ELECTRONS AND PHOTONS @ CMS

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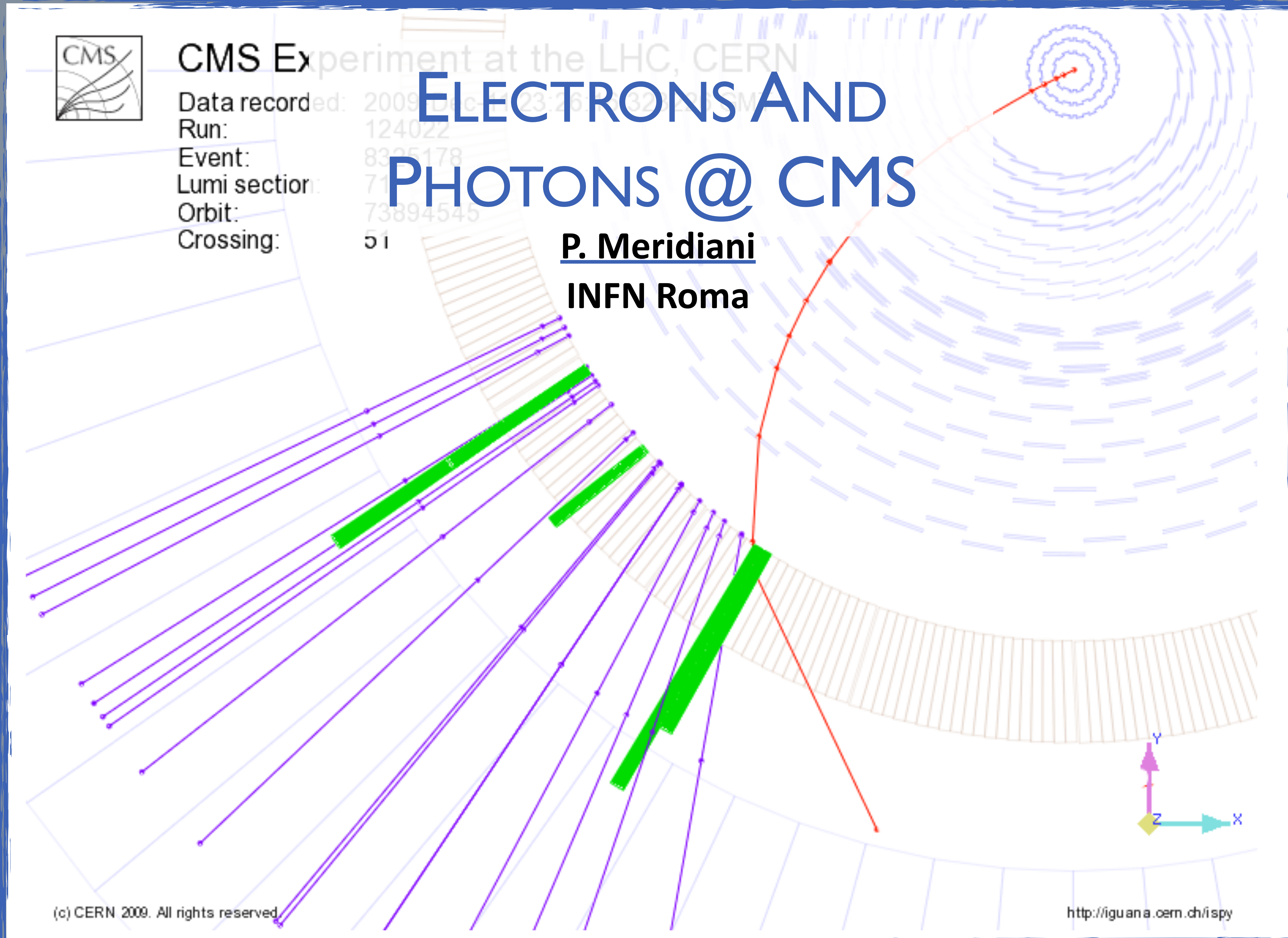

CMS ECAL

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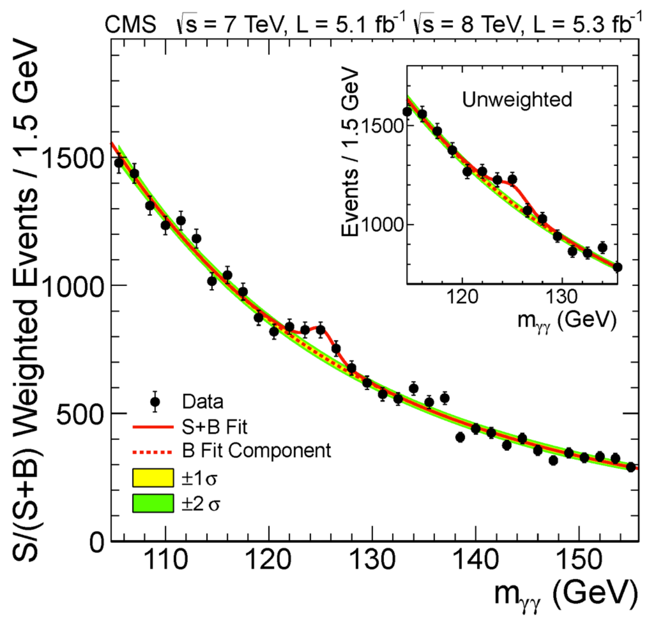
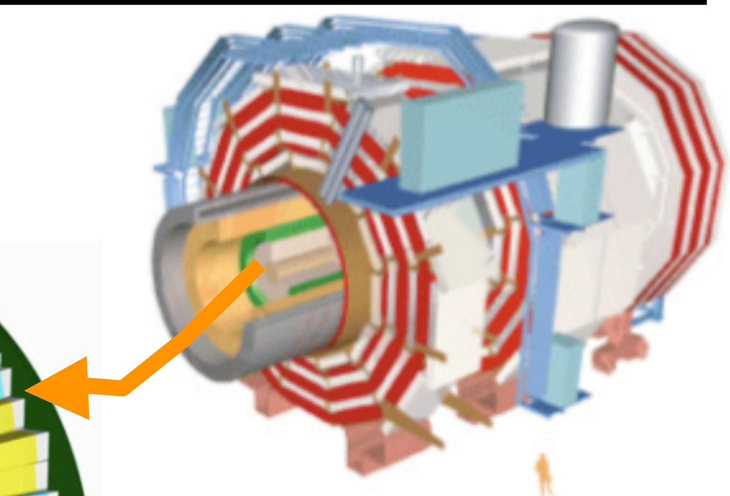
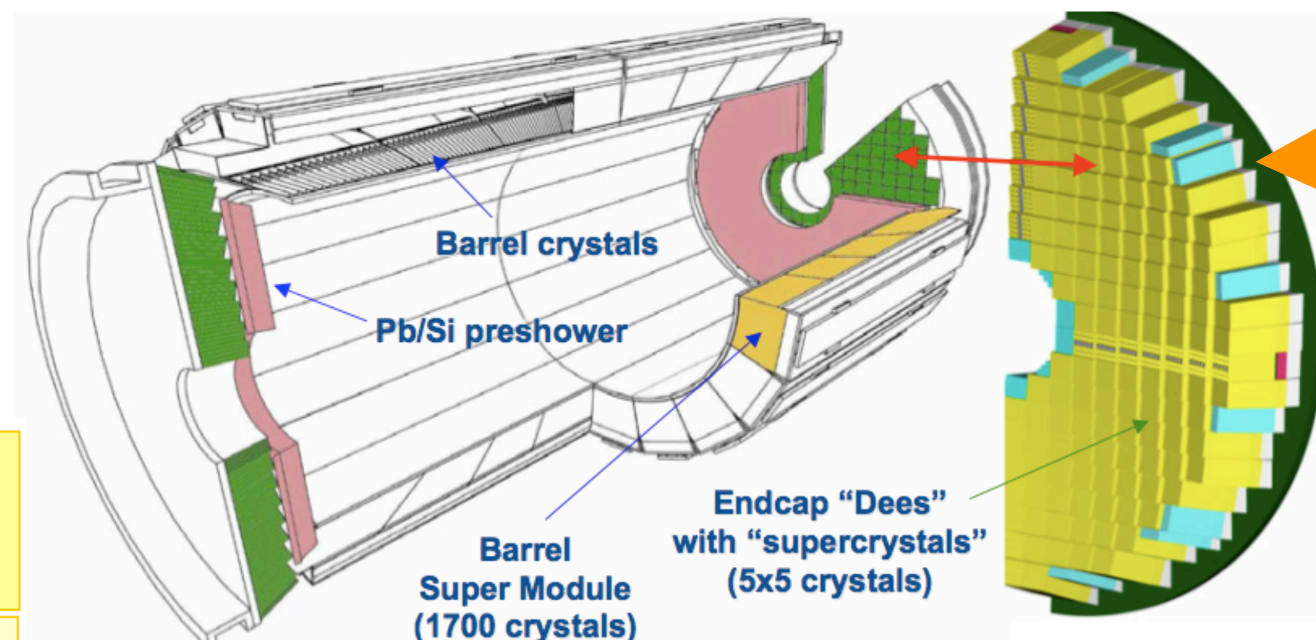
Emphasis on low mass Higgs in $\gamma\gamma$



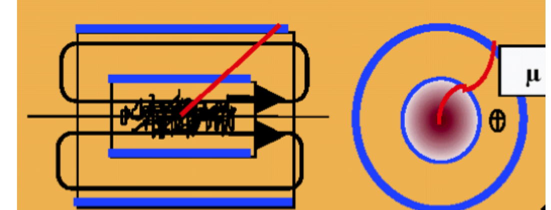
Homogeneous $PbWO_4$ crystals
low stochastic term for excellent energy resolution
No longitudinal segmentation:
to measure γ direction needs interaction vertex position

Tracker coverage $|\eta|<2.5$
ECAL placed inside the coil
Designed for 14 TeV, $L=10^{34}cm^{-2}s^{-1}$, 500 fb^{-1}





3.8 T magnetic field



Magnet radius 6 m

EB Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2x2x23cm³) $26X_0$

EE EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals (3x3x22cm³) $24X_0$

ES Preshower: $1.65 < |\eta| < 2.6$
$3X_0$ of Pb/Si strips
1.90 × 61 mm² x-y view

Barrel - Avalanche Photo-Diodes (APD)
Gain: 50 QE ~ 75% @ λ_{peak}=420nm
$\Delta G/\Delta T$=-2.4%/°C $\Delta G/\Delta V$=3.1%/V
Endcap - Vacuum Photo Triodes (VPT)
Gain: 10 QE ~ 20% @ λ_{peak}=420nm
Conditioning with cumulated charge

ECAL INTRINSIC RESOLUTION

Intrinsic resolution measured in the test beam (with an electron beam)

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

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

a) Stochastic term

- Statistic fluctuations (shower containment + photo-statistics).
- Minimised for an homogeneous calorimeter (sampling fraction=1)

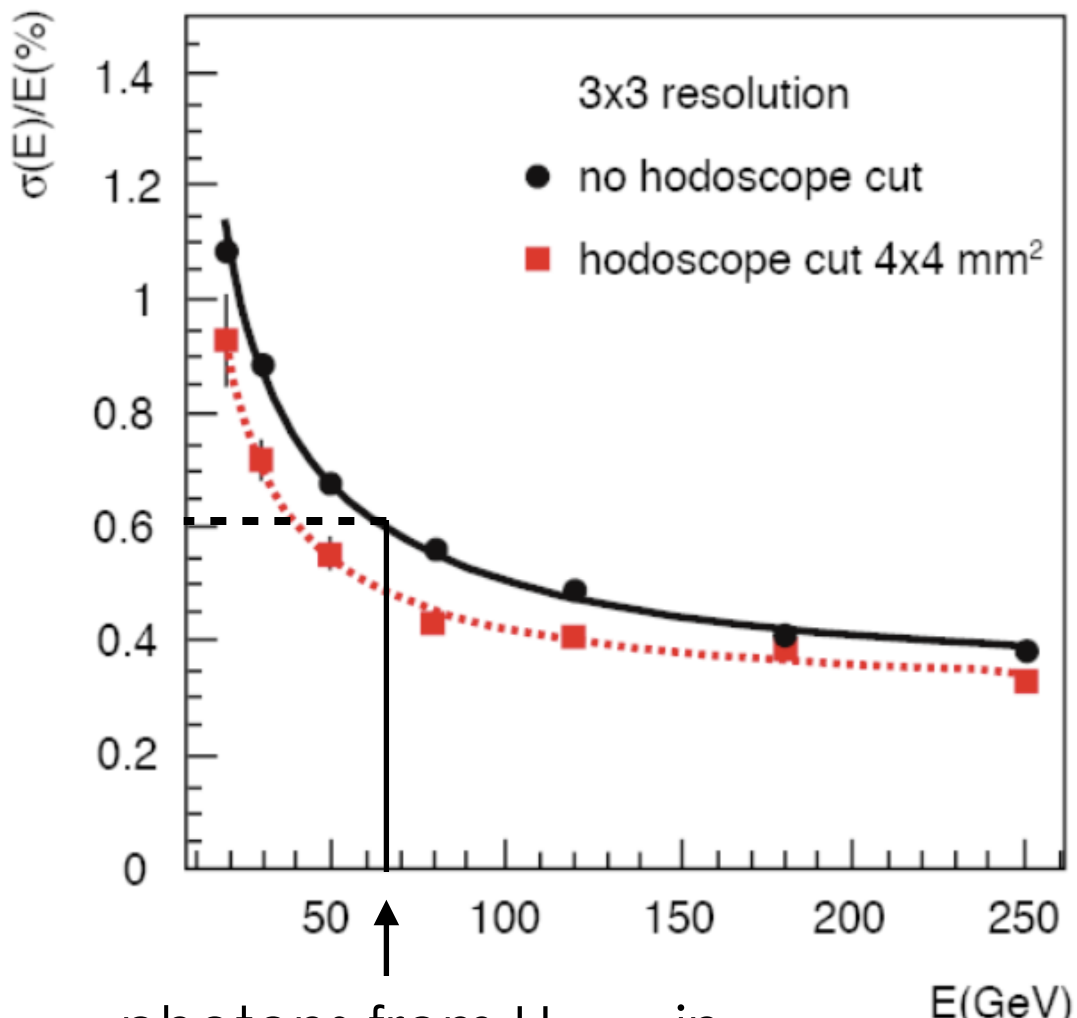
b) Noise term

- electronics and pile-up

c) Constant term. Aim at <1% in-situ

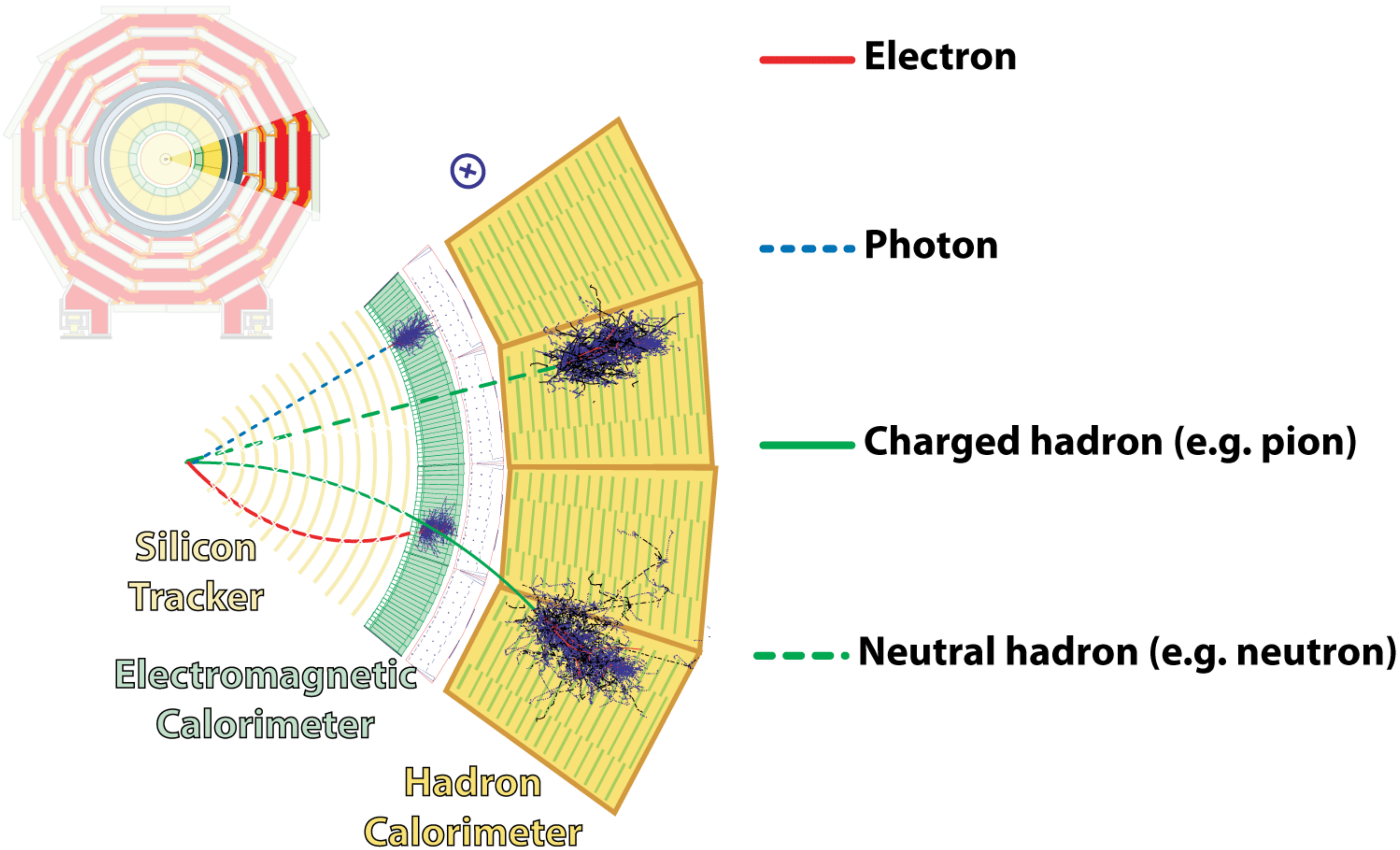
- channel-intercalibration
- system stability (temperature & HV)

In-situ we will have to deal also with the tracker material (electrons and photons)



photons from H→γγ in central barrel

CMS: Electrons (Positrons) & Photons



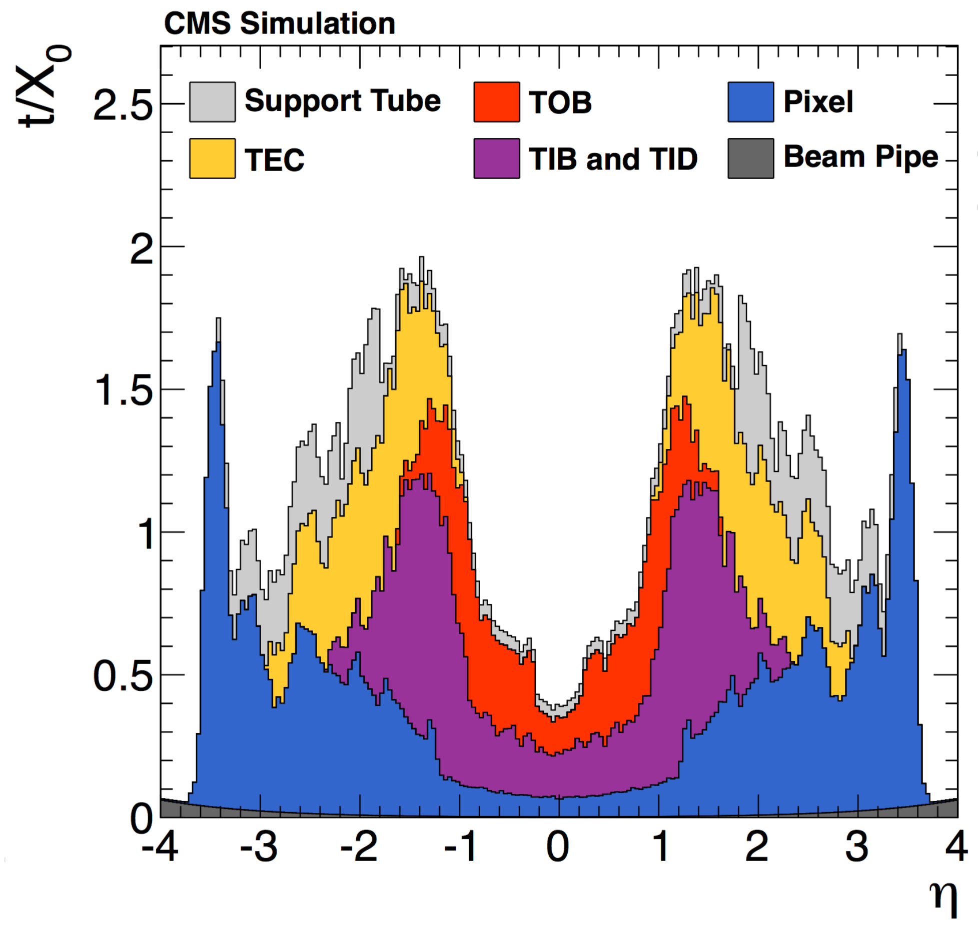
Curves in B field: R=P/0.3B
Signals in Tracker
Energy deposit in ECAL
No energy in HCAL

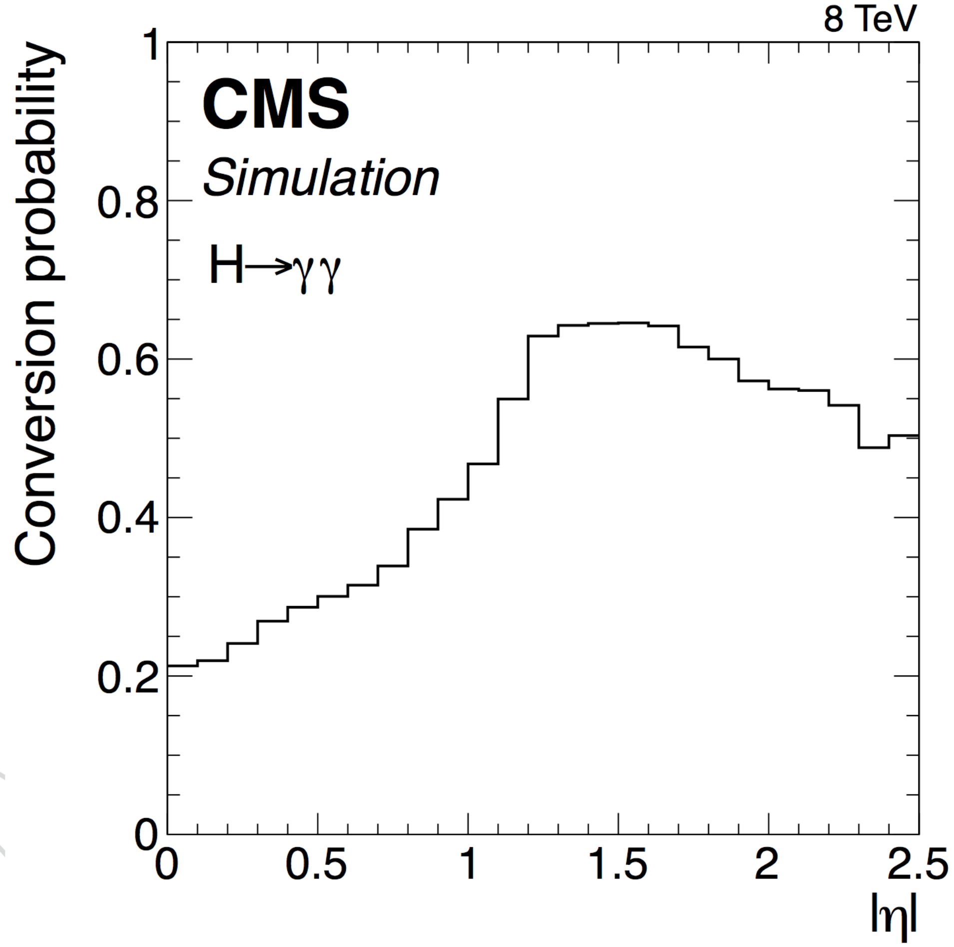
No curve in B field
No signals in Tracker
Energy deposit in ECAL
No energy in HCAL

Curves in B field: R=P/0.3B
Signals in Tracker
Possible energy deposit in ECAL
Energy deposit in HCAL

No curve in B field
No signals in Tracker
Possible energy deposit in ECAL
Energy deposit in HCAL

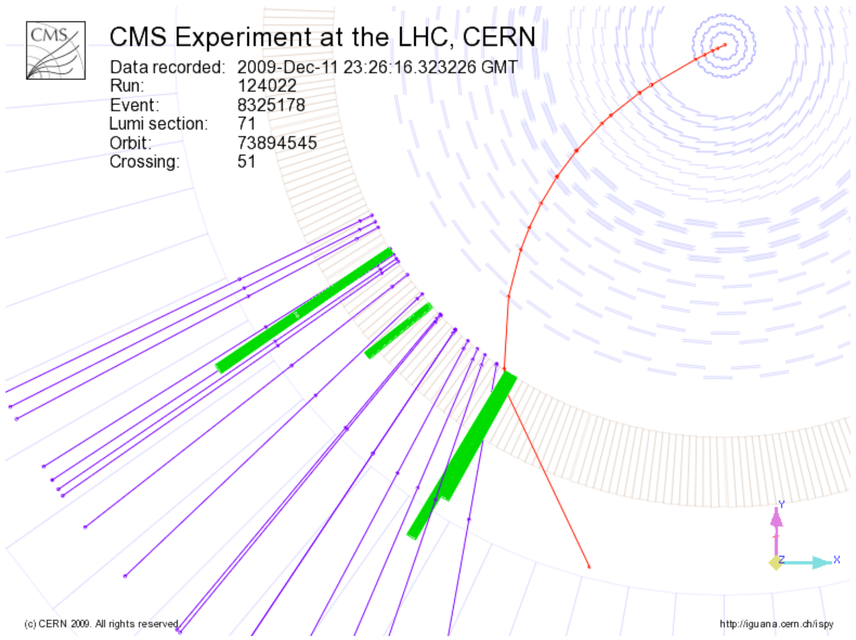
e/γ Reconstruction: Tracker Material



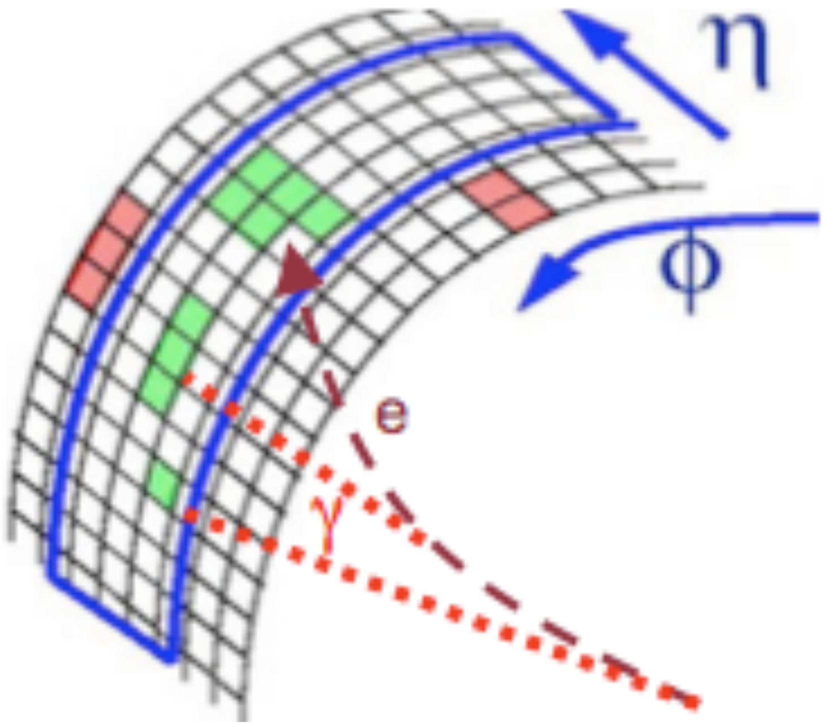


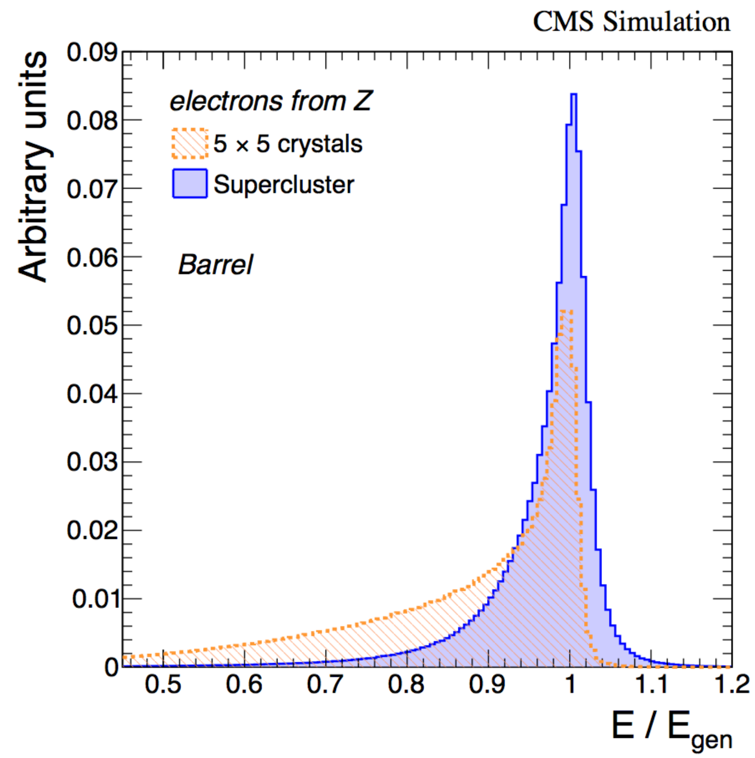
Main issue to deal with in electron and photon reconstruction is the tracker material

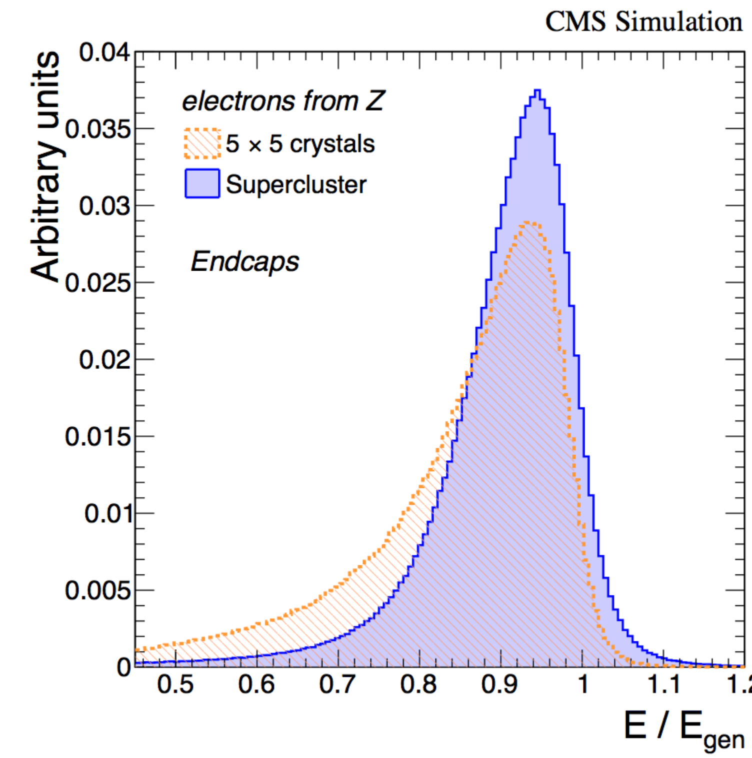
~$2X_0$ @ |η|~1.5 (end of barrel): an electron radiates on average more than 50% of its energy



e/γ Reconstruction: SuperClusters







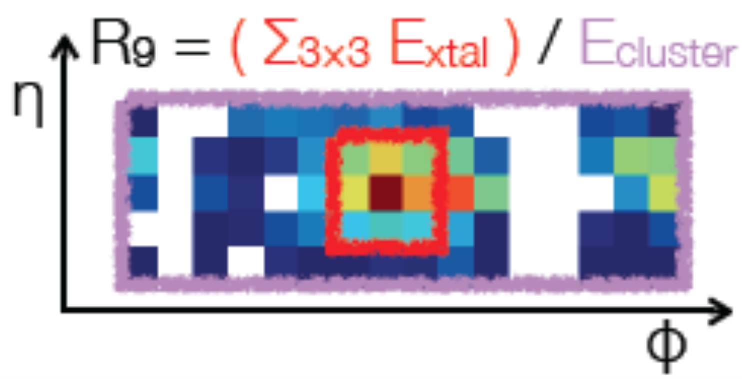
Dynamic clustering algorithm that works both for (un)converted photons & electrons

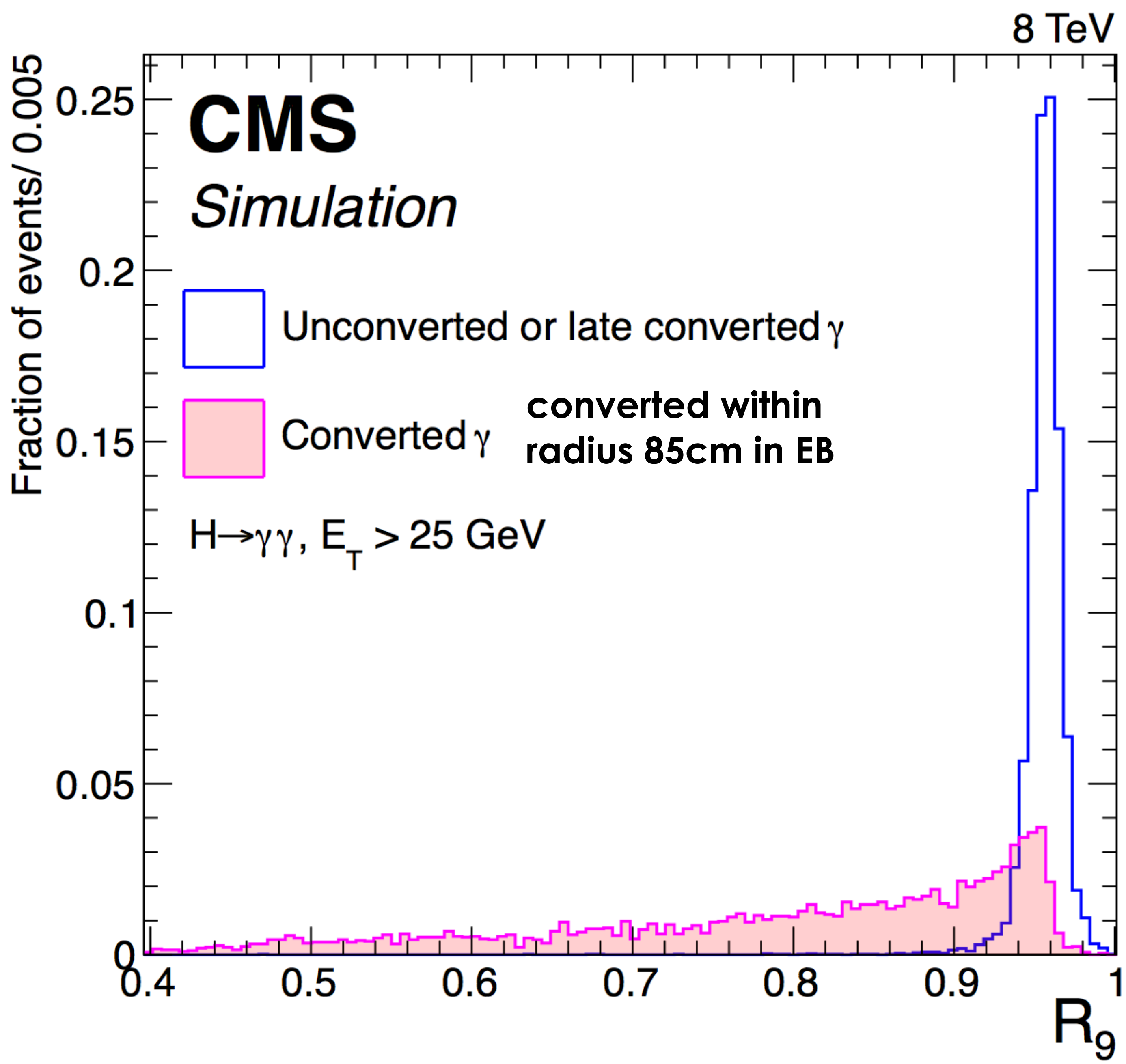
Energy spread ~ only in magnetic bending direction ϕ direction

Asymmetric search window η x ϕ to recover energy from brems or conversions

EM objects which have irradiated can be identified already at SC level

Use R_9 shower-shape variable to discriminate:
- low / high bremsstrahlung electrons
- unconverted / converted photons

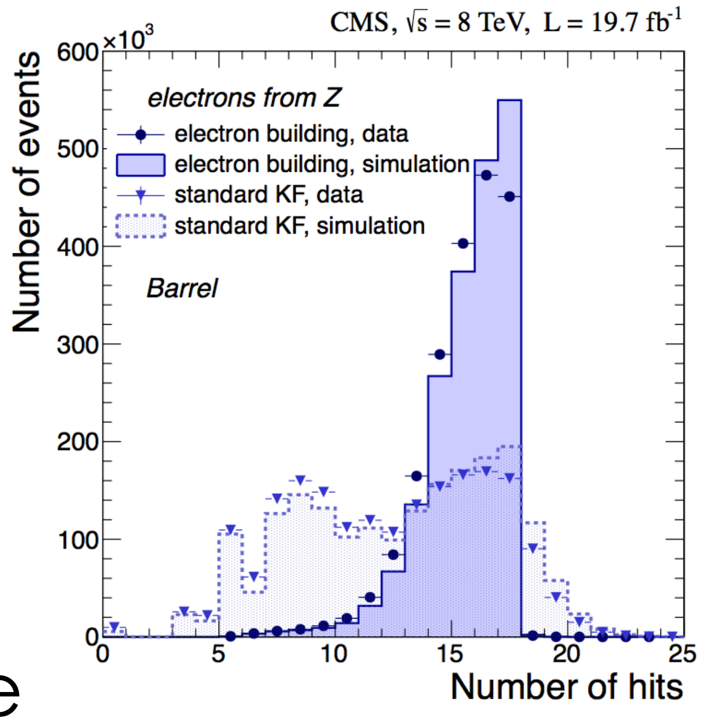


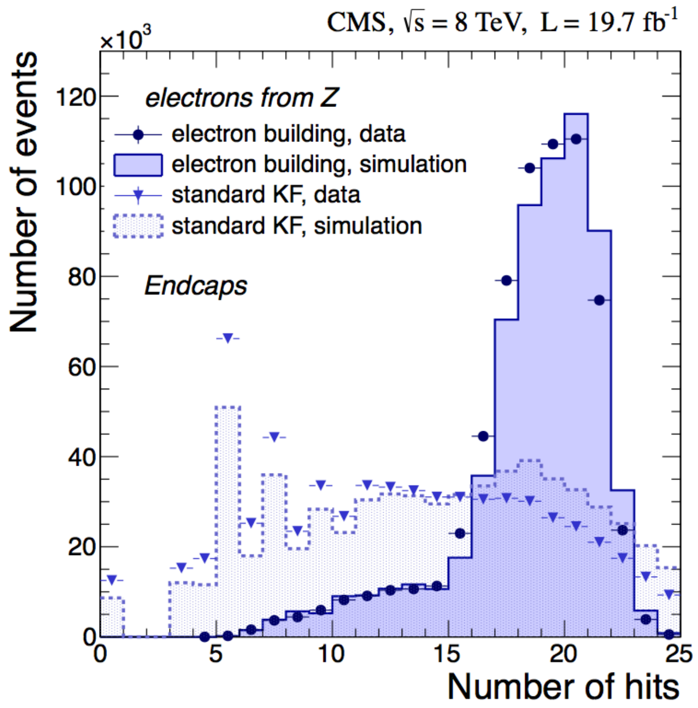


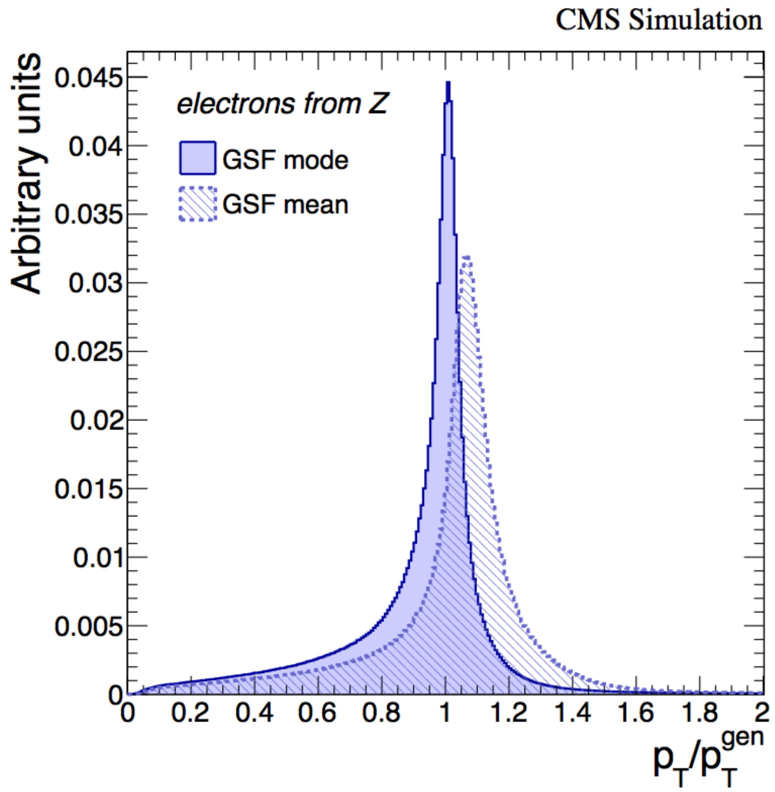
e: GSF Track

Specific track algorithm for electron

- **Seed algorithm**: ECAL driven (pixel matching) + track driven (short or ECAL matched tracks)
- **Building**: iterative combinatorial KF with loose χ^2 cuts (allows to build longer tracks)
- **Fit**: model Bethe-Heitler energy loss at each layer with linear combinations gaussians (GSF). For each track parameter can compute either weighted mean or mode



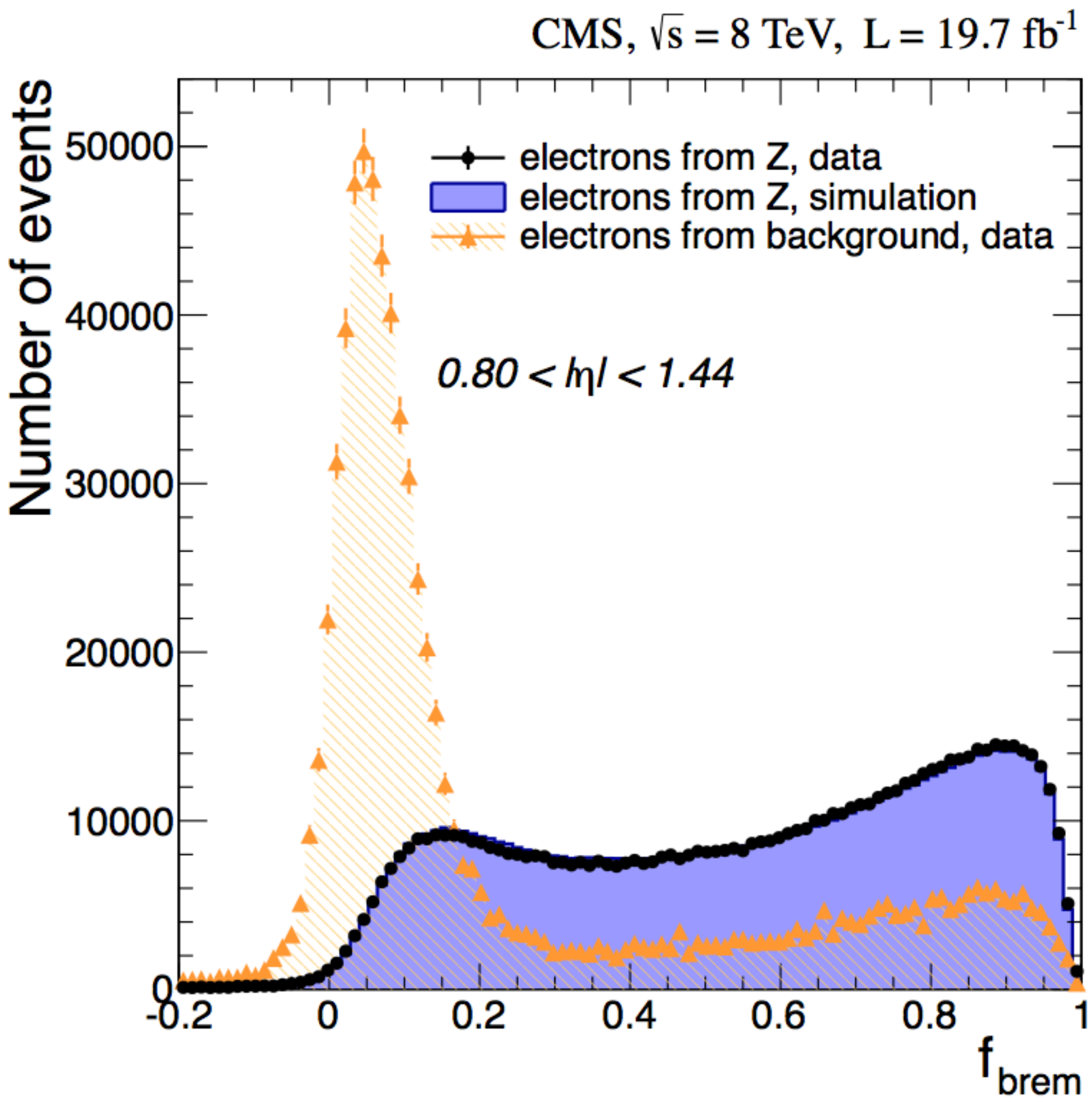




TRACK RECONSTRUCTION: BREMSSTRAHLUNG

GSF fit allows to measure bremsstrahlung fraction comparing momentum at begin/end of the track

brem fraction can be used also to discriminate fake electrons (pions do not radiate!)

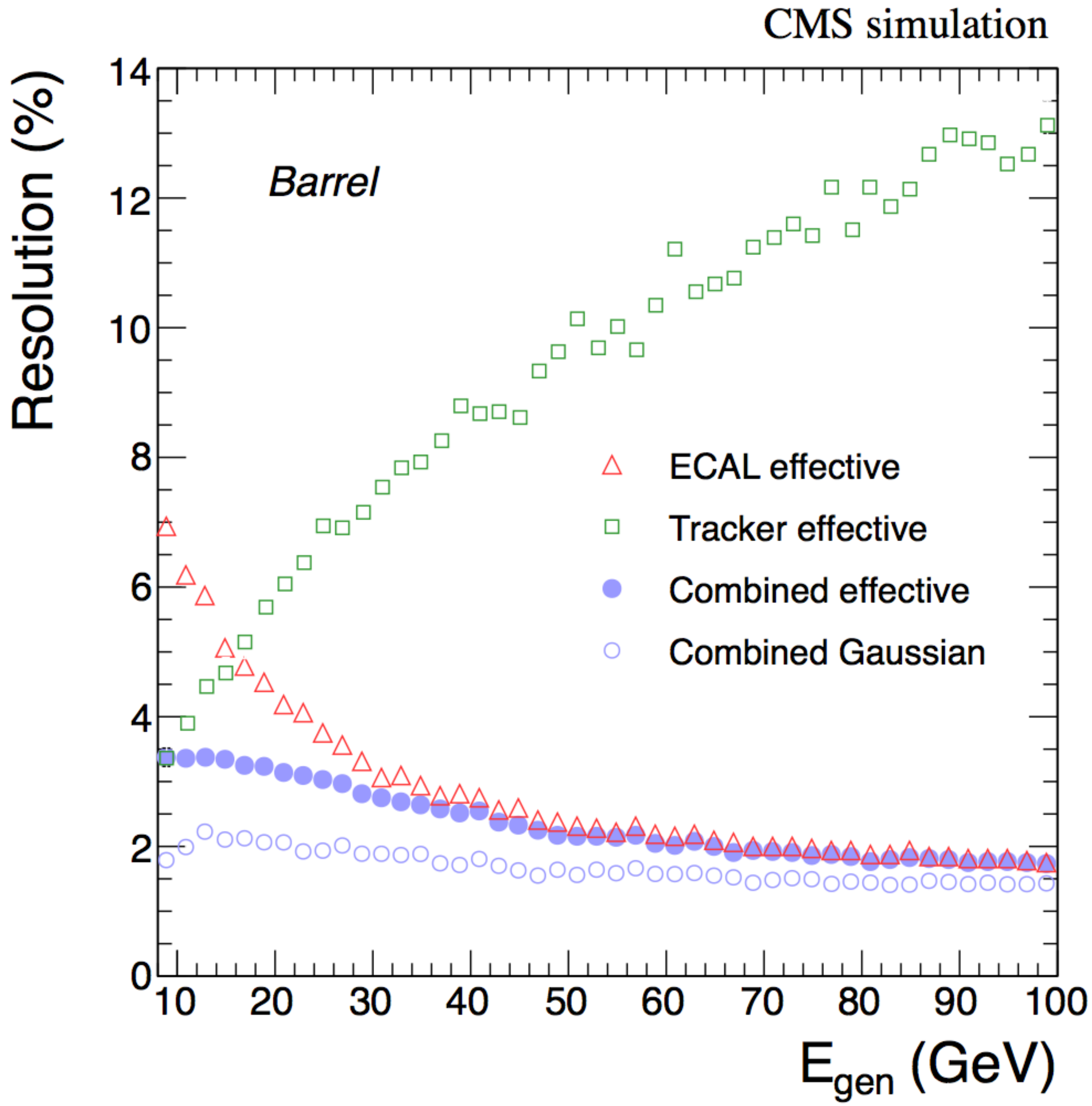


ELECTRON: ECAL VS TRACKER

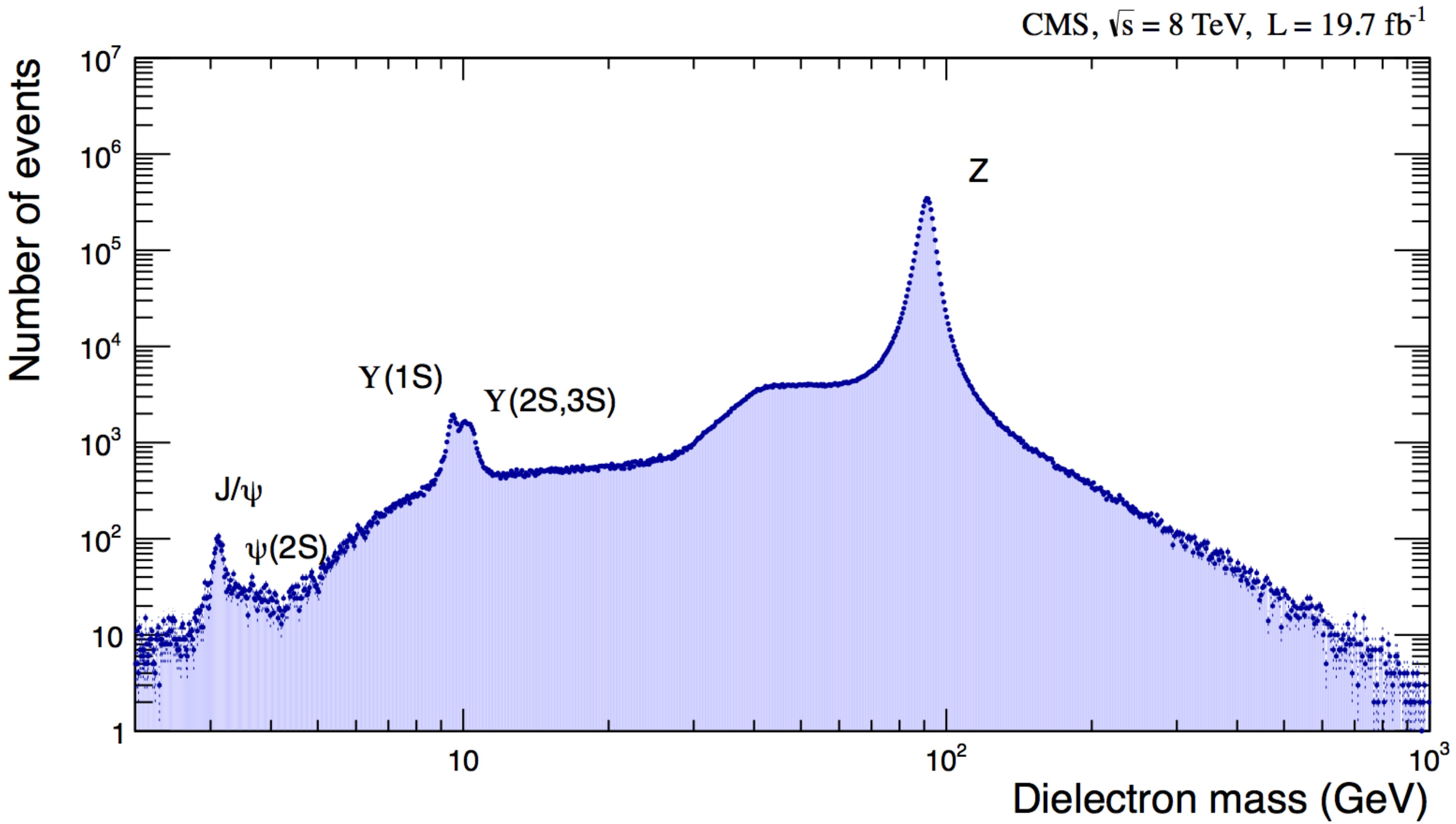
Electron momentum/energy measurement:

E>20 GeV ECAL dominates energy resolution

Optimal momentum estimate for electrons from combination of ECAL energy and track momentum



DI-ELECTRON SPECTRUM



ENERGY RECONSTRUCTION: e/γ

- Measurement of electron/photon energy:

$$E_{e,\gamma} = F_{e,\gamma} \cdot \sum_{xtal} (G \cdot C_{xtal} \cdot L_{xtal}(t) \cdot A_{xtal})$$

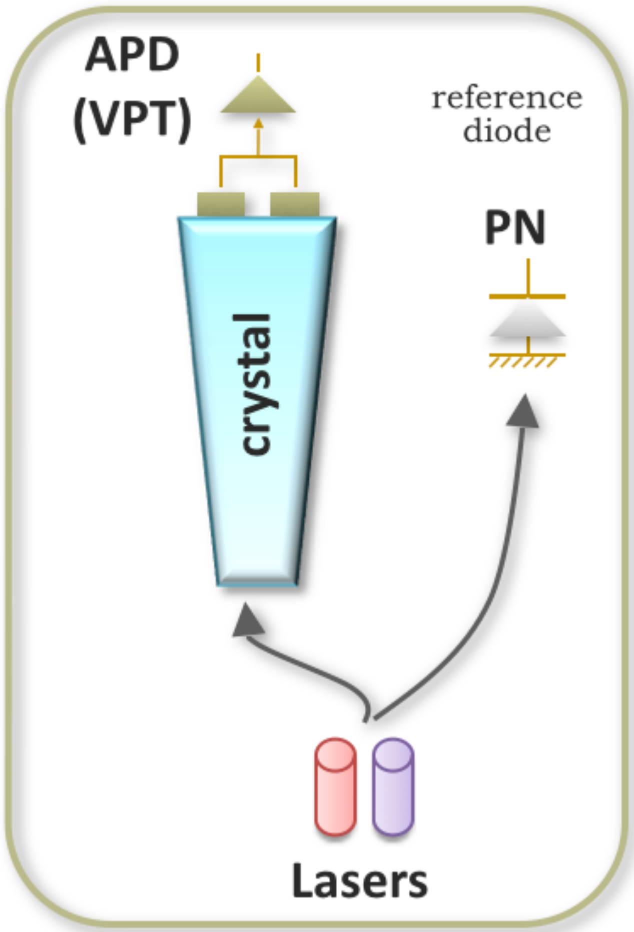
- A_{xtal} [ADC counts] → signal channel amplitude
- L_{xtal} → laser monitoring correction (time dependent)
- C_{xtal} → crystal inter-calibration ($\langle C_{xtal} \rangle = 1$)
- G [GeV/ADC] → ECAL energy scale
- Σ →e.m. shower, energy deposited over several crystals clustered with dynamic algorithms
- F → cluster energy corrections
  - particle dependent
  - compensate shower leakage and bremsstrahlung losses for electrons

The evaluation of above contributions in the next slides

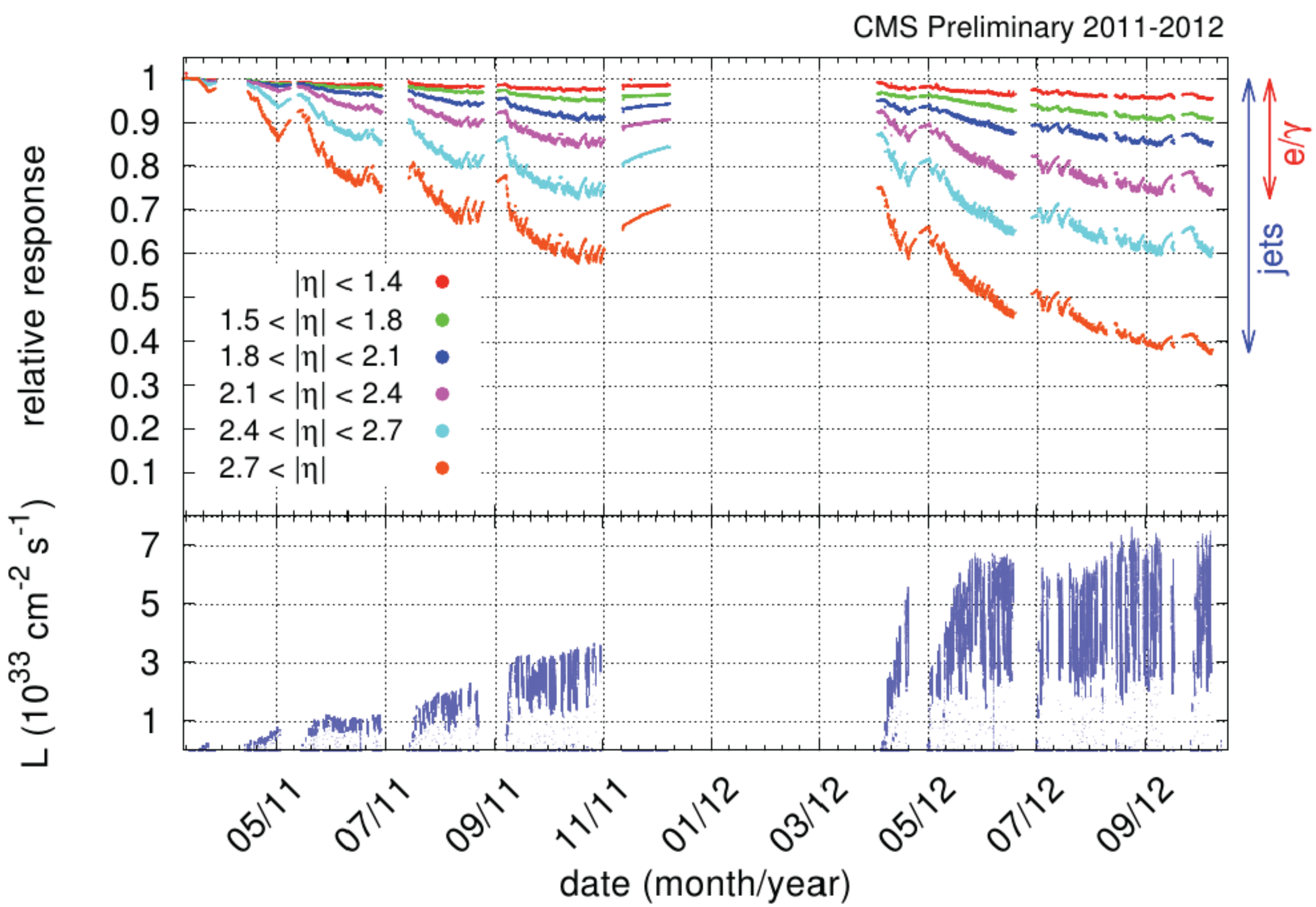
ECAL VARIATION WITH TIME

Radiation ⇨ Loss of light transmission (w/o changes in scintillation)

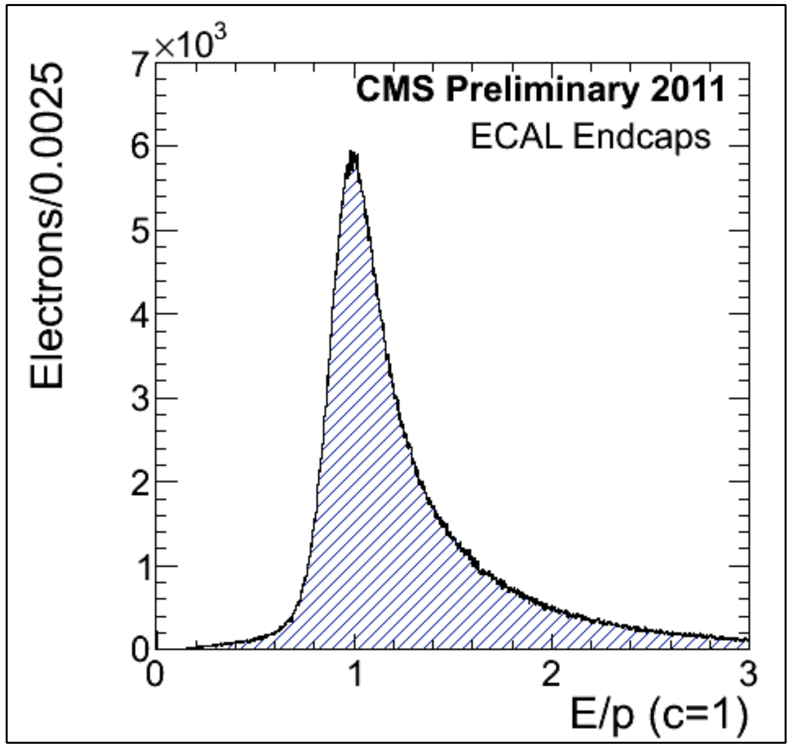
Crystal Transparency ***drops*** within a run by a few percent but ***recovers*** in the inter-fill periods



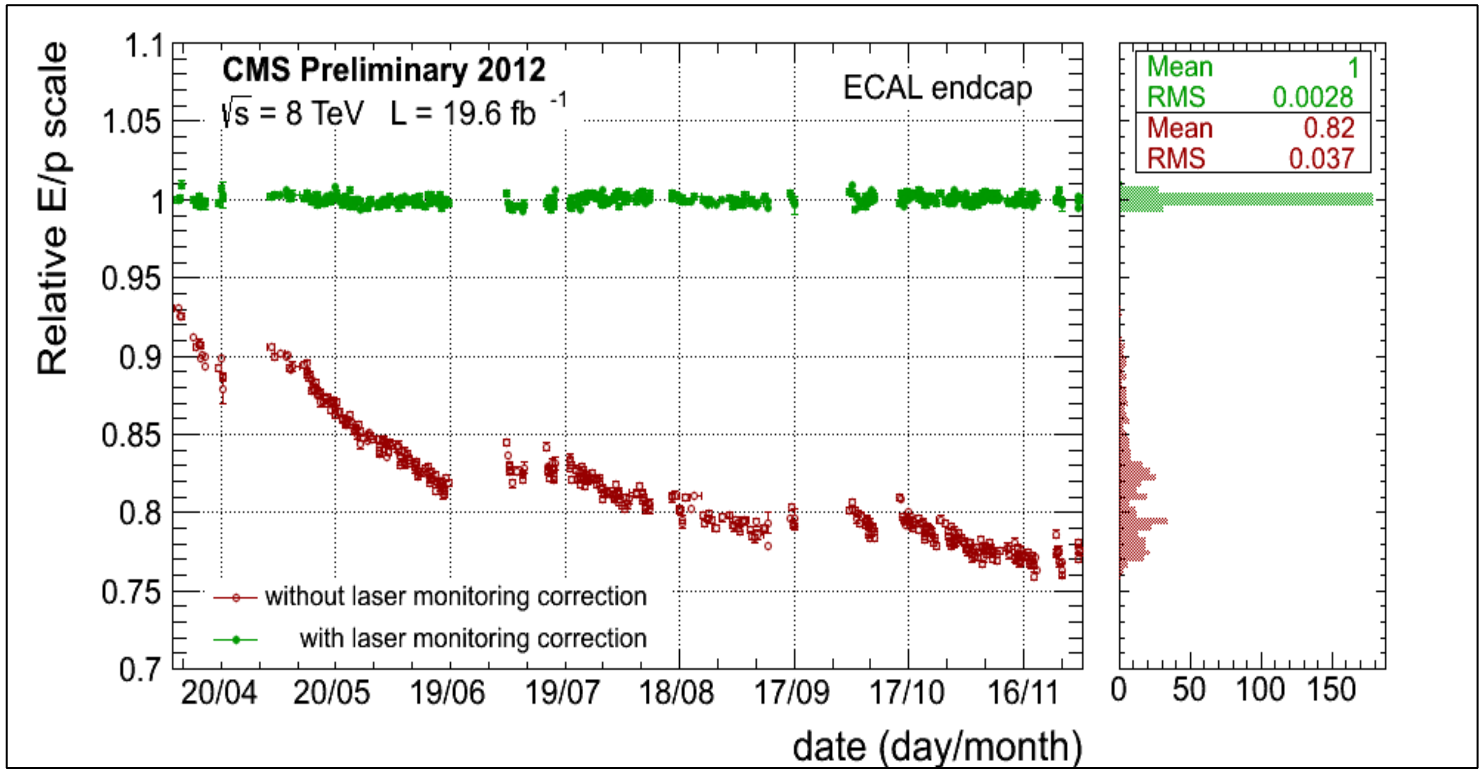
Cycle of response loss during irradiation and recovery in beam-off periods



ECAL Response Stability



E/p peak ~ 1. Can use high statistics of electrons from W→eν (~10 Hz) to monitor the variation of ECAL response



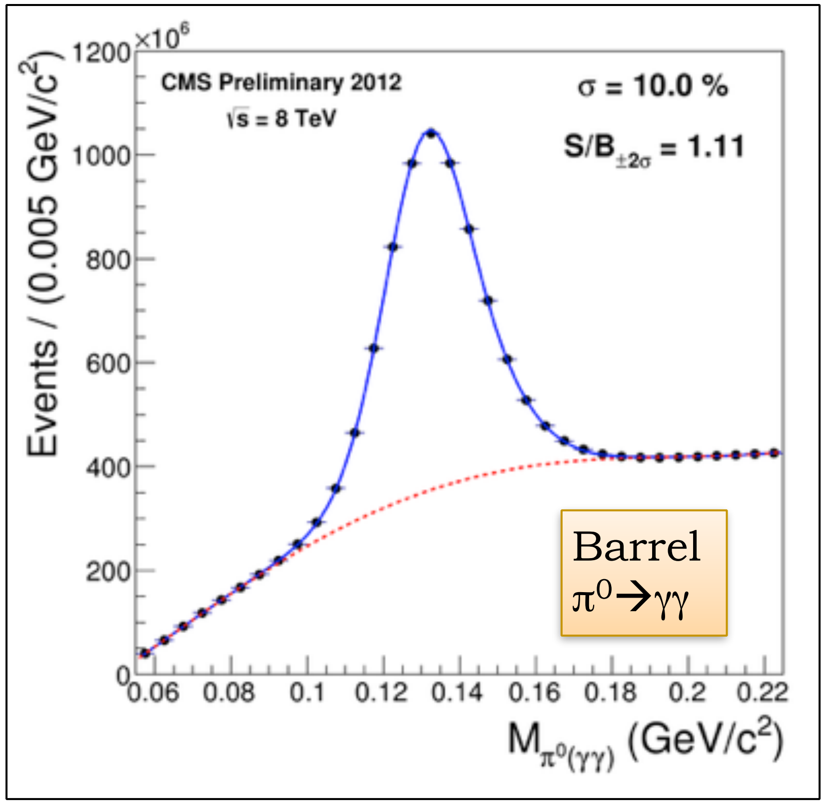
Stability of the energy scale after monitoring corrections

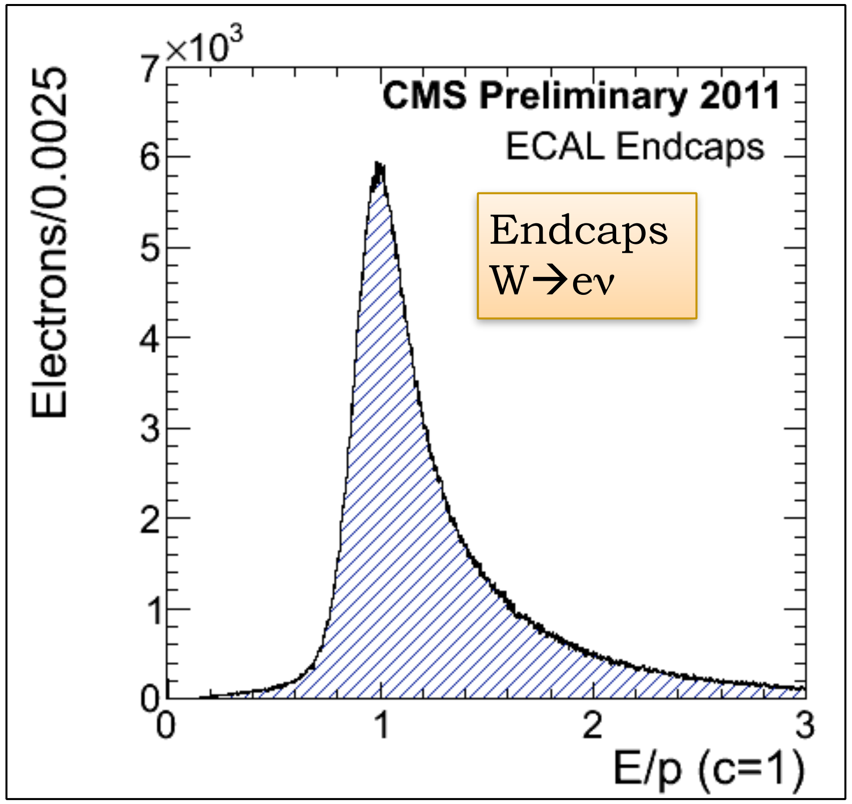
- **Barrel:** average signal loss ~5%
  RMS stability ~0.1%
- **Endcaps:** average signal loss ~25%
  RMS stability ~0.3%

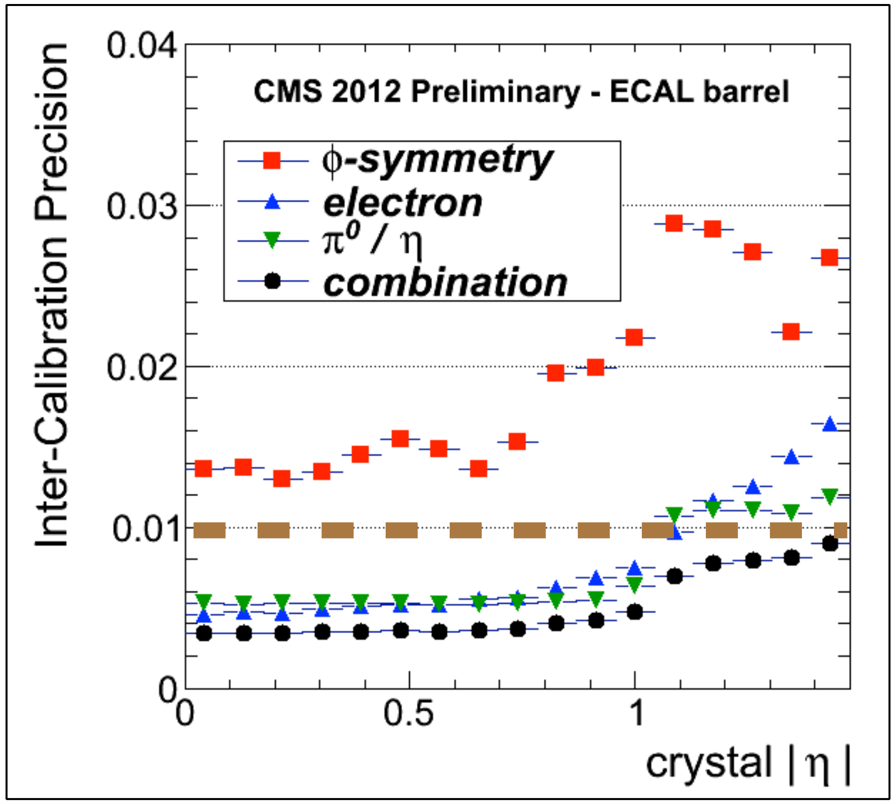
ECAL INTERCALIBRATION

- After correcting time variation, you need to equalise the channel response
  - **ϕ-symmetry calibration**: invariance around the beam axis of energy flow in minimum bias events. Intercalibrate crystals at the same pseudorapidity.
  - **π^0 and η calibration**: mass constraint on photon energy, use unconverted γ's reconstructed in 3x3 matrices of crystals.
  - **High energy electron** from W and Z decays (E/p with single electrons and invariant mass with double electrons).

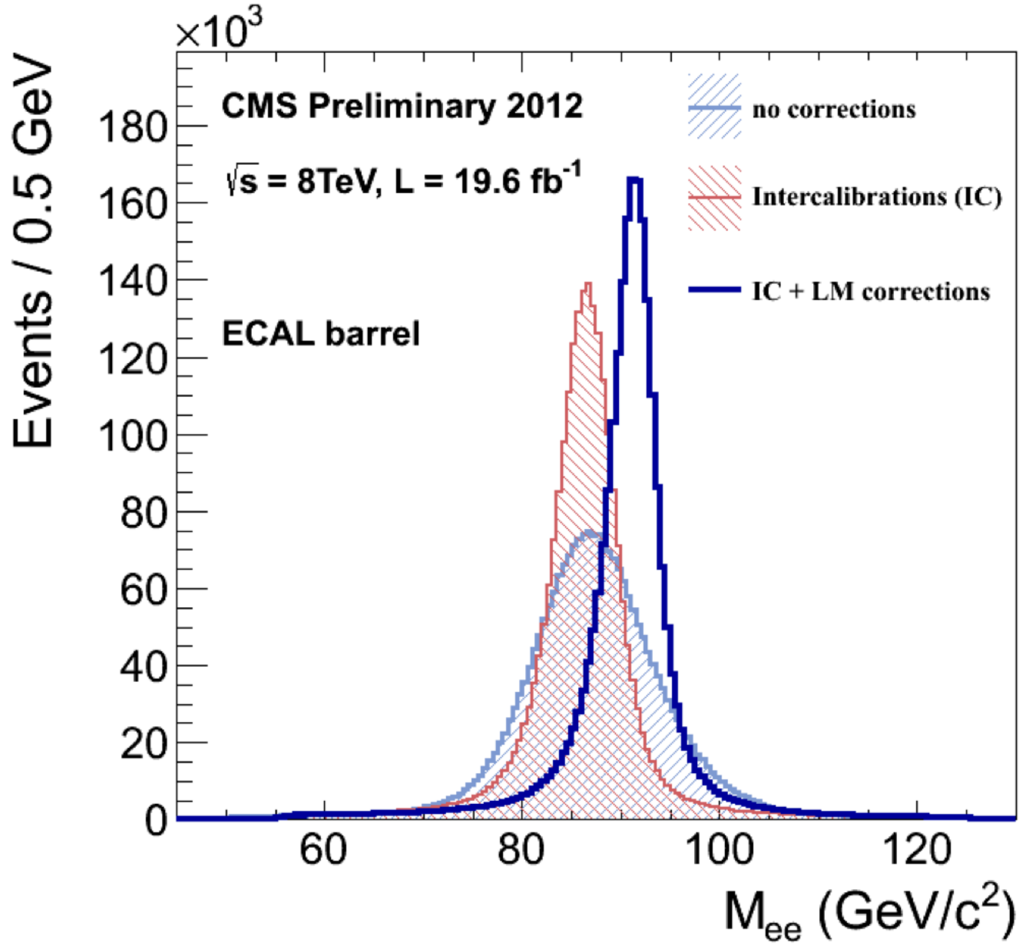
Barrel: <1% (~0.4% for |η|<1)
Endcaps: ~2% (almost everywhere)

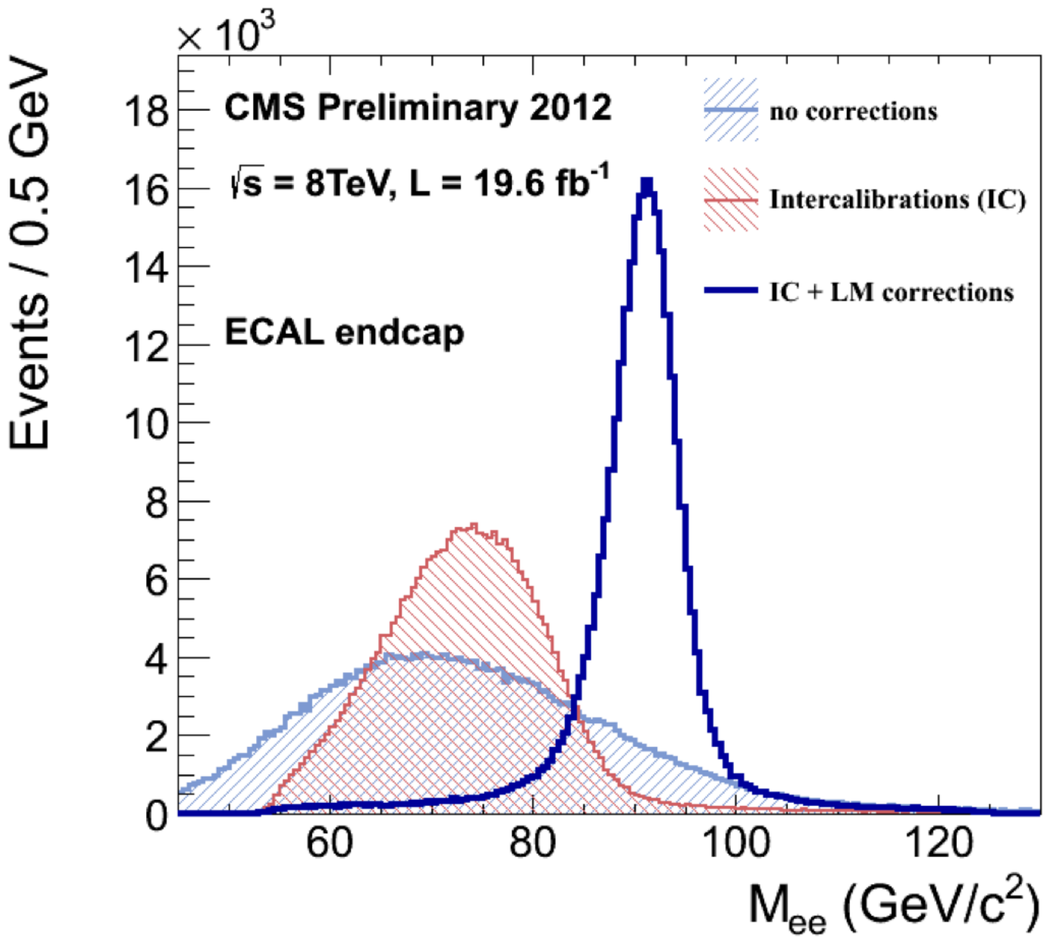






All This Work Pays Off…



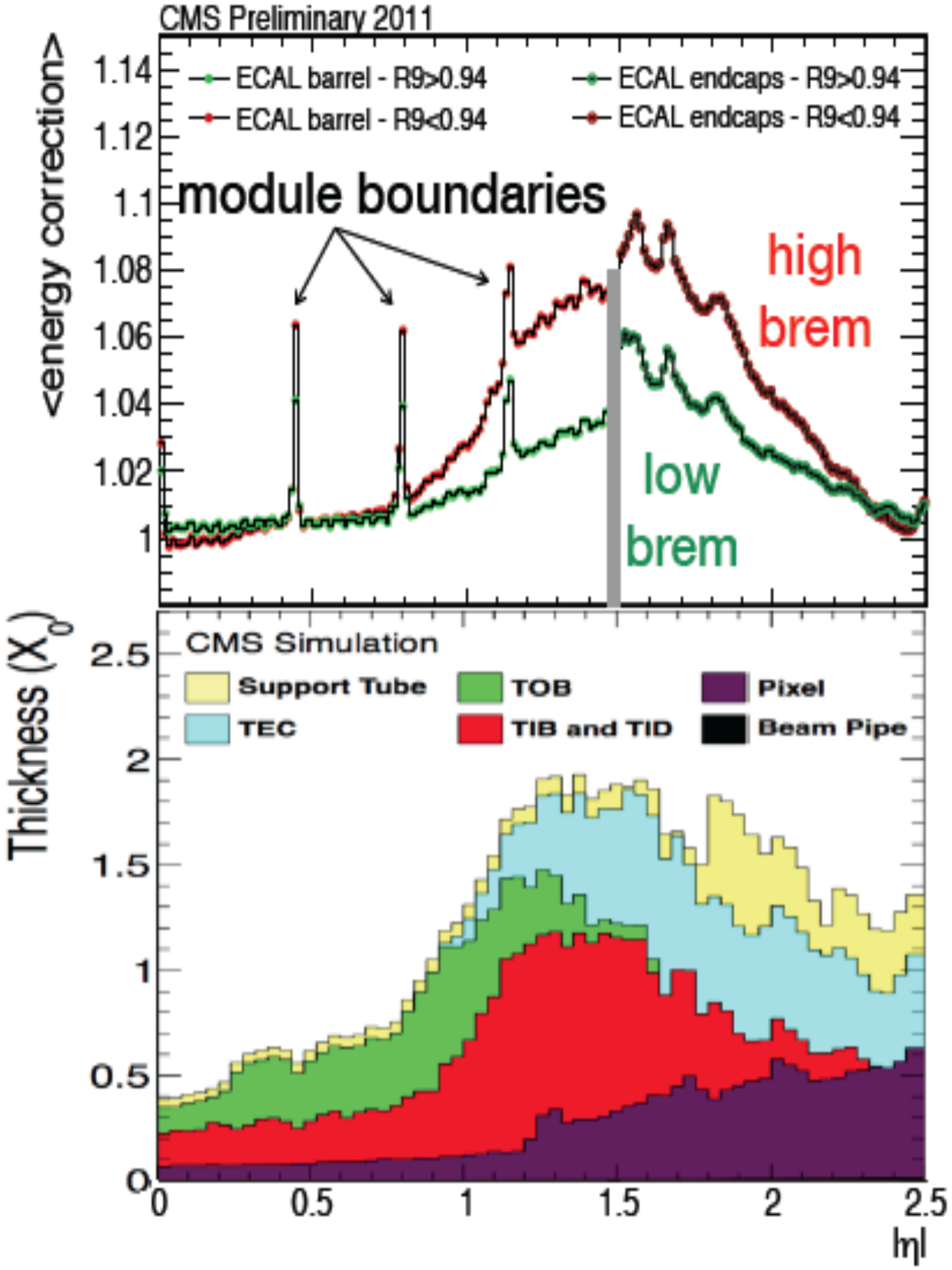


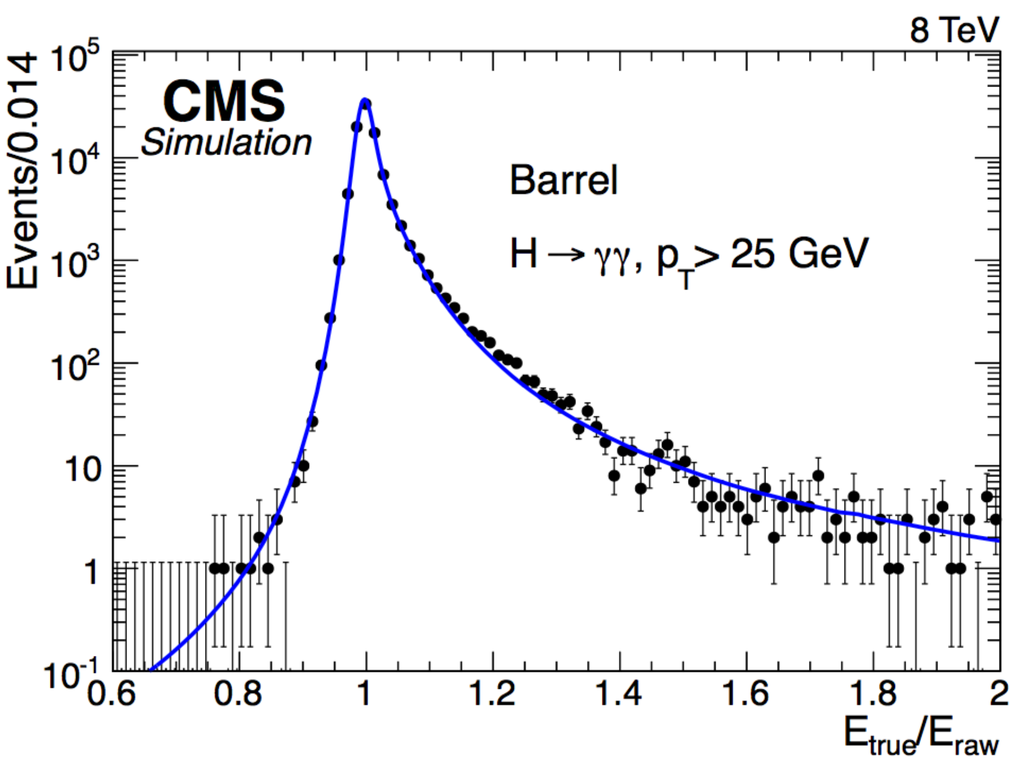
$Z \rightarrow e^+e^-$ used to validate and monitor ECAL resolution

Cluster Energy Corrections

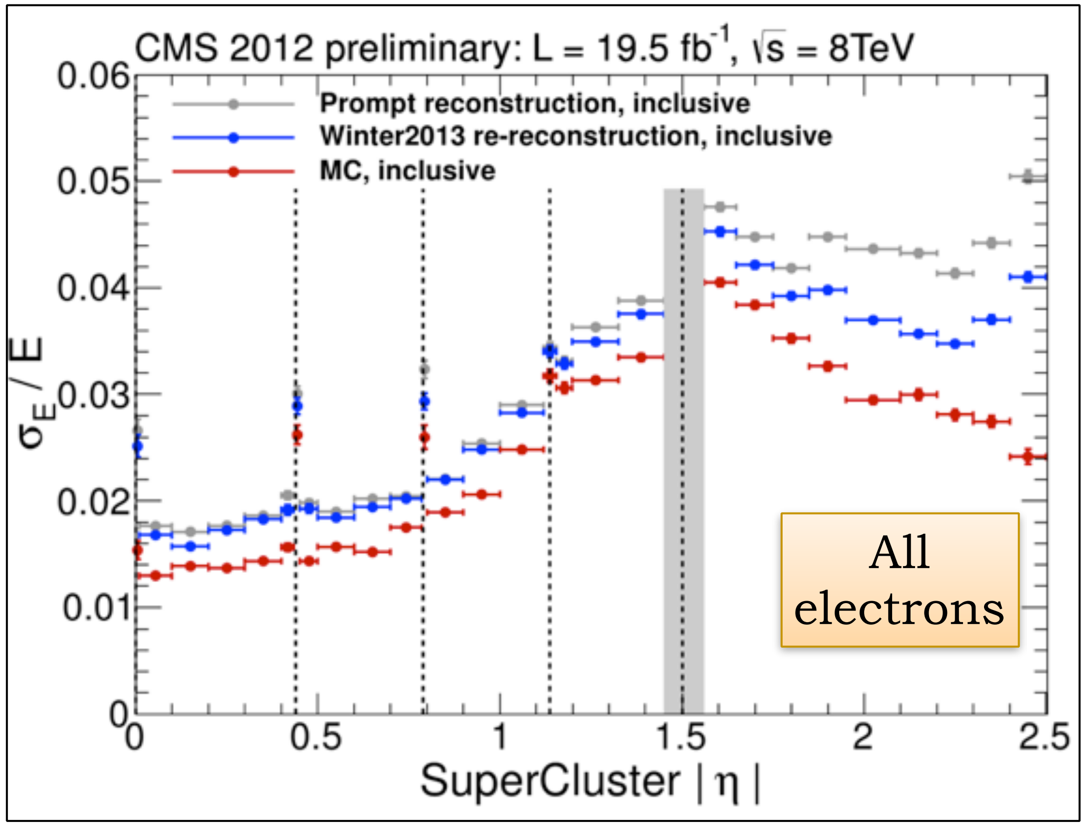
Cluster energy corrections:

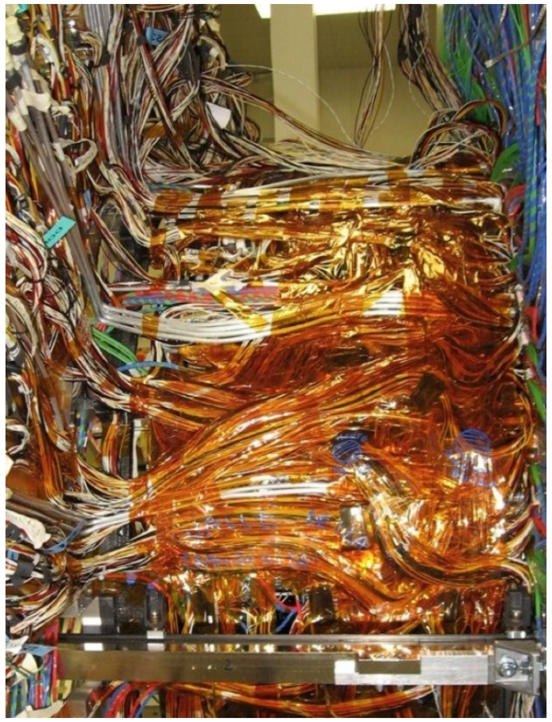
- based on multivariate regression tuned on MC. **Fundamental good MC description** (EM shower + material in front of ECAL)
- MVA is specific for electrons or photons
- Corrections for
  - **energy not reaching the calorimeter**
  - **energy lost inside gaps**
  - **impact point position**





Data/MC Agreement

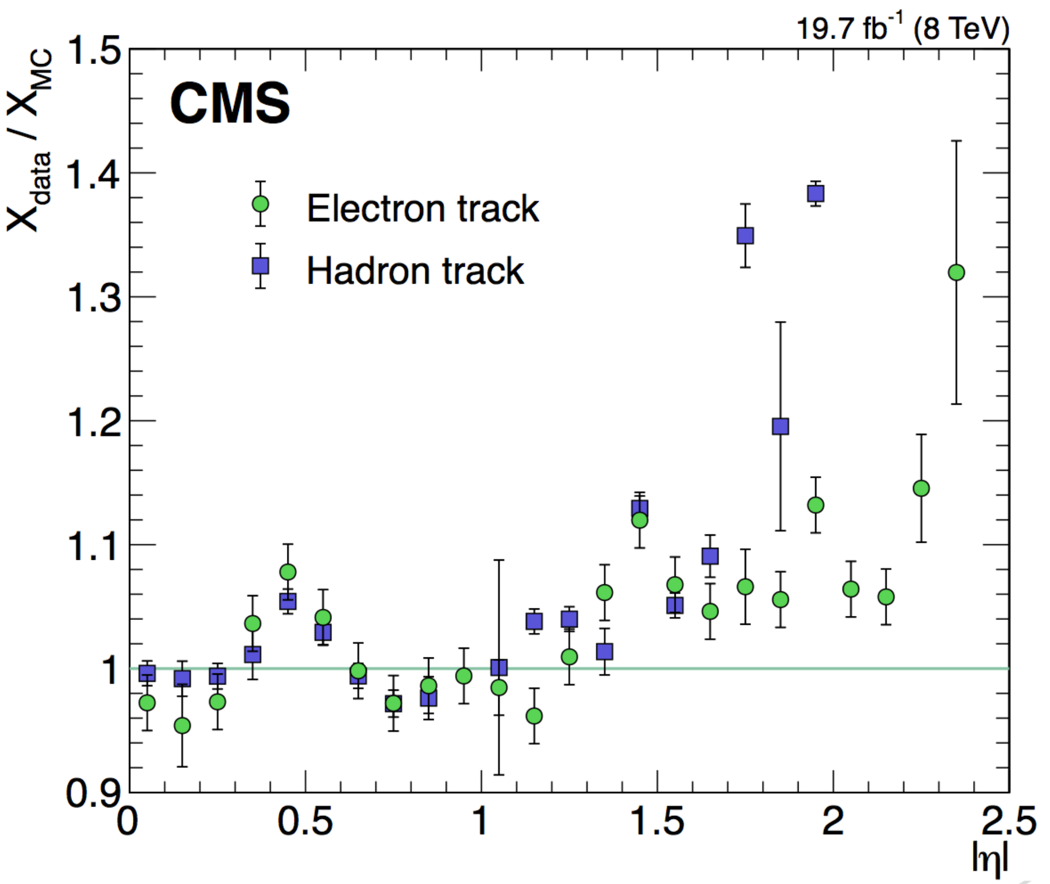




A perfect simulation of all the cables and services is a mission impossible !

Differences between data and MC due to:

- missing contributions to energy resolution constant term not present in MC
- imperfect modelling of tracker material in MC (some regions show ~10-20% X_0 in discrepancy)



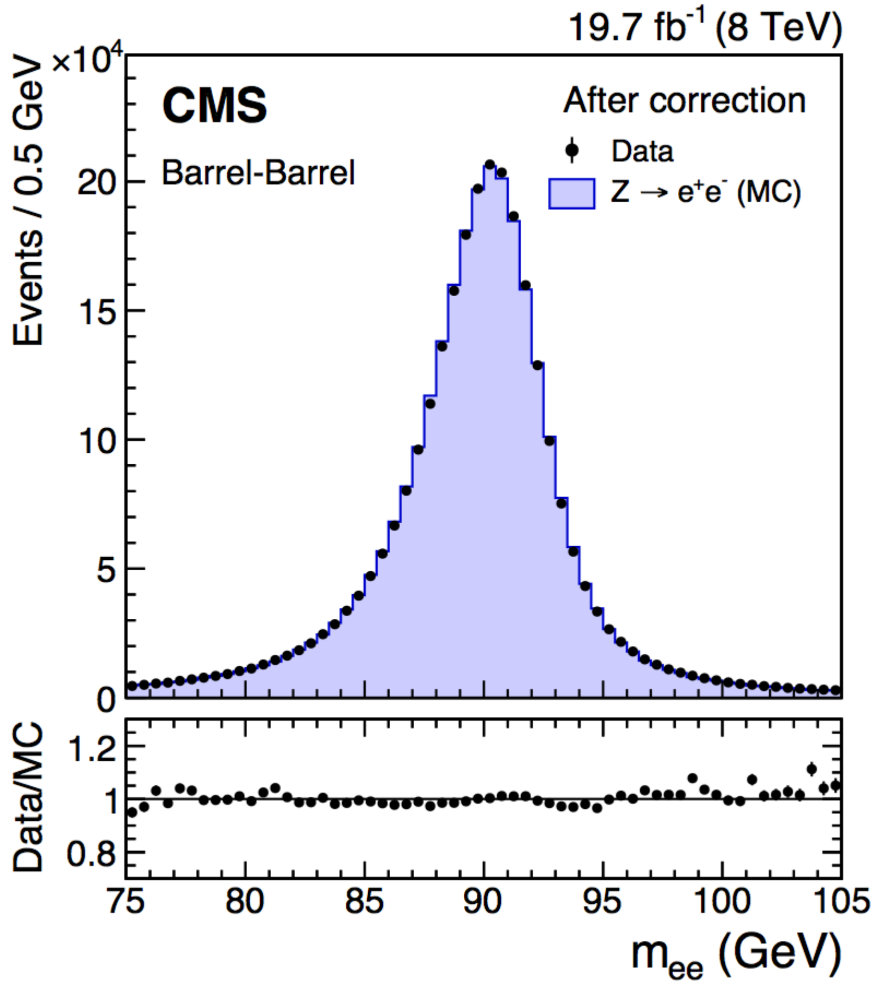
DATA/MC AGREEMENT

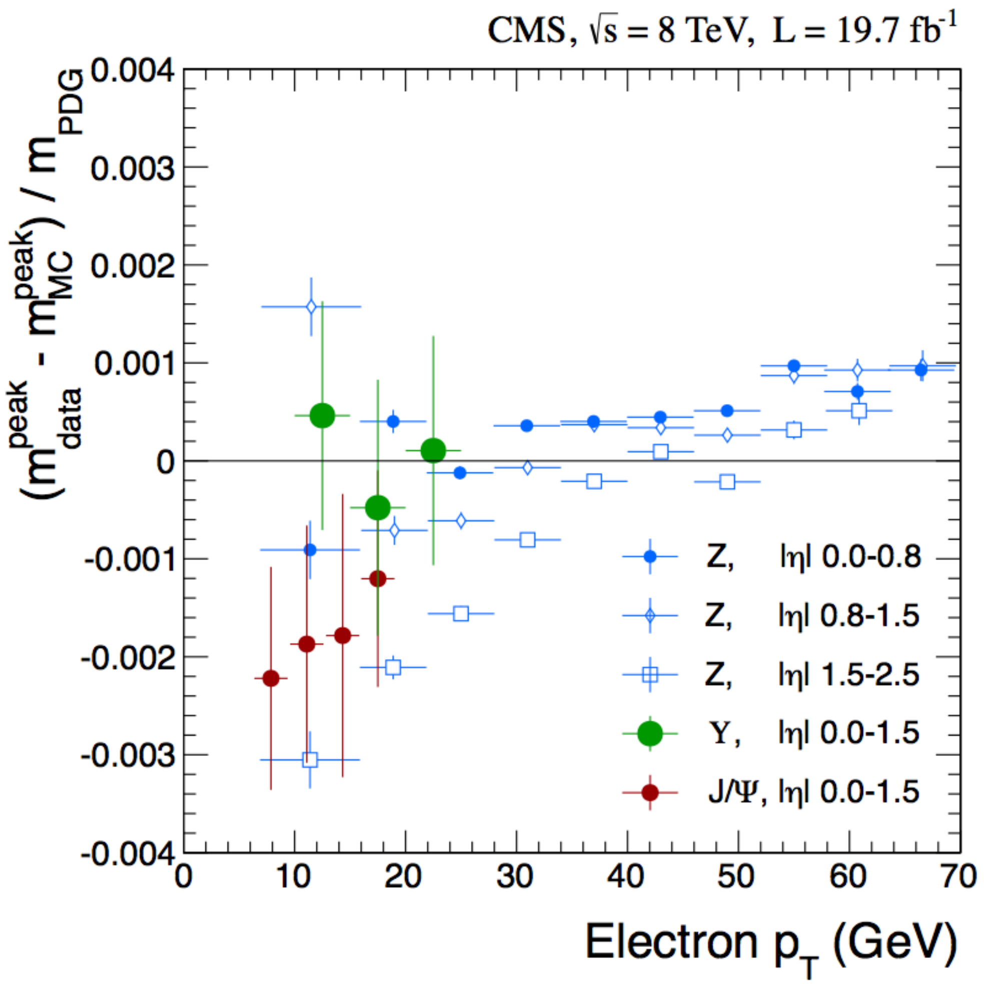
Final energy correction: residual calibrations to match data peak on MC, MC is tuned (gaussian smearings) to match data peak width.

Corrections & smearings obtained from $Z \rightarrow e^+e^-$: computed in $E_T \times \eta \times R_9$ bins (minimize systematic uncertainties)

Systematic error on $H \rightarrow \gamma\gamma$ energy scale dominated by electron to photon extrapolation (~0.3%)

$H \rightarrow ZZ \rightarrow 4e$ error dominated by low p_T electron extrapolation (0.3%)





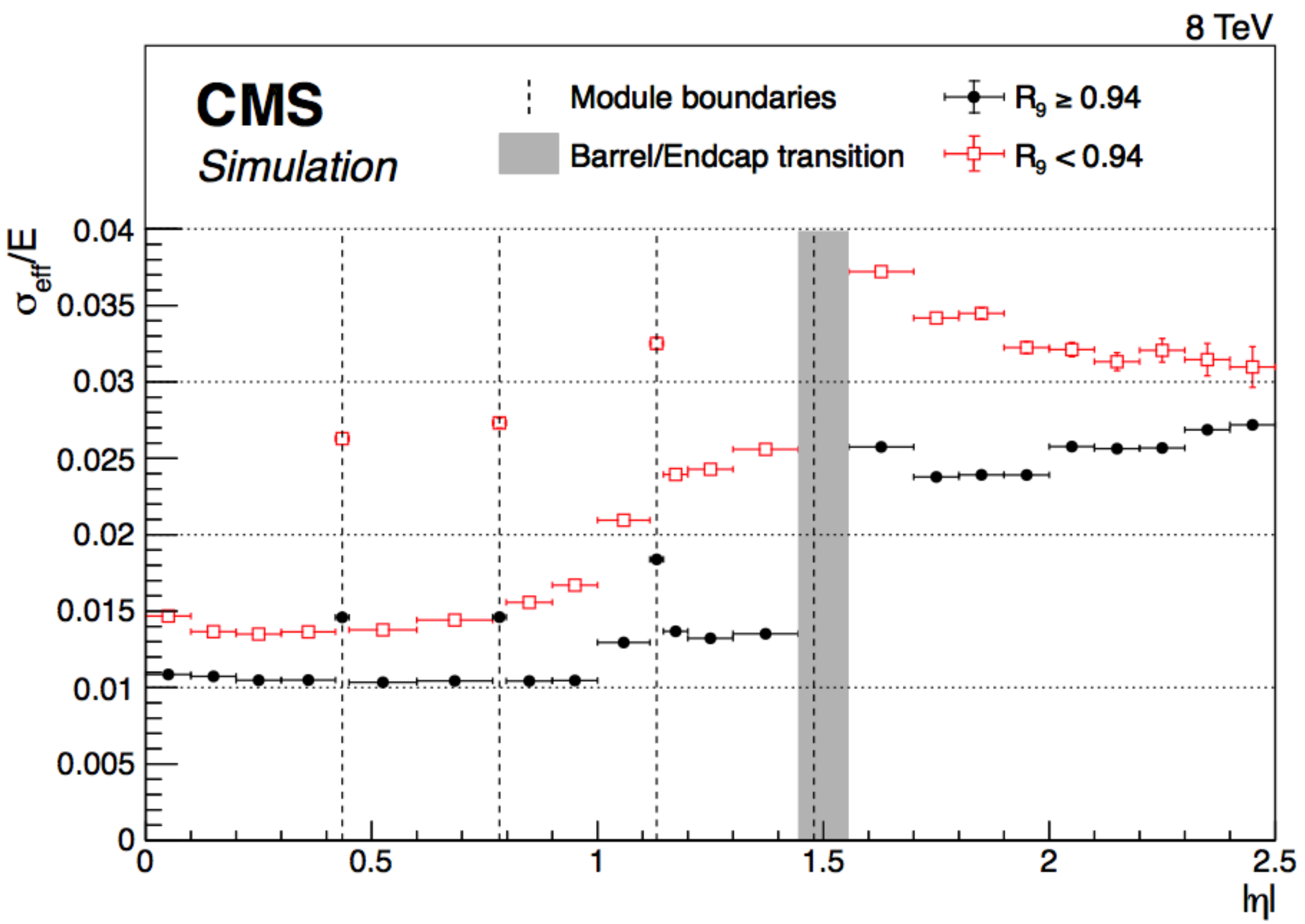
H→γγ Photon Energy Resolutions

Final estimated energy resolution for H→γγ photons

~ 1% for unconverted photons |η|<1

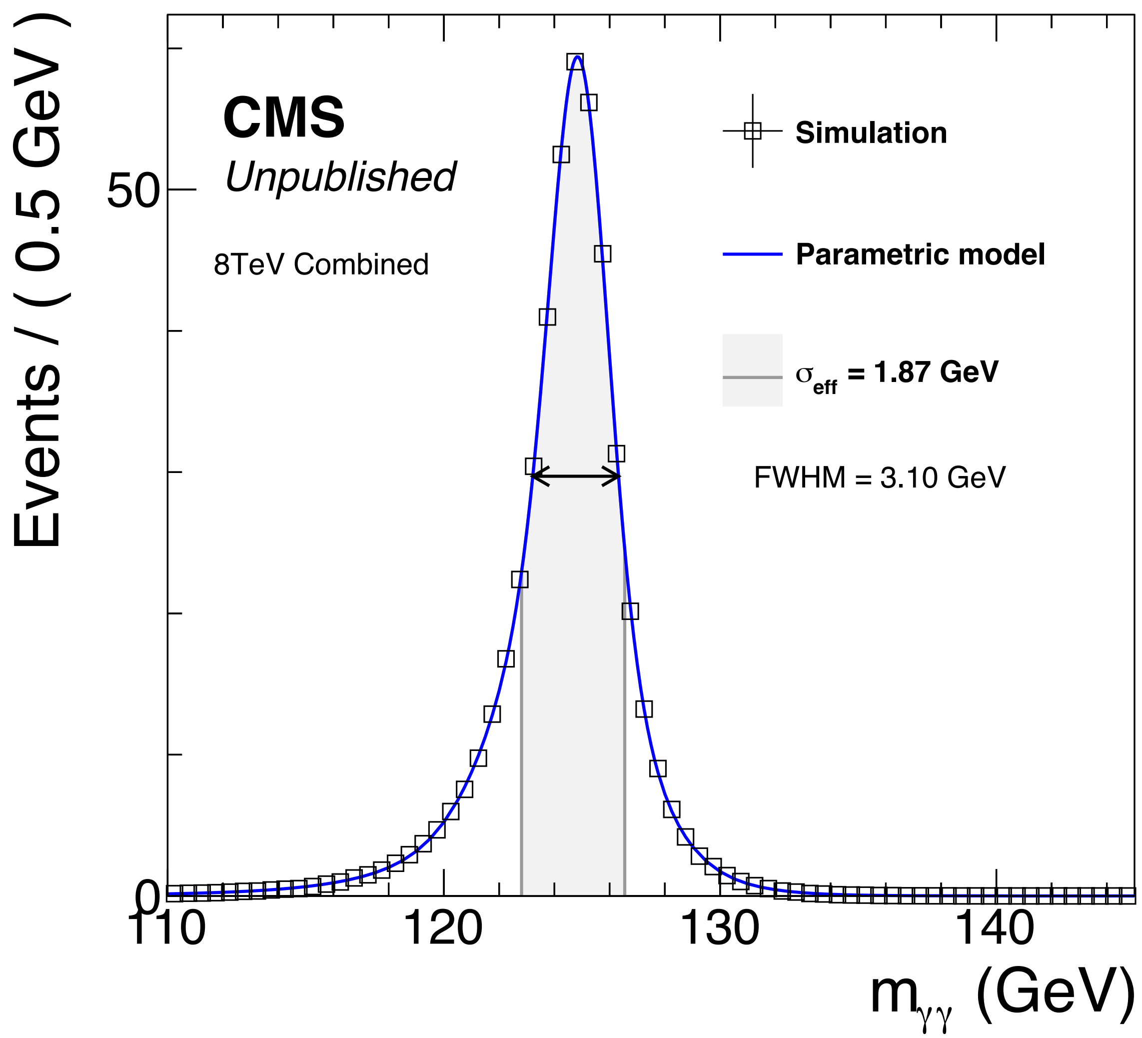
~ 1.5 % for converted photons |η|<1

2.5-3% in the end cap

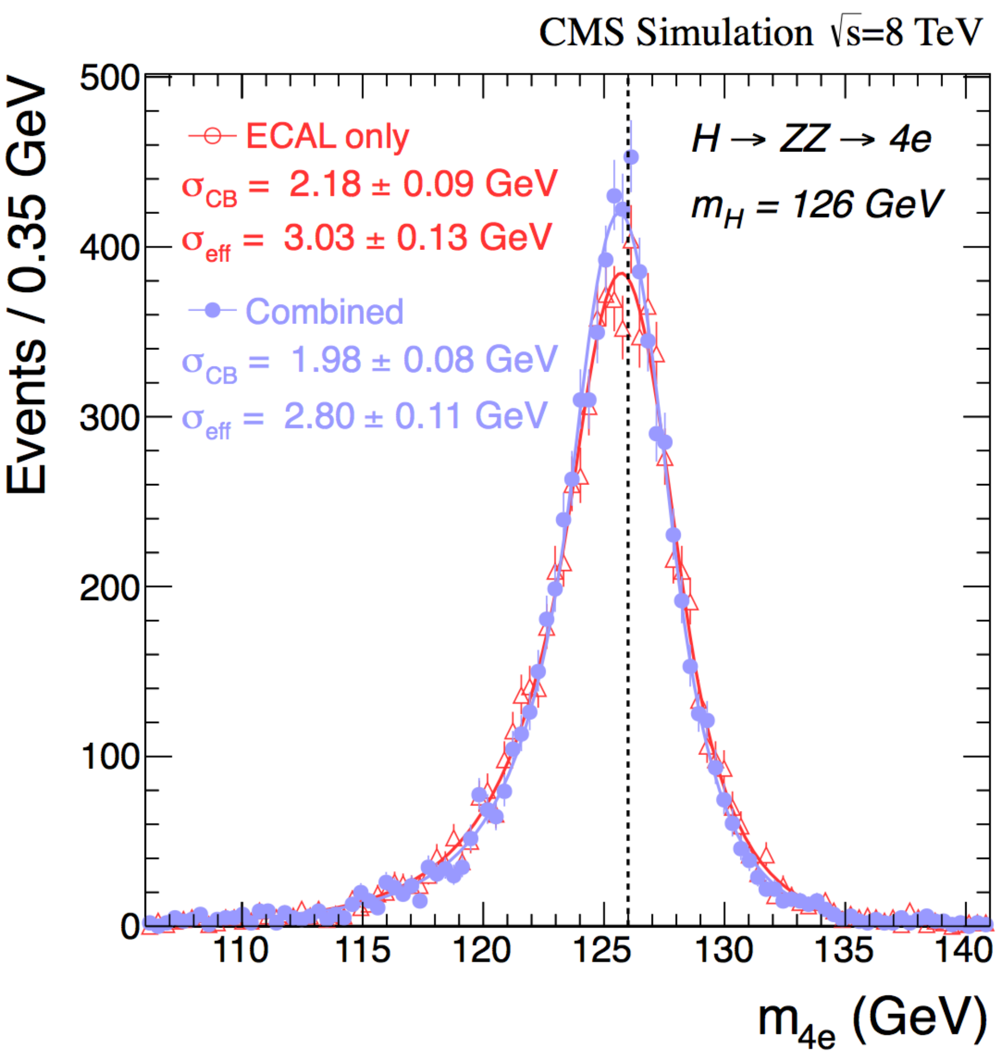


READY FOR HIGGS HUNTING!

$H \to \gamma\gamma$



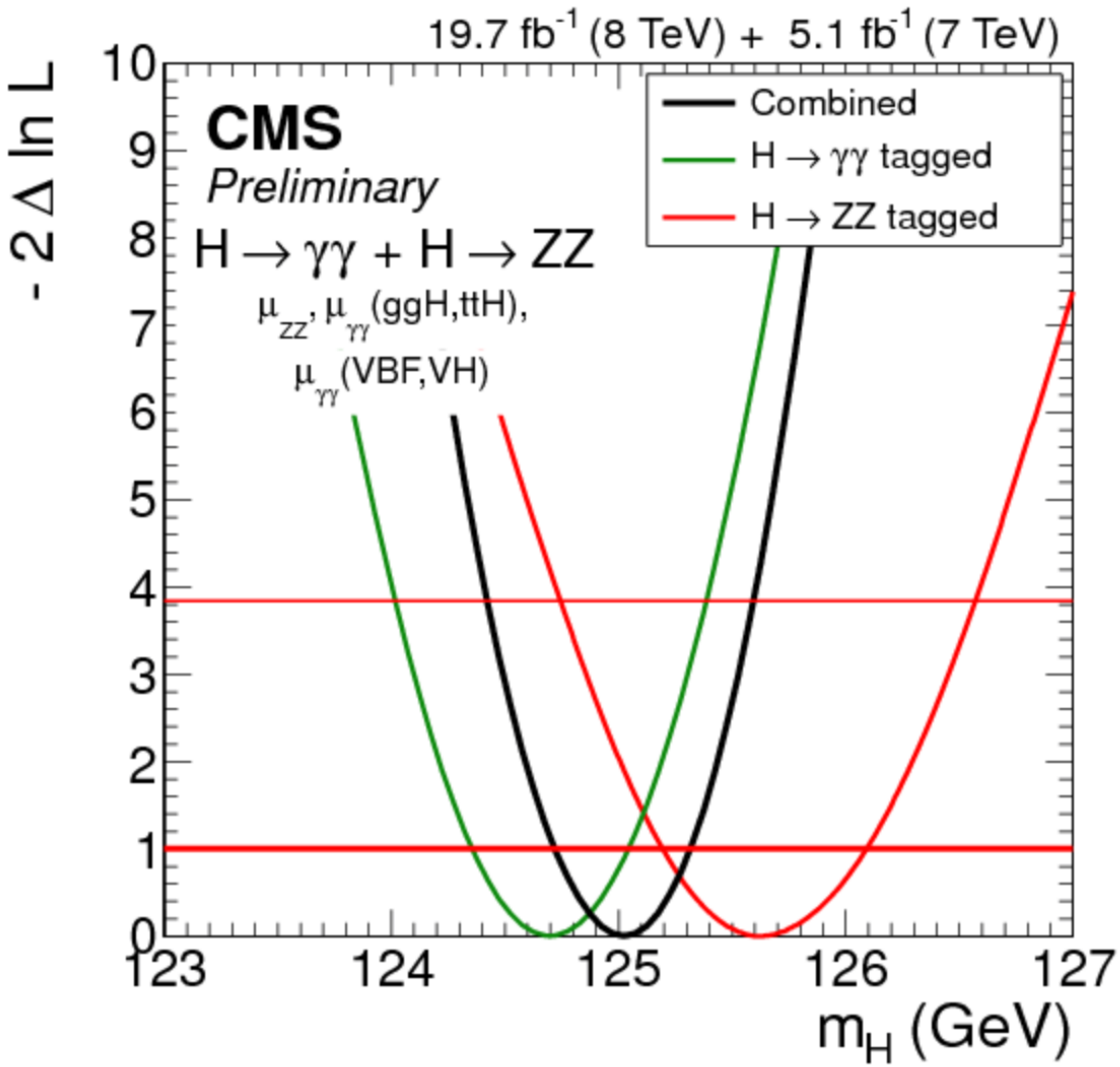
$H \to ZZ \to 4e$



$H \to \gamma\gamma$ mass resolution has also contribution also from di-photon angle resolution

need to identify primary Higgs production vertex (@PU 20 ~80% efficiency)

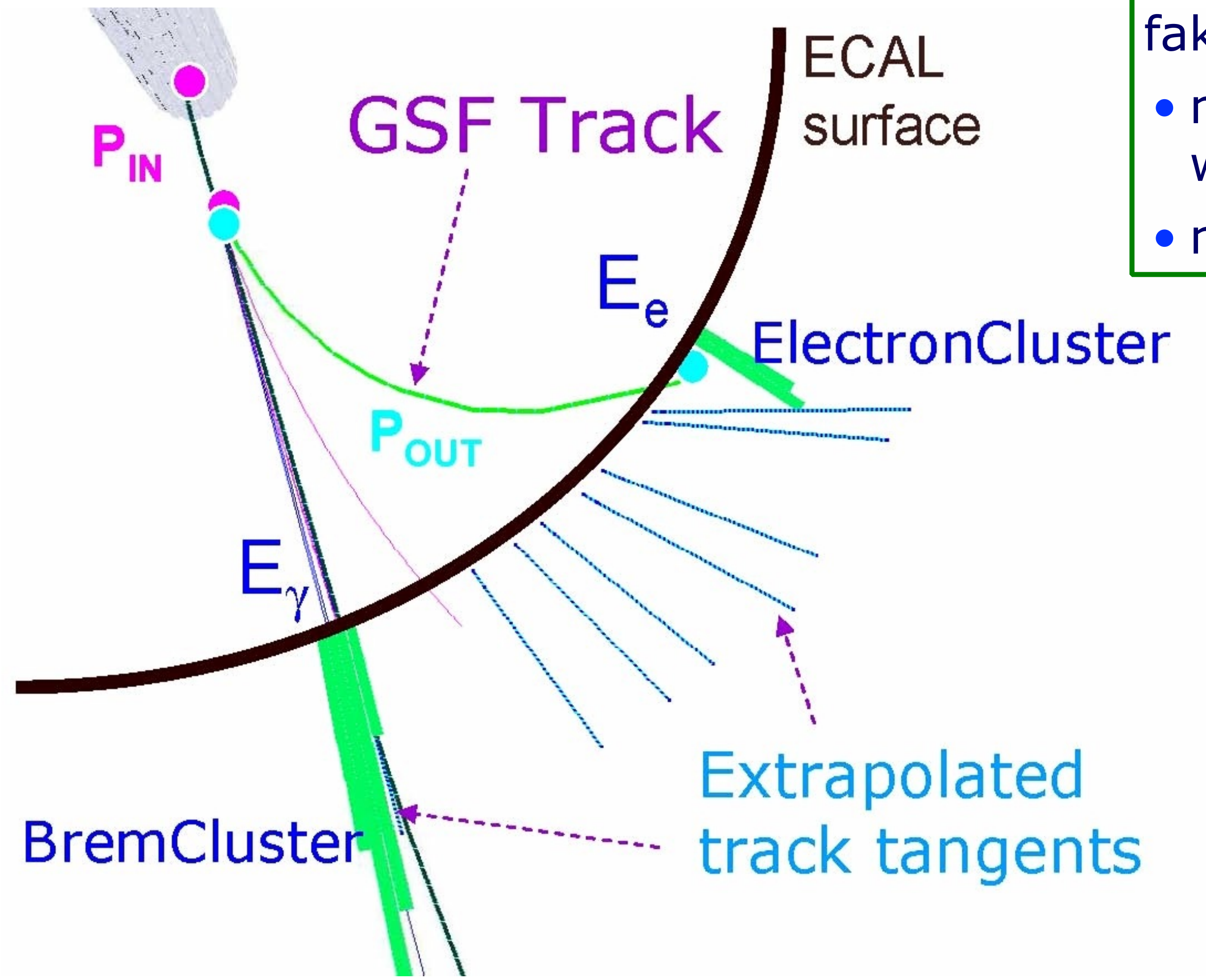
HIGGS MASS MEASUREMENT



CMS H→γγ is currently the most precise single Higgs mass measurement

$$124.70 \pm 0.31\,(\text{stat}) \pm 0.15\,(\text{syst})\,\text{GeV}$$

ELECTRON IDENTIFICATION



Aim to select prompt isolated electrons. Rejection of fakes from jets

- misidentified pions (charge exchange, also $\pi^0 \rightarrow \gamma\gamma$ with early conversion)
- non-isolated electrons (e.g. from b decays)

❖ Pure tracking observables

1. P_{IN}-P_{OUT}/P_{IN} (GSF) = fbrem
2. # hits KF
3. χ^2 KF & GSF

❖ Pure ECAL observables

1. Cluster shape in η direction $\sigma_{i\eta i\eta}$
2. Cluster shape in ϕ direction $\sigma_{i\phi i\phi}$
3. Cluster shape for circularity (E_{5x5}-E_{5x1})/E_{5x5}
4. Cluster width in η
5. Cluster width in ϕ
6. R9

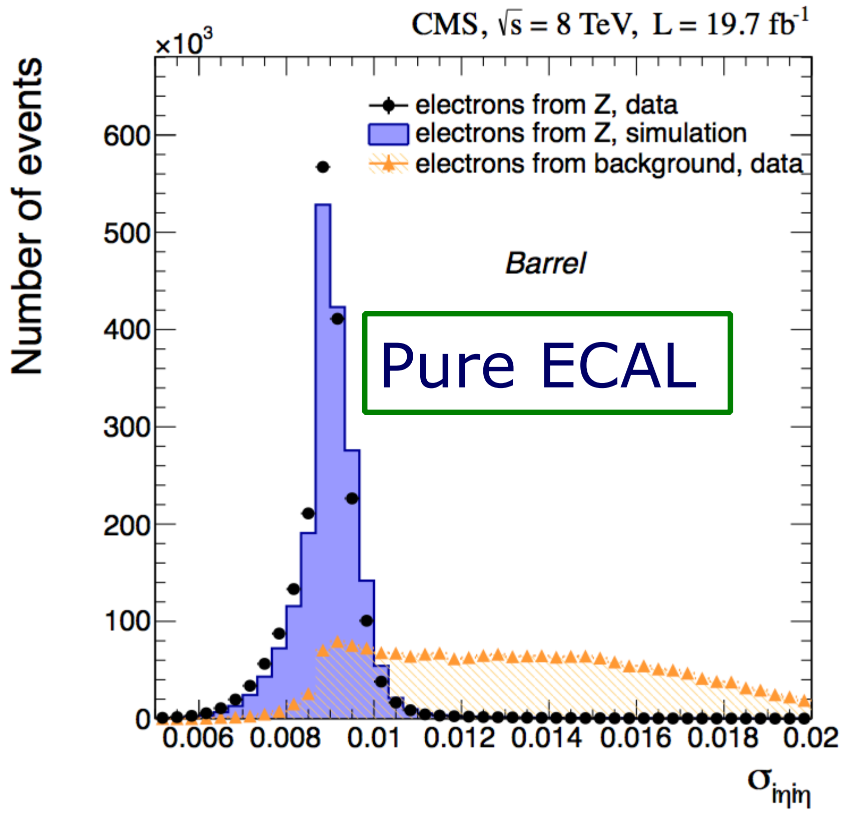
❖ Track-ECAL-HCAL-ES matching observables

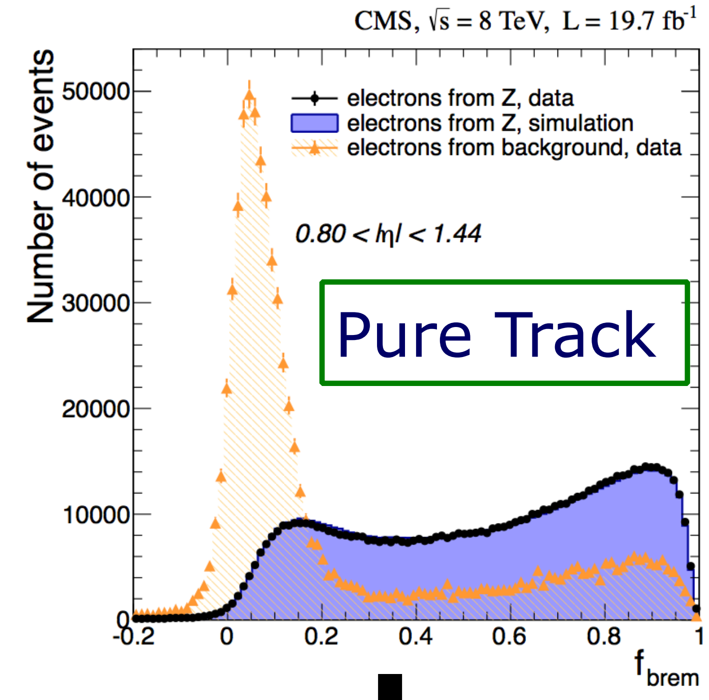
1. E_{Tot}/ P_{IN}
2. E_{Ele}/ P_{OUT}
3. $\Delta\eta_{OUT}$ (GsfTrackAtECAL-EleClus)
4. $\Delta\eta_{IN}$ (GsfTrackAtVertex-Superclus)
5. $\Delta\phi_{IN}$ (GsfTrackAtVertex-Superclus)
6. H/E
7. ES/E(Raw)
8. 1/E – 1/p (p combination of gsfmean

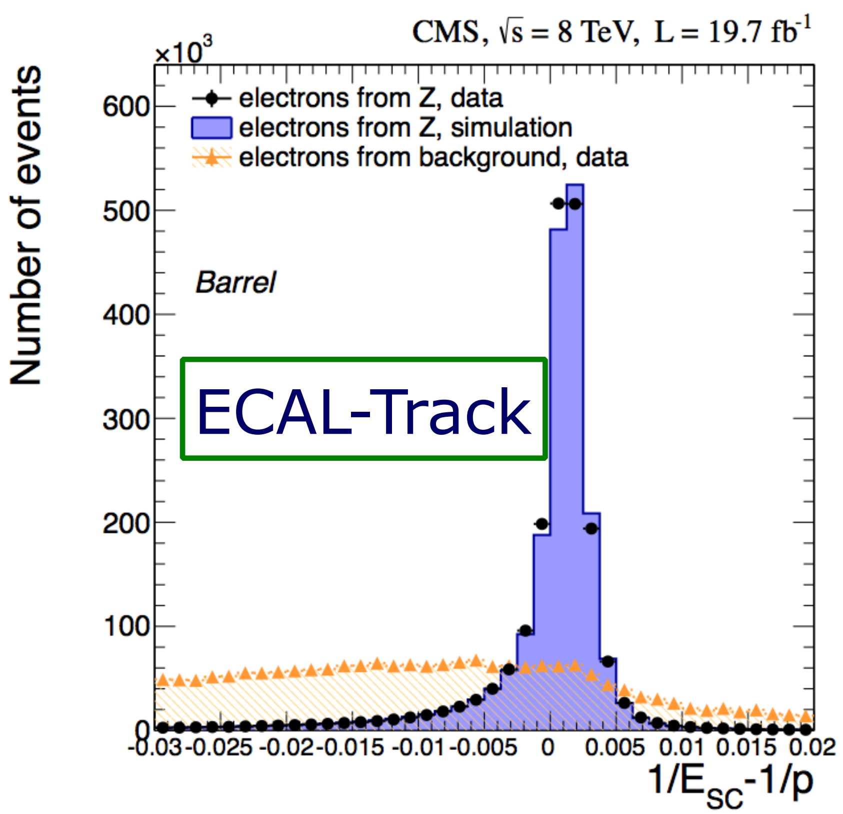
❖ Isolation

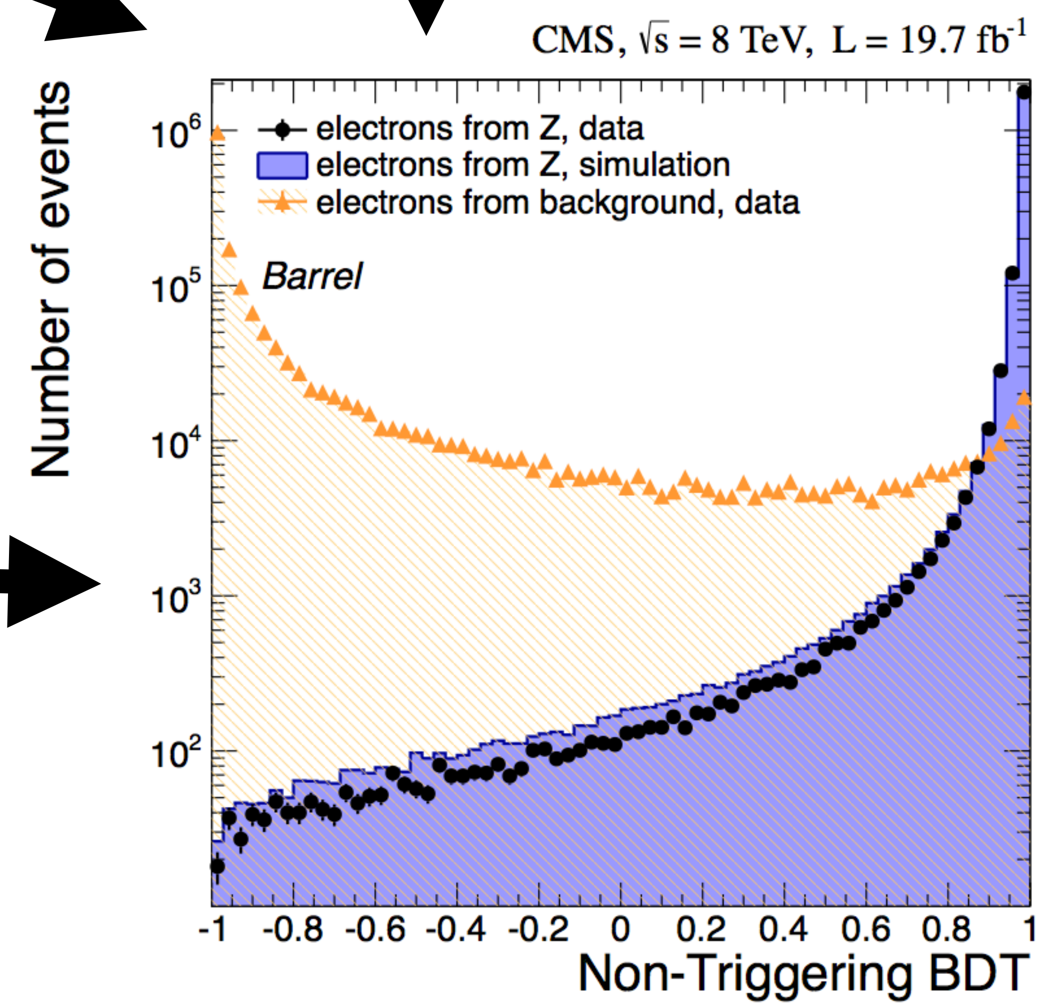
➢ Combining several variables is the typical optimization to be performed with a multivariate analysis (MVA).

ELECTRONID MVA

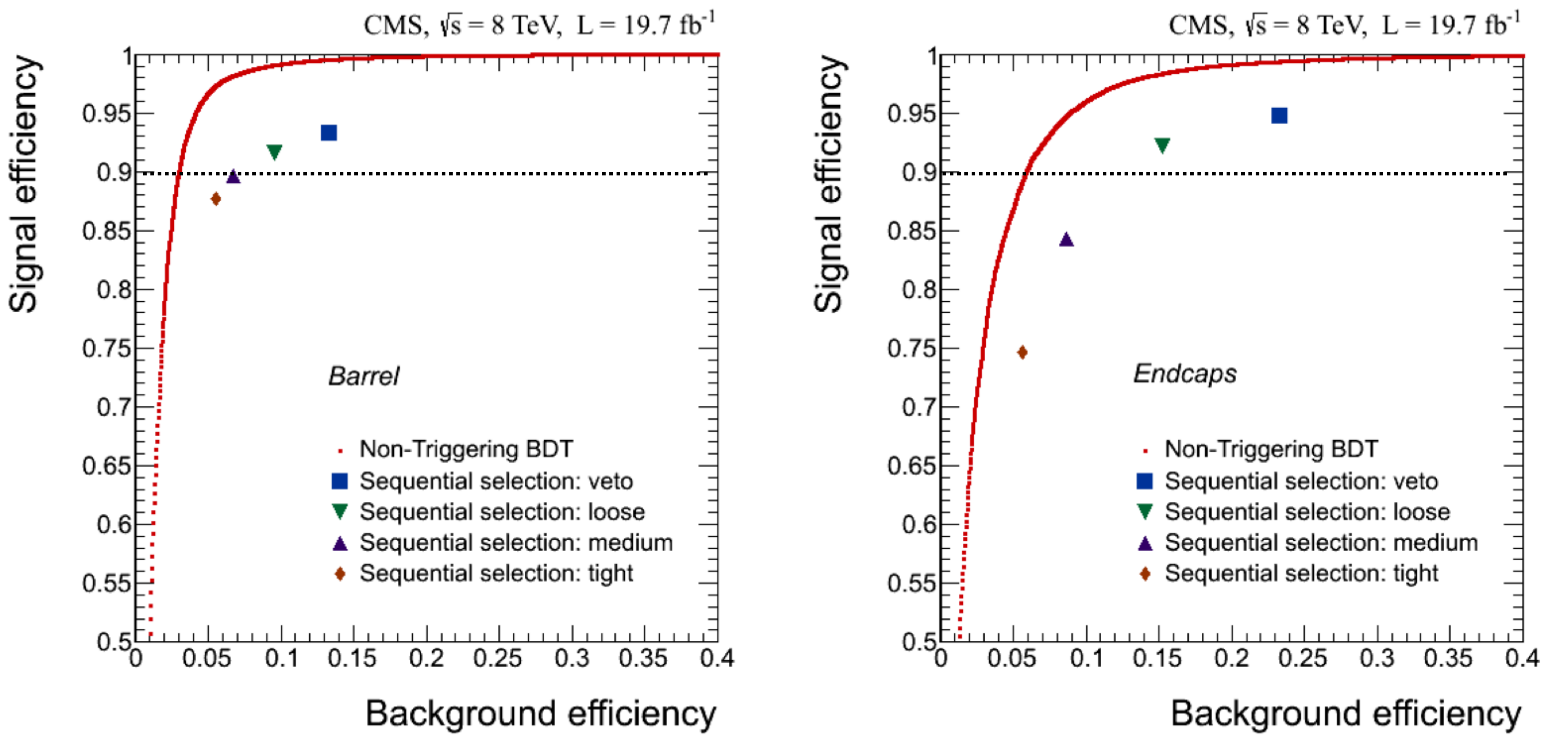








ELECTRONID MVA VS CUTS



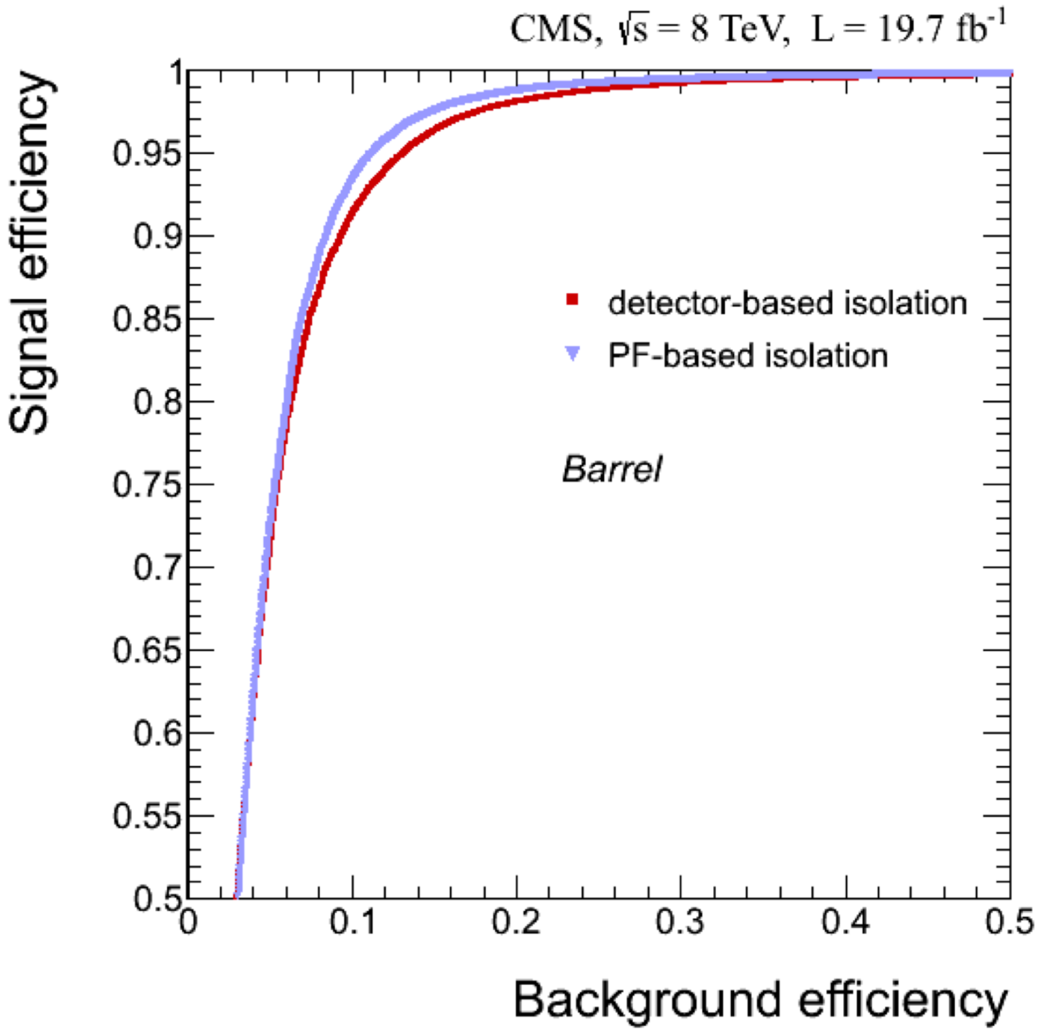
MVA brings about x2 background rejection for the same signal efficiency

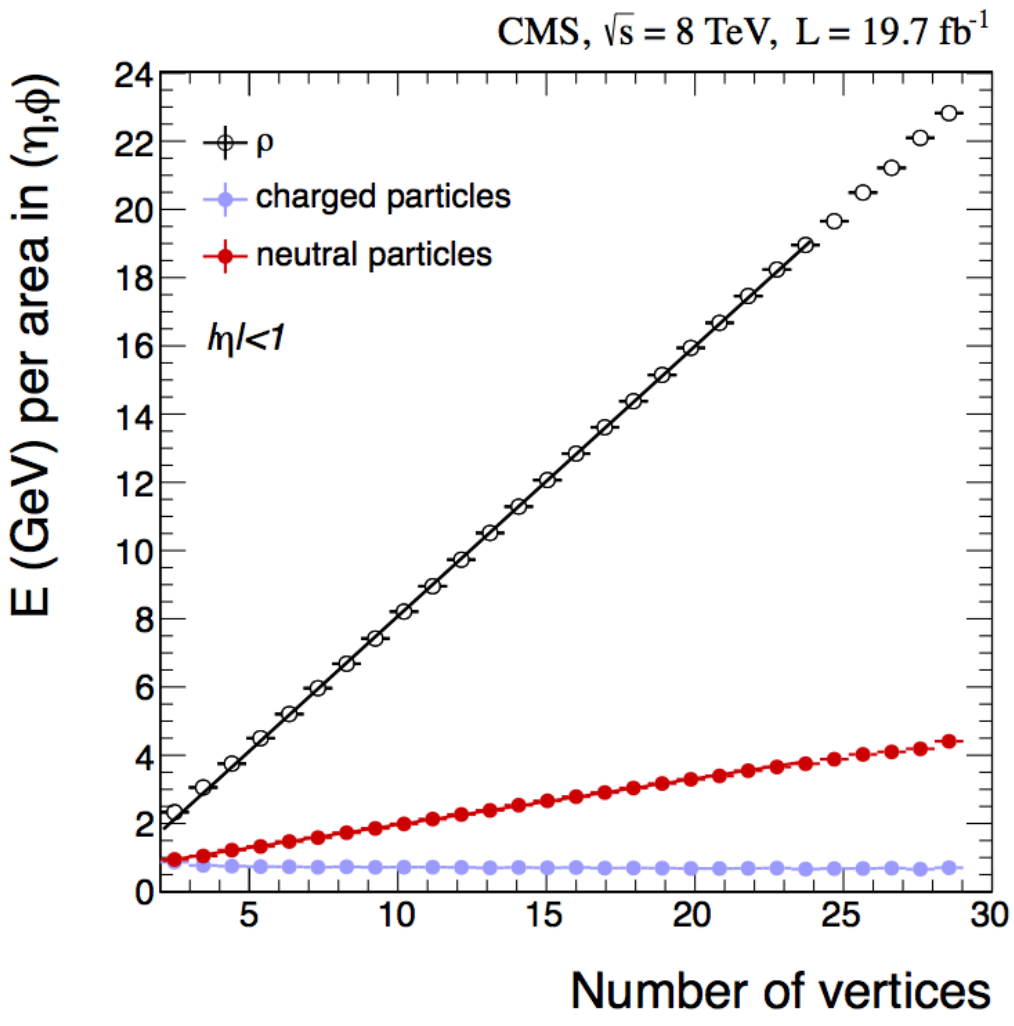
Isolated Electron Selection

Isolation powerful to reject electrons (or fakes) inside jets.

Isolation defined as the sum of the energy deposits in a cone $\Delta R=\sqrt{(\delta\eta^2+\delta\phi 2)}$ around the electron. ΔR=0.3 or 0.4 are typically used. Particle based isolation (based on Particle Flow candidates) is slightly better then detector based (avoids double counting)

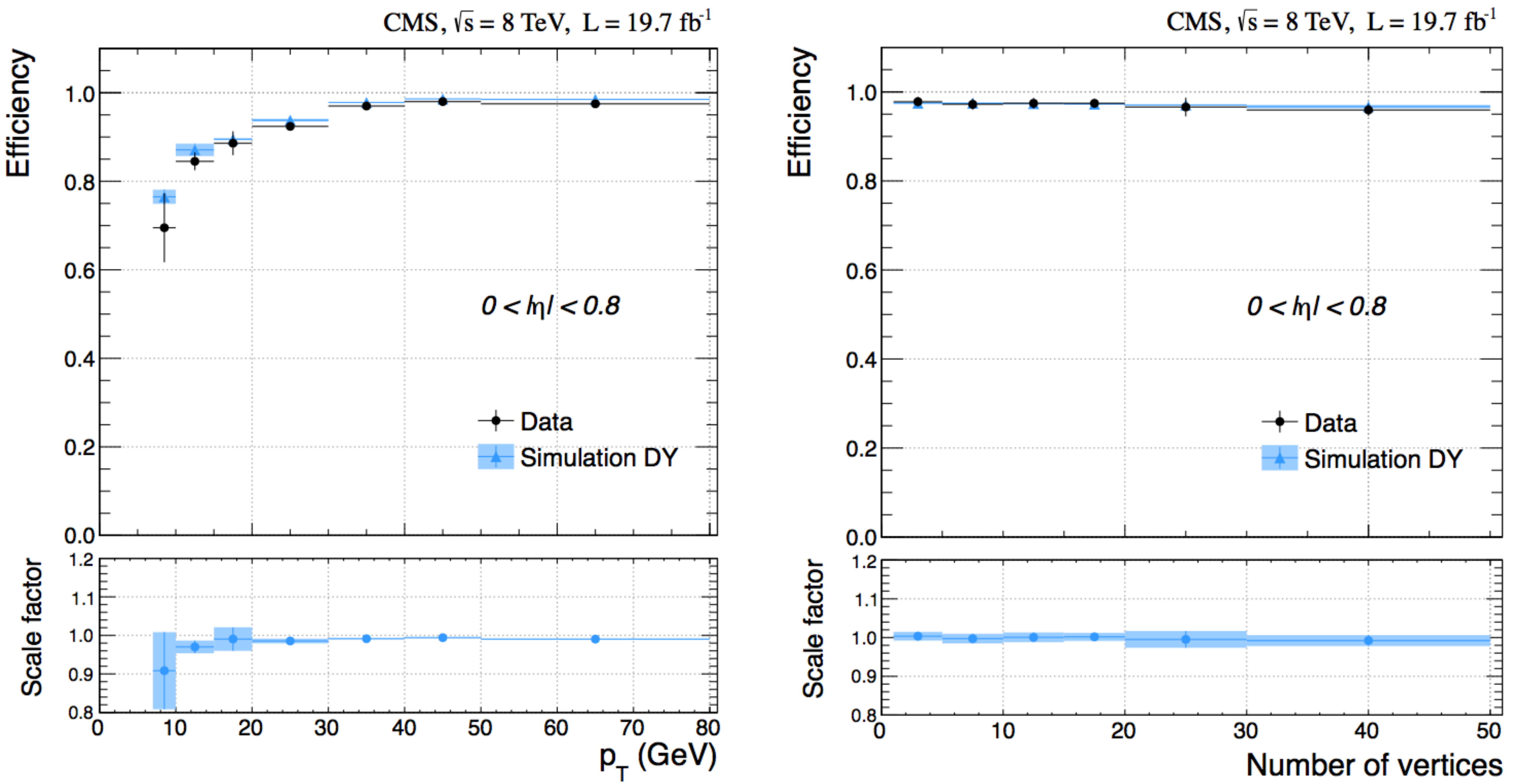
$$\mathrm{Iso}_{\mathrm{PF}} = (\sum_{\Delta R} p_{\mathrm{T}}^{\text{charged had}} + \mathrm{Max}[0, \sum p_{\mathrm{T}}^{\text{neutral had}} + \sum p_{\mathrm{T}}{}^{\gamma} - p_{\mathrm{T}}^{\mathrm{PU}}])$$





Isolation is corrected (neutral component) to maintain efficiency flat vs pile-up

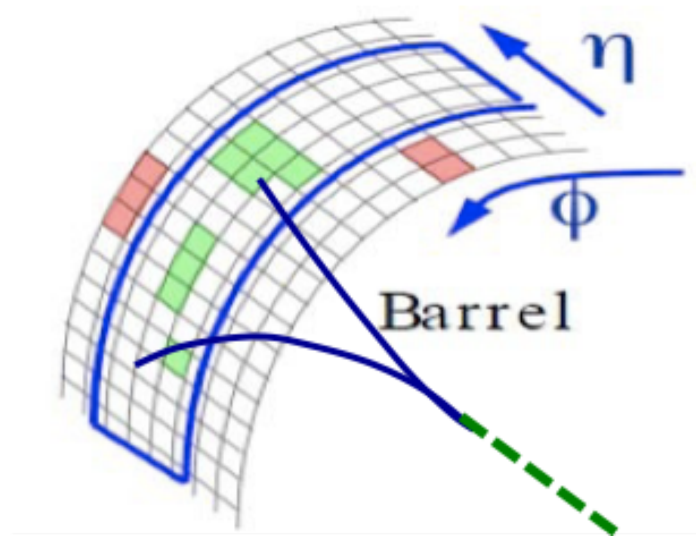
ELECTRONID EFFICIENCY



PHOTON IDENTIFICATION

Selection of prompt isolated photons. Rejection of fakes from jets

- mostly fakes come from $\pi^0, \eta \rightarrow \gamma\gamma$



❖ Lateral shower development

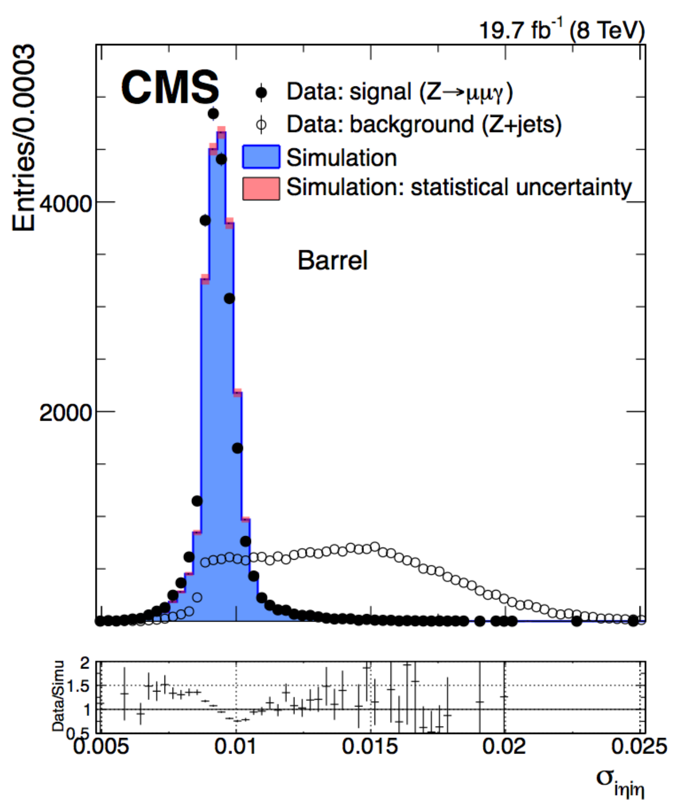
1. Cluster shape in η direction $\sigma_{i\eta i\eta}$
2. Cluster shape in ϕ direction $\sigma_{i\phi i\phi}$
3. Cluster shape for circularity $(E_{5x5}-E_{5x1})/E_{5x5}$
4. Cluster width in η
5. Cluster width in ϕ
6. R9
7. …

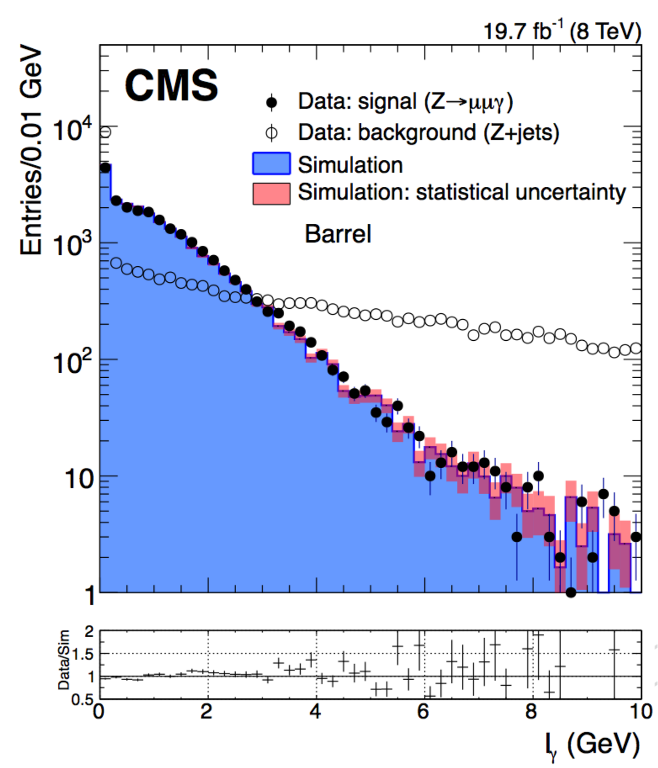
❖ Longitudinal shower development

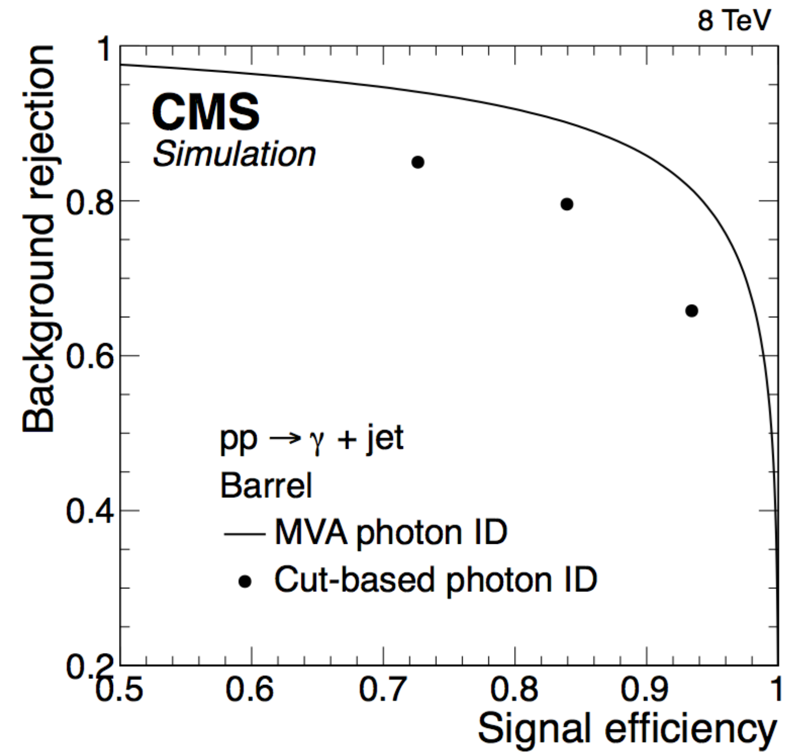
1. H/E
2. ES/E(Raw)

❖ Conversion safe electron veto

➢Several variables combined in a multivariate analysis (Boosted decision tree)

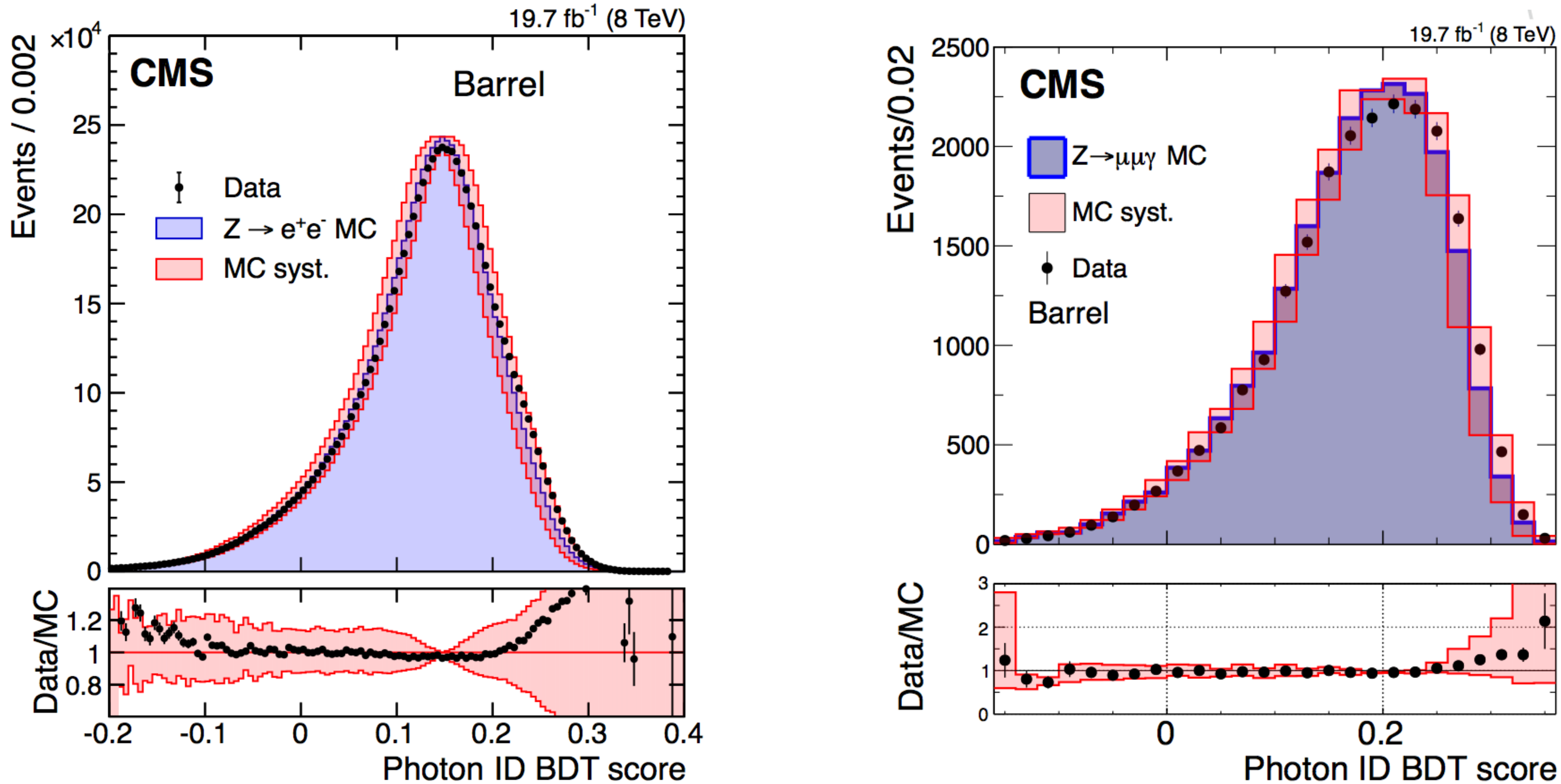




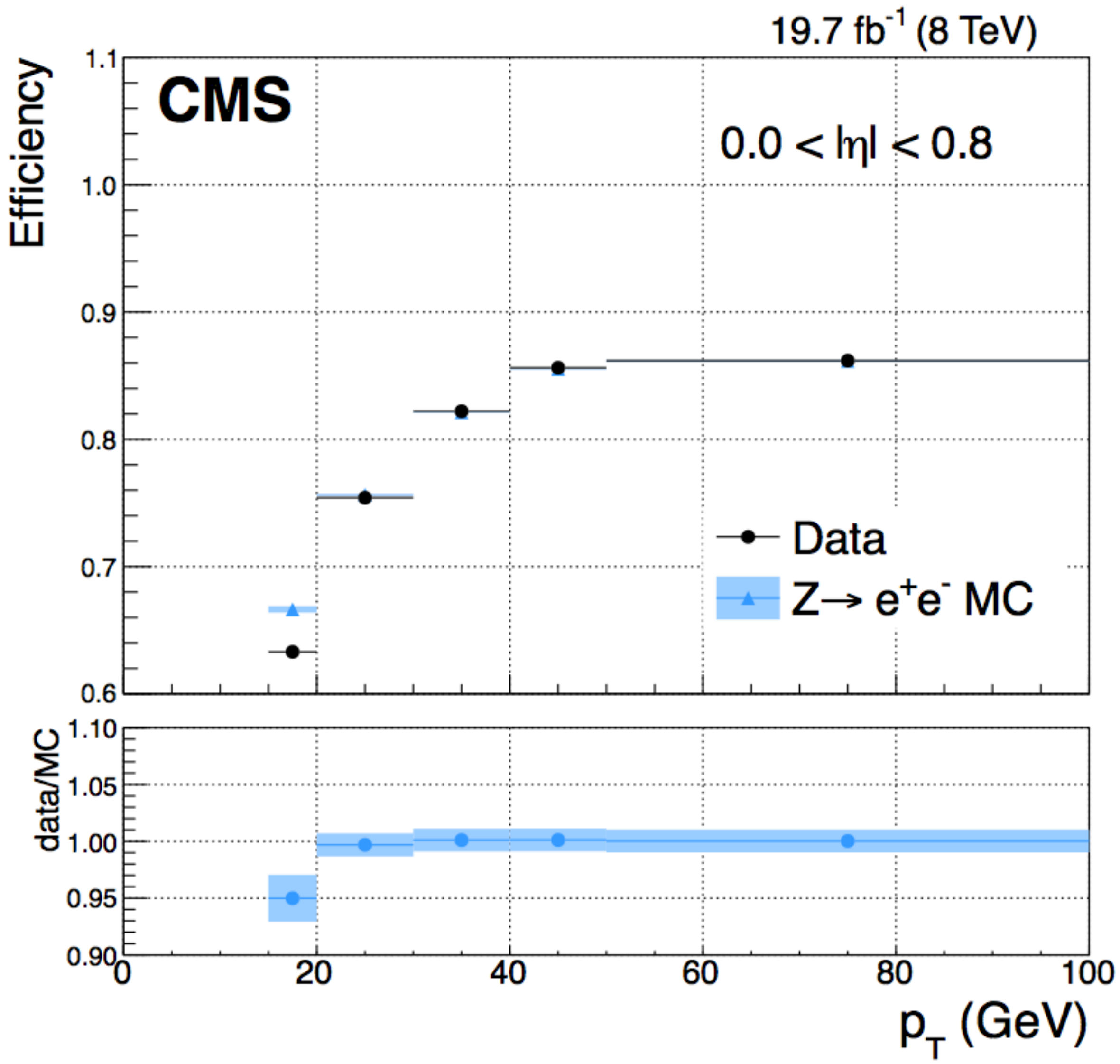


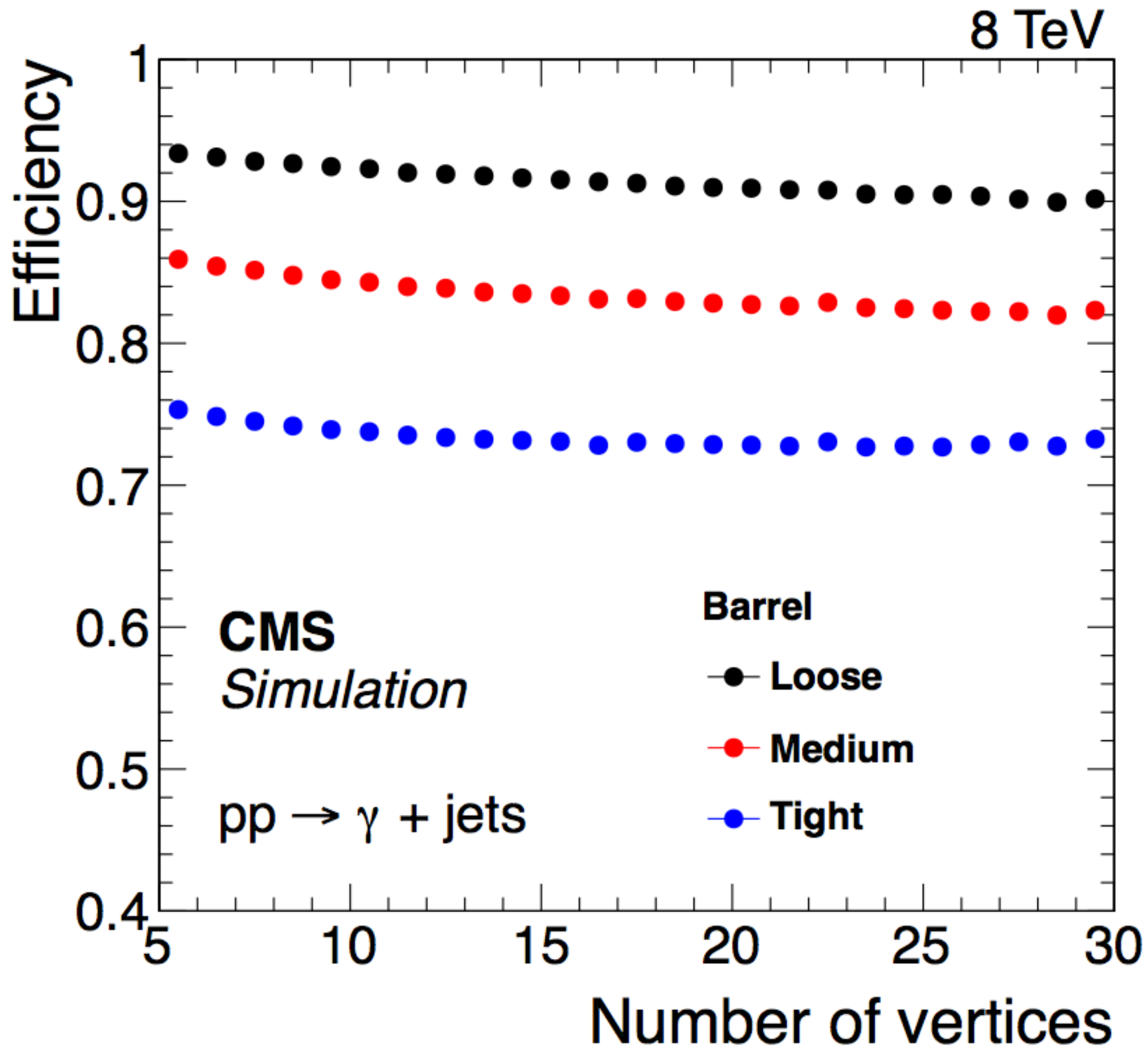
PhotonID Efficiency

- **Can use both $Z \to e^+e^-$ and $Z \to \mu\mu\gamma$ to check prompt isolated γ efficiency with data**
  - **Caveat:** electrons have to be treated as photons (no electron veto, need to reweight R_9 distribution)
  - **Caveat:** γ from $Z \to \mu\mu\gamma$ limited to E_T<35 GeV (& limited statistics)

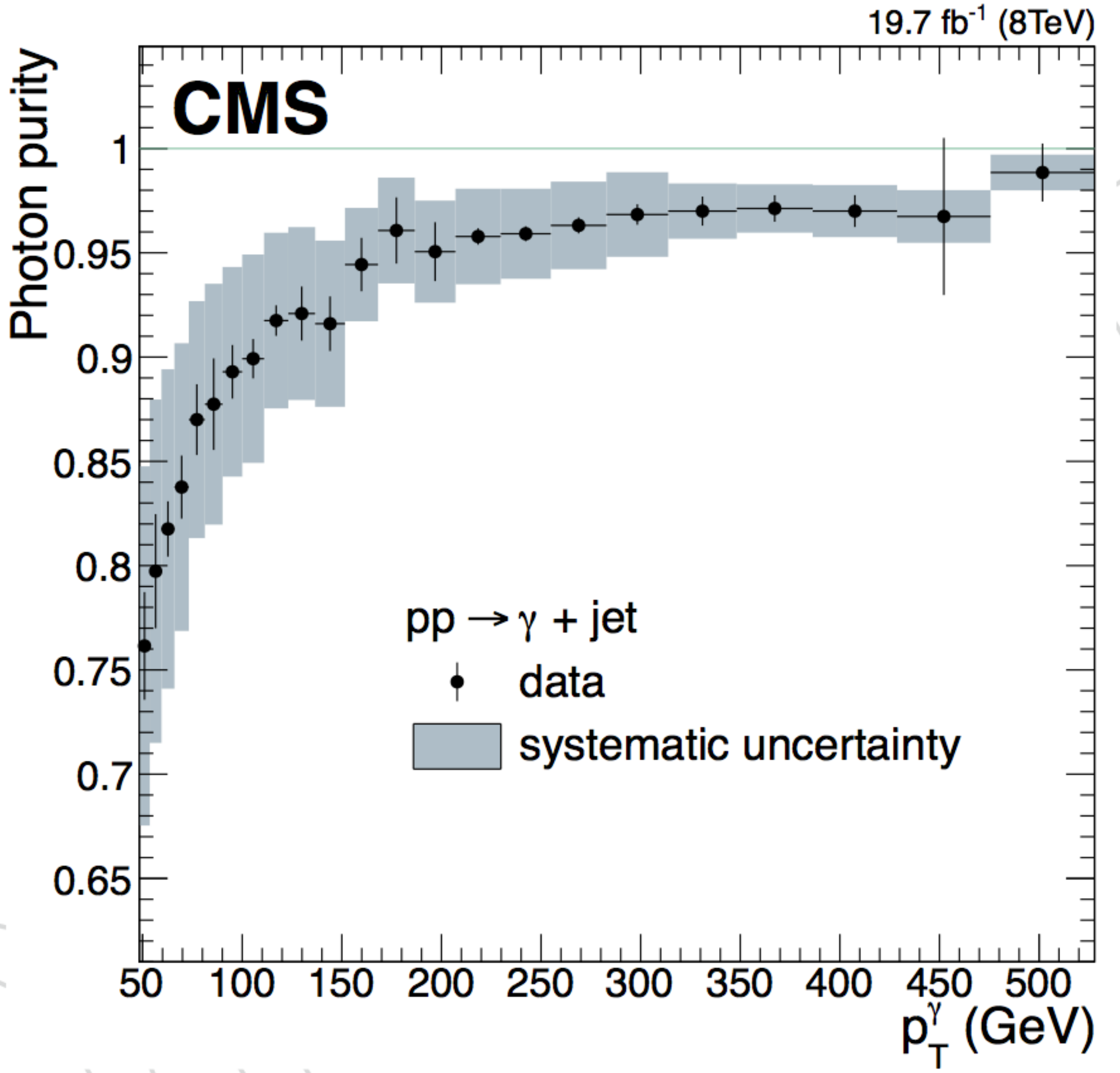


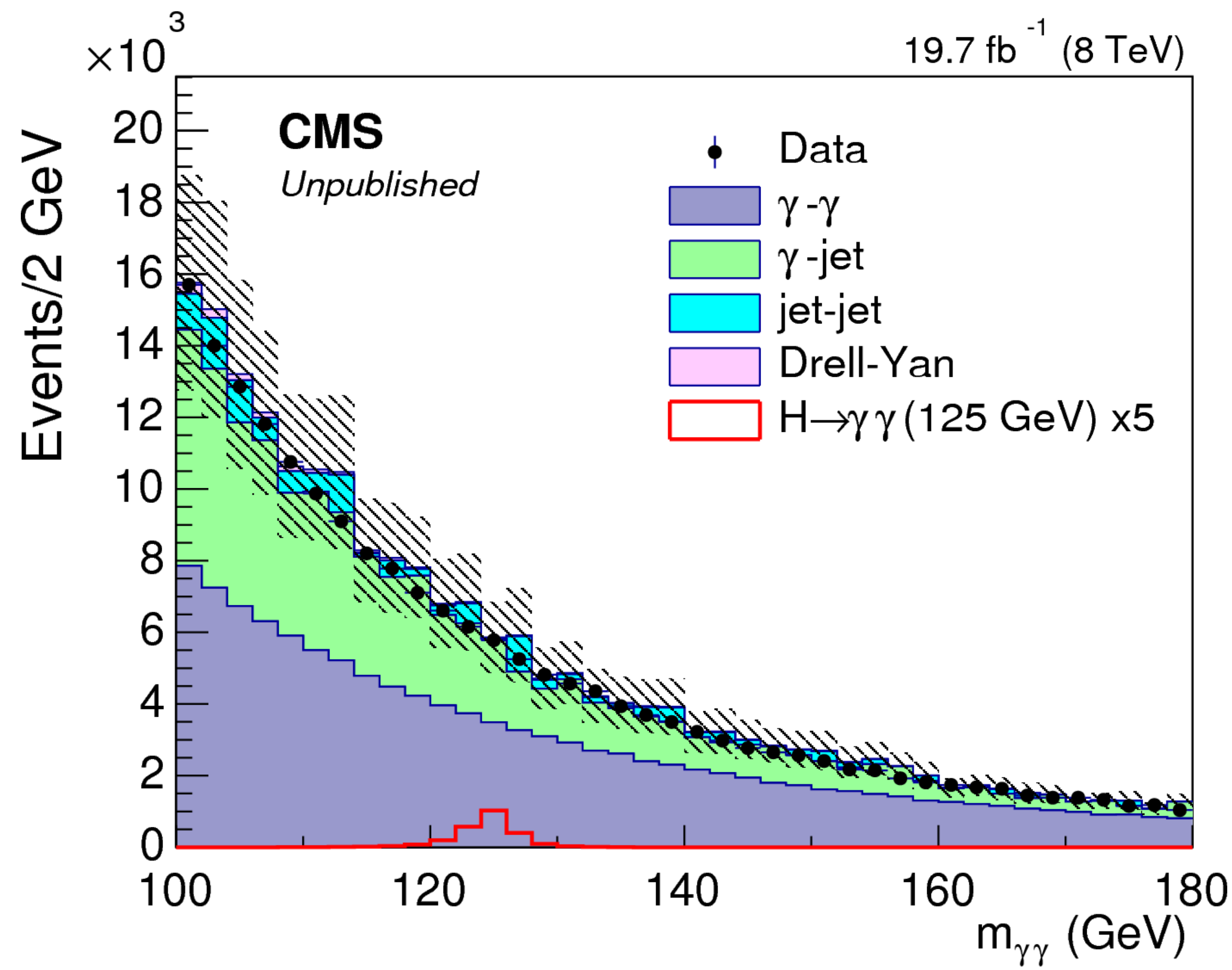
PhotonID Efficiency





PHOTON PURITY





Single photon purity (e.g. in inclusive prompt isolated γ selection)

Background components for H→γγ selection (prompt di-photon ~70%)

Quick References

- Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at $\sqrt{s}$ = 7 TeV http://arxiv.org/pdf/1306.2016.pdf
- Observation of the diphoton decay of the Higgs boson and measurement of its properties http://arxiv.org/pdf/1407.0558.pdf
- Measurement of the properties of a Higgs boson in the four-lepton final state http://arxiv.org/pdf/1312.5353.pdf
- Papers in preparation
  - EGM-13-001: Performance of electron reconstruction and selection with the CMS detector at $\sqrt{s}$=8TeV
  - EGM-14-001: Performance of photon reconstruction and selection with the CMS detector at $\sqrt{s}$=8TeV

Backup

In matter electrons and photons loose energy interacting with nuclei and atomic electrons

Electrons and positrons

- Ionization (atomic electrons)
- Bremsstrahlung (nuclei)

Photons

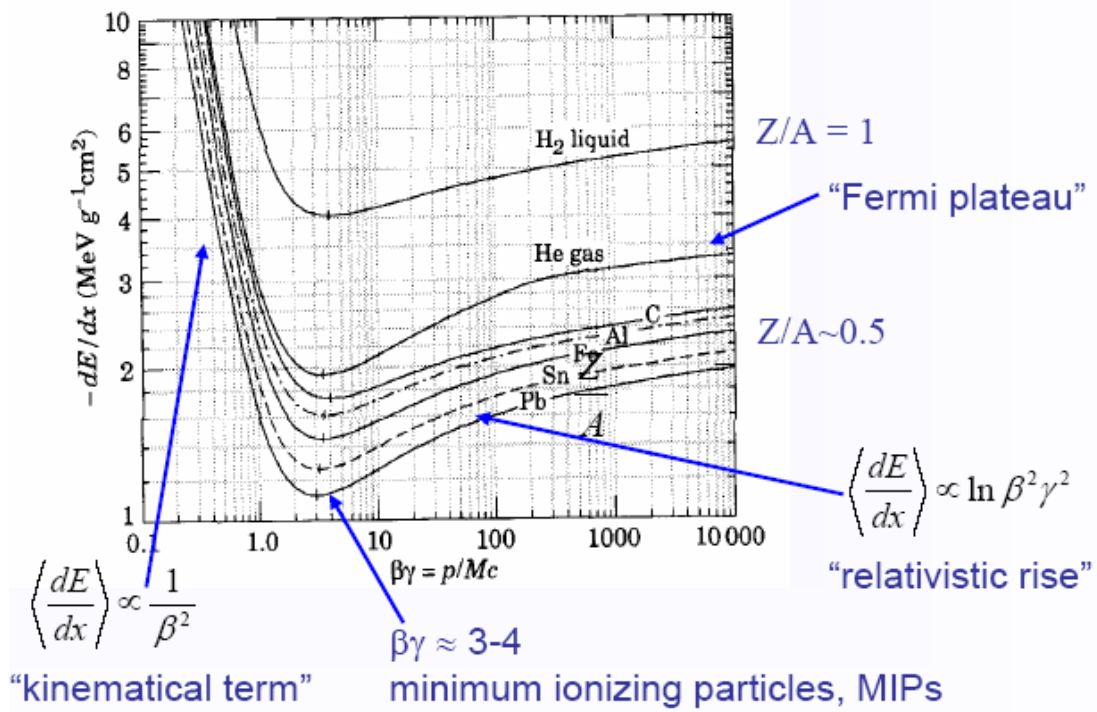
- Compton scattering (atomic electrons)
- Photoelectric effect (atomic electrons)
- Pair production (nuclei)

Reminder: Electrons Interactions

Ionisation: continous energy loss for charged particles

Average energy lost traversing a medium of dx thickness

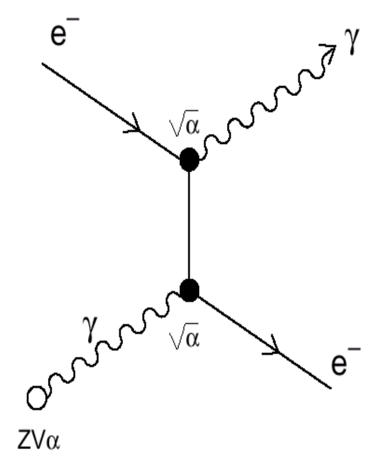
$$-\frac{dE}{dx} = 4\pi N_A \cdot r_e \cdot m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right]$$



Bremsstrahlung: important for light charged particles

$$-\frac{dE}{dx} = 4\alpha N_A\left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 z^2 \frac{Z^2}{A} E \cdot \ln\frac{183}{Z^{1/3}}$$

$$-\frac{dE}{dx}\bigg|_\mu \approx \frac{1}{40000}\frac{dE}{dx}\bigg|_e$$



Radiation length X_0
thickness required to reduce E_0 by 1/e

$$-\frac{dE}{dx}\bigg|_{Brem} = \frac{E}{X_0}$$

$$E = E_0 \cdot e^{-x/X_0}$$

Critical energy E_c

same average energy loss due to ionisation and brem

$$E_c \approx \frac{610\text{MeV}}{Z+1.24}$$

Strongly material dependent:
7 MeV for lead, 20 MeV for copper,
~500 GeV for muons in copper

REMINDER: PHOTONS INTERACTIONS

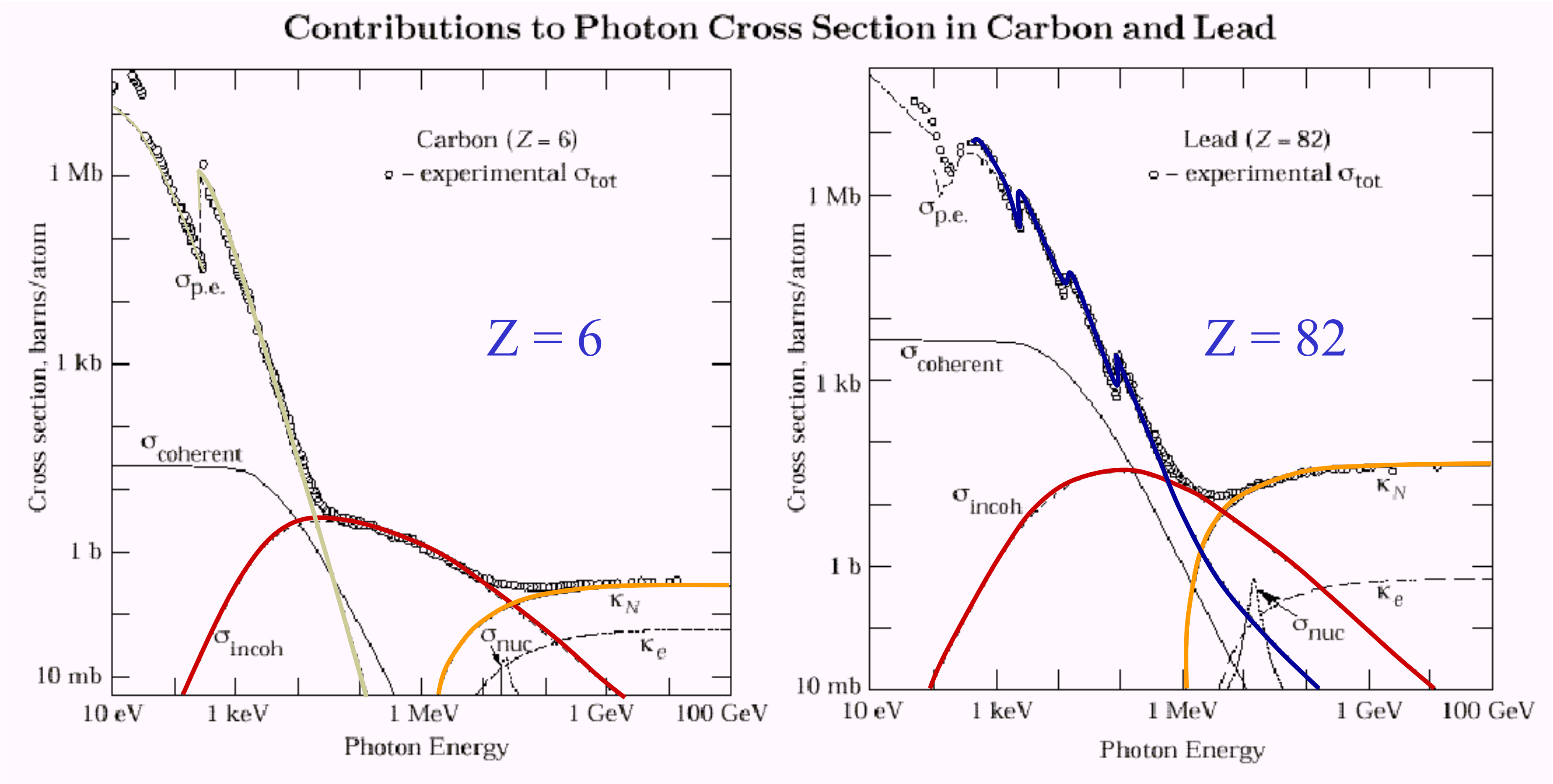


photo-electric
$$\sigma_{pe} \approx Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma} \right)^{\frac{7}{2}} \qquad \sigma \propto Z^5 \,,\ E^{-3.5}$$

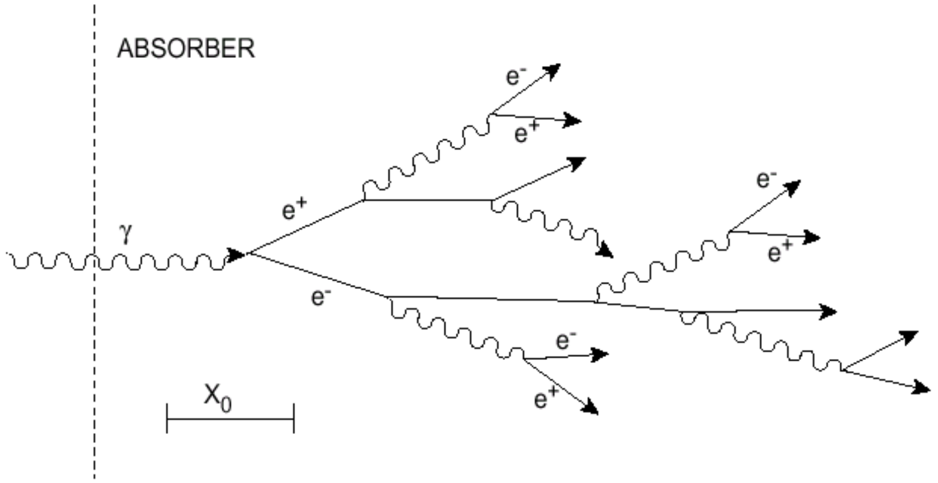
Compton scattering
$$\sigma_c \approx Z \frac{\ln E_\gamma}{E_\gamma} \qquad \sigma \propto Z \,,\ E^{-1}$$

pair production
$$\sigma_{pair} \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

- independent of energy above 1 GeV
- Mean free path $L_{pair} = 9/7\ X_0$

High energy electrons and photons produce EM showers in matter

- Bremsstrahlung & pair-production becomes energy dependent > 1GeV
- For electrons above E_C a simple model can be made: assume X_0 as a generation length. After 1 X_0 number of particles in shower is doubled
- Electromagnetic cascade propagates until the critical energy E_C for e^+/e^- is reached ($E<E_C$ ionisation losses)

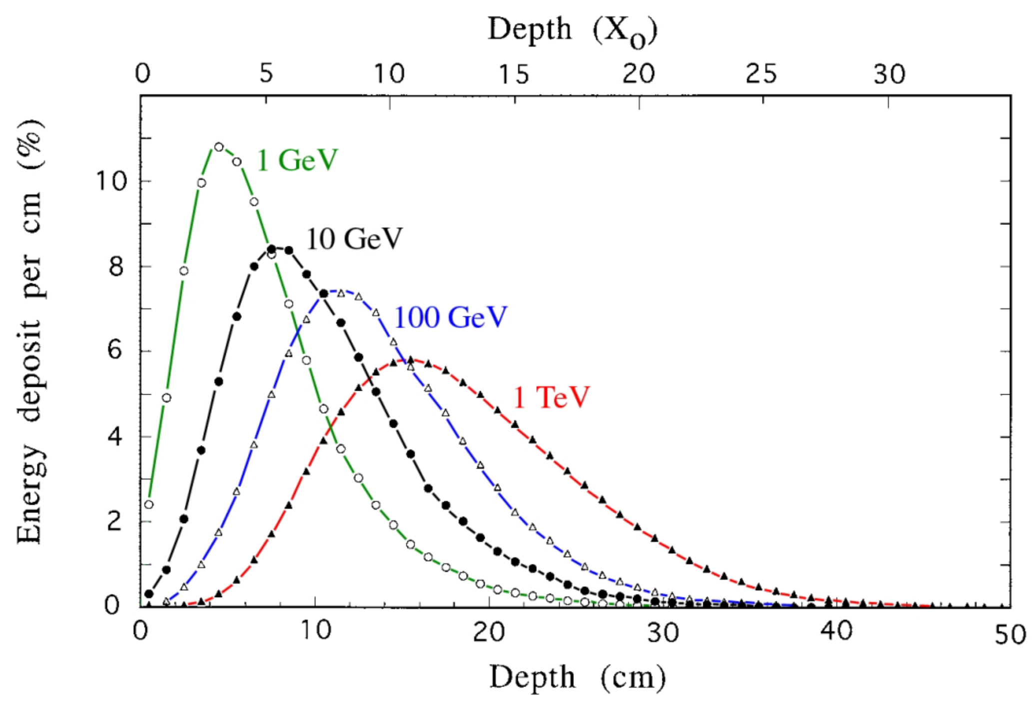


at $\Delta x = tX_0$ $\quad N(t) = 2^t \quad E(t) = E_0 / 2^t$

at $\Delta x = t_{max}X_0$ (shower max) $\quad E(t_{max}) = E_0 / 2^{t_{max}} = E_c$

$t_{max} = \ln(E_0/E_c)/\ln(2) \propto \ln(E_0) \quad N(t_{max}) \sim E_0/E_c$

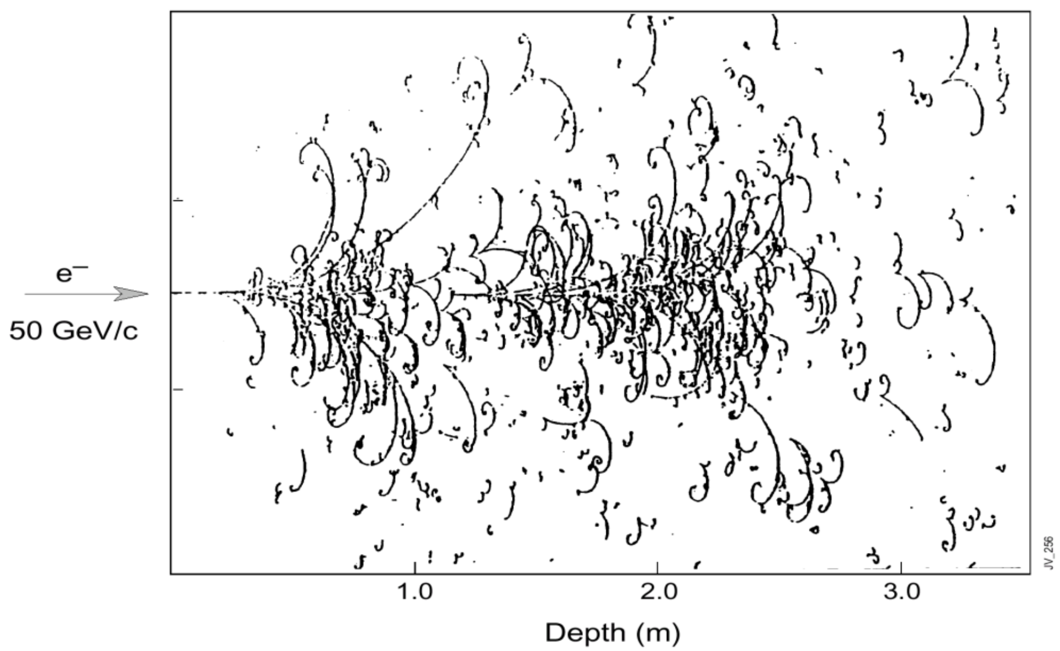
e- EM shower longitudinal development in copper



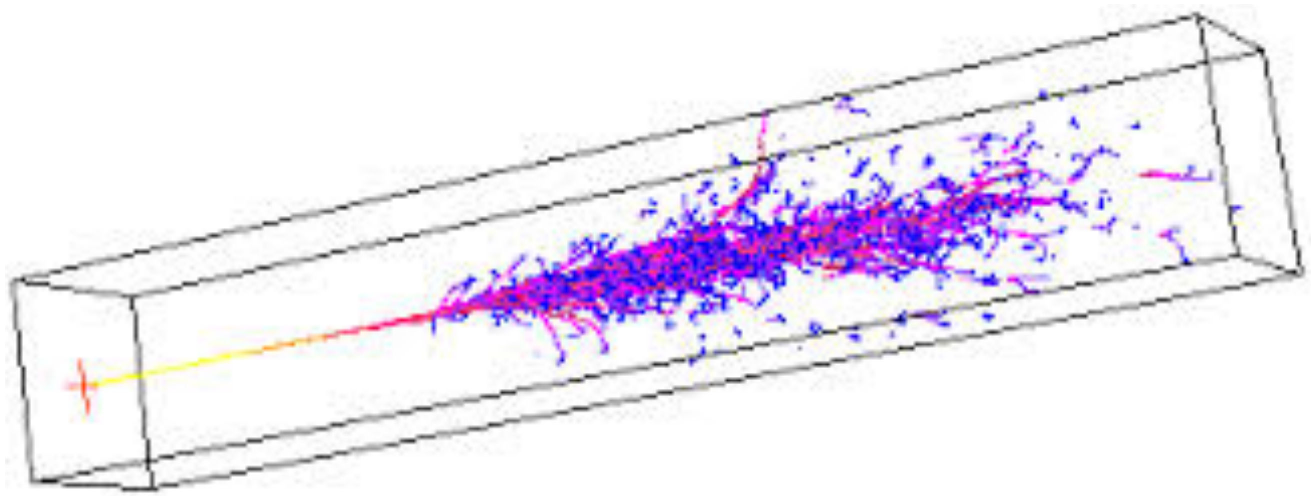
$$t_{max} = 1.45\ln(E_0/E_c)$$

1 GeV electron in copper:
95% in 11 X_0 and 99% in 16 X_0

1 TeV electron in copper:
95% in 22 X_0 and 99% in 27 X_0



Big European Bubble Chamber filled with Ne:H_2 = 70%:30%, 3T Field, L=3.5 m, X_0≈34 cm, 50 GeV incident electron



simulated EM shower for γ E=50 GeV in CMS ECAL crystal