Directions in High-Resolution Particle Measurement

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Outline

- Calorimetry
  - Ongoing R&D and the future Calorimeters
  - Current Electromagnetic Calorimeters in ATLAS and CMS
- Calibration of the Atlas Electromagnetic Calorimeter
  - Impact on Higgs searches
    - Brief status of the $H \rightarrow \gamma\gamma$ search in ATLAS
- Searches for SUSY in multilepton events (in backup slides)
- Summary

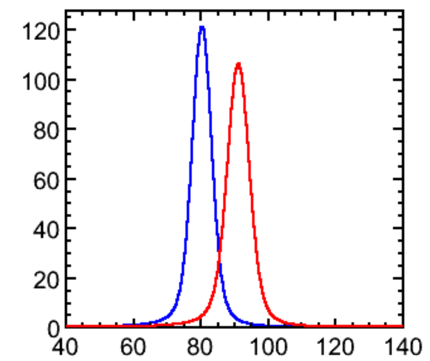
Calorimetry

- Measure energies of charged and neutral particles, jets as well as measure total missing transverse energy
- Consists of:
  - Dense absorber material to fully absorb incident particles
  - Active material to produce an output signal proportional to the input energy
- Fast processing time, could recognize and select interesting events in real time, used for triggering
- The intrinsic resolution of calorimeters improves with energy(as $1/\sqrt{E}$) in contrast to magnetic spectrometer
- Calorimetry is widely used, very much matured and effective technique
  - But still need to improve resolution, achieve even faster response and more radiation hardness for future experiments

Particle-Flow Calorimetry (1/2)

- A novel idea for high resolution calorimetry
  - Partly motivated by the need to distinguish dijet invariant masses of W and Z bosons on event-by-event basis(e.g in future e^+e^- linear collider)
- The idea is to measure the energy of all particles in a jet using
  - Tracker for charged particles
  - EM calorimeter for prompt photons
  - Hadronic calorimeter for neural hadrons
  - A typical jet has:
    - 60 % of jet energy in charged hadrons
    - 30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
    - 10 % in neutral hadrons (mainly from n and K_L)

3% jet resolution give 2.6σ separation in W/Z

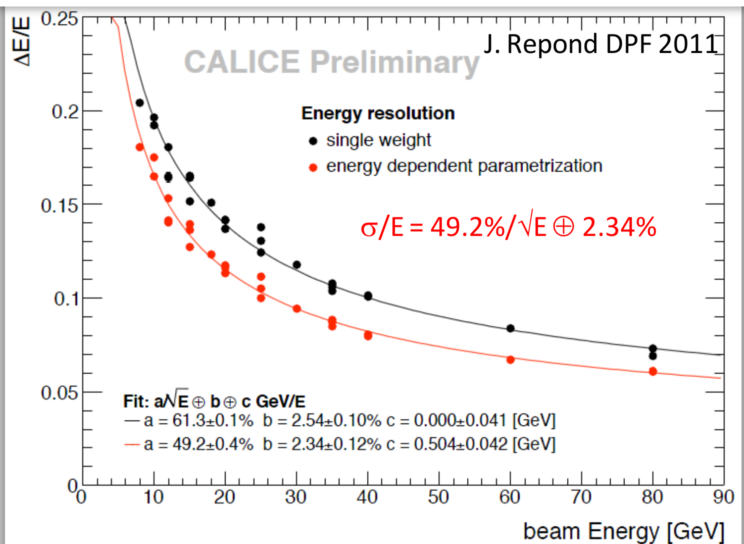


  - Normally jet energy is measured in calorimeters(HCAL and ECAL)
    - 70% of the jet energy is measured in HCAL with poor resolution, for ATLAS $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$
    - Could improve resolution using PFC by a factor 3 , $\sigma/E < 20\%/\sqrt{E}$, enough to distinguish W/Z decays
    - Only 10% of the energy is measured in HCAL
- Need to isolate the energy deposited by charged particles from that by photons and neutral hadrons

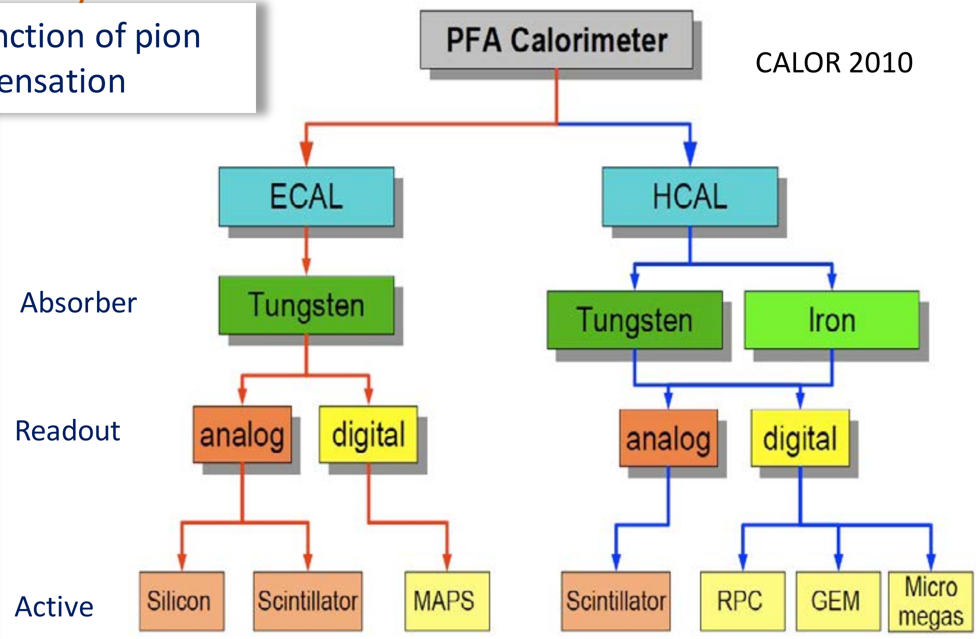
Particle-Flow Calorimetry (2/2)

- The concept is a combination of both advance Hardware and Software
  - Need highly segmented detectors(ECAL and HCAL), for example SiW sampling ECAL from CALICE
    - Using tungsten as absorber and silicon as active layer
  - Need very good pattern recognition algorithms optimized with highly segmented high resolution detector
  - Like PandoraPFA, such NIM 611 (2009) 24-40

Hadronic resolution with CALICE Analog HCAL as function of pion energy before(black) and after (red) software compensation

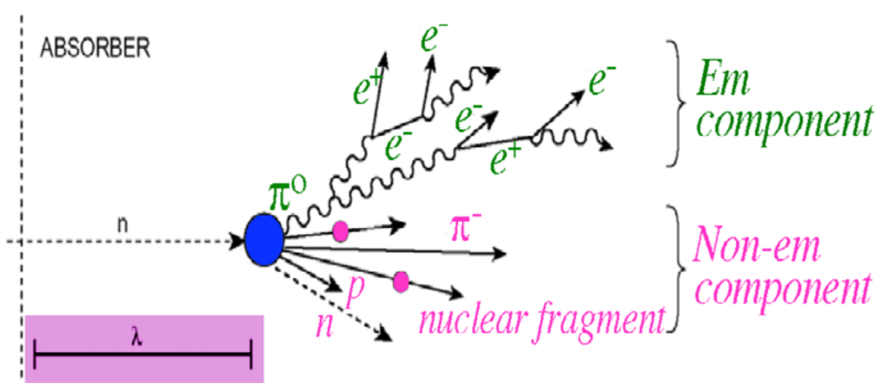


CALOR 2010



Dual-Readout Calorimetry(1/2)

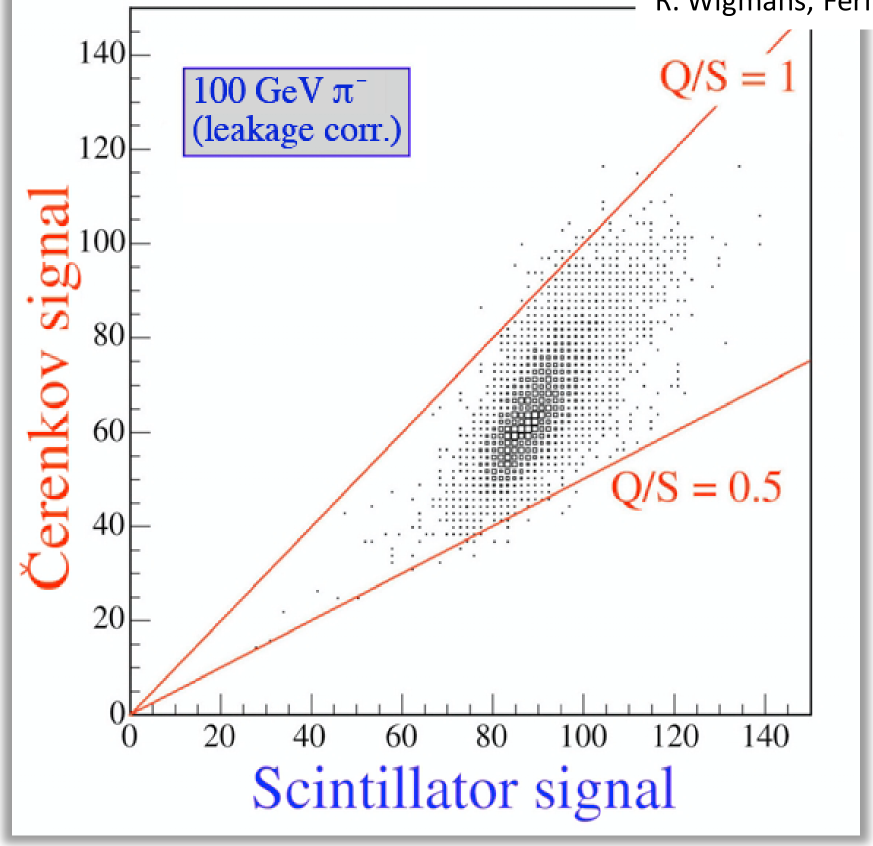
- A hadronic shower consists of two components: EM and hadronic

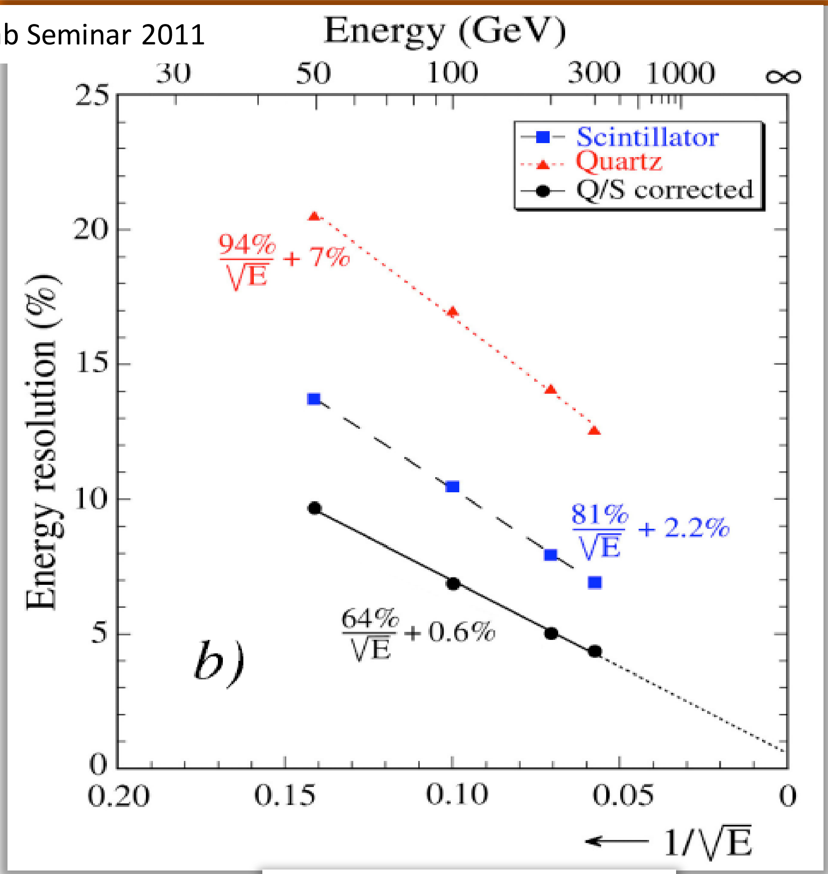


- Calorimeters(e/h≠1) give a larger signal per unit deposited energy for the EM shower component (mostly initiated by $\pi^0 \rightarrow \gamma\gamma$) than for non-EM components
  - fluctuations in the intrinsic energy-sharing between the EM and non-EM component of the deposited energy
  - Hence large fluctuation in hadronic response
  - Poor resolution, non linearity and non Gaussian response
- One way out as adopted by DREAM collaboration is Dual-Readout Calorimetry
- Measurement of both the ionization/scintillation(hadronic fraction) and the Cherenkov signals(EM fraction) generated by a hadronic shower in order to determine on event by event basis the electromagnetic fraction of the shower
  - The total shower energy can be reconstructed by using the measured values of EM fraction
  - Resolution, linearity can be improved

The effect of Dual-Readout corrections

R. Wigmans, Fermilab Seminar 2011





Jet Energy Resolution

- Improved resolution to $\sigma/E = 64\%/\sqrt{E} \oplus 0.6\%$ after corrections
- Small constant term means resolution improve with energy
- The DREAM Calo. suffers from limited lateral coverage, therefore particle leakage occurs. Space for improvement, goal is to have hadronic resolution as good as EM

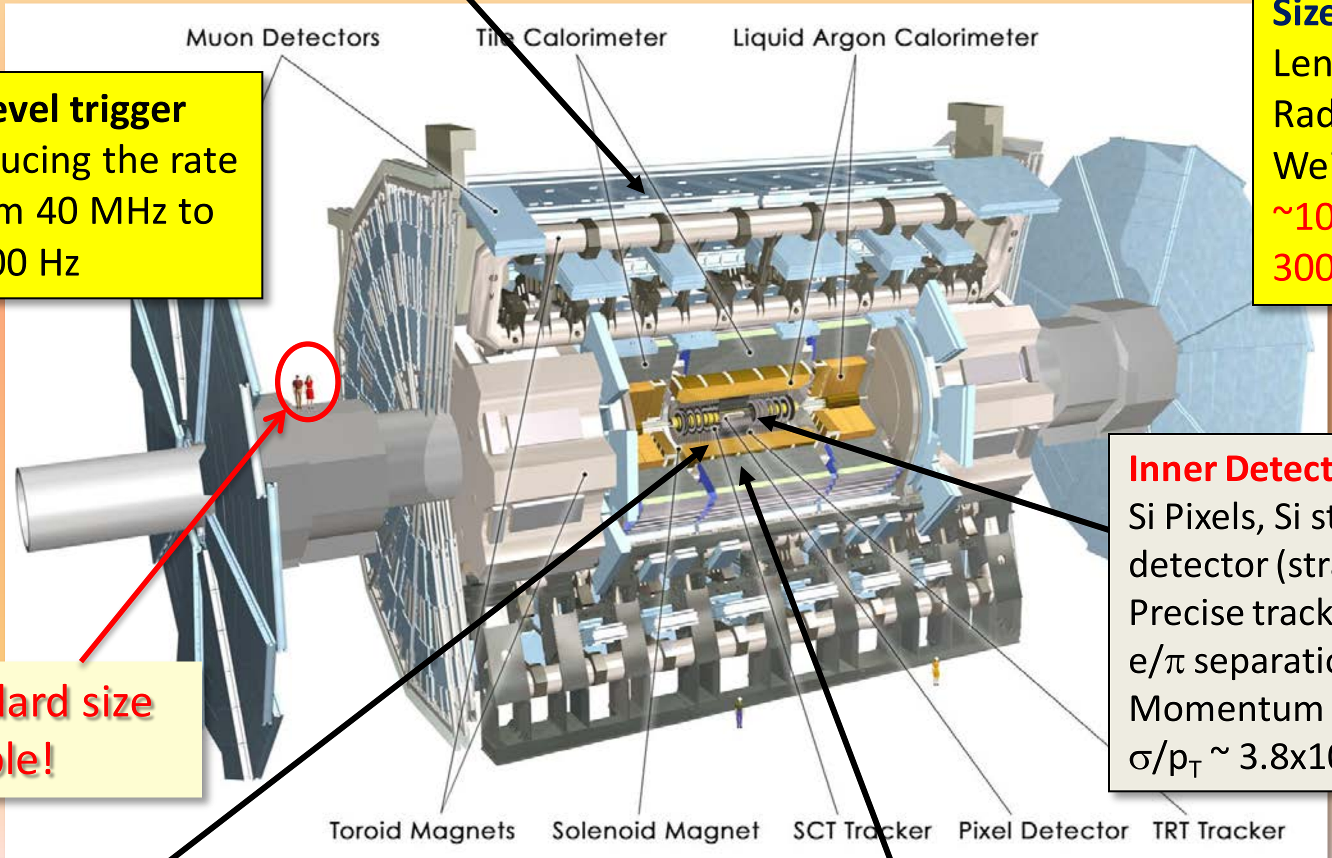
State of the Art:
ATLAS and CMS Electromagnetic Calorimeters

The ATLAS(A ToroidaL LHC ApparatuS) Detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Size of the detecor
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger
reducing the rate from 40 MHz to ~200 Hz



Standard size people!

Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\ p_T(\text{GeV}) \oplus 0.015$

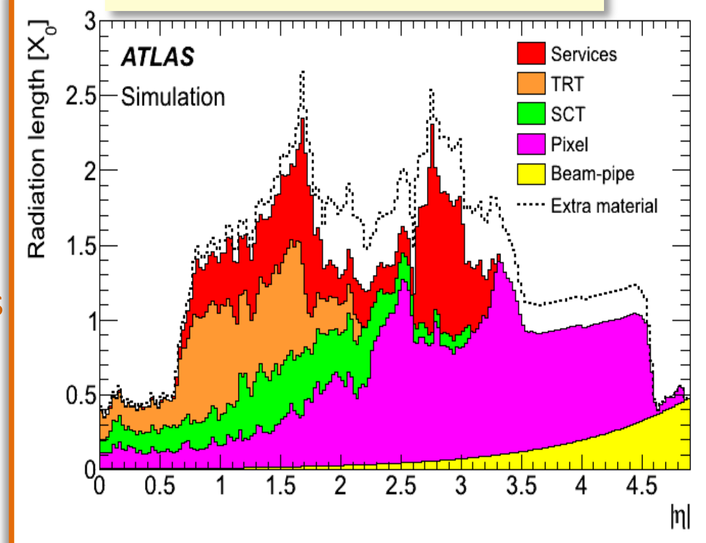
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

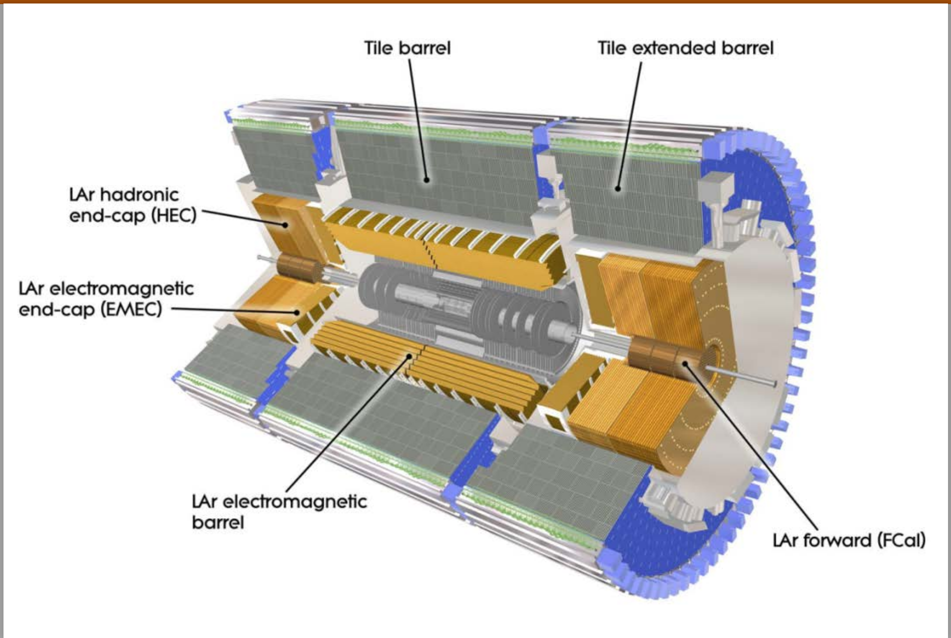
ATLAS: A Huge Detector

- Building such a huge apparatus which involves millions of channels and sophisticated technology is not a trivial task
- Need decades of R&D, thousands of people and a lot of money
- Once components are built, the next step is the assembly
  - Need to weigh all components and assemble them precisely
  - A small distortion or misplacement could affect position and momentum resolution
    - After careful assembly particle tracks have to be used in-situ to correct for distortions/misalignments
    - The so called CSC book(~2000 page book about ATLAS and it's performance is based on my alignment related work that I did a few years back)
- Also involve a lot of passive material
  - Power cables, cooling pipe, solenoid etc
  - As a result:
    - Electrons initiate showers , hence Identification, efficiency Problems, charge misID, jet fakes etc
    - Photons converts to e+ e- pairs before reaching EM Calorimeter
  - All material has to be properly mapped and it's effects has to be understood

Material budget within ID



ATLAS Calorimeters

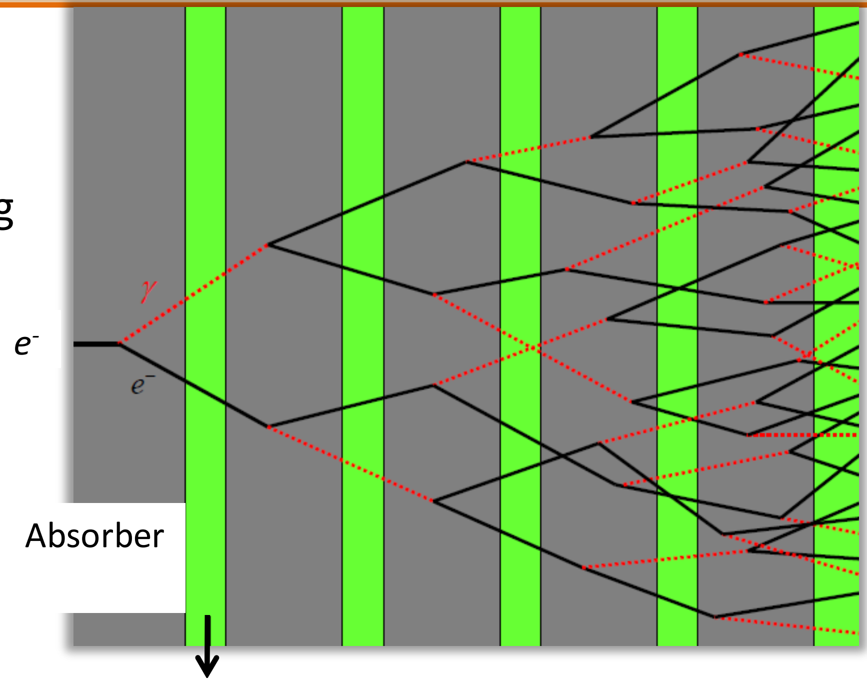


- Identify and measure energies of electrons, photons, taus, hadronic jets
- Measure missing energy signatures to spy for weakly interacting particles
- Need high granularity and hermitic detector
- The ATLAS LAr Calorimeter consists of
  - Electromagnetic calorimeter Barrel (EMB)
  - Electromagnetic calorimeter End-Cap (EMEC)
  - Hadronic end-cap calorimeter (HEC)
  - Forward calorimeter (FCAL)

Optimization of parameters like sampling, thickness, transverse and longitudinal granularity done with detail simulation and beam tests

Sampling Calorimeters

ATLAS uses Sampling calorimeters



Active medium : Ionization or scintillation

- A SAMPLING calorimeter is a calorimeter in which the medium in which the particle energy is deposited is interleaved with additional layers to periodically sample the energy

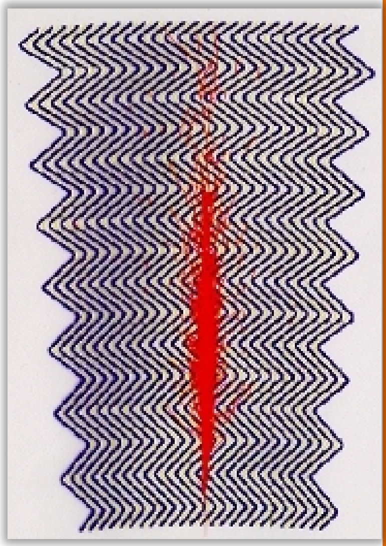
- We infer the total energy deposited from the ionization deposited in the sampling layers - by converting it to an electrical signal and digitizing it

ATLAS LAr Electromagnetic Calorimeter

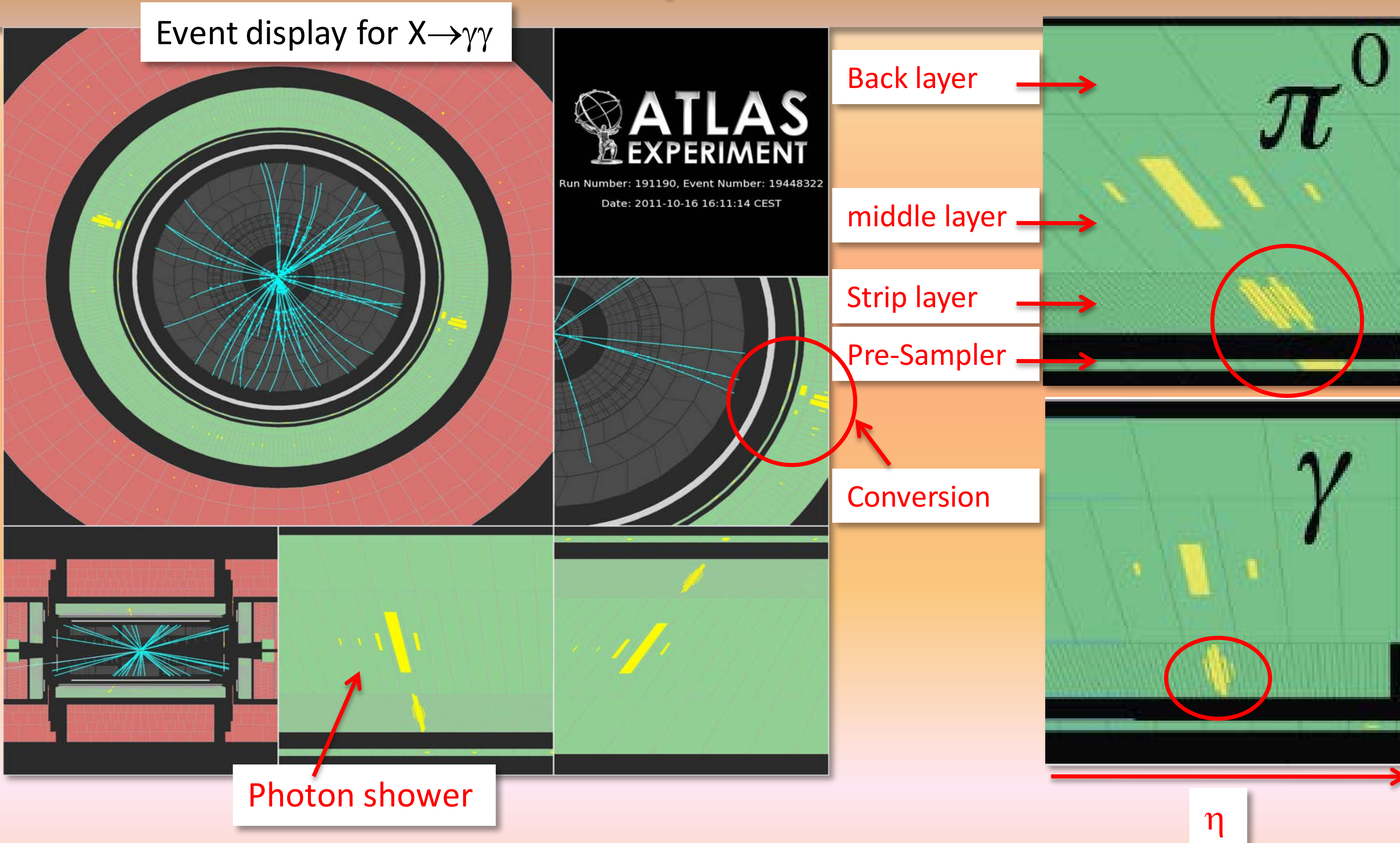
- LAr calorimeters play a central role in ATLAS detector
  - Pb-LAr sampling calorimeter with Pb as a passive (absorber) and LAr as active medium
    - Energy is measured through ionization
  - Measure energies of electrons and photons with high resolution and detect hadronic jets and missing energy signatures

- Excellent γ/π^0 , γ/jet and e/jet separation power
  - Rejection factor of ~10^5 for e and ~10^4 for photon

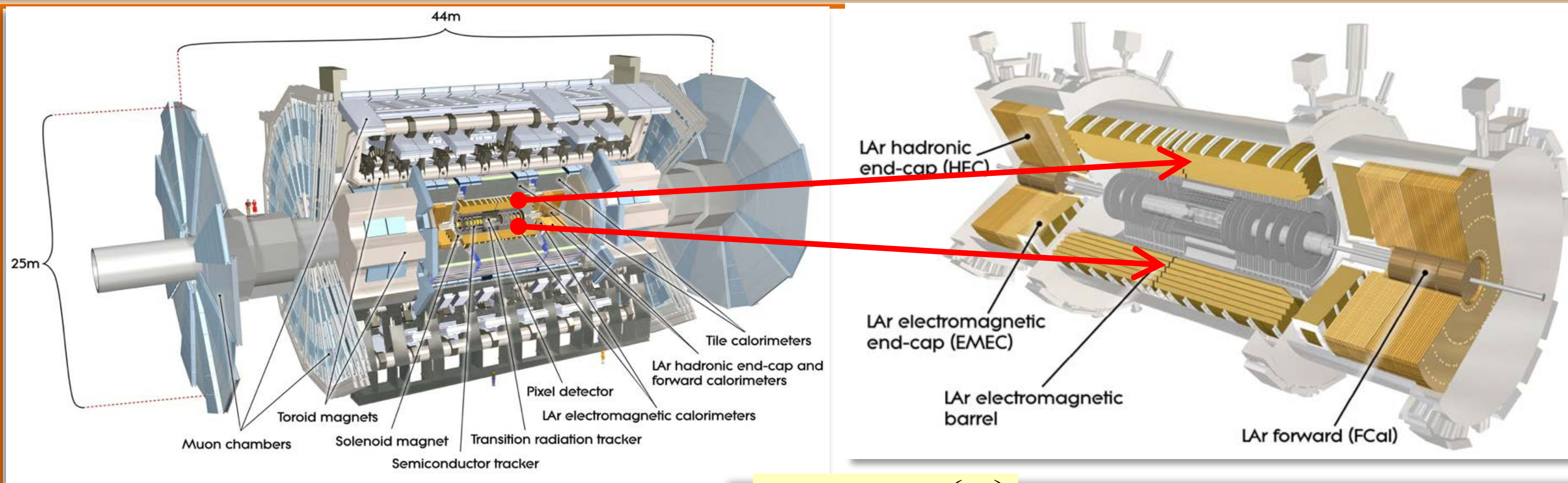
- To cope with pile-up, detector is designed to have fast response (40MHz, against pile-up) and fine granularity to separate overlapping photon from single photon (see later)



How does photon look?

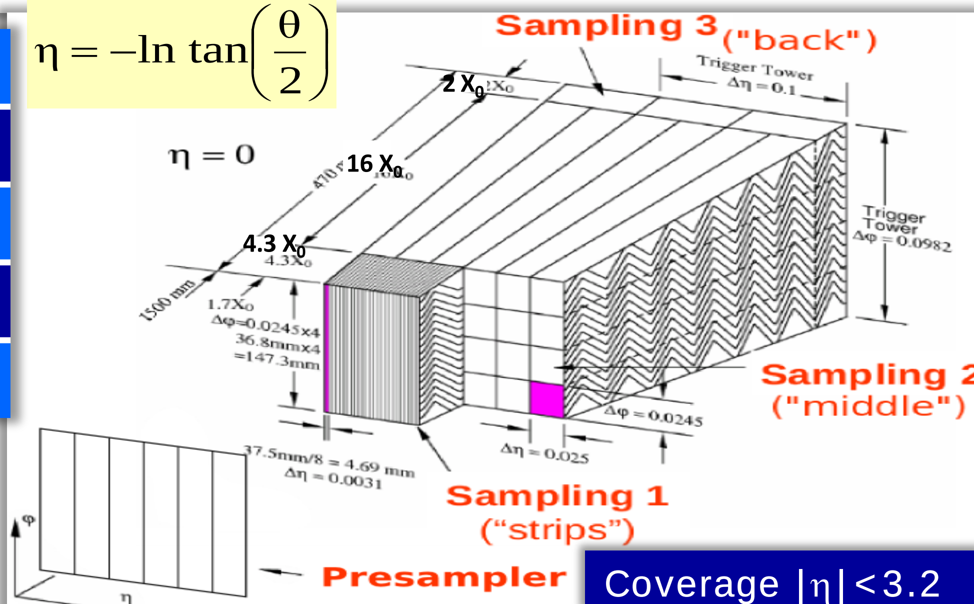


Liquid Argon (LAr) Electromagnetic Calorimeter



Layer	$\Delta\eta$ x $\Delta\phi$
preSampler	0.025 x 0.1
Strip	0.003 x 0.1
middle	0.025 x 0.025
back	0.05 x 0.025

$$\eta = -\ln\tan\left(\frac{\theta}{2}\right)$$



Coverage |η|<3.2

Good angular resolution : $\sigma(\Phi) \sim 10^{-3}$ rad

$\sigma(\eta) \sim 5.10^{-4}$ rad

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c_{tot} \qquad c_{tot} = c_L \oplus c_{LR} \leq 0.7$$

Detector Design

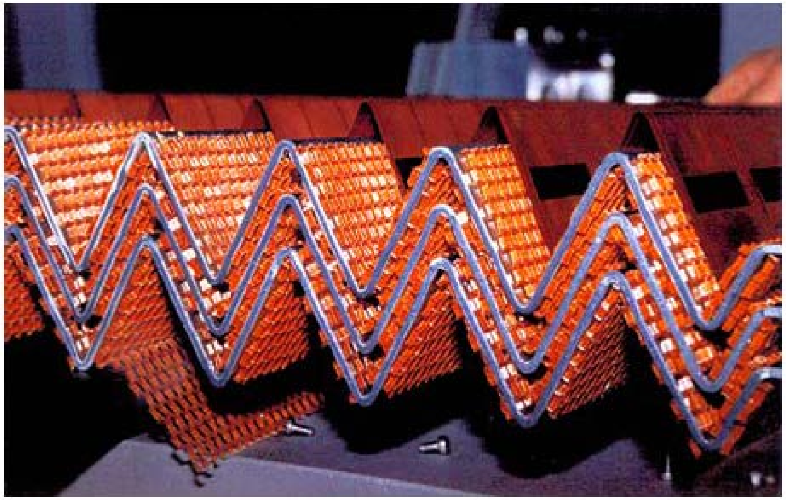
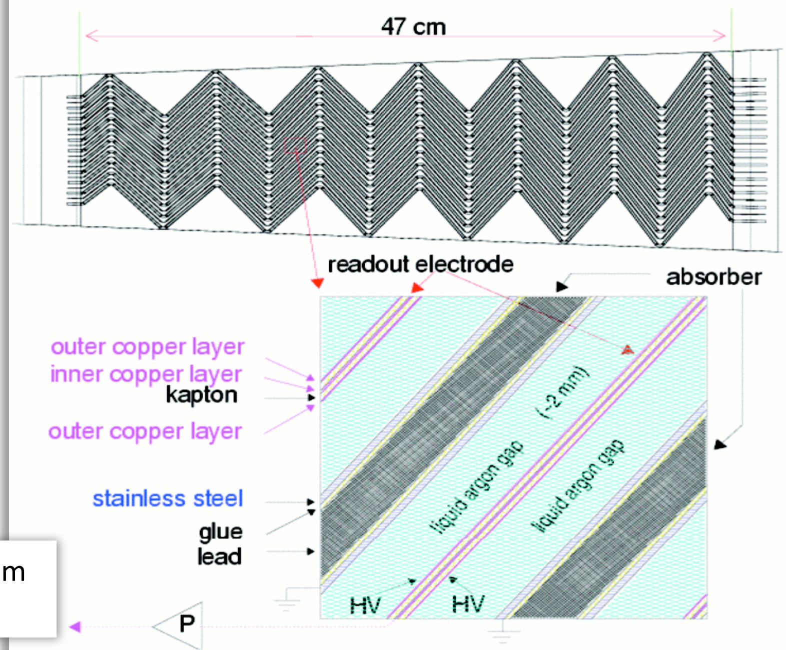


Fig. 3. The accordion structure of EMB calorimeter. Honeycomb spacers position the electrodes between the lead absorber plates.

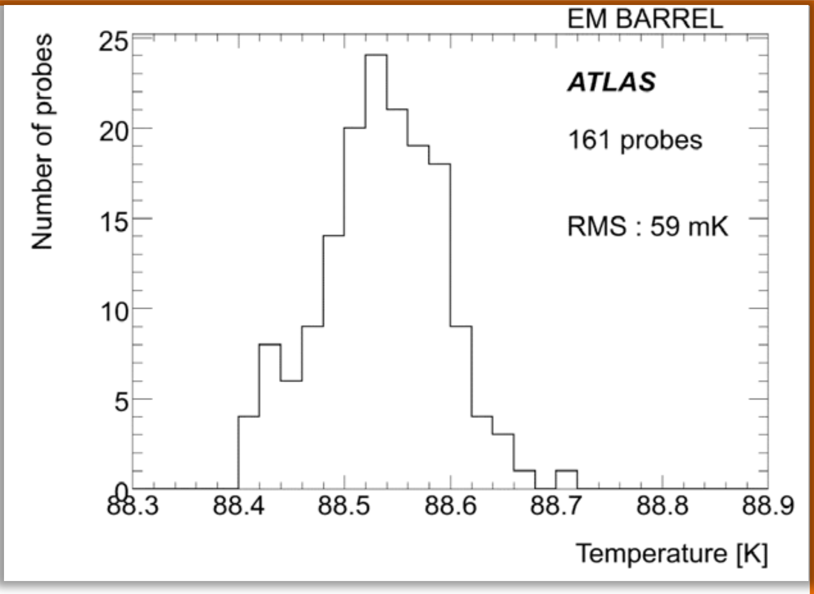
Lead ~ 2mm
LAr ~4mm

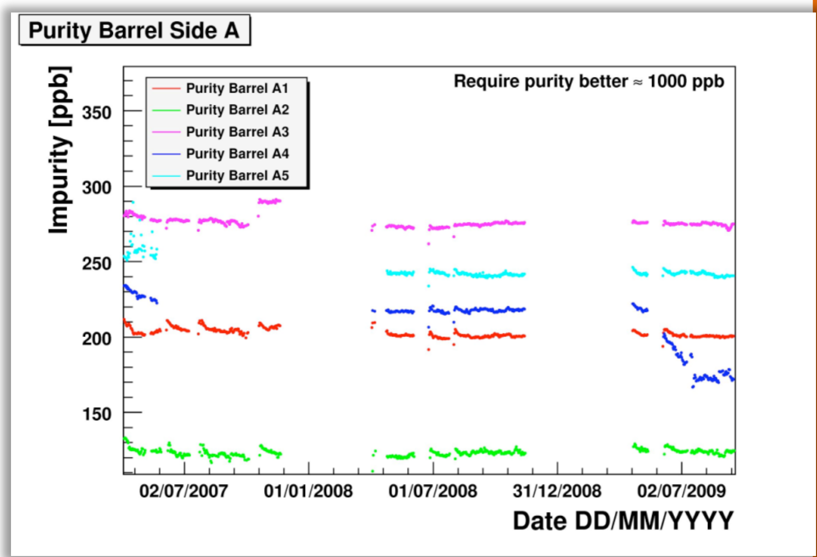


- ❑ Accordion geometry to design a hermetic detector and to minimize signal deterioration due to calo. cell capacitance and connections to preamplifier
- ❑ Longitudinal depth should be enough to contain the full shower, typically ~25X_0
  - ➢ Divided into three compartments/sampling plus a pre-sampler for measurement of energy loss upstream
- ❑ Lateral segmentation to fully contain the shower, 95% of the shower energy contained in a cylinder of radius = 2xMoliere radius ~9.5cm (layout with 2mm Lead and 4mm LAr)
  - ➢ Lateral segmentation 1/3 of the above to separate electron/photon from hadrons(~0.025 in the middle layer)

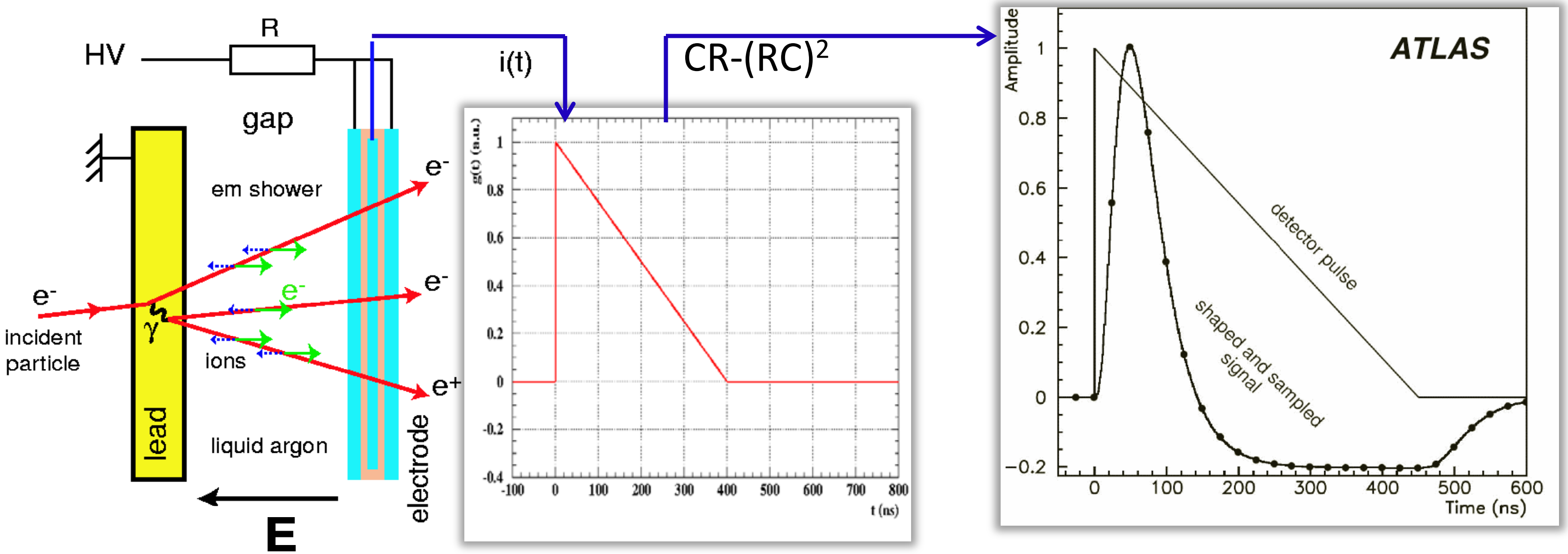
LAr Temperature and Purity

- LAr temperature stability
  - 59 mK RMS
- Excellent homogeneity and stability for LAr temperature
  - Each cryostat: ~ 88 K
  - Designed value of < 100 mK for stability
  - Signal sensitivity to temperature change: 2% / K
- LAr purity in each cryostat is well within required limits
- Measured signal reduced by electronegative impurities
- Requirement: < 1000 ppb O2 equivalent
- Measured with purity monitors:
  - Barrel ~ 200 ppb, EndCap ~ 140 ppb
  - Impurity level in LAr is in the range of 200±100 ppb
- Temperature stability and purity within limits
  - Negligible impact on constant term of energy resolution



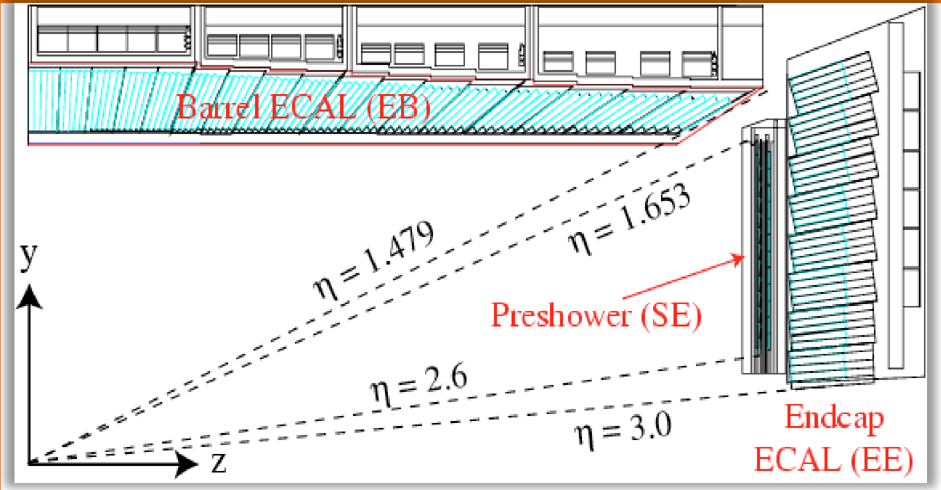


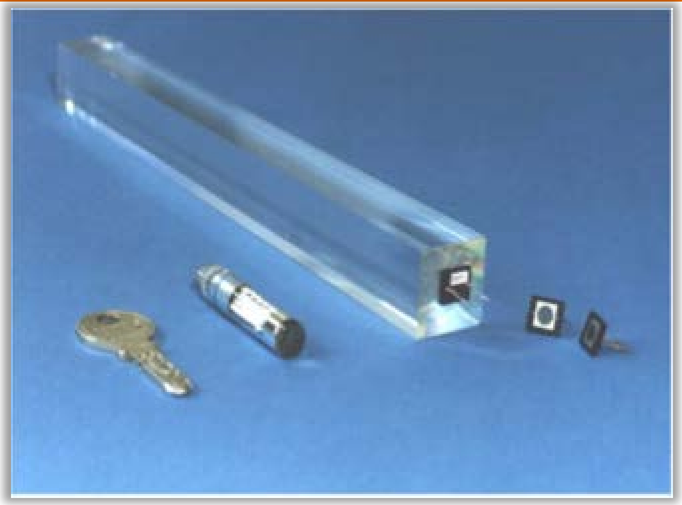
LAr Pulse Shaping

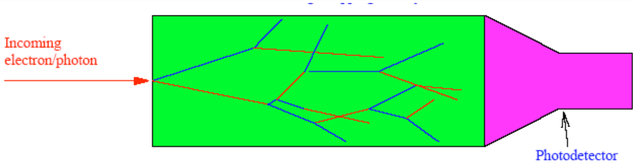


- Slow signal collection in LAr via ionization as compared to LHC bunch crossing of 25ns
  - Drift time of electrons in ~2mm gap is 400ns
- Solve the problem by shaping the triangular current signal with preamplifier-shaper system which has a bipolar shape
  - Shaped signal sampled at 40MHz
- Energy deposited can be measured from the amplitude(current) of the measured pulse

CMS Electromagnetic Calorimeter







- Homogeneous calorimeter
- One of the CMS EM barrel calorimeter PbWO4 crystals (230x22x22 mm^3)
- Read by APD (Avalanche PhotoDiodes)

ATLAS and CMS Electromagnetic Calo. Comparison

	Atlas			CMS	
Technology	Lead/LAr accordion			PbWO4 scintillating crystals	
	Sampling Calorimeter			Homogenous Calorimeter	
Radiation hardness	Radiation resistant			Radiation damage, stability~0.2%	
	Barrel		**Endcaps**	**Barrel**	**Endcaps**
η coverage	0-1.475		1.4-3.2	0-1.48	1.48-3
channels	110208		63744	61200	14648
Granularity	longitudinal segmentation			no longitudinal segmentation	
	$\Delta\eta x \Delta\Phi$			$\Delta\eta x \Delta\Phi$	
pre-sampler	0.025x0.1		0.025x0.1		
Strips	0.003x0.1		0.003-0.006x0.1		Pb/Si preshower
Main sampling	0.025x0.025		0.025x0.025	0.017x0.017	0.018x0.003 to 0.088x0.015
Back	0.05x0.025		0.05x0.025		
Depth					
pre-sampler	10 mm		2x2mm	-	-
Strips/Si-preshower	~4.3 Xo		~4.0 Xo	-	~3 Xo
Main sampling	~16 Xo		~20 Xo	26 Xo	25 Xo
Back	~2 Xo		~2 Xo	-	-
Design resolution					
Stochastic Term	10%		10-12%	3%	5.50%
Local constant term	0.20%		0.35%	0.50%	0.50%
Noise per cluster(MeV)	250		250	200	550

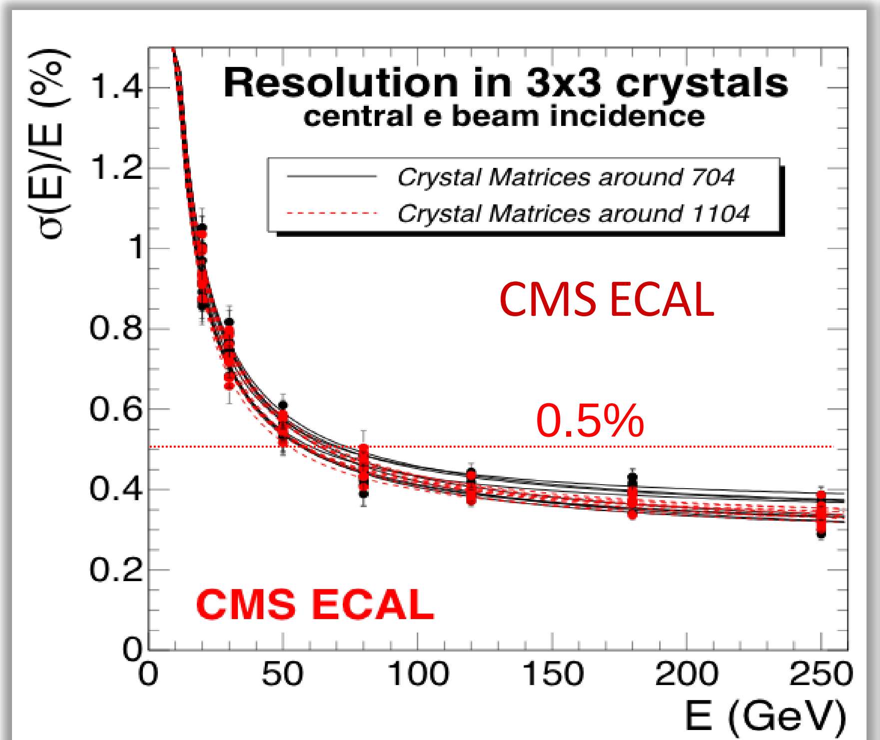
Design resolution(Barrel)

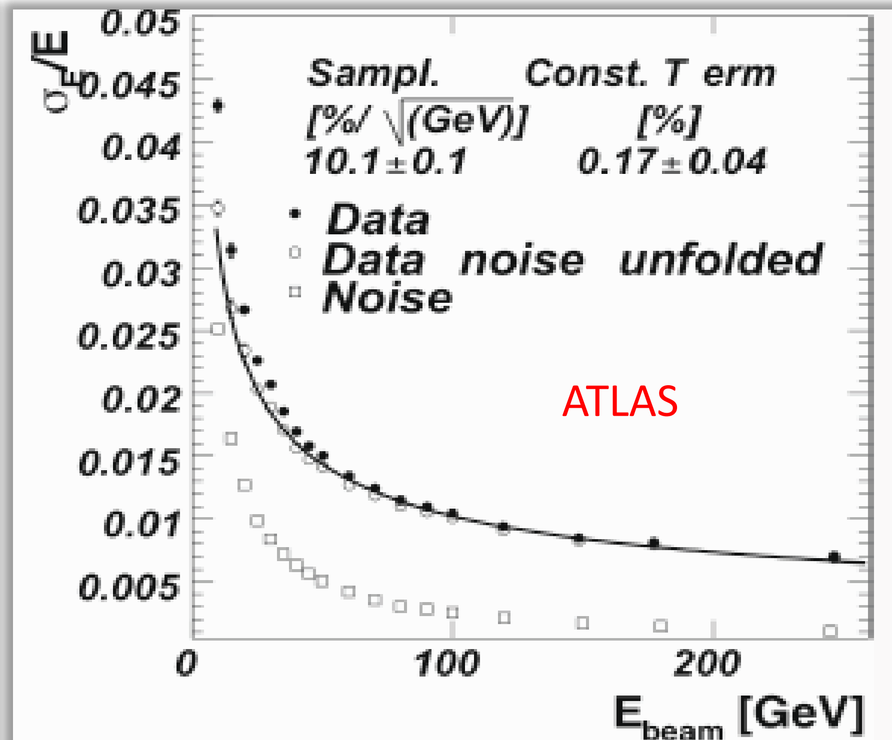
$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{170MeV}{E} \oplus 0.7\%$$

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

CMS gain in energy resolution is compensated by ATLAS gain in pointing resolution, comparable sensitivity for $H \rightarrow \gamma\gamma$

ATLAS and CMS Test beam performance



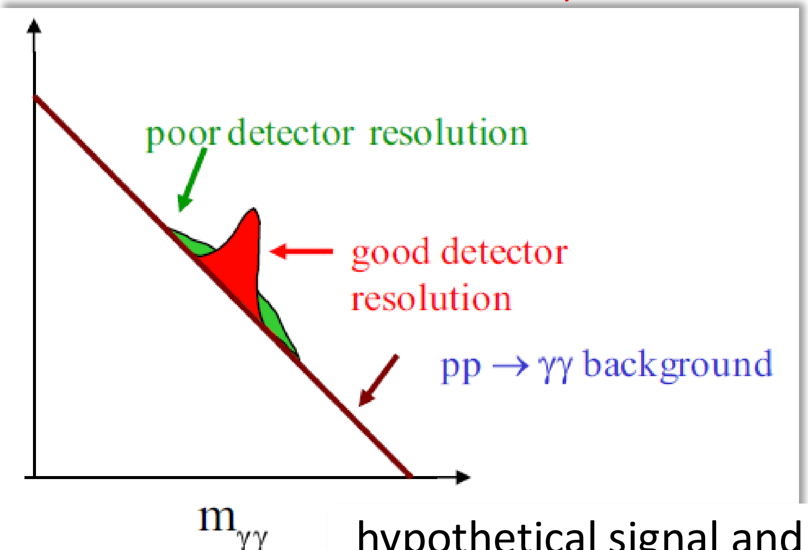


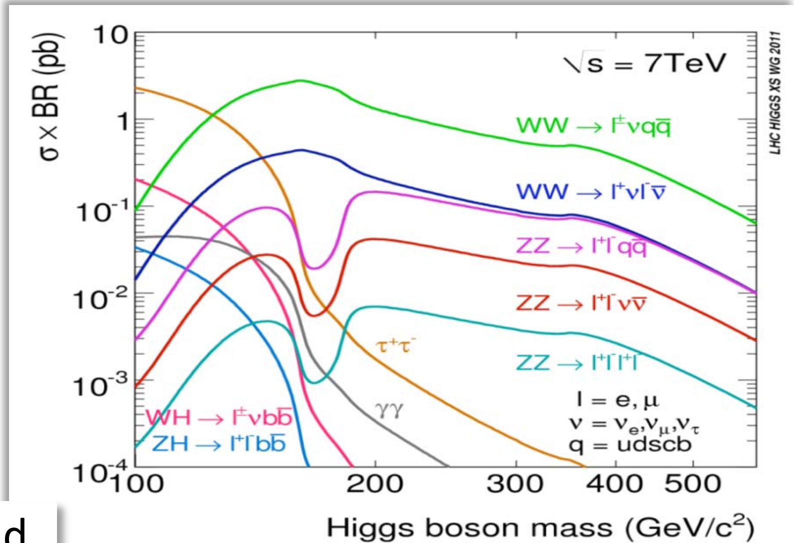
ATLAS and CMS: different technology and design, complementary performance

ATLAS Electromagnetic Calorimeter Calibration

Motivation for calibration

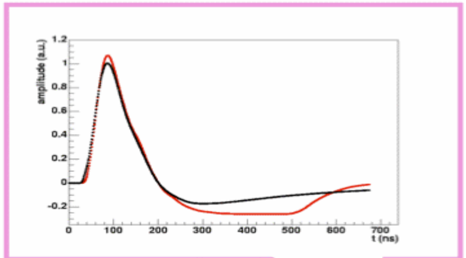
- H→γγ and H→4e are the most promising channels for low mass Higgs
  - Need good mass resolution
  - Powerful γ/jet separation
  - Robustness against pileup
  - Good understanding of the detector
- Stringent requirement on the performance of EM Calorimeter are imposed by H→γγ search above the huge γγ continuum
  - need γγ mass resolution of ~1% , hence better energy and angle resolution
  - response uniformity ≤ 0.7% over |η| < 2.4
    - Could be achieved by in-situ measurement from Z, W and J/ψ(see later)





hypothetical signal and background

Energy Reconstruction



ADC to DAC (Ramps)

Pulse Samples

$$E_{\text{cell}} = F_{\mu\text{A}\rightarrow\text{MeV}} \cdot F_{DAC\rightarrow\mu\text{A}} \cdot \frac{1}{\frac{\text{M}_{\text{phys}}}{\text{M}_{\text{cali}}}} \sum_{i=1}^{M_{\text{ramps}}} R_i \left[\sum_{j=1}^{N_{\text{samples}}} a_j \left(s_j - p \right) \right]^i$$

Cell energy

Sampling fraction

Calibration board

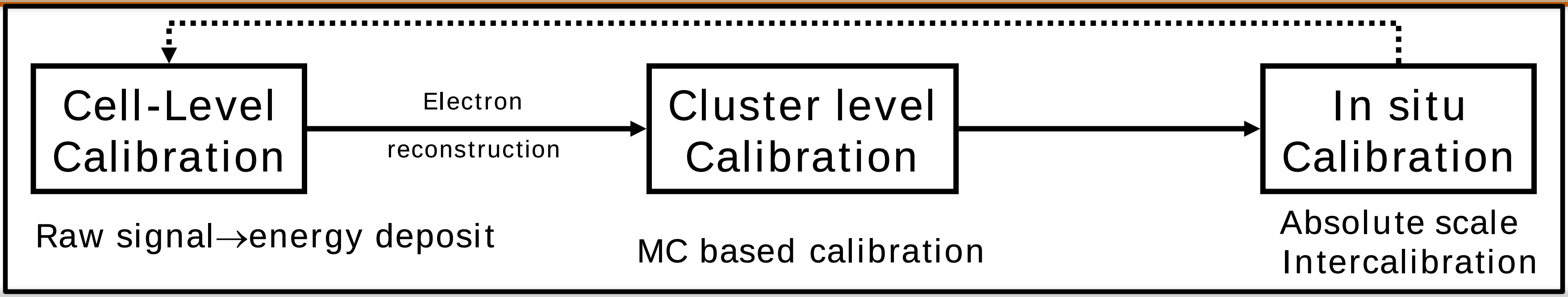
Optimal Filtering Coefficients

Pedestals

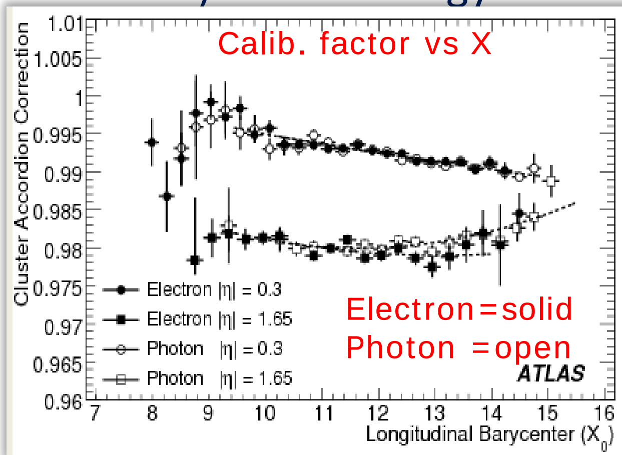
The above formula describe the LAr electronic calibration chain (from the signal ADC samples to the raw energy in the cell. Note that this version of the formula uses the general M_{ramps}-order polynomial fit of the ramps. Actually we just use a linear fit (electronic is very linear, and additionally we only want to apply a linear gain in the DSP in order to be able to undo it offline, and apply a more refined calibration). In this case, the formula is simply:

$$E_{\text{cell}} = F_{\mu\text{A}\rightarrow\text{MeV}} \cdot F_{DAC\rightarrow\mu\text{A}} \cdot \frac{1}{\frac{\text{M}_{\text{phys}}}{\text{M}_{\text{cali}}}} \cdot R \left[\sum_{j=1}^{N_{\text{samples}}} a_j \left(s_j - p \right) \right]$$

Cluster Calibration

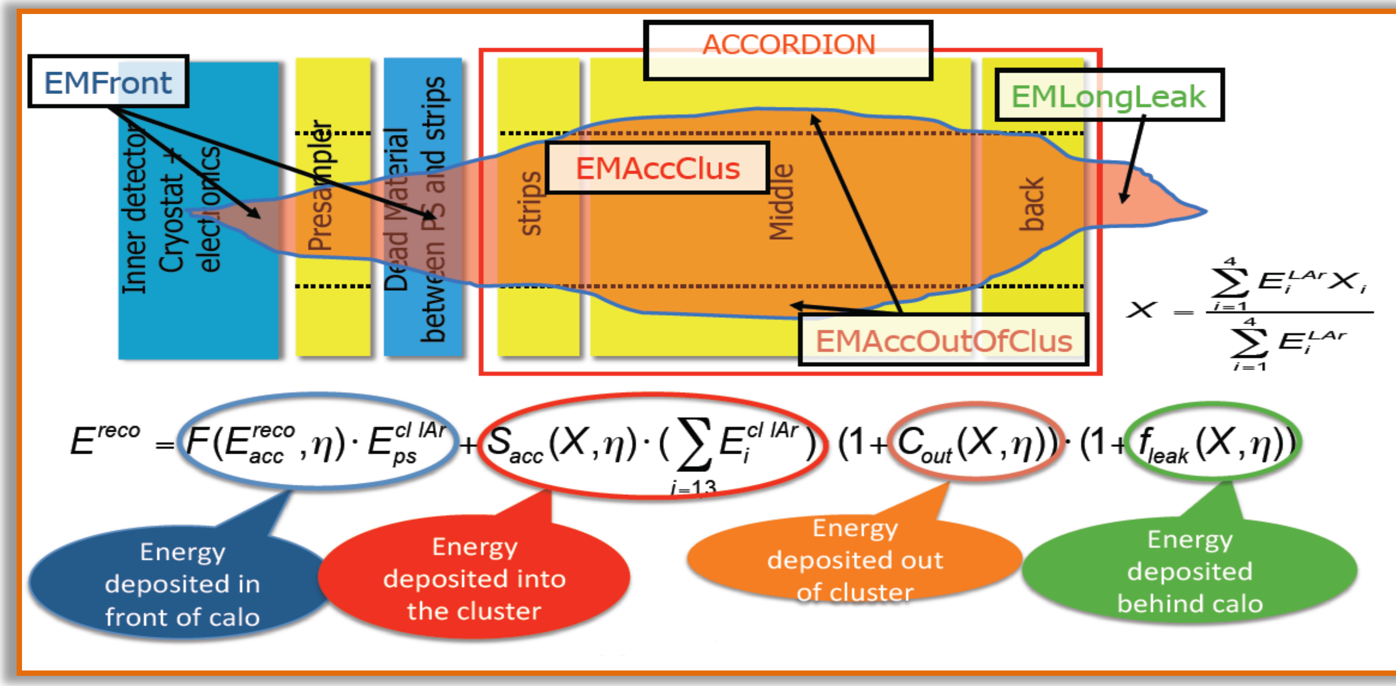


- Combine energy deposits in each layer and the presampler
- Compute corrections by using special simulations (Calibration Hits) where energy deposited in all material (active + inactive) is recorded
- Energy depositions in the inactive material can be correlated with the measurable quantities
- Corrections are derived for electrons and photons separately



X = Shower depth
X_i = long. depth of layer "i"
E_i = energy deposit in layer "i"
$S_{acc}(X,\eta)$ = calib. factor

Cluster Calibration

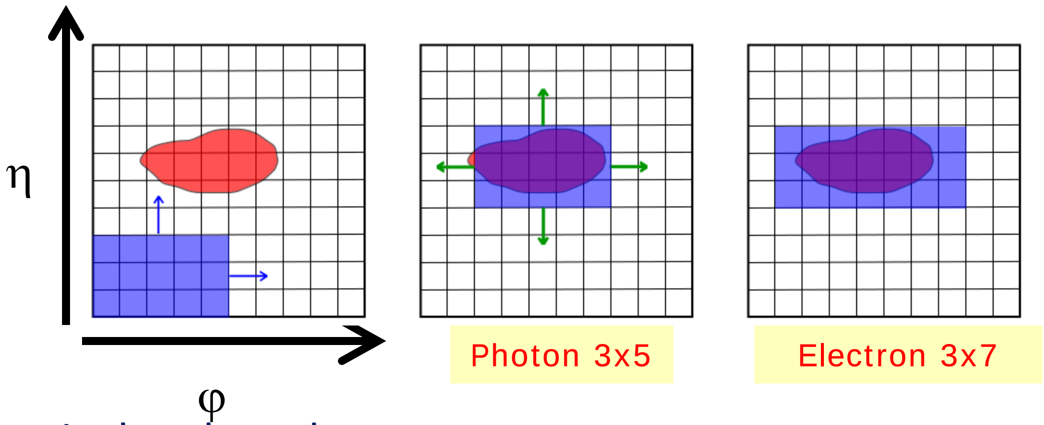


Electromagnetic objects in ATLAS

- In ATLAS an electron or a photon candidate is defined as a cluster of cells in the calorimeters representing the energy deposit to which we can associate tracks reconstructed in the inner detector

- Clustering algorithms group cells together and sum the total deposited energy within each cluster

- Sliding-Window algorithm is used to reconstruct the energy deposits



- Apply cluster calibrations

- The identification of such objects is then based on :
  - The shower shape in the calorimeter
  - Track quality (number of hits, direction wrt the cluster,...)
  - Transition radiation (TRT “high threshold hits”)
  - E/p

In-situ Calibration

- Determination of energy scales and resolution is crucial for precision measurements and searches

- The methods and algorithms that I developed for the calibration of EM calorimeter are officially used by ATLAS as a baseline
  - Provide scales and resolutions and the required infrastructure to the whole collaboration as well as lead a group working on these issues

- The purpose of In-situ calibration is to establish
  - Absolute EM scale to an accuracy of ~0.1%
  - Inter-calibrate different regions of Calorimeter to establish long-range constant term to be ≤ 0.5%

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

$$c_{tot} = c_L \oplus c_{LR} \leq 0.7$$

- Energy scale was initially measured in 2004 test beam, then tested with $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ in the beginning of data taking

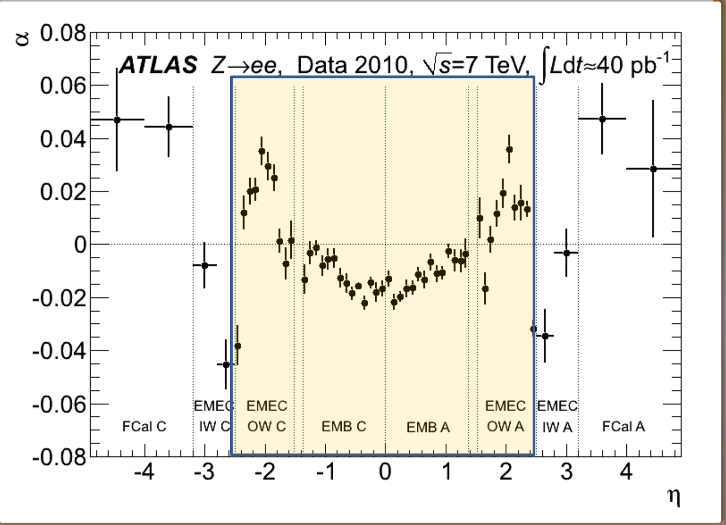
- To measure Energy scale with a better accuracy, the precise knowledge of the well known Z lineshape has to be used

The Method

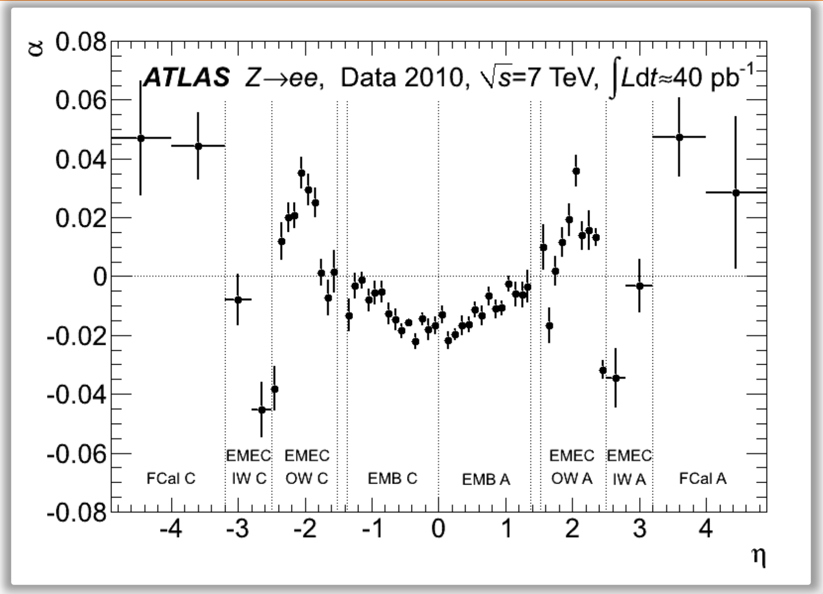
- The energy of electron in zone "i" is parameterized as

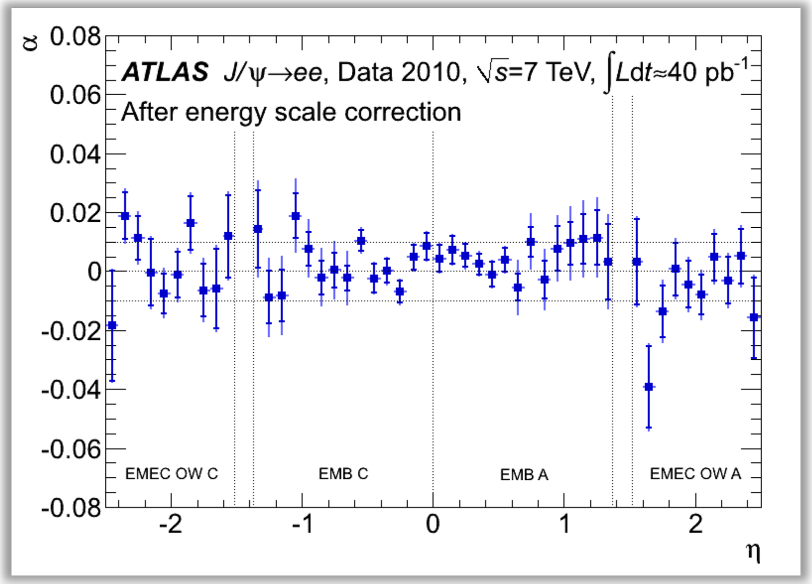
$$E_i^{reco} = E_i^{true}(1+\alpha_i)$$

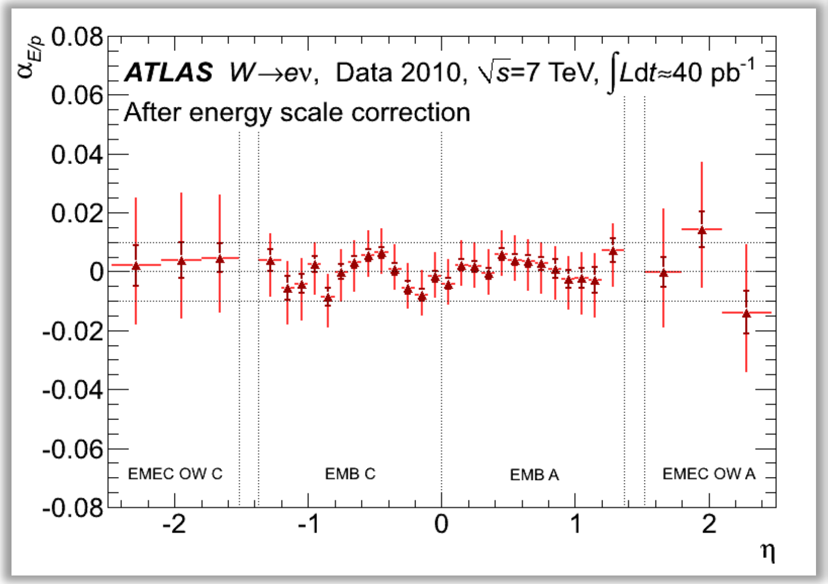
  - where zone is a slice in $\Delta\eta\times\Delta\phi$=0.2×0.4
- Where α's are obtained from unbinned likelihood fit by constraining the measured di-electron invariant mass to the Z boson line shape
- Linearity of response at low energy is cross checked by using electrons from $J/\psi\rightarrow ee$
  - Also use E/p for electron from $W\rightarrow e\nu$ as a cross check, need better knowledge of momentum scale from Inner Tracker
- Three different algorithms optimized for performance, computing time etc
- Performance based on 2010 data described in the egamma paper, Eur. Phys. J. C(In Press), arXiv:1110.3174
- CONF Note based on full 2011 data is under review



Energy Scales from Z→ee, J/ψ→ee and W→eν

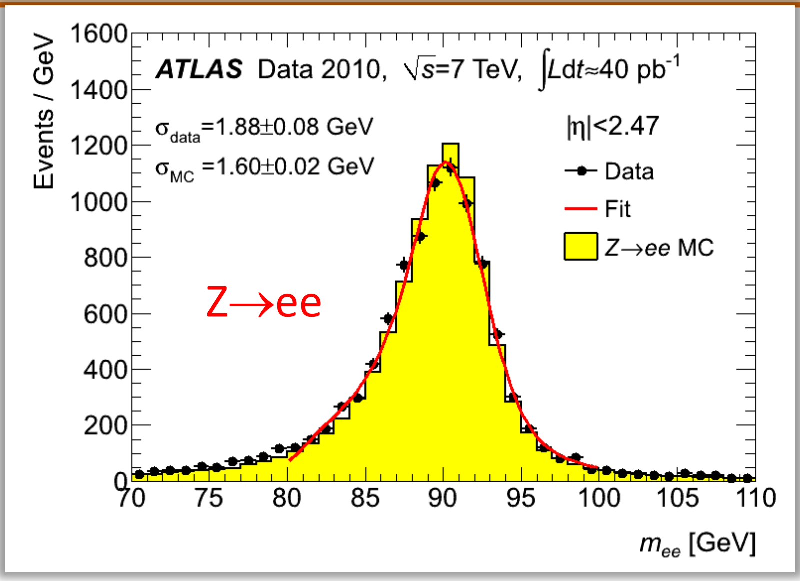


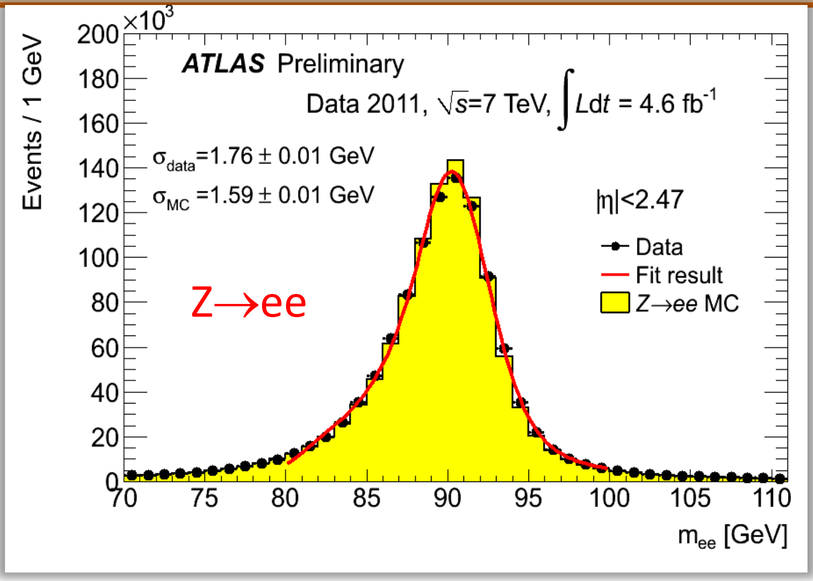


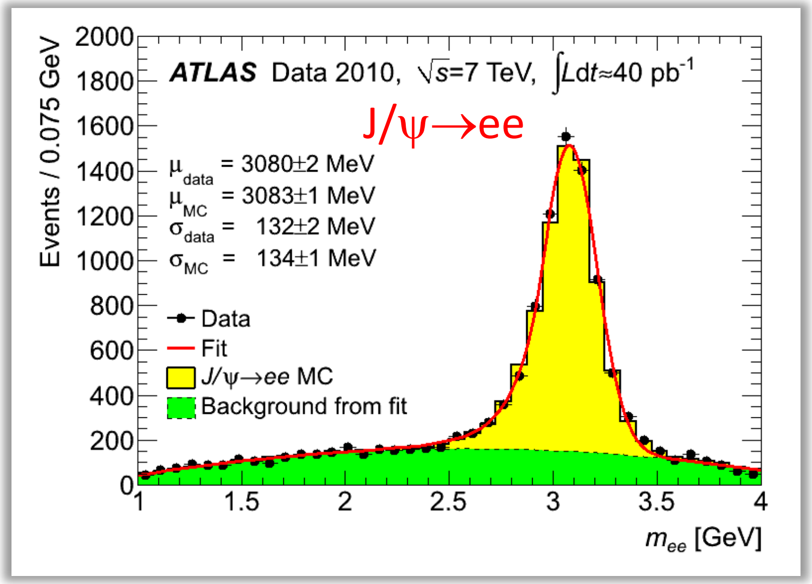


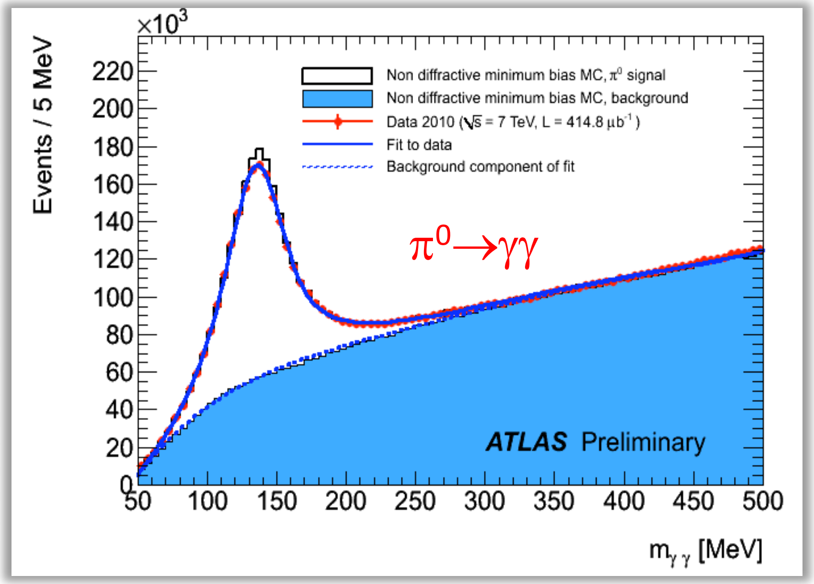
- The J/ψ and W plot were made after the Z corrections were applied
- Inner error bars are statistical only, while outer are total uncertainty
- J/ψ plot shows good linearity of EM Calo. and modeling of material in front of Calorimeter
- Please note the same plot for ~5fb^{-1} are under review
- Statistics is no more an issue, more than a million good Z's after selection
- Calibration at low energy with J/ψ is very important for H→4l and SUSY searches

Performance of the Detector



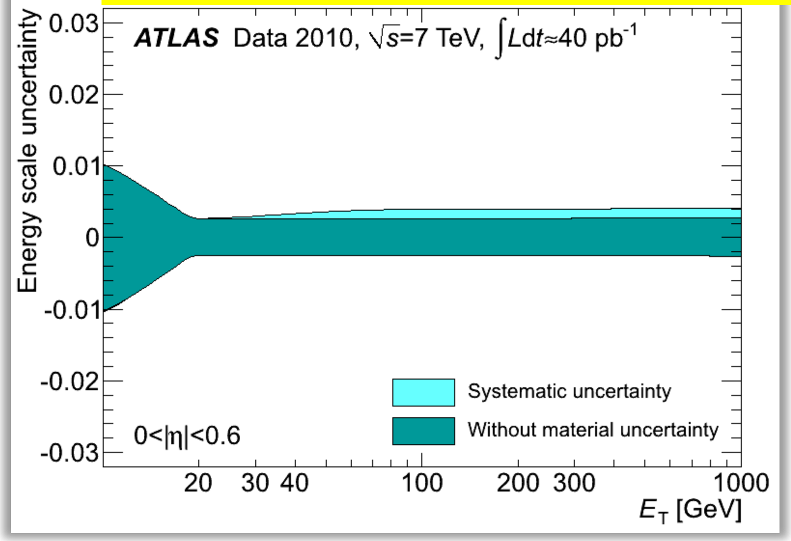


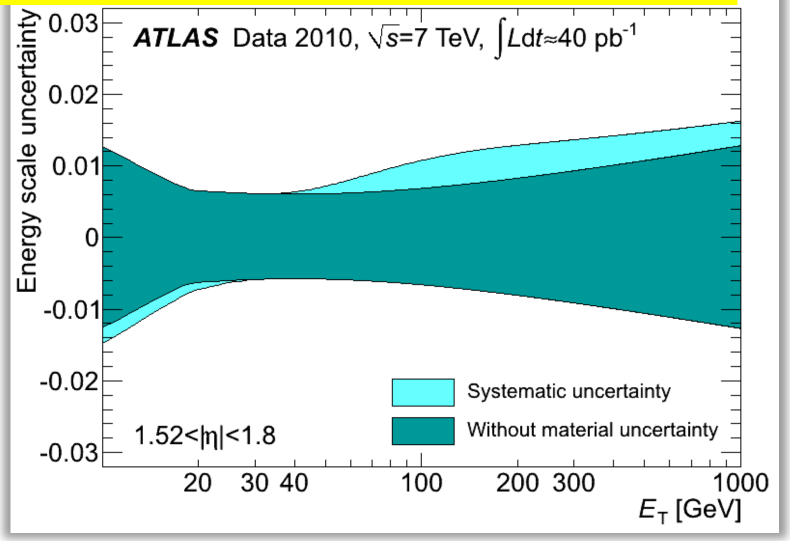




Energy Scale Systematics

Important to understand systematics, have strong impact on physics searches

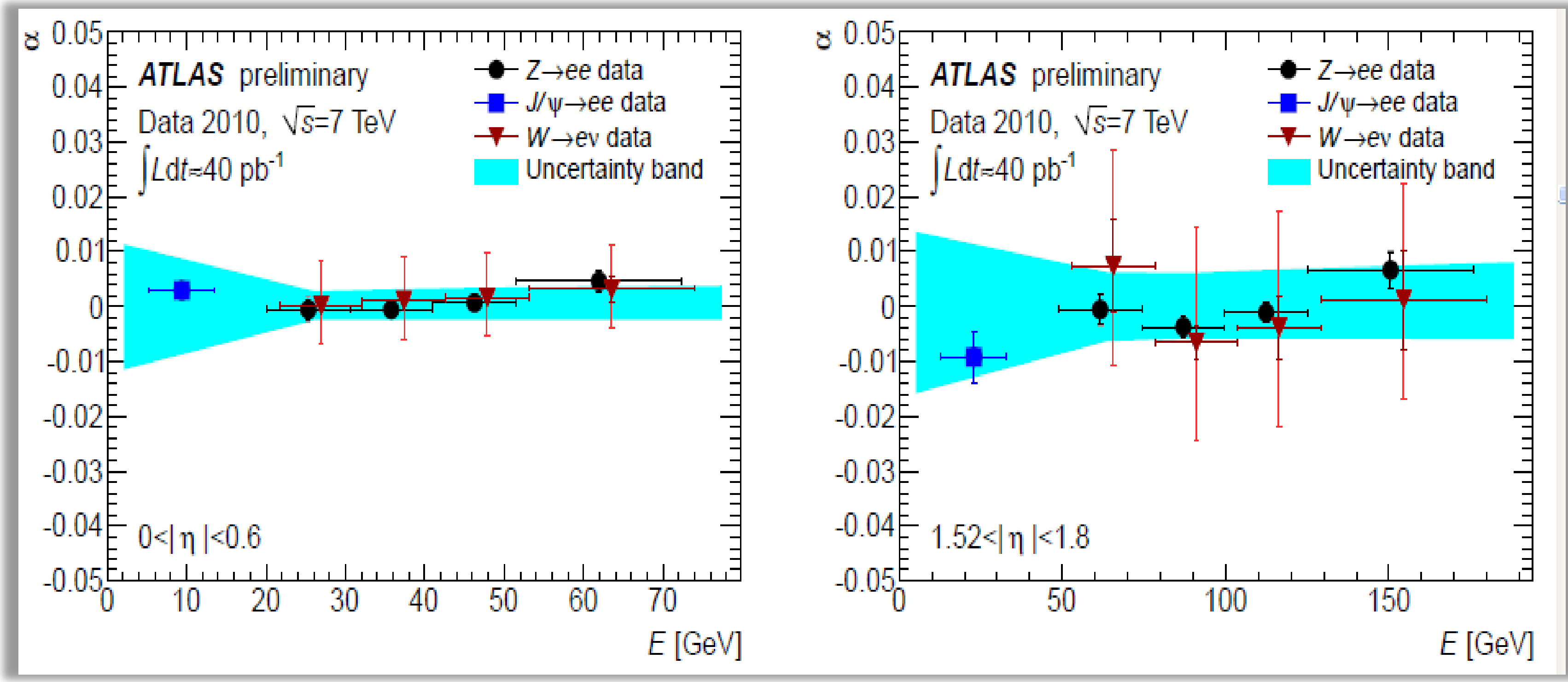




Systematic uncertainties (in %) on the electron energy scale in different detector regions.

	Barrel	Endcap	Forward
Additional material	E_T- and η-dependent, from -2% to $+1.2\%$		
Low-E_T region	E_T-dependent, from 1% at 10 GeV to 0% at 20 GeV		
Presampler energy scale	E_T- and η-dependent, $0-1.4\%$		
Strip layer energy scale	0.1	0.1	0.1
Electronic non-linearity	0.1	0.1	0.1
Object quality requirements	<0.1	<0.1	0.6–0.8
Background and fit range	0.1	0.3	1.2
Pile-up	0.1	0.1	0.1
Bias of method	0.1	0.1–0.5	0.8–1.0

Linearity



- Linearity ~1% and within uncertainty bands

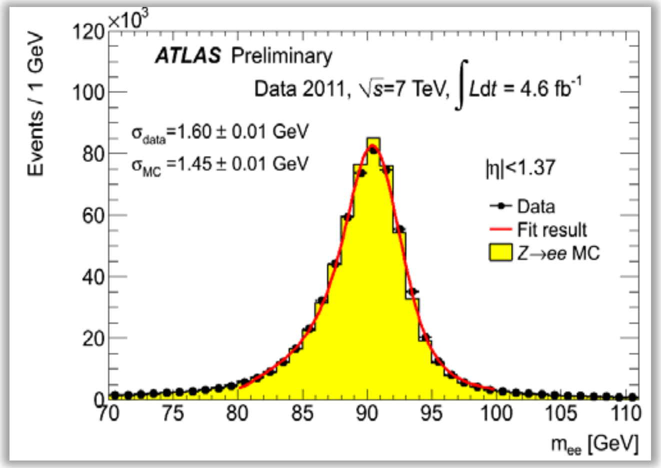
Resolution

- Any data/MC differences can be attributed to the constant term (C) because the MC reproduces reasonably the invariant mass distribution for $J/\psi \rightarrow ee$ events for central electrons
  - For such a low energy the electron energy resolution is dominated by the sampling term
- An effective constant term is extracted by comparing Z mass resolution in data and MC by using the formula

$$C_{data} = \sqrt{2.\left(\left(\frac{\sigma_M^{data}}{M_Z}\right)^2 - \left(\frac{\sigma_M^{MC}}{M_Z}\right)^2\right) - C_{MC}^2}$$

- Resolution was obtained by fitting a convolution of Breit Wigner and Crystal ball
  - BW mean is fixed to the Z width and resolution is described by Crystal ball function

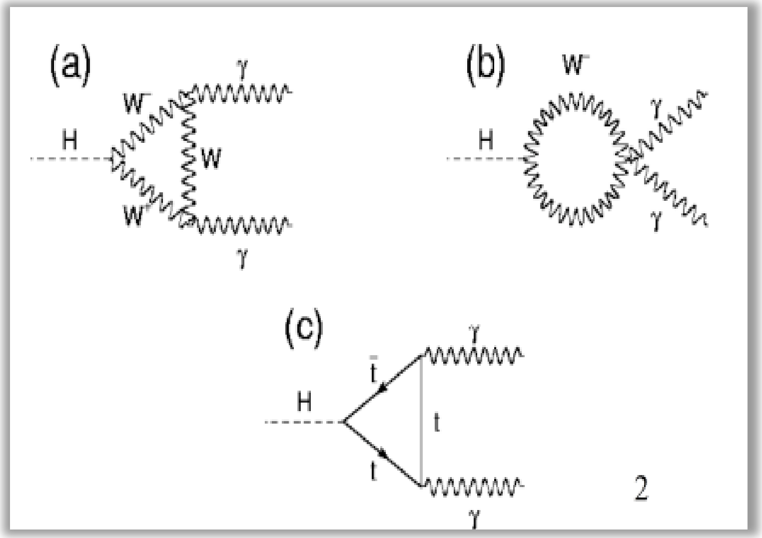
2010	constant term
Barrel	$1.2\ \% \pm 0.1\ \%\ \text{(stat)}\ ^{+0.5}_{-0.6}\ \%\ \text{(syst)}$
EMEC outer wheel	$1.8\ \% \pm 0.4\ \%\ \text{(stat)} \pm 0.4\ \%\ \text{(syst)}$
EMEC inner wheel	$3.3\ \% \pm 0.2\ \%\ \text{(stat)} \pm 1.1\ \%\ \text{(syst)}$
FCal	$2.5\ \% \pm 0.4\ \%\ \text{(stat)}\ ^{+1.0}_{-1.5}\ \%\ \text{(syst)}$



Search for Higgs Boson

Search for $H \to \gamma\gamma$ in ATLAS

- The search for a Higgs boson in the $\gamma\gamma$ final state is looking for a small and narrow peak on a falling background continuum
- Higgs boson decay to $\gamma\gamma$ either through W/top loop
- Need very good $m_{\gamma\gamma}$ resolution, applied the corrections ($\pm$1%) and smearing that I derived using $Z \to ee$



- Selection:
  - $E_T(\gamma_1)$> 40GeV, $E_T(\gamma_2)$ > 25GeV
  - $|\eta|$< 1.37 or 1.52 < $|\eta|$ < 2.37,

  Isolation energy < 5 GeV , photon identification
- Main background:
  - irreducible $\gamma\gamma$(30 pb)
  - reducible γj (200 nb)
  - reducible jj (500 μb)
- Total background from fit to $m_{\gamma\gamma}$ spectrum
  - Simultaneous fit to all 9 categories
  - Exponential function, free slope and normalization
  - Background composition validated with control data

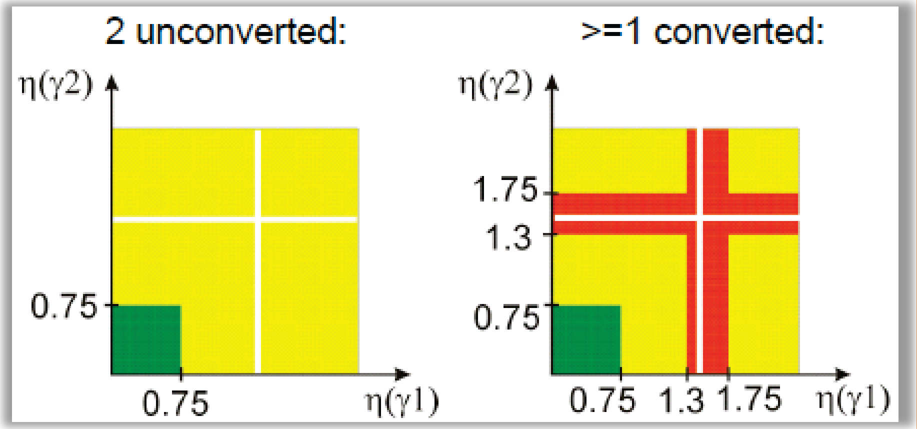
H→γγ Search Strategy

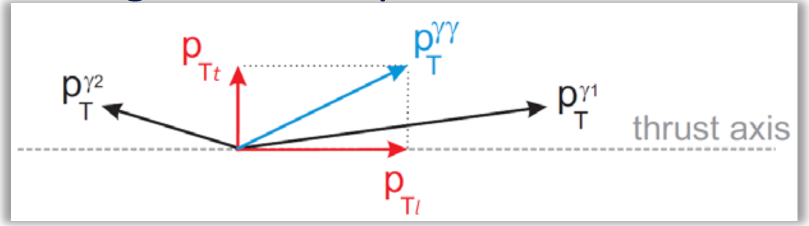
- To increase sensitivity events have been divided in 9 different categories with different $m_{\gamma\gamma}$ resolution and S/B

arXiv:1202.1414 (to PRL)

- Categorize events based on
  - Conversion status, Photon η and $p_T^{\gamma\gamma}$
- Both unconverted:
  - Central
  - Rest
- At least one converted:
  - Central
  - Transition
  - Rest
- Central and Rest further divided into two categories based on $p_T^{\gamma\gamma}$
- Signal events have larger pTt than the backgrounds, in particular the VBF and associated production modes

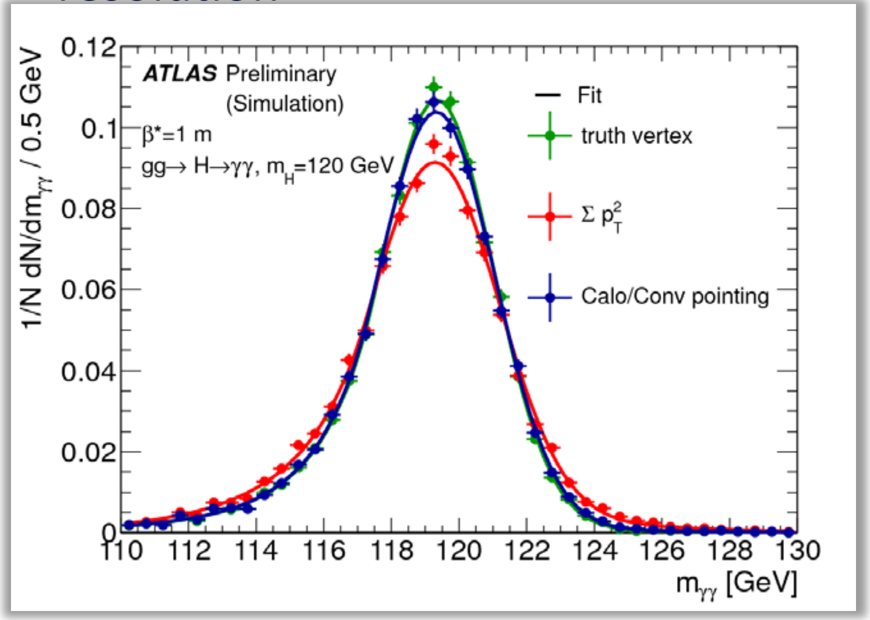
Resolution: Good, Medium, Poor

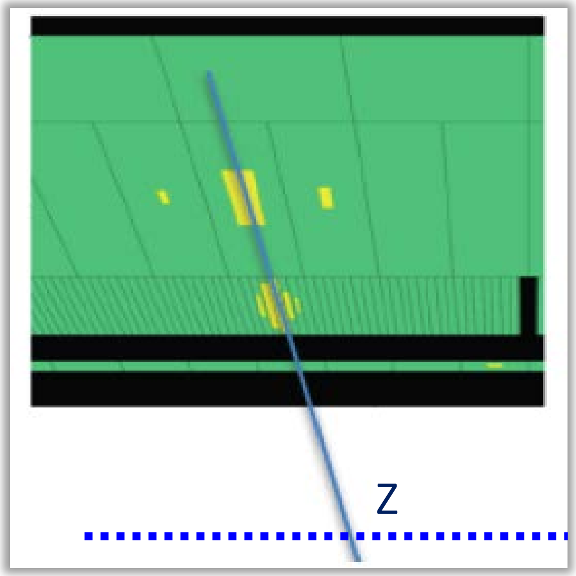




Mass Reconstruction

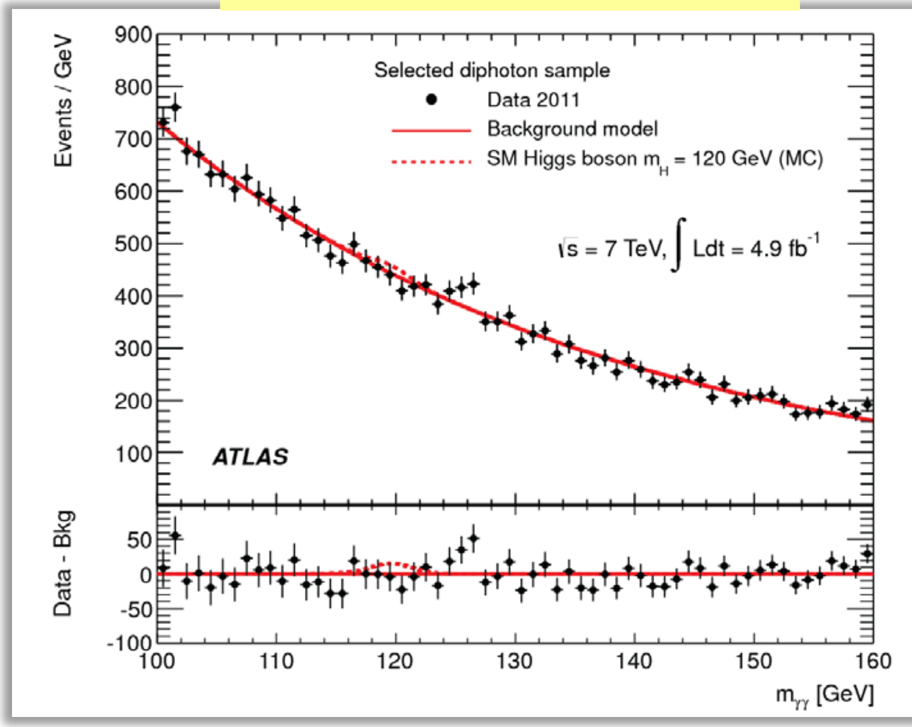
- Calorimeter pointing to deduce PV
  - Determine photon direction from 1st and 2nd calorimeter layer
  - Combine 1st layer with inner detector information if photon is converted
  - $\sigma(z)$ = 1.5 cm for unconverted photon
  - $\sigma(z)$ = 0.6 cm for converted photon
- Contribution of resulting angular resolution to mass resolution is negligible
- Uncertainty on mass resolution($\pm$14%) dominated by uncertainty on energy resolution





Diphoton mass after event selection

Summed over all categories

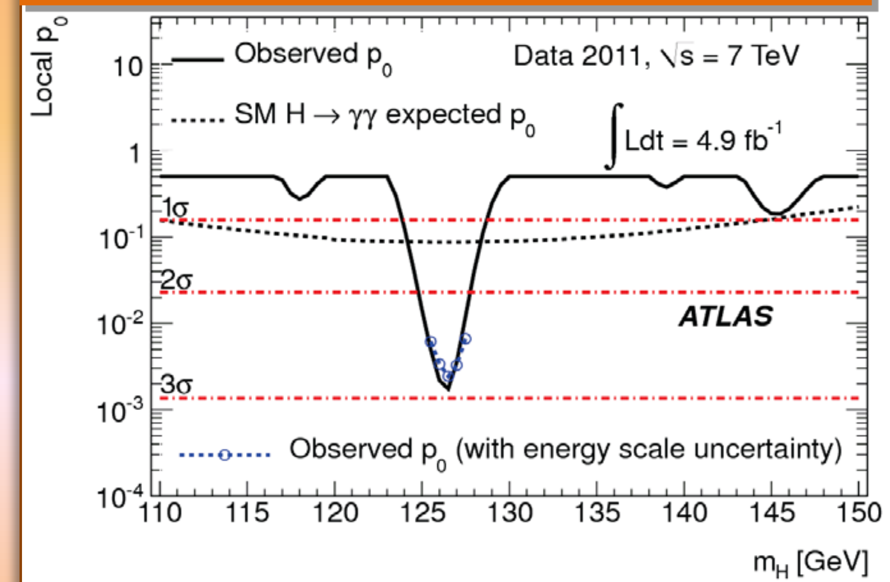


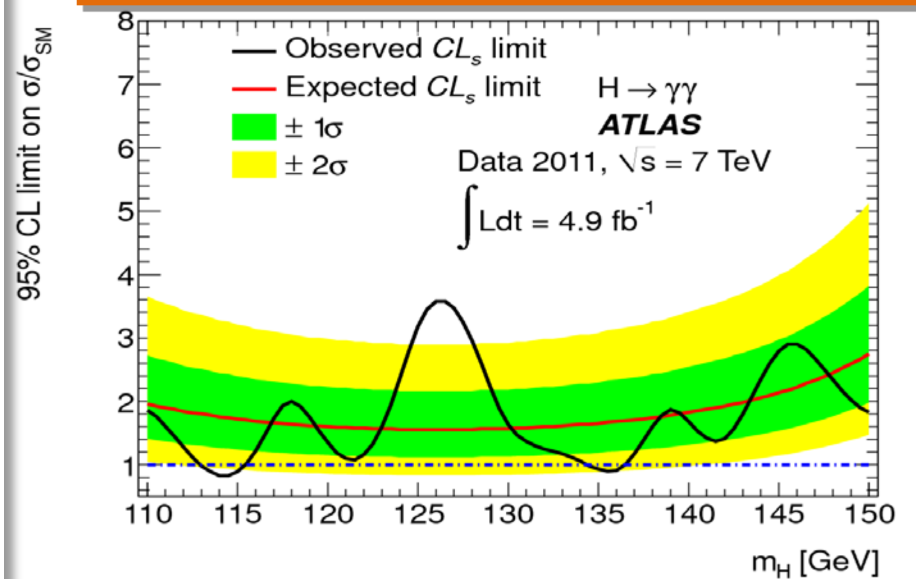
- 22489 events in total ($100<m_{\gamma\gamma}<160$GeV)
  - ~70% of them are true photon
  - A sidebands technique is used to estimate the number of γγ, γj and jj
  - Exponential fit to the background is shown in red

H→γγ Significance/Limit

- The largest excess is found at 126 GeV, with a local significance of 2.9σ (2.8σ with ESS)
- Considering the probability of such excess appearing anywhere in the mass range investigated (Look Elsewhere Effect), the significance would be 1.5σ

- Expected limit is around 1.6-2.7 times the SM cross section
- Observed limit lies between 0.84 and 3.6 times the SM cross section
- A SM Higgs boson is excluded at 95% CL in the mass ranges of 113 - 115 GeV and 134.5 - 136 GeV





Summary

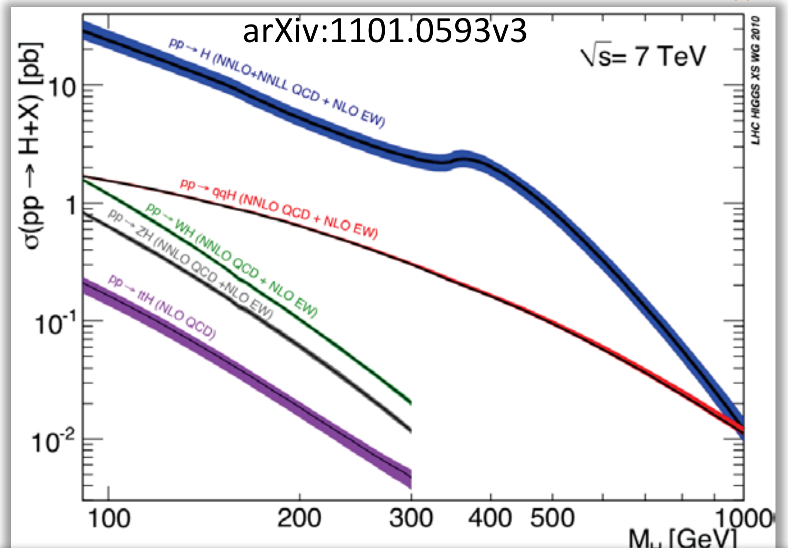
- ATLAS EM Calorimeter is performing well

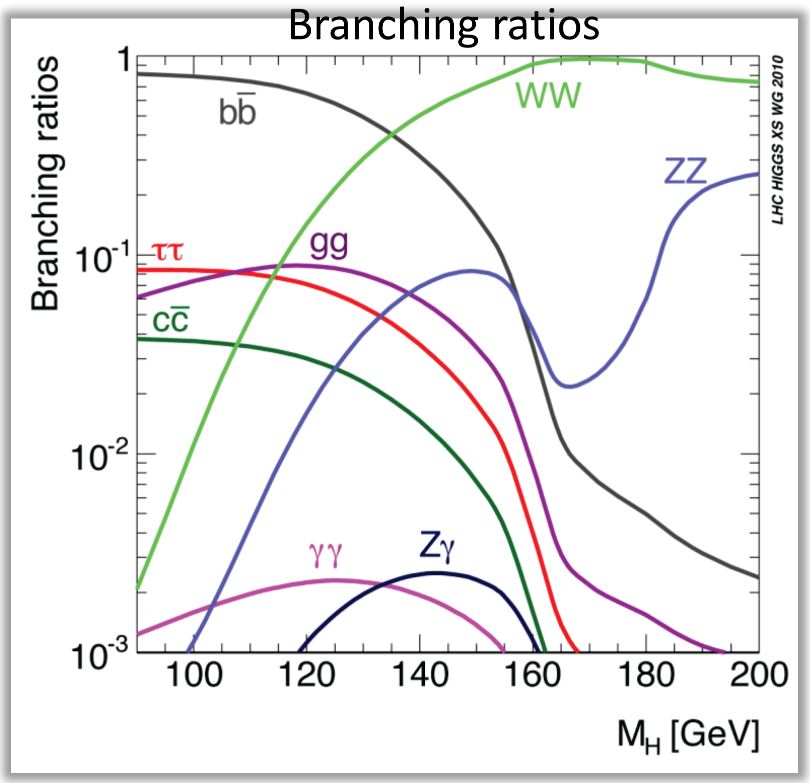
- Well advance in-situ calibration with electrons from $Z \rightarrow ee$, $J/\psi \rightarrow ee$ and $W \rightarrow e\nu$
  - Design resolution within reach
  - Energy scale within ~1% for central calorimeter
  - Linearity ~1% for central calorimeter
  - Calibration is very important for Higgs, BSM and all searches where scales and resolutions are important

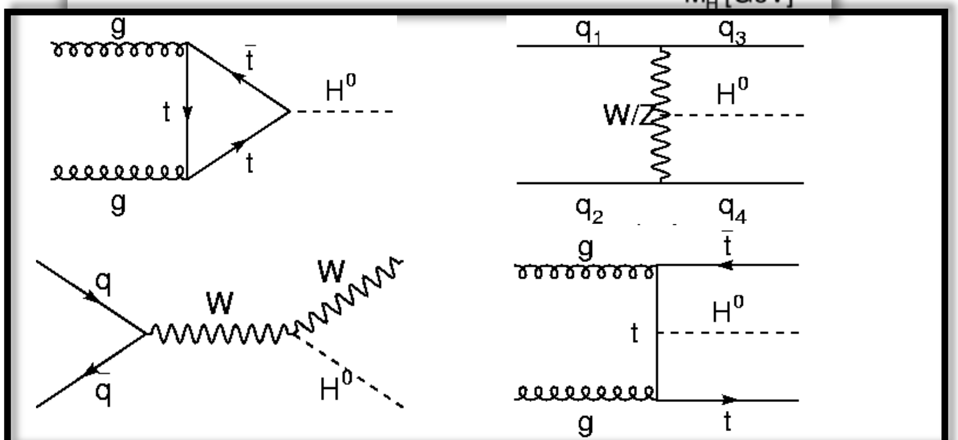
- Novel idea's to improve resolution(especially for hadronic showers) in future colliders
  - Especially in less busy environments like ILC and CLIC
  - R&D for future calorimeter well advance
- Search for $H \rightarrow \gamma\gamma$ channel which heavily rely on the results of insitu-calibration reveals a small excess of 1.5σ around 126 GeV
  - Statistical significance not large enough (yet) to draw definite conclusions
- For more higgs results and my my work on SUSY searches, please take a look at backup slides

Higgs Production and Decays at the LHC

- The dominant Higgs production at the LHC is via gluon fusion
  - The fraction of gluon fusion, VBF, WH, ZH and ttH production are 87%, 7%, 3%, 2% and 1% at the LHC (7 TeV) for M_H = 120GeV



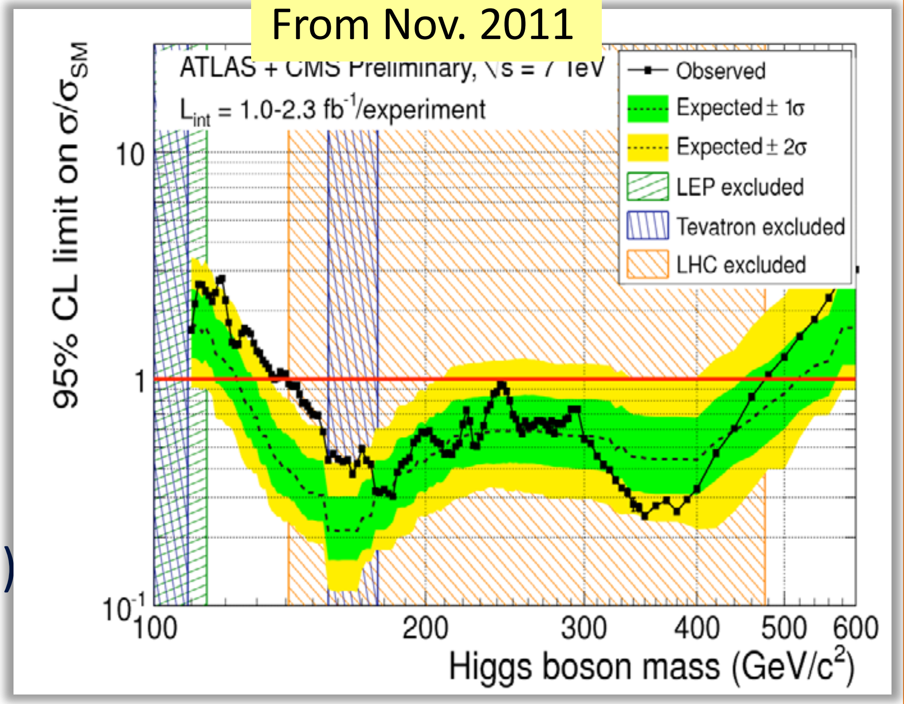




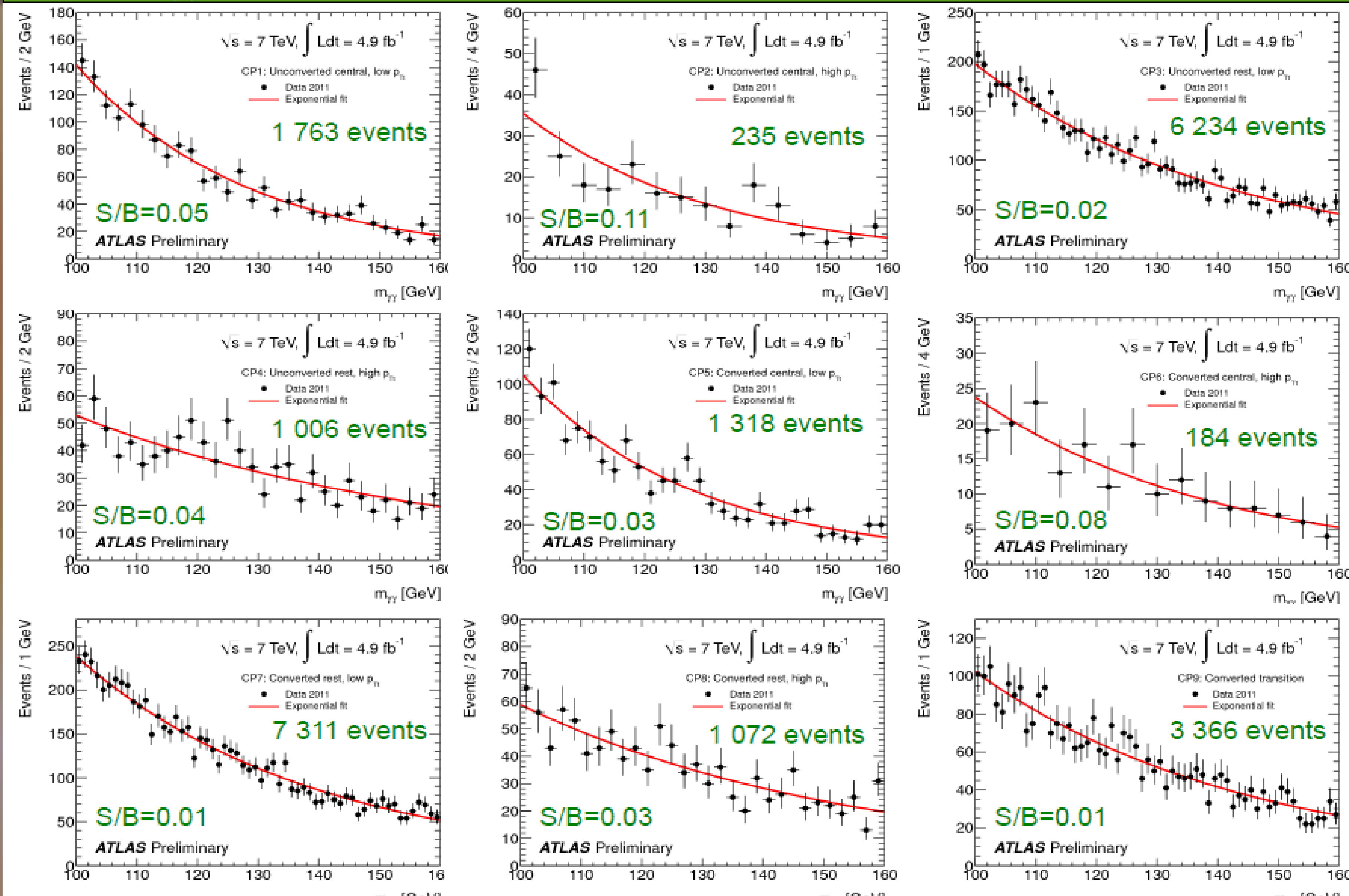
Search for Higgs Boson

- Search for Higgs boson is one of the most important goal of the LHC
- A wide range of masses(141-476 GeV) has been excluded by previous searches (as of Nov. 2011)
- The two most sensitive channels in the low mass Higgs region, namely
  - $H \rightarrow \gamma\gamma$ (will cover only this one)
  - And $H \rightarrow 4l$ (where $l = e$ or μ)
  - Can reconstruct invariant mass
- Profile likelihood ratio is used to calculate p0-value/significance of excess (Eur.Phys.J.C71:1554,2011)
- Exclusion limits on signal strength $\mu = (\sigma/\sigma_{SM})$ are set at a 95% confidence level using the CLs method (J. Phys. G 28 (2002) 2693-2704)

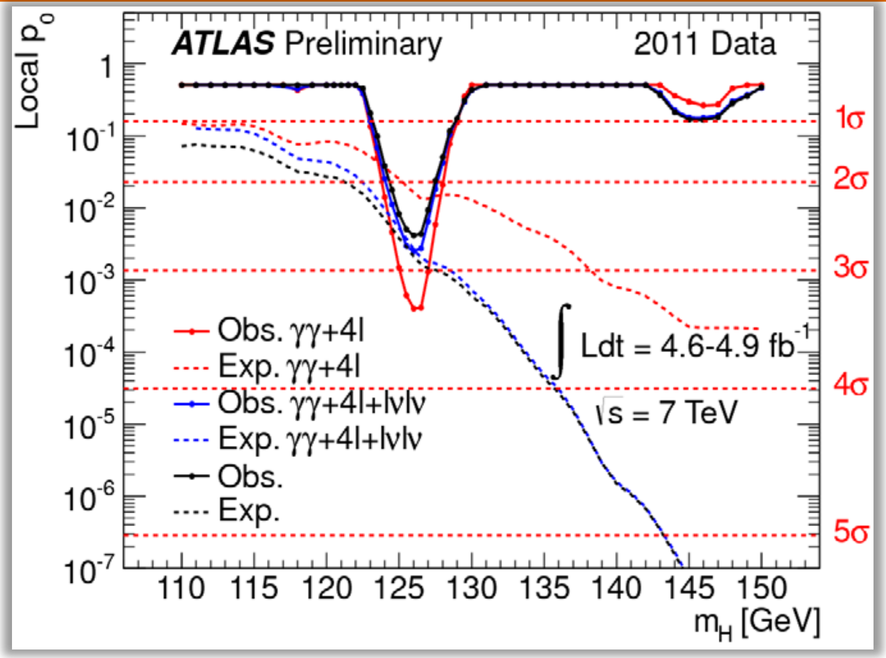
From Nov. 2011

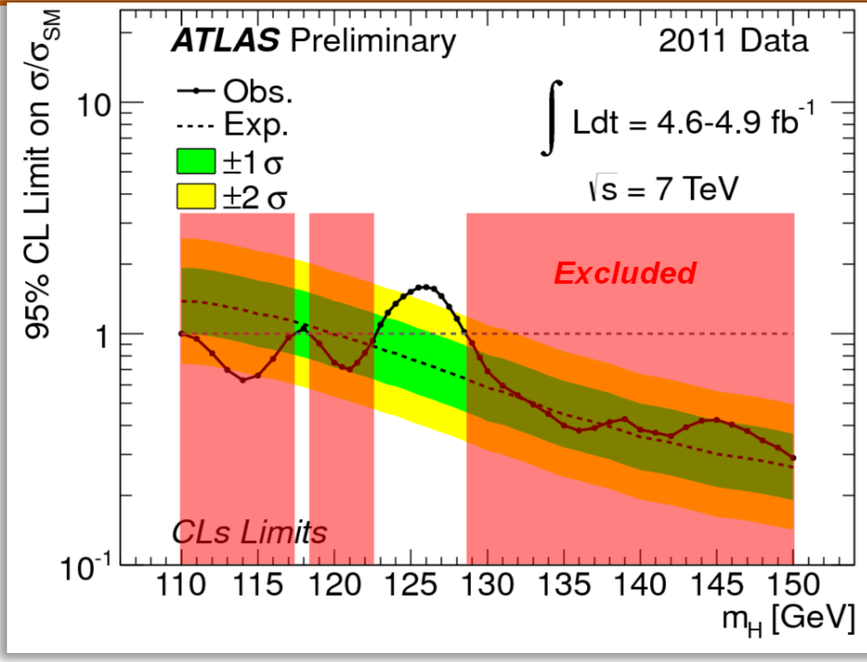


Higgs H→γγ Categories



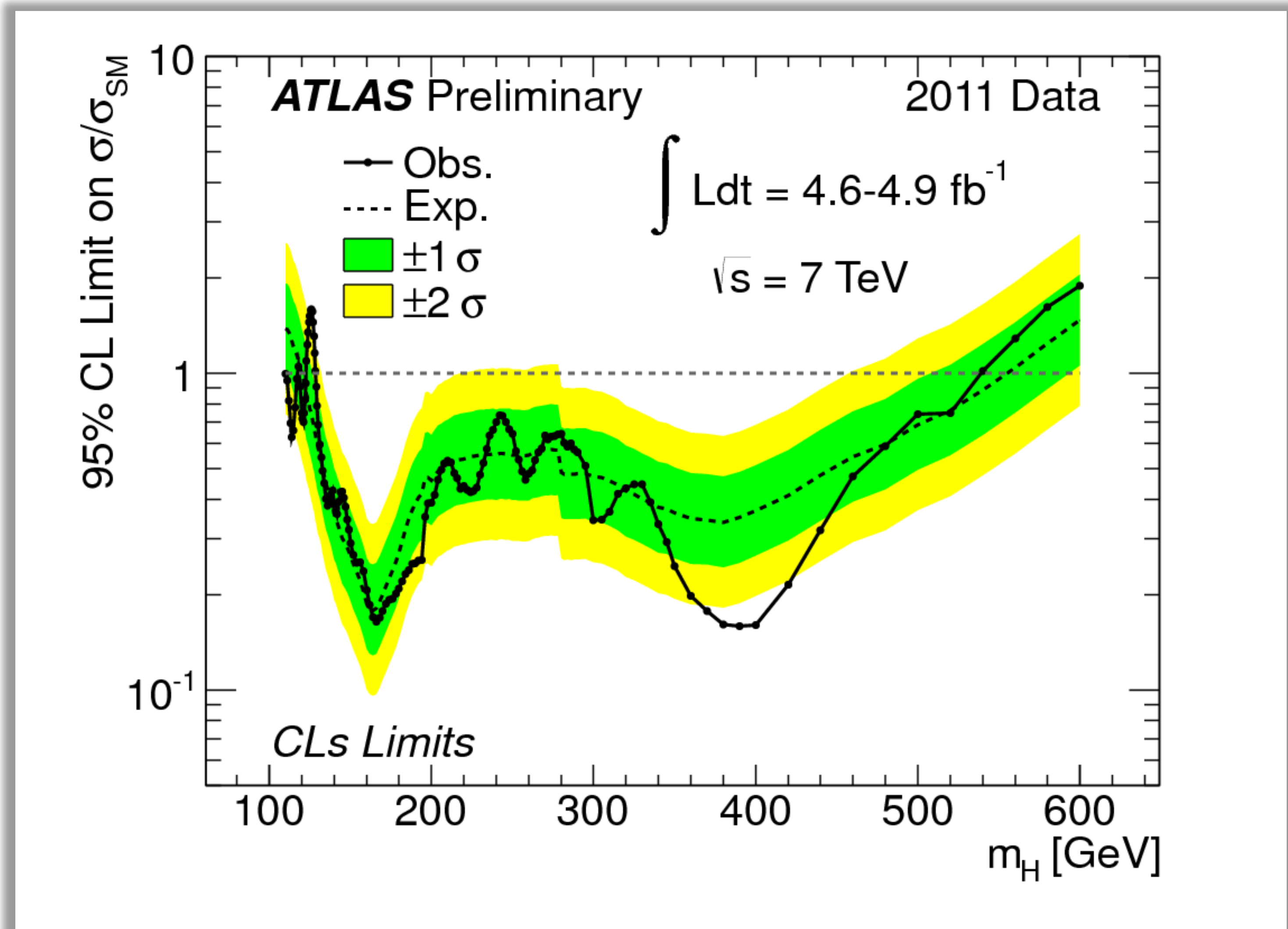
Combination





- Higgs Boson search in 12 distinct channels
- Excess is mainly observed in two high-resolution channels (Improved calibration has been used)
  - $H\rightarrow\gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ combined local significance : 3.4σ
- No such excess in other channels
- All channels combined: 2.5σ local significance
- Higgs mass has been squeezed to a tiny region 117.5-118.5 GeV or 122.5-129 GeV, excess is most compatible with 126 GeV but statistical significance not large enough yet to draw any conclusion

Combined exclusion limit



Observed exclusion at 95% CL: 110-117.5, 118.5-122.5, 129-539 GeV

SUSY Multilepton searches

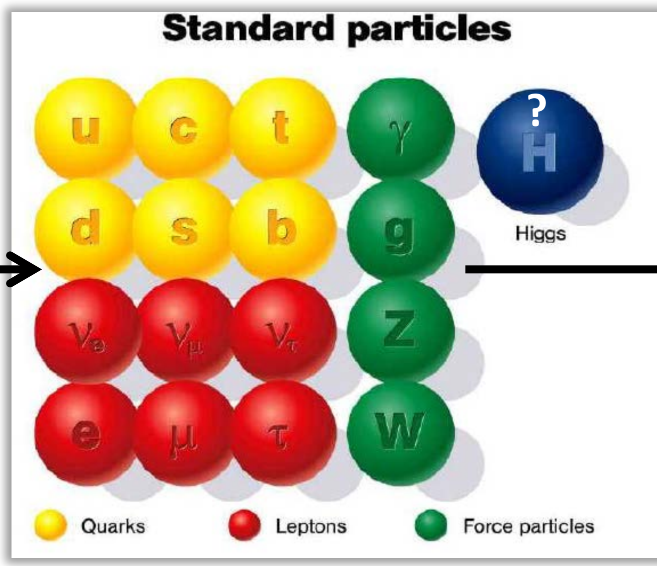
The Search for New Physics

- Limitation of the Standard Model indicates that there should be new particles at the ~TeV scale. At minimum, this includes the Higgs and a Dark Matter candidate. One possibility is Super Symmetry

1950's

Gauge Bosons	Y
Leptons and neutrinos	e+, ν_e μ+, ν_μ
Mesons	K, π
Baryons	P, N

1995

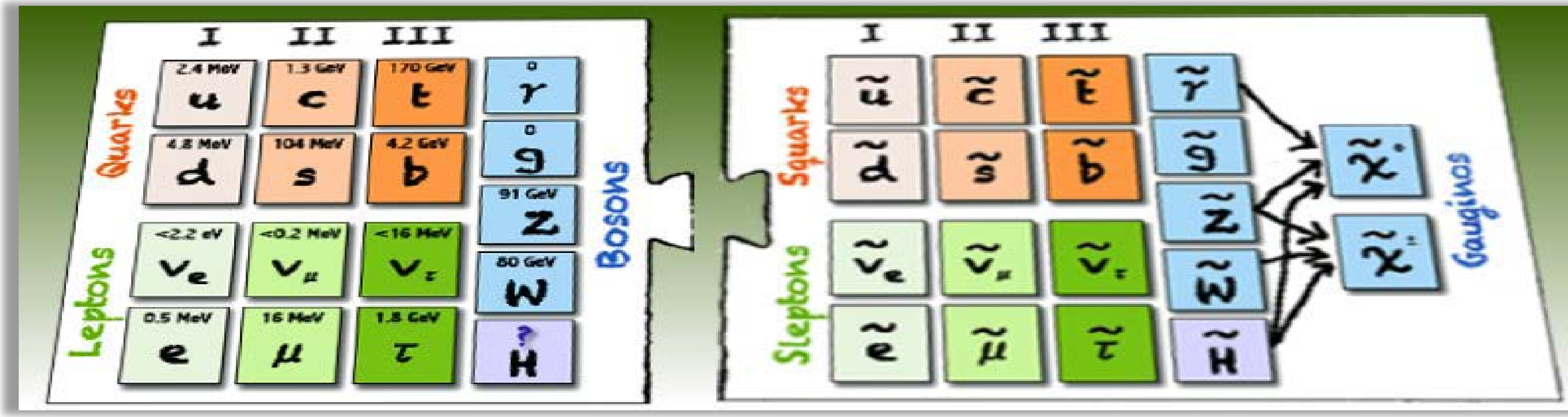


2012 – 2020?

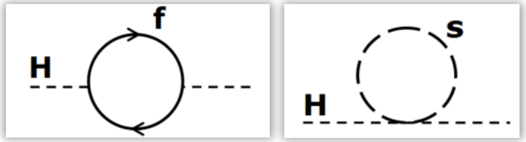
Some Possibilities:

- Super Symmetry
- Extra dimensions
- New quark generation
- Lepto-quarks
- Something unexpected!

Supersymmetry (SUSY)



- ❑ Symmetry between fermions and bosons
- ❑ For each Standard Model particle there is a superpartner which differ by a half unit of spin
- ❑ Physics Motivation:
  - ➢ Natural solution to hierarchy problem
    - ❖ Stabilize Higgs mass,
      - ▪ Cancellation of quadratic divergences from fermionic loops by contributions from superpartners



  - ➢ Provide a dark matter candidate (stable Lightest SUSY Particle(LSP) in R-parity conserving models i,e conserved quantum number: $R = (-1)^{3B+2S+L}$, for SM R = +1, SUSY R = -1)
  - ➢ Provide Unification of coupling at high energy ~GUT scale

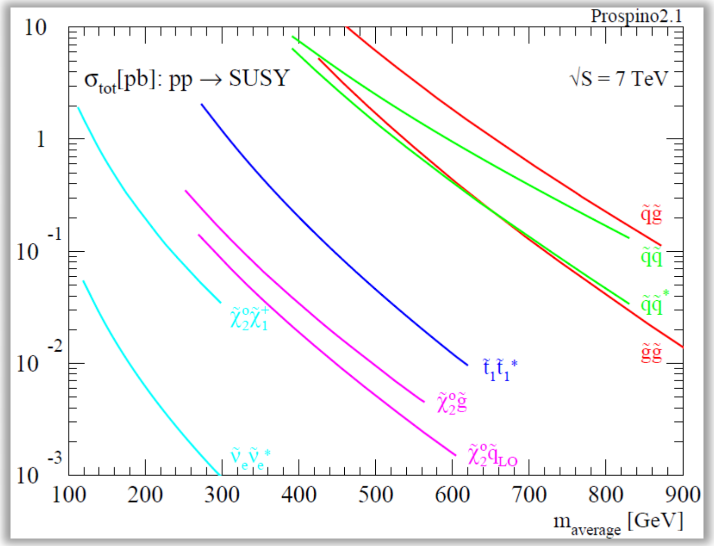
Is SUSY an exact symmetry?

- Must be a broken symmetry
  - otherwise we should have seen sparticle with same masses as SM particles
  - This allows super partners to take large mass
- Several mechanisms to break SUSY
  - Gravity mediated SUSY breaking, SUSY breaking transmitted by hidden sector through gravitational interactions to MSSM
    - minimal supergravity is mSUGRA
  - Anomaly mediated
  - Gauge mediated (GMSB), messenger sector communicates with MSSM via gauge interaction
    - Messenger sector could be particle from large group like SU(5)
  - General Gauge Mediation (GGM) Symmetry Breaking of SUSY
    - The lightest MSSM sparticle is NLSP and LSP is always gravitino

SUSY searches in Multilepton(>=4 leptons) events

- If sparticle masses are within LHC reach, then squarks and gluinos can be abundantly produced
  - Multileptons can arise from cascade decays of squarks and gluinos via charginos, neutralinos and sleptons
  - Sensitive to weak production
  - Can also be produced via RPV where LSP are Stau's
- Significant Missing Transverse Energy(MET) Which can be used to suppress SM background
- Each extra lepton makes the analysis clean, reduce background and the need to cut tight on MET
- SM events with 4 leptons are rare

MET: momentum imbalance in the detector caused by neutral, weakly interacting particles (e.g. neutrinos … or SUSY neutralinos, "dark matter" candidates)



Event Selection

- Electron
  - pT > 10 GeV, $|\eta_{cl}| < 2.47$
  - overlap removal
  - Isolation, ptcone20/pT < 0.1
  - …
- Jet
  - pT > 20 GeV, $|\eta| < 2.8$
  - AntiKt4Topo

- Muon
  - Baseline pT > 10 GeV, $|\eta| < 2.40$
  - Using information from both ID and Muon system
  - overlap removal
  - Isolation ptcone20 < 1.8 GeV and etcone30 < 4 GeV
  - …

- Signal Region 1(SR1)
  - At least 4 signal electrons+muons,
  - pT > 25/20(e,mu),10,10,10 GeV
  - Must satisfy trigger plateau requirements
  - MET > 50 GeV
  - Choice of MET cut effective for wide range of SUSY scenarios
- Signal Region 2(SR2) = SR1+Z-veto
  - Veto events with MSFOS within 10 GeV of Z mass
- Background estimation from MC, validated in background rich control region (i,e MET<50GeV)

Results

Table 3: Number of events in SR1 and SR2 for MC simulation and 2.06 fb^{-1} of 2011 data. SM background expectations listed in this table have been estimated using MC simulation. The uncertainties quoted for the "All" column are inclusive and not the summed uncertainties of the different flavour combinations. Where MC samples yield zero events, the uncertainty is quoted based on the integrated luminosity of the MC sample (see text).

SR1	All	$eeee$	$eee\mu$	$ee\mu\mu$	$e\mu\mu\mu$	$\mu\mu\mu\mu$
$t\bar{t}$	0.17±0.14	0.011±0.042	0.027±0.042	0.09±0.06	0.05±0.07	0±0.018
Single t	0±0.04	0±0.04	0±0.04	0±0.04	0±0.04	0±0.04
$t\bar{t}V$	0.48±0.21	0.072±0.037	0.12±0.06	0.14±0.07	0.08±0.04	0.059±0.032
ZZ	0.44±0.19	0.14±0.08	0.016±0.012	0.21±0.12	0.047±0.032	0.025±0.045
WZ	0.25±0.10	0.015±0.022	0.07±0.04	0.050±0.032	0.11±0.06	0±0.011
WW	0±0.015	0±0.015	0±0.015	0±0.015	0±0.015	0±0.015
$Z\gamma$	0±0.5	0±0.5	0±0.5	0±0.5	0±0.5	0±0.5
$Z+(u,d,s$ jets)	0.33±0.67	0.33±0.67	0±0.29	0±0.29	0±0.29	0±0.29
$Z+(c,b$ jets)	0.024±0.035	0±0.17	0±0.17	0±0.17	0.024±0.035	0±0.17
Drell-Yan	0±0.05	0±0.05	0±0.017	0±0.017	0±0.016	0±0.017
Σ SM	1.7±0.9	0.6±0.8	0.24±0.57	0.5±0.6	0.32±0.55	0.08±0.57
Data	4	0	1	2	0	1

SR2	All	$eeee$	$eee\mu$	$ee\mu\mu$	$e\mu\mu\mu$	$\mu\mu\mu\mu$
$t\bar{t}$	0.13±0.11	0±0.018	0.027±0.042	0.05±0.04	0.05±0.07	0±0.018
Single t	0±0.04	0±0.04	0±0.04	0±0.04	0±0.04	0±0.04
$t\bar{t}V$	0.07±0.04	0.007±0.007	0.024±0.017	0.022±0.021	0.011±0.008	0.005±0.005
ZZ	0.019±0.020	0.008±0.011	0±0.012	0.010±0.018	0±0.012	0±0.012
WZ	0.09±0.05	0±0.020	0.0021±0.0024	0.050±0.032	0.039±0.028	0±0.011
WW	0±0.015	0±0.015	0±0.015	0±0.015	0±0.015	0±0.015
$Z\gamma$	0±0.5	0±0.5	0±0.5	0±0.5	0±0.5	0±0.5
$Z+(u,d,s$ jets)	0.33±0.67	0.33±0.67	0±0.29	0±0.29	0±0.29	0±0.29
$Z+(c,b$ jets)	0.024±0.035	0±0.17	0±0.17	0±0.17	0.024±0.035	0±0.17
Drell-Yan	0±0.05	0±0.05	0±0.017	0±0.017	0±0.016	0±0.017
Σ SM	0.7±0.8	0.35±0.83	0.05±0.57	0.13±0.57	0.12±0.55	0.005±0.567
Data	0	0	0	0	0	0

No significant excess seen in data

Visible cross section
= σ x BR x A x ε

SR1
p-value 0.10
95% CL on visible cross section
expected < 2.1 fb
observed < 3.5 fb

SR2
p-value >0.5
95% CL on visible cross section
expected < 1.5 fb
observed < 1.5 fb

Leptons E_T distributions

Good agreement between data and MC

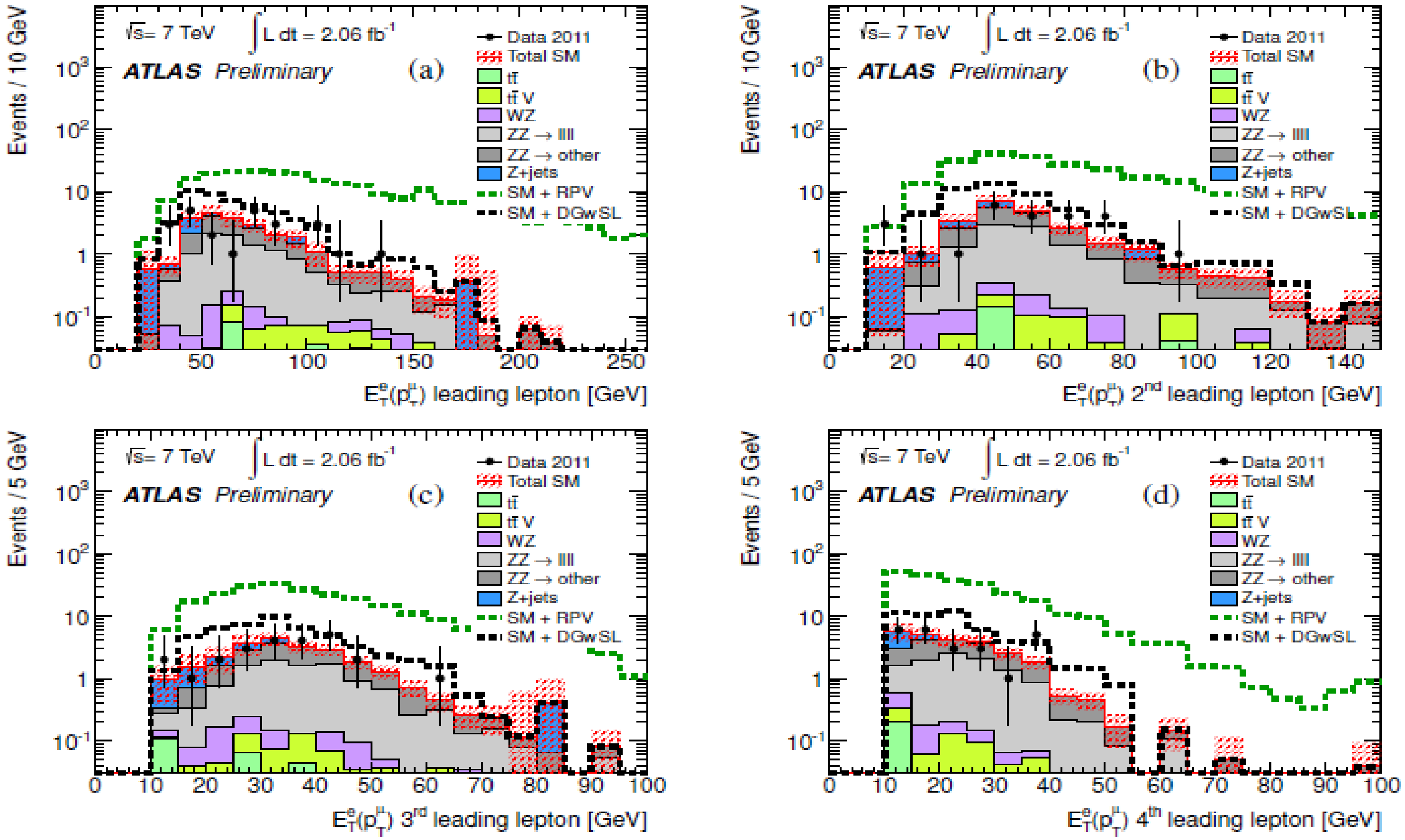


Figure 1: For events with at least four leptons with $E_T^e(p_T^\mu)$ above 10 GeV, the $E_T^e(p_T^\mu)$ distributions of (a) the leading, (b) second-leading, (c) third-leading and (d) fourth-leading lepton are shown for data and MC simulation. The two SUSY benchmark scenarios are also shown. The hatched band represents systematic uncertainties added in quadrature.

Data/MC distributions

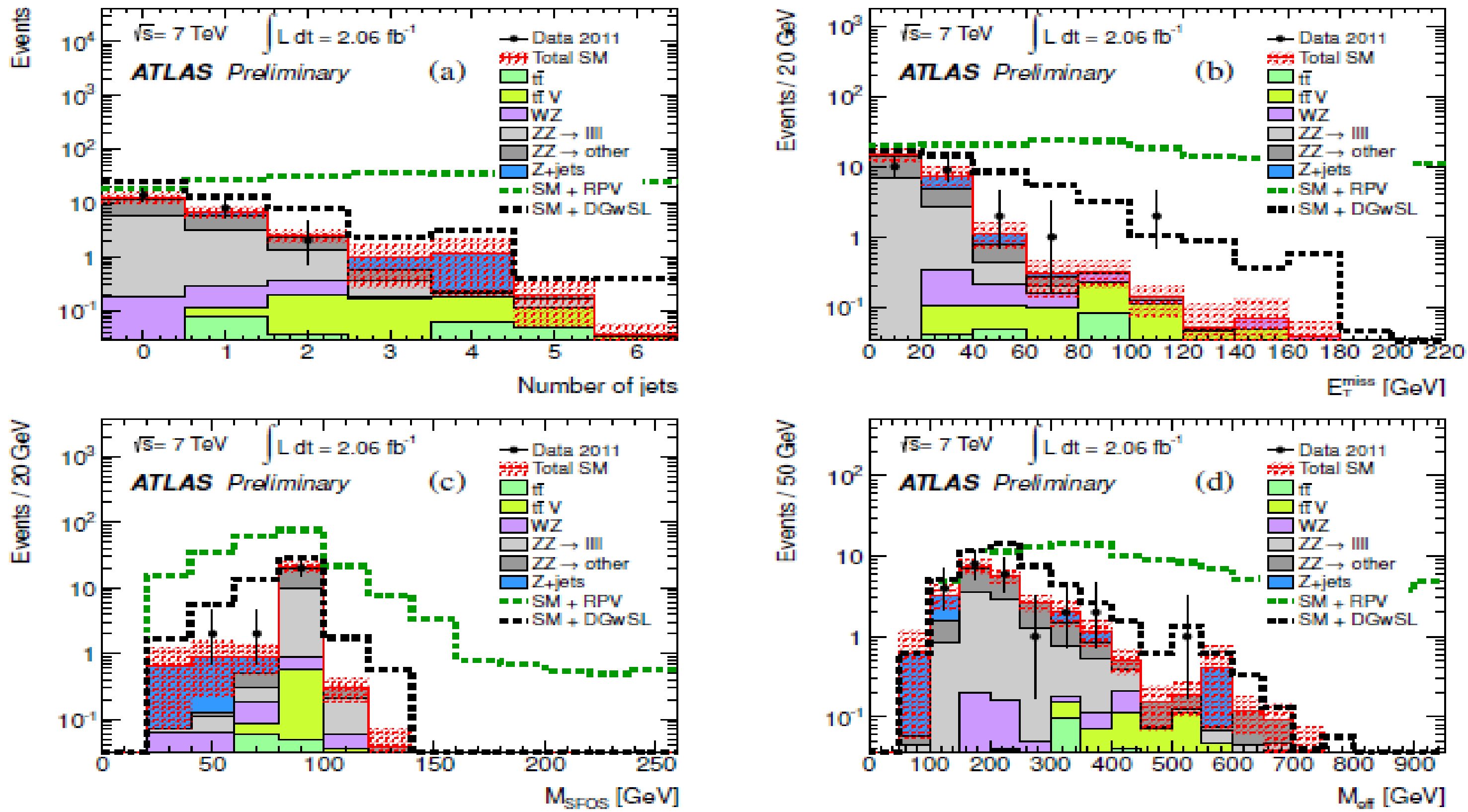
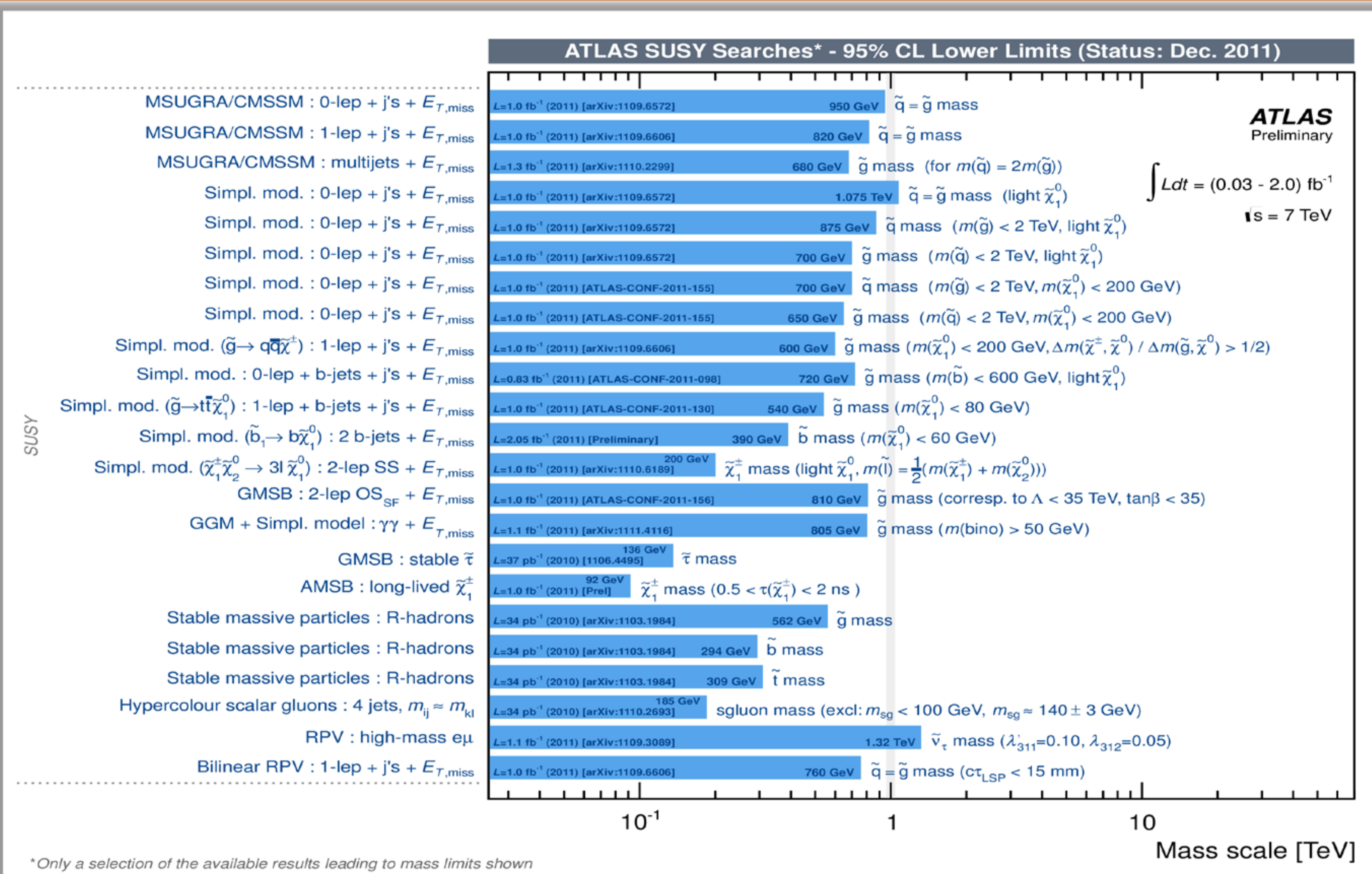


Figure 2: For events with at least four leptons with $E_T^e(p_T^\mu)$ above 10 GeV, distributions of (a) the jet multiplicity, (b) E_T^{miss}, (c) M_{SFOS} and (d) M_{eff} are shown for data and MC simulation. Also shown are the two SUSY benchmark scenarios. In events where multiple SFOS lepton pairs are present, the pair with invariant mass closest to the Z boson mass is plotted in (c). M_{eff} is defined as the scalar sum of the E_T^{miss}, the p_T of the leptons and the p_T of the jets with $p_T > 40$ GeV in the event. The hatched band represents systematic uncertainties added in quadrature.

ATLAS SUSY searches limits



Already excluding sparticles masses at TeV scale

ATLAS Calorimeter parameters

Table 1.3: Main parameters of the calorimeter system.

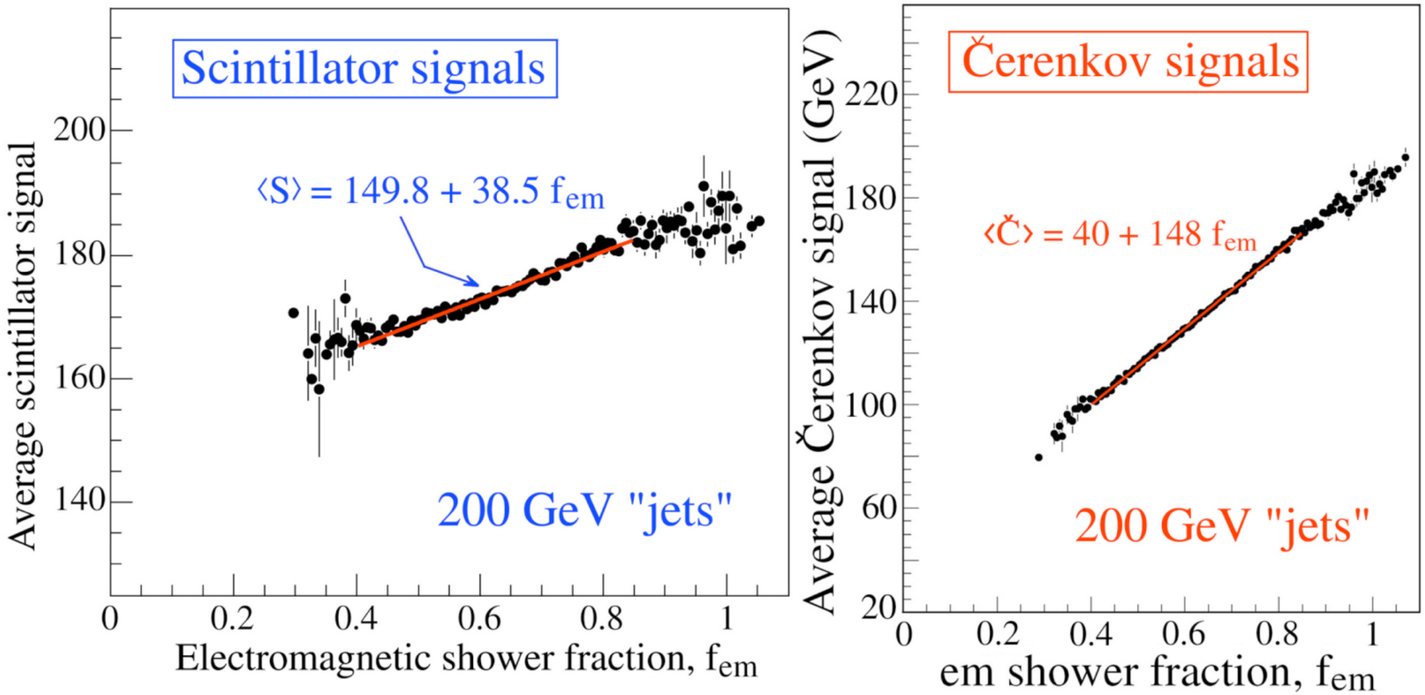
	Barrel		End-cap	
EM calorimeter				
Number of layers and $\|\eta\|$ coverage				
Presampler	1	$\|\eta\| < 1.52$	1	$1.5 < \|\eta\| < 1.8$
Calorimeter	3	$\|\eta\| < 1.35$	2	$1.375 < \|\eta\| < 1.5$
	2	$1.35 < \|\eta\| < 1.475$	3	$1.5 < \|\eta\| < 2.5$
			2	$2.5 < \|\eta\| < 3.2$
Granularity $\Delta\eta \times \Delta\phi$ versus $\|\eta\|$				
Presampler	0.025×0.1	$\|\eta\| < 1.52$	0.025×0.1	$1.5 < \|\eta\| < 1.8$
Calorimeter 1st layer	$0.025/8 \times 0.1$	$\|\eta\| < 1.40$	0.050×0.1	$1.375 < \|\eta\| < 1.425$
	0.025×0.025	$1.40 < \|\eta\| < 1.475$	0.025×0.1	$1.425 < \|\eta\| < 1.5$
			$0.025/8 \times 0.1$	$1.5 < \|\eta\| < 1.8$
			$0.025/6 \times 0.1$	$1.8 < \|\eta\| < 2.0$
			$0.025/4 \times 0.1$	$2.0 < \|\eta\| < 2.4$
			0.025×0.1	$2.4 < \|\eta\| < 2.5$
			0.1×0.1	$2.5 < \|\eta\| < 3.2$
Calorimeter 2nd layer	0.025×0.025	$\|\eta\| < 1.40$	0.050×0.025	$1.375 < \|\eta\| < 1.425$
	0.075×0.025	$1.40 < \|\eta\| < 1.475$	0.025×0.025	$1.425 < \|\eta\| < 2.5$
			0.1×0.1	$2.5 < \|\eta\| < 3.2$
Calorimeter 3rd layer	0.050×0.025	$\|\eta\| < 1.35$	0.050×0.025	$1.5 < \|\eta\| < 2.5$
Number of readout channels				
Presampler	7808		1536 (both sides)	
Calorimeter	101760		62208 (both sides)	
LAr hadronic end-cap				
$\|\eta\|$ coverage			$1.5 < \|\eta\| < 3.2$	
Number of layers			4	
Granularity $\Delta\eta \times \Delta\phi$			0.1×0.1	$1.5 < \|\eta\| < 2.5$
			0.2×0.2	$2.5 < \|\eta\| < 3.2$
Readout channels			5632 (both sides)	
LAr forward calorimeter				
$\|\eta\|$ coverage			$3.1 < \|\eta\| < 4.9$	
Number of layers			3	
Granularity $\Delta x \times \Delta y$ (cm)			FCal1: 3.0×2.6	$3.15 < \|\eta\| < 4.30$
			FCal1: $\sim$ four times finer	$3.10 < \|\eta\| < 3.15$,
				$4.30 < \|\eta\| < 4.83$
			FCal2: 3.3×4.2	$3.24 < \|\eta\| < 4.50$
			FCal2: $\sim$ four times finer	$3.20 < \|\eta\| < 3.24$,
				$4.50 < \|\eta\| < 4.81$
			FCal3: 5.4×4.7	$3.32 < \|\eta\| < 4.60$
			FCal3: $\sim$ four times finer	$3.29 < \|\eta\| < 3.32$,
				$4.60 < \|\eta\| < 4.75$
Readout channels			3524 (both sides)	
Scintillator tile calorimeter				
	Barrel		Extended barrel	
$\|\eta\|$ coverage	$\|\eta\| < 1.0$		$0.8 < \|\eta\| < 1.7$	
Number of layers	3		3	
Granularity $\Delta\eta \times \Delta\phi$	0.1×0.1		0.1×0.1	
Last layer	0.2×0.1		0.2×0.1	
Readout channels	5760		4092 (both sides)	

ATLAS Sub-Detectors Resolution

Table 1.1: General performance goals of the ATLAS detector. Note that, for high-p_T muons, the muon-spectrometer performance is independent of the inner-detector system. The units for E and p_T are in GeV.

Detector component	**Required resolution**	**η coverage**	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \lvert\eta\rvert < 4.9$	$3.1 < \lvert\eta\rvert < 4.9$
Muon spectrometer	σ_{p_T}/p_T=10% at p_T = 1 TeV	± 2.7	± 2.4

DREAM: Signal dependence on f_{em}

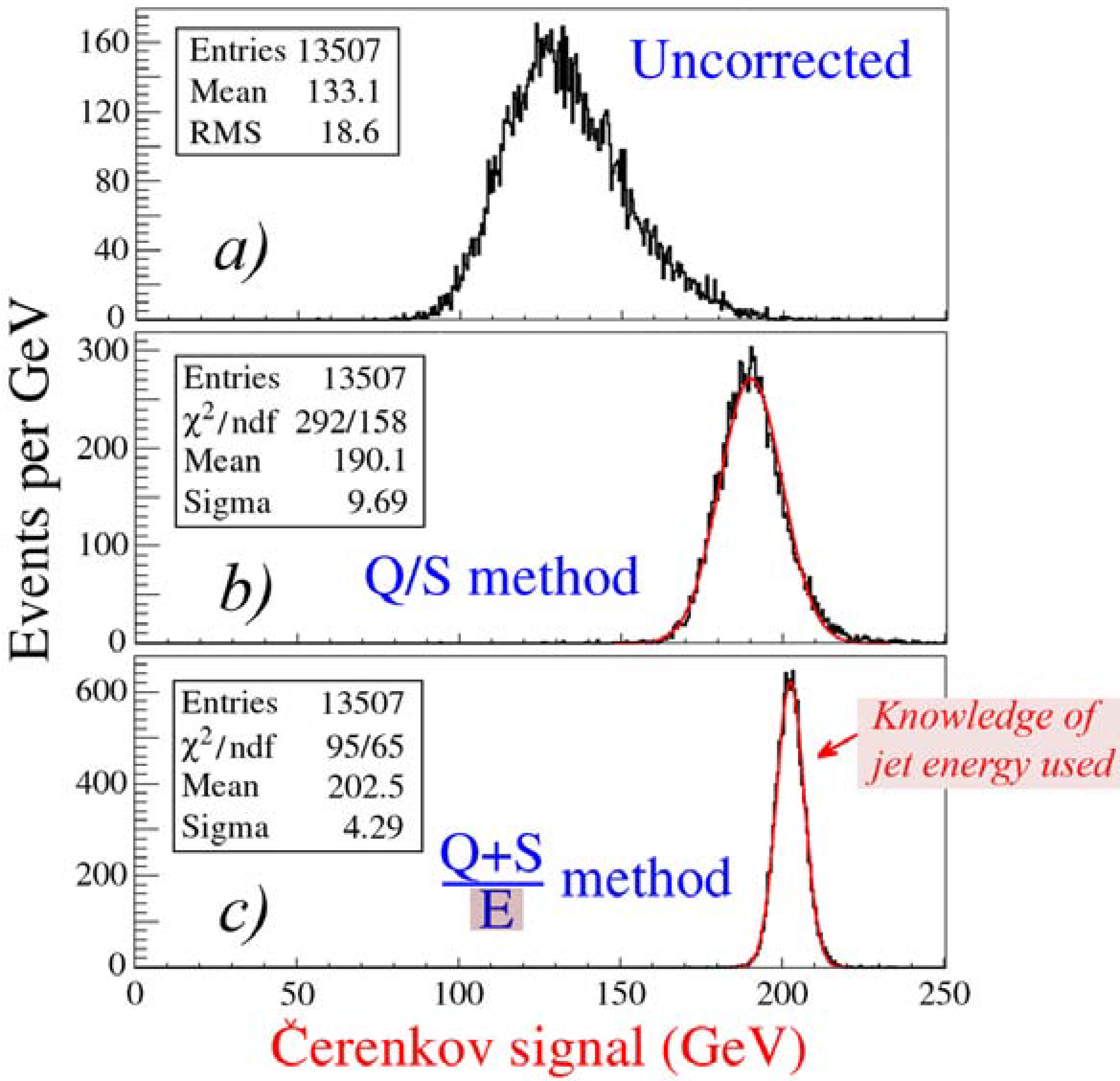


$$\boxed{R(f_{em}) = p_0 + p_1 f_{em}} \quad \text{with} \quad \boxed{\frac{p_1}{p_0} = e/h - 1}$$

Cu/scintillator $e/h = 1.3$ Cu/quartz $e/h = 4.7$

From:
NIM A537 (2005) 537

Dual-Readout Calorimetry



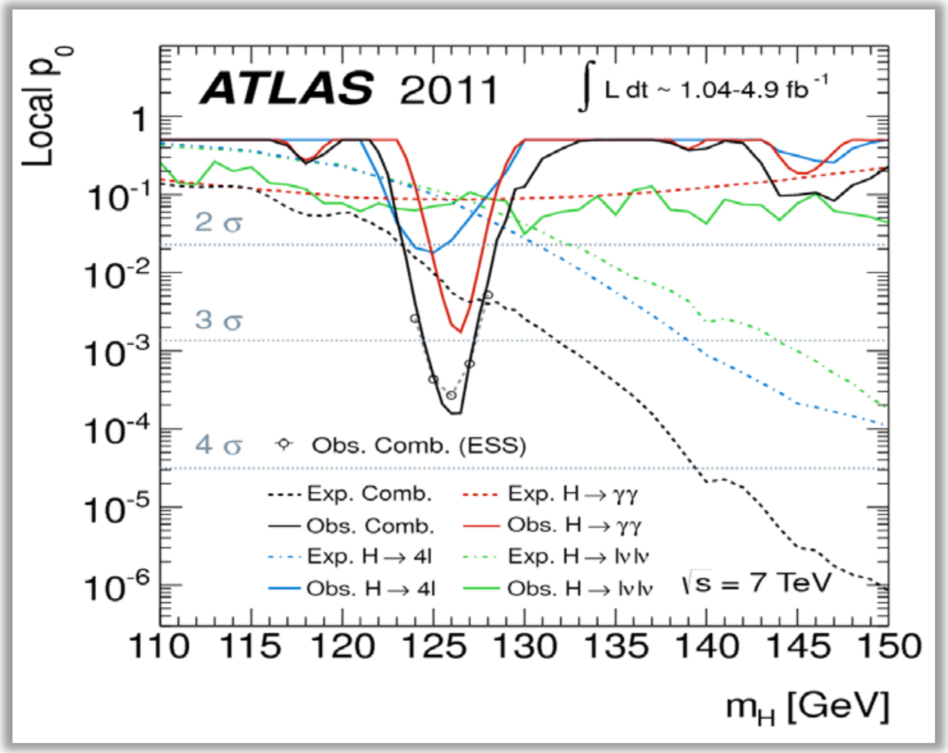
A word about Look Elsewhere Effect (LEE)

- SM doesn't predict the value of Higgs boson mass
  - Therefore mass resonance (excess of events) has to be searched in a wide mass range in experiments
  - An excess of events at a given mass point could also be the result of background fluctuation
    - Non zero probability, like 3σ excess due to background would be 0.13% X LEW
      - Where LEW = mass range/mass resolution
- Therefore in a search for new mass resonance the significance of observing local excess of events anywhere in a possible mass range must take into account the probability of observing such an excess anywhere in the range, the so called Look Elsewhere Effect (LEE)
  - Different ways to quantify LEE, e.g, in terms of the ratio between the probability of observing the excess at some fixed mass point to the probability of observing it anywhere in the range
- P-value:
  - Is the probability that the background fluctuates to the observed number of events or higher
  - Or measure of how much evidence we have against the null or background only hypothesis
  - Small (<0.05) p-value means evidence against null hypothesis while large p-value means little or no evidence against null hypothesis

Search for long-lived Neutralino NLSP

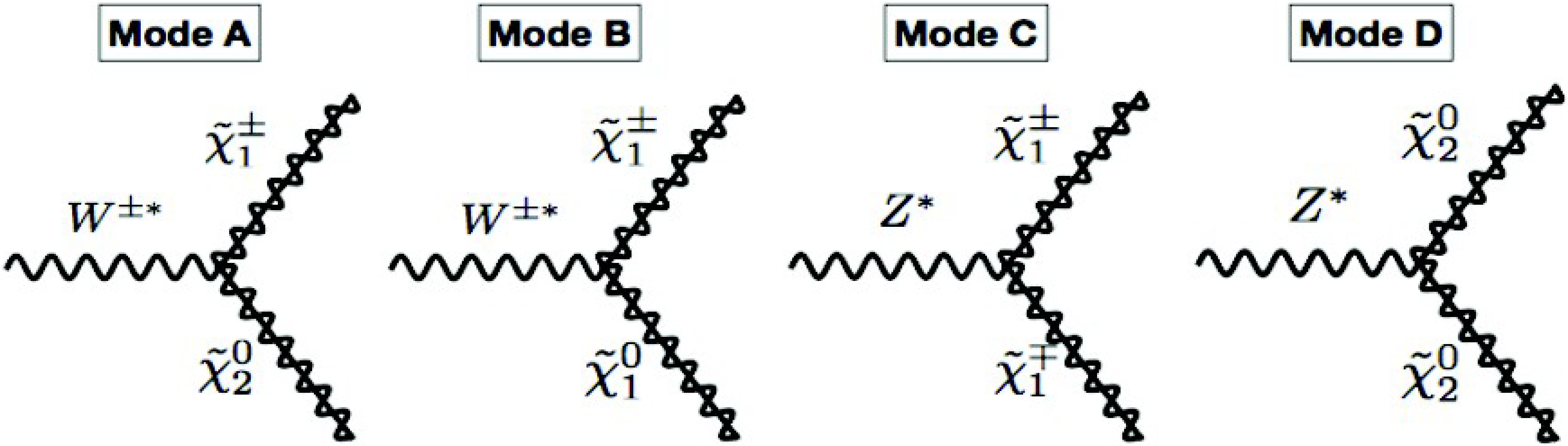
- While we continue searching for SUSY and any new Physics BSM, it's possible that any new physics may not look the way we use to search for it
  - one possibility is that we may have non-prompt decays instead of the usual prompt physics that we are focused on
- Exploring GMSB with long lived neutralino
  - In gauge mediated SUSY models, we may have long lived NLSP depending on SUSY breaking scale
    - For example NLSP decay lengths of 0.1mm to 10's m for SUSY breaking scale from few hundred to few thousand TeV
  - Many other scenarios allowing for such a signature like split-SUSY, stealth-SUSY, hidden-valley or meta-stable SUSY breaking etc
- The general neutralino NLSP is a mixture of bino/higgsino/wino eigenstates
  - For NLSP with significant higgsino or wino component can decay ~100% time to Z+G and h+G
  - So the final states could be ZZ/WZ/gg/hh/Wg +MET
  - Note In the final states we can have both or one non-prompt neutralino's
- Paper in progress, aim for summer

Combination plot (old)



- The major channels, γγ(4.9 fb^{-1}) and 4l(4.9 fb^{-1}) have comparable sensitivities around 126GeV
- The γγ excess is in coincidence with a smaller 4l excess, leading to a 3.5σ excess in the Higgs combination

Multilepton production



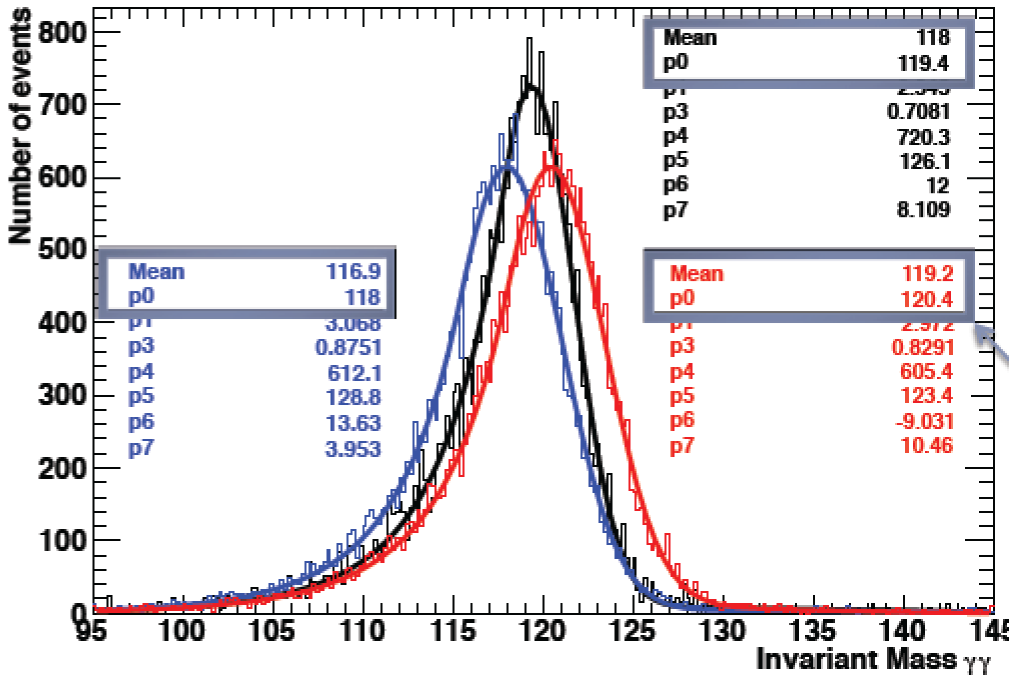
All Mode A, C, D are relevant for ≥ 4-lepton analysis as well

- Mode A: 1/6 of the mass points have 5-lepton final states; the rest are 3-lep
- Mode C: 75% of events are ≥ 4-lep.
- Mode D: purely 4-lep

Example of Energy scale systematics

Example of Converted Bad category.

+ : I photon whose energy is corrected with the upper limit of the error on the energy scale
- : I photon whose energy is corrected with the lower limit of the error on the energy scale
- A Configuration means : ++, +-, ++, -+ (in the same histogram)
- B Configuration means : -+, --, +-, -- (in the same histogram



- Without any correction
- A Configuration
- B Configuration

p0= mean of the Crystal Ball

Systematics for $H \rightarrow \gamma\gamma$ mass resolution/scale

Signal mass resolution	
Calorimeter energy resolution	$\pm 12\%$
Photon energy calibration	$\pm 6\%$
Effect of pileup on energy resolution	$\pm 3\%$
Photon angular resolution	$\pm 1\%$
Signal mass position	
Photon energy scale	± 0.7 GeV
Signal category migration	
Higgs boson p_T modeling	$\pm 8\%$
Conversion rate	$\pm 4.5\%$
Background model	$\pm (0.1 - 7.9)$ events

Fit Function

Relativistic Breit-Wigner

$$BW(m; M_Z, \Gamma_Z) = \frac{\Gamma_Z^2 m^2 / M_Z^2}{(m^2 - M_Z^2)^2 + \Gamma_Z^2 m^4 / M_Z^2}$$

Resolution function: Crystal Ball

$$CB(x; \alpha, n, \mu, \sigma) = \begin{cases} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right) & for \ \frac{(x-\mu)}{\sigma} > -\alpha \\ A.\left(B - \frac{(x-\mu)}{\sigma}\right)^{-n} & for \ \frac{(x-\mu)}{\sigma} \leq -\alpha \end{cases}$$

with

$$A = \left(\frac{n}{|\alpha|}\right)^n .\exp\left(-\frac{|\alpha|^2}{2}\right)$$

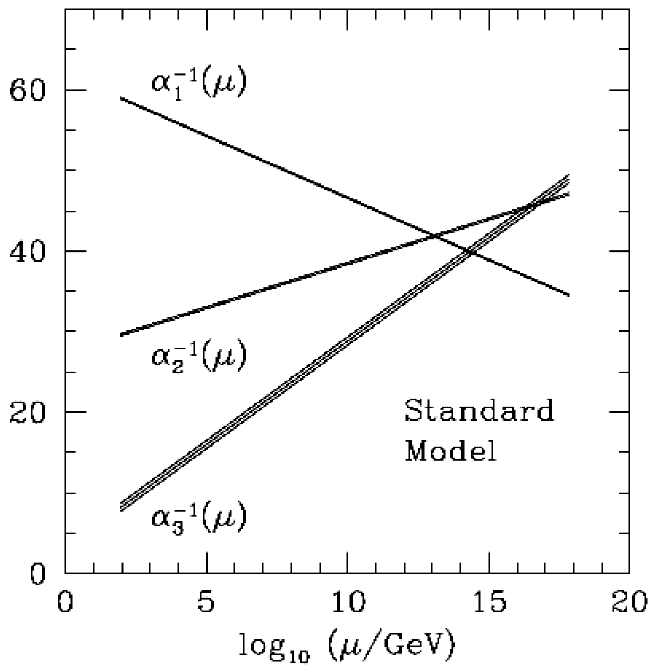
$$B = \frac{n}{|\alpha|} - |\alpha|$$

Convolution of BW and CB

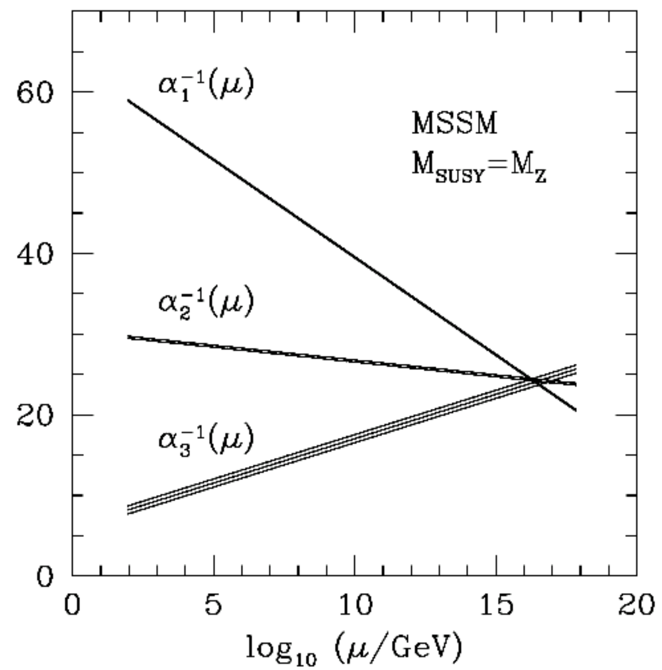
$$fit(m) = N \int BW(m - t; M_Z, \Gamma_Z).CB(t; \alpha, n, \mu, \sigma) dt$$

Unification

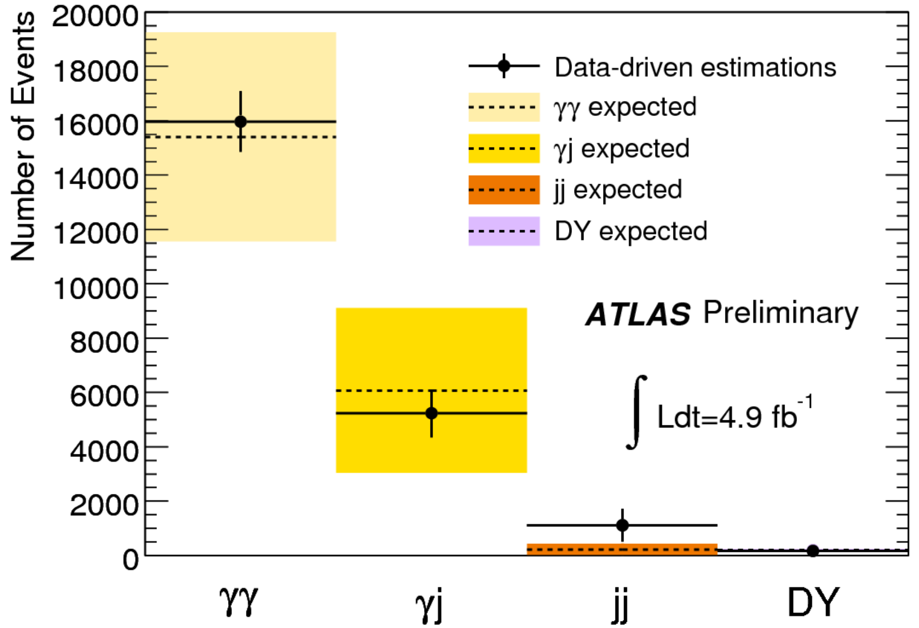
Standard Model

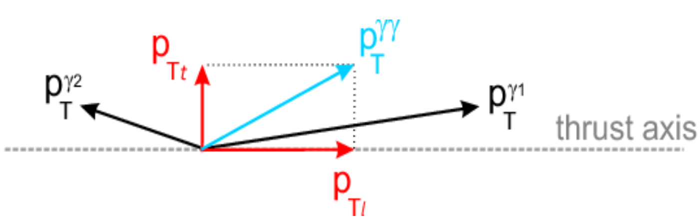


SUSY



Background Composition





$$\hat{t} = \frac{\vec{p}_{\mathrm{T}}^{\gamma_1} - \vec{p}_{\mathrm{T}}^{\gamma_2}}{|\vec{p}_{\mathrm{T}}^{\gamma_1} - \vec{p}_{\mathrm{T}}^{\gamma_2}|}$$

$$\vec{p}_{\mathrm{Tt}} = \vec{p}_{\mathrm{T}}^{\gamma\gamma} - (\vec{p}_{\mathrm{T}}^{\gamma\gamma} \cdot \hat{t}) \cdot \hat{t},$$

H→γγ Categories