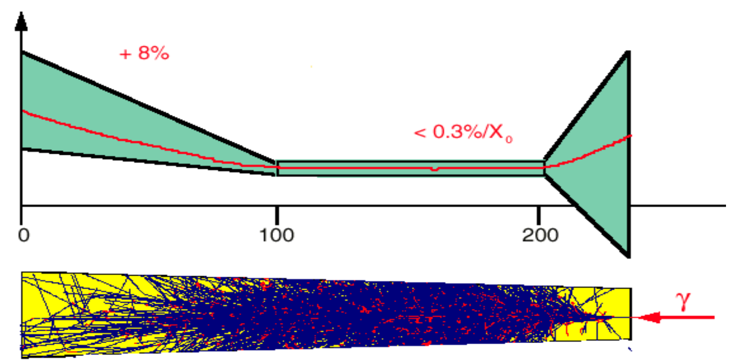
- leakage (front, rear, blind material)

  CMS full shower simulation < 0.2 %

- system instabilities designed to be at the permill level
  - temperature stabilization < 0.1 °C (dLY/dT = -1.9 %/°C)
  - APD bias stable at 20 mV (dG/dV = 3%/V)
- light collection uniformity,

  Specifications to stay < 0.3% ⇒

  reached through
  single face depolishing



- **Key issue to have c ~ 0.5 %**

  ⇒ intercalibration by monitoring and physics signals at 0.5 %

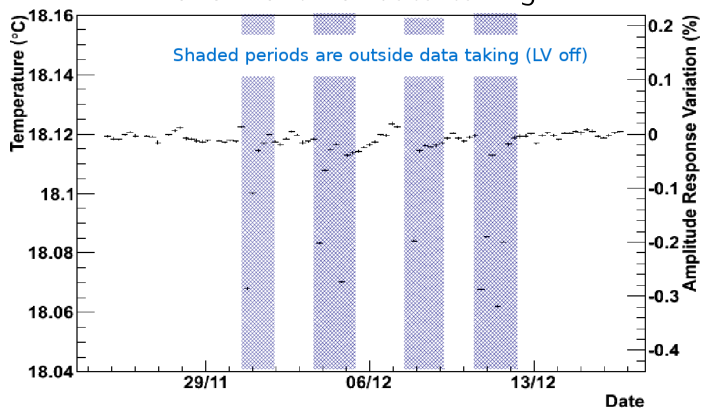
  including the radiation damage effect

Temperature stability

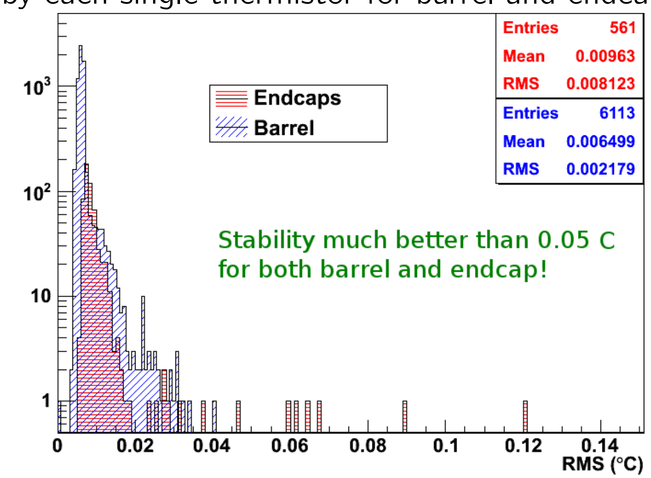
- nominal temperature of 18 °C
- water flow to stabilize the detector temperature
- thermistors with nominal sensitivity of 0.012 °C: on the back of each 5×2 (5×5) matrix of crystals in the barrel (endcap)

- the APD temperature dependence is absorbed into the transparency corrections
- local in-homogeneities are absorbed into the definition of the inter-calibration constants; only the time stability is relevant for the energy resolution.

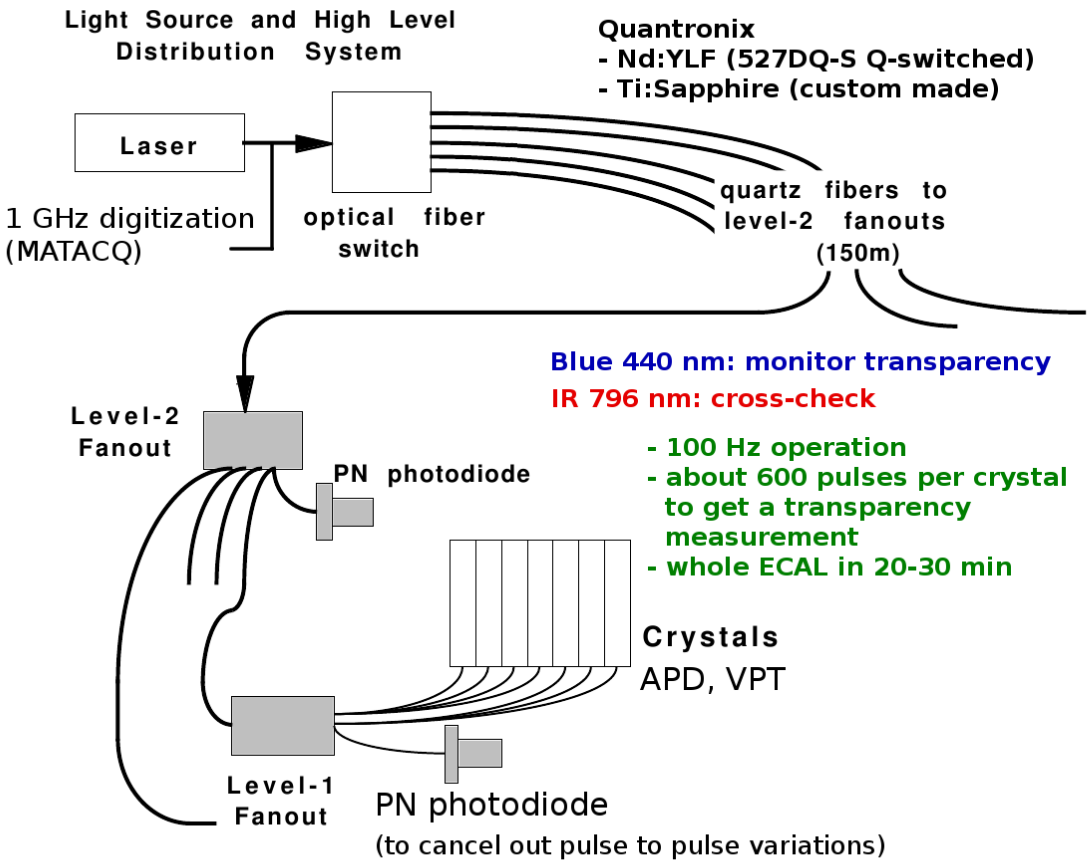
average temperature of the ECAL barrel over one month of data taking



Corresponding tempeature stability measured by each single thermistor for barrel and endcap

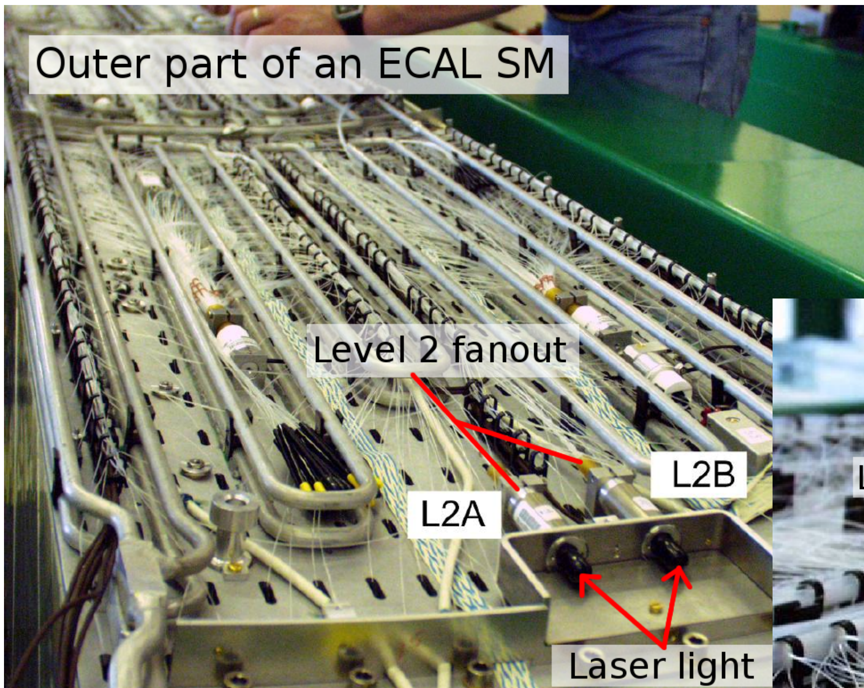


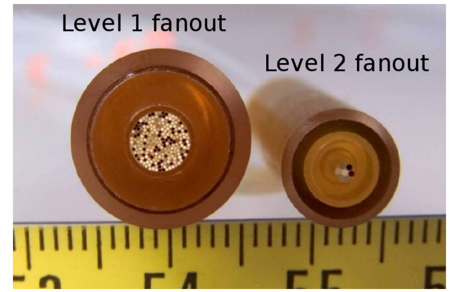
Laser monitoring system

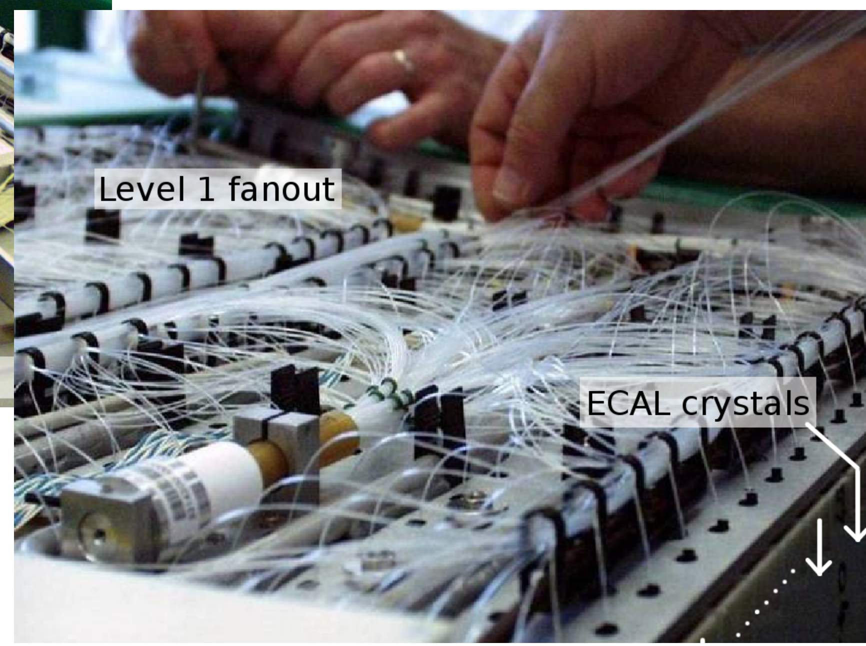


- Spectral contamination: $< 10^{-3}$
- Pulse energy: 1 mJ at the source, dynamic range up to 1.3 TeV equivalent
- Pulse width: < 40 ns FWHM to match the ECAL readout
- Pulse jitter: < 4 ns (24 hours), < 2 ns (30 min).
- Pulse to pulse instability: < 10%

Laser monitoring system

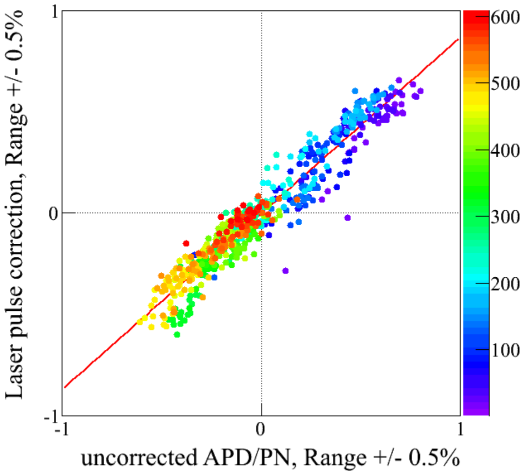




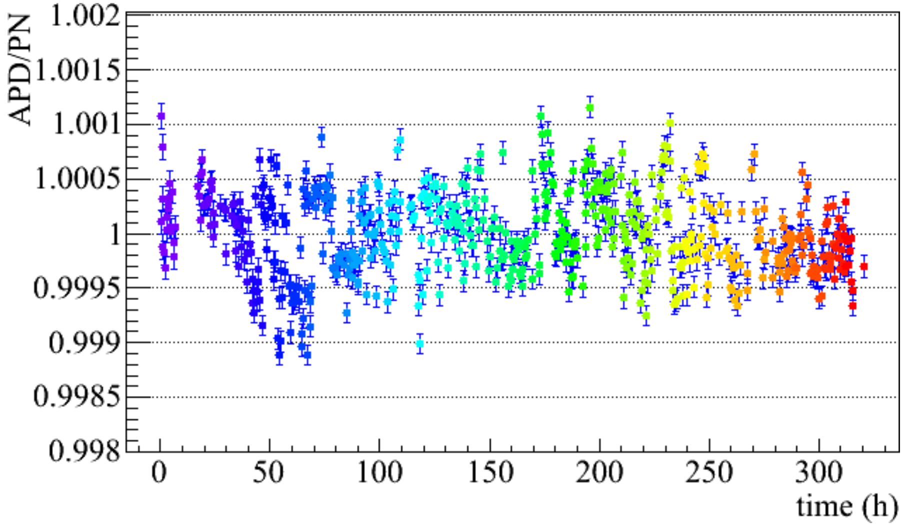


Crystal transparency measurement

- PN linearity correction
- correction for the different shaping time of APD (VPT) and PN using the Single Pulse Response of each individual channel of APD (VPT) and PN convoluted with the laser shape from the 1 GHz digitization



Stability for a typical channel over about 350 h

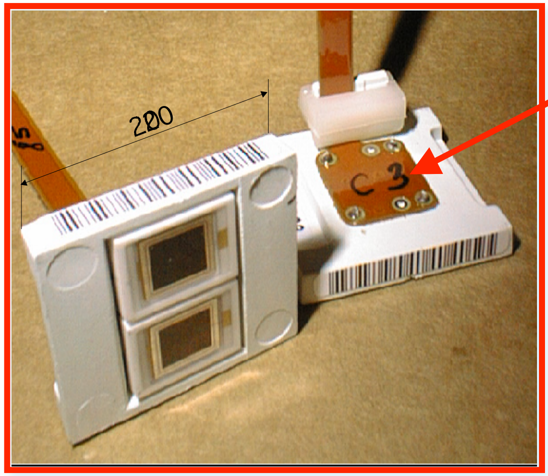


- stability defined as the r.m.s. of the considered quantity

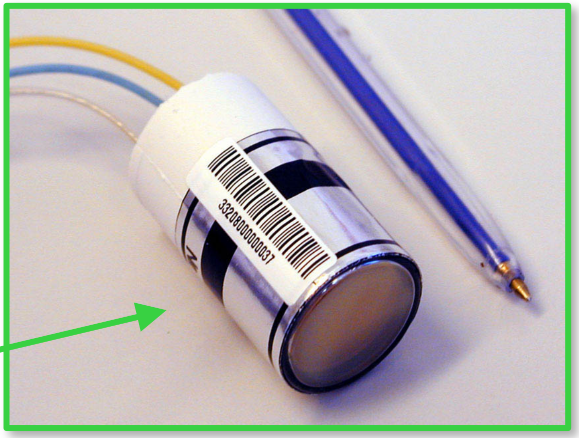
- standard loose quality selections applied
- excellent stability: $< 4 \cdot 10^{-4}$

Photodetectors

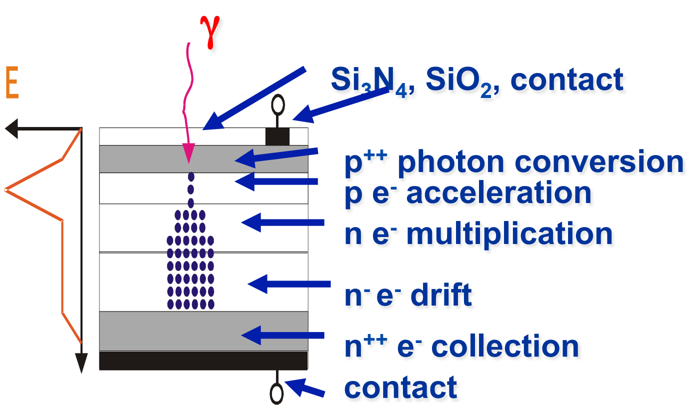
- $PbWO_4$ crystals have fairly low light yield – need photodetectors with gain
- Need to work in a 4T field and an intense radiation environment



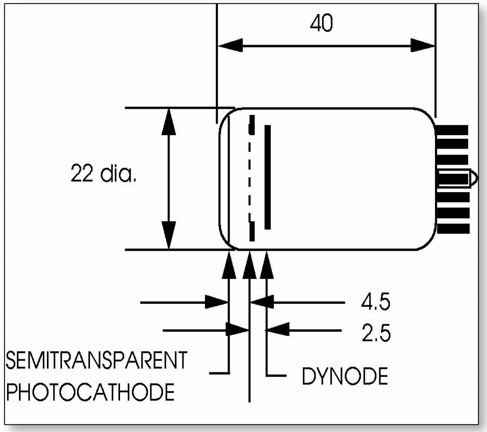
Barrel: Avalanche PhotoDiodes (APDs)



Endcaps: Vacuum PhotoTriodes (VPTs)



APDs (Hamamatsu), VPTs (RIE, Russia)



About the CMS ECAL calibration

Energy Measurement of EM Objects

$$E_{e,\gamma} = F_{e,\gamma}(\eta)\; G(GeV/ADC) \sum_i S_i(T,t) \times c_i \times A_i$$

(5) $F_{e,\gamma}(\eta)$ — (4) $G(GeV/ADC)$ — (3) $S_i(T,t)$ — (2) c_i — (1) A_i

1) A_i : Measured Amplitude in each channel (ADC counts)
2) C_i: Inter-Calibration Constants
3) $S_i(T,t)$: Corrections for Transparency Loss (T= crystal transparency, t = time)
4) G: ECAL Energy Scale: ADC to GeV Conversion Factor
5) F(η): Object Dependent Correction Factor → Factorises Geometry from Material Effects

Design Energy Resolution

$$\frac{\sigma(\mathrm{E})}{\mathrm{E}} = \frac{2.8\%}{\sqrt{\mathrm{E(\,GeV)}}} \oplus \frac{12\%}{\mathrm{E(\,GeV)}} \oplus 0.3\%$$

stochastic — noise — constant

$$E_{e,\gamma} = F_{e,\gamma}(\eta)\, G(GeV/ADC) \sum_i S_i(T,t) \times c_i \times A_i$$

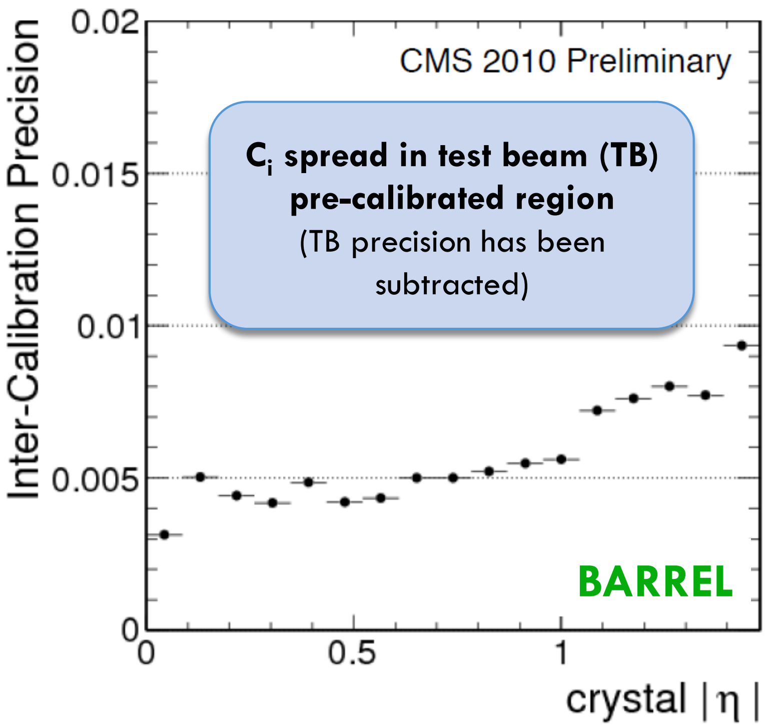
Inter-Calibration Methods

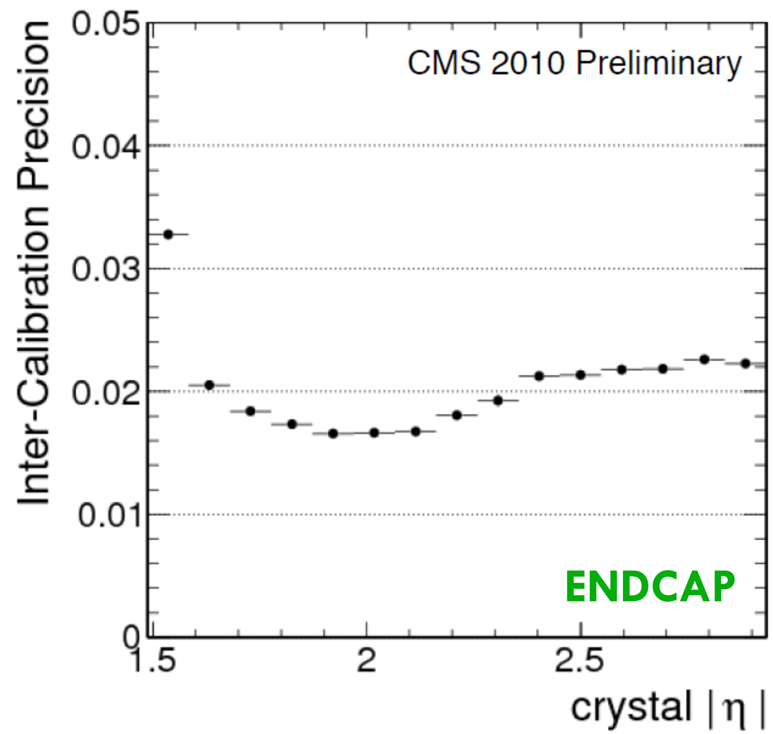
Calibration Strategies:

- **ϕ-symmetry** calibration: exploit the energy flow invariance around the beam axis
  - Fast method. Calibration precision limited to ~1.4%
- **π^0 calibration**: photon pairs selected as $\pi^0 \rightarrow \gamma\gamma$ candidates
  - High statistics available (dedicated data stream in data acquisition flow)
  - Allows both crystal inter-calibration and absolute scale calibration
- **Isolated electrons** from $W \rightarrow e\nu$ and $Z \rightarrow e^+e^-$: compare the energy measured in ECAL to the track momentum
  - Several fb^{-1} needed to perform single crystal inter-calibration: integrated luminosity accumulated is not yet sufficient
- **Di-electron resonances** such as $J/\psi \rightarrow e^+e^-$ and $Z \rightarrow e^+e^-$: standard candles to define the ECAL energy scale.
  - Larger data sample is needed. So far Z used to compute only global scale

Inter-Calibration Results

- Inter-Calibration precision combining all the methods
- Barrel: $|\eta|\sim 1$ rapid increase of material budget in front of ECAL
- Endcap: ($|\eta| < 1.6$) U ($|\eta| > 2.5$) No Preshower Coverage

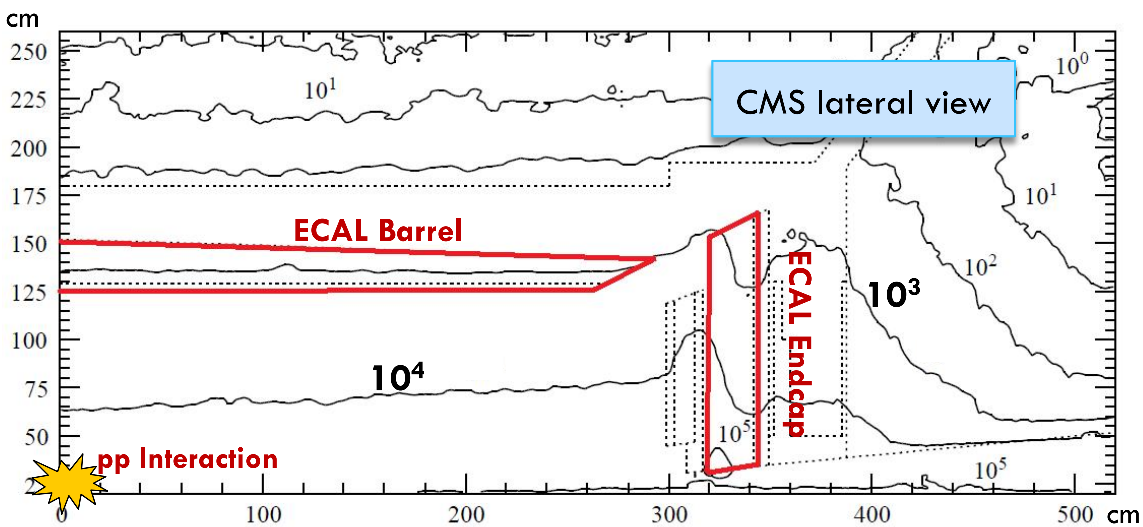




$$E_{e,\gamma} = F_{e,\gamma}(\eta)\, G(GeV/ADC) \sum_i S_i(T,t) \times c_i \times A_i$$

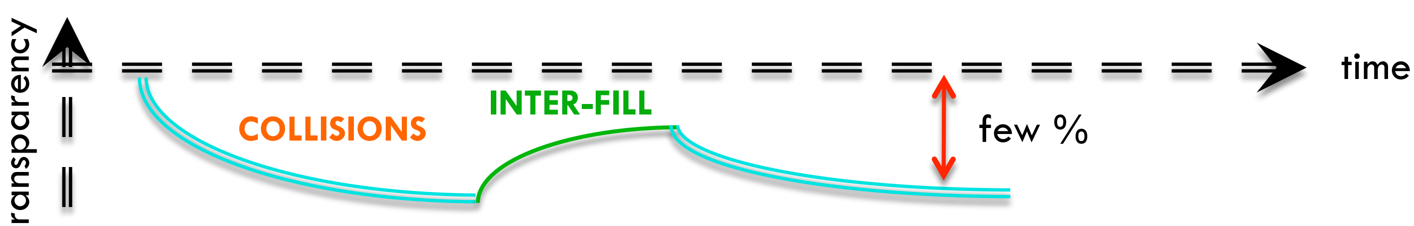
Crystal Radiation Damage

- ECAL crystals have to withstand huge radiation levels

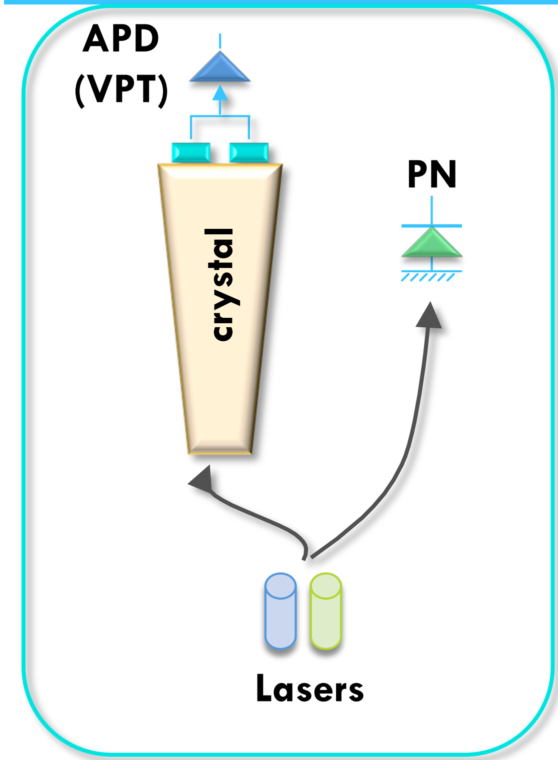


Radiation dose (in Gy) absorbed by ECAL. Corresponding integrated luminosity: 500 fb^{-1}

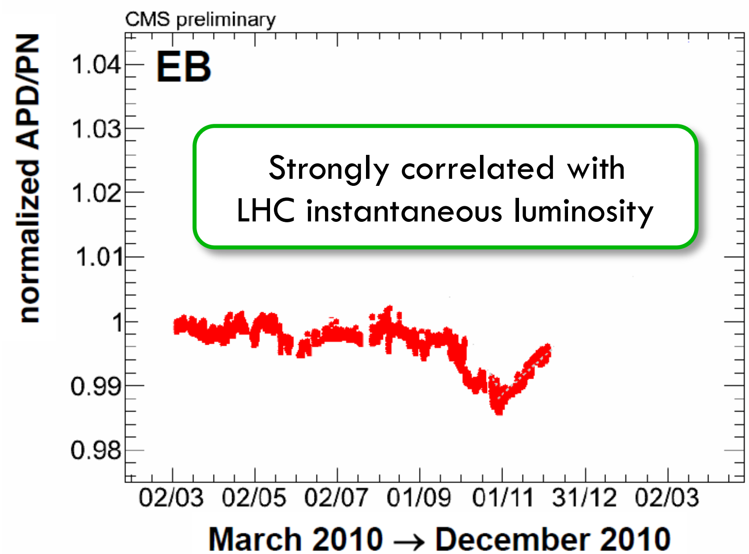
- Radiation ⇨ Wavelength-dependent loss of light transmission (w/o changes in scintillation)
- Crystal Transparency ***drops*** within a run by a few percent and ***recovers*** in the inter-fill periods



Correction for Crystal Transparency Loss

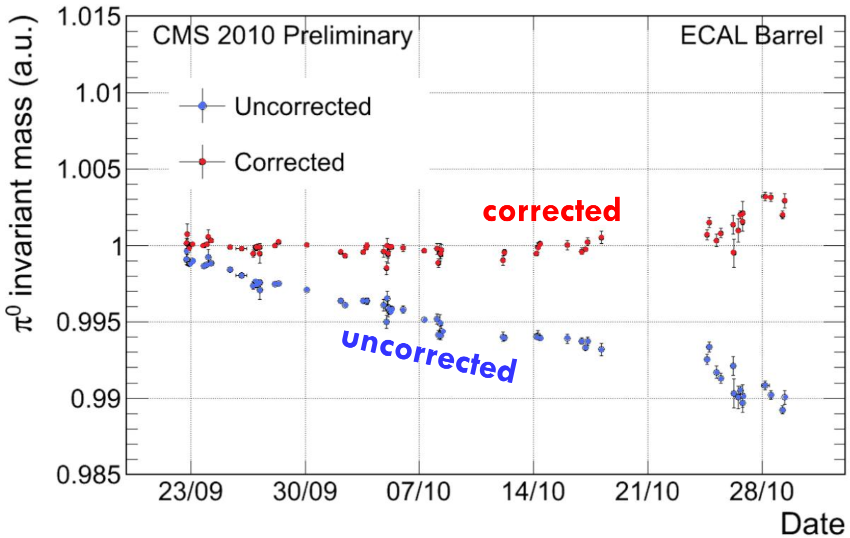


- Inject fixed amount of light (laser) to monitor transparency loss
- **Blue Laser:** check transparency at scintillation wavelength
- **I-Red Laser:** check response stability (blind to color centers)
- Transparency Loss of **~1% in EB** (**~3% in EE**) during 2010

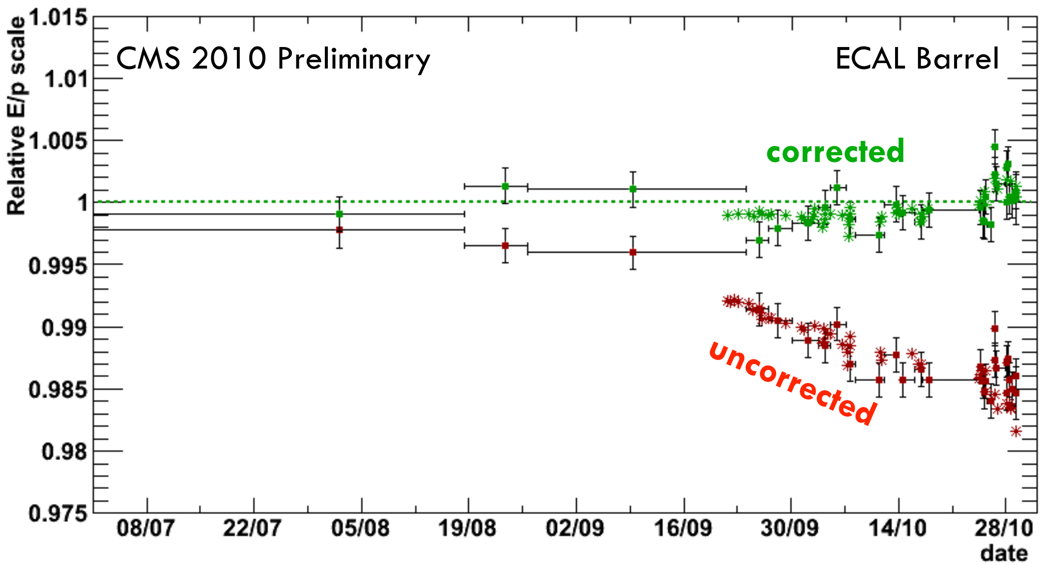


APD: Avalanche Photodiode (EB)
VPT: Vacuum Phototriode (EE)
PN: Reference diode

Correction for Crystal Transparency Loss



- Normalized π^0 **invariant mass** history from di-photon events
- Data before/after laser energy corrections
- In Barrel 1% drop if not accounting for crystal transparency loss



- **Energy/Momentum Ratio** for high energy electrons
- Electrons selected from $W \rightarrow e\nu$ decays
- π^0 and e histories are not directly comparable (different rapidity reconstruction efficiency)

$$E_{e,\gamma} = F_{e,\gamma}(\eta)\, G(GeV/ADC) \sum_i S_i(T,t) \times c_i \times A_i$$

Energy Scale Using Z → e^+e^- Decay

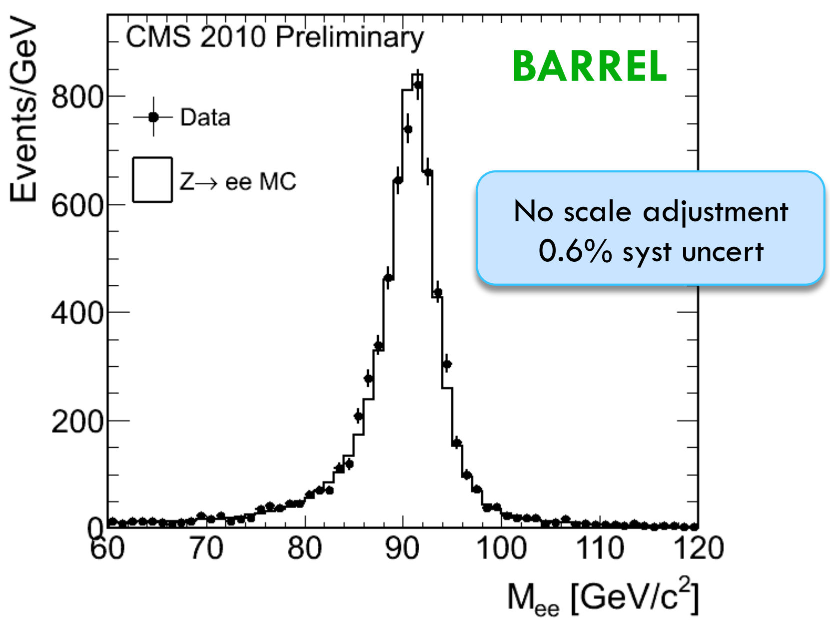
Energy scale measured at **test beam** for EB and EE separately

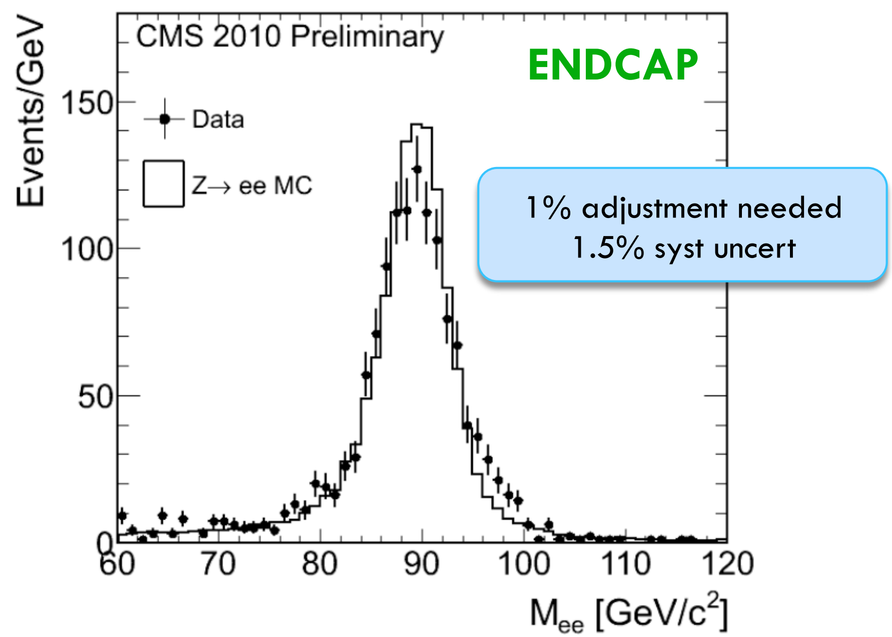
- Goal: equalizing energy sum of 5x5 crystal matrix to the electron beam energy

In-situ determination: reconstructing di-electron invariant mass of Z

- Requiring electrons emitting very low Bremsstrahlung

Method: matching reconstructed invariant mass peak position in data with MonteCarlo position (G-independent)

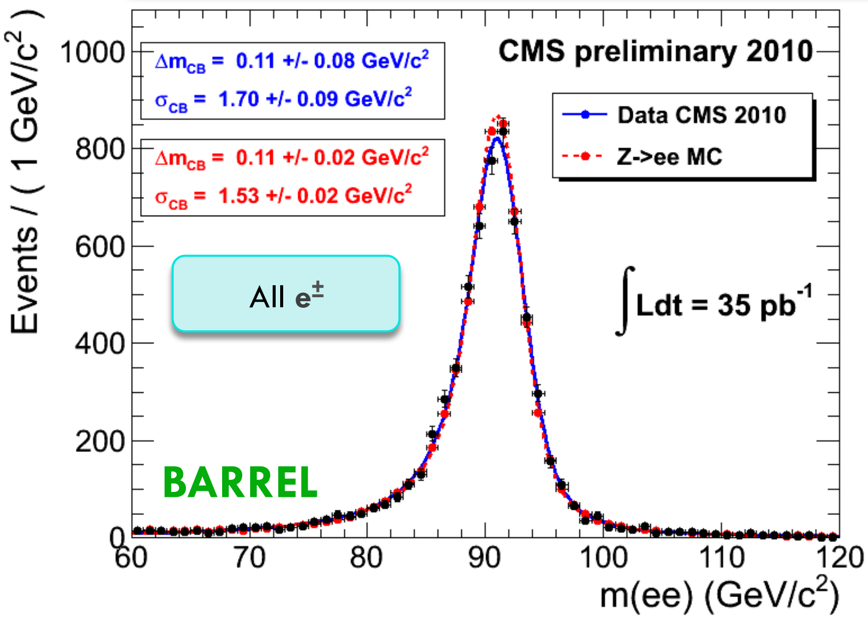


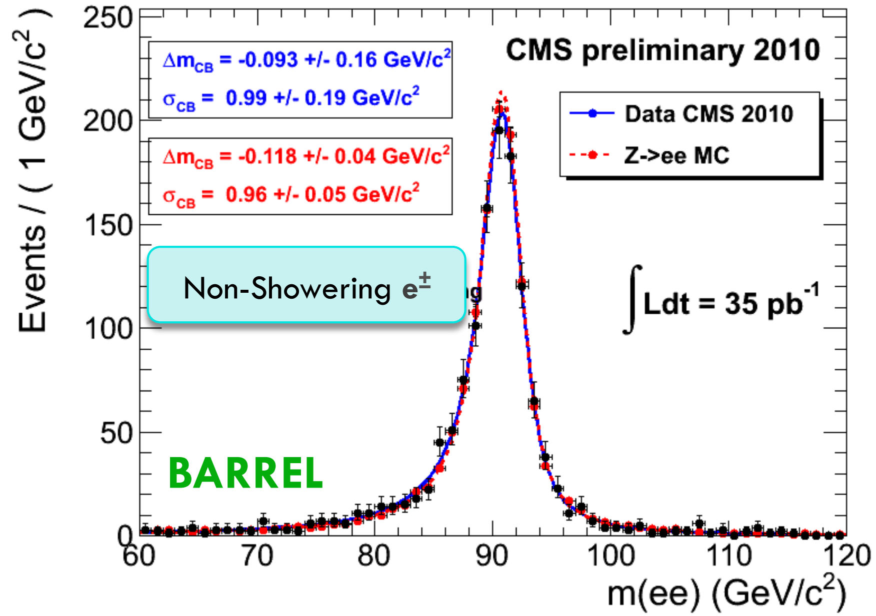


Energy Resolution using Z width

- Fit to the Z shape using convolution of Breit-Wigner and Crystal-Ball (CB)
- Δm_{CB}: difference between CB mean and true Z mass. σ_{CB}: width of CB function
- Energy scale of data distribution ***scaled*** to match the mean of the MC distribution

Resolution measured on data matches MC expectation (σ_{CB}~1GeV for non-showering $e^{\pm}$)





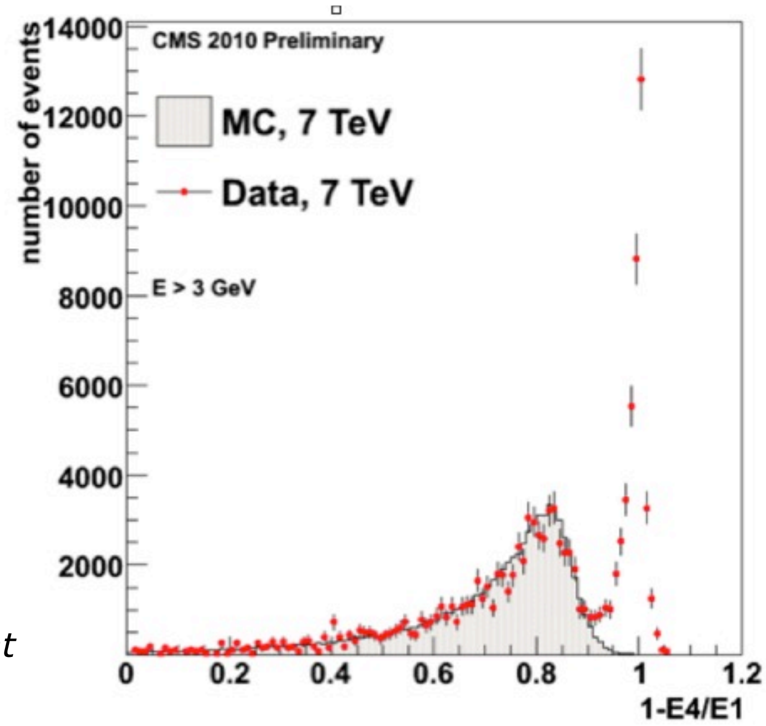
CMS ECAL anomalous signals

Anomalous signals

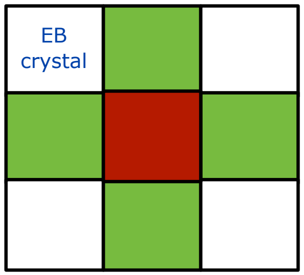
In a small fraction of collision data we observe anomalous signals in ECAL:

- distinct pulse shape
- different timing
- single crystal energy deposit
- uniformly distributed in EB
- not seen in EE (VPTs readout)

Origin: highly ionizing particles in the APDs

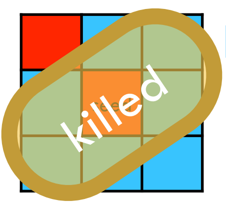


pulse shape exhibits faster rising time and is *inconsistent* with the signal shape from scintillation

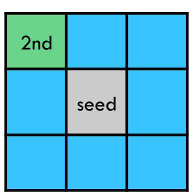


Easily identified and removed by a quality selection (e.g. an energy ratio **E4**/**E1**). Timing and pulse shape discriminants could also be deployed to tag these signals.

Double spikes after swiss-cross cleaning

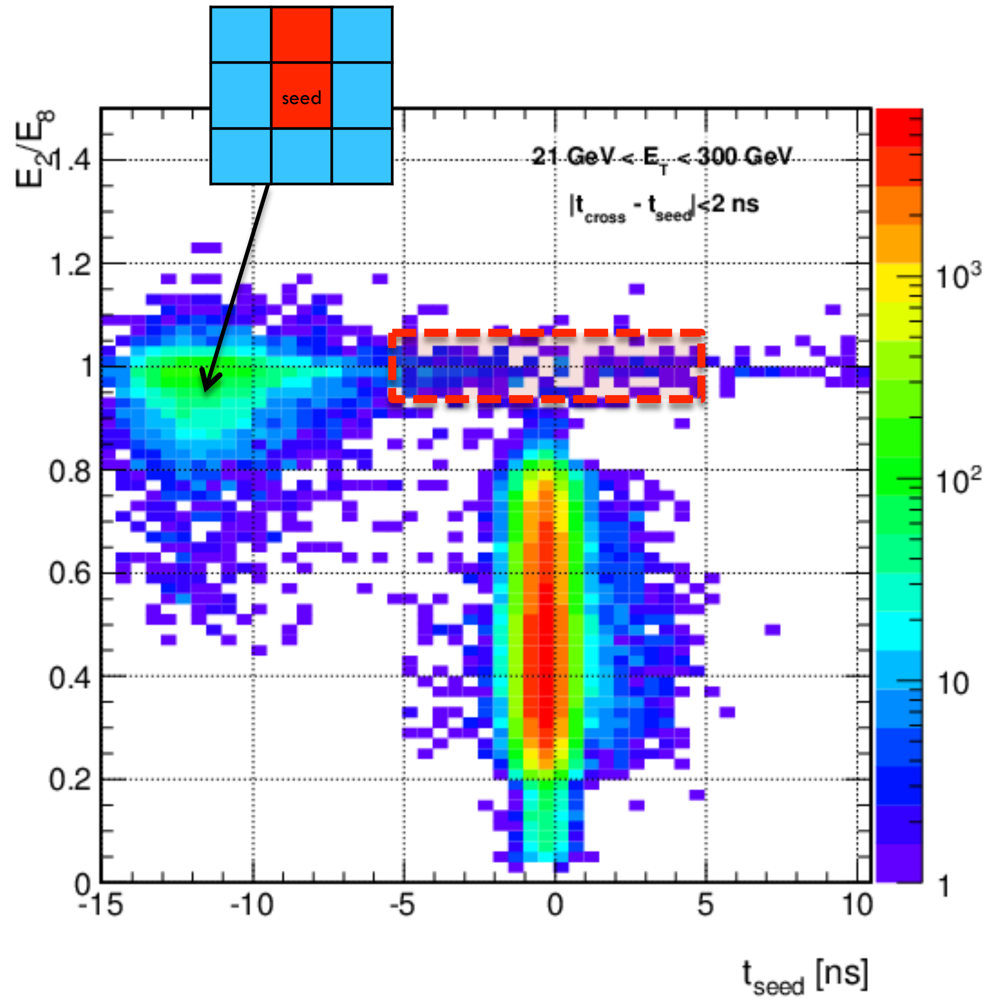


- Require
  - Photon ID
  - $\sigma_{\eta\eta}<0.01$
  - Swiss-cross cleaning: $1-S_4/S_1<0.95$



- Remaining double spikes clearly visible at $E_{2nd}/E_{3\times3\ rim}\sim 1$ ↗

- Removed using $\sigma_{\eta\eta}>0.001$ or $\sigma_{\varphi\varphi}>0.001$



Spike contamination

- Estimate remaining spikes in data
  - Crucial for ECAL-driven analysis
- Pre-select events with
  - $\sigma_{\eta\eta}<0.01$
  - $(1-S_4/S_1)<0.95$ (Swiss-cross)
- Perform ABCD on ➔
  - Seed time vs pass/fail topological cleaning
    - $\sigma_{\eta\eta}>0.001$ or $\sigma_{\varphi\varphi}>0.001$
- **Effect on the signal <0.2%**