Searching for New Physics with Displaced Vertex signatures in the ATLAS Detector

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Why Long-lived Particles

- Standard Model (SM) completed by discovery Higgs boson in 2012
- Focused attention on what SM does not address
  - Dark Matter
  - Matter-antimatter asymmetry of our universe
  - Naturalness of electro-weak scale absent obvious TeV-scale signals of physics Beyond the SM (BSM)
- Virtually every theory that extends the SM to address these open issues either allows for or requires long-lived particles
  - Life-times ($c\tau$) can range from a few 100 μm to the Big Bang Nucleosynthesis (BBN) limit of $10^6 - 10^8$ meters
  - Covering such a large $c\tau$ range poses a major experimental challenge
  - Detecting decays displaced from the IP in LHC detectors where triggers designed to select prompt decays presents interesting challenges
- CMS, ATLAS and LHCb experiments have developed new triggers (ATLAS) or improved displaced vertex reconstruction in the inner tracker (CMS and ATLAS) and vertex reconstruction in the muon spectrometer (ATLAS)

Theories with Long-lived Particles

- BSM Theories that extend SM require or allow for LLPs*
  - Mini split supersymmetry (arXiv:1212.6971)
  - Gauge mediation (arXiv:hep-ph/9801271)
  - RPV (R-parity violating) SUSY (arXiv:1309.5957)
  - Models of Baryogenesis (arXiv:1409.6729)
  - Hidden Valleys (arXiv:hep-ph/0605193)
  - Dark Photons (arXiv:1604:00044)
  - Theories of Neutral Naturalness (arXiv:1512.05782)
  - Models generating neutrino masses (arXiv:1604.06099)

* Reference are to a relatively recent paper that contains earlier work.

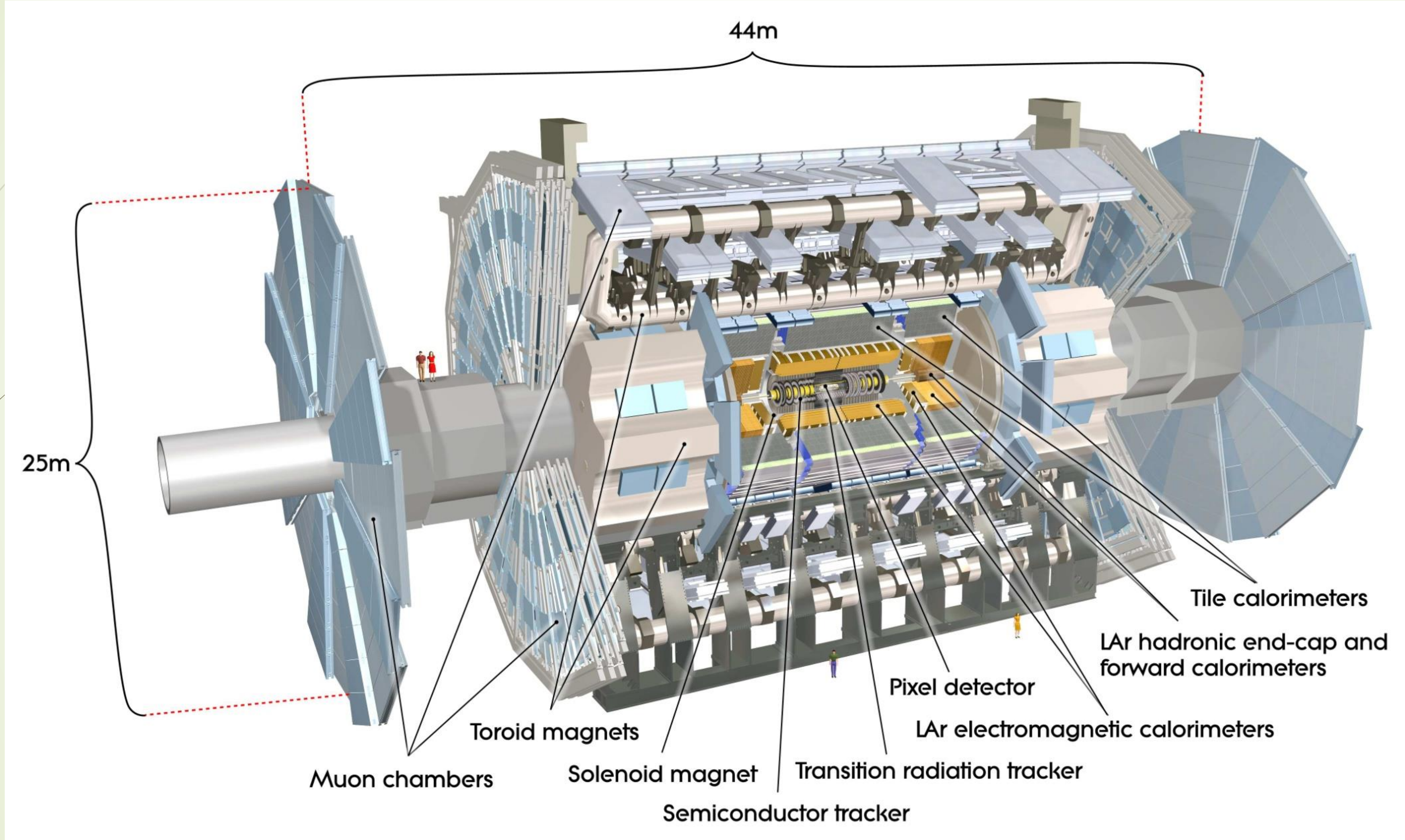
Signature space of Displaced vertex searches

- Detector signature depends of production and decay operators of a given model
  - Production determines cross section and number and characteristics of associated objects
  - Decay operator coupling determines life time, which is effectively a free parameter
- Common Production modes
  - Production of single object - with No associated objects (AOs)
    - Higgs-like scalar Φ that decays to a pair of long-lived scalars, ss, that each in turn decay to quark pairs – Hidden Valley and Neutral Naturalness
    - Vector Z′ mixing with SM gauge bosons – kinetic mixing
  - Production of a single object P with an AO – Many SUSY models
    - AO jets if results from decay of a colored object
    - AO leptons if LLP produced via EW interactions with SM
- Common detector signatures $\Rightarrow$ generic searches

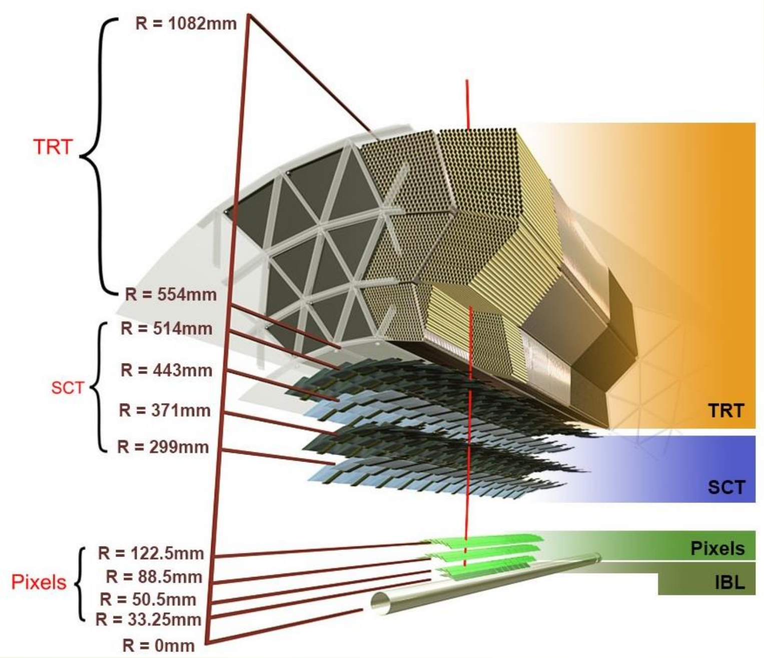
Focus on neutral LLPs

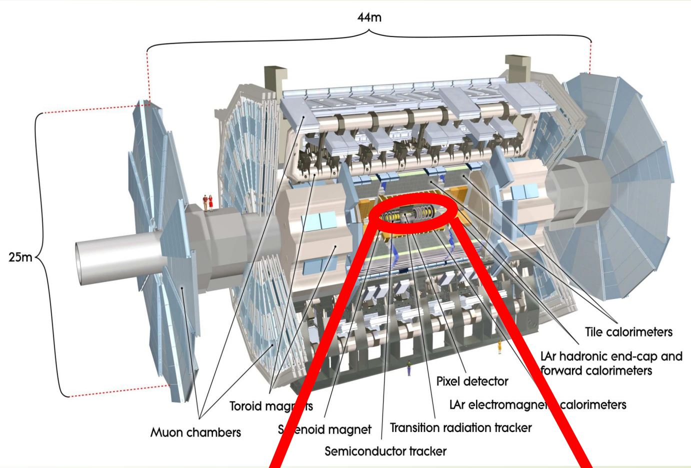
- **Neutral LLPs lead to displaced decays with no track connecting to the IP, a distinguishing signature**
  - SM particles predominantly yield prompt decays (good news)
  - SM cross sections very large (eg. QCD jets) (bad news)
- To reduce SM backgrounds most Run 1 ATLAS searches required two identified displaced vertices or one displaced vertex with an associated object
  - Resulted in good rejection of rare SM backgrounds
  - BUT limited the kinematic region and/or lifetime reach
- None the less, many Run 1 searches were able to probe a broad range of the LLP parameter space (LLP-mass, LLP-$c\tau$)
- ATLAS search strategy for displaced decays - based on signature driven triggers that are detector dependent

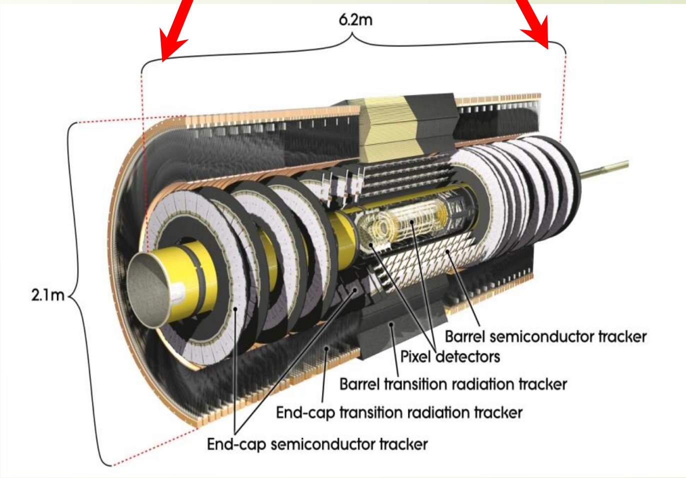
ATLAS Detector



ATLAS Inner Detector



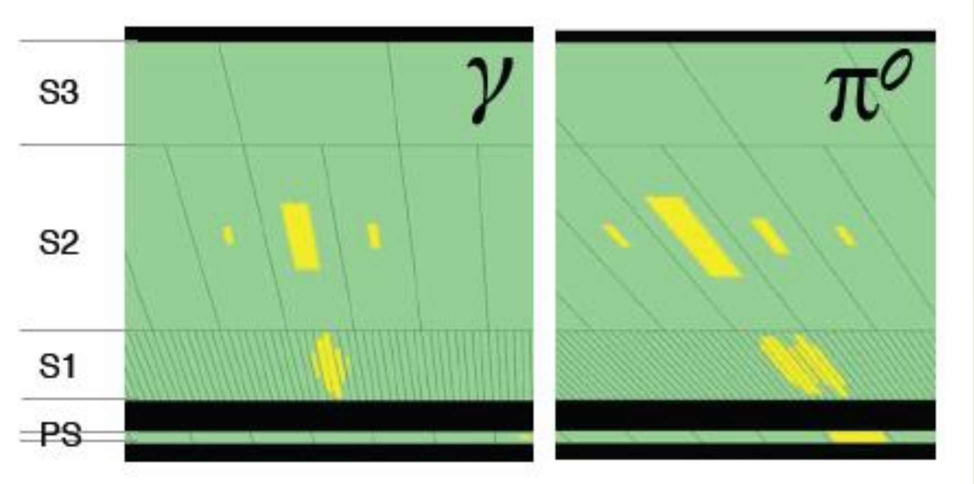


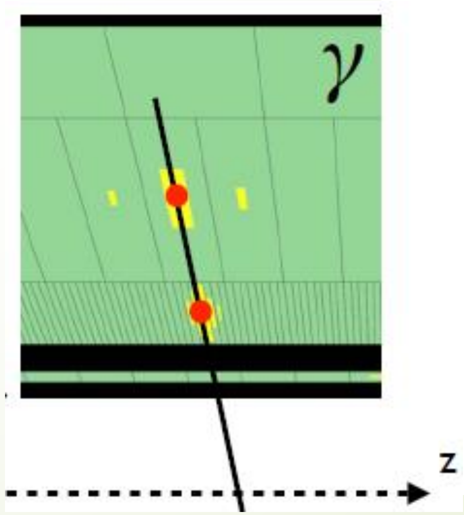


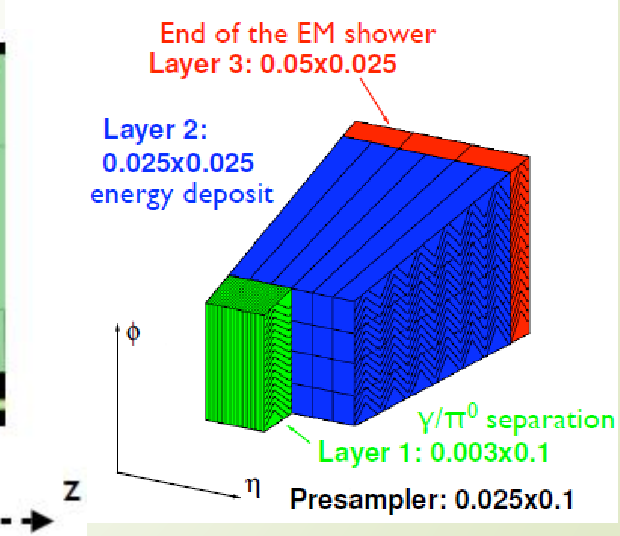
- Pixel Detector (Three + IBL layers - double sided)
  - $|\eta| < 2.5$ with $\sigma_{r\phi} \sim 10\ \mu m$, $\sigma_z \sim 115\ \mu m$ (80M channels)
- Semiconductor Tracker (SCT): single sided Si strips
  - stereo pairs
  - Four barrel layers and 2x9 end-cap disks stereo
  - $|\eta| < 2.5$ with $\boldsymbol{\sigma}_{r\phi} \sim 17\ \mu m$, $\sigma_{\mathbf{z}} \sim 580\ \mu m$ (6.3M channels)
- Pixel and strips provide good resolution tracking measurements
- Transition Radiation Tracker (tracking and e-p separation)
  - 73 barrel straw layers and 2x160 end-cap radial layers
  - $|\eta| < 2.0$ with $\boldsymbol{\sigma}_{r\phi} \sim 130\ \mu m$ (350k channels)
  - Average of 32 hits/track
- The ID embedded in a 2 Tesla solenoidal magnetic field

ECAL Segmentation

- Allows for Photon ID based on longitudinal and lateral segmentation of the ECAL (shower shapes)
- High granularity in S1 gives in good γ direction and separation power for π^0 decays to γγ
- Photon direction from shower centroids in layers 1 and 2 gives longitudinal (z) position
- For two γ (eg. H → γγ) combine to improve z-resolution of interaction point (IP)
- For displaced decays get γ direction in layers 1 and 2 to determine z of closest approach

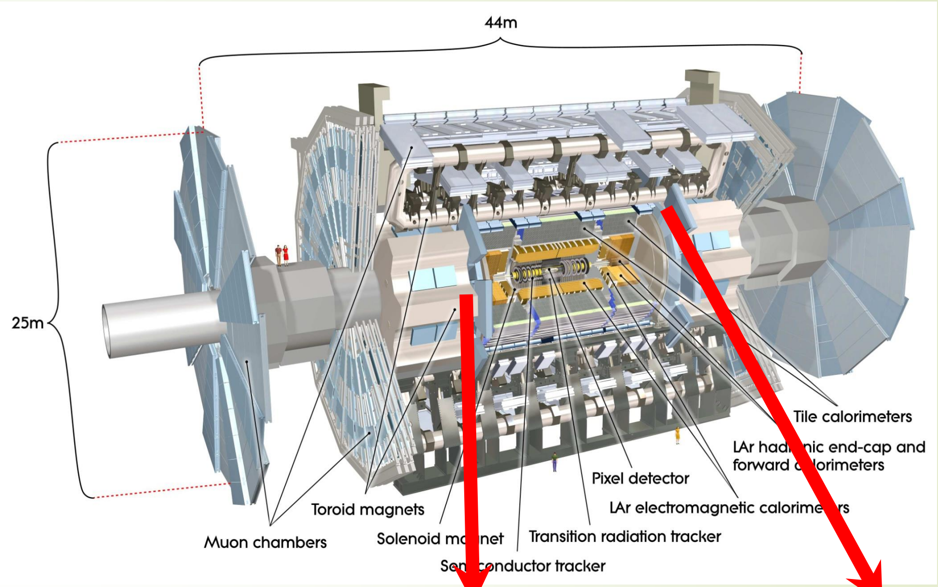


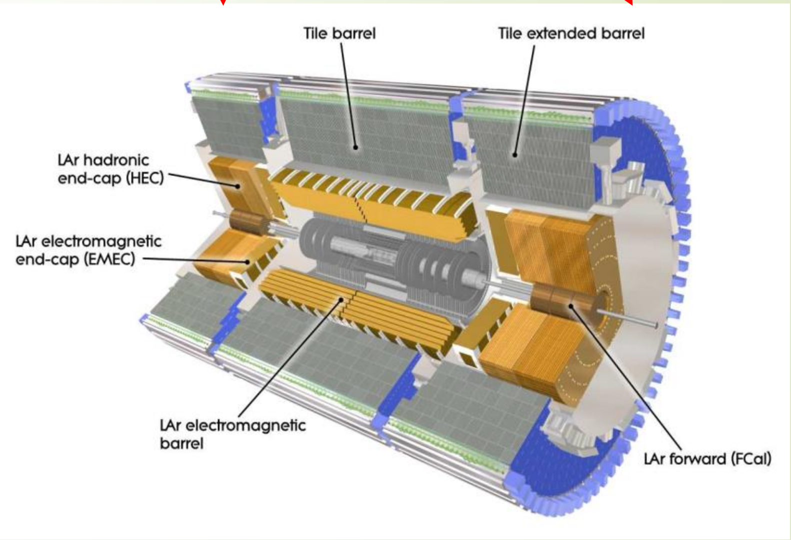




ATLAS Calorimeters

- Electromagnetic Calorimeter (ECAL)
  - **Lead accordion with liquid argon**
  - **Three longitudinal segments**
- Hadronic Calorimeter (HCAL)
  - **Barrel Fe Scintillator plates with polystyrene**
  - **Forward Cu Liquid Ar**
- Barrel Dimensions
  - ECAL 1.1m < r < 2.25m
  - HCAL 2.25m < r < 4.25m
- Calorimeters cover $|\eta| \leq 3.9$





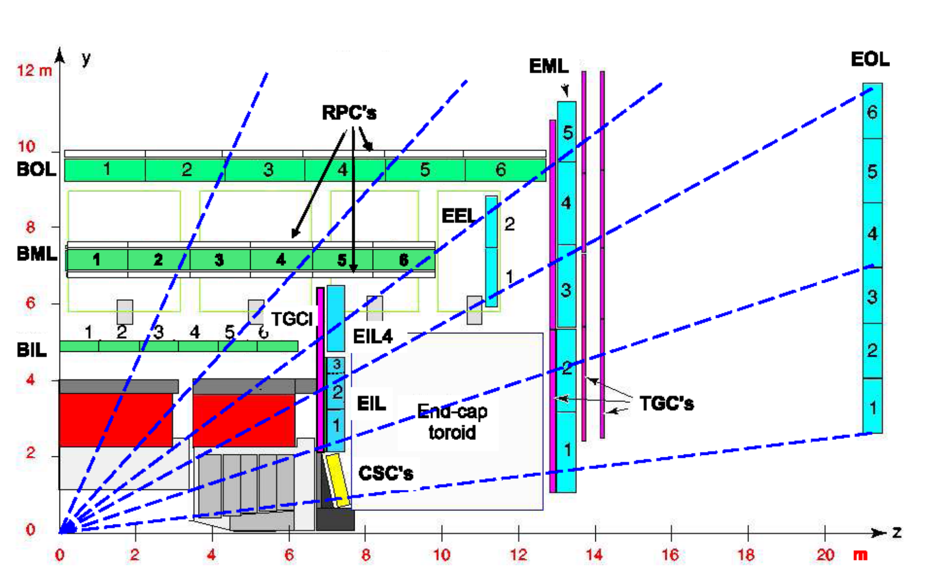
ATLAS Muon Spectrometer (MS)

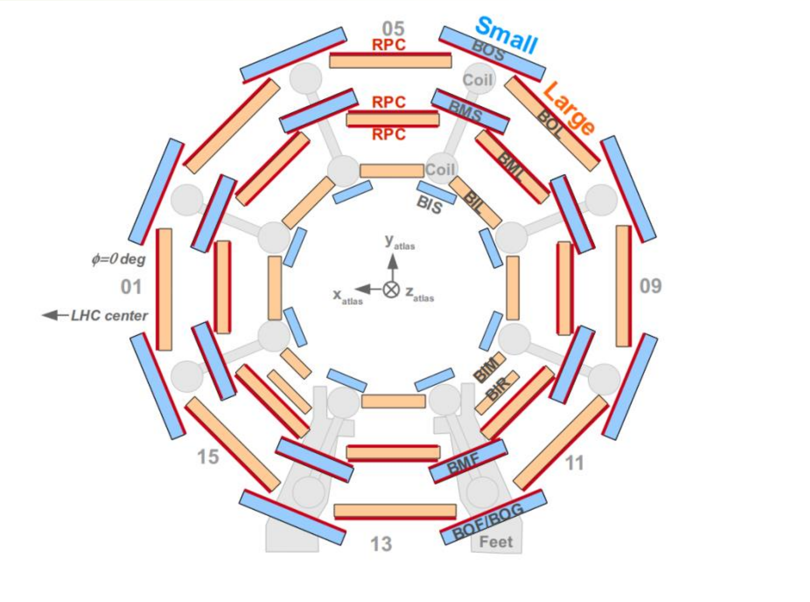
- Air core toroid - magnetic field allows for stand-alone momentum measurements and vertex reconstruction

Trigger Chambers

RPC's in barrel region covering |η|<1.05 and TGC's in Forward region 1.05< |η|< 2.4

Trigger chambers provide second coordinate (φ) for track reconstruction

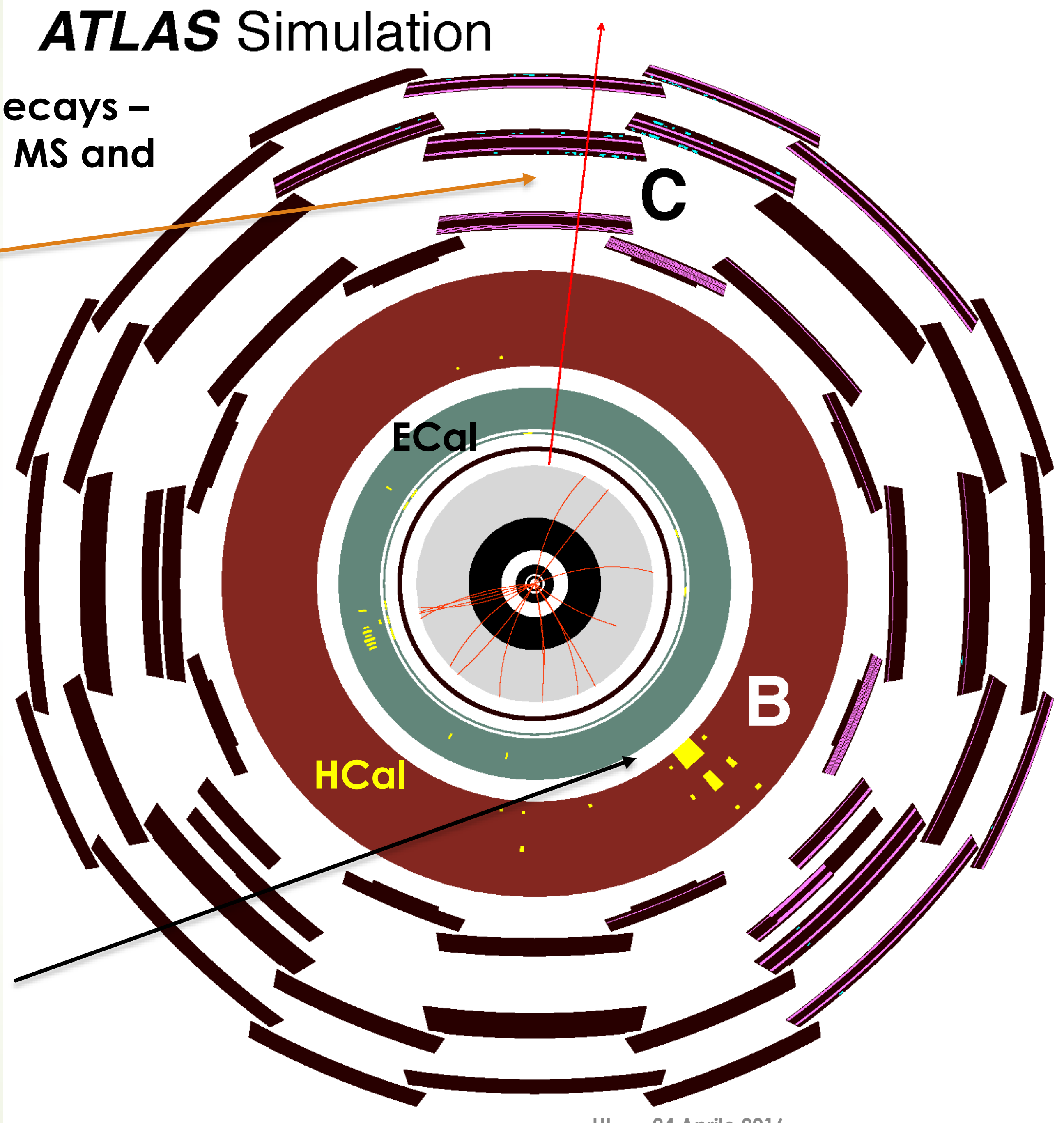




- Precision Chambers
  - Monitored Drift Tube (MDT) chambers in barrel and most of forward spectrometer
    - Barrel MDTs ~ 4.5, 7 and 10 m
    - Forward MDTs ~ 7.5 and 14 m
  - MDT chamber has two multilayers (ML) with 3 or 4 layers of MDT tubes
  - Multilayers separated: up to 32 cm
- Cathode Strip Chambers (CSC's) for 2.0 < η < 2.7
- Resolution σ_{p_T}/p_T ~ 4% at 50 GeV and ~ 11% at 1 TeV

ATLAS simulation of two displaced decays – Note unique signatures of decays in MS and HCal

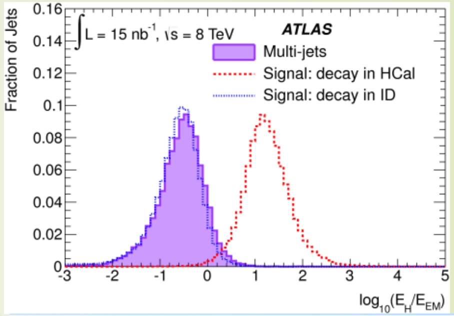
Decay in MS
Cluster of His in RPCs

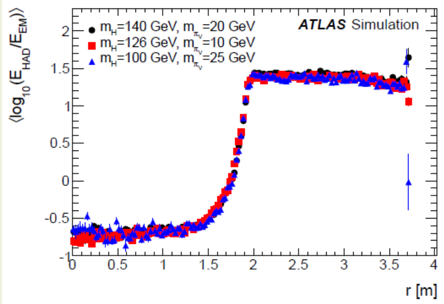


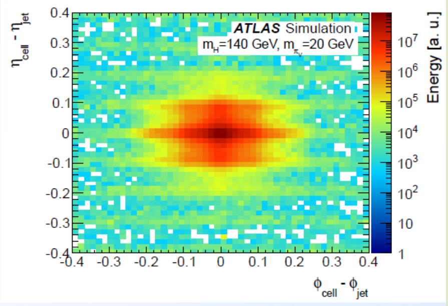
Decay at beginning of HCal
Low EM energy deposition

ATLAS LLP trigger for displaced Hadronic Jets

- Signatures of a displaced decay of neutral particle to a hadronic jet
  - Inner Detector displaced vertex with no tracks pointing to IP
    - Trigger under development for Run-2
  - Decay at end of ECal or in Hcal
  - Trigger selects isolated jet with low EM fraction
  - Run-1 rigger selects isolated jet with low EM fraction
    - Large E_{HCal}/E_{EM}, narrow jet and no ID tracks in jet cone
    - TAU40 L1 seed then reconstruct tracks and jet at HLT
    - Isolation: no $p_T > 1$ GeV tracks in $\Delta R < 0.2$ cone around jet axis
    - $E_T > 30$ GeV Jet with $\text{Log}_{10} [E_{HCal}/E_{EM}] > 1.2$
    - Beam halo removal: Calorimeter cell timing
  - Run_2 L1 Topo triggers → combine objects from different subsystems
    - Tau30 & no associated EM cluster (once L1 Topo triggers available)
    - Until it is available use L1_Tau_60
    - $E_T > 30$ GeV Jet with $\text{Log}_{10}[E_{HCal}/E_{EM}] > 1.2$
    - No $p_T > 2$ GeV tracks in $\Delta R < 0.2$ cone around jet axis
    - Beam Halo Veto (improved in 2016)
    - Dedicated jet cleaning to avoid spikes in the trigger rates due to LAr noise





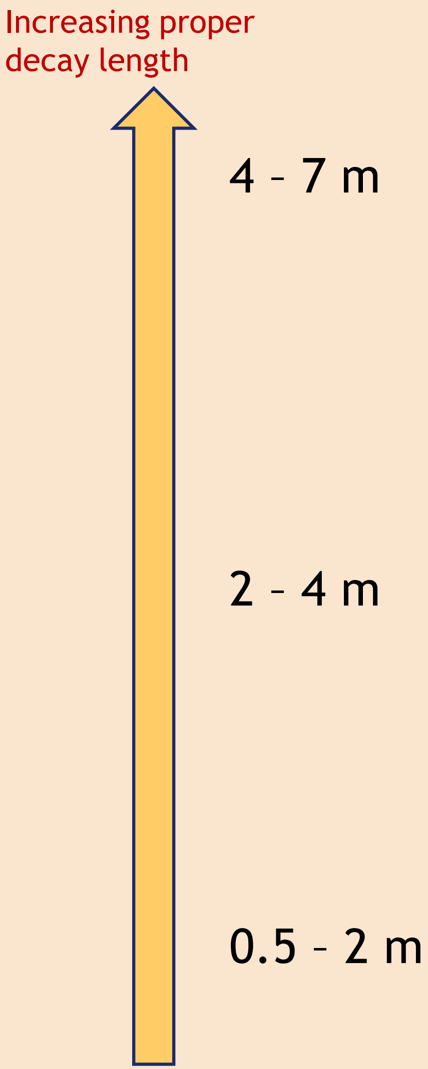


ATLAS LLP trigger for decays in the muon spectrometer

- Muon RoI cluster trigger selects cluster of tracks in MS
  - The signature of neutral particle decay at end of HCal or in MS
- Trigger selects an isolated cluster of muon RoIs (Run-1& Run-2)
  - L1_2MU10
  - Require 3 (4) muon RoIs in $\Delta R < 0.4$ cone in MS Barrel (endcaps)
  - No tracks with $p_T > 5$ GeV in $\Delta R < 0.4$ cone around the muon cluster direction
  - No $E_T > 30$ GeV jet in a $\Delta R < 0.7$ cone around the muon cluster center with $Log_{10}[E_{HCal}/E_{EM}] < 0.5$
- New Run-2 MS trigger
  - Same first two criteria
  - NO ISOLATION
  - Provides and orthogonal back-ground sample
    - Can be used to compare to "signal Trigger" sample
    - Becomes powerful when used for sample of reconstructed MS vertices
    - More details later
  - Lepton-jet: new narrow-scan μ-trigger (20GeV L1 μ seed; HLT_mu6_Msonly in $\Delta R<0.5$)

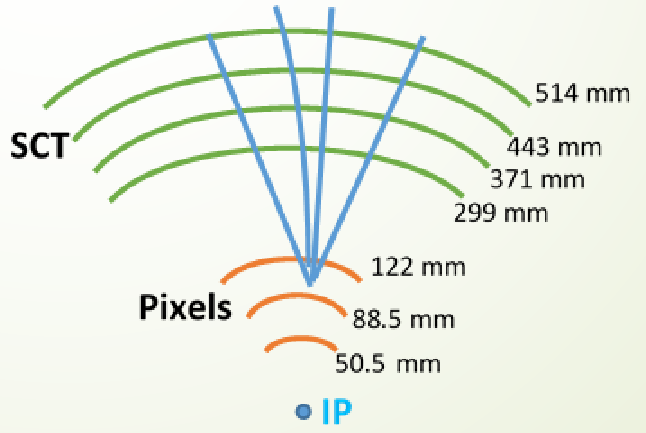
Signature driven triggers

- Muon Spectrometer RoI cluster trigger
  - Selects decays inside of MS (only active in barrel)
  - Events with at least 3 muon RoI's in Δ R < 0.4 cone
  - Isolation
    - Jets with E_T>35 GEV in DR < 0.4 around cluster center
    - ID tracks (p_T > 5 GeV) in Δhx Δ f = 0.2x0.2
- Calorimeter energy ratio trigger (E_{HAD}/E_{EM})
  - Selects decays at end of E_{CAL} or in H_{CAL}
  - Log[E_{HAD}/E_{EM}] > 1.2
  - Isolation
    - No tracks > 1 GeV in DR = 0.2 cone around the jet axis
- Trackless jet trigger (decays in ID…)
  - In development



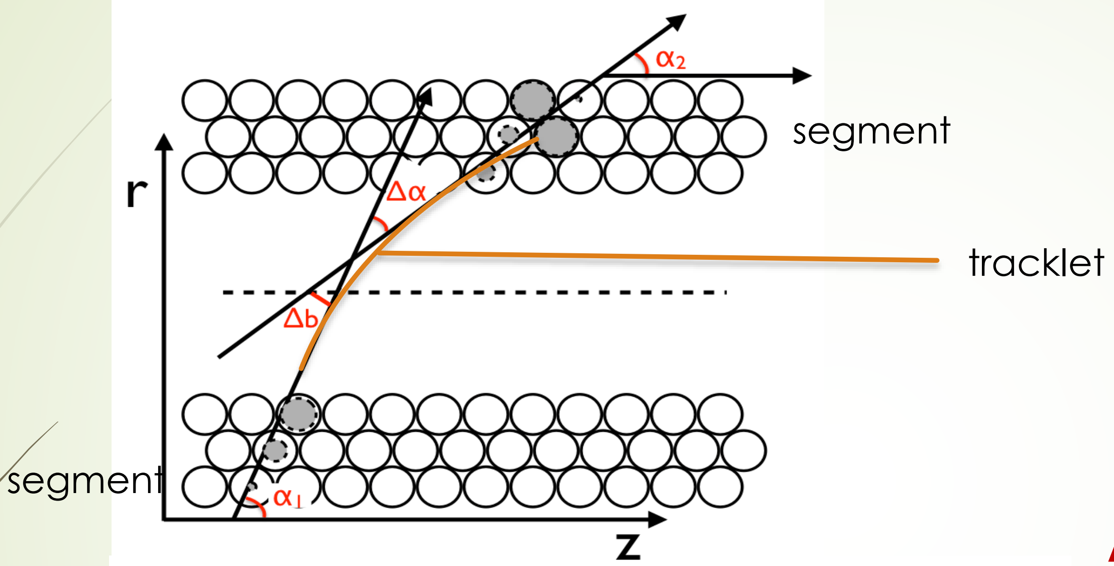
ATLAS Displaced Vertex reconstruction

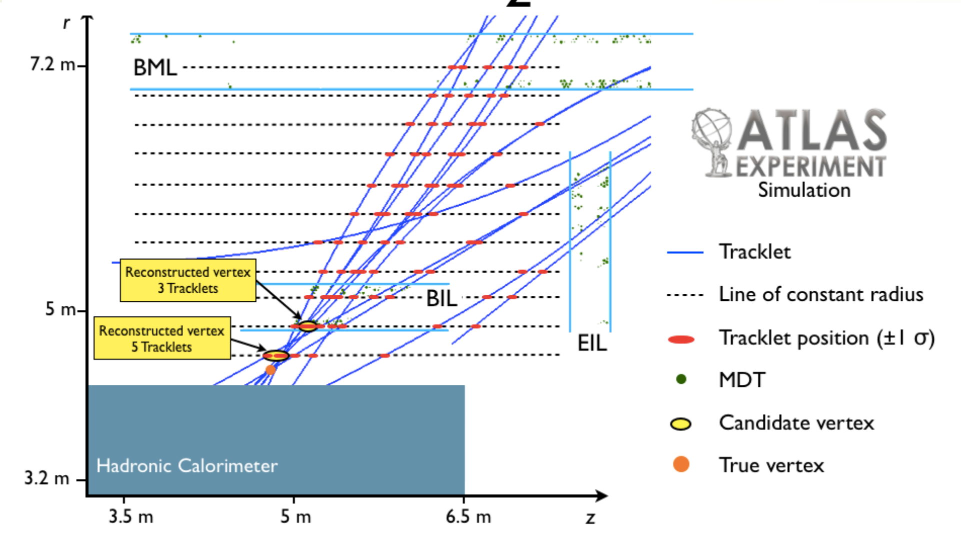
- Custom ID and MS displaced vertex reconstruction algorithms developed and used in several Run-1 ATLAS analyses
  - Two ID displaced vertex reconstruction algorithms used in Run-1
    - Modification of IP vertex reconstruction algorithm
    - Modifications of secondary vertex reconstruction algorithm used for B-decays
    - Require a calorimeter jet consistent with displaced vertex



ATLAS Displaced Vertex reconstruction

- MS stand-alone vertex reconstruction (JINST 9 P02001, arXiv:1311.7070) G. Ciapetti, HL





In barrel MS track segments formed in the two layers of muon chamber are combined to form a "tracklet" that are Grouped (cone algorithm).

These tracklets are back extrapolated and an iterative fit made to get vertex position.

Analyses need to define "good vertex" Criteria (Jet isolation, MDT/TGC activity…)

MS vertex reconstruction used for the ATLAS Run-1 searches for displaced hadronic jets decaying in MS

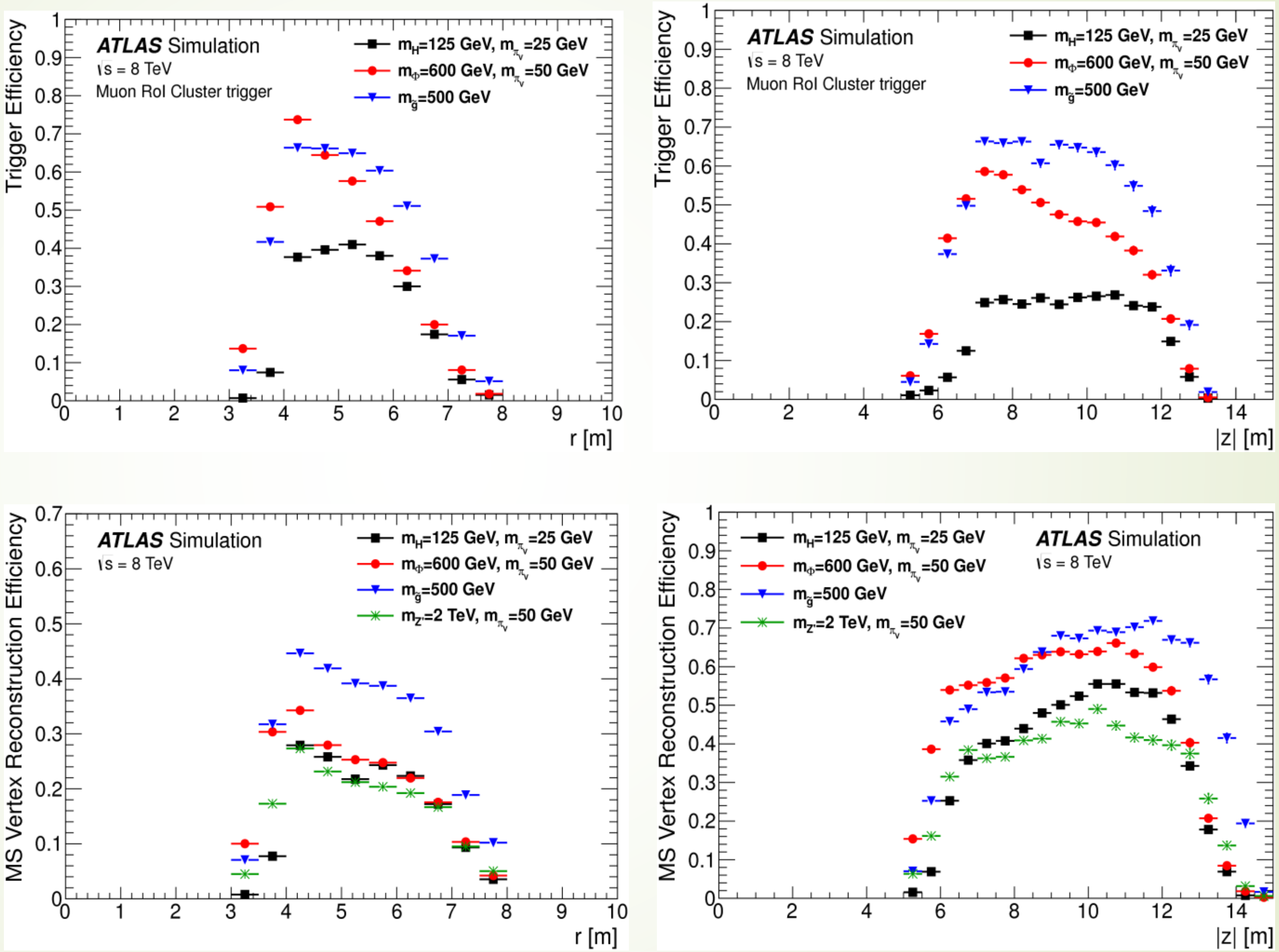
NEW Run- 2 MS vertex reconstruction run on every event accepted by an ATLAS trigger – part of data stream

RoI Cluster Trigger and MS vertex reconstruction efficiencies

- **Run-1 trigger and MS vertex reconstruction efficiencies**

Trigger

Vertex

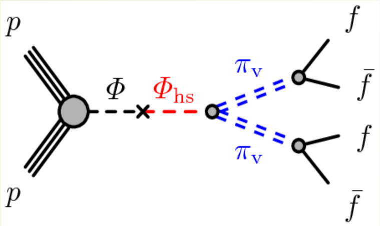
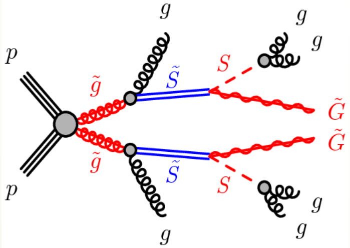
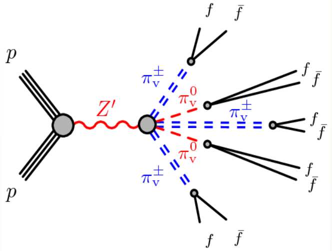


barrel **endcaps**

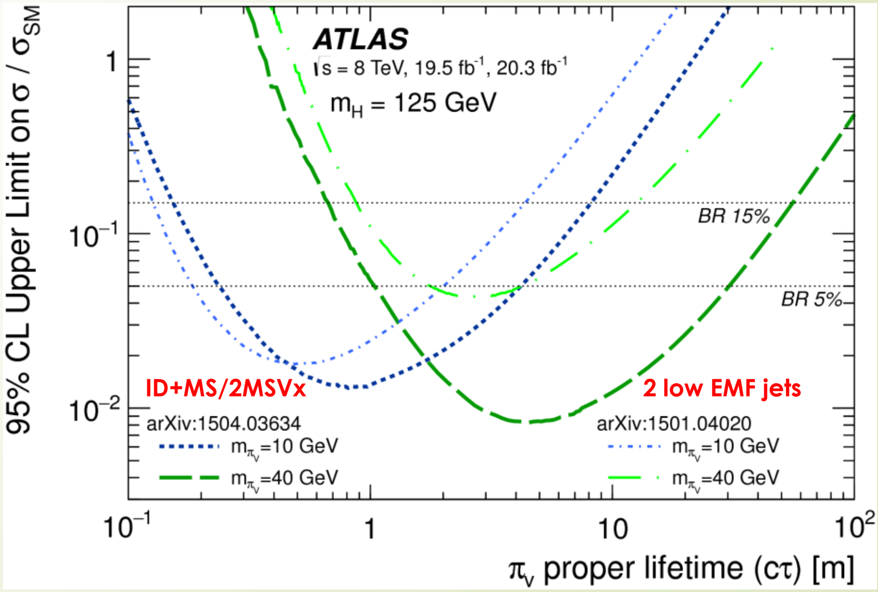
Run-1

- Searches requiring two displaced decays
  - Two low EM fraction (EMF) jets (decays in the HCal)
  - Two reconstructed displaced vertices
    - 2MS vertices or MS vertex plus ID vertex
  - Sensitive to Higgs decaying to long-lived scalar pairs
  - **No evidence for two vertex events in the Run-1 data** set limits for Higgs decay to long-lived scalar pairs, Stealth SUSY and heavy Z' decay (long-lived particles indicated by double lines)

Scalar boson mass [GeV]	π_v mass [GeV]
100	10, 25
125	10, 25, 40
140	10, 20, 40
300	50
600	50, 150
900	50, 150
Z'mass [TeV]	π_v mass [GeV]
1	50
2	50
2	120
$\tilde{g}$ mass [GeV]	$\tilde{S}$, S mass [GeV]
110	100, 90
250	100, 90
500	100, 90
800	100, 90
1200	100, 90

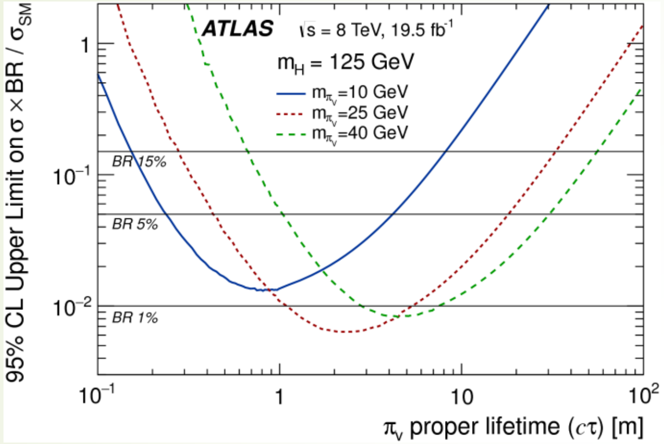




Trigger	Applicable topologies	Benchmarks
Muon RoI Cluster	IDVx+MSVx, 2MSVx	Scalar boson, Stealth SUSY
Jet+E_T^{miss}	2IDVx, IDVx+MSVx, 2MSVx	Z'



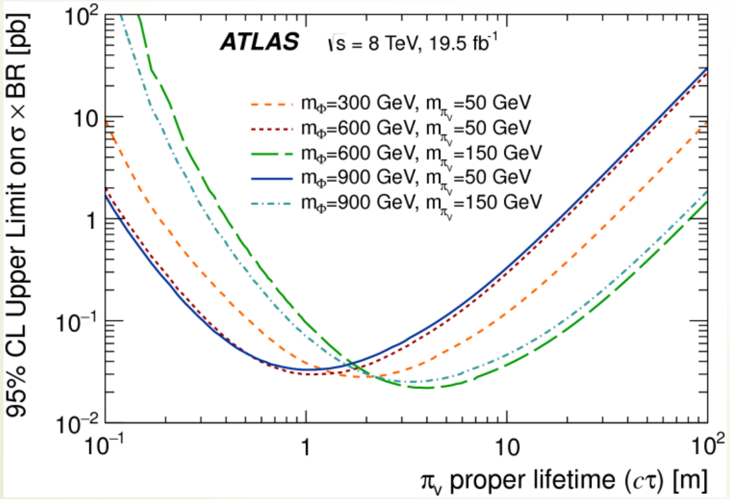
Run-1 Results

- 2MS vertices or MS vertex plus ID vertex [arXiv:1504.03634, Phys. Rev D92, 012010 (2015)]
  - π_v proper decay lengths excluded at 95% CL assuming 30%, 15%, 5%, or 1% BR for m_H = 125 GeV.



m_{π_v} [GeV]	Excluded $c\tau$ range [m] 1% BR	5% BR	15% BR	30 % BR
10	no limit	0.24–4.2	0.16–8.1	0.12–11.8
25	1.10–5.35	0.43–18.1	0.28–32.8	0.22–46.7
40	2.82–7.45	1.04–30.4	0.68–55.5	0.52–79.2

- σ × BR 95% CL limits for scalar boson samples: m_Φ = 300 GeV, 600 GeV, and 900 GeV



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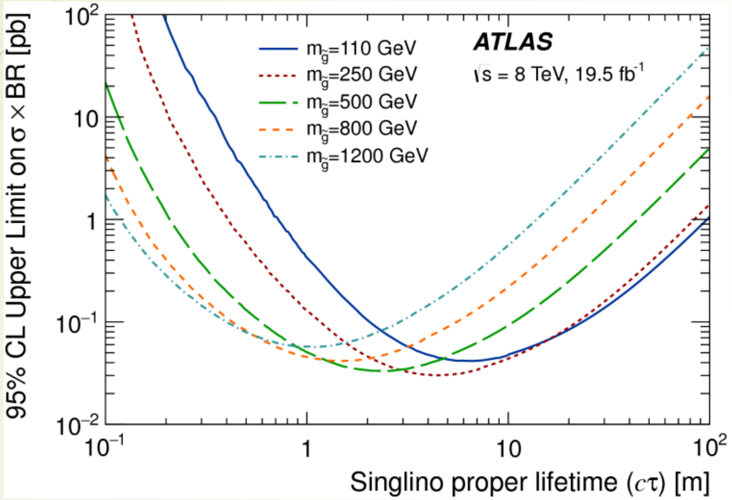
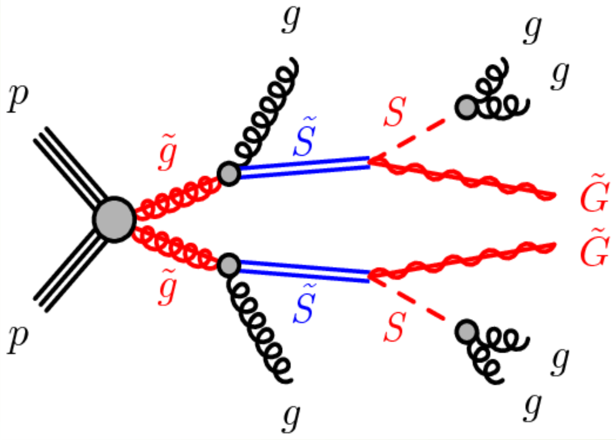
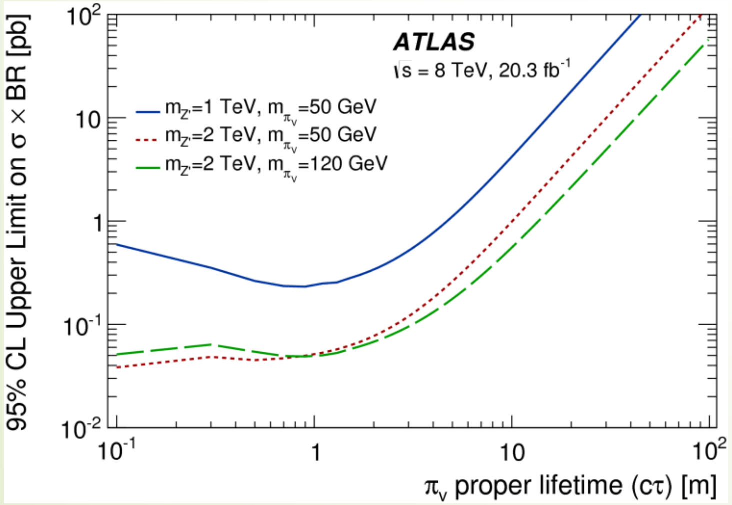
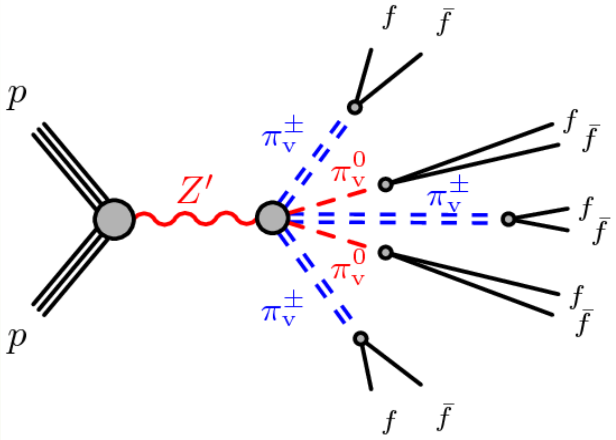




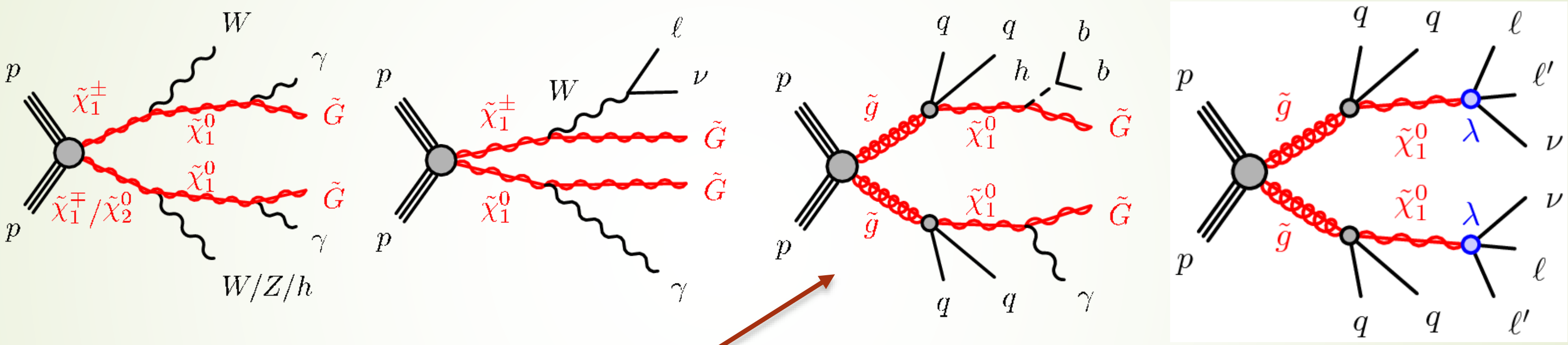


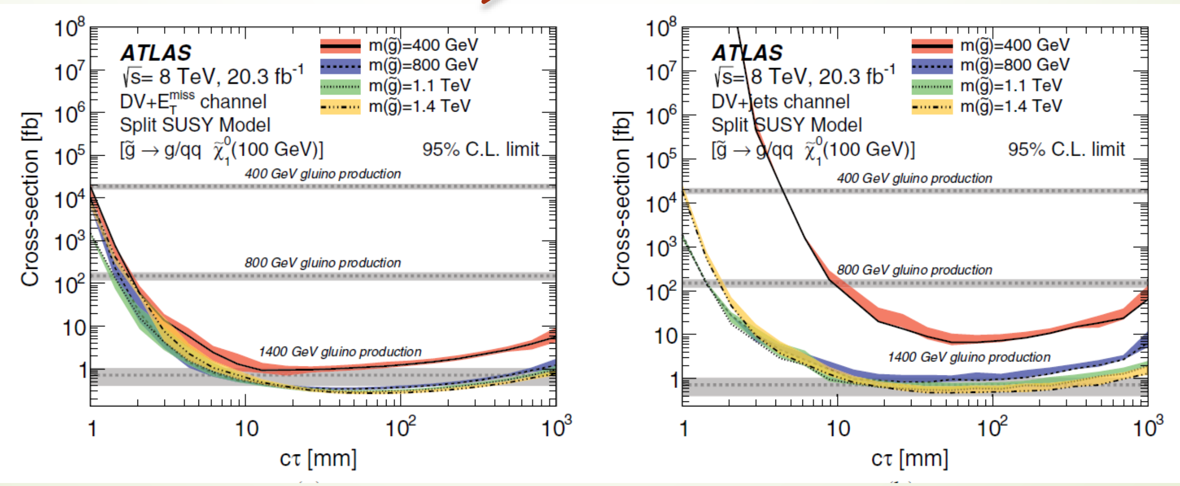


RPV SUSY LLP Searches

PhysRevD.92.072004
arXiv:1504.05162

- Extensive Analysis with no observed events
- Require DV with hi-p_T μ or e that comes from DV, missing E_T and one DV per event
  - Limits for various scenarios





ATLAS Non-pointing Photon Search

- Gauge mediated SUSY Breaking (GMSB) – R-parity conserving
  - lightest neutralino $\tilde{\chi}_1^0$ is the NLSP, with finite lifetime
  - decays $\tilde{\chi}_1^0$ → γ $\tilde{G}$
  - Signature: displaced, non-pointing gamma arrives late and MET from $\tilde{G}$
  - Snowmass Points and Slopes parameter set 8 (SPS8) interpretation

ATLAS Run-1 – 8 TeV
Phys. Rev. D. 90, 112005 (2014)
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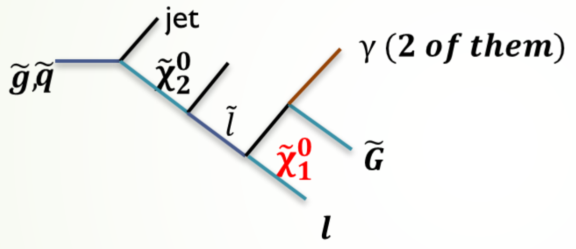
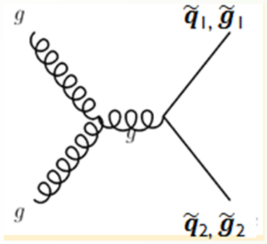
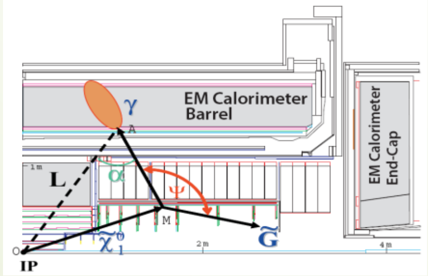


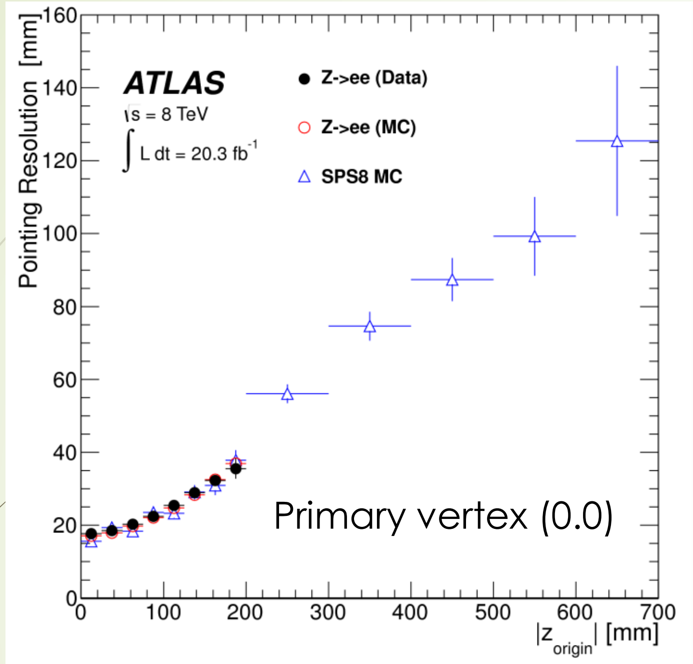


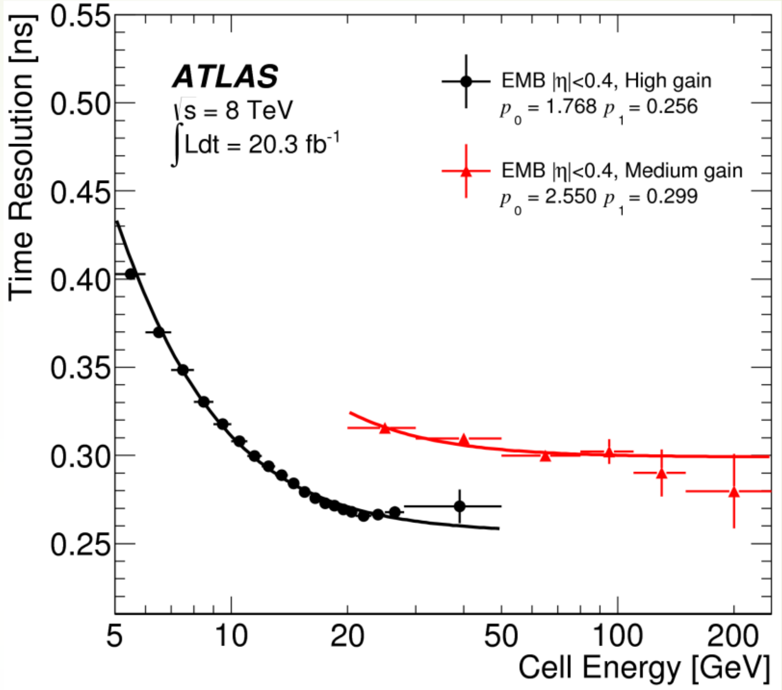
- LAr energy deposition in first two ECal layers gives measure of displacement from IP; identifies displaced photon candidate
- Set limits in context of GMSB SP8 model for region of (Λ, τ_{NLSP}) space



Potentially longer path plus slow NLSP gives late arrival
Use ECal timing information

EM shower pointing and Timing resolution





- In limit of large energy deposits have 256 ps (299 ps) for High (Medium) gain
- Time resolution: contribution of ≈ 220 ps from LHC bunch-spread along the beamline.
- Data are in good agreement with the background only fit and no evidence for non-pointing and delayed photons is observed.
- Set limits in context of GMSB SP8 model for region of (Λ,τ_{NLSP}) space

ECAL Segmentation

- Allows for Photon ID based on longitudinal and lateral segmentation of the ECAL (shower shapes)
- High granularity in S1 gives in good γ direction and separation power for π^0 decays to γγ
- Photon direction from shower centroids in layers 1 and 2 gives longitudinal (z) position
- For two γ (eg. H → γγ) combine to improve z-resolution of interaction point (IP)
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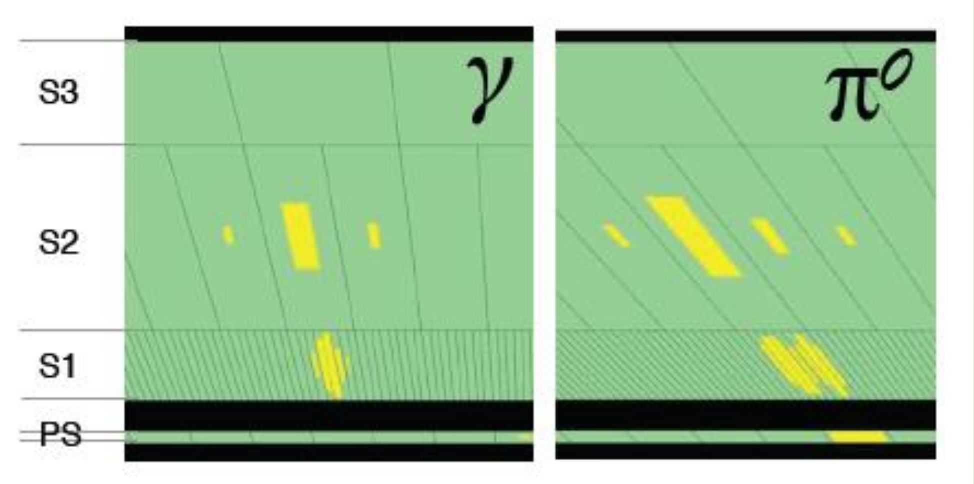
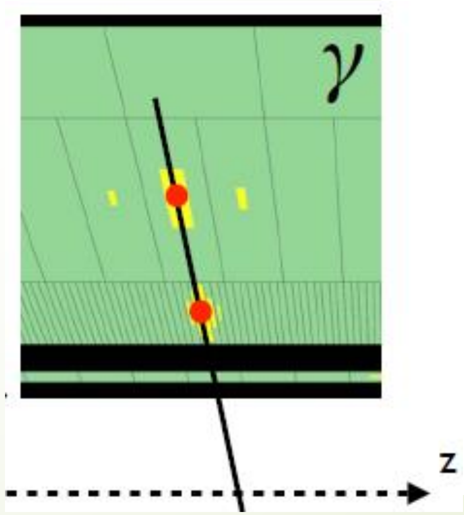
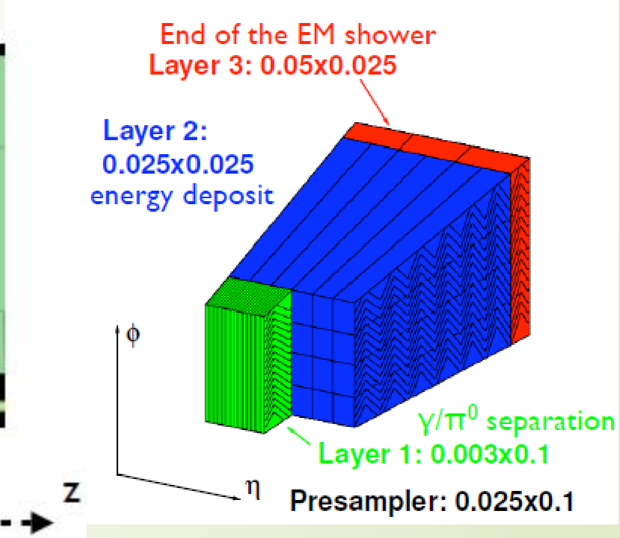
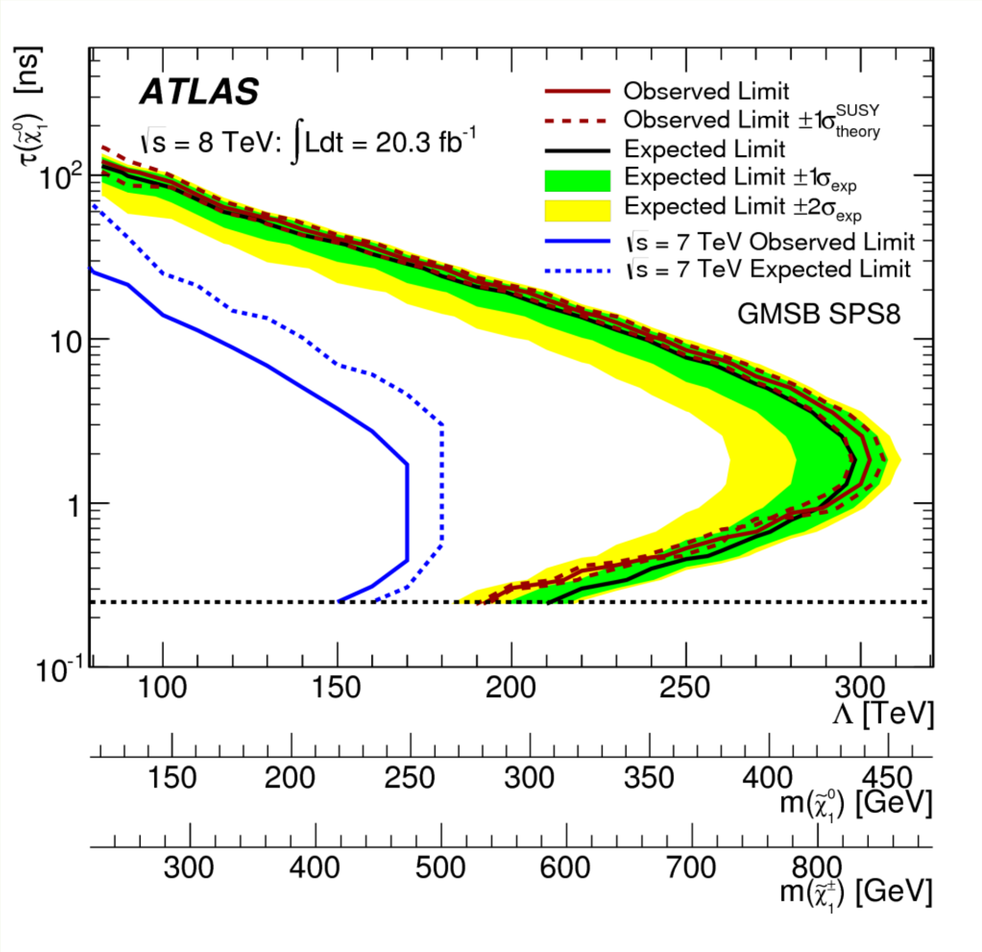






Exclusion Limit – GMSB SPS8 model

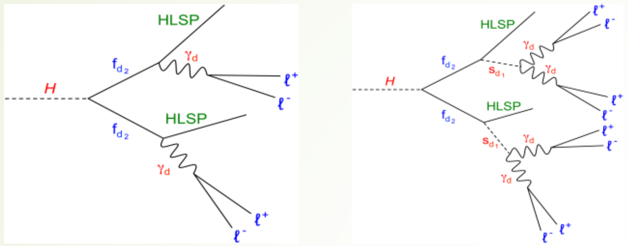


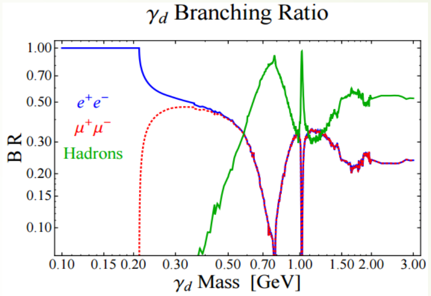
Λ effective scale of SUSY breaking scale

95% CL exclusion limits for 0.25 < t < 100 ns and 80 < Λ < 300

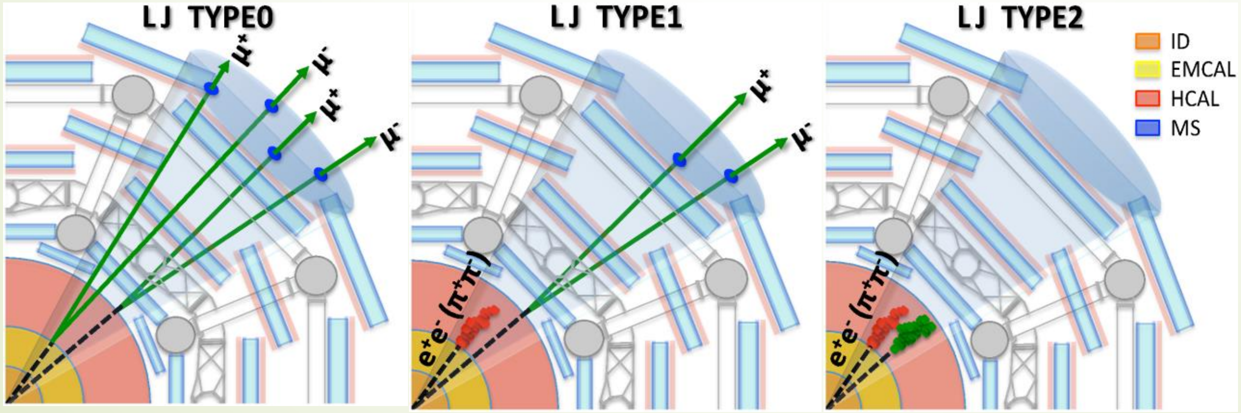
Displaced lepton-jets Run-1Results

- Displaced Lepton-Jets arXiv:1409.0746 JHEP11(2014)088 G. Ciapetti, S. Giagu
  - kinetic mixing of light γ_d with SM γ through vector portal
  - ATLAS search based on FRVZ bench marks: JHEP 05 (2010) 077 [arXiv:1002.2952]





- Searched for $2\gamma_d$ and $4\gamma_d$ decaying to lepton jets
- Used a lepton-jet gun to simulate individual displaced LJs from one γ_d decay and hidden scalar $s_d \rightarrow \gamma_d \gamma_d$
- Generate efficiency maps uniform in p_T, η, and decay position with LJ gun samples that are independent of a specific model



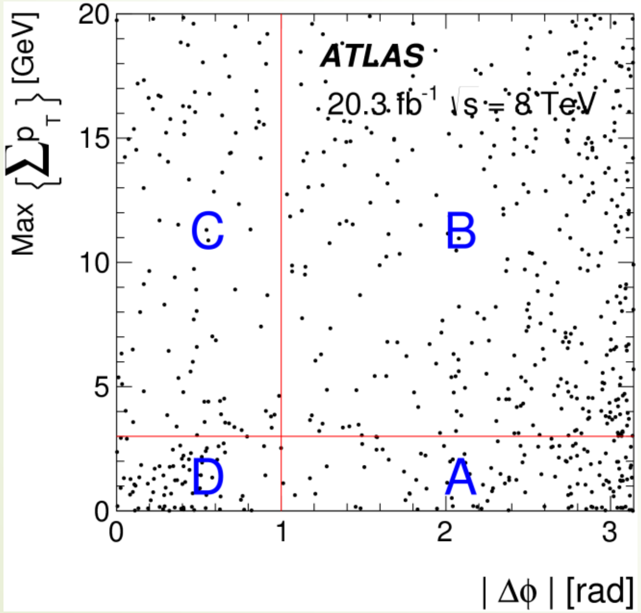
Type 0: all γ_d -> μ's
Type 1: $1\gamma_d$ -> ee or $\pi\pi$, $1\gamma_d$ -> 2μ
Type 2: all γ_d -> ee or $\pi\pi$

Displaced lepton-jets Run-1Results

- Main Backgrounds are cosmic and QCD jets
  - Used empty bunches to determine cosmic background

Data Type	Events in B	Events in C	Events in D	Expected Events in A
Cosmic-ray data	0	0	60 ± 13	40 ± 10
Data (cosmic rays subtracted)	362 ± 19	99 ± 10	19 ± 16	70 ± 58

  - QCD jets is irreducible background - evaluated using ABCD method where $\Delta\phi$ is azimuthal angle between the two lepton jet
  - Data is consistent with expected backgrounds
  - Type2-Type2 have largest background – most sensitive limit by excluding these events



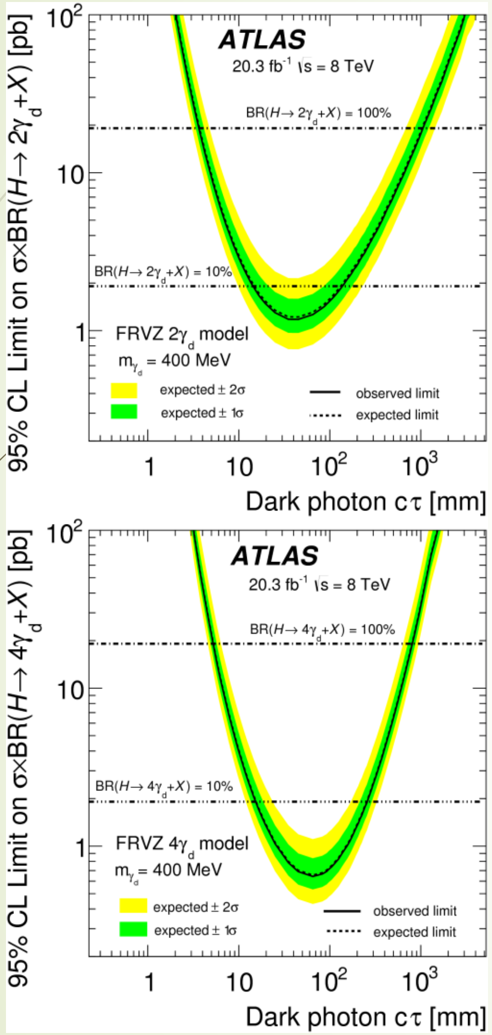
	All LJ pair types	TYPE2-TYPE2 LJs excluded
Data	119	29
Cosmic rays	$40 \pm 11 \pm 9$	$29 \pm 9 \pm 29$
Multi-jets (ABCD)	$70 \pm 58 \pm 11$	$12 \pm 9 \pm 2$
Total background	$110 \pm 59 \pm 14$	$41 \pm 12 \pm 29$

No Type2-Type2

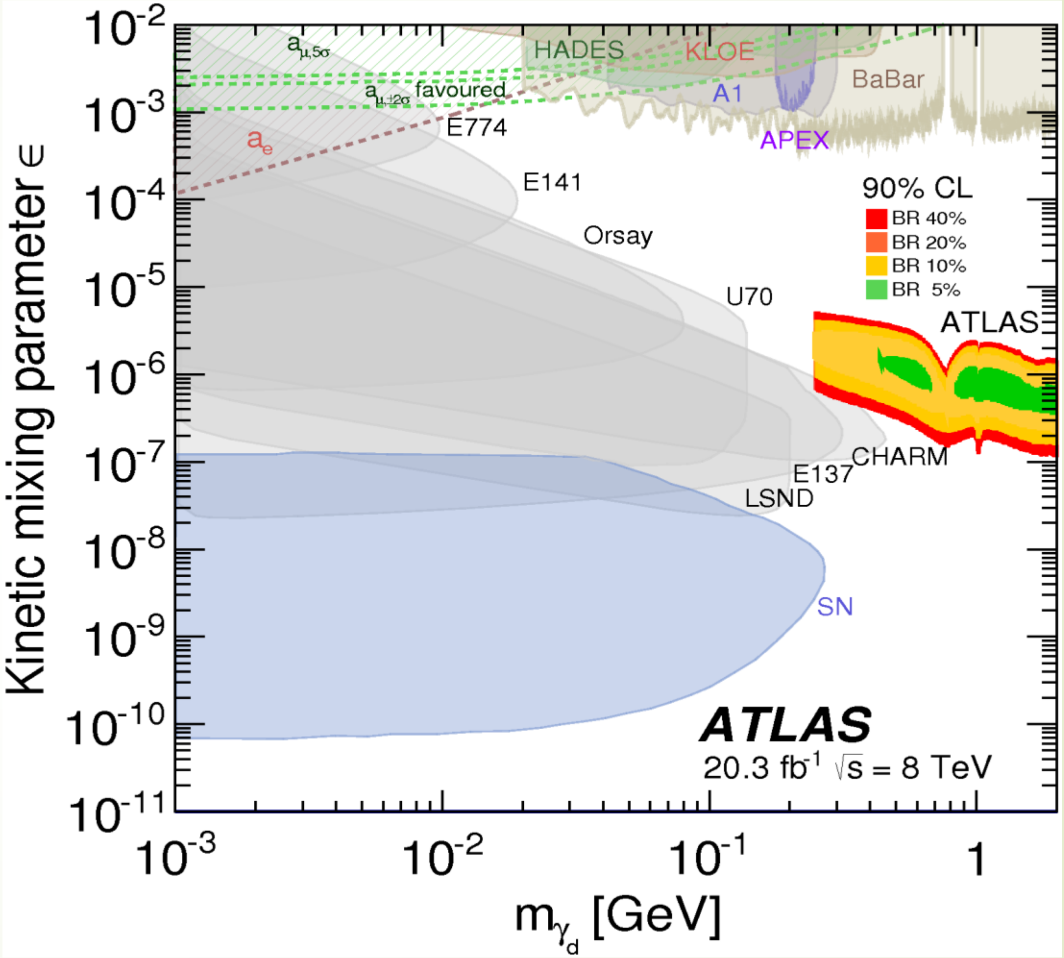
FRVZ model	Excluded $c\tau$ [mm] BR(10%)
$H \rightarrow 2\gamma_d + X$	$14 \leq c\tau \leq 140$
$H \rightarrow 4\gamma_d + X$	$15 \leq c\tau \leq 260$

Run-1

- **Results obtained from the lepton-gun MC efficiencies**



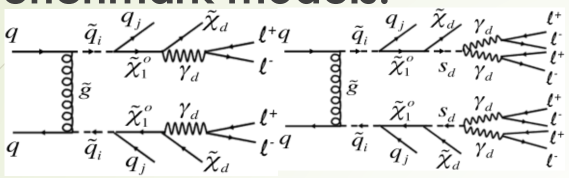
Type 0 and 1 only limits



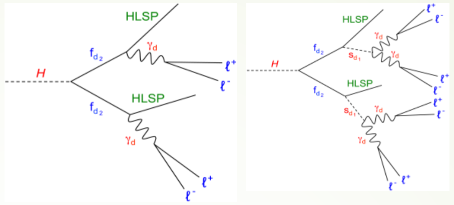
ATLAS limits in the global ε vs $m_{\gamma d}$ plot
NB: ATLAS result depend on BRs and are for specific final states.

Prompt lepton-jets Run-1 results

- Prompt Lepton-Jets [JHEP02(2016)062, arXiv:1511.05542]
  - Benchmark models:



SUSY production of dark χ



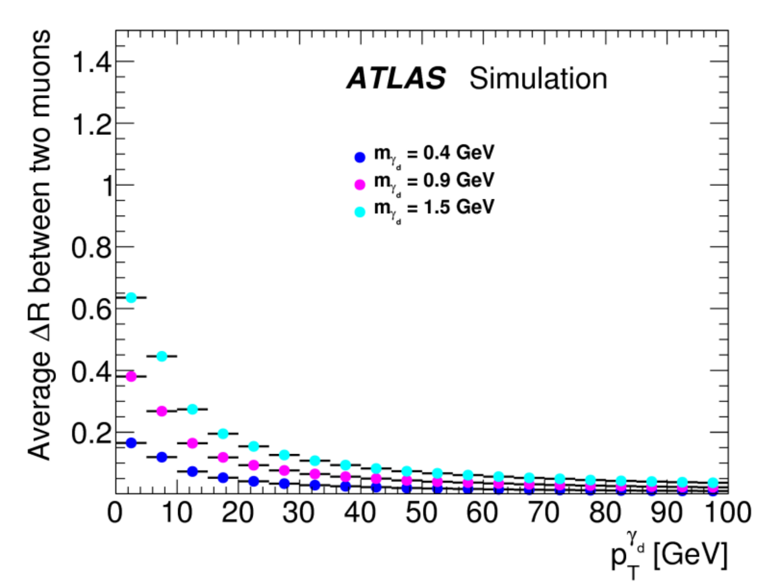
FRVZ Higgs-portal

  - Two scenarios $\gamma_d \rightarrow ee$, $\mu\mu$ or $\pi\pi$ and $s_d \rightarrow \gamma_d \gamma_d$
  - Event selection: requires 2 LJs from combinations of e-jet (eLJ), μ-jet (μLJ), mixed (eμLJ) where jet ≥ 2 tracks

Use EM-Cal segmentation to separate electrons from π^o

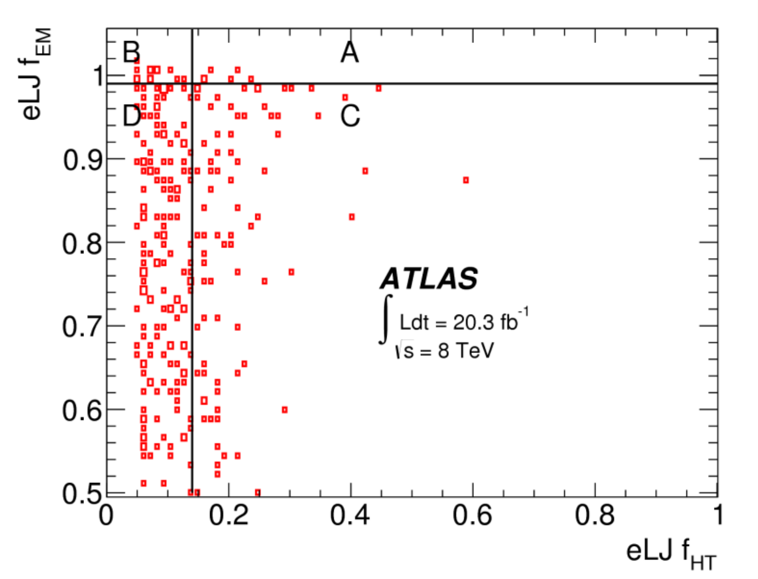
6 categories of events:
eLJ-eLJ, μLJ-μLJ, eLJ- μLJ
eLj-e μLJ, μLJ-e μLJ, e μLJ-eμLJ

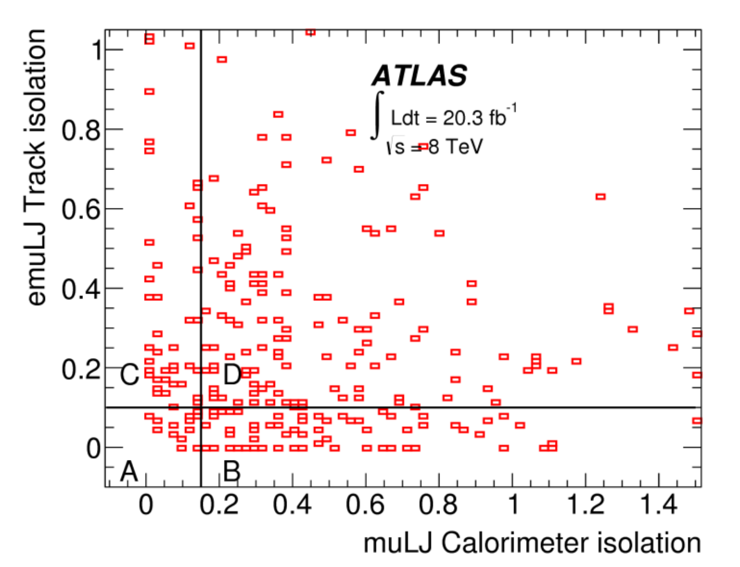
  - γ_d high boost – small opening angles
  - μLJ requires at least two muons with p_T > 10 GeV within ΔR = 0.5 of LJ



Prompt Lepton Jets Run-1 results

- . Main SM backgrounds from OCD jets
  - Use ABCD method to determine SM backgrounds
  - For each of the 6 categories of events have 2 “uncorrelated” variables



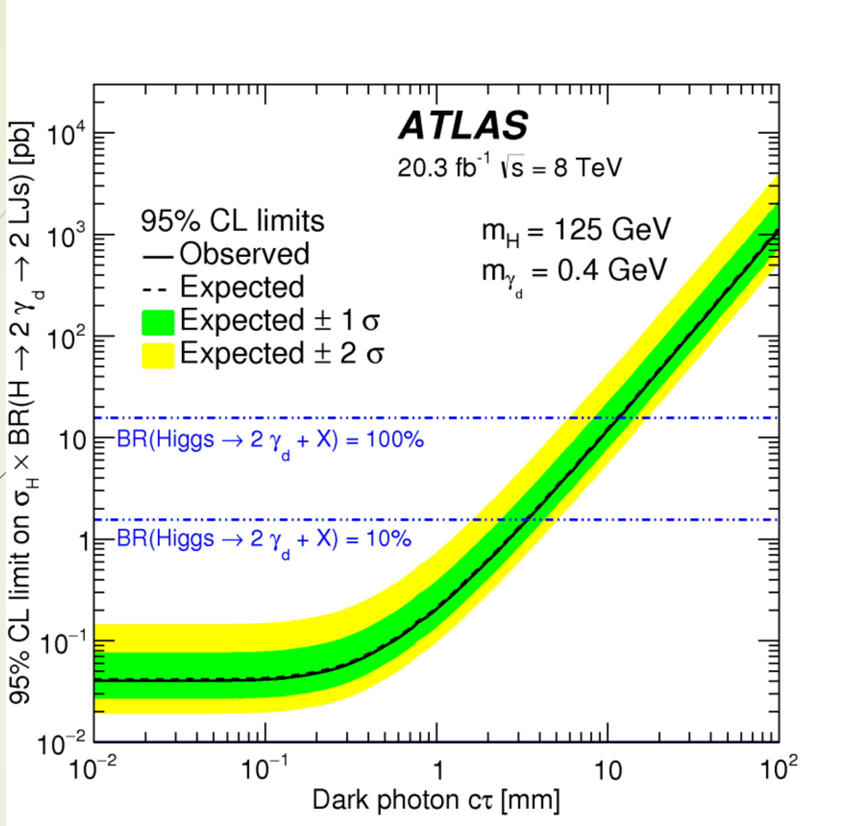


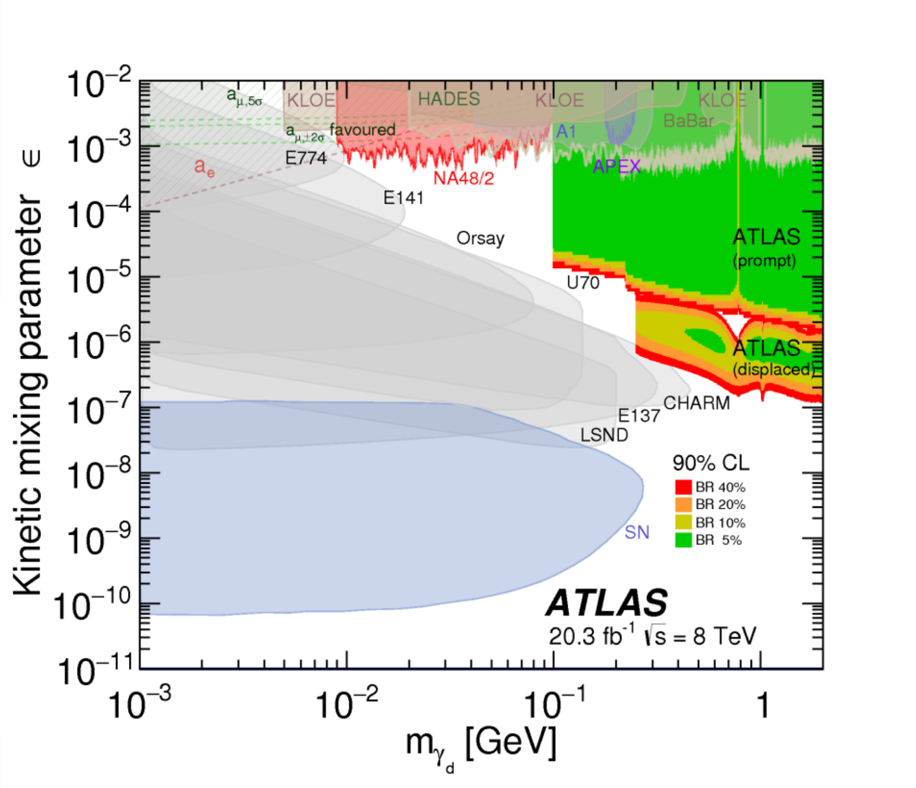
No deviations from SM expectations – set 95% CL

Channel	Background (ABCD-likelihood method)	Background (total)	Observed events in data
eLJ–eLJ	2.9 ± 0.9	4.4 ± 1.3	6
muLJ–muLJ	2.9 ± 0.6	4.4 ± 1.1	4
eLJ–muLJ	6.7 ± 1.4	7.1 ± 1.4	2
eLJ–emuLJ	7.8 ± 2.0	7.8 ± 2.0	5
muLJ–emuLJ	20.2 ± 4.5	20.3 ± 4.5	14
emuLJ–emuLJ	1.3 ± 0.8	1.9 ± 0.9	0

Prompt Lepton-jets Run-1 Results

- Sensitive to very small $c\tau$





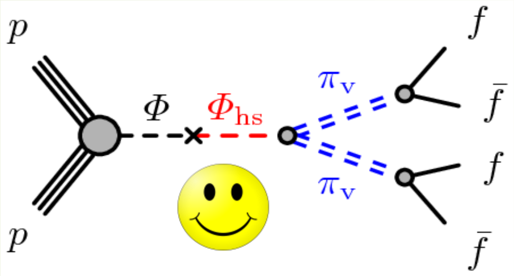
NB the ε vs $m_{\gamma d}$ results from both prompt and displaced LJs is model dependent (FRVZ)

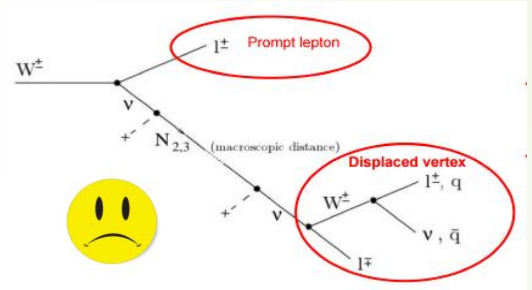
Run-2 displaced analysis – can we do better

- Current displaced decay searches either

(I) Require two displaced object per event

- Works only for LLPs that are produced in pairs



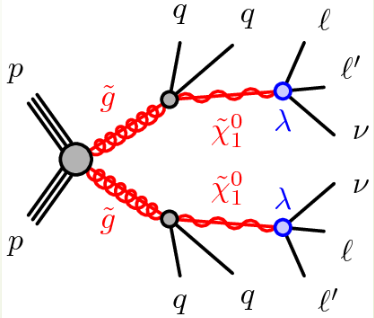


- reduced lifetime sensitivity - scales like $1/(c\tau)^2$

(II) Require one displaced vertex plus an associated high energy object (m, MET..)

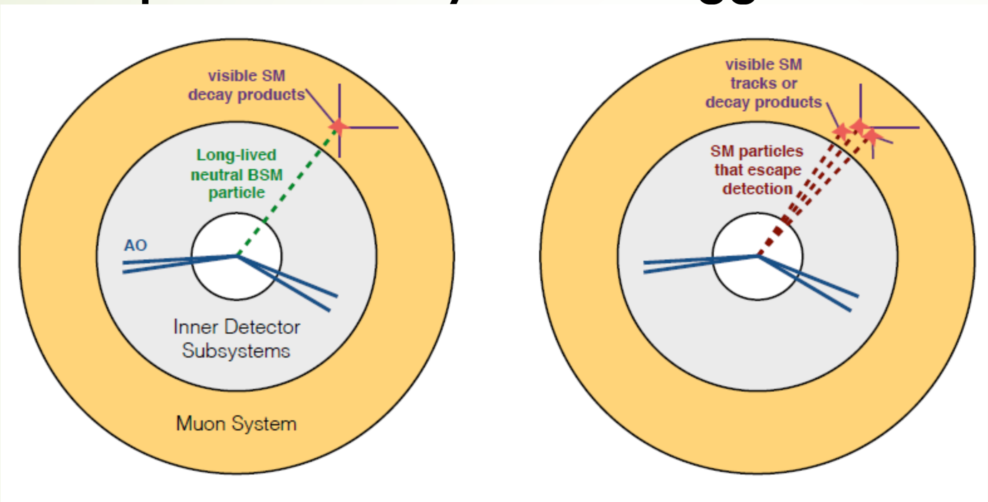
- OK for SUSY models but not for many other BSM models

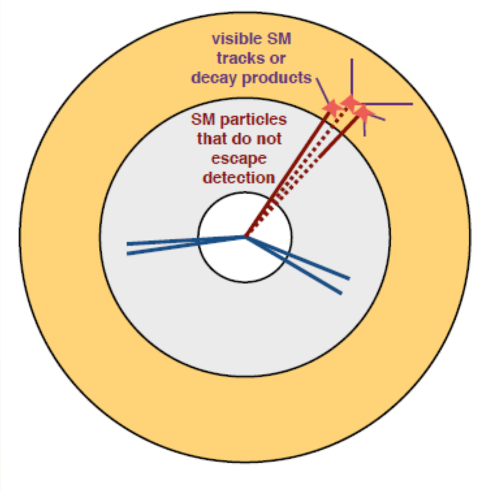
e. g. RPV with long-lived neutralino



Single vertex analyses – New approach

- No SM displaced objects, but plenty of jet production
  - Main source of background for LLP searches is from jets that fake a displaced object in HCal or punch through to MS and reconstruct as a displaced vertex that look exactly like expected signal
    - Requiring 2 reconstructed displaced vertices in MS (Run-1) kills this background
- **MS displaced decay in MS - trigger selection**





arXiv:1605.0274
A. Coccaro, D. Curtin,
J. Shelton, H, Russell, HL

MS RoI cluster trigger selects cluster of isolated MS activity

Orthogonal MS RoI non-isolated cluster trigger selects events rejected by the RoI cluster trigger

- **Note Life-time reach of 2 vertrex analysis scales like $1/(c\tau)^2$, while for single vertex scales like $1/c\tau$**

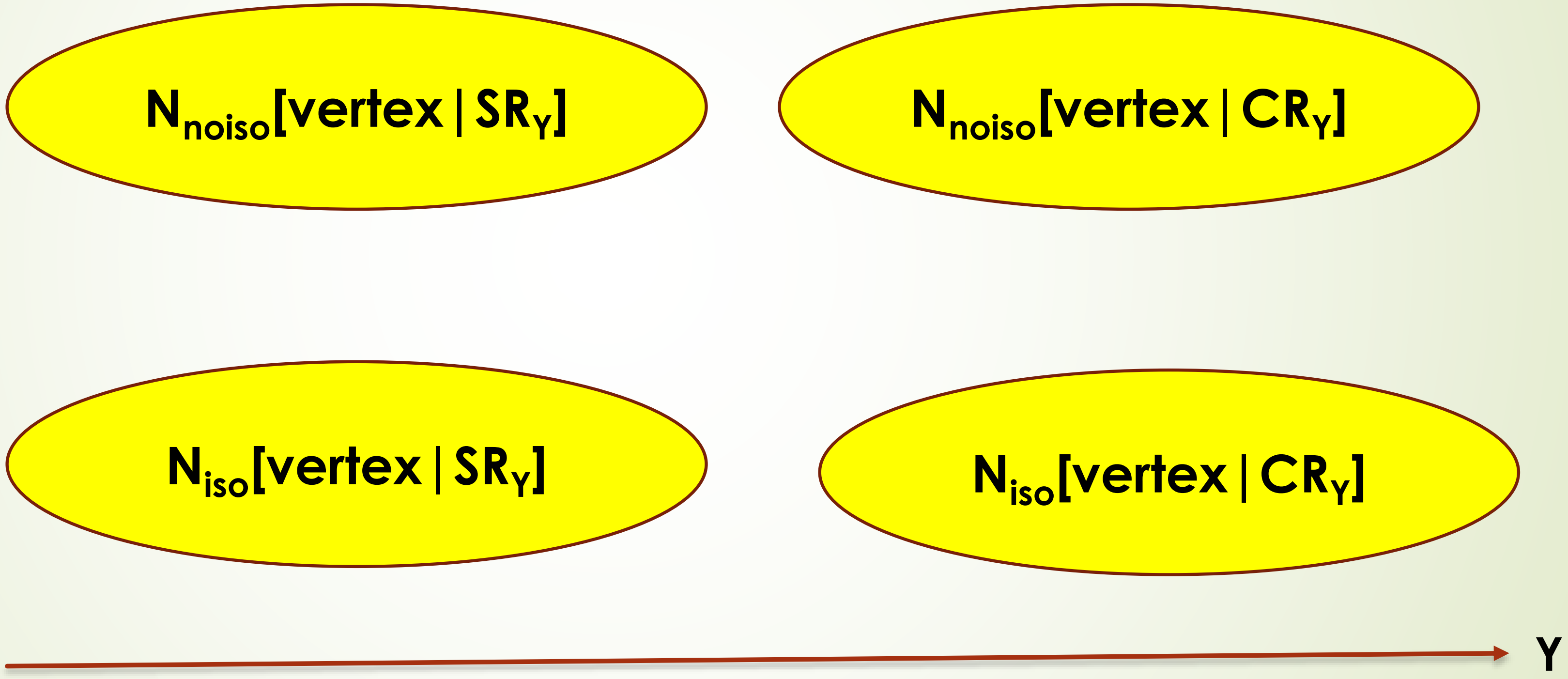
New Strategy

- Have Two Samples with N reconstructed vertices

Selection	Events
Orthogonal selection No isolation	N_{noiso}(vertex) events
Isolated selection	N_{iso}(vertex) events

New Strategy

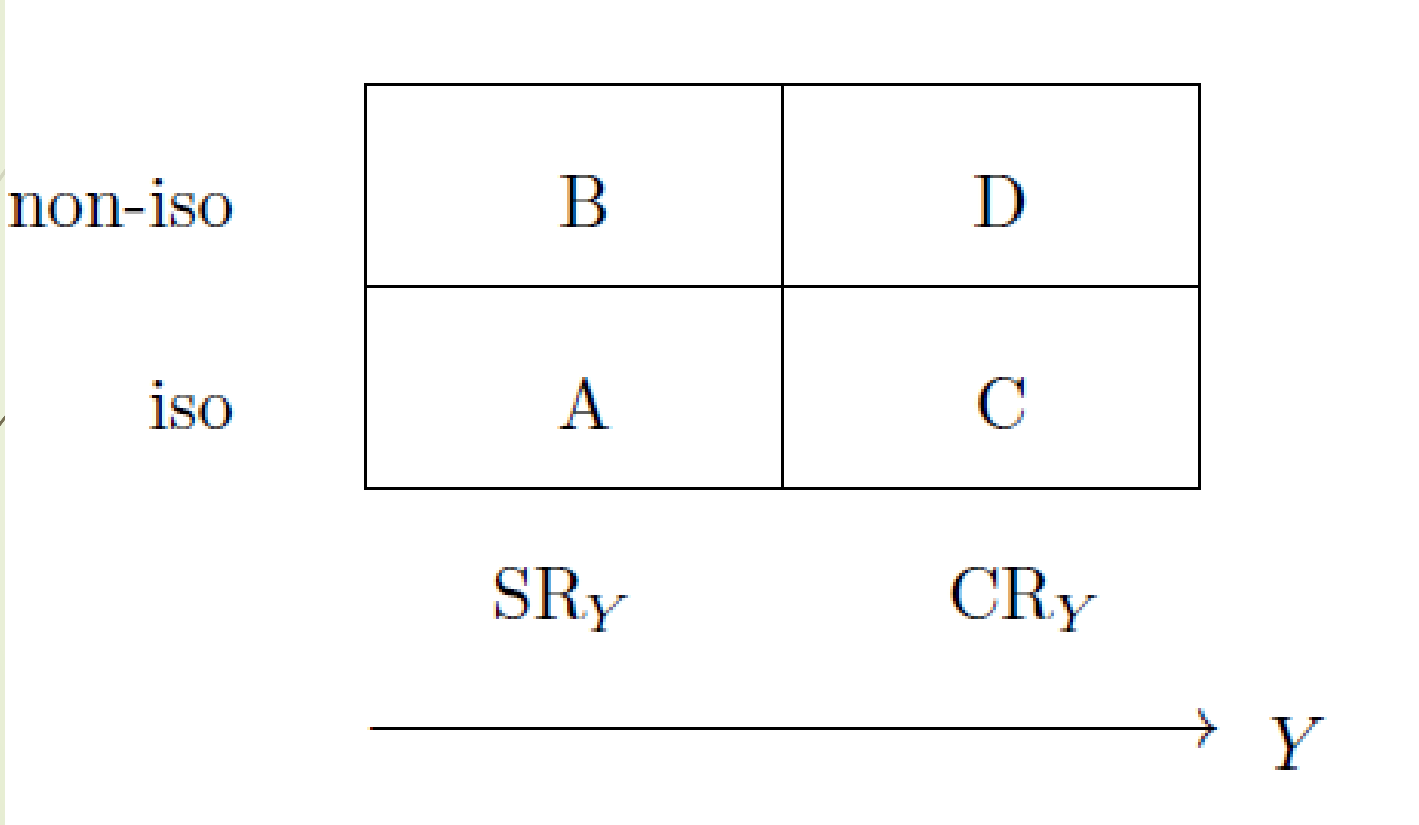
- Use non-iso-region events to estimate number of expected iso region events from SM backgrounds.
- Divide events into a control region and signal region using in addition a variable Y (e.g., number of leptons, MET…)



ABCD Method

- **Can use ABCD method to estimate background in signal region**

Rescaling function $r_{noiso \rightarrow iso} = N_C/N_D$



Choice of Y depends on search goals –tailored To a specific model or class of models

Comparing rescaling functions

- Using this approach can get rescaling functions with different kinematics such as $M_{eff} = \sum|p_{Ti}| + \sum|-p_{Ti}| = H_T + H_{T(miss)}$
  - Differential rescaling function $r_{\text{non-iso}\rightarrow\text{iso}}$ allows for estimate of SM background events in iso-region by using the non-iso-region events

$$\frac{d\sigma^{SM}_{\text{iso}}}{dx_1 dx_2 \ldots} \approx \frac{d\sigma_{\text{non-iso}}}{dx_1 dx_2 \ldots} \cdot r_{\text{non-iso}\rightarrow\text{iso}}(x_1, x_2, \ldots)$$

$r_{\text{noiso}\rightarrow\text{iso}}(M_{eff})^C = N_C(M_{eff})/N_D(M_{eff})$ Control Region

$r_{\text{noiso}\rightarrow\text{iso}}(M_{eff})^S = N_A(M_{eff})/N_B(M_{eff})$ Signal Region SR_Y

$r_{\text{non-iso}\rightarrow\text{iso}}$ measured from data

Distribution of ratio of ratios

$$R(M_{eff}) = \frac{r^S_{noiso\rightarrow iso}(M_{eff})}{r^C_{noiso\rightarrow iso}(M_{eff})}$$

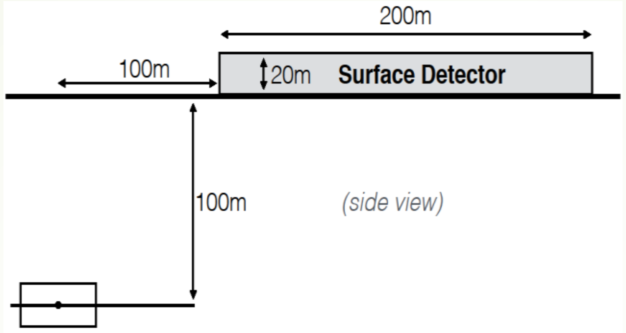
Search for excesses (bump hunting)!!!

Searching for ultra Long-lived Particles

- **MATHUSLA Detector** – Massive Timing Hodoscope for Ultra Stable neutral pArticles (arXiv:1606.06298v1 - J-P. Chou, D. Curtain, HL)
  - Dedicated detector sensitive to long-lived neutral long-lived particles with life times up to the Big Bang Nucleosynthesis (BBN) limit (10^7 – 10^8 meters) for the HL-LHC
  - A large volume detector located on the surface above and somewhat displaced from ATLAS or CMS interaction point
- HL-LHC will produce order of N_h= 1.5 x 10^8 Higgs Bosons
  - Observed decays: $N_{obs} \sim N_h \cdot Br(h \to ULLP \to SM) \cdot \varepsilon_{geom} \cdot \frac{L}{bc\tau}$
    - L-size of detector along ULLP direction of travel
    - ε_{geom} geometrical acceptance
    - $b(Lorentz\ boost) \sim \frac{m_h}{n m_X} \leq 3$ for Higgs boson decaying to $n = 2$ $m_X \geq 20\ GeV$
    - Requires $L \sim (20\ \mathrm{m}) \left(\frac{b}{3}\right) \left(\frac{0.1}{\epsilon_{\mathrm{geometric}}}\right) \frac{0.3}{\mathrm{Br}(h \to \mathrm{ULLP})}$.
  - To collect a few ULLP decays with c$\tau \sim 10^7$ m requires a 20 meter detector along direction of travel of ULLP and about 10% geometrical acceptance

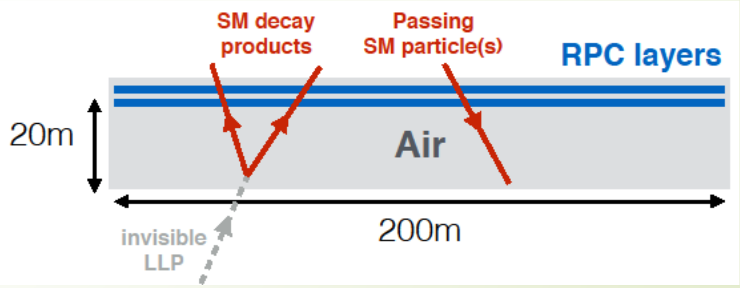
MATHUSLA Surface Detector

- Placing MATHUSLA surface above ATLAS or CMS provides shielding from pp interaction particles but requires a very large detector



LHC detector

- **To establish a displaced decays requires tracking and good cosmic background rejection**
  - **RPCs planes** can be attractive choice for trcking and vertex reconstruction
  - Scintillator planes for redundant background rejection and timing
- Could implement a small scale unit and place over ATLAS or CMS during Run 2 for background rejection tests



Comparing rescaling functions

- Standard Model (SM

Comparing rescaling functions

- **Standard Model (SM**