Long Lived Particles

C. Gemme, INFN Genova

V ATLAS – Italia Physics Workshop

Napoli, 18-19 Maggio, 2011

LLP searches

- ✓ Long Lived Particles (LLP) studies focus on new particles whose lifetime is long enough for them to travel through at least part of the detector without decaying. Such objects often leave very specific signatures and are good candidates for early LHC searches.
- ✓ Analysis are done in two physics groups. In general we can summarize:
  - Exotics => Long-Lived **Neutral** Particles (Hidden Valley)
  - SUSY => Long-Lived **Charged** Particles (Stable Massive Particles)
- ✓ Many more subgroups…
  - LLP Exotics Sub-group (convener Stefano Giagu/Roma1):
    - Multicharges; HIP; R-Hadron; Hidden Valley (Cosenza, Roma1, Seattle), many others…
  - R-Parity Violating and Long-Lived Susy Sub-group (convener P. Jackson/SLAC):
    - SMPs (Genova, Oxford, NYU, Stockholm, UBC, Indiana, NBI, Technion); eμ resonance; Displaced vertices; Prompt RPV; Stopped Gluinos; Kinked disappearing track…
- ✓ Joint workshop in Rome (7-8 April) to discuss common tools and strategies.
  - Common dESD and D3PD production, etc..; Displaced vertices, etc..

Detection of Higgs decay to LLNP

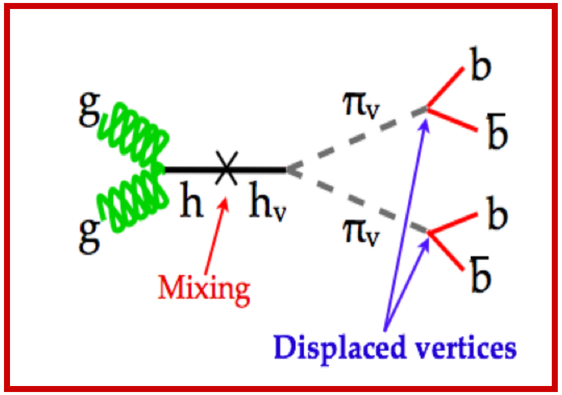
Cosenza, Roma1, Seattle

✓ Many recent models predict Long Lived Neutral Particles (LLNP) from hidden/dark sectors.

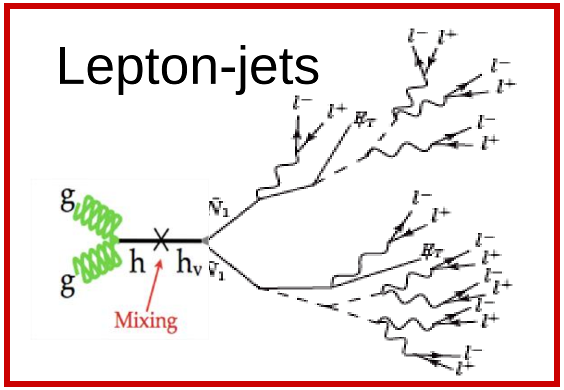
✓ Transition to our sector possible at LHC energies. Higgs can be a mediator between these sectors and our sector. Benchmark analysis:

- $H \rightarrow \pi_V \pi_V \rightarrow$ b-bbar
- $H \rightarrow n\,\gamma_D \rightarrow$ Lepton-Jets

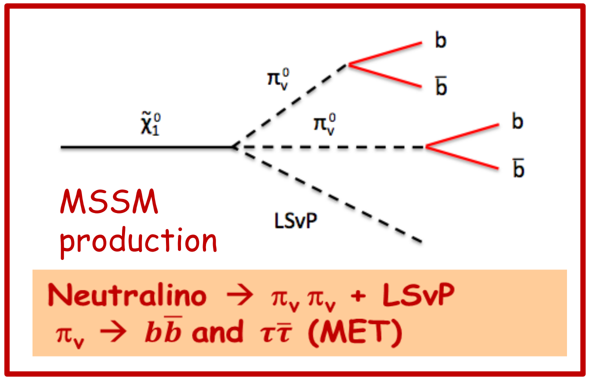
✓ Detection of LLNP decays in ID, Calo and MS is a challenge for the trigger and for the reconstruction capabilities of the apparatus. Need of specific triggers and reconstruction tools to find displaced vertices.



M. Strassler & K. Zurek, Phys Lett B 661 (2008)



J. Zupanar et al,, Xiv:1002.2952v2

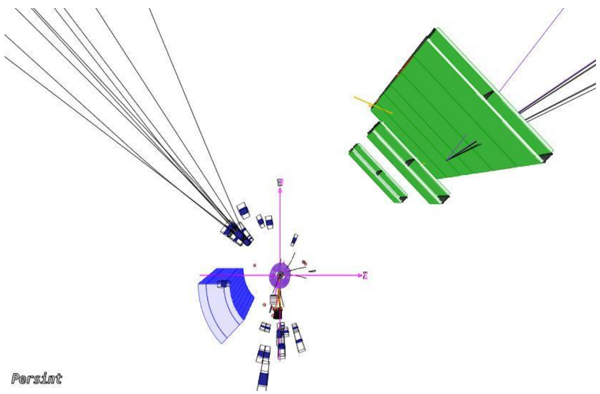


M.J. Strassler, [hep-ph/0607160]

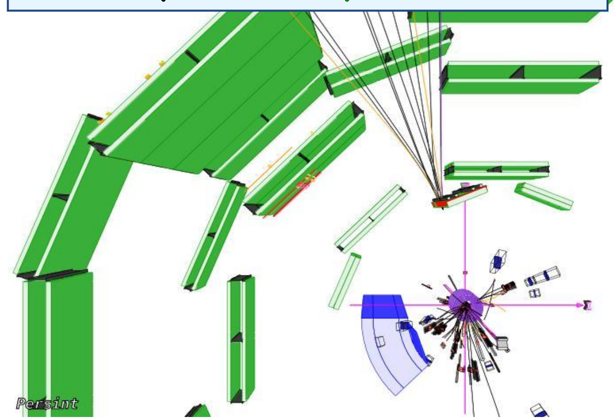
Exotics LLP - Displaced Decays

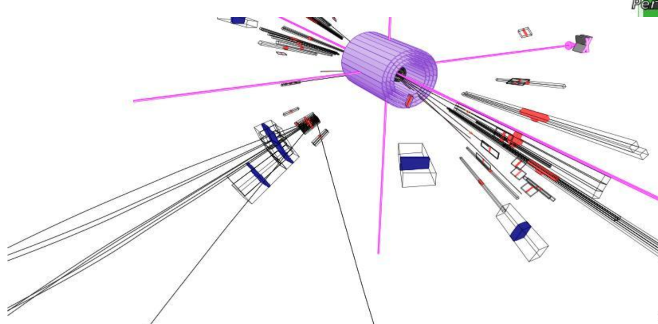
- ✓ **Monte Carlo simulation of gg → $\pi_v \pi_v$ with displaced decay**
  - Calorimeter cells greater 300 MeV and tracks in ID and Muon Spectrometer greater than 1 GeV are shown
  - Note the absence of activity in other regions of ATLAS detector

Decay in Hcal and Muon Spectrometer



Decay in Muon Spectrometer





Decay in Ecal

Exotics LLP – Trigger

- Specific triggers developed to detect LLNP decays in ID, Calo and MS

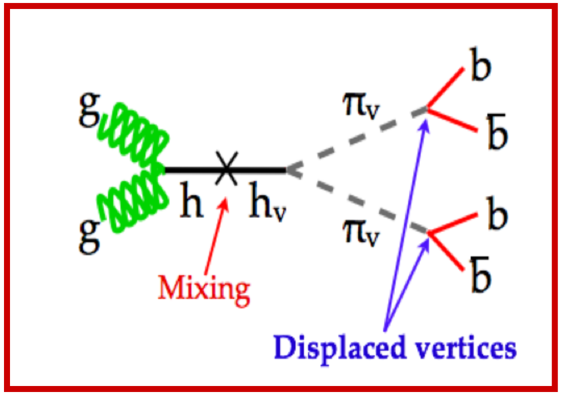
  Trackless Jet trigger : neutral decays in the ID and Ecal.

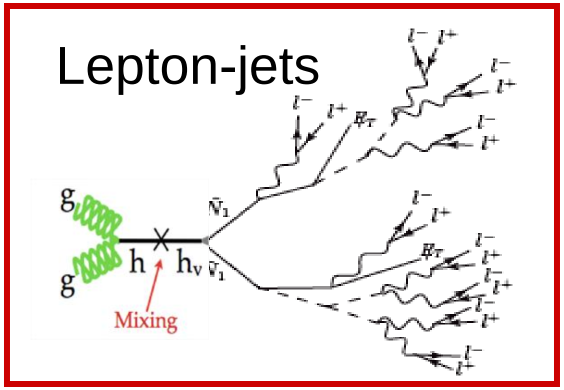
  Cal Energy Ratio : neutral decays in Hcal. Ratio E_{HAD}/E_{EM} is larger than from jets originated at the IP.

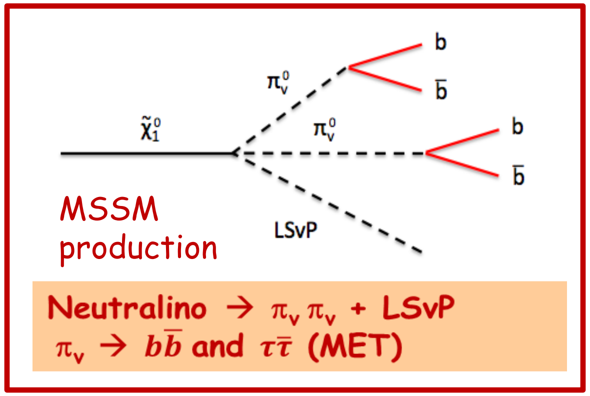
  Muon cluster trigger: neutral decays in MS. Large number of hadrons traversing a narrow (η,ϕ) region resulting in several L1 RoIs in a small (η,ϕ) region.

  3muMS only and 2m6g10: lepton jets from dark γ with displaced vertices.

- All triggers deployed at P1 and running also on empty/unpaired to evaluate bkg.
- Rates ~ 1Hz for each trigger at 10^{33} cm^{-2} s^{-1} → no prescaling.

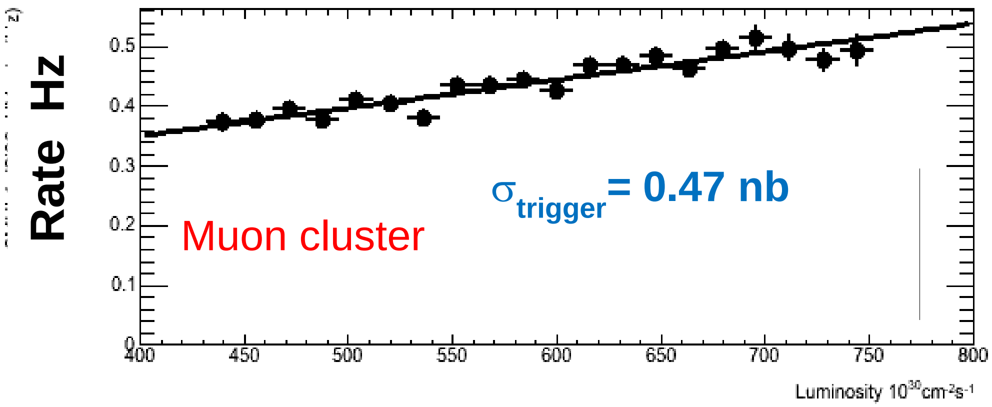


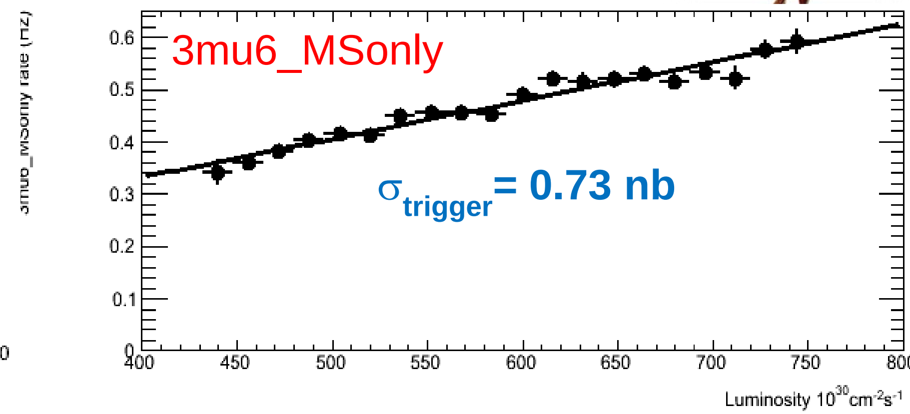


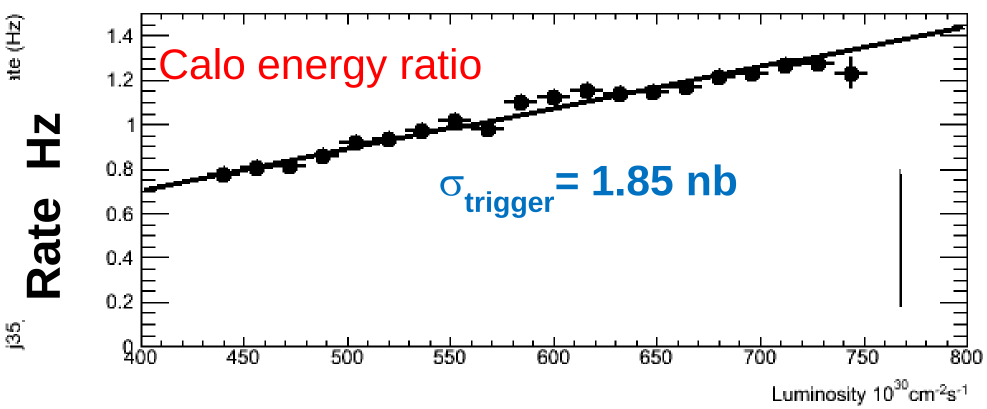


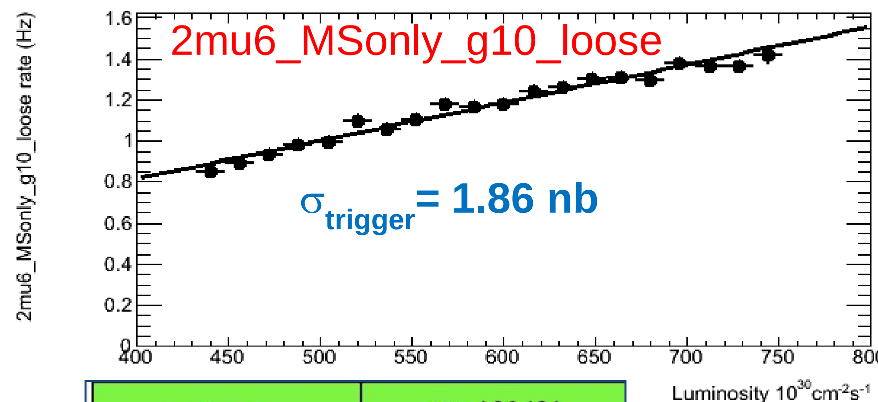
Exotics LLP – Trigger rates

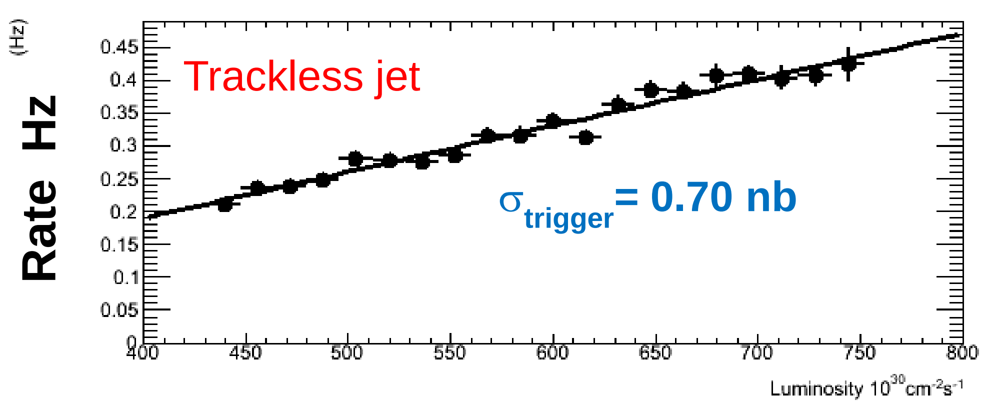
$\mathscr{L} = 6\ 10^{32}\ cm^{-2}\ s^{-1}$









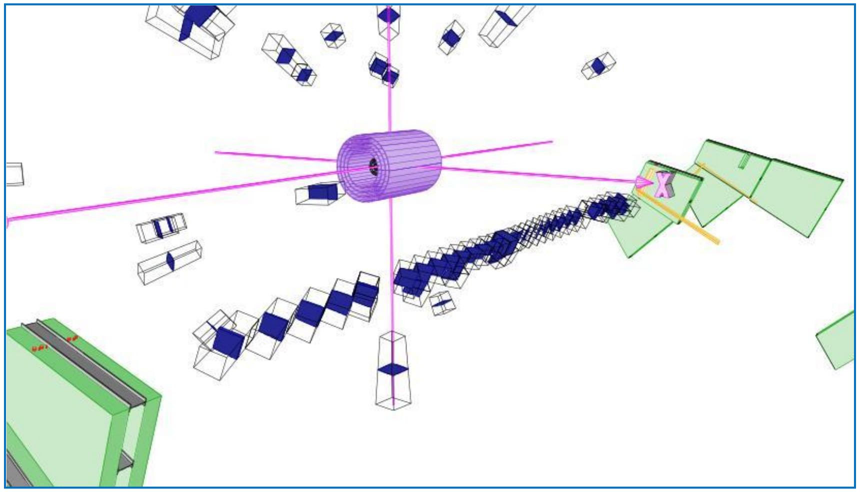


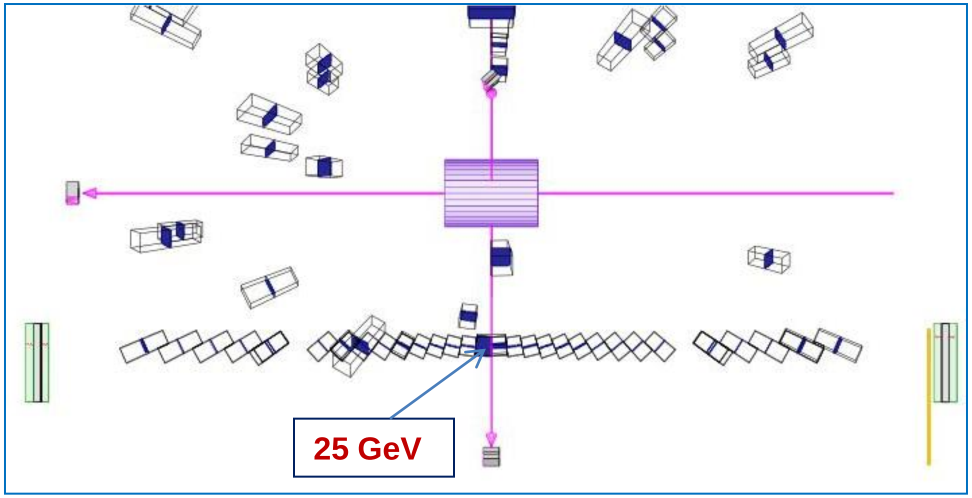
trigger	run 180481 peak lumi 7E32, 598 colliding bunches
EF_l2j30_Trackless_HV	σ_{eff}=0.70±0.03 nb
	p1= -0.091±0.016 Hz
EF_j35_a4tc_EFFS_L1TAU_HV	σ_{eff}=1.85±0.06 nb
	p1= -0.033±0.030 Hz
EF_2MUL1_l2j30_HV (|η|<1)	σ_{eff}=0.47±0.04 nb
	p1= 0.163±0.020 Hz
EF_3mu6_MSonly	σ_{eff}=0.73±0.04 nb
	p1= 0.039±0.020 Hz
EF_2mu6_MSonly_g10_loose	σ_{eff}=1.86±0.06 nb
	p1= 0.076±0.033 Hz

Cosmics contribution in muon cluster trigger

Exotics LLP – Trigger backgrounds

- ✓ Line of Fire Events (muon beam halo) can fake the Cal Energy Ratio Hidden Valley trigger

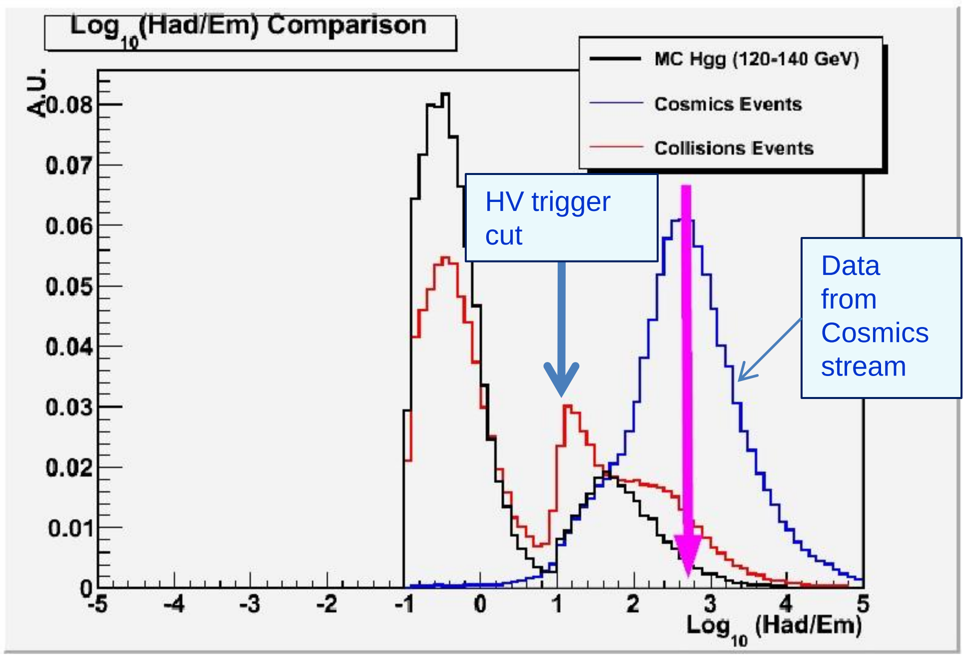


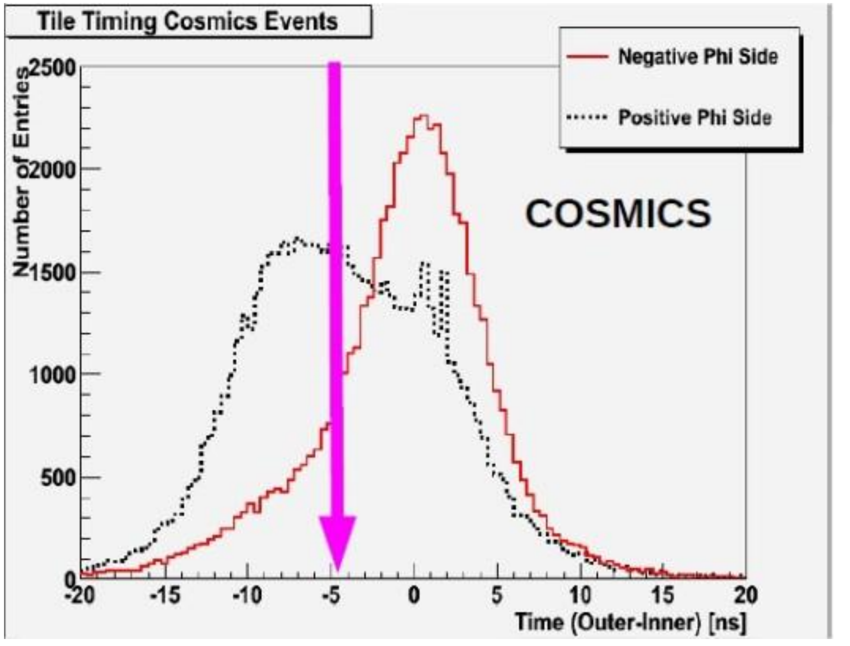


- ✓ A muon parallel to the proton beam travels through the hadronic calorimeter and has a catastrophic energy loss that "fires" the Cal Energy Ratio trigger
- ✓ This accounts for more than 30% of the Cal Energy ratio triggers in our 2010 data set

Exotics LLP – Trigger backgrounds

✓ Cosmics can fake the Cal Energy Ratio Hidden Valley trigger.



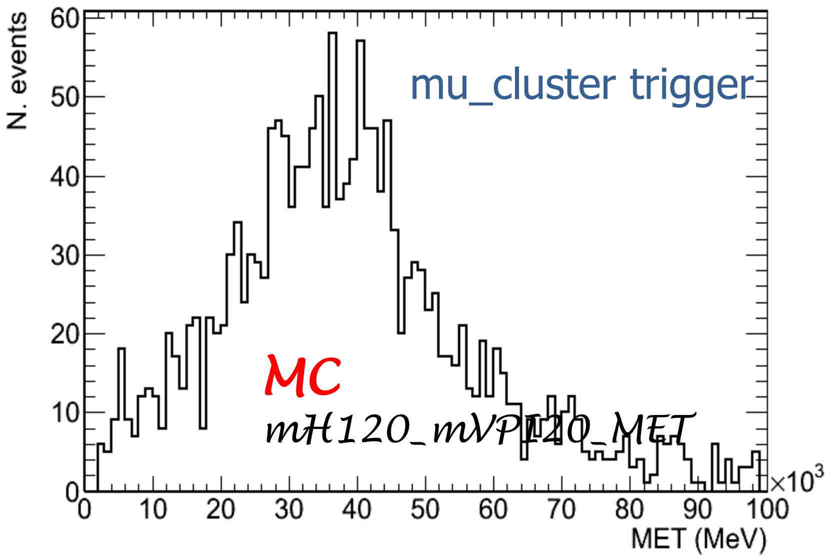


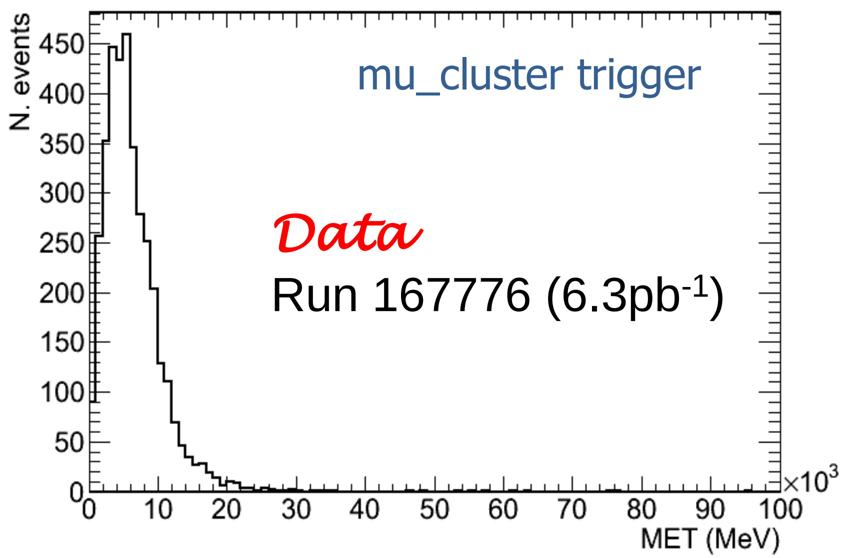
✓ Cosmics firing HV Calo Ratio trigger exhibit a large value of the Cal Energy Ratio

- The Cosmics contribution can be reduced as in the top part of Hcal they exhibit a negative *time difference* between outer and inner cells of Hcal. Moreover they can be studied/controlled using the empty bunches events.
- The residual contribution in HV triggered collisions events is studied, mainly due to QCD di-jets.

Exotics LLP – Physics backgrounds

- QCD di-jets
  - Large cross section (approximately 0.1 mb) is a large bkg.
  - But QCD di-jets in principle have no MET
- Many processes (SUSY) have intrinsic MET
- Decays of π_v hadronic jets in MS have MET





- Will be a handle against QCD jet backgrounds; study on-going ……

Exotics LLP – Tools

- ✓ We have or are developing various tools for analysis: determination of the vertex is central to establishing the presence of a signal and rejecting backgrounds.
  - Vertex in the Muon (→ Italian contribution)
    - A note (ATL-COM-PHYS-2011-215) describing this work is available on CDS AND has been presented by D.Ventura at March 31 Exotics group meeting
  - Vertex in the Inner Detector
    - Work on vertex determination in the TRT is underway
  - Vertex in the calorimeter
    - Being evaluated for use in muon-jets in the lepton-jet analyses
- ✓ Because there are no SM processes that result in displaced hadronic jets events firing our dedicated triggers
  - backgrounds such as cosmic showers, punch-through etc. will not have a vertex in the detector. The vertex is a background rejection tool and a signal confidence.
- ✓ Non standard analysis→ DESD needed. Common DESD with Susy group. Ntuples structure ready, production just started.

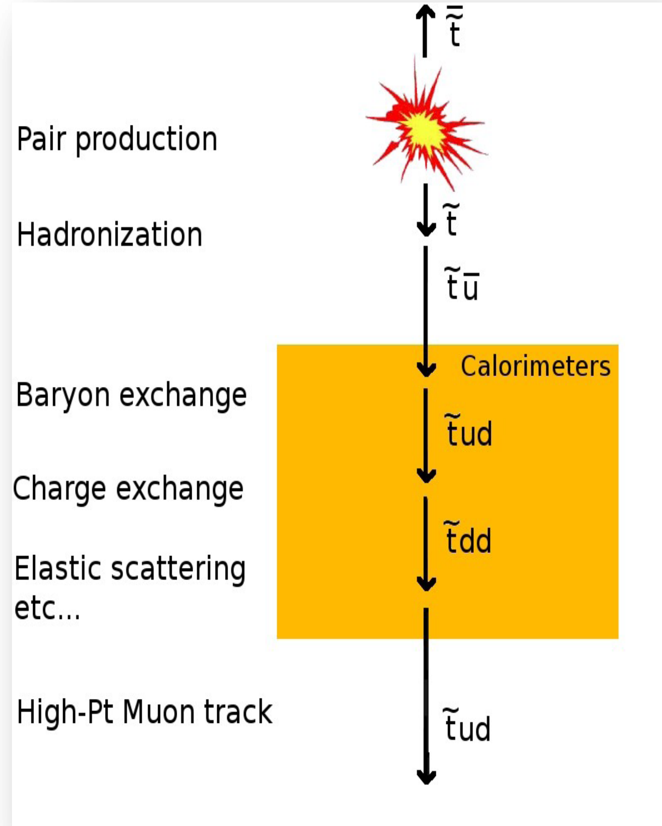
Exotics LLP – Analysis status

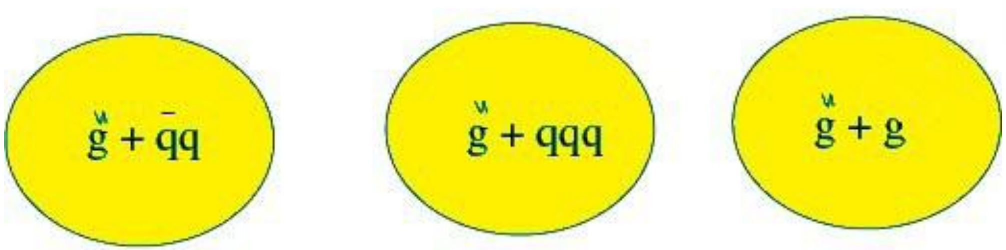
- ✓ Analysis strategy defined; Editorial Board assigned for 2 Conf Notes:
  - $H \rightarrow \pi_V \pi_V \rightarrow$ b-bbar
  - $H \rightarrow n\, \gamma_D \rightarrow$ Lepton Jets
- ✓ Analysis based on muon identification in MS and vertex reconstruction.
- ✓ Critical points will be the cosmics/machine background rejection and the "data-driven" evaluation of the QCD backgrounds.
- ✓ Expected results by the end of 2011.

- ✓ Italian contribution is extremely relevant for trigger and MS-vertex study:
  - (Roma1) Guido Ciapetti, Stefano Giagu, Andrea Gabrielli, Alessia D'Orazio, Antonio Sidoti
  - Cosenza: Marco Schioppa, Daniela Salvatore, Anna Mastroberardino, Giancarlo Susinno
  - Italiani temporaneamente "fuori-sede" (Seattle): Antonio Policicchio, Monica Verducci.

Stable Massive Particles

- Stable Massive Particles (SMPs) predicted in a range of SUSY and other BSM scenarios
- Within SUSY: SMPs with different color and electric charges, squarks and gluinos could form bound states with a light quark system: **R-hadrons**
- Some models foresee charge exchange in the calos.
- Generic signature:
  - Slow and high pT particles



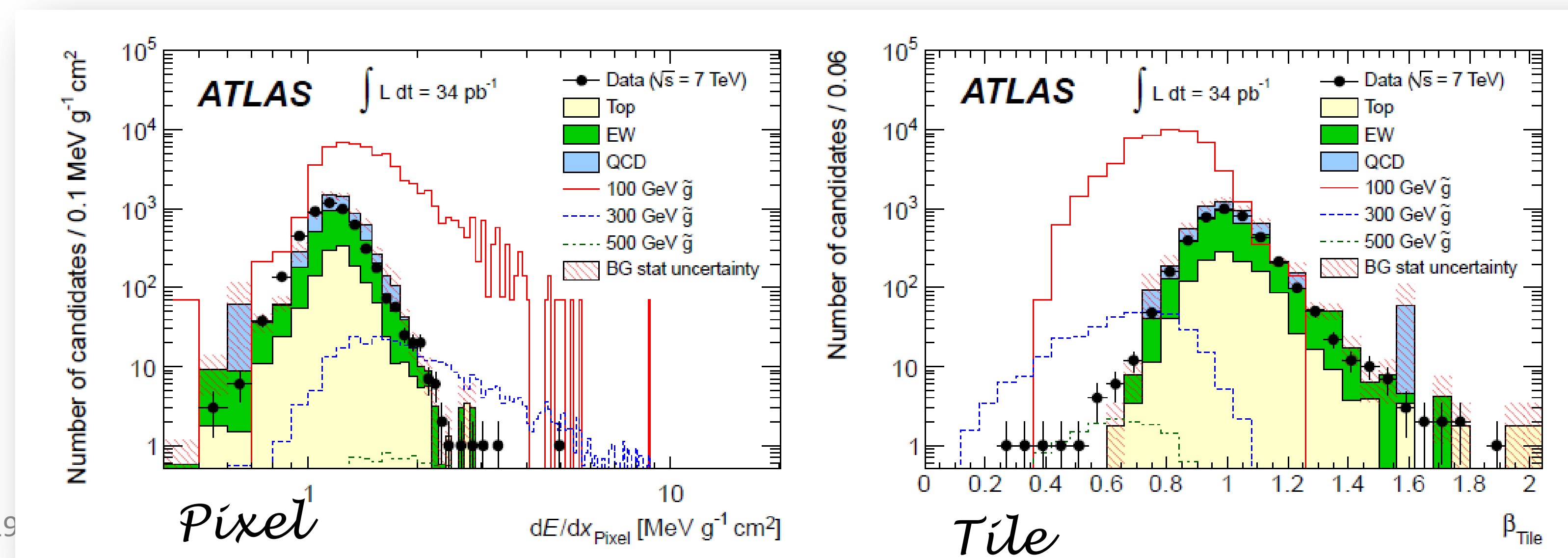


R-meson R-baryon gluino ball

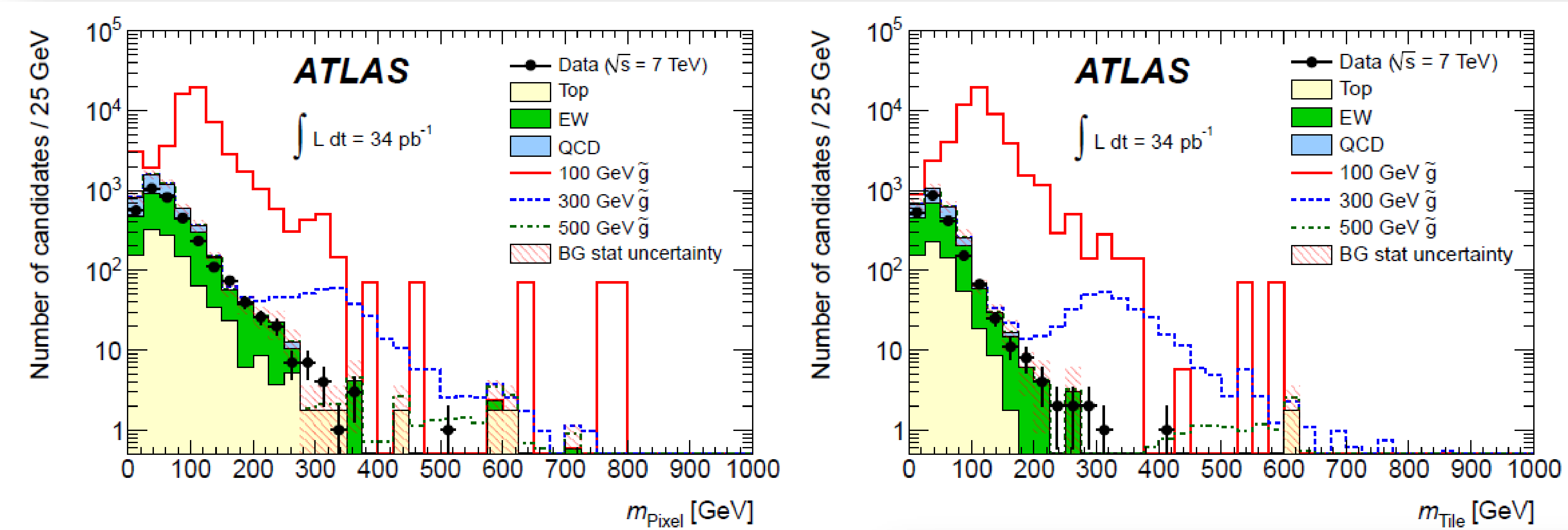
Stable Massive Particles: 2010

ArXiV:1103.1984 contributes from Genova

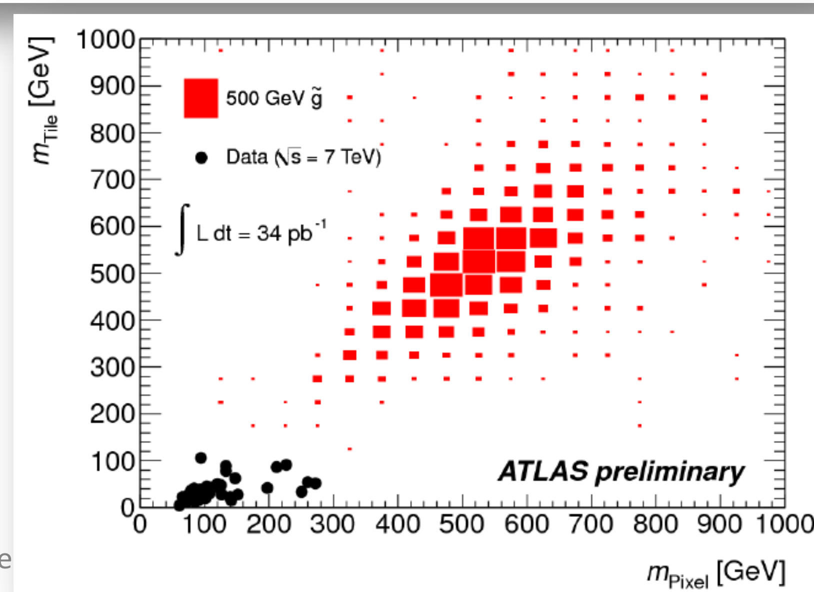
- ✓ ***Trigger*** : hard to trigger directly on R-hadrons (no guaranteed signal in muon spectrometer, small energy loss in calorimeter) . Use data collected with missing E_T trigger: L1_XE25 + EF_xe40_noMu
- ✓ ***Analysis*** : signature is a slow moving track with $\beta < 1$. Use *independent detectors (Pixel & Tile) and different observables (dE/dx & β).*
  - Pixel dE/dx monitored with light hadrons (p,K)
  - TOF measured with 1ns resolution, β_{Tile} calibrated with muons from Z->μμ
- ✓ Quality cuts on PV, ID track; Min ΔR distance from jets, pT> 50 GeV.



Stable Massive Particles: 2010

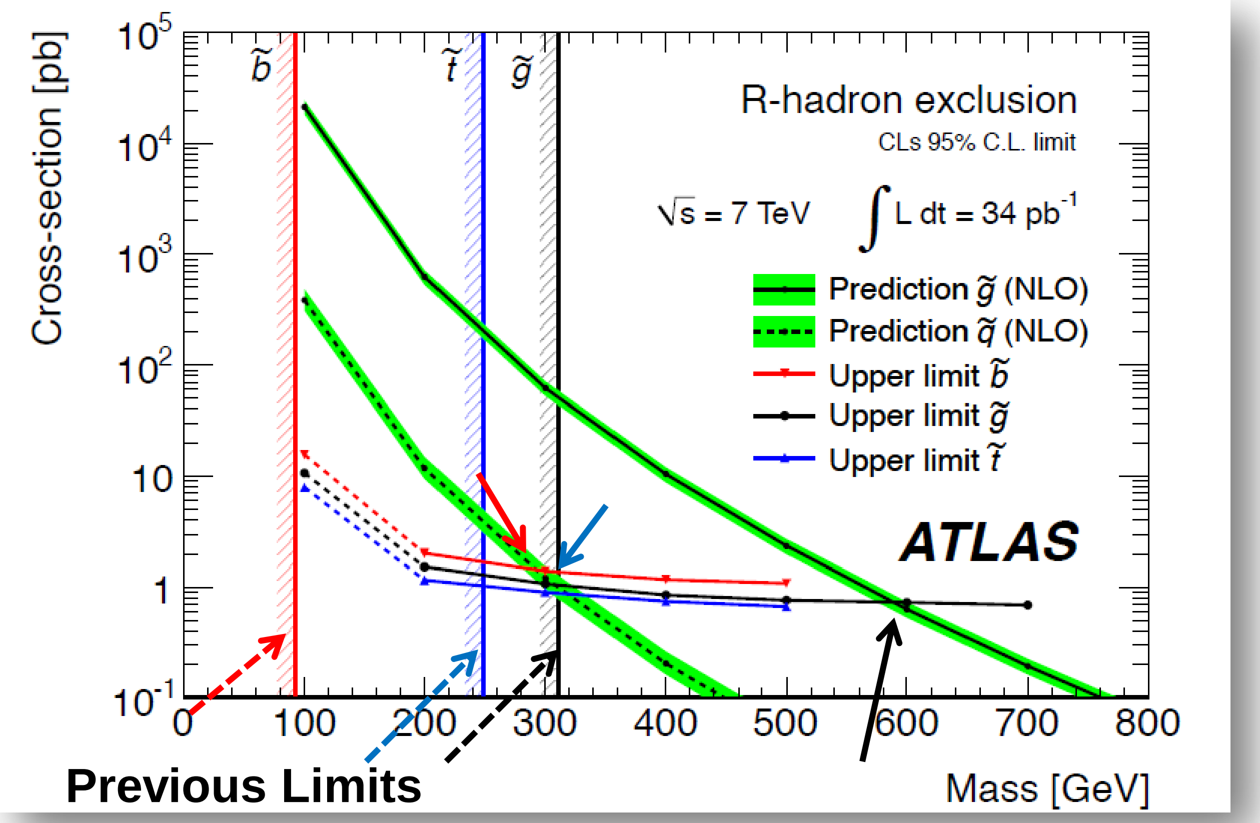


- ✓ Consider each variable separately, compute mass estimate and then combine them.
- ✓ Data are consistent with SM expectation.
- ✓ Correlation in mass variables for data is favoured by using the same momentum measurement.



Stable Massive Particles: 2010

- ✓ New limits set: hadronizing gluino: 562-586 GeV; stop R-hadron : 309 GeV; sbottom R-hadron : 294 GeV



- ✓ LLP muon-agnostic search (Pixel,Tile) → ArXiV:1103.1984, Accepted by PLB
- ✓ LLP muon spectrometer search → Paper in preparation, ATL-COM-PHYS-2011-309

Stable Massive Particles: Plans 2011

- ✓ In general, 2011 strategy is to include discriminators from other sub-detectors (TRT, LAr) and to combine them.
- ✓ For these searches Genova provides expertise to analysis that use the Pixel dE/dx. ATL-COM-CONF-2010-109

Genova proposes a different strategy and pursues a Pixel-only analysis (T. Cornelissen, C. Gemme, E. Guido, S. Passaggio, L. Rossi, C. Schiavi).

- ✓ Pixel has the big advantage to be *the closest detector* to the IP and therefore less sensitive to decay/interaction of the SMP within ATLAS.
- ✓ We are open to SMPs that *do not reach the Tile*, or that behave differently than a CaloMuon (for instance they become *neutral* in dense calo). Moreover we can enlarge the η-coverage (Tile $|\eta|<1.7$, Pixel $|\eta|<2.5$).
- ✓ We are *not sensitive to reduced bunch spacing* (ok with 50 ns or less).
- ✓ We can continuously check and *monitor* how low-β particles behave while crossing it (light hadrons, done in Data Quality)!
- ✓ Reachable Limits in mass are likely to be worse using silicon-only but we are open to different processes .

SMP Pixel-only

Data selection/Format

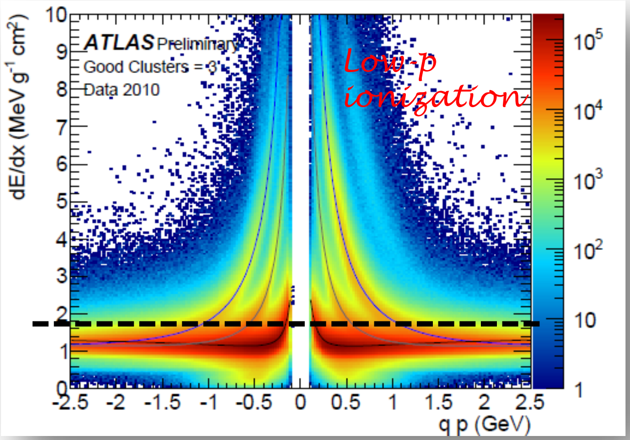
- ✓ Starting from the JetTauEtmiss stream, DESDM RPVLL samples are generated (DESDM_RPVLL production is in place)
  - an EF ETmiss (EF_xe60_noMu or higher threshold) request is done
  - our selection (TrackParticleFilter) is in OR with other analysis (SmpCaloId , etc…)
- ✓ TrackParticleFilter to skim events with at least one high-pT track:
  - Requires a track with nPix>=1, nSCT>=6 and pT higher than a threshold cut.
  - Overall skimming efficiency in the JetTauEtmiss stream of SMP Calo+ TrackParticleFilter with the current settings (pT>40 GeV) is ~ 0.2% (~50% for Rhadrons 500 GeV)
  - TrackParticleFilter rate can be easily scaled down if needed by tightening the cut on pT (factor ~6 scaling at 70 GeV)

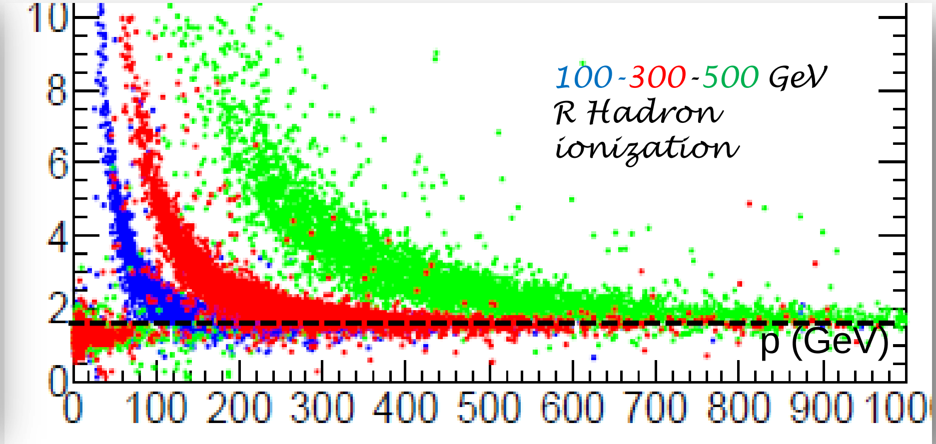
SMP Pixel-only

- ✓ D3PD_RPVLL format is almost ready
  - Some samples available, automatic production should start soon

Analysis

- ✓ Signature are events with large MET; R-hadrons will have large pT and large ionization in Pixel, above the MIP release.





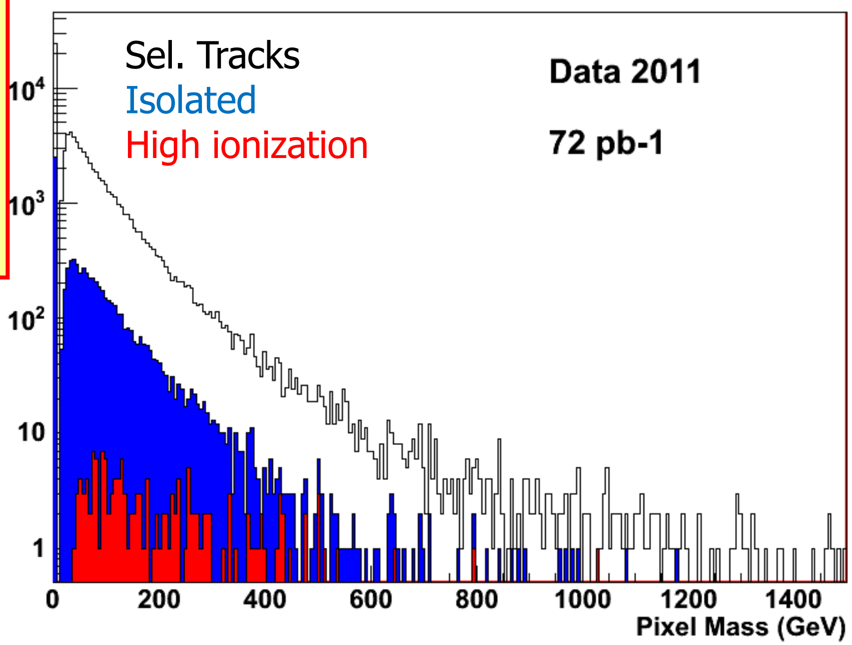
SMP Pixel-only

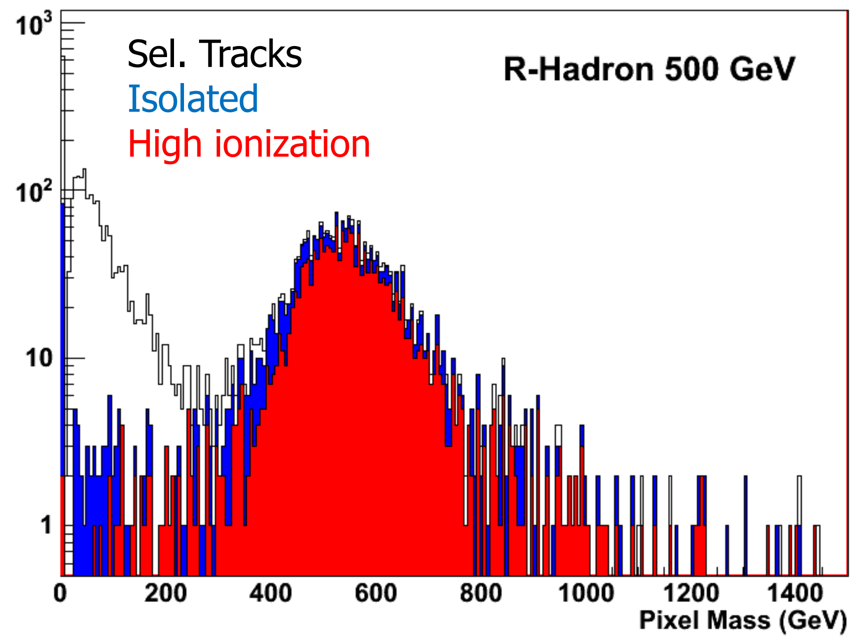
- ✓ Can't be a pure Pixel-only measurement as SCT hits are needed to have a good p measurement, needed for mass estimate.
- ✓ The key point is the background suppression as we miss the track confirmation in Tile wrt the previous analysis, fake rates of high pt-tracks can easily increase a lot.
- ✓ Next slide very preliminary plots without cuts optimization.

(Preliminary!) Analysis

- Events from the skimming, and with MET>60 GeV
- Sel. tracks with pT>40 GeV, nGoodPixel Clusters >=3, SCT hits>=6
  - Isolation: no tracks with pT >5 GeV in a cone ΔR = 0.5
  - High (well above the MIP) track ionization: dE/dx > 1.8 MeV g^{-1} cm^2

SMP Pixel-only





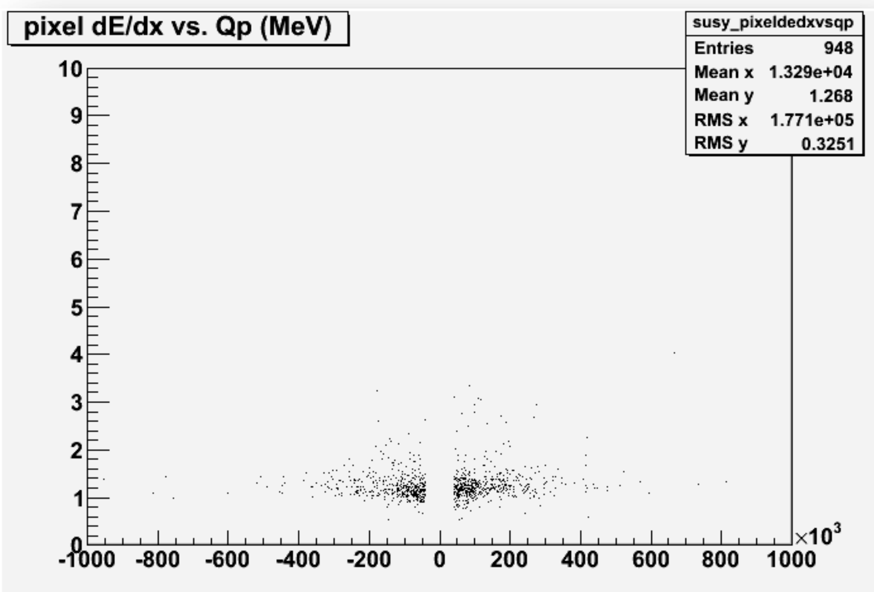
Analysis

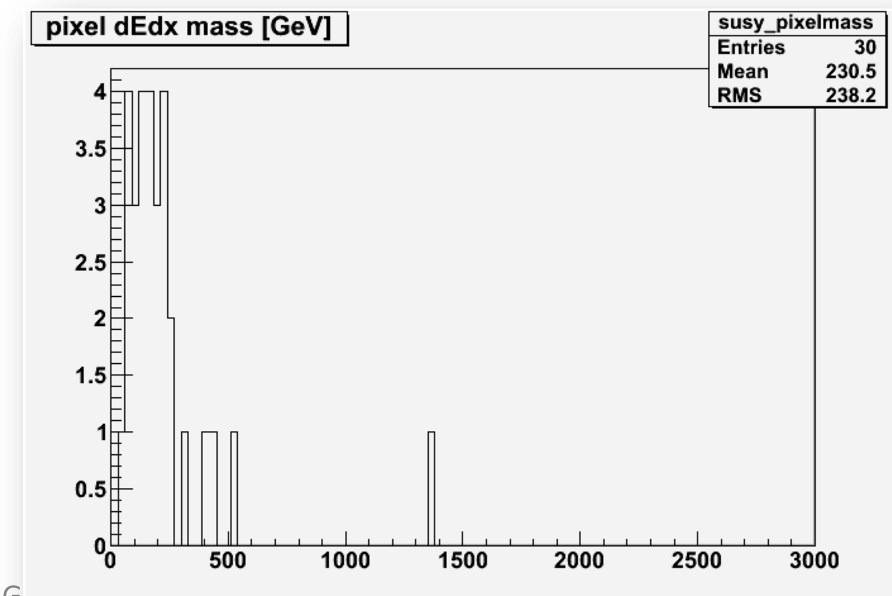
SMP Pixel-only

- ✓ Plans are to optimize the current cuts for S/N optimization.
- ✓ Look for further variables:
  - Event Level : Good run list!, Primary Vertex, Total Energy, presence of two selected tracks, etc…
  - Track level: ID χ^2, Si-only χ^2, TRT information, etc.
- ✓ While waiting for large MC production and systematic data D3PD production, in ~ one month understand if/how we can control the background rejection and which limits we can reach (or discovery). Then few months to finalize the analysis.
  - In the meanwhile we have implemented similar algorithm in the Fast Monitoring Plots (see next slide).

Analysis in Fast Monitoring Plots

- FMP is not designed to be a framework for a detailed analysis, only to get a hint of new physics
  - Wiki: https://twiki.cern.ch/twiki/bin/view/AtlasProtected/FastPhysicsMonitoring
- Tier0 will produce small ntuples from AOD and Basic histograms produced from the ntuples.
- For the SMP pixel only we apply similar cuts as above and we save dE/dx, nGoodClusters, track parameters





Spare

Data format

What does LongLivedParticleDPDMaker do?

Skimming - we have a strict limit of 1% of total ESD size

- 2010: `((trig1 || trig2 || ... ) && (offline1 || offline2 || ... ))`
  $\Rightarrow$ Simple, but not optimal
- 2011: One set of skimming criteria per analysis, global OR of these in each stream
  $\Rightarrow$ tightest possible skimming
- Example: skimming criteria for stable massive particle search based on Calo+ID discriminators
  - `(EF_xe60_noMu || EF_xe70_noMu || EF_xe80_noMu || EF_xe90_noMu)`
  - ($\geq$1 offline muon (of *any* type) with $p_T > 25$ GeV) || ($\geq$1 track with 2 pixel & 6 SCT hits and $p_T > 40$ GeV)

Thinning/slimming $\Rightarrow$ smaller per-event size $\Rightarrow$ can accept more events

- Despite DESDM, for now keeping full ESD per-event contents
- Hope to eventually discard ~90% CaloCells (those far away from interesting physics objects, and have $E < 100$ MeV) excluded $\Rightarrow\sim$ 30% reduced per-event size

So

- DESDM_RPVLL *is used for physics* $\Rightarrow$ do not want to prescale!
- Selections include trigger, which will evolve with lumi $\Rightarrow$ some automatic rate regulation
- Can modify triggers/offline thresholds via `preExec` in `Reco_trf.py` command

Data format

Rate estimates per stream (for 178109)

Extracted from LBs 160-169 of run 178109, $\mathcal{L} \sim (2.43 - 2.46) \times 10^{32}$

Egamma

Analyses (skim. eff.)

- HIP search
  $(1.41 \pm 0.07)\%$
- Non-pointing γ
  $(0.74 \pm 0.05)\%$

Total:

- Skimming eff.:
  $(2.06 \pm 0.08)\%$
- Per-event size:
  1.44 MB (1.17 MB)

JetTauEtmiss

Analyses (skim. eff.)

- Kinked track
  $(0.04 \pm 0.01)\%$
- SMP Calo+ID
  $(0.18 \pm 0.01)\%$
- Hidden Valley
  $(0.35 \pm 0.02)\%$
- Stopped
  $\lesssim 0.001\%$

Total:

- Skimming eff.:
  $(0.56 \pm 0.03)\%$
- Per-event size:
  1.26 MB (1.32 MB)

Muons

Analyses (skim. eff.)

- Displaced Vertex
  $\lesssim 0.003\%$
- Hidden Valley
  $(0.70 \pm 0.05)\%$
- SMP MS
  $\lesssim 0.003\%$

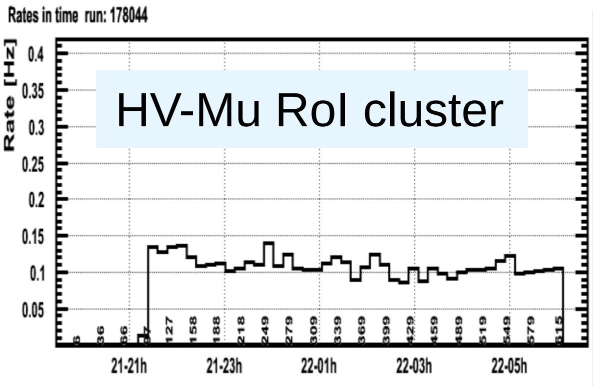
Total:

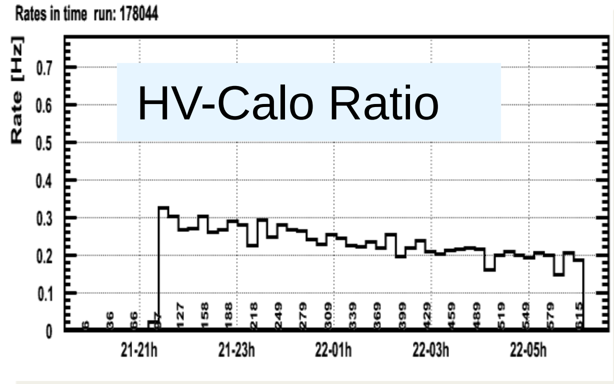
- Skimming eff.:
  $(0.7 \pm 0.05)\%$
- Per-event size:
  1.32 MB (1.19 MB)

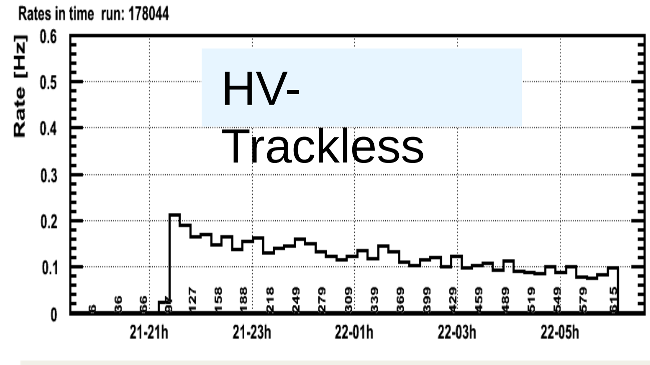
Exotics LLP - Triggers

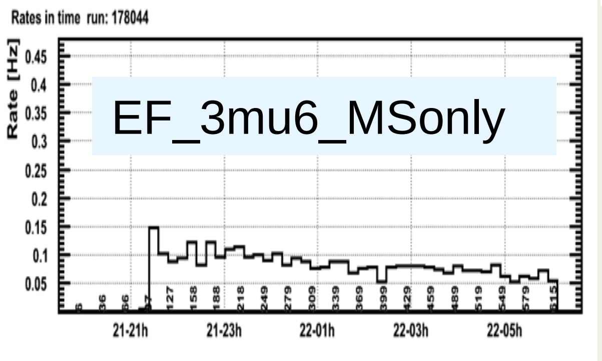
- ✓ Hidden Valley Triggers (ATL-COM-PHYS-2008-020)
  - *Trackless Jet trigger* (l2j30_Trackless_HV) selects decays in the ID and Calorimeters
  - *Cal Energy Ratio* (j35_a4tc_EFFS_L1TAU_HV) selects decays in HCal
  - *Muon cluster trigger* (2MU1_l2j30_HV) selects decays between end of HCal and before first muon spectrometer trigger plane.
- ✓ l2j30_Trackless_HV
  - Seeded by L1_MU0_J15 & L2 jet with $|\eta|>2.5$ & $E_T \geq 30$GeV & NO $p_T \geq$ 1GeV level 2 ID tracks in a $(\eta,\phi)=(0.2,0.2)$ region around the jet cone axis & an L1 muon in the jet cone to reduce QCD backgrounds
- ✓ j35_a4tc_EFFS_L1TAU_HV
  - Seeded by L1_TAU30 & level2 jet with $|\eta|<2.5$ & $E_T \geq 30$GeV & $\log_{10}[E_{HCal}/E_{EM}] \geq 1$ & NO $p_T \geq$ 1GeV level 2 ID tracks in a $(\eta,\phi)=(0.2,0.2)$ region around the jet cone axis and EF_j35_a4tc_EEFS
- ✓ 2MU1_l2j30_HV
  - Seeded by L1_2MU6
  - At Level2 require 3 or more muon RoIs in $\Delta R=0.4$ cone & NO L2 jets with ET>30GeV & $\log 10[E_{HCal}/E_{EM}]<0.5$ in a $\Delta R=0.4$ cone centered on the cluster center & NO ID tracks with $p_T \geq 5$GeV in a $(\eta,\phi)=(0.2,0.2)$ region around center of RoI cluster.

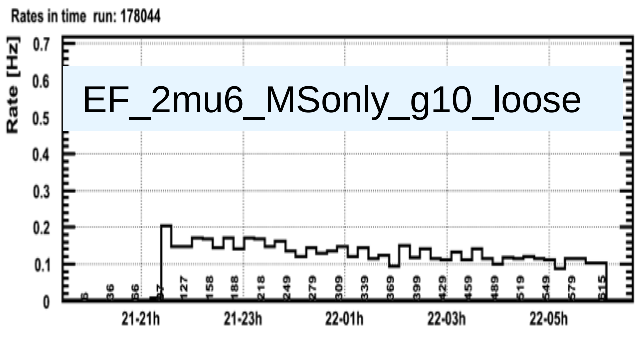
Exotics LLP – Trigger rates 2011

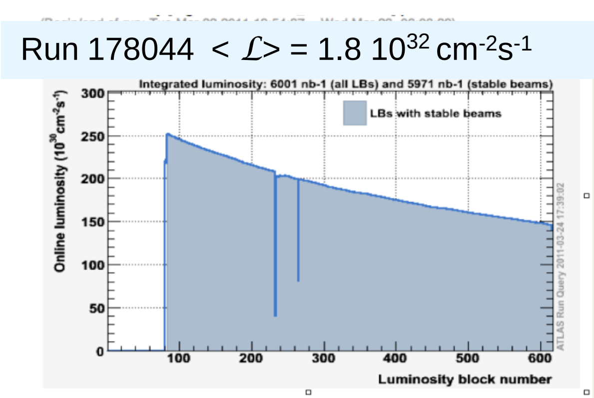










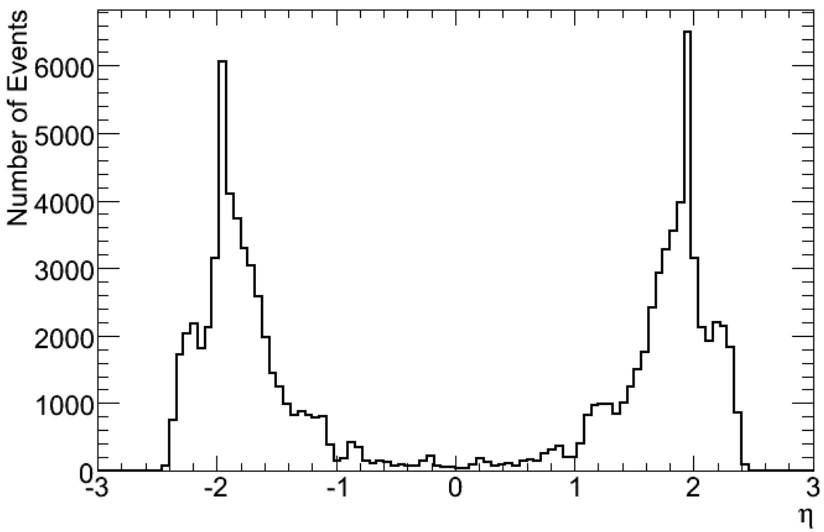


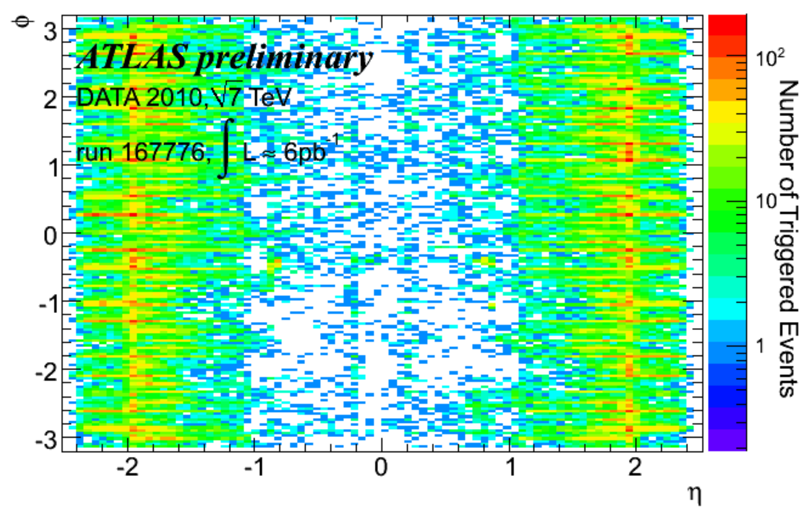
✓ Expected rates at 10^{33} cm^{-2} Hz with 50 ns bunch spacing still around 1 Hz

Exotics LLP – Trigger backgrounds

✓ Multi RoI triggers from RPC/TGC chamber overlap

- Results in fake Muon Cluster triggers → for 2011 trigger menu the muon cluster trigger is constrained to $|\eta| < 1$





- A firmware fix to remove the MDT overlap RoI's is almost ready to be deployed

SMP - cut flow

Efficiency table for data

Cut level	# candidates	Efficiency (%)	Total eff. (%)
(Skim)	146605	100	100
Trigger	89237	60.87	60.87
VxCln	89232	99.99	60.87
TrkCln	81321	91.13	55.47
$\|\eta\| < 1.7$	68677	84.45	46.84
$\Delta R > 0.5$	56065	81.64	38.24
$p_T > 25$ GeV	15361	27.40	10.48
$p_T > 50$ GeV	5208	33.90	3.55
$\beta_{Tile} > 0$	4068	78.11	22.63
Pixel $dE/dx > 0$	3944	96.95	21.94
$\beta_{Tile} < 1$	1336	33.87	7.43
Pixel $dE/dx > 1.8$	22	1.65	0.12
$m_{Tile} > 0$ GeV	22	100.00	0.12
$m_{Pixel} > 0$ GeV	22	100.00	0.12
$m > 0$ GeV	22	100.00	0.12
$m > 50$ GeV	6	27.27	0.03
$m > 100$ GeV	0.00	0.00	0.00

Efficiency table for 500 GeV $\tilde{g}$

Cut level	# candidates	Efficiency (%)	Total eff. (%)
(Skim)	72.87	100.00	100.00
Trigger	23.84	32.72	32.72
VxCln	23.84	100.00	32.72
TrkCln	22.82	95.73	31.32
$\|\eta\| < 1.7$	19.64	86.06	26.95
$\Delta R > 0.5$	19.24	97.97	26.41
$p_T > 25$ GeV	17.90	93.01	24.56
$p_T > 50$ GeV	17.80	99.46	24.43
$\beta_{Tile} > 0$	15.23	85.53	74.63
Pixel $dE/dx > 0$	14.72	96.71	72.18
$\beta_{Tile} < 1$	14.72	99.96	72.15
Pixel $dE/dx > 1.8$	10.97	74.51	53.76
$m_{Tile} > 0$ GeV	10.97	100.00	53.76
$m_{Pixel} > 0$ GeV	10.97	100.00	53.76
$m > 0$ GeV	10.97	100.00	53.76
$m > 50$ GeV	10.97	100.00	53.76
$m > 100$ GeV	10.97	100.00	53.76