Constraining the Standard Model with Rare Electroweak Processes: $W\gamma\gamma$ and $Z\gamma\gamma$ in CMS 8TeV Data

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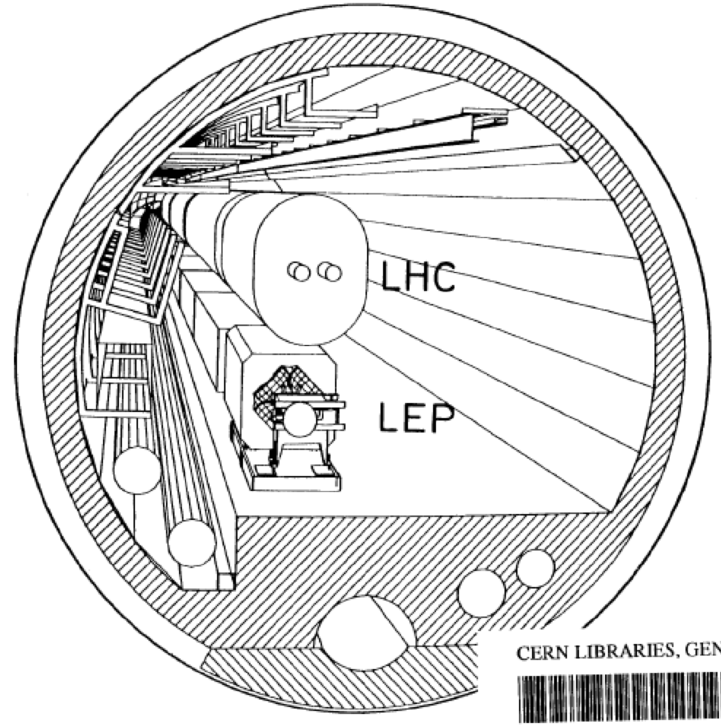
A New Frontier

- LHC started 2016 collisions less than two weeks ago
  – Very hectic period for collaboration, restarting operations after long break
- The 2015 run left some interesting hints at possible new physics
  – Di-photon resonances?
- We expect to collect about an order of magnitude more 13TeV data this year
  – Ambitious plans for precision measurements and discoveries



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

A feasibility study of possible options

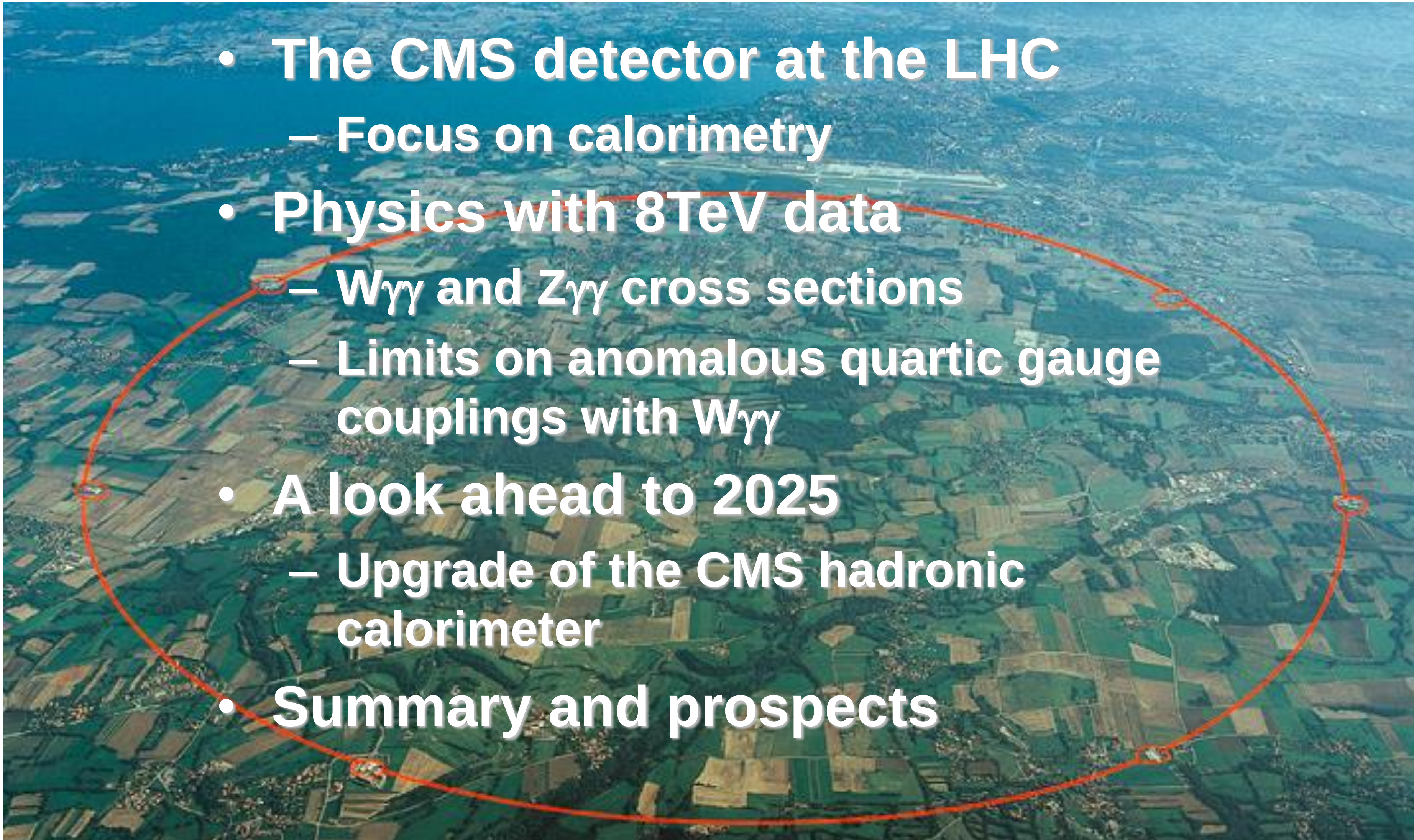
by

The CERN Machine Group

Why Electroweak Physics?

- The Standard Model (SM) is extremely successful at describing particle interactions
  - But it does not tell the full story: neutrino masses? Dark matter and dark energy? Gravitation?
- The SM allows us to do very precise predictions of electroweak processes
  - Discrepancies between predictions and measurements clearly indicate the presence of new physics
- Final states with multiple bosons are particularly interesting
  - They are rare processes, only recently becoming measurable
  - They shed light on possible corrections to the interaction vertices contained in the SM Lagrangian

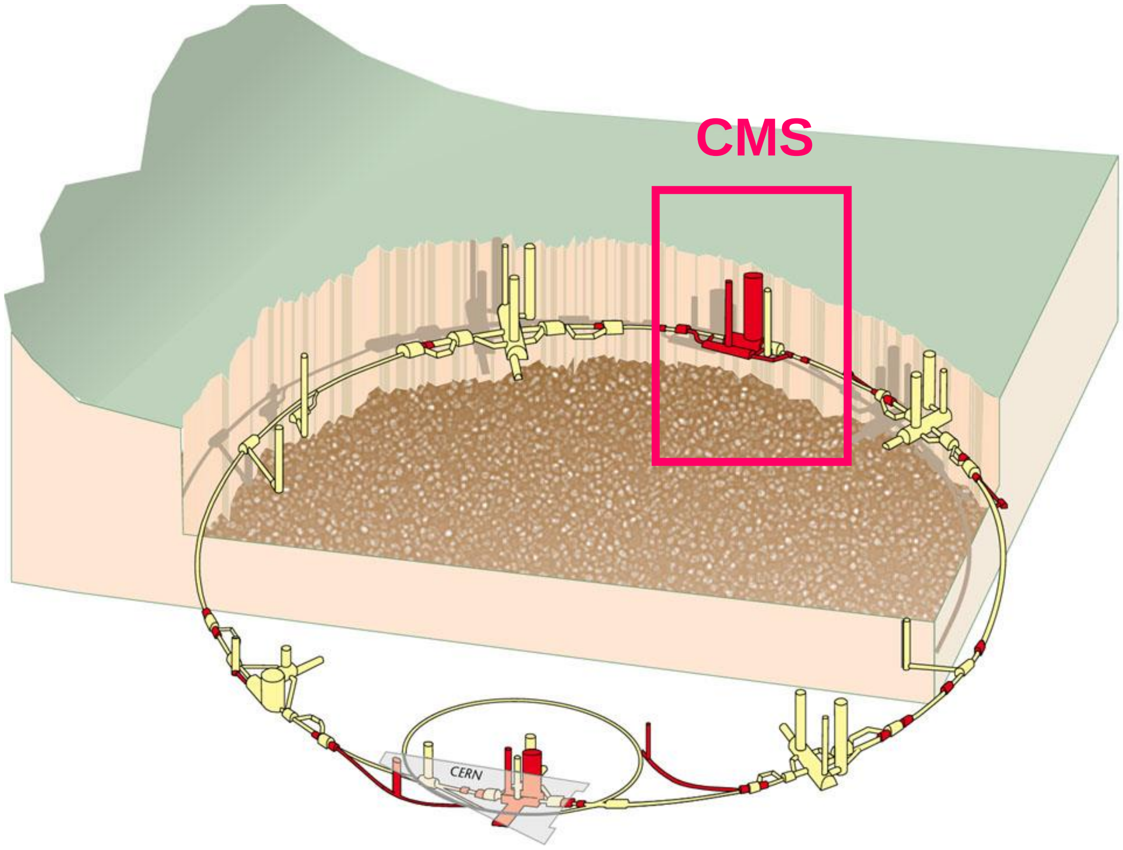
Outline



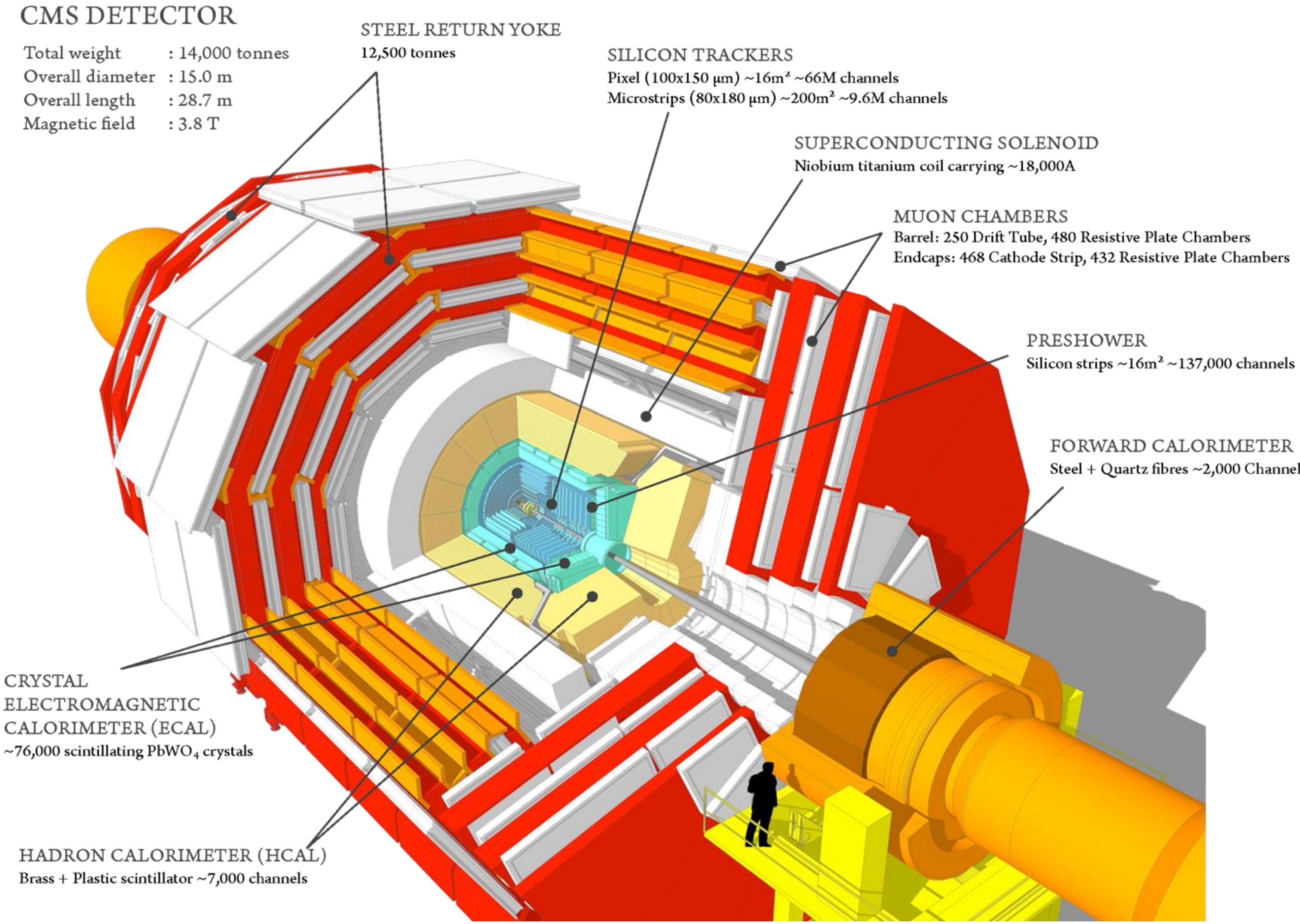
- **The CMS detector at the LHC**
  - **Focus on calorimetry**
- **Physics with 8TeV data**
  - **W$\gamma\gamma$ and Z$\gamma\gamma$ cross sections**
  - **Limits on anomalous quartic gauge couplings with W$\gamma\gamma$**
- **A look ahead to 2025**
  - **Upgrade of the CMS hadronic calorimeter**
- **Summary and prospects**

The Large Hadron Collider

- Record luminosity in 2012: $7.67 \cdot 10^{33}$ cm^{-2}s^{-1}
- Up to 1380 colliding bunches
  - Up to ~35 interactions per bunch crossing
- 10^{11} protons / bunch
- Stored Energy: 362MJ per beam
  - Tevatron: 2MJ
  - LHC magnets: 10GJ
    - Kinetic energy of 90kton aircraft carrier at battle speed (30knots)

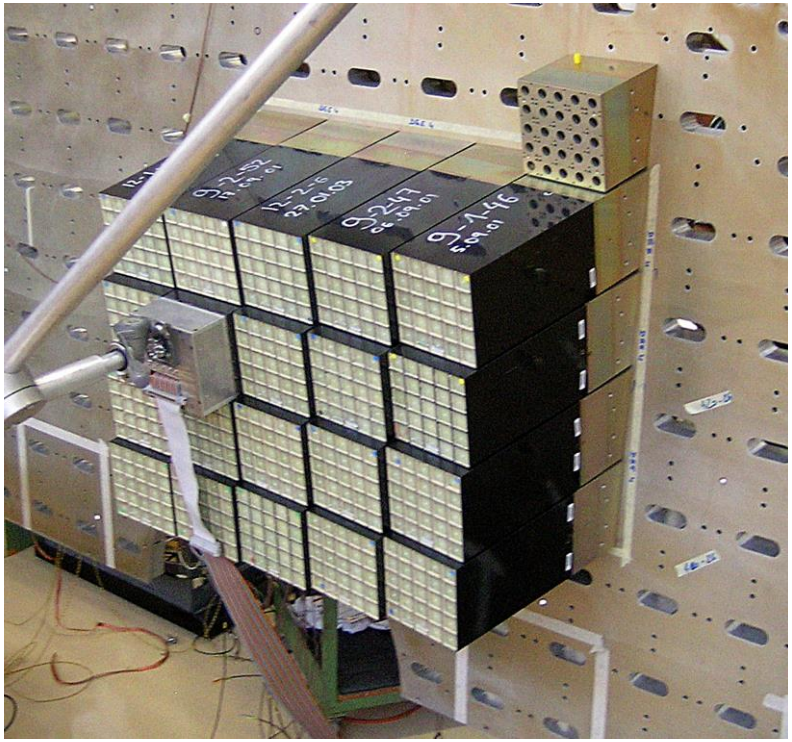


The CMS Detector

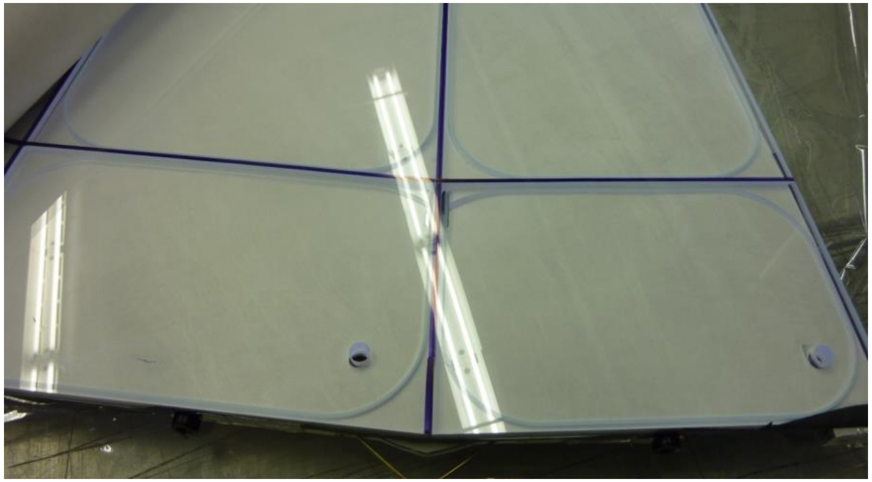


Electromagnetic Calorimetry

- Homogeneous calorimeter built with lead-tungstate crystals
  - $PbWO_4$: large-Z elements very effective in stopping electrons and photons
- About 80,000 $3\text{x}3\text{x}20\text{cm}^3$ crystals, individually read by photo-diodes
  - Transverse size ~ 1 R_M; typical photon contained in one cell, electron in 3-4 cells
- Crystal production took about 10 years
  - 2 days needed to grow each 1.5kg crystal

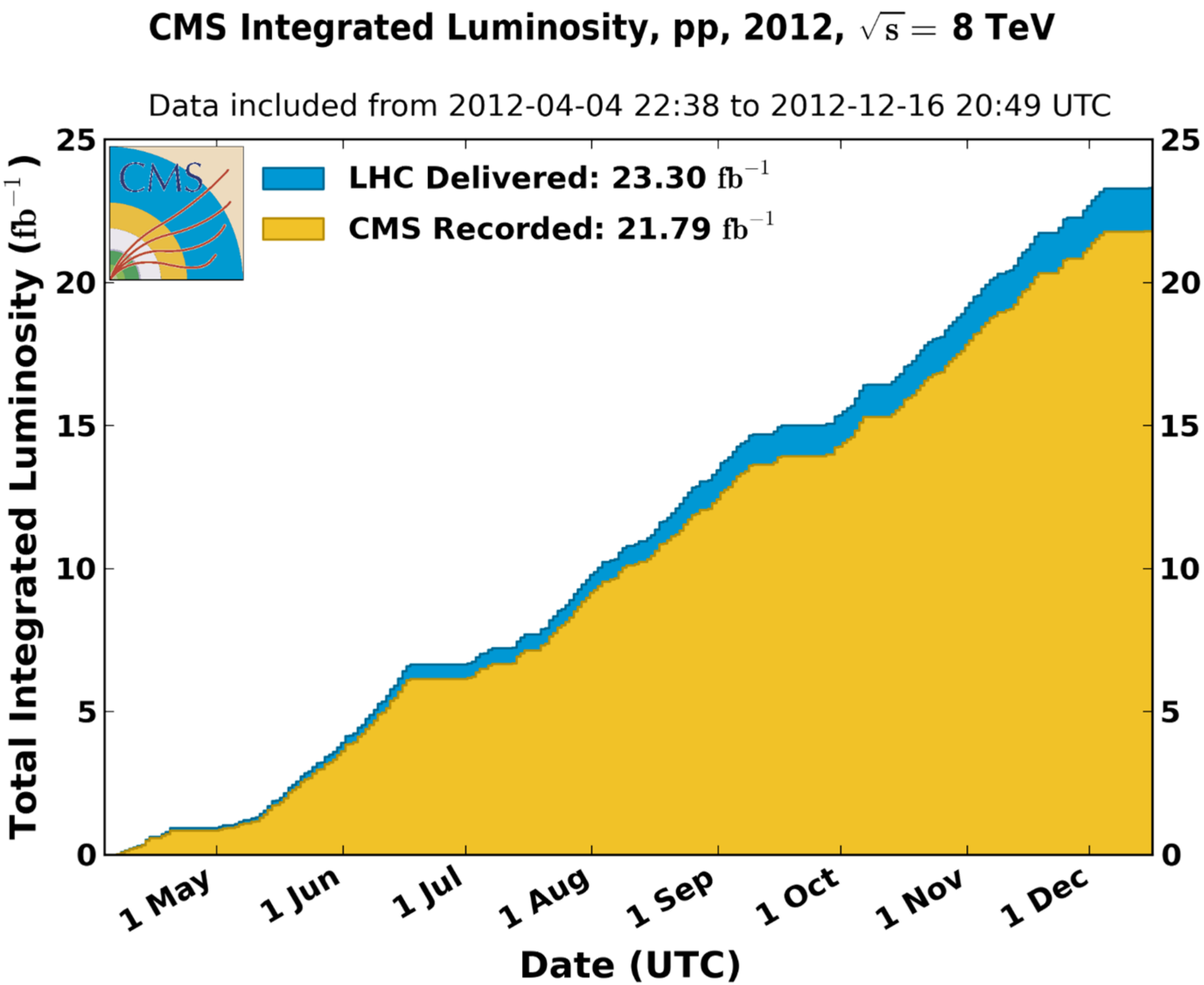


Hadronic Calorimetry



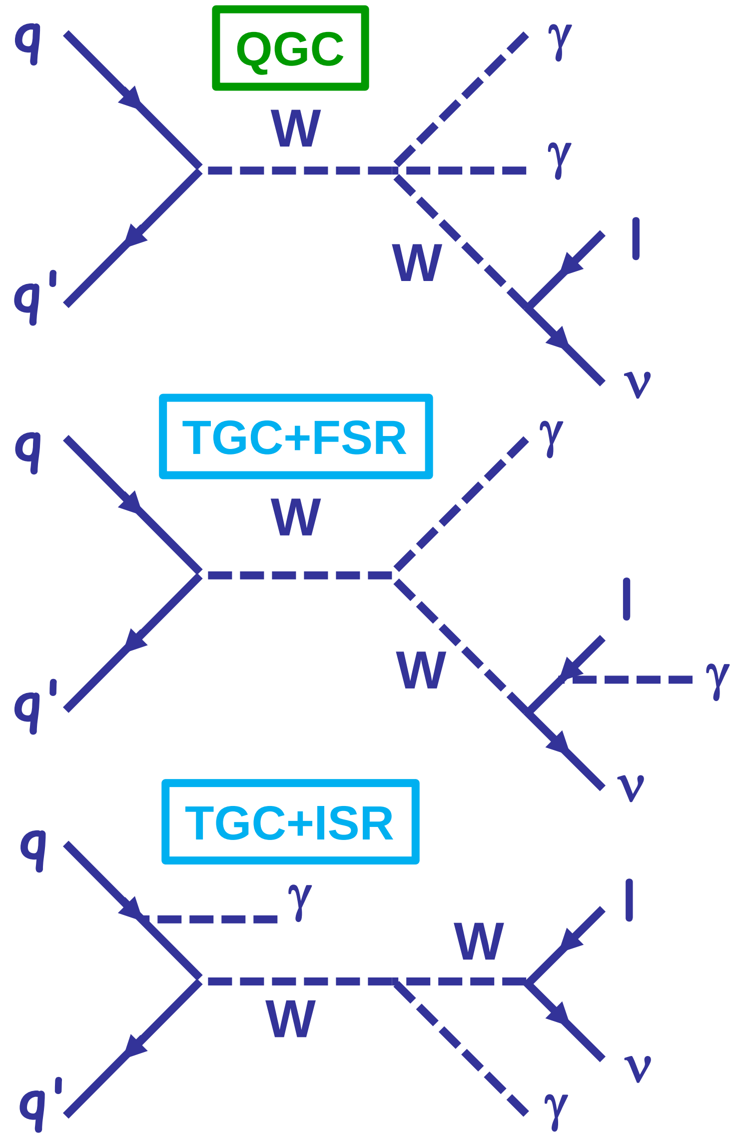
- Plastic-scintillator/brass sampling calorimeter
  - 9cm brass layers are interleaved with ~4mm layers of plastic scintillator
  - Wavelength-shifting fibers bring the light from the plastic tiles to the photo detectors
- About 11,000 readout channels
  - $\delta\eta \times \delta\phi$ towers
  - 3200m^2 of plastic scintillator

8TeV Data Sample



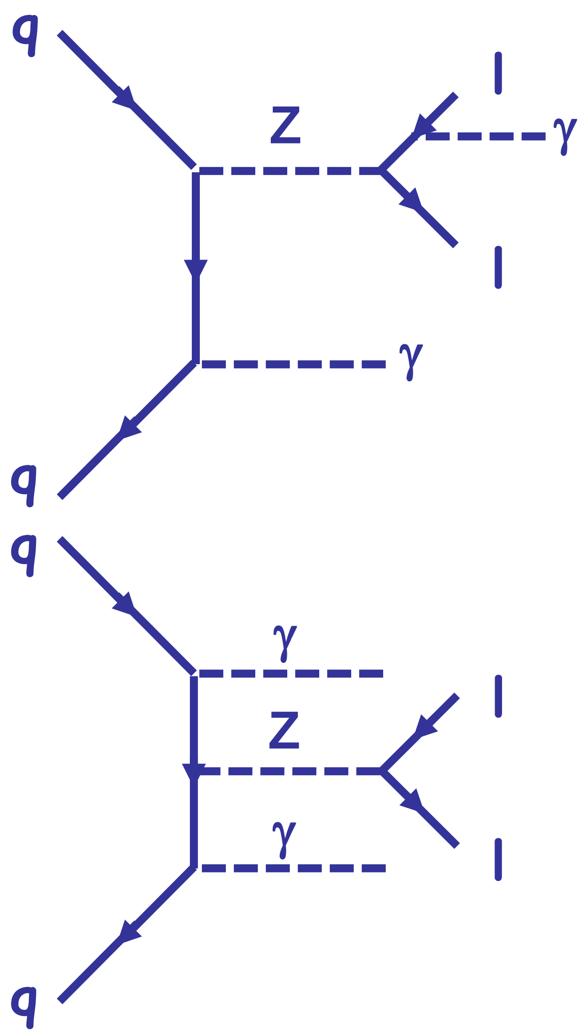
Physics of Wγγ and Zγγ

- The part of the SM Lagrangian that describes electroweak interactions contains multi-boson vertices
  - WWγγ, WZγγ, WWWW
  - WWγ, WWZ
- Interested in measuring 4-boson vertices in SM Lagrangian
  - Quartic gauge couplings
- Very difficult to separate contribution of QGC from 3-boson vertices (triple gauge couplings) plus radiation of a photon
  - Final state radiation (FSR): a photon emitted by the charged lepton from the W decay
  - Initial state radiation (ISR): a photon emitted by a quark in the initial state

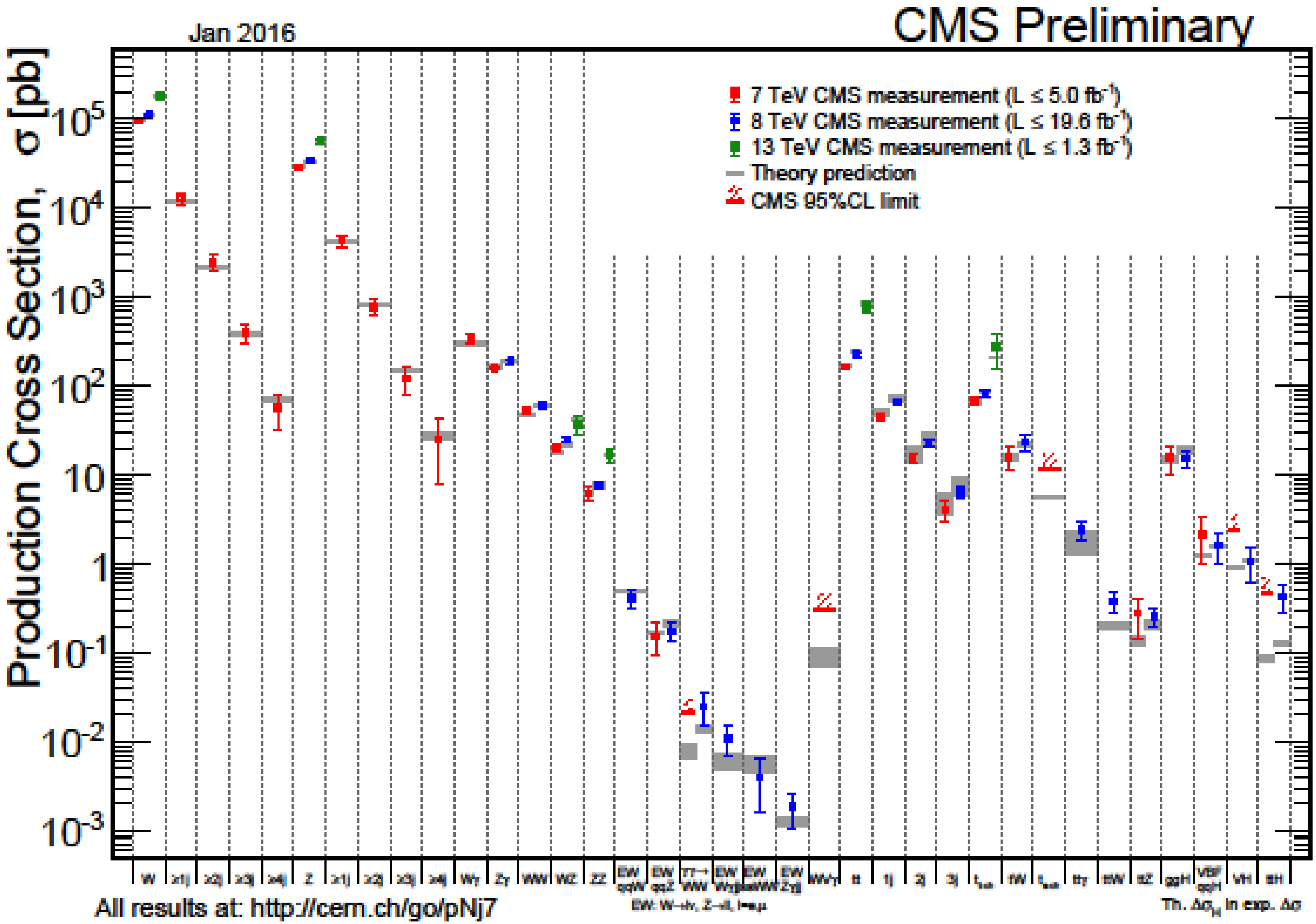


More on Physics

- No ZZZZ, ZZγγ, ZZγ, Zγγ vertices in SM
  - Zγγ can only result by a combination of ISR and FSR photons
  - <u>Any evidence of a vertex with only neutral bosons indicates new physics</u>



How rare are Vγγ events?



Methodology

- The Cross-Section Master Formula:

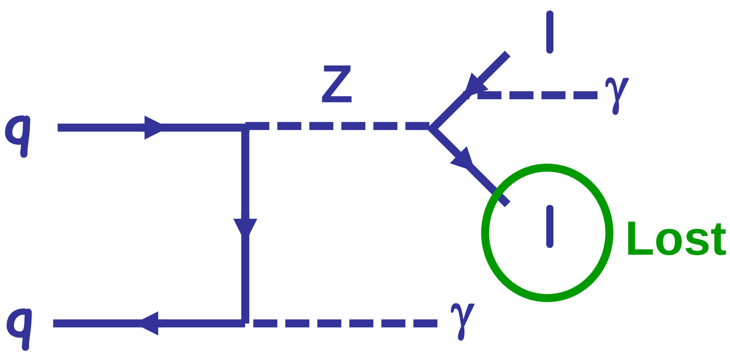
$$\sigma \cdot BR = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C_{\text{V}\gamma\gamma} \cdot \mathcal{L}_{\text{int}}}$$

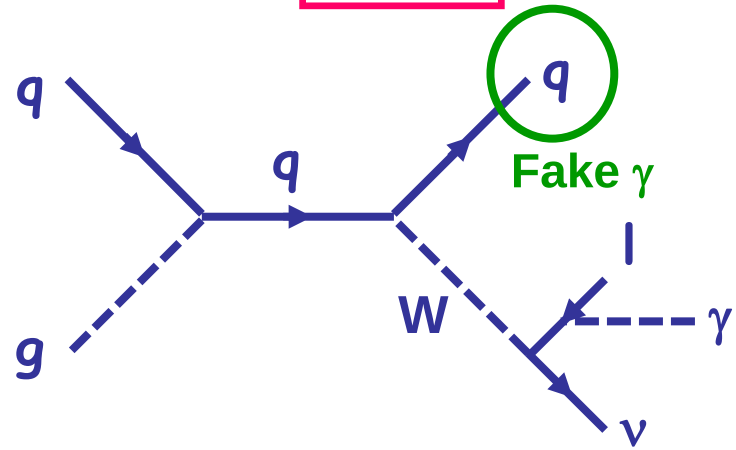
- N_{obs}: number of selected candidates in data sample
- N_{bkg}: expected number of background events
- $C_{V\gamma\gamma}$: fraction of signal expected to pass selection
- L_{int}: integrated luminosity

Main Backgrounds

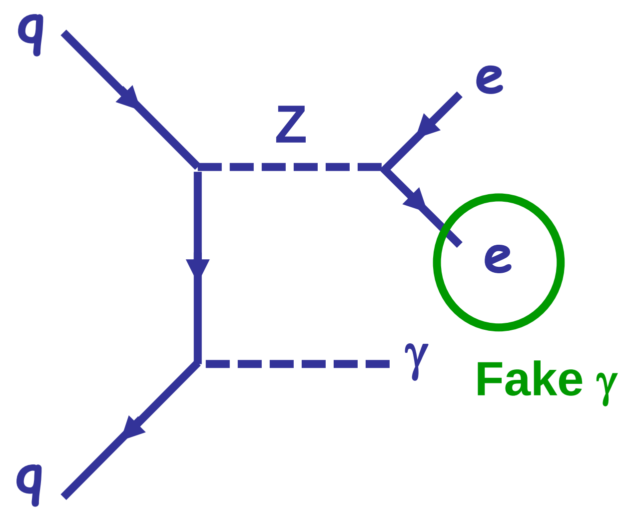
$$\sigma \propto N_{\mathrm{obs}} - \boxed{N_{\mathrm{bkg}}}$$

- Electroweak and top backgrounds
  - WW$\gamma\gamma$, WZ$\gamma\gamma$, tt$\gamma\gamma$, Z$\gamma\gamma$
  - Estimated using Monte Carlo





- Electron and jets faking a photon
  - Wjj and Wγj production cross sections are a few orders of magnitude larger than W$\gamma\gamma$
  - Data-driven methods: it is difficult for MC to correctly model how a jet or an electron can be mis-identified as a photon



Jets Mis-reconstructed as γ

- Difficult to estimate with Monte Carlo
  - Probability that jet is reconstructed as a photon crucially depends on how hadronization is modeled: difficult to do properly
  - Fake rates (hopefully) small: a huge MC sample would be needed to obtain a robust estimate
- A data-driven method can solve both issues
  - Rely on actual data to model mis-reconstruction
- A generalization of the *matrix method* is used
  - Allows us to properly account for mis-identification of jets as being the leading and/or sub-leading photon

Matrix Method for Jet Fakes

- Release photon identification cuts to build three “loose” samples
  - Either or both the leading and sub-leading reconstructed photons can fail identification cuts
- Difference in efficiency of identification cut for jets mis-reconstructed as photons and for real photons allows one to separate the various components in data

Counted in data

$$\begin{pmatrix} \boxed{\begin{matrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{matrix}} \end{pmatrix} = \begin{pmatrix} \boxed{\begin{matrix} \epsilon^{TT}_{RR} & \epsilon^{TT}_{RF} & \epsilon^{TT}_{FR} & \epsilon^{TT}_{FF} \\ \epsilon^{TL}_{RR} & \epsilon^{TL}_{RF} & \epsilon^{TL}_{FR} & \epsilon^{TL}_{FF} \\ \epsilon^{LT}_{RR} & \epsilon^{LT}_{RF} & \epsilon^{LT}_{FR} & \epsilon^{LT}_{FF} \\ \epsilon^{LL}_{RR} & \epsilon^{LL}_{RF} & \epsilon^{LL}_{FR} & \epsilon^{LL}_{FF} \end{matrix}} \end{pmatrix} \begin{pmatrix} \alpha_{RR} \\ \alpha_{RF} \\ \alpha_{FR} \\ \alpha_{FF} \end{pmatrix}$$

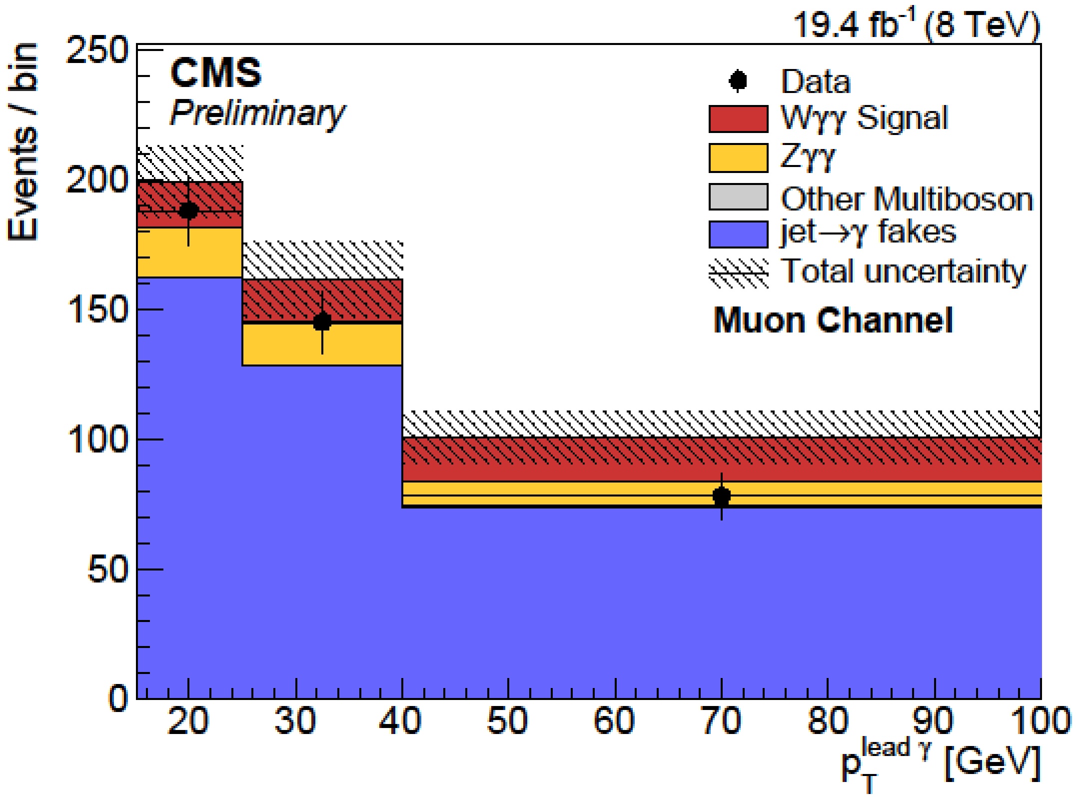
Measured in background-enriched data samples (ε for fake photons) and in MC (ε for real photons)

E.g.: ε_{RF}^{TT}: probability that an event with a Real leading photon and a Fake sub-leading photon enters the Tight-Tight region (i.e., both objects satisfy the photon identification cuts

Invert the matrix and solve for α’s to obtain background estimate:

$$N_{bkg}^{TT}=\alpha_{RF}\varepsilon_{RF}^{TT}+\alpha_{FR}\varepsilon_{FR}^{TT}+\alpha_{FF}\varepsilon_{FF}^{TT}$$

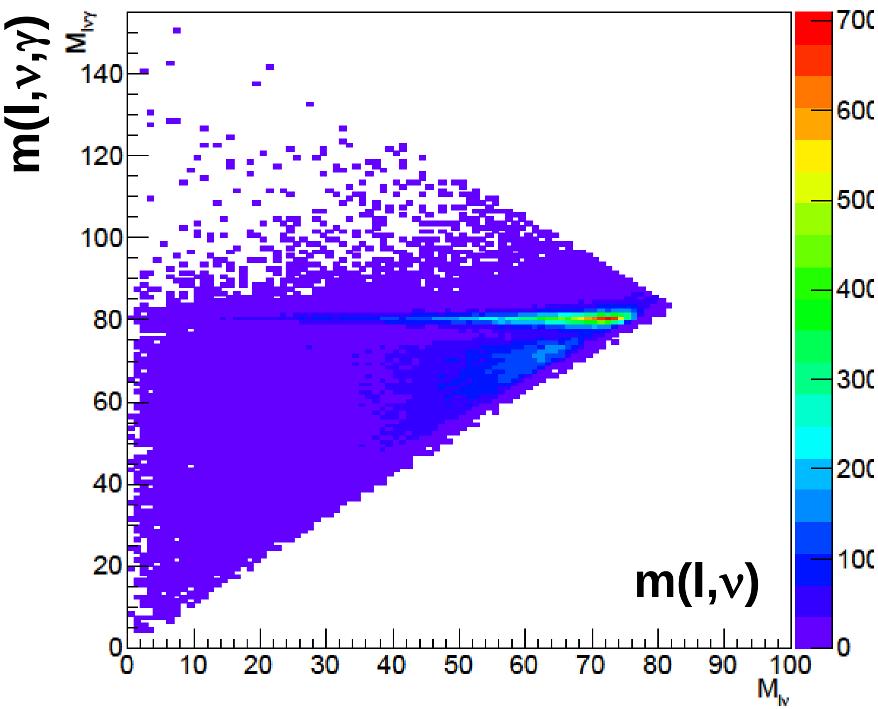
Background Estimate Validation



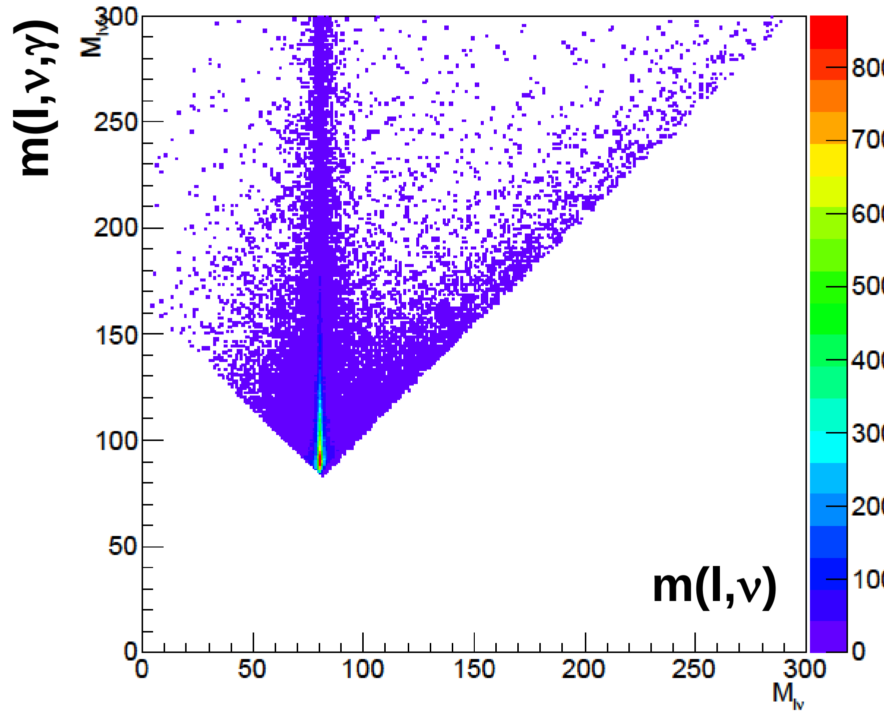
- Validation of background estimate performed using control region enriched in fake photons (sub-leading photon p_T fails analysis cut)
  - Test satisfactorily passed: data and re-normalized Monte Carlo samples agree within uncertainties

Signal Generation

FSR-enhanced



ISR-enhanced



- Monte Carlo Wγγ sample split between ISR- and FSR-enhanced samples
  - Clear distinction in m(l,ν,γ) vs. m(l,ν) plane
- FSR diagrams dominate the cross section, but TGC and QGC appear predominantly in ISR-enhanced sample
  - Separation of MC signal important to guarantee that phase-space sensitive to TGC and QGC is well sampled

Correction to Truth Level

- Each cross section is measured in a *fiducial* region
  - $C_{V\gamma\gamma}$ corrects for efficiencies and geometric acceptance
- The fiducial region is defined by cuts as similar as possible to the analysis selection cuts
  - This allows to minimize the theory uncertainties on the cross-section measurement

$$\sigma \propto 1/\boxed{C_{V\gamma\gamma}}$$

Fiducial cuts

$p_T(l,\gamma)$, $\eta(l,\gamma)$
$m(ll)$, $m_T(l,\nu)$
$\Delta R(l,\gamma)$, $\Delta R(\gamma,\gamma)$

#MC W/Z after analysis cuts on reconstructed quantities

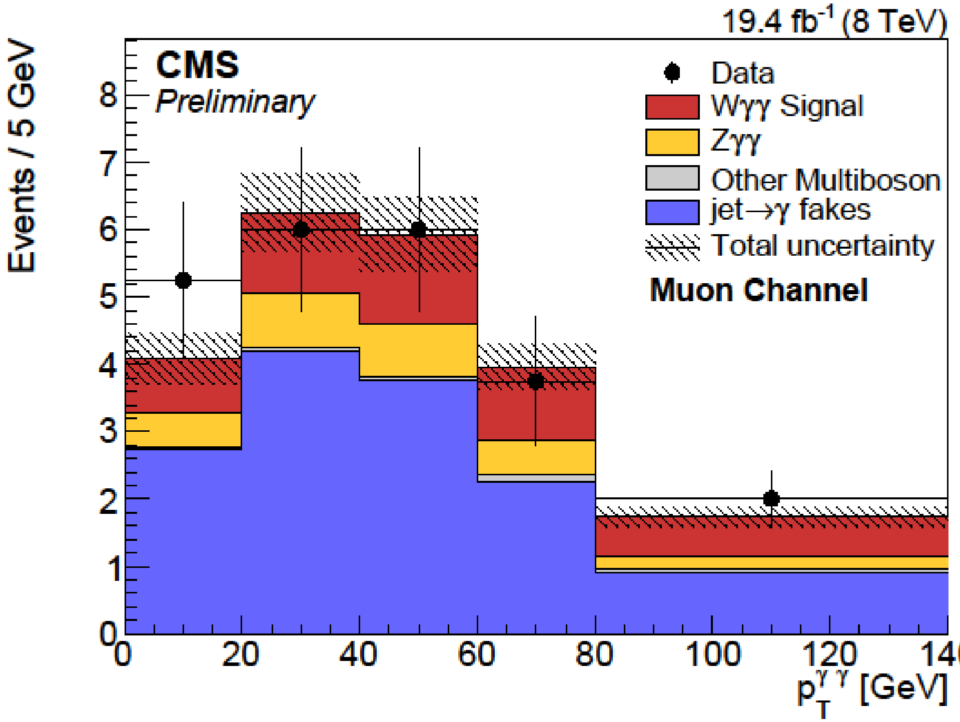
#MC W/Z after fiducial cuts on truth quantities

$$C_{V\gamma\gamma} = \frac{\boxed{N_{\mathrm{reco}}}}{\boxed{N_{\mathrm{truth}}}} \cdot \frac{\epsilon^{\mathrm{data}}_{\mathrm{trigger}}}{\epsilon^{\mathrm{MC}}_{\mathrm{trigger}}} \cdot \frac{\epsilon^{\mathrm{data}}_{\mathrm{reco}}}{\epsilon^{\mathrm{MC}}_{\mathrm{reco}}}$$

Candidate Selection – Wγγ

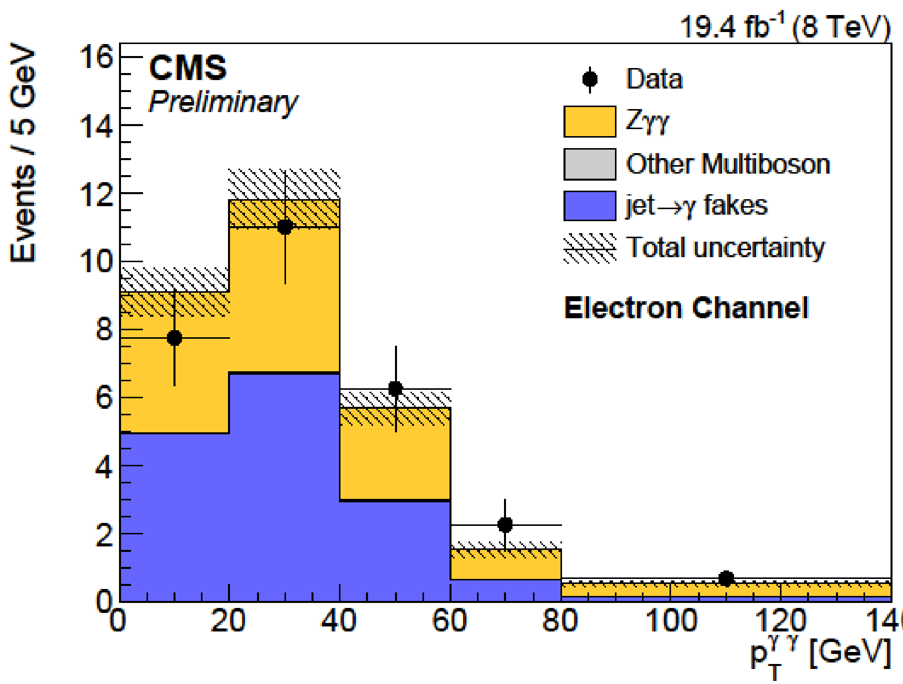
- Analysis cuts enhance the fraction of signal events
  - Lepton transverse momentum
  - Lepton isolation
    - Sum of energy in ΔR cone around lepton
  - Photon transverse momentum
  - Transverse mass m_T
- Events surviving selection are used to measure cross section
  - "Cut & count" analysis

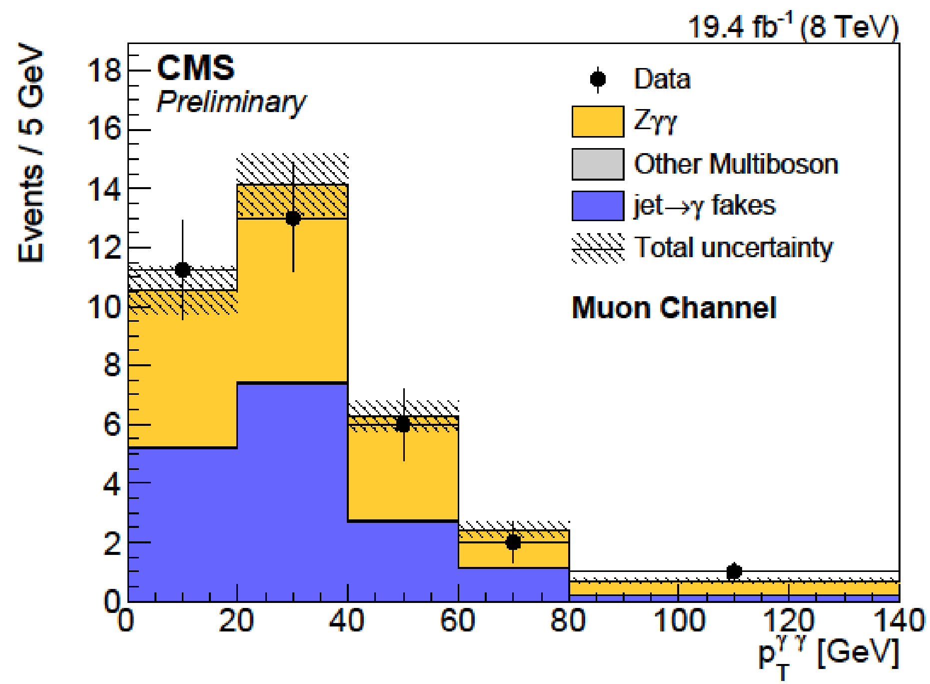
$$\sigma \propto \boxed{N_{\text{obs}}} - N_{\text{bkg}}$$



$$m_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{\text{miss}} \left(1 - \cos(\phi_\ell - \phi_{E_T^{\text{miss}}})\right)}$$

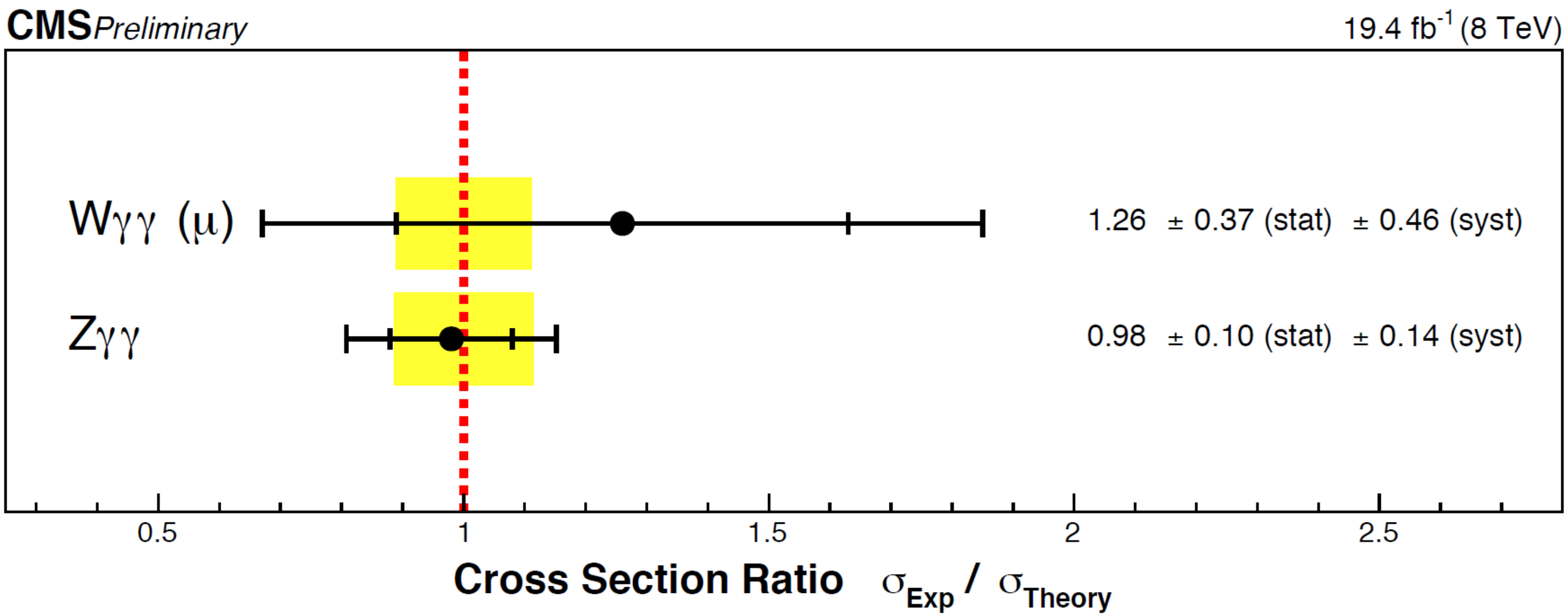
Candidate Selection – Zγγ





- Cleaner sample: requiring two well-reconstructed leptons removes most backgrounds
- Main background: Z+jets where one (or two) jets are reconstructed as a photon

Cross-Section Results



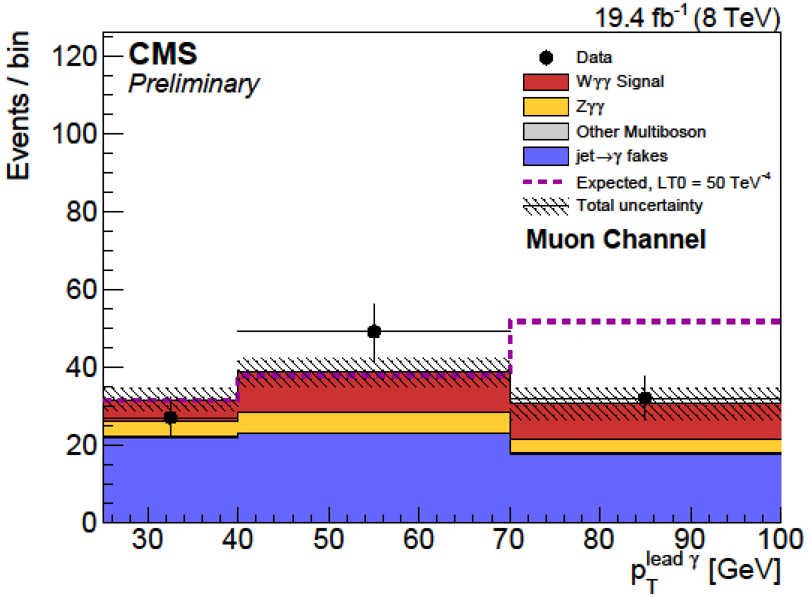
- Putting together observation in data, background estimates, and acceptance corrections, we obtain:
  - $\sigma^{(fid)}(pp\rightarrow W\gamma\gamma) \bullet \text{B.R.}(W\rightarrow\mu\nu) = 6.0\pm1.8^{(stat)}\pm2.3^{(syst)}\pm0.2^{(lumi)}$ fb
  - $\sigma^{(fid)}(pp\rightarrow Z\gamma\gamma) \bullet \text{B.R.}(Z\rightarrow ll) = 12.7\pm1.4^{(stat)}\pm1.8^{(syst)}\pm0.3^{(lumi)}$ fb

QGC Framework

- Effective Field Theory (EFT) provides a method to express the contribution of anomalous QGC to the SM Lagrangian

$$\mathcal{L}_{\rm aQGC} = \mathcal{L}_{\rm SM} + \sum_i \frac{f_i}{\Lambda^4}\mathcal{O}_i + \ldots$$

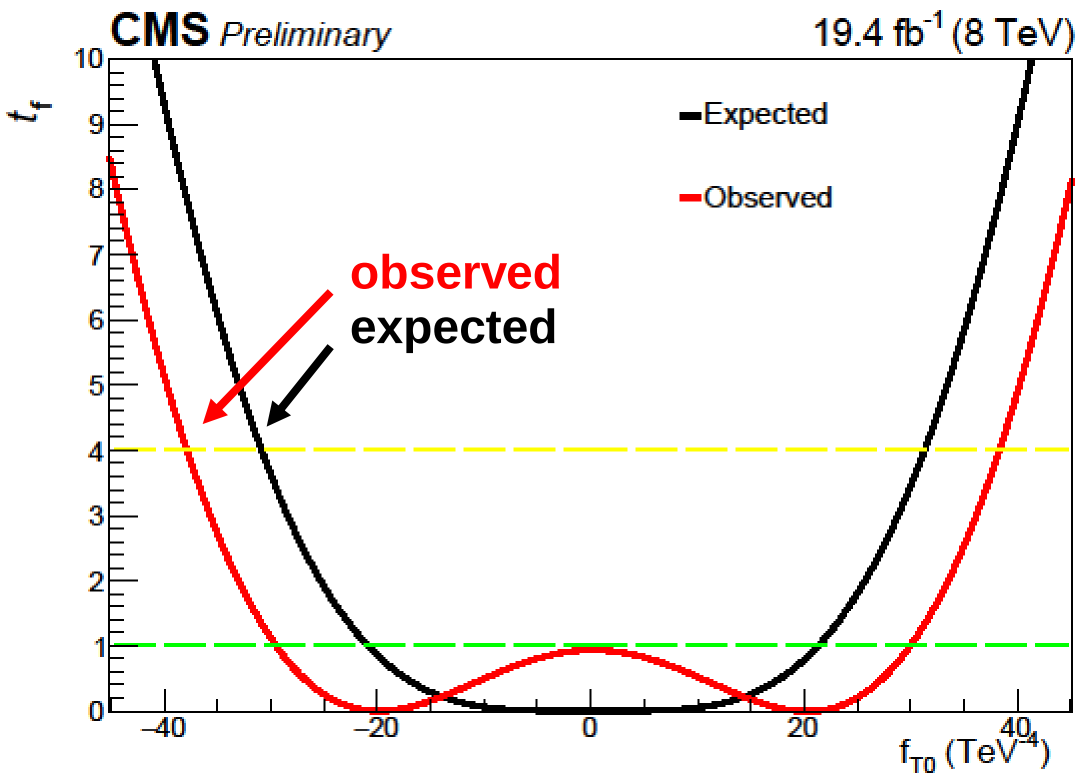
  - O_i is a dimension-8 operator: it is the lowest order at which we can have anomalous QGC without anomalous TGC (not seen in data so far)
- Among the 14 operators that contribute to the $WW\gamma\gamma$ vertex, our analysis is sensitive to five of them
  - Largest sensitivity offered by events with leading photon p_T>70GeV, and both photons reconstructed in the CMS barrel calorimeter



Effect of anomalous QGC stronger at high Q^2: expect improved sensitivity in 13TeV data analyses

QGC Limits

- Likelihood ratio used as test statistic
  - Distributed as a χ^2 with one degree of freedom
- Expected limits indicate how sensitive analysis is
  - They indicate which limit we could set if data agreed with SM prediction
- Small excess over SM prediction observed in data
  - Observed limits are weaker than expected



Standard Model (almost) excluded at 1σ!

Summary – σ • B.R.

Definition of $W^{\pm}\gamma\gamma$ Fiducial Region
$p_T^{\gamma} > 25\,\mathrm{GeV},\ \lvert\eta^{\gamma}\rvert < 2.5$
$p_T^{\ell} > 25\,\mathrm{GeV},\ \lvert\eta^{\ell}\rvert < 2.5$
Exactly one candidate muon and two candidate photons
$m_T(\ell,\nu_{(s)}) > 40\,\mathrm{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$ and $\Delta R(\gamma,\ell) > 0.4$

Definition of $Z\gamma\gamma$ Fiducial Region
$p_T^{\gamma} > 15\,\mathrm{GeV},\ \lvert\eta^{\gamma}\rvert < 2.5$
$p_T^{\ell} > 10\,\mathrm{GeV},\ \lvert\eta^{\ell}\rvert < 2.5$
Exactly two candidate leptons and two candidate photons
lead $p_T^{\ell} > 20\,\mathrm{GeV}$
$M_{\ell\ell} > 40\,\mathrm{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\gamma,\ell) > 0.4$, and $\Delta R(\ell,\ell) > 0.4$

$\sigma^{(\text{fid, exp})}(W\gamma\gamma) \bullet$ B.R. = 6.0±1.8±2.3±0.2 fb

$\sigma^{(\text{fid, theory NLO})}(W\gamma\gamma) \bullet$ B.R. = 4.76±0.53 fb

$\sigma^{(\text{fid, exp})}(Z\gamma\gamma) \bullet$ B.R. = 12.7±1.4±1.8±0.3 fb

First at hadronic collider!

$\sigma^{(\text{fid, theory NLO})}(Z\gamma\gamma) \bullet$ B.R. = 12.95±1.47 fb

Summary – aQGC

Expected Limits (TeV^{-4})
$-30.5 < \frac{f_{T0}}{\Lambda^4} < 31.1$
$-36.9 < \frac{f_{T1}}{\Lambda^4} < 37.5$
$-83.2 < \frac{f_{T2}}{\Lambda^4} < 83.2$
$-623 < \frac{f_{M2}}{\Lambda^4} < 603$
$-1080 < \frac{f_{M3}}{\Lambda^4} < 1110$

Observed Limits (TeV^{-4})
$-37.5 < \frac{f_{T0}}{\Lambda^4} < 38.1$
$-46.1 < \frac{f_{T1}}{\Lambda^4} < 46.9$
$-103 < \frac{f_{T2}}{\Lambda^4} < 103$
$-751 < \frac{f_{M2}}{\Lambda^4} < 729$
$-1290 < \frac{f_{M3}}{\Lambda^4} < 1340$

- Expected limits
  - Define sensitivity of analysis
- Observed limits
  - Worse than expected due to up fluctuation of data yield vs. prediction

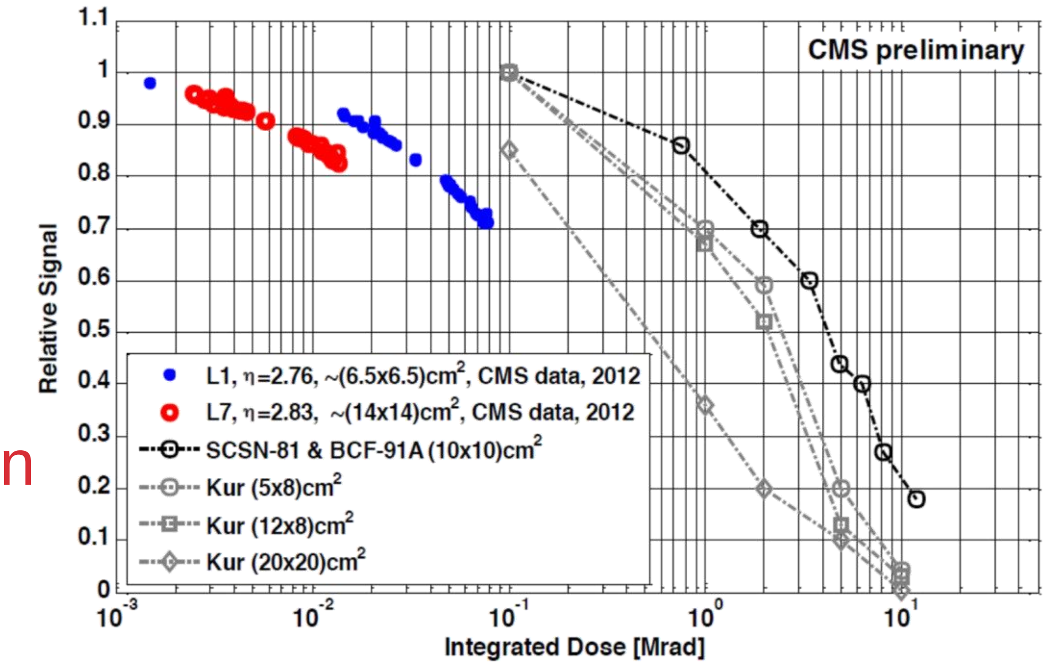
- Comparison with other measurements (f_{T0}/Λ^4):
  - $W\gamma\gamma$ (ATLAS): (-16,16)
  - $WV\gamma$: (-25, 24)
  - $Z\gamma \rightarrow WW$: (-3.8,3.4)

Note: CMS $W\gamma\gamma$ uses only muon channel

Calorimetry in 2025-2035

HCAL Ageing

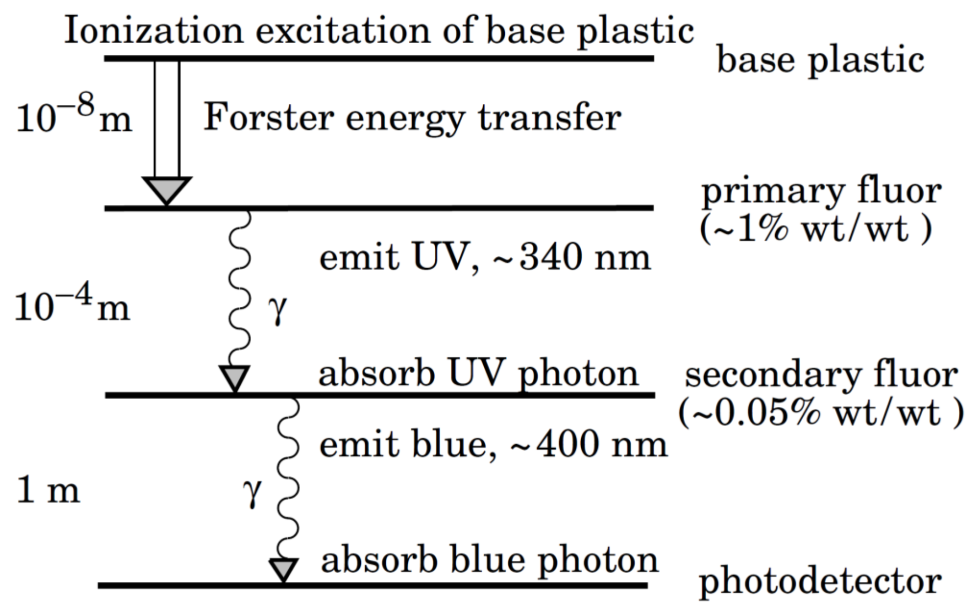
- The CMS Hadronic calorimeter uses plastic scintillator as active material
  - It is know that radiation breaks the plastic and creates “color centers” which absorb scintillation light
- The crucial question is: how long will it take the HCAL to become dark?
  - The lesson from 2012 data: shorter than it was originally thought



After an irradiation of 10krad, we see the light-yield reduction predicted for 1Mrad

How does a Scintillator work?

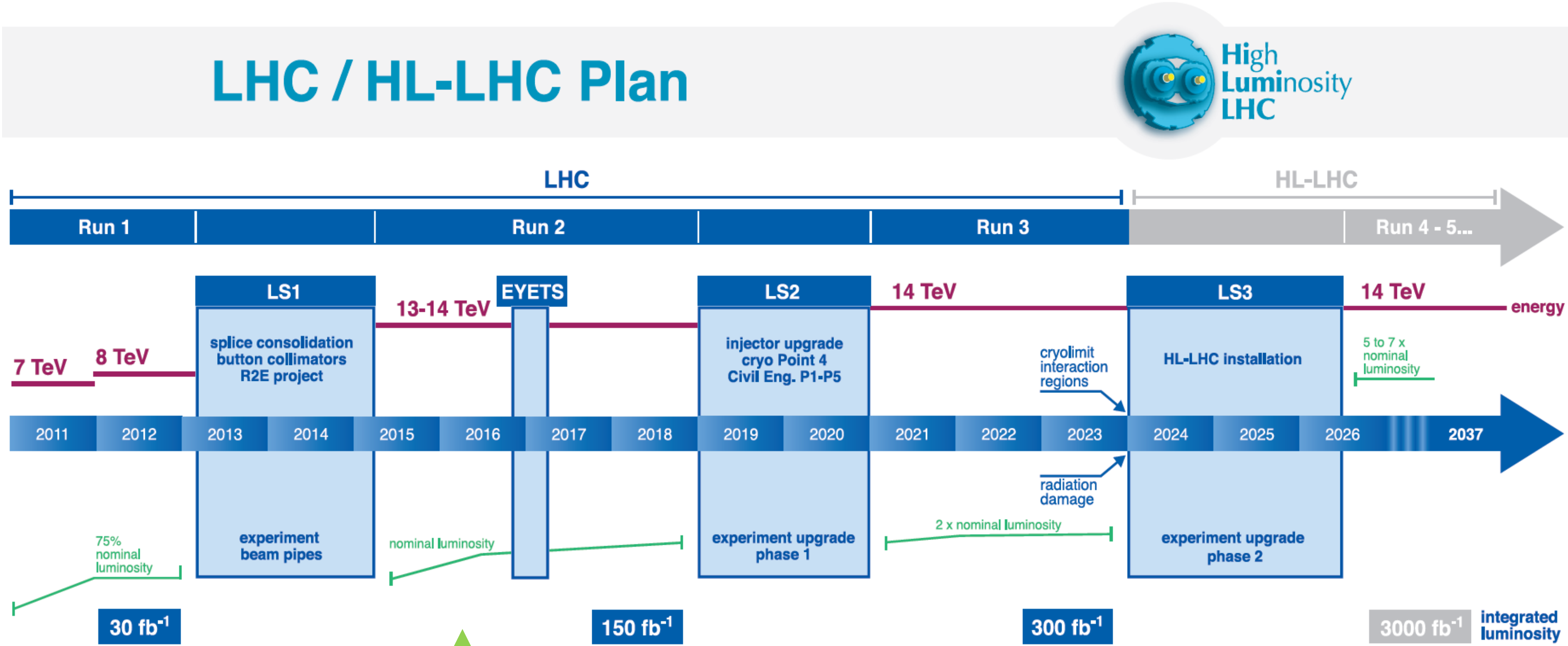
- An organic scintillator is typically composed of three parts
  - A polymer base (typically PVT, polystyrene, or Silicon-based materials)
  - A primary dopant (~1%)
  - A secondary dopant (~0.05%)
- Particles excite the base, the excitation of the base can migrate to the primary dopant, producing detectable light
  - In crystals, excitons transfer the energy; in liquids, solvent-solvent interactions and collisions
- The secondary dopant shifts the light to longer wavelengths, to make it more easily detected
  - Maximize the overlap with the wavelength range at which photodetectors are most efficient



Effects of radiation:
- Breaks polymer chains and create radicals that absorb UV light
- Damages fluors, reducing their ability to shift light to longer wavelengths

Some parameters to model radiation damage
- Presence of oxygen
- Total irradiation dose and dose rate
- Temperature of irradiation

Upgrade Timeline

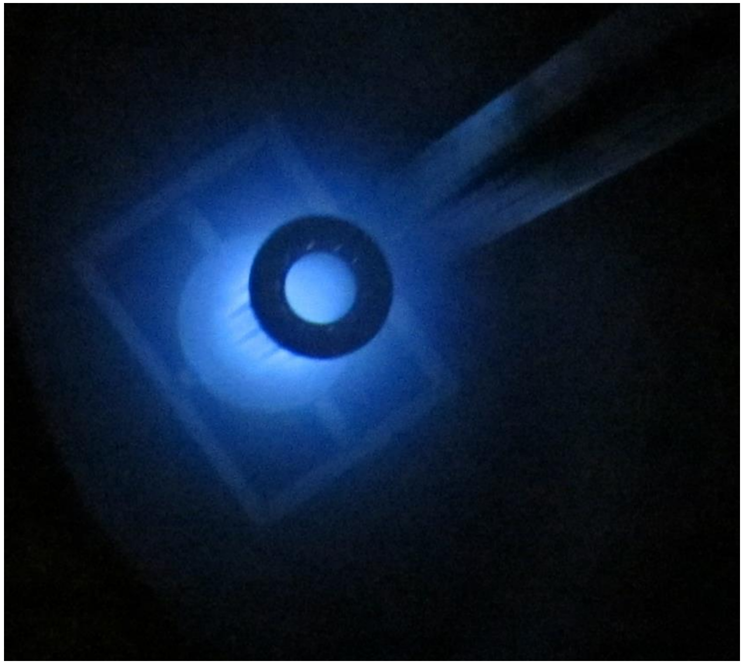


We are here

We plan to upgrade here

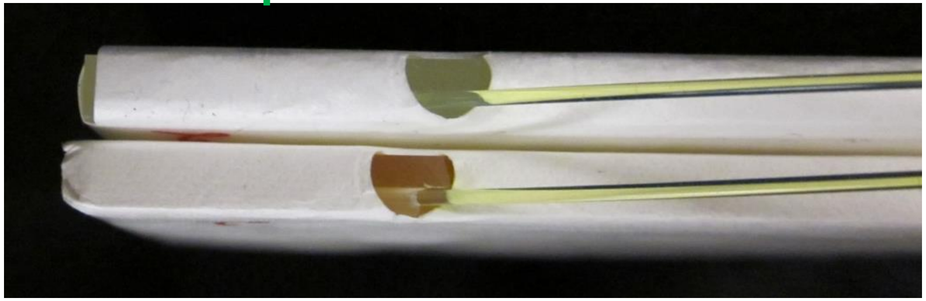
R & D Directions and Plans

- Identify candidate materials offering improved radiation tolerance
  - Tune dopant concentration
  - Emit at a longer wavelength
- Irradiate materials in different environment, at different total doses and dose rates
  - Radioactive sources (Co-60, Cs-137)
  - LHC beam halo
- Measure light yield with different methods
  - Spectrofluorometers, cosmic rays, radioactive sources (Pu-239: α source)
- Map light-yield reduction as a function of multiple parameters
  - O_2 concentration; total dose; dose rate; temperature; dopant concentration…

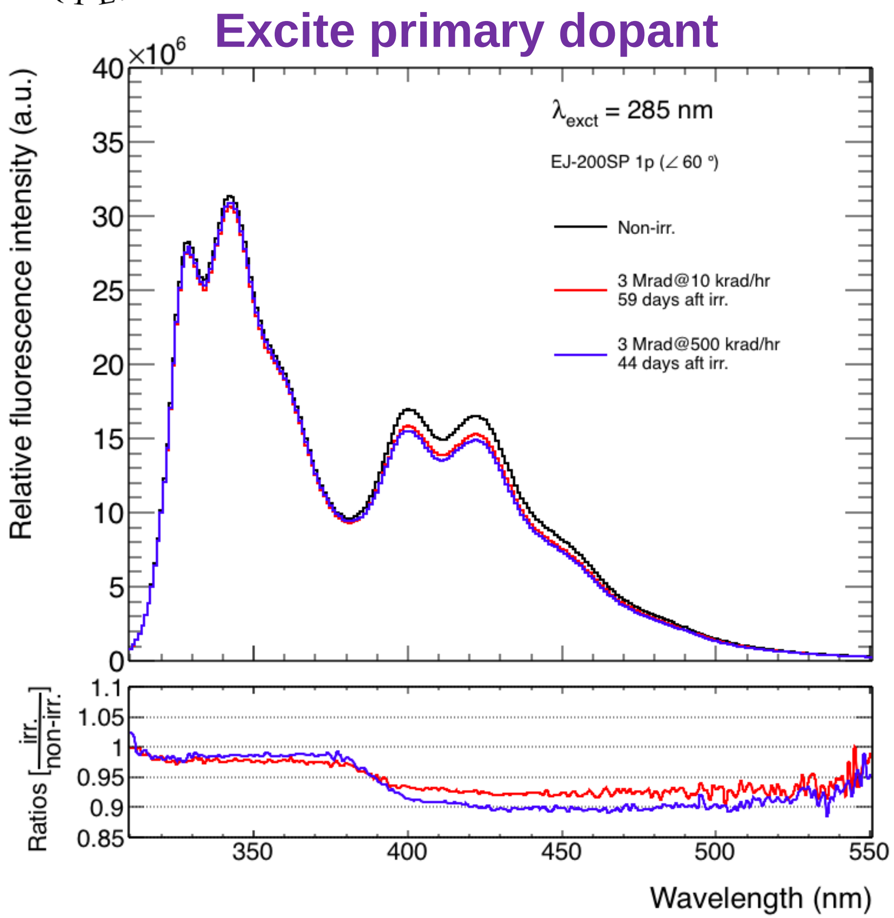


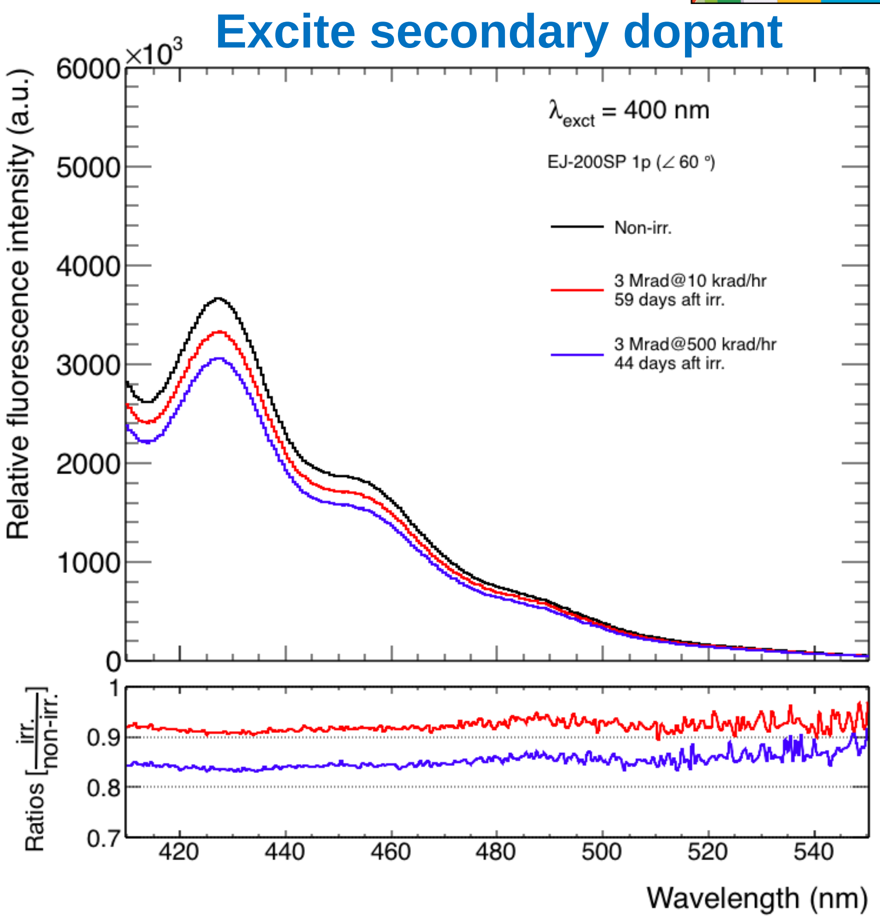
UMD Co-60 source

Irradiated plastic scintillator vs. new



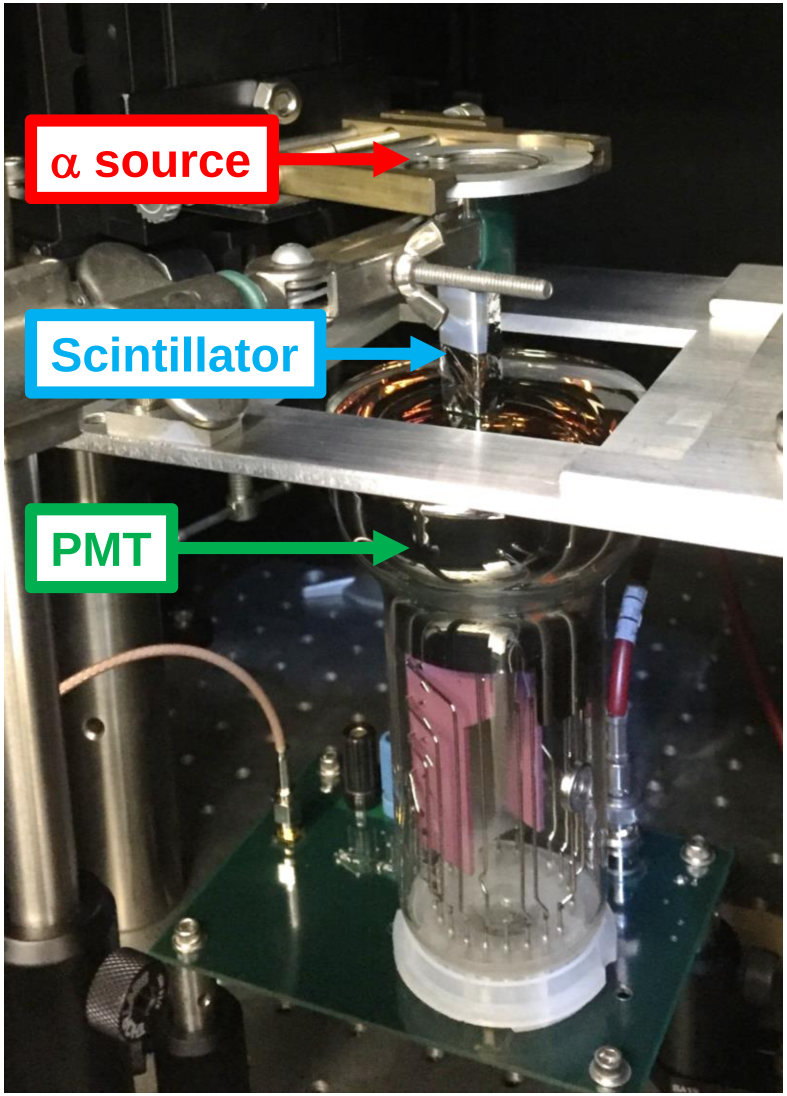
Spectrofluorometry

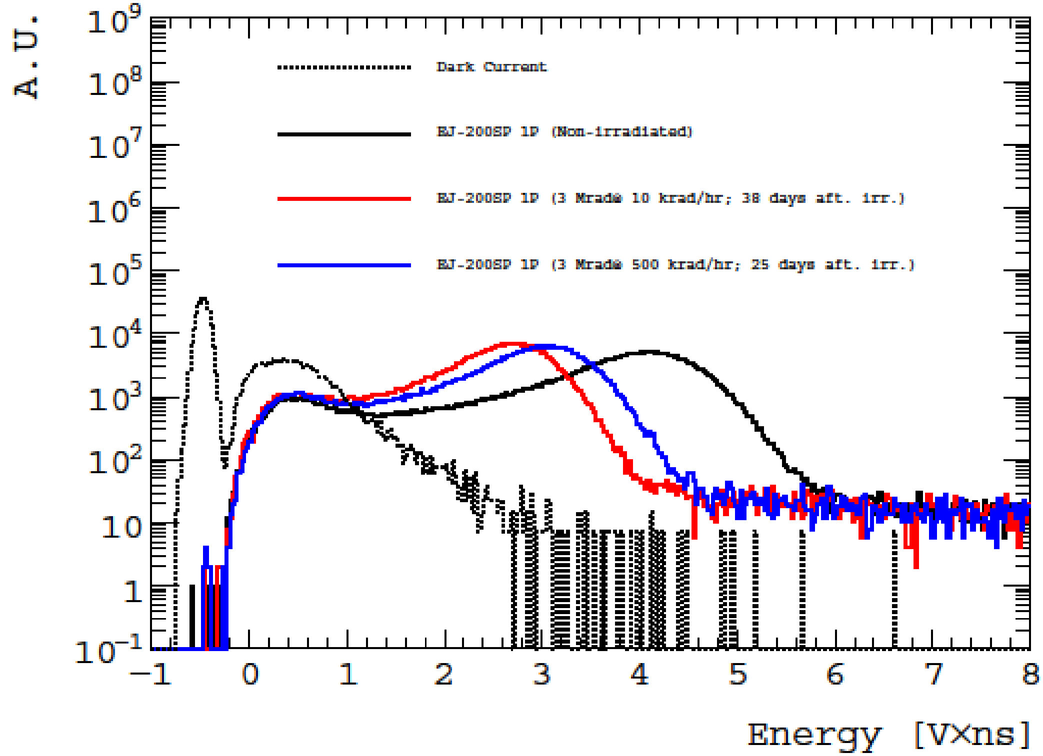




- Promising technique to understand effect of radiation on material
  - One can excite separately dopants

α-source Measurements



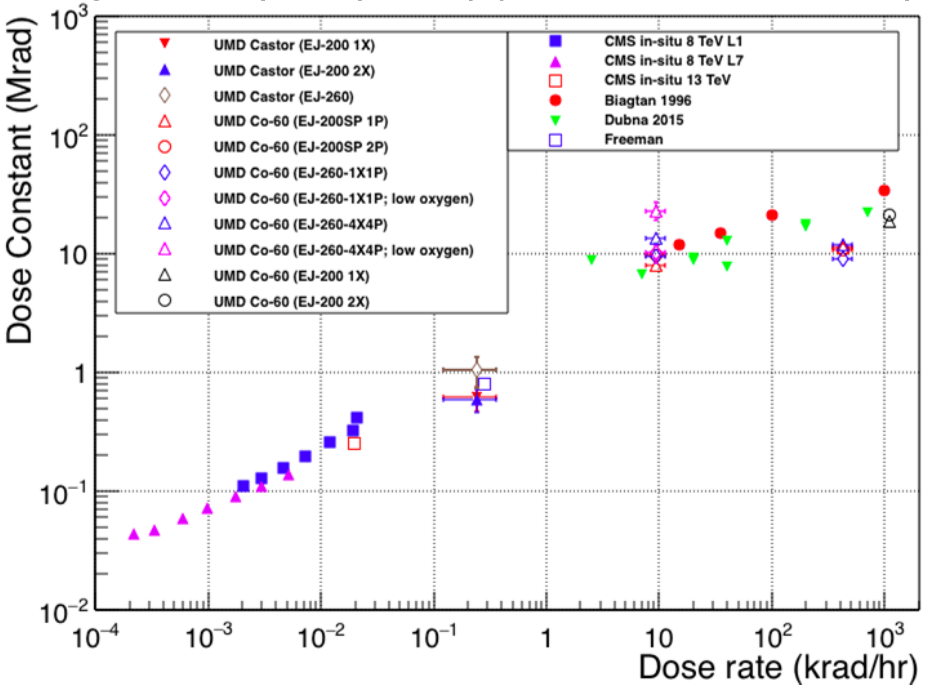


Compare irradiation of same type of scintillator at different dose rates

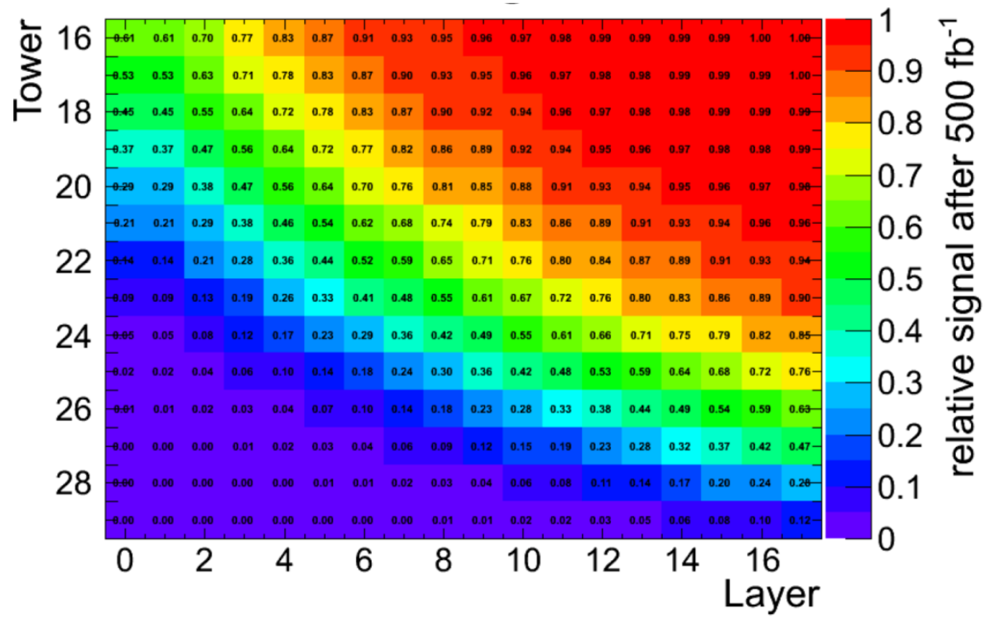
The lower the dose rate, the higher the damage

Input to CMS Ageing Model

Light-Yield(dose) ~ exp(-dose/Dose Constant)



CMS Hadronic Endcap Calorimeter
Light-Yield (500/fb)/Light-Yield(0/fb)



Measurements in laboratory indicate how fast radiation damage proceeds as a function of dose, dose-rate (shown), environment

Detector simulation is tuned to reproduce the dose/dose-rate-dependent damage on calorimeter tiles

Response maps for different materials, environmental conditions, beam conditions can be produced, and used to steer the upgrade decisions

Concluding Remarks

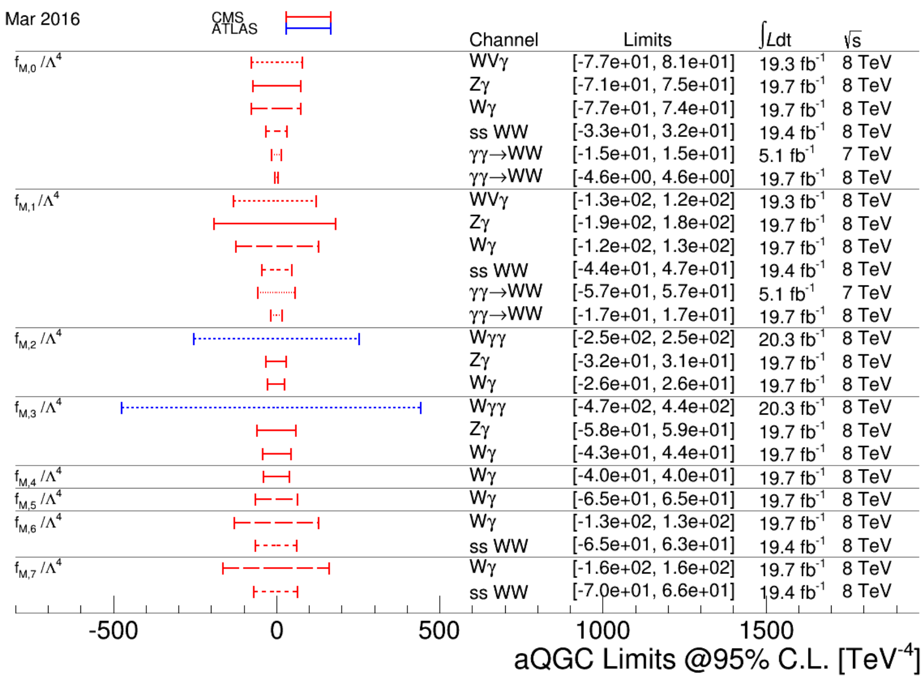
- Concluded (?) 8TeV precision measurements
  - First observation of Z$\gamma\gamma$ at hadronic collider
- Already enough data to look for rare processes
  - Electroweak cross-section measurements spanning almost seven orders of magnitude
- Very exciting R&D program to define calorimeters for the next decade(s)
  - First round at systematic study of radiation damage as a function of environment and material characteristics
- Ready to catch any new physics
  - Started collecting more statistics at 13TeV

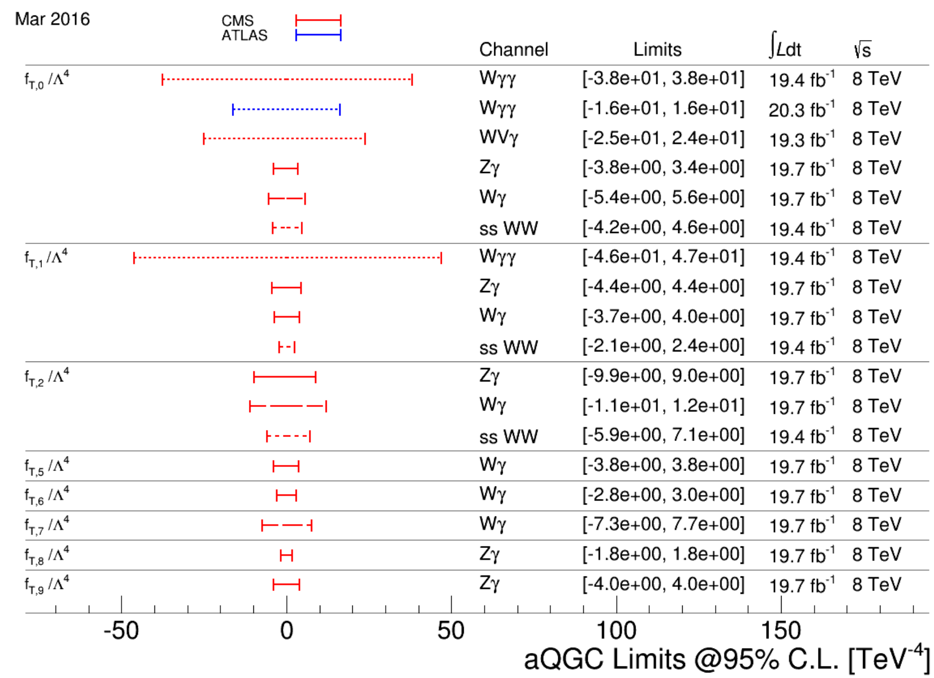
Backup

First pp Collisions in 2009!

Disclaimer: this is the ATLAS control room…

Current aQGC Limits





$\boxed{f_{M,x}/\Lambda^4}$

$\boxed{f_{T,x}/\Lambda^4}$