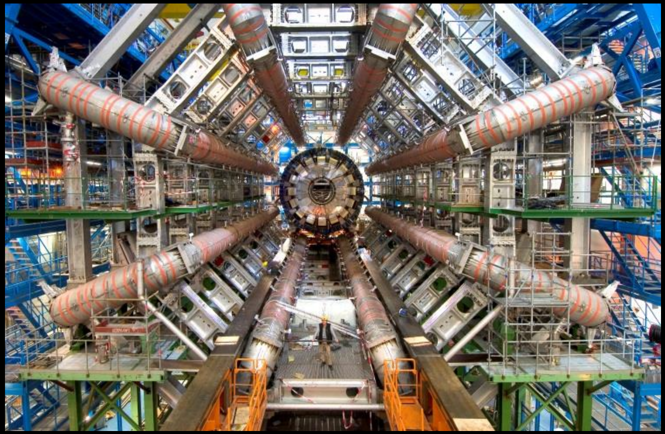
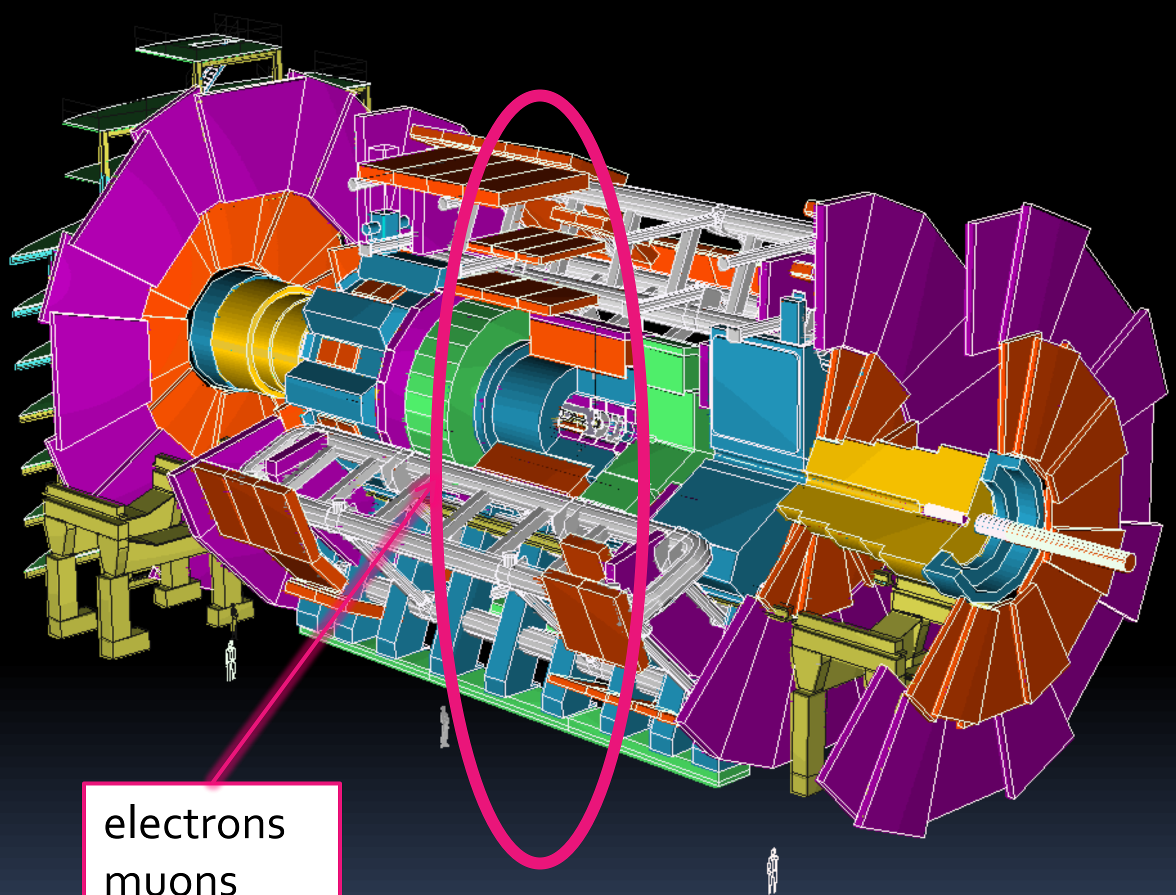


G. Watts (UW/Seattle) on behalf of the ATLAS Collaboration

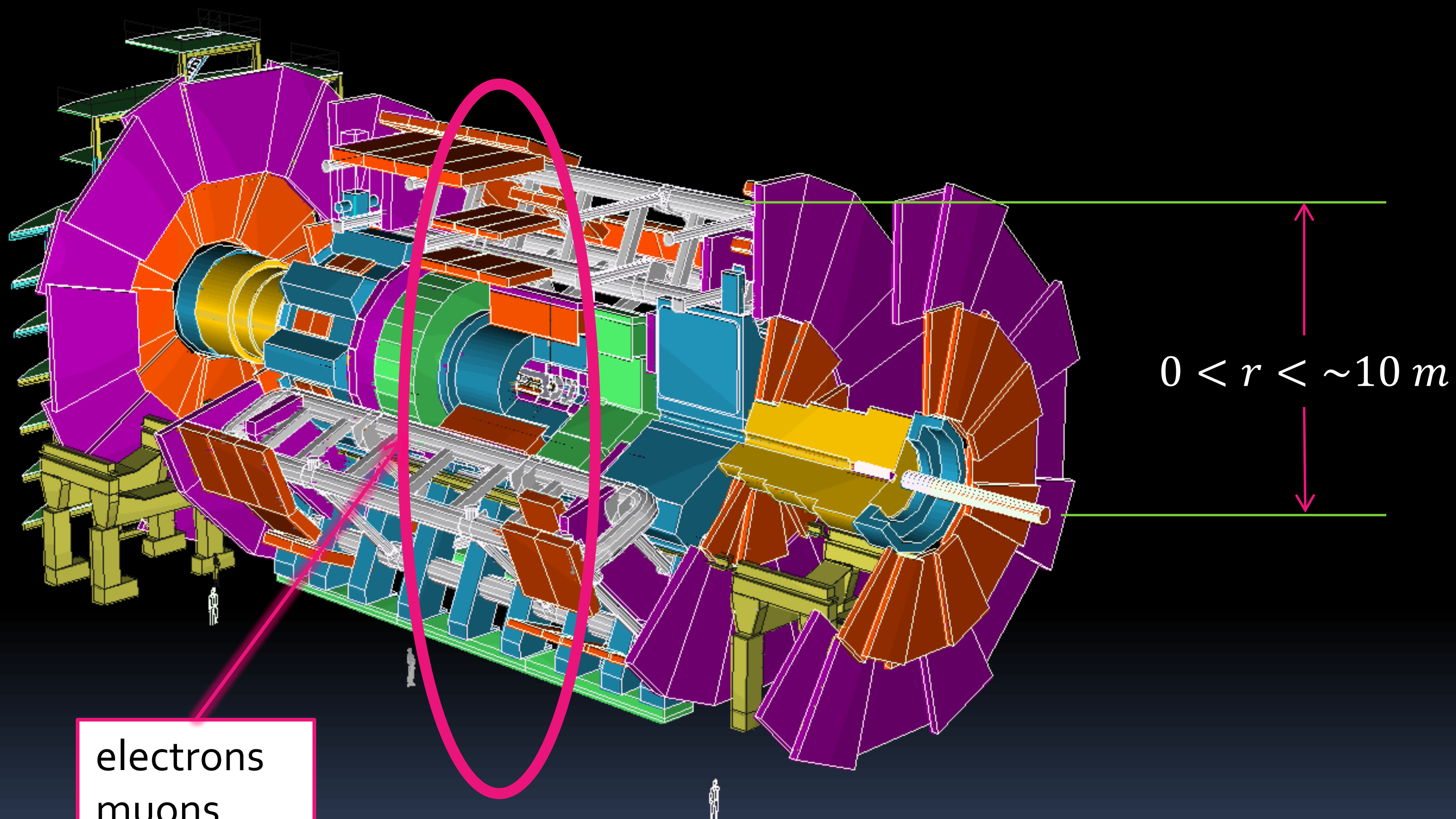
ATLAS – SEARCHES FOR LONG LIVED PARTICLES

long lived particles



electrons
muons
tau's
E_T^{missing}
jets

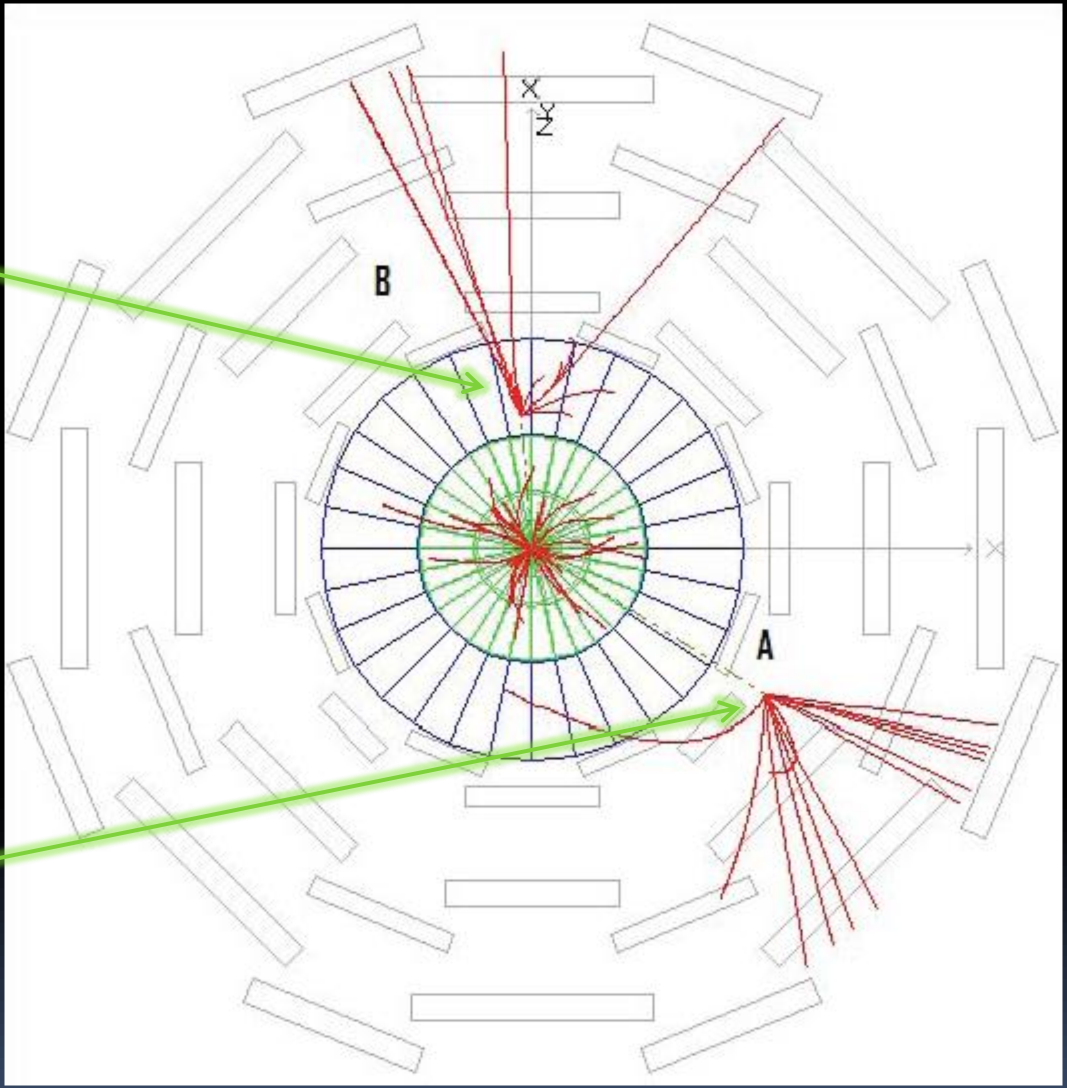
long lived particles



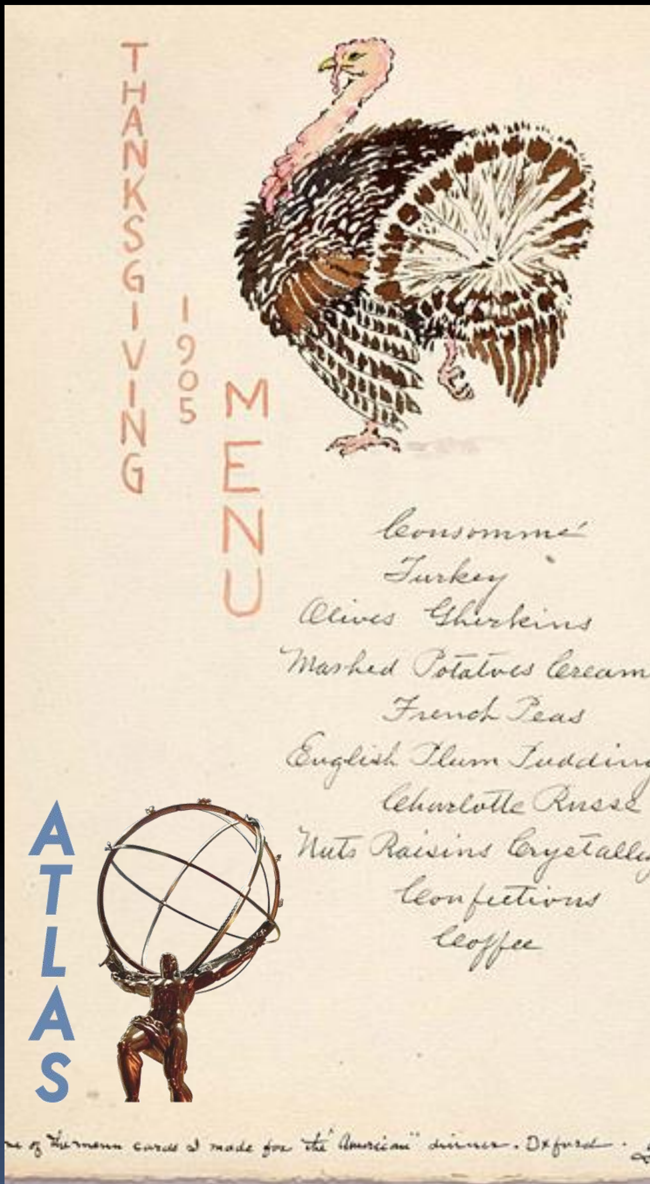
electrons
muons
tau's
$E_T^{missing}$
jets

$E_T^{missing}$ is not a primary signature

calorimeter



muon spectrometer

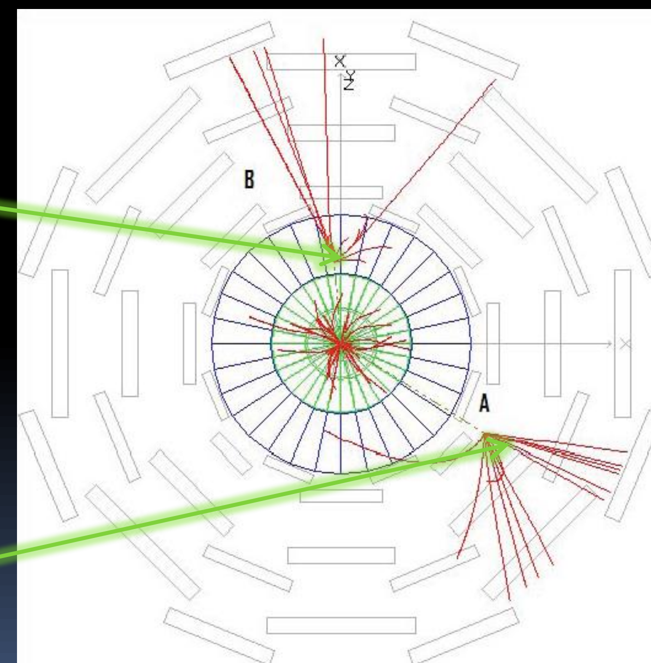


recent analyses

Hidden Valley	Jets appearing late
Charged, Massive Particles	dE/dx
Anomaly-Mediated SUSY Breaking	Truncated Tracks

calorimeter

muon spectrometer



triggering is grim…

getting long lived signatures on tape is tricky

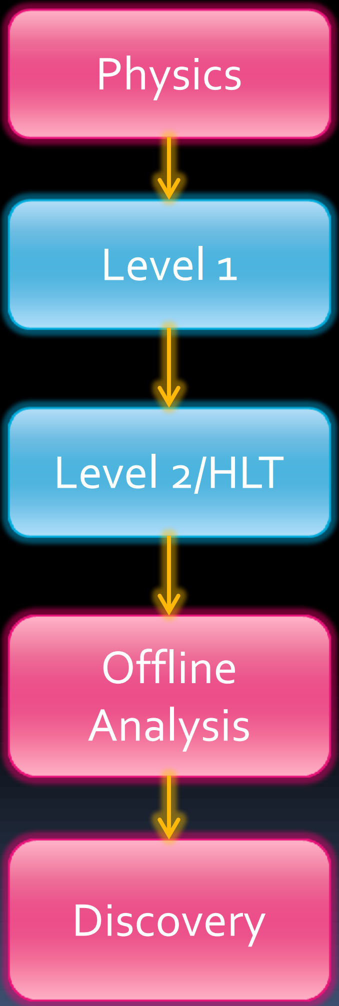
- associated production
- specially designed triggers

specially designed triggers

level 1 is typically hardware – restricted!!
mostly designed at upper levels

Level 2/High level triggers

room for innovation
full event in HLT
some hardware restrictions in Level 2 (ATLAS).



triggering is grim… … and getting grimmer

single medium-p_T objects not an option!

bunch spacing, protons in bunch, beam tunes and focus → your favorite trigger squeezed here ← rate limit driven by $$ disk, cpu, etc.

unprescaled @ end of 2011

em: 1e@22, 2e@12, 1e@12+2e@6, 1γ@80, 2γ@20, 1e@20+$E_T^{miss} > 40$
muon: 1μ@18, 1μ@40sl, 1μ@15+1μ@10, 1μ@15+$E_T^{miss} > 30$
tau: 1τ@125, 1τ@29+1τ@20, 1τ@29+$E_T^{miss} > 35$
jets: 1j@250, 3j@100, 4j@45, 5j@30, 1j@75+$E_T^{miss} > 55$, 1j@100+$H_T > 400$,
4j@40+$H_T > 350$
combo: 1μ@18+1j@10, 1e@5+1μ@6, 1τ@20+1e@15, 1τ@20+1μ@15

offline analysis

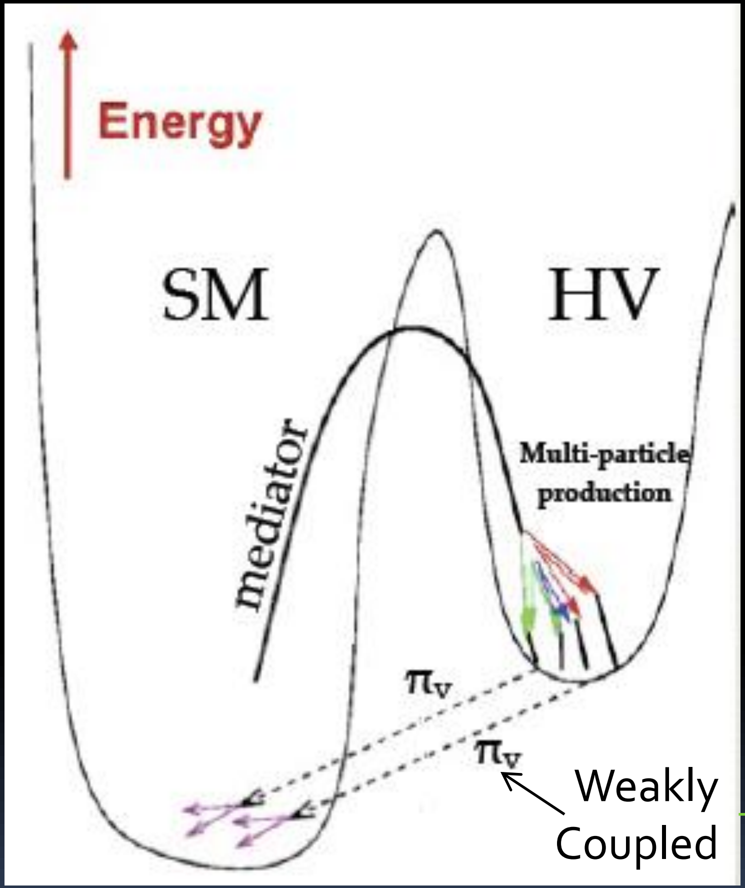
standard analyses

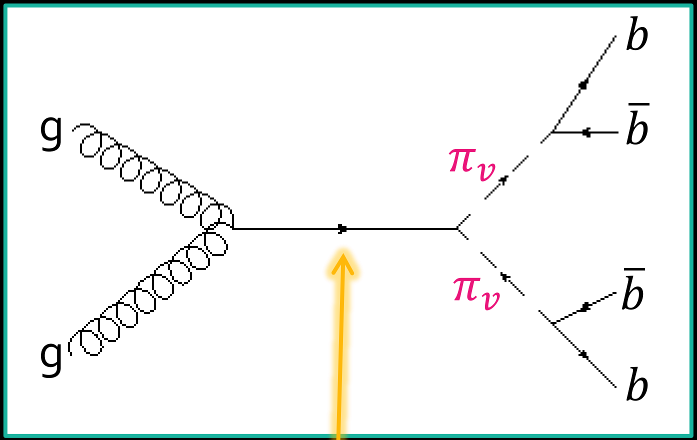
- jets $p_T > 50$ GeV
- electrons $p_T > 10 - 20$ GeV
- muons $p_T > 10 - 20$ GeV
- $E_T^{miss} > 50$ GeV

long-lived searches

- highly ionizing particles
- highly displaced vertices
- kinked tracks
- truncated tracks
- out-of-time energy deposits

hidden valley





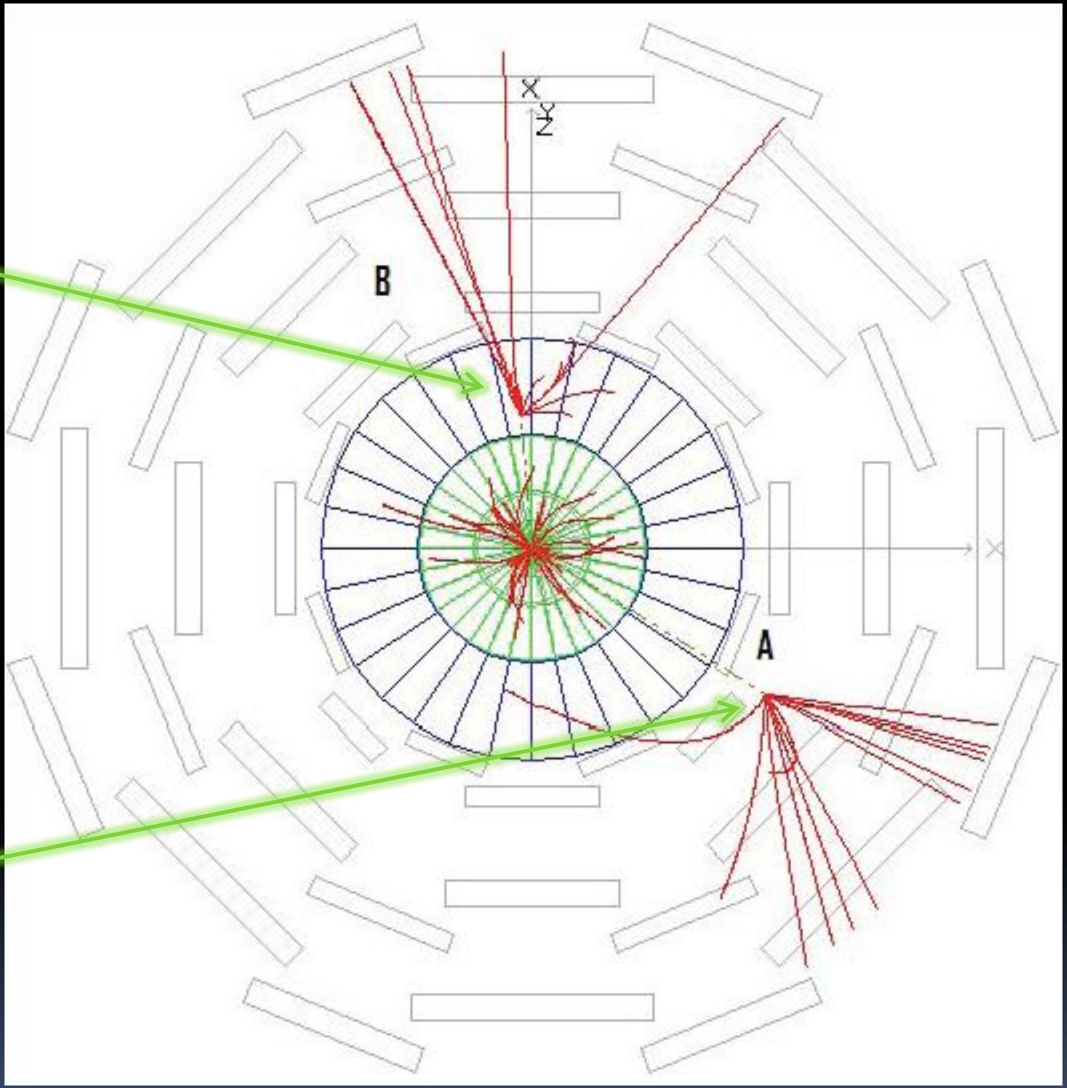
h/h_v mixing
Z/Z_v mixing

the π_v is long lived
it decays *late* in the detector

Phys.Lett.B651:374-379,2007 (M. Strassler, K. Zurek)

calorimeter

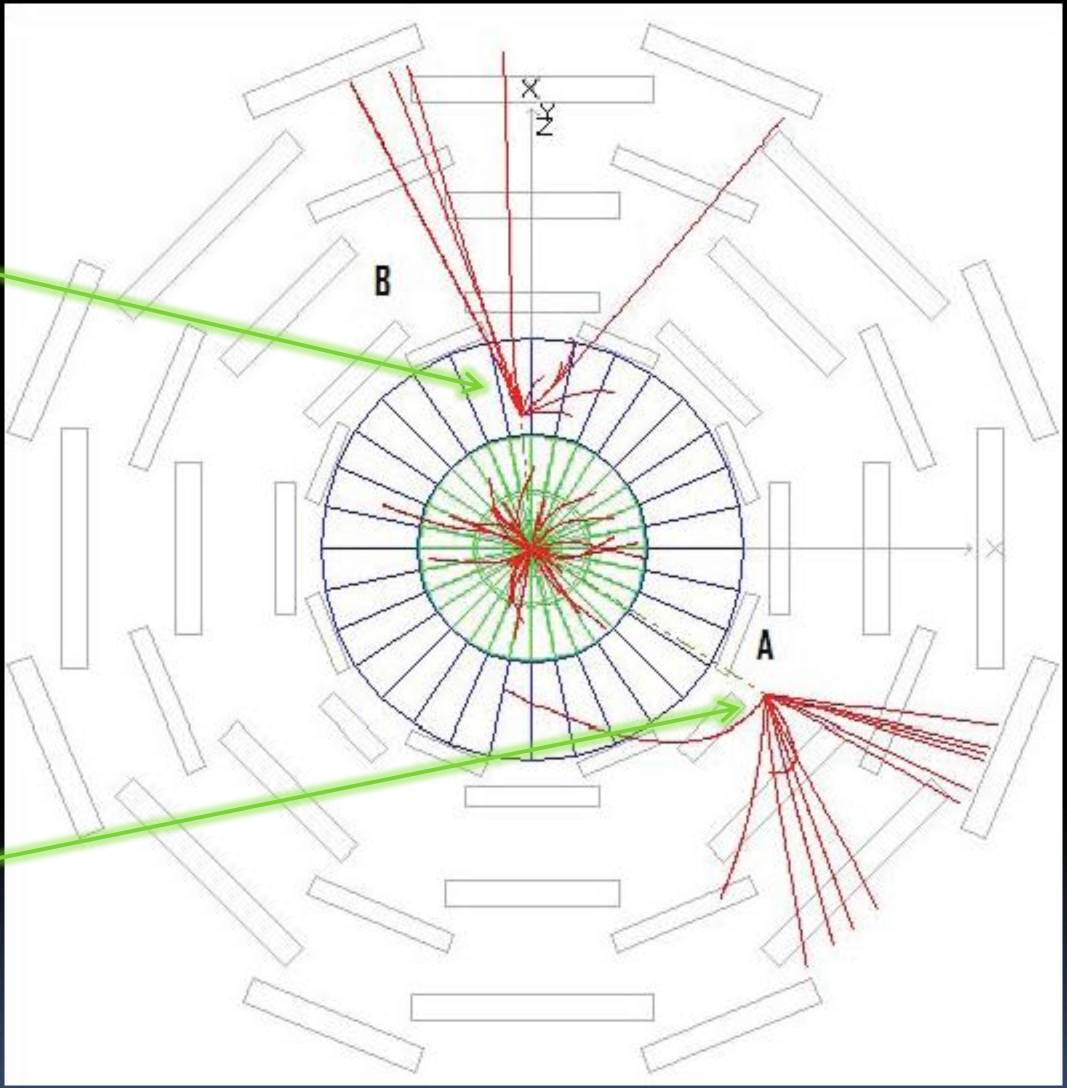
muon spectrometer



calorimeter

Different techniques are required for each section of the detector

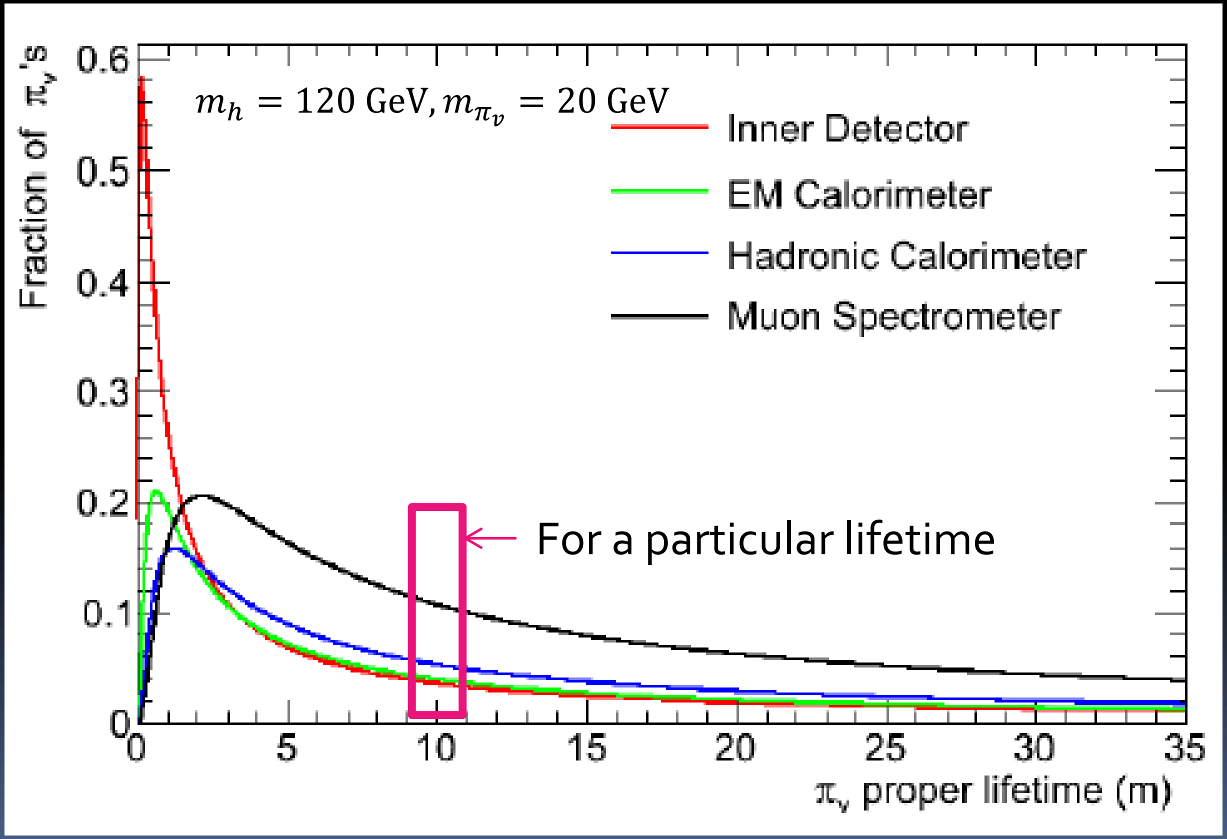
muon spectrometer



the models

$m_h = 120$ GeV, 140 GeV
$m_{\pi_v} = 20$ GeV, 40 GeV

allow proper lifetime ($c\tau$) to vary to give decays through out the detector



long lived particle triggers

b-tagging triggers

- good for a decay a few millimeters from primary vertex
- commissioned
- huge backgrounds from QCD $b\bar{b}$ production

long lived neutral particle triggers

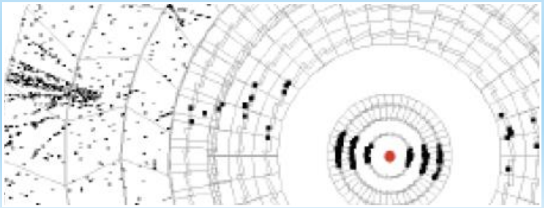
- neutral particle decays mid-detector
- appearance trigger
- run for full 2011 dataset (5 fb^{-1})

3 triggers

trackless jet trigger

- jet $E_T > 35$ GeV
- no tracks with $p_T > 1$ GeV near jet
- *muon spectrometer activity*
- low efficiency

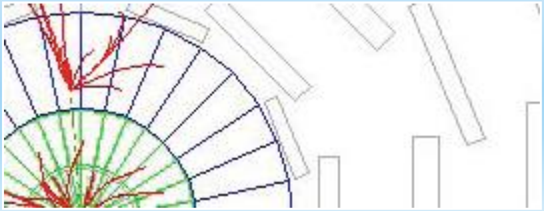
decays late in inner detector



$\log(E_{had}/E_{EM})$

- jet $E_T > 35\ GeV$
- no tracks with $p_T > 1$ GeV near jet
- $\log(E_{had}/E_{EM}) > 1.0$
- very good efficiency

decays beyond the EM calorimeter



muon spectrometer cluster trigger

- three RoI clusters all close by
- no jets
- no tracks
- really very good efficiency

decays beyond the calorimeter

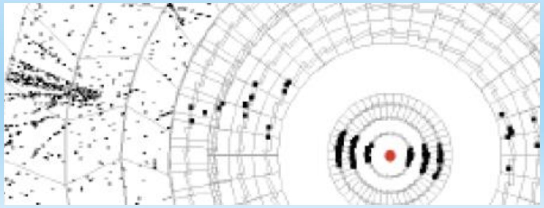
ATL-PHYS-PUB-2009-082

3 triggers

trackless jet trigger

jet $E_T > 35$ GeV
no tracks with $p_T > 1$ GeV near jet
muon spectrometer activity
low efficiency

decays late in inner detector



$\log(E_{had}/E_{EM})$

jet $E_T > 35\ GeV$
no tracks with $p_T > 1$ GeV near jet
$\log(E_{had}/E_{EM}) > 1.0$
very good efficiency

decays beyond the EM calorimeter

muon spectrometer cluster trigger

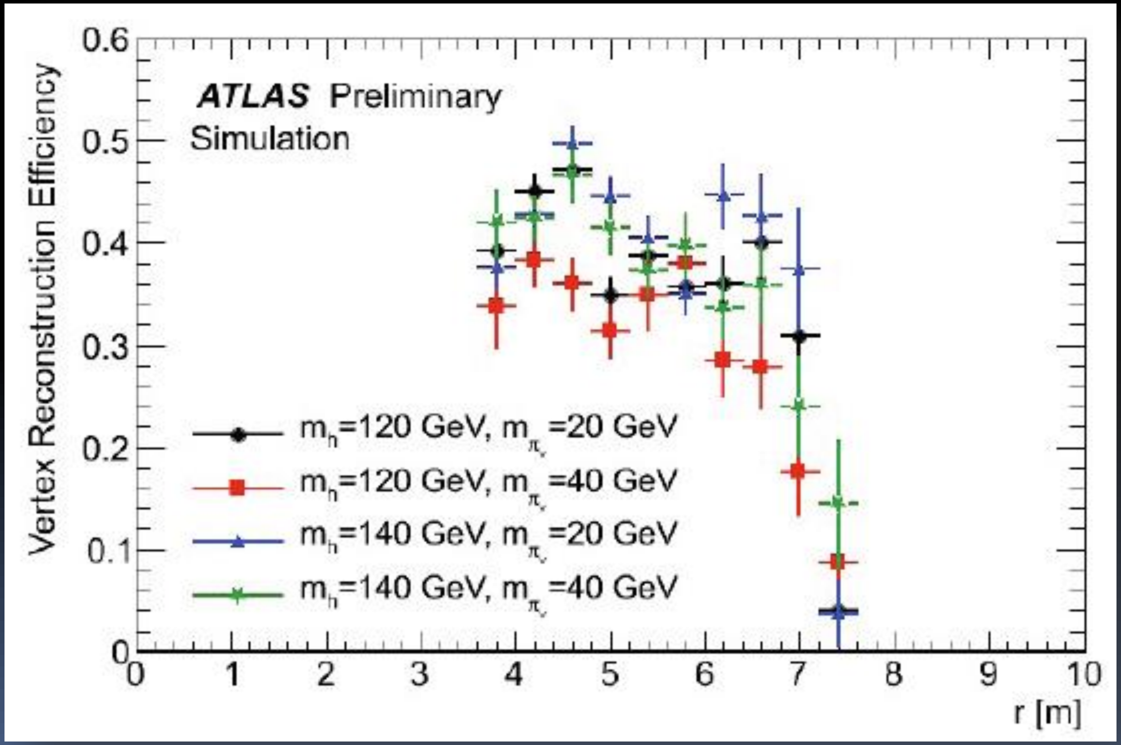
three muon clusters all close by
no jets
no tracks
really very good efficiency

decays beyond the calorimeter

muon spectrometer vertex

The ATLAS muon spectrometer is designed to reconstruct muon tracks stand alone

It can do more than particle ID!



Efficiency x-checked with punch-thru jets

Analysis Strategy

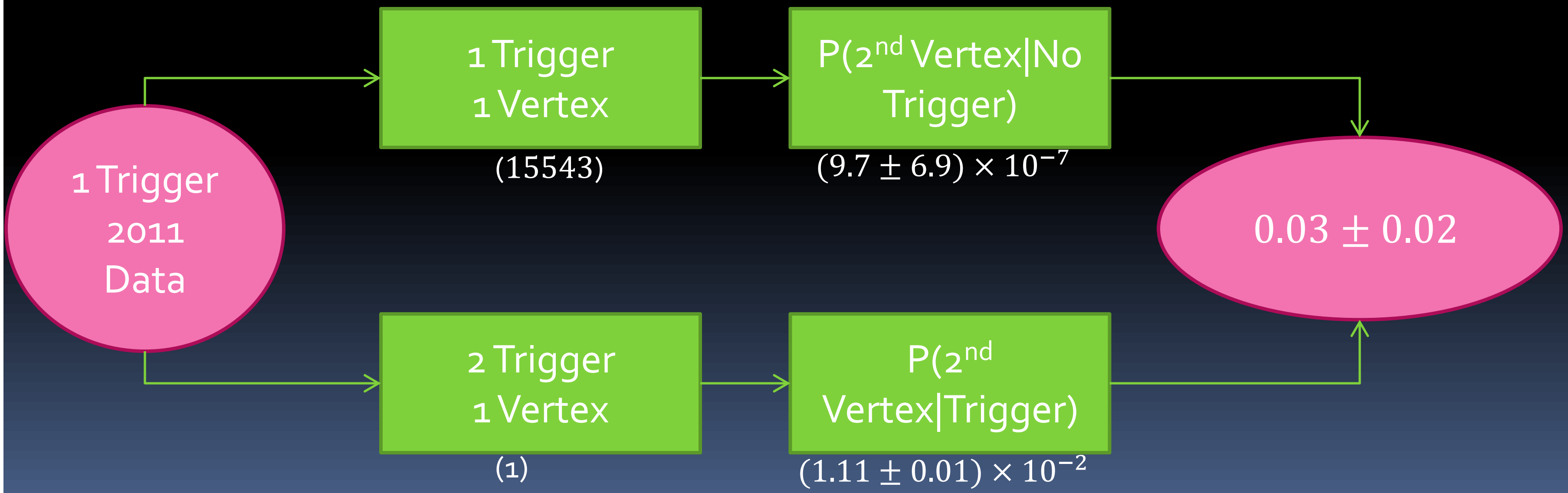
>= 1 Muon Cluster Trigger
2 back-to-back Vertices found in the Muon Spectrometer
No Jet or Track activity near the vertex

$\Delta R(\text{jet, vertex}) \geq 0.7$

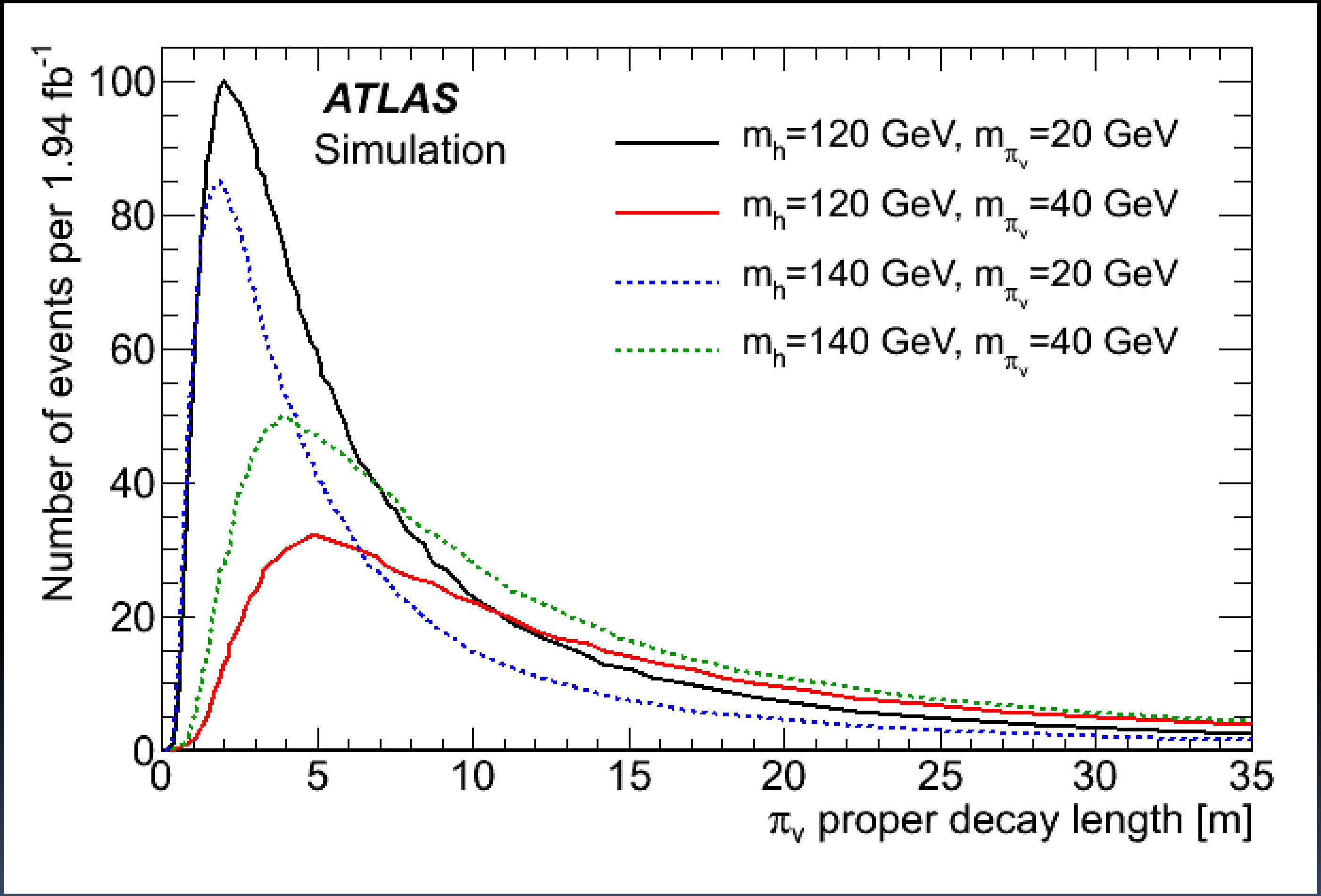
$\Delta \mathrm{R}(5 \text{ GeV Track, vertex}) \geq 0.4$

In **1.94** fb^{-1} of data 0 events seen

Expected Backgrounds:



expected signal

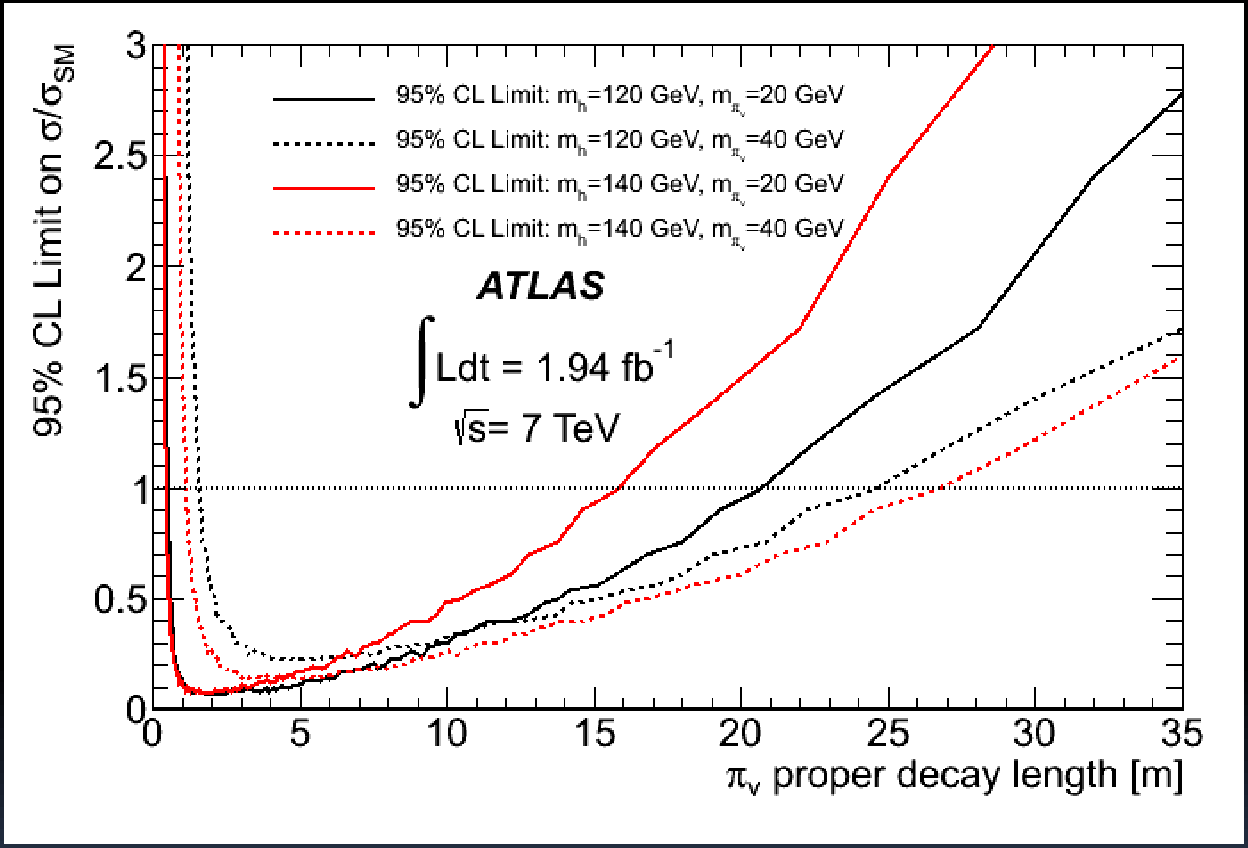


limits

equal systematic error contributions from theory and efficiency verification for our signals.

Quantity	Systematic uncertainty
Higgs cross section	
m_{h^0} = 140 GeV	+18.8% -14.9%
m_{h^0} = 120 GeV	+19.7% -15.1%
RoI cluster trigger	14%
MS vertex (per vertex)	16%
Luminosity	3.7%

Table 7.2: List of the systematic uncertainties.



m_{h^0} (GeV)	m_{π_v} (GeV)	Excluded Region
120	20	$0.50 < c\tau < 20.65$ m
120	40	$1.60 < c\tau < 24.65$ m
140	20	$0.45 < c\tau < 15.8$ m
140	40	$1.10 < c\tau < 26.75$ m

anomaly-mediated SUSY breaking

compressed mass spectra

$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0$ LSP, escapes detector, E_T^{missing}

$\tilde{\chi}_1^{\pm} \rightarrow \pi^{\pm}$ small p_T - perhaps 100 MeV

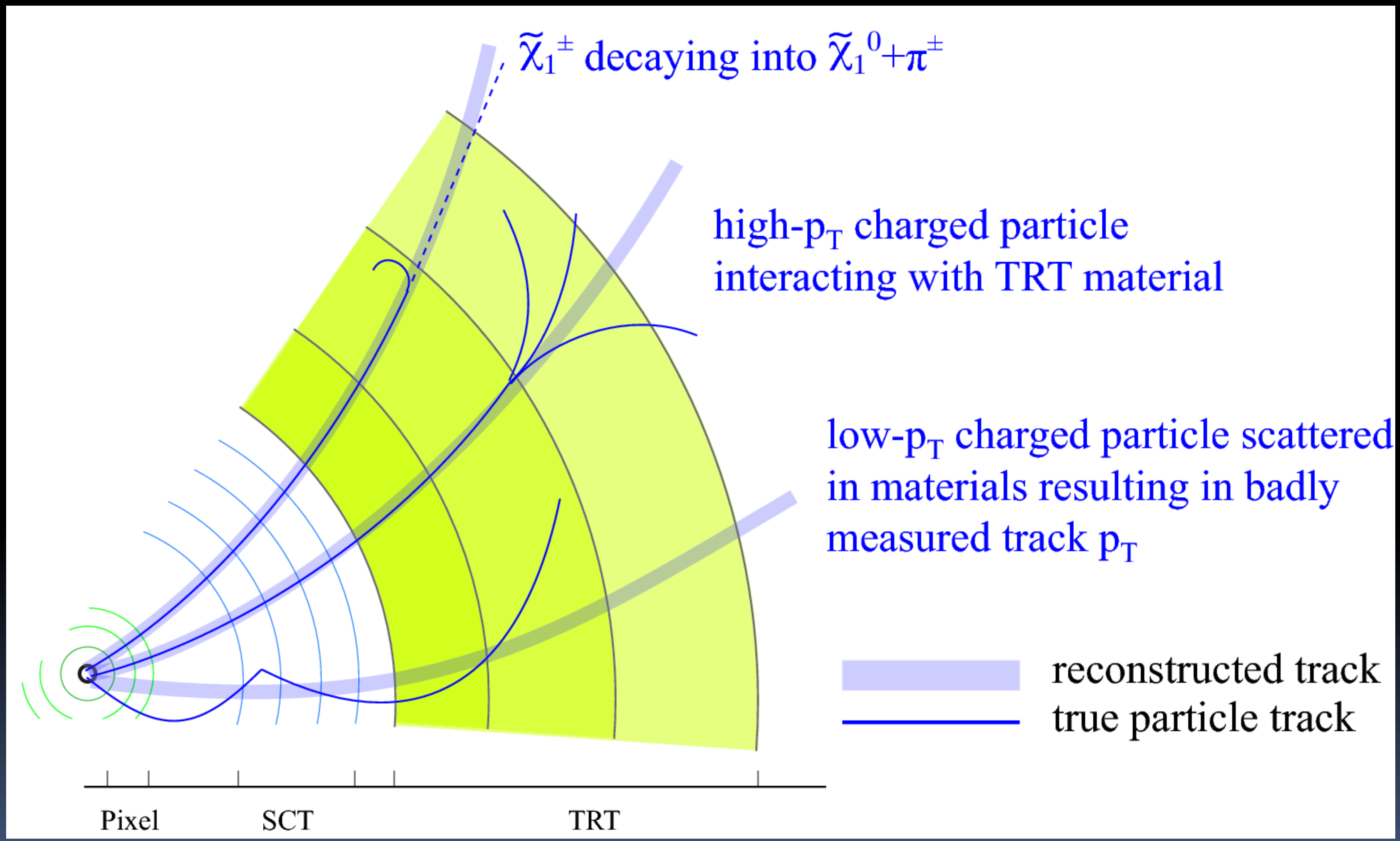
mass differences between $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ is so small it has a long lifetime → analysis is sensitive to decays occurring somewhere in ATLAS inner tracker

Chargino leaves hits in tracker until it decays!

Looked at $m_{\tilde{\chi}_1^{\pm}} = 90.2, 117.8, 147.7$ GeV, BR$(\tilde{\chi}_1^{\pm} \rightarrow \pi^{\pm}\tilde{\chi}_1^0) = 1.0$

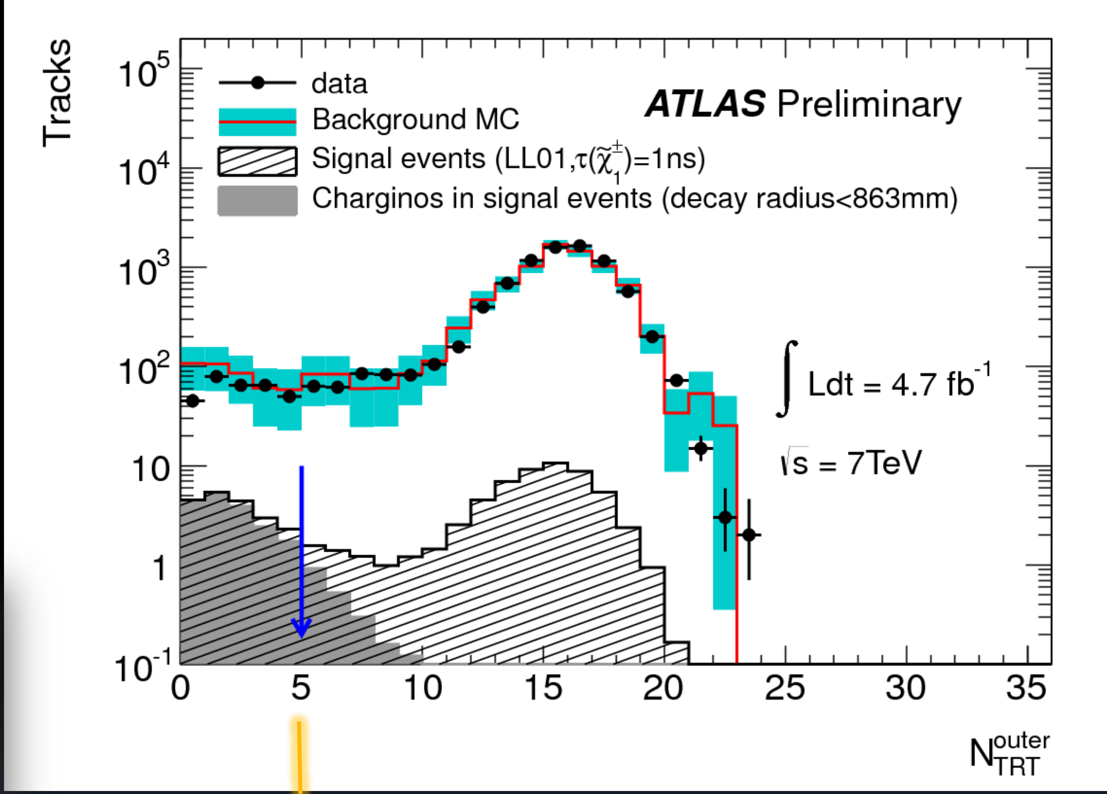
L.Randall,R.Sundrum,Nucl.Phys.B 557,79(1999)
G.F.Giudice,M.A.Luty,H.Murayama,R.Rattazzi,JHEP 12, 027(1998).

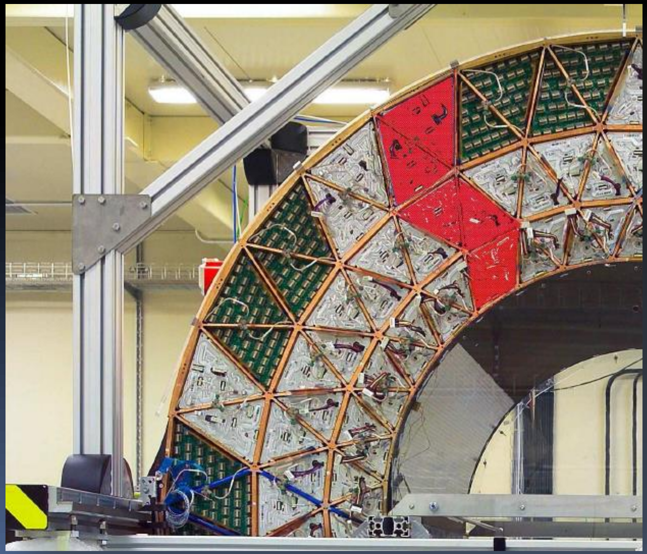
detector signature



transition radiation tracker

- between the silicon strips and the calorimeter
- $0.5\text{m} < r < 1.1\text{ m}$
- average of 15 hits for a charged track in the *outer* TRT (N_{TRT}^{outter})





truncated Tracks have 5 hits or less

normal tracks

the analysis

trigger

1 jet, $p_T > 75$ GeV
$E_T^{\text{missing}} > 55$ GeV

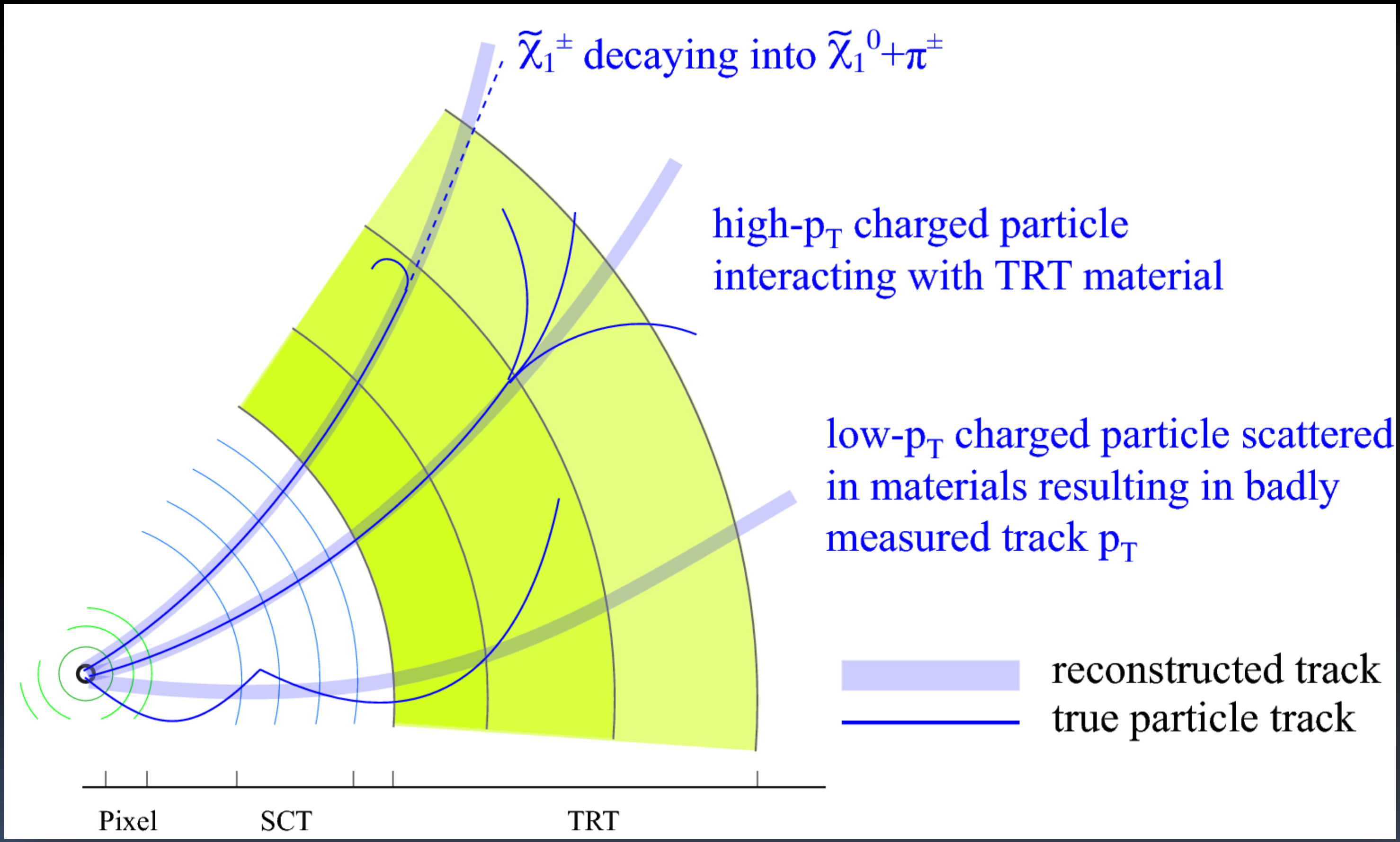
offline

3 jets, $p_T > 130, 60, 60$ GeV
$E_T^{\text{missing}} > 130$ GeV
lepton veto
track: well measured, $\Delta R(\text{track}, \mathrm{p_T} > 0.5\text{ GeV}) > 0.1$, $p_T > 10\ GeV$
less than 5 hits in the TRT

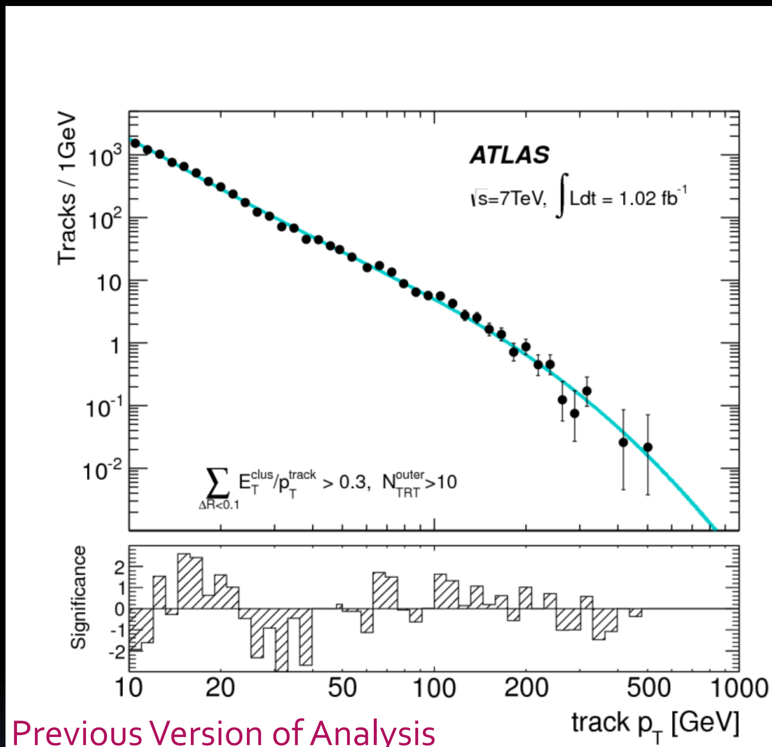
the shape of the track p_T spectra differentiates signal and backgrounds

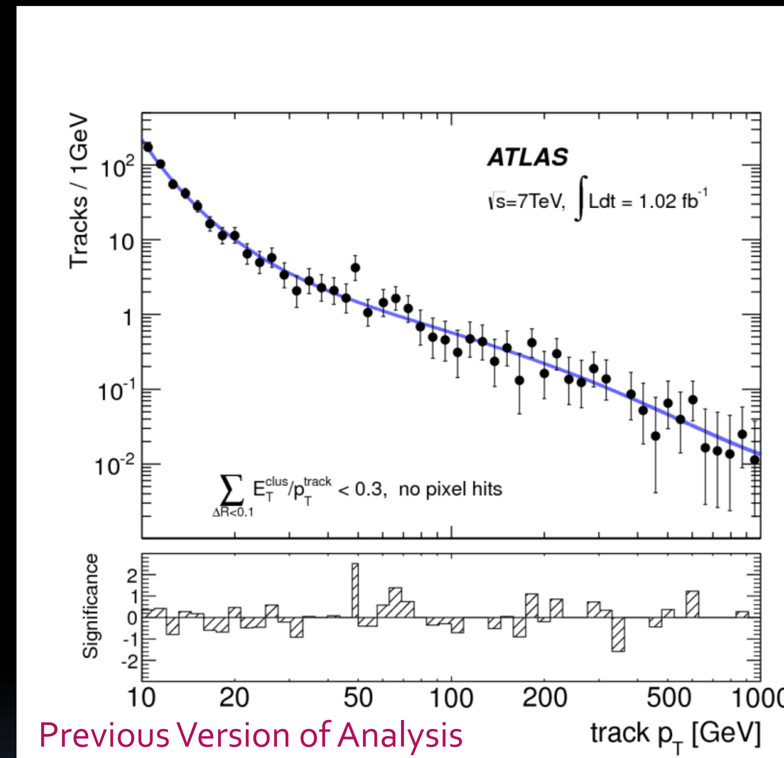
304 events remain in 4.7 fb^{-1} of data
optimized for $514 < r < 863$ mm

backgrounds



background track p_T shapes





shape for high p_T tracks that interact

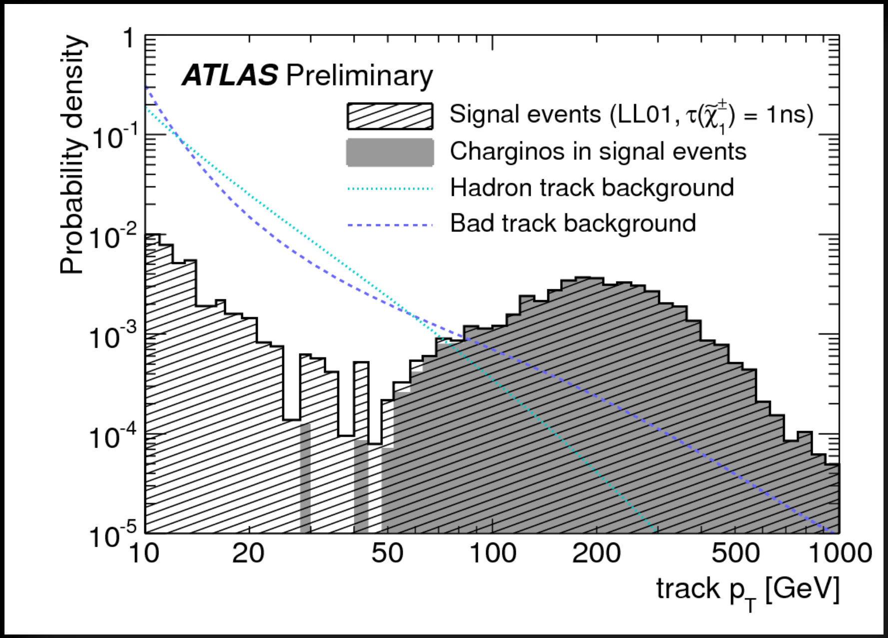
select tracks with $N_{TRT}^{outter} > 10$.

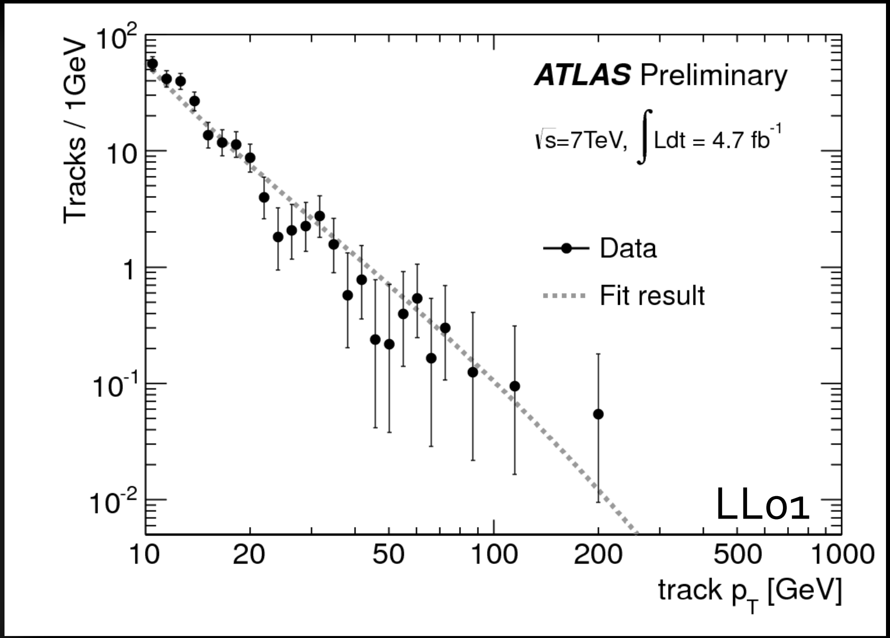
shape for mismeasured low p_T tracks

require $E_T^{\text{missing}} < 100$ GeV

no pixel hits

fit track p_T shape





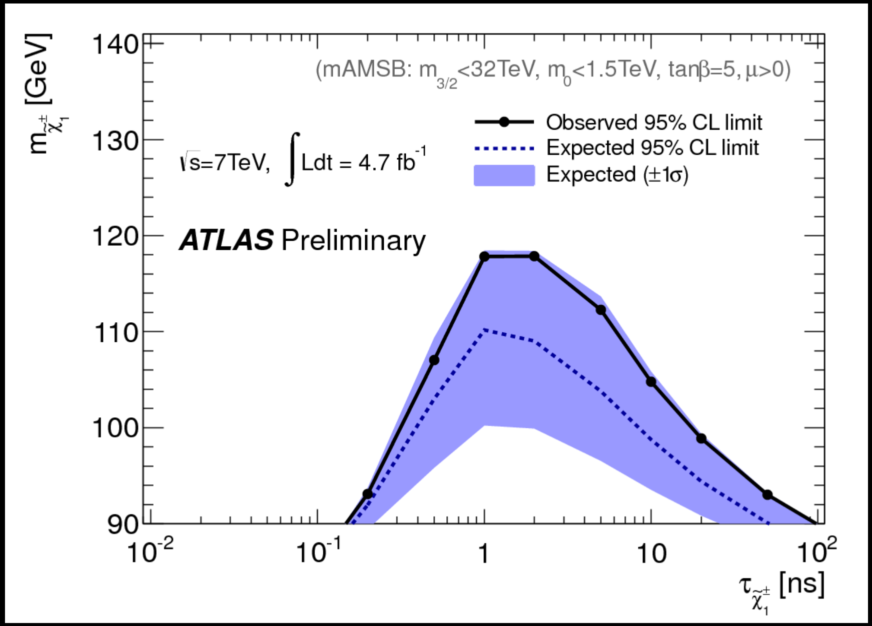
the 3 templates are fit to data:

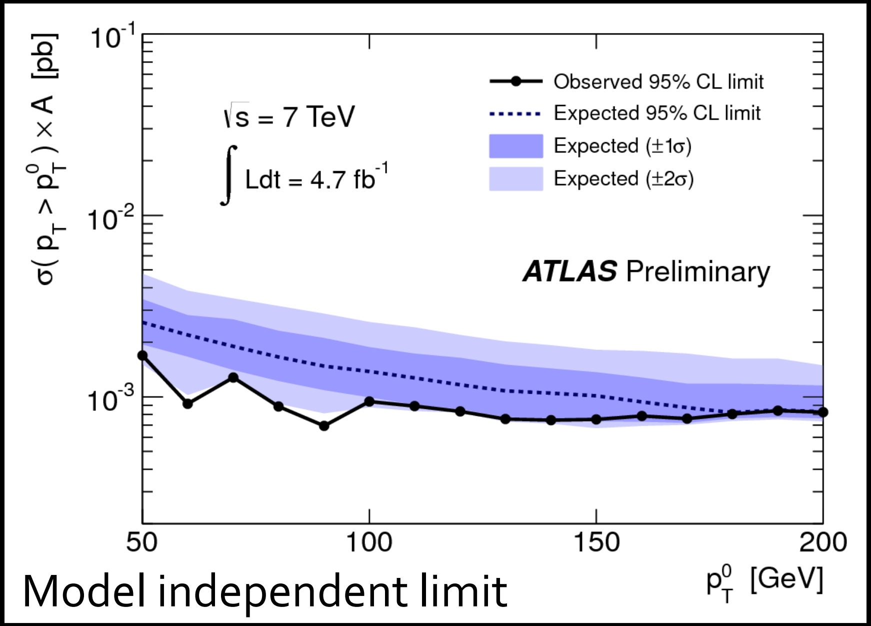
- the two background templates are fit for $p_T > 10$ GeV
- the signal template is included in the fit for $p_T > 50$ GeV

data and background fit
best fit has zero contribution from signal template

Fit prefers zero signal contribution!

limits





limit for the mass

previous LEP2 limit: $m_{\chi_0^\pm} > 92$ GeV

limit on production of truncated tracks

primary uncertainty is the theoretical cross section (27%)

backgrounds are data driven and so have very small uncertainty

ATLAS-CONF-2012-034 (Submitted EPJC)

massive & long lived

Travel *slowly* through the detector ($\beta \ll 1$)
Lifetime makes them stable w.r.t. the ATLAS detector.

Two good handles to look for this sort of signal:

Time-of-Flight

TileCal can measure timing
Previous version of this analysis used this techniqe
Model dependence on interaction of R-Hadrons with TileCal material
Skipped for this version of the analysis

Mass (dE/dx)

Pixel detector fires if > $3100e^{-}$ deposited
Measures time-above-threshold
Timer maximum is equivalent to about 8.5 MIPS for a track perpendicular to the pixel detector

A MIP is ~ 20Ke

Use Bethe-Block to infer mass

R-Hadron models

Generic model

SUSY, but the LSP is colored

→ hadronizes into colored hadrons

$\tilde{g}g$, $\tilde{g}q\bar{q}$, $\tilde{g}qqq$, $\tilde{q}\bar{q}$, $\tilde{q}qq$, etc.

R-Hadrons ← "they carry one unit of R-Parity"

the R-Hadron will, unlike a normal neutral LSP, have interactions in the ATLAS detector!

three models are used (regge, generic, and "intermediate")
the generic is used for limits, the other models are taken as a systematic error

G.R.Farrar, P.Fayet, Phys.Lett. B76 (1978)575–579.

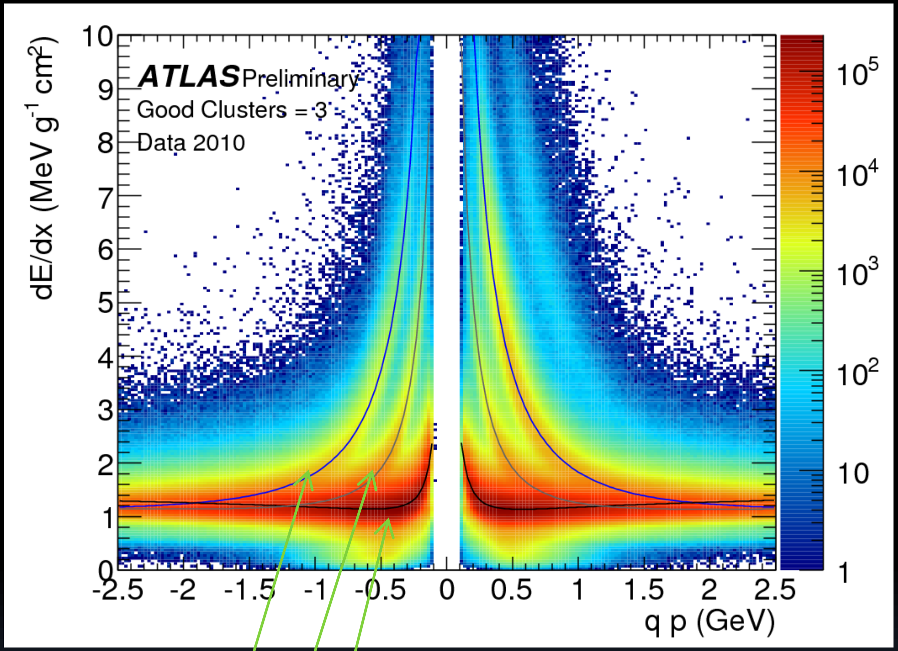
backup: model details

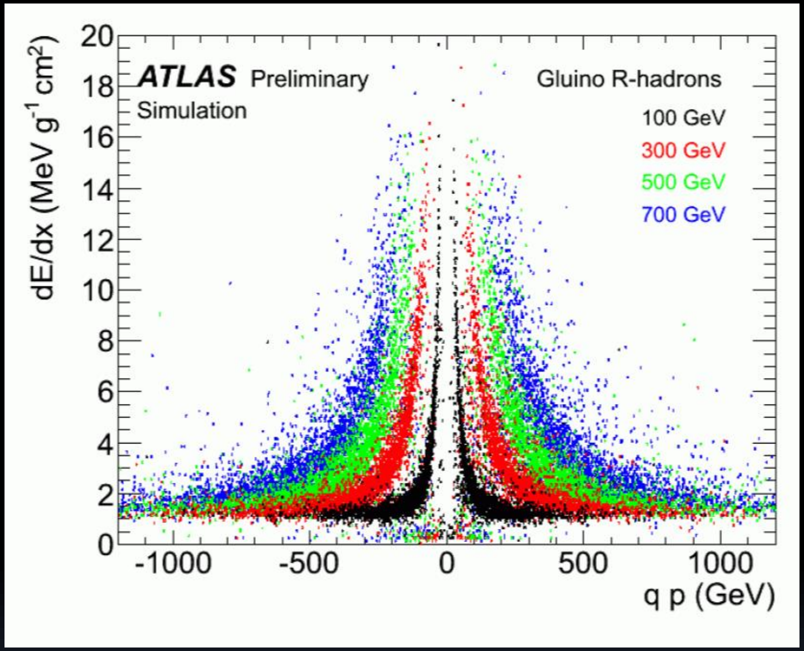
The first model assumes that *R*-hadrons containing gluinos are simulated according to [19]. This model employs a triple-Regge formalism to describe hadronic scattering, and will henceforth be referred to as *Regge*.

The second physics model described in [30, 31] and hereafter referred to as *generic* has been used in other publications [32–34] and it imposes few constraints on allowed stable states. Doubly charged *R*-hadrons and a wide variety of "charge reversal" signatures in the detector are possible. Hadronic scattering is described through a purely phase space driven approach.

More recent models for the hadronic scattering of gluino *R*-hadrons predict that the majority of all produced *R*-hadrons will be electrically neutral after just a few hadronic interactions. The third model belongs to this family, is based on the bag-model calculations presented in [35] and is referred to as *intermediate*.

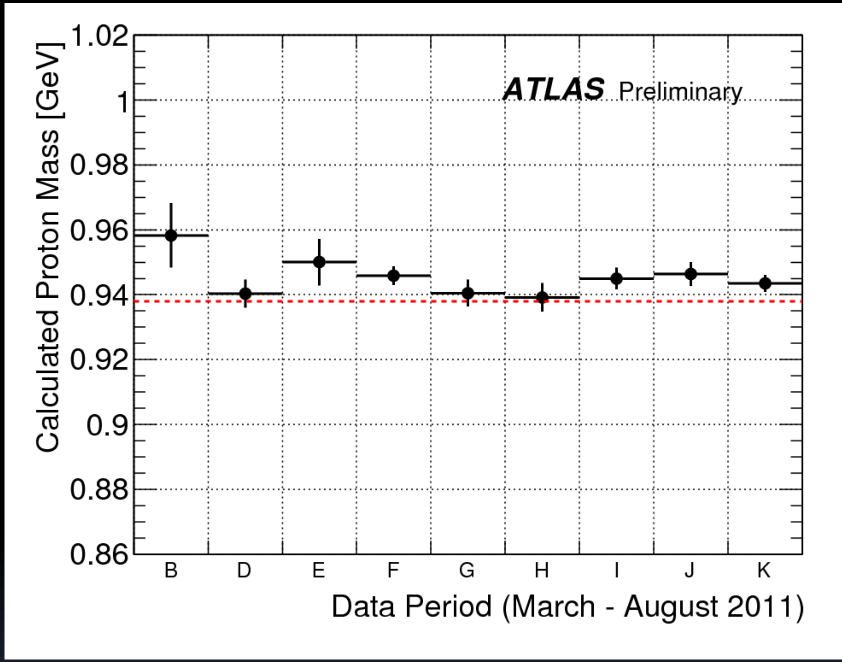
dE/dx

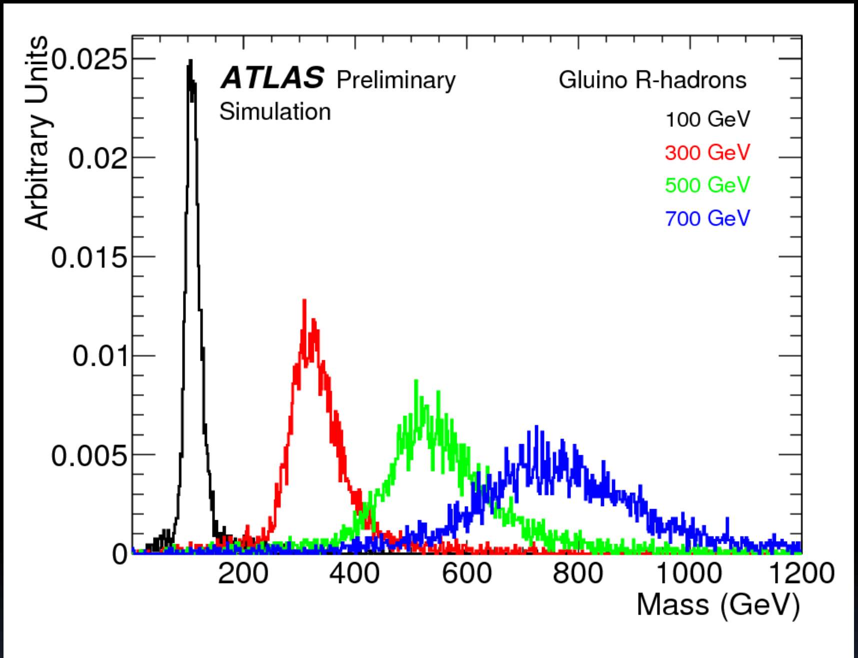

ATLAS Preliminary
Good Clusters = 3
Data 2010
dE/dx (MeV g^{-1} cm^2)
q p (GeV)
-2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5
0 1 2 3 4 5 6 7 8 9 10
1 10 10^2 10^3 10^4 10^5


ATLAS Preliminary
Simulation
Gluino R-hadrons
100 GeV
300 GeV
500 GeV
700 GeV
dE/dx (MeV g^{-1} cm^2)
q p (GeV)
-1000 -500 0 500 1000
0 2 4 6 8 10 12 14 16 18 20

p, K, π

mass resolution





analysis

trigger

no dE/dx information available

MIP in Calorimeter means E_T^{missing}

$E_T^{\text{missing}} > 70$ GeV

20% efficient

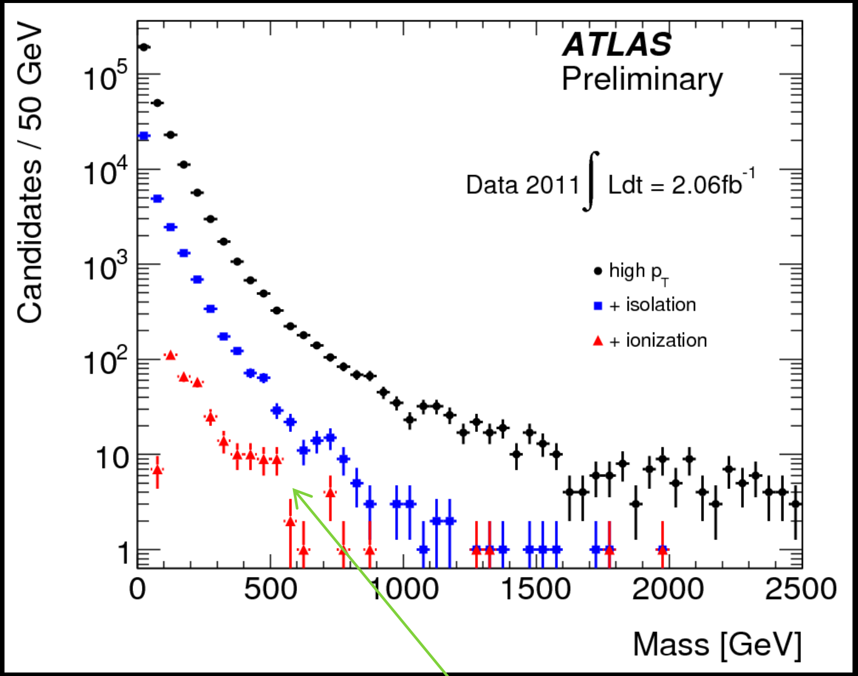
offline

$E_T^{\text{missing}} > 85$ GeV

isolated track $p_T > 50\ GeV, p > 100$ GeV

$\Delta R(\text{track}, p_T > 5\ GeV\ \text{track}) > 0.25$

dE/dx cut depends on η.



333 events left over in 2.1 fb^{-1} data

data driven background

apply all cuts except for the dE/dx cut

→ expected background η and p distributions

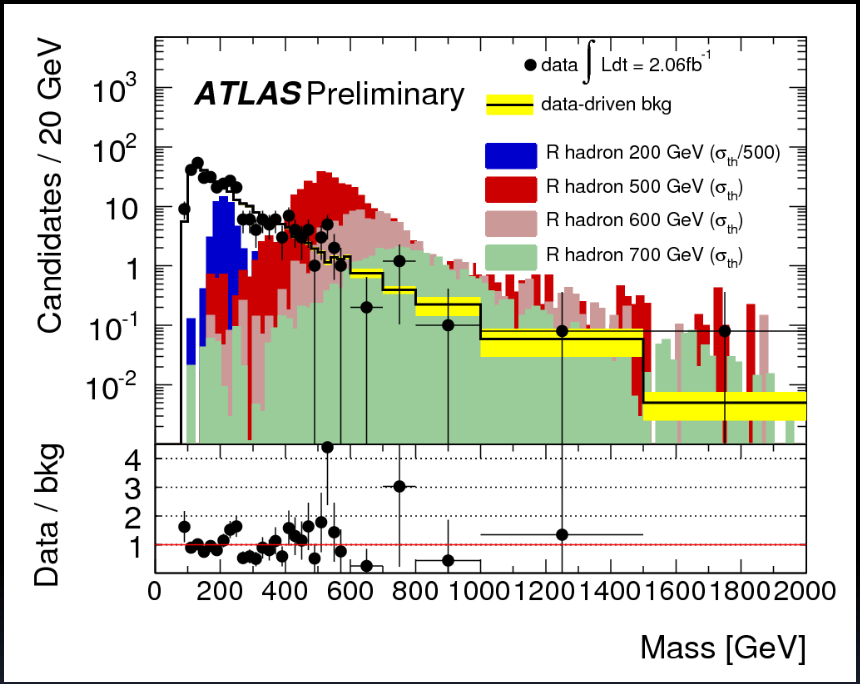
all tracks with $p < 100$ GeV

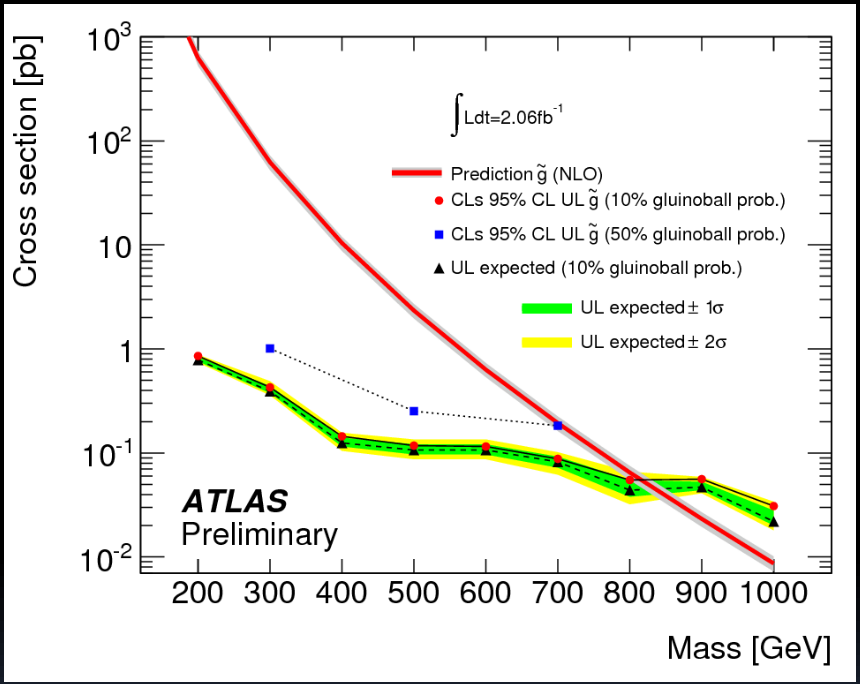
→ expected background dE/dx distributions

randomly sample $p, \eta, dE/dx$ from these distributions

normalize to data in low mass region before dE/dx cut

results

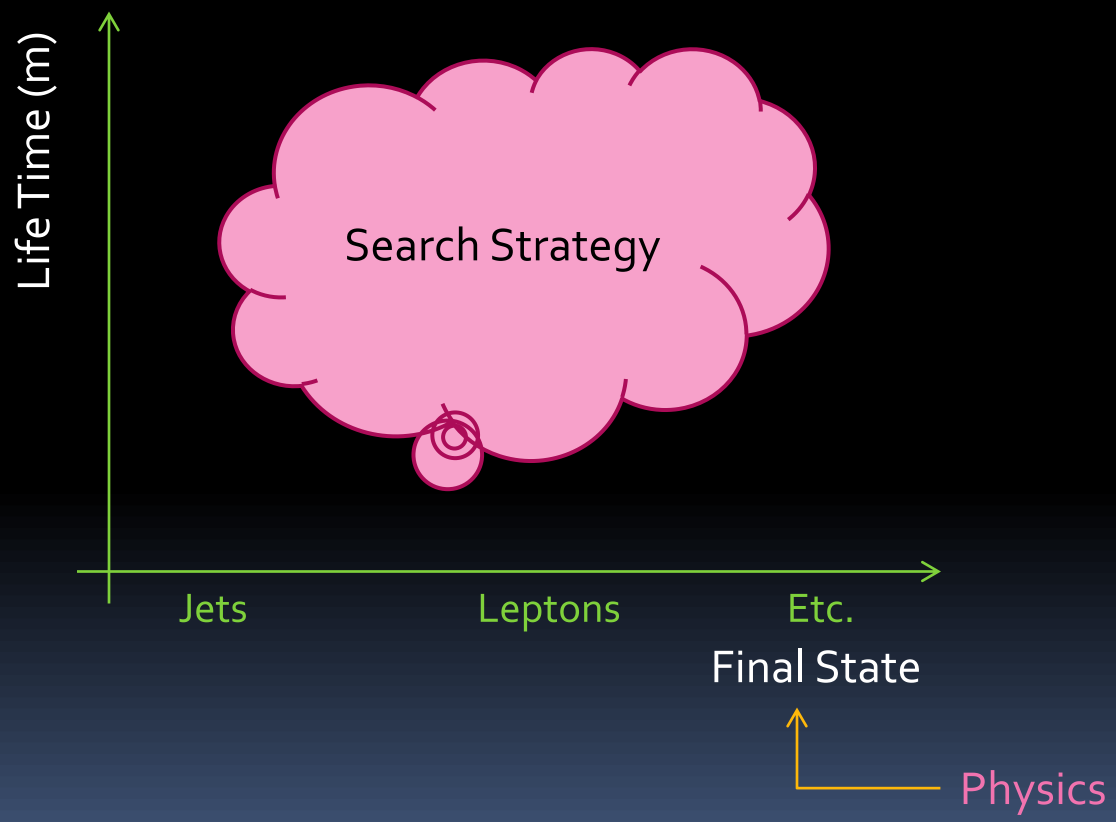

ATLAS Preliminary
data ∫ Ldt = 2.06fb-1
data-driven bkg
R hadron 200 GeV (σth/500)
R hadron 500 GeV (σth)
R hadron 600 GeV (σth)
R hadron 700 GeV (σth)
Candidates / 20 GeV
Data / bkg
Mass [GeV]


∫Ldt=2.06fb-1
Prediction g̃ (NLO)
CLs 95% CL UL g̃ (10% gluinoball prob.)
CLs 95% CL UL g̃ (50% gluinoball prob.)
UL expected (10% gluinoball prob.)
UL expected ± 1σ
UL expected ± 2σ
ATLAS
Preliminary
Cross section [pb]
Mass [GeV]

analyses on 2010 data

Analysis	
stopped gluinos	Particles come to rest in the ATLAS detector volume, and decay out-of-time. (1201.5595, submitted to EPJC)
displaced vertices	R-parity violating SUSY. Displaced vertices with $r > 4$ mm. Shown yesterday
R-Hadron	Neutral R-hadron becomes charged in calorimeter and leaves track in muon system (1103.1984, PLB 701 (2011) 1)
HIP search	Massive long lived highly ionizing particles with large electric charge (q-balls, stable micro black holes, etc.). Energy loss in calorimeter and tracker used (arxiv:1102.0459; PLB698:353-370,2011)

Search Strategies



conclusions

- three analyses presented
  - Hidden Valley search, AMSB search, R-hadron search
- new triggering algorithms required
  - appearance triggers
  - unlikely possible to design new triggers for this run, but…
- non standard object ID
  - late appearance of jets, truncated tracks, out-of-time energy, displaced vertices
- improving algorithms all the time
  - pile-up is improving too…
- lots of information from the these detectors!!
  - how else can we combine this information to search for new things!?

BACKUP

stable, charged (μ-based)

electrically charged by the time they leave the calorimeter

GMSB SUSY

- charged, long lived particles
- colored, but interact in calorimeter leading to a spray of charged particles in the muon spectrometer

L=37 pb^{-1}

trigger is the muon drift tube

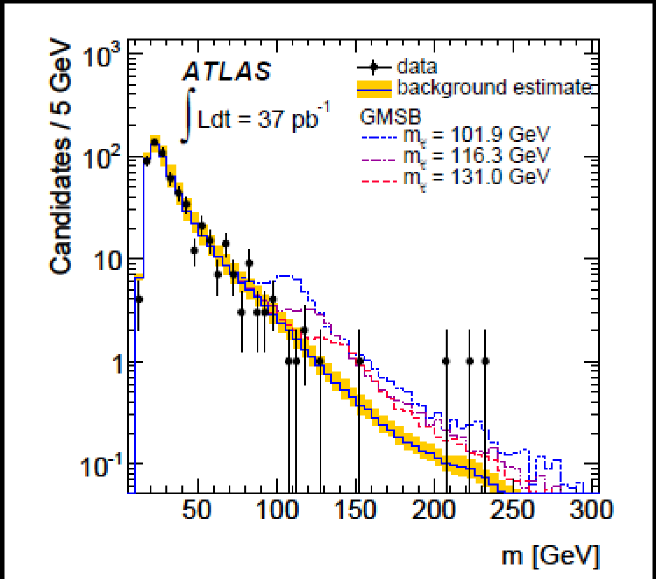
reconstruction method 1:

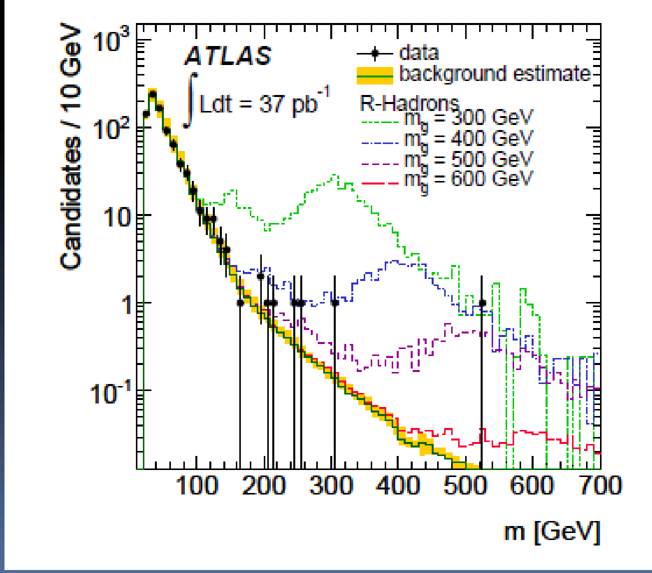
- fit inner detector track to imperfect muon spectrometer segments
- take into account β which alters drift time
- sub-par muon spectrometer segments also used

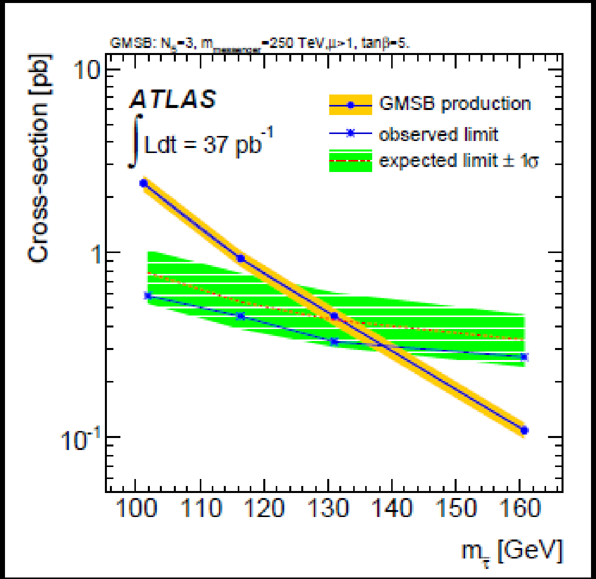
reconstruction method 2:

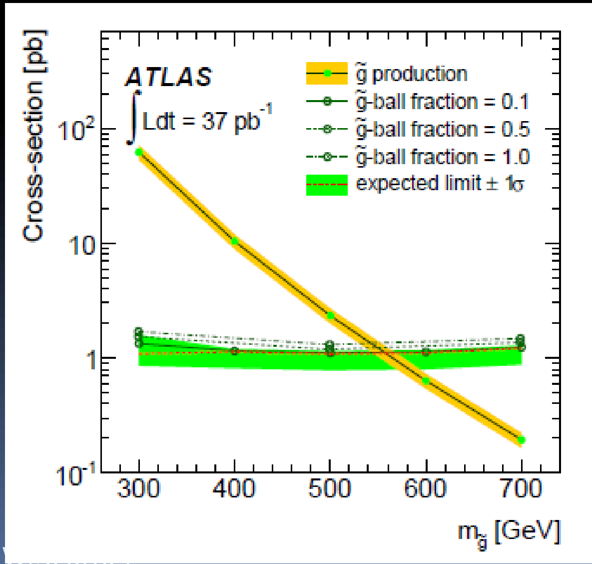
- muon spectrometer based only
- segment reconstruction starts from trigger information
- efficiency is not great for low β.

Stable, charged (μ-based)





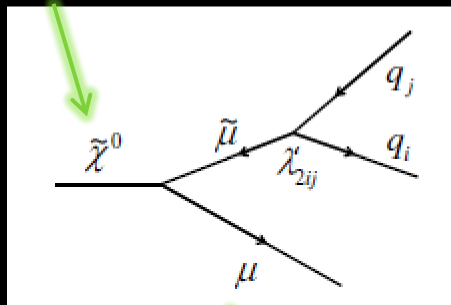




scale [2]. Additional scenarios allowing for such a signature include split-supersymmetry [3], hidden-valley [4], dark-sector gauge bosons [5], stealth supersymmetry [6], or a meta-stable supersymmetry-breaking sector [7].

displaced vertices

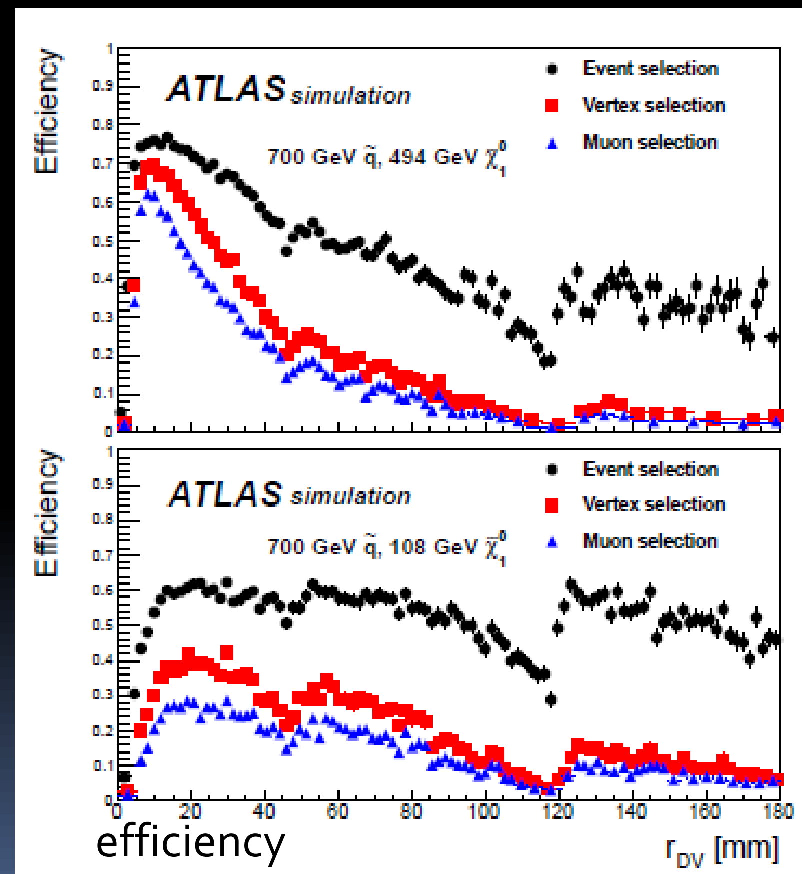
displaced vertex



trigger

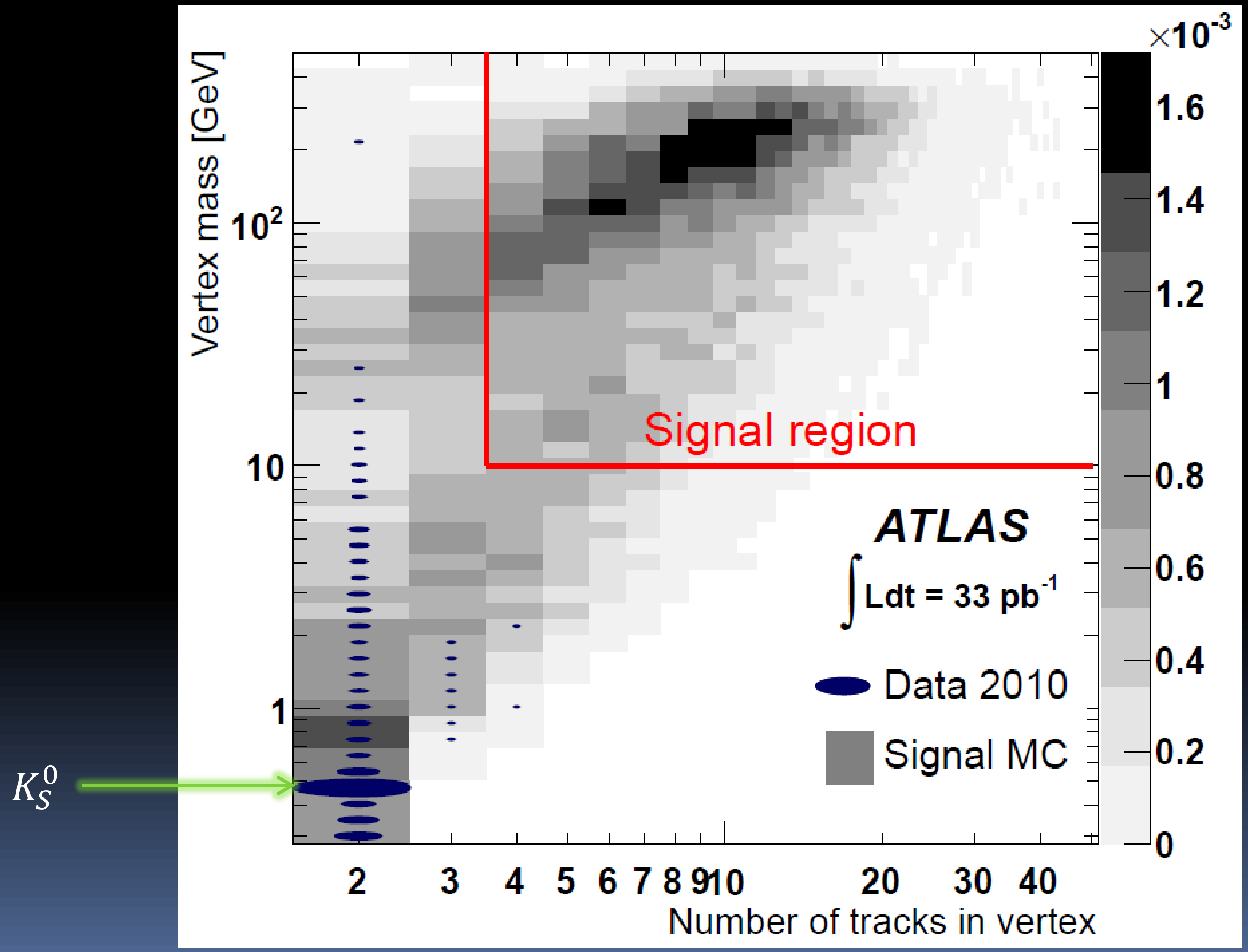
SUSY++

L=33 pb^{-1}

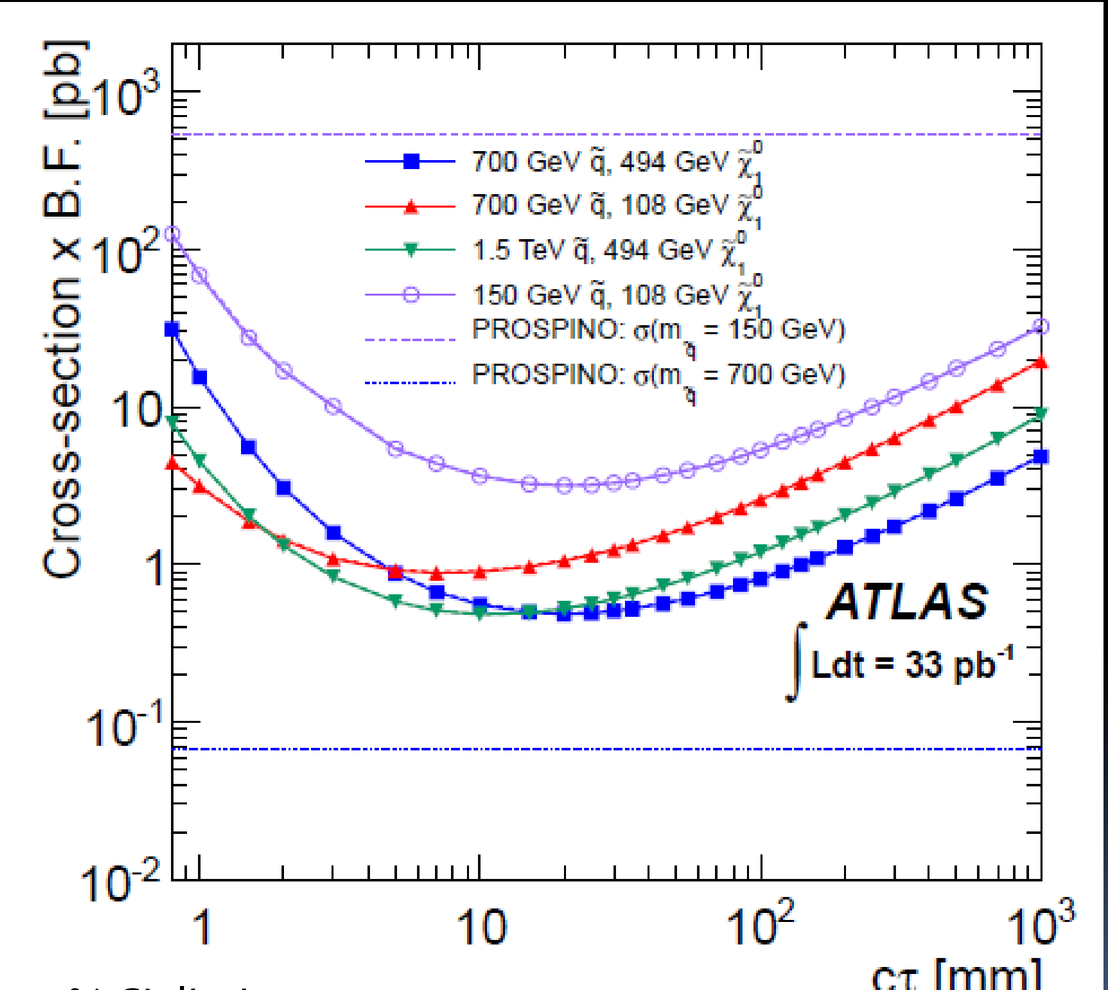


vertex reconstruction
- standard
- use tracks that have no pixel hits
- reject vertices near material
- sensitive starting at 4mm from PV

displaced vertices



displaced vertices

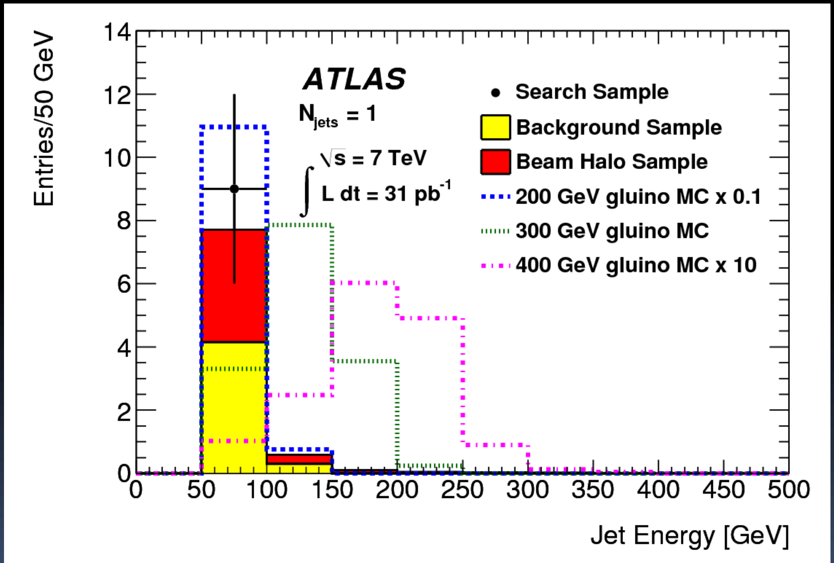


95% CL limit

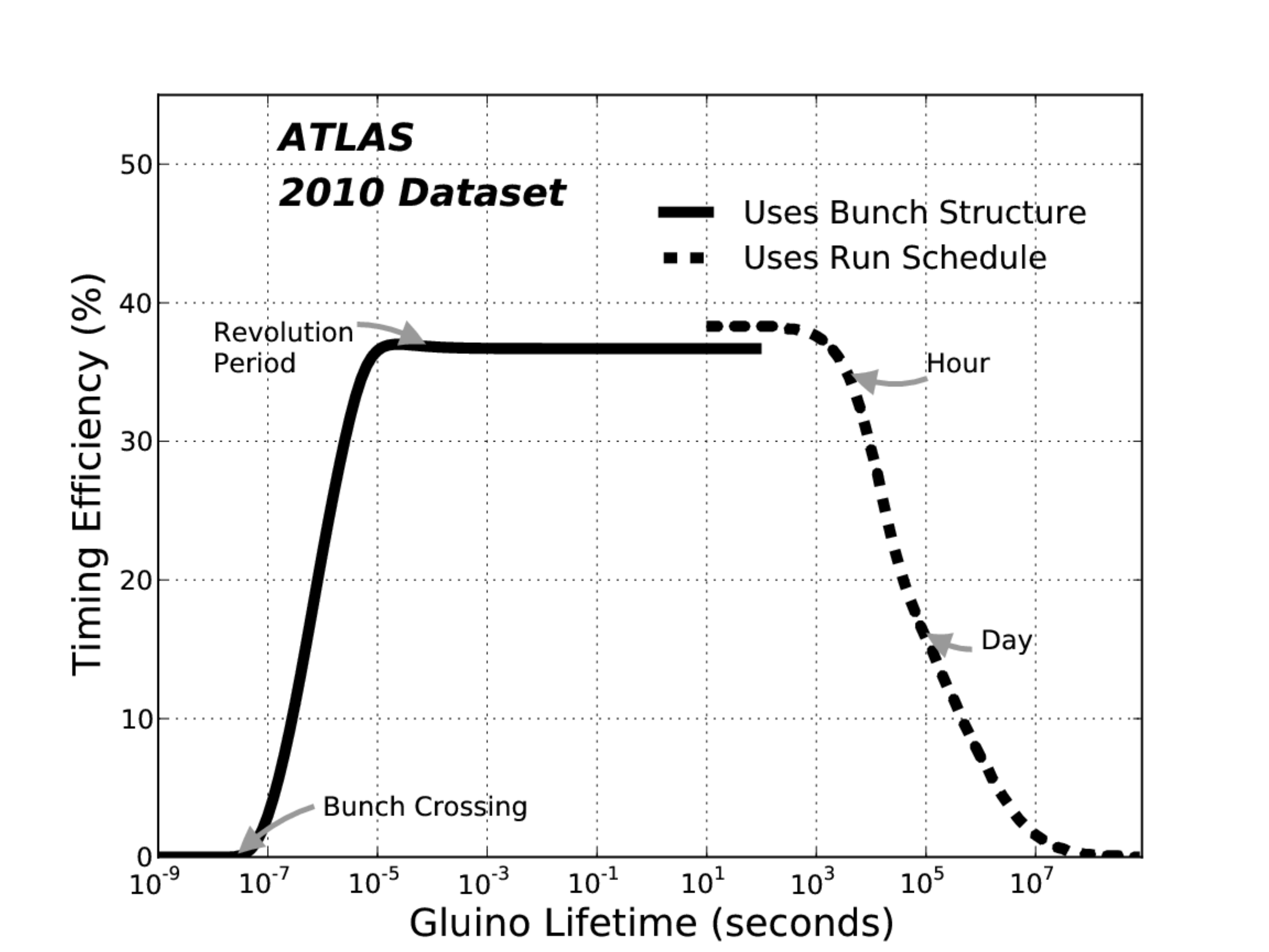
stopped particles

- Long-lived particles produced with low β can stop in detector material and decay much later.
- Most likely to stop in densest part of ATLAS $\Rightarrow$ calorimeters.
- Look for events with large energy deposits in calorimeter in "empty" bunches.

backgrounds: calorimeter noise, cosmics, beam-halo



stopped particles



stopped particles