Prompt Photons at ATLAS

Mike Hance, UPenn
For the ATLAS Collaboration
Les Houches Winter Workshop
16 February 2011

Overview

Prompt photon studies at ATLAS began with a **measurement of the inclusive isolated photon cross section** with the earliest 2010 data.

- `http://arxiv.org/abs/1012.4389` (accepted by PRD)

- (Very) quick overview of prompt photon physics/challenges
- Quick review of the ATLAS detector
  - Inner Tracker
  - EM and Hadronic Calorimetry
- Photon Reconstruction and ID
  - Shower evolution in the calorimeter
  - Efficiencies
- Isolation
- Background Estimation
  - Using shower shapes and isolation
- Cross Section Measurement
  - Using 880 nb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV
  - Covering $|\eta| < 1.81$, $15 < E_{\mathrm{T}}^{\gamma} < 100$ GeV
- Current/Future Work
  - Extended inclusive photon studies
  - Diphotons
  - Future plans

Prompt Photons at Hadron Colliders

What are prompt photons?

- Photons emerging intact from the hard scatter or parton fragmentation
- *Not* the products of secondary hadronic decays

Prompt photons are clean probes of hard collisions at relatively high rates

- Sensitive to gluon content of proton via QCD Compton-like process
- A good QCD measurement without using jets

But, large backgrounds make this a challenging signal to extract:

- Primary background is $\pi^0 \rightarrow \gamma\gamma$ (two photons faking a single photon)
- Additional contributions from η, ρ, ω

"Isolation" used to reduce backgrounds

- "Isolation Energy" means "additional hadronic energy near the photon axis"
- Signal has low isolation energy, background (from jets) has higher isolation

Prompt Photons at Hadron Colliders

What are prompt photons?

- Photons emerging intact from the hard scatter or parton fragmentation
- *Not* the products of secondary hadronic decays

Prompt photons are clean probes of hard collisions at relatively high rates

- Sensitive to gluon content of proton via QCD Compton-like process
- A good QCD measurement without using jets

But, large backgrounds make this a challenging signal to extract:

- Primary background is $\pi^0 \rightarrow \gamma\gamma$ (two photons faking a single photon)
- Additional contributions from η, ρ, ω

“Isolation” used to reduce backgrounds

- “Isolation Energy” means “additional hadronic energy near the photon axis”
- Signal has low isolation energy, background (from jets) has higher isolation

Prompt Photons at Hadron Colliders

What are prompt photons?

- Photons emerging intact from the hard scatter or parton fragmentation
- *Not* the products of secondary hadronic decays

Prompt photons are clean probes of hard collisions at relatively high rates

- Sensitive to gluon content of proton via QCD Compton-like process
- A good QCD measurement without using jets

But, large backgrounds make this a challenging signal to extract:

- Primary background is $\pi^0 \rightarrow \gamma\gamma$ (two photons faking a single photon)
- Additional contributions from η, ρ, ω

"Isolation" used to reduce backgrounds

- "Isolation Energy" means "additional hadronic energy near the photon axis"
- Signal has low isolation energy, background (from jets) has higher isolation

Prompt Photons at Hadron Colliders

What are prompt photons?

- Photons emerging intact from the hard scatter or parton fragmentation
- *Not* the products of secondary hadronic decays

Prompt photons are clean probes of hard collisions at relatively high rates

- Sensitive to gluon content of proton via QCD Compton-like process
- A good QCD measurement without using jets

But, large backgrounds make this a challenging signal to extract:

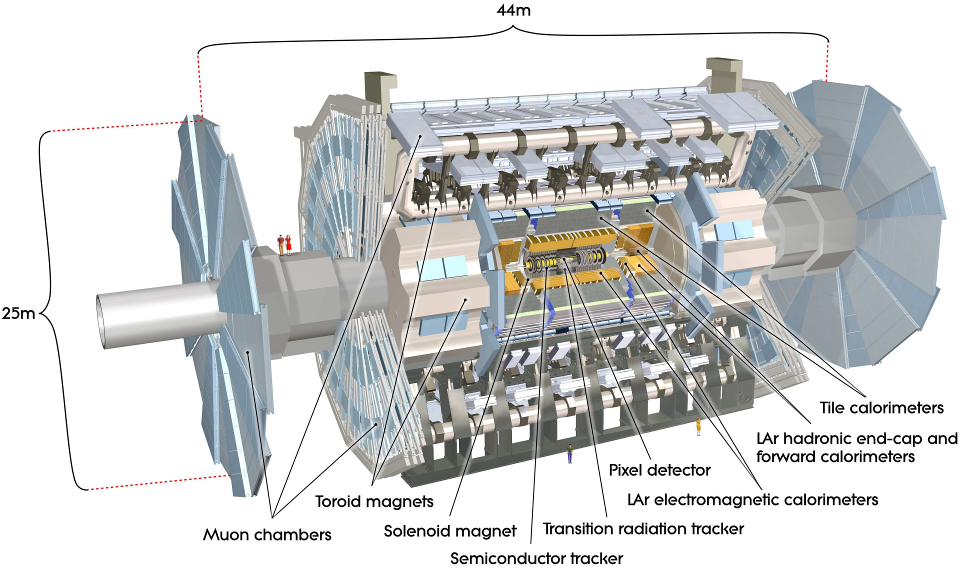
- Primary background is $\pi^0 \to \gamma\gamma$ (two photons faking a single photon)
- Additional contributions from η, ρ, ω

“Isolation” used to reduce backgrounds

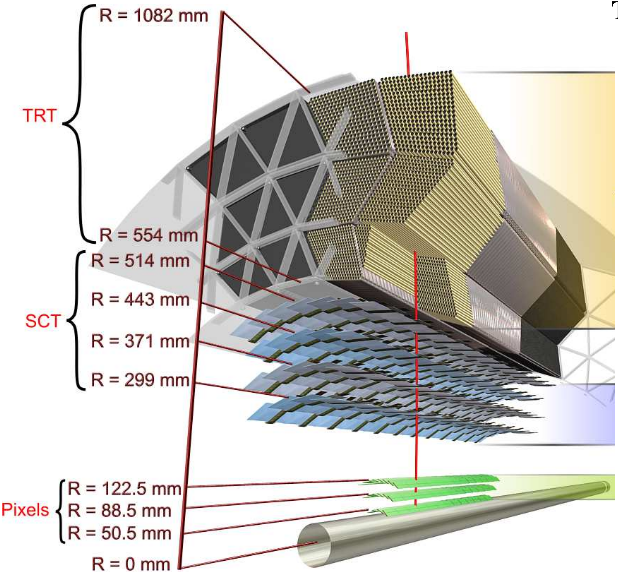
- “Isolation Energy” means “additional hadronic energy near the photon axis”
- Signal has low isolation energy, background (from jets) has higher isolation

The ATLAS Detector

A Toroidal LHC ApparatuS



Inner Detector



Transition Radiation Tracker

- 350k channel tracker
- 4mm (diameter) straws
- TR detection: $e/\pi^{\pm}$ discrimination
- $\approx$36 hits on track
- $\approx 130\mu$m resolution

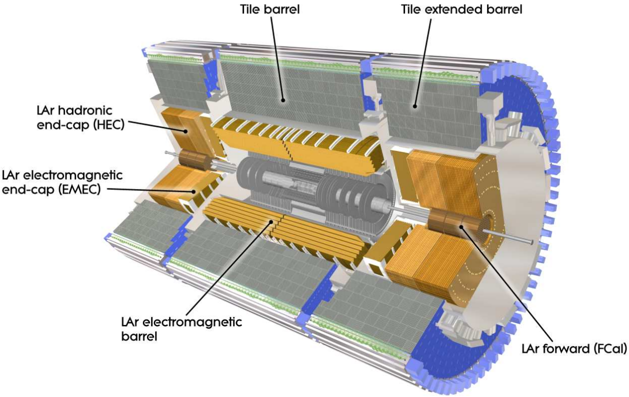
Semi-Conductor Tracker

- 6.3M channels
- 4 cylinders, 8 hits/track
- $\approx 17\mu$m resolution

Pixel Tracker

- 80M channels, 3 layers
- $\approx 10\mu$m resolution

Calorimetry



EM Calorimeter

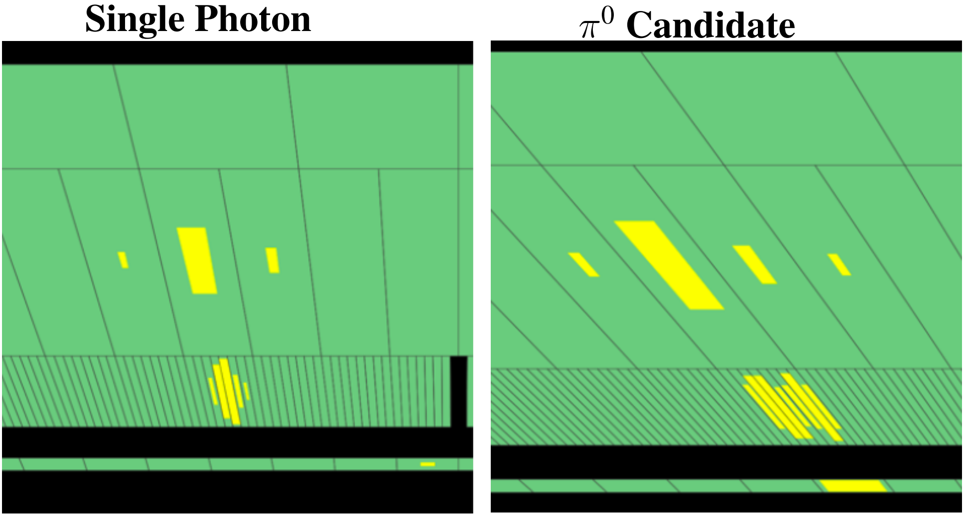
- PB-LAr Accordion
- $\Delta E/E = \left(10\%/\sqrt{E}\right) \oplus .7\%$
- $.025 \times .025$ cells $(\eta \times \phi)$
- Angular res.: 50 mrad / $\sqrt{E}$

Hadronic Calorimeter

- Fe-scintillator for $|\eta| < 1.7$
  - $\Delta E/E = \left(50\%/\sqrt{E}\right) \oplus 6\%$
- Cu-LAr for $1.5 < |\eta| < 3.2$
  - $\Delta E/E = \left(50\%/\sqrt{E}\right) \oplus 3\%$

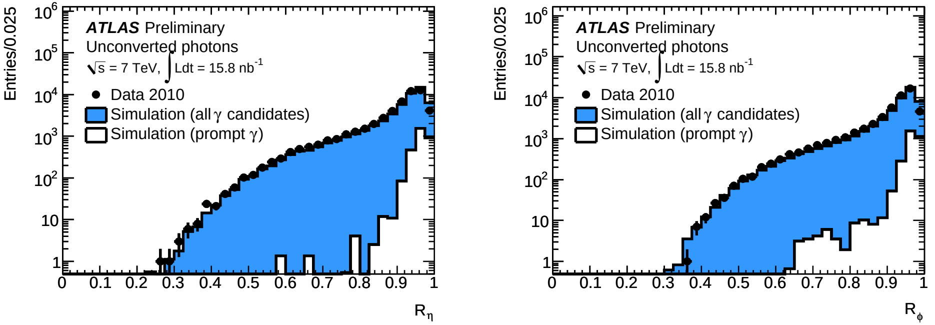
Photon Reconstruction and ID

Photon/π^0 Discrimination



Shower Evolution - Layer 2

The layer 2 (primary calorimeter sampling layer) shower shape cuts require compact clusters consistent with single photons:

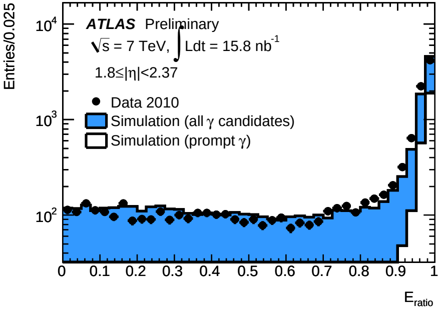


- Energy distribution - width in η (R_η)
- Energy distribution - width in ϕ (R_ϕ)
- Leakage into hadronic calorimeter

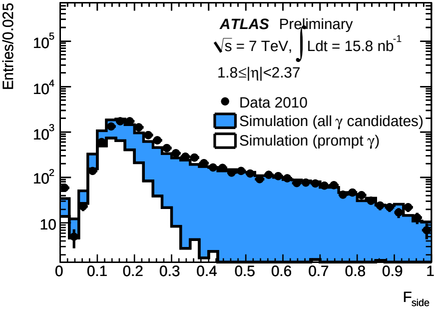
Shower Evolution - Strips

The layer 1 (strips) provide excellent eta resolution, and allow increased discrimination of single photons from π^0's

Peak-to-trough in strips

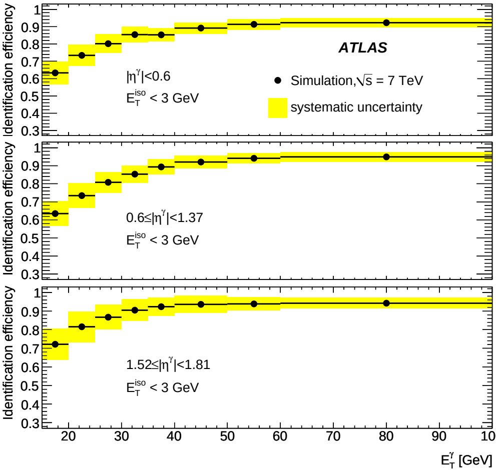


Spread of Energy in Strips



- Look for two local maxima, or wider showers in η or ϕ
- Usually measured over the equivalent of a few cells at layer 2
  - $\Rightarrow$ Largely uncorrelated with isolation variables

Measured Efficiencies



Trigger Efficiency: **99.5%**

Reconstruction efficiency: **82%**

- Including recoverable acceptance losses

ID efficiency determined from MC:

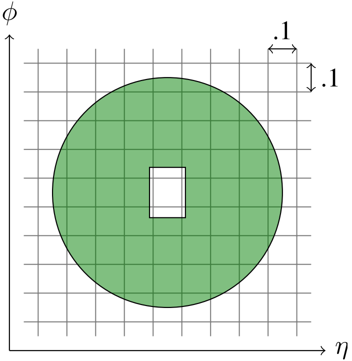
- Shift shower-shapes in MC to match data
- Separately for converted/unconverted
- Verified using $W \rightarrow e\nu$
- Systematics from:
  - Material effects
  - Pileup
  - Conversions
  - Many more....

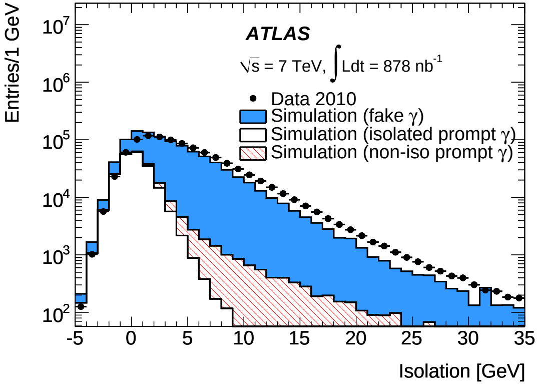
Overall systematics ≈15% (relative)

- Will improve with $Z \rightarrow ll\gamma$ (several inverse femtobarns)

Isolation

Calorimeter Isolation

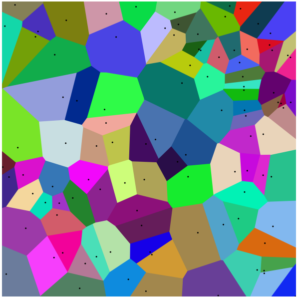




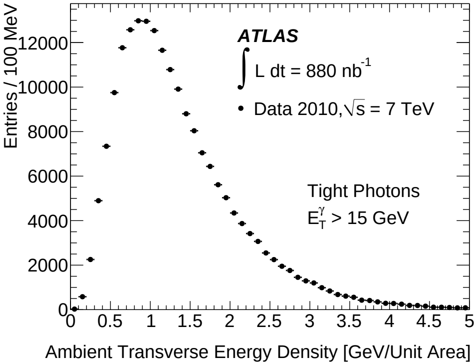
(Uncalibrated) sum of cells outside of 5×7 central core:

- In this case: $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < .4$
- Need to correct for out-of-core leakage
- Also need to account for non-perturbative effects....

Ambient Energy Corrections



(Courtesy of Wikipedia)



- Method proposed by Cacciari, Salam, Sapeta, and Soyez (`http://arxiv.org/abs/0912.4926`)
- Take median jet-energy density to be representative of the ambient energy in the event

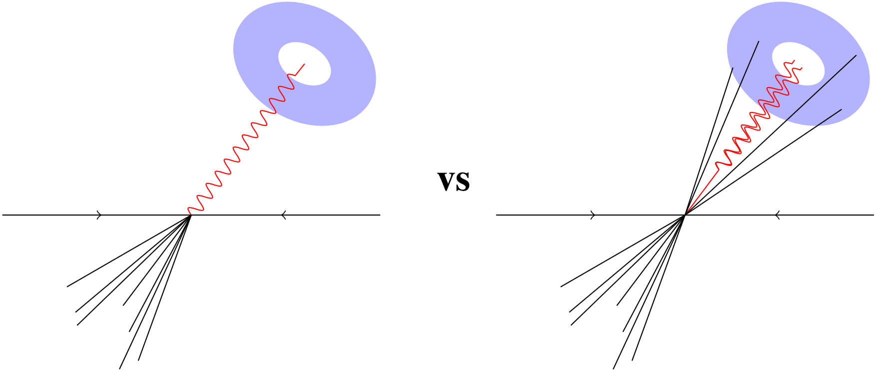
For events with 1 primary vertex (no pileup):

- `PYTHIA`: 440 MeV
- `HERWIG`: 550 MeV
- Data: 540 MeV

Background Estimation

Background Estimates

To estimate the residual background: use **isolation**.



Main challenge: modeling signal and background isolation profiles:

- Stay data-driven as much as possible
- Avoid biases from untuned MC

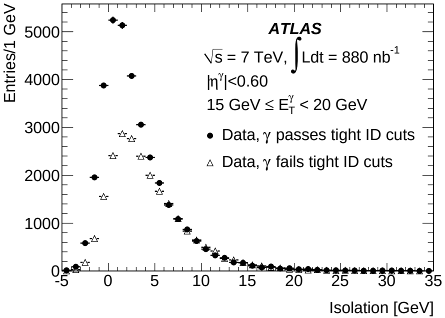
Background Estimates

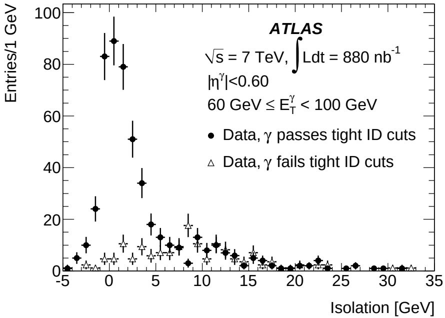
Strong desire to extract the isolation profile of the background directly from data.

- Signal should be well understood, but background modeling in MC may not be as good.

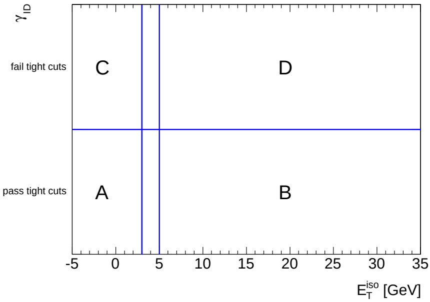
To model the background - reverse some photon ID cuts:

- Cuts on the strip (layer-1) variables are good candidates
- Not strongly correlated with isolation



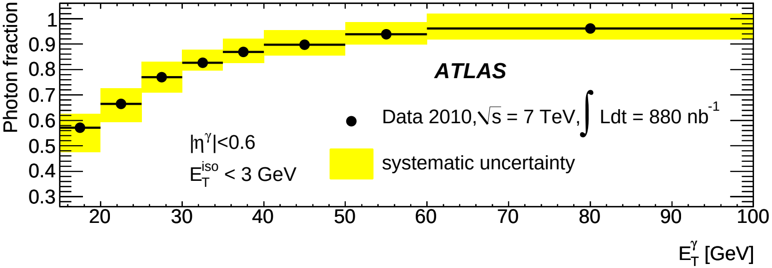


2-D Sideband (ABCD) Technique



$$\boxed{N_A^{sig} = N_A - N_B \frac{N_C}{N_D}}$$

- Assumes "reverse cuts" not correlated with isolation
  - → systematic uncertainty
- Also assumes $N_X^{sig} \ll N_X$ for $X \neq A$
  - Correct N_X to account for signal leakage



Cross Section Measurement

Cross Section Measurement

We now have most of the ingredients for the cross section measurement:

$$\boxed{\frac{d\sigma}{dE_{\mathrm{T}}^{\gamma}} = \frac{N_{\mathrm{yield}}\ U}{\left(\int \mathcal{L}dt\right)\ \Delta E_{\mathrm{T}}^{\gamma}\, \varepsilon_{\mathrm{trigger}}\ \varepsilon_{\mathrm{reco}}\ \varepsilon_{\mathrm{ID}}}}$$

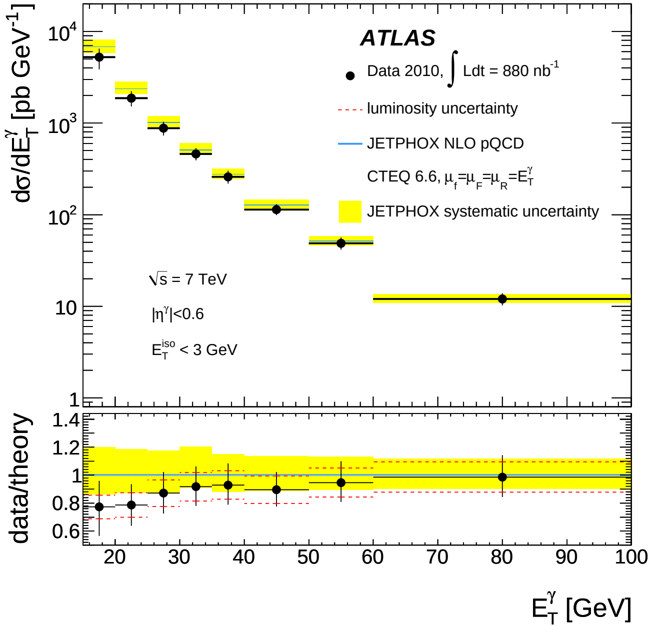
N_{yield} $(= N \cdot P)$ extracted from purity measurements, ε from efficiency measurements.

Unfolding coefficients (U) evaluated using `PYTHIA` signal MC:

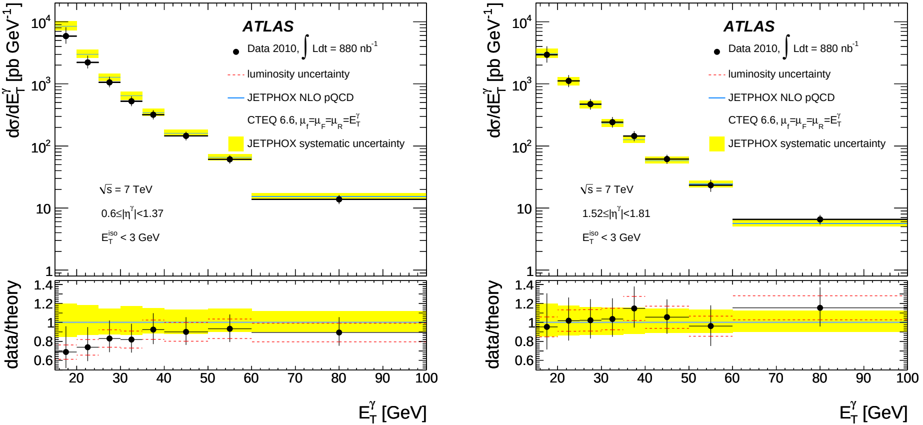
Compare with theoretical predictions from `JETPHOX`:

- CTEQ 6.6 PDFs (also done with MSTW 2008)
- Standard choice of scales: $\mu_R = \mu_F = \mu_f = E_{\mathrm{T}}^{\gamma}$
    - Vary scales independently from $\mu = .5E_{\mathrm{T}}^{\gamma}$ to $\mu = 2E_{\mathrm{T}}^{\gamma}$
    - Largest source of uncertainty
- Isolation requirement: **Iso $<$ 4 GeV (cone $\Delta R = .4$)**
    - Vary isolation from 2 GeV to 6 GeV

Cross Section Measurement



Cross Section: Higher $|\eta|$

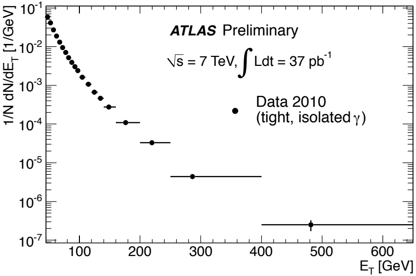


Results compared with theoretical predictions from `JETPHOX`

- Systematically limited across the full E_T range
- Good agreement at high E_T, where the systematics on both experiment and theory are smallest

Most Recent Photon Studies with ATLAS

To higher energies....



A factor of 40 more data has been accumulated since the last analysis was frozen....

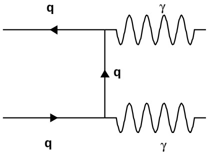
- Can extend the E_T-reach to ≈400 GeV
- Tight, isolated photons above 100 GeV are very pure ($> 90\%$)

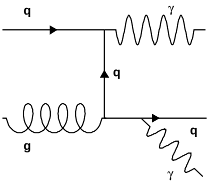
Compton process still dominant at high $E_T \rightarrow$ constrain gluon content of proton for PDFs.

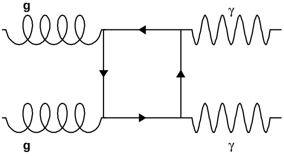
In addition to the inclusive analysis, we plan to measure the γ+jet cross section separately:

- Event kinematics provide more information
- Angular separation sensitive to fragmentation component

Diphoton Measurements

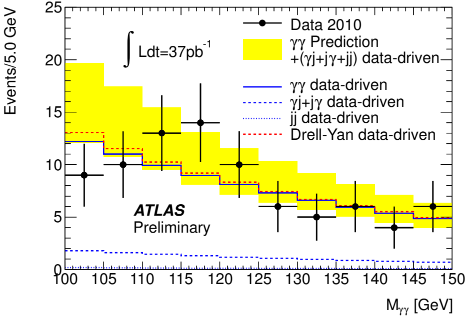

Born


Brem


Box

SM Diphoton Production

- Around 1 nb for $E_T > 15$ GeV
- Largest (irreducible) background to $H \rightarrow \gamma\gamma$
- Biggest challenge is extending the analysis to low E_T



Conclusion

Conclusion

First ATLAS measurement of prompt photon production

- Photons are characterized for the first time by ATLAS
- Good efficiency for very high purity, especially at high E_{T}
- Cross-section measurement up to 100 GeV, in three η regions
  - Extending to $\approx$ 500 GeV with all 2010 data
- Good agreement with theory for $E_{\mathrm{T}}^{\gamma} > 30$ GeV
  - Some things to be understood at lower E_{T}^{γ}

Lots of interesting γ physics to come

- Inclusive photons to much higher E_{T}^{γ}
- Di-photon cross section
- Photon+Jet measurements
- More studies of photon isolation
- Higgs, SUSY, Exotics signatures with photons... all start with this work

Conclusion

First ATLAS measurement of prompt photon production

- Photons are characterized for the first time by ATLAS
- Good efficiency for very high purity, especially at high E_{T}
- Cross-section measurement up to 100 GeV, in three η regions
    - Extending to $\approx$ 500 GeV with all 2010 data
- Good agreement with theory for $E_{\mathrm{T}}^{\gamma} > 30$ GeV
    - Some things to be understood at lower E_{T}^{γ}

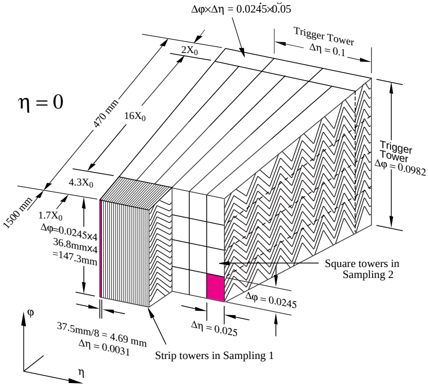
Lots of interesting γ physics to come

- Inclusive photons to much higher E_{T}^{γ}
- Di-photon cross section
- Photon+Jet measurements
- More studies of photon isolation
- Higgs, SUSY, Exotics signatures with photons... all start with this work

Bonus

Calorimeter Clusters

- Sliding Window cluster finding (5×5 cells)
- Clusters of different sizes for photons and electrons:
  - Electrons: 3×7 cells
  - Unconverted photons: 3×5 cells
  - Converted photons: 3×7 cells
- Electrons identified by associated track

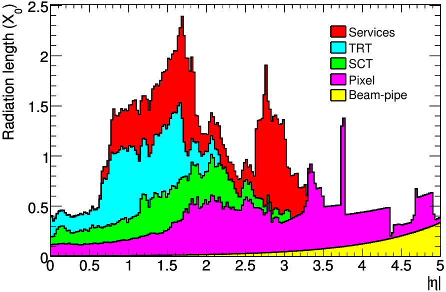


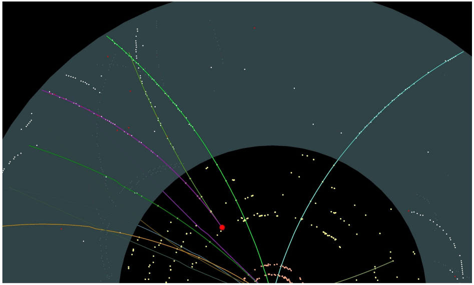
Clusters are fully calibrated offline:

- Simulation tuned using Test Beam data
- Energy scale uncertainty: 3% in TB, better than that with $Z \to ee$

Conversion Finding

All that ID material comes at a price....





Conversion reconstruction is critical, especially outside of central barrel:

- Look for secondary vertices consistent with pair production
- Also a clean source of low E_T electrons

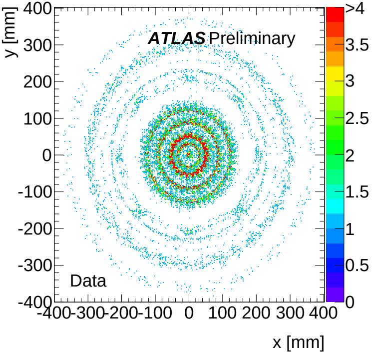
Conversion Finding

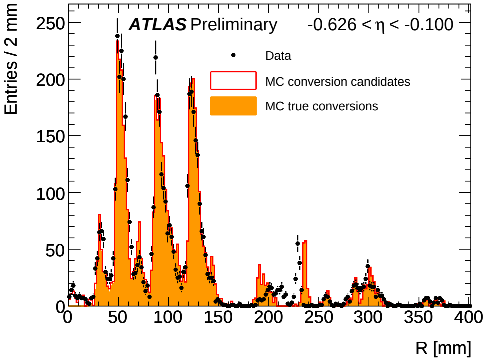
Dedicated algorithms reconstruct conversion vertices with high efficiency up to $R \approx 800$ mm:

- Back-tracking, from TRT into Si detectors, for vertex finding
- Cluster-seeded vertex matching to 'recover' photons tagged as electrons

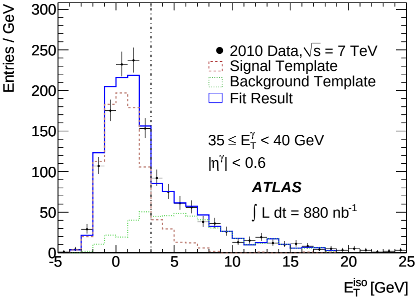
Conversion finding is also a powerful way to map the detector material:

- Material mapping (only uses vertices) is critical for precision measurements (W mass)





Isolation Templates

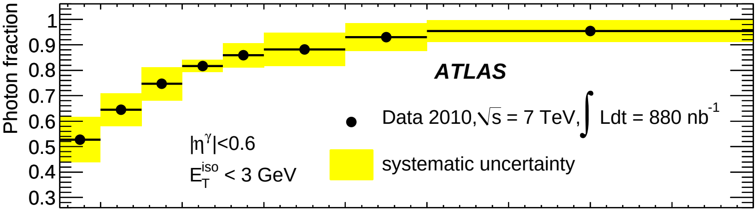


A full template fit is also possible

- Signal from $Z \rightarrow ee$ and $W \rightarrow e\nu$
- Background from reverse cuts
- MLL fit for signal yield for $E_{\mathrm{T}}^{\mathrm{iso}} < 3$ GeV

Results compatible with ABCD method

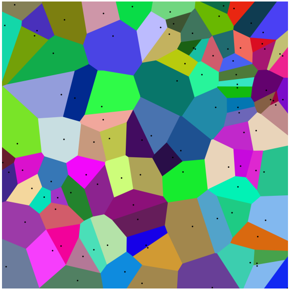
- Agree within uncorrelated uncertainties



Subtracting the Non-perturbative Contributions

Basic procedure of the jet area correction method:

- Bin the detector in strips of η
  - In our case: 0.00, 1.50, 3.00, 4.00, 5.00
  - If bins are too small, results are not stable
- Run jet finding
  - k_T algorithm, to avoid overly smoothed jet shapes
  - Minimum p_T at 0, to allow for very soft objects



Courtesy of Wikipedia

- Compute Voronoi areas of jets (partitioning the (η, ϕ) space into regions defined by nearest jet)
- From the jets and their areas, find the **median** energy density for the η bin
  - Median helps to avoid any scale effects from setting an upper bound on jet p_T
  - For events with low multiplicity and hard interactions, can remove n most energetic jets from event (where $n \approx 2$)
- Correction to isolation variables made based on the cone size

Isolation Studies

Stefano Frixione proposed an isolation prescription for reducing the fragmentation component in the inclusive analysis:

$$\boxed{\mathrm{E}_{\mathrm{T}}^{\mathrm{isolation}}(\mathrm{R}) < (\epsilon_s \cdot \mathrm{E}_{\mathrm{T}}^{\gamma}) \cdot \left(\frac{1 - \cos(\mathrm{R})}{1 - \cos(\mathrm{R}_0)} \right)^n}$$

- Apply progressively tighter cuts on smaller and smaller cones
- Terminates at $R = 0$ with a cut at 0
- Eliminates collinear fragmentation component, leaving only the direct component
    - Theoretically attractive, as the fragmentation component is less well understood

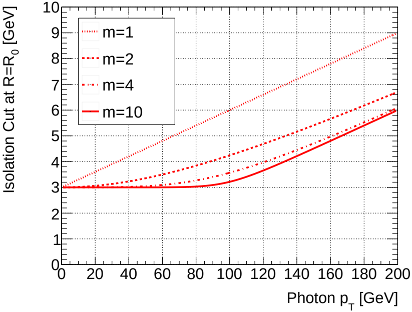
We worked with Frixione and the `JETPHOX` authors to modify the prescription to take into account experimental constraints:

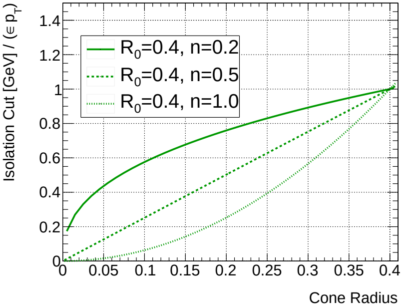
- Discrete calorimeter granularity → discrete cone sizes
- Molière radius not zero → terminate at $R \approx .1$
- Needs 'corrections' to to reconstructed isolation to properly remove non-perturbative contributions to the isolation cone

Frixione Isolation

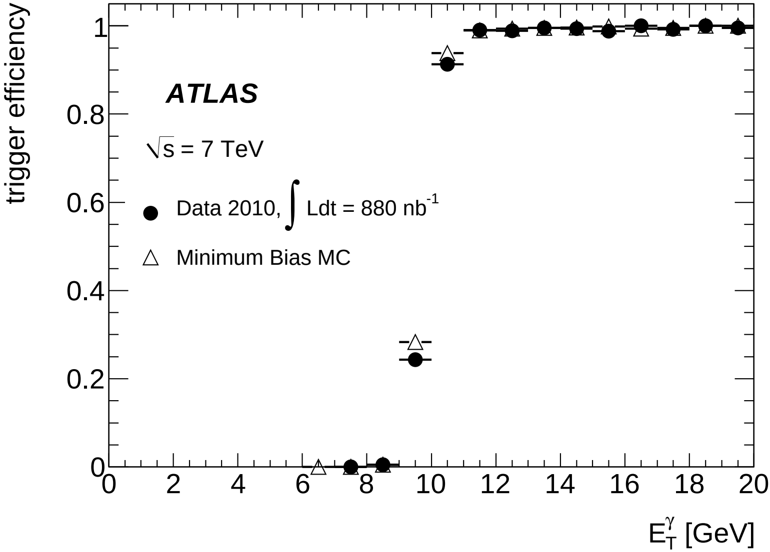
A discrete, generalized form of this prescription will be used in the next analysis:

$$E_T^{\text{isolation}}(R) < \underbrace{\left(\left(E_T^{R_0}\right)^m + \left(\epsilon_s \cdot E_T^{\gamma}\right)^m\right)}^{1/m} \cdot \underbrace{\left(\frac{1-\cos(R)}{1-\cos(R_0)}\right)}^{n}$$

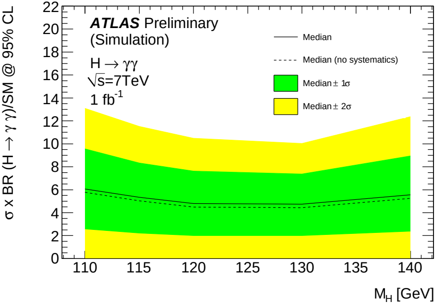


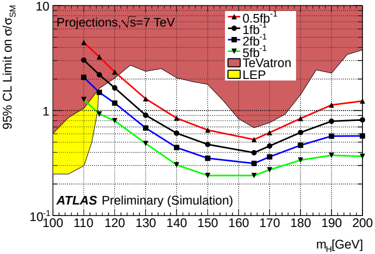


Single Photon Trigger Efficiency

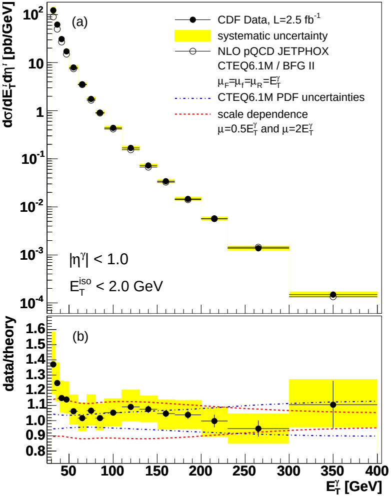


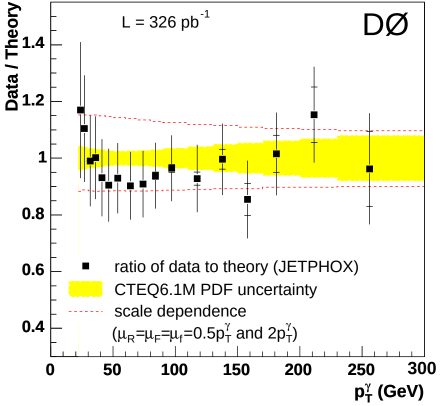
Higgs


ATLAS Preliminary
(Simulation)
H → γγ
√s=7TeV
1 fb⁻¹
Median
Median (no systematics)
Median ± 1σ
Median ± 2σ
σ x BR (H → γ γ)/SM @ 95% CL
0
2
4
6
8
10
12
14
16
18
20
22
110
115
120
125
130
135
140
M_H [GeV]

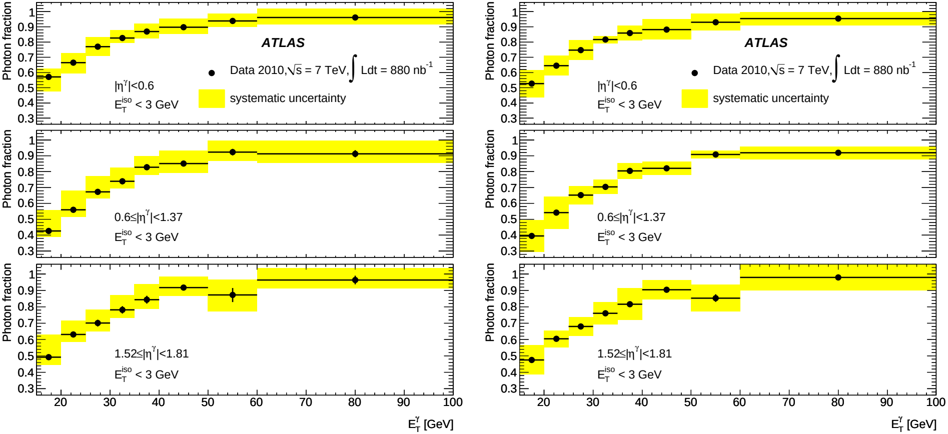

Projections,√s=7 TeV
0.5fb⁻¹
1fb⁻¹
2fb⁻¹
5fb⁻¹
TeVatron
LEP
ATLAS Preliminary (Simulation)
95% CL Limit on σ/σ_SM
10
1
10⁻¹
100
110
120
130
140
150
160
170
180
190
200
m_H[GeV]

Previous Measurements

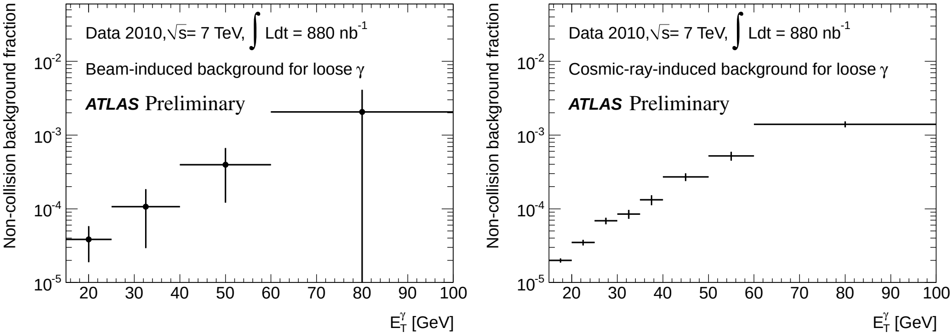




Purity Estimates



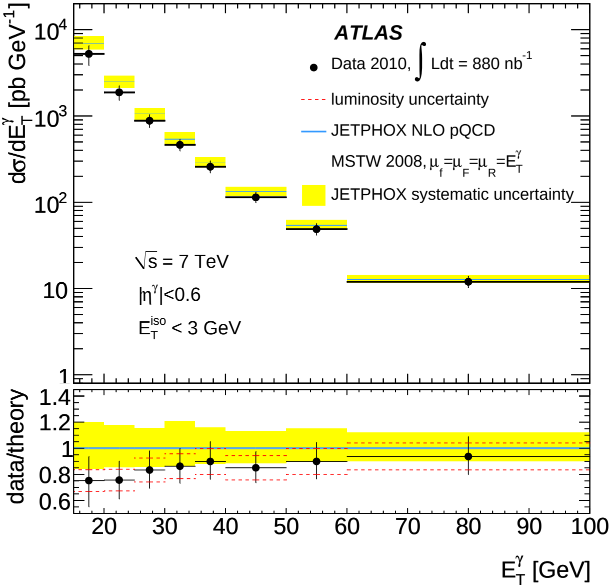
Non-Collision Backgrounds



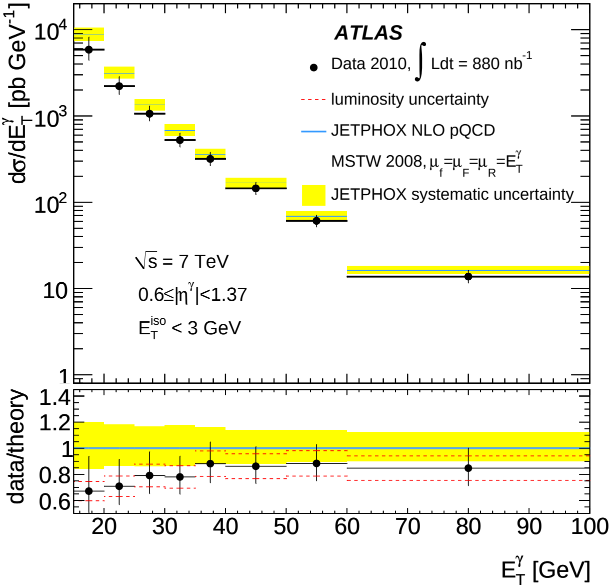
Non-collision backgrounds not an issue for this analysis:

- Will become more critical when extending past 100 GeV
- Also more serious issue when requiring E_T^{miss}

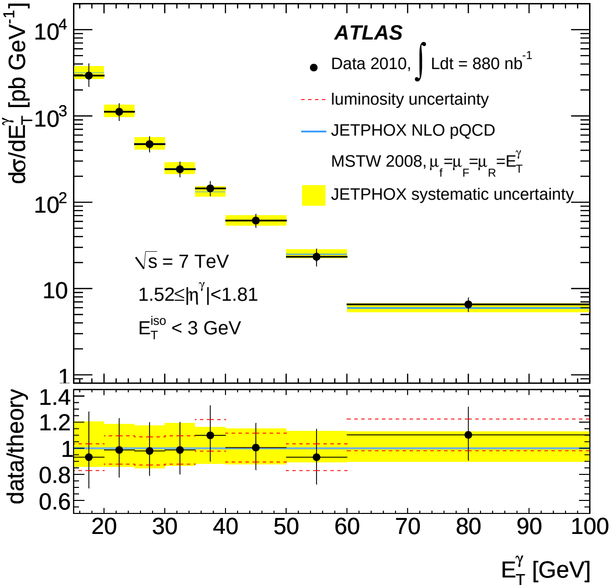
MSTW PDFs


ATLAS
● Data 2010, ∫Ldt = 880 nb^{-1}
luminosity uncertainty
JETPHOX NLO pQCD
MSTW 2008, $\mu_f=\mu_F=\mu_R=E_T^\gamma$
JETPHOX systematic uncertainty
$\sqrt{s}$ = 7 TeV
$|\eta^\gamma|<0.6$
E_T^{iso} < 3 GeV
$d\sigma/dE_T^\gamma$ [pb GeV^{-1}]
10^4
10^3
10^2
10
1
data/theory
1.4
1.2
1
0.8
0.6
20
30
40
50
60
70
80
90
100
E_T^γ [GeV]

MSTW PDFs


ATLAS
Data 2010, $\int$ Ldt = 880 nb^{-1}
luminosity uncertainty
JETPHOX NLO pQCD
MSTW 2008, $\mu_f=\mu_F=\mu_R=E_T^\gamma$
JETPHOX systematic uncertainty
$\sqrt{s}$ = 7 TeV
$0.6\leq|\eta^\gamma|<1.37$
E_T^{iso} < 3 GeV
$d\sigma/dE_T^\gamma$ [pb GeV^{-1}]
10^4
10^3
10^2
10
1
data/theory
1.4
1.2
1
0.8
0.6
20
30
40
50
60
70
80
90
100
E_T^γ [GeV]

MSTW PDFs


ATLAS
● Data 2010, $\int Ldt$ = 880 nb^{-1}
luminosity uncertainty
JETPHOX NLO pQCD
MSTW 2008, $\mu_f=\mu_F=\mu_R=E_T^\gamma$
JETPHOX systematic uncertainty
$\sqrt{s}$ = 7 TeV
$1.52\leq|\eta^\gamma|<1.81$
E_T^{iso} < 3 GeV
$d\sigma/dE_T^\gamma$ [pb GeV^{-1}]
10^4
10^3
10^2
10
1
data/theory
1.4
1.2
1
0.8
0.6
20
30
40
50
60
70
80
90
100
E_T^γ [GeV]