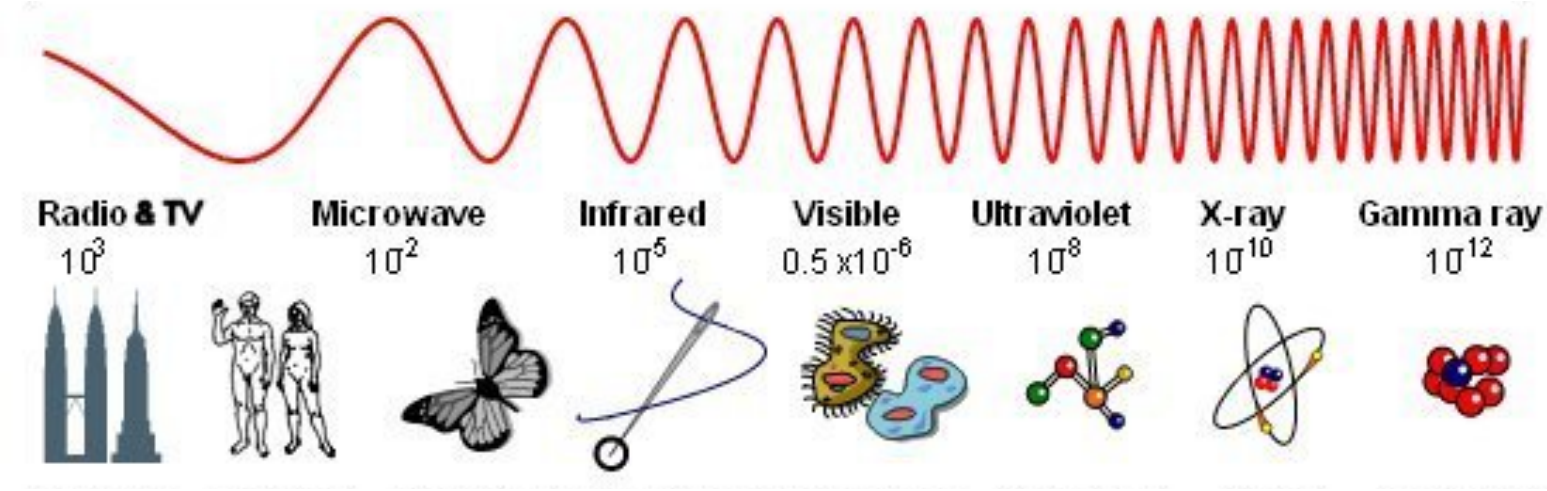
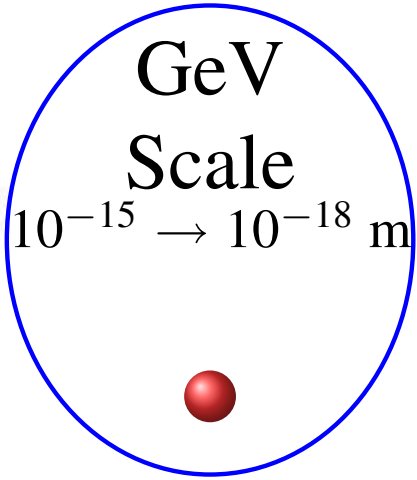
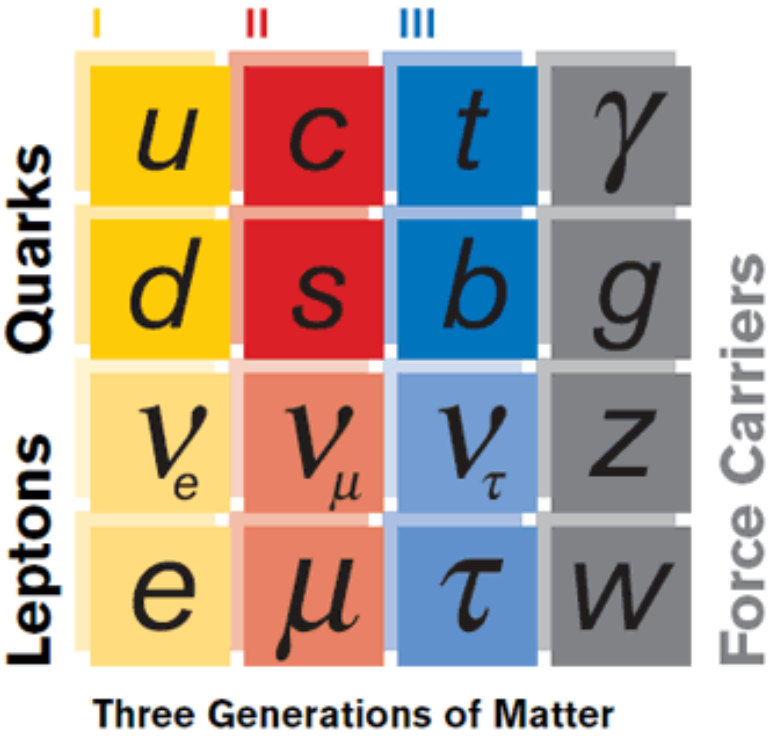
Prompt Photon Production at ATLAS

Mike Hance
University of Pennsylvania
16 December 2010

Photons







Photons were the focus of our first (built-in) particle detectors....

- One of the basic objects reconstructed at modern detectors
- Present in many interesting final states
- Probes QCD and new physics

Outline

Outline of today's seminar:

- Prompt Photons at ATLAS
  - SM Prompt Photon Physics (Overview)
  - The LHC and ATLAS
  - Photon ID
  - Background Estimates
  - Inclusive Isolated Cross Section
- Future Work With Photons
  - More Inclusive Studies
  - SM Diphotons
  - Higgs
  - Exotics

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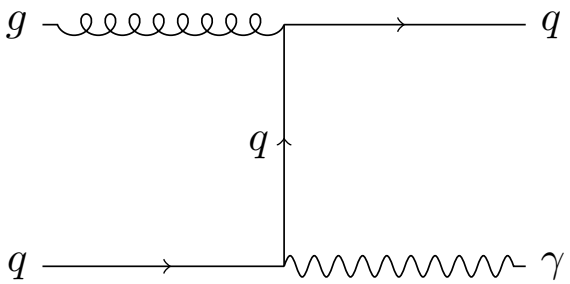
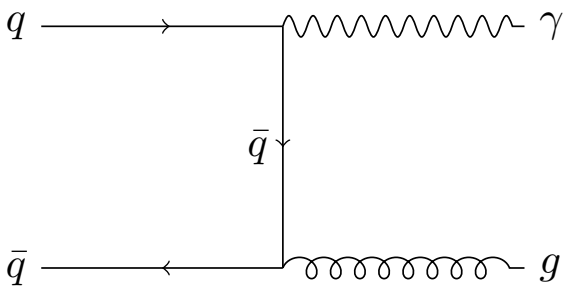
Prompt Photon Physics

How are photons produced in pp collisions?



Compton Scattering

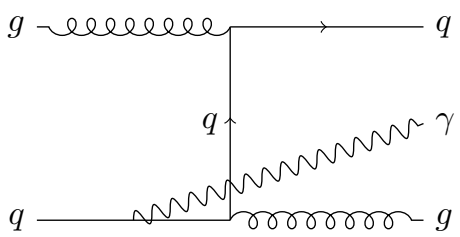


Annihilation

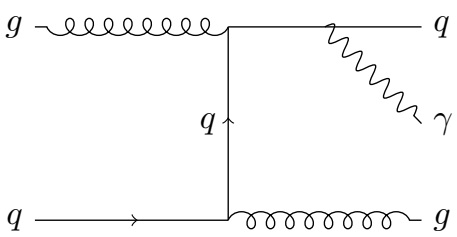
At leading order, the dominant mechanism at the LHC is the Compton-like process.

- This is true for all E_{T}^{γ}(at Tevatron, annihilation process dominates at high E_{T}^{γ})
- Allows us to probe the gluon content of the proton
- We call these **direct** photons

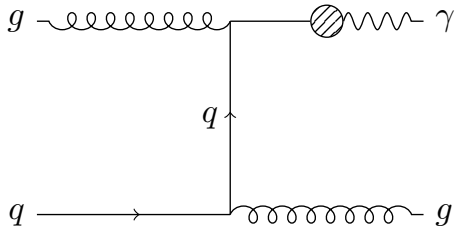
But the story goes beyond leading order....



ISR



FSR



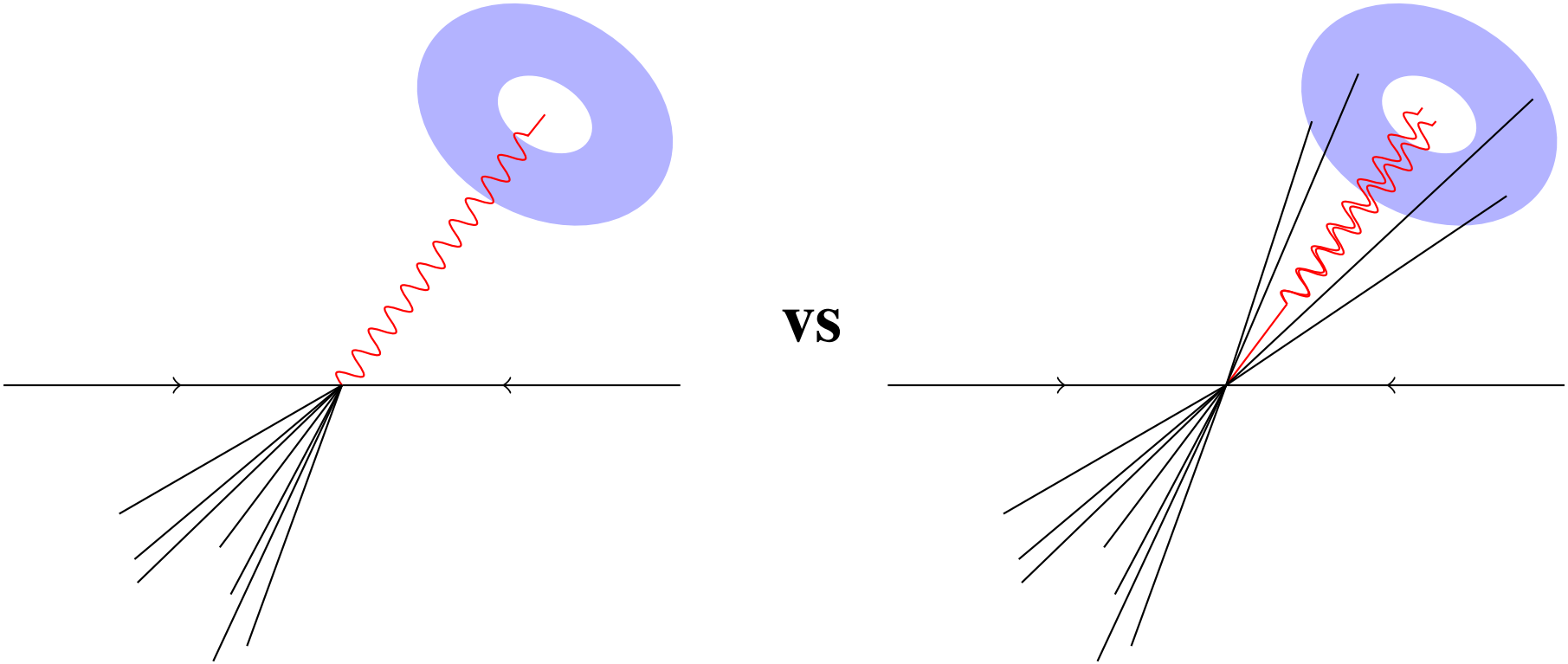
Fragmentation

At **NLO**, photons are produced via QED radiation off quark lines (brems) or via fragmentation

- At low E_{T}^{γ}, these processes are very important
- At higher E_{T}^{γ}, the LO diagrams are dominant
- We call these **fragmentation** photons

Isolation?

Why only consider *isolated* prompt photons?

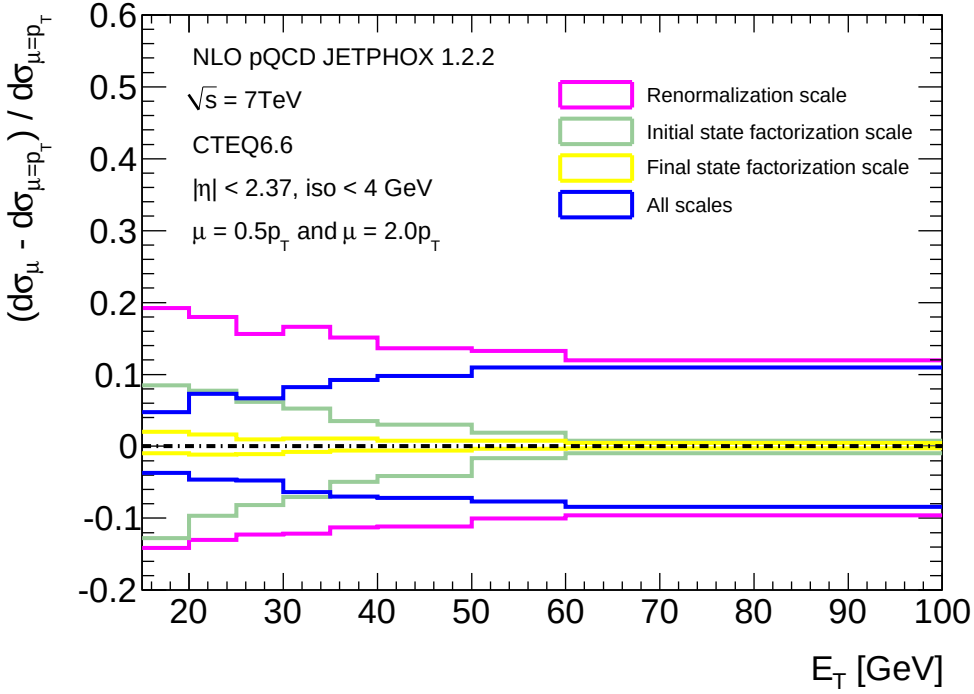


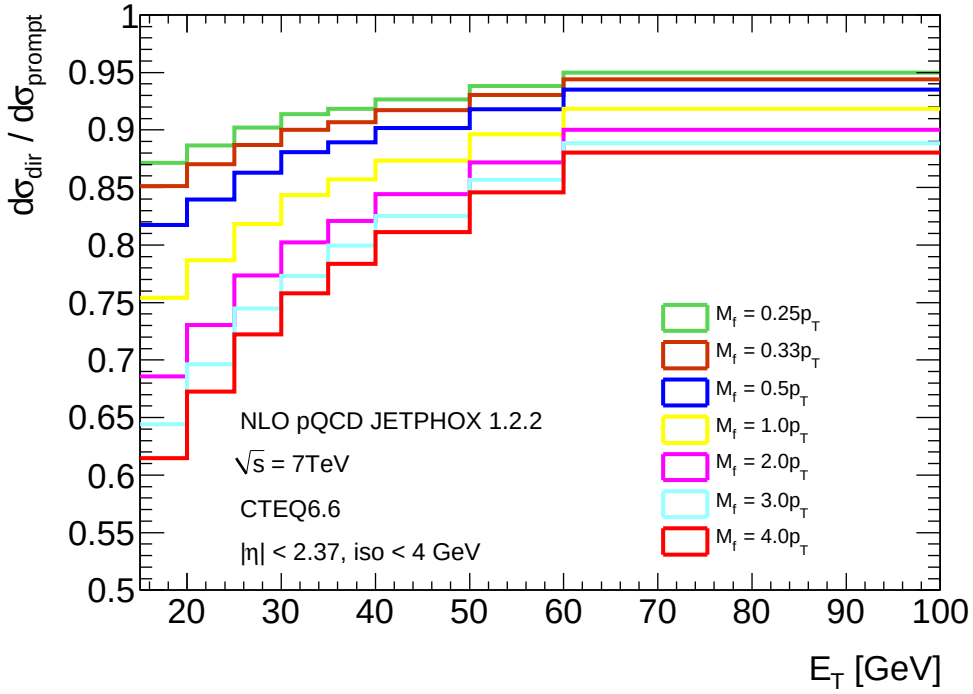
Isolation helps suppress backgrounds (*e.g.* $\pi^0 \to \gamma\gamma$), also helps suppress fragmentation photons.

Prompt Photons at NLO

State of the art for theoretical predictions:

- Fully NLO calculators available - most commonly used is `JETPHOX`
  - Allows for different isolation prescriptions
  - Benchmark for most recent Tevatron analyses
  - Sister package to `DIPHOX`, for diphoton production
- Some recent work at NNLL by Becher *et al*, but still relies on `JETPHOX` for isolation
- All rely on unphysical scales to make finite predictions at NLO
  - Renormalization, factorization, fragmentation scales, all set to $\approx E_{\mathrm{T}}^{\gamma}$





Measuring the Cross Section

One of the first questions we can ask (and answer): **how many do we see?**

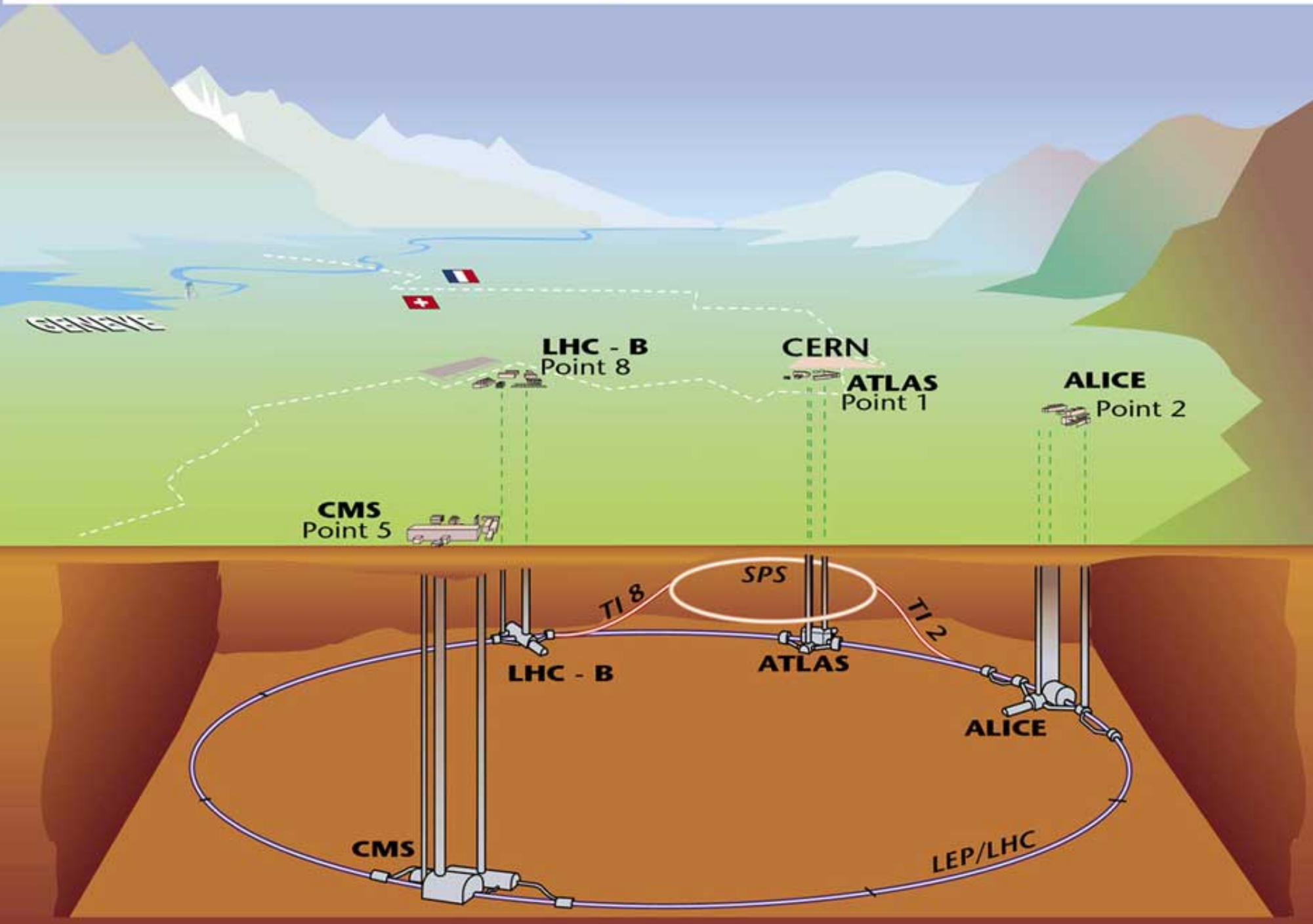
$$\boxed{\frac{d\sigma}{dE_{\mathrm{T}}^{\gamma}} = \frac{N \cdot P \cdot U}{\Delta E_{\mathrm{T}}^{\gamma} \cdot \varepsilon \cdot \mathcal{L}}}$$

- N: Number of candidates
- P: Purity of candidates
- $\Delta_{p_{\mathrm{T}}}$: Size of p_{T} bin
- ε: Efficiency (trigger, reconstruction, selection)
- U: Unfolding factors (detector response)
- $\mathcal{L}$: Integrated luminosity

Fortunately, we have just the detector for the job....

The LHC and ATLAS

Overall view of the LHC experiments.

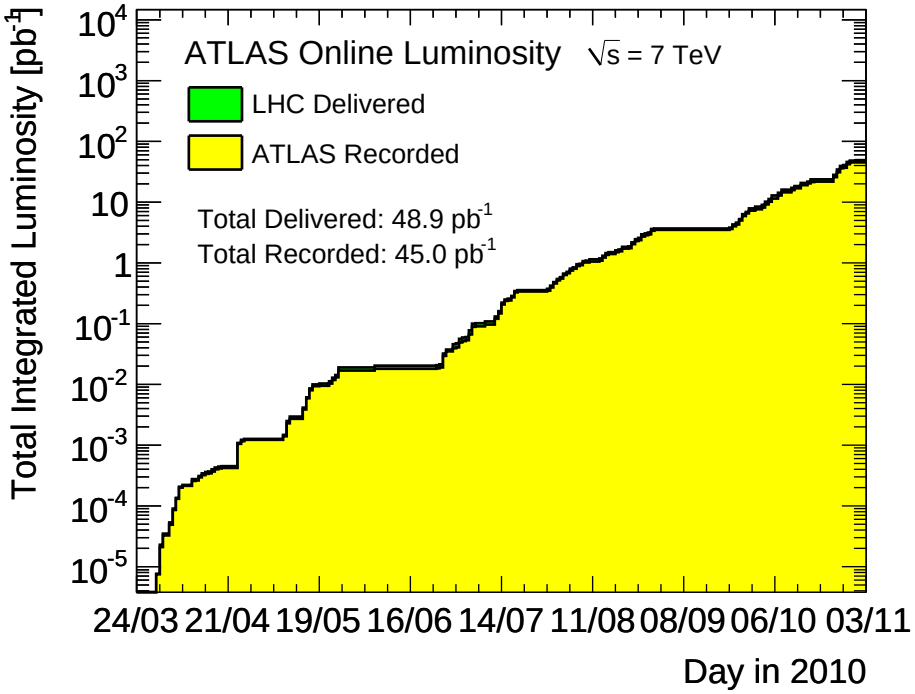


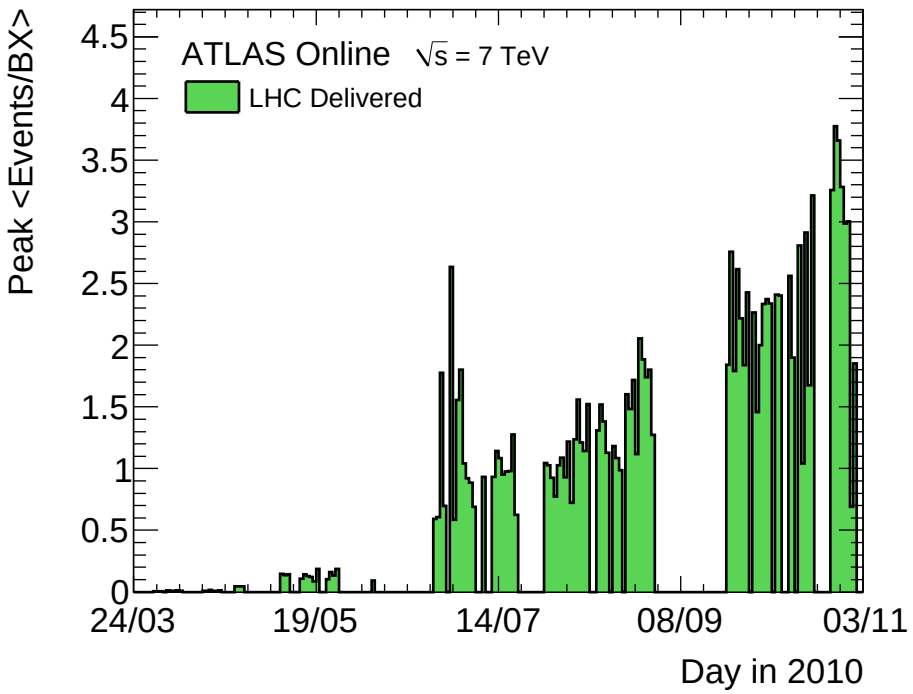
First beam in 2009

First 7 TeV collisions in 2010

Luminosity

After all of the initial fits and starts... the machine performance has been excellent:

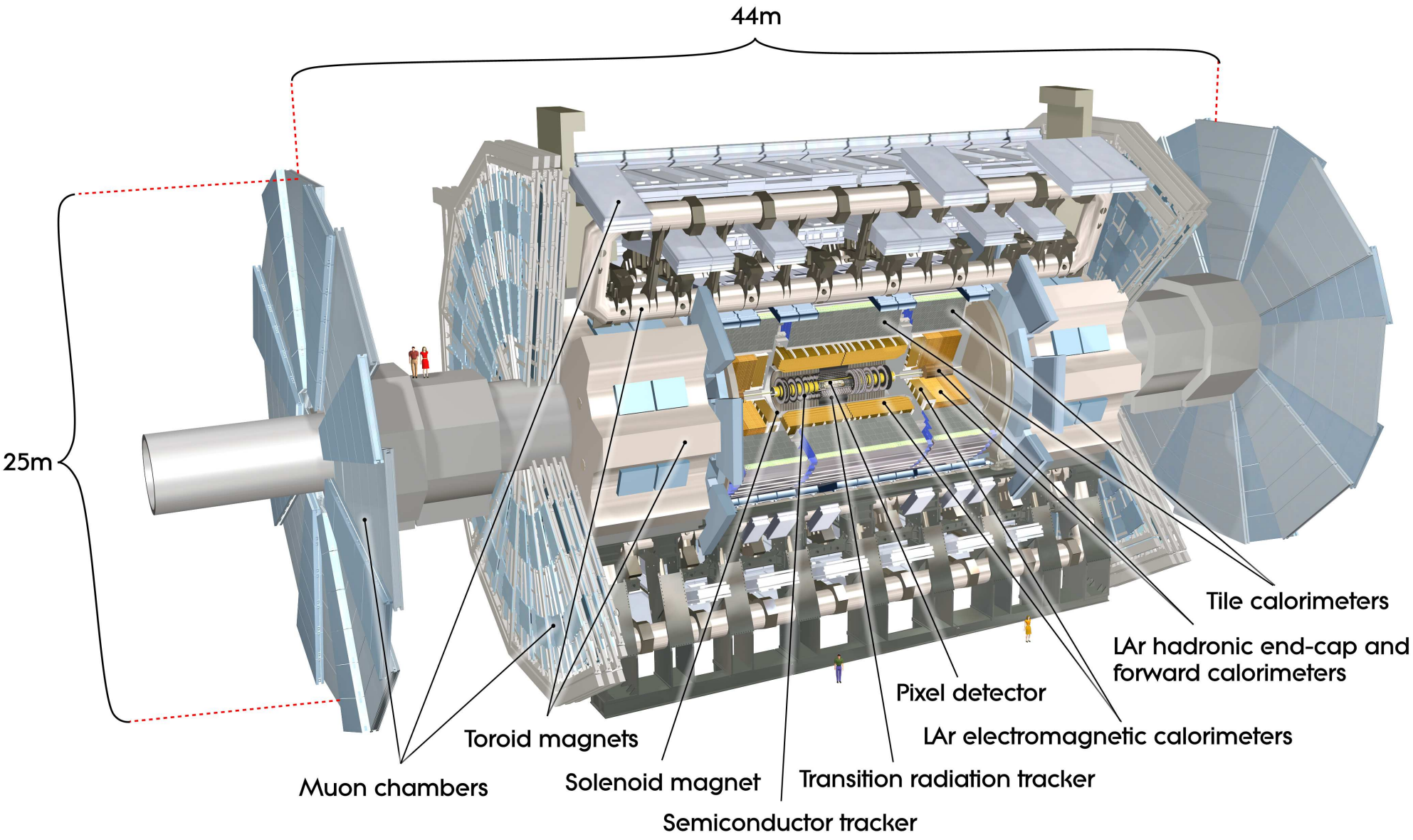




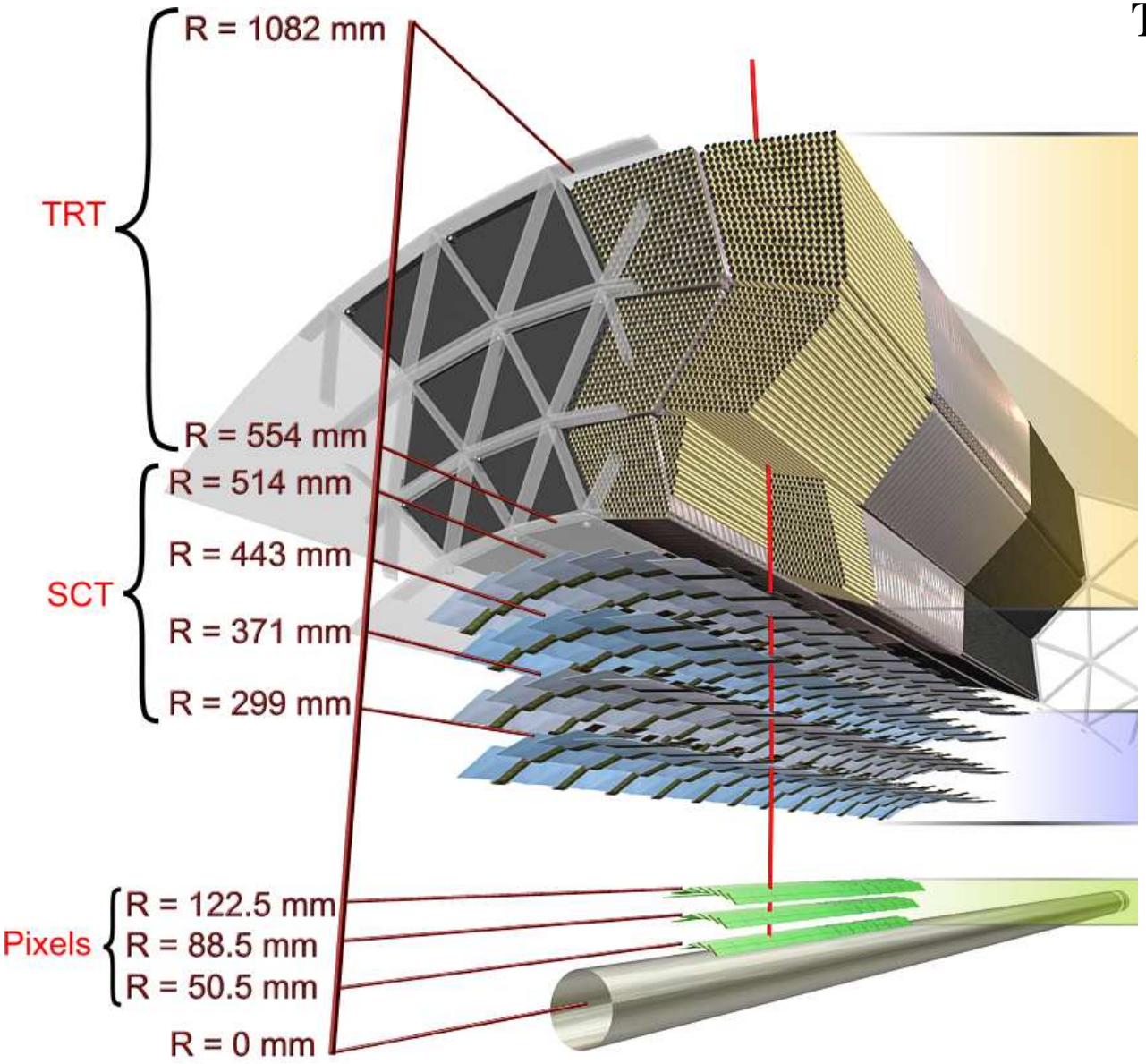
Absolute luminosity calibration using van der Meer scans:

- Many methods within ATLAS - all agree within a few percent
- 11% total uncertainty on luminosity - dominated by bunch intensity

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$130μm resolution

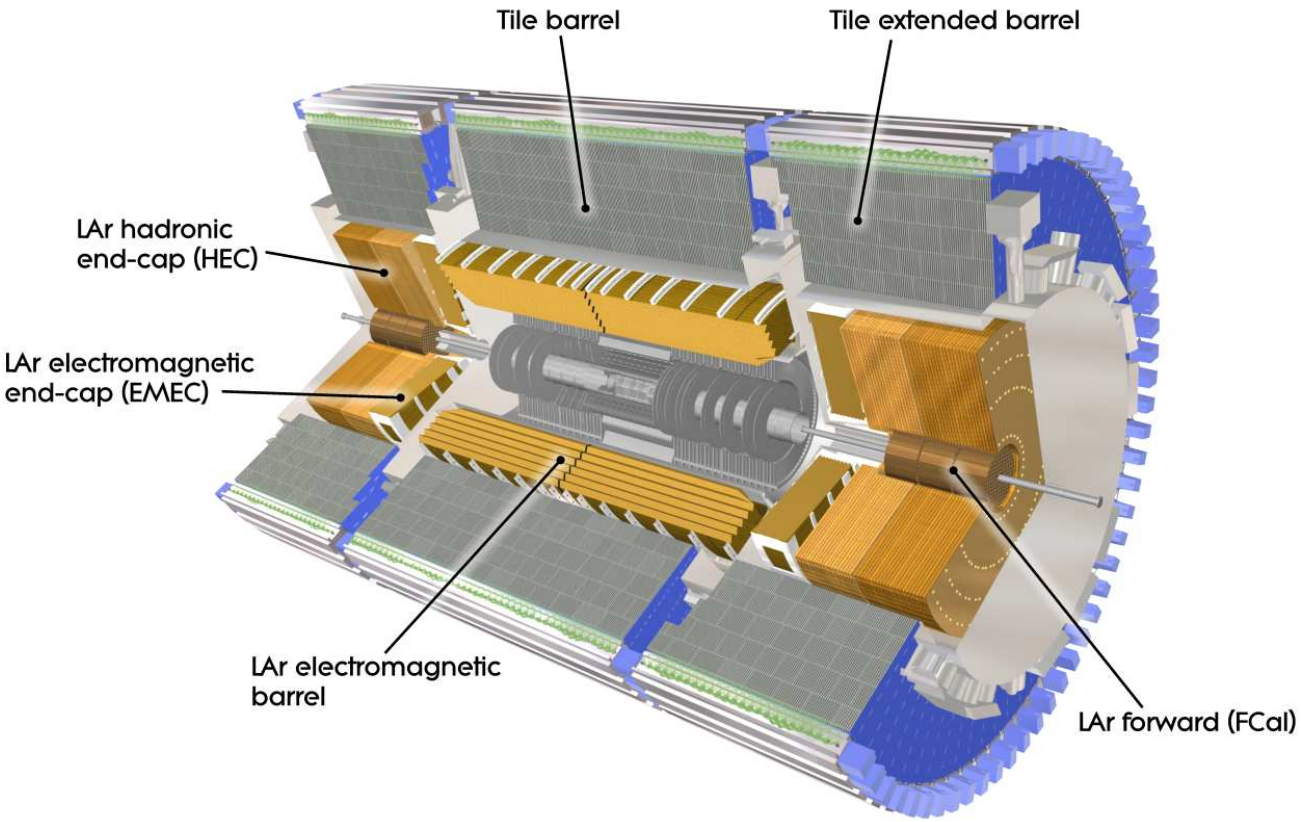
Semi-Conductor Tracker

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

Pixel Tracker

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

Calorimetry



EM Calorimeter

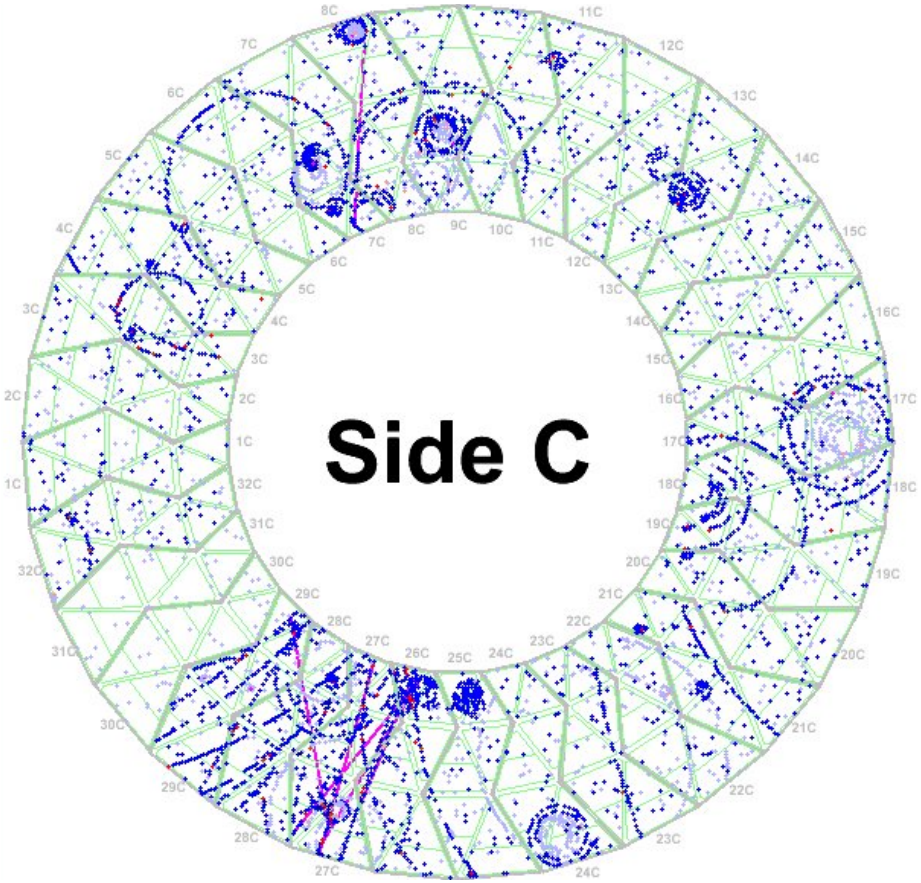
- PB-LAr Accordion
- $\Delta E/E = \left(10\%/\sqrt{E}\right) \oplus .7\%$
- $.025 \times .025$ cells $(\eta \times \phi)$
- Angular res.: 50 mrad / $\sqrt{E}$

Hadronic Calorimeter

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

Detector Operations

- Several years worth of cosmics runs paid off for first collisions!
- Good operational efficiency from all subsystems - will improve.

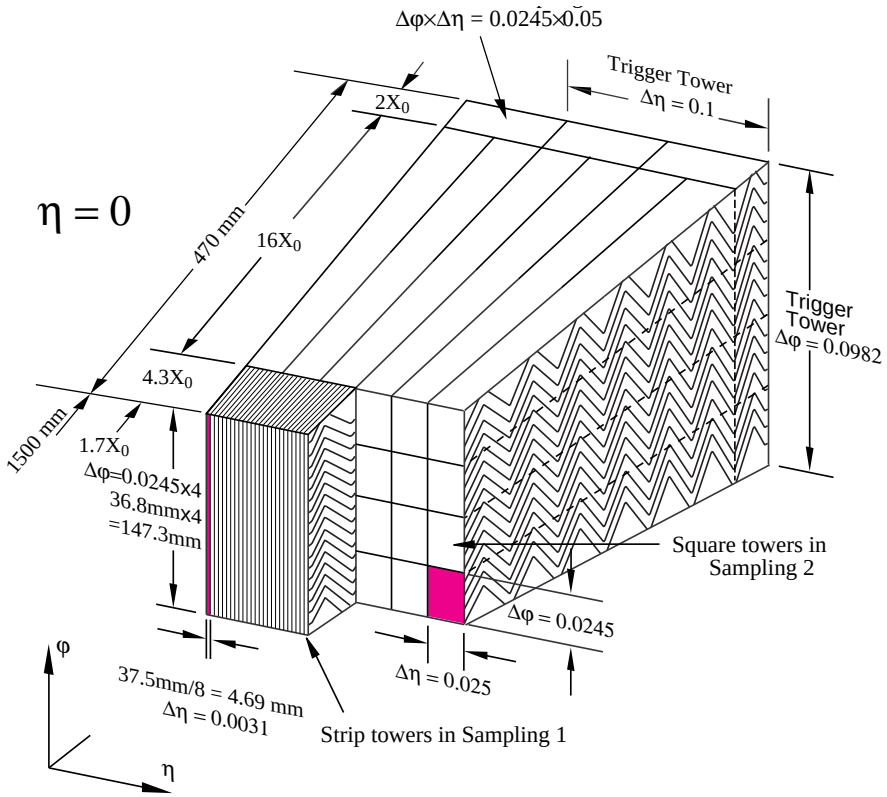


Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.0	99.9	100	90.5	96.6	97.8	94.3	99.9	99.8	96.2	99.8

Photon Reconstruction and ID

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

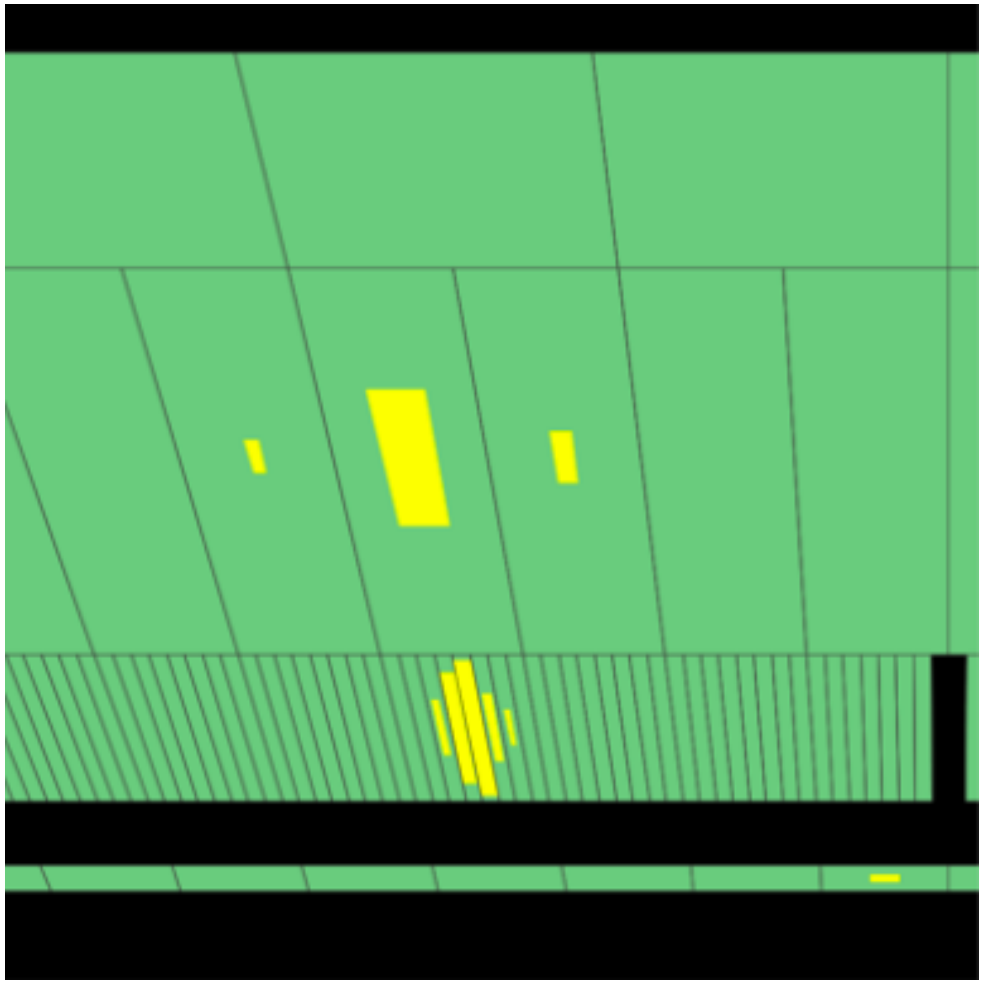


Clusters are fully calibrated offline:

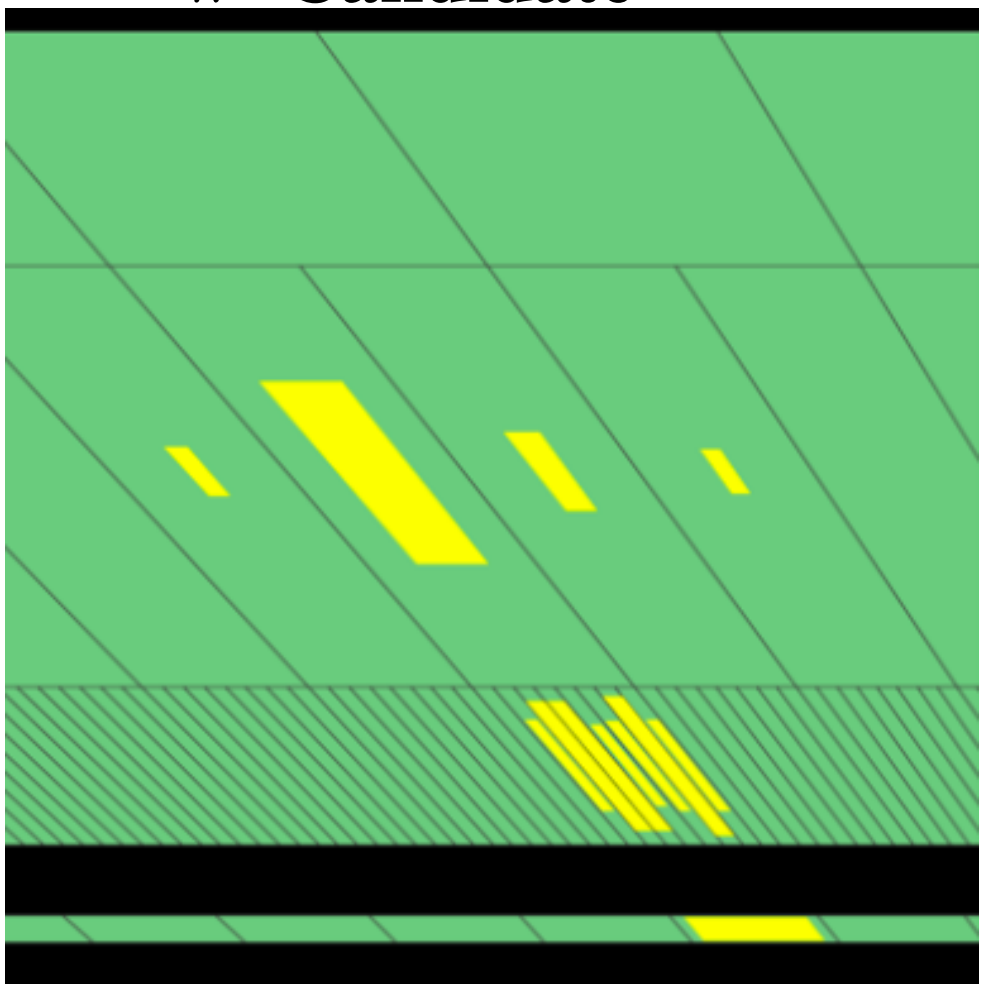
- Simulation tuned using Test Beam data
- Energy resolution: 3% in TB, better than that with $Z \rightarrow ee$

Photon/π^0 Discrimination

Single Photon

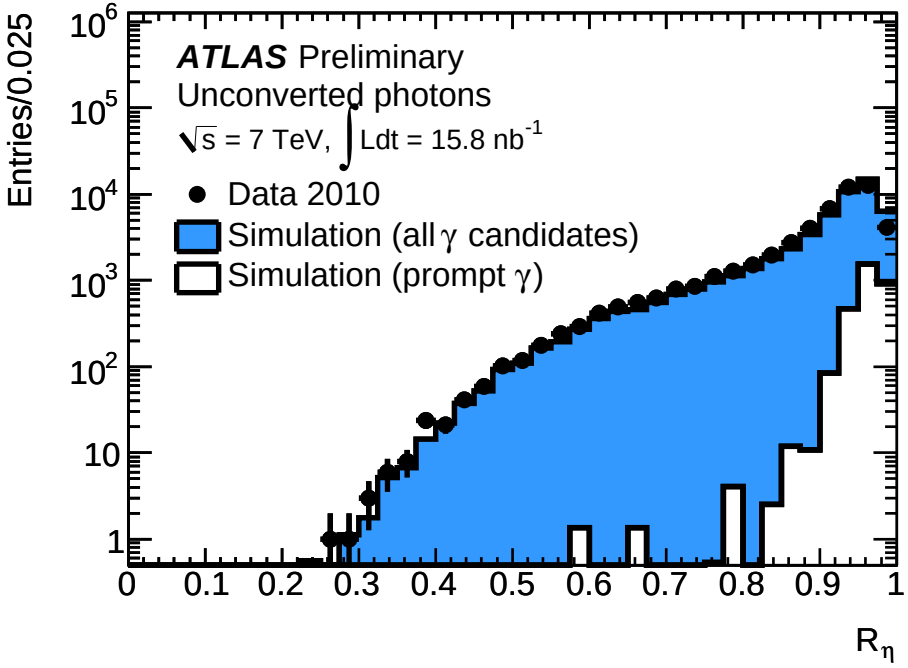


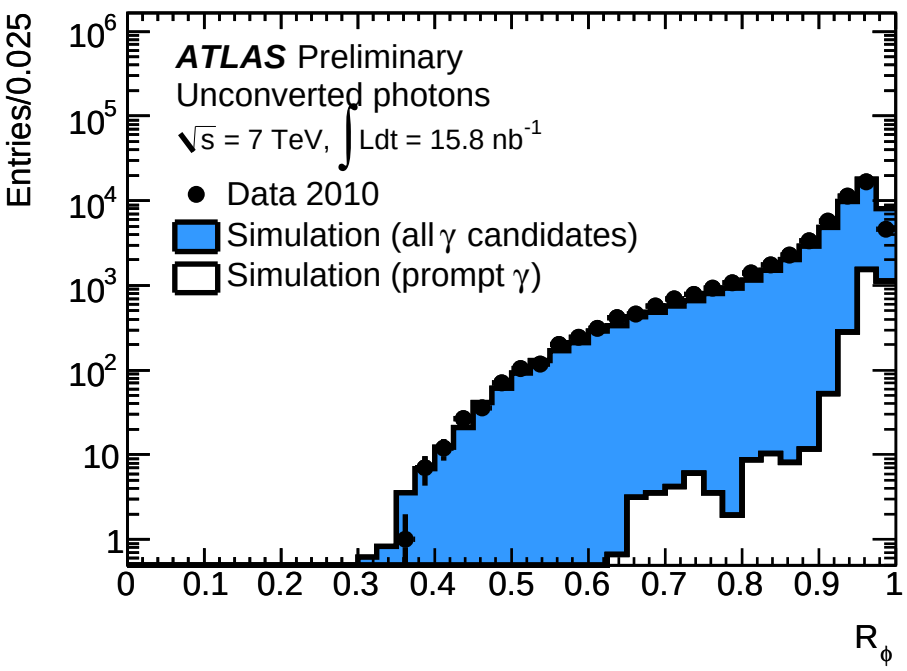
π^0 Candidate



Shower Evolution - Layer 2

The layer 2 shower shape cuts require compact clusters consistent with single photons:

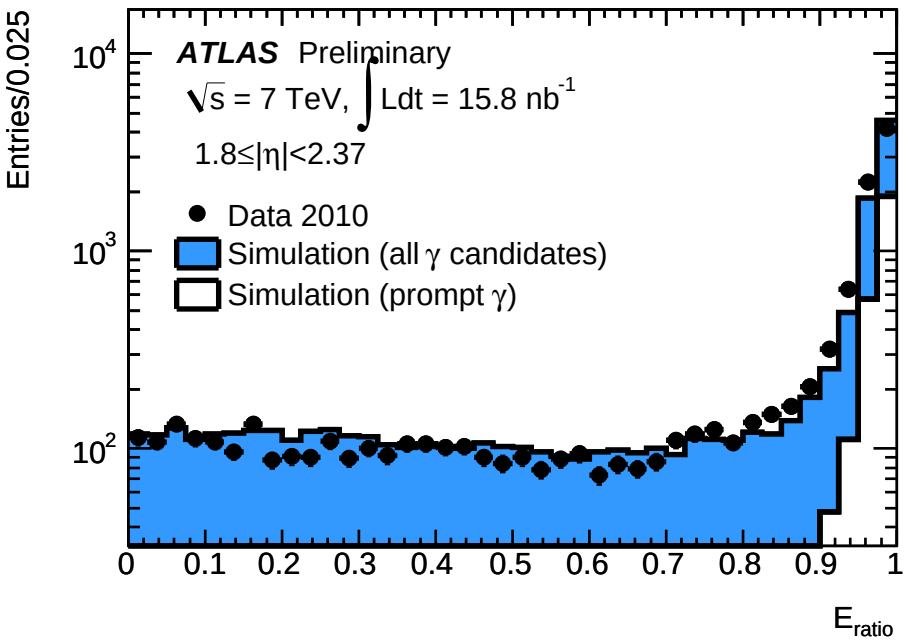


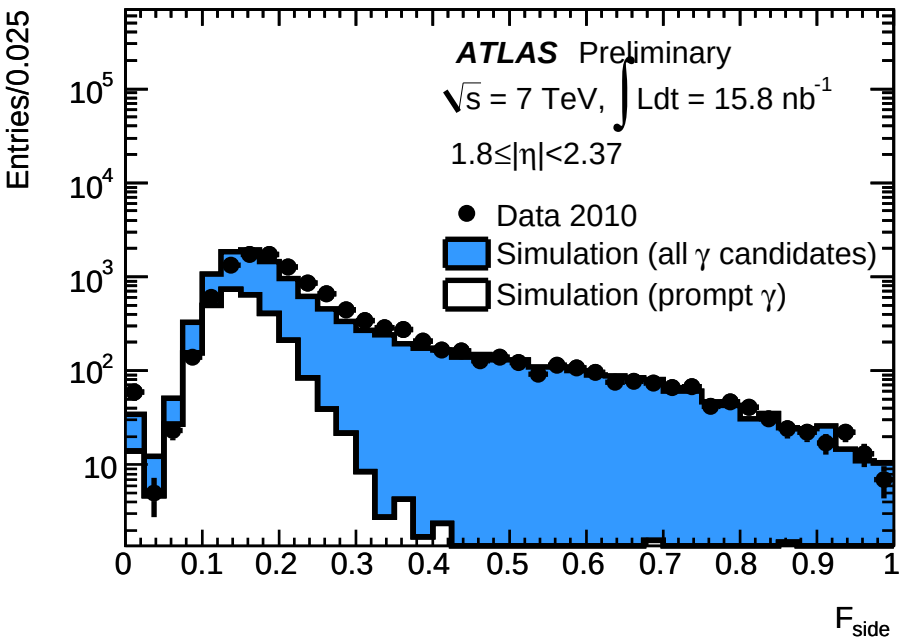


- Width in η
- Width in ϕ
- Leakage into hadronic calorimeter

Shower Evolution - Strips

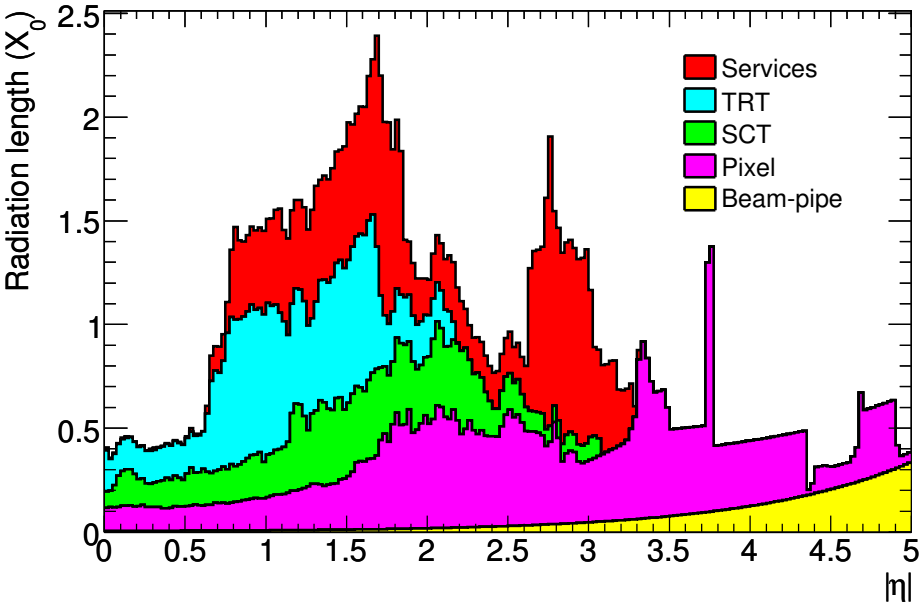
The layer 1 (strips) provide excellent eta resolution, and allow increased discrimination of single photons from π^0's

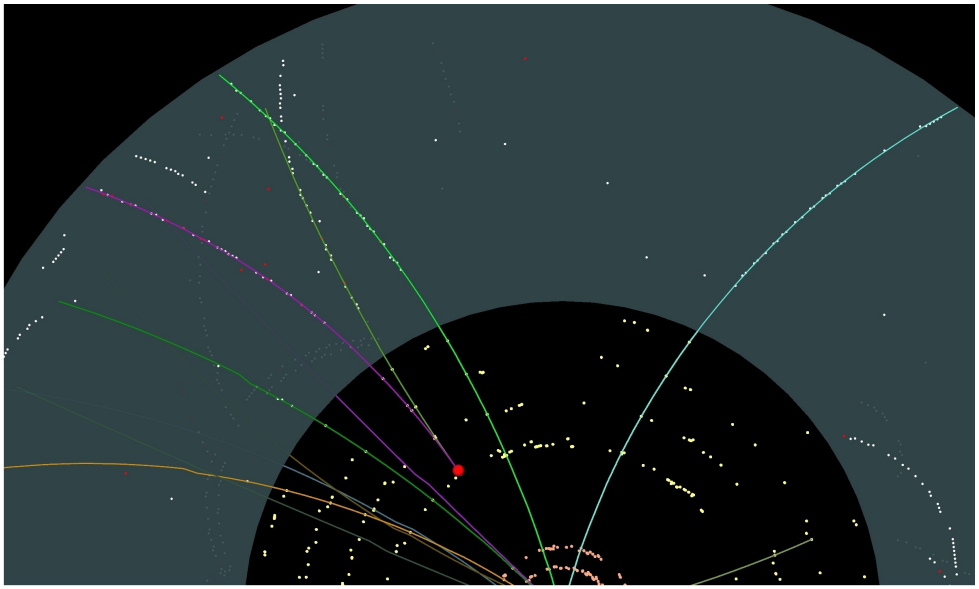




- Look for two local maxima, or wider showers in η or ϕ
- Usually measured over the equivalent of a few cells at layer 2
  - $\Rightarrow$ Largely uncorrelated with isolation variables

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





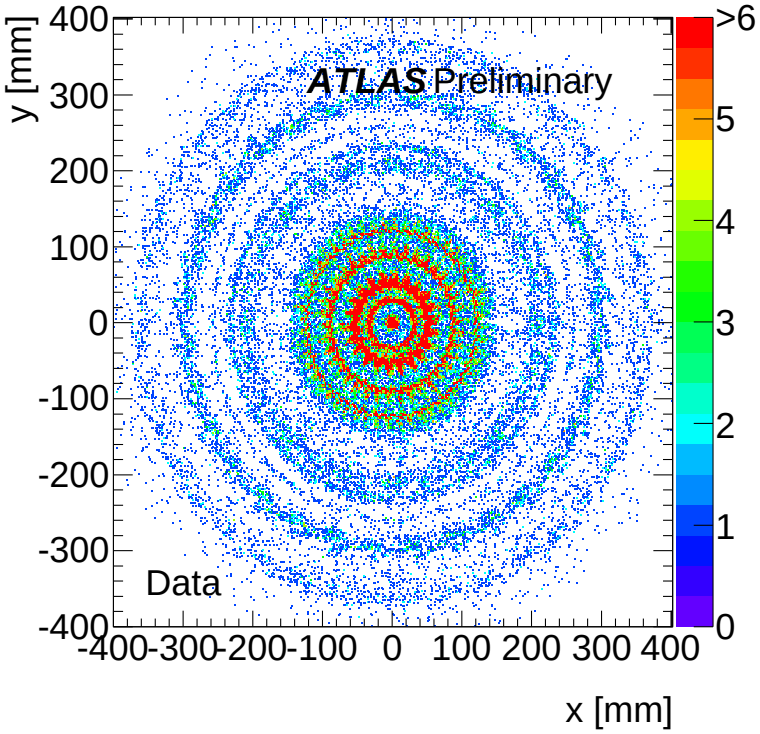
Conversion reconstruction is critical, especially outside of central barrel:

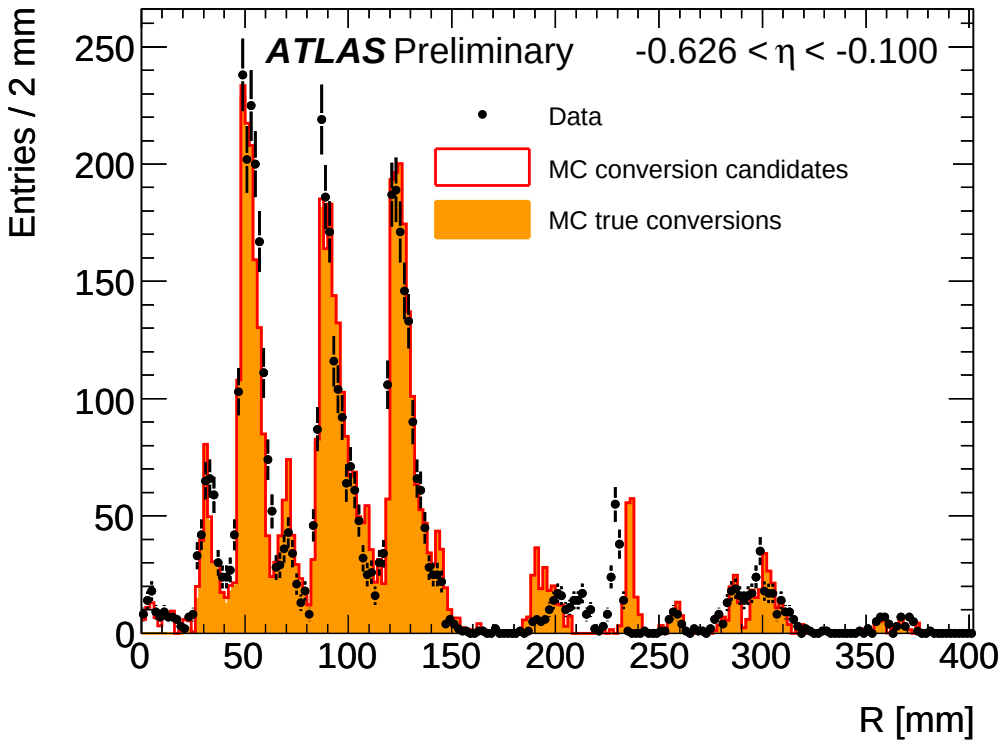
- Look for secondary vertices consistent with pair production
- Also a clean source of low E_{T} electrons

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

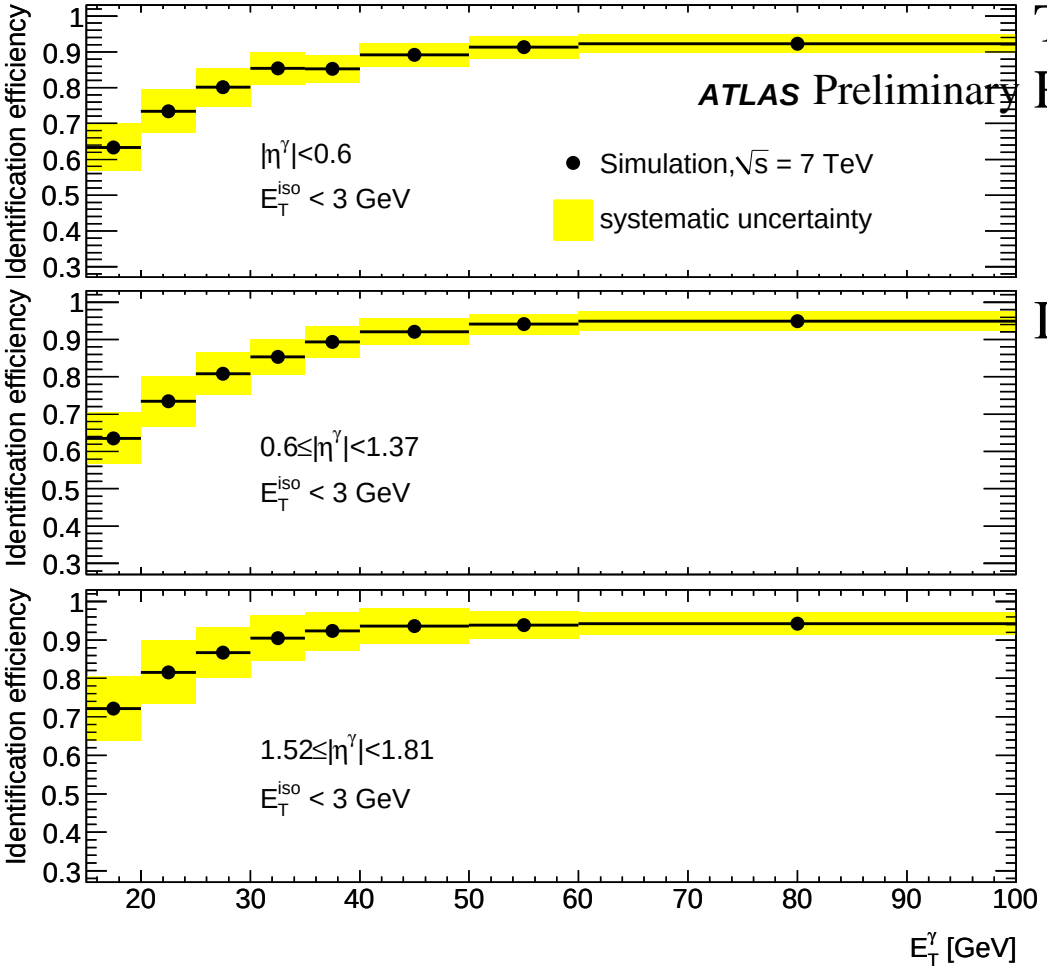




Conversion finding is also a powerful way to map the detector material:

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

Measured Efficiencies



Trigger Efficiency: **99.5%**

Reconstruction efficiency: **82%**

- Including recoverable acceptance losses

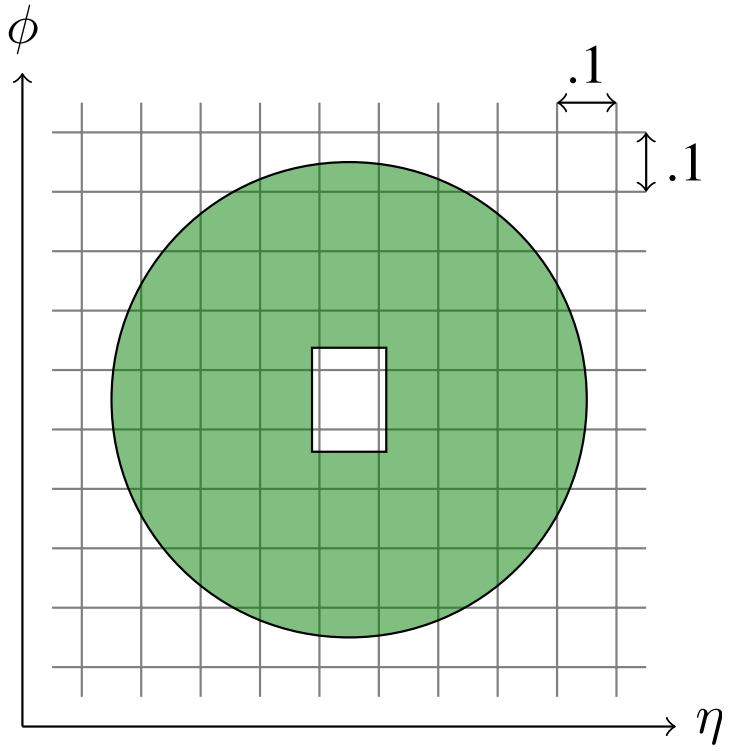
ID efficiency determined from MC:

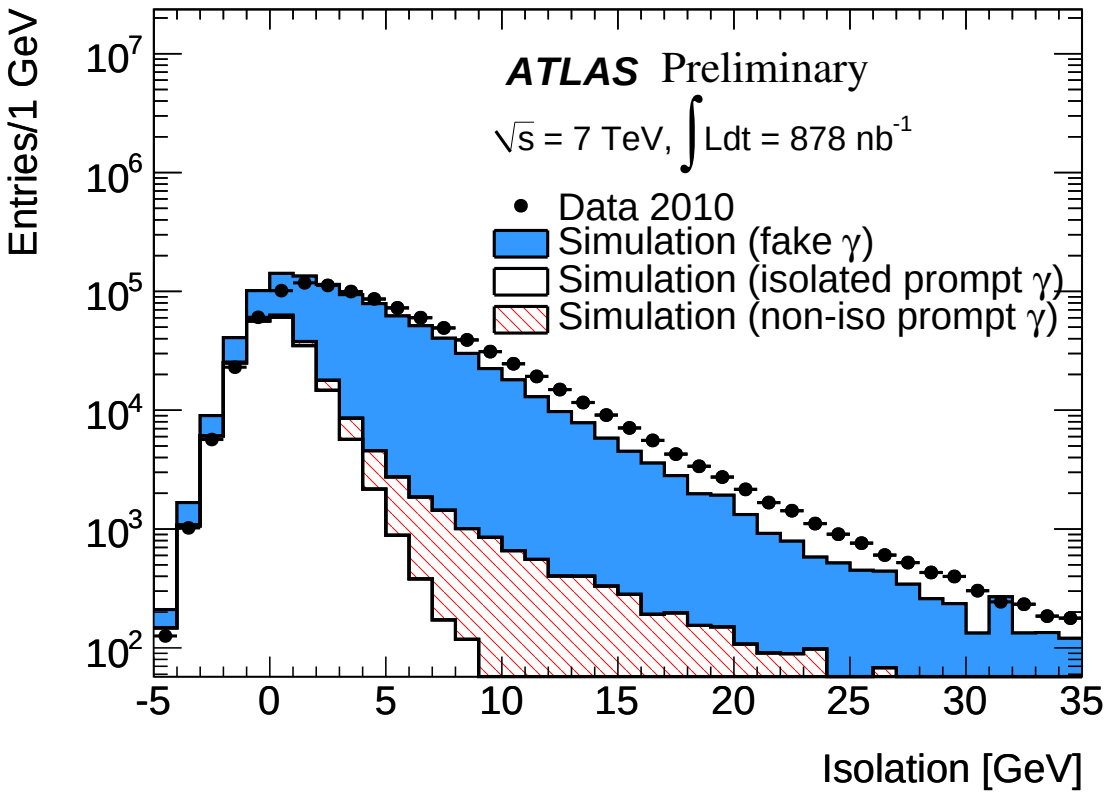
- Shift shower-shapes in MC to match data
- Separately for converted/unconverted
- Verified using $W \rightarrow e\nu$
- Systematics from:
  - Material effects
  - Pileup
  - Conversions
  - Many more....

Overall systematics ≈15% (relative)

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

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 (Molière radius $\approx .1$)
- Also need to account for non-perturbative effects....

Corrections for Underlying Event/Pileup

To correct for ambient energy not associated with the hard scatter, there are several different techniques on the market:

- "Look at 90°" technique, AKA `TransMin`/`TransMax` methods, AKA ...
  - Event-by-event correction, using transverse regions to estimate ambient energy from underlying event
- Counting primary vertices
  - Assume a certain amount of energy contributed by each min-bias interaction
  - Can combine this with tracking information to get the charged particle contribution to the cone of interest, making it more event-driven
- Others?

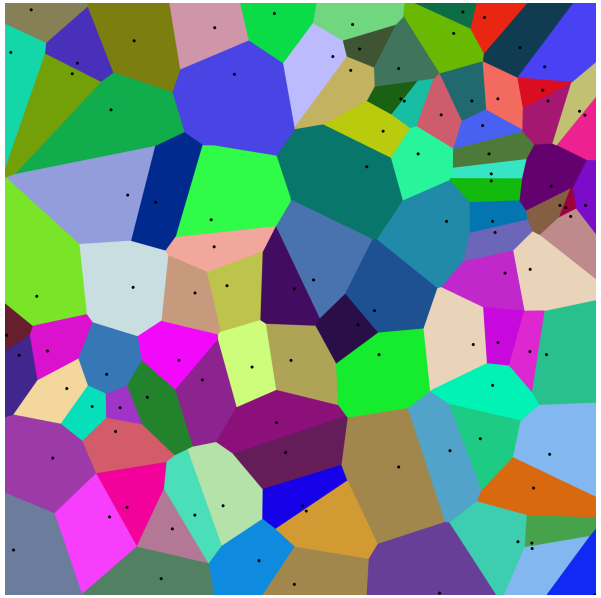
A relatively new method, different from the above, uses low p_{T} jets (and their areas) to estimate the ambient energy:

- Method proposed by Cacciari, Salam, and Sapeta (`http://arxiv.org/abs/0912.4926`)
- Developed for ATLAS by Brian Martin and Joey Huston

Subtracting the Non-perturbative Contributions

Basic procedure of the jet area correction method:

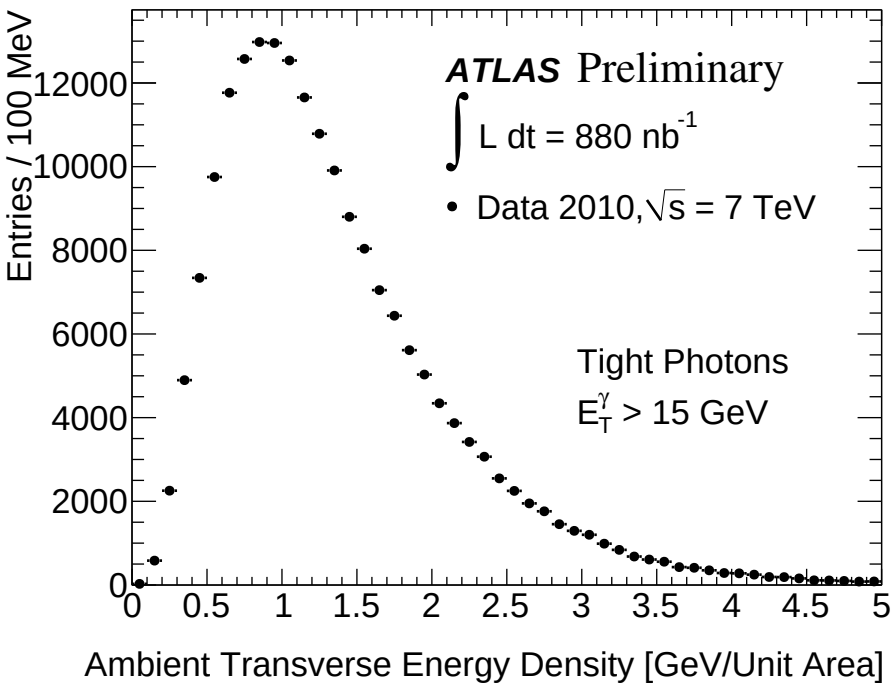
- Bin the detector in strips of η
  - In our case: 0.00, 1.50, 3.00, 4.00, 5.00
  - If bins are too small, results are not stable
- Run jet finding
  - k_T algorithm, to avoid overly smoothed jet shapes
  - Minimum p_T at 0, to allow for very soft objects

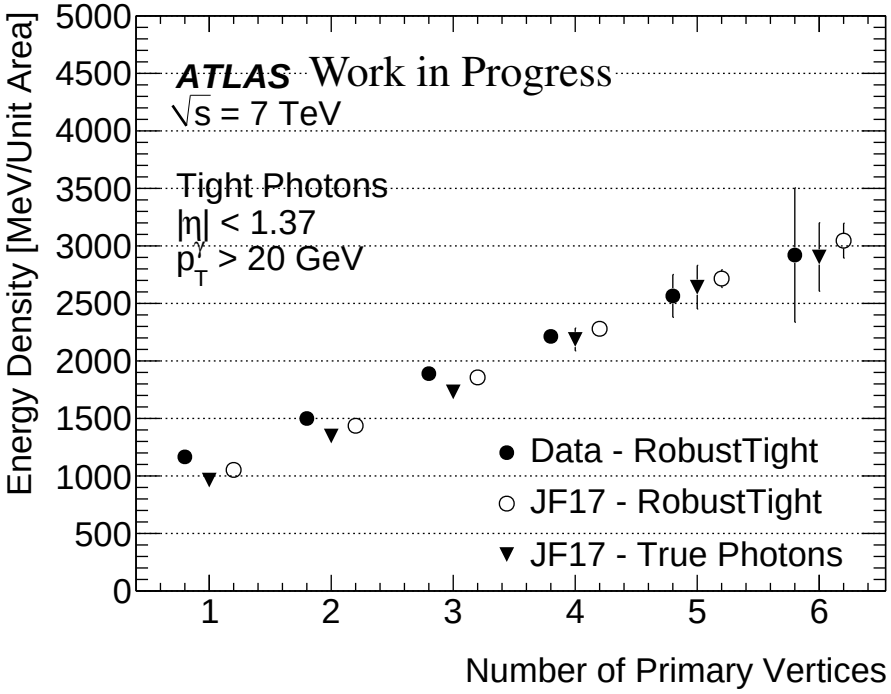


Courtesy of Wikipedia

- 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

Ambient Energy Corrections





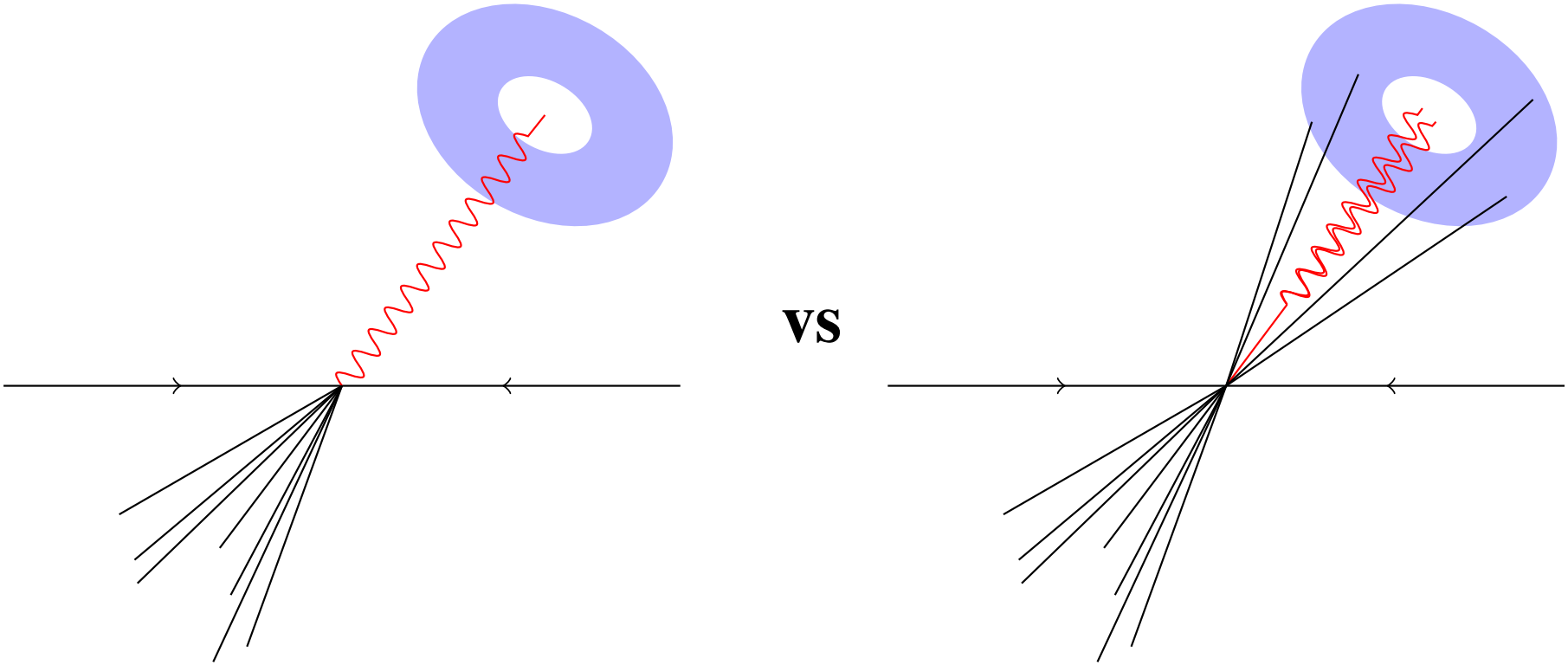
Corrections appear to be well behaved, and consistent with MC. Average correction for 1 PV:

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

Background Estimation

Background Estimates

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



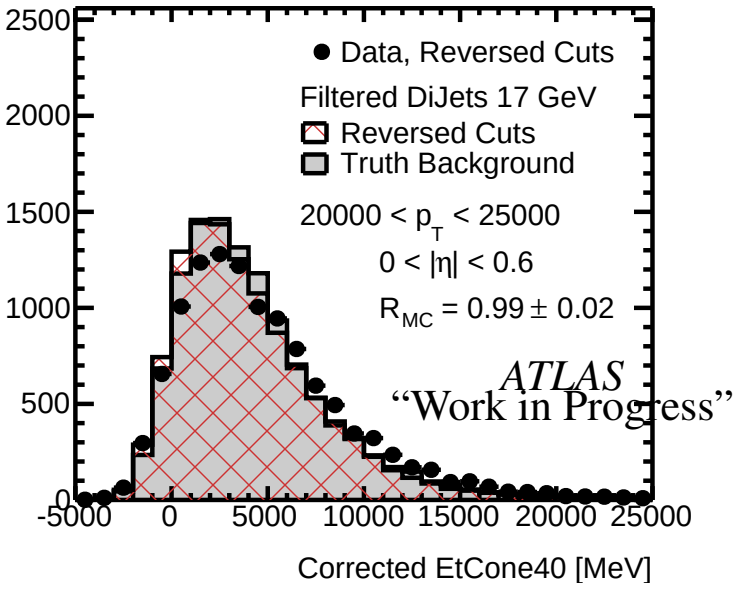
Main challenge: modeling signal and background isolation profiles:

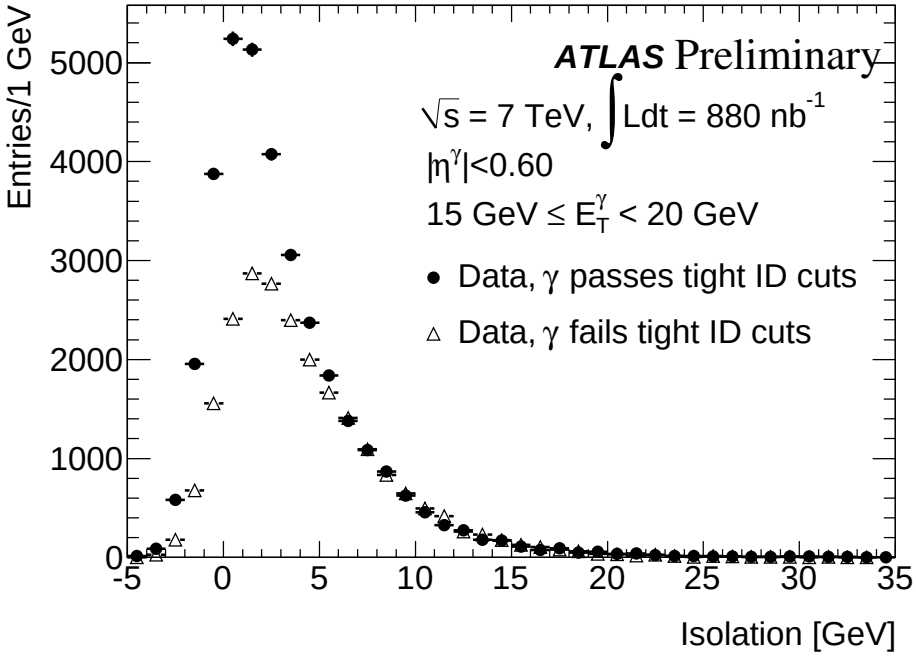
- Stay data-driven as much as possible
- Avoid biases from untuned MC

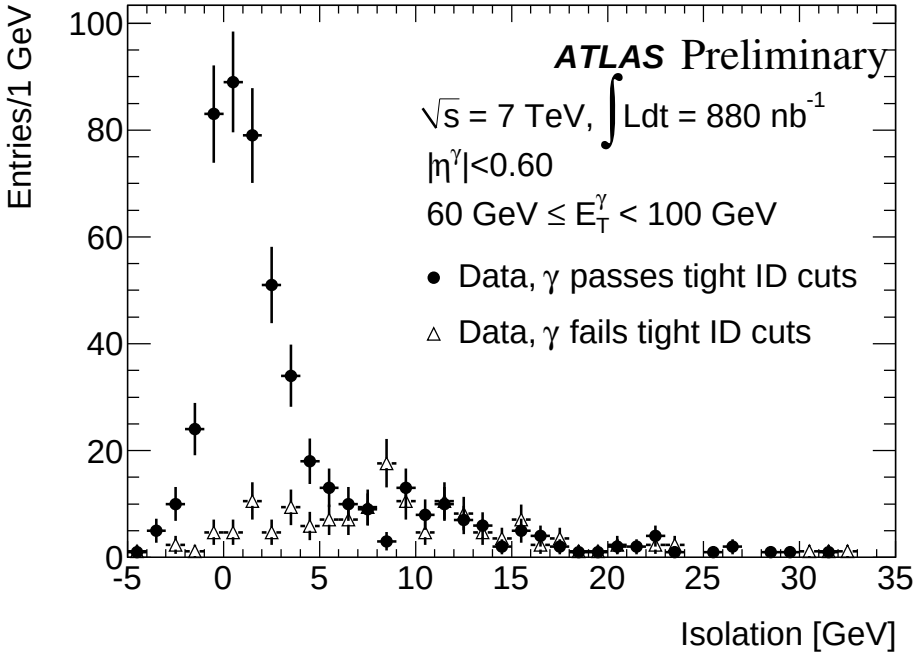
Background Estimates

To model the background - reverse some photon ID cuts:

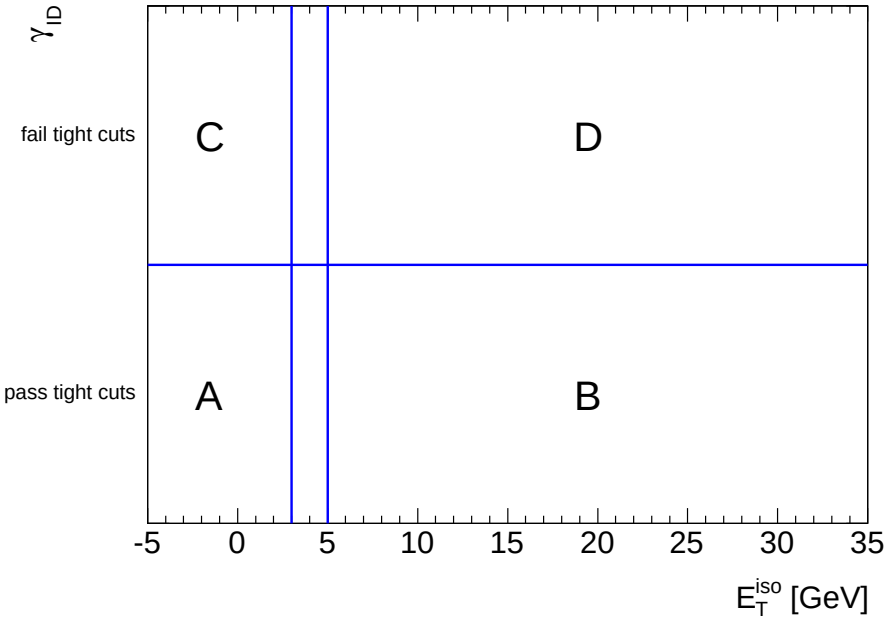
- Cuts on the strip variables are good candidates
- Not strongly correlated with isolation





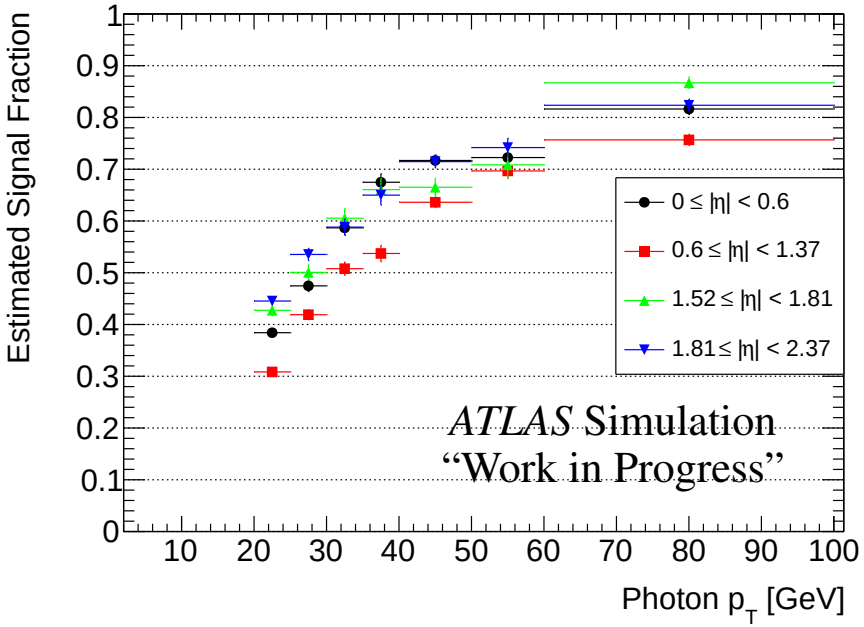


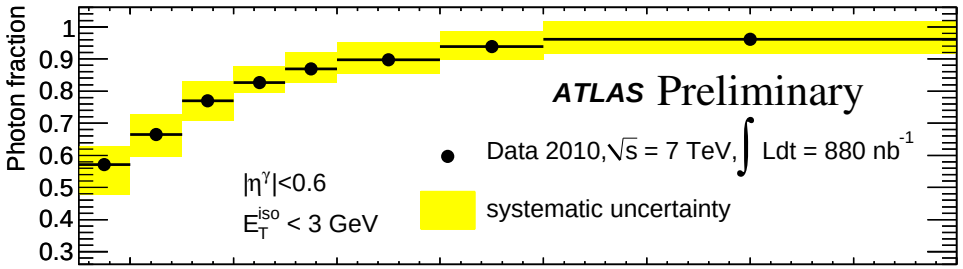
2-D Sidebands



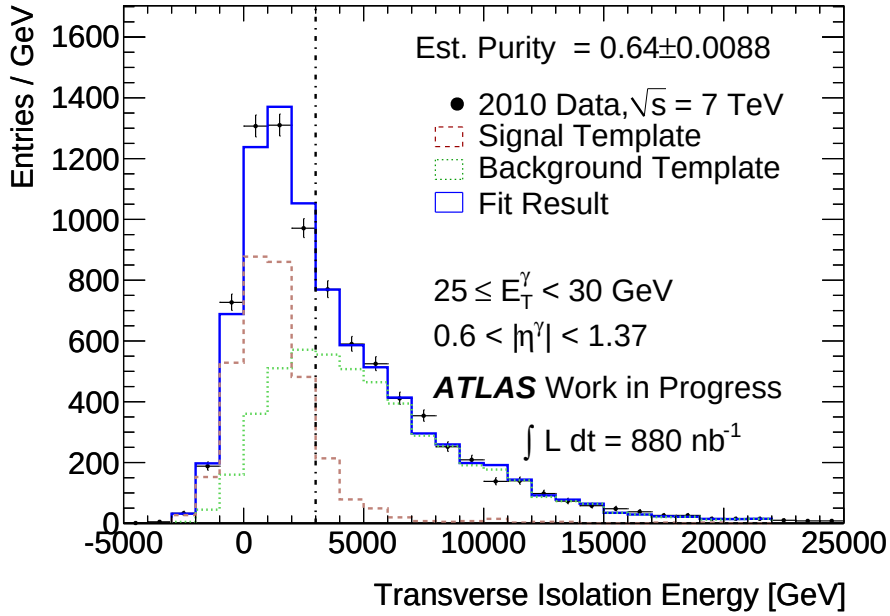
$$N_A^{sig} = N_A - N_B \frac{N_C}{N_D}$$

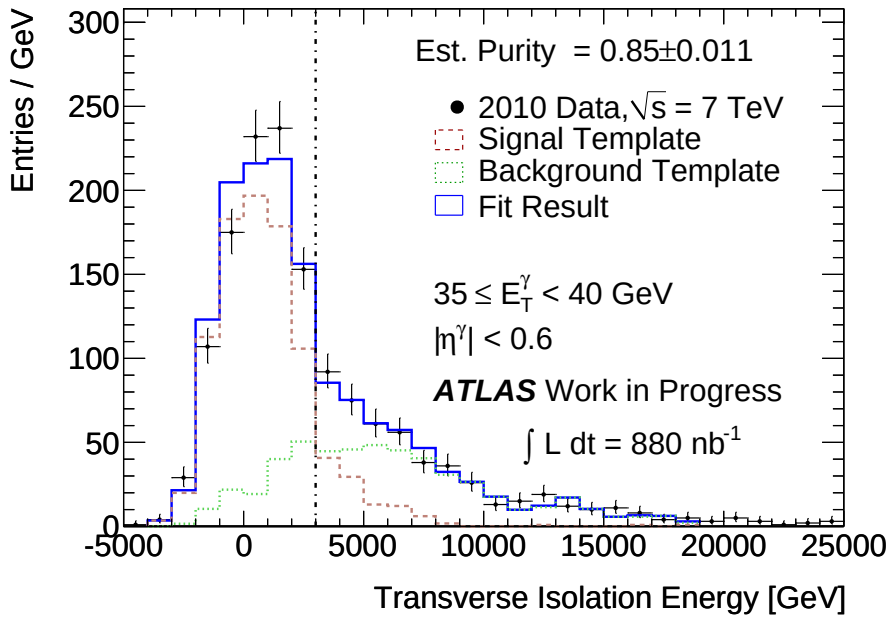
- Assumes "reverse cuts" not correlated with isolation
  - $\rightarrow$ systematic uncertainty
- Also assumes $N_X^{sig} \ll N_X$ for $X \neq A$
  - Correct N_X to account for signal leakage
- Additional uncertainties:
  - Definition of control regions
  - Statistical uncertainties





Isolation Templates



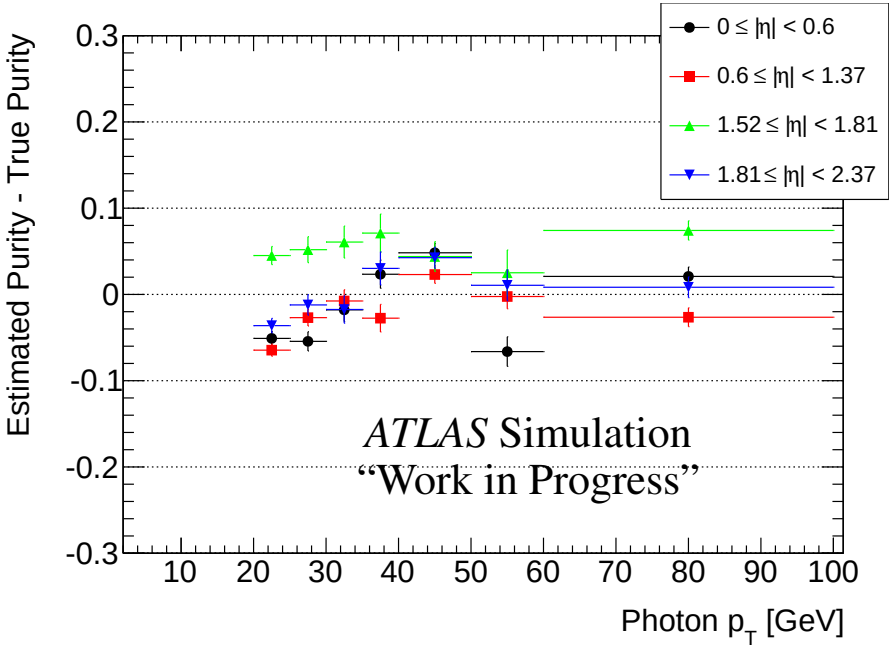


A full template fit is also possible

- 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



Cross Section Measurement

Cross Section Measurement

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

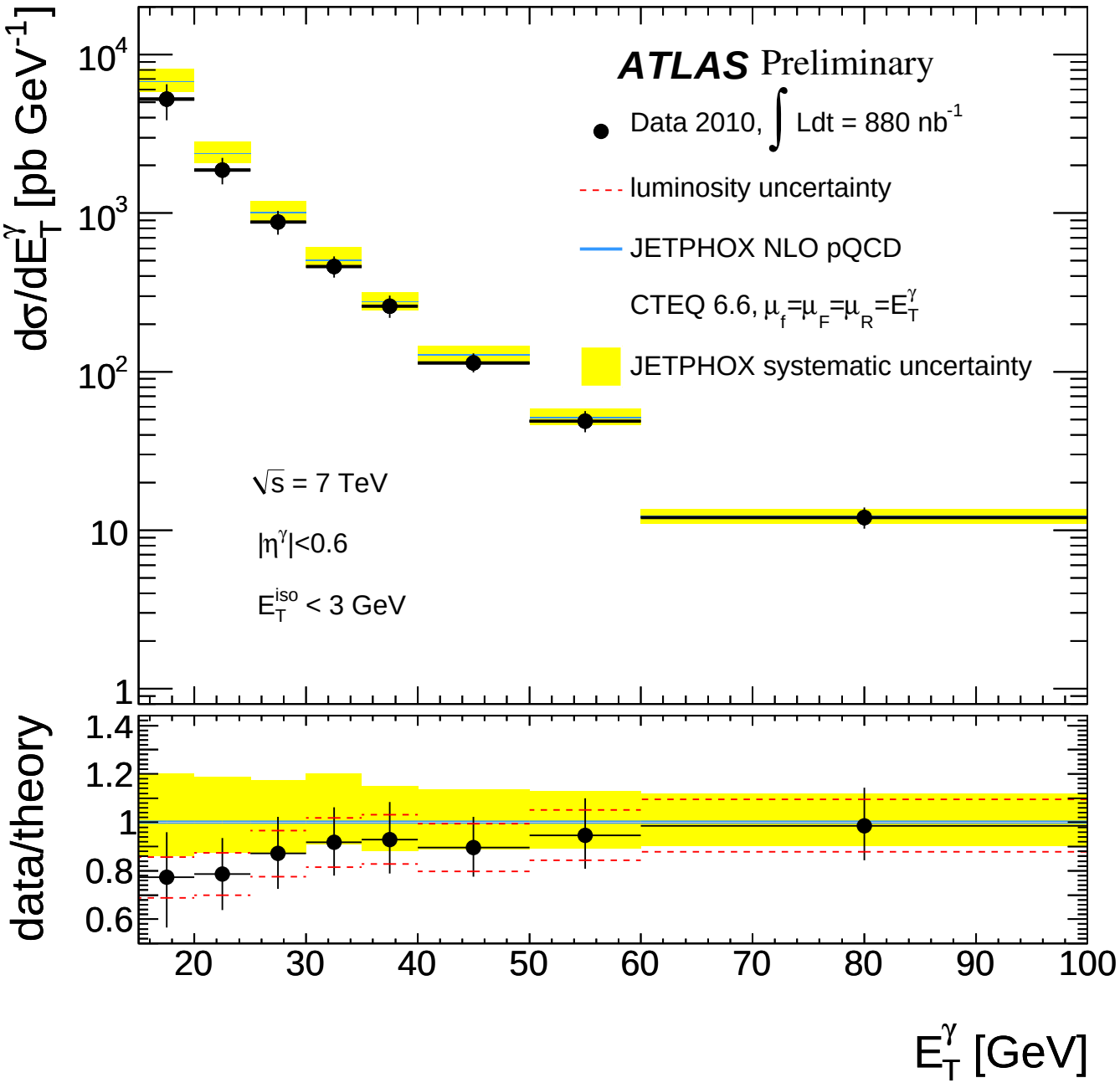
$$\boxed{\frac{d\sigma}{dE_{\mathrm{T}}^{\gamma}} = \frac{N_{\mathrm{yield}}\ U}{\left(\int \mathcal{L} dt\right)\ \Delta E_{\mathrm{T}}^{\gamma}\ \varepsilon_{\mathrm{trigger}}\ \varepsilon_{\mathrm{reco}}\ \varepsilon_{\mathrm{ID}}}}$$

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

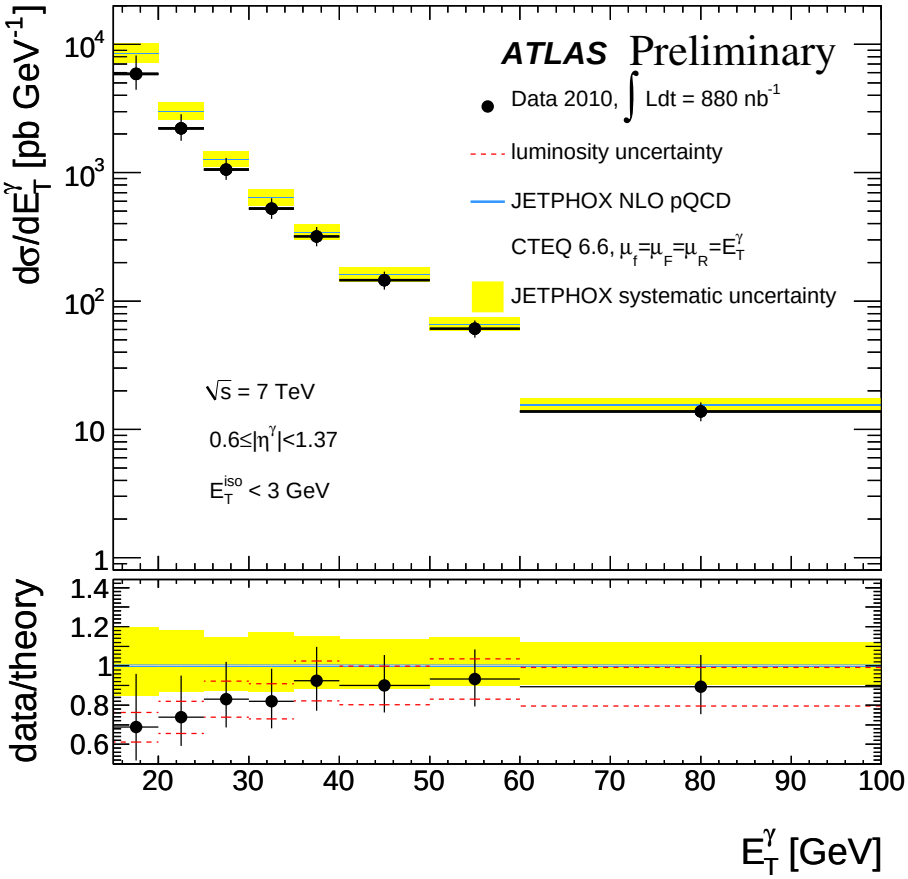
Unfolding coefficients (U) evaluated using `PYTHIA` signal MC:

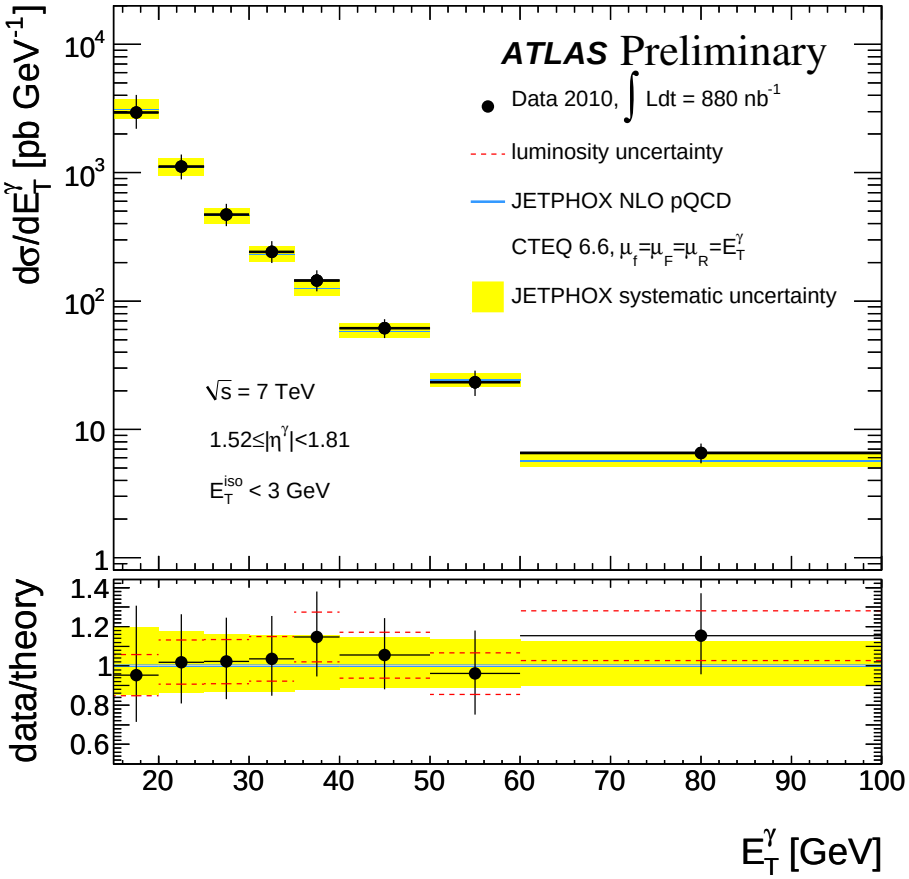
- Ratio of true:reconstructed E_{T} distributions
- Overall small bin-to-bin migrations because of good resolution in calorimeter
  - A few percent, always larger than 1.0, approaching 1.0 at high E_{T}
- Depend on $|\eta|$ (material effects) and E_{T}(resolution + bin size effects)

Cross Section Measurement



Cross Section: Higher $|\eta|$



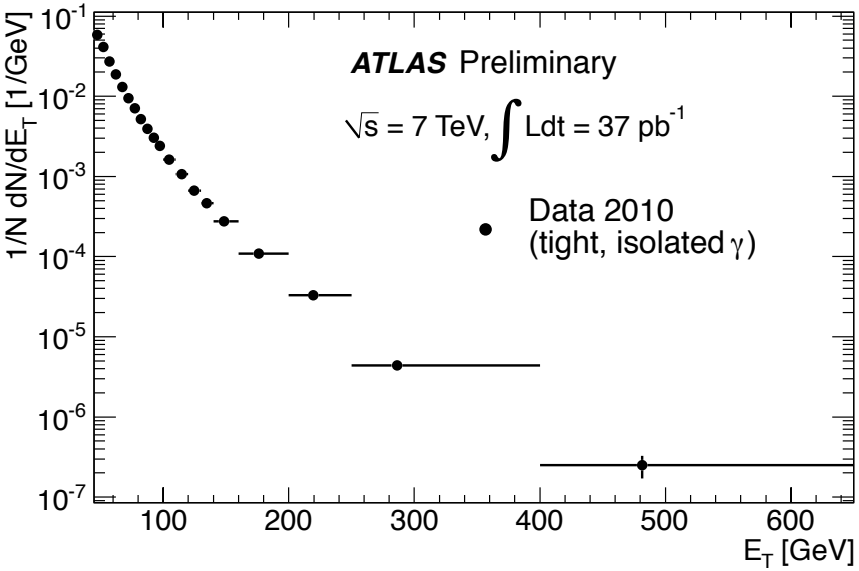


Results compared with theoretical predictions from `JETPHOX`

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

Future 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 $\approx$400 GeV
- Tight, isolated photons above 100 GeV are very pure ($> 90\%$)

Compton process still dominant at high $E_{\mathrm{T}} \rightarrow$ 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

Isolation Studies

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

$$\boxed{\mathrm{E_T^{isolation}(R)} < (\epsilon_s \cdot \mathrm{E_T^{\gamma}}) \cdot \left(\frac{1-\cos(\mathrm{R})}{1-\cos(\mathrm{R_0})}\right)^n}$$

- 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

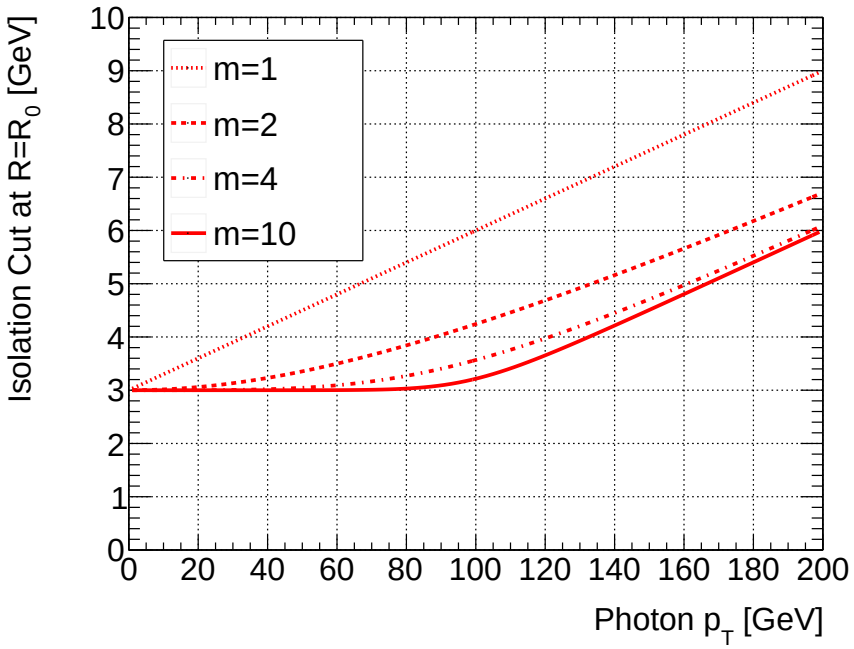
We worked with Frixione and the `JETPHOX` authors to modify the prescription to take into account experimental constraints:

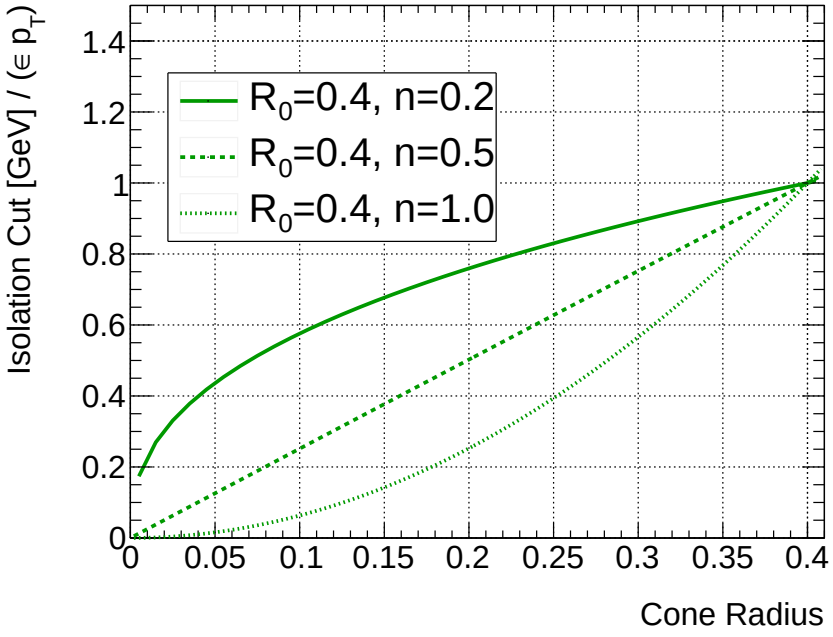
- Discrete calorimeter granularity $\rightarrow$ discrete cone sizes
- Molière radius not zero $\rightarrow$ terminate at $R \approx .1$
- Needs 'corrections' to to reconstructed isolation to properly remove non-perturbative contributions to the isolation cone

Frixione Isolation

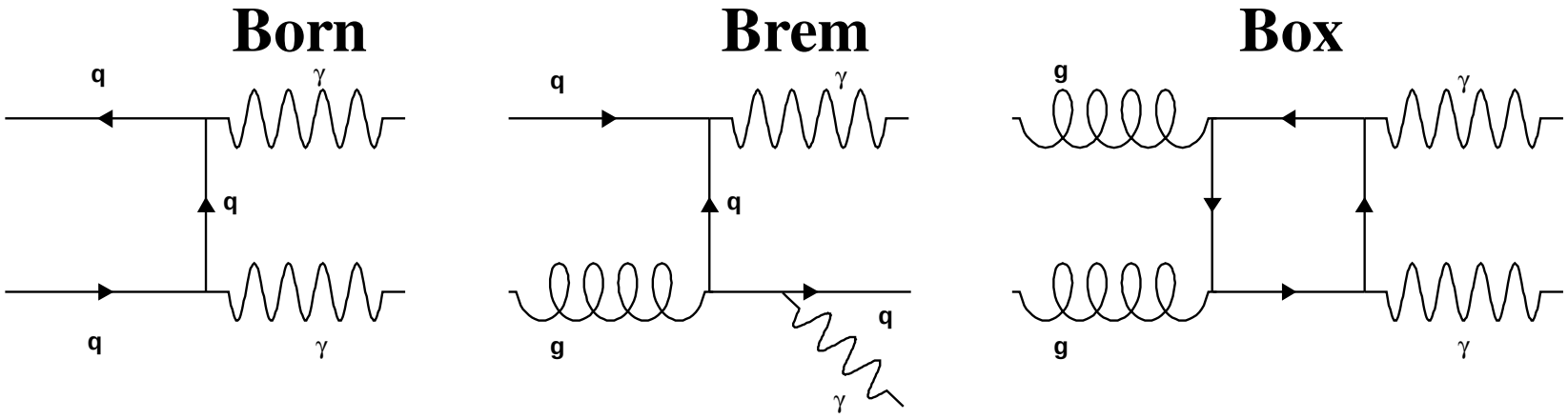
A discrete, generalized form of this prescription will be used in the next analysis:

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





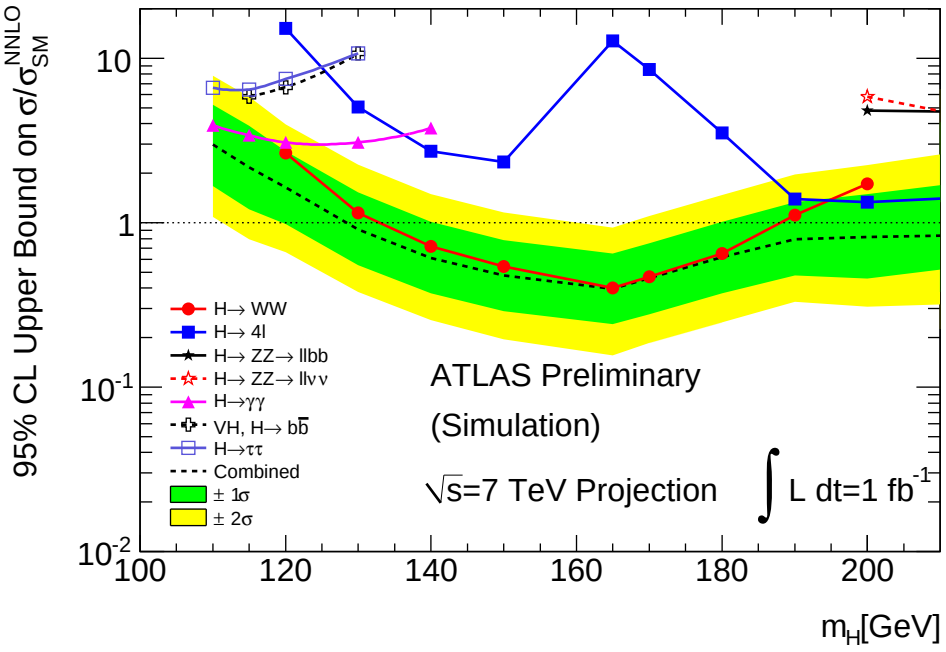
Diphoton Measurements

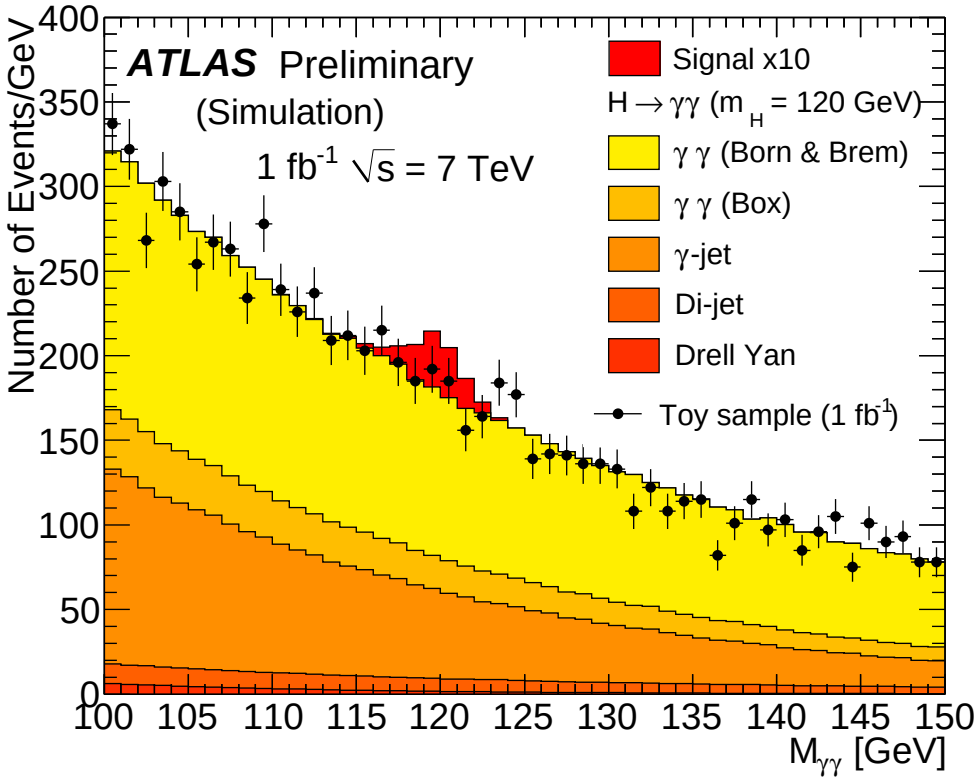


- Around 1 nb for $E_T > 15$ GeV
- Largest (irreducible) background to $H \to \gamma\gamma$
- Biggest challenge is extending the analysis to low E_T

A critical step towards finding a low mass Higgs!

Higgs Physics





$H \rightarrow \gamma\gamma$ remains one of the more powerful channels at low m_H.

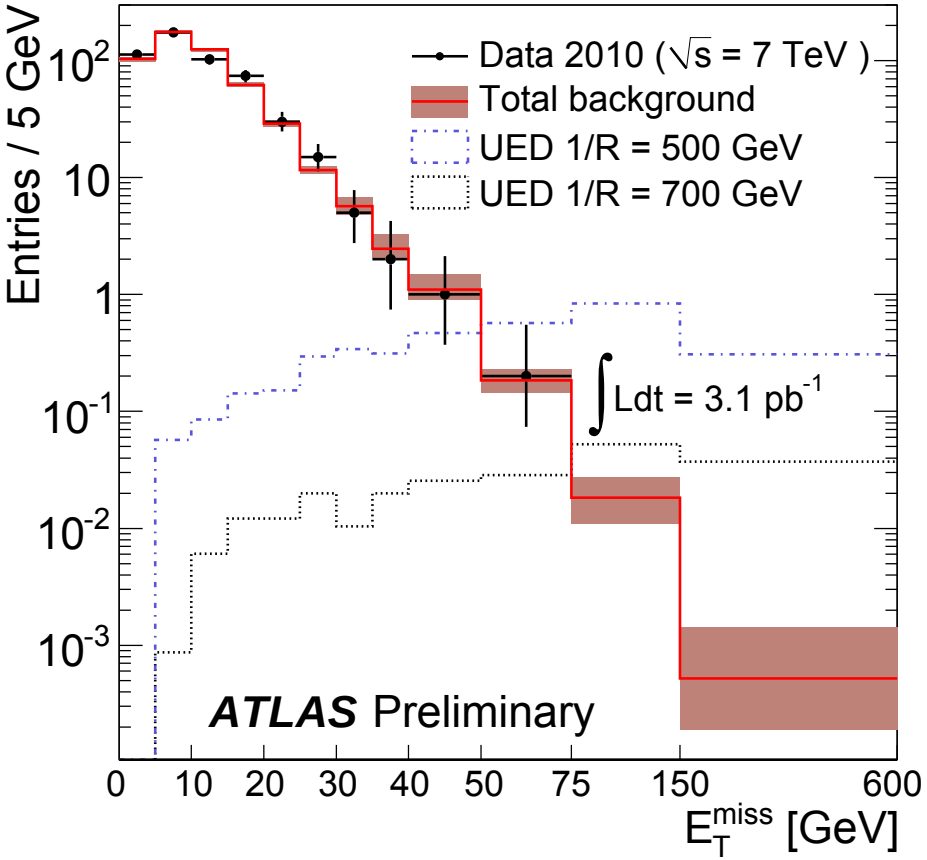
- Critical for probing near the LEP limit
- These plots from 2009/2010 MC studies: roughly 50% gains in sensitivity since then (analysis improvements, pessimistic MC WRT data)

SUSY and Exotic Searches

Getting a bit more exotic....

Most recent work in ATLAS: UED searches in $\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$

- Probing TeV^{-1} sized UED
- $2\times(\gamma^* \rightarrow \gamma + G) = \gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$
  - Λ: UV cutoff for radiative corrections
  - R: compactification radius
  - Set $\Lambda R = 20$
- D0 limit: $1/R > 477$ GeV (6.3 fb^{-1})
- ATLAS: $1/R > 728$ GeV (3 pb^{-1})



Along these same lines:

- Some SUSY searches (GMSB) have identical signatures
- $\gamma\gamma$ resonances (Direct RS-graviton search)
- Model-independent resonance searches
- $\gamma + l + E_{\mathrm{T}}^{\mathrm{miss}}$ (sleptons) and many other combinations

Conclusion

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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

- UED searches (currently)
- Di-photon cross section, resonance searches
- Higgs searches at low mass
- SUSY, exotics, model independent searches...

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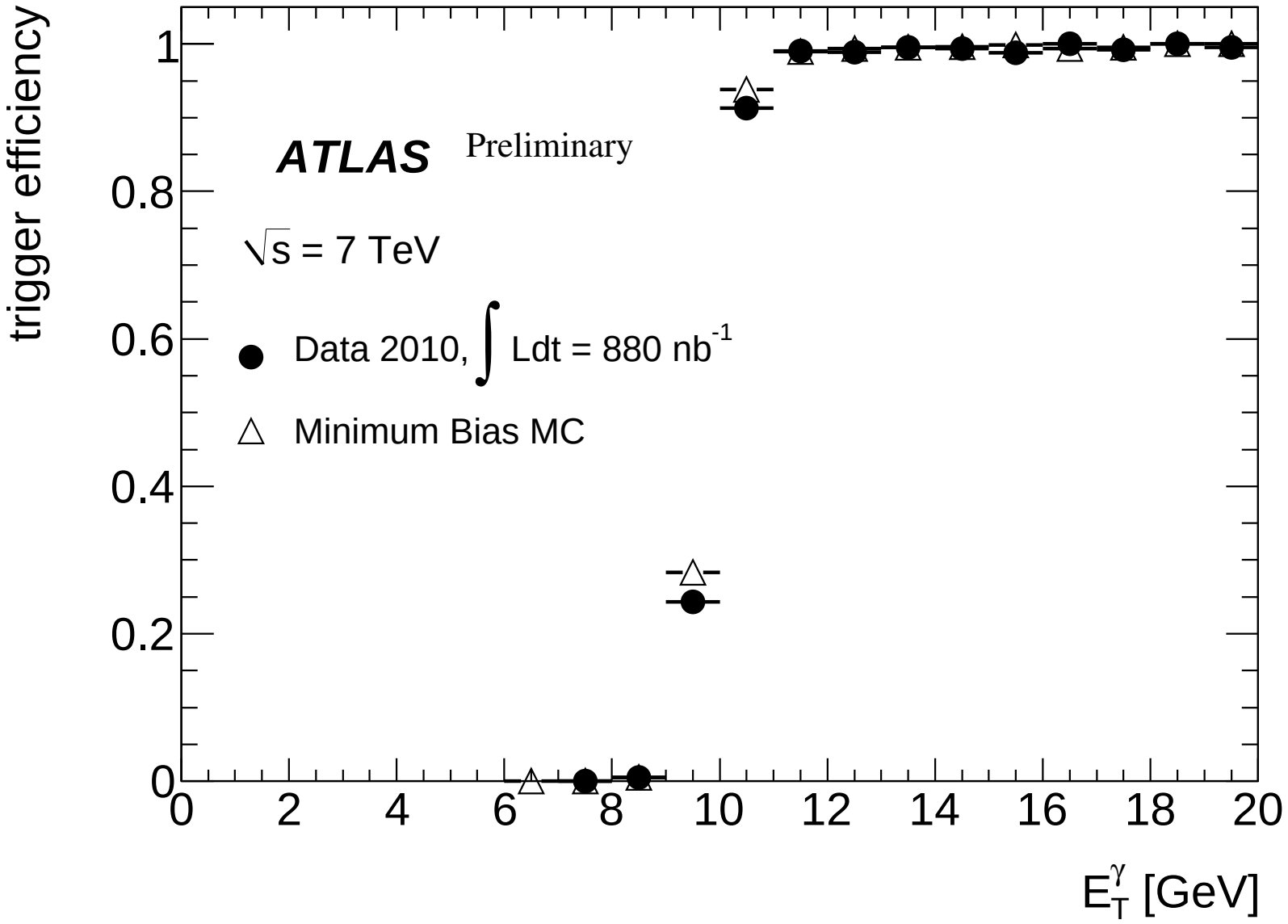
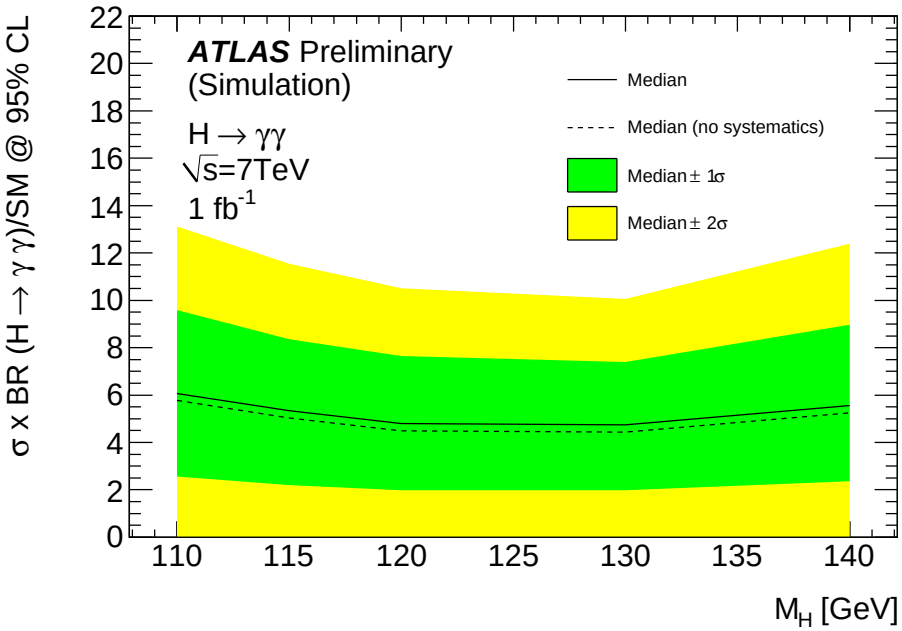
- SUSY, exotics, model independent searches...

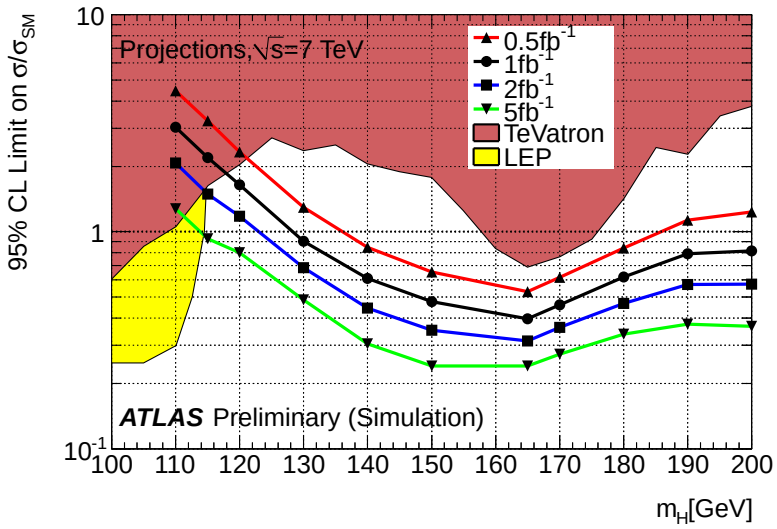
Bonus

Single Photon Trigger Efficiency

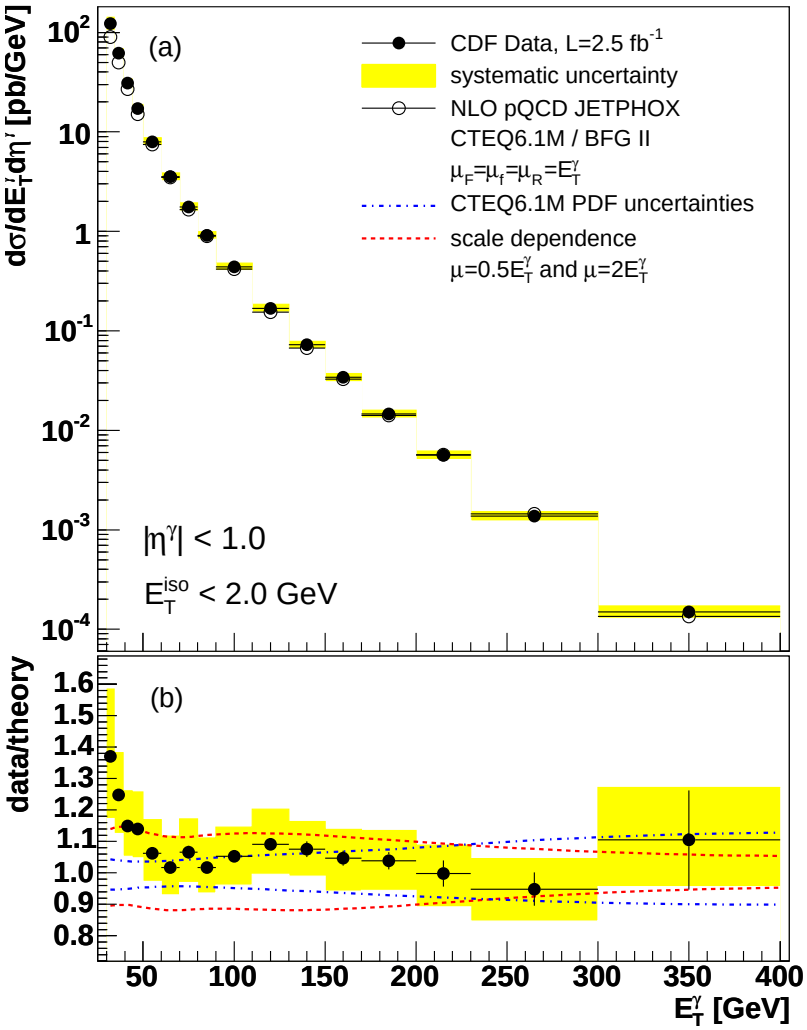


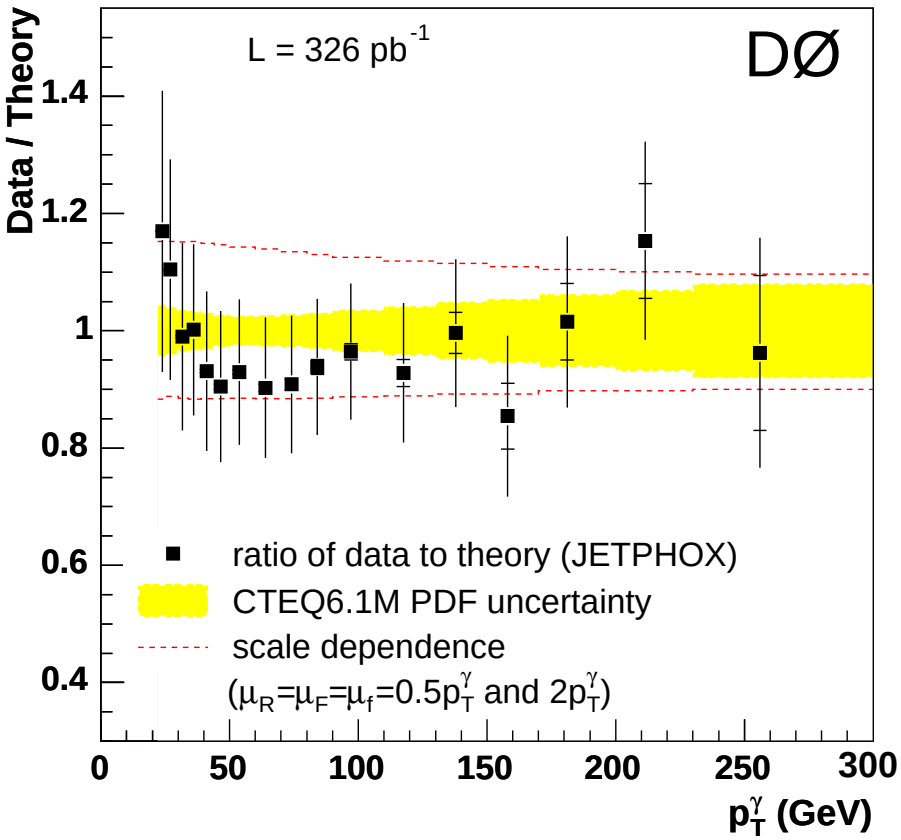
Higgs


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
M_H [GeV]

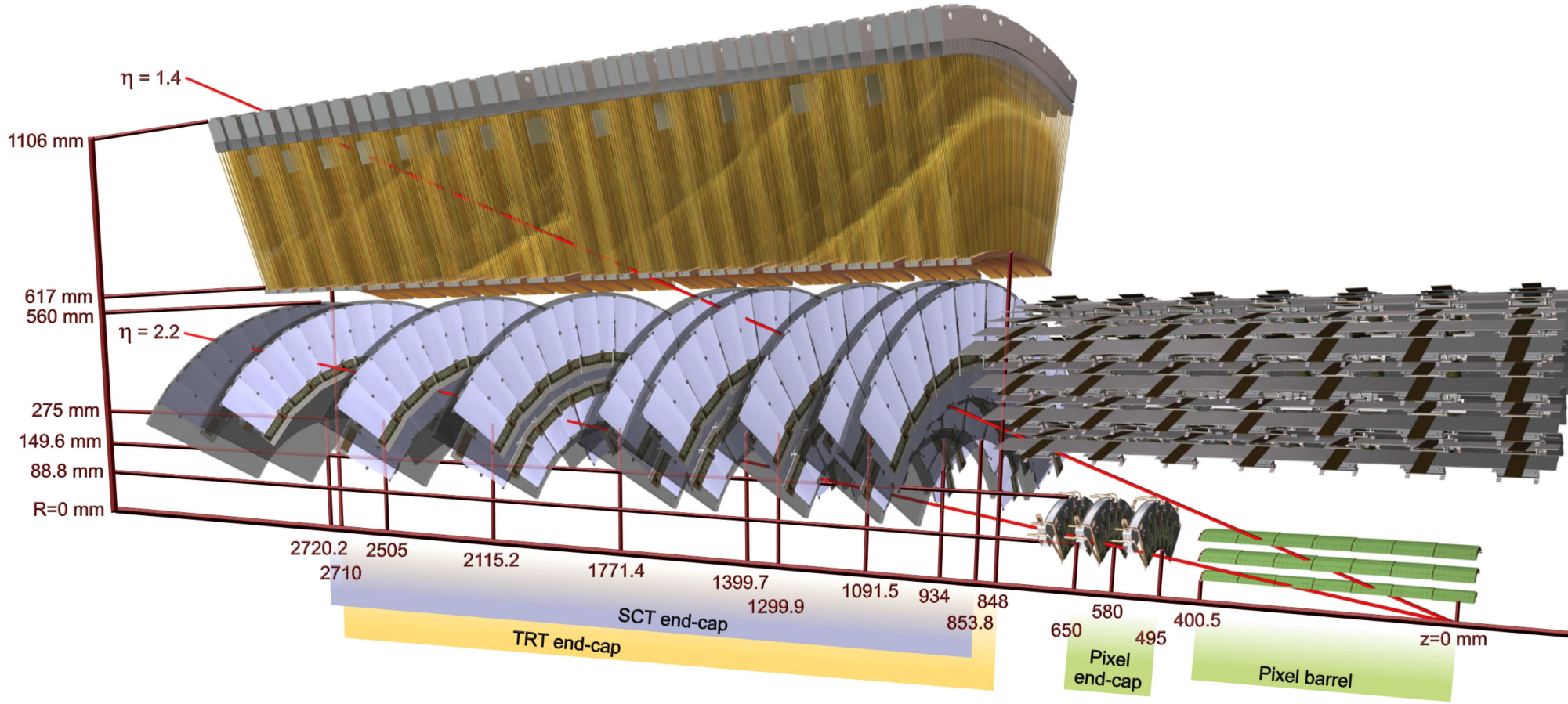

Projections, √s=7 TeV
0.5fb-1
1fb-1
2fb-1
5fb-1
TeVatron
LEP
ATLAS Preliminary (Simulation)
95% CL Limit on σ/σ_SM
m_H[GeV]

Previous Measurements

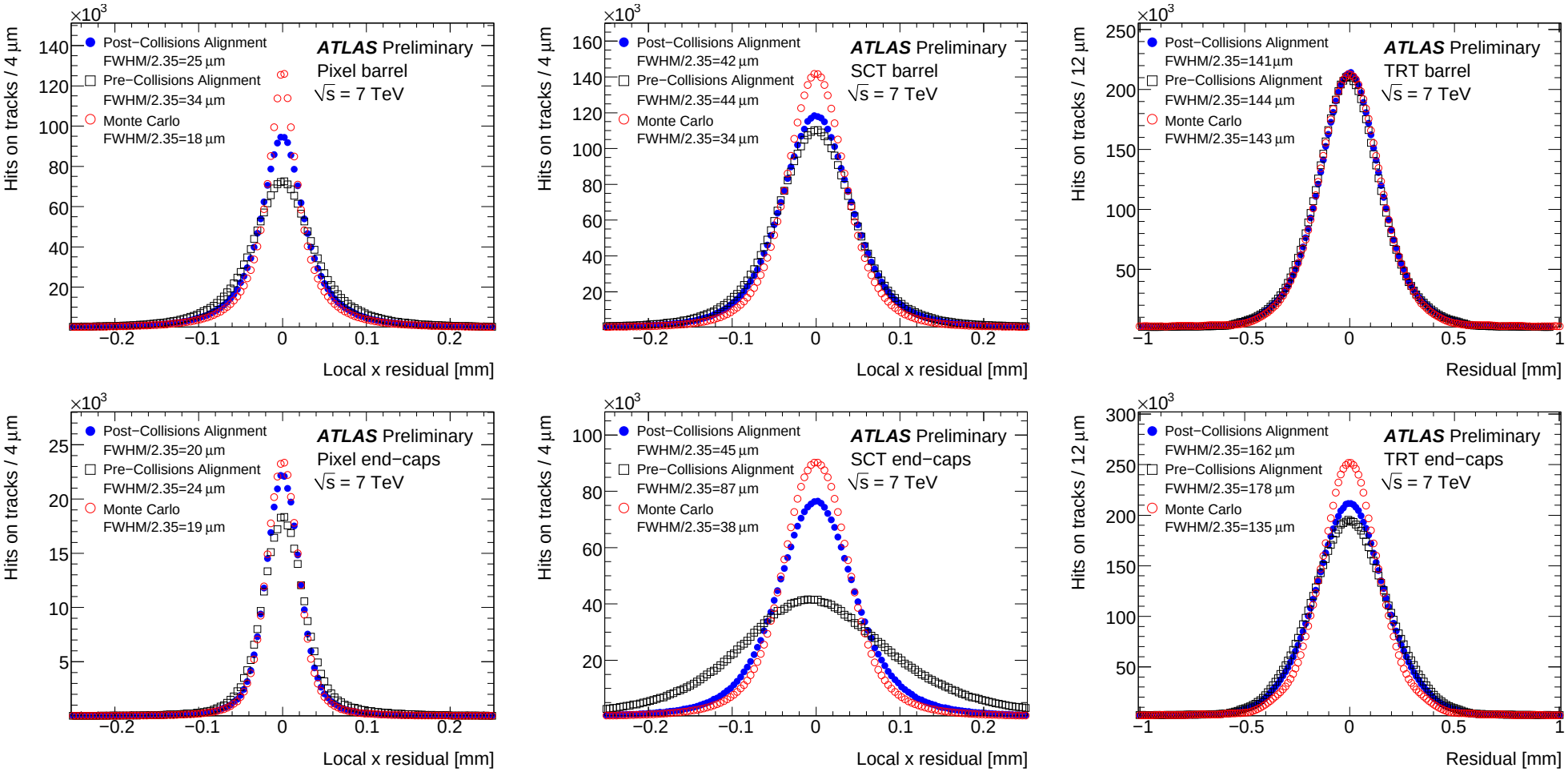




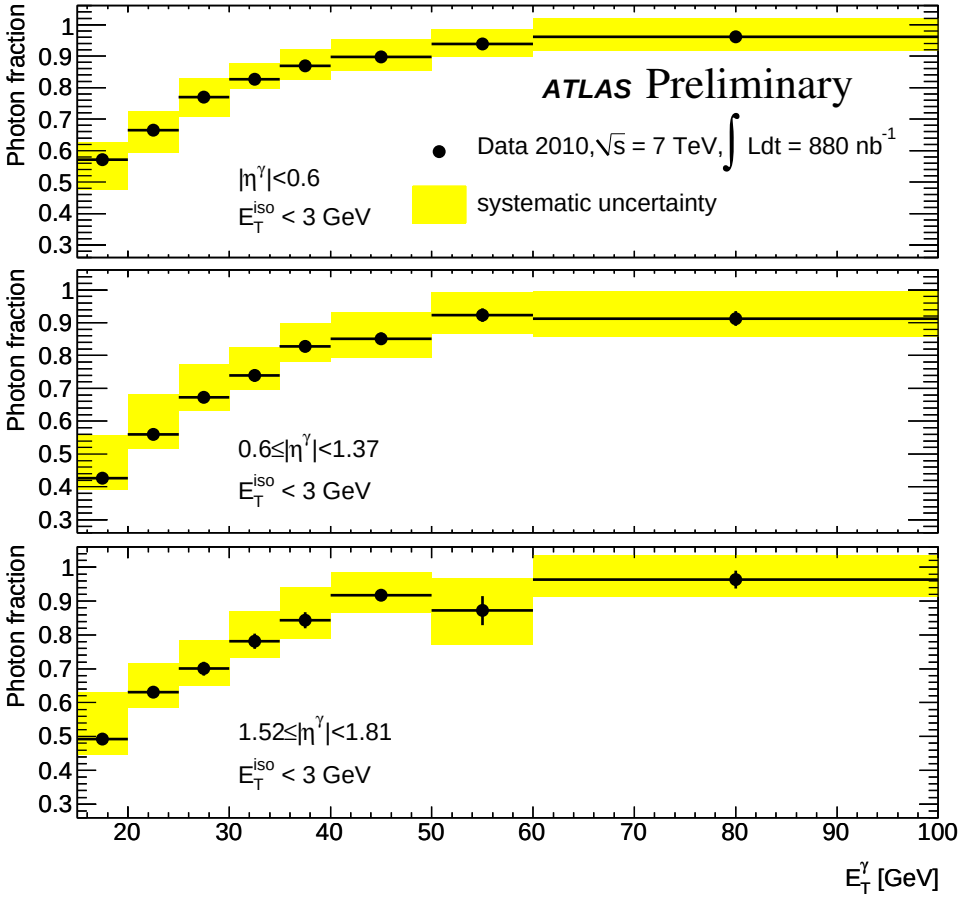
Inner Tracker Endcap

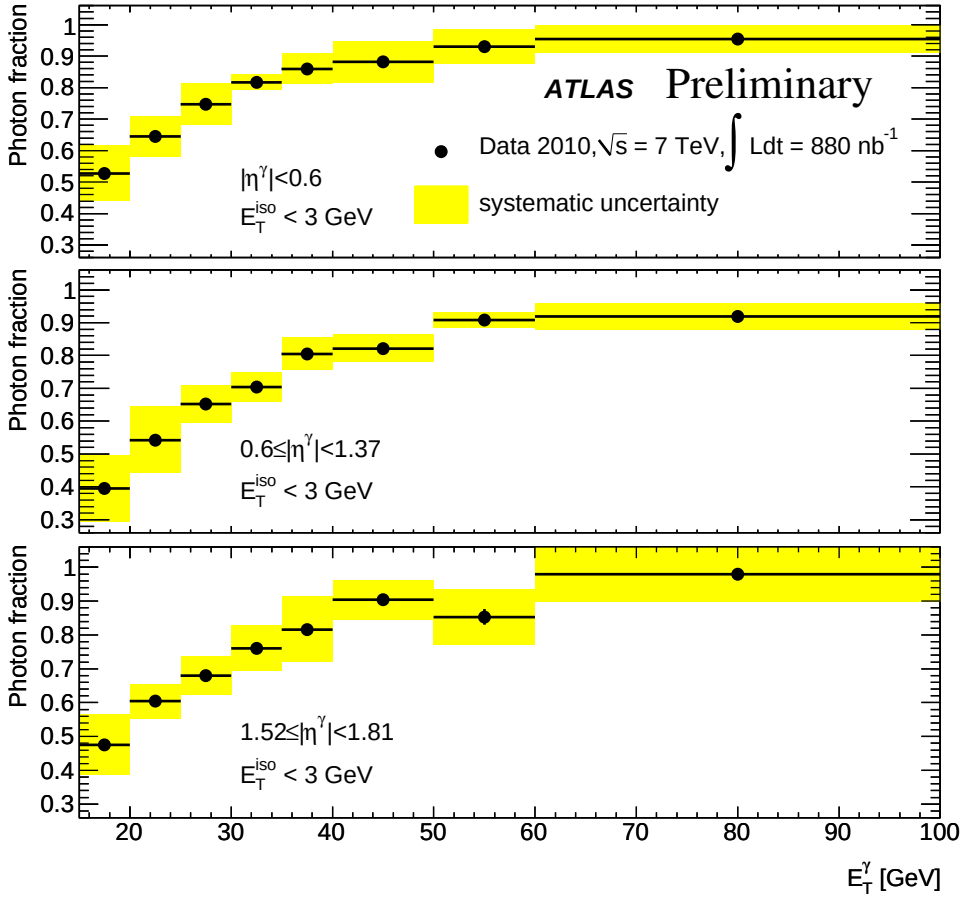


Inner Detector Alignment

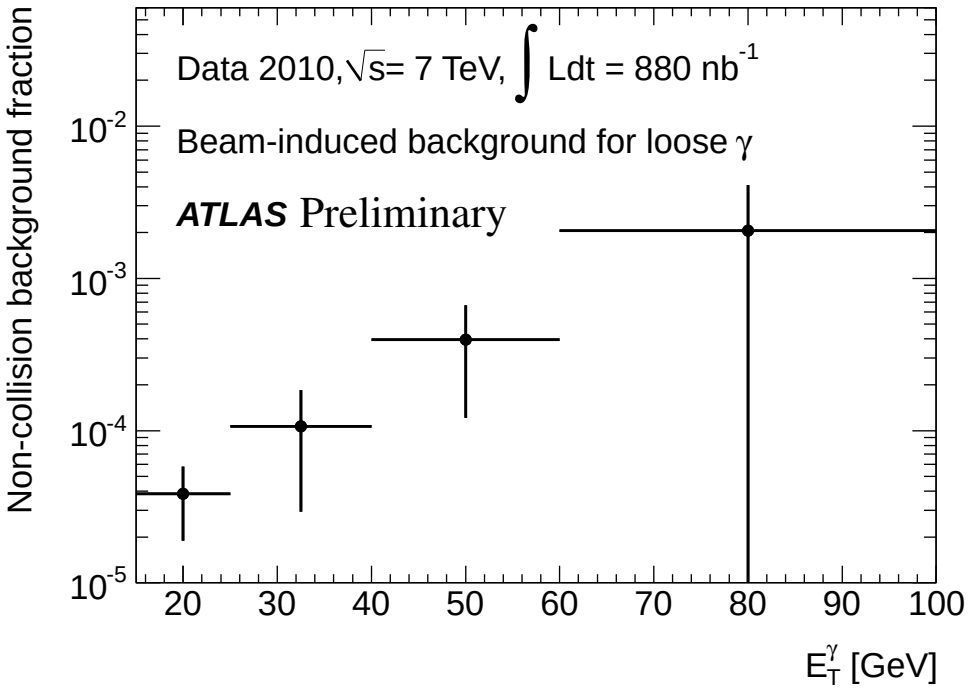


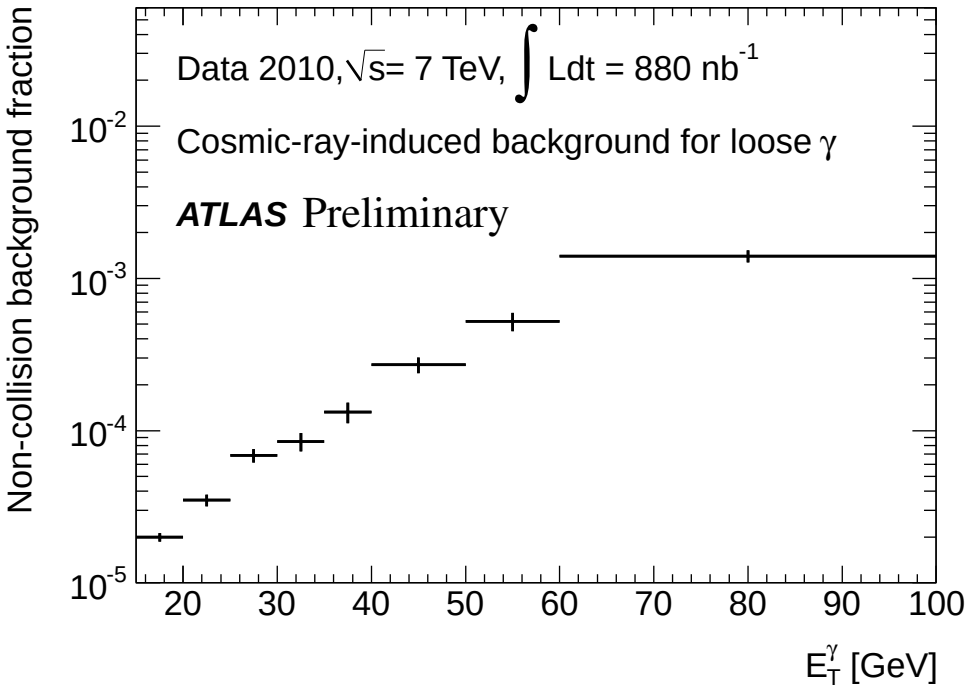
Purity Estimates





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 $E_{\mathrm{T}}^{\mathrm{miss}}$