Title: Long-Lived Neutral Particles at the LHC

Date: Oct 15, 2010 01:00 PM

URL: http://pirsa.org/10100059

Abstract: I will discuss the collider signatures of heavy, long-lived, neutral particles that decay to charged particles plus missing energy. The focus will be the case of a neutralino NLSP decaying to Z and gravitino within the context of General Gauge Mediation (based on arXiv:1006.4575). I will show that the LHC has the potential for early discovery of such a long-lived particle if its lifetime (c tau) is between about 0.1 millimeters and 100 meters. I will also discuss the use of timing and pointing measurements to fully reconstruct kinematics in events with displaced decays.

Why Long Lifetimes?

- The LHC is taking data!
- Much attention (rightly) focuses on traditional, prompt signals like jets and missing Et
- Long lifetimes offer another interesting channel for early discoveries: potentially very low background

The Scales Involved

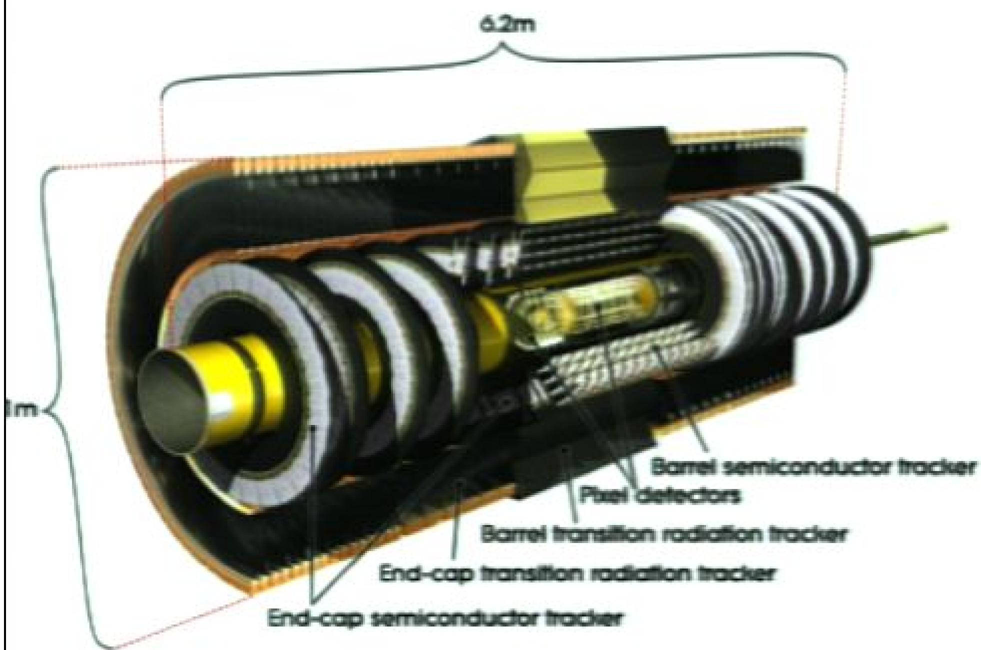
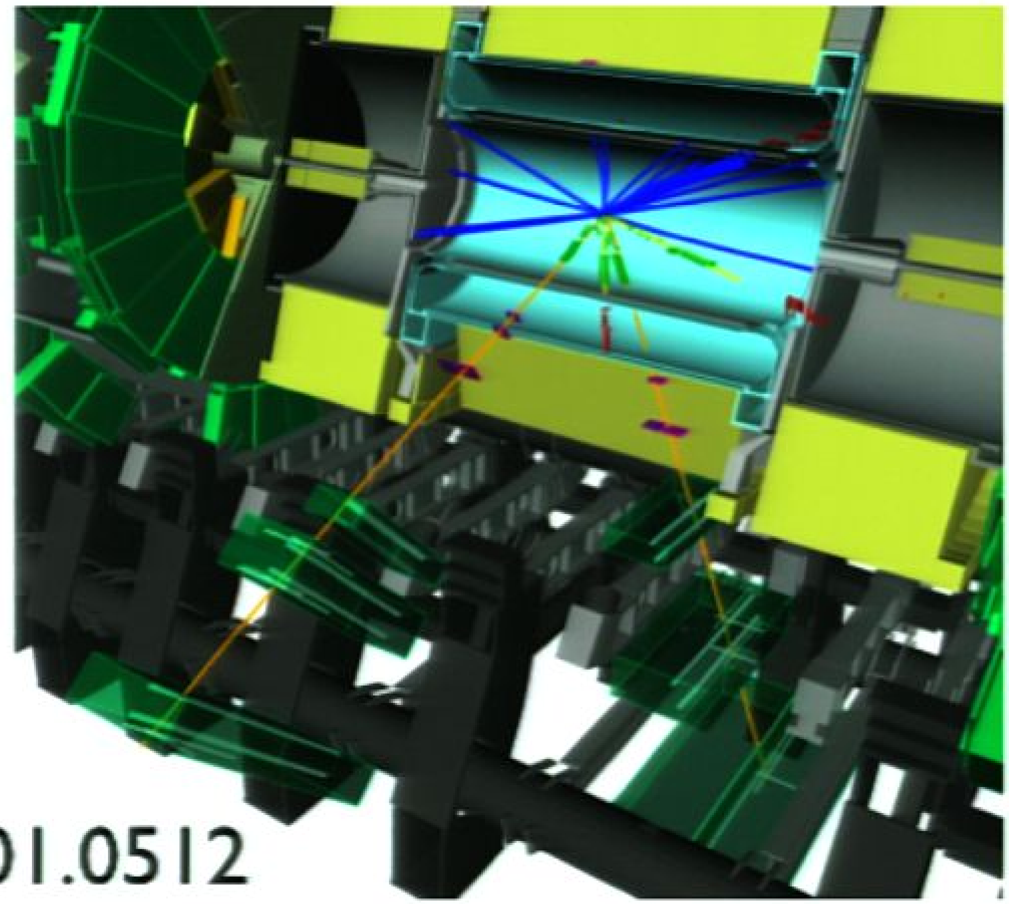


Figure 1: Cut-away view of the ATLAS inner detector.



ATLAS illustrations from 0901.0512

Pixel detectors have resolution of order 10 microns near the beamline; muon systems extend to around 10

Some Examples

- Various decays can happen on collider time/ distance scales. Higher-dim ops, scales not too far above TeV
- Gauge mediation: $\Gamma \sim \frac{m^5}{16\pi F_0^2}$

  $\tau \sim 0.1$ mm for $m \sim 100\text{GeV}, \ \sqrt{F_0} \sim 100\text{TeV}$
- Axino: $\Gamma \sim \frac{\alpha^2}{128\pi^3} \frac{m^3}{f_a^2}$

  $\tau \sim 10$ mm for $m \sim 100$ GeV, $f_a \sim 1000$ TeV
- Kinetic mixing: $\Gamma \sim \alpha\epsilon^2 m$

  $\tau \sim 0.1$ mm for $m \sim 100$ GeV, $\epsilon \sim 10^{-6}$

Gauge Mediation

- How is SUSY breaking mediated to the SM?
- One hint: flavor. Difficult to achieve in gravity mediation, without many ingredients
- Gauge mediation is automatically flavor-blind
- This talk: some phenomenological aspects of gauge mediation at the Tevatron and LHC

(mostly prompt decays at Tevatron and long lifetimes at ATLAS)

Gauge Mediation

- The key phenomenological characteristic of gauge mediation is a light gravitino:

$$m_{3/2} = F_0/(\sqrt{3}M_{Pl})$$

- SUSY-breaking scale $10 \text{ TeV} \lesssim \sqrt{F_0} \lesssim 10^6 \text{ TeV}$
- The lightest MSSM partner is the "NLSP," decaying down to the gravitino.
- This decay drives the phenomenology.

Basic GMSB Pheno.

- Gauge mediation is characterized by decays of the NLSP to the gravitino plus SM particles
- Traditionally: NLSP is bino or stau
- Long-lifetime signals: non-pointing photons (Kawagoe et al., hep-ph/0309031) or long-lived staus as highly ionizing tracks
- Photons aren't ideal signals as they don't leave tracks (except when they convert)

- More generally, have Z or Higgs!

Beyond Minimal GMSB

- The simplest GMSB models ("minimal" or "ordinary" gauge mediation) predict that the NLSP is a bino or a stau.
- Small μ and Higgsino NLSP can help reduce fine-tuning (Agashe, Graesser, hep-ph/9704206)
- As explained by Cheung et al, 0710.3585:

$$\mu^2 \approx -\frac{1}{2}m_Z^2 - m_{H_u}^2(m_{\tilde{t}})$$

$$m_{H_u}^2(m_{\tilde{t}}) \approx m_{H_u}^2 - \frac{3}{4\pi^2}y_t^2 m_{\tilde{t}}^2 \log\frac{M_{\mathrm{mess},3}}{m_{\tilde{t}}}$$

$$m_{H_u}^2 \propto \frac{3}{4}\frac{\alpha_2(M_{\mathrm{mess},2})^2}{N_{\mathrm{eff},2}}, \qquad m_{\tilde{t}}^2 \propto \frac{4}{3}\frac{\alpha_3(M_{\mathrm{mess},3})^2}{N_{\mathrm{eff},3}}$$

Beyond Minimal GMSB

- Higgsino NLSP is also common in "extra-ordinary gauge mediation," i.e. generic renormalizable messenger models (Cheung, Fitzpatrick, Shih, 0710.3585)
- Also for $\mu/B\mu$ with $\mu^2 << B\mu$, $B\mu << m_{Hd}^2$ (Csaki, Falkowski, Nomura, Volansky 0809.4492)
- Usually in GMSB $B\mu \sim 16\pi^2\mu^2$:

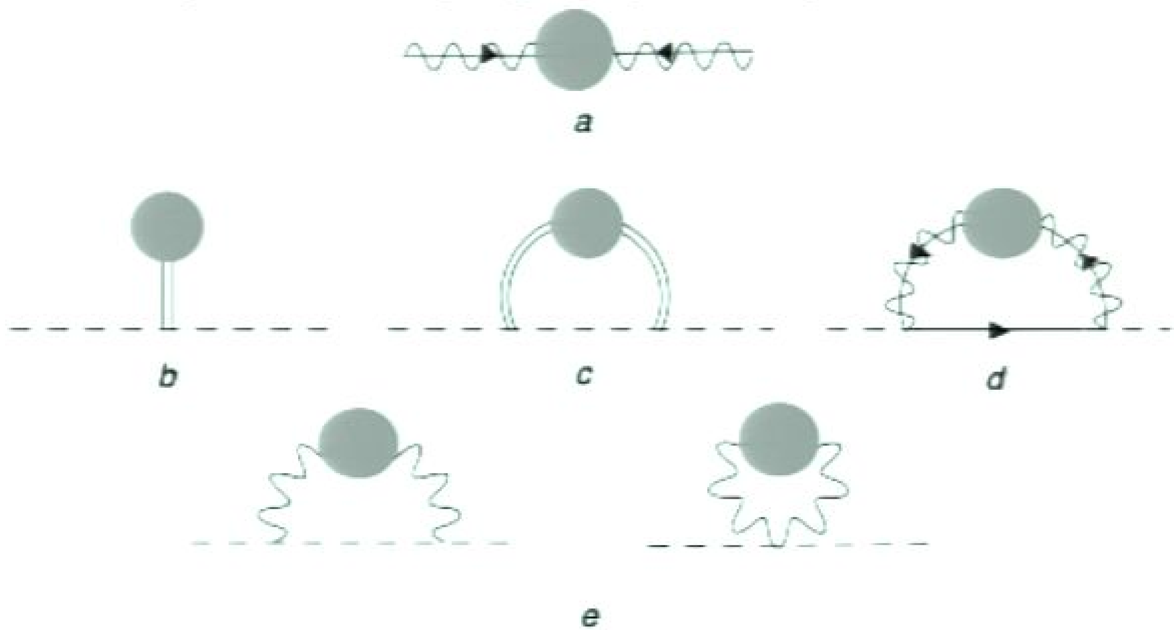
$$\frac{m_Z^2}{2} = -|\mu|^2 - \frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{\tan^2\beta - 1},$$

$$\sin 2\beta = \frac{2B_\mu}{2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2}.$$

so take $\tan\beta \approx \dfrac{m_{H_d}^2}{B_\mu}$

General Gauge Mediation

- A SUSY-breaking hidden sector has a global symmetry weakly gauged by the SM



- Soft terms calculated from hidden-sector correlation functions (Meade, Seiberg, Shih, 0801.3278); extensions for μ/Bμ

GGM Phenomenology

- In general gauge mediation, any MSSM particle can be the NLSP
- Squark or gluino, if prompt, are well-studied jets + Met signature; otherwise, R-hadrons
- Sleptons have been studied somewhat; sneutrinos also interesting (Katz/Tweedie)
- Our focus will be general neutralino NLSP (possibly with charginos as co-NLSPs)

NLSP Decays to Gravitino

Partial Widths:

$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G} + \gamma) = |N_{11}c_W + N_{12}s_W|^2 \mathcal{A}$$

$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G} + Z) = \left(|N_{12}c_W - N_{11}s_W|^2 + \frac{1}{2}|N_{13}c_\beta - N_{14}s_\beta|^2\right)\left(1 - \frac{m_Z^2}{m_{\tilde{\chi}_1^0}^2}\right)^4 \mathcal{A}$$

$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G} + h) = \frac{1}{2}|N_{13}c_\beta + N_{14}s_\beta|^2 \left(1 - \frac{m_h^2}{m_{\tilde{\chi}_1^0}^2}\right)^4 \mathcal{A}$$

Overall rate (easily long-lived!):

$$\mathcal{A} = \frac{m_{\tilde{\chi}_1^0}^5}{16\pi F_0^2} \approx \left(\frac{m_{\tilde{\chi}_1^0}}{100\ \mathrm{GeV}}\right)^5 \left(\frac{100\ \mathrm{TeV}}{\sqrt{F_0}}\right)^4 \frac{1}{0.1\ \mathrm{mm}}$$

Limiting Cases

- Bino NLSP: $N_{11} \gg N_{12}, N_{13}, N_{14}$, decays to photons at least $c_W^2 \approx 76\%$ of the time.

- Wino NLSP: $N_{12} \gg N_{11}, N_{13}, N_{14}$. Very degenerate chargino and neutralino:

$$\Delta m \sim m_Z^4/\mu^3$$

- For most of the talk I will be assuming neutralino decays promptly down to the gravitino. In this case, wino chargino and neutralino are "co-NLSPs", with

$$\tilde{\chi}^+ \to W^+ + \tilde{G}$$

Limiting Cases

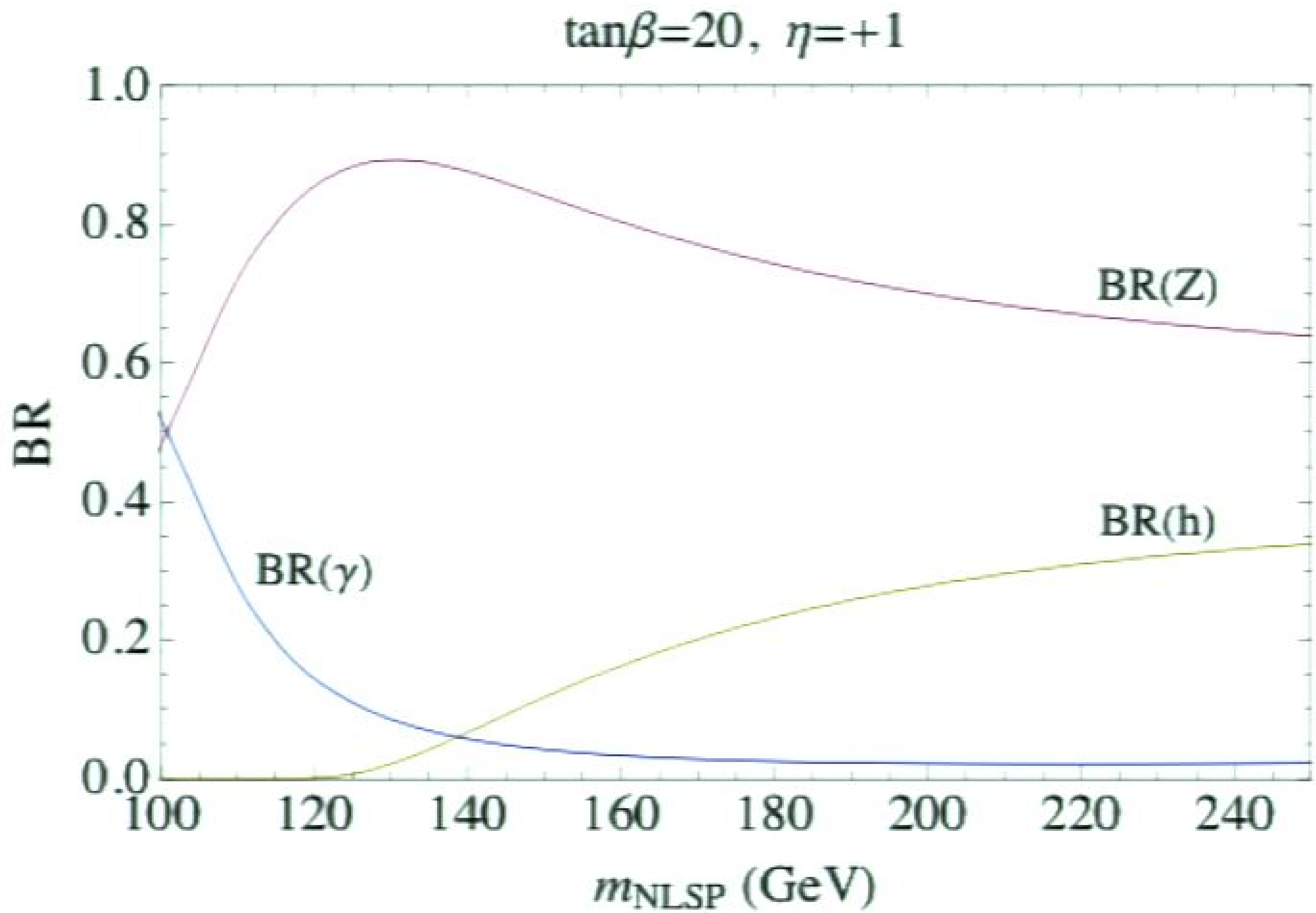
- Higgsino NLSPs can decay to either a Higgs + gravitino or a longitudinal Z + gravitino.
- At large tan(β) and large enough masses, these are 50/50.
- At small tan(β), depends on a sign:

$$N_{13} = -\eta N_{14} = \frac{1}{\sqrt{2}}$$

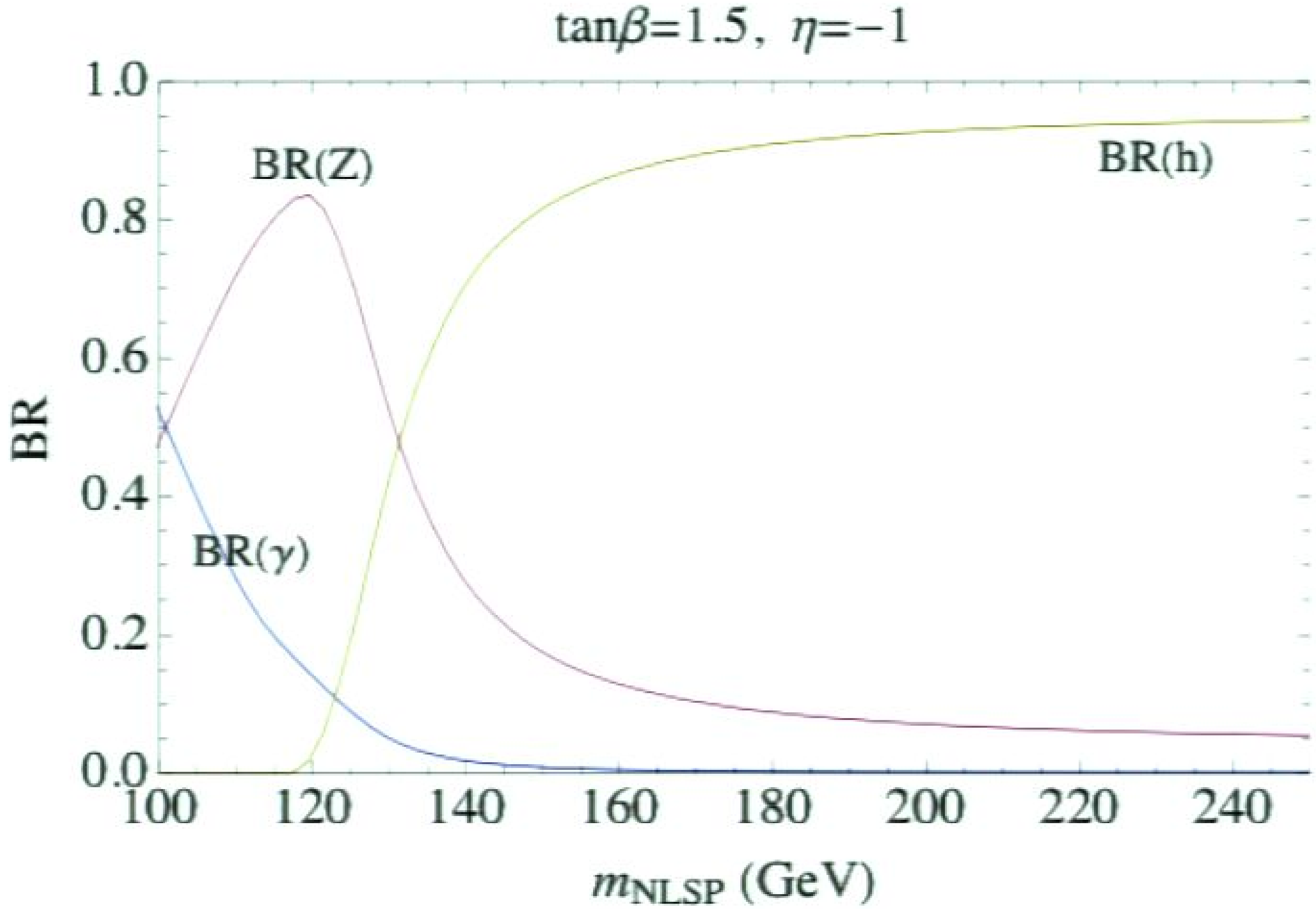
$$\eta \equiv \text{sign}(\mu) \times \text{sign}\left(\frac{M_1}{M_2} + \tan^2\theta_W\right)$$

- Will assume $M_1, M_2 > 0$. Ignoring the interesting case of chargino NLSP (see Kribs, Martin, Roy 0807.4936)

Z-Rich Higgsino



Higgs-rich Higgsino



Prompt Case: Tevatron Exclusion Capabilities

Table 3: Summary of Results

NLSP Scenario	Search Channel	Current Est. Limit	Projected Limit
bino ($\mu \gg M_2 > M_1$)	$\gamma\gamma + \not{E}_T$	$m_{\tilde{\chi}_1^\pm} > 270$ GeV	$m_{\tilde{\chi}_1^\pm} >300$ GeV
wino co-NLSP	$W(\to \ell\nu) + \gamma + \not{E}_T$	$m_{NLSP} > 135$ GeV	$m_{NLSP} >170$ GeV
higgsino	$Z(\to \ell^+\ell^-) + \not{E}_T + X^a$	None	$m_{NLSP} > 150$ GeV
higgsino	$Z(\to \ell^+\ell^-) + \not{E}_T + X^b$	None	$m_{NLSP} > 170$ GeV
Higgs-rich higgsino	multi-b+ $\not{E}_T$	None	$m_{NLSP} \not\approx 160$ GeV?[c]

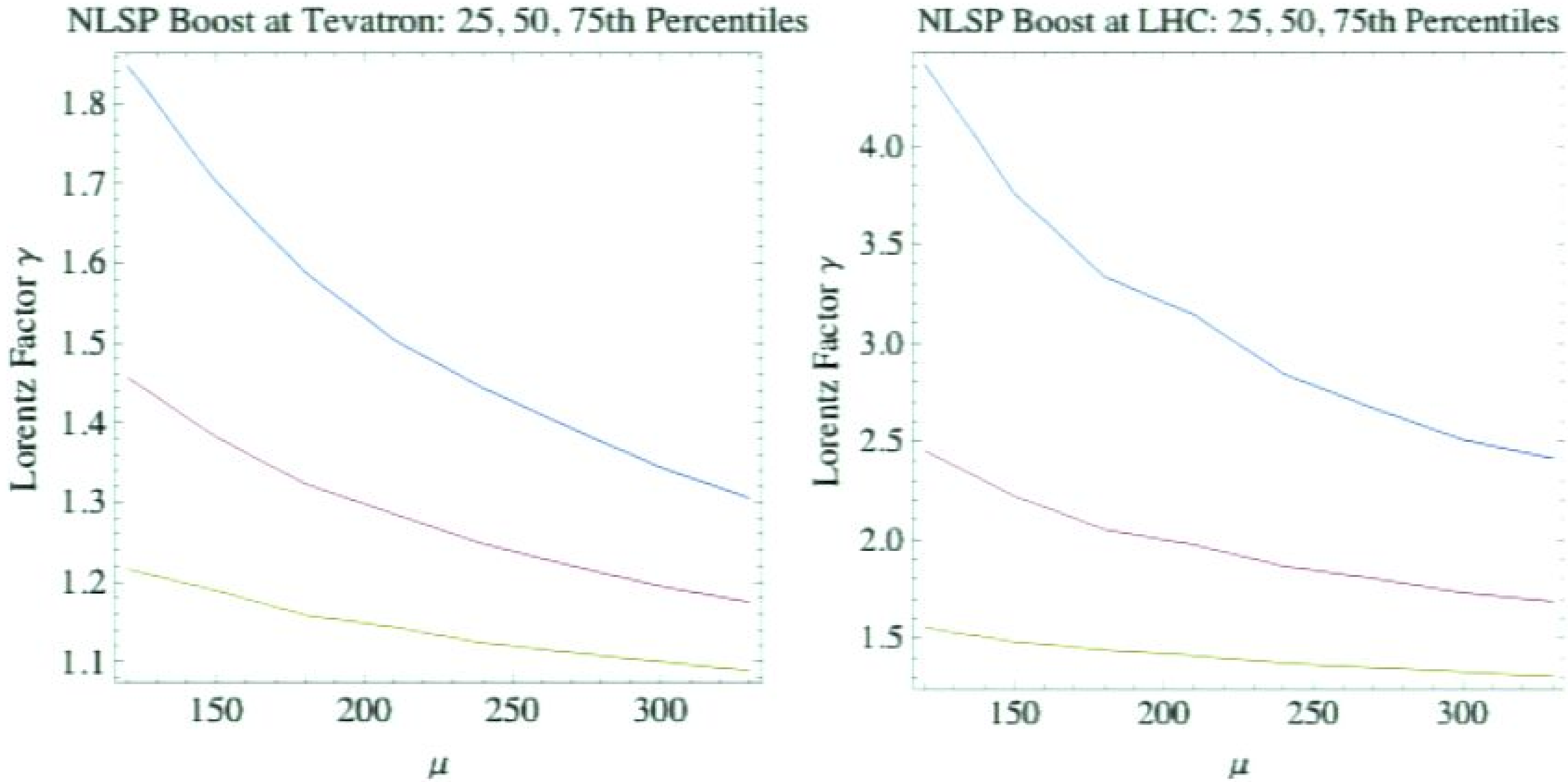
[a] Extrapolating an existing analysis.

[b] With an analysis optimized for higgsinos.

[c] In this case, it remains unclear how feasible an exclusion is.

The Tevatron has a large sample of well-understood data already recorded -- it would be a shame not to push it as far as possible!

Boosts



More energetic objects at the LHC. Possibility of using substructure analysis

(See Kribs, Martin, Roy, Spannowski, 0912.4731)

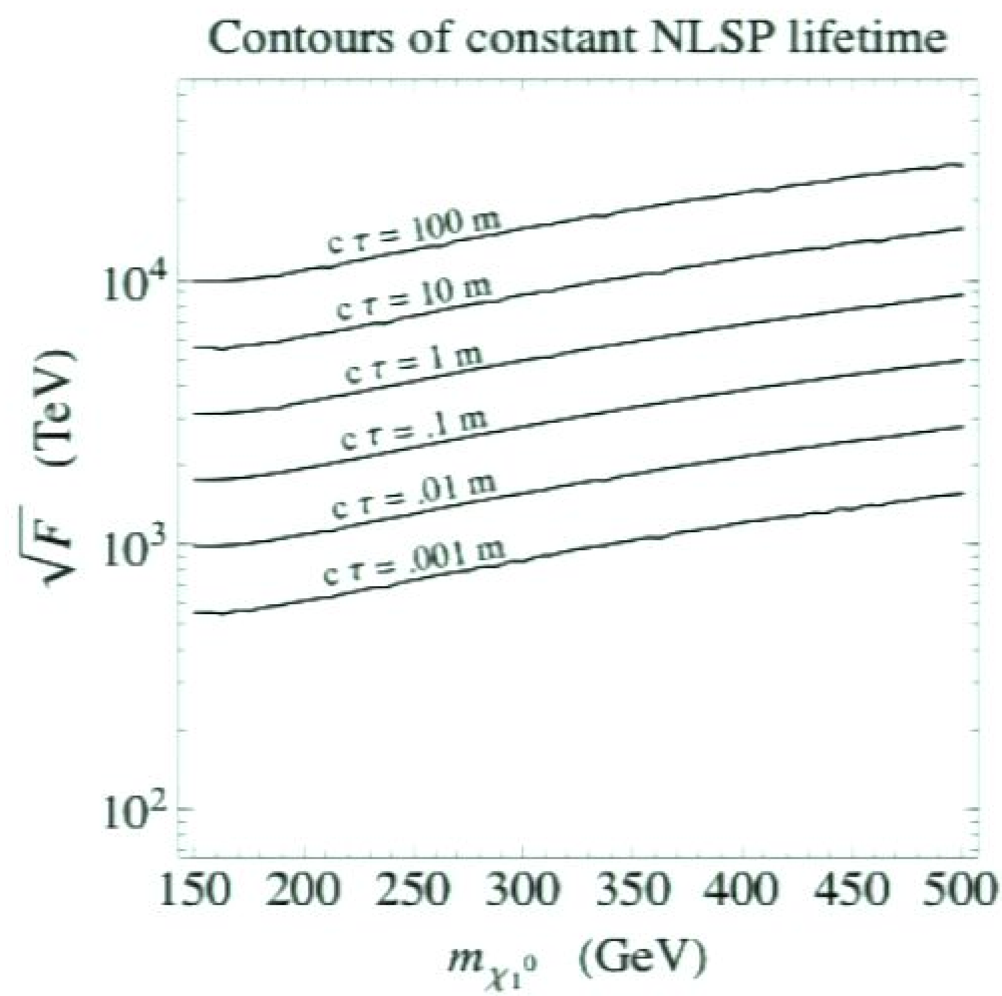
Delayed Decays

Generic in GMSB to have long lifetimes. If any value of $\sqrt{F_0}$ were equally likely, would expect decays outside the detector.

Macroscopic decays of order the detector size are especially interesting phenomenologically, although not obviously preferred theoretically.

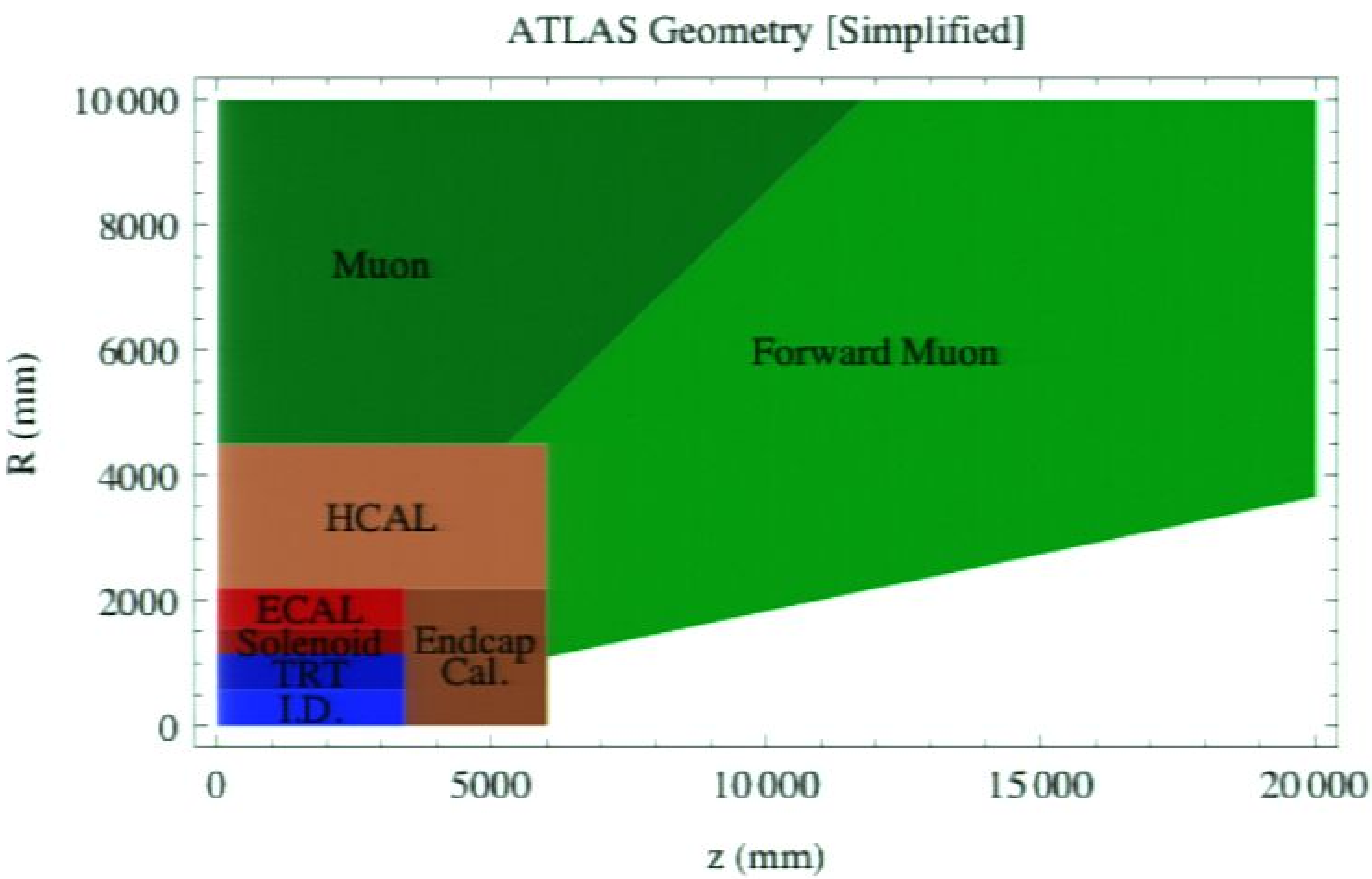
- Measure lifetime, hence SUSY-breaking scale
- Better kinematic reconstruction -- hope to find NLSP rest frame, resolve vertex structure?

Lifetimes in GMSB



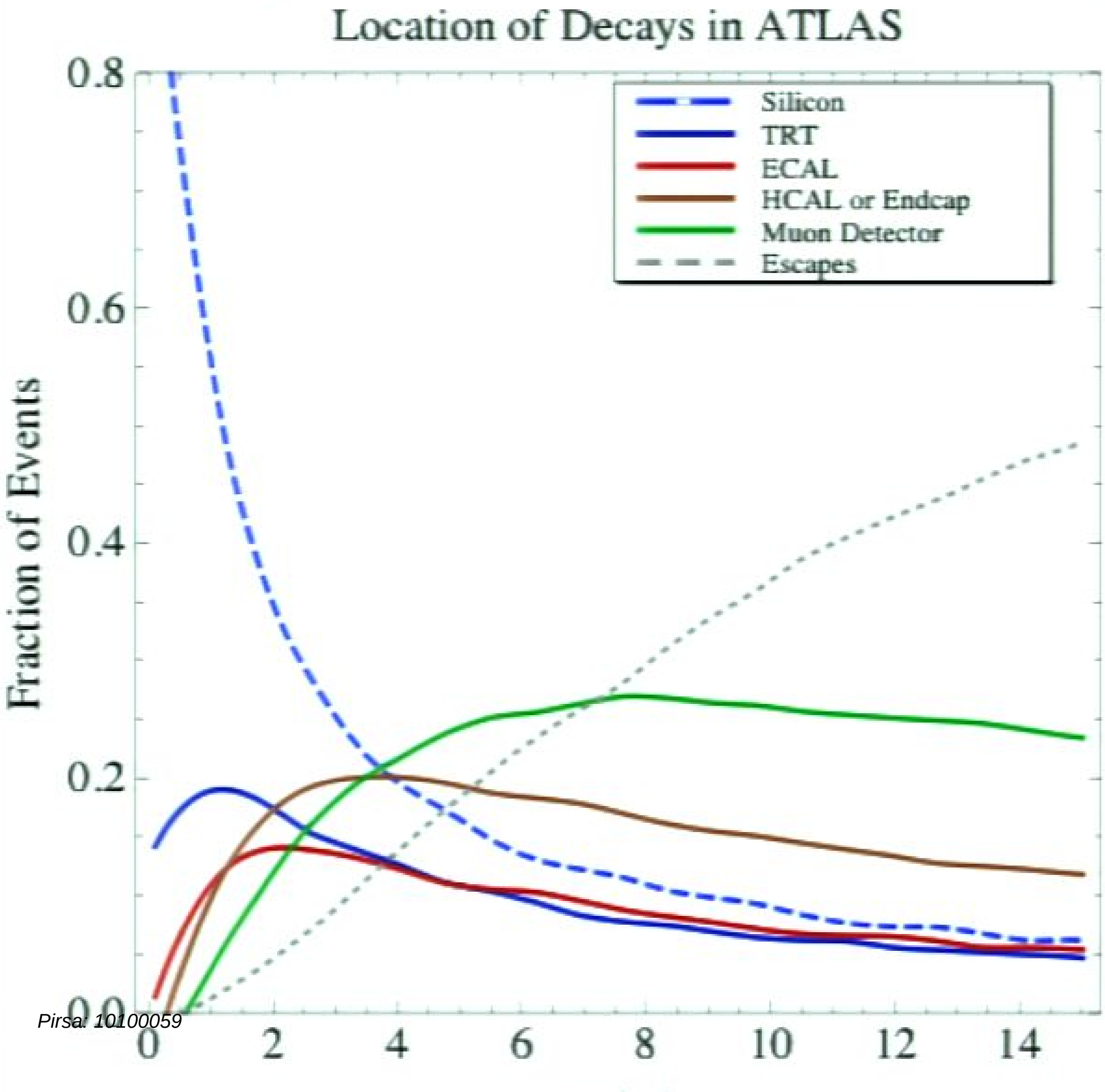
Long collider-scale lifetimes happen for low-scale

Detector Geometry

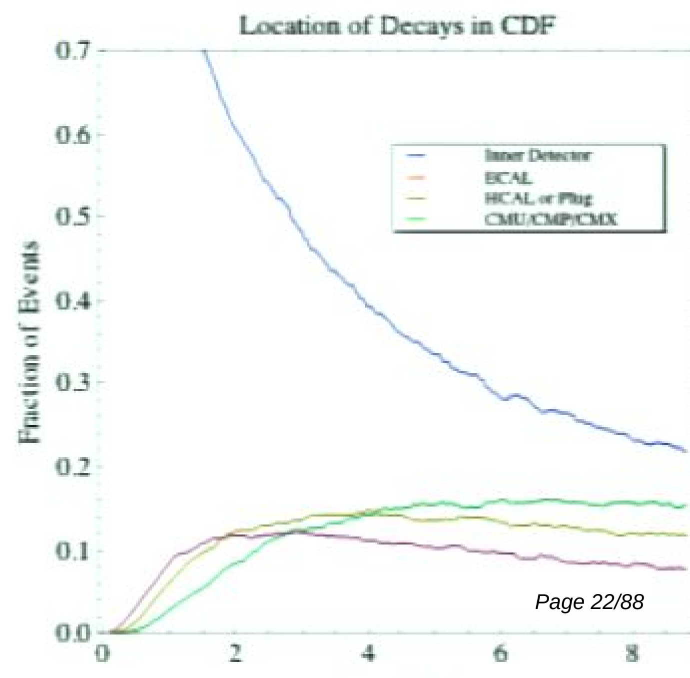


Relying mostly on decays in the inner detector (before ECAL) or in the muon system is reasonable

Displaced Decays: Where?



For a 250 GeV Higgsino, but mostly a function of cτ and geometry



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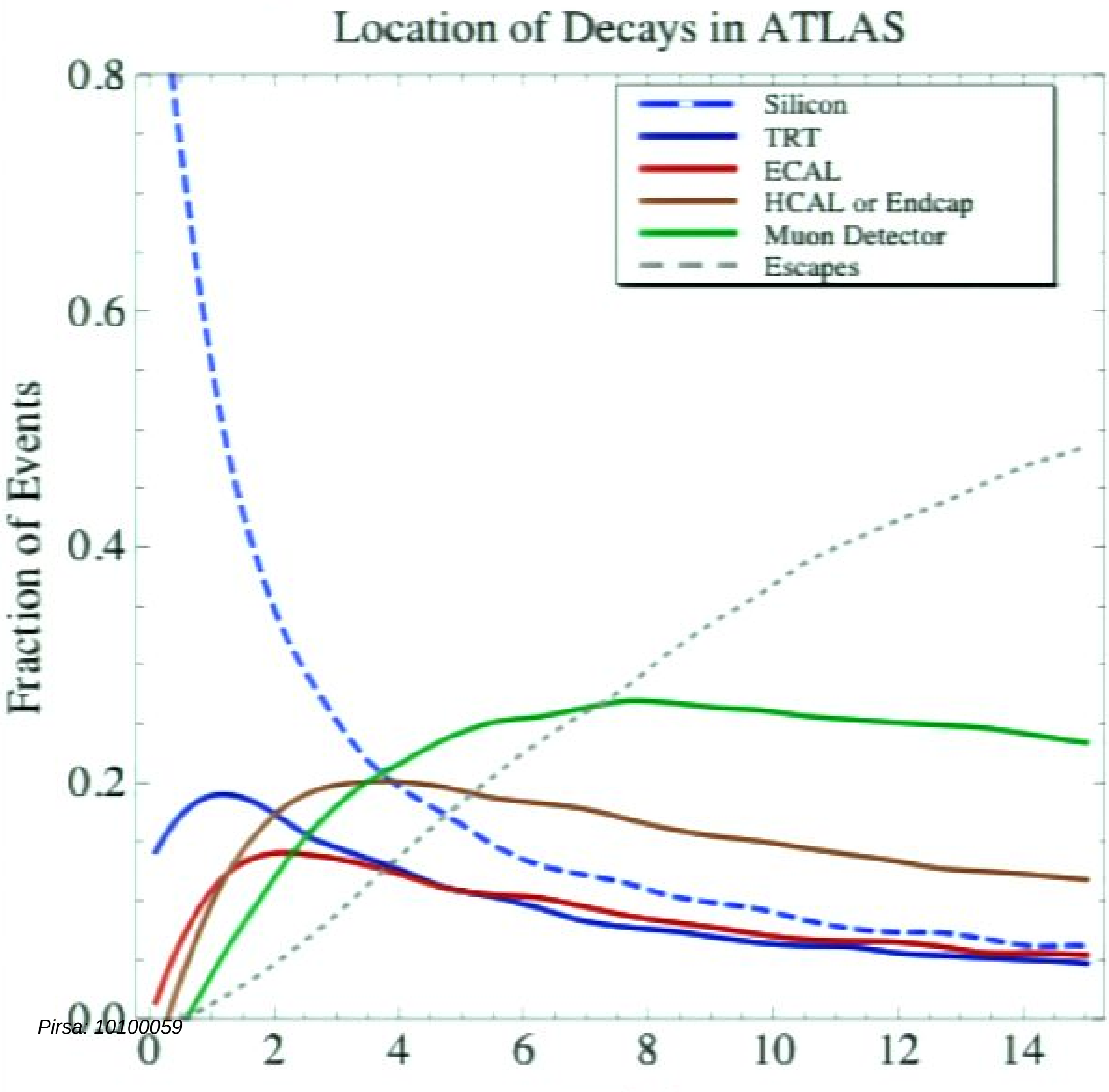

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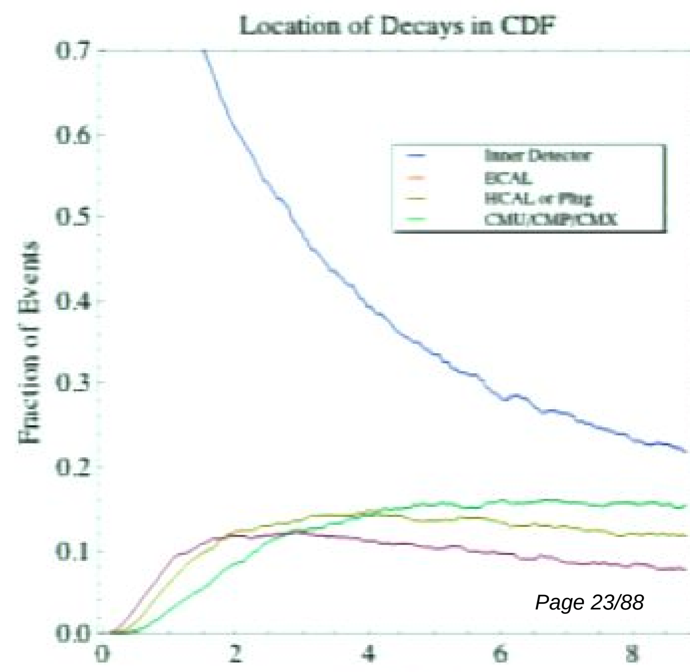
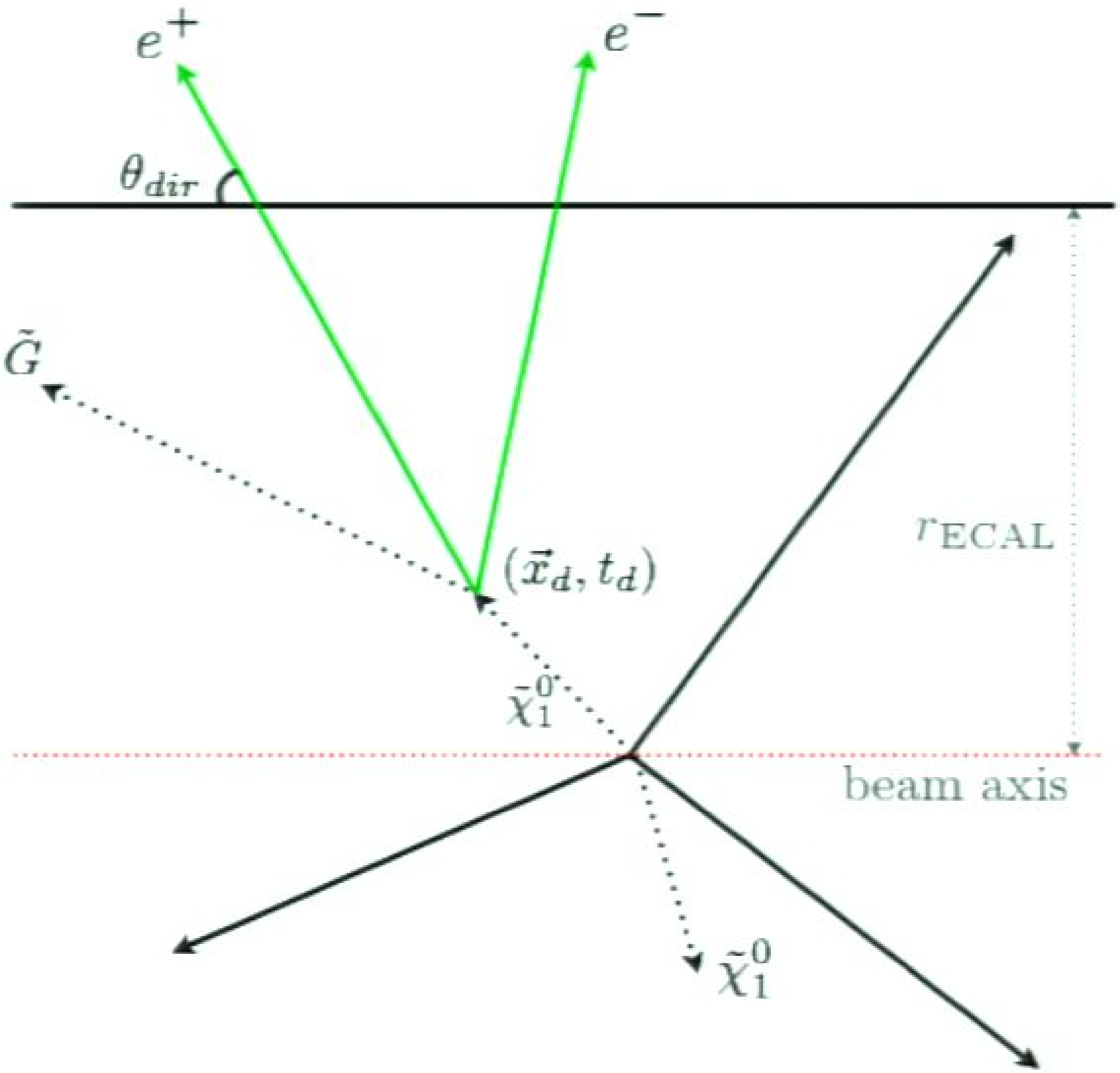


Schematic of a Long-Lifetime Event



First Goal: Discovery

- Long lifetimes can make the reconstruction of kinematics, fitting of masses, determination of underlying Lagrangian relatively easy
- But first: what are the minimal requirements to determine that a signal exists?
- Use detector components that can point an object back, and insist it didn't come from the interaction point.

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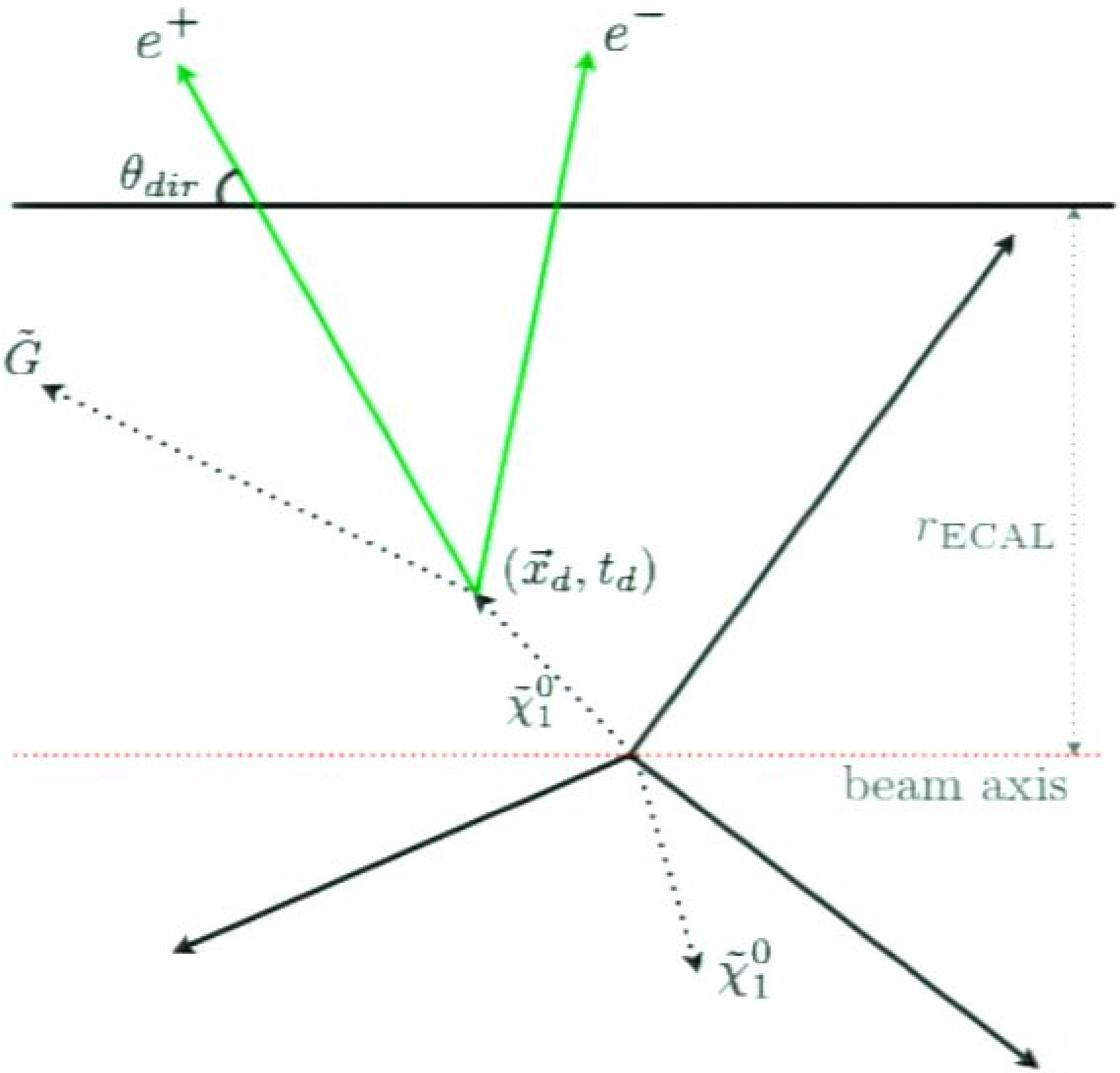

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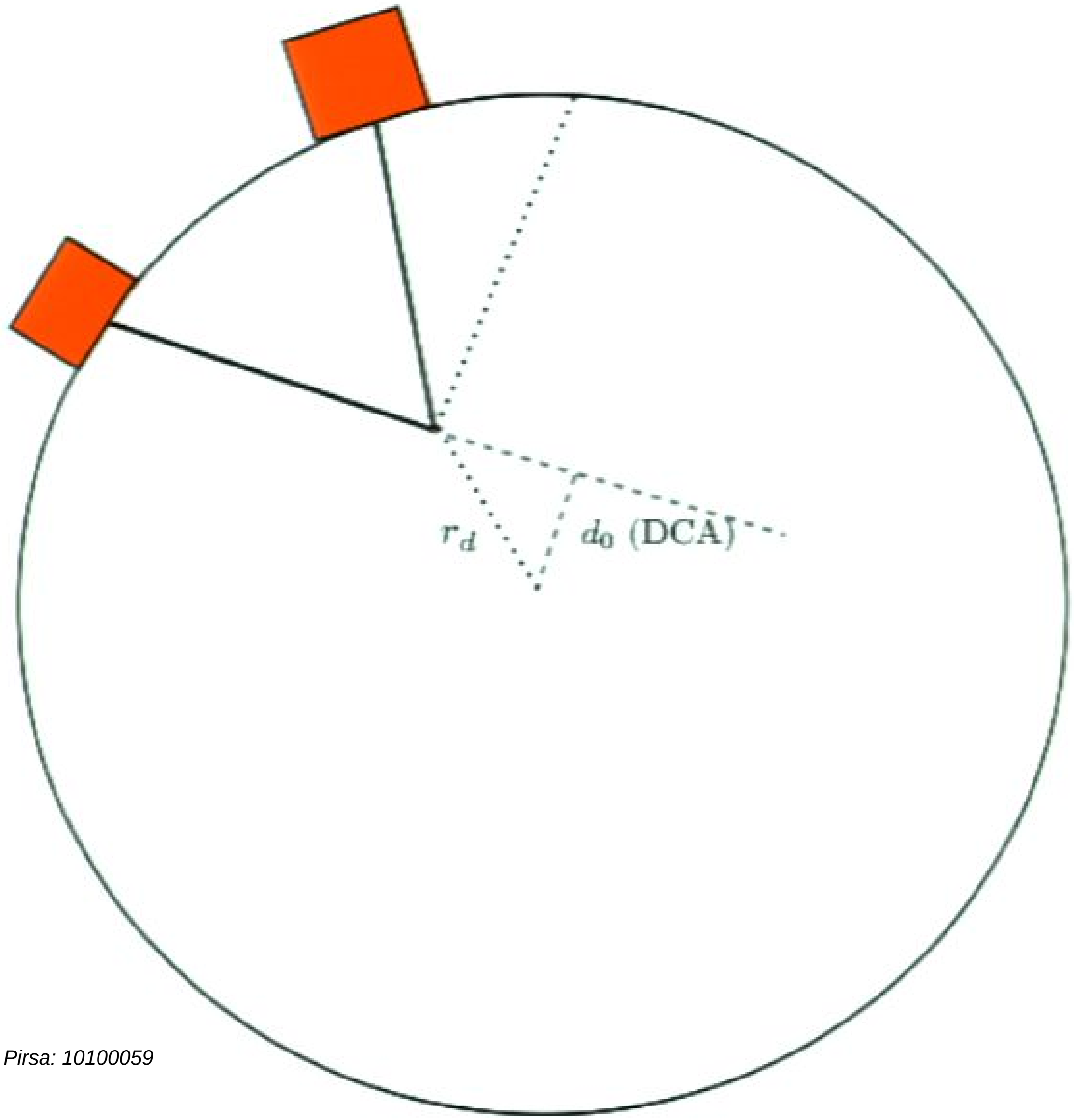

r_d: Decay radius; use absence of hits closer to beamline

d_0: Impact parameter or distance of closest approach; find via track fitting

t_{det}: Time of detector signal in calorimeter

$Z \rightarrow e^+e^-$ Cuts

Cuts Shared by Discovery and Reconstruction Analyses:	
$\lvert\eta_{det}\rvert < 0.8$	Passes through barrel TRT
$r_d < 800$ mm	Leaves sufficiently many TRT hits for track to be found
$\Delta R(e^+, e^-) > 0.4$	Well-separated, unlike conversions
$E_T > 20$ GeV	Triggerable (2gamma20)
Cuts Specific to Discovery with Silicon:	
$r_d < 50$ mm	Electrons pass through all Si layers
$r_d > 0.05$ mm	Reduce background
DCA > 0.05 mm (either)	Reduce background
Cuts Specific to Discovery with TRT:	
$r_d > 1$ cm	Reduce background
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Cuts Specific to Reconstruction with ECAL+TRT:	
$z_{e.v.} < 1200$ mm	Pointing resolution not too degraded
$\Delta t > 0.3$ ns	Significantly delayed

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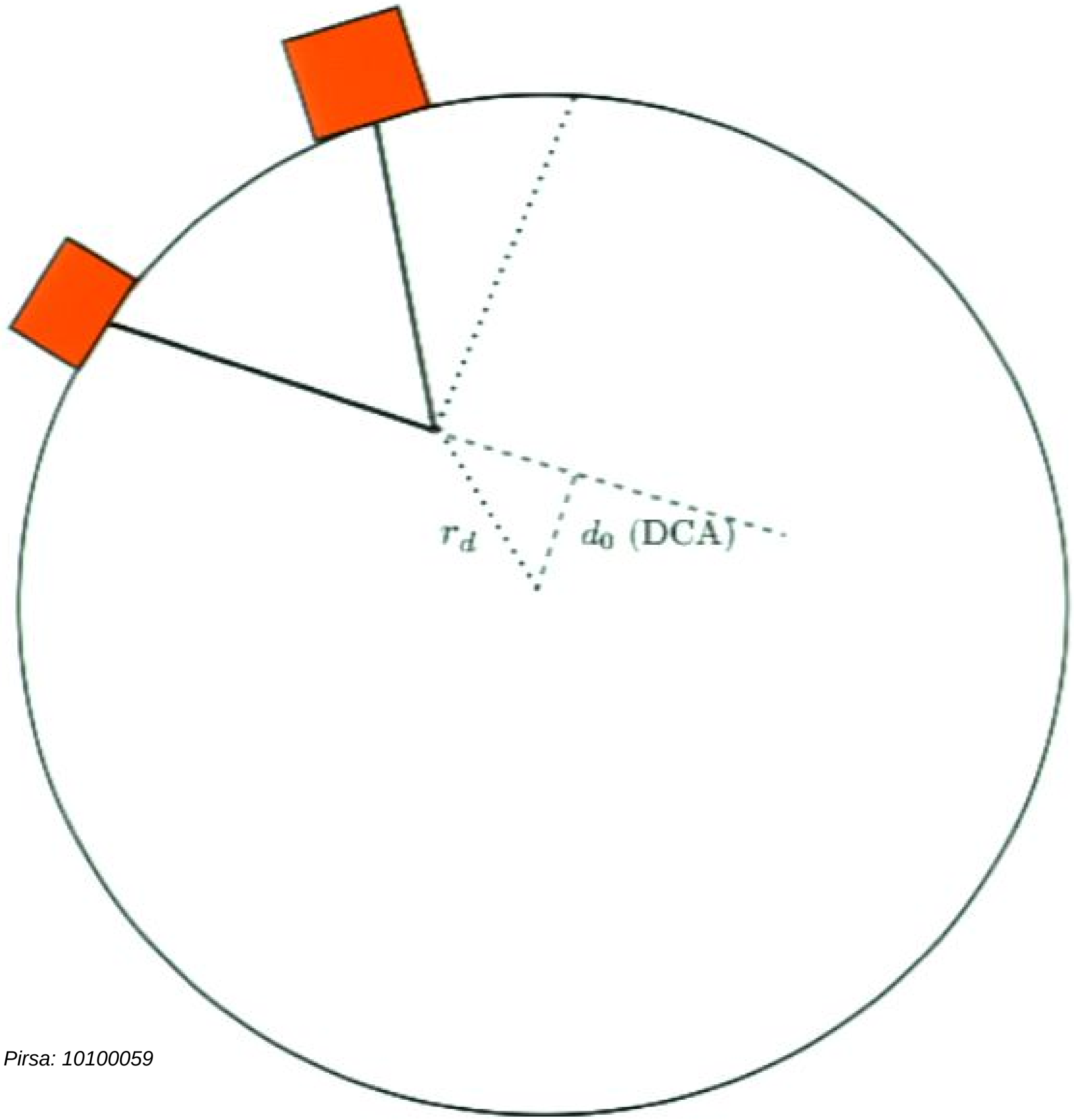

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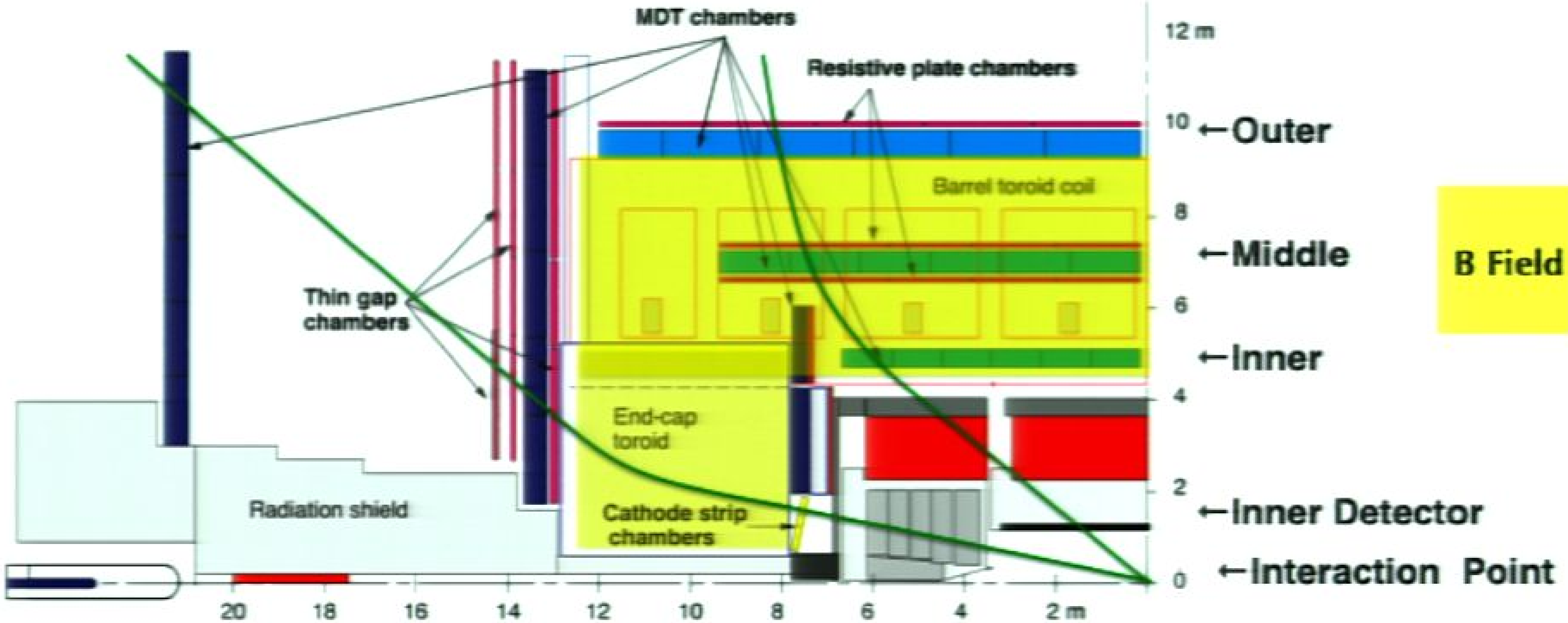
The ATLAS Muon System

(ATL-MUON-SLIDE-2010-122)



Precision

Monitored Drift Tubes (MDT): $|\eta| < 2$ (3 chamber layers), $2 < |\eta| < 2.7$ (2 chamber layers)

✧ 80 μm point resolution (in η) in 339,000 tubes

Cathode Strip Chambers (CSC): $2 < |\eta| < 2.7$ (1 chamber layer) **← Endcap**

✧ 60 μm point resolution (in η) in 67,000 channels

Trigger

Resistive Plate Chambers (RPC): $|\eta| < 1$ (3 chamber layers) **← Barrel**

✧ 1 cm point resolution (in η and φ) 359,000 strips

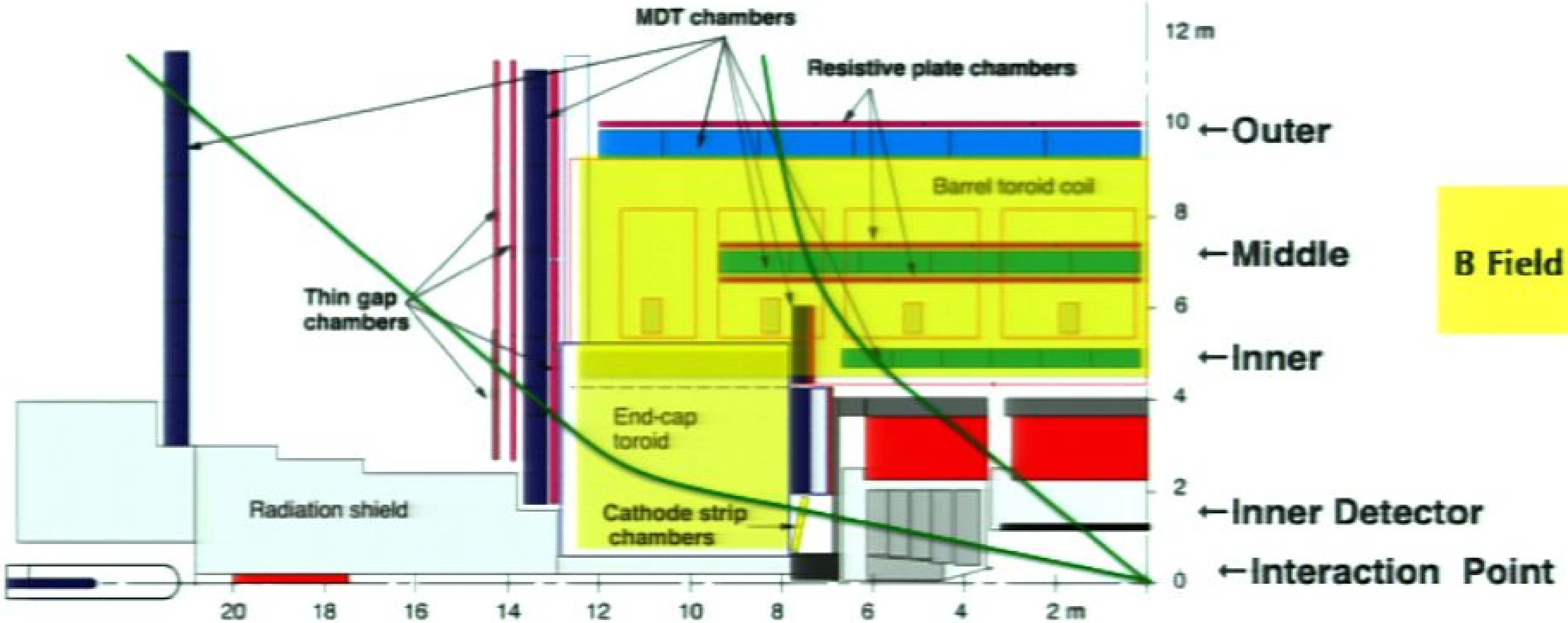
Thin Gap Chambers (TGC): $1 < |\eta| < 2.4$ (3 chamber layers) **← Endcap**

$Z \to \mu^+\mu^-$ Cuts

Cuts Shared by Discovery and Reconstruction Analyses:	
$r_d < 4500$ mm	Passes through all muon layers
$\lvert\eta_{det}\rvert < 1.1$ at $r = 4.5, 7.0, 10.0$ m	Contained in the central muon spectrometer
Separation > 30 mm at $r = 4.5, 7.0, 10.0$ m	Resolve two muons
$r_d > 500$ mm	Significantly displaced vertex
$p_T > 20$ GeV	Triggerable
$\Delta t < 6$ ns (either)	Correct bunch-crossing ID

Here we use decays to muons happening before the start of the muon system. Direction is measured well by all muon layers, allowing a determination that the vertex was far from the interaction point.

The ATLAS Muon System
(ATL-MUON-SLIDE-2010-122)



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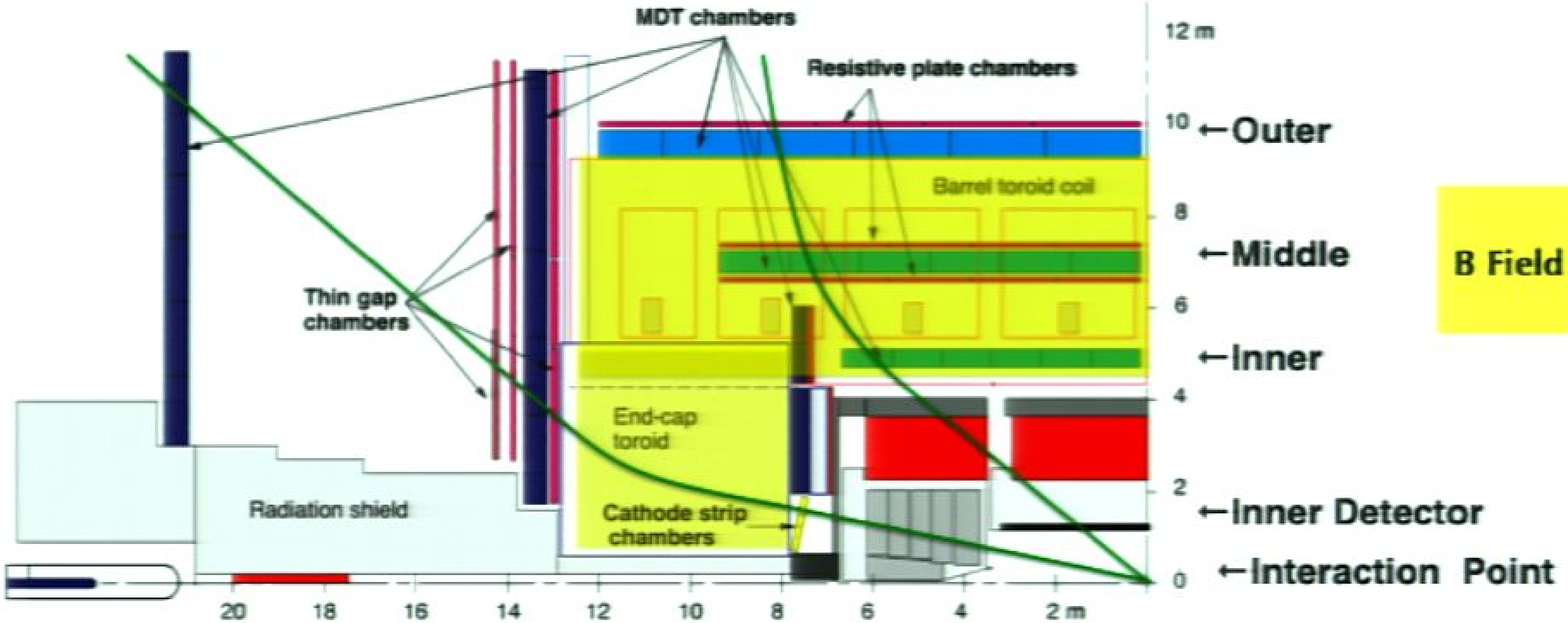

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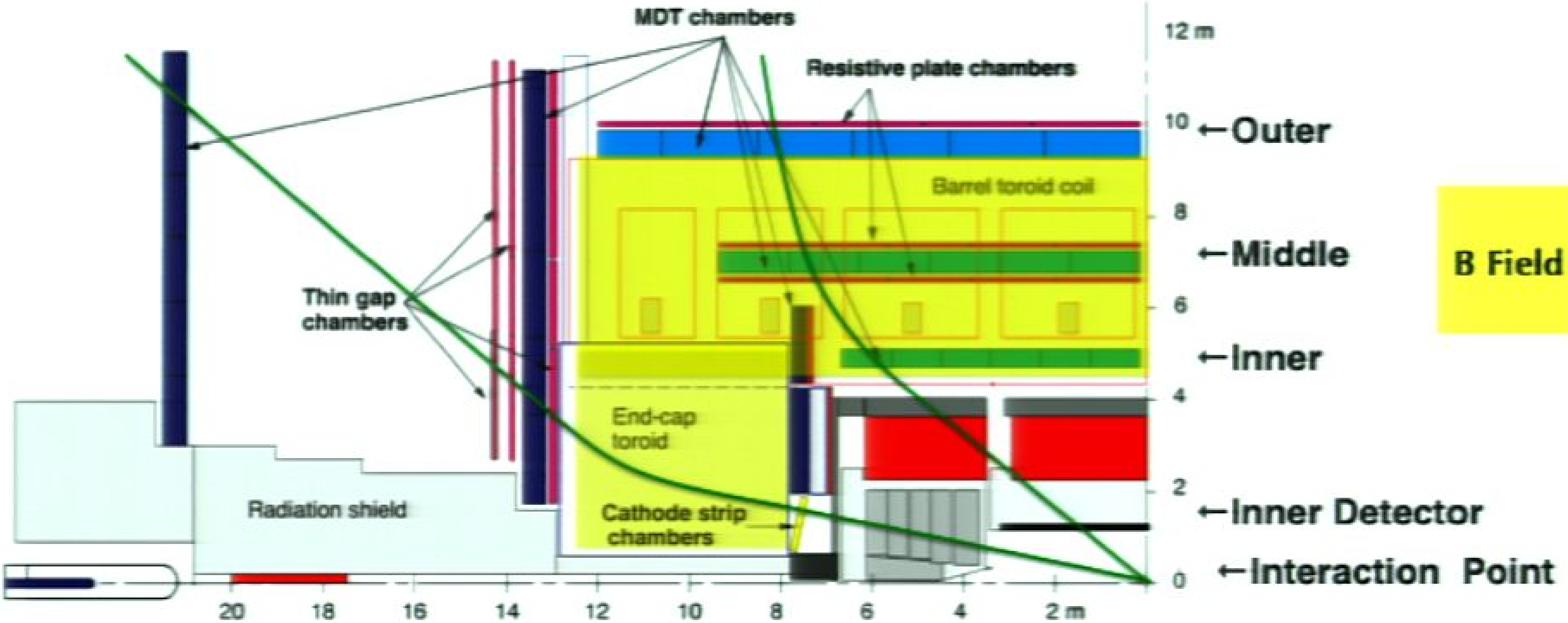

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$Z \rightarrow$ Jets

- If the decay occurs in the muon system, we can take advantage of triggers designed for hidden valleys.
- Can decay to jets after the HCAL, but before 7 meters, and still trigger.
- 3 regions of interest without calorimeter activity.

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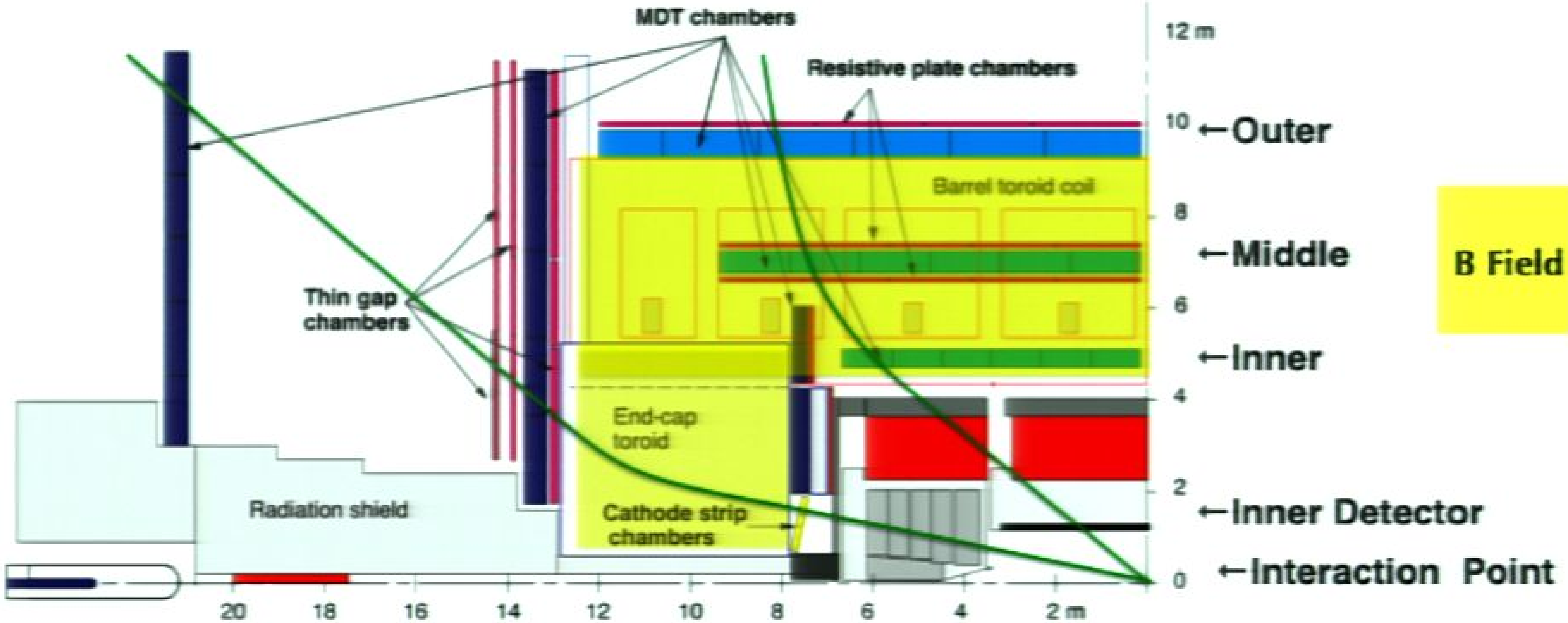

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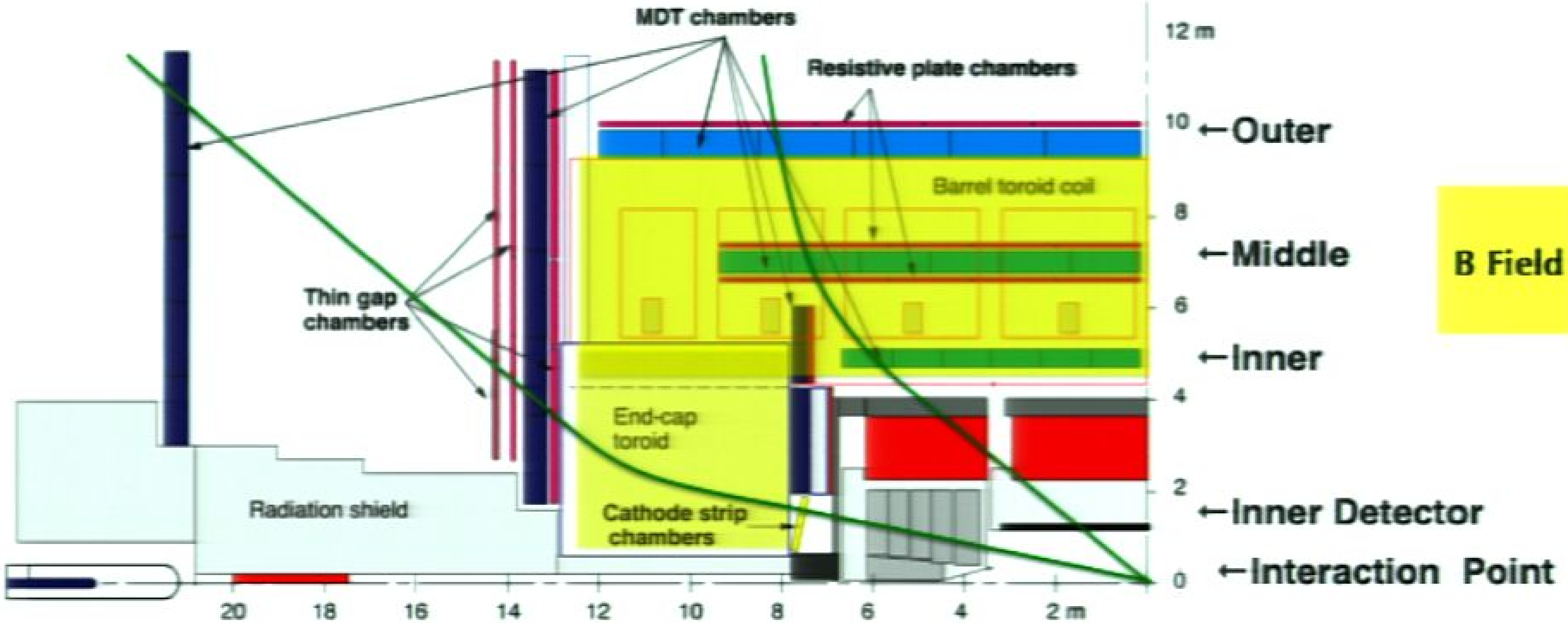
$\lvert\eta_{det}\rvert < 1.1$ at $r = 4.5, 7.0, 10.0$ m	Contained in the central muon spectrometer
Separation > 30 mm at $r = 4.5, 7.0, 10.0$ m	Resolve two muons
$r_d > 500$ mm	Significantly displaced vertex
$p_T > 20$ GeV	Triggerable
$\Delta t < 6$ ns (either)	Correct bunch-crossing ID

Here we use decays to muons happening before the start of the muon system. Direction is measured well by all muon layers, allowing a determination that the vertex was far from the interaction point.

The ATLAS Muon System

(ATL-MUON-SLIDE-2010-122)



Precision

Monitored Drift Tubes (MDT): $|\eta| < 2$ (3 chamber layers), $2 < |\eta| < 2.7$ (2 chamber layers)

✧ 80 μm point resolution (in η) in 339,000 tubes

Cathode Strip Chambers (CSC): $2 < |\eta| < 2.7$ (1 chamber layer) **← Endcap**

✧ 60 μm point resolution (in η) in 67,000 channels

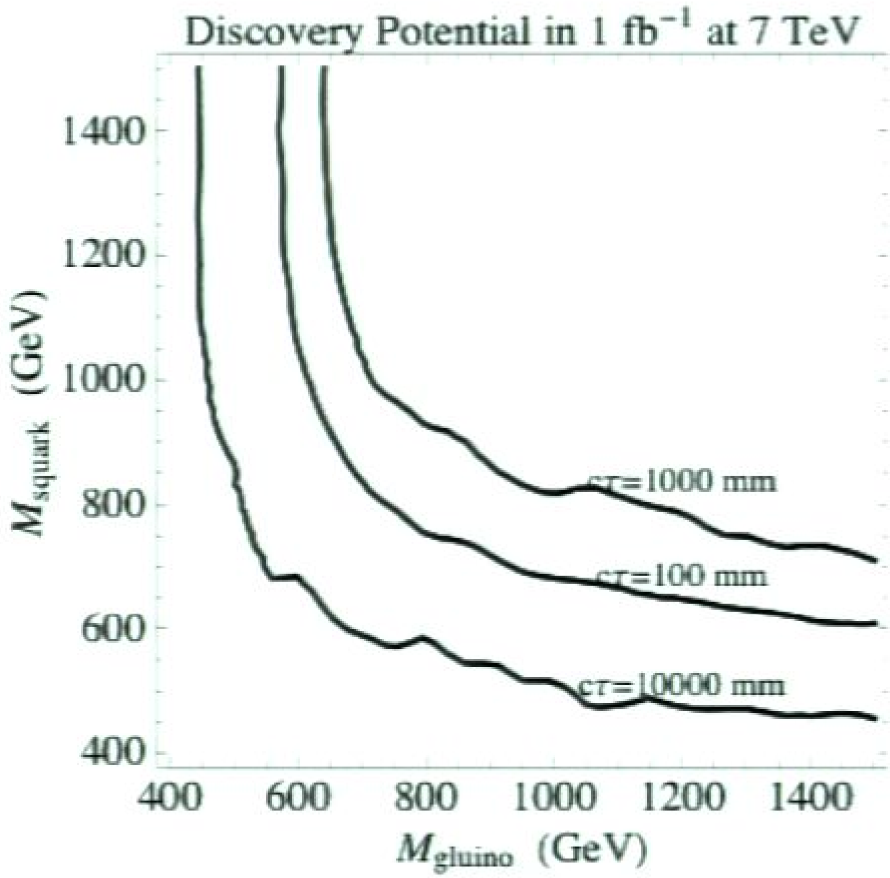
Trigger

Resistive Plate Chambers (RPC): $|\eta| < 1$ (3 chamber layers) **← Barrel**

✧ 1 cm point resolution (in η and ϕ) 359,000 strips

Thin Gap Chambers (TGC): $1 < |\eta| < 2.4$ (3 chamber layers) **← Endcap**

Discovery Potential



Lines of constant estimated $\sigma \times Br \times \varepsilon = 5$. NLSP is 250 GeV Higgsino.

$Z \to \mu^+\mu^-$ Cuts

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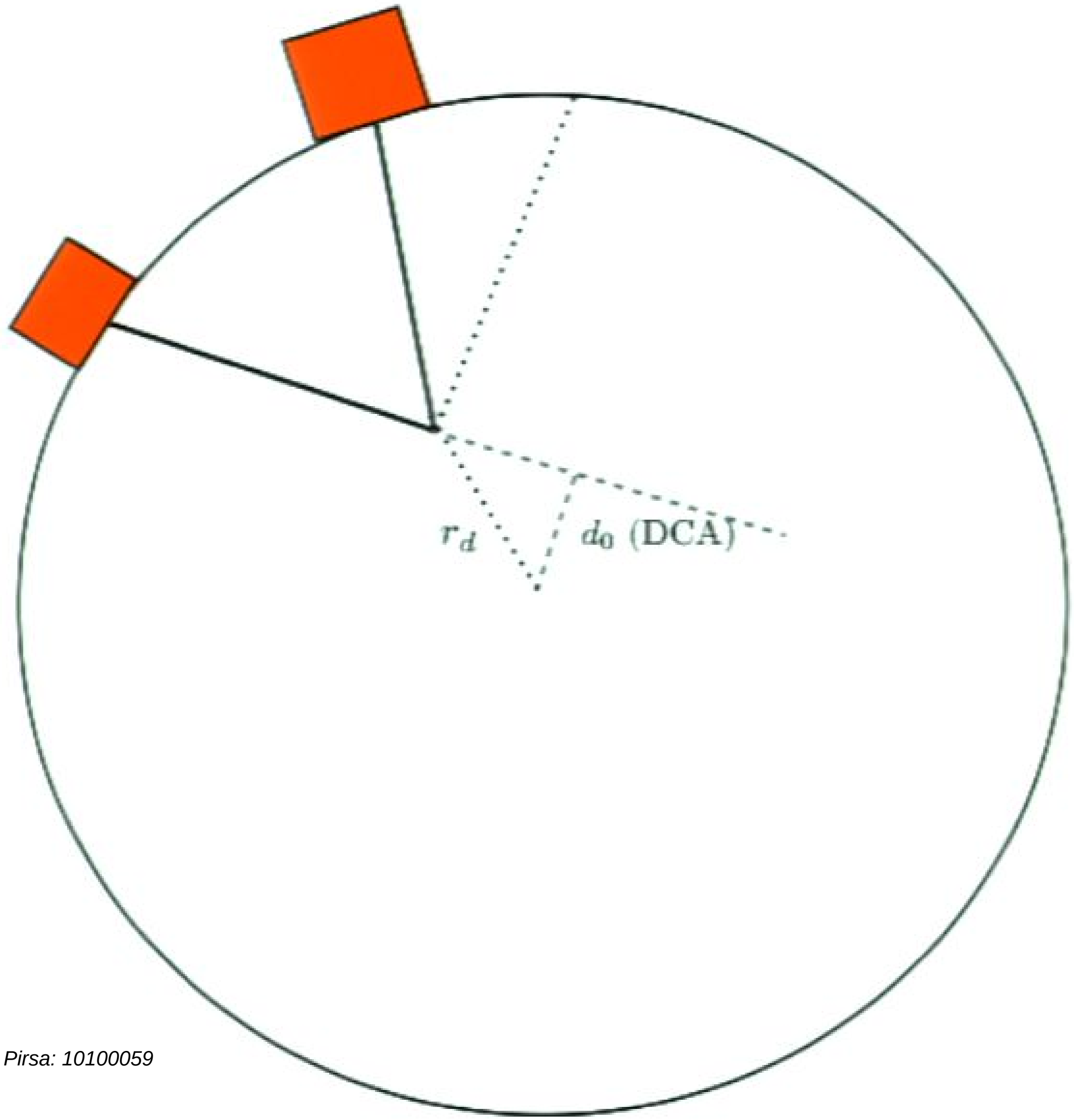
Extrapolating Back



r_d: Decay radius; use absence of hits closer to beamline

d_0: Impact parameter or distance of closest approach; find via track fitting

t_{det}: Time of detector signal in calorimeter

$Z \rightarrow \mu^+\mu^-$ Cuts

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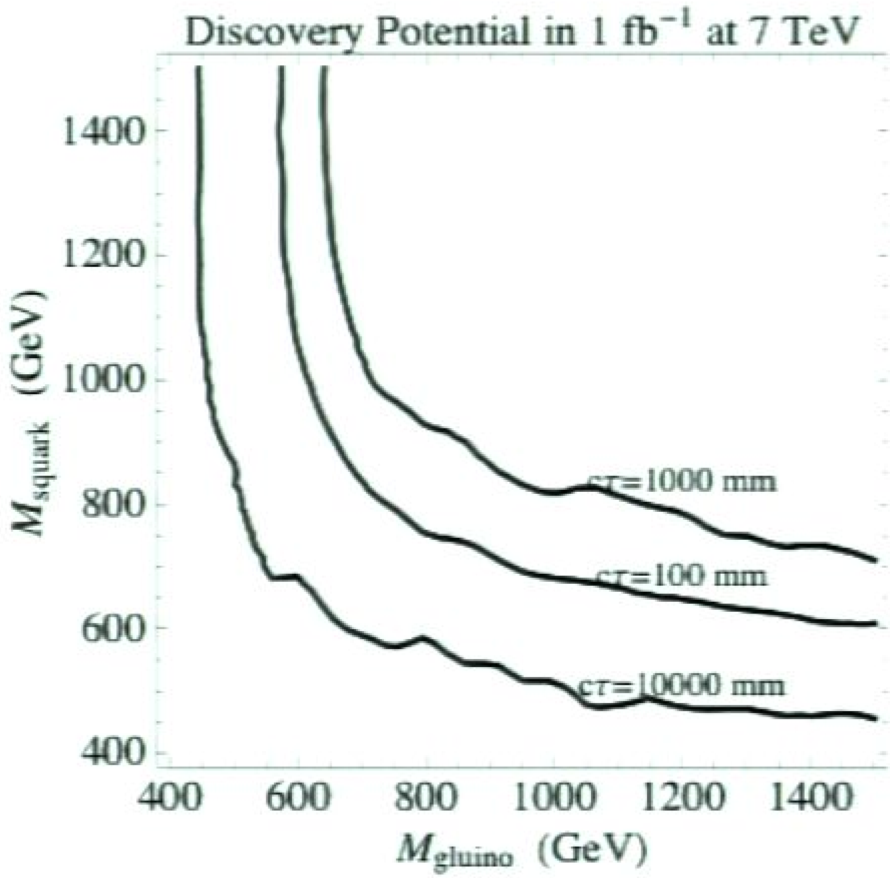

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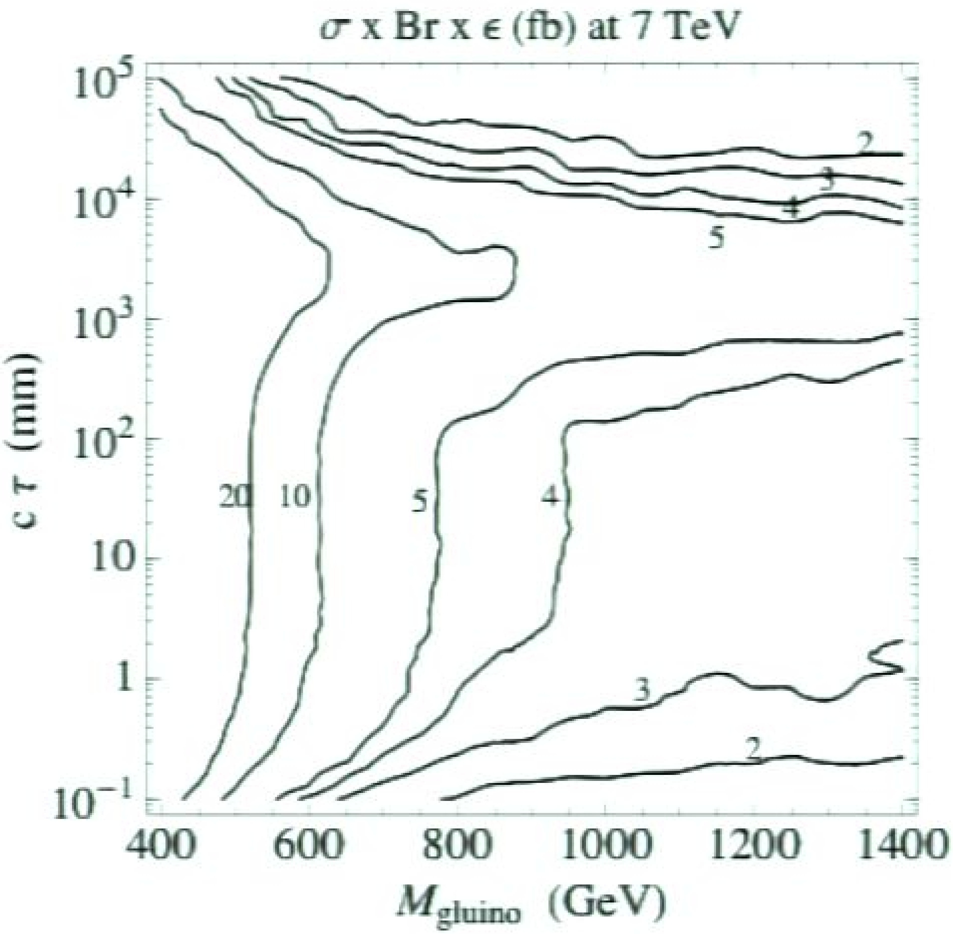

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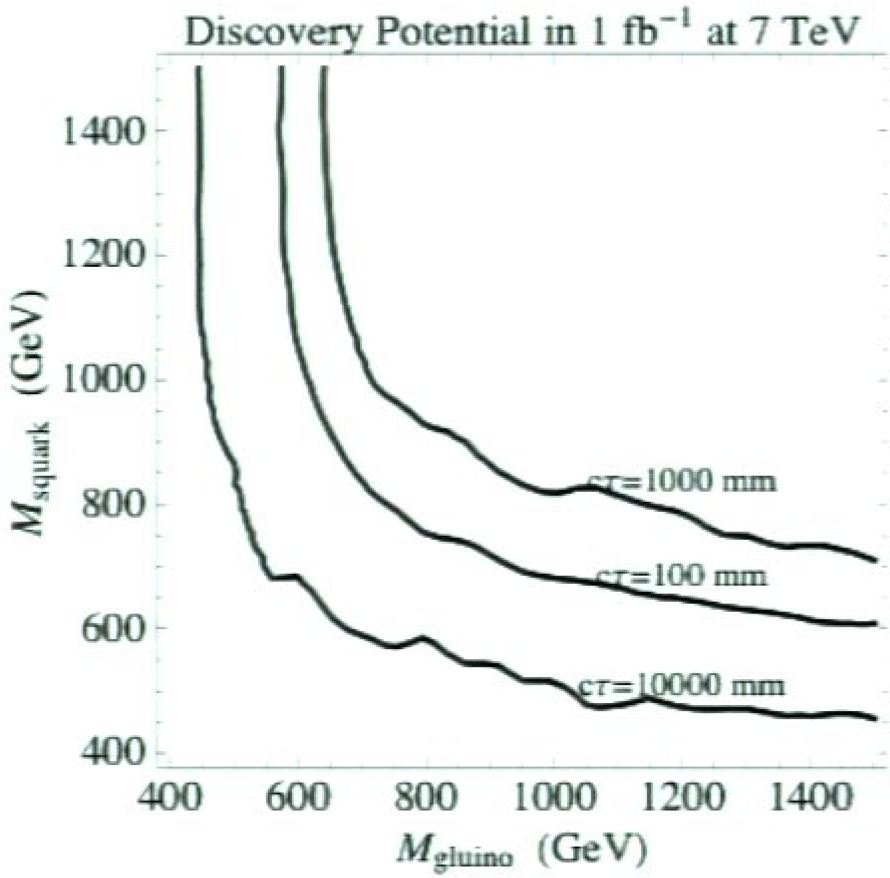

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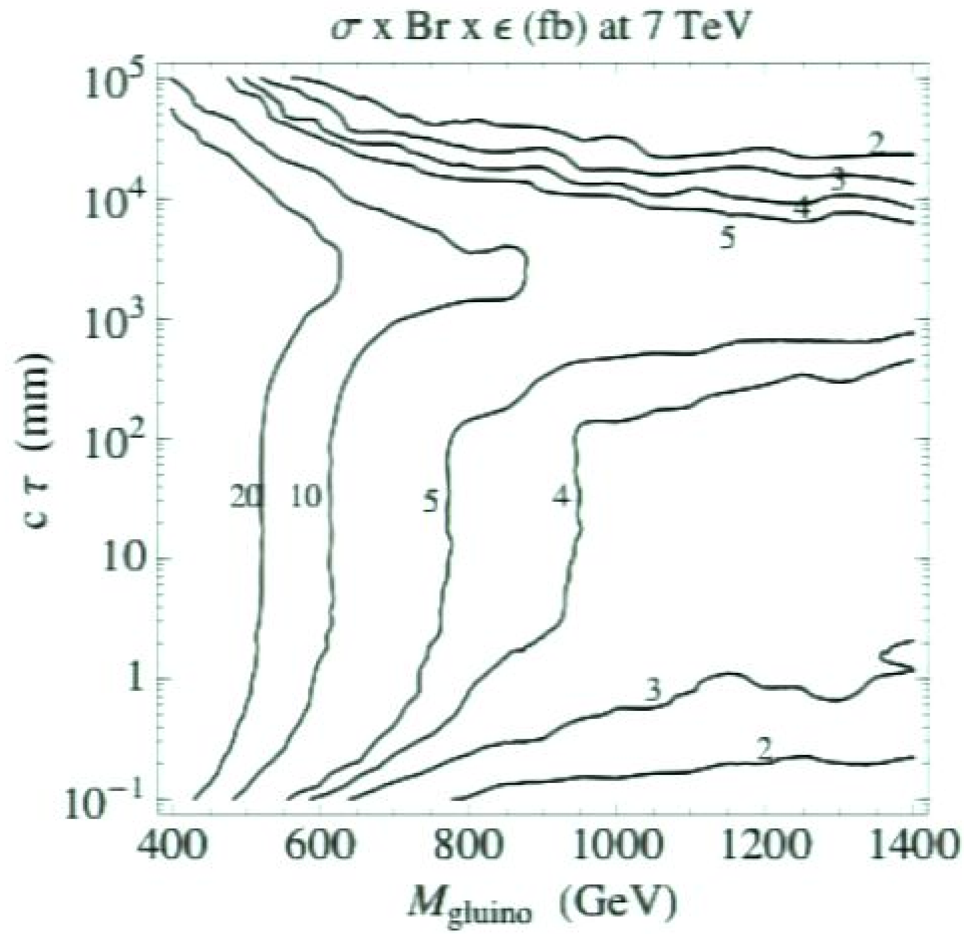

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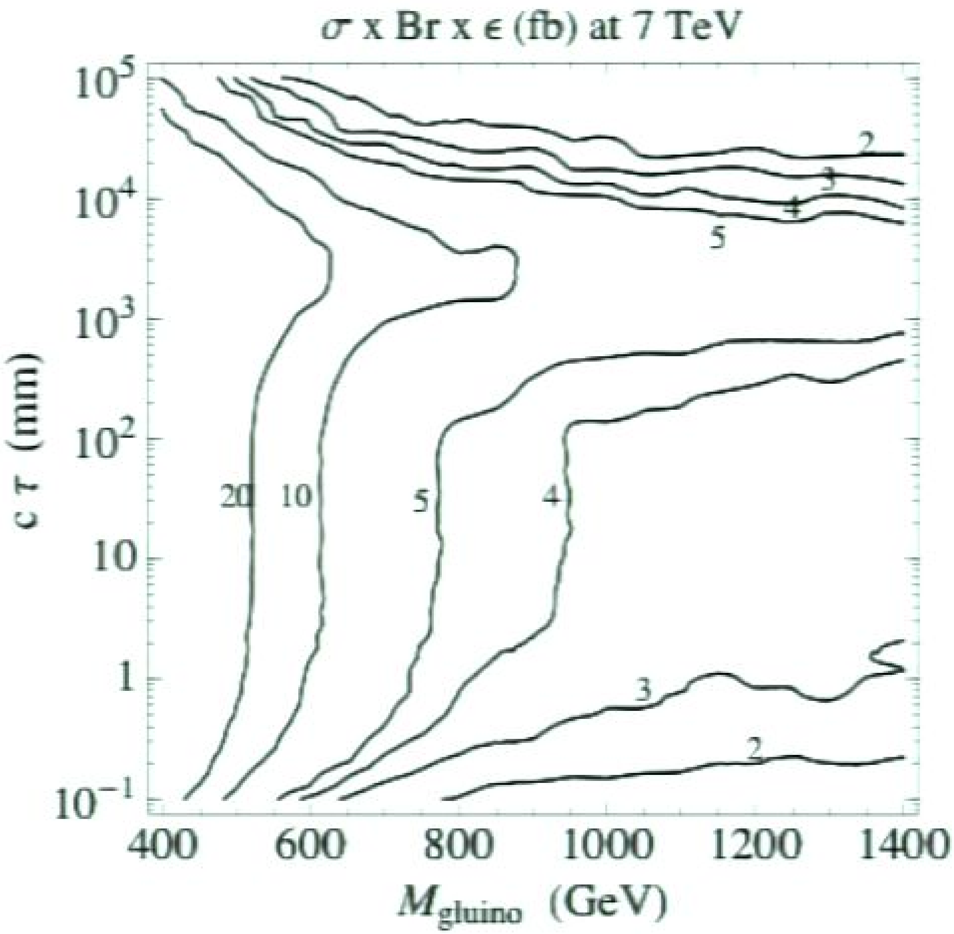

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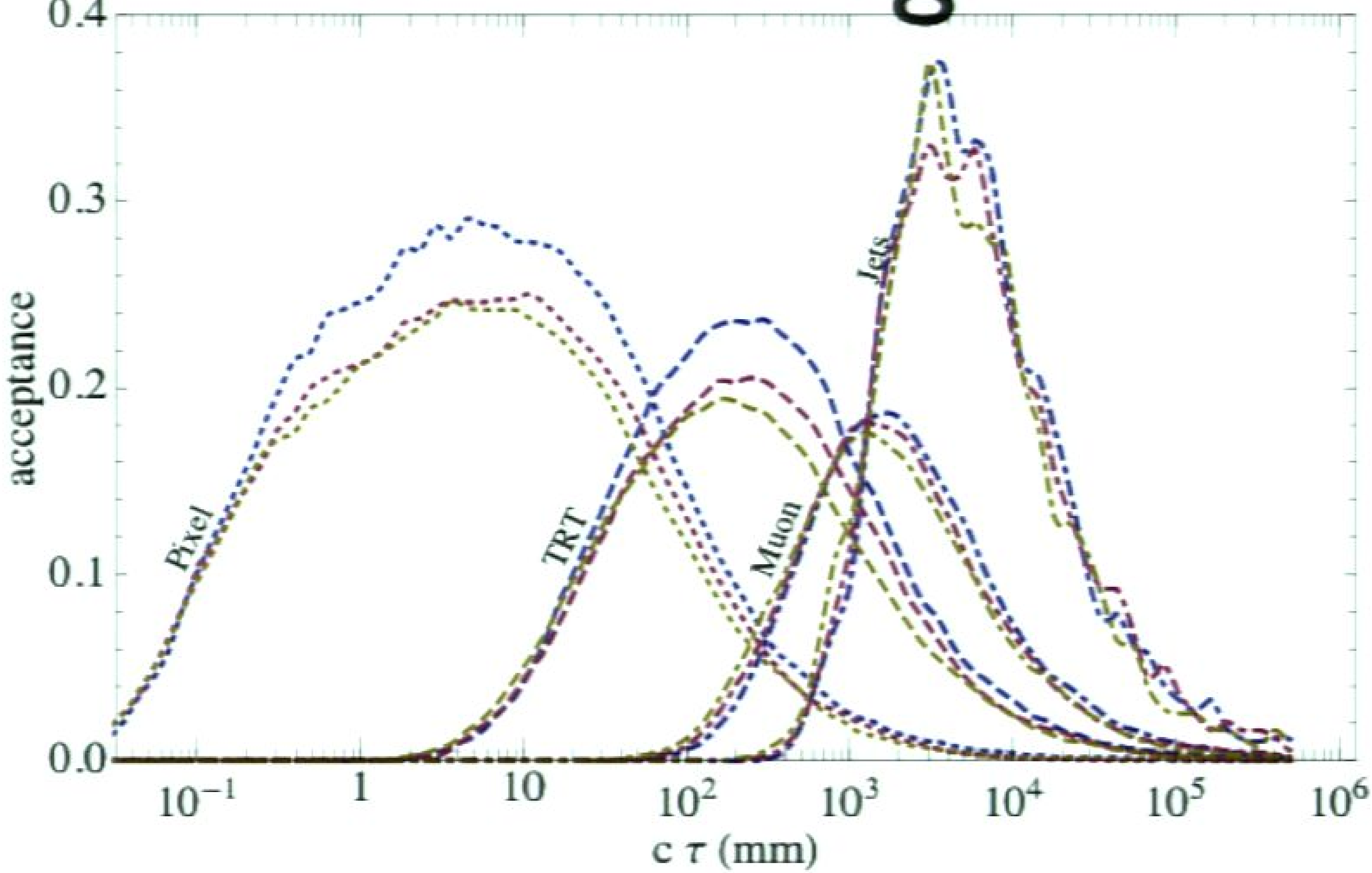
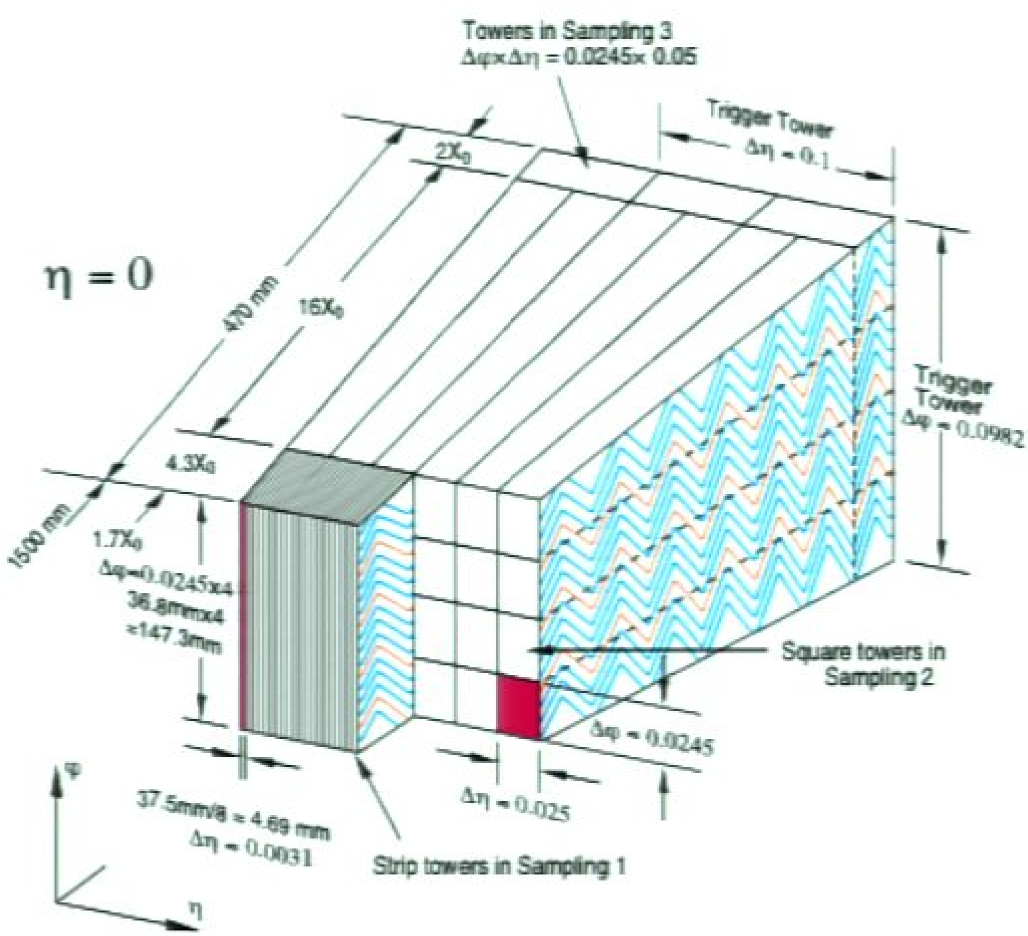
Acceptance estimate: 6 orders of magnitude!



Jets have been rescaled by Br(Z→jets)/Br(Z→e^+e^-)

Measurements



The ATLAS ECAL is granular: can measure the direction in η of an object traversing it (Resolution: $\sigma_\theta \approx 0.06/\sqrt{E}$, but degraded w/ eff. z vtx.)

Timing: 100 ps arrival time? (Disputed....)

See Kawagoe et al., hep-ph/0309031 for use of these

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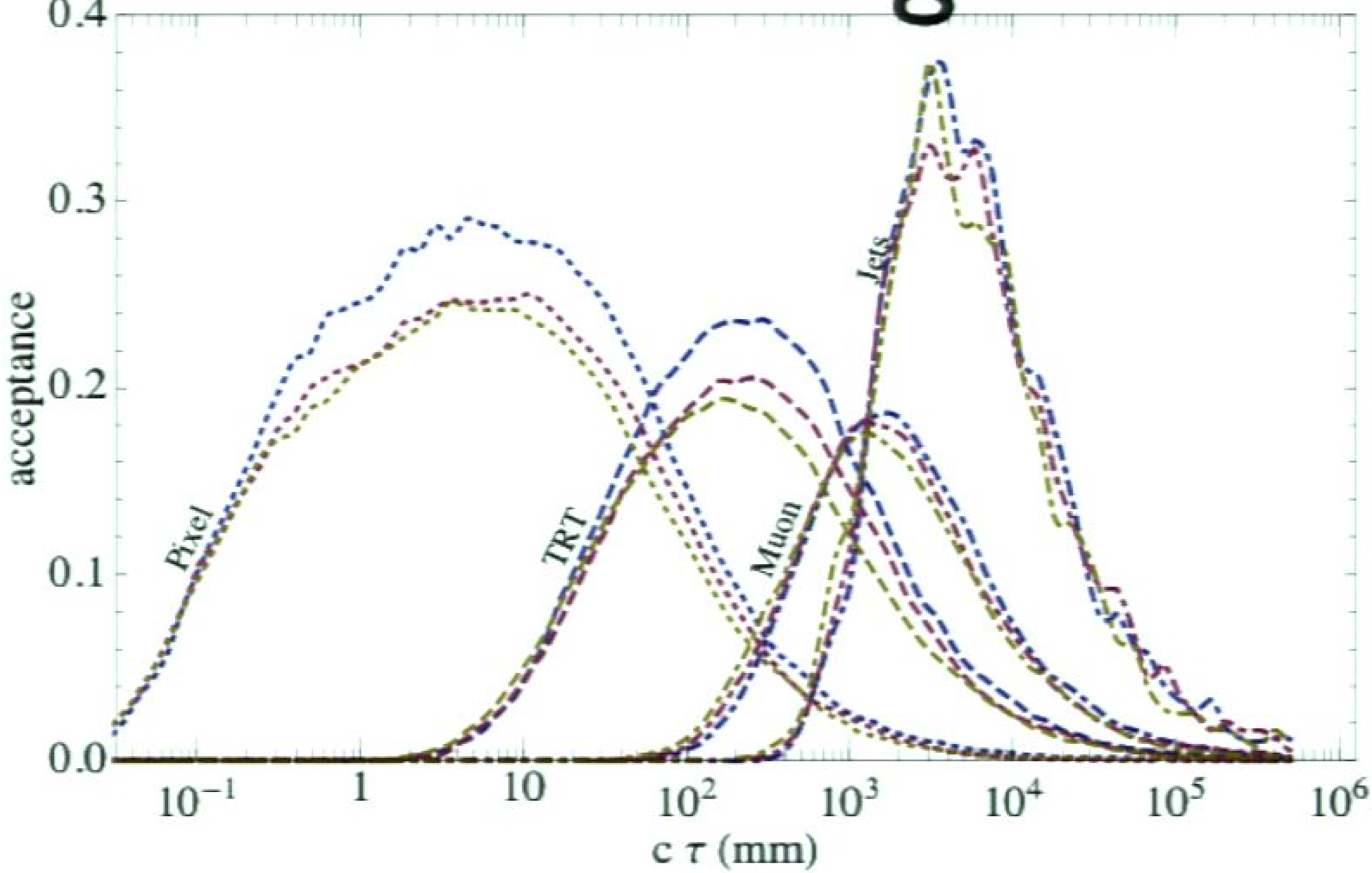

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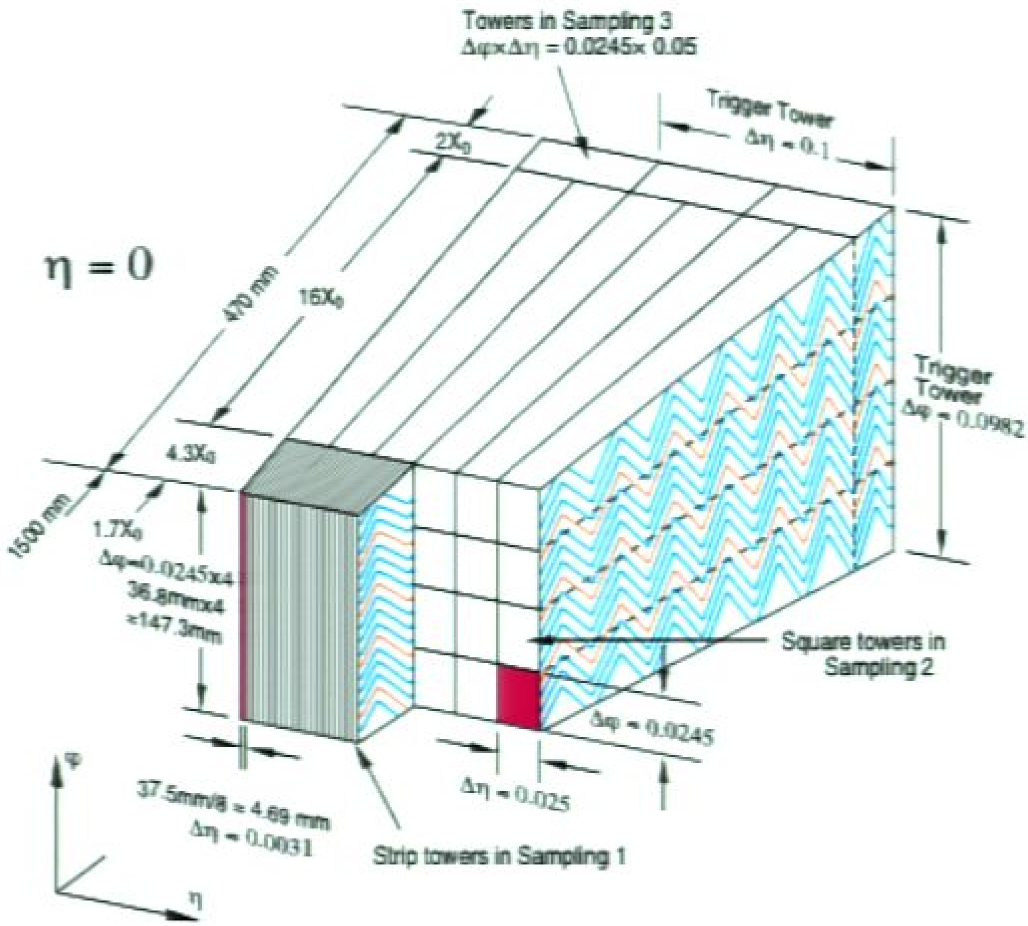

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Pointing Angle Measurement

From public ATLAS note ATL-PHYS-PUB-2007-010 by Damien Prieur

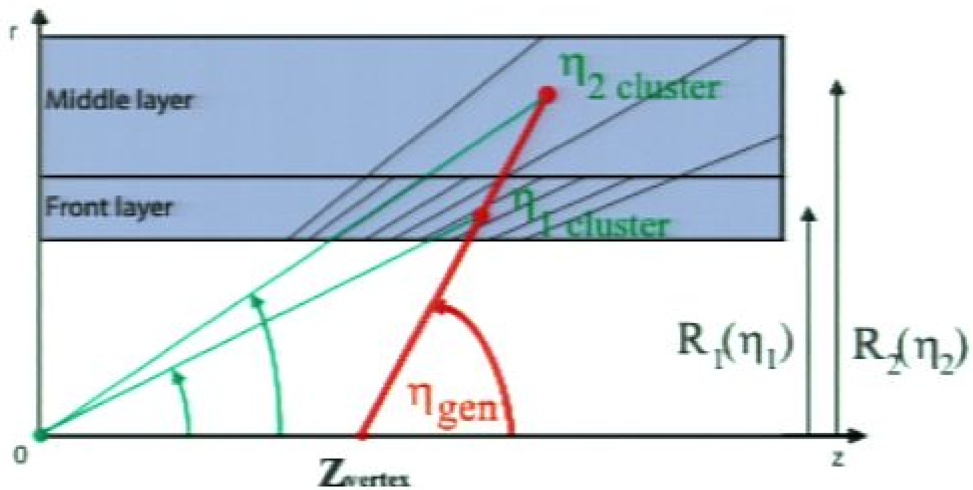
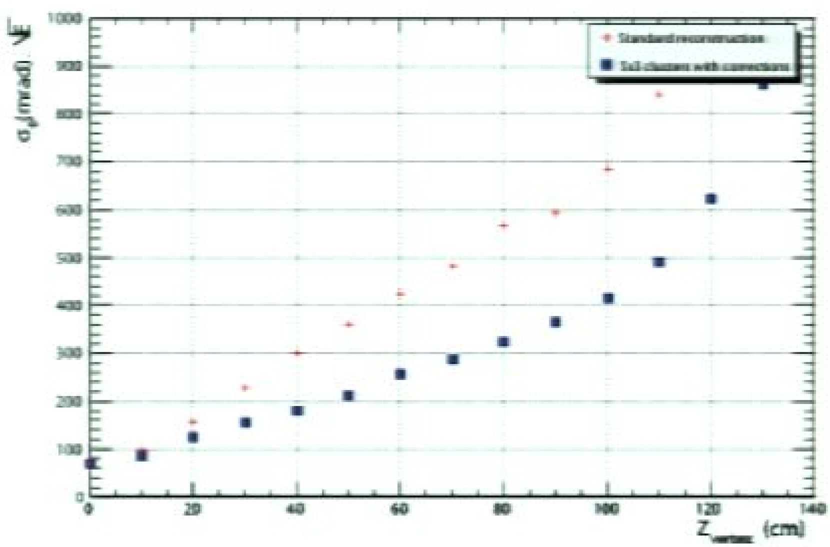


Figure 1: Sketch of the barrel part of the electromagnetic calorimeter and its first two layers showing the principle of the direction reconstruction for a photon generated at a distance Z_{vertex} from the ATLAS interaction point.



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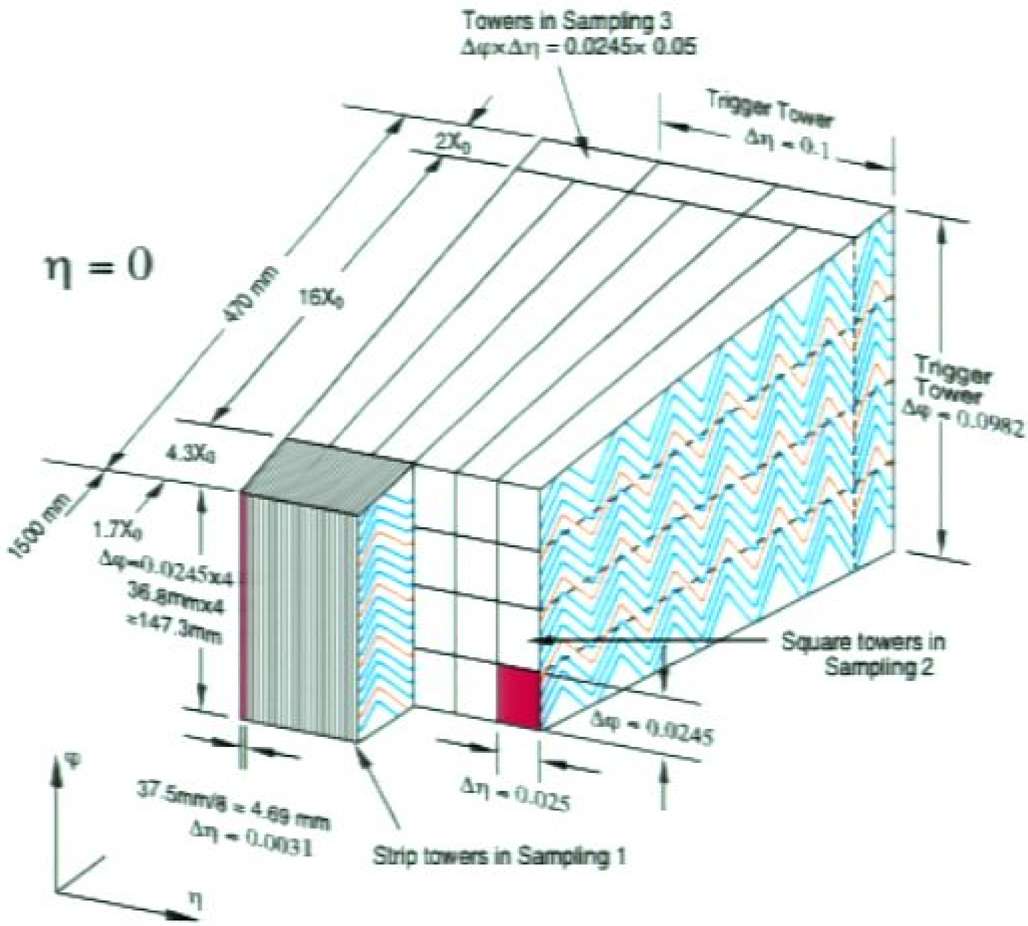

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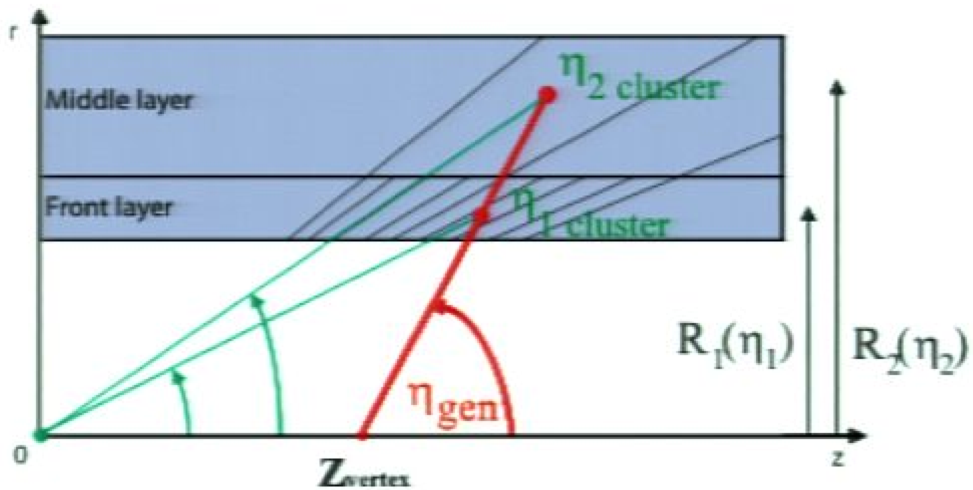

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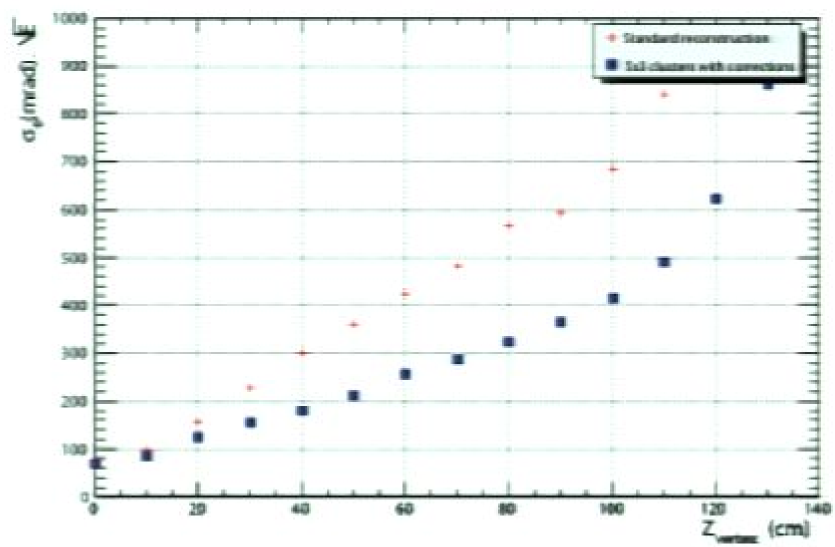

Counting

ECAL measures, for each electron:

1. Energy
2. Position in η
3. Position in Φ
4. Direction in θ
5. Arrival time

To fully reconstruct NLSP $\rightarrow$ e^+e^- Gravitino decay, have 10 unknowns:

(3+3): three-momenta of e^+ and e^-

4: (x, y, z, t) of the decay vertex

Reconstruction: Z →ll

- Two massless particles hit the ECAL at known positions and times. Solve for the unknown decay vertex.
- Pointing gives $\frac{z_i - z_d}{\sqrt{(x_i - x_d)^2 + (y_i - y_d)^2}}$, timing

$$c(t_i - t_d) = |\mathbf{x}_i - \mathbf{x}_d|$$

- Four equations, four unknowns. Constraints: time order, speed < c.

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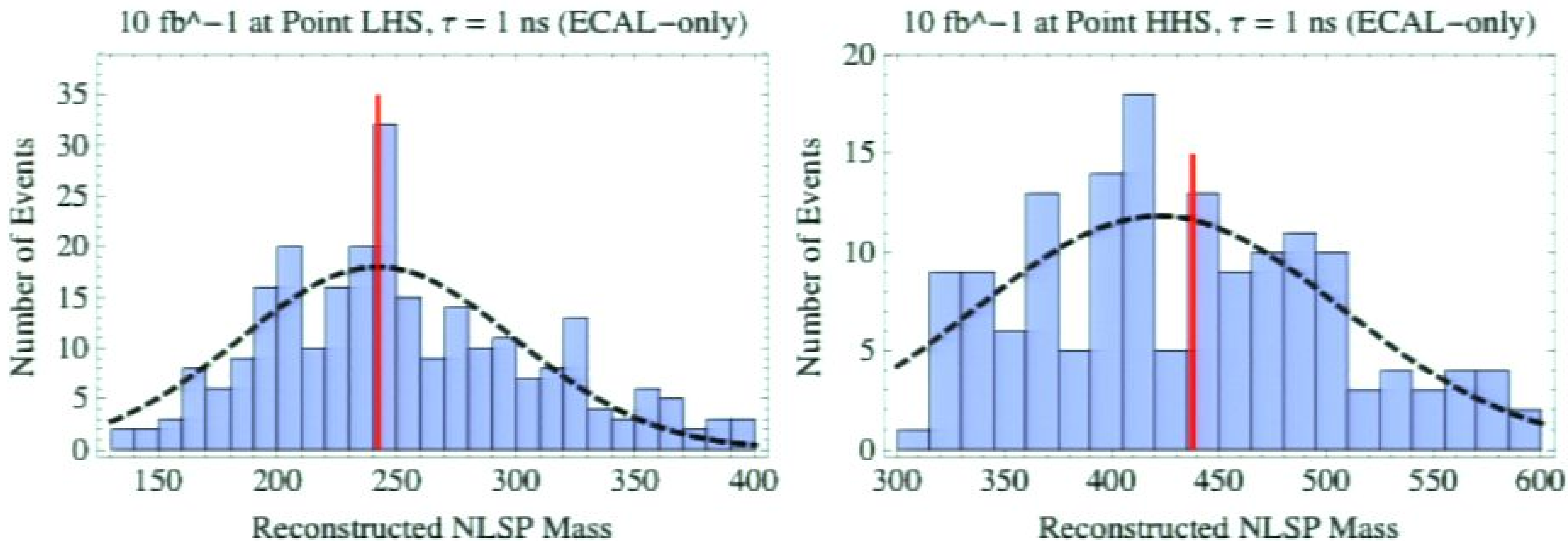
Further Reconstruction

- Once we know the location and time of the NLSP decay, assuming a massless gravitino gives us the full four-vector:

$$m_{\tilde{G}}^2 = (E_\chi - E_1 - E_2)^2 - (E_\chi \mathbf{v}_\chi - \mathbf{p}_1 - \mathbf{p}_2)^2 = 0$$



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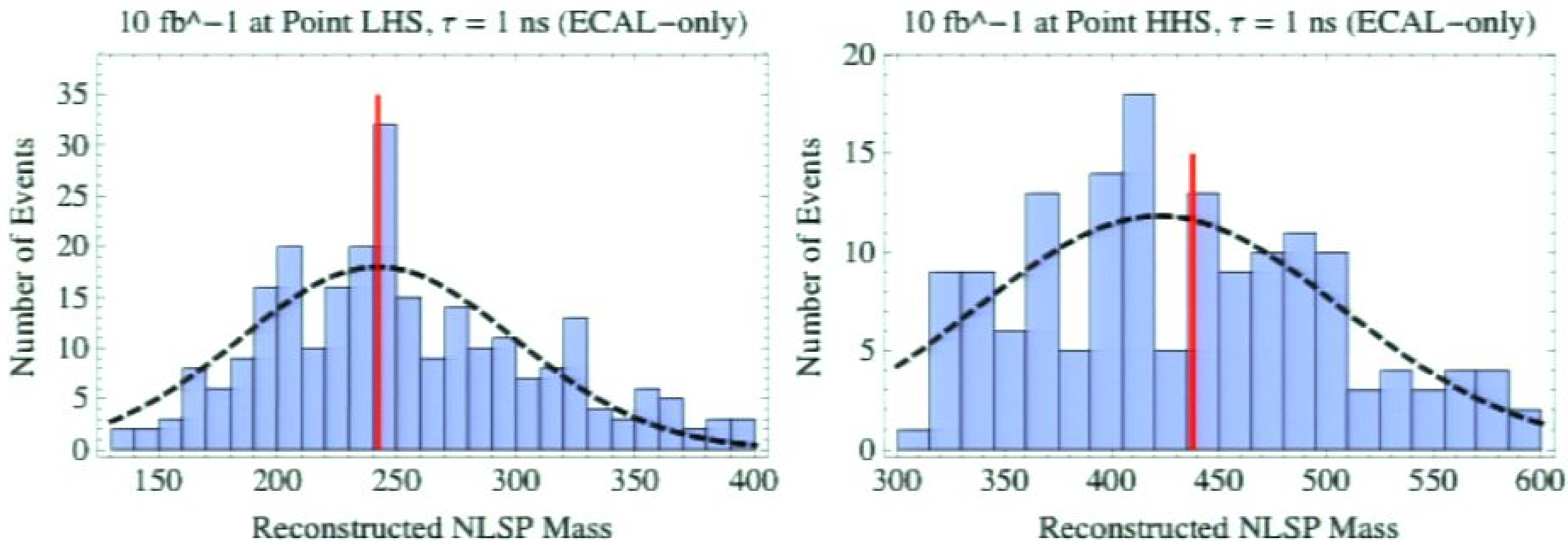

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Using the Tracker

We have Z →e+e-, so we would like to be able to use not just the ECAL but the tracker (don't solve, overconstrain and fit).

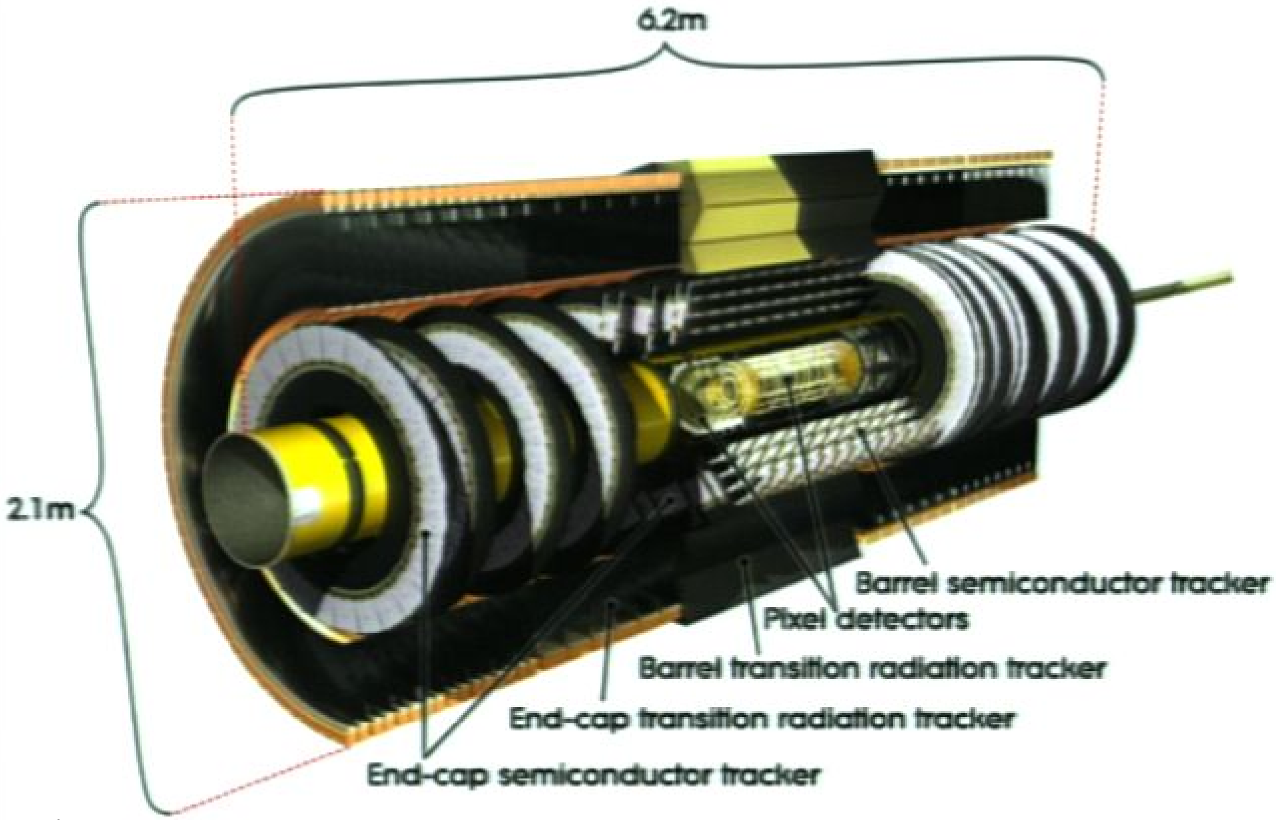

Figure 1: Cut-away view of the ATLAS inner detector

The barrel TRT can measure direction in φ, for $|\eta| < 0.8$, $r < 800$ mm.

(Figure from 0901.0512)

Track Reconstruction

The default tracking algorithms miss our tracks -- no silicon hits, because the decays are very displaced!

One common setting for looking for tracks from faraway vertices are photon conversions. But those point back to the beamline!

Will need a new algorithm, but seems very possible.

Anchor the track search at the ECAL deposit; look for high-pT tracks, so nearly linear. Two unknowns: phi direction, and impact parameter. Hough transform?

Precision Observables

	Measurement	Resolution
ECAL	E	$\delta E \sim 0.1\sqrt{E\ \mathrm{GeV}}$
	$\eta_{det}, \varphi_{det}$	$\sigma_\eta = 0.004/\sqrt{E/\mathrm{GeV}}, \sigma_\varphi = 0.005/\sqrt{E/\mathrm{GeV}}$
	θ_{dir}	$\sigma_\theta = \left(0.080 + \frac{\lvert z_{e.v.}\rvert}{100\ \mathrm{cm}} 0.340\right)/\sqrt{E/\mathrm{GeV}}$
	t_{det}	$\sigma_t = 100$ ps
TRT	φ_{dir}	$\sigma_{\varphi_{dir}} = 1$ mrad
Muon	p	$\sigma_p = 0.04p$
	$\theta_{dir}, \varphi_{dir}$	$\sigma_{\varphi_{dir}} = \sigma_{\theta_{dir}} = 15$ mrad
	t_{det}	$\sigma_t = 2$ ns

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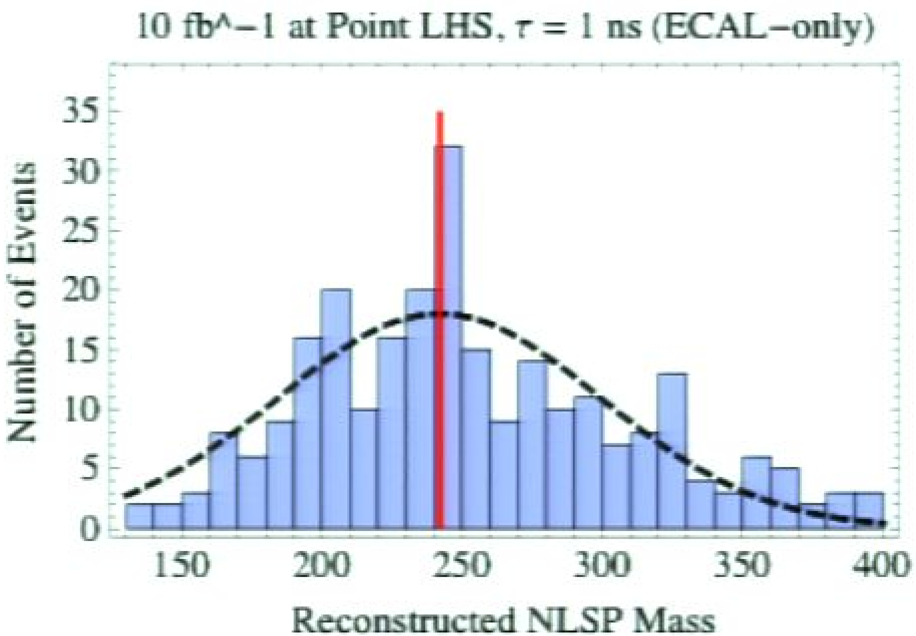

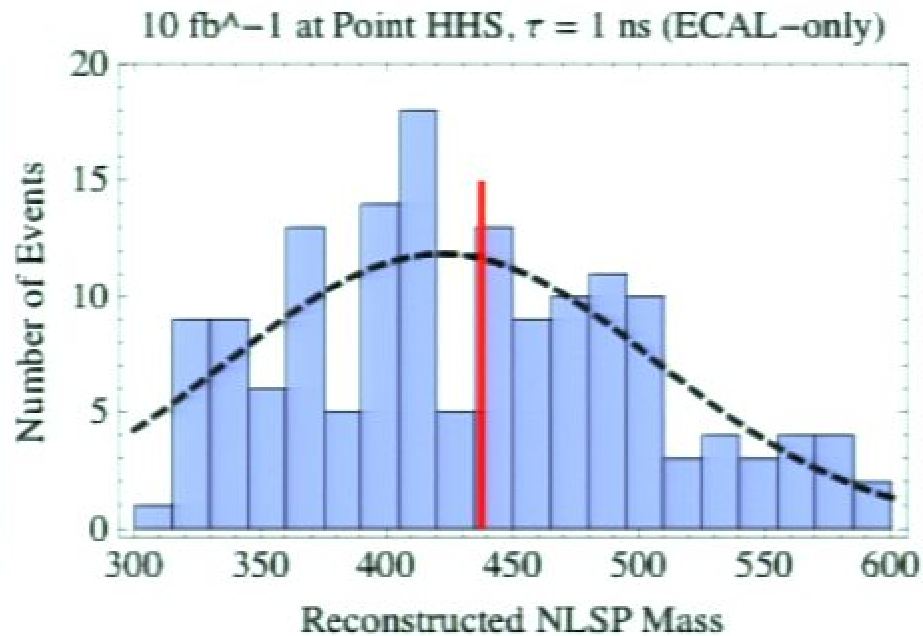

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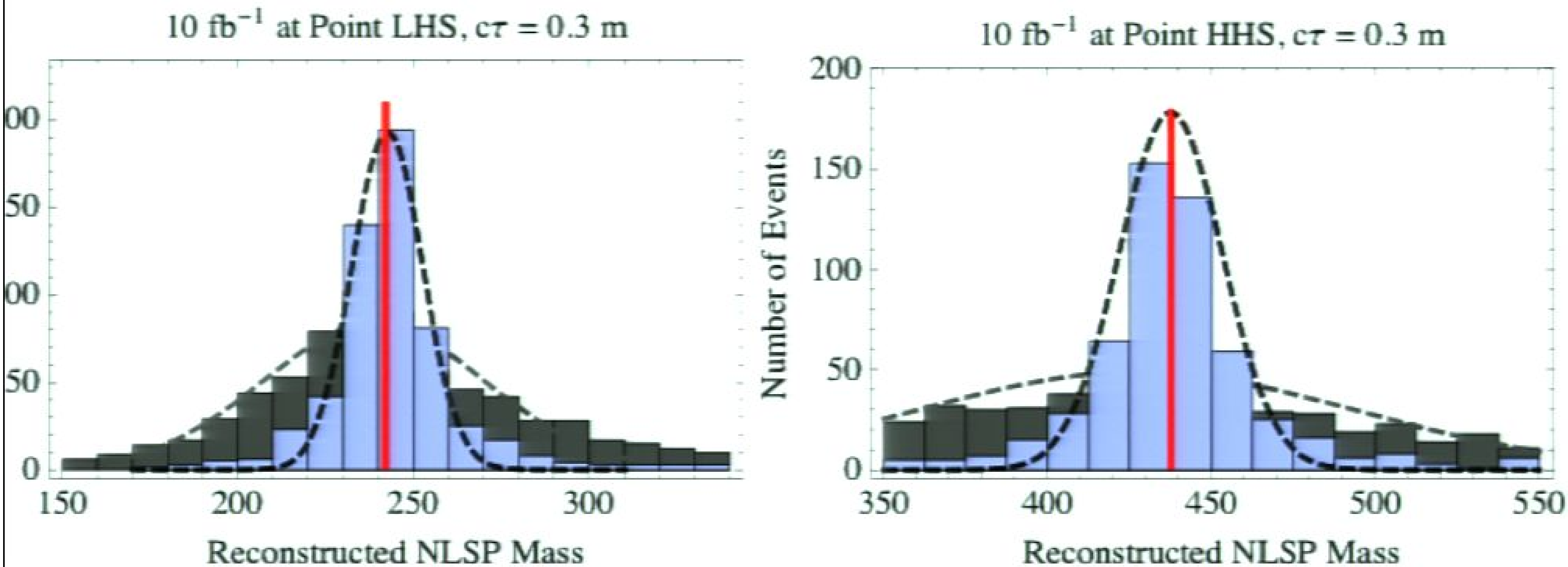
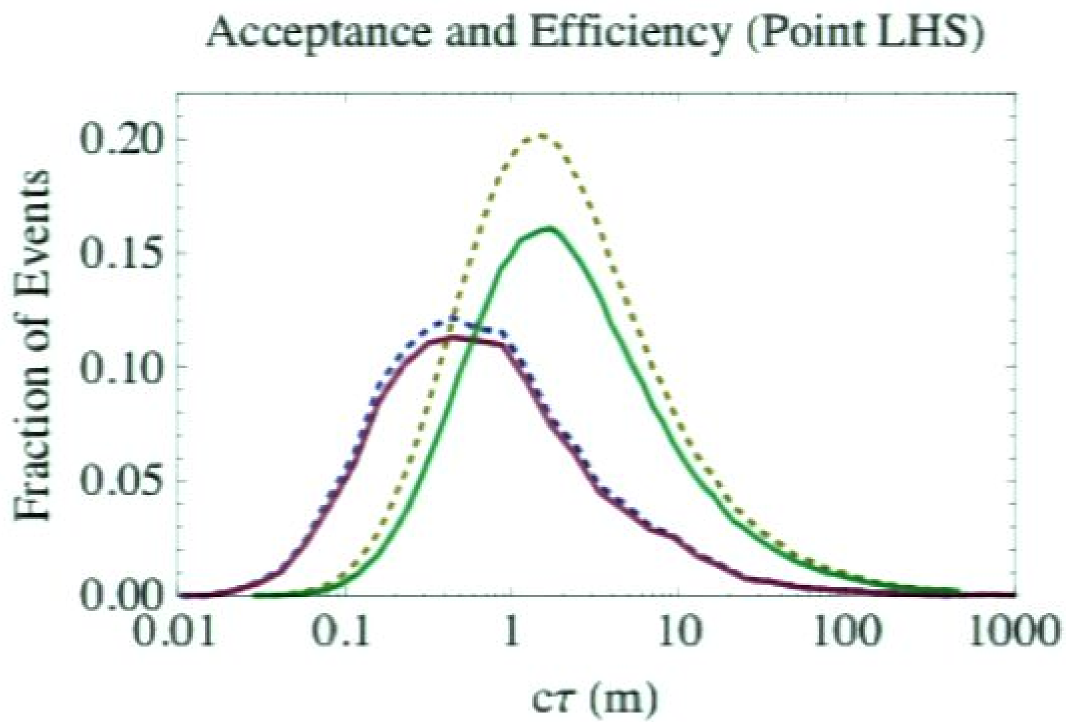
Results with TRT



Significant improvement over ECAL-only. (Gray histogram in the background)

Assumes tracks are reconstructed well in the TRT.

Acceptances for Full Reconstruction



Purple curve: final efficiency for reconstruction using the ECAL and the TRT; Green curve: for

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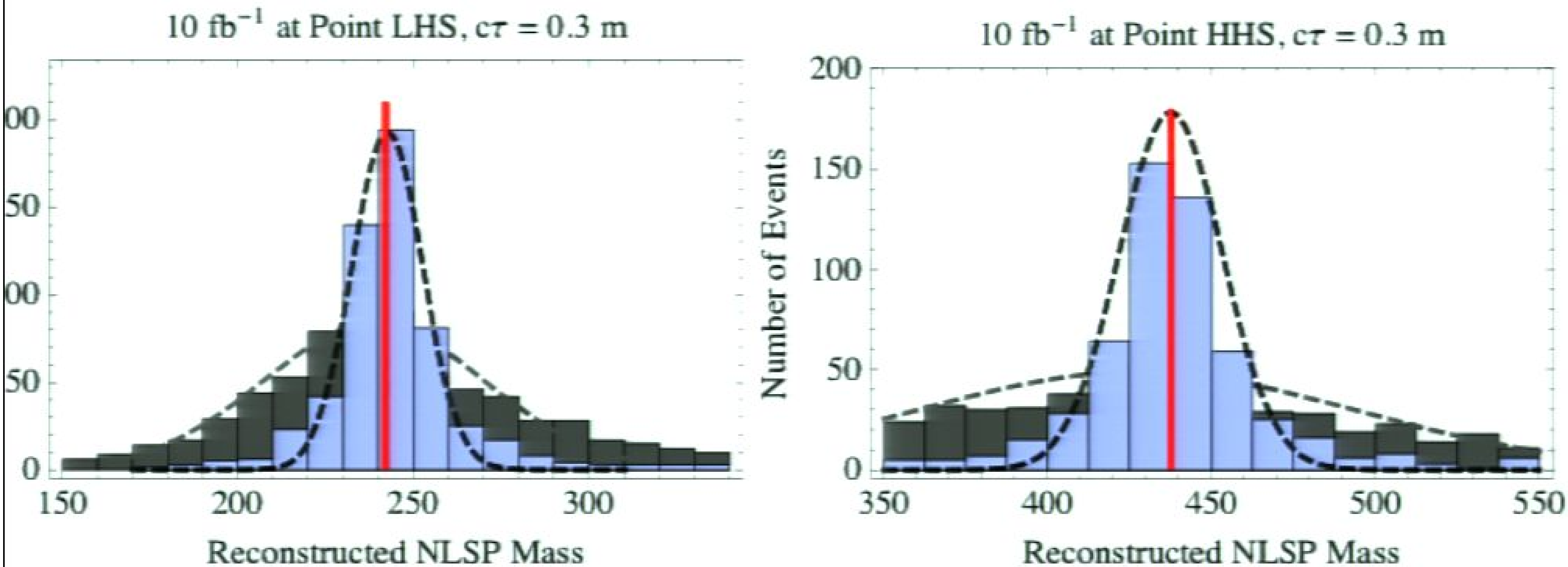

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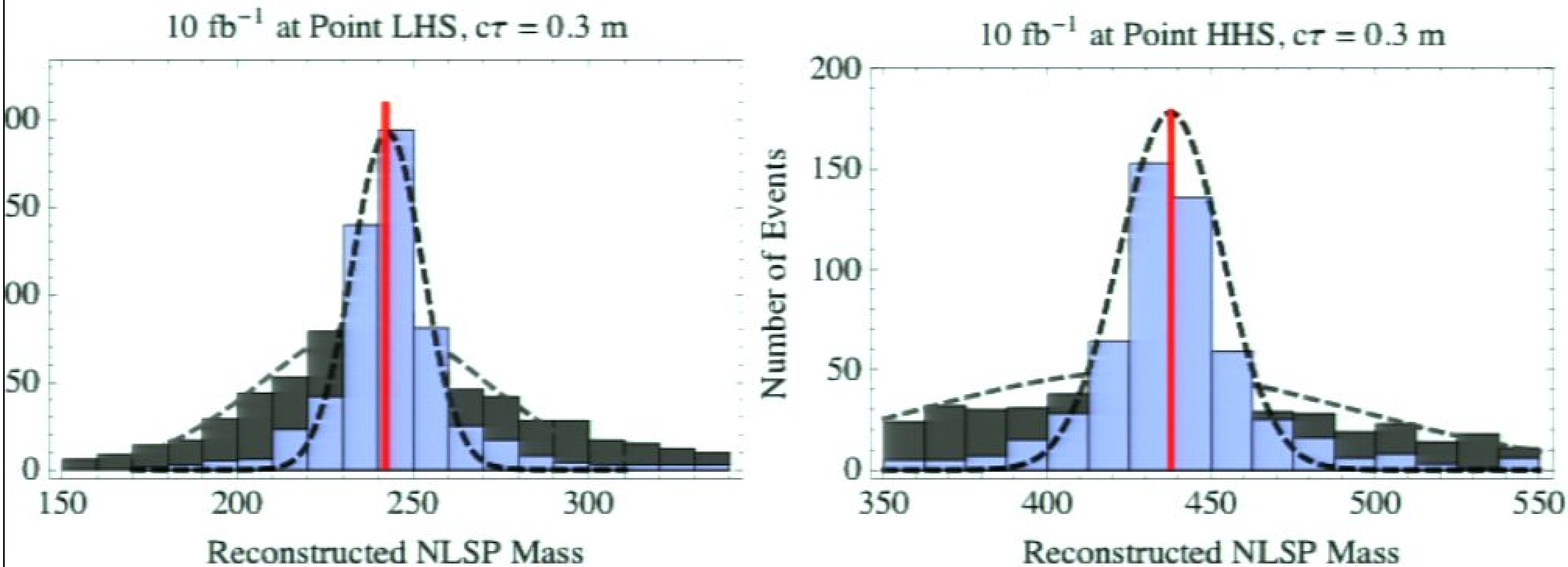

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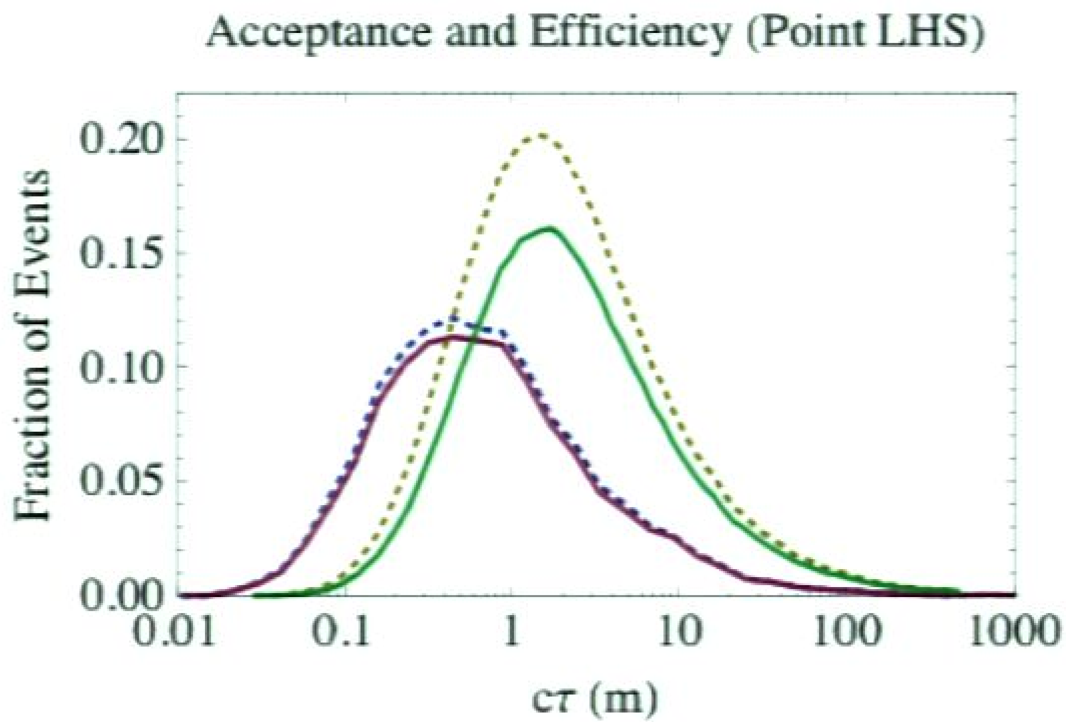

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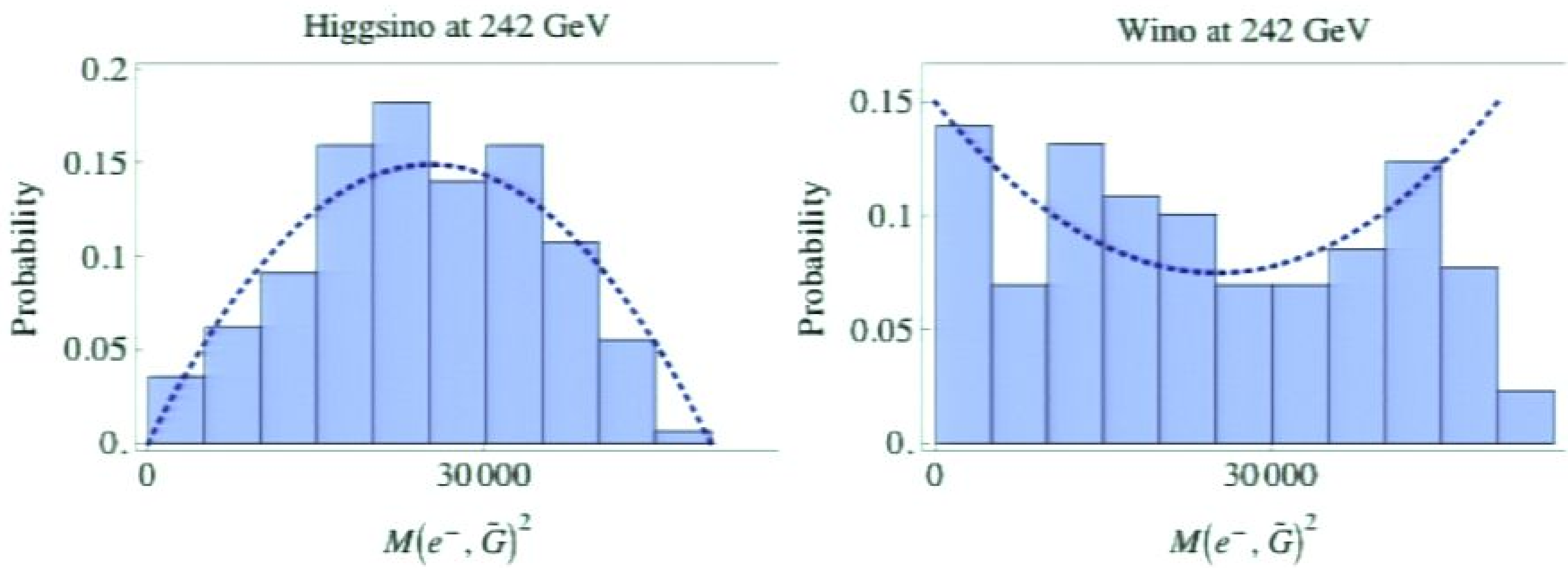
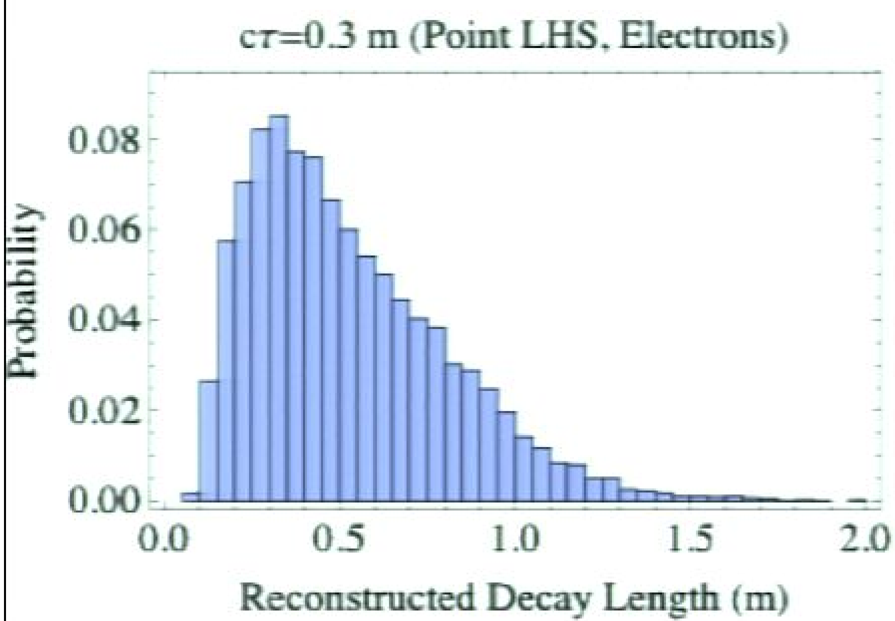
Finding the underlying model

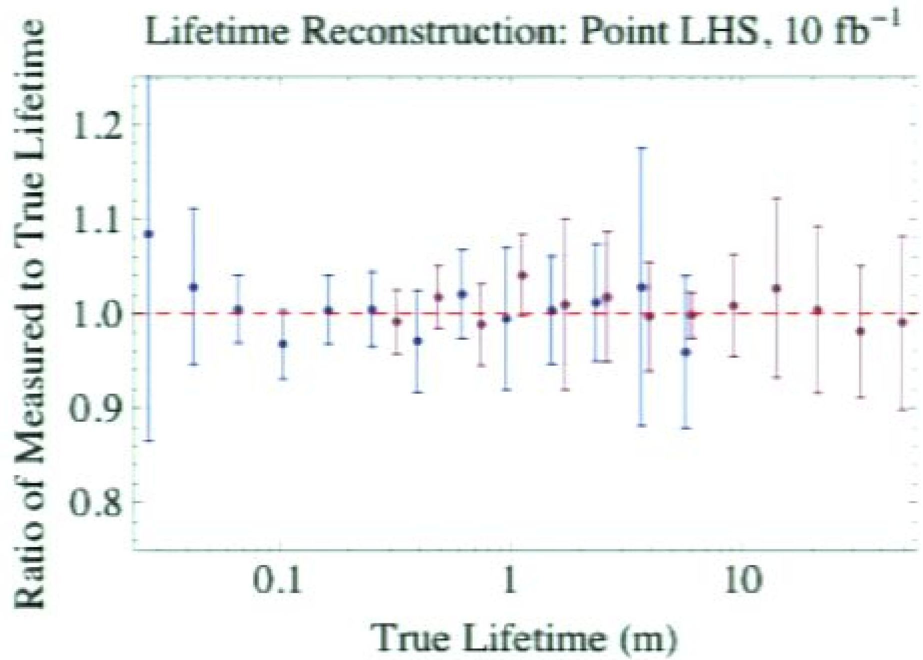


Accurate kinematic reconstruction gives information on polarization: longitudinal vs. transverse Z boson tells us Higgsino vs. Wino.

Shown: cτ = 0.3 m, 10 fb^{-1} at 14 TeV

Measuring Lifetimes





An exponential distribution is modified by boosts and by geometric effects at both short and long distances.

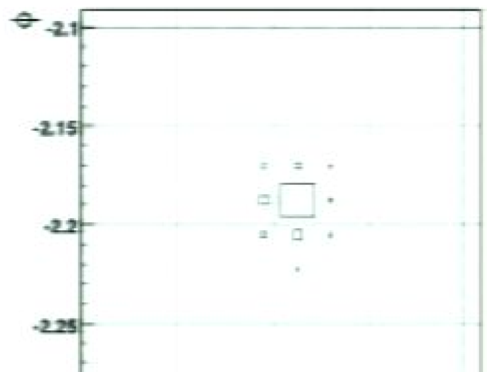
Given accurate mass measurements, can simulate and

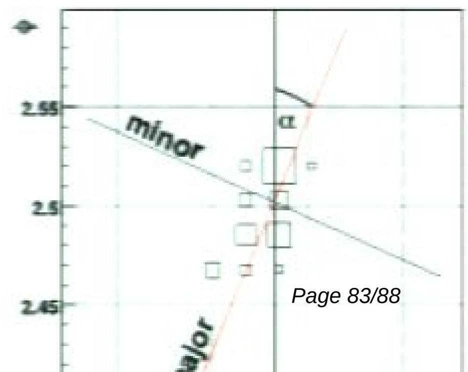
What About Jets?

- I've been focusing on electrons because the ECAL measures time, which is useful for reconstruction
- Jets leave some fraction of their energy in the ECAL, so potentially can use the larger $Z \rightarrow jj$ rate.
- TRT would be less useful for jets
- Trigger issues? Use trackless jets?

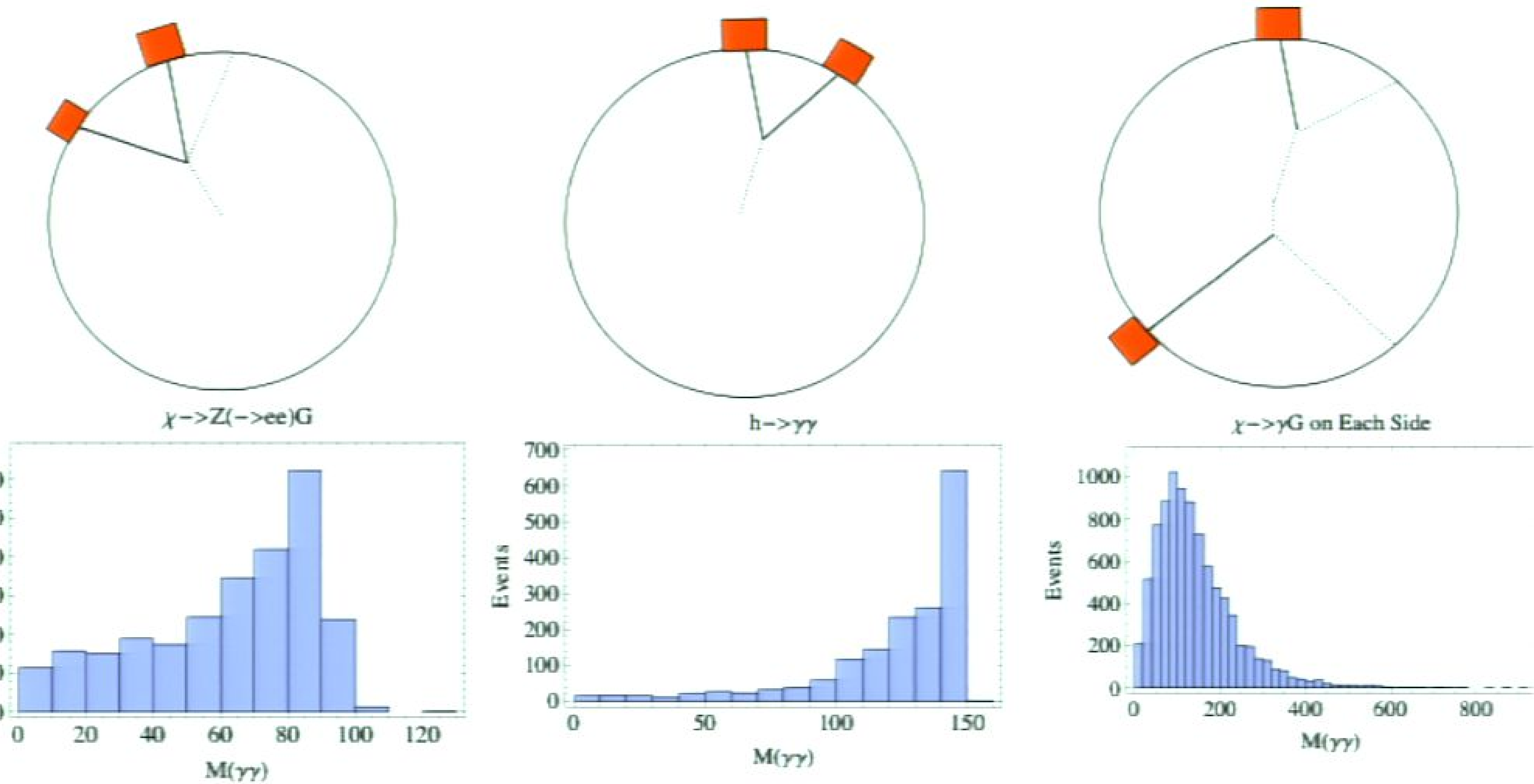
What About CMS?

- CMS is comparable to ATLAS for the types of measurements we've discussed
- Smaller: radius 7.3 m versus 10 m
- 1 ns timing for muons; 100 ps for ECAL
- Crude measurement for non-pointing photons (0710.2647 by P. Zalewski):
- However, 3d tracking



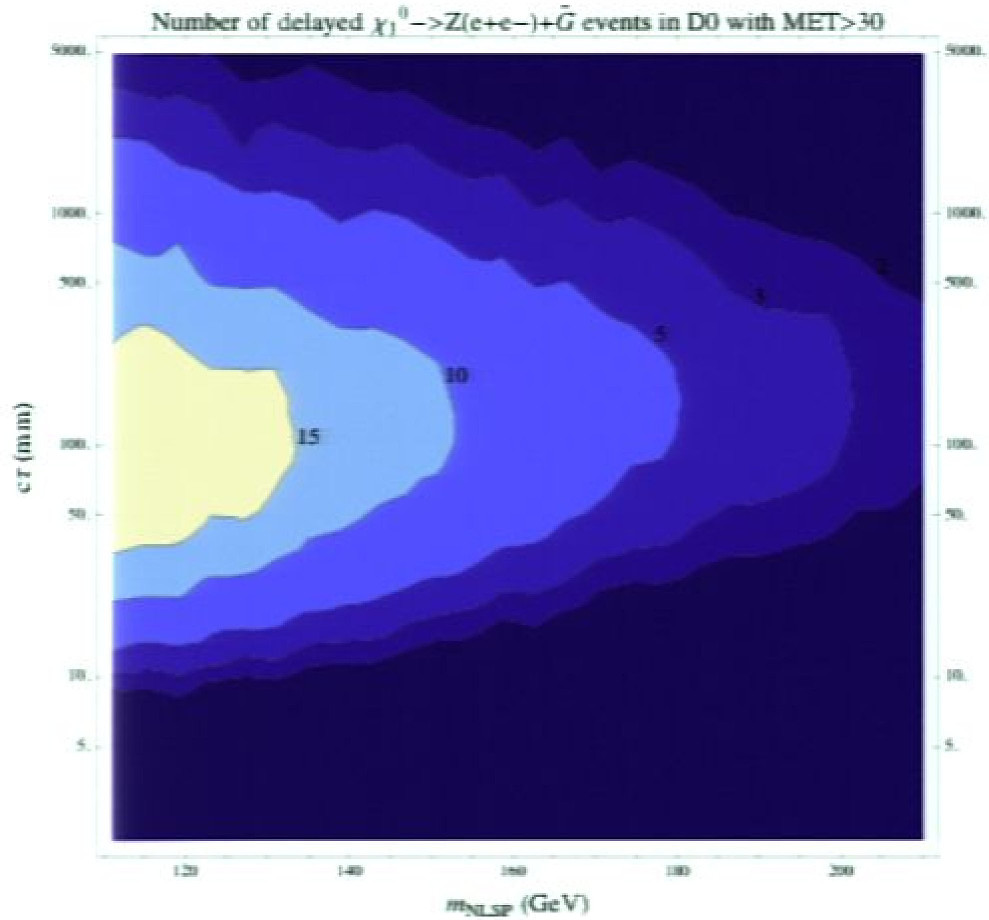


Diphoton Diagnostics



Recent discussions with Matt Strassler and Yuri Gershtein -

D0 Reach: Z to e^+e^-



A simple extension of an existing study (0806.2223)

Conclusions

- General neutralino NLSPs relatively unconstrained.
- Long-lifetime decays to Z bosons can give clean events; possibility of early discovery over a wide range of lifetimes
- With more data, such events would also give very clean kinematic reconstruction
- The next few years will be exciting!

Further Reconstruction

- Once we know the location and time of the NLSP decay, assuming a massless gravitino gives us the full four-vector:

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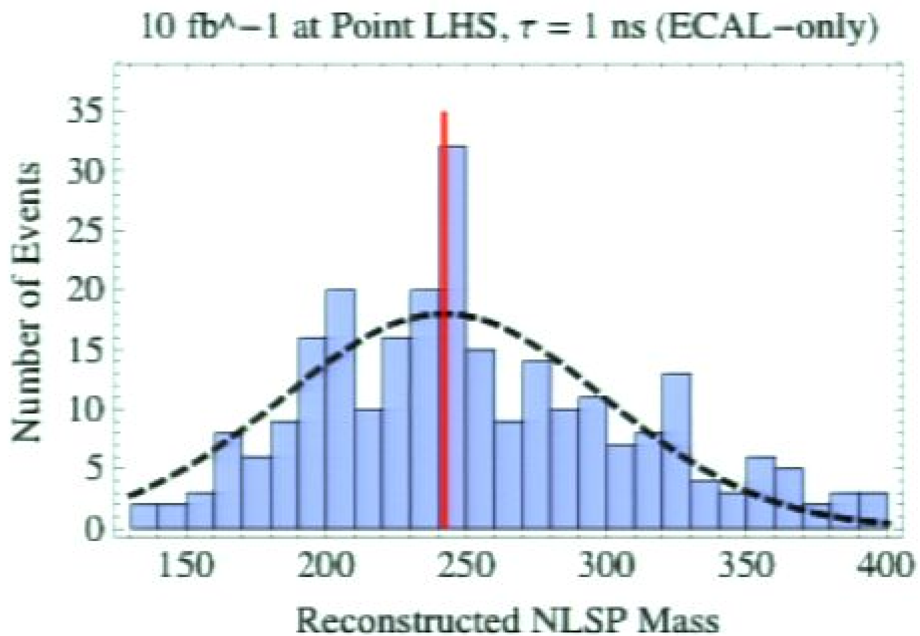

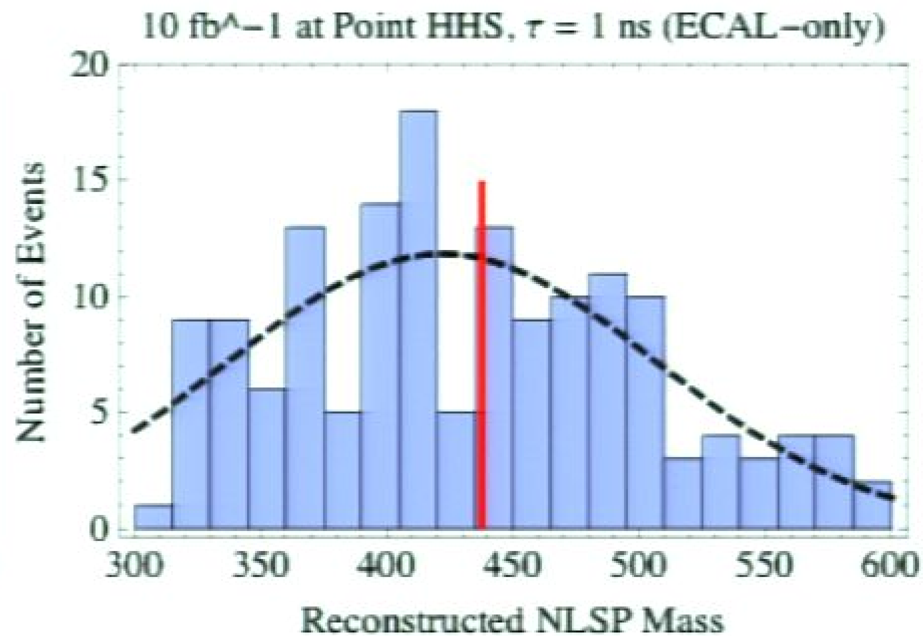

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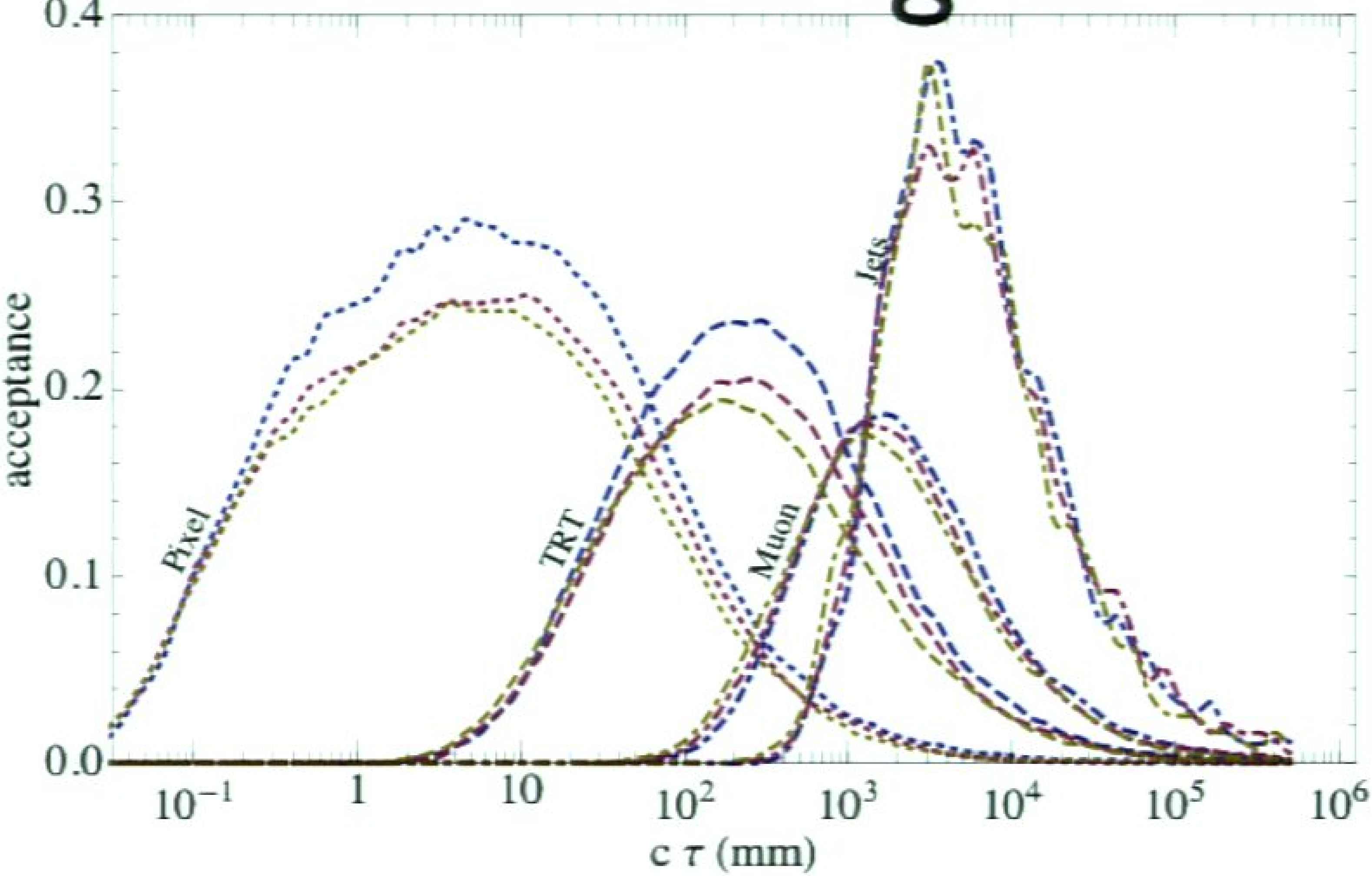

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