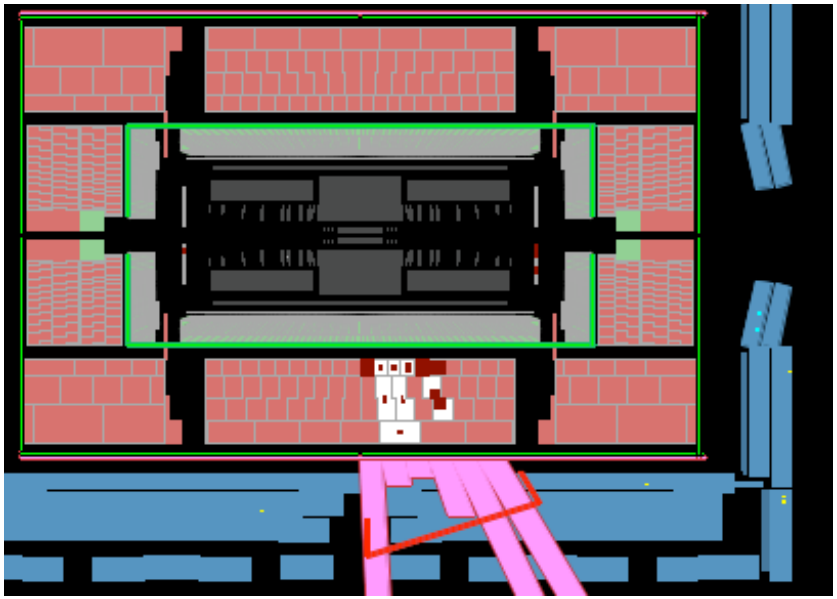
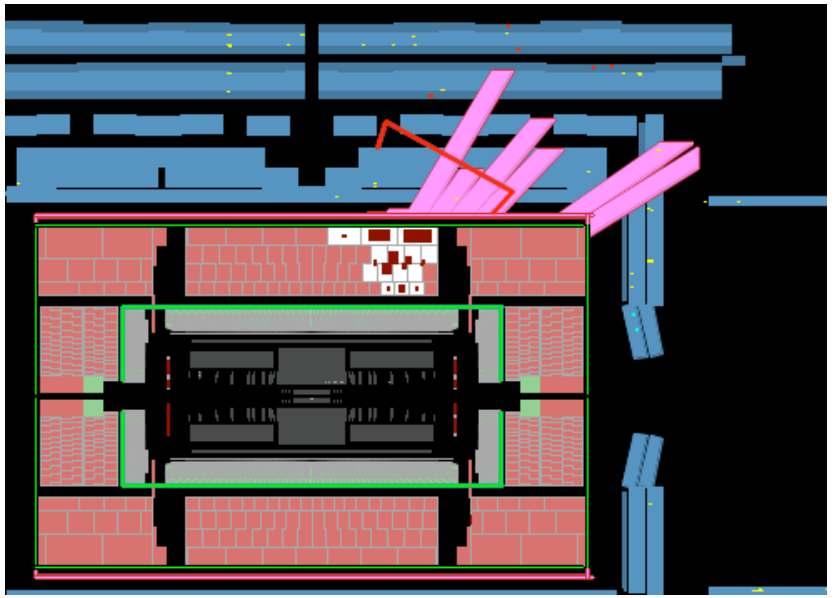
# Search For Stopped Long-Lived Particles in ATLAS

Josh Cogan



*Data Candidate*



*Data Candidate*

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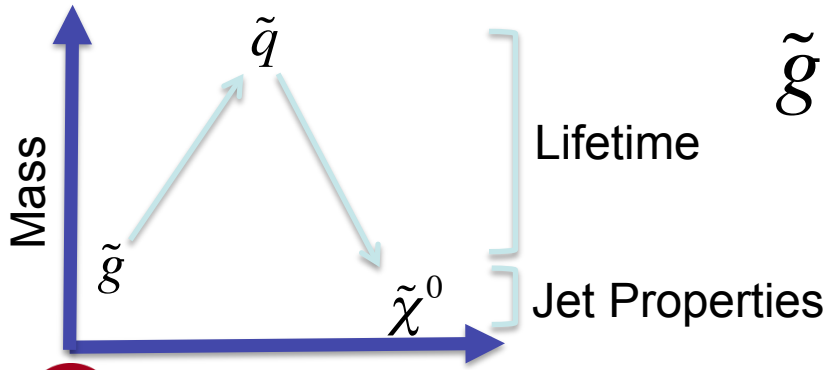
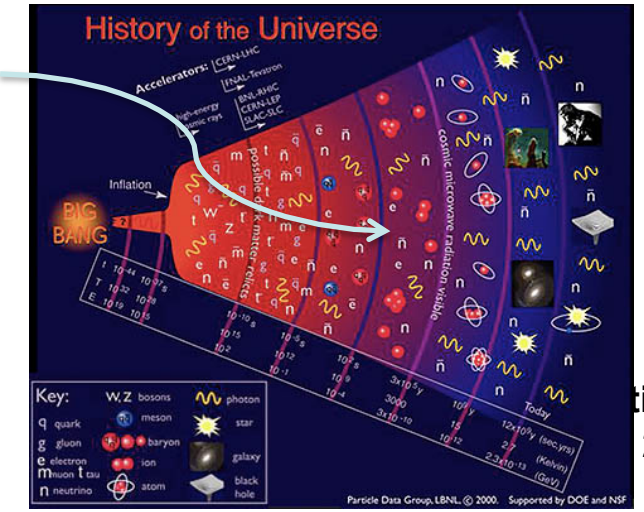
# Motivation



- All the normal reasons we like SUSY and…
- Split-SUSY provides a mechanism:
  - $\tilde{g}$ tunnels through SUSY scale $\tilde{q}$
  - Allows long lived $\tilde{g}$ with energetic decay
- Motivated by sBBN $^{7}$Li / $^{6}$Li discrepancy
  - Convenient delayed neutron source: τ ~< 100 sec




$\tilde{g}$ ?

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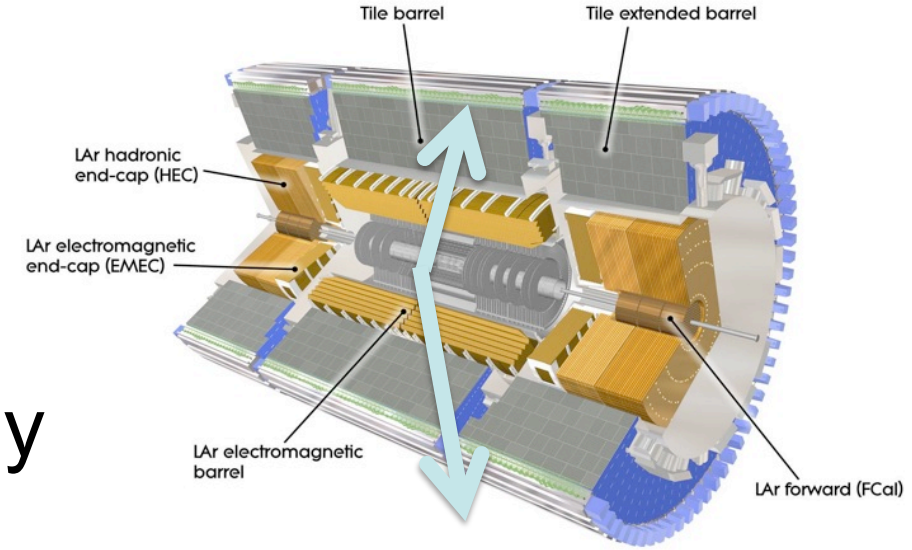
ticles
2011

# Signature Overview



- Produce two $\tilde{g}$ in pp collision, which pick up SM quarks from the vacuum → *R*-hadron
- Travels into ATLAS detector volume
  - Loses energy through dE/dX and nuclear scatters
  - Can exchange charge
- Stops in calorimeter
- Decays at a later time
- Detect decay event only



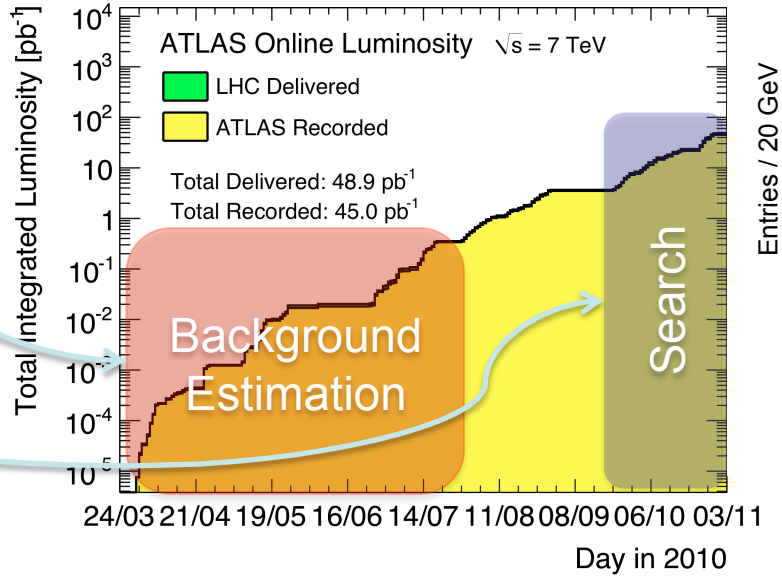
# Search Strategy

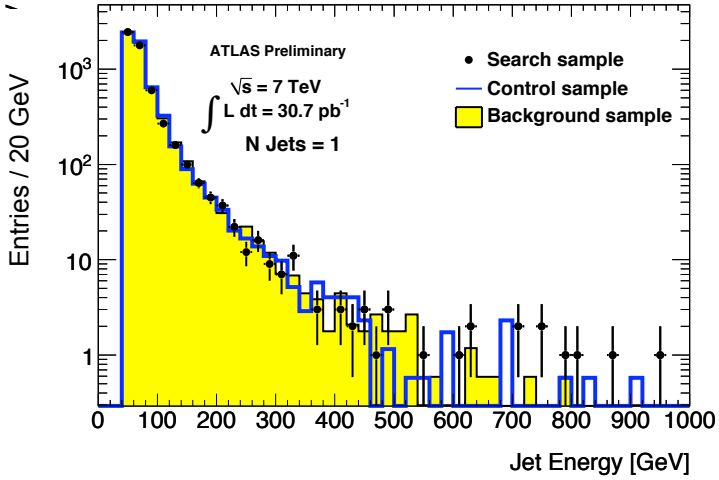


- Leverage long lifetime ($\tau$ > 100 ns):
  - R-hadrons decay significantly out of time
  - Look for decays in **empty** bunches
- Cosmic muon events dominate background
  - Don't scale with luminosity! Compare 2010 regions

Many Cosmics
"No" R-hadrons

400x higher
S/B!

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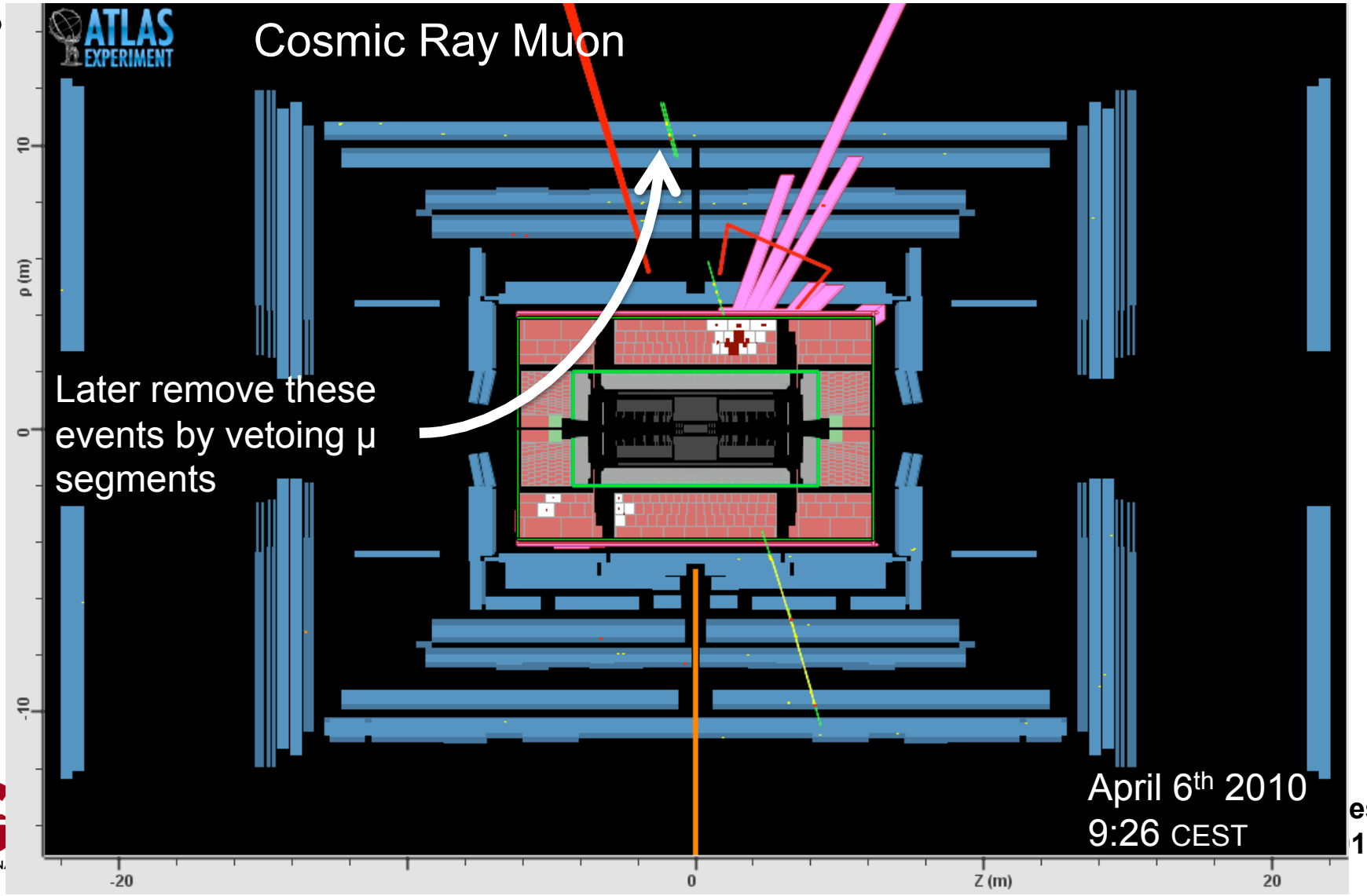
# Backgrounds: Cosmics

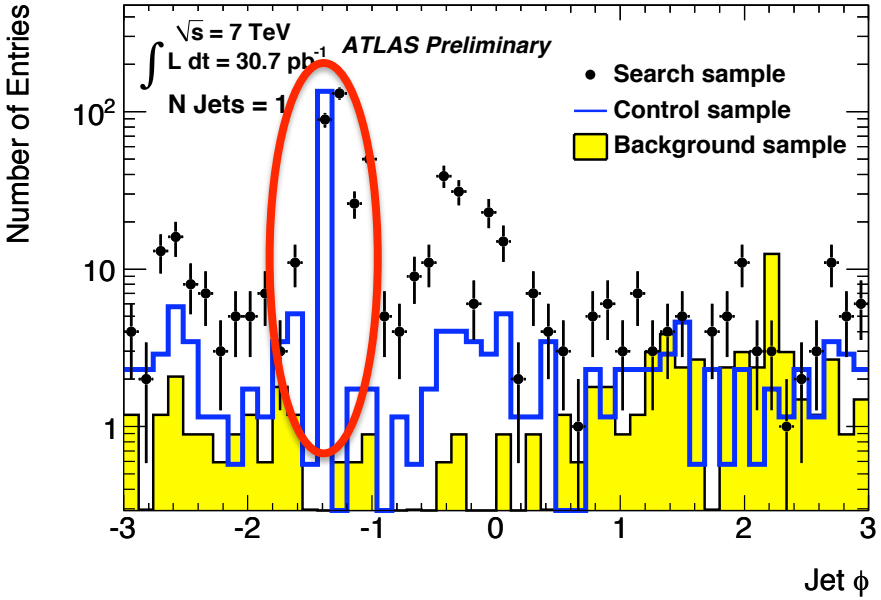


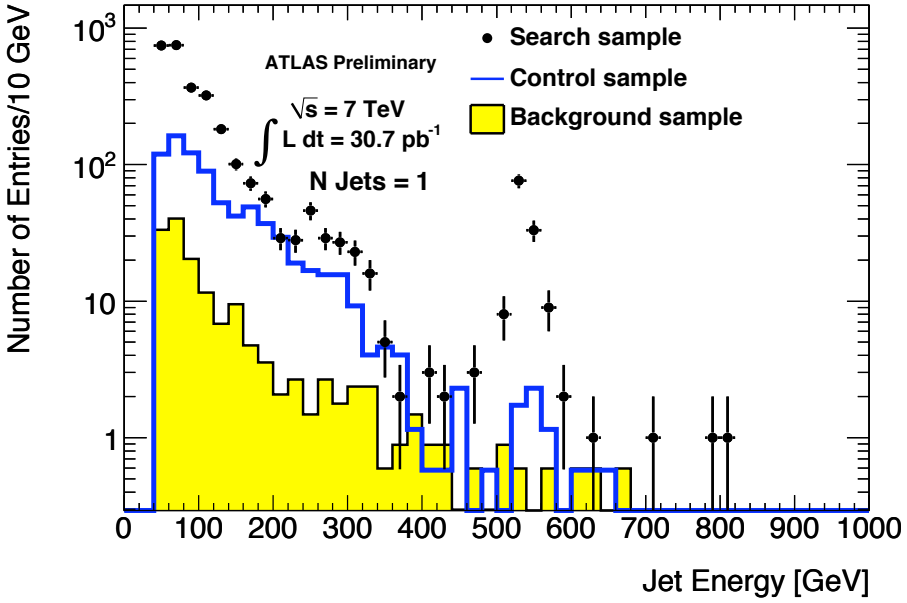
- 

# Background Sources: Noise



- Plots show events after muon segment veto
- Events show strong noise signature!
- Control noise with jet shape and jet location

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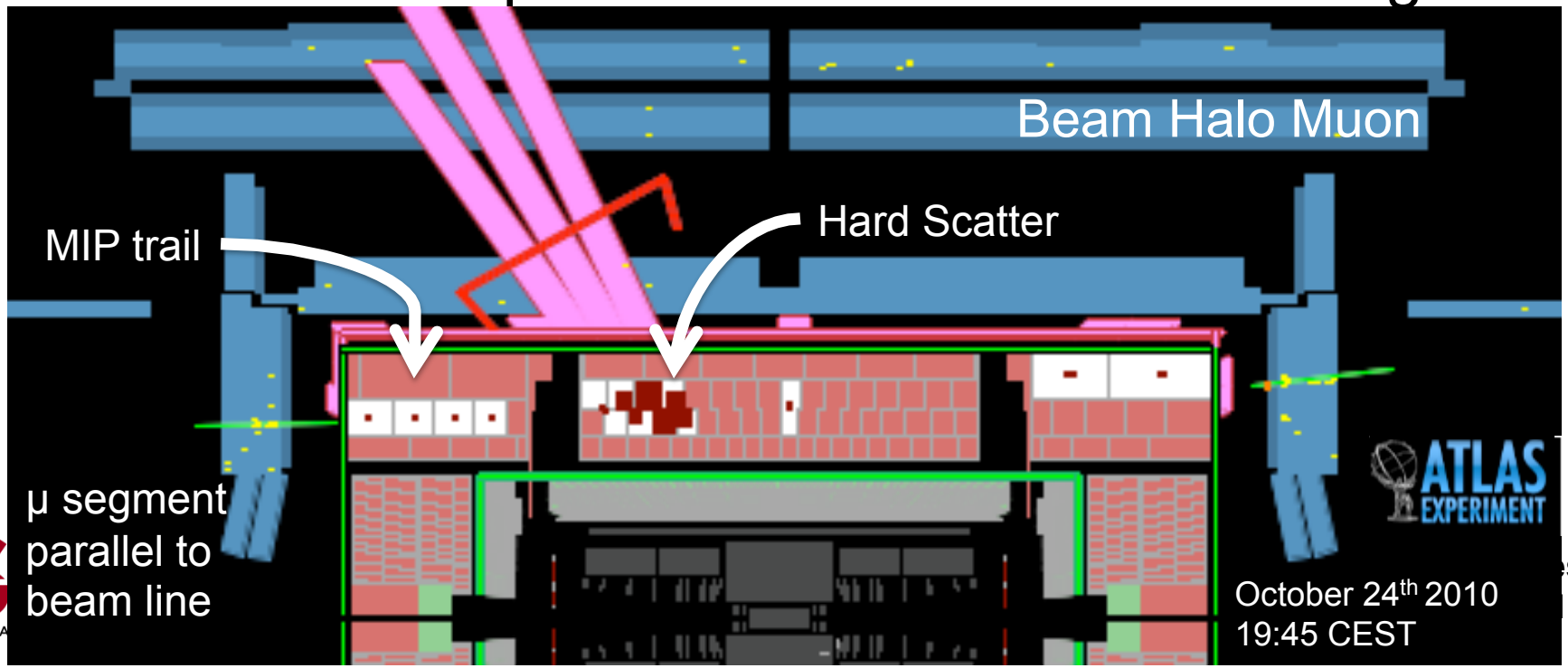
# Background Sources: Beam



- Beam gas and pp collisions: ID Tracks, $E_T^{miss} / P_T^0$
  - Rare events easily removed in empty bunches
- Halo muons often leave muon segment
  - Studied in unpaired bunches and control region



# Background Estimation 1/2



- Beam halo changes with current & conditions
  - Affected by vacuum, collimators, # bunches …
  - Need an orthogonal sample in search region
- Unpaired can provide pure beam halo sample
- Apply "ABCD"-method to estimate beam halo yield without a segment in the empty bunches!

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| *Halo* | With Muon | No Muon |
|---|---|---|
| Unpaired | 2021 | 2 |
| Empty | 429 | .43±.3!! |

*The estimate*
*(1st Jet E > 50 GeV)*

*Beam Halo ≈ 0*
*(1st Jet E > 100 GeV)*

*Orthogonal samples*

# Background Estimation 2/2



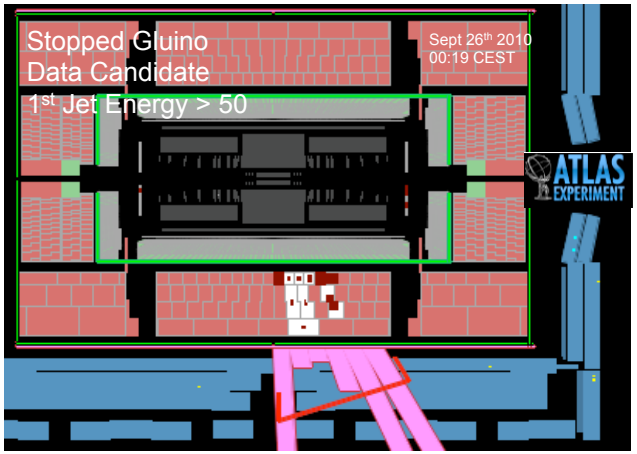
- Cosmics scale perfectly with livetime $\frac{N_s}{T_s} = \frac{N_b}{T_b}$
- For limit setting conservatively ignore noise

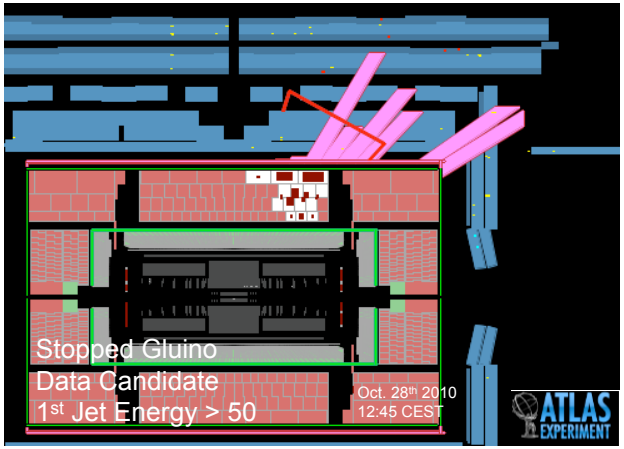
ATLAS Preliminary

| *Cosmics* (weighted) | Background | Control | Search |
|---|---|---|---|
| Jet Cleaning | 5859 ± 42 | 5859 ± 56 | 5615 |
| Muon Veto | 4.4 ± 1.1 | 4.6 ± 1.6 | 9 |
| 1st Jet Energy > 100 | 0.3 ± 0.3 | 0.58 ± 0.58 | 0 |

*Event Displays*

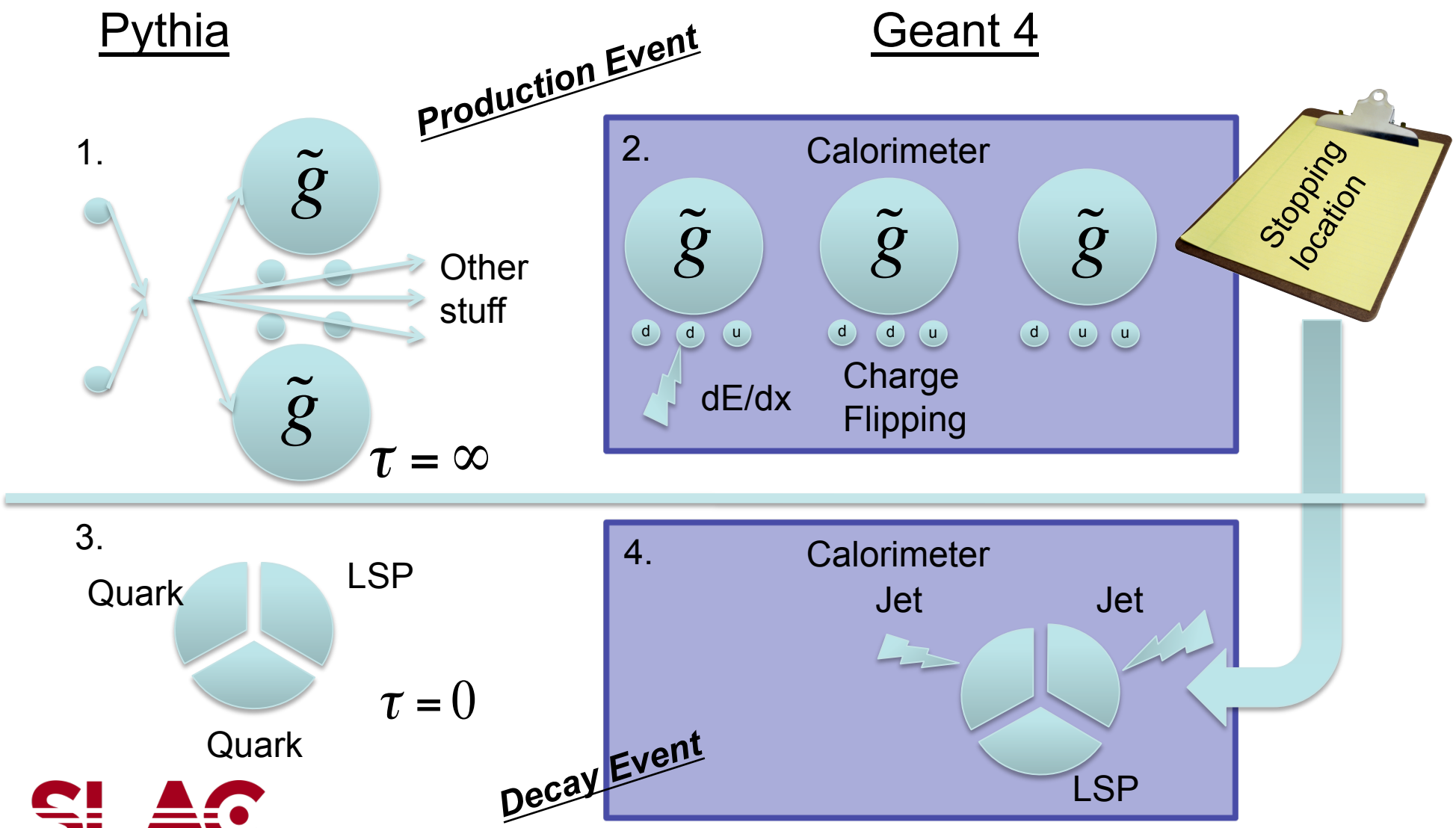
*Limit Setting*



# Signal Simulation



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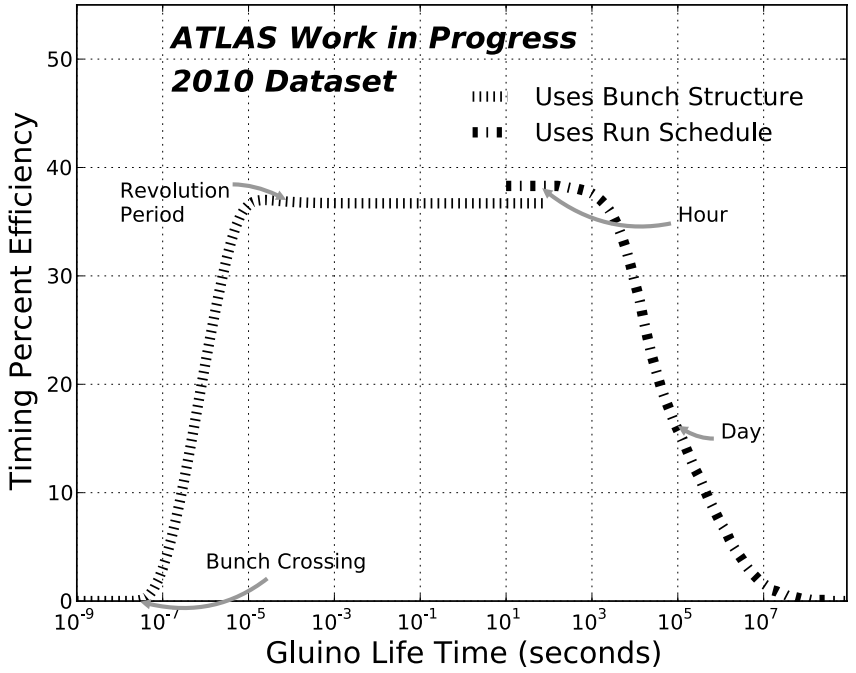
# Additional Signal Efficiency Loss



- Stopping: ~10% *R*-Hadrons remain in detector
  - Depends on matter interaction model. Studied 2
- Timing: some *R*-hadrons decay out of a run or in filled bunch
  - 37% $10^{-5} < \tau < 10^{3}$
  - Used 2010 schedule
- Random μ segment causes veto
  - Used random trigger



# Signal Summary



- Left: Table of efficiencies effecting final yield
- Right: Locations of *R*-Hadron if it stopped

| Marginal Efficiency | Nota Bene | Value @ 200 GeV | Value @ 600 GeV |
|---|---|---|---|
| Stopping | "Generic" | 11% | 11% |
| Timing | $10^{-5} < \tau < 10^{3}$ | 37% (not affected by mass) | |
| Accidental μ | For all models | 93% (not affected by mass) | |
| Recon. | Total | 0.94% | 8.33% |
| | Preselection | 41.2% | 37.4% |
| | Jet Cleaning | 25.0% | 31.3% |
| | Muon Veto | 90.2% | 71.1% |
| | 1st Jet E > 100 | 10.1% | 100% |
| Total | "Bottom line" | .036% | .31% |

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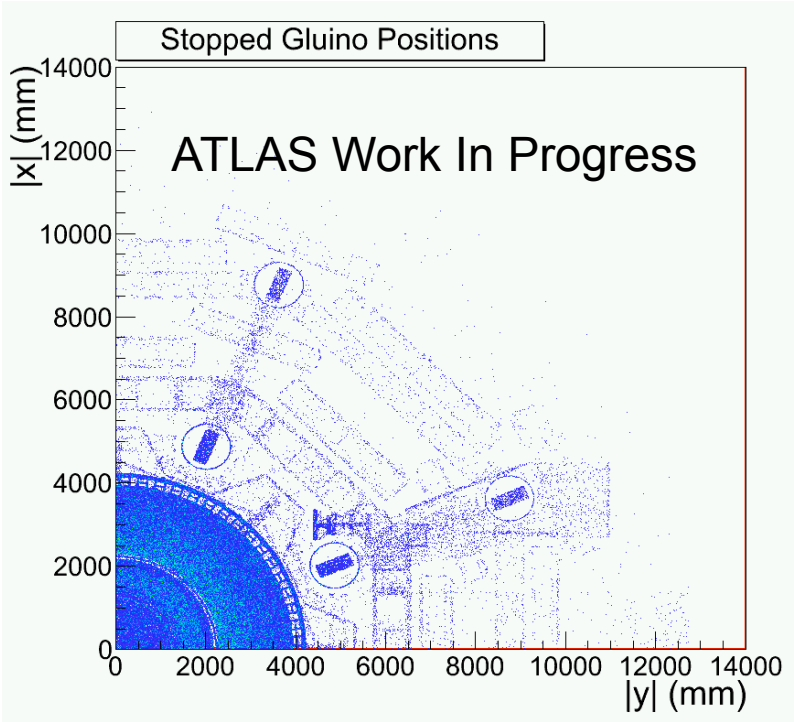
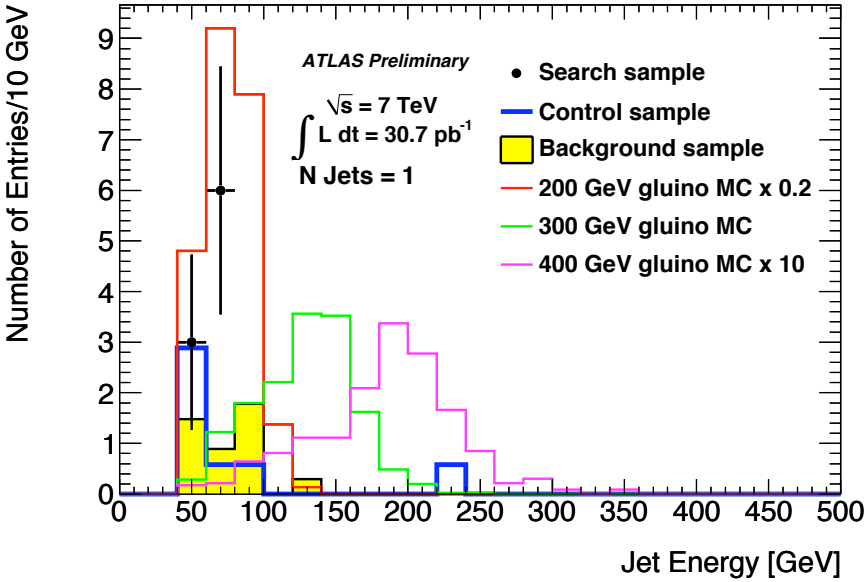
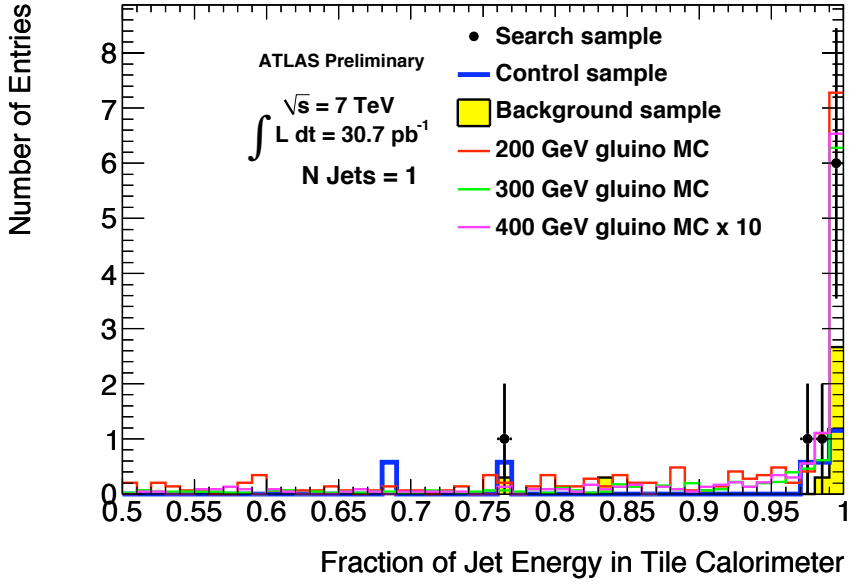


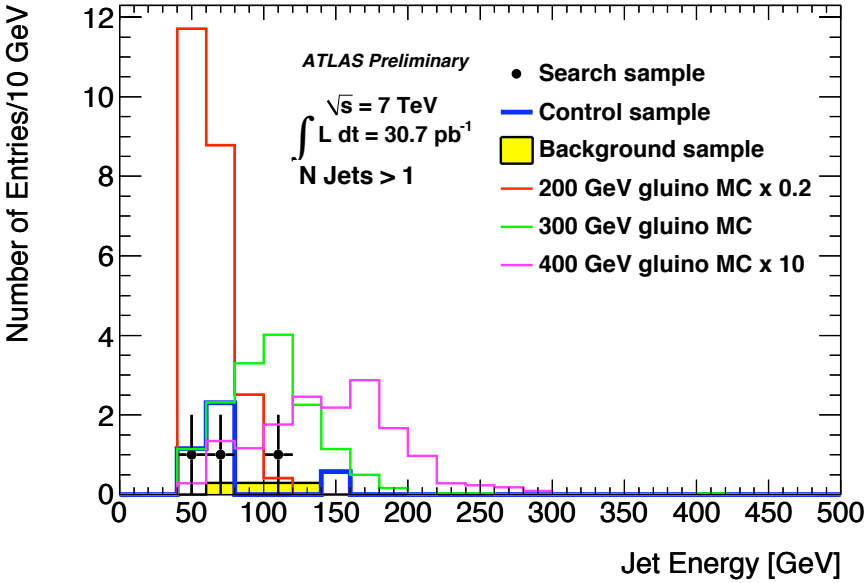
# Final Yield for 1 Jet Bin

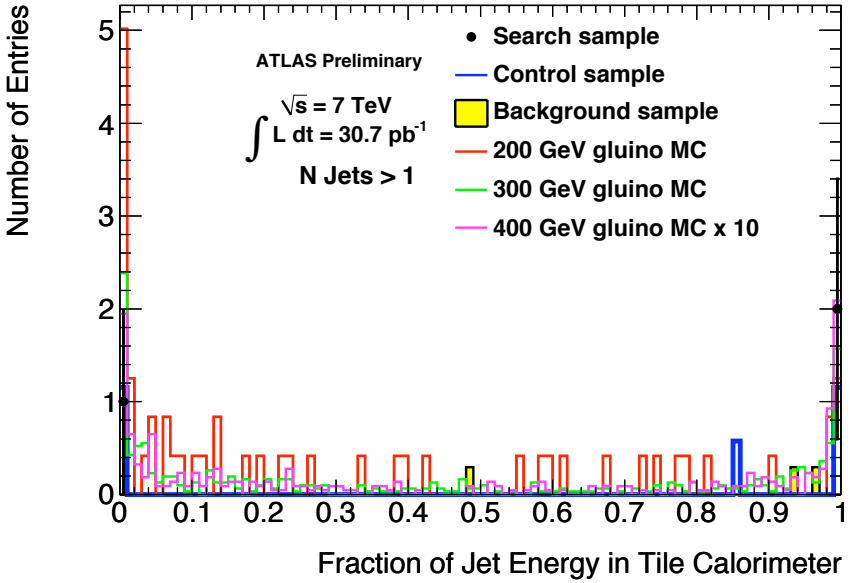





# Final Yield for >1 Jet Bin

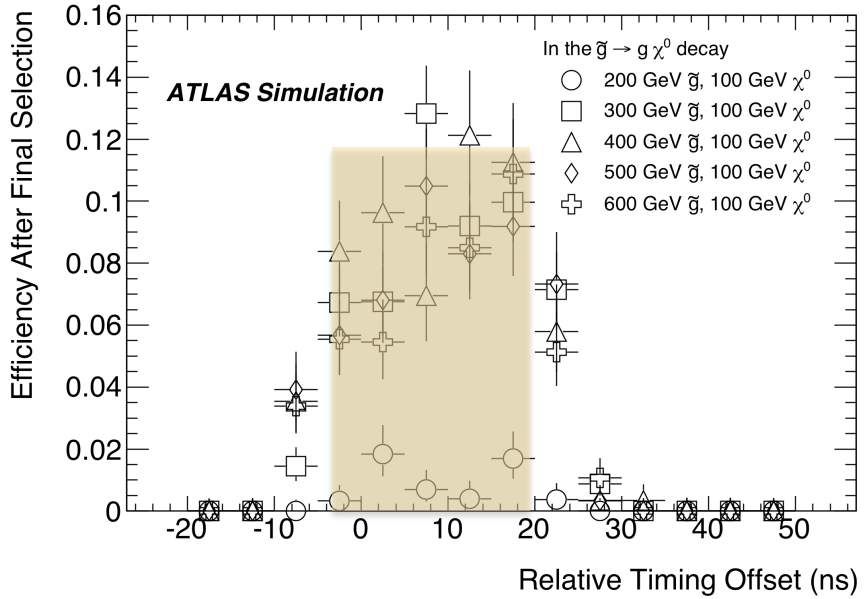


# Systematic Uncertainties



- *R*-hadron Matter Interactions, nuclear xsection
  - Measure stopping fraction varying xsec x2, /2
- Selection Criteria: conservatively varied efficiency within allowed region→9.9%
- Calorimeter Timing: $\varepsilon_{recon}$ varies with decay time
- L1 trigger efficiency drops when energy split across BCIDs

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# Limit Setting



- Use $CL_s$ to set 95% confidence upper limit
  - Applies to # signal events model produces
- Set limit for 2 measurements (1 vs >1 Jets)
  - Use one with strongest expected limit
- Divide out efficiencies (page 12) derive limits…
  - Generic $M_{\tilde{g}} > ???$ GeV for $10^{-5} < \tau < 10^{3}$ seconds
  - Regge $M_{\tilde{g}} > ???$ GeV for $10^{-5} < \tau < 10^{3}$ seconds

| | # of Events | | Fractional Error | | Limits | |
|---|---|---|---|---|---|---|
| # Jets | Observed | Expected | Signal | Bkgnd | Expected | Observed |
| 1 | 0 | .3 | .23 | 1.06 | | |
| >1 | 1 | .6 | .23 | 1.06 | | |

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# Conclusion



- ATLAS search for decays in empty bunches
- 3 samples varied by x400 in expected S/B
- 95% CLs limit for $10^{-5} < \tau < 10^{3}$ seconds
  - Generic $M_{\tilde{g}} >$ ??? GeV
  - Regge $M_{\tilde{g}} >$ ??? GeV
- Big gains in 2011!
  - **More** empty bunches
  - Empties inside trains
  - Femtobarns of data!

# Back Up Slides

# Trigger Strategy



- L1_J10_EMPTY = Normal L1_J10 && “empty”
- Empty defined at LHC ramp using BPTXs
  - Requires no filled bucket in either direction
  - Requires no paired bunch 5 before or 20 after
- Bunch * Hour = $\sum_{runs} \#\ Empty\ Bunches \bullet Run\ Duration$

| Region Name | Periods | Int. Lumi ($pb^{-1}$) | Live Time (Bunch Hours) |
|---|---|---|---|
| Background | A-D | 0.26 | 1,070,000 |
| Control | E-F | 2.56 | 550,000 |
| Search | G-I | 30.7 | 317,000 |
| Total | 2010 A-I | 33.47 | 1,937,000 |

# Data Sample Used



- Empty J10 and RD1 go to CosmicCalo stream
- Used ESD for the cell level information
- Heavily rely on Data Quality flags
  - Only use data10_7TeV tag
  - ATLAS Ready4Physics && LHC stablebeams
  - LAr and Tile must be in “y+” states
- Unpaired J10 to study beam backgrounds
  - Go to JetTauEtMiss stream

# Selection Criteria



- Split into 1 and >1 jet bins
  - Signal regions with leading jet > 50 or 100 GeV

| Number of Jets | 1 | >1 | Rejects |
|---|---|---|---|
| Number μ Segments | = 0 | = 0 | Cosmics + beam halo |
| MET / 1st Jet PT | > 0.5 | > 0.5 | pp + beam gas |
| ID Tracks | = 0 | = 0 | pp + beam gas |
| \|Jet η\| | < 1.2 | < 2.2 | Noisy endcaps |
| Jet Width | > 0.04 | -- | Noise |
| Jet Fraction Tile | > 0.5 | 1st or 2nd > 0.1 | Beam halo + noise |
| N90 | > 3 | 1st Jet > 3 | Noise+cosmics |
| Jet Energy | > 50 GeV | 1st > 50 and 2nd >15 | *Also measure 1st > 100 |

# Signal Simulation 2/3



- MC10 Pythia: $gg \rightarrow \tilde{g}\tilde{g}$ and $q\bar{q} \rightarrow \tilde{g}\tilde{g}$
- Using standard ATLAS G4 R-Hadron extension
  - Handles EM dE/dx and nuclear interactions
- Complimentary matter interaction models
  - Generic, Regge, Intermediate
  - Different nuclear interaction cross sections and R-Hadron spectra
- Used Prospino (@NLO) and CTEQ6.6 for cross section to produce gluinos

# Background Sources: Noise



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- Events show strong noise signature!
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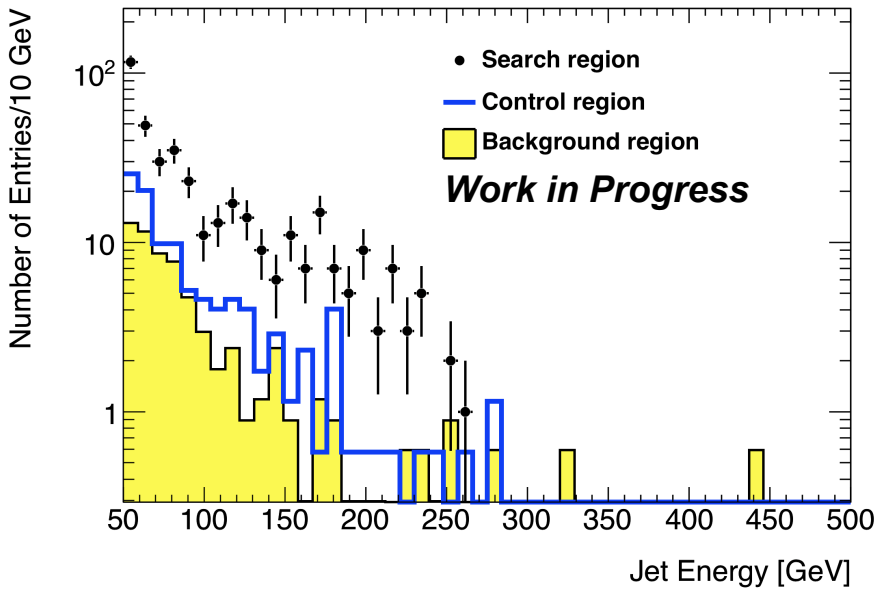


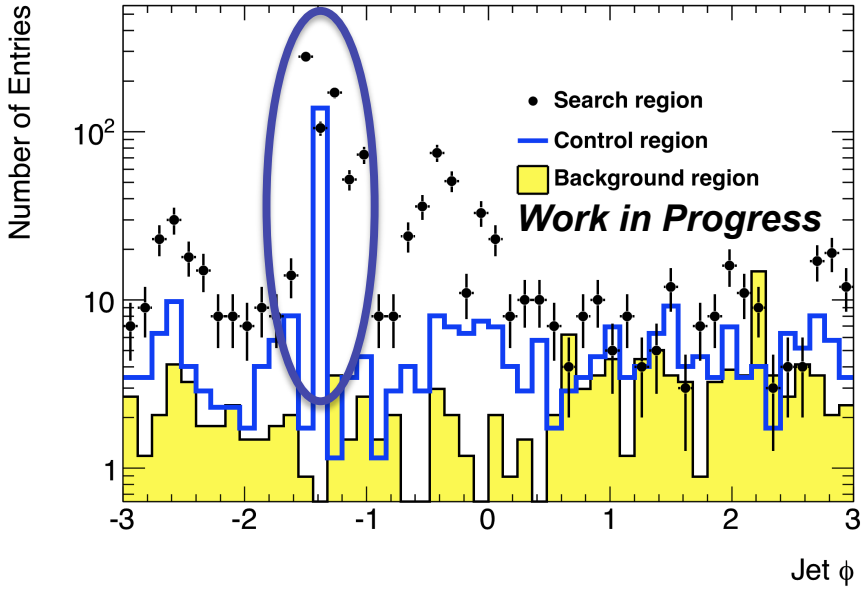


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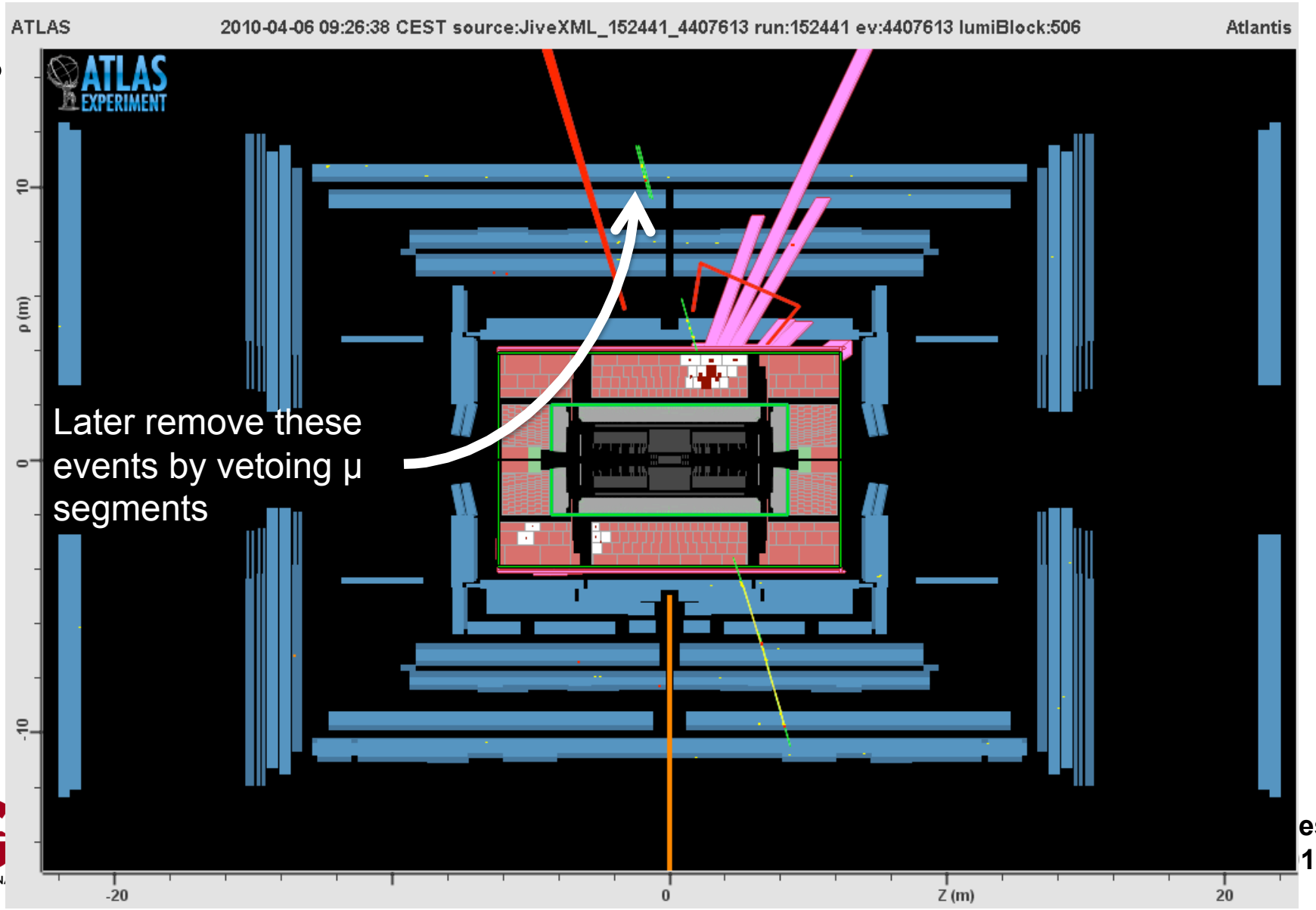
# Backgrounds: Cosmics





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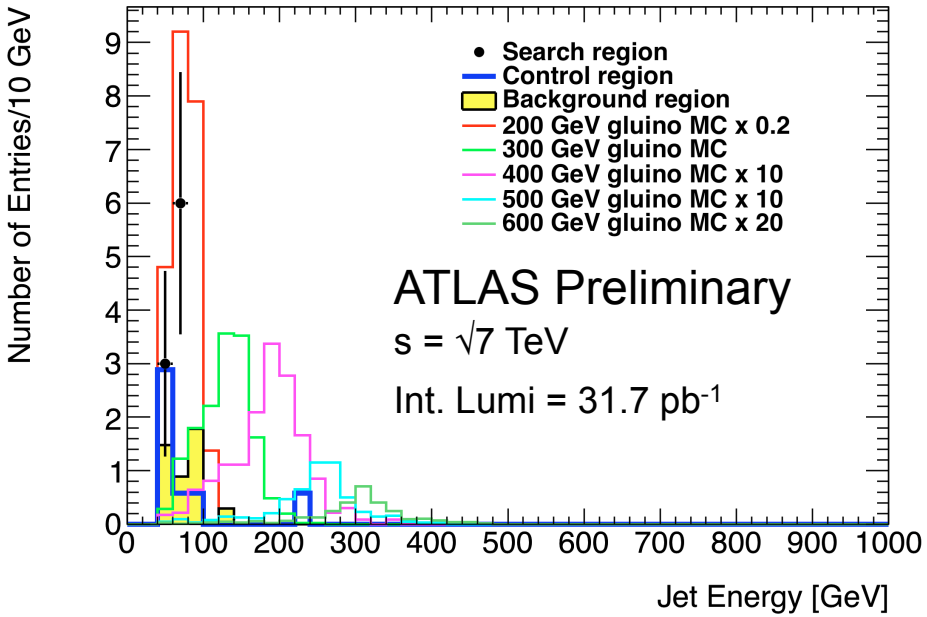


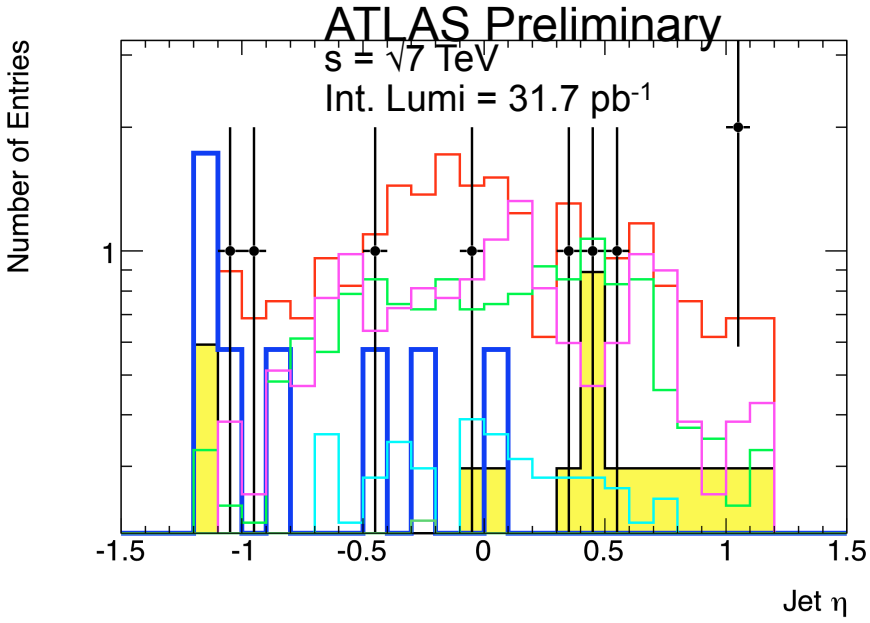


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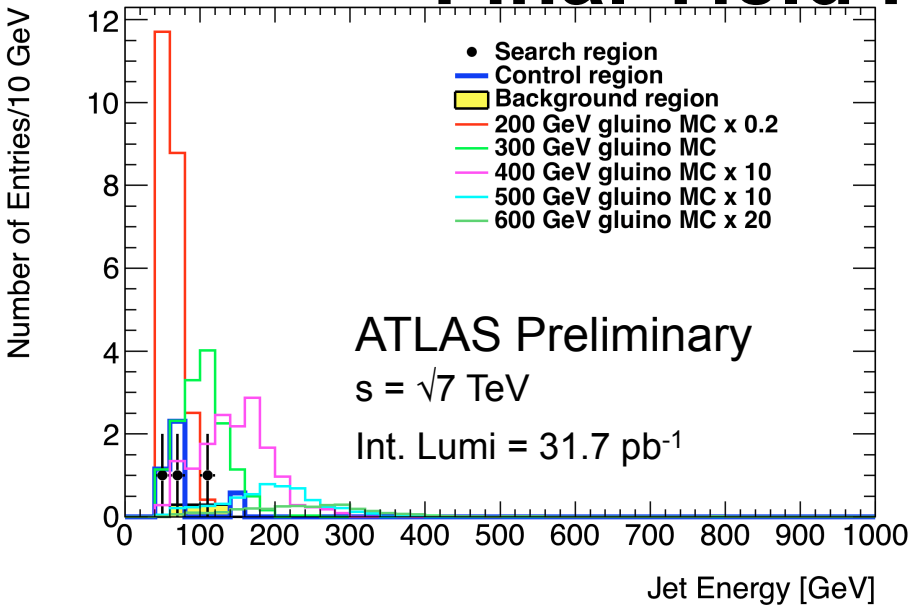


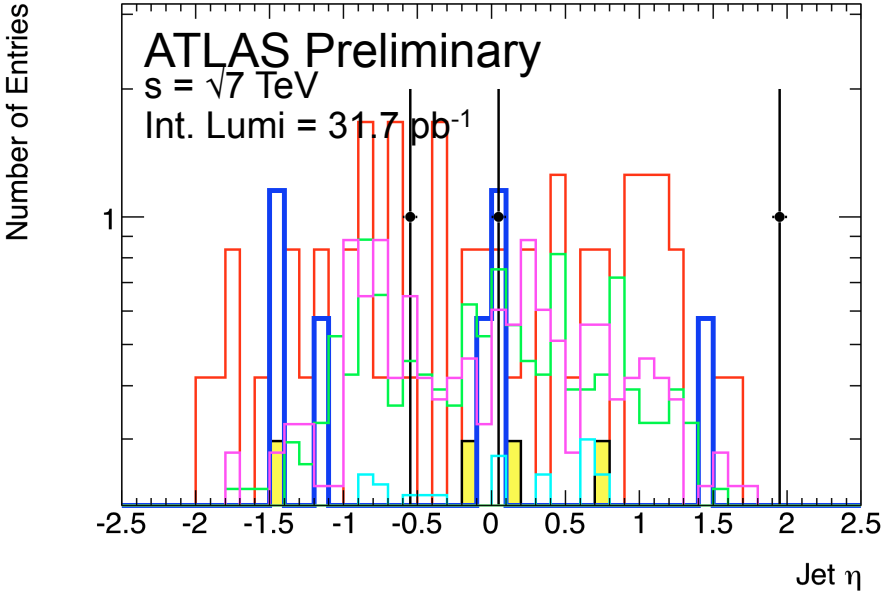

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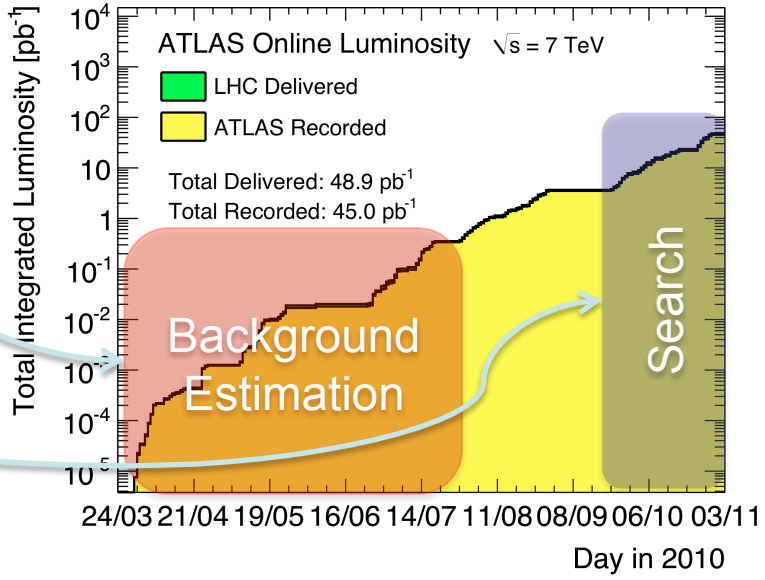


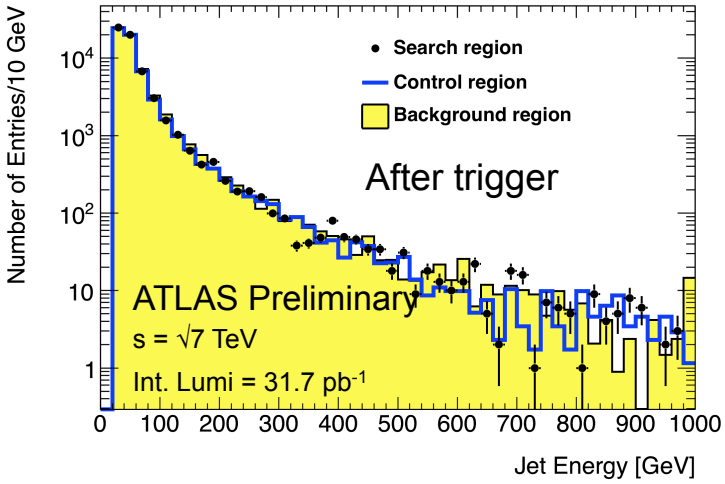


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