# Search for Signatures of Large Extra Dimensions in High-Mass Diphoton Events from Proton-Proton Collisions at $\sqrt{s}$ = 13 TeV with CMS

*Dissertation Defense*

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University of Alabama

07 November 2018

# Dissertation committee members

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Members

- Prof. Nobuchika Okada (UA)
- Prof. Toyoko Orimoto (NU)
- Prof. Andreas Piepke (UA)
- Prof. Paolo Rumerio (UA)
- Prof. Dawn R. Williams (UA)

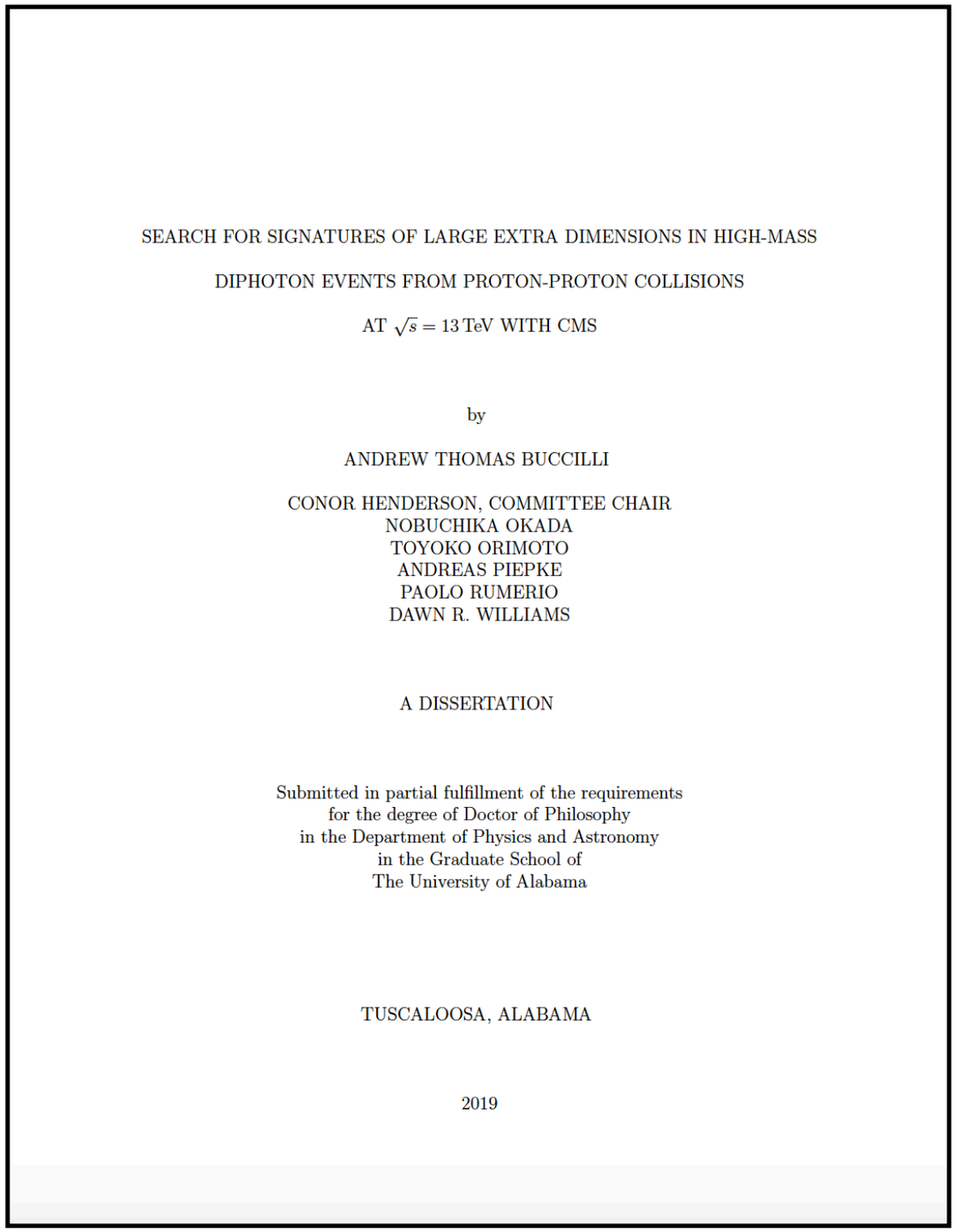
- Thank you for your 3 years of service since November 2015!

# Introduction

- Dissertation research
  - 2015 - 2018

- CMS Collaboration
  - 2016 LHC data
  - **diphoton ($\gamma\gamma$)** channel

- Search for nonresonant excess of high-mass diphoton events over the Standard Model background prediction
  - large extra-dimensional signal



SEARCH FOR SIGNATURES OF LARGE EXTRA DIMENSIONS IN HIGH-MASS

DIPHOTON EVENTS FROM PROTON-PROTON COLLISIONS

AT $\sqrt{s} = 13\,\text{TeV}$ WITH CMS

by

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A DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Physics and Astronomy
in the Graduate School of
The University of Alabama

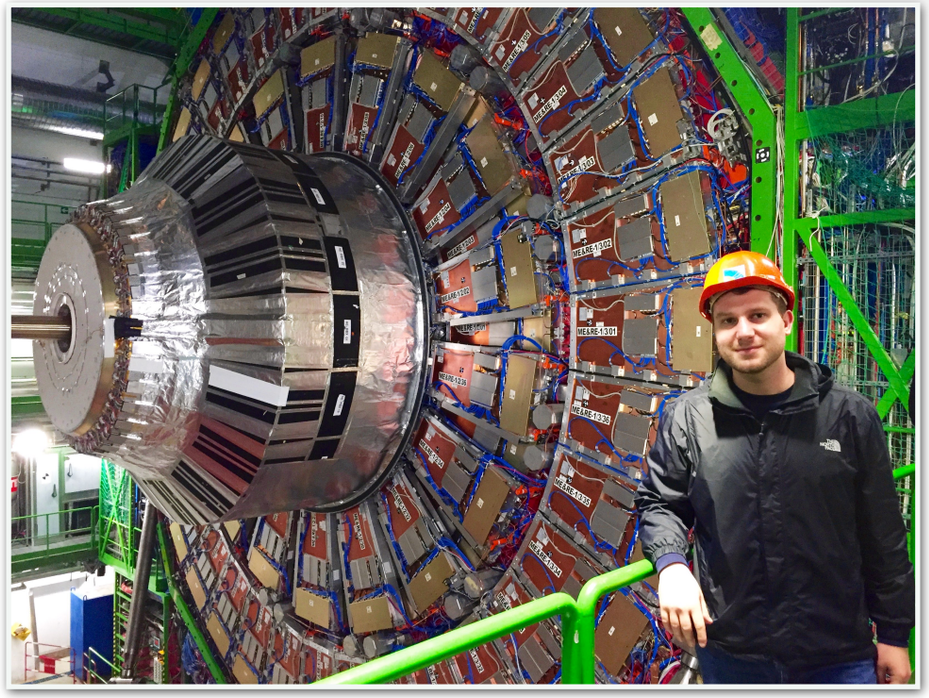
TUSCALOOSA, ALABAMA

2019

# Outline

- Theoretical motivation
  - Standard Model
  - Beyond the Standard Model

- Experimental apparatus
  - Large Hadron Collider
  - CMS detector



- Photon reconstruction and diphoton selection

- High-mass diphoton search
  - Signal simulation
  - Background determination

- Sources of systematic uncertainty

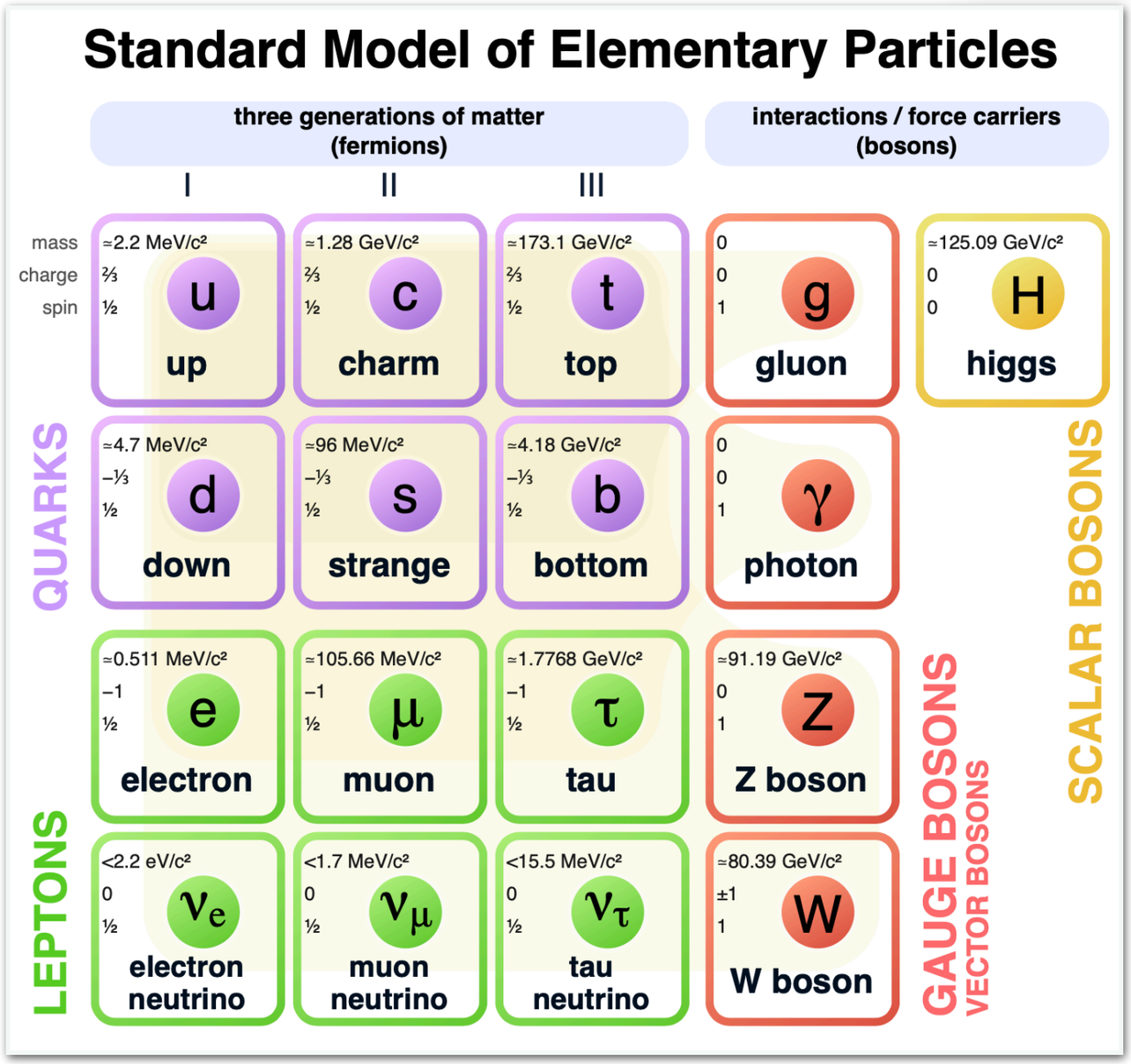
- Results and limit setting

# Standard Model

Gauge group

$SU(3)_C \times SU(2)_L \times U(1)_Y$

- Lagrangians invariant under local symmetry transformations
- Forces
  - strong $SU(3)_C$
  - electroweak $SU(2)_L \times U(1)_Y$
- Fermion representations
  - singlets not influenced by interaction



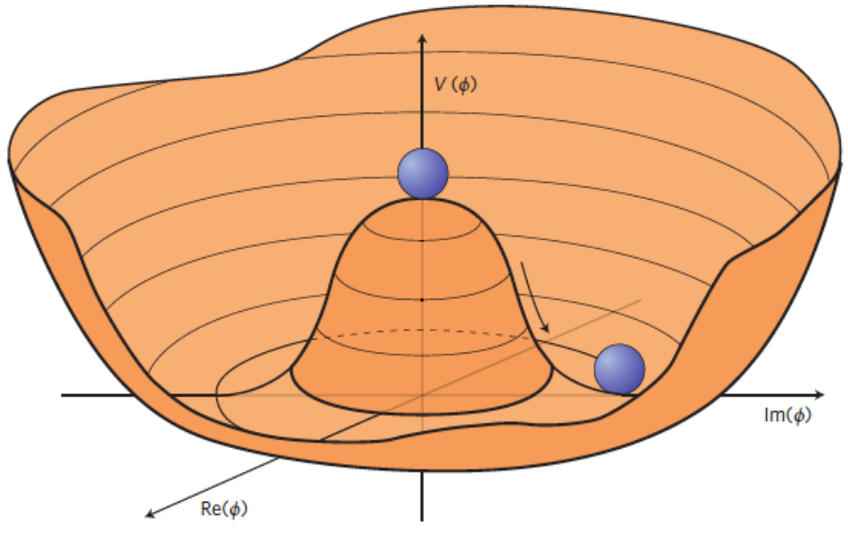

| SM fermion | $q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ | $u_R$ | $d_R$ | $\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | $e_R$ |
|---|---|---|---|---|---|
| $(SU(3)_c, SU(2)_L, U(1)_Y)$ representation | $(\mathbf{3}, \mathbf{2}, \frac{1}{6})$ | $(\mathbf{3}, \mathbf{1}, \frac{2}{3})$ | $(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ | $(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ | $(\mathbf{1}, \mathbf{1}, -1)$ |

# Electroweak symmetry breaking

- Higgs mechanism
  - spontaneous symmetry breaking of a local gauge symmetry

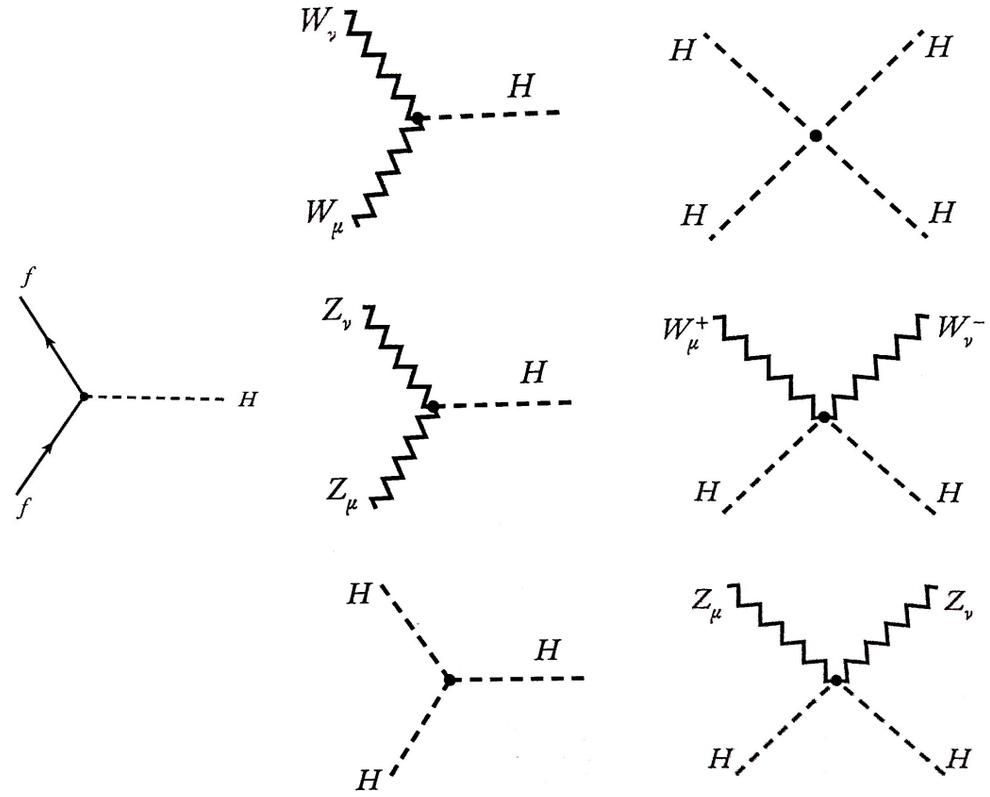
- Higgs field $\phi$ (**1**,**2**,1/2)

- $SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$




- Massive, neutral scalar boson *H*
  - couples to mass
  - $m_H \simeq 125$ GeV

- Responsible for generating masses
  - massive vector bosons
  - fermions (Yukawa interaction)
  - *H* boson



# SM interactions

## SM Lagrangian density

$$\mathcal{L} = -\frac{1}{4}G^{\alpha}_{\mu\nu}G^{\alpha\mu\nu} - \frac{1}{4}W^{a}_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

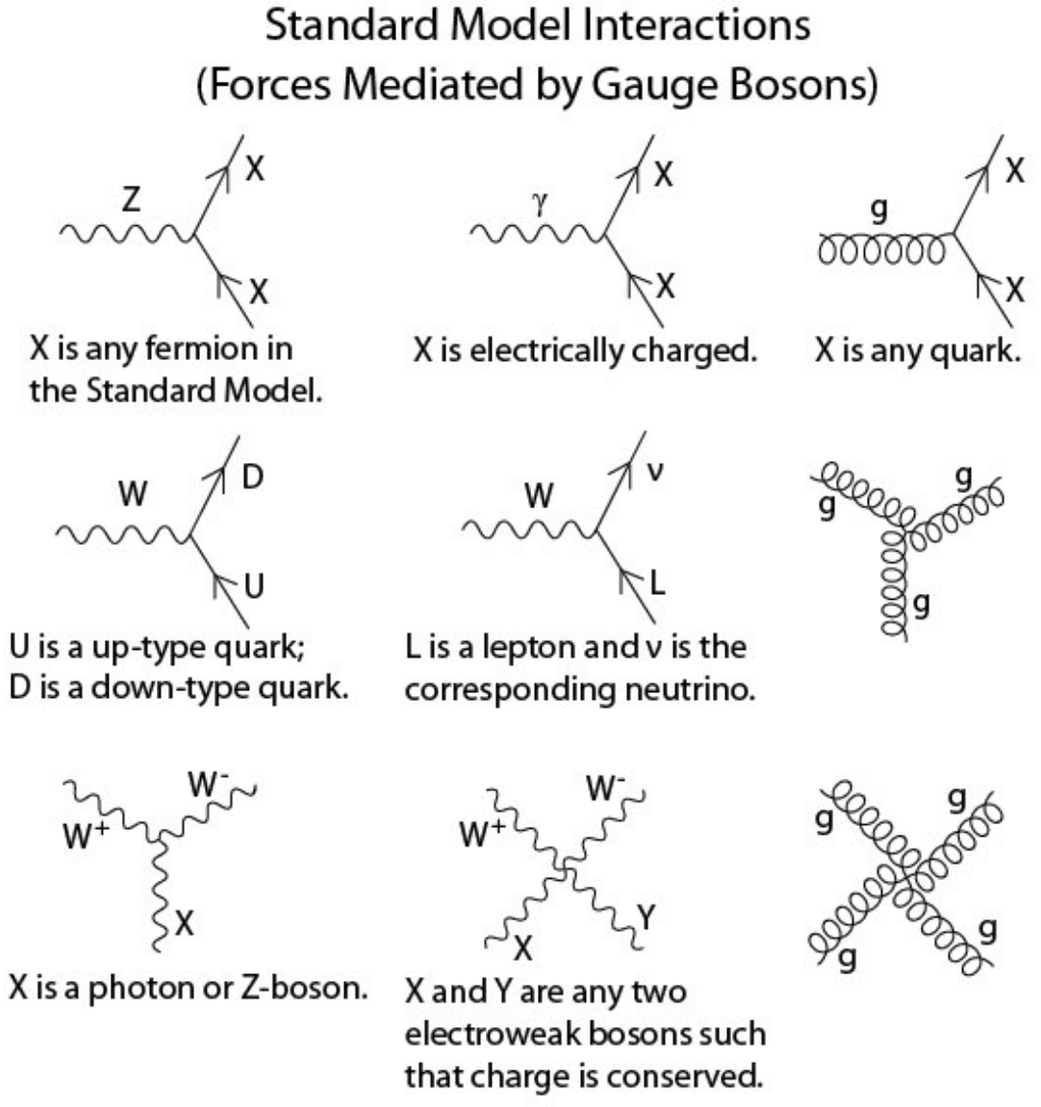
$$+ \bar{q}_L i \not{D} q_L + \bar{u}_R i \not{D} u_R + \bar{d}_R i \not{D} d_R$$

$$+ \bar{\ell}_L i \not{D} \ell_L + \bar{e}_R i \not{D} e_R$$

$$+ (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi)$$

$$- y_u \bar{q}_L \tilde{\phi} u_R - y_d \bar{q}_L \phi d_R - y_e \bar{\ell}_L \phi e_R$$

- Gauge invariance determines possible interactions and couplings
- gluons carry color and can self-interact

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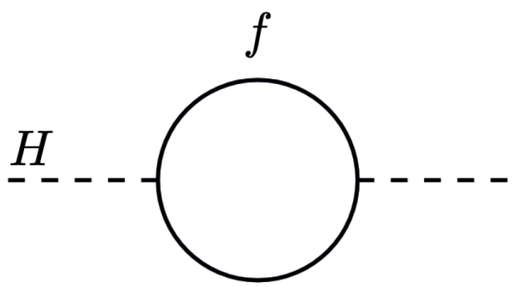
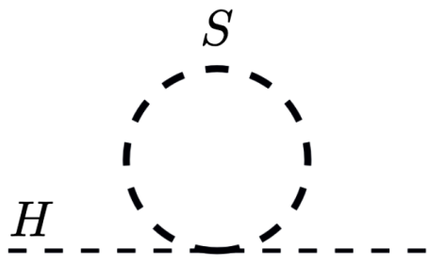
# Hierarchy problem

- Large difference between 2 fundamental scales
  - electroweak scale $M_{EW} \sim 10^2$ GeV
  - Planck scale $M_{Pl} = (\hbar c/G_N)^{1/2} \sim 10^{19}$ GeV

- Higgs boson (being a scalar) receives large quantum corrections proportional to the ultraviolet cutoff scale $\Lambda^2$

$$m_H^2 = m_0^2 + \Delta m_H^2$$




- Dominant one-loop corrections

$$\Delta m_H^2 = \frac{G_F \Lambda^2}{4\pi^2\sqrt{2}}(6m_W^2 + 3m_Z^2 + m_H^2 - 12m_t^2)$$

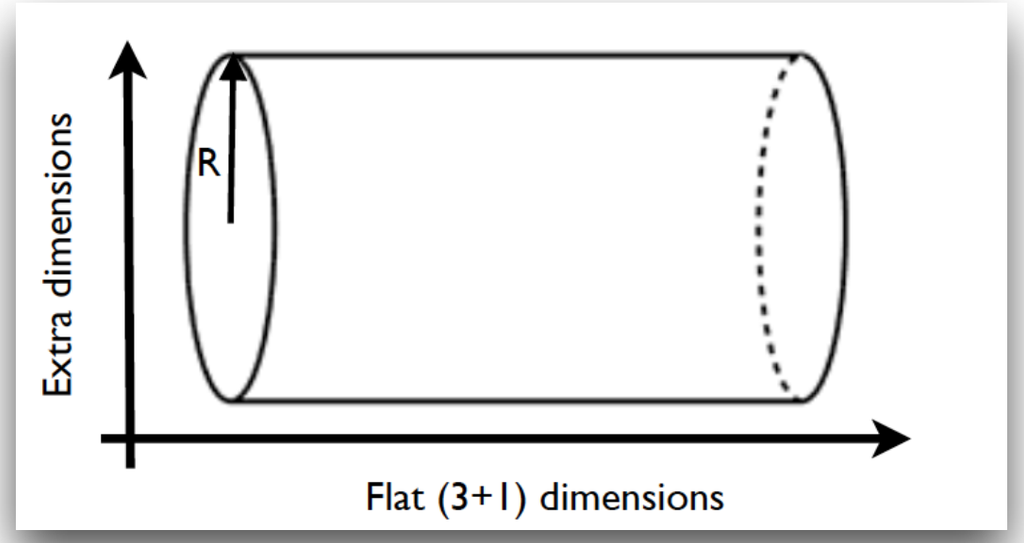
- Only choice of cutoff is $M_{Pl}$
  - Fine-tuning $\mathcal{O}(10^{34}$ GeV) required; seems unnatural

# Extra dimensions

- The presence of extra spatial dimensions can modify the scale of gravity
  - fundamental Planck scale $M_D$ in (4+$n_{ED}$)-dimensions is strong
  - observed Planck scale $M_{Pl}$ in (3+1)-dimensions appears weak

- Arkani-Hamed, Dimopoulos, and Dvali (ADD) model (*Phys. Lett. B* **429** (1998) 263)

- Proposes $n_{ED}$ additional flat extra dimensions
- Gravity propagates through entire "bulk" space
- SM particles and gauge interactions are confined to (3+1)-dimensional "brane" embedded in the bulk




- Extra dimensions are curled up and compactified in a sphere or torus of (average) radius $R$

# Large extra dimensions

- Gravitational potential energy in (4+$n_{ED}$)-dimensions:

$$U(r) \sim \frac{m_1 m_2}{M_{\mathrm{D}}^{n_{\mathrm{ED}}+2}} \frac{1}{r^{n_{\mathrm{ED}}+1}}, \text{ for } r \ll R$$

$$U(r) \sim \frac{m_1 m_2}{M_{\mathrm{D}}^{n_{\mathrm{ED}}+2} R^{n_{\mathrm{ED}}}} \frac{1}{r}, \text{ for } r \gg R$$

$$n_{\mathrm{ED}} = 1, \quad R \sim 10^{11}\ \mathrm{m};$$

$$n_{\mathrm{ED}} = 2, \quad R \sim 0.1\ \mathrm{mm};$$

$$n_{\mathrm{ED}} = 3, \quad R \sim 1\ \mathrm{nm};$$

$$n_{\mathrm{ED}} = 4, \quad R \sim 1\ \mathrm{pm};$$

$$n_{\mathrm{ED}} = 5, \quad R \sim 100\ \mathrm{fm};$$

$$n_{\mathrm{ED}} = 6, \quad R \sim 10\ \mathrm{fm};$$

$$n_{\mathrm{ED}} = 7, \quad R \sim 1\ \mathrm{fm}$$

- For $r \gg R$, we get the usual $1/r$ potential and

$$M_{\mathrm{Pl}}^2 \sim M_{\mathrm{D}}^{n_{\mathrm{ED}}+2} R^{n_{\mathrm{ED}}}$$

- If $M_D \sim M_{EW} \sim 1$ TeV, we find

$$R \sim 10^{\frac{30}{n_{\mathrm{ED}}}-19}\ \mathrm{m}$$

- We get large extra dimensions

- $n_{ED} = 1$ ruled out as deviations from Newton's law of gravity would be observed

# Phenomenology

- Graviton's momentum is quantized in (4+$n_{ED}$)-dimensions
  - appears as a tower of graviton excitations called Kaluza-Klein (KK) modes in (3+1)-dimensions, contributing to its mass

- Ultraviolet cutoff scale $\Lambda_G$ set to string mass scale ***$M_s$***
  - Regularize cross section
  - Multiple cutoff conventions

- Cross section parameterized by ***$\eta_G$***
  - interference between ADD signal and SM background can be large

- Energy spacing between adjacent modes 1/$R$
  - 1 meV - 100 MeV ($n_{ED}$ = 2-7)
  - effectively producing a nonresonant enhancement

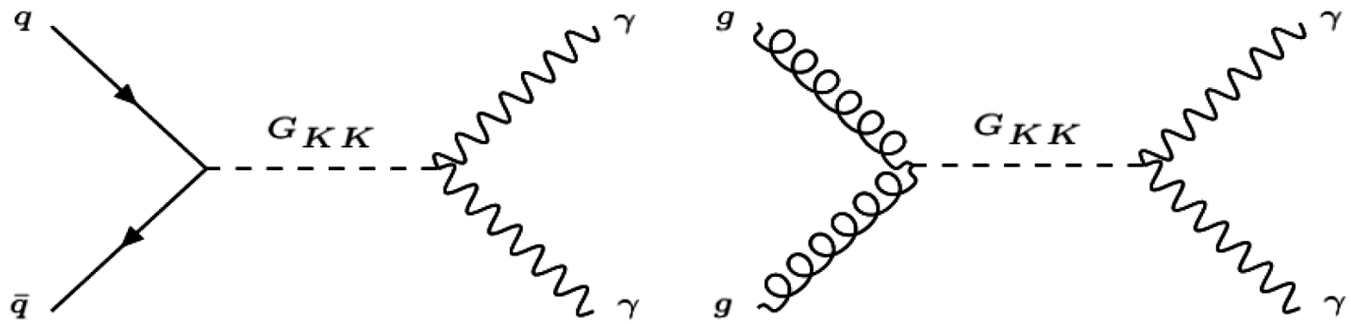
$$\eta_{\mathrm{G}} = \mathcal{F}/M_{\mathrm{S}}^4$$

$$\mathcal{F} = \begin{cases} 1 \quad (\mathrm{GRW}), \\ \log\left(\frac{M_{\mathrm{S}}^2}{\hat{s}}\right), \ \text{if } n_{\mathrm{ED}} = 2 \quad (\mathrm{HLZ}), \\ \frac{2}{n_{\mathrm{ED}}-2}, \ \text{if } n_{\mathrm{ED}} > 2 \\ \pm\frac{2}{\pi} \quad (\mathrm{Hewett}), \end{cases}$$

$$\sigma_{\mathrm{total}} = \sigma_{\mathrm{SM}} + \eta_{\mathrm{G}}\,\sigma_{\mathrm{int}} + \eta_{\mathrm{G}}^2\,\sigma_{\mathrm{ADD}}$$

# Diphoton channel

- $G_{KK} \rightarrow \gamma\gamma$
  - CMS detector provides excellent energy resolution for electromagnetic particles
  - Clean, isolated photon signature




- Dijet channel suffers from large background at the LHC
- Dilepton channel has a smaller branching ratio than diphoton
- Dilepton phase space is restricted since graviton *G* is spin-2

- Decay width for a KK Graviton is: $\Gamma_G \simeq \frac{293 m_G^3}{960\pi\Lambda_G^2}$

| $G_{\mathrm{KK}}$ decay mode | $HH$ | $gg$ | $\gamma\gamma$ | $W^+W^-$ | $ZZ$ | $t\bar{t}$ | $q\bar{q}$ | $l^+l^-$ |
|---|---|---|---|---|---|---|---|---|
| Branching ratio | 2/293 | 96/293 | 12/293 | 24/293 | 12/293 | 16/293 | 90/293 | 12/293 |

# Current limits

- Previous CMS nonresonant high-mass diphoton search used 2011 LHC data at $\sqrt{s}$ = 7 TeV

| Search | $\sqrt{s}$ | Data | Year | Limits on $M_S$ |
|---|---|---|---|---|
| CMS-EXO-10-026 | 7 TeV | $36\,\mathrm{pb}^{-1}$ | 2010 | 1.31-2.23 TeV |
| CMS-EXO-11-038 | 7 TeV | $2.2\,\mathrm{fb}^{-1}$ | 2011 | 2.28-3.50 TeV |

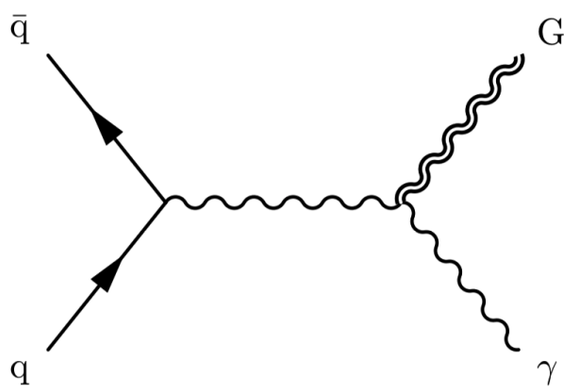
- CMS dijet angular search offers best limits on $M_S$ to date ranging between 8.5-12 TeV depending on the model convention
  - using 35.9 fb$^{-1}$ with $\sqrt{s}$ = 13 TeV

- ATLAS diphoton search sets limits on $M_S$ from 5.7-8.1 TeV
  - using 37 fb$^{-1}$ with $\sqrt{s}$ = 13 TeV

- Note: complementary searches for large extra dimensions
  - *direct graviton emission*
    - sets limits on $M_D$
  - *microscopic black hole production*
    - collision energy exceeds $M_D$

$q\bar{q} \to \gamma G$

**virtual graviton exchange**



# Large Hadron Collider

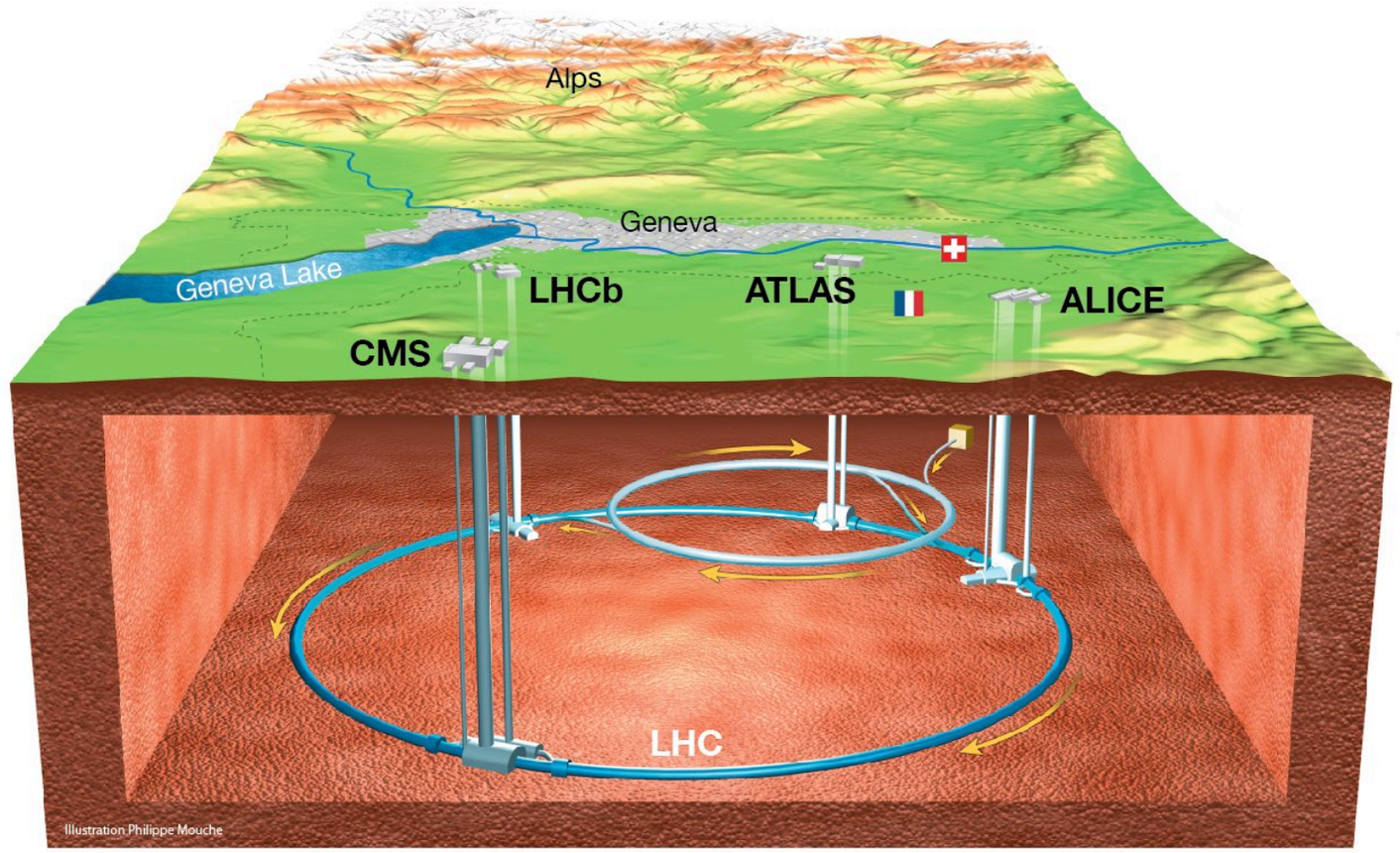
# LHC overview

- Large Hadron Collider
  - 27 km circumference
  - ~100 m underground

- pp, pPb, PbPb, XeXe collisions

- 1232 superconducting magnets
  - 8.3 T
  - 15 m long

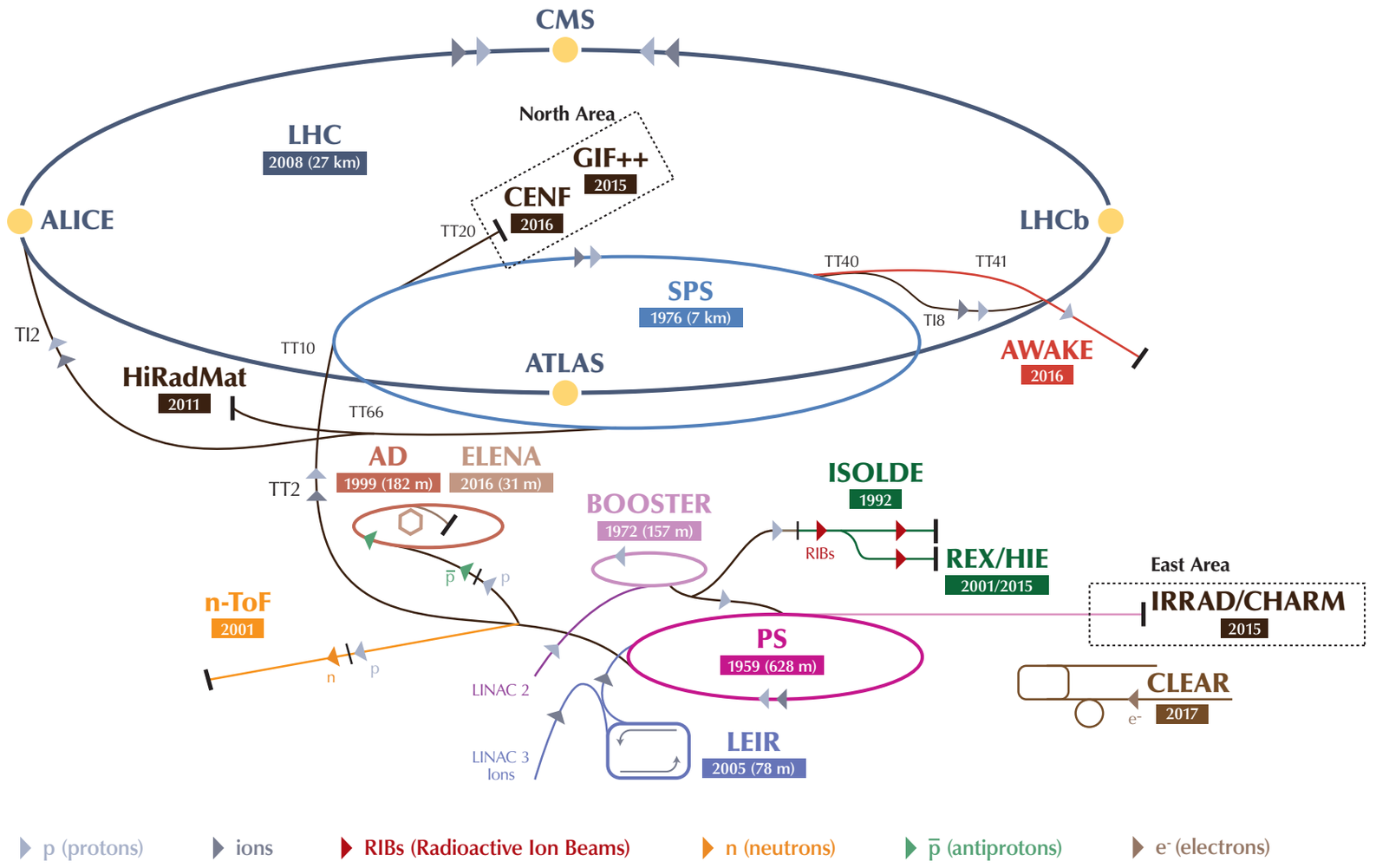
- proton bunches
  - 2808 bunches
  - 25 ns spacing
  - $10^{11}$ protons/bunch



# CERN accelerator complex

## Proton acceleration chain:

1. Linac 2 (50 MeV)
2. PSB (1.4 GeV)
3. PS (25 GeV)
4. SPS (450 GeV)
5. LHC (14 TeV)




**LHC** - Large Hadron Collider // **SPS** - Super Proton Synchrotron // **PS** - Proton Synchrotron // **AD** - Antiproton Decelerator // **CLEAR** - CERN Linear Electron Accelerator for Research // **AWAKE** - Advanced WAKefield Experiment // **ISOLDE** - Isotope Separator OnLine // **REX/HIE** - Radioactive EXperiment/High Intensity and Energy ISOLDE // **LEIR** - Low Energy Ion Ring // **LINAC** - LINear ACcelerator // **n-ToF** - Neutrons Time Of Flight // **HiRadMat** - High-Radiation to Materials // **CHARM** - Cern High energy AcceleRator Mixed field facility // **IRRAD** - proton IRRADiation facility // **GIF++** - Gamma Irradiation Facility // **CENF** - CErn Neutrino platForm

# Luminosity

- Instantaneous luminosity

$$\mathcal{L} = \frac{N_{\mathrm{b}}^2 f n_{\mathrm{b}}}{4\pi\sigma_{\mathrm{x}}^{*}\sigma_{\mathrm{y}}^{*}} F$$

- Integrated luminosity

$$L = \int \mathcal{L}\,\mathrm{d}t$$

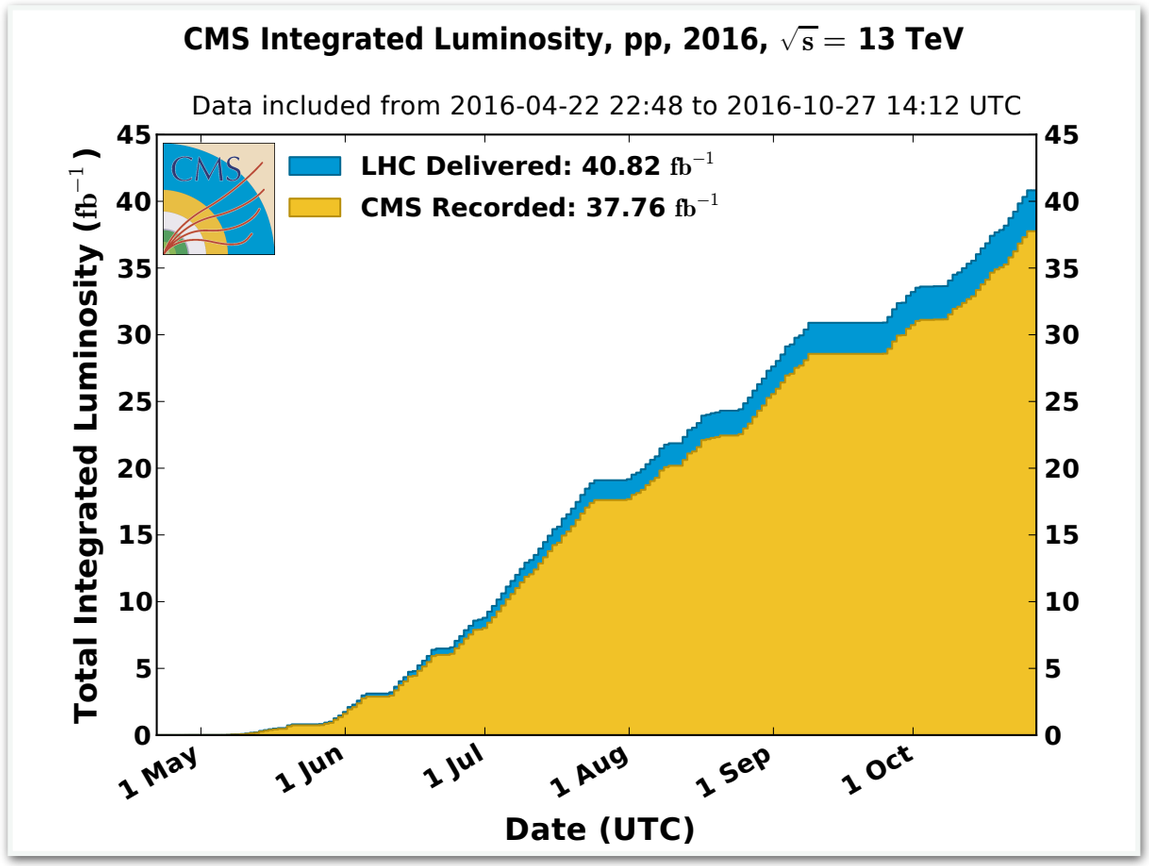
- Number of events *N*

$$L = N\sigma$$

- $\sigma$ is pp interaction cross section
  - ~100 mb

$1\ \mathrm{fb}^{-1} = 10^{39}\ \mathrm{cm}^{-2}$

- $N_b$: number of protons/bunch
- $n_b$: number of bunches
- $f$: LHC revolution frequency
- $F$: geometric loss factor
- $\sigma^*_{x,y}$: transverse beam width at IP



# LHC schedule

LHC physics production schedule for pp collisions with integrated luminosity recorded by CMS

- **Run 1:** 2010-2012
  - 2010: $\sqrt{s}$ = 7 TeV, 41.47 $pb^{-1}$, 50 ns
  - 2011: $\sqrt{s}$ = 7 TeV, 5.55 $fb^{-1}$, 50 ns
  - 2012: $\sqrt{s}$ = 8 TeV, 21.79 $fb^{-1}$, 50 ns

physics production run

- **LS1:** 2013-2014

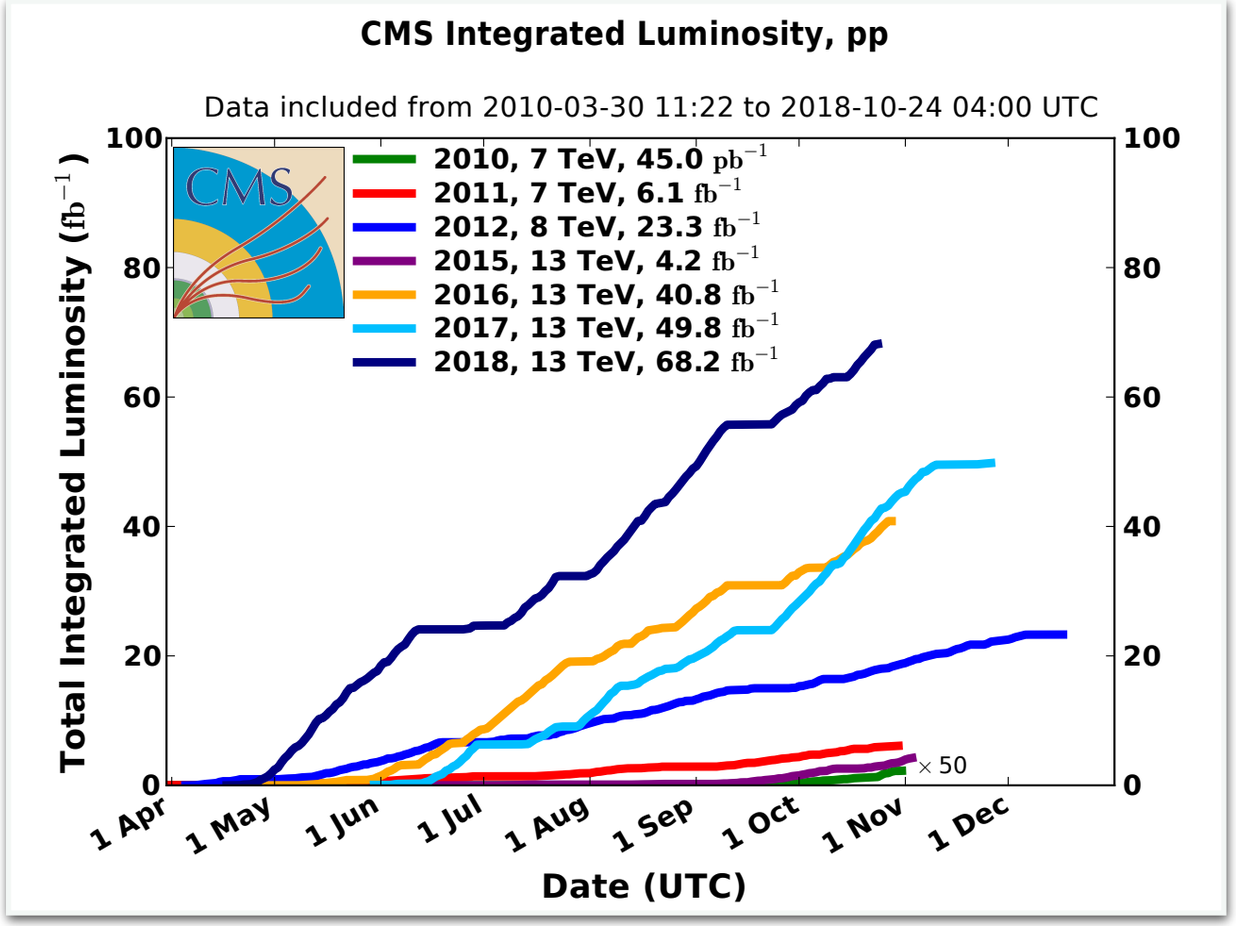
long shutdown

- **Run 2:** 2015-2018
  - 2015: $\sqrt{s}$ = 13 TeV, 3.81 $fb^{-1}$, 50 ns -> 25 ns
  - 2016: $\sqrt{s}$ = 13 TeV, 37.76 $fb^{-1}$, 25 ns
  - 2017: $\sqrt{s}$ = 13 TeV, 44.98 $fb^{-1}$, 25 ns
  - 2018: $\sqrt{s}$ = 13 TeV, 63.97 $fb^{-1}$, 25 ns

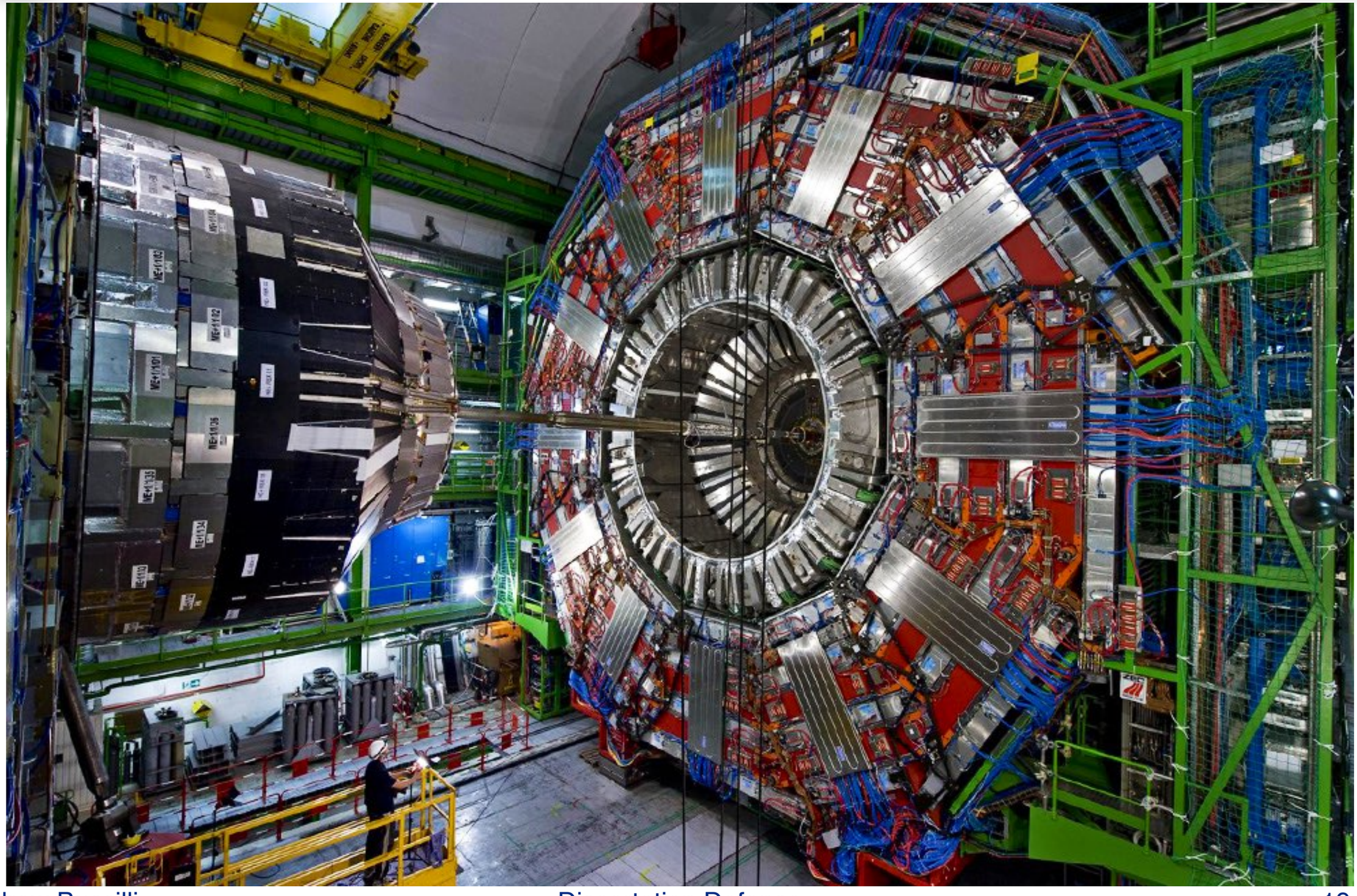
- **LS2:** 2019-2020

- **Run 3:** 2021-2023
  - $\sqrt{s}$ = 14 TeV

- **LS3:** 2024-?
  - High-Luminosity Large Hadron Collider



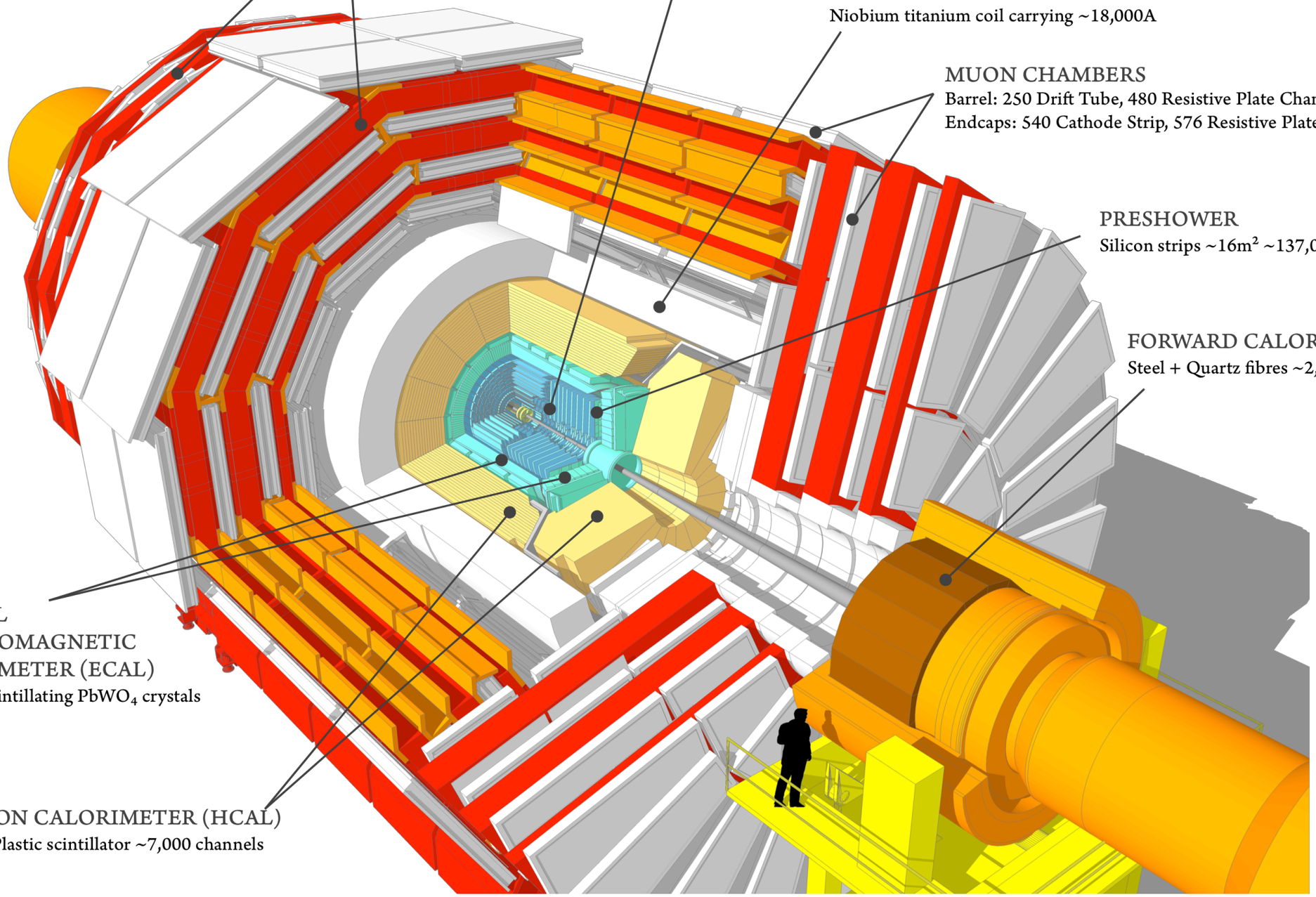
# Compact Muon Solenoid



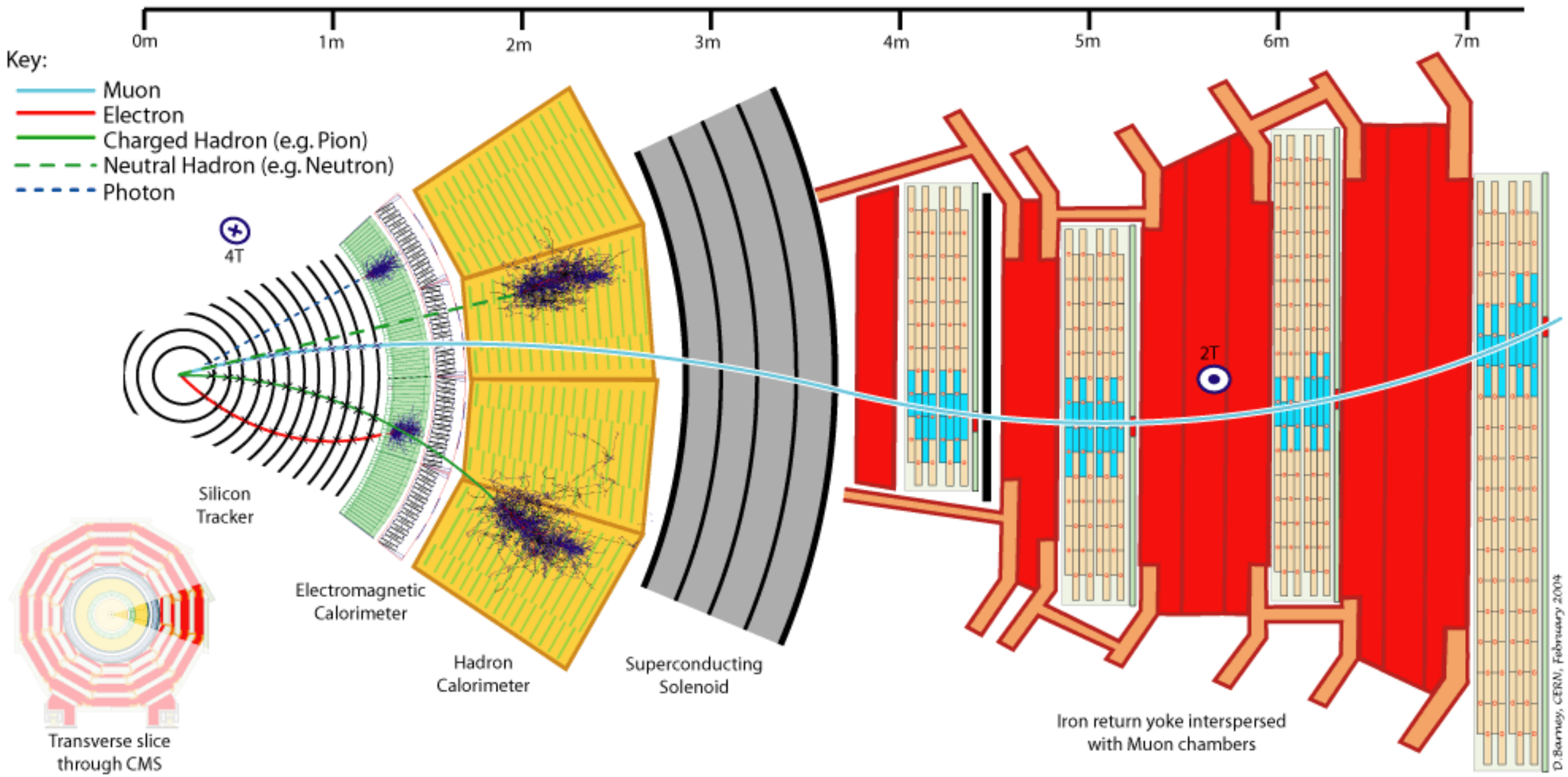
# CMS detector

## CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



# CMS particle identification

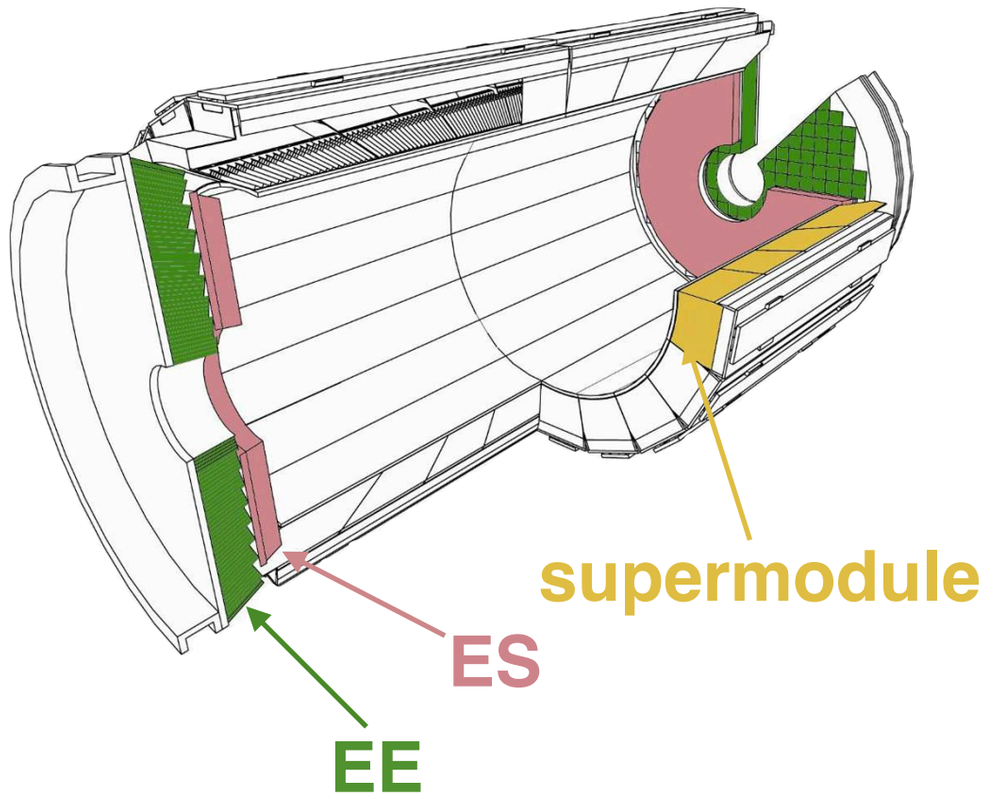


# ECAL

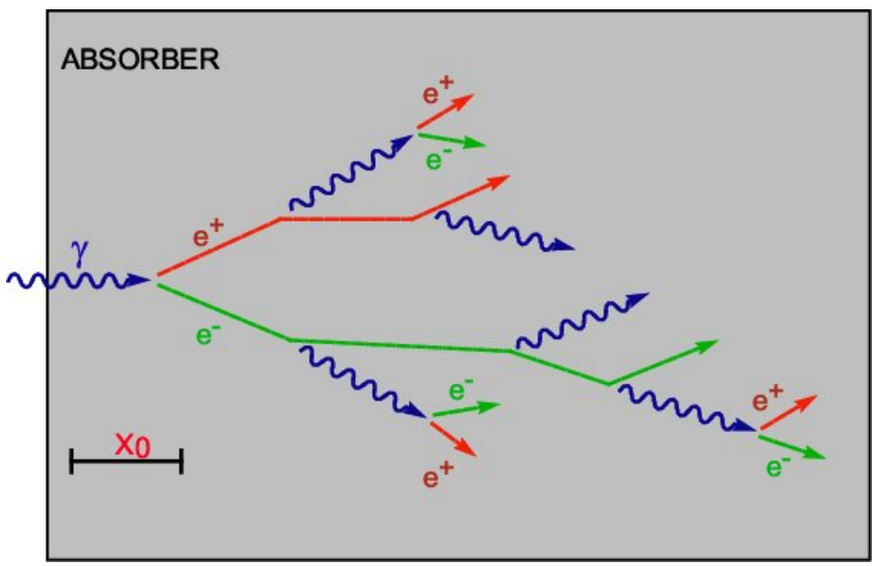
- Hermetic, homogeneous calorimeter comprising 75,000 $PbWO_4$ scintillating crystals

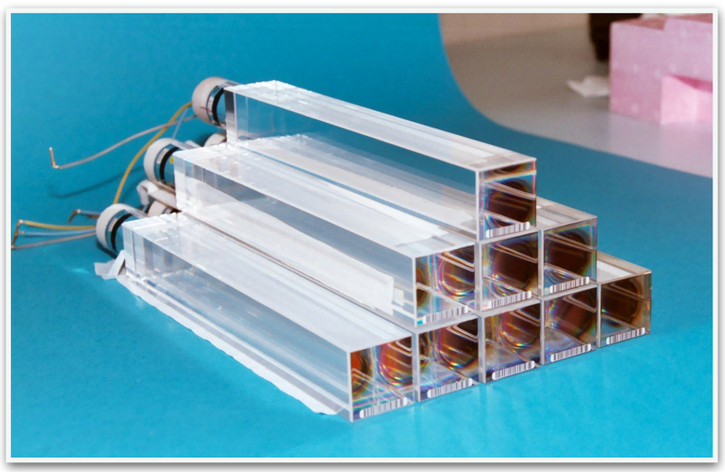
- ECAL barrel (**EB**) [$|\eta| < 1.48$]
  - 36 supermodules
  - $\Delta\eta x \Delta\phi$ = 0.0174x0.0174

- ECAL endcap (**EE**) [$1.48 < |\eta| < 3.0$]
  - 2 endcap disks
  - crystals grouped into 5x5 arrays of supercrystals
  - $\Delta \boldsymbol{x} x \Delta \boldsymbol{y}$ = 28.6x28.6 $mm^2$




- ECAL preshower (ES) [$1.65 < |\eta| < 2.6$]
  - sampling calorimeter (lead and silicon strips)



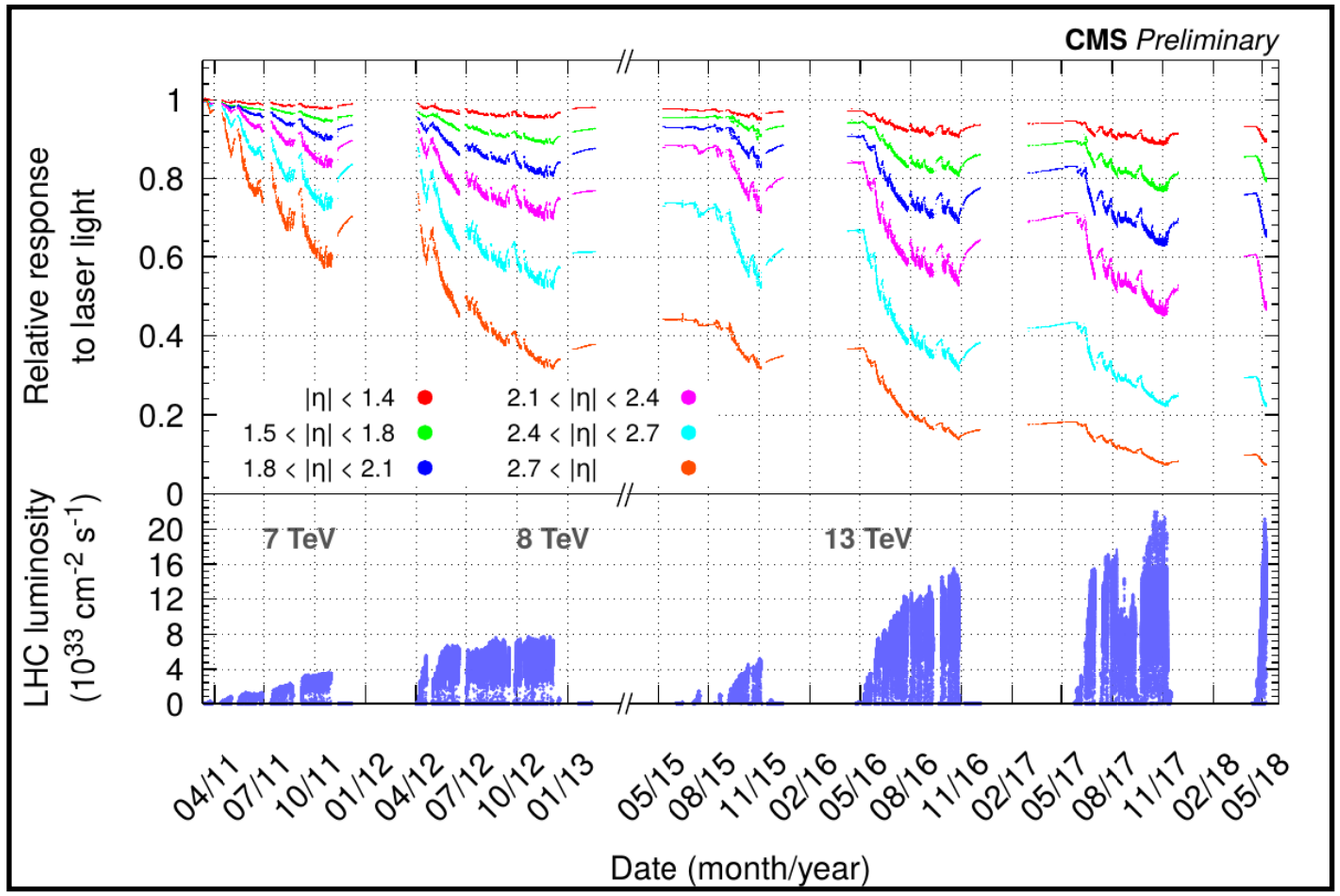
# ECAL energy resolution

- Energy resolution
  - stochastic term $a$ = 2.8%
  - noise term $b$ = 12%
  - constant term $c$ = 0.3%

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Active laser monitoring system corrects the crystal response during collisions, reducing the dominant constant term

- High-energy photons have an energy resolution of about
  - 1.3-2.5% in the EB
  - 3-4% in the EEs

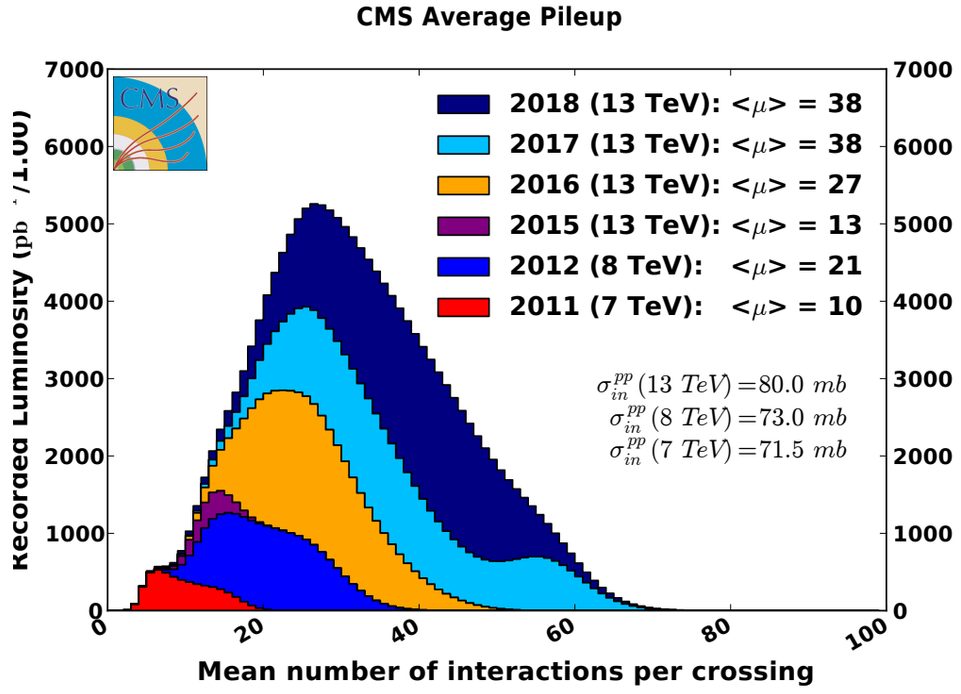


# Trigger system

- pp collisions occur every 25 ns at 40 MHz
- Multiple pp interactions within a single bunch crossing, *pileup*

- 1 MB/event for full CMS info

- Two-tier trigger system:
  - L1 trigger and HLT

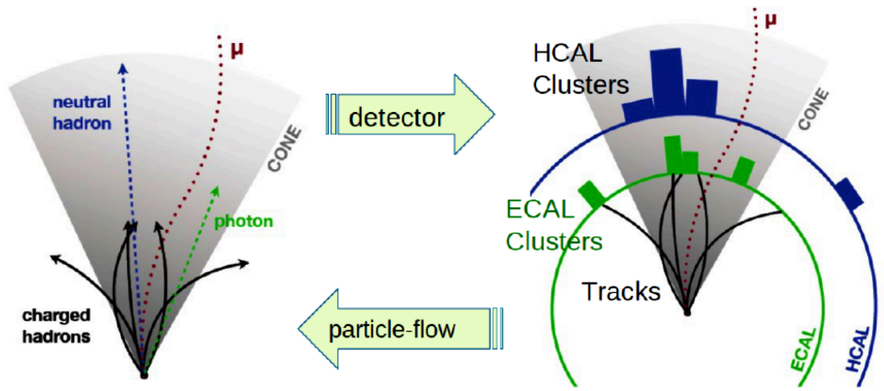



- L1 trigger
  - custom hardware
  - uses info from ECAL, HCAL, muon system
  - filters at 100 kHz (3.2 $\mu$s latency)

- HLT
  - processor farm running CMS online reconstruction software
  - works with DAQ to reduce event rate to about 1 kHz

# Event reconstruction

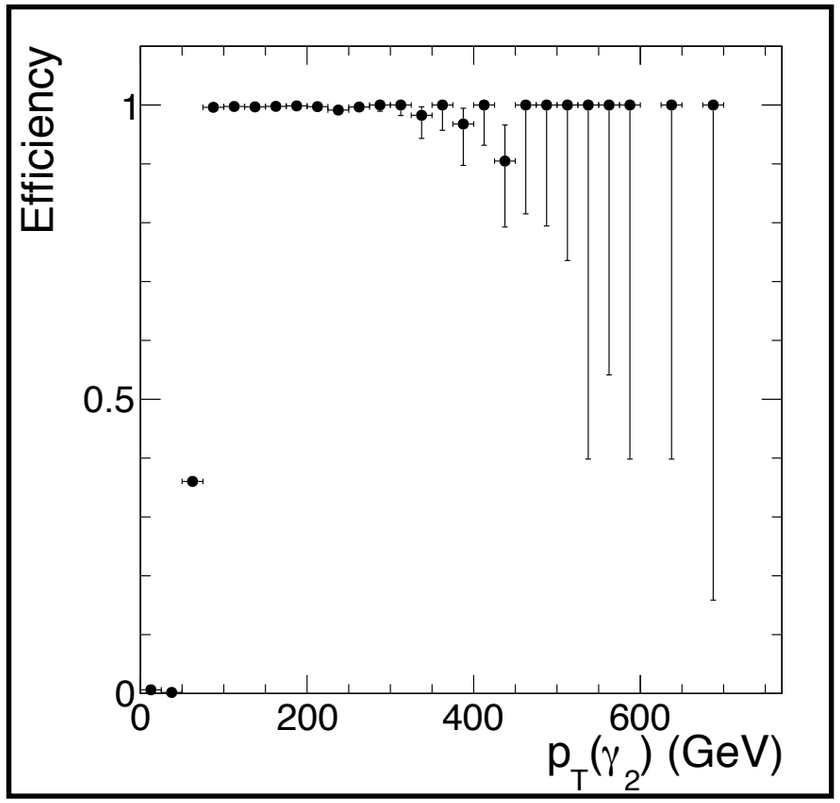
- Global event reconstruction uses the CMS particle-flow algorithm



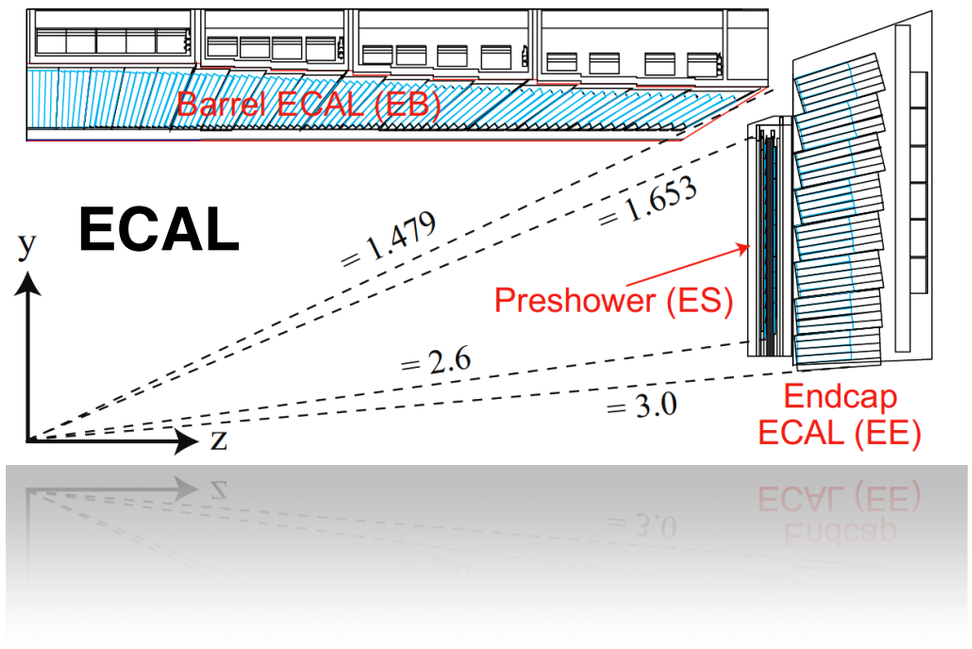

- Tracks
  - hits in the silicon tracker are fit to form tracks
- Vertices
  - primary vertices have largest summed charged-particle track $(p_T)^2$
- Photons
  - ECAL energy deposits are clustered into 5x5 arrays of crystals called superclusters centered on a seed
  - converted photons deposit energy extended along the $\phi$ direction
  - energy calibrated using $Z \rightarrow e^+e^-$ decays
  - ECAL electronics may saturate for high-energy photons depositing into a single crystal (~2 TeV)
  - scale factors derived from simulation are used to correct the energy scale and resolution
- Electrons
  - matching a track to an ECAL supercluster
- Muons
  - muon candidates in the muon system are fit to tracks in the inner tracking system
- Jets
  - quarks and gluons hadronize and are clustered into jets
- MET
  - missing energy in the transverse plane can be inferred given the initial transverse momentum is negligible

# Diphoton event selection

- Trigger selection
  - events with 2 photon candidates each with $p_T$ > 60 GeV




- Kinematic preselection
  - photon $p_T$ > 75 GeV (fully efficient trigger selection)
  - diphoton invariant mass $m_{\gamma\gamma}$ > 500 GeV
  - $\Delta R$ < 0.45
  - EBEB: two photons in EB
  - EBEE: one photon in EB and one in either EE




**EB**: ECAL barrel, $|\eta| < 1.44$
**EE**: ECAL endcap, $1.57 < |\eta| < 2.5$

- Diphoton vertex selection
  - primary vertex algorithm suboptimal for photons
  - $H \rightarrow \gamma\gamma$ analysis algorithm
  - both methods coverage at high-mass

# Photon identification

- Further criteria a imposed to suppress misidentifications from jets and electrons
  - $\pi^0 \rightarrow \gamma\gamma$

- Custom high-$p_T$ photon ID developed for this analysis

- Shower shape variables sensitive to multiple photon showers
  - $\boldsymbol{\sigma_{i\eta i\eta}}$: shower shape along the $\eta$ direction
  - **H/E**: ratio of HCAL over ECAL energy deposit
  - $\boldsymbol{R_9}$: ratio of the energies of 3x3 crystal array over supercluster

- Isolation variables sensitive to extra activity around the photon
  - $\textbf{Iso}_{\gamma}$: $p_T$ sum of other photons around photon candidate within $\Delta R = 0.3$
  - $\textbf{Iso}_{\textbf{Ch}}$: same for charged hadrons

$$\Delta R = \sqrt{(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2}$$

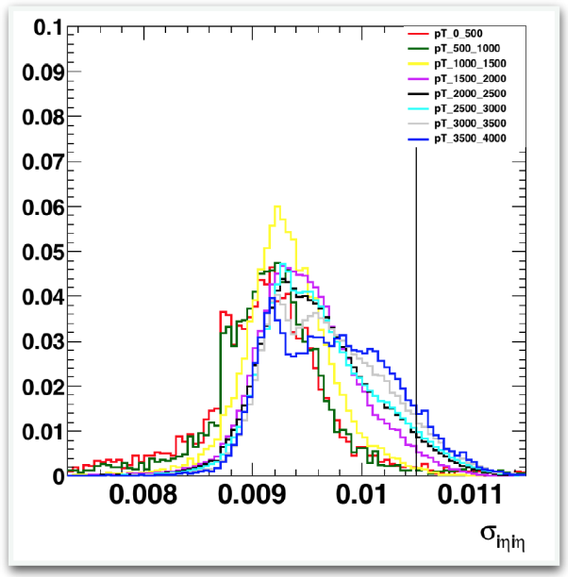
- Electron veto to eliminate electron candidates with mis-assigned tracks
  - **CSEV**: further checks to ensure that tracks assigned to photon did not result from a photon conversion

# Photon ID

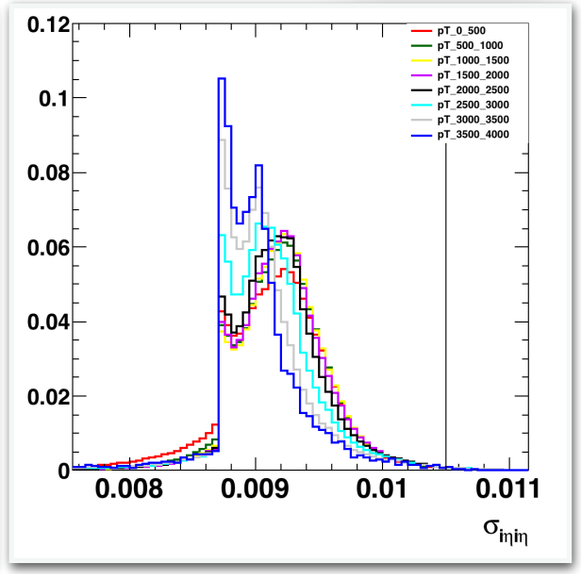
- $\text{Iso}_\gamma$ is corrected for pileup and $p_T$ dependence
- Saturation is accounted for in $\sigma_{i\eta i\eta}$

$$\overline{\text{Iso}_\gamma} = \alpha + \text{Iso}_\gamma - \rho A - \kappa p_\text{T}$$

| Detector region | $\alpha$ (GeV) | $A$ | $\kappa$ |
|---|---|---|---|
| $\lvert\eta_\text{SC}\rvert < 0.9$ | 0.99 | 0.15 | 0.0016 |
| $0.9 < \lvert\eta_\text{SC}\rvert < 1.4442$ | 0.99 | 0.13 | 0.0016 |
| $1.566 < \lvert\eta_\text{SC}\rvert < 2.0$ | 0.77 | 0.093 | 0.00075 |
| $2.0 < \lvert\eta_\text{SC}\rvert < 2.2$ | 0.77 | 0.15 | 0.00075 |
| $2.2 < \lvert\eta_\text{SC}\rvert < 2.5$ | 0.77 | 0.21 | 0.00075 |



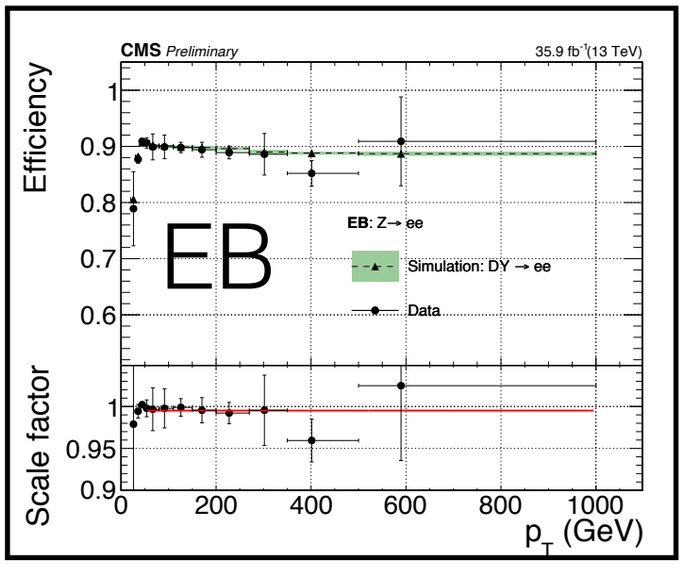

saturated

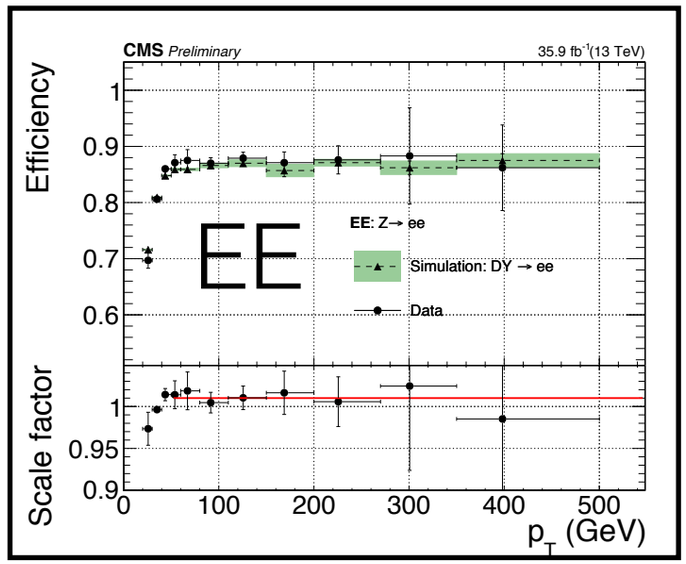



not saturated

| Photon category | $\text{Iso}_\text{Ch}$ (GeV) | $\overline{\text{Iso}_\gamma}$ (GeV) | H/E | $\sigma_{i\eta i\eta}$ | $R_9$ | CSEV |
|---|---|---|---|---|---|---|
| EB | 5 | 2.75 | 0.05 | 0.0105 (0.0112) | 0.8 | applied |
| EE | 5 | 2.0 | 0.05 | 0.028 (0.030) | 0.8 | applied |

- Photon selection is 90 (87)% for single photons in the EB (EE) region

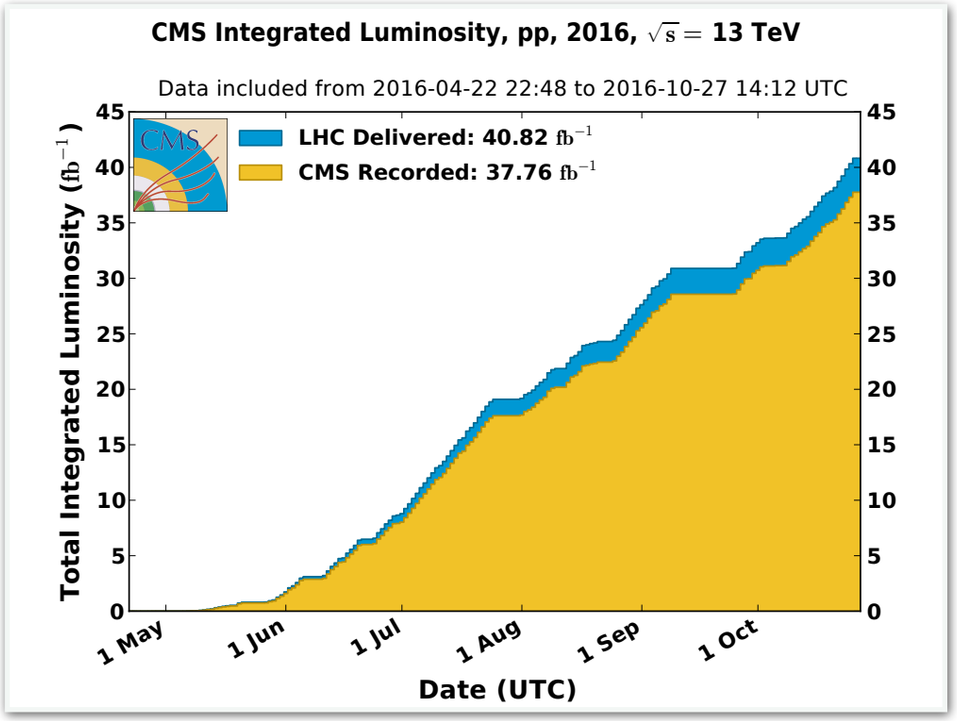


# Analysis strategy

- Search for a nonresonant excess in the high-mass diphoton spectrum at $\sqrt{s}$ = 13 TeV using the full 2016 dataset corresponding to an integrated luminosity of 35.9 $fb^{-1}$

- ADD signal modeled using Monte Carlo (MC) simulation



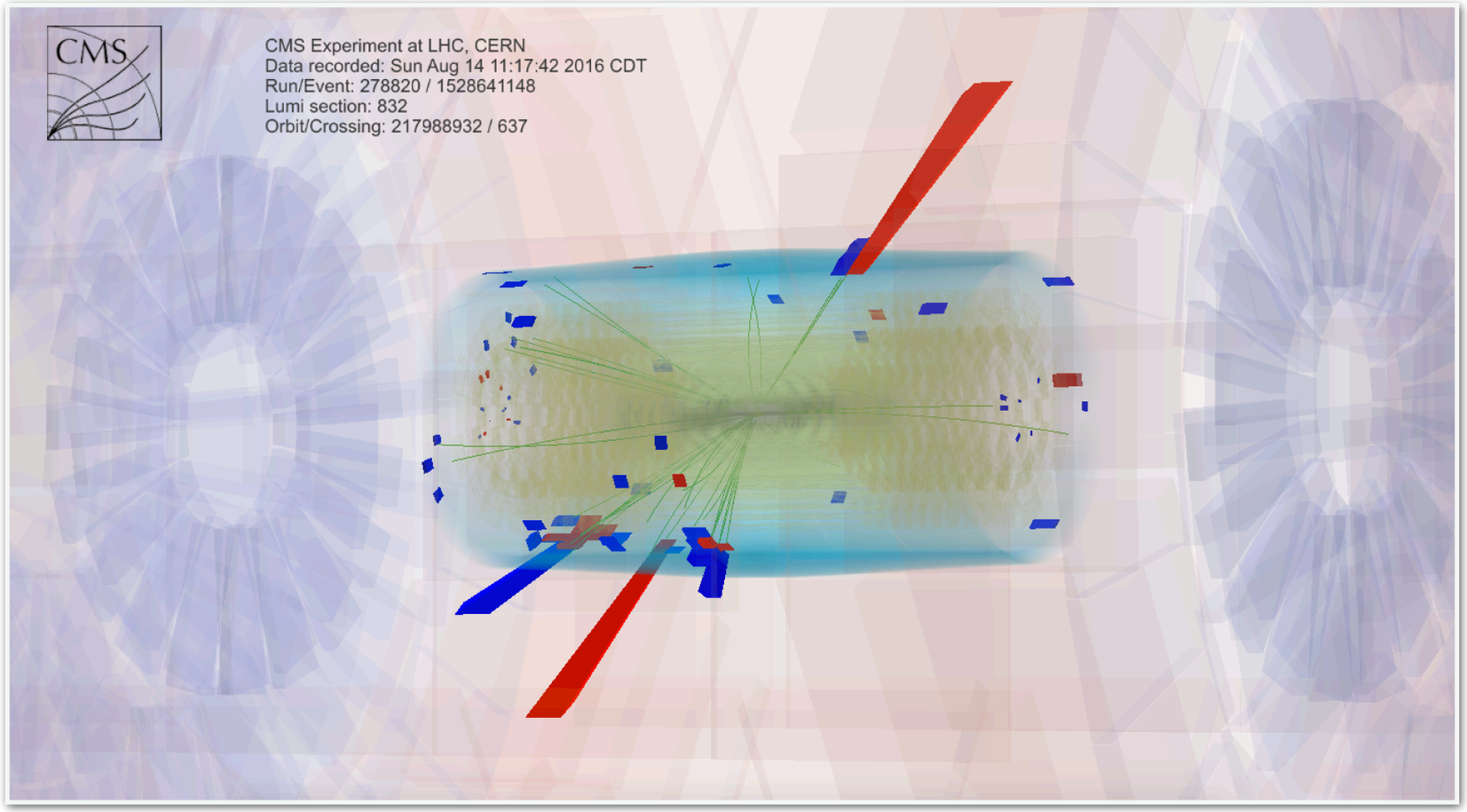

<u>Full background prediction is made:</u>

1. Dominant, irreducible prompt SM diphoton (***γγ***) background
   - Next-to-next-to-leading order (NNLO) MC calculation

2. Sub-dominant, reducible jet-faking-photon (***γj*** / ***jj***) background
   - Data-driven estimate using control samples

# Event display

- Highest-mass diphoton event recorded on August 14, 2016 in EBEB at $m_{\gamma\gamma}$ = 1840 GeV

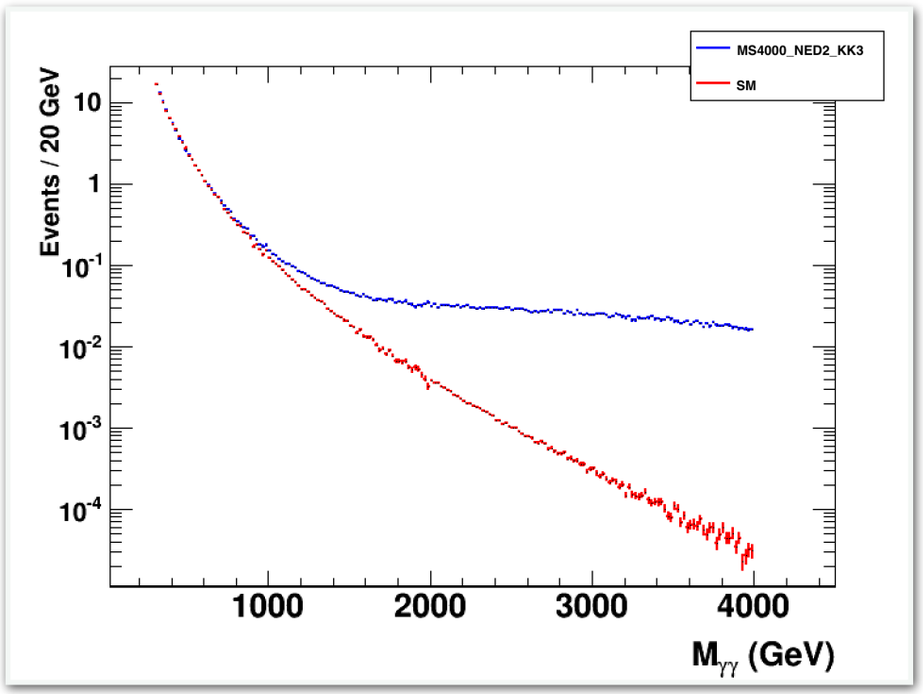


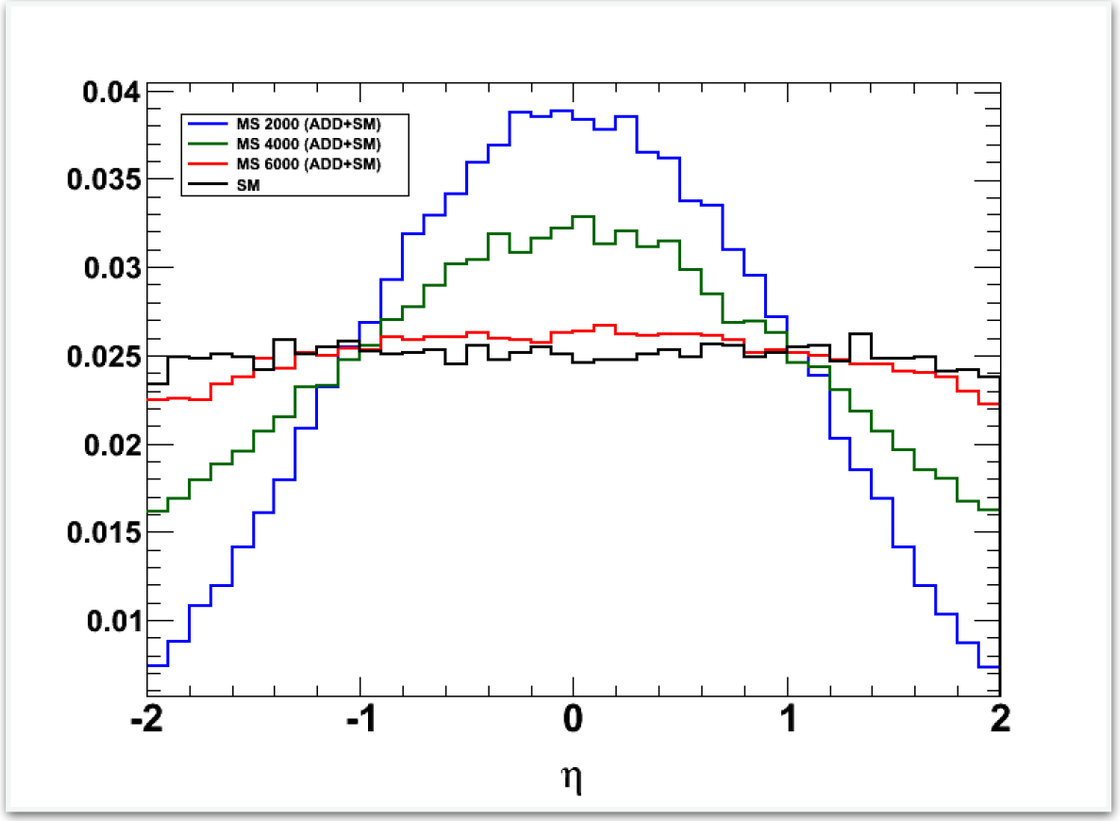

| | $m_{\gamma\gamma}$ (GeV) | $\gamma_1$ ($p_T$, $\eta_{SC}$) | $\gamma_2$ ($p_T$, $\eta_{SC}$) | Run:LS:Event | Dataset path | Date |
|---|---|---|---|---|---|---|
| EBEB | 1840.38 | (964.15, -0.881) | (429.01, 0.916) | 278820:832:1528641148 | /Run2016G-X-v1 | Aug 14 |
| | 1816.31 | (833.60, -0.160) | (679.74, -1.424) | 276810:249:448659898 | /Run2016D-X-v1 | Jul 14 |
| | 1777.39 | (508.64, -1.053) | (451.83, 1.405) | 276437:452:753595848 | /Run2016D-X-v1 | Jul 6 |
| EBEE | 2444.38 | (415.88, -2.484) | (272.98, 1.442) | 279794:445:700510844 | /Run2016G-X-v1 | Aug 30 |
| | 2134.42 | (570.82, -0.695) | (515.46, 1.916) | 284039:18:31148565 | /Run2016H-X_ver3-v1 | Oct 26 |
| | 1985.68 | (577.69, -2.443) | (397.34, 0.273) | 276585:21:32975214 | /Run2016D-X-v1 | Jul 10 |

# ADD signal model

- ADD model is parameterized by $n_{ED}$ and $M_S$
- Interference effects
  - signal generated with LO SM background using Sherpa v.2.1.1
    - samples generated with $m_{\gamma\gamma} \leq M_S$
- $M_S$ cutoff conventions $\mathcal{F}$
  - consider **HLZ**, **GRW**, and **Hewett**

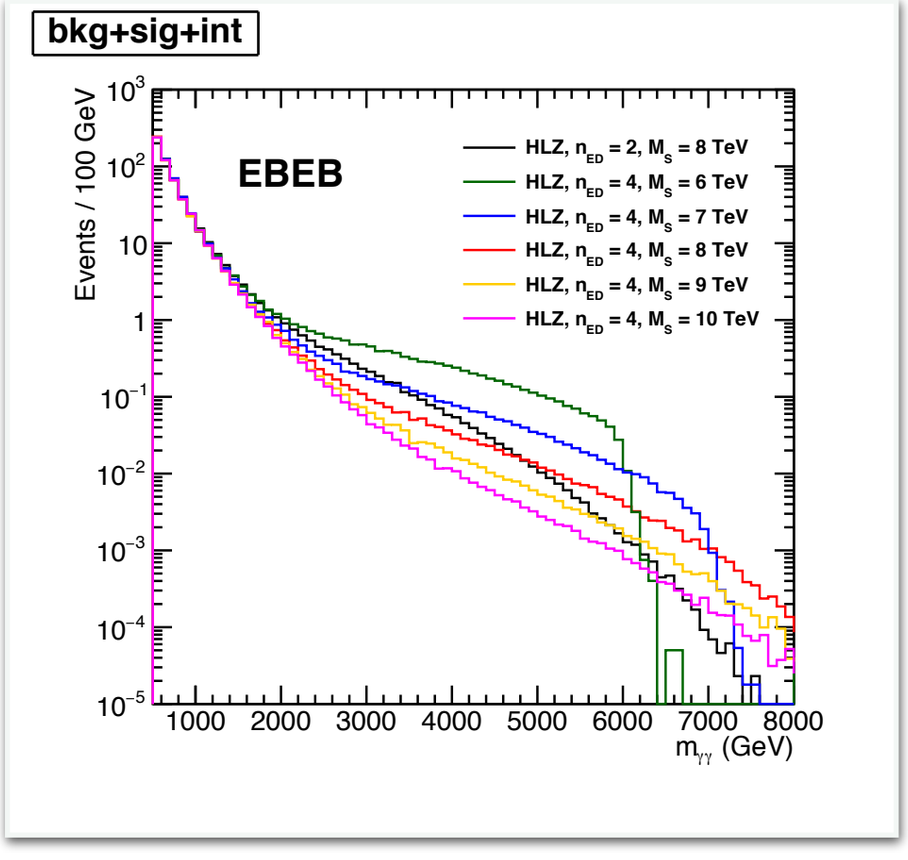
- Parameter space:
  - $M_S$ = 3-11 TeV
  - $n_{ED}$ = 2,3,…,7



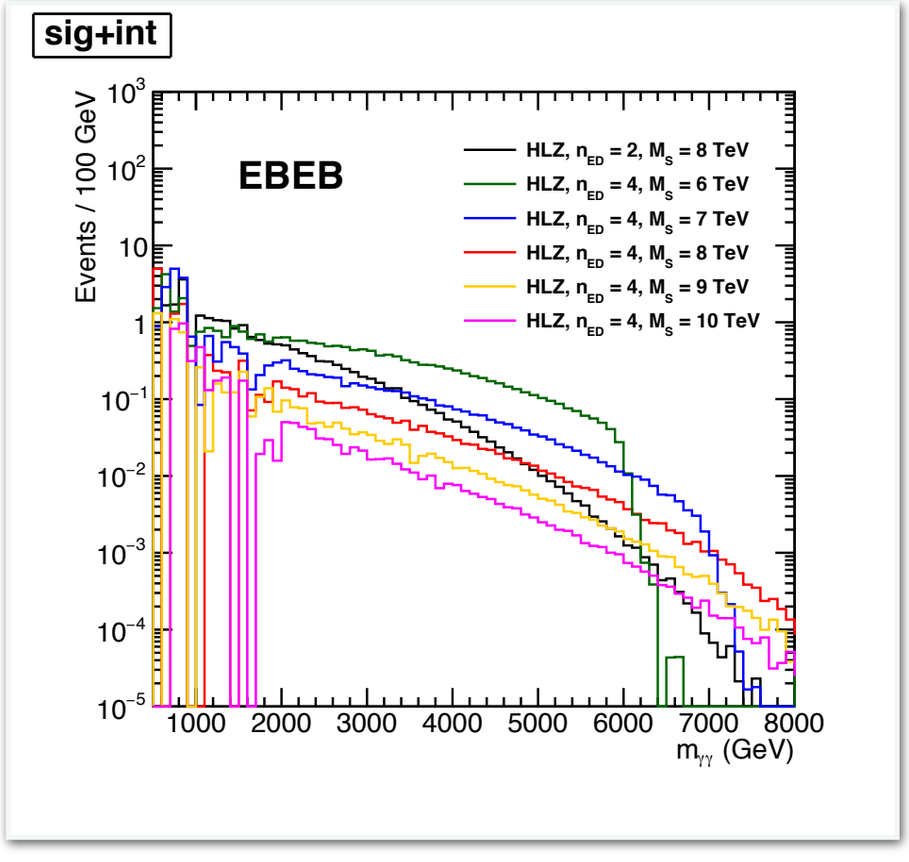



# ADD convention reduction

- Diphoton invariant mass distributions from different conventions are equivalent if they have the same value of $\eta_G$
  - Hewett+ with $M_S$ = 4000 GeV <-> GRW with $M_S$ = 4478 GeV
- Reduction in distinct signal points
  - **GRW** (constant positive interference)
  - **HLZ assuming $n_{ED}$ = 2** (positive interference with energy dependence)
  - **Hewett-** (negative interference)
- Each signal point broken into different $m_{\gamma\gamma}$ bins to improve statistics
  - 122 different samples totaling 12.2 million events



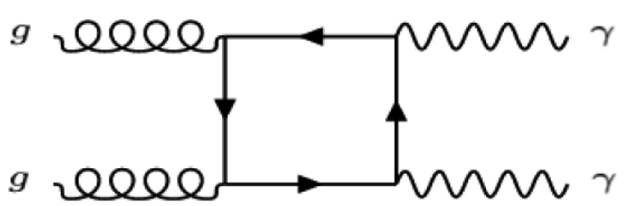

**sig.+bkg.+int.**



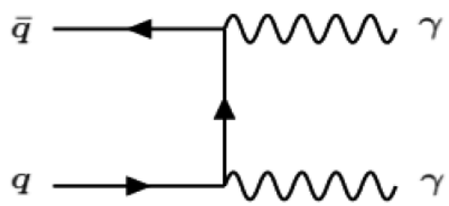

**sig.+int.**

# Real background

- Irreducible, prompt SM $\gamma\gamma$ background generated using Sherpa v.2.1.1 with:




**Box**

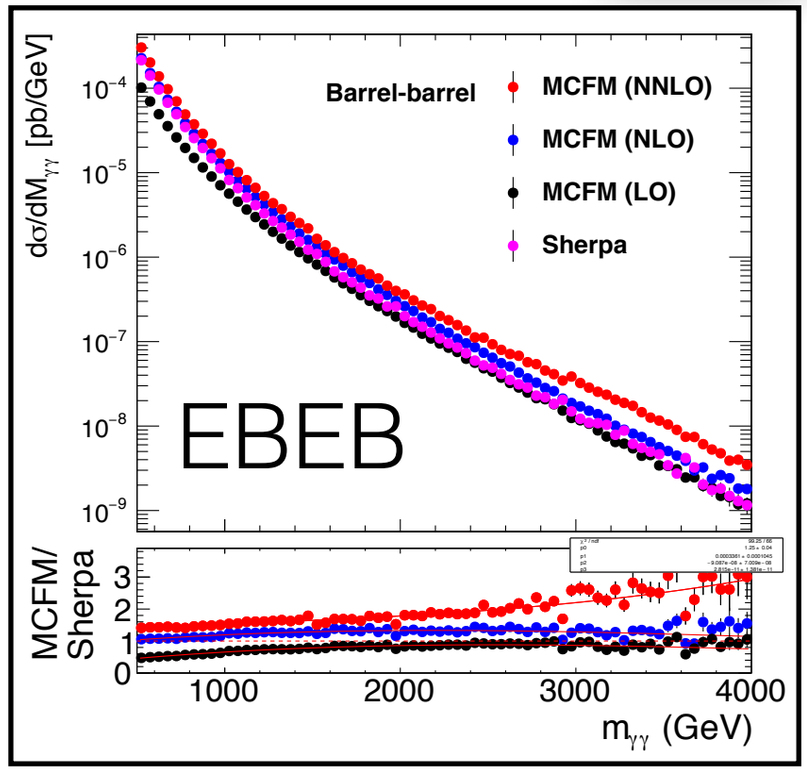


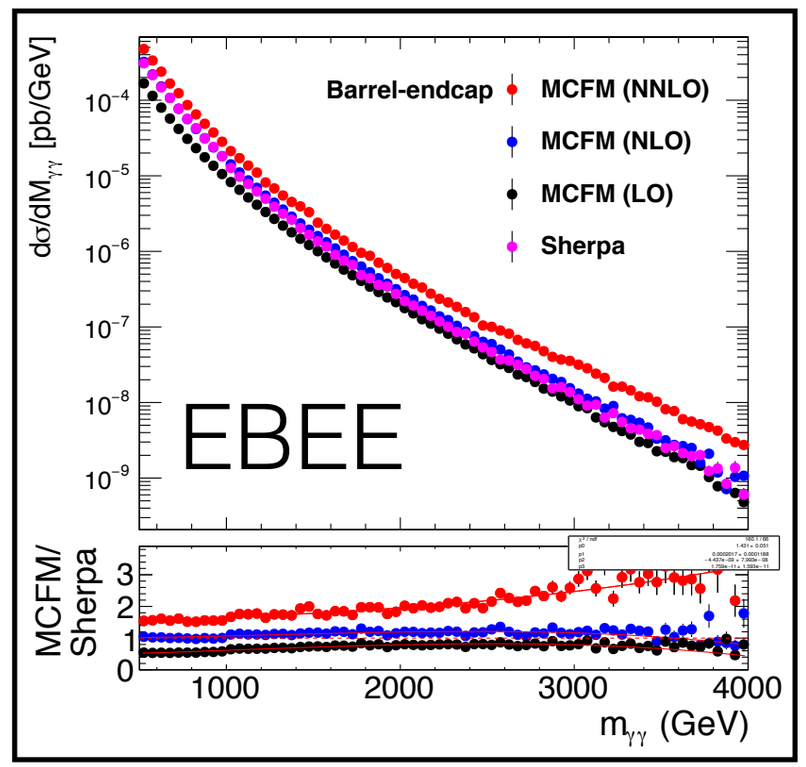

**Born + 0, 1, 2, or 3 jets**

- NNLO contribution to SM processes calculated using MCFM v.8.0
  - includes virtual corrections missing in Sherpa

- ***K* factor = MCFM / GEN-level Sherpa**
  - Function of $m_{\gamma\gamma}$
  - Used to reweight fully simulated prompt diphoton events (from Sherpa) for final prediction

- *K* factor: 1.4-2.2(2.5) in EBEB(EBEE) for $m_{\gamma\gamma}$ < 3 TeV



# Scale variations on *K* factor

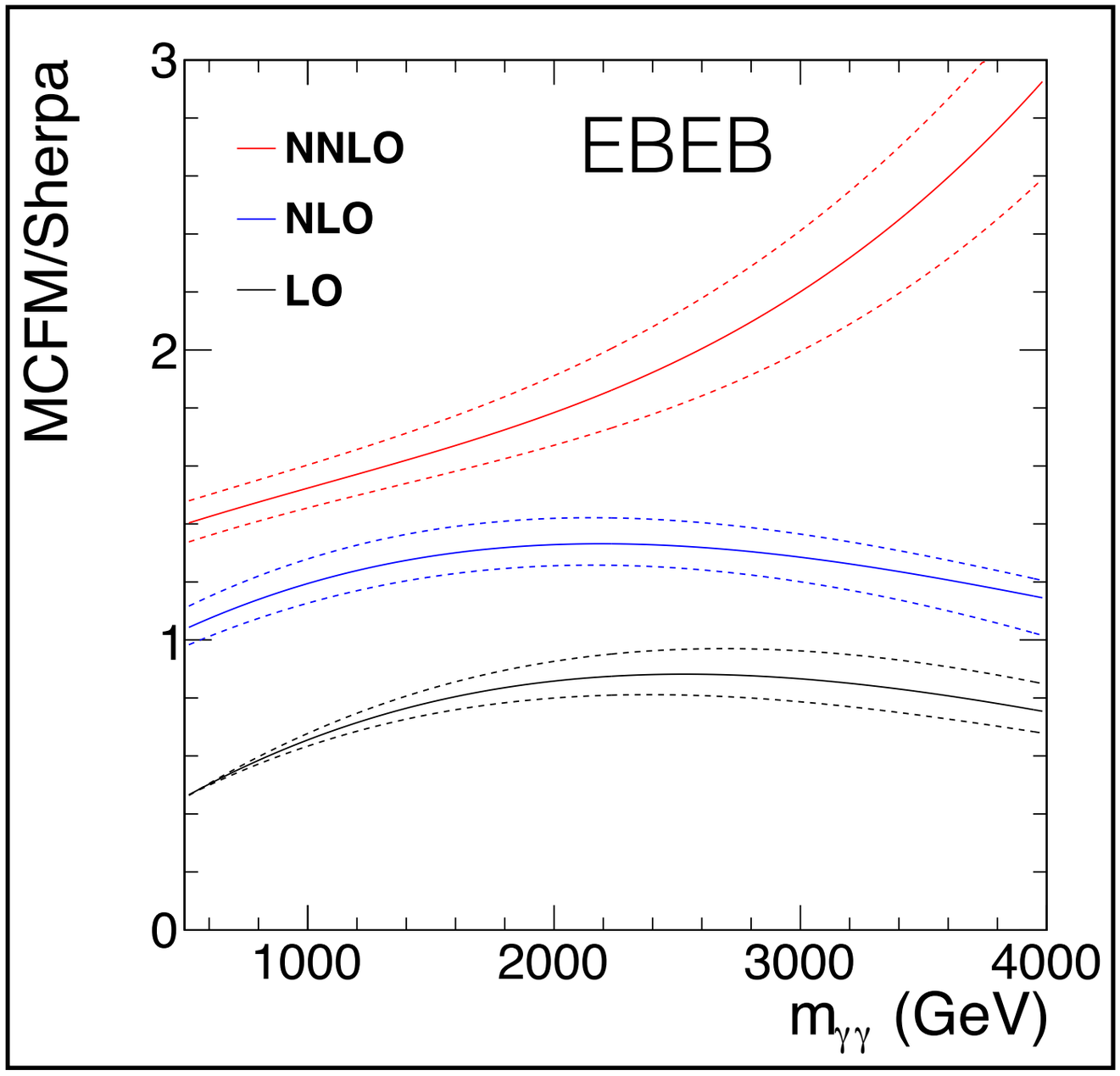
- Renormalization scale $\mu_r$
  - sets the truncation of the perturbative calculation

- Factorization scale $\mu_f$
  - sets the transition point between the hard calculation and the PDFs (separating long- and short-distance processes)

- Scale variations
  - $\mu_f = \mu_r = 2\ m_{\gamma\gamma}$
  - $\mu_f = \mu_r = m_{\gamma\gamma}$
  - $\mu_f = \mu_r = 1/2\ m_{\gamma\gamma}$

- Similar level of variation observed in EBEE

- Treated as a systematic uncertainty



# Fake background

- Reducible background from SM ***γj*** or ***jj*** events where one or two jets with large EM activity fake a photon signature
  - misreconstructed as a photon in the ECAL

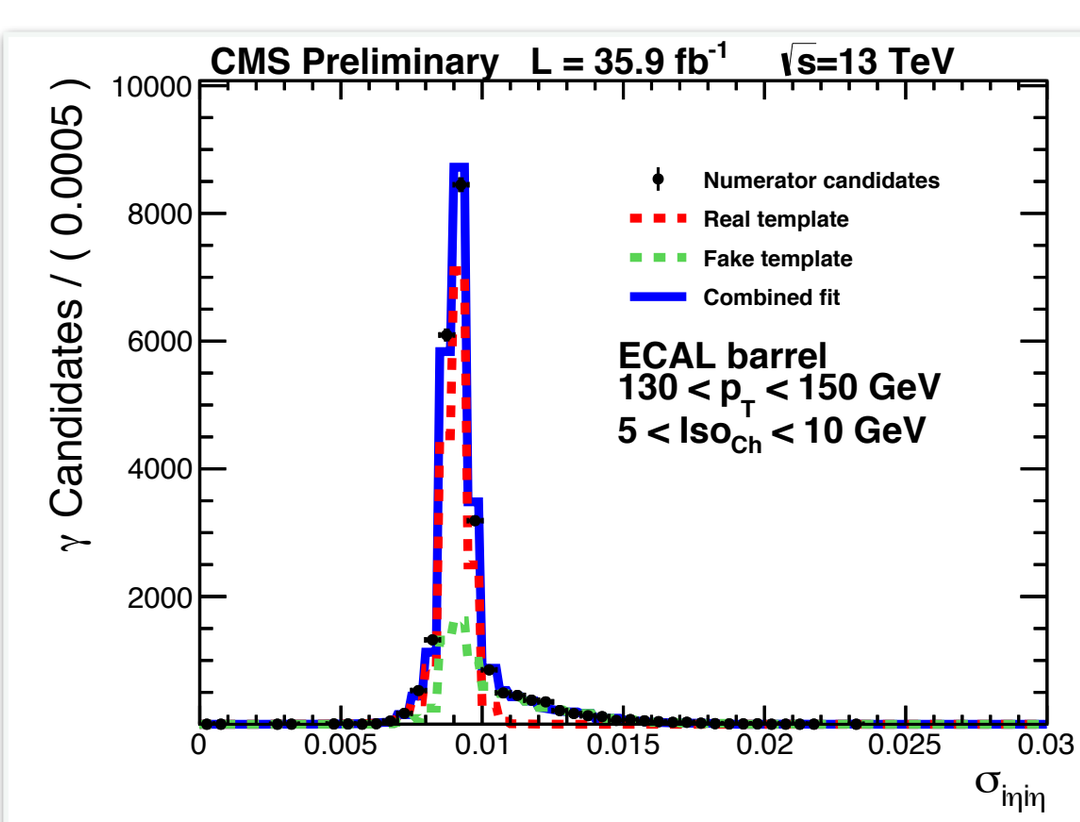
- Fake rate function ***f*($p_T$)** is measured in a jet-enriched <u>data reference sample</u> as a function of photon $p_T$ in EB and EE
  - combined jet- and muon-triggered dataset

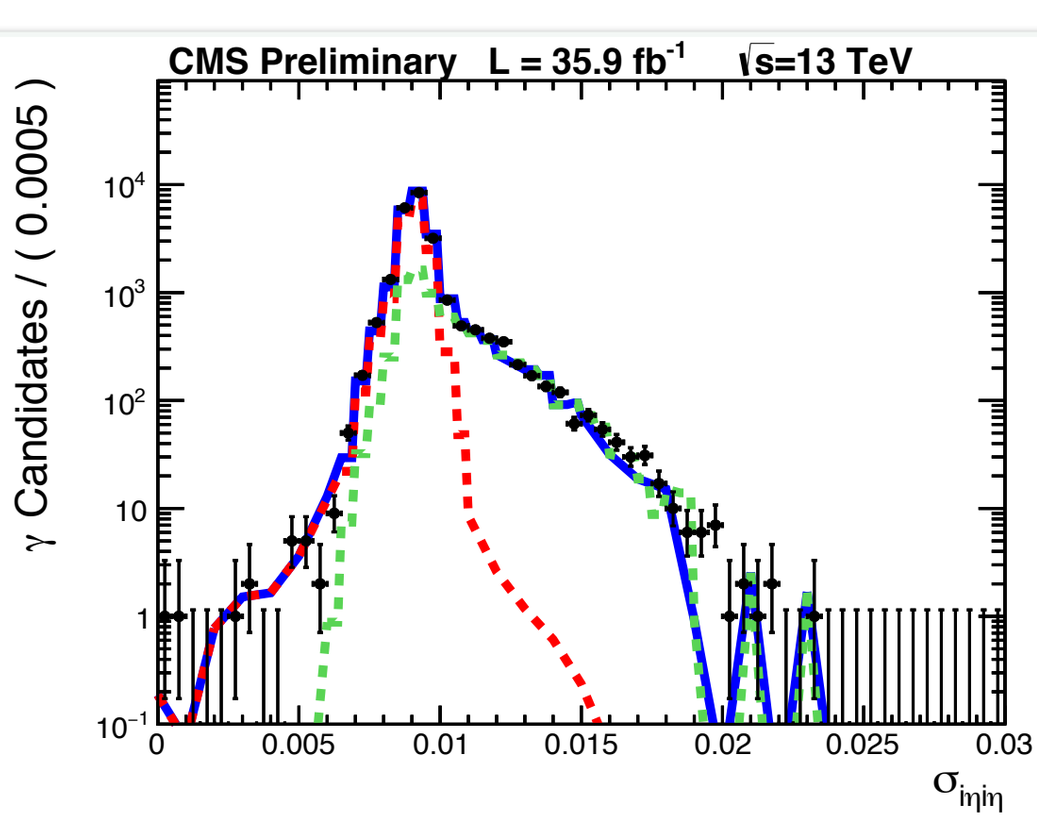
- **fake rate: *f*($p_T$) = numerator / denominator**
  - **numerator:** number of jets passing photon ID
  - **denominator:** number of jets passing a looser photon-like ID

- Contamination from real photons is removed from **numerator** through a template fit

# Template fit

- **Template variable** - Shower shape variable $\sigma_{i\eta i\eta}$
- **Real template** - Constructed from photon-rich MC using MC truth information to identify real photons
- **Fake template** - Constructed from reference data sample using a sideband in the isolation variable $Iso_{Ch}$
- **Template fit** - Performed using MLE on data with relaxed $\sigma_{i\eta i\eta}$



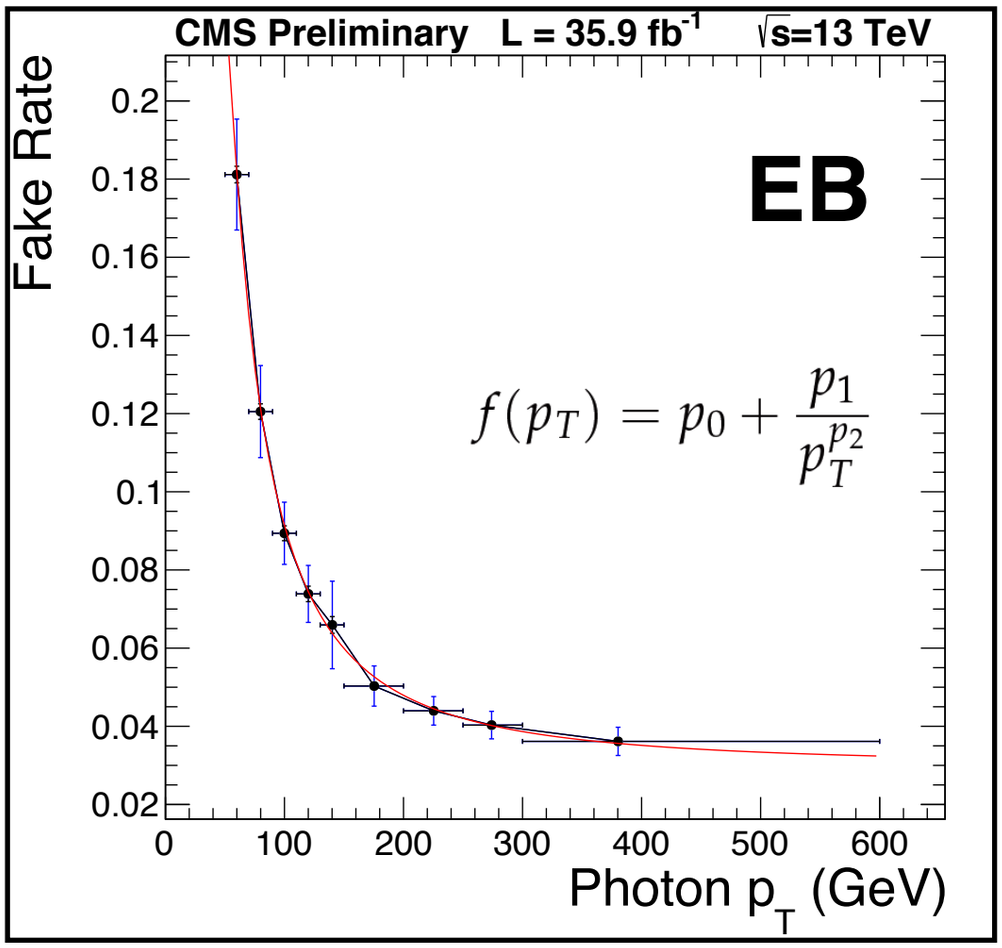



# Fake rate

- **Denominator** objects in <u>analysis diphoton data sample</u> are reweighed by ***f*($p_T$)** to give a fake prediction

$$\mathrm{jj} = (f_1 F_1)(f_2 F_2)$$

$$\begin{aligned}\gamma\mathrm{j} &= (R_1 N_2) + (N_1 R_2) \\ &= (T_1 - f_1 F_1)(f_2 F_2) + (f_1 F_1)(T_2 - f_2 F_2) \\ &= T_1(f_2 F_2) + (f_1 F_1) T_2 - 2(f_1 F_1)(f_2 F_2)\end{aligned}$$

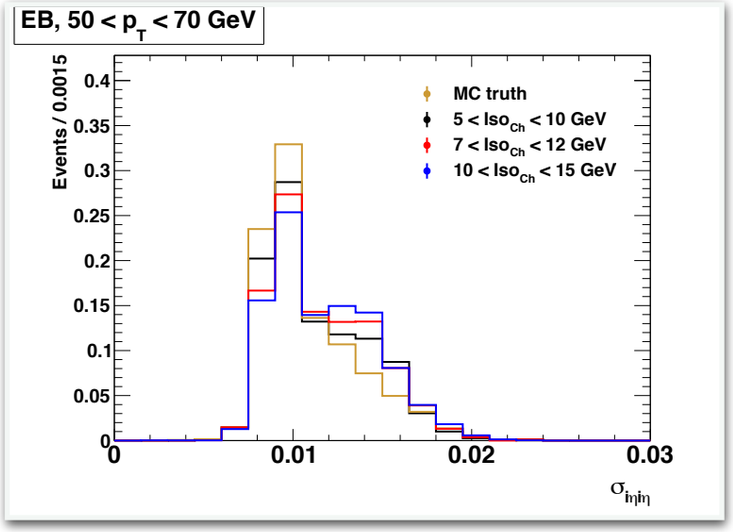


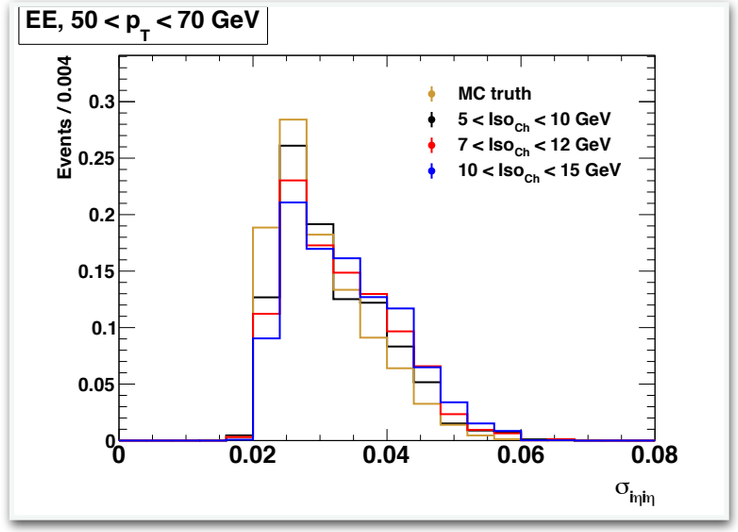

- Fake contribution is less than 4 (14)% in EBEB (EBEE) for $m_{\gamma\gamma}$ > 1 TeV

# Closure test to photon fake rate method

MC based closure test is performed by comparing

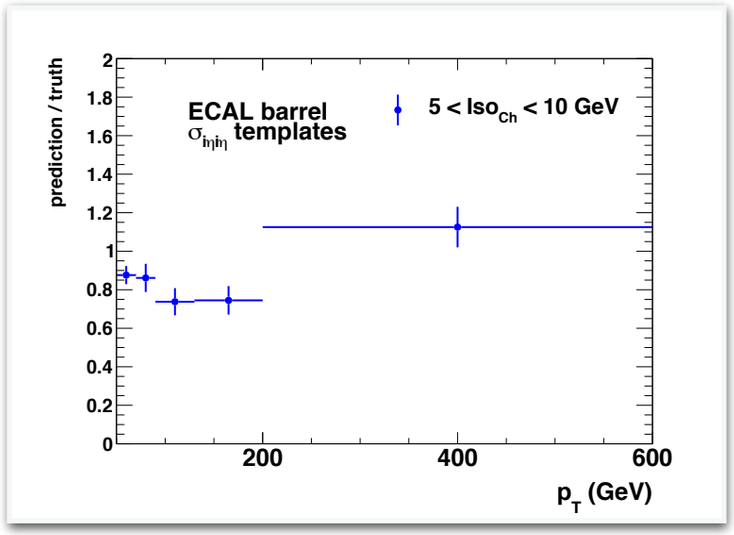
1. Fake rate method applied to jet-enriched MC sample ("treat MC as data") to determine a **fake prediction** in MC sample
2. **MC truth** calculation to identify known fake photons in MC sample

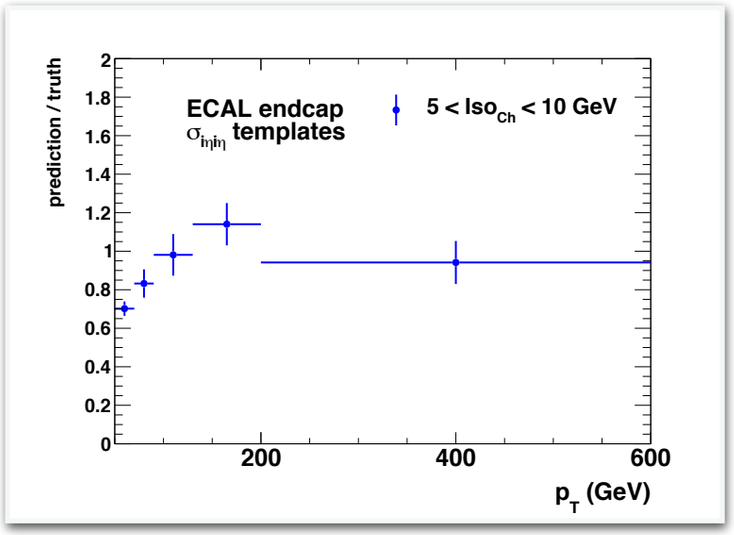



- MC fake templates to MC truth
  - choosing templates from a sideband has some bias

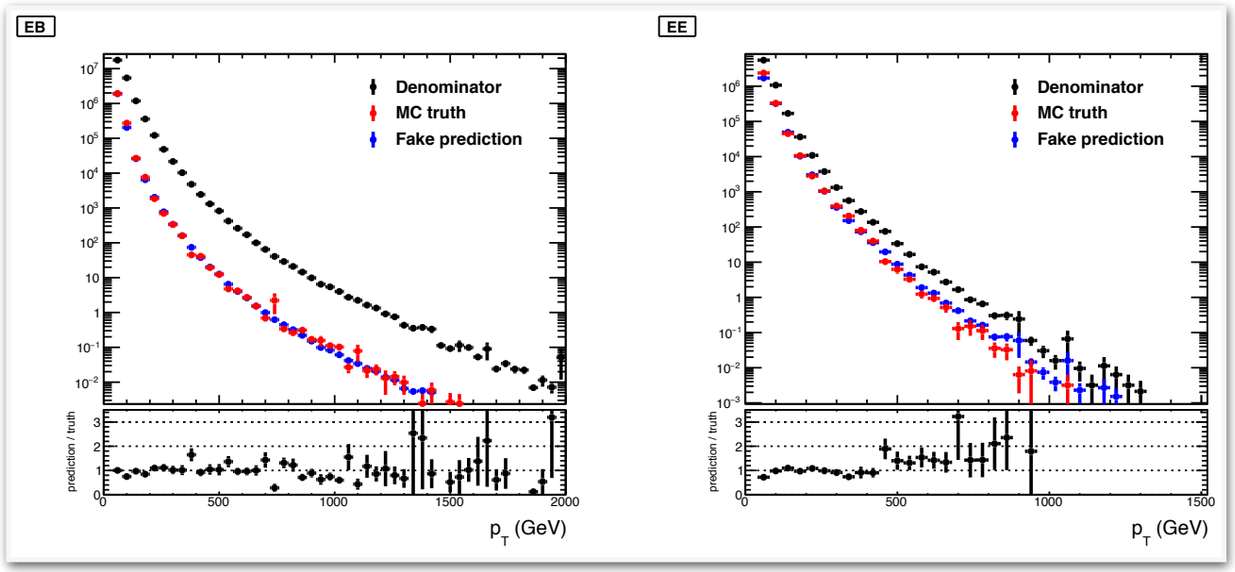
- Closure test predicted fake rate compared to truth fake rate
  - similar agreement for inverted relationship between template and sideband variables
  - deviation consistent with total systematic uncertainty applied to this method



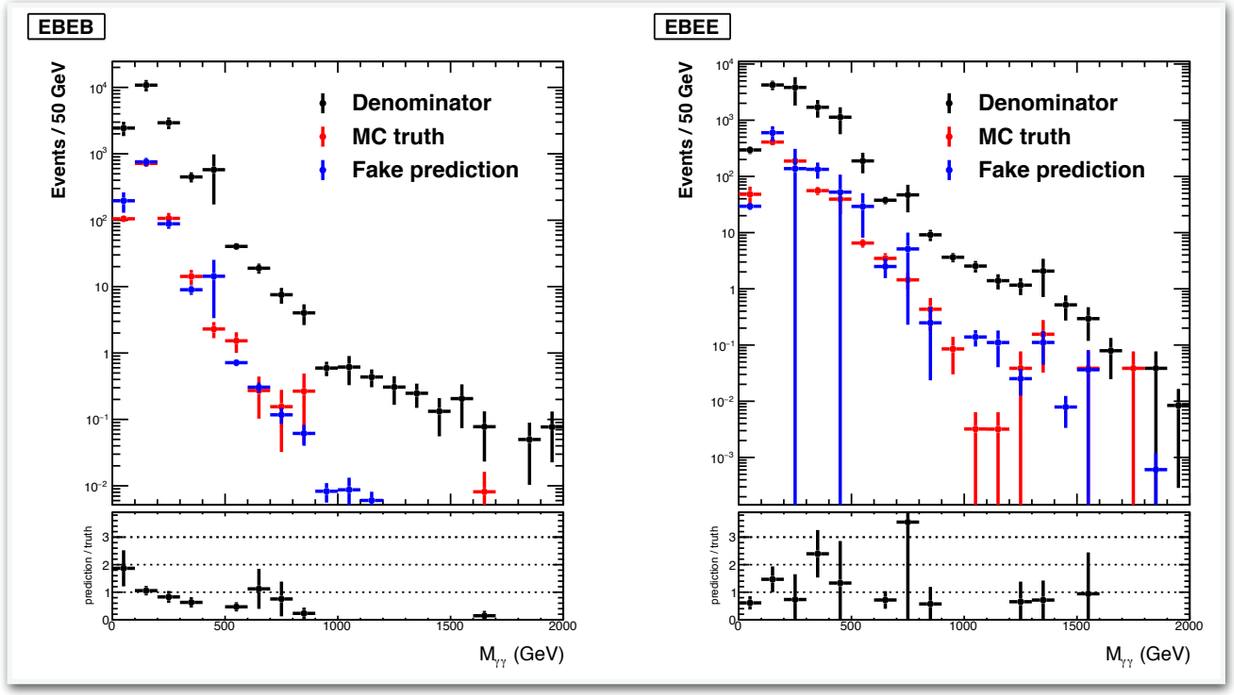



# Closure test of kinematics

- The **re-weighted denominator objects** reflect the kinematics of known fake objects from **MC truth**




- Photon $p_T$ in EB and EE




- Diphoton $m_{\gamma\gamma}$ $\gamma j$ objects in EBEB and EBEE

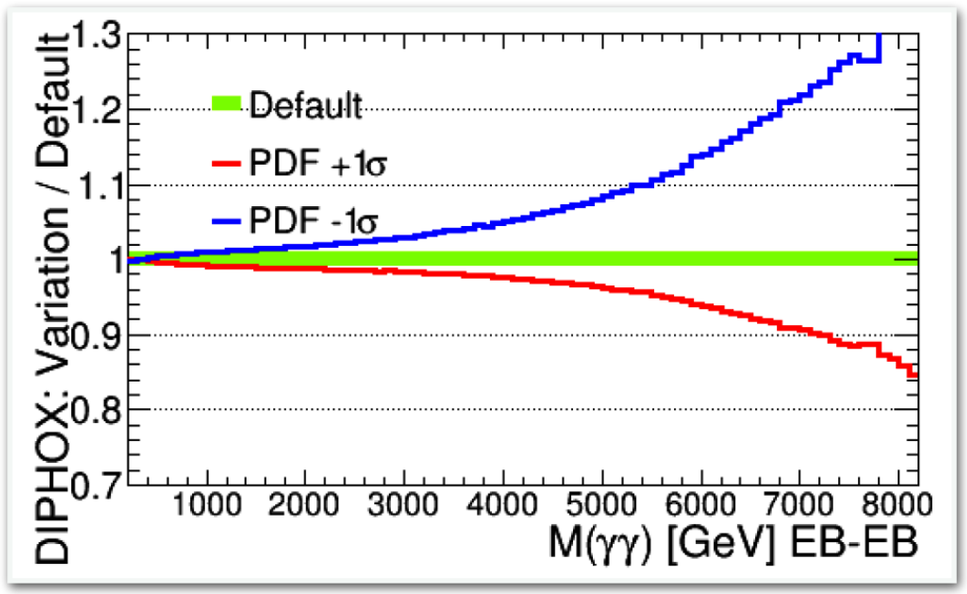
# Systematic uncertainties

- Systematic uncertainties are considered for
  - real background prediction
  - fake background measurement
  - signal calculation

- Affecting either the shape or normalization of distribution

- CT10 PDF set is used for signal and background simulation

- PDF uncertainties are calculated using the MC calculator DIPHOX at NLO
  - 26 eigenvector pairs are varied by ±1σ around nominal value
  - each eigenvector variation is considered a separate systematic



# Summary of systematic uncertainties

## Prompt diphoton background

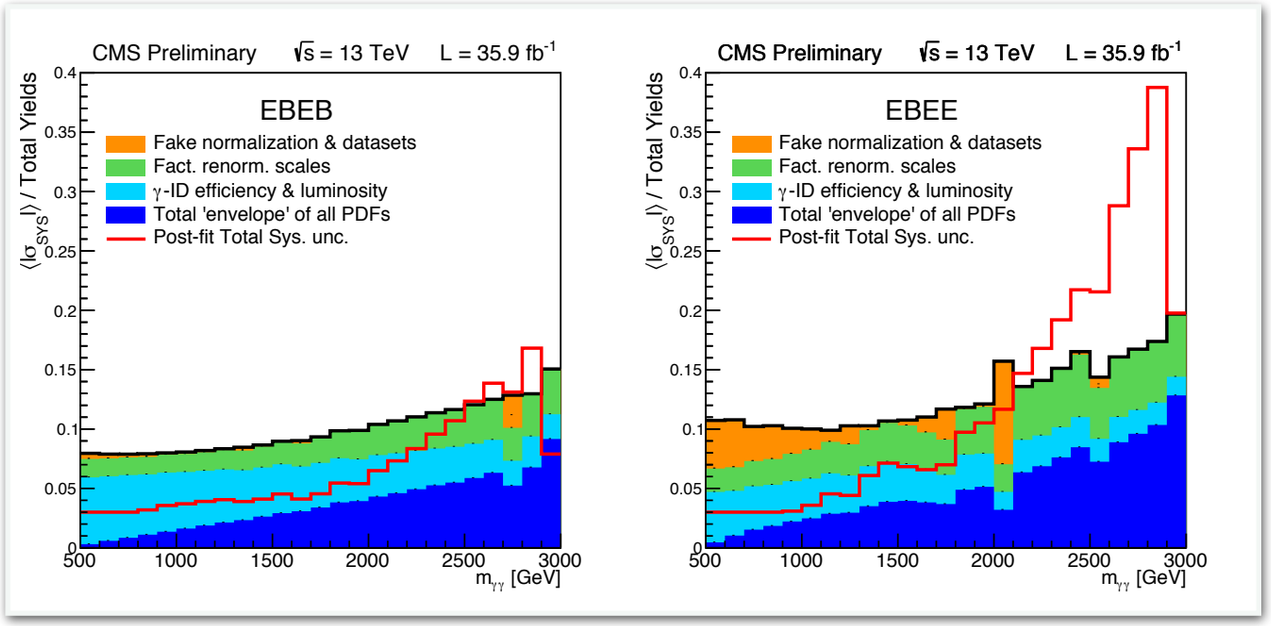
- normalization is allowed to float arbitrarily, which absorbs uncertainties in
  - higher order terms not included in our NNLO *K* factor
  - luminosity and photon selection efficiency
- scale variations on $\mu_r$ and $\mu_f$ for the MCFM *K* factor calculation (shape)
- 26 PDF eigenvector pair variations (shape)
- shape differences in NNLO MCFM and NLO MCFM and NLO DIPHOX

## Fake background

- 30% uncertainty on fake rate normalization
  - pileup, photon $\eta$, change in sideband, change in template, non-closure, real photon contamination
- shape differences in fake rate from jet- and muon-triggered datasets

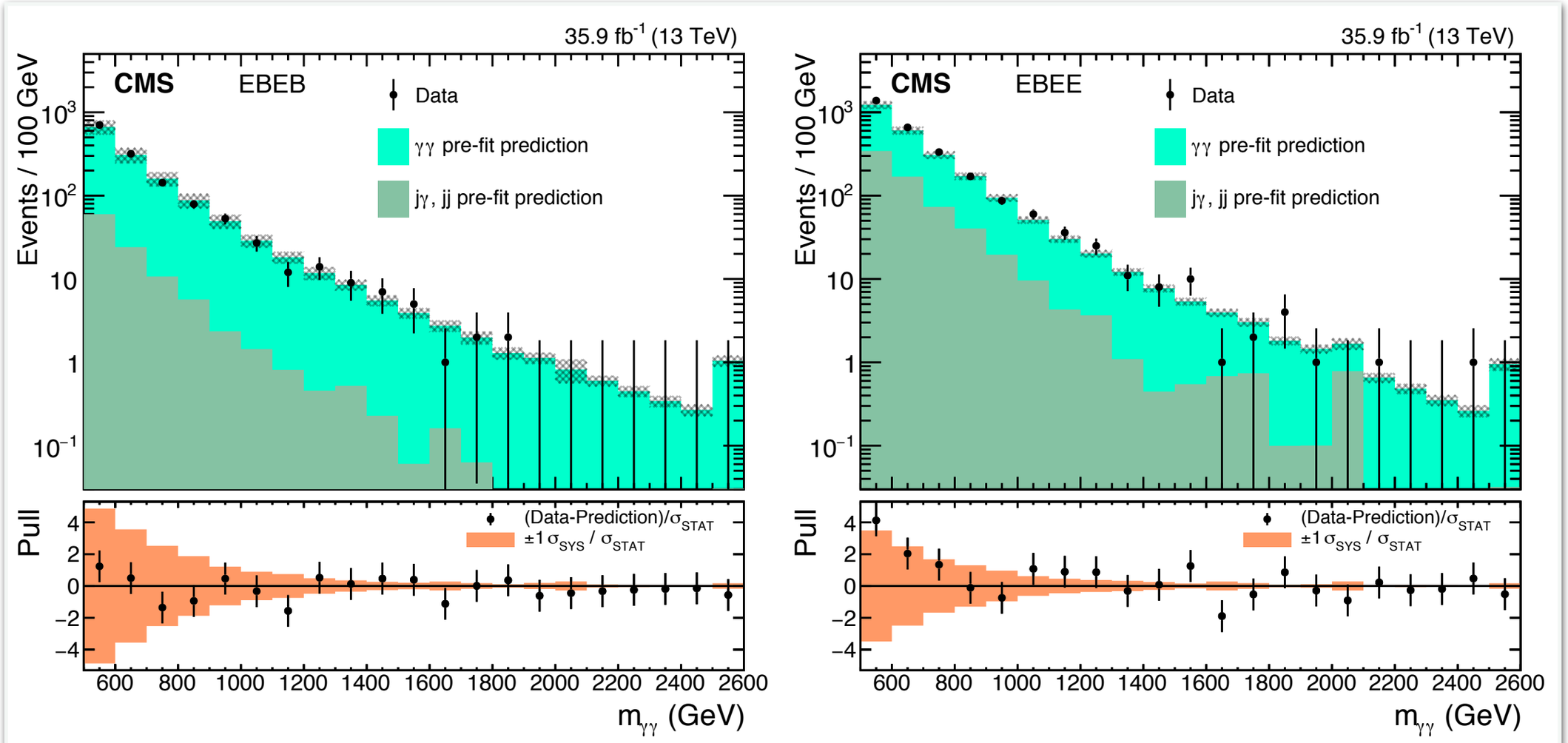
## MC signal

- 2.5% for integrated luminosity (normalization)
- 6% for photon selection efficiency (normalization)
- 26 eigenvector pair variations (shape)



# Diphoton invariant mass spectrum

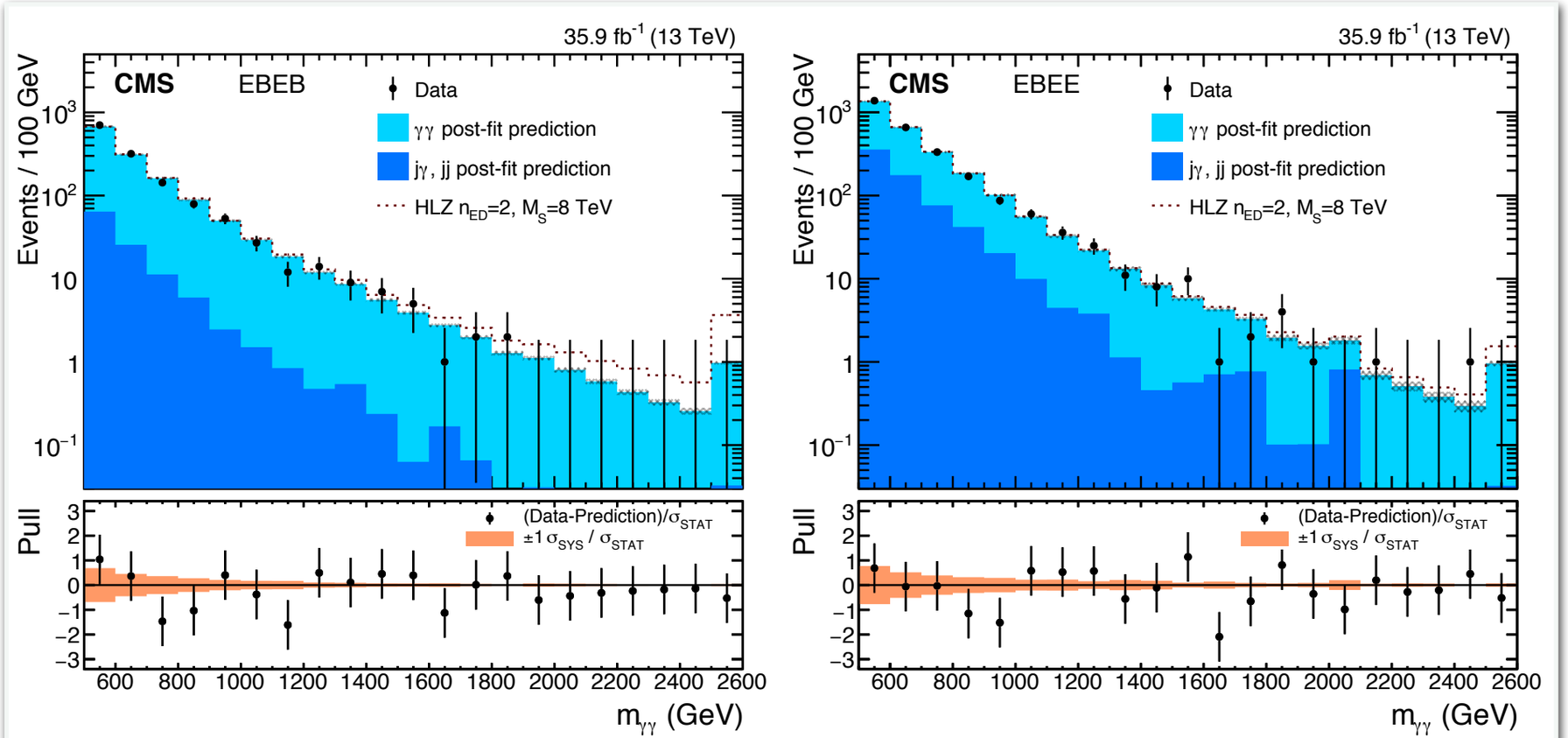
- Search region $m_{\gamma\gamma}$ > 500 GeV (initially blind above 1 TeV)
- **Pre-fit** prediction of $m_{\gamma\gamma}$ spectra in excellent agreement with data




- Highest $m_{\gamma\gamma}$ events
  - 1840 GeV (EBEB)
  - 2444 GeV (EBEE)
- No significant excess of data over background

# Diphoton invariant mass spectrum

- **Post-fit** in $m_{\gamma\gamma}$ gives final prediction
  - allow real background normalization to float, constrained primarily by data at low $m_{\gamma\gamma}$
  - performed simultaneously with limit extraction
  - example signal distribution superimposed




| Category | Type | 0.5-1 TeV | 1-1.5 TeV | 1.5-2 TeV | 2-13 TeV | 0.5-13 TeV |
|---|---|---|---|---|---|---|
| EBEB | Total pre-fit background | 1275.7 | 73.0 | 11.1 | 3.5 | 1363.3 |
| | Total post-fit background | $1285 \pm 40$ | $73.7 \pm 2.9$ | $11.0 \pm 0.5$ | $3.30 \pm 0.22$ | $1373.0 \pm 40.1$ |
| | Data | 1296 | 69 | 10 | 0 | 1375 |
| EBEE | Total pre-fit background | 2406.1 | 121.4 | 15.6 | 4.4 | 2547.5 |
| | Total post-fit background | $2645 \pm 60$ | $128 \pm 6$ | $16.1 \pm 1.2$ | $4.1 \pm 0.5$ | $2793.2 \pm 60.3$ |
| | Data | 2631 | 140 | 18 | 2 | 2791 |

# Statistical methods

- Bayesian inference is used

- Bayes' theorem
  - P($A$) prior
  - P($A|B$) posterior
  - P($B|A$) likelihood

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

$$\mathcal{L}_i(n_i|\mu) = \frac{(\mu s_i + b_i)^{n_i} e^{-(\mu s_i + b_i)}}{n_i!}$$

- Binned (Poissonian) likelihood on number of data events ***n*** given signal ***s*** and background ***b***
  - signal strength $\mu$

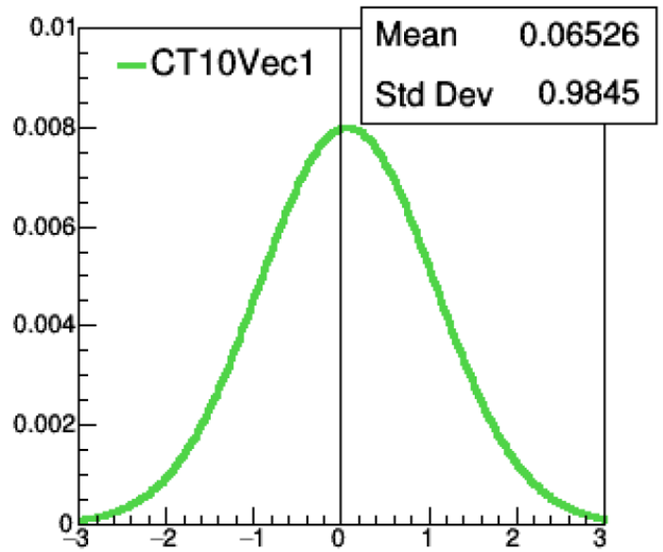
- Flat prior $\pi(\mu)$ considered on ADD signal strength

$$P(\mu|n_i) = \mathcal{L}_i(n_i|\mu)\pi(\mu)$$

- Signal and background depend on systematic uncertainties
  - nuisance parameters $\theta$ assigned to each systematic and marginalized using a choice of prior $\pi(\mu, \theta)$

$$P(\mu|n_i) = \int P(\mu, \theta|n_i)d\theta = \int \mathcal{L}_i(n_i|\mu, \theta)\pi(\mu, \theta)d\theta$$

- Maximum likelihood estimate provides
  - posterior background prediction
  - posterior signal strength prediction



# Limit setting

- Posterior signal strength predictions used to derive 95% CL exclusion limits on ADD model parameters

- Integrate to find $\mu_{\mathrm{up}}$

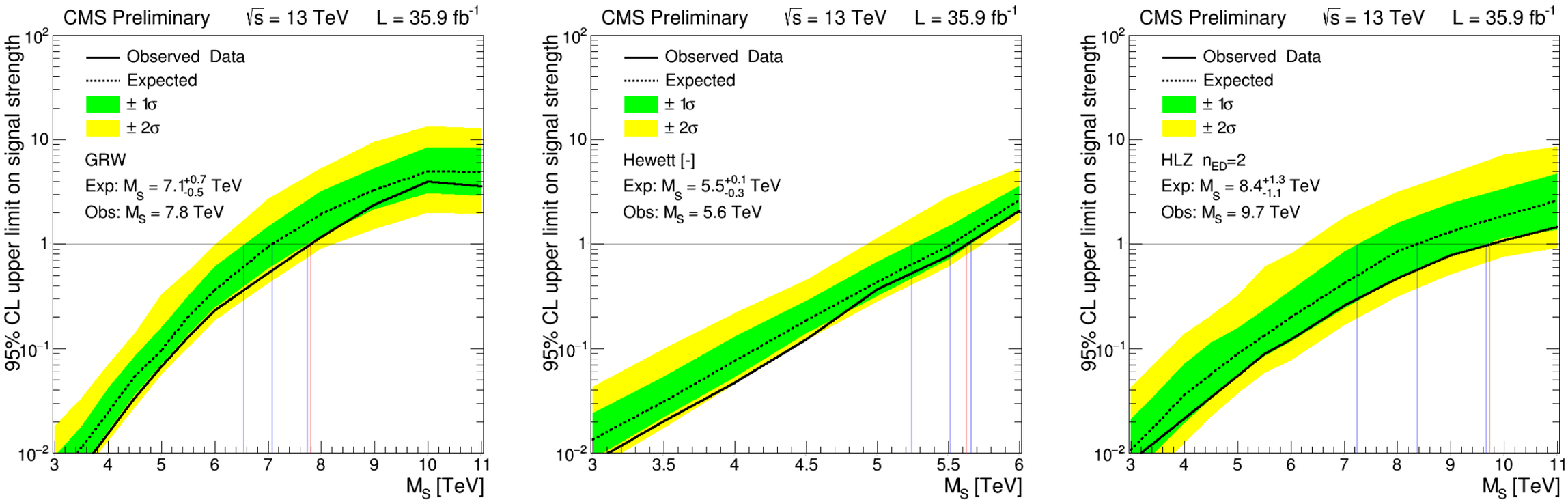
$$0.95 = \frac{\int_0^{\mu_{\mathrm{up}}} P(\mu|n_i)d\mu}{\int_0^{\infty} P(\mu|n_i)d\mu} = \frac{\int_0^{\mu_{\mathrm{up}}} \mathcal{L}_i(n_i|\mu)d\mu}{\int_0^{\infty} \mathcal{L}_i(n_i|\mu)d\mu}$$

- Upper limits on the ADD signal strength are translated into lower limits of $M_S$
  - signal strength 1.0 excluded

- Done separately for GRW, HLZ assuming $n_{ED} = 2$, and Hewett- conventions
  - limits on other conventions achieved using $\eta_{\mathrm{G}}$

# Limits on ADD model

- Upper limits on the ADD signal strength are translated into lower limits of $M_S$




- Exclusion limits on $M_S$ range from 5.6-9.7 TeV

| Signal | GRW | Hewett | | HLZ | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | negative | positive | $n_{ED}=2$ | $n_{ED}=3$ | $n_{ED}=4$ | $n_{ED}=5$ | $n_{ED}=6$ | $n_{ED}=7$ |
| Expected | $7.1^{+0.7}_{-0.5}$ | $5.5^{+0.1}_{-0.3}$ | $6.3^{+0.6}_{-0.4}$ | $8.4^{+1.3}_{-1.1}$ | $8.4^{+0.8}_{-0.6}$ | $7.1^{+0.7}_{-0.5}$ | $6.4^{+0.6}_{-0.5}$ | $6.0^{+0.6}_{-0.4}$ | $5.6^{+0.6}_{-0.4}$ |
| Observed | 7.8 | 5.6 | 7.0 | 9.7 | 9.3 | 7.8 | 7.0 | 6.6 | 6.2 |

# Conclusion

- A nonresonant, high-mass diphoton search using 35.9 fb$^{-1}$, corresponding to the full 2016 dataset, was performed with CMS
  - NNLO prediction of the prompt SM diphoton background
  - data-driven estimate of the fake background

- Data are consistent with background-only hypothesis

- Limits set on the ADD model of large extra dimensions
  - exclusion limits on $M_S$ = 5.6-9.7 TeV depending on the cutoff convention
    - improves current best limits by ATLAS (*arXiv: 1707.04147*)

- First CMS nonresonant, high-mass diphoton search done using LHC Run 2 data
  - previous CMS result used 2011 data with √s = 7 TeV pp collisions (*arXiv:1112.0688*)

- Result has been published in PRD

- Extra dimensions are not ruled out, but their solution to the hierarchy problem has been narrowed by this effort

PHYSICAL REVIEW D **98,** 092001 (2018)

**Search for physics beyond the standard model in high-mass diphoton events from proton-proton collisions at $\sqrt{s}=13$ TeV**

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)

(Received 1 September 2018; published 2 November 2018)

A search for physics beyond the standard model is performed using a sample of high-mass diphoton events produced in proton-proton collisions at $\sqrt{s} = 13$ TeV. The data sample was collected in 2016 with the CMS detector at the LHC and corresponds to an integrated luminosity of 35.9 fb$^{-1}$. The search is performed for both resonant and nonresonant new physics signatures. At 95% confidence level, lower limits on the mass of the first Kaluza-Klein excitation of the graviton in the Randall-Sundrum warped extra-dimensional model are determined to be in the range of 2.3 to 4.6 TeV, for values of the associated coupling parameter between 0.01 and 0.2. Lower limits on the production of scalar resonances and model-independent cross section upper limits are also provided. For the large extra-dimensional model of Arkani-Hamed, Dimopoulos, and Dvali, lower limits are set on the string mass scale $M_S$ ranging from 5.6 to 9.7 TeV, depending on the model parameters. The first exclusion limits are set in the two-dimensional parameter space of a continuum clockwork model.

DOI: 10.1103/PhysRevD.98.092001

**I. INTRODUCTION**

While the standard model (SM) of particle physics has been an enormously successful description of observed phenomena, it is still widely believed to be incomplete. In the SM, the Higgs boson mass receives quantum corrections from loops containing SM particles. Because the Higgs boson is a fundamental scalar, the magnitude of the mass corrections is set by the cutoff parameter of the loop integrals and the only natural mass scale in the SM that can act as a cutoff is the Planck scale ($M_{\rm Pl} \sim 10^{19}$ GeV) at which quantum gravity is expected to emerge. Therefore, unless the Higgs boson mass parameter is fine-tuned to an extreme degree, there must exist some new physics beyond the SM to constrain these quantum corrections and stabilize the mass of the Higgs boson. Many models for such new physics have been proposed. We consider three such models in this paper.

Through their modification of the effective Planck scale, extra spatial dimensions have been proposed as a possible solution to this hierarchy problem [1,2], which arises from the large difference between the gravitational and electroweak scales. In the model proposed by Arkani-Hamed, Dimopoulos, and Dvali (ADD) [3–5], the existence of $n_{\rm ED}$ additional spatial dimensions, compactified with an average radius $r_c$, produces an effective Planck mass $M_{\rm Pl}$ in our four-dimensional (4D) world that is related to the true Planck mass by $M_{\rm Pl}^2 \sim M_{\rm Pl(4+n_{ED})}^{2+n_{\rm ED}} r_c^{n_{\rm ED}}$. It is therefore possible, with appropriate values for $n_{\rm ED}$ and $r_c$, that the value of the Planck scale in $(4+n_{\rm ED})$-dimensional spacetime, $M_{\rm Pl(4+n_{ED})}$, could be of the order of the electroweak scale, thus solving the SM hierarchy problem, while still producing the much larger apparent Planck scale that we observe in our 4D world. In effect, the true strength of gravity could actually be comparable to the electroweak force, and it merely appears weaker because of its propagation in the extra dimensions. At the same time, the SM gauge forces and particles are confined to our 4D spacetime.

Randall and Sundrum (RS) proposed an alternative model [6,7] with just one additional dimension that has a warped geometry, described by a curvature parameter $k$. The extra dimension is compactified with radius $r_c$. From the point of view of a 4D observer, a fundamental mass parameter $m_0$ defined on the SM brane in the full five-dimensional (5D) theory will appear as a physical mass $m = e^{-kr_c\pi}m_0$. In this model, solving the hierarchy problem requires that the fundamental mass should be $m_0 \sim M_{\rm Pl}$ and the observed mass should be at the TeV scale. Because of the exponential warp factor, this large hierarchy can be generated if $kr_c \approx 11$–$12$, thus requiring very little fine-tuning.

A third proposed solution to the hierarchy problem that we consider in this paper is the continuum clockwork

[*]Full author list given at the end of the article.



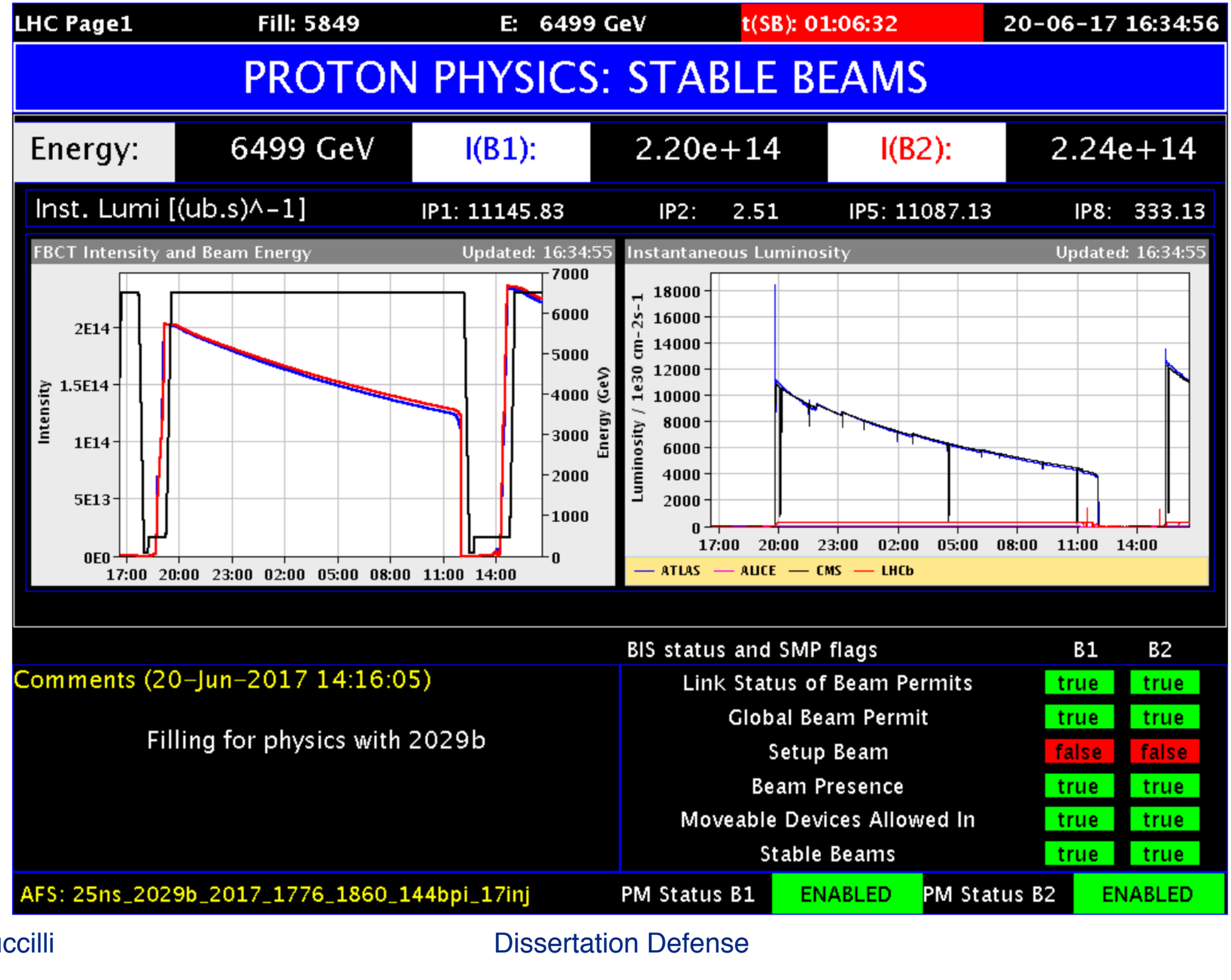
Phys. Rev. D **98**, 092001 (2018)
arXiv:1809.00327 [hep-ex]

# Thank you

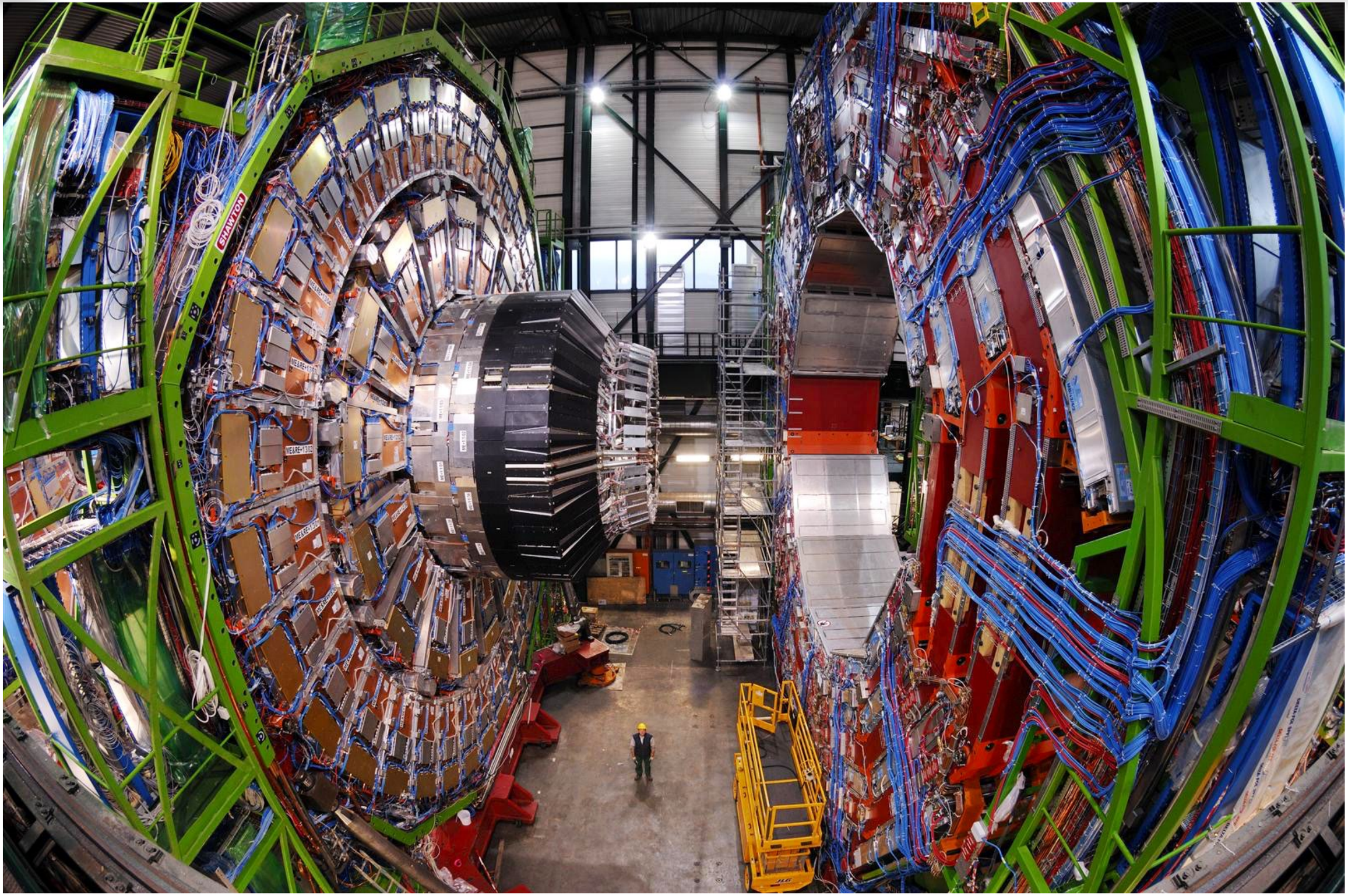
*Thank you to the many*
*friends, family, teachers, mentors,*
*officemates, roommates, and collaborators,*
*all having an enormous impact during my*
*time as a graduate student*

# Backup

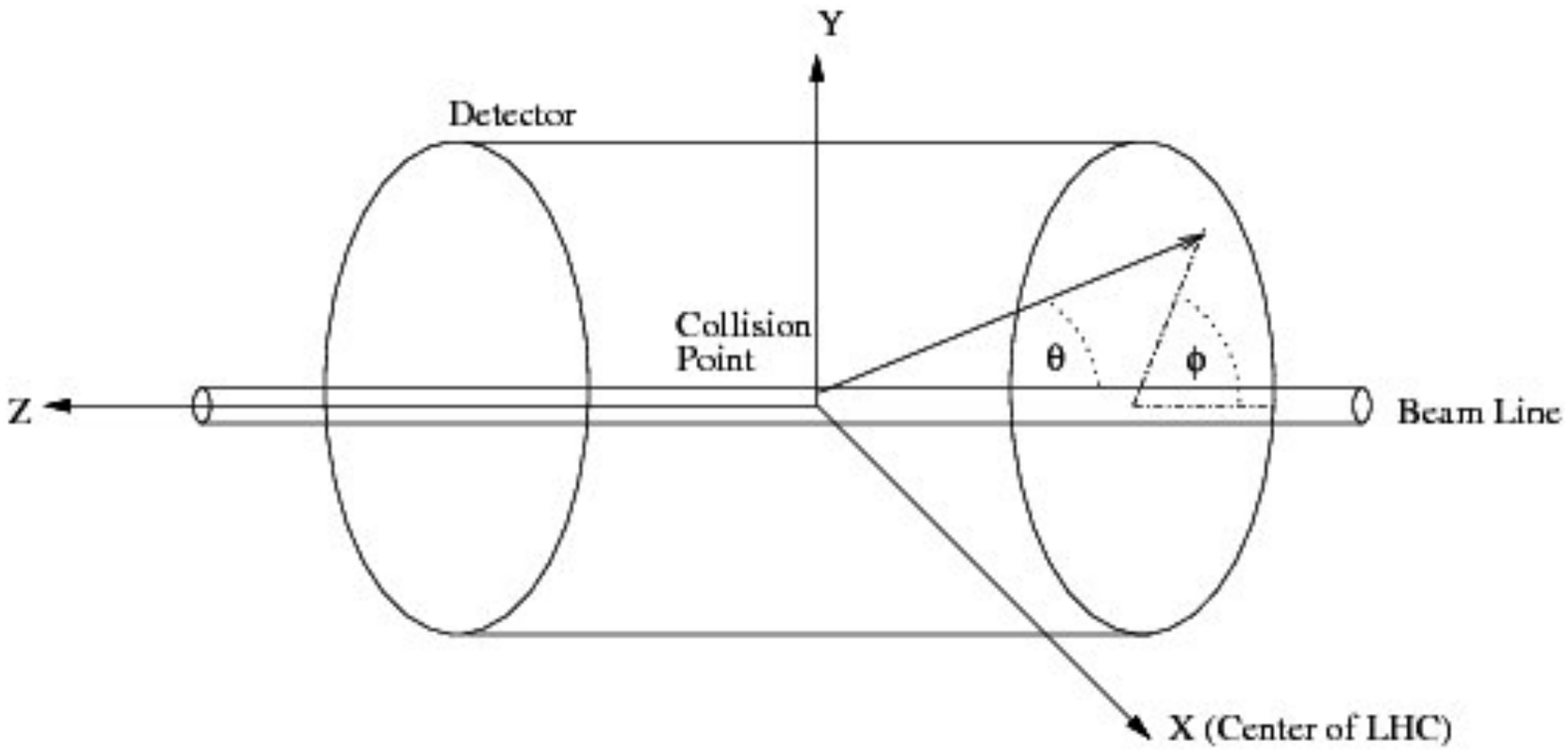
# LHC fill decay



# Compact Muon Solenoid



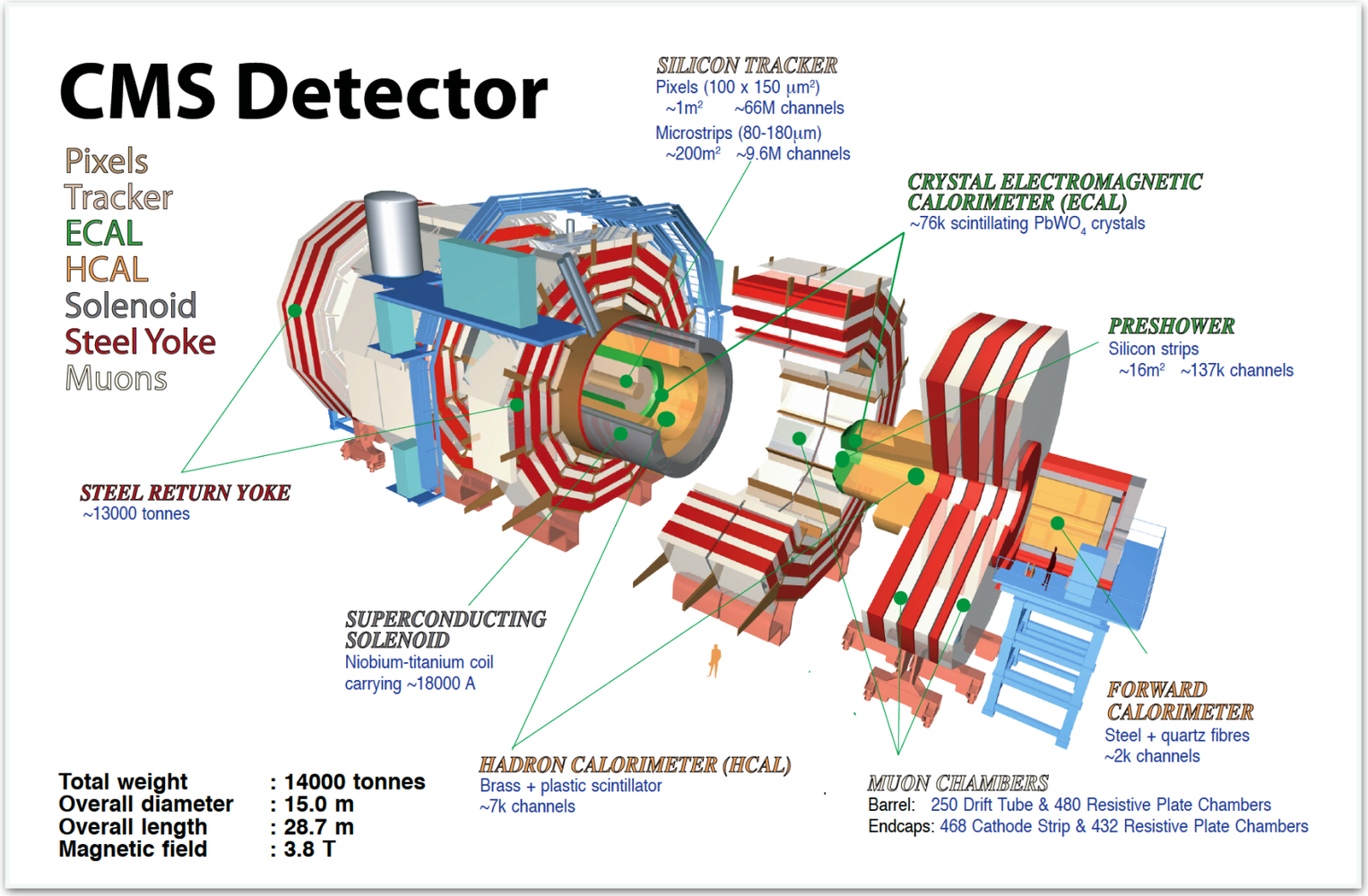
# CMS coordinate system



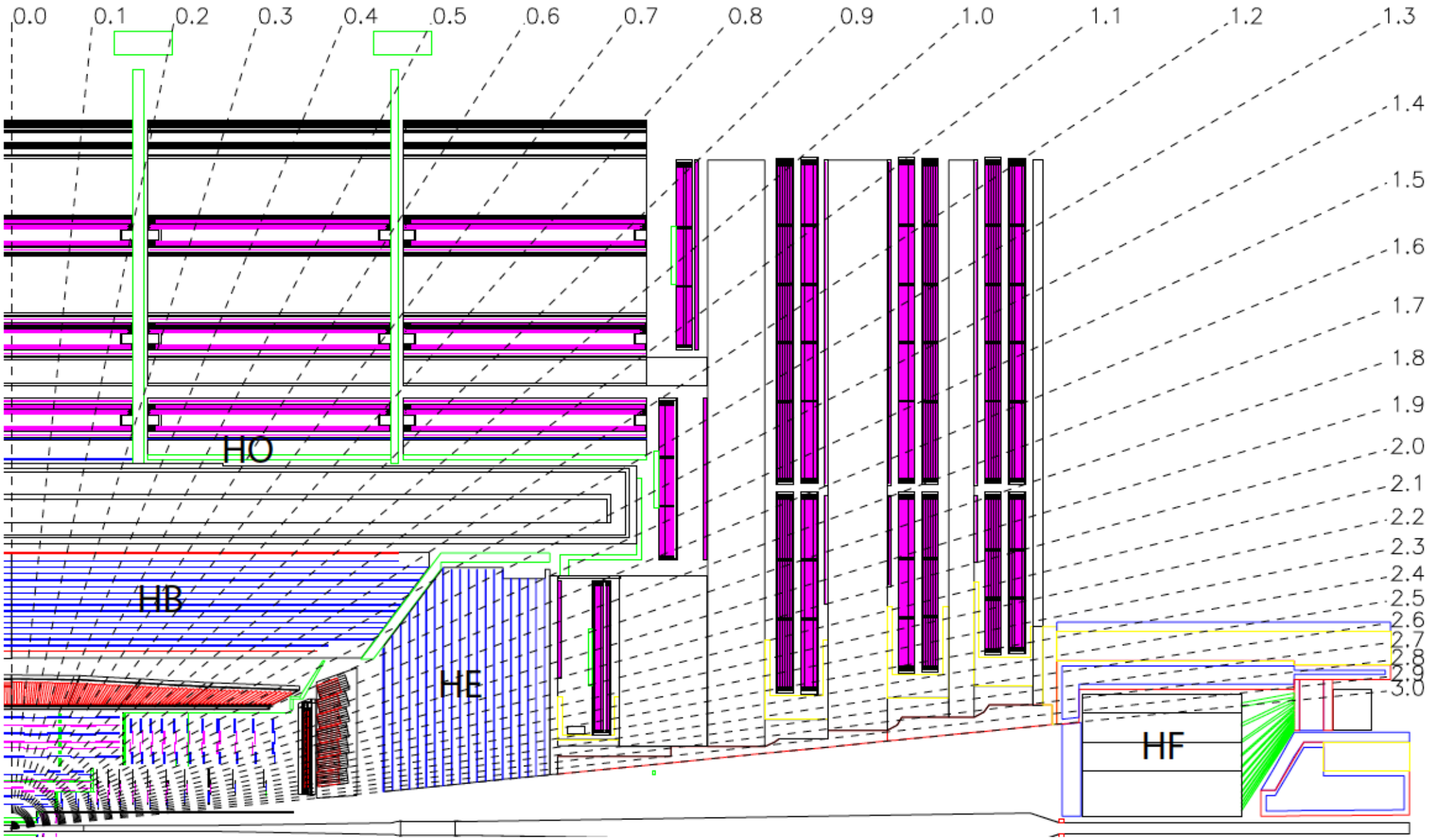
# Hadron calorimeter

- Hadron Calorimeter (**HCAL**) detector
  - sampling calorimeter
  - barrel-endcap design located inside the CMS solenoid and outside of the tracker and Electromagnetic Calorimeter (ECAL)
  - separate outer and forward detectors
  - 4 sub-detectors

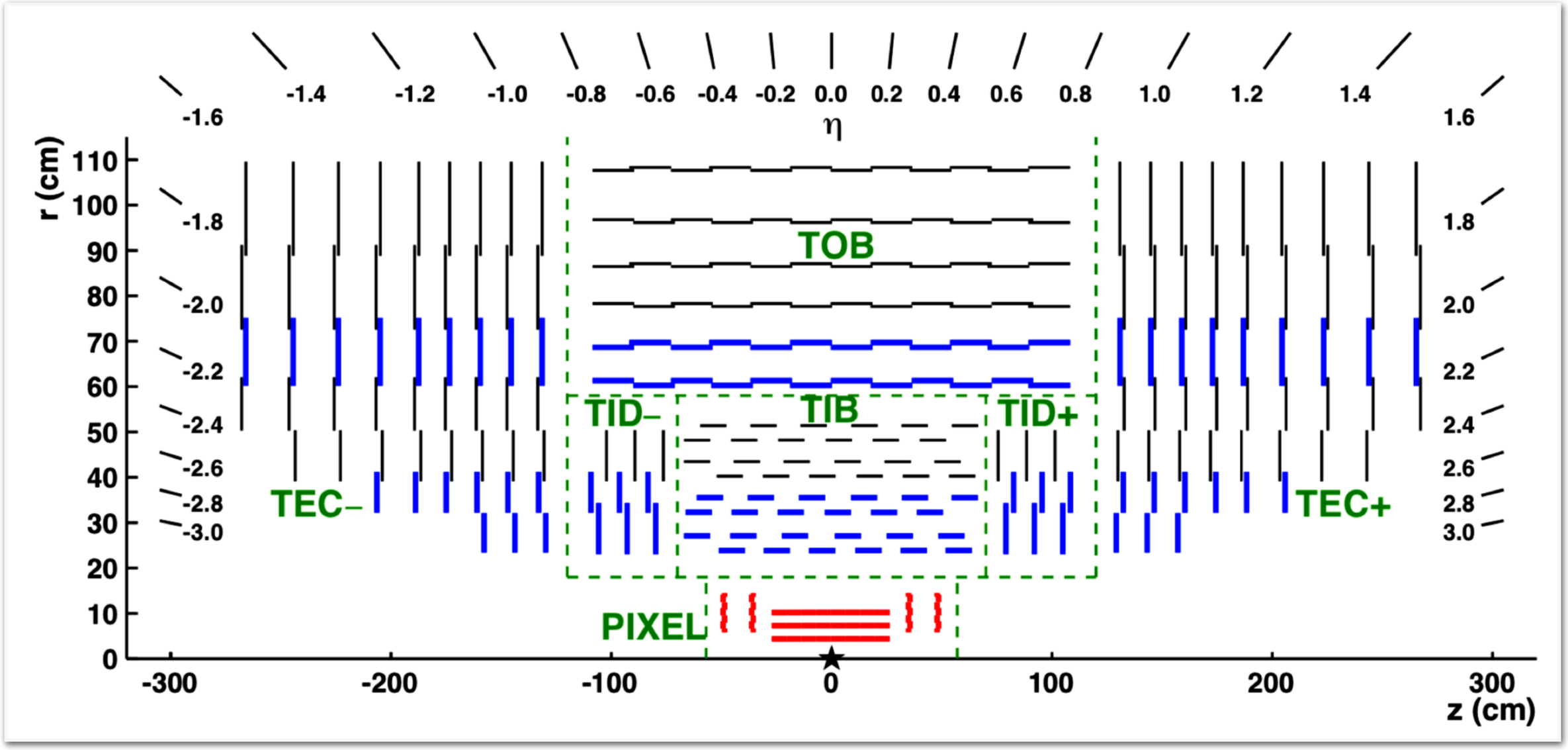
- Hadron Barrel (**HB**), Hadron Endcap (**HE**)
  - Brass absorber, plastic scintillator tiles
  - HPD photodetectors
- Hadron Outer (**HO**)
  - Outside solenoid
  - barrel section only
  - uses steel/iron absorber
  - hadron shower “tail catcher”
  - SiPM photodetectors
- Hadron Forward (**HF**)
  - Steel absorber, quartz fibers
  - high radiation
  - PMT photodetectors



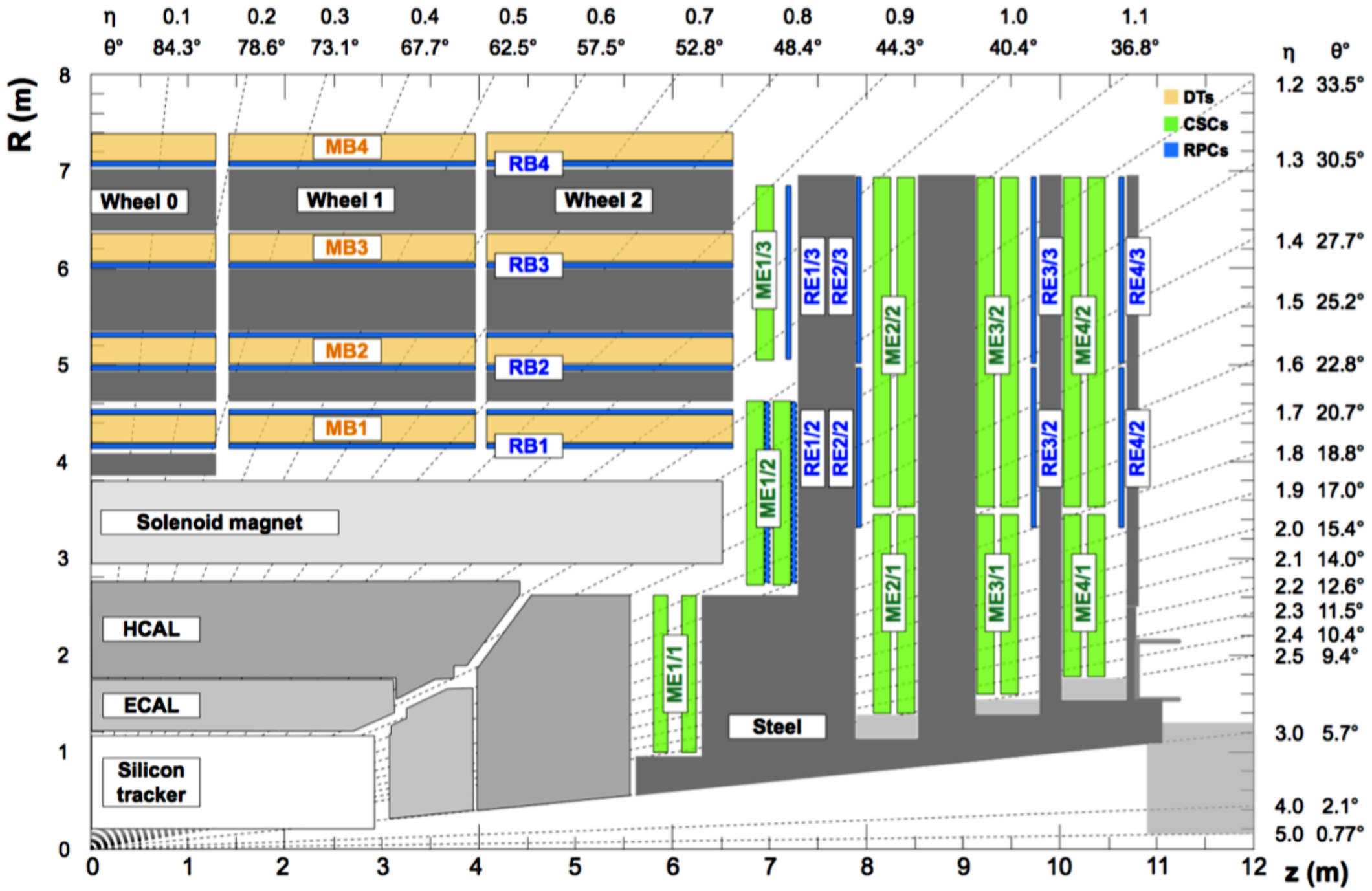
# HCAL detailed view



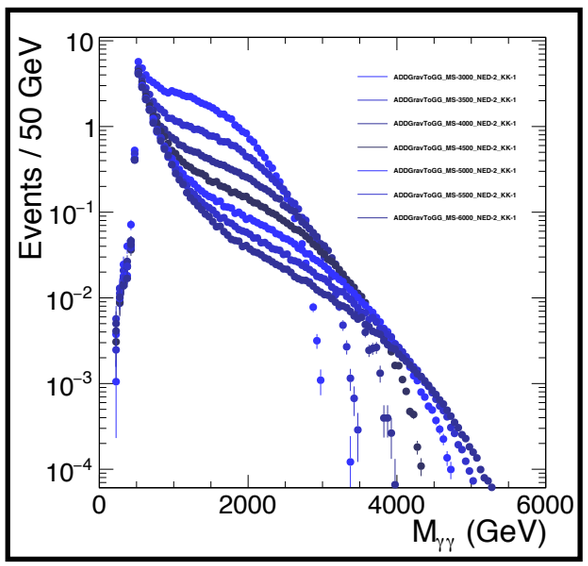
# CMS tracking system



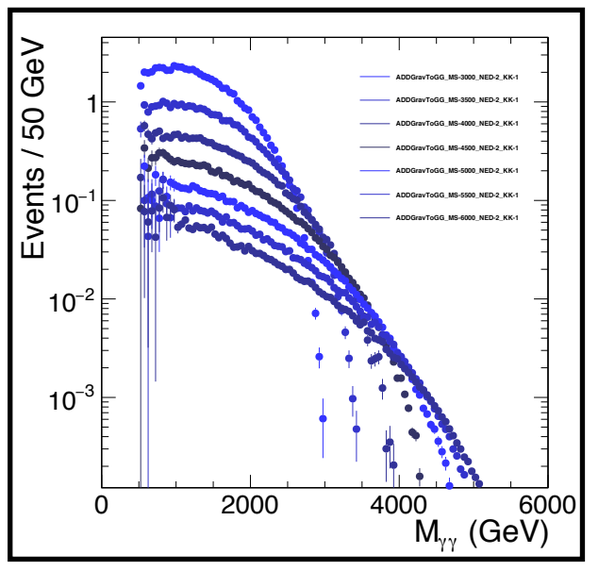
# CMS muon system



# ADD signal model

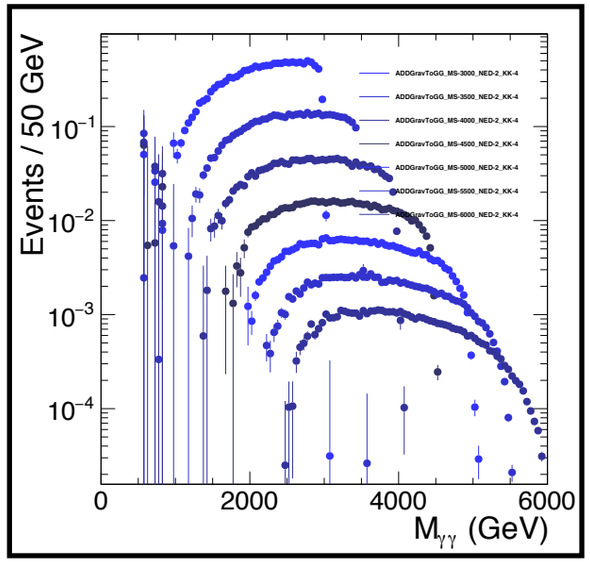



**signal+background**



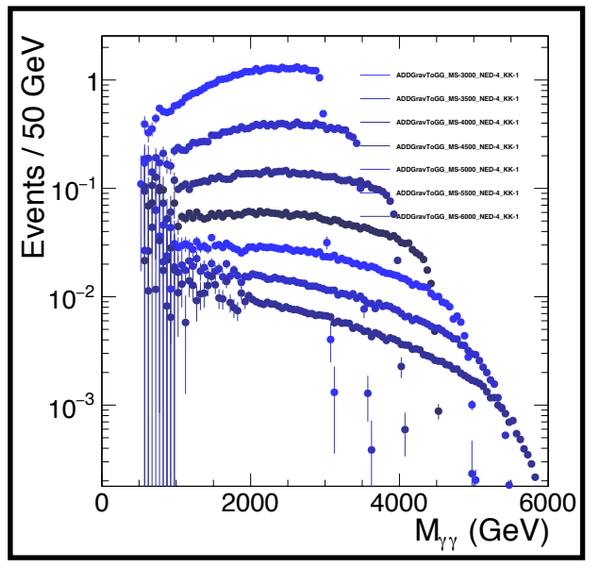

**signal**

**HLZ ($n_{ED} = 2$)**




**signal**

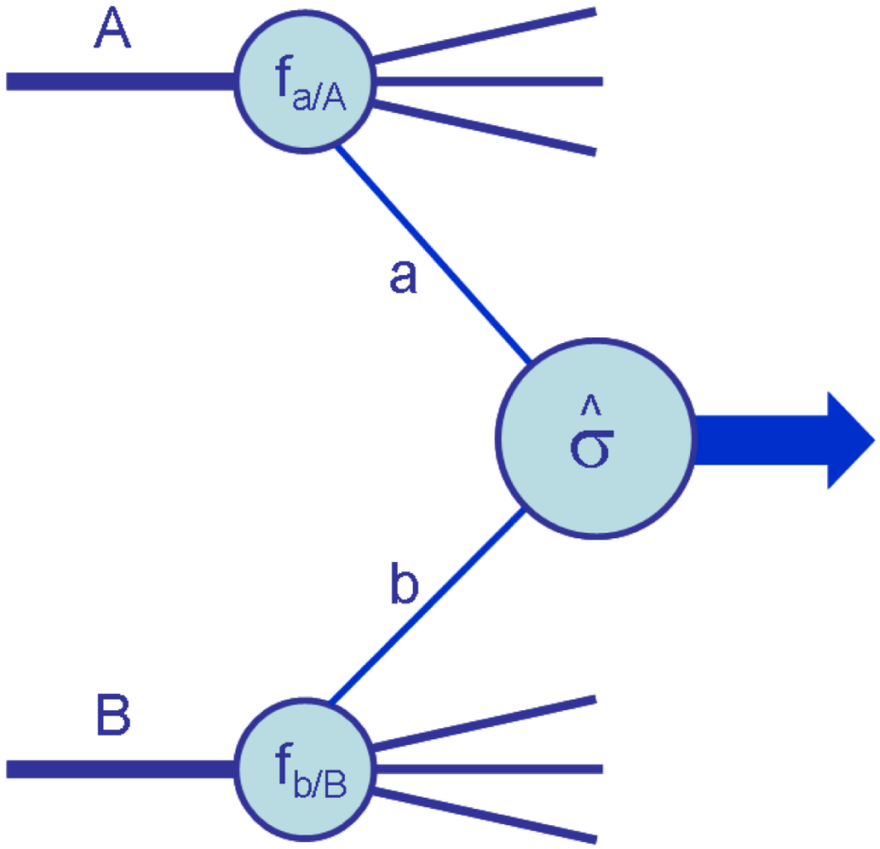
**Hewett-**



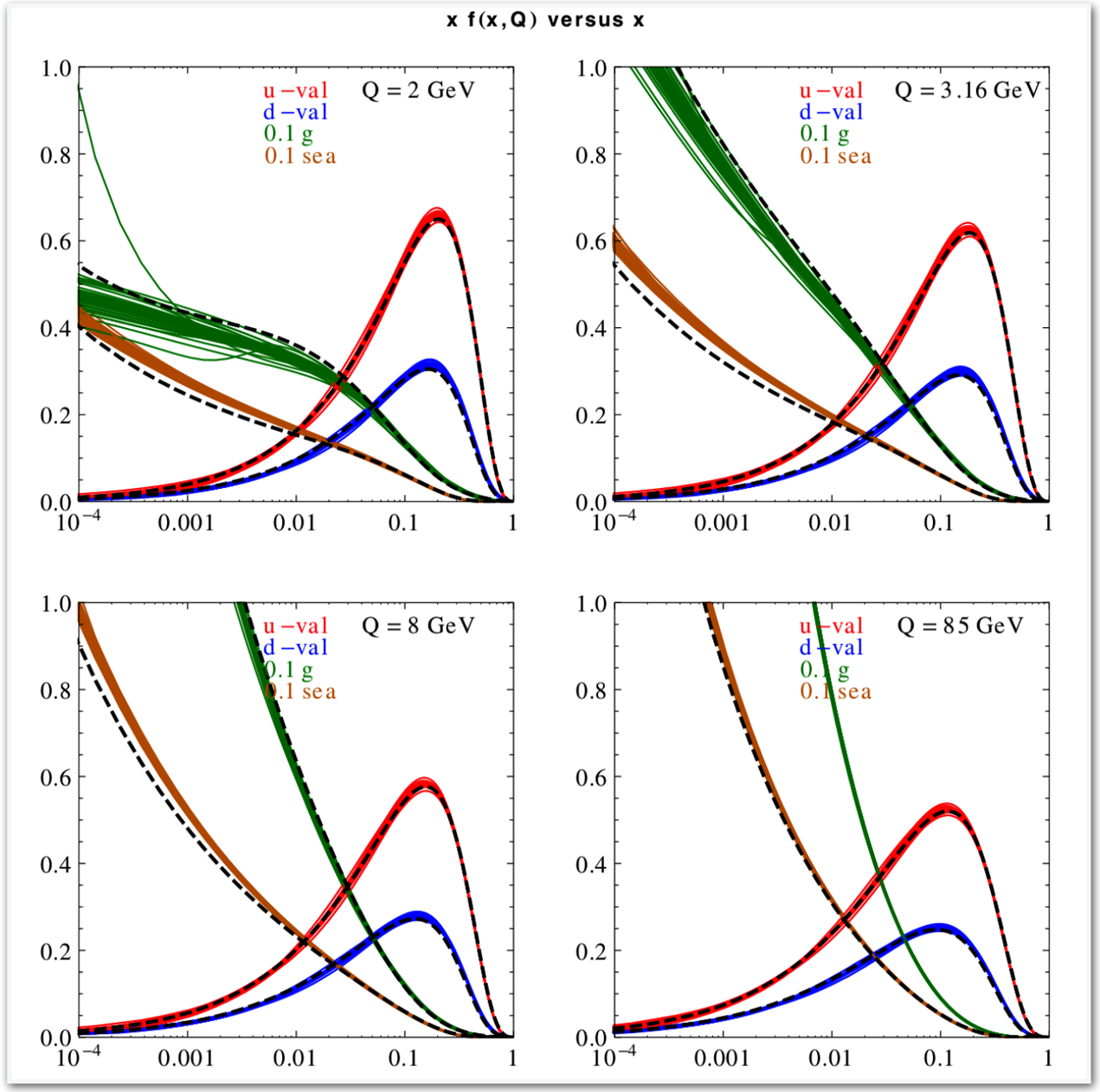

**signal**

**GRW**

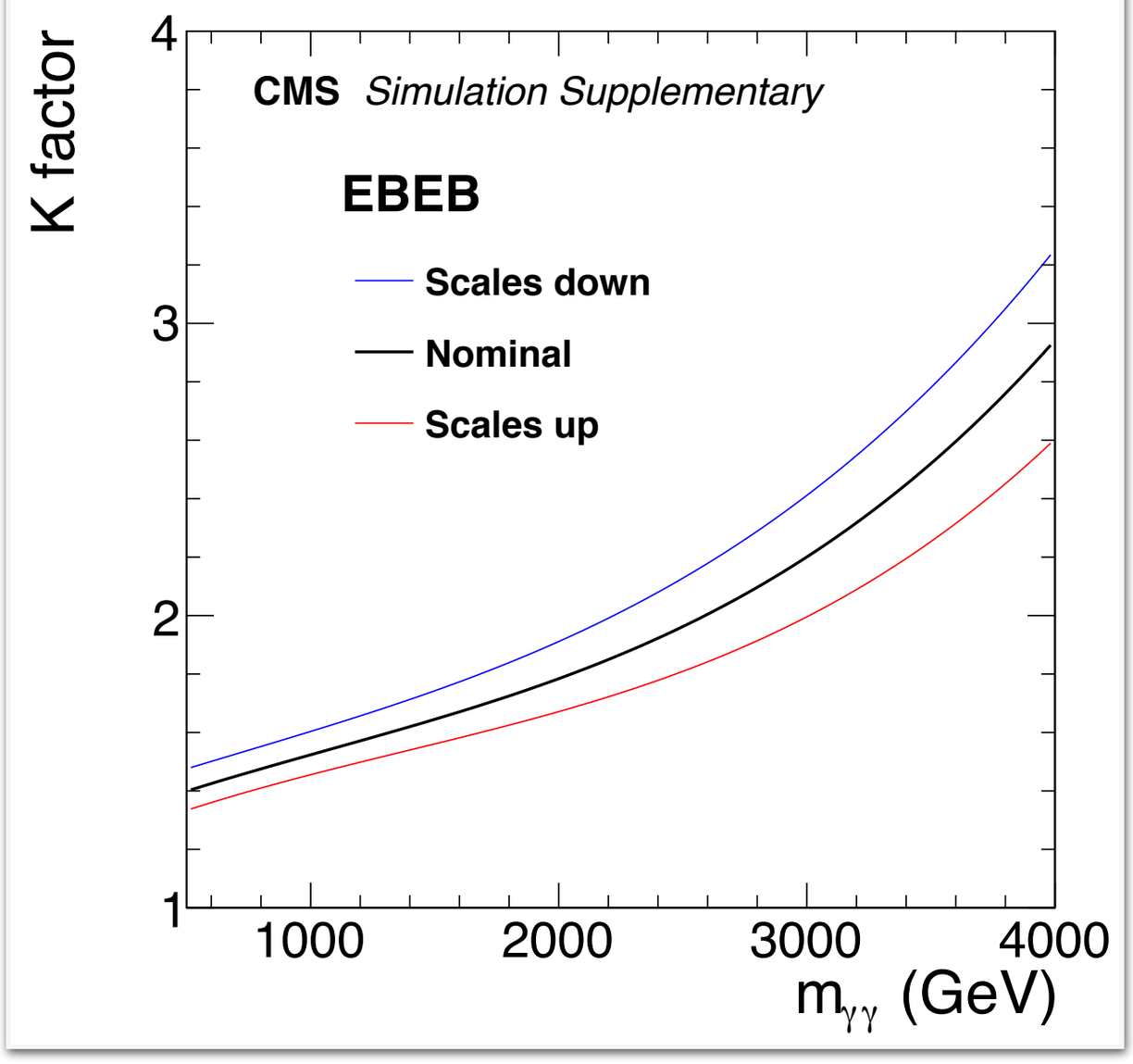
# PDF set

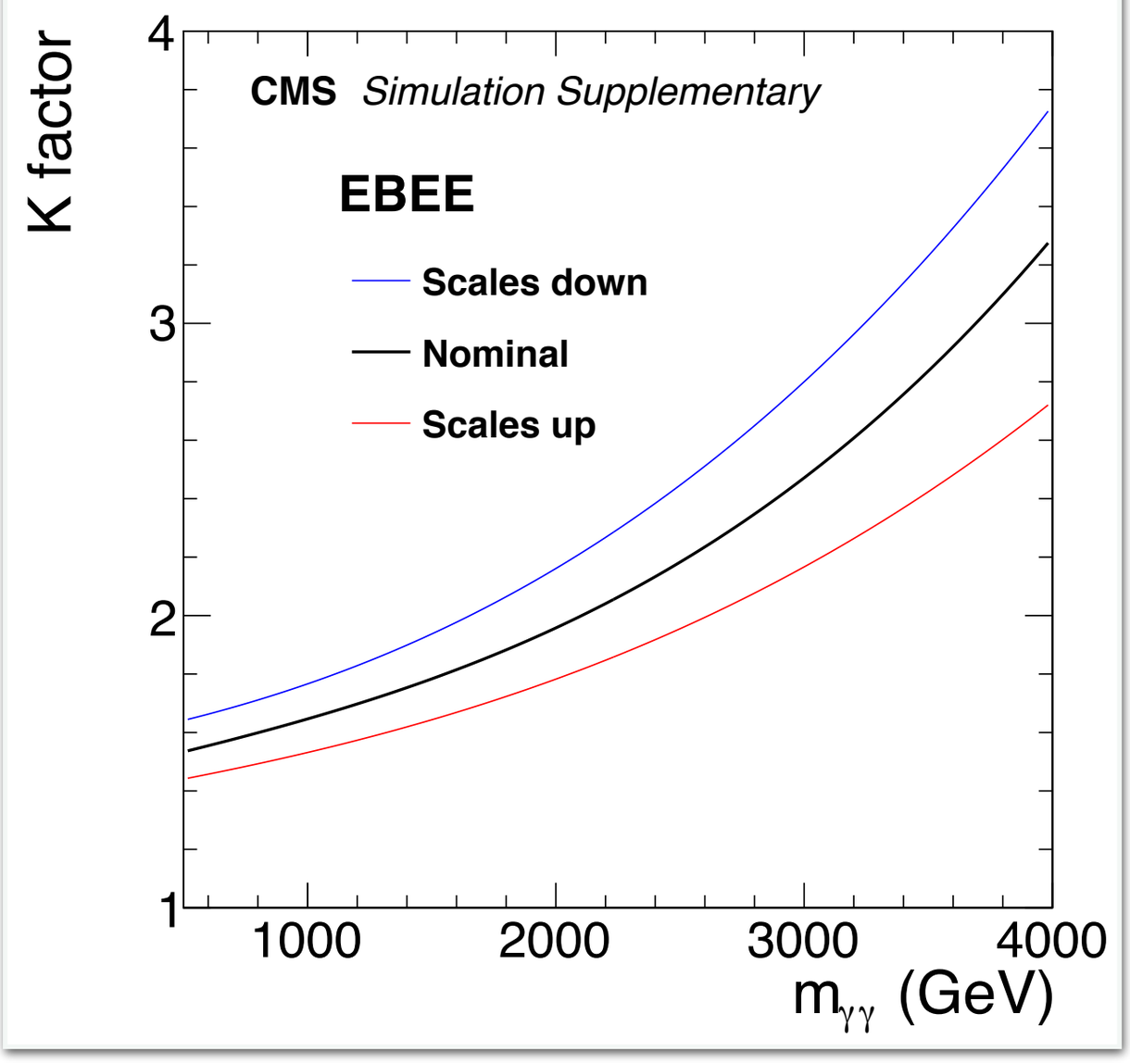



$$\sigma_{AB\to X} = \sum_{a,b} \int dx_a dx_b f_{a/A}(x_a, \mu_f^2) f_{b/B}(x_b, \mu_f^2) \hat{\sigma}_{ab\to X}$$

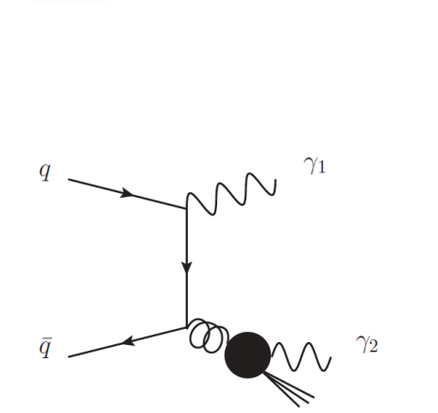


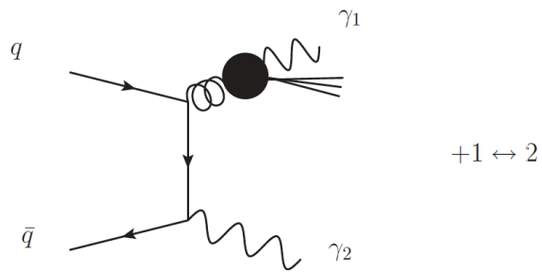
# *K* factor variation

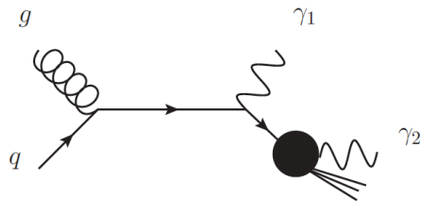


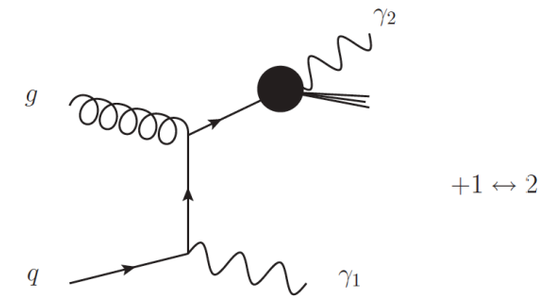



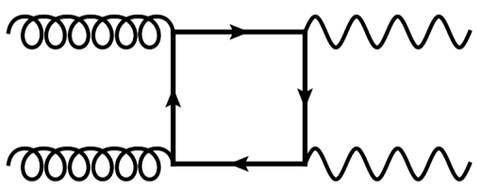
# SM diphoton diagrams

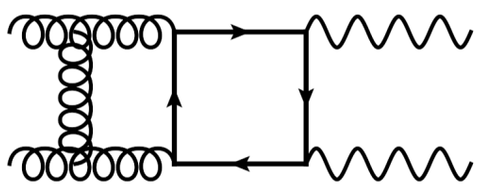


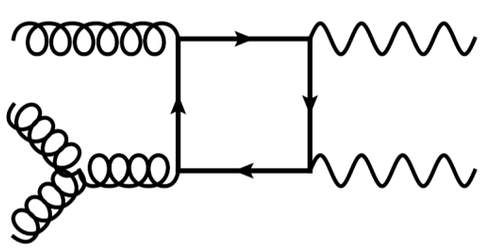



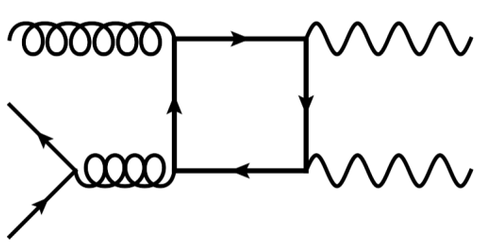



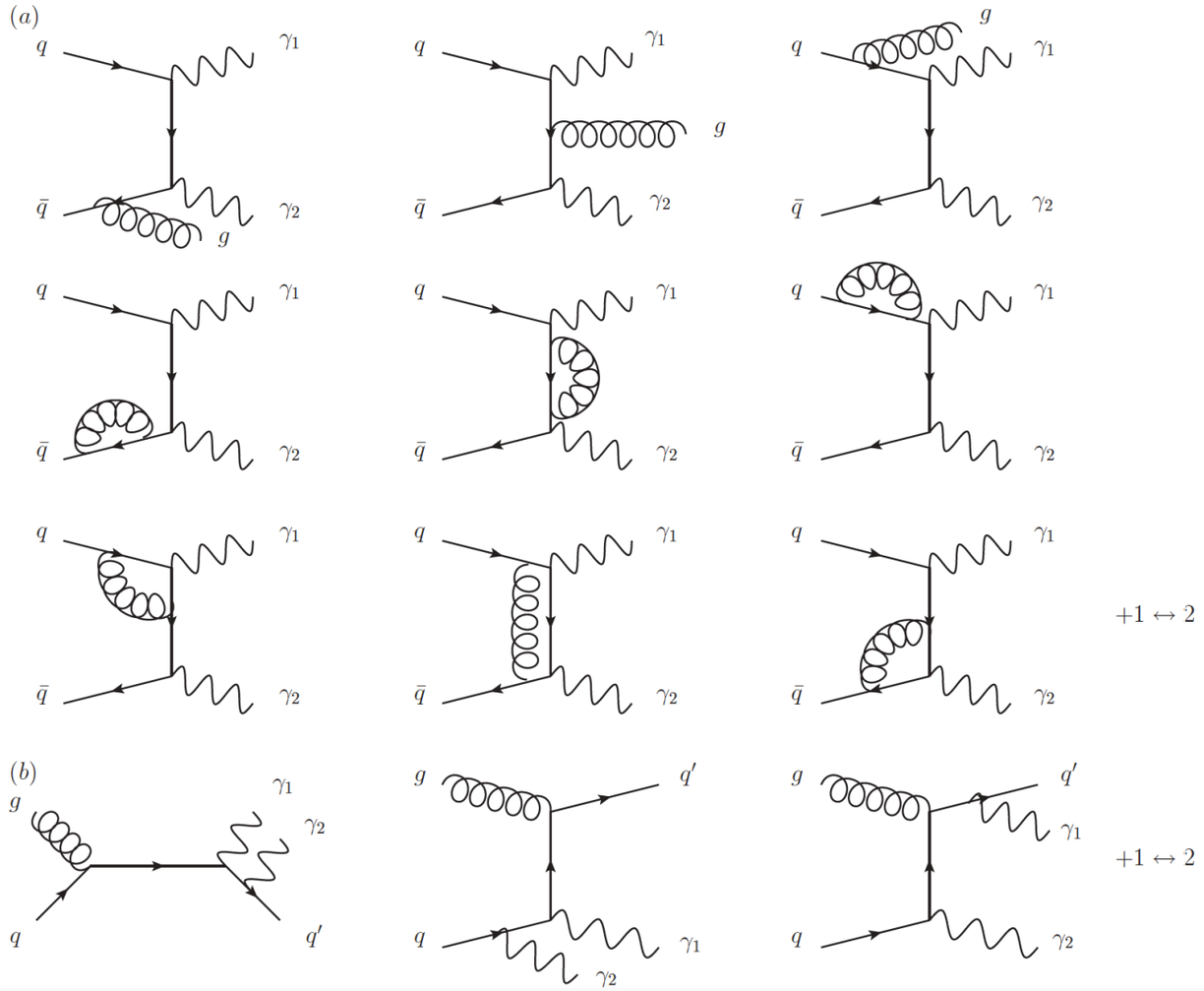



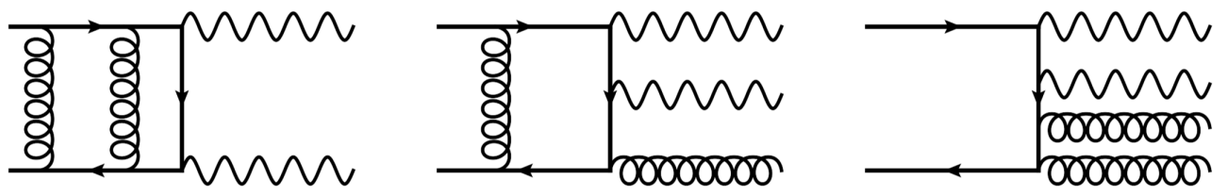









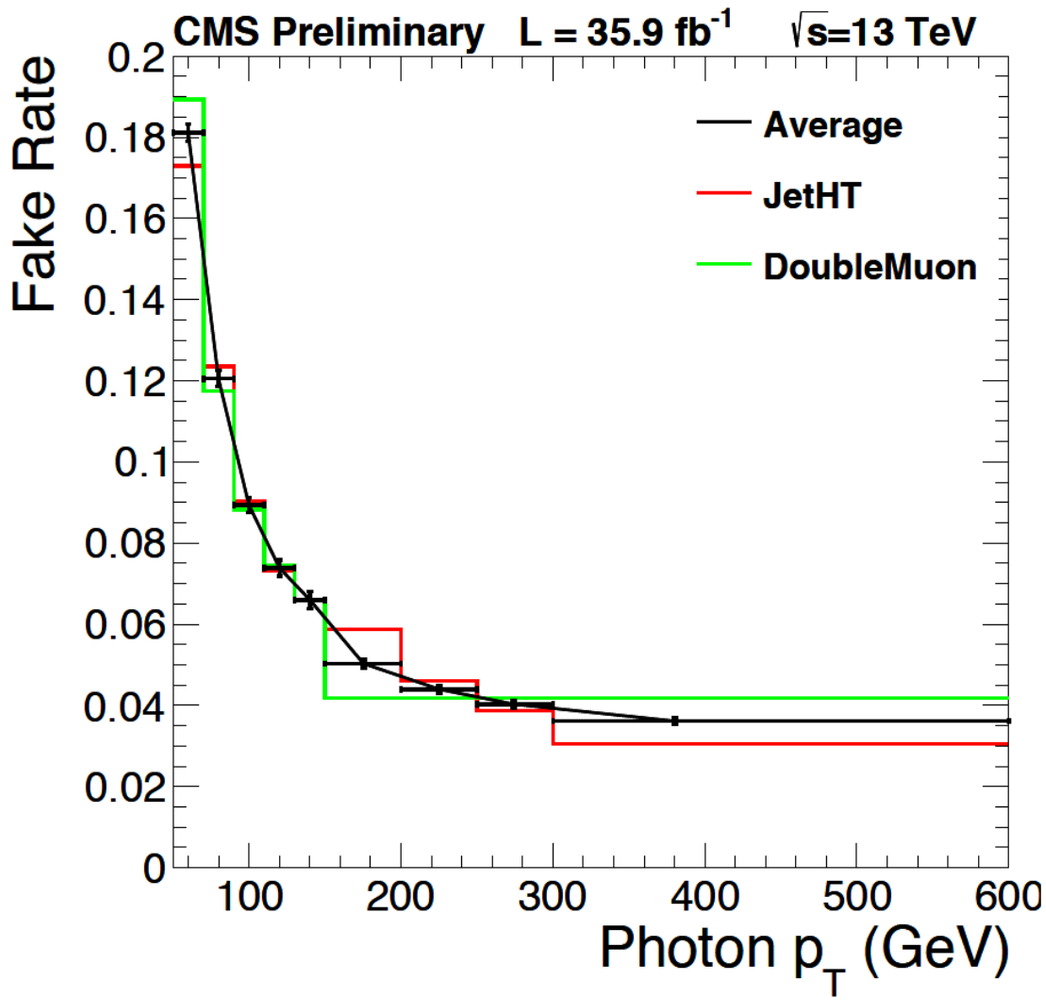


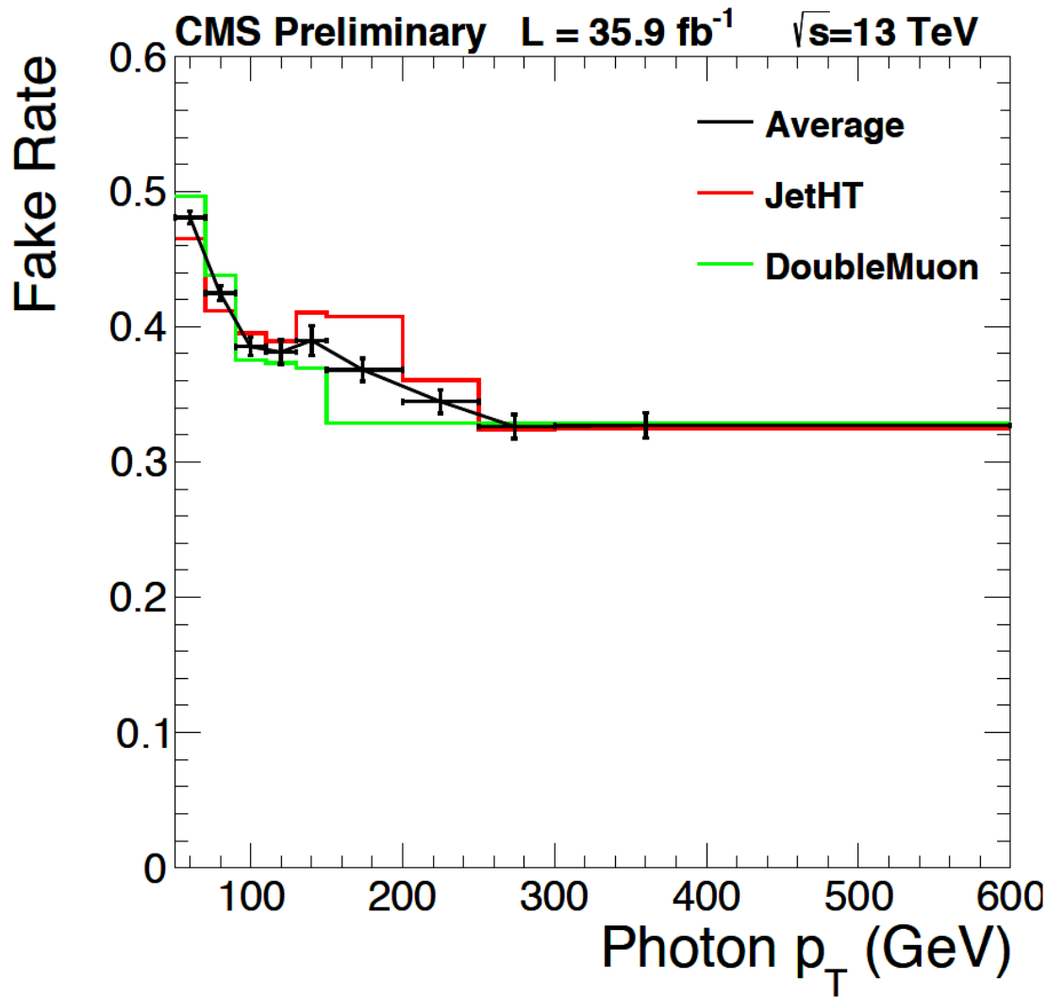



# Fake rate definitions

| Cut [EB {sat.} (EE {sat.})] | Photon ID | Num. | Real template | Fake template | Denom. (EB) | Denom. (EE) |
|---|---|---|---|---|---|---|
| **Photon ID cuts** | | | | | | |
| $H/E < 0.05$ | pass | pass | pass | pass | | |
| $\sigma_{i\eta i\eta} < 0.0105\,\{0.0112\}\,(0.028\,\{0.030\})$ | pass | template | template | template | | |
| $\mathrm{Iso}_{\mathrm{Ch}} < 5\,\mathrm{GeV}$ | pass | pass | pass | not applied | fail at least one | fail at least one |
| $\overline{\mathrm{Iso}}_{\gamma} < 2.75\,(2.00)\,\mathrm{GeV}$ | pass | pass | pass | pass | | pass |
| $R_9 > 0.8$ | pass | pass | pass | pass | pass | pass |
| **Electron veto** | | | | | | |
| CSEV | pass | pass | pass | pass | pass | pass |
| **Additional fake rate cuts** | | | | | | |
| $\sigma_{i\phi i\phi} > 0.009$ | not applied | pass | pass | pass | pass | pass |
| $5 < \mathrm{Iso}_{\mathrm{Ch}} < 10\,\mathrm{GeV}$ | not applied | not applied | not applied | pass | not applied | not applied |
| $\mathrm{Hadronic/E} < 0.1$ | not applied | not applied | not applied | not applied | pass | pass |
| $\mathrm{Iso}_{\mathrm{Ch}} < 0.2\,p_{\mathrm{T}}$ | not applied | not applied | not applied | not applied | pass | pass |
| $\overline{\mathrm{Iso}}_{\gamma} < 0.2\,p_{\mathrm{T}}$ | not applied | not applied | not applied | not applied | pass | not applied |

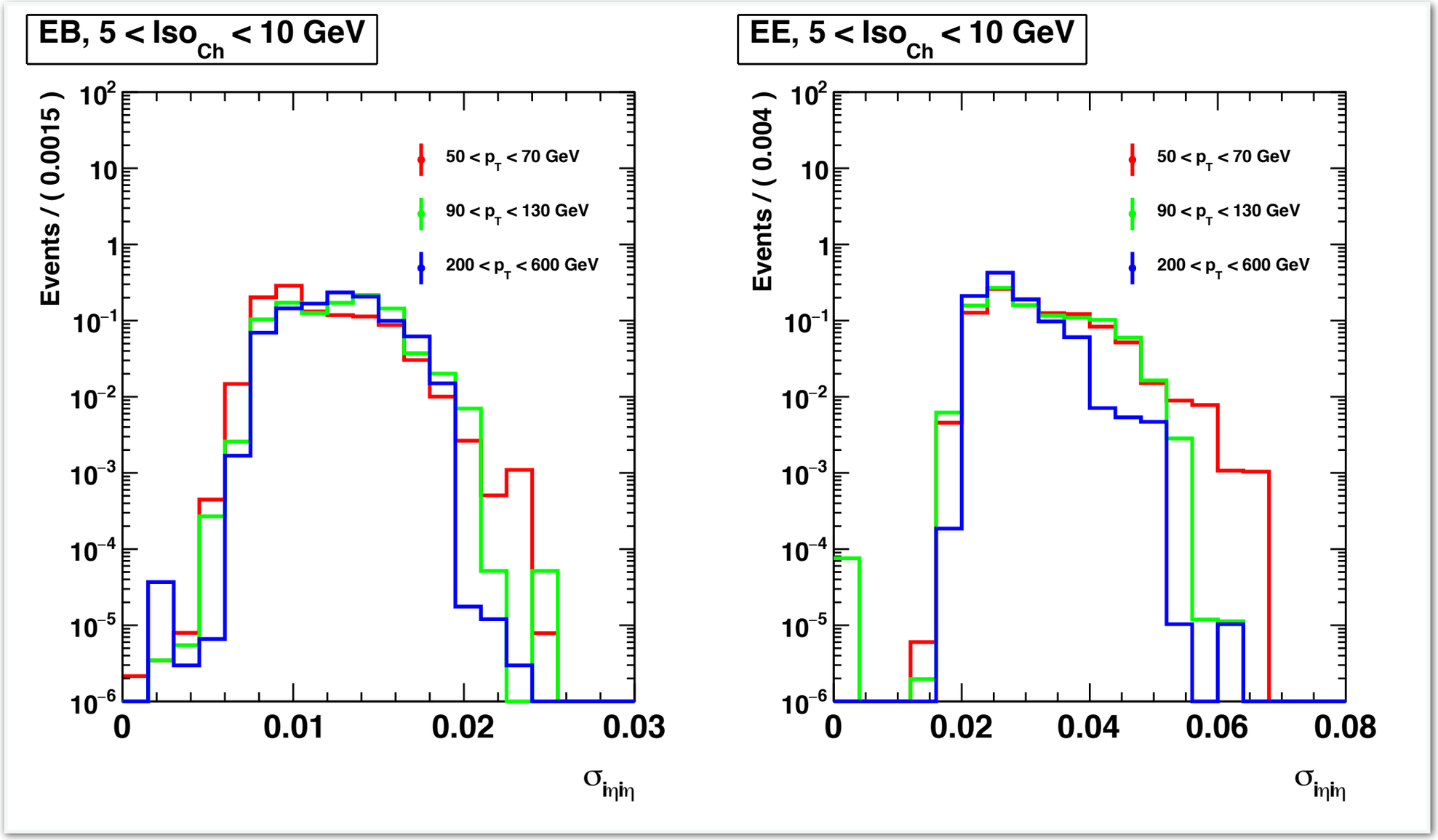
# Fake rate


CMS Preliminary L = 35.9 fb-1 √s=13 TeV
Fake Rate
Average
JetHT
DoubleMuon
Photon pT (GeV)


CMS Preliminary L = 35.9 fb-1 √s=13 TeV
Fake Rate
Average
JetHT
DoubleMuon
Photon pT (GeV)

# MC fake templates vs. $p_T$

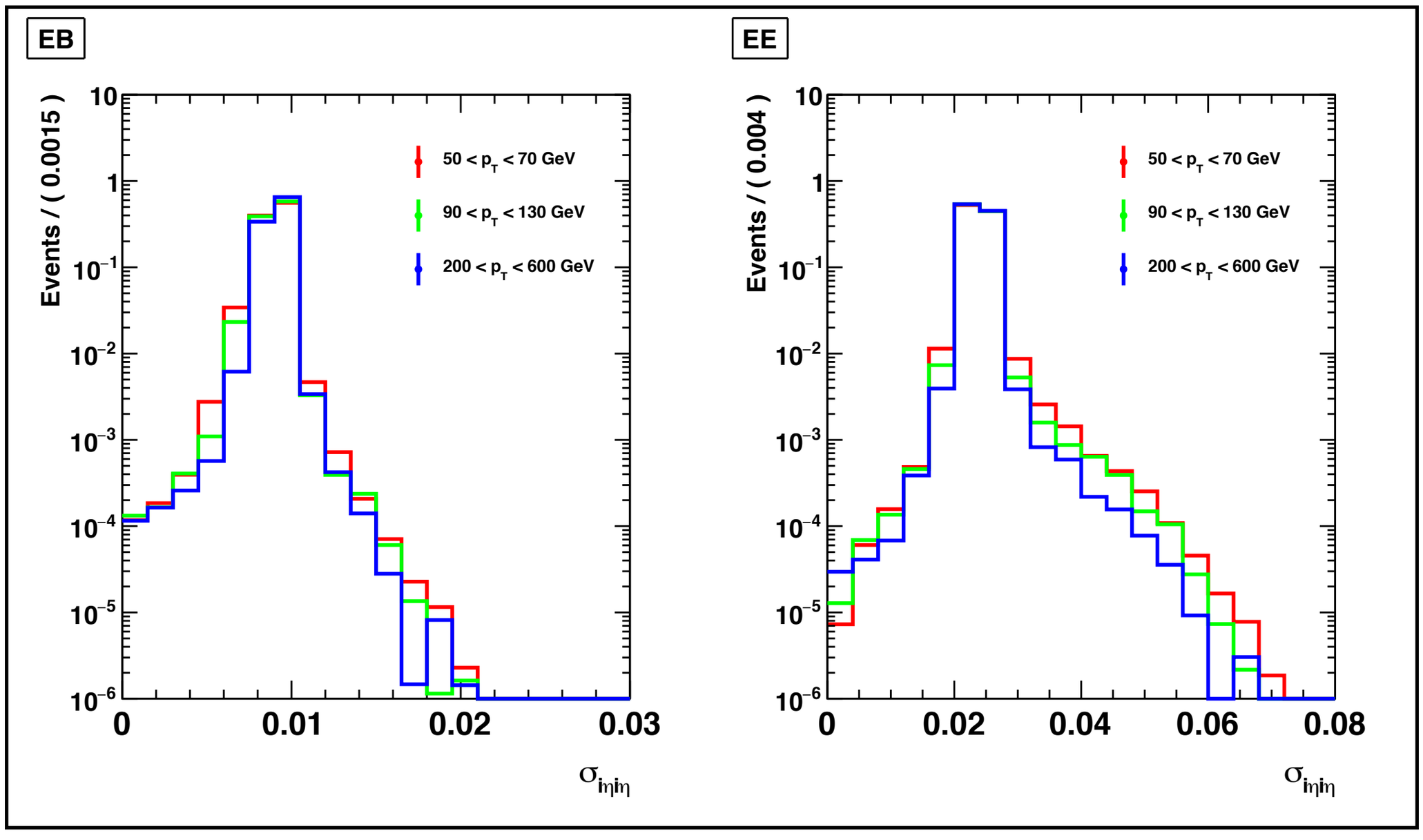
- Fake templates have dependence on photon $p_T$, so we preform the method in photon $p_T$ bins



# Real templates

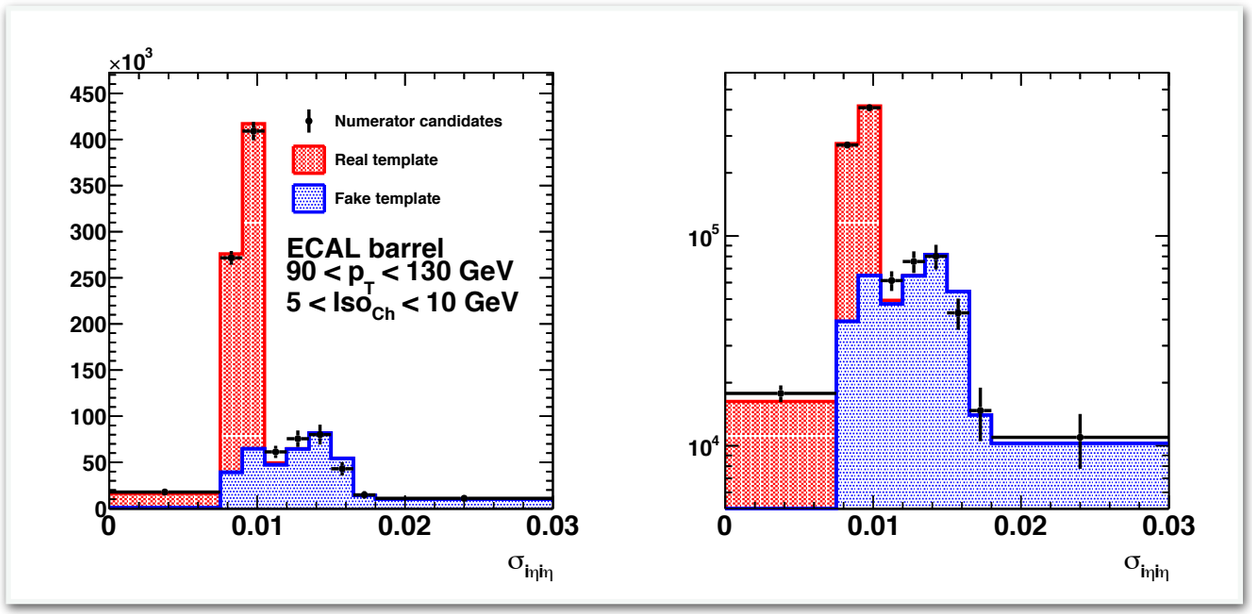
- Real templates taking from photon rich MC
- Templates has dependence on photon $p_T$

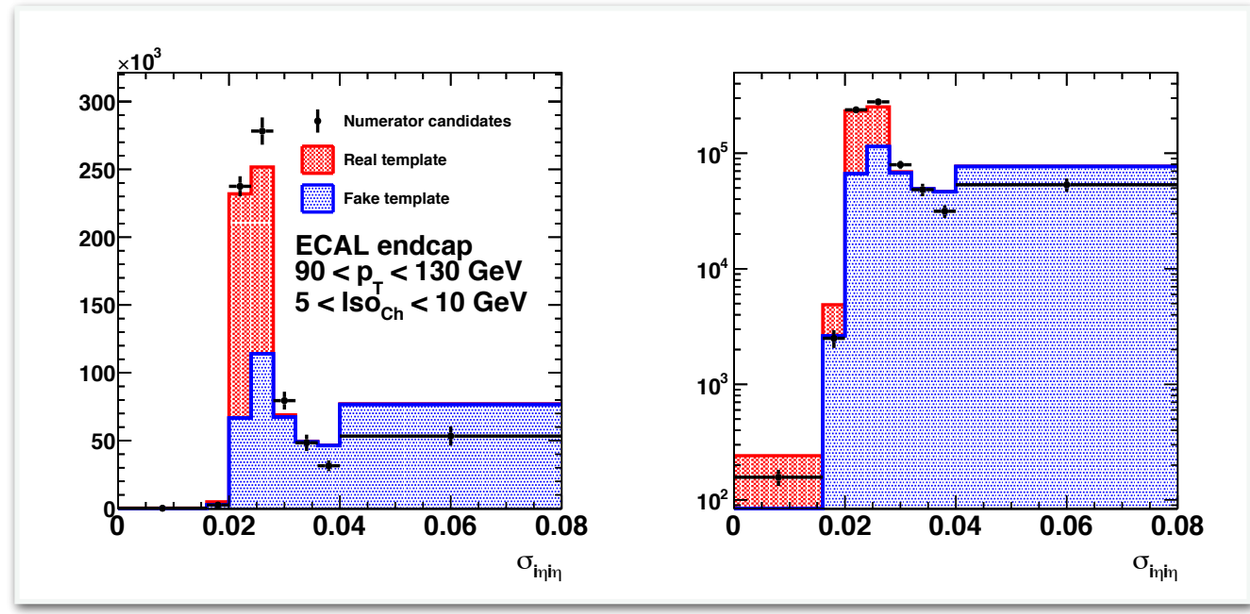
$\sigma_{i\eta i\eta}$ templates



# MC template fits

- Numerator obtain after integrating the post template fits in each $p_T$ bin for EB and EE separately

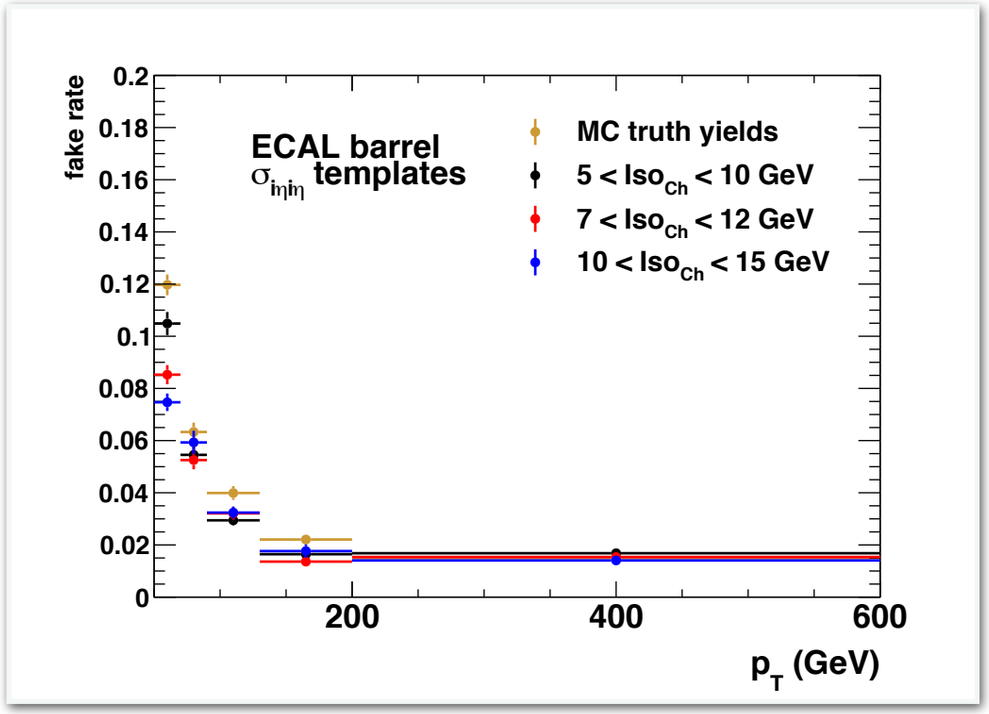


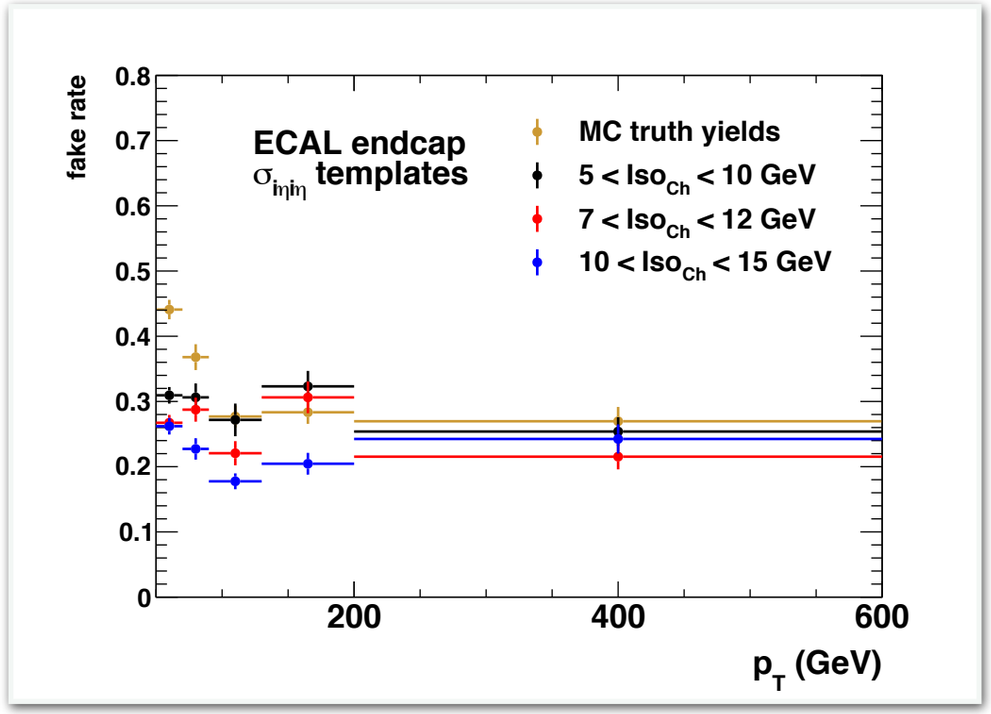




- Count number of object passing denominator definition in each $p_T$ bin to form fake rate

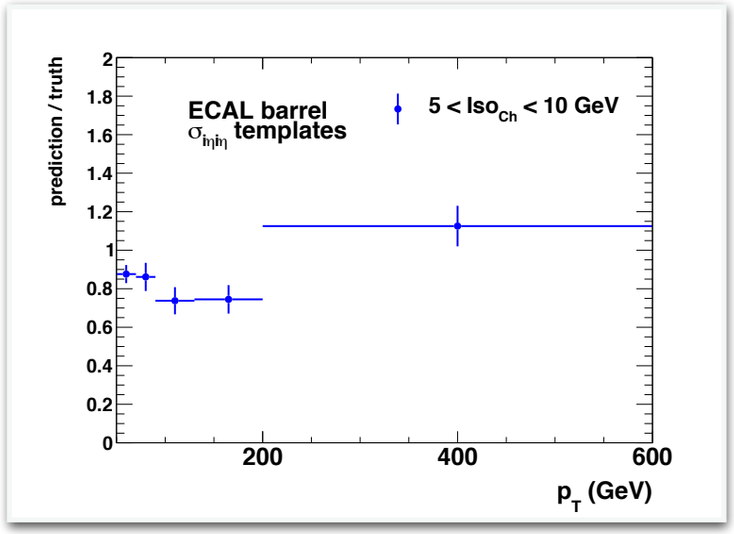
# MC fake rates and closure test

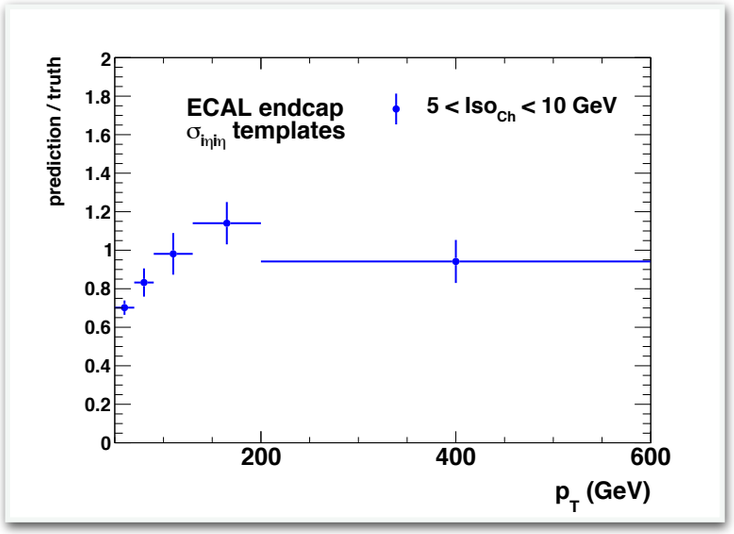
- MC fake rates compared to MC truth




- Closure test predicted fake rate compared to truth fake rate

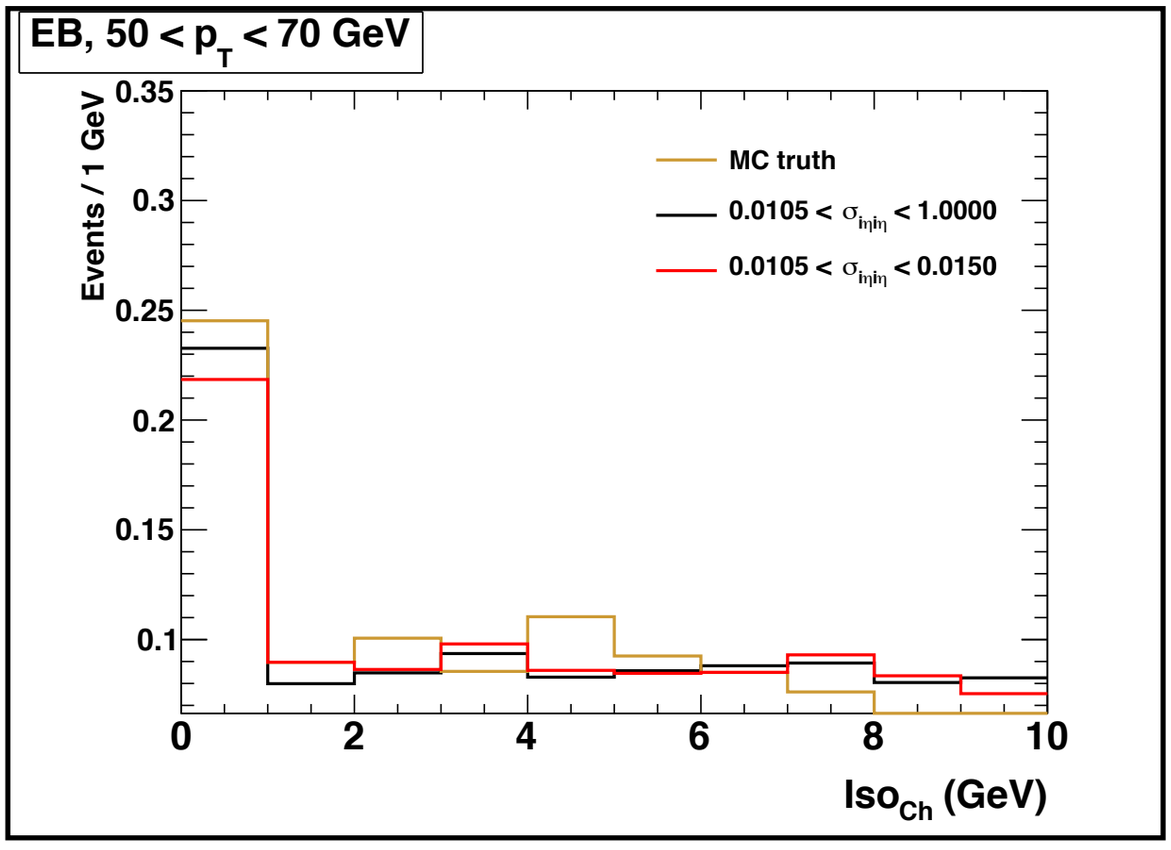


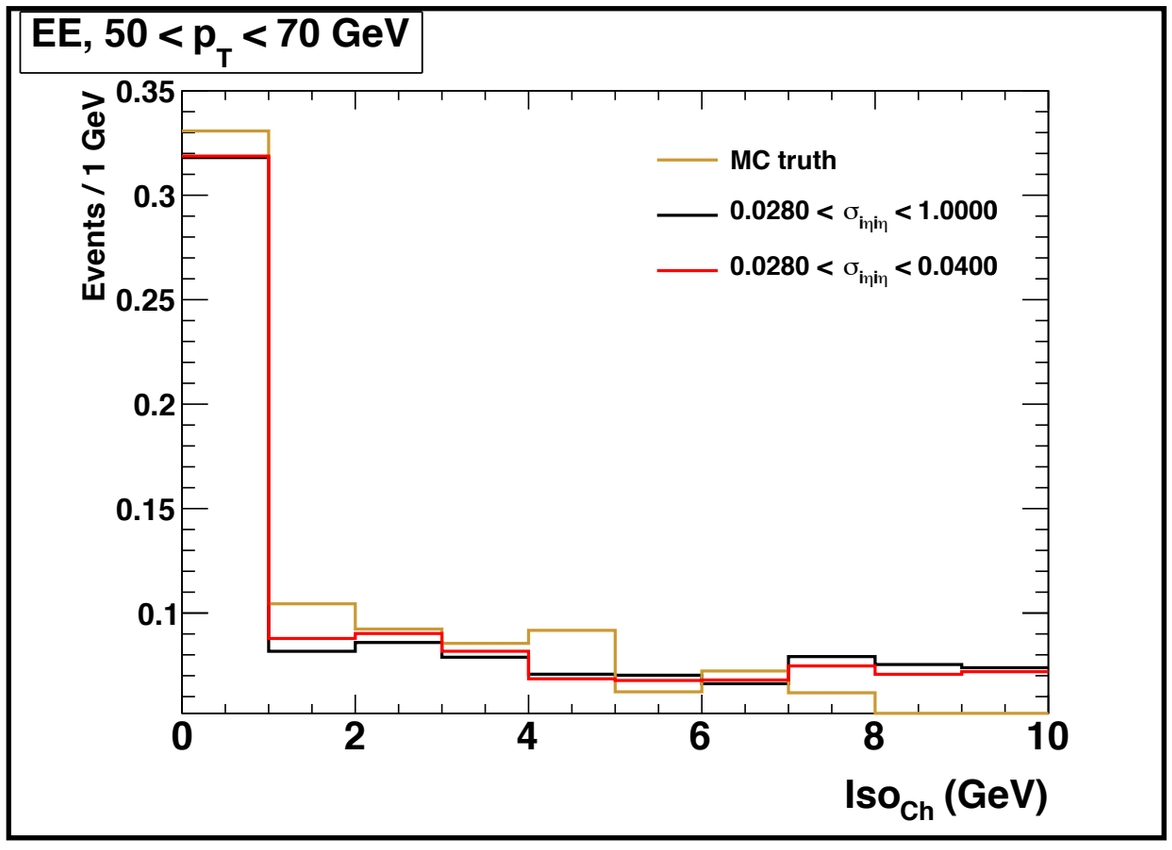



# MC $Iso_{Ch}$ fake templates

- One systematic can be studied by inverting the template and sideband variables

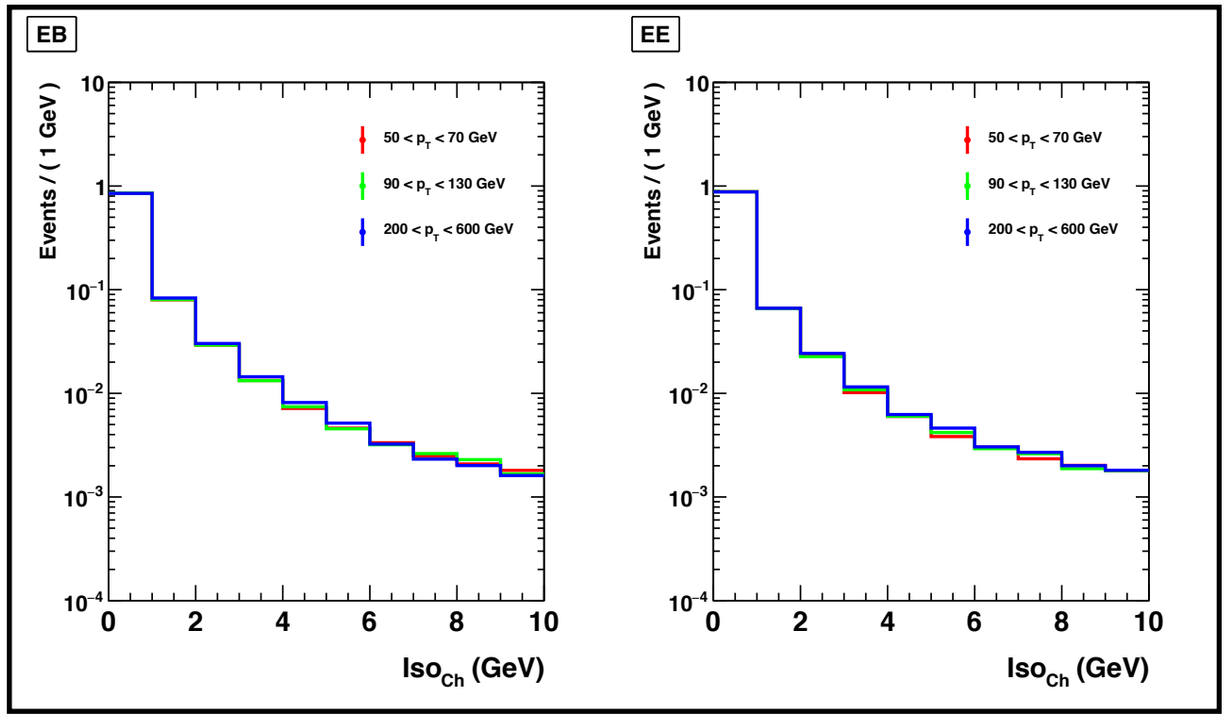
- Now use
  - template variable $Iso_{Ch}$
  - sideband variable $\sigma_{i\eta i\eta}$



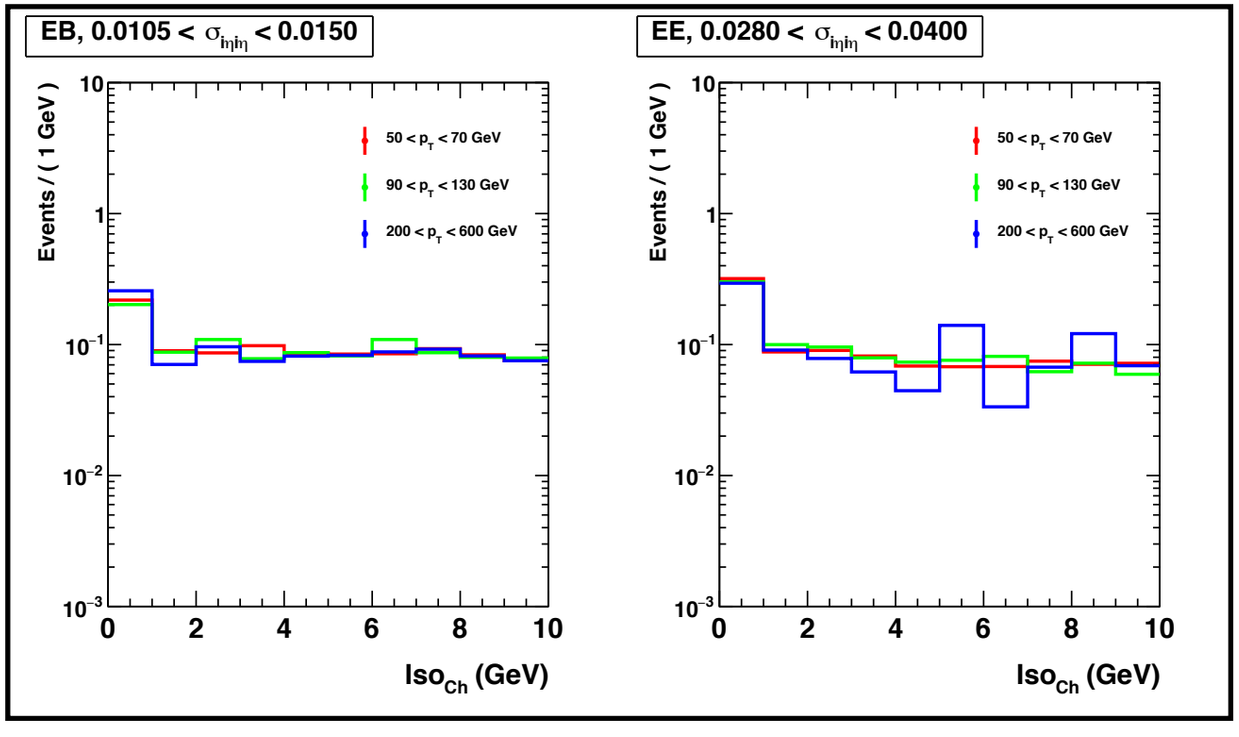



# MC $Iso_{Ch}$ templates vs. $p_T$

- One nice feature, no dependence on $p_T$



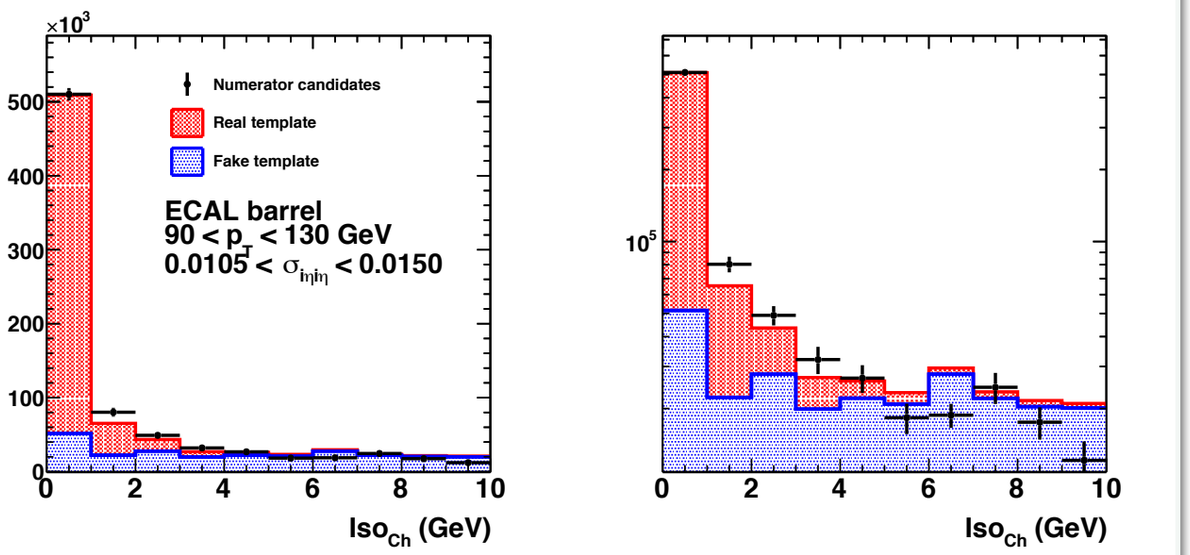

$Iso_{Ch}$ fake templates

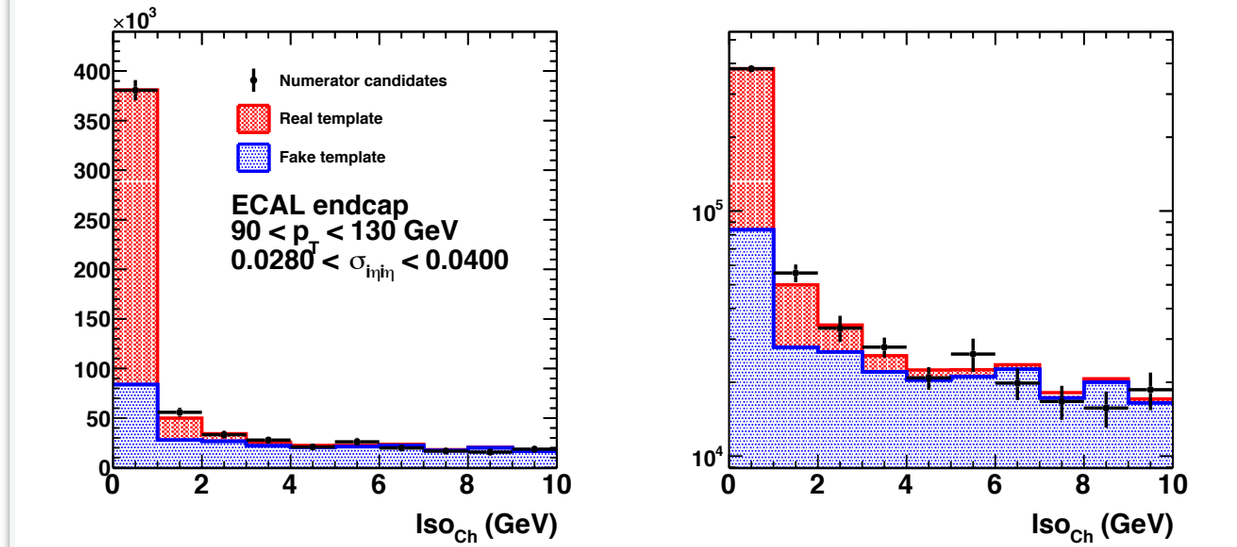


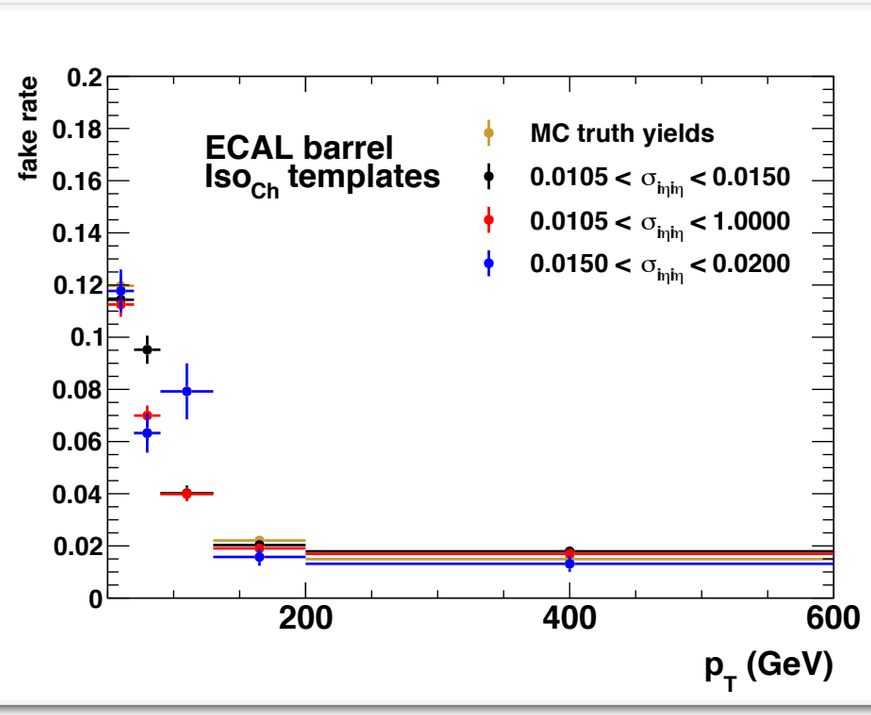

$Iso_{Ch}$ real templates

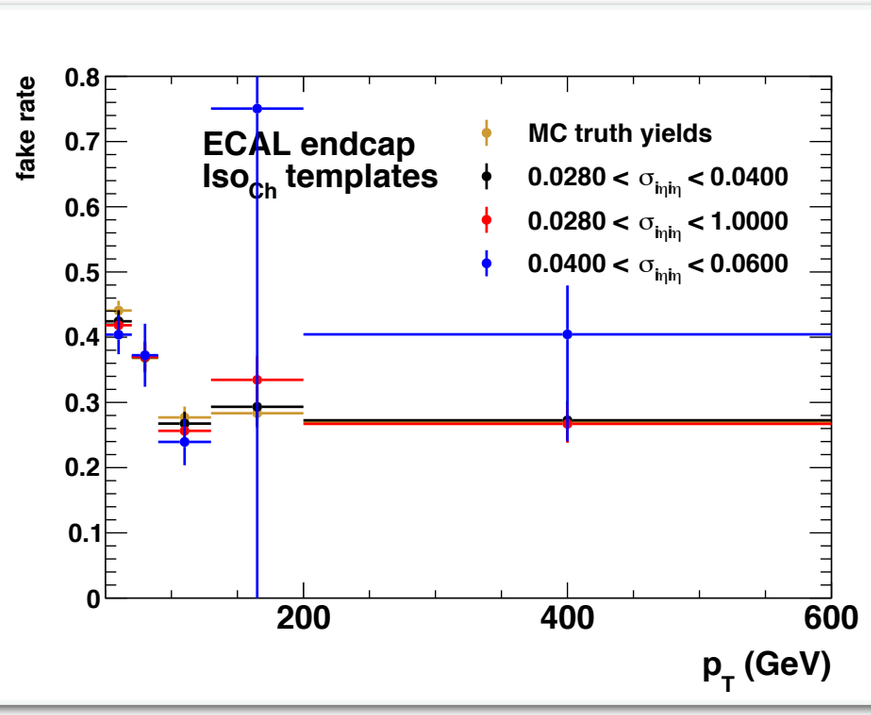
# MC $Iso_{Ch}$ template fits

- MC template fit example and MC fake rate with MC truth



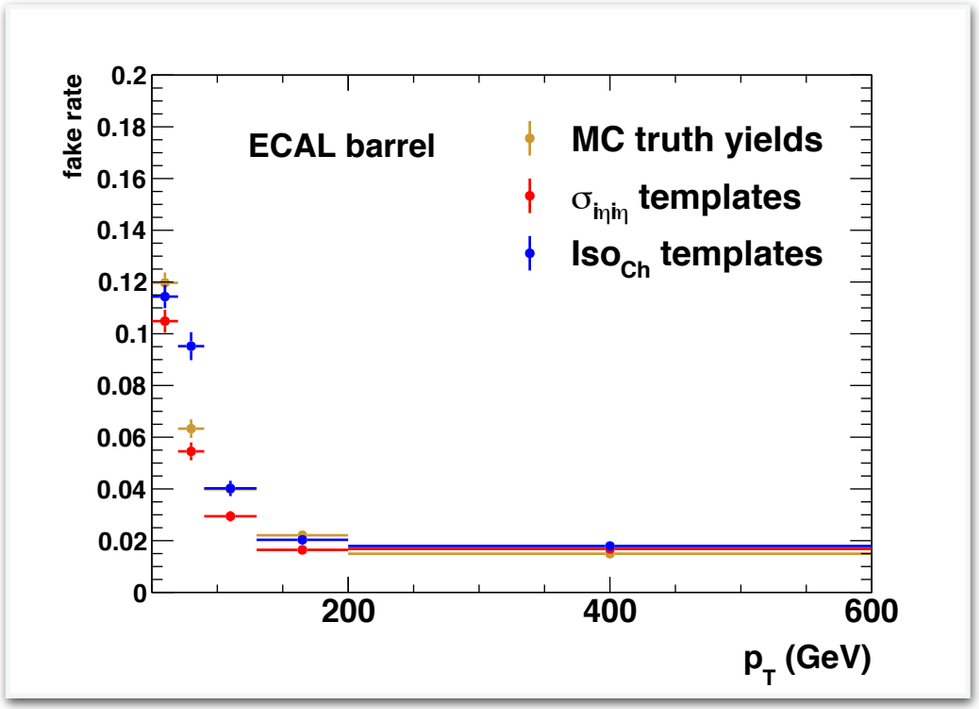



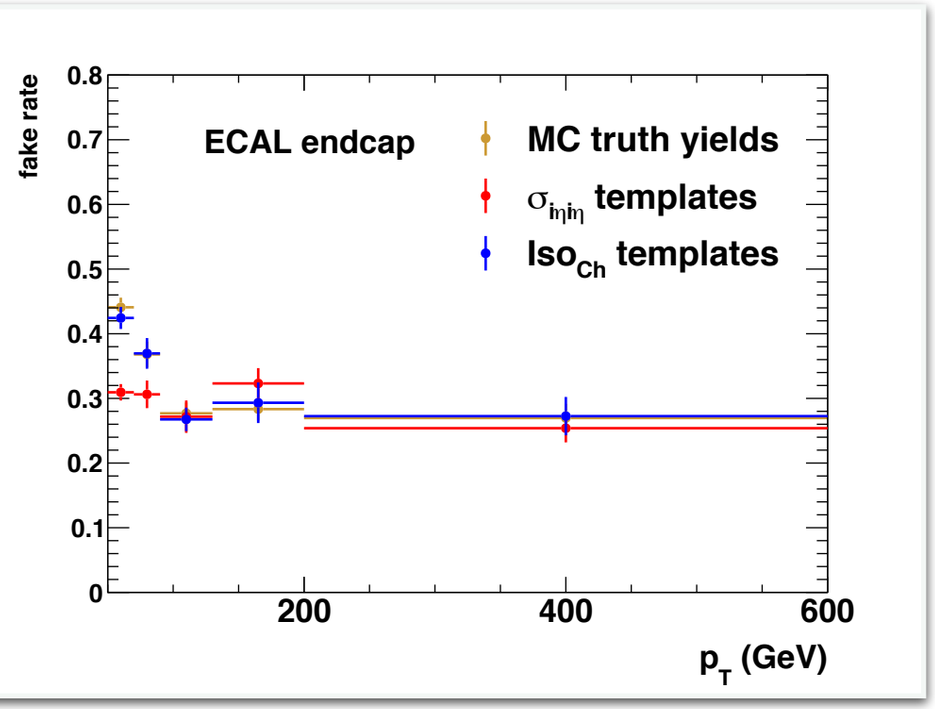



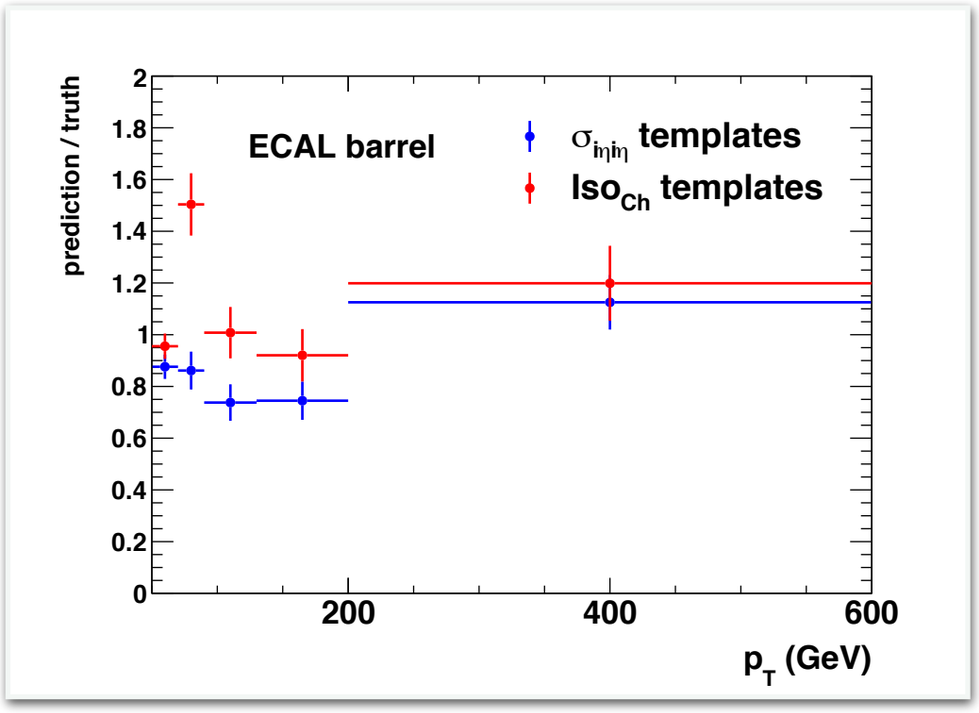



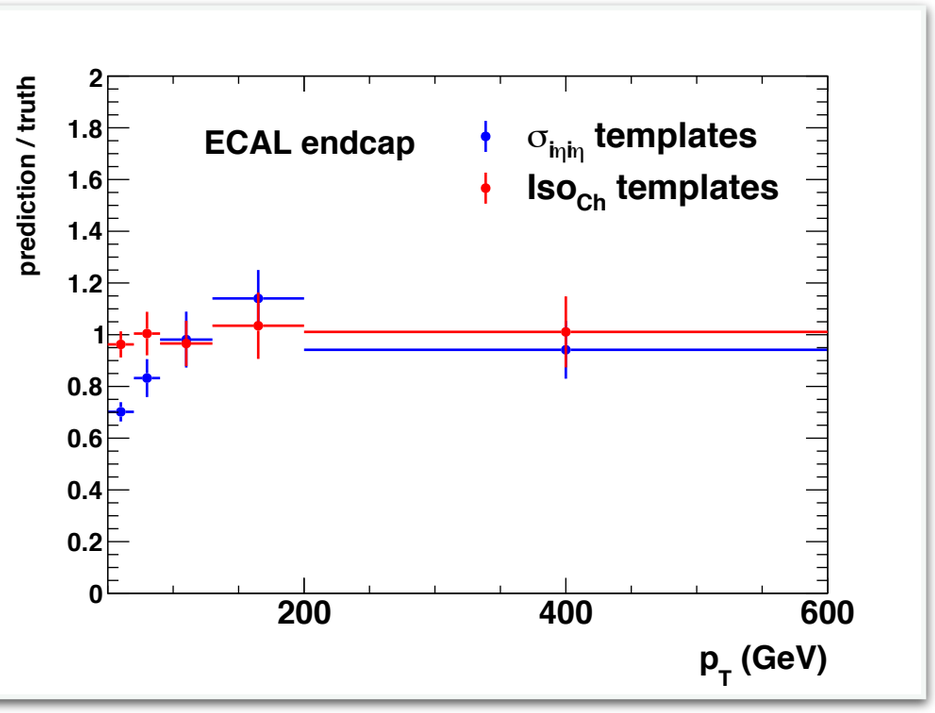
# MC closure test comparison

- Agreement in MC fake rate and MC closure test with both template choices



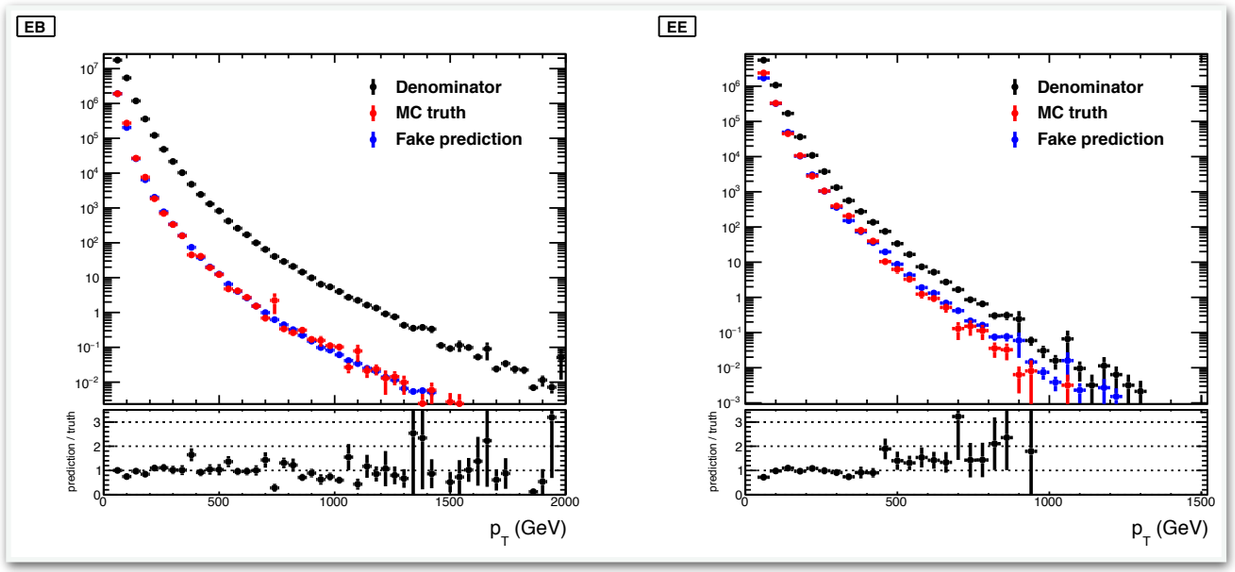



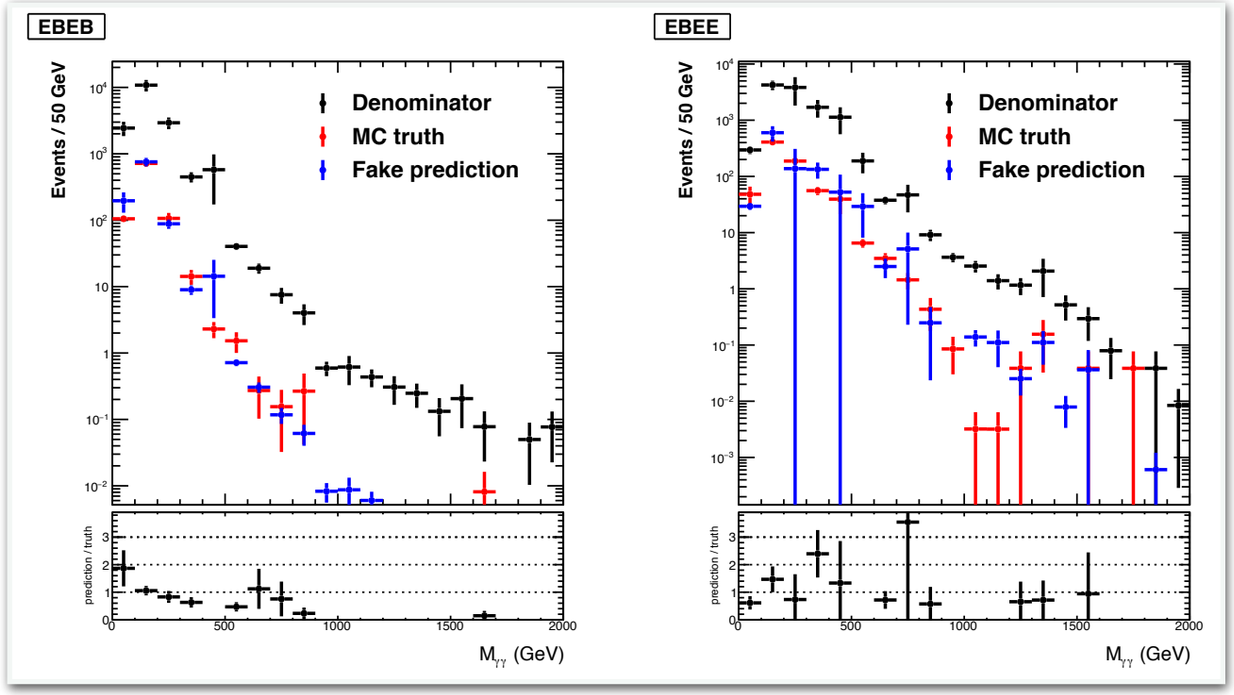



# Closure test of kinematics

- The **re-weighted denominator objects** reflect the kinematics of known fake objects from **MC truth**



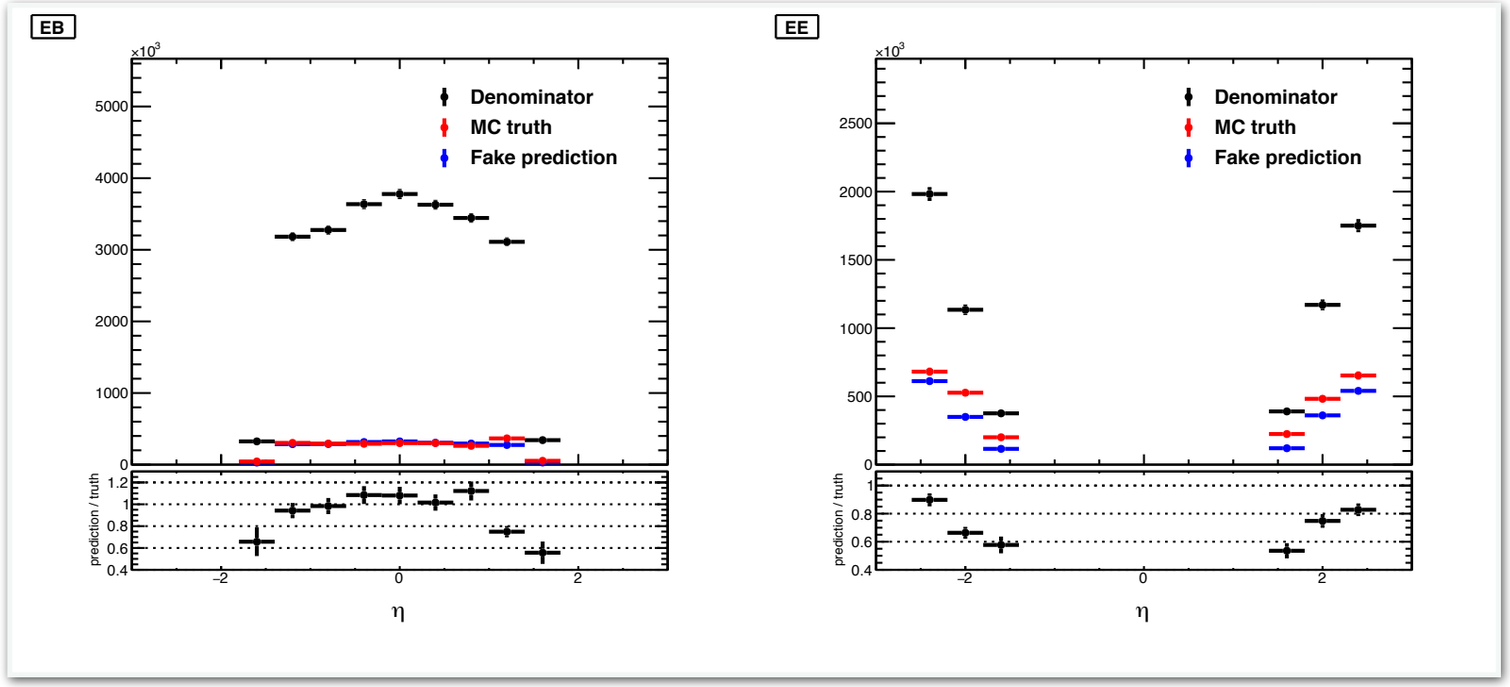

- Photon $p_T$ in EB and EE

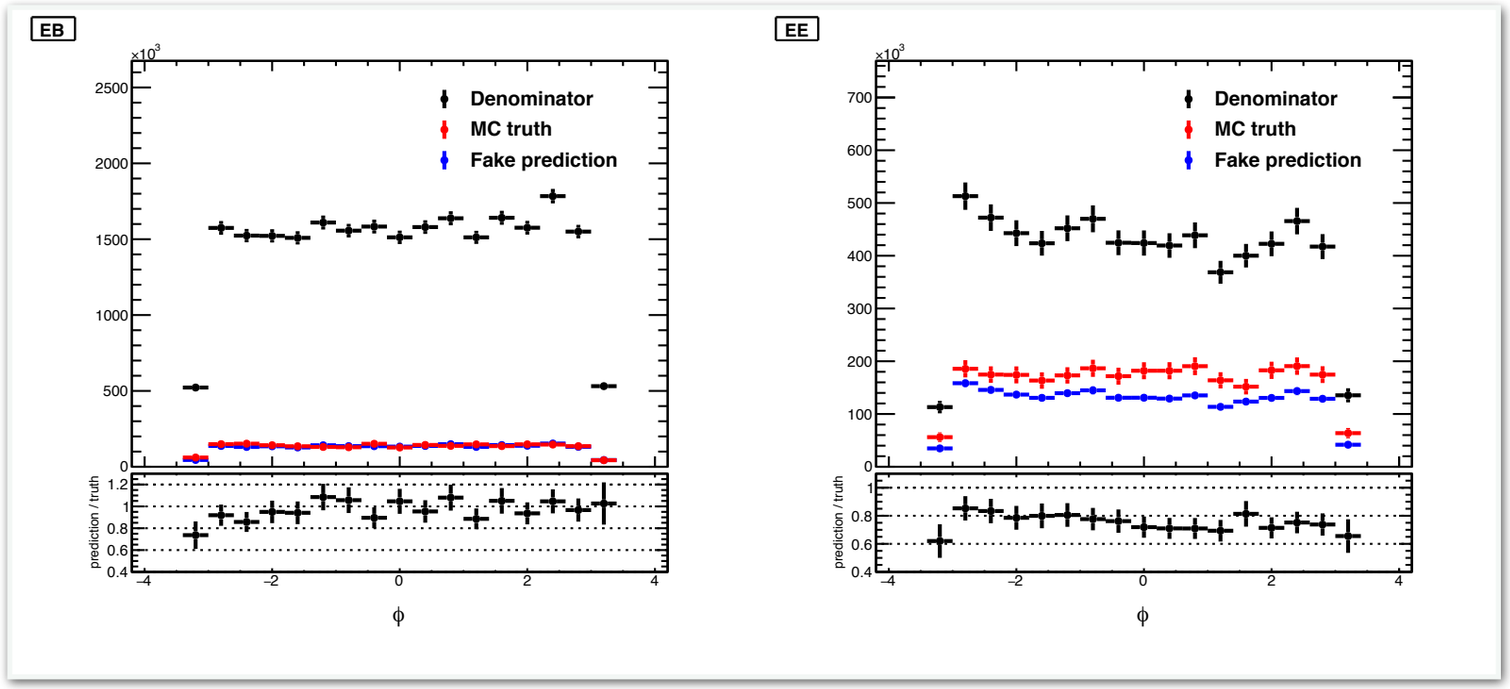



- Diphoton $m_{\gamma\gamma}$ $\gamma$+j objects in EBEB and EBEE

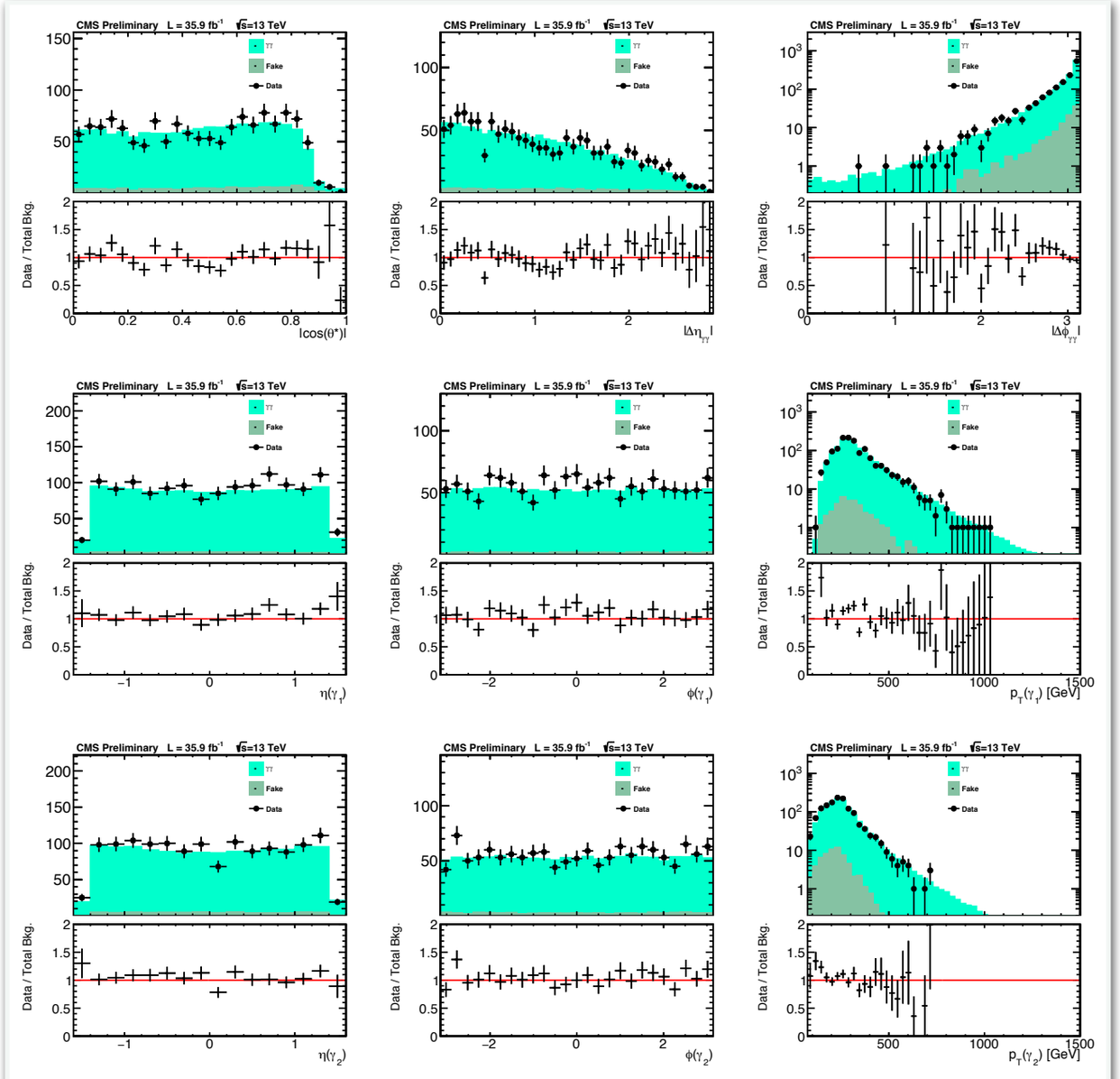
# Closure test photon kinematics

- Photon $\eta$ and $\phi$
  - EB, EE
- Some $\eta$ dependence

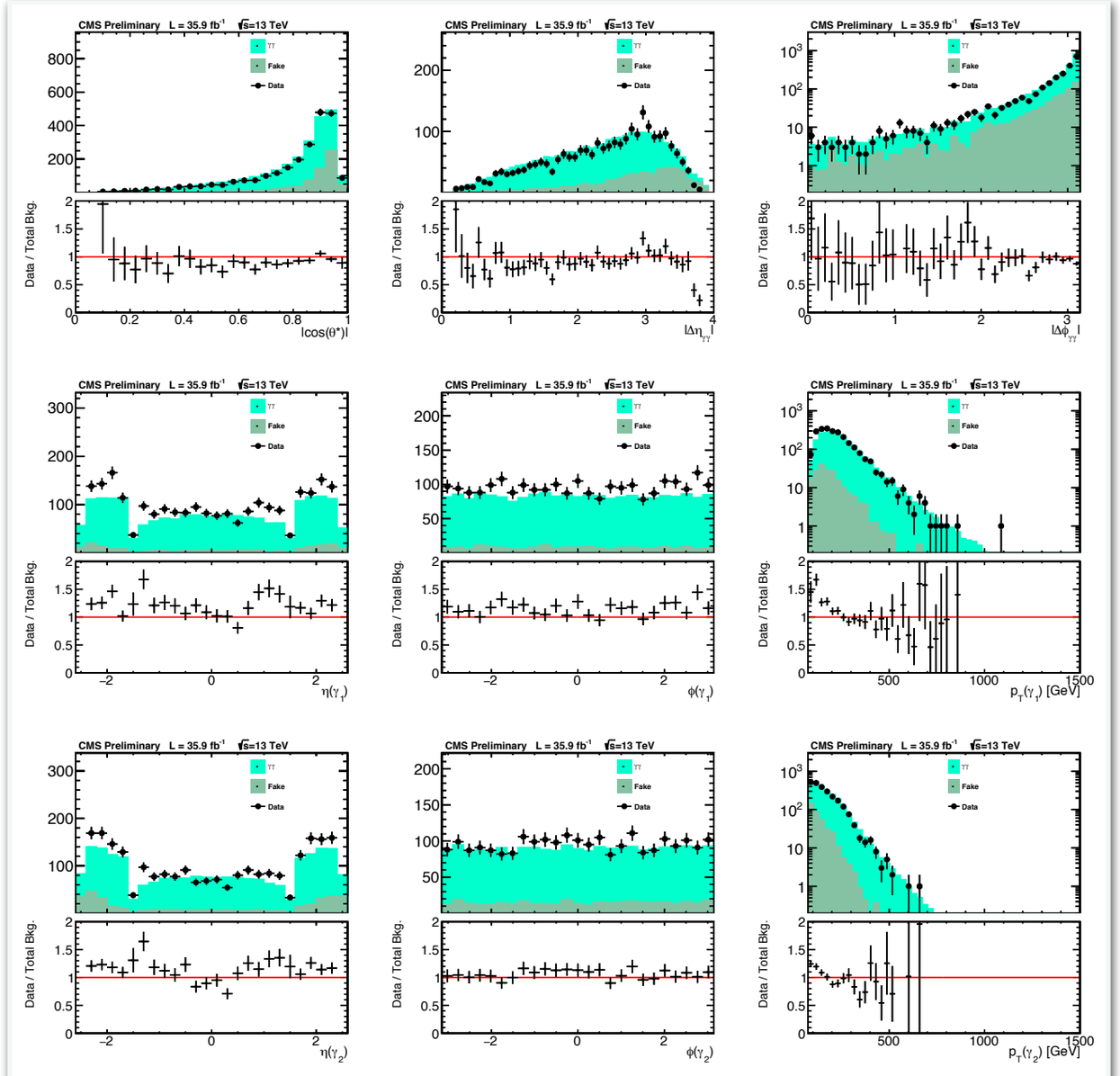


# Photon kinematics




**EBEB**




**EBEE**

# Systematic uncertainty correlation matrix