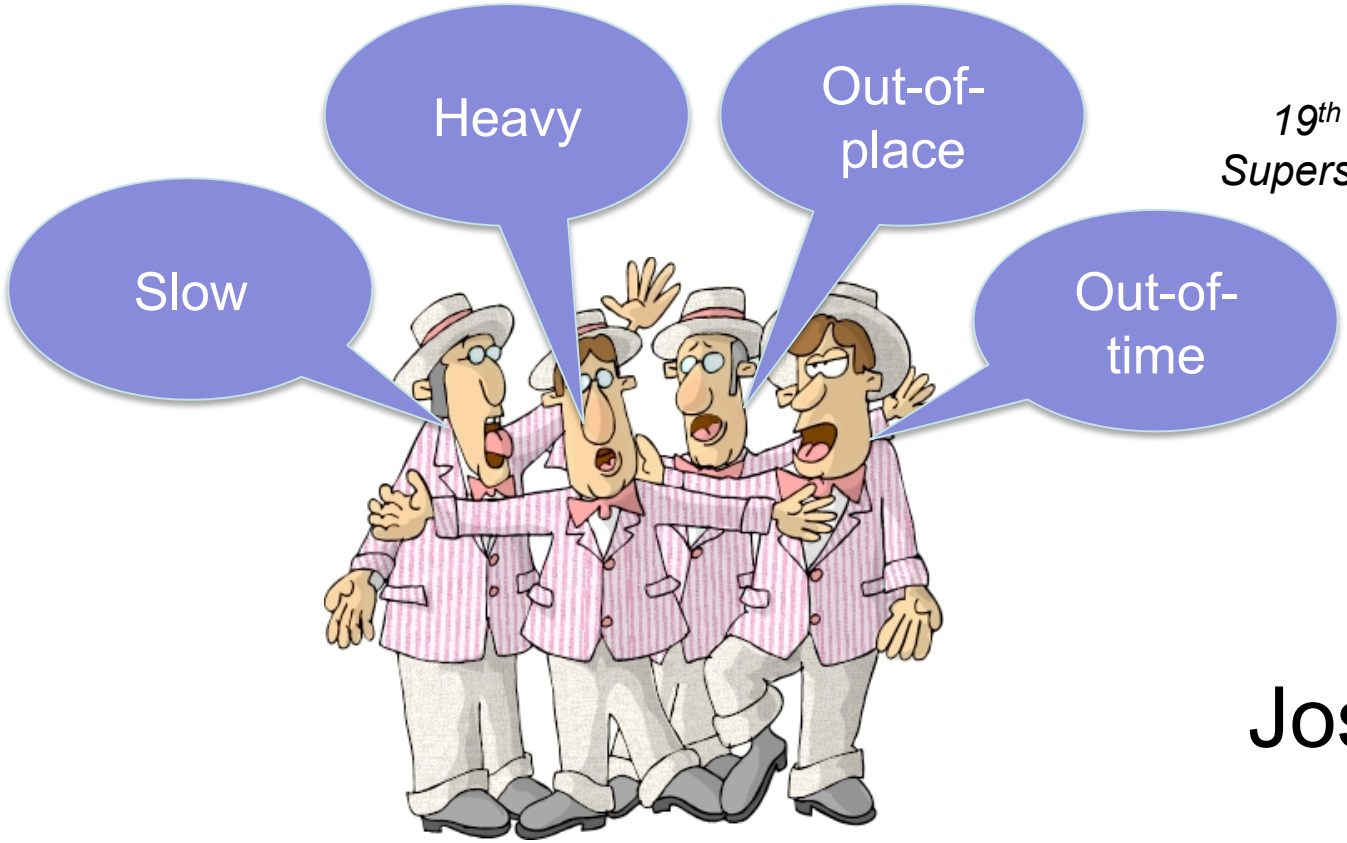
Search for Supersymmetry in Final States with Measurable Lifetimes with the ATLAS Detector



19th International Conference on Supersymmetry and Unifications of Fundamental Interactions

Josh Cogan

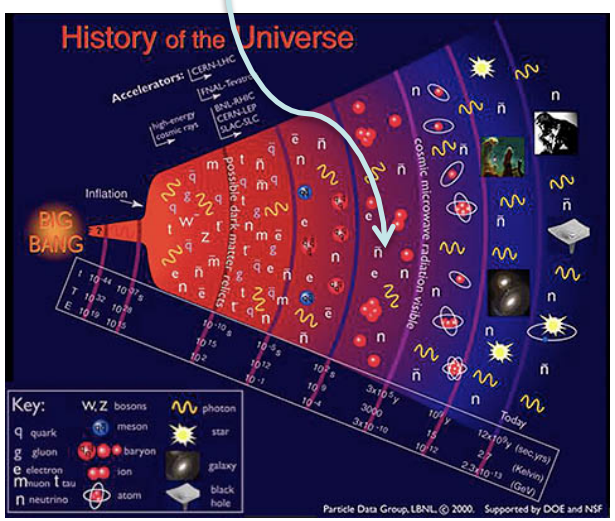
SLAC NATIONAL ACCELERATOR LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

Mechanism & Motivation

- Several SUSY models allow a particle with decay length > ATLAS
  - Split, RPV, Stealth, GMSB (and hidden valley!)
  - New coupling, small phase space, large scales
- Cosmological & sBBN ^{7}Li / ^{6}Li discrepancy
  - Convenient delayed neutron source: $\tau \sim< 100$ sec

Long Lived Particle?

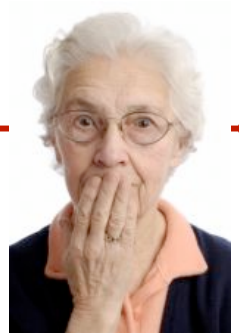


Any 400 GeV particle in your detector is BSM

Observing jets
vs
Observing LLPs

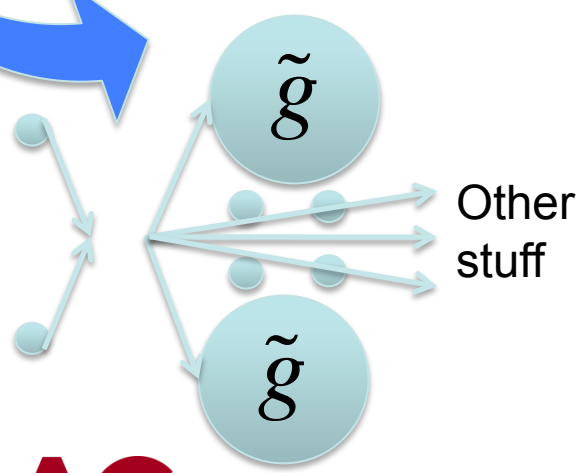
SUSY 11/LLP Final States in ATLAS, Fermilab, Aug 28 2011

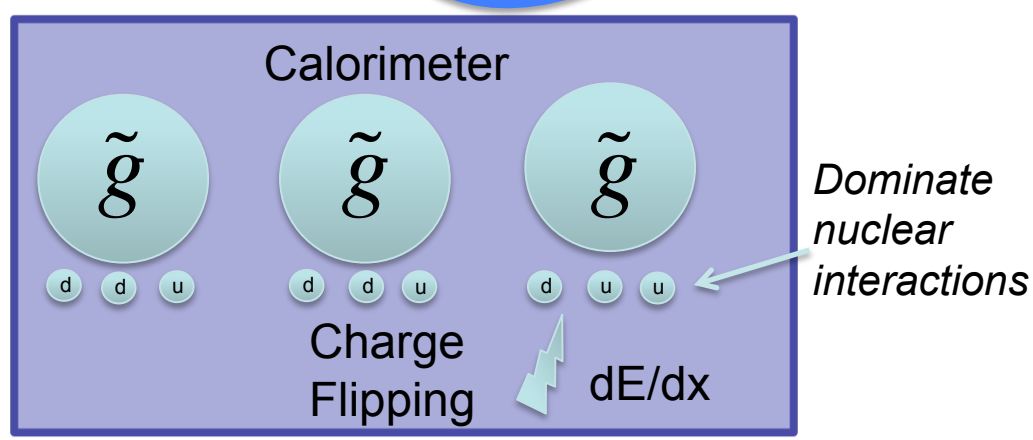
R-hadron Signature



- Not your Grandmother's particle!
- Given an LLP w/ *color charge* $\left(\tilde{g},\ \tilde{b},\ \tilde{t},\ \ldots\right)$
  - Hadronize w/ SM quarks→glueball/meson/baryon
  - Spectator quarks dominate nuclear interaction
  - *R*-hadron exchanges electric charge with nuclei!
- Energy loss: dE/dX, nuclear scatter & trapping
- Nuclear xsec and hadron spectrum unknown

Where in ATLAS are the *R*-hadrons charged?





Search Signatures

Inner Detector + Calorimeter

Muon Spectrometer

Stopped Particle

$\otimes$

Phenomenology + Selection

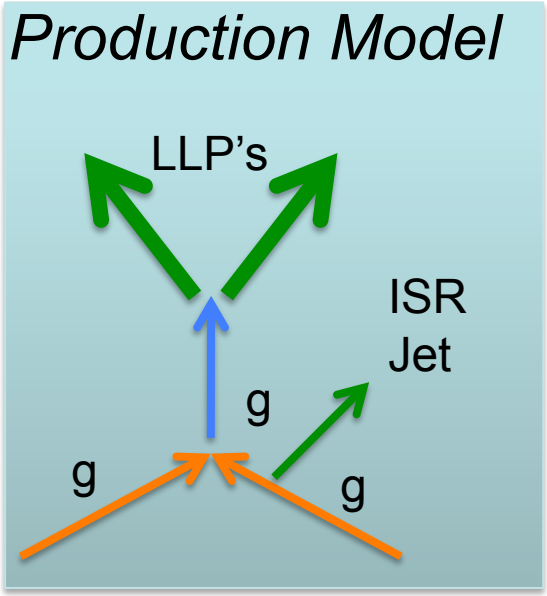
Detection Methods

Backgrounds

Results

doi:10.1016/j.physletb.2011.05.010

ID and Calorimeter: Phenomenology



LLP's produced near threshold

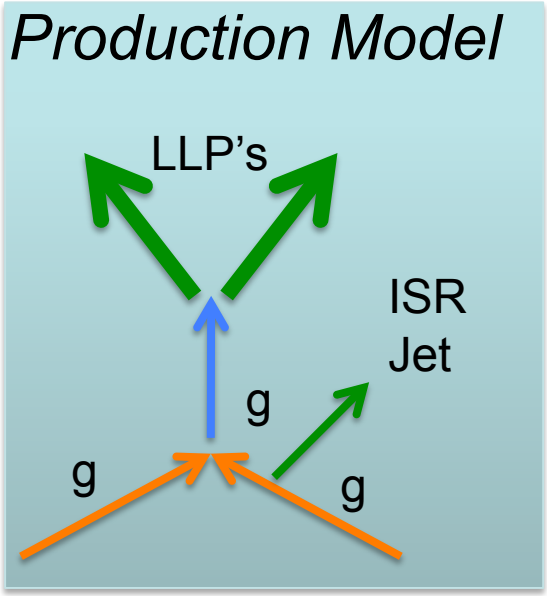
↓

Kinetic Energy $\approx M_{LLP}$

From Theory
Analysis Selection

doi:10.1016/j.physletb.2011.05.010

ID and Calorimeter: Phenomenology



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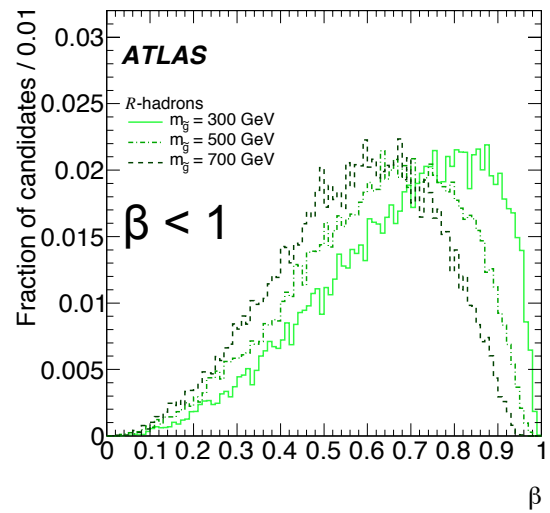
Candidate Track
$p_T > 50$ GeV



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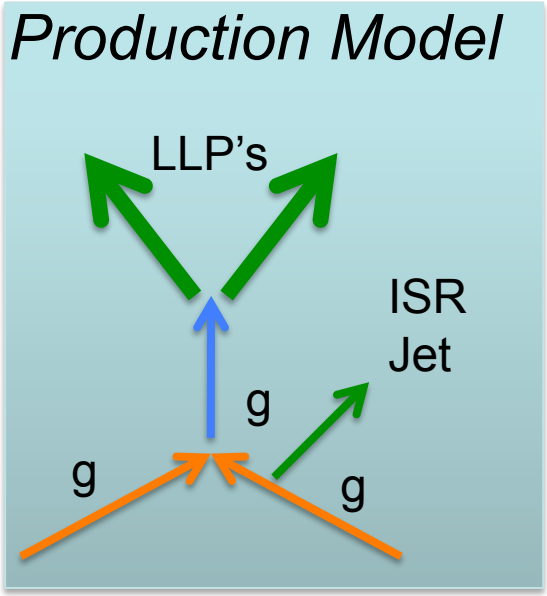

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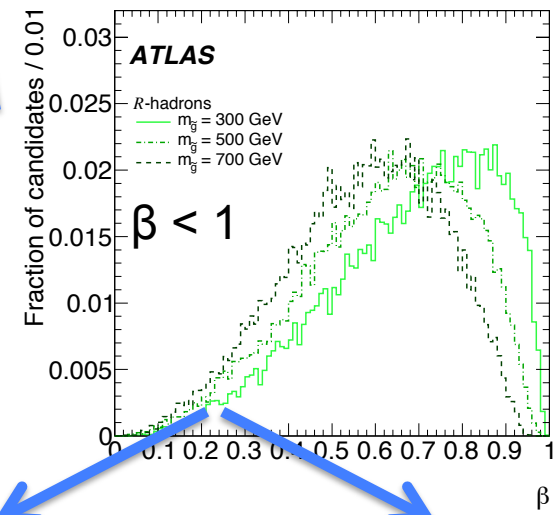

TileCal ToF $\beta < 1$

dE/dX in Pixel > 1.8 MeV cm^2 /g

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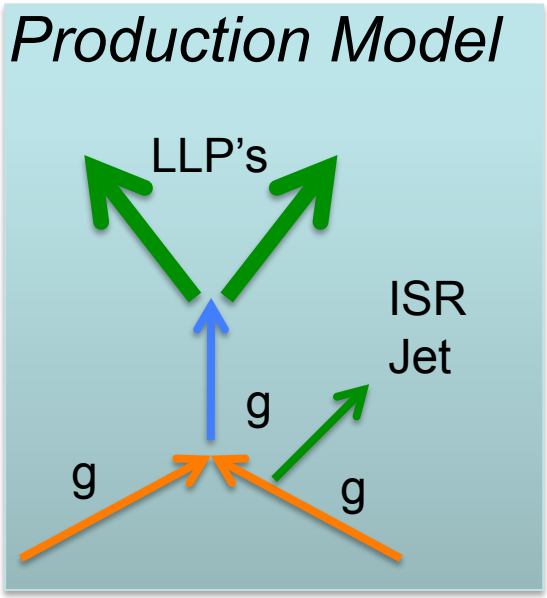
ID and Calorimeter: Phenomenology



LLP's produced near threshold

Kinetic Energy $\approx M_{LLP}$

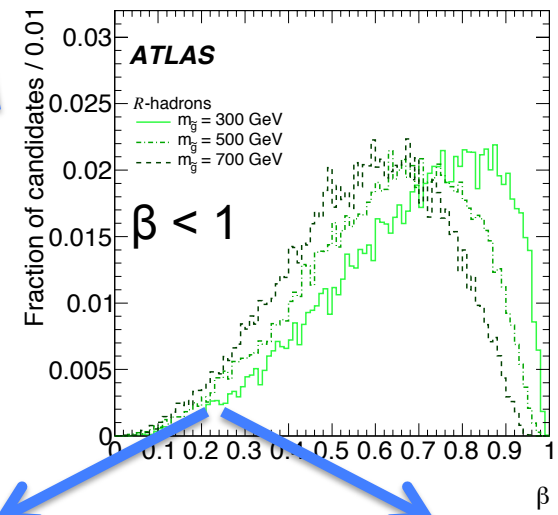
LLP's leave small fraction of their energy in ATLAS

Total EM energy loss ≈ 10 GeV

From Theory

Analysis Selection

Candidate Track $p_T > 50$ GeV



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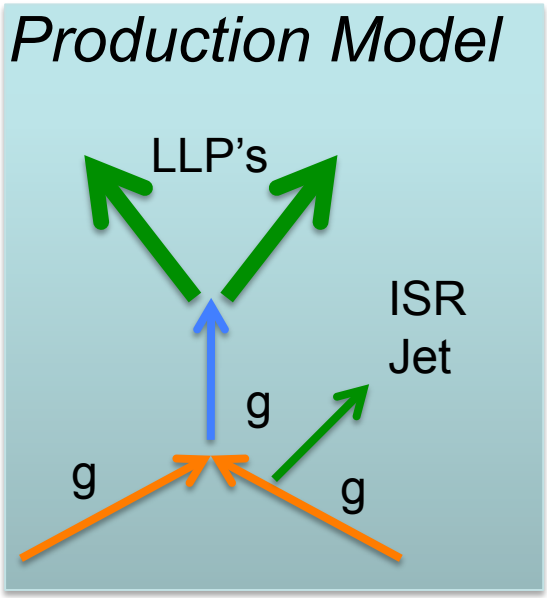


LLP's produced near threshold

Kinetic Energy $\approx M_{LLP}$

LLP's leave small fraction of their energy in ATLAS

Total EM energy loss ≈ 10 GeV

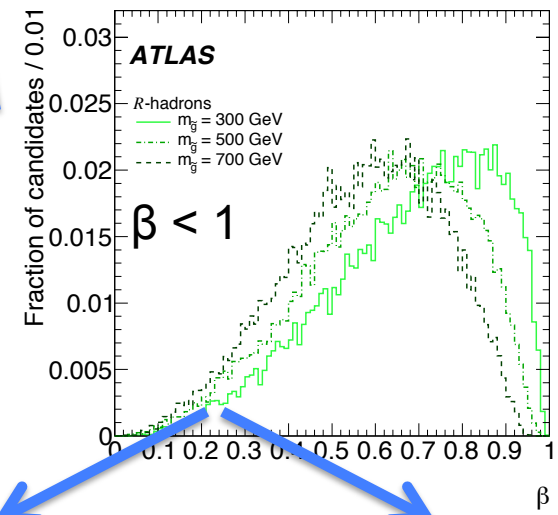
ISR jet still very large

Trigger on MET > 40 GeV

From Theory

Analysis Selection

Candidate Track p_T > 50 GeV



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dE/dX in Pixel > 1.8 MeV cm^2 /g

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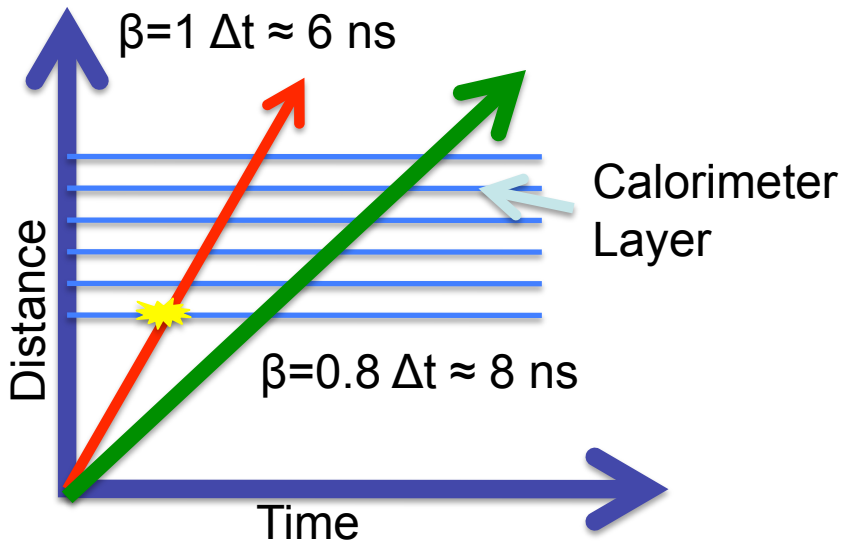
ID and Calorimeter: Detector

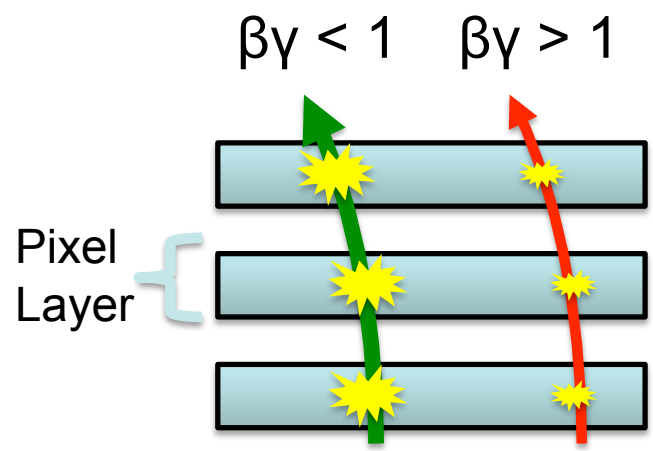
Tile Calorimeter Time of Flight

SM Particles (Fast)
Heavy LLP (Slow)



- Each cell δt = 1-2 ns
- Average cells over 500 MeV → δt ≈ 1 ns

Pixel Tracker dE/dX



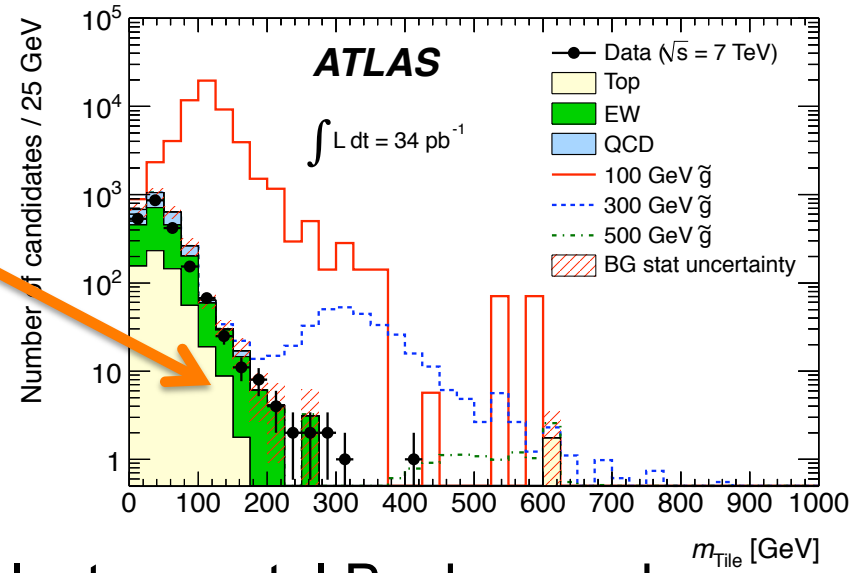
- MIPS leave ~1 MeV cm^2/g
- LLP leave 2-10 MeV cm^2/g

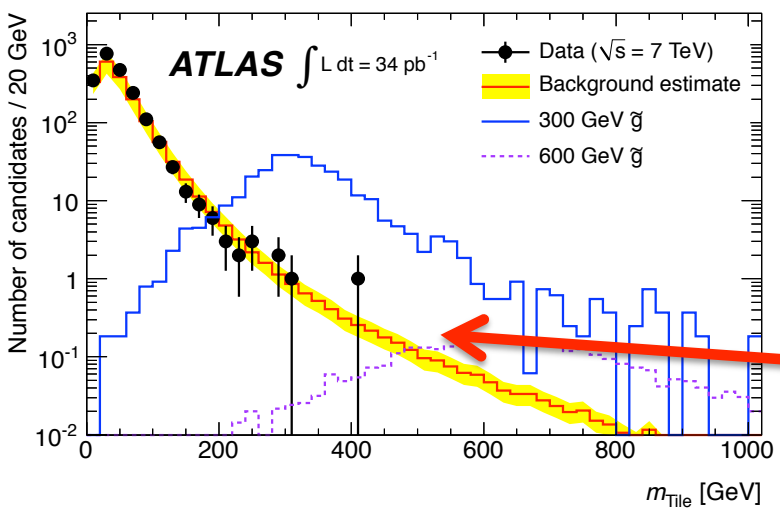
doi:10.1016/j.physletb.2011.05.010

ID and Calorimeter: Backgrounds

SM Backgrounds

- Top and EW biggest
  - Not real massive particles
  - Instrumental effects!
- After all cuts too few statistics
- Need to estimate high mass yield





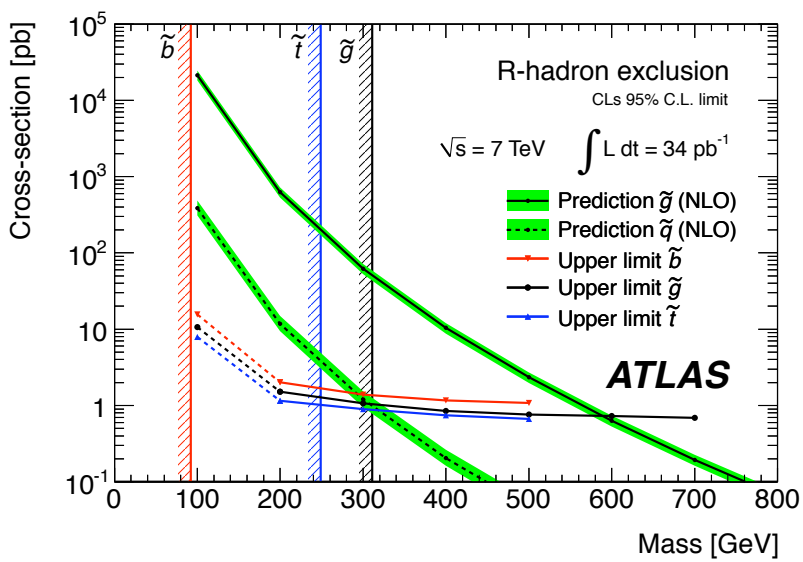
Instrumental Backgrounds

- Combine measured p with random β
  - PDF(β) derived from data
  - Many random β's for each p
- Calculate m_{Tile}
- Similar treatment for m_{Pixel} and combination → $N_{bkg} < 1$

doi:10.1016/j.physletb.2011.05.010

ID and Calorimeter: Results

Cut	Data	Background	600 GeV ~g
Preselection	49205	49.4×10^3	4.13
$p_T > 50$ GeV	5116	6.56×10^3	3.95
1 Mass Cut	36	56.0	2.75
Both Mass Cuts	0	0.028	2.62



No signal like events observed

- In 34 pb^{-1} of data
- Studied several mass regions
- Proceed to set 95% CL_S limit
  - Interpret as *R*-hadron
  - 30% bkgd systematic
  - 10% on eff from PYTHIA scale

$m_{\tilde{b}} > 294\ GeV$ $m_{\tilde{g}} > 586\ GeV$ $m_{\tilde{t}} > 309\ GeV$

doi:10.1016/j.physletb.2011.05.010

Search Signatures

Inner Detector + Calorimeter

Muon Spectrometer

Stopped Particle

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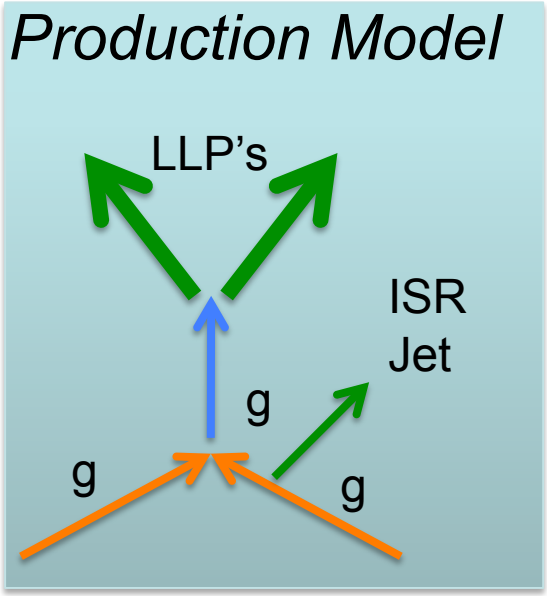
Detection Methods

Backgrounds

Results

arXiv:1106.4495v1 [hep-ex]

Muon Spectrometer: Phenomenology



LLP's produced near threshold

Kinetic Energy
≈ M_{LLP}

From Theory
Analysis Selection

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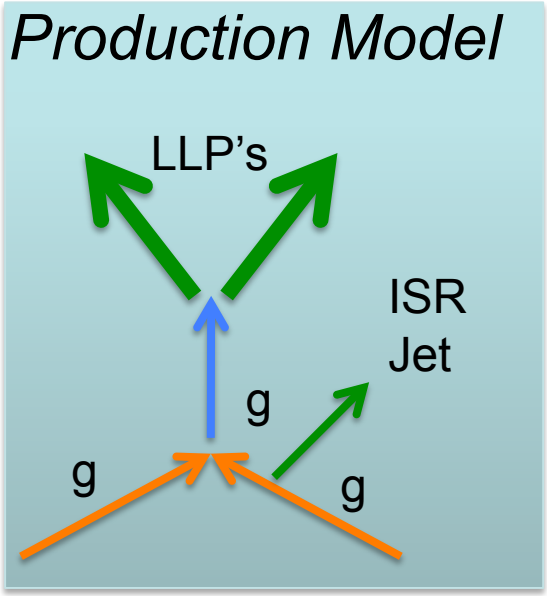


LLP's produced near threshold

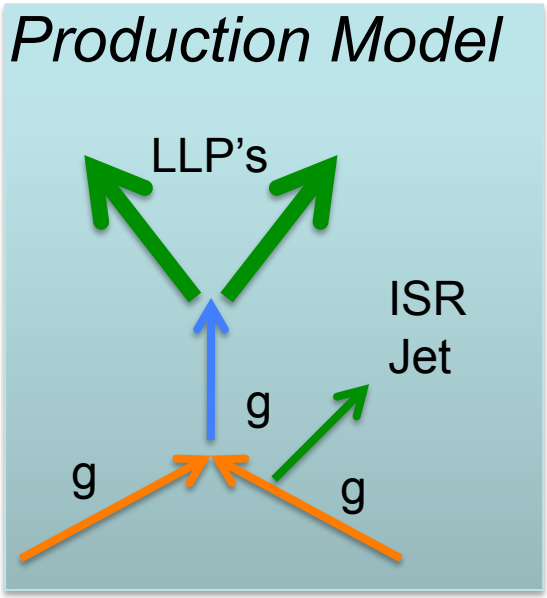
Kinetic Energy $\approx M_{LLP}$

- Candidate Track $p_T > 60$ GeV
- $\beta < 0.95$
- Late Arrival to MS

From Theory
Analysis Selection

arXiv:1106.4495v1 [hep-ex]

Muon Spectrometer: Phenomenology



LLP's produced near threshold

Kinetic Energy $\approx M_{LLP}$

LLP's traverse the muon system

Total EM energy loss ≈ 10 GeV

From Theory
Analysis Selection

Candidate Track $p_T > 60$ GeV

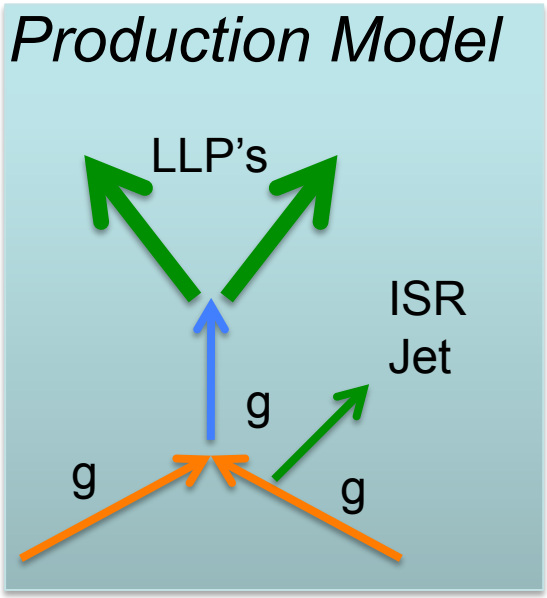
$\beta < 0.95$

Late Arrival to MS

Trigger on "μ" $p_T > 40$ GeV

arXiv:1106.4495v1 [hep-ex]

Muon Spectrometer: Phenomenology



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R-hadron might not be charged in ID

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Drop Inner Detector info…

arXiv:1106.4495v1 [hep-ex]

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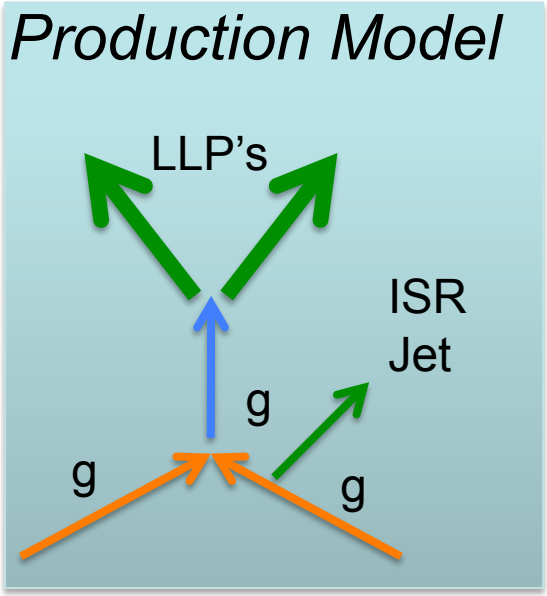

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Late Arrival to MS

Trigger on "μ" $p_T > 40$ GeV

Drop Inner Detector info…

Optimized 2nd set of cuts for slepton search (using ID tracking as well)!

106.4495v1 [hep-ex]

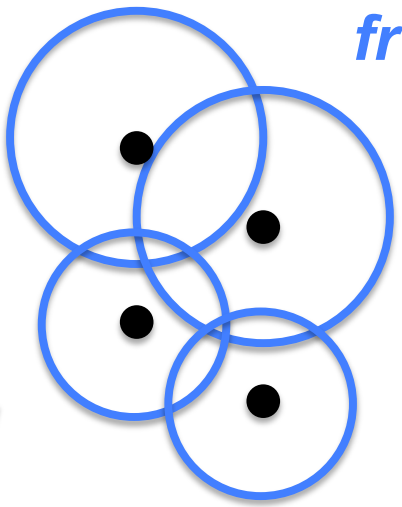
Muon Spectrometer: Detector

- Use Resistive Plate Chamber for ToF
- Not so easy for Drift Tube Tracking
  - Provides high spatial resolution (20 μm)
  - Need to **recalculate drift times** for $\beta \neq 1$

arXiv:1106.4495v1 [hep-ex]

Muon Spectrometer: Detector

Reconstructed drift circles from a slow particle



Try tracking with β = 1

- Use Resistive Plate Chamber for ToF
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  - Need to **recalculate drift times** for β ≠ 1

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Muon Spectrometer: Detector

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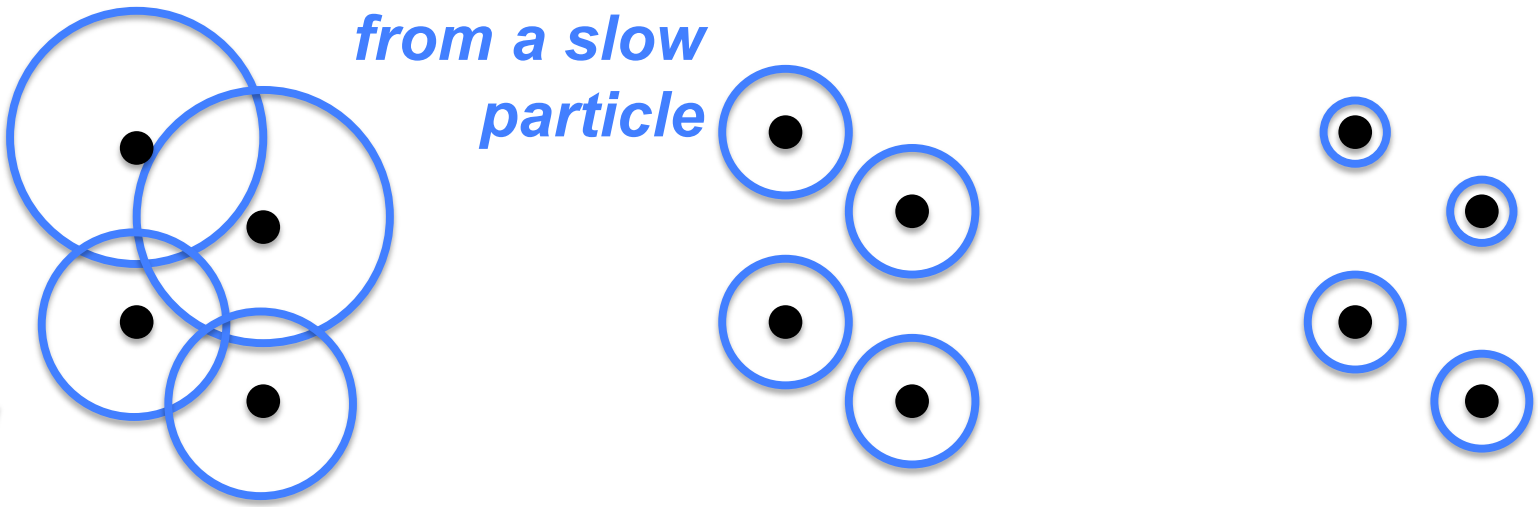

Try tracking with β = 1

Try tracking with β = 0.8

Try tracking with β = 0.6

- Use Resistive Plate Chamber for ToF
- Not so easy for Drift Tube Tracking
  - Provides high spatial resolution (20 μm)
  - Need to **recalculate drift times** for β ≠ 1

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arXiv:1106.4495v1 [hep-ex]

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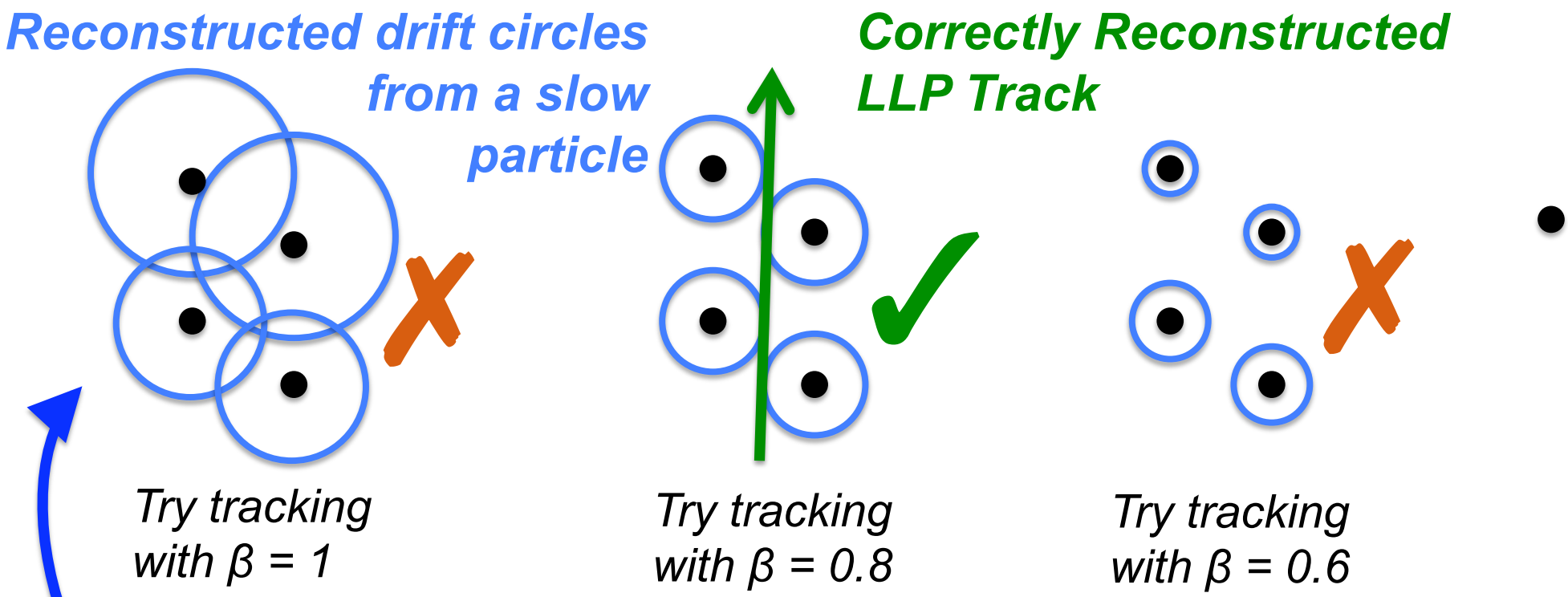


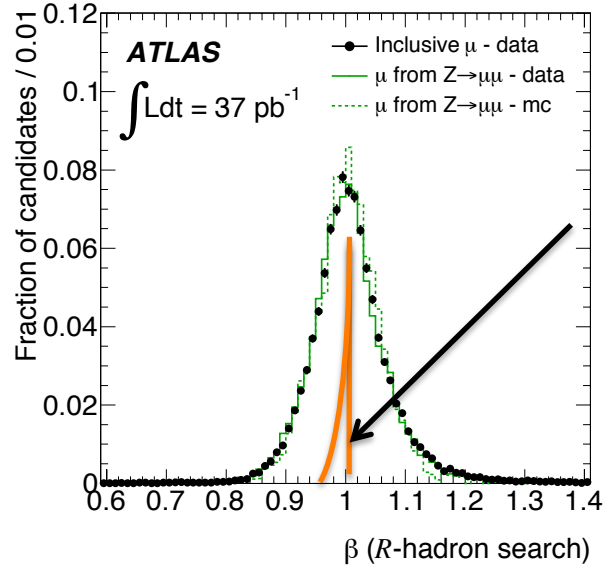
- Use Resistive Plate Chamber for ToF
- Not so easy for Drift Tube Tracking
  - Provides high spatial resolution (20 μm)
  - Need to **recalculate drift times** for $\beta \neq 1$

arXiv:1106.4495v1 [hep-ex]

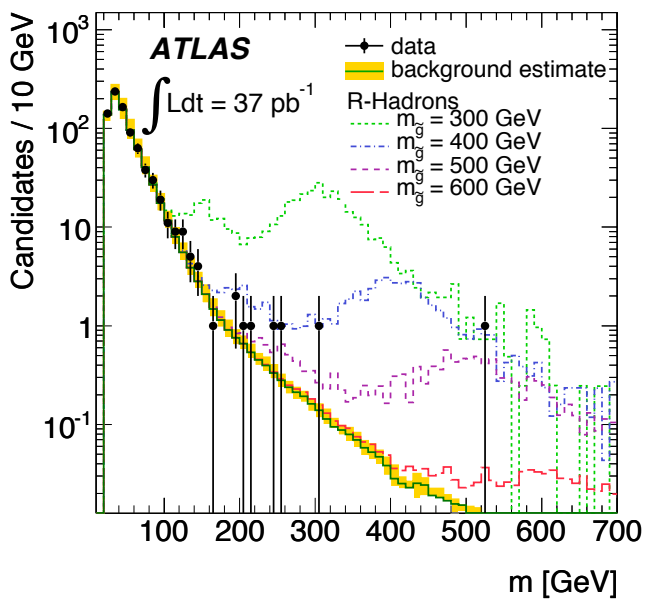
Muon Spectrometer: Backgrounds

SM Backgrounds

- Basically, no slow muons ($m_\mu \approx 0$)
  - PDF(β) $\neq \delta(\beta-1)$??
  - Instrumental effects!
  - And ~1.3 cosmics in sample
- Need to estimate $\beta<1$ yield from mis-measured muons



~ Underlying muon PDF



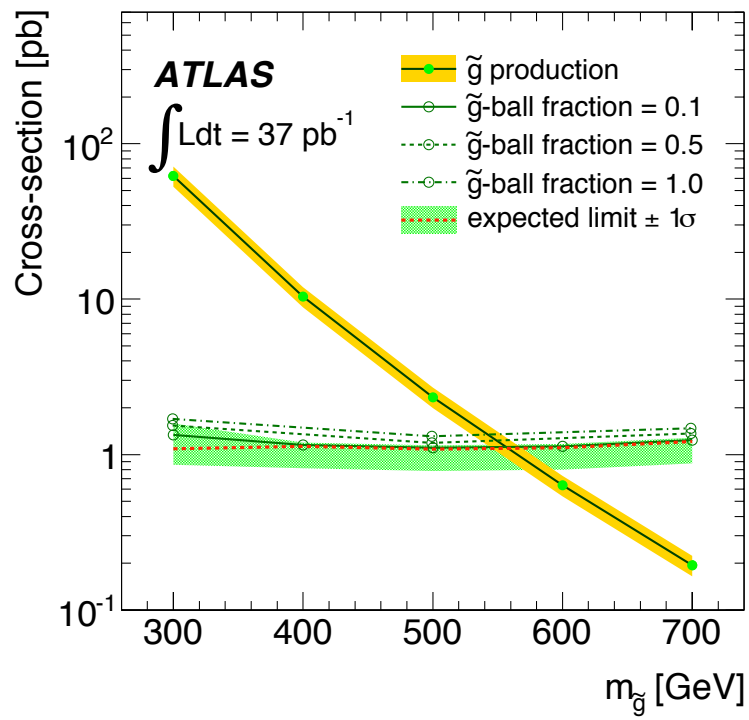
Instrumental Backgrounds

- Combine measured p with random β
  - PDF(β) derived from data
  - Many random β's for each p
  - PDF calculated in η slices
- Calculate m_{LLP}
- $N_{bkg} = 2.3$ (for $m_{LLP} > 250$ GeV)

arXiv:1106.4495v1 [hep-ex]

Muon Spectrometer: Results

Cut	Data	$\langle N_{bkgd} \rangle$	$\langle N_{sig} \rangle$ 600 GeV ~g
Preselection	6334	--	3.8
β Quality	4998	--	3.3
β < 0.95	830		3.2
M > 350 GeV	1	0.7	2.2



<u>No excess of events observed</u>

- In 37 pb^{-1} of data
- Studied several mass regions
- Proceed to set 95% CL_S limit
  - Interpret as *R*-hadron/Stau
  - 20% bkgd systematic
  - 6% systematic on signal yield

$$m_{\tilde{g}} > 544\ GeV$$

~g-ball fraction =10%

$$m_{\tilde{\tau}} > 136\ GeV$$

N_5 = 3, $m_{messenger}$= 250 TeV, μ>0, tanβ=5

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arXiv:1106.4495v1 [hep-ex]

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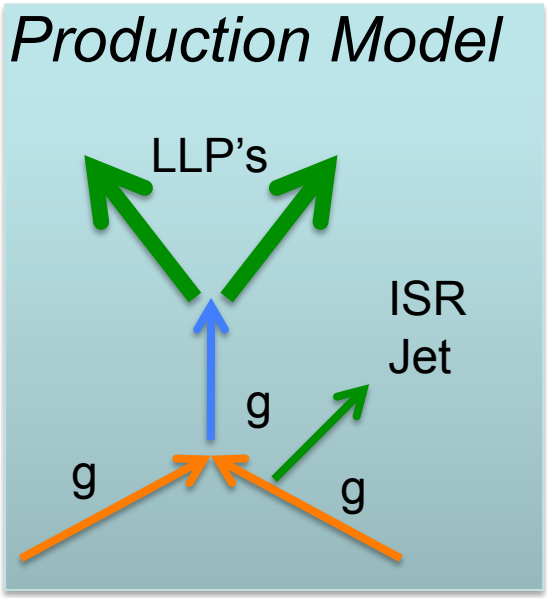

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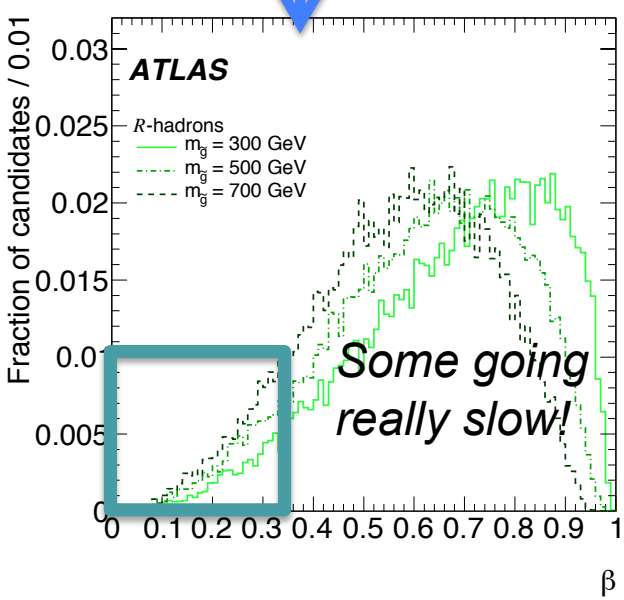
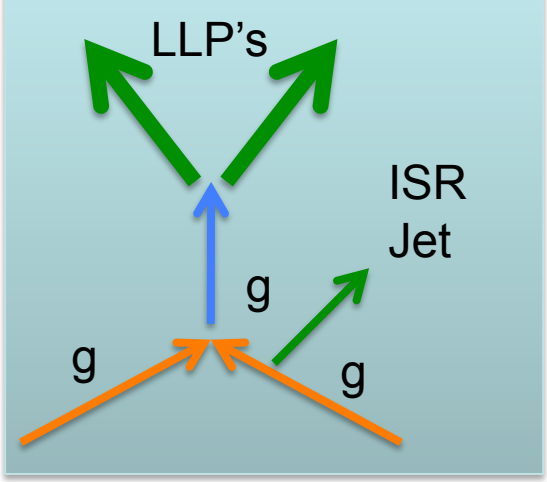


- From Theory
- Analysis Selection

Stopped Particles: Phenomenology

Production Model



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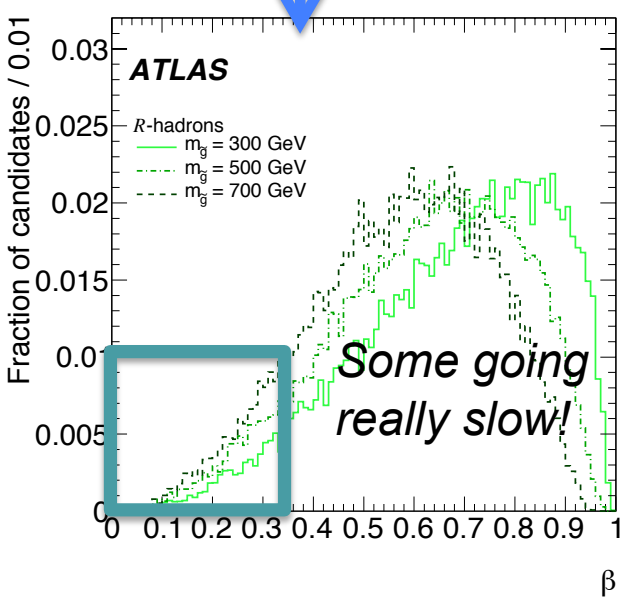
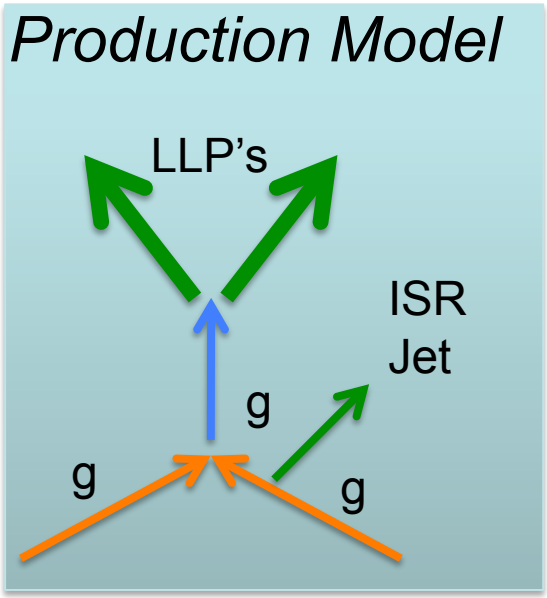


From Theory
Analysis Selection

$dE/dX \approx \beta^{-2}$

Occasional nuclear scatter

Stopped Particles: Phenomenology



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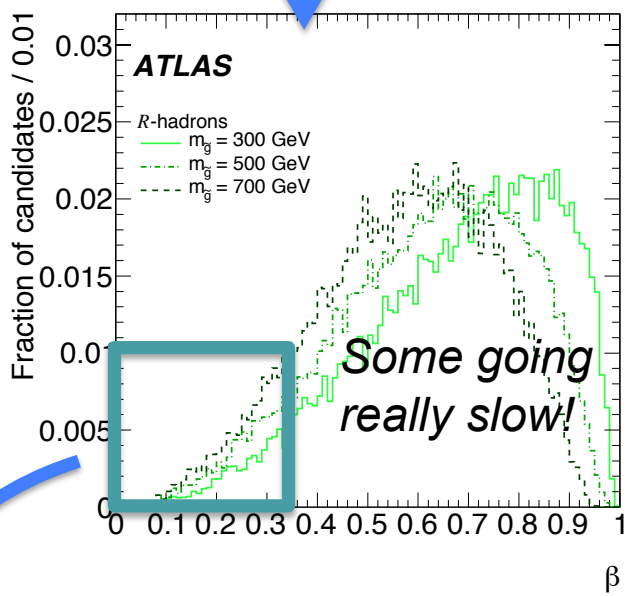


From Theory
Analysis Selection

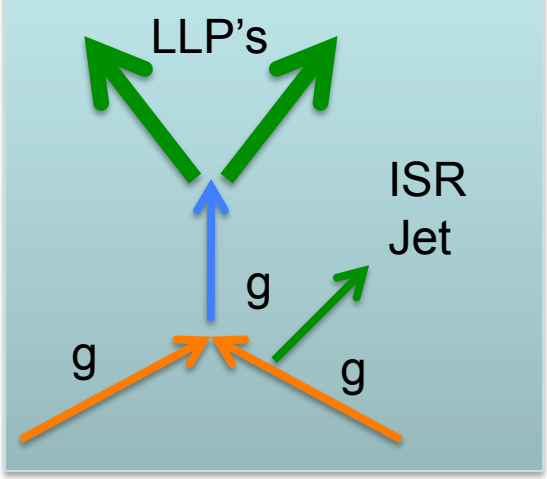
$dE/dX \approx \beta^{-2}$

Occasional nuclear scatter

Some ***LLPs*** stop in detector, and decay **<u>much</u>** later

Stopped Particles: Phenomenology

Production Model



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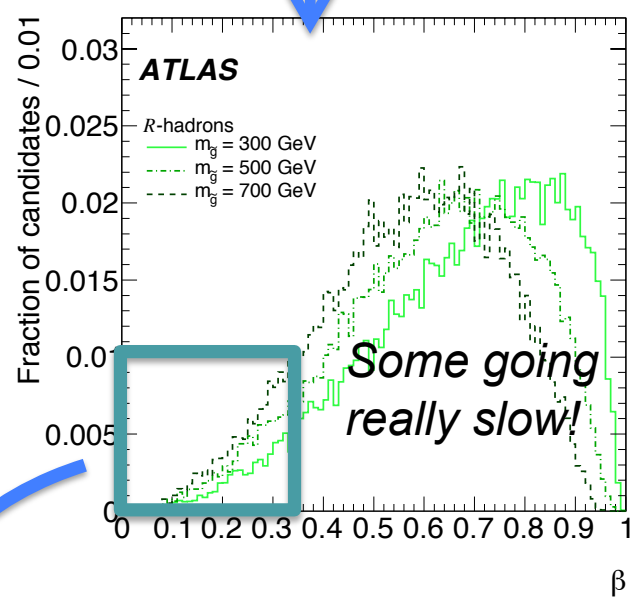


From Theory
Analysis Selection

Not all "bunches" have protons

Look for decay in "empty" bunches

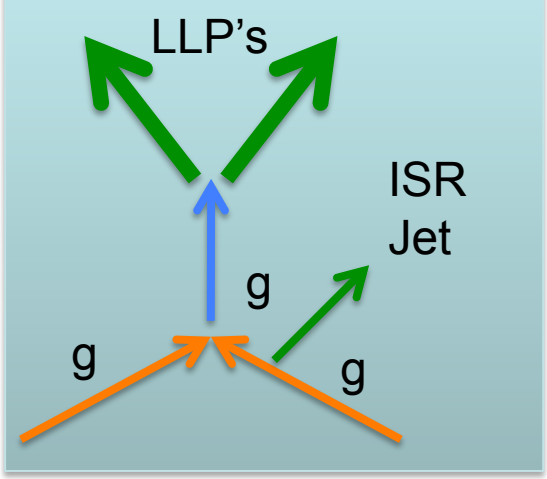
$dE/dX \approx \beta^{-2}$

Occasional nuclear scatter

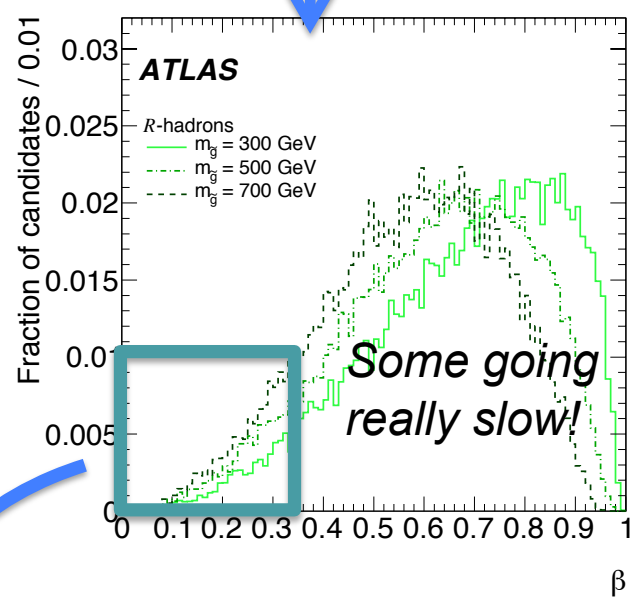
Some ***LLPs*** stop in detector, and decay **<u>much</u>** later

Stopped Particles: Phenomenology

Production Model



LLP's produced near threshold



From Theory
Analysis Selection

Not all "bunches" have protons

Look for decay in "empty" bunches

Handle non-collision backgrounds

$dE/dX \approx \beta^{-2}$

Occasional nuclear scatter

Some ***LLPs*** stop in detector, and decay **<u>much</u>** later

Stopped Particles: Detector

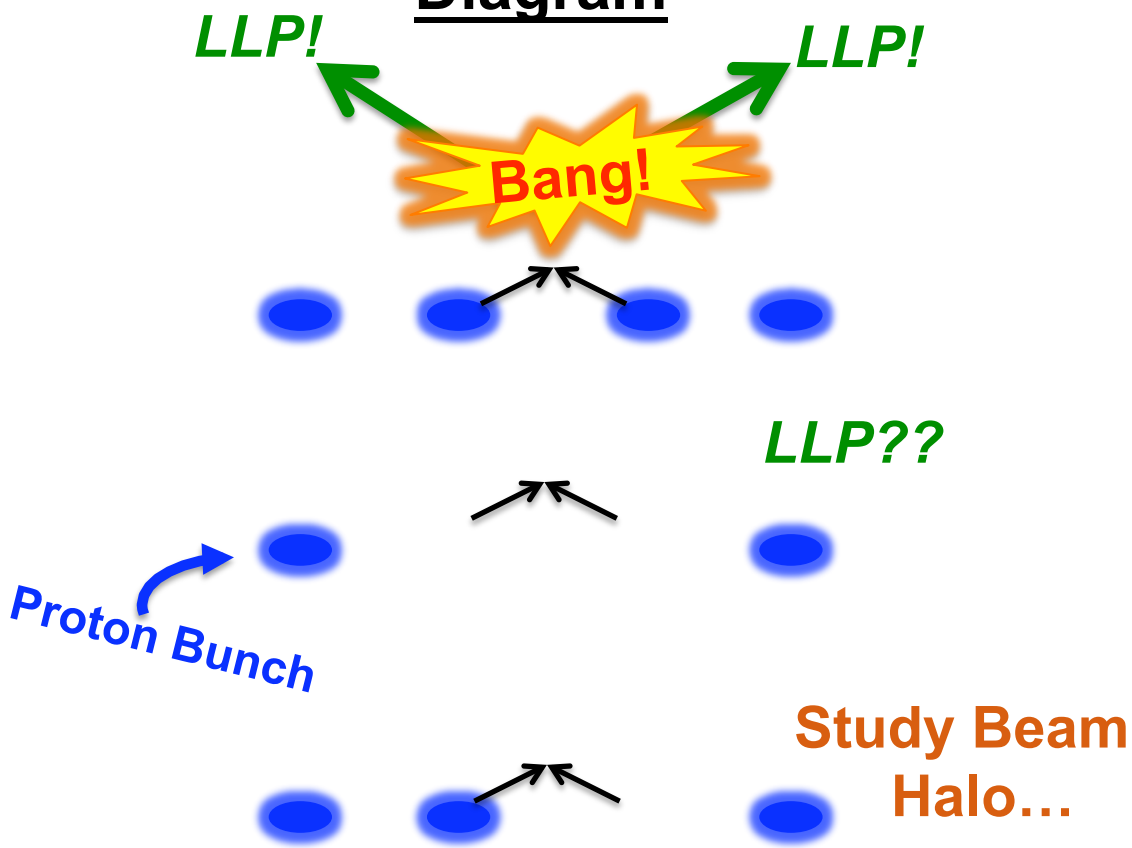
Bunch Type

Colliding

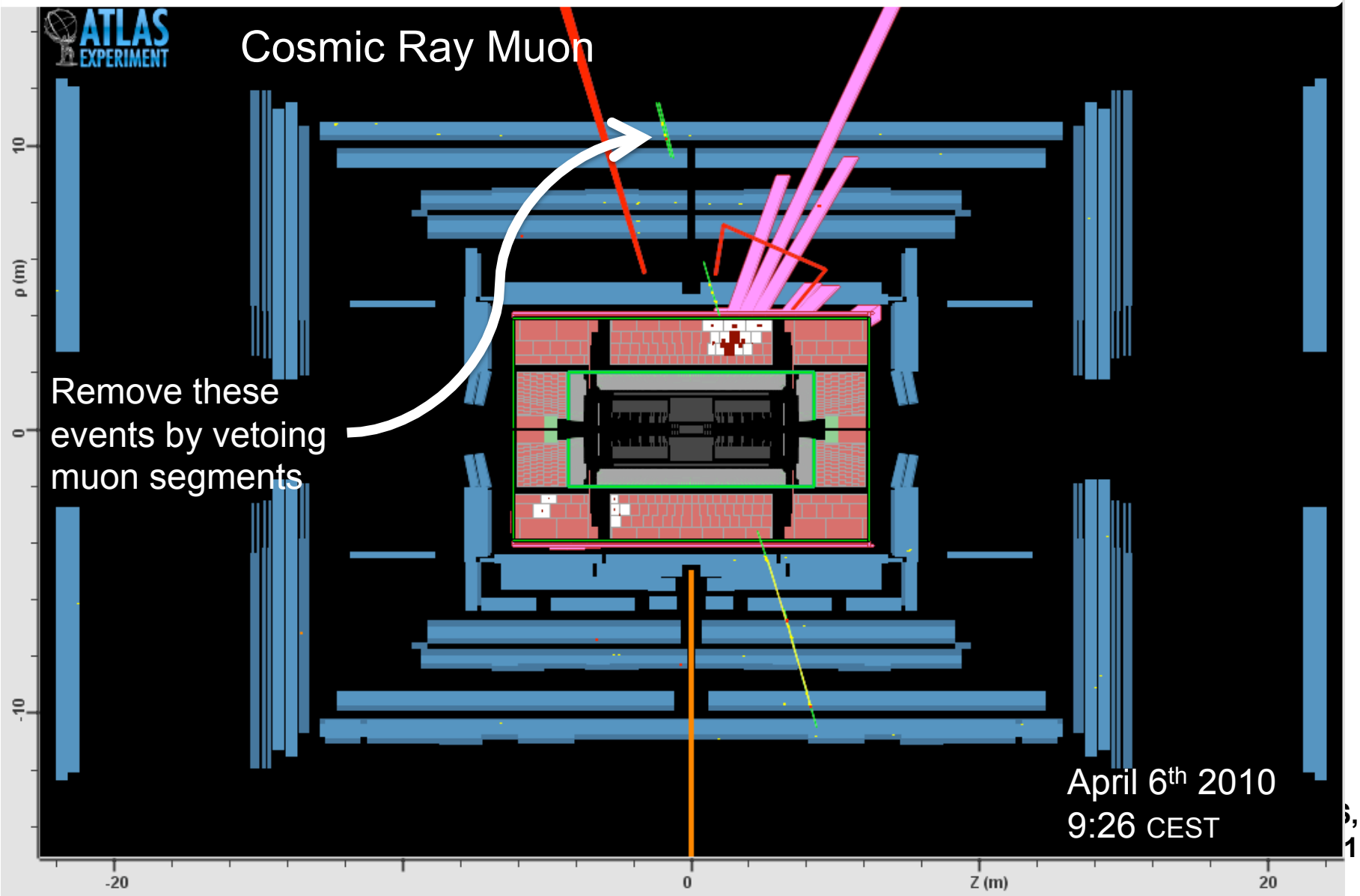
Empty

Unpaired

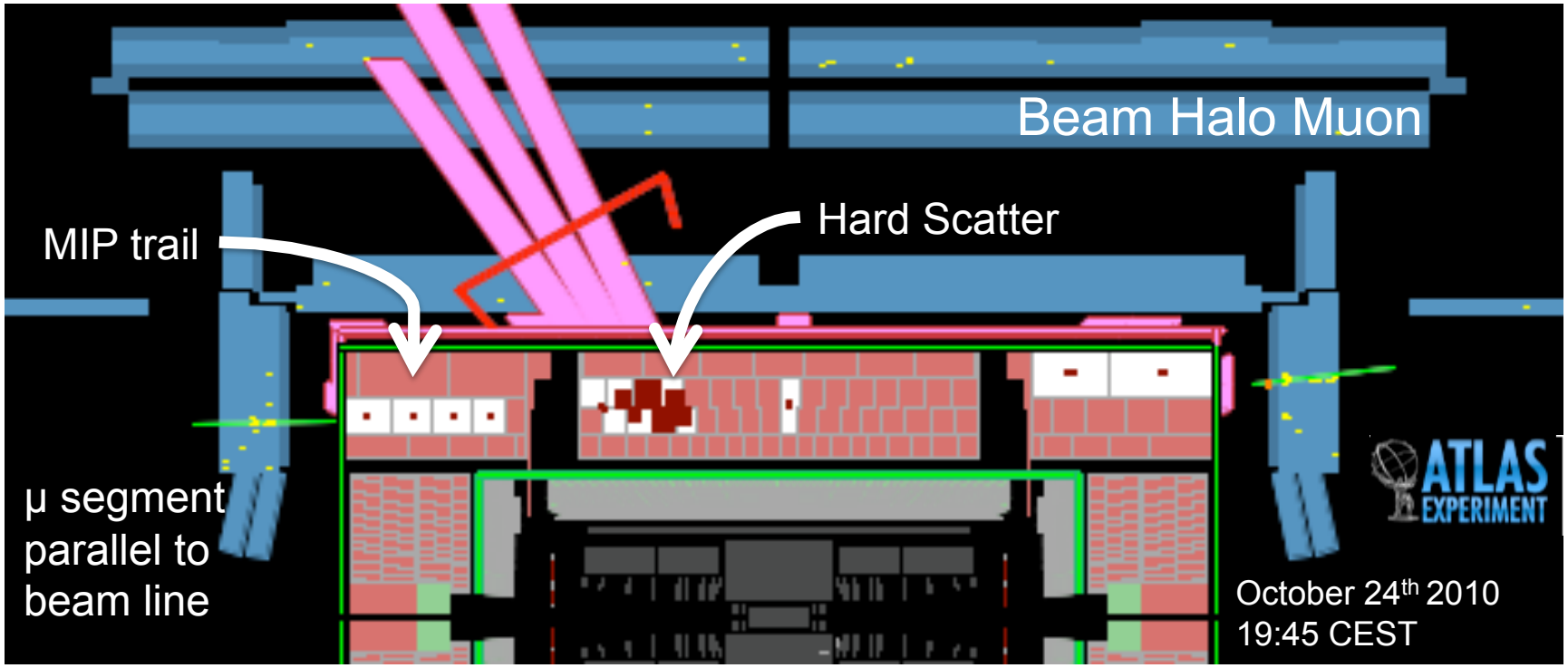
Diagram



Stopped Particles: Backgrounds



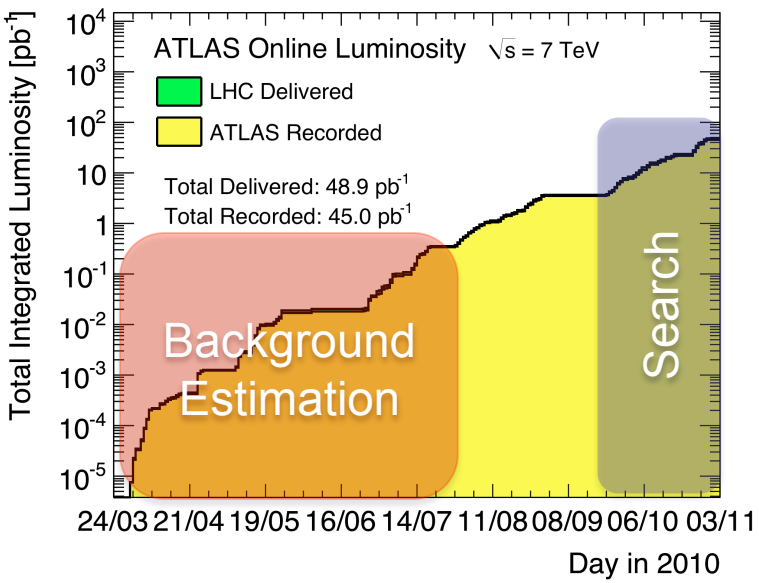
Stopped Particles: Backgrounds



Stopped Particles: Backgrounds

Cosmic Ray Muons
- Veto with muon segment
- Scale with data taking time
- Estimate with early 2010
  - Essentially signal free!

Beam Halo Muons
- Veto with jet location, jet shape
- Scales with
  - LHC vacuum, collimators
  - Filling scheme, etc.
- Need sideband in late 2010 data
- Estimate with unpaired bunches!



ATLAS Preliminary

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

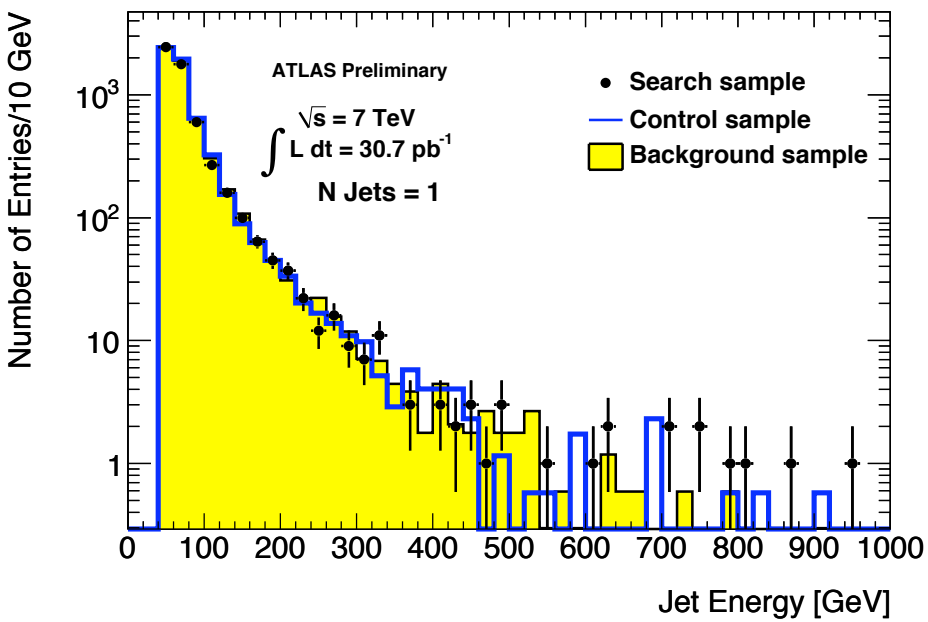
Same running conditions, orthogonal sample

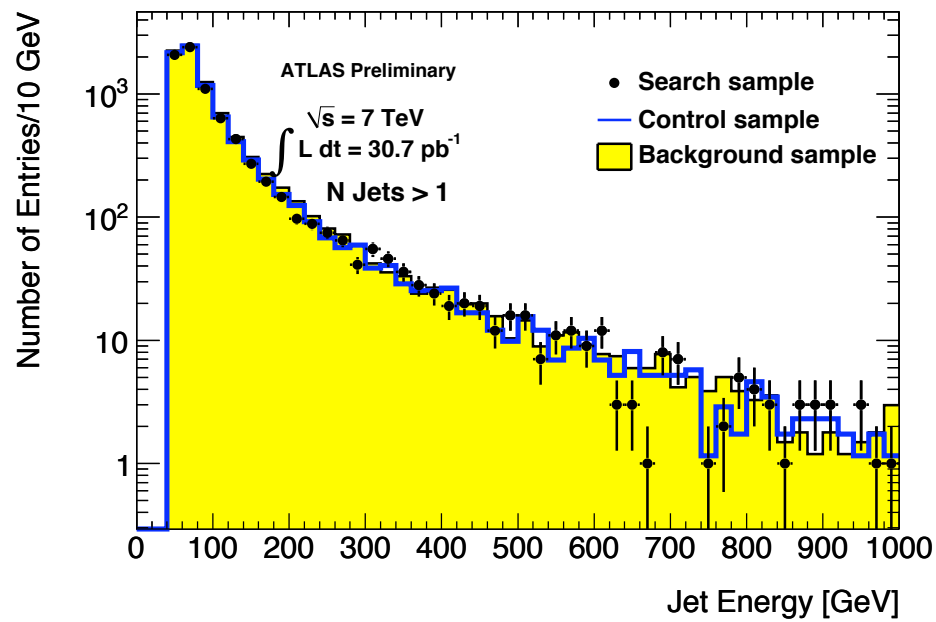
The estimate (1st Jet E > 50 GeV)

Stopped Particles: Background

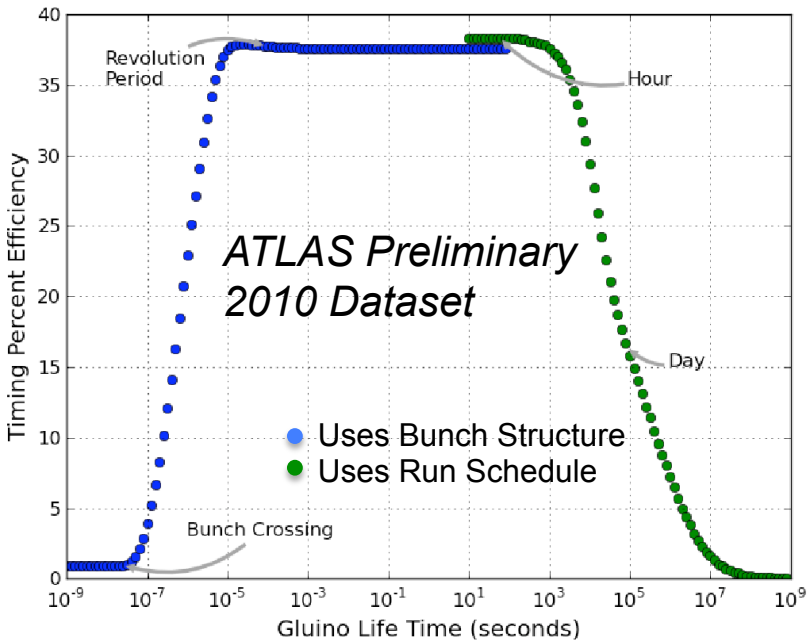
Background Agreement

- Showing distribution after Trigger and Data Quality
- Samples scaled to amount of time ATLAS "live"
- Agreement is excellent!!
- →Dominant background scales with time (ie cosmics)





Stopped Particles: Results



Extra Inefficiencies

- Stopping: Particles aren't trapped
  - Model dependent ~10%
  - Studied "Generic" + "Regge"
- Timing: Particles decay when ATLAS not ready
  - Complicated function of lifetime
  - 37% when τ in $[10^{-5}, 10^{3}]$ sec

	# of Events		Fractional Error	
#Jets	Obs	Exp	Signal	Bkgd
1	0	.3	.23	1.06
>1	1	.6	.23	1.06

No excess of events observed

- In 31 pb^{-1} of data
- Studied single-and multi-jet yield
- Limits not ready to show
  - Full efficiency ~0.3%

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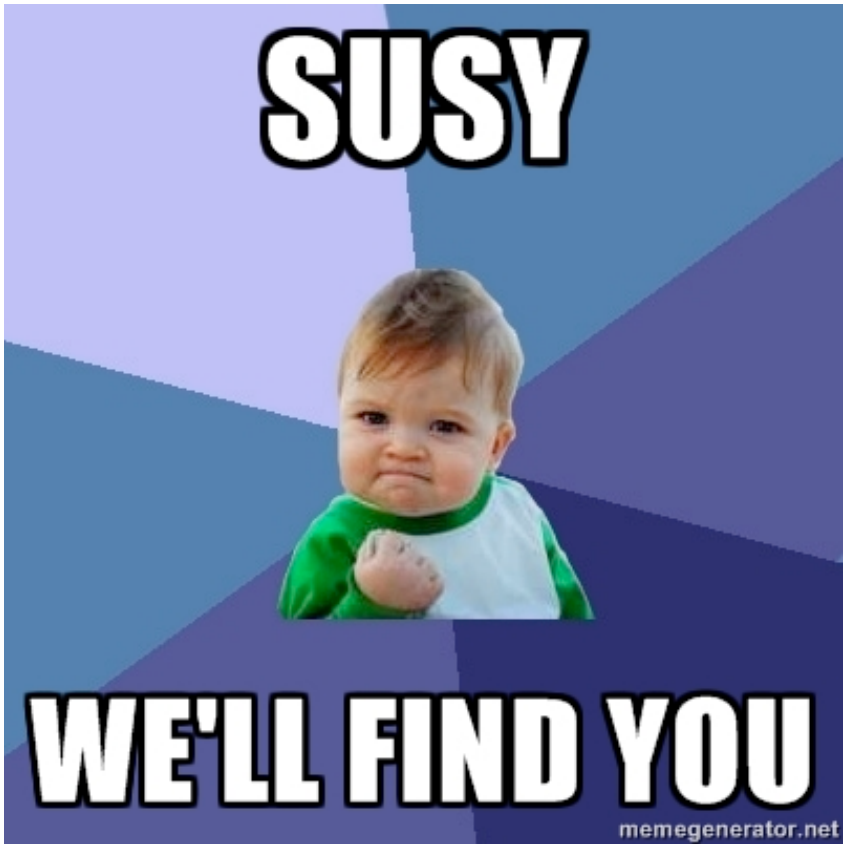
Conclusion

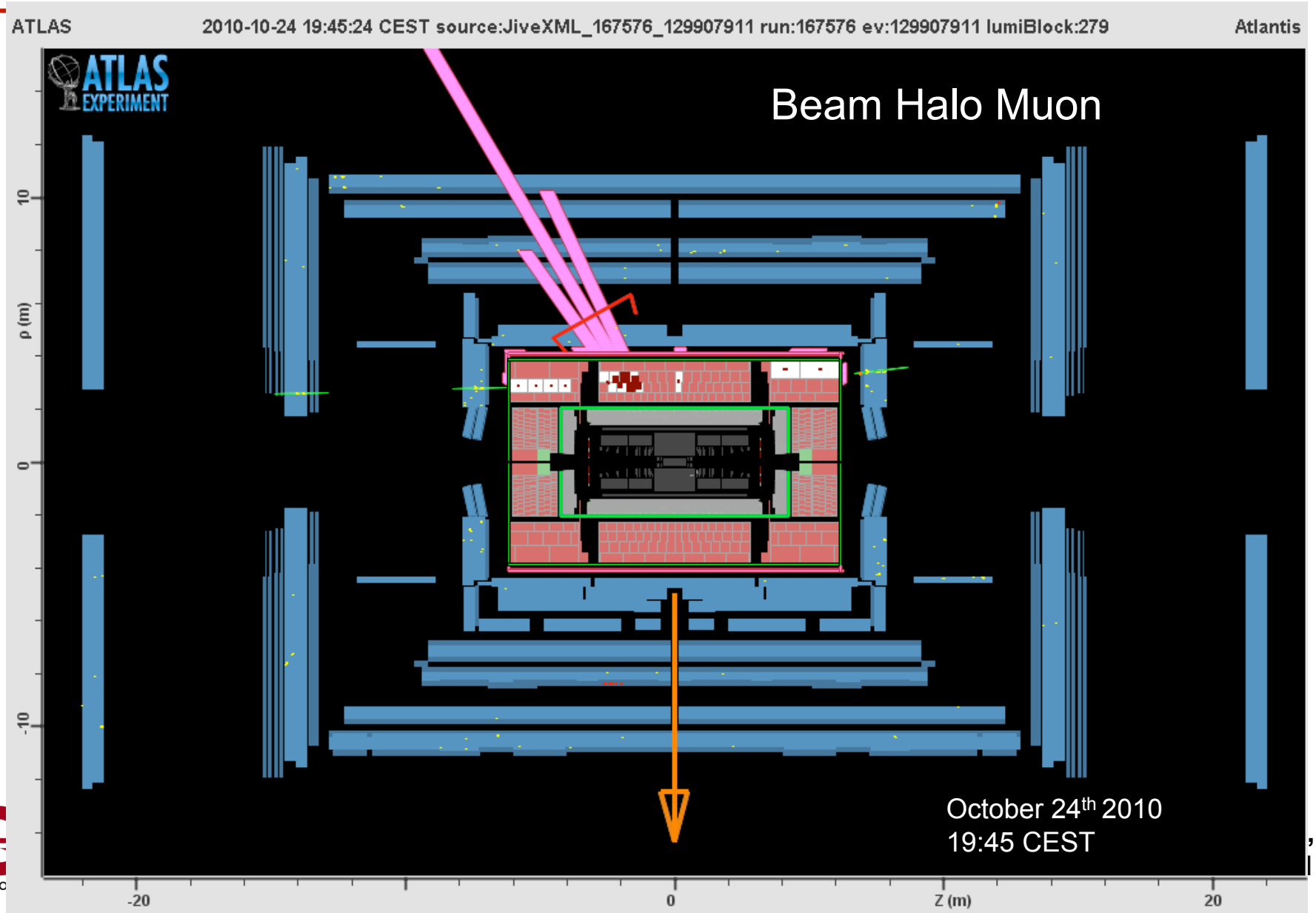
- 3 ATLAS direct detection searches for long lived particles
  - dE/dX in Pixel, ToF in Tile
  - ToF + Drift Circle in Muon System
  - Decays in the empty bunches
- No significant excesses…
- Keep an eye out for **2011** updates!



Back Up

- It begins here.

Full Beam Halo Event



Detector (new look)

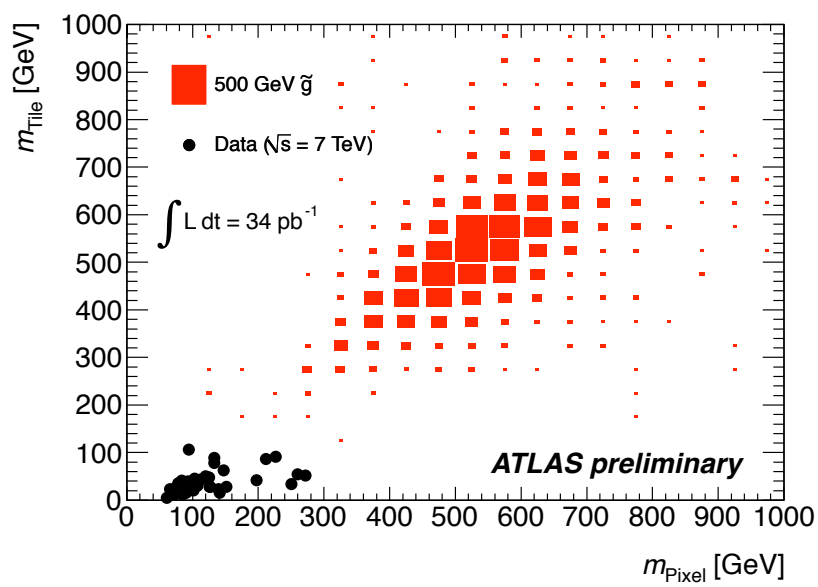
- 3 layer silicon pixel detector calculates dE/dX
  - Reconstructs trajectory of LLP $|\eta| < 2.5$ & $R < 12$ cm
  - Truncated mean of clusters' charge on the track
- Tile Calorimeter ToF with $2.3 < r < 4.3$ m
  - 6 independent time measurements (δt = 1-2 ns)
  - Average all cells > 500 MeV → $\delta t \sim 1$ns
- Muon Spectrometer ToF with $5 < r < 10$ m
  - Uses drift tubes and fast RPC/TGC

Pixel: ATLAS-CONF-2011-016

ID and Calorimeter Search

- Theoretical Needs. Think: $gg \xrightarrow{Threshold} 2\ R\text{-}hadron$
  - m_{LLP} > 100 GeV & charged in pixel and tile
  - Decays outside of ATLAS (Trigger MET > 40)
- Use dE/dX in pixel (βγ) and ToF in Tile (β)
  - Both independently calculate mass!
  - Candidate pT > 50 GeV
- 10% dE/dX resolution using simplified Bethe Bloch parameterization

5 constants optimized for 0.2 < βγ < 1.5



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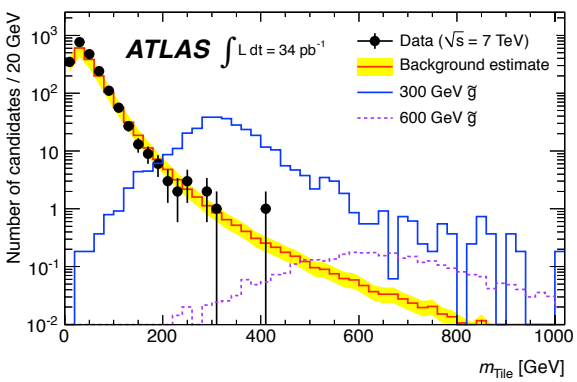
ID and Calo: Background

- Handle pixel and tile separately
- Data noise estimate
  - Apply selection
  - Extract mass PDF

    Random p,
    dE/dX given $10 < p_T < 20$



  - Normalize to data yield
- Combined estimate
  - Only generate p!
  - Agrees with observed data very well

$N_{predicted} < 1$

Random p, β