SEARCH FOR DISPLACED VERTICES FROM THE DECAYS OF NEW LONG-LIVED HEAVY PARTICLES AT ATLAS

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ATLAS EXPERIMENT

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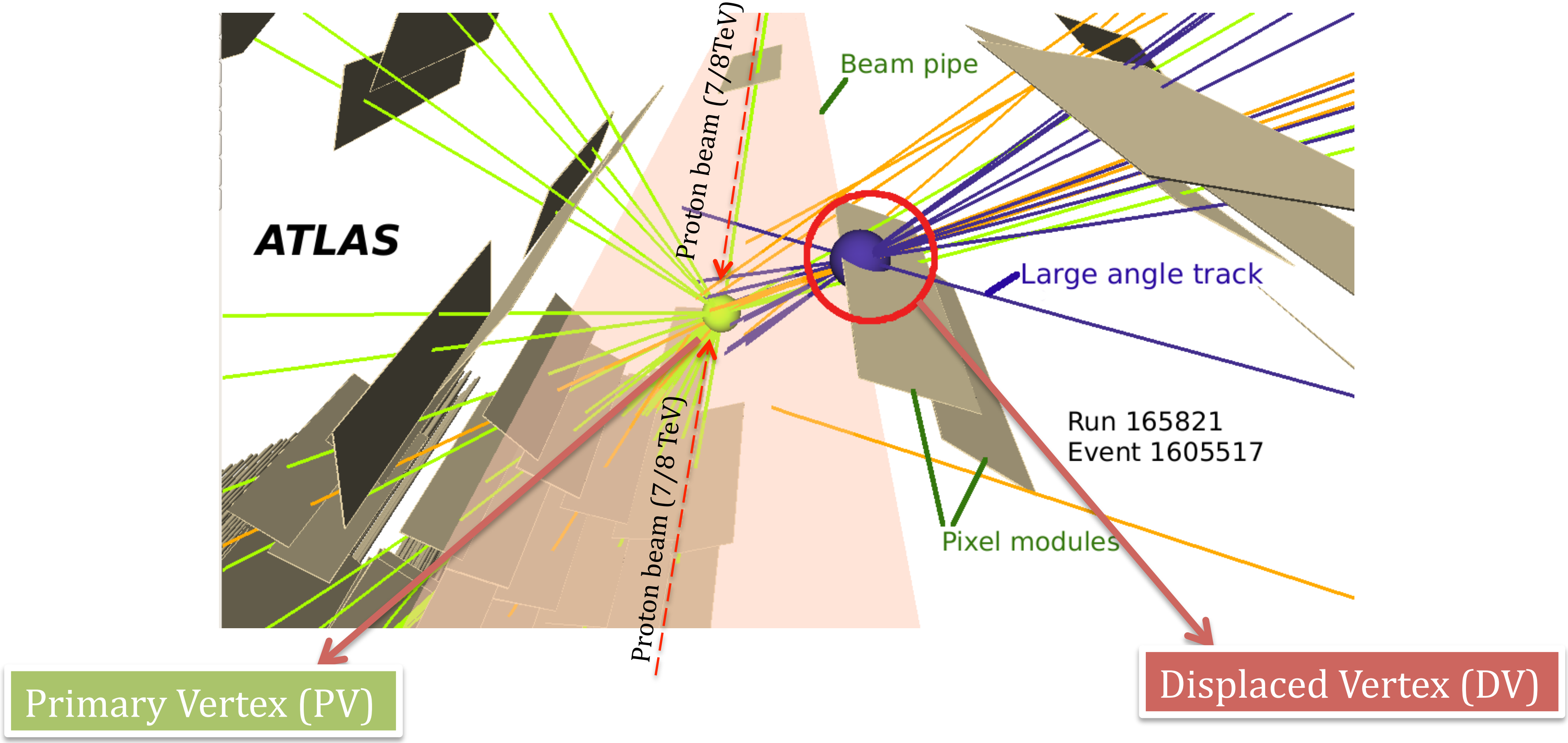
DEFINITION OF DISPLACED VERTICES



Prediction in several theoretical extensions of Standard Model: Production of heavy particles with lifetimes of the order of about picoseconds to about a nanosecond : basically look for long lived particle/s (LLPs)

Motivation to search for Long-Lived particles

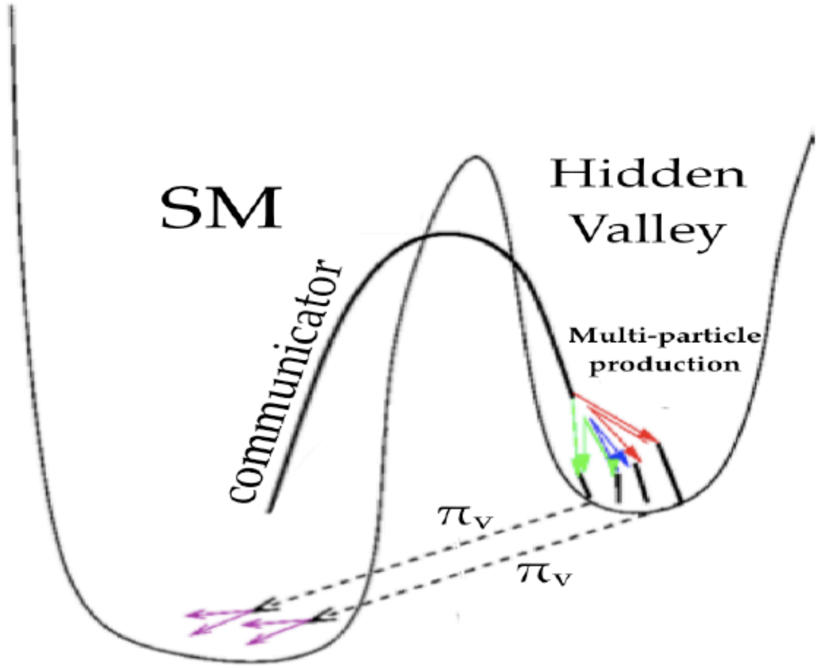
- R-parity Violating (RPV)
  - In SUSY, each particle associated with a multiplicative quantum number known as *R-parity* $(R_P) = (-1)^{3(B-L)+2s}$ where s: spin and B, L are baryon and lepton numbers of a particle
  - In RPV scenario, the Lightest Supersymmetric Particle (LSP) is *NOT* stable and can decay through Standard Model (SM) particles
  - We can write the superpotential as

$$W_{RPV} = \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k}_{\text{Lepton Violating}} + k_i L_i H_2 + \underbrace{\lambda''_{ijk} \bar{D}_i \bar{D}_j \bar{D}_k}_{\text{Baryon Violating}}$$

If these couplings $(\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk})$ are weak then LSP can have a long life time

Motivation to search for Long-Lived particles

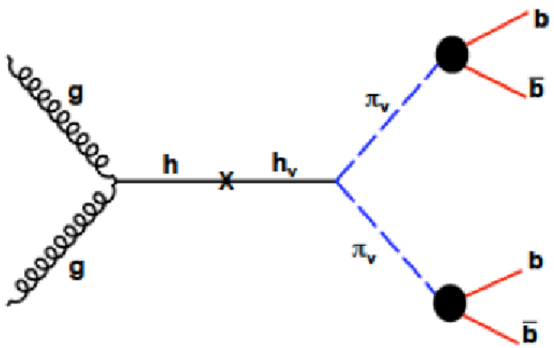
- Hidden Valley Scenario
  - Hidden Valley particles are SM neutral but some communication is allowed via mediators
  - Lightest v particle: π_v stable in hidden sector and can decay in to SM particle via mediator



e.g.

$$h \rightarrow \pi_v \pi_v \rightarrow b\bar{b}b\bar{b}$$

$BR(\pi_v \rightarrow f\bar{f}) \propto m_f$



Weak coupling between SM and HV could lead to particle having longer life time

Motivation to search for Long-Lived particles

and few more examples…..

- Gauge-Mediated SUSY breaking (GMSB)
  - SUSY breaking communicated via SM gauge interactions
  - Gravitino acquires mass (LSP)

Depending on SUSY-breaking scale, the NLSP can be long-lived

- Split SUSY
  - All the scalars have large masses while the gaugino and higgsino masses remain at the weak scale

gluino lifetime can be longer, somewhat similar to the case of muon in SM

- Anomaly mediated SUSY-breaking (AMSB)
  - Explicit SUSY-breaking terms are switched off/heavily suppressed
  - Ratios of gaugino masses are approximately $M_{bino} : M_{wino} : M_{gluino} \sim 2.8 : 1 : 8$
  - making the masses of lightest chargino and neutralino (LSP) are nearly degenerate

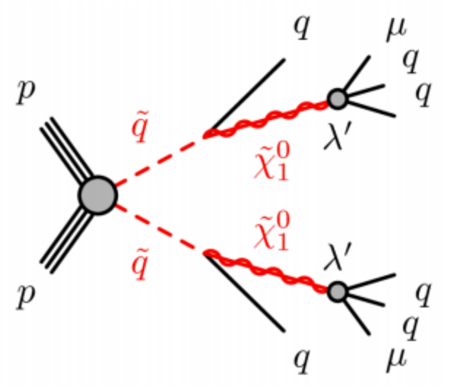
chargino can have longer life time

- …….. and many more
  - Dark sector gauge bosons
  - Stealth susy……

in TODAY'S TALK

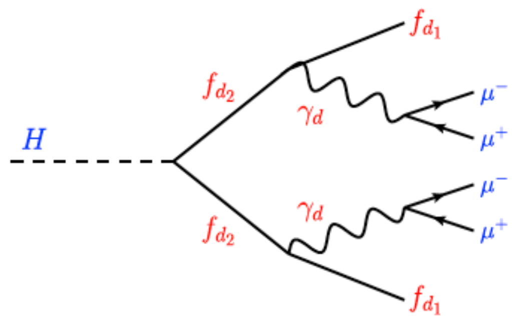
1) Search a Muon and multitrack displaced vertices from heavy particle such as neutralino

……. experimental challenges and latest results



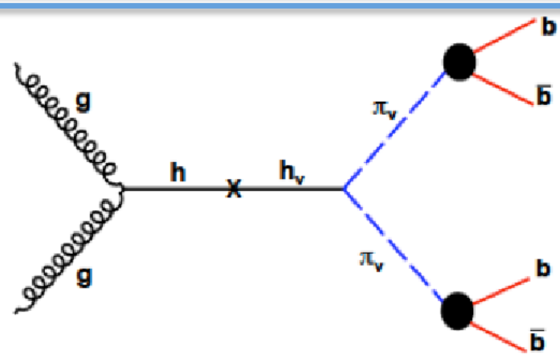
2) Search for the displaced lepton muonic jets from light higgs boson decay

…. almost similar to 1) but some special techniques



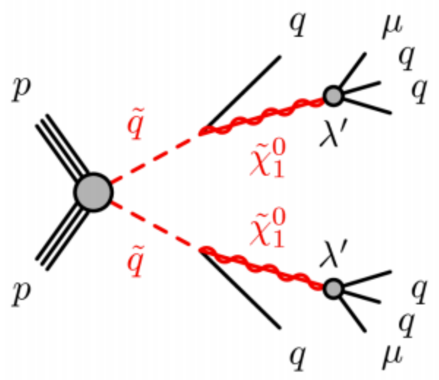
3) Search for displaced hadronic jets from light-higgs boson decay into long-lived weakly interacting particle

….. almost similar to 1) and 2) and additional details



1) A MUON AND MULTITRACK DISPLACED VERTICES

- Search is performed for the decay of heavy particle in the *Inner Detector (ID)* , producing a multi-track vertex that contains a high p_T muon
- The signature studied in context of *RPV scenario* where λ'_{211} is non-zero and small



- *Multitracks* are good to reconstruct the *Displaced Vertices (DV)*
- *Muon* provides a good handle to reject the *backgrounds* and also useful for *triggering*

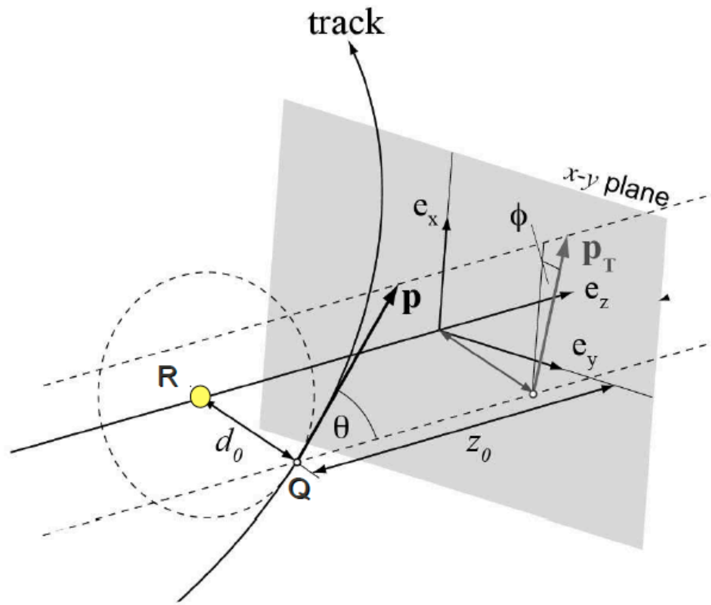
- Sensitivity of the decay under study $10^{-6} < \lambda'_{211} < 10^{-4}$

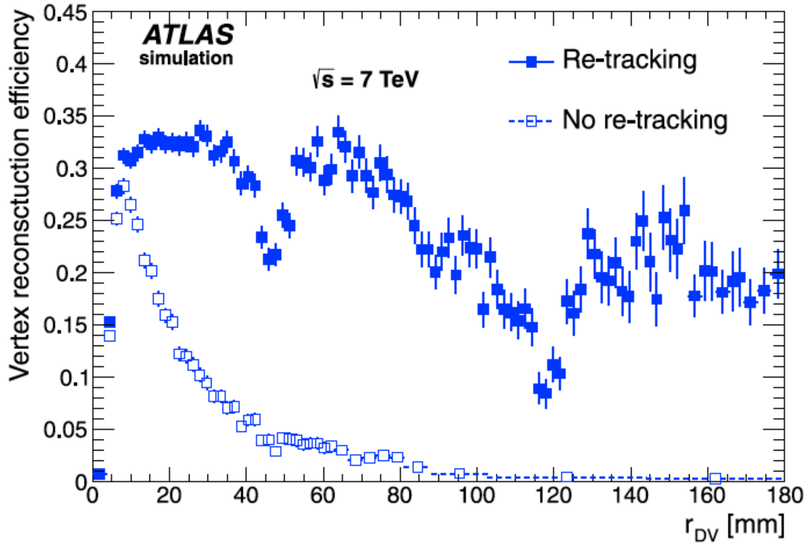
- Lifetime *($c\tau$)* of a *neutralino* $\rightarrow \mu u d$

$$c\tau \sim \frac{m_{\tilde{\mu}}{}^4}{\lambda'^2_{211} m_{\tilde{\chi}_1^0}{}^5}$$

TRACKS SELECTION AND RECONSTRUCTION

- In general, d_0, z_0, φ, θ and q/p used to parameterize the track
- For DV analysis: tracks with two or more associated SCT hits and $|d_0| > 2$ *mm* (98% rejection of tracks from PV)
- *Standard ATLAS tracking* work effectively for the tracks originate close to PV but have *reduced efficiency* from those originate from DV
- ***"Re-tracking"*** : Re-run the silicon-seeded tracking algorithm with looser requirements on radial and z-impact parameters and on the number of detector hits and using *"left over hits"* from Standard tracking
- to reduce the false seed tracks, the additional tracks have $p_T > 1$ *GeV*





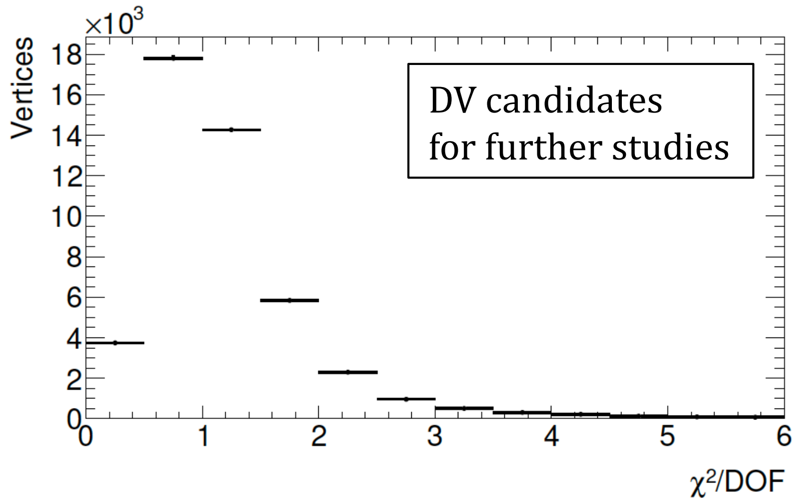
DISPLACED VERTEX RECONSTRUCTION

- Algorithm based on incompatibility-graph approach

IEEE Trans. Comput. 22 (2) 1973, 187

- Step 1:
  - two-track seed vertices formed from all pair of tracks
  - Perform vertex fit and apply quality cuts
  - There should be no track hits between PV and the vertex position
- Finally vertices combined and refitted if they are separated by *less than 1mm*
- For a good quality DV fit, the χ^2/ d.o.f. < 5

- Step 2:
  - Multitrack vertices formed from combination of seed vertices in an iterative process
  - *iteration continue until no track is associated more than one vertex*



DV Selection

- *Trigger* on events with muon candidate with high $p_T > 40$ *GeV* in muon spectrometer (MS) and *No Inner Detector (ID)* track requirement
- $|z_{DV}| < 300$ *mm* and $|r_{DV}| < 180$ *mm* : Fudicial volume roughly corresponds to the *pixel barrel*
- and to reject the background from PVs: $sqrt[(x_{DV} - x_{PV})^2 - (y_{DV} - y_{PV})^2] \geq 4$ *mm*

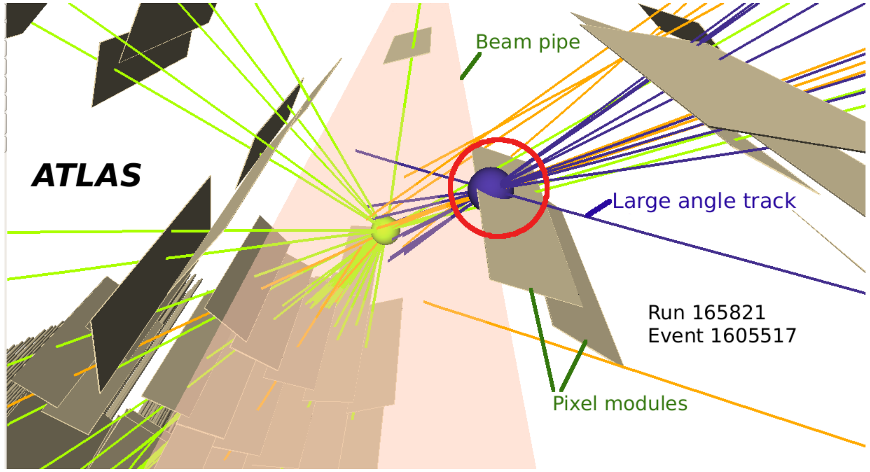
- Number of tracks associated with the DV $(N_{DV}^{trk}) \geq 5$: reduces the background from random combination

- Muon Candidate:
  - Combine information from MS and ID
  - $p_T > 50$ *GeV*, $|\eta| < 1.07$, $|d_0| > 1.5$*mm*

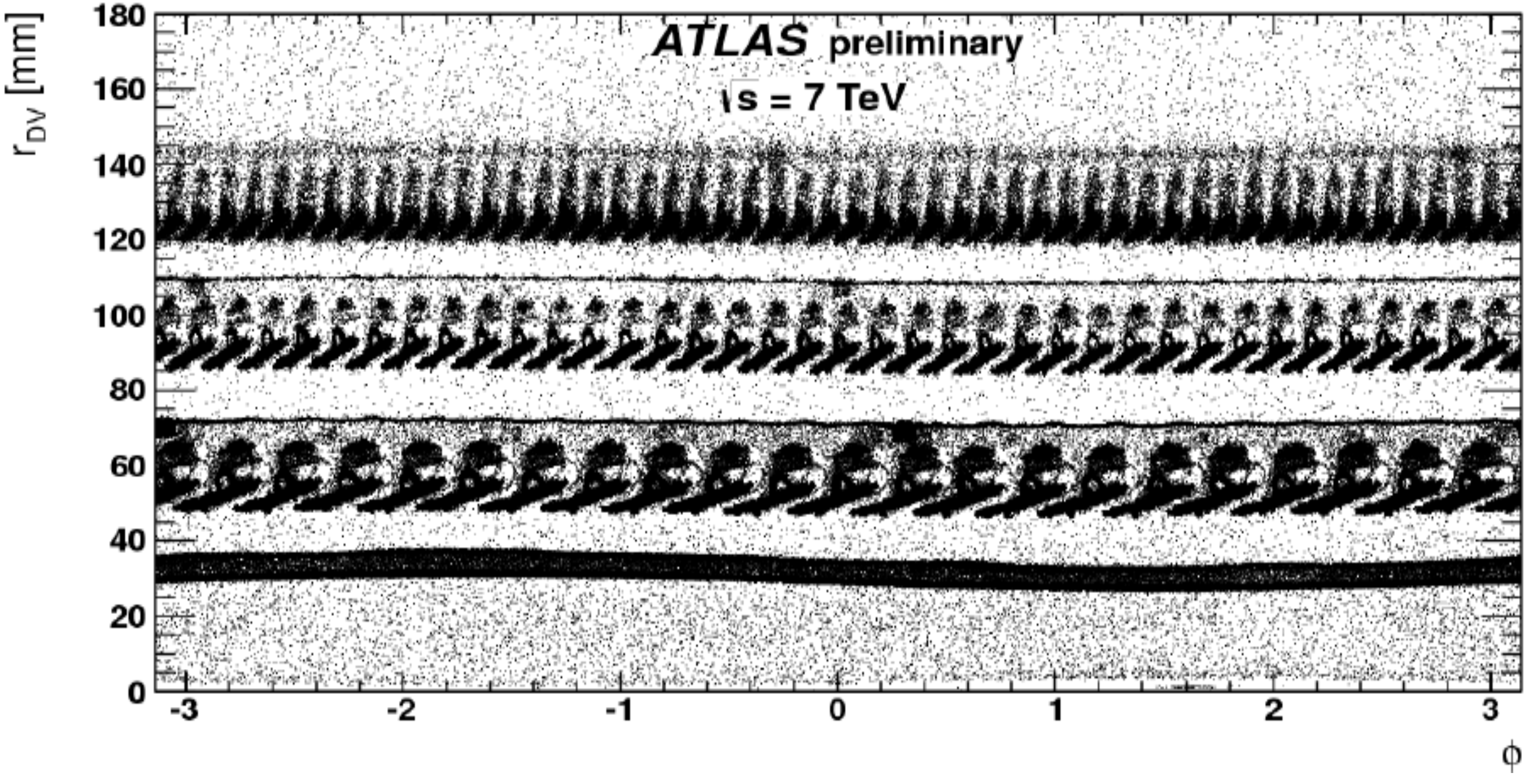
  (required to reject the backgrounds from $Z \rightarrow \mu\mu$ *and* $W \rightarrow \mu\nu$*)*
  - Matching of triggered muon with reconstructed vertex
    - $\sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2} < 0.15$
  - The distance of closest approach of the muon *w.r.t.* DV < 0.5 mm

DV Selection

- Invariant mass of DV (m_{DV}) as a discriminator between signal and background
  - Vertex satisfy (fail) $m_{DV} > 10$ GeV high-mass (low-mass) DV

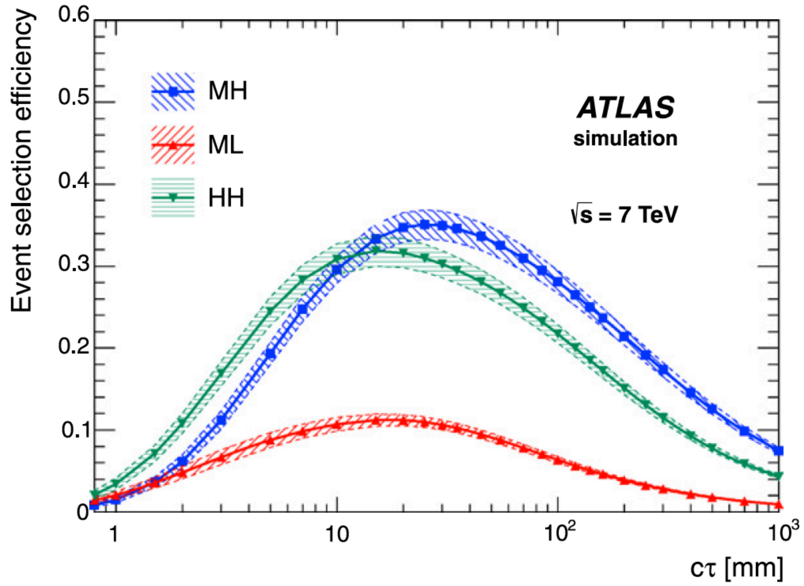


vetos on the vertices reconstructed in high dense materials



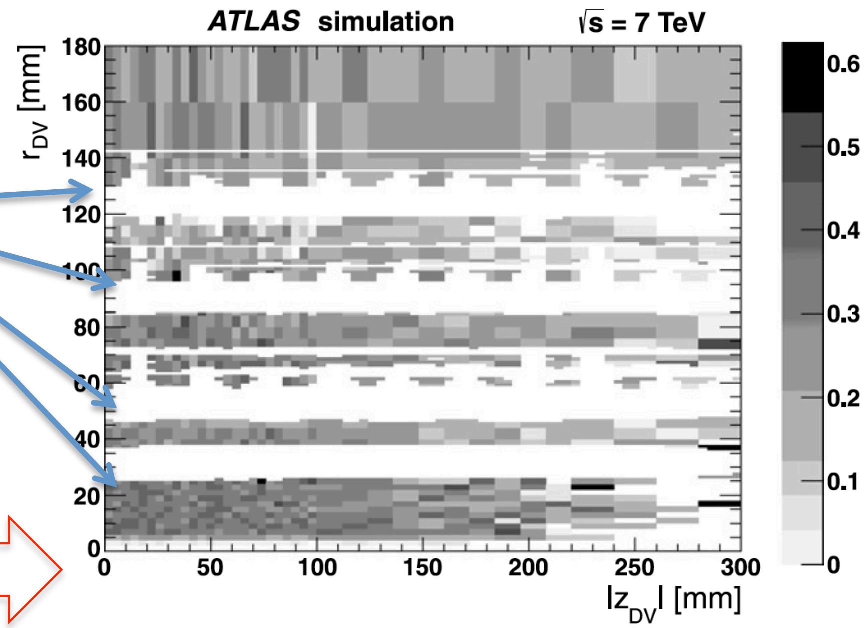
Signal Efficiency

Sample	$m_{\tilde{q}}$ [GeV]	σ [fb]	$m_{\tilde{\chi}_1^0}$ [GeV]	$\langle\gamma\beta\rangle_{\tilde{\chi}_1^0}$	$c\tau_{MC}$ [mm]	$\lambda'_{211} \times 10^{-5}$
MH	700	66.4	494	1.0	78	0.3
ML	700	66.4	108	3.1	101	1.5
HH	1500	0.2	494	1.9	82	1.5



- Signal Efficiency depends on
  - Track Reconstruction and
  - Track Selection

Blank areas represents the region of dense materials and are not considered when looking for DVs



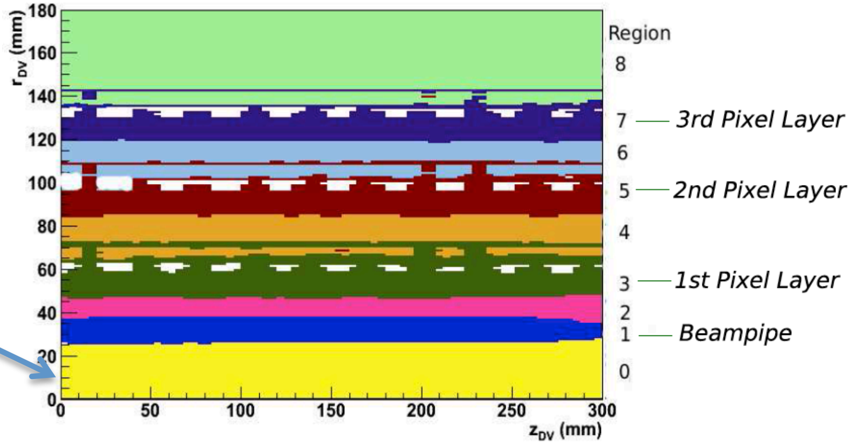
Eff. as a function of r_{DV} vs $|z_{DV}|$ for vertices in signal MC sample MH

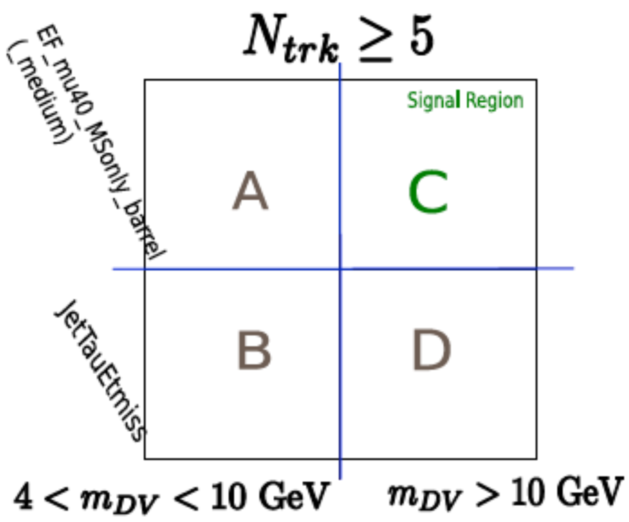
Background Estimation

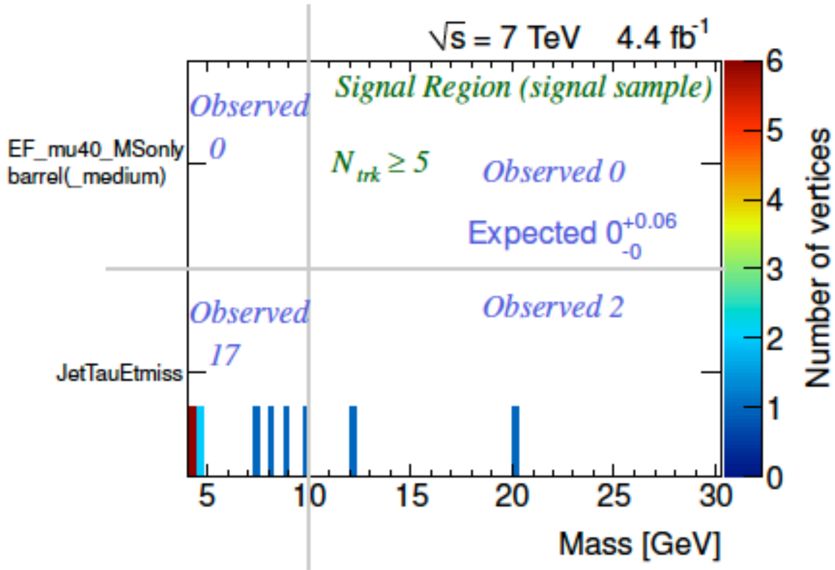
- Two sources of background in non-material region
  1. Inside the beam-pipe (region 0)

     Purely random combination of tracks (real/fake)

     - Estimated using the large sample of jet triggered events (data-driven technique)
     - *found (0.00 +0.06)*







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  1. Inside the beam-pipe (region 0)

     Purely random combination of tracks (real/fake)
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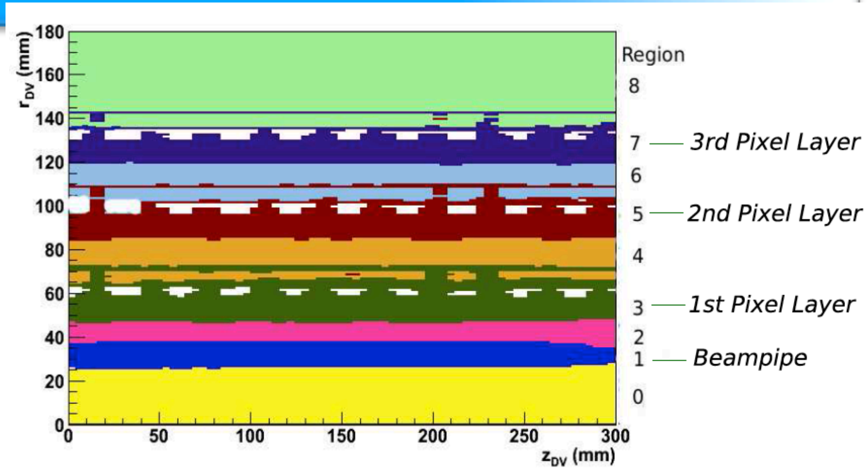
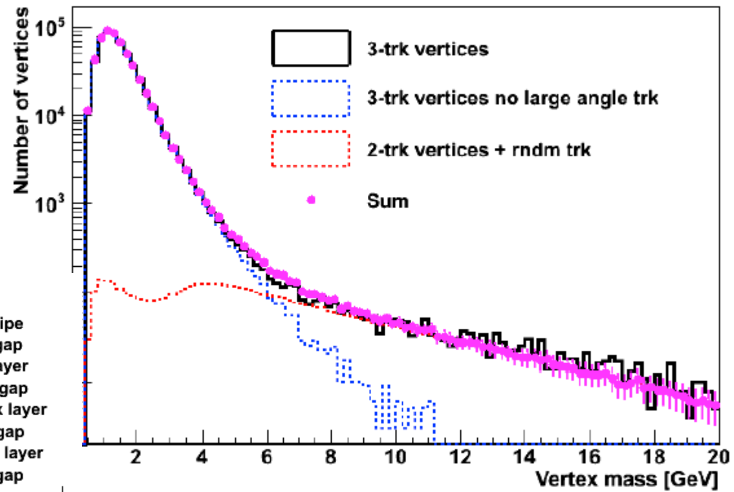
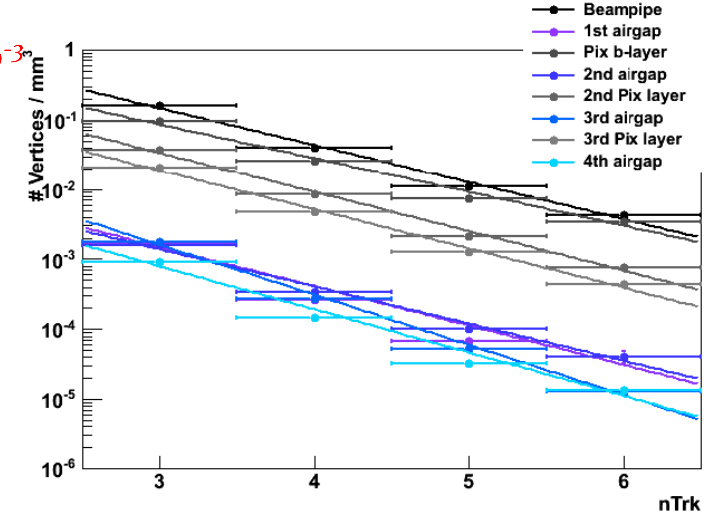
     - *Found (0.00 +0.06)*
  2. Outside the beam pipe (regions 2,4,6 and 8)

     (Vertices from real hadronic interactions with gas molecules : if the DV is crossed by a random track at large X-ing angle)
     - High mass tail of the distributions, in particular if the vertex is crossed by a random track at large crossing angle
     - *Found (3.7 ± 4.4) X 10^{-3}*



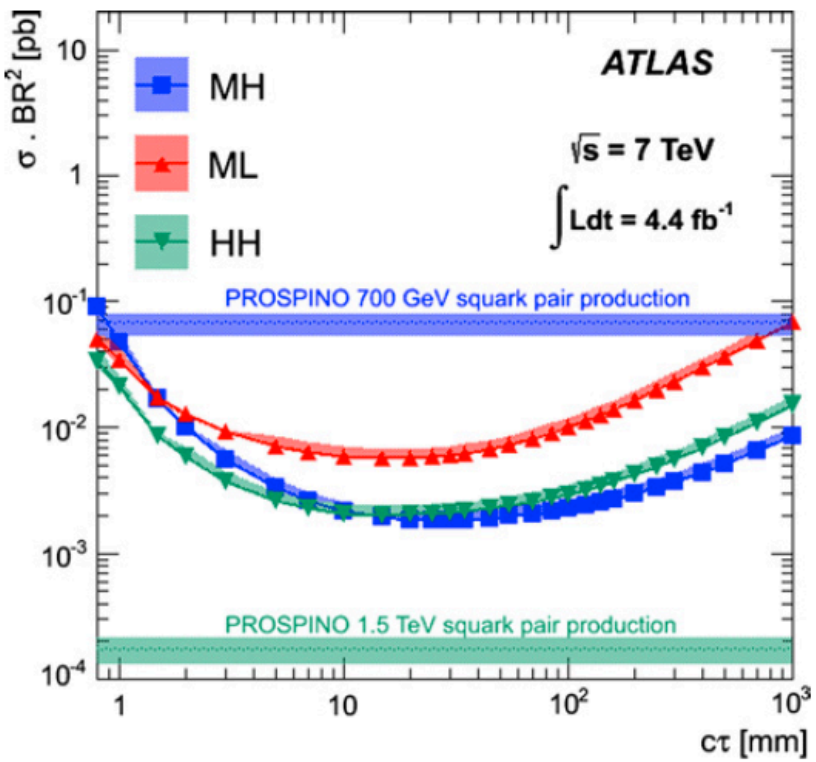


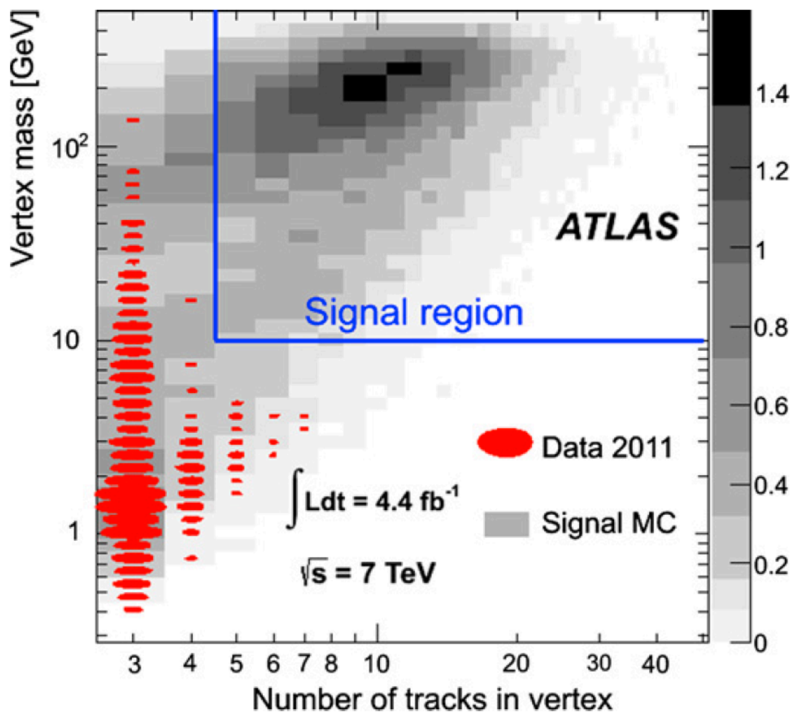
Total background (4± 60) X 10^{-3}



RESULTS AND INTERPRETATION

- *Zero* events (vertices) are observed in the signal region in 2011 data set (4.4 fb^{-1})





- Null signal and less than 0.06 background events
- Use RPV simplified models to set the limits

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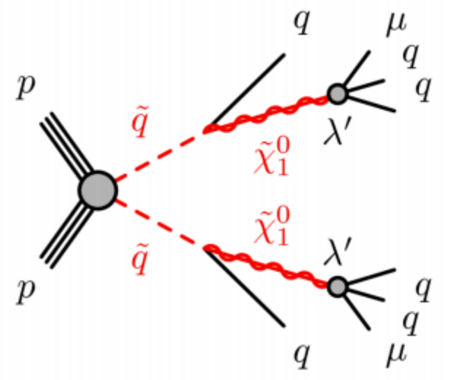
Null Results and interpretation in RPV scenario

……. experimental challenges and latest results



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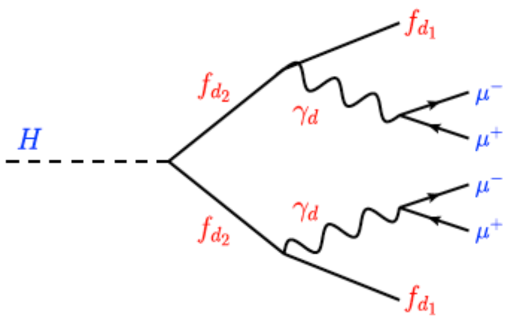

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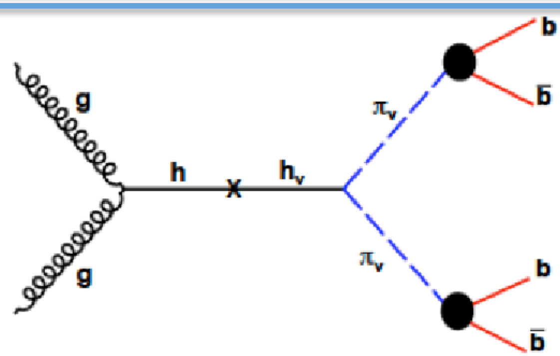
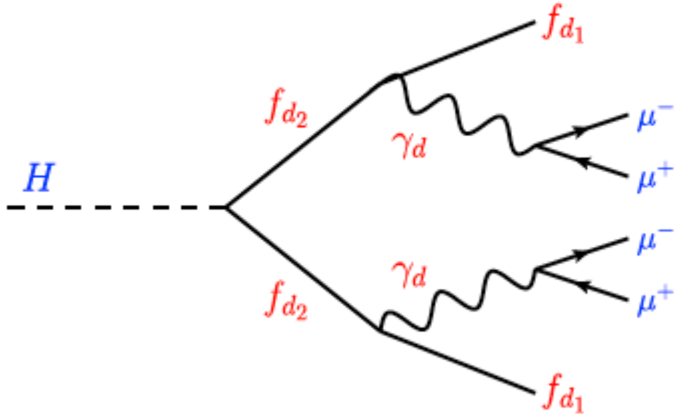


2.) Displaced muonic lepton jets

- In *"Light Hidden Sector"* particles may produced with large boosts at LHC
- Light unstable particles with masses in the range MeV to GeV (e.g. dark photon γ_d) decays predominately into SM particles

- Higgs boson *(rare and non-SM)* decays to a pair of neutral hidden fermions (f_{d2}) and each of which decays into one *long lived dark photon* (γ_d) and one stable neutral hidden fermions (f_{d1}) which escape from detector undetected
- γ_d decays into *"highly collimated"* a pair of muons (signature are *lepton-jets)*

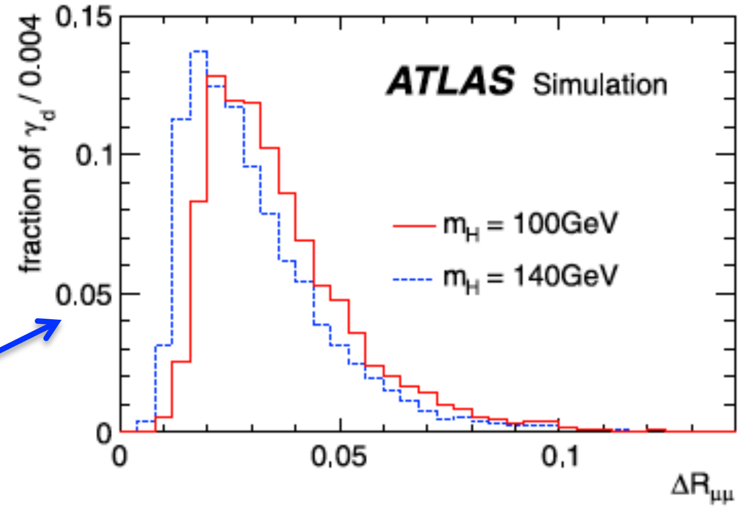


- Experimental challenges *(almost similar to the one discussed for the previous analysis)*
  - Triggering
  - Reconstruction capabilities of displaced vertex
  - Muon Spectrometer *(MS) plays a crucial role* in detecting muons not originating from PV

Signal MC and Trigger

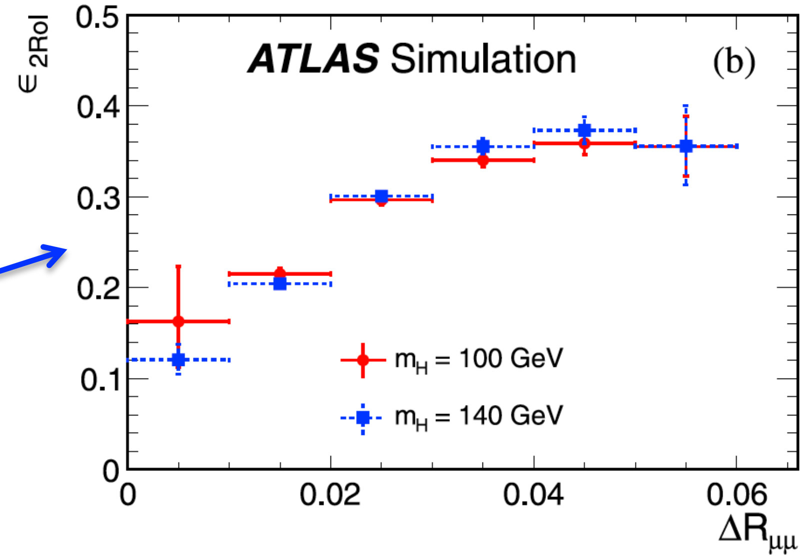
Parameter used to Generate the Signal MC

Higgs mass [GeV]	$m_{f_{d2}}$ [GeV]	$m_{f_{d1}}$ [GeV]	γ_d mass [GeV]	$c\tau$ [mm]
100	5.0	2.0	0.4	47
140	5.0	2.0	0.4	36



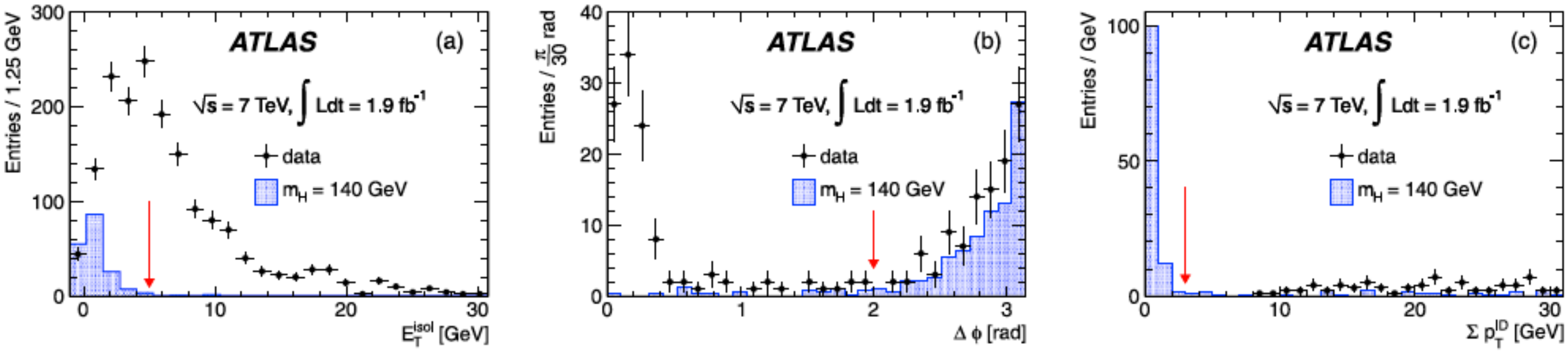
- Four μ's coming from two displaced vertices:
  - *narrow cone ($\Delta R < 0.1$)*,
  - production of hidden fermions also back-to-back the *E_T^{miss} is very small* and *can't be used as a discriminator* between signal and background

- Special Trigger
  - *Low p_T Multi-muon trigger with muon reconstructed only in the MS*
  - Triggering Eff. is *low* because of special conditions



EVENT SELECTION AND BACKGROUND ESTIMATION

- **Muon Jets (MJs)**
  - Use clustering algorithm that associates all muons in the cone size $\Delta R = 0.2$
  - Perform the iterative process until we end up MJs with at least two reconstructed muons
- **Sources of Backgrounds**
  - SM processes which leads to "prompt real muon" production *negligible*
  - Multijet Background (from decay-in-flight K/π and heavy flavor decays):
    - Calorimeter isolation variable $(E_T^{isol}) \leq 5GeV$
    - $\Delta\varphi \geq 2$ and scalar sum of $p_T^{ID} < 3\ GeV$ for both MJs
  - Cosmic Backgrounds:
    - $|d_0| < 200\ mm$ and $|z_0| < 270\ mm$

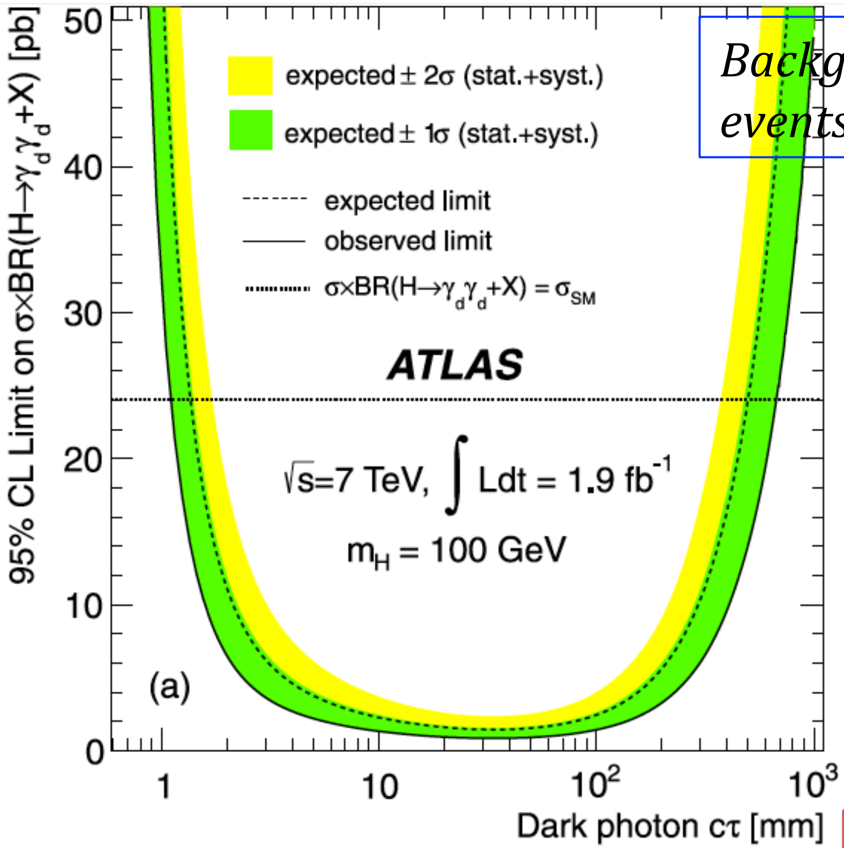


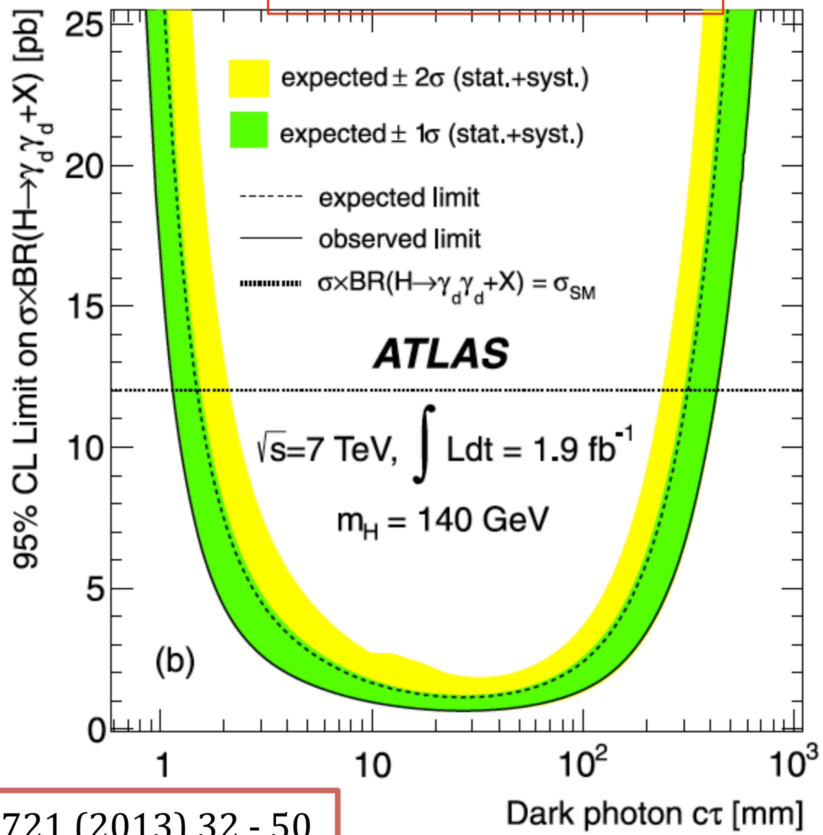
Results and interpretation

Cut	Cosmic-rays	Multi-jet	Total background	$m_H = 100$ GeV	$m_H = 140$ GeV	Data
$N_{MJ} = 2$	3.0 ± 2.1	N/A	N/A	$135 \pm 11^{+29}_{-21}$	$90 \pm 9^{+17}_{-13}$	871
$E_T^{isol} \leqslant 5$ GeV	3.0 ± 2.1	N/A	N/A	$132 \pm 11^{+28}_{-21}$	$88 \pm 9^{+17}_{-13}$	219
$\lvert\Delta\phi\rvert \geqslant 2$	1.5 ± 1.5	$153 \pm 18 \pm 9$	$155 \pm 18 \pm 9$	$123 \pm 11^{+26}_{-19}$	$81 \pm 9^{+15}_{-12}$	104
$Q_{MJ} = 0$	1.5 ± 1.5	$57 \pm 15 \pm 22$	$59 \pm 15 \pm 22$	$121 \pm 11^{+26}_{-19}$	$79 \pm 8^{+15}_{-12}$	80
$\lvert d_0\rvert, \lvert z_0\rvert$	$0^{+1.64}_{-0}$	$111 \pm 39 \pm 63$	$111 \pm 39 \pm 63$	$105 \pm 10^{+22}_{-16}$	$66 \pm 8^{+12}_{-10}$	70
$\sum p_T^{ID} < 3$ GeV	$0^{+1.64}_{-0}$	$0.06 \pm 0.02^{+0.66}_{-0.06}$	$0.06^{+1.64+0.66}_{-0.02-0.06}$	$75 \pm 9^{+16}_{-12}$	$48 \pm 7^{+9}_{-7}$	0

Background events

ZERO event survive





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Null Results and interpretation in RPV scenario

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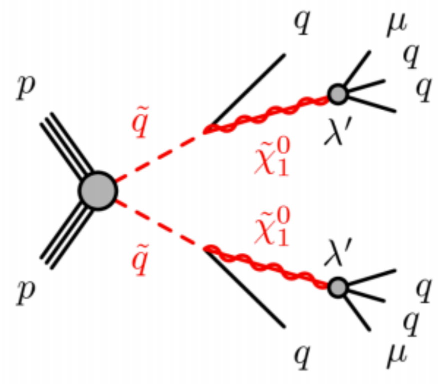

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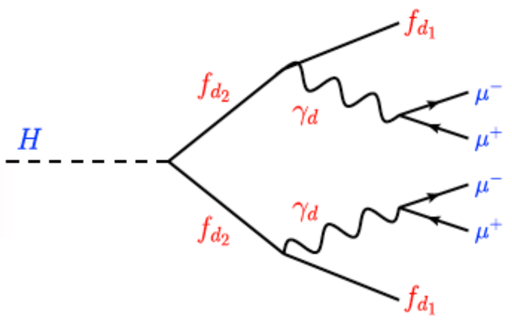
Null Results and interpretation in higgs → hidden sector.

…. almost similar to 1) but some special techniques



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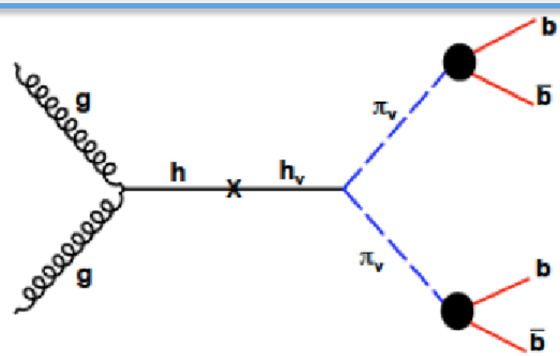
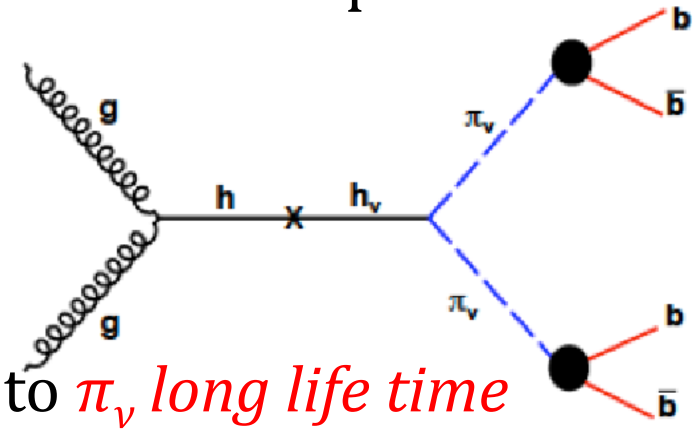


3.) Hidden Valley: Displaced hadronic jets

- Search strategy required that both long-lived particles decays inside the *"Muon Spectrometer"* or *"outer radius (4m) of calorimeter"*
- Light higgs decays into two identical neutral particles and that have a displaced decay to fermions and anti-fermions pairs

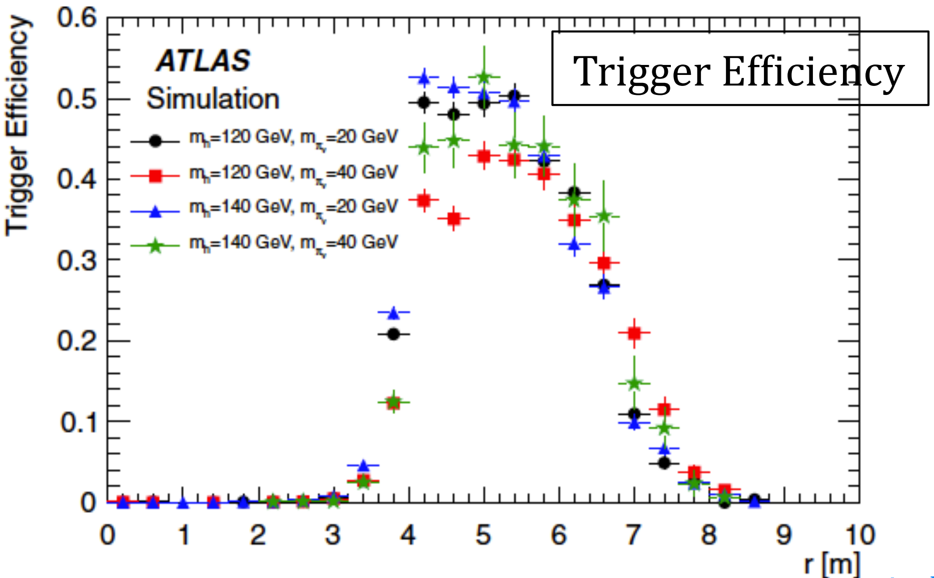
$$h^0 \rightarrow \pi_v \pi_v \rightarrow f\bar{f}$$
$$f\bar{f} = b\bar{b} : c\bar{c} : \tau^+\tau^- :: 85 : 5 : 8\%$$

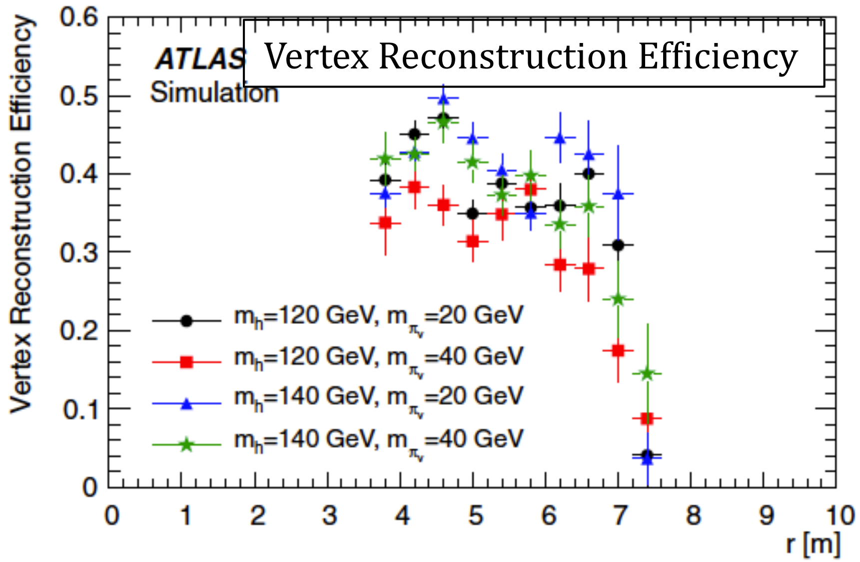


- Weak coupling between SM and HV leads to π_v *long life time*
- Searches extended up to the *whole range of detector volume*
- Challenge is to develop the *signature-driven triggers* to select the displaced decays throughout the ATLAS detector volume
- Signature would be two *back-to-back charged or neutral hadron clusters* and well separated vertices: *$\Delta R > 2.0$*

TRIGGER AND VERTEX RECONSTRUCTION

- **Trigger**
  - Level -1 muon trigger creates the *Region of interest (ROI)*
  - Select events a cluster of *three or four muons ROIs* in *ΔR ~ 0.4* in the muon barrel chambers
  - Background suppression (from punch through jets and muon bremstrahlung)
    - no Calorimeter jets with $E_T \geq 30$ *GeV* in a cone $\Delta R = 0.7$
    - no ID tracks with $p_T \geq 5$ GeV in $\Delta\eta \times \Delta\varphi \sim 0.2 \times 0.2$
- **Vertex Reconstruction**
  - Reconstruct *tracklets* from MDT hits
  - Extrapolate back through B-field, and reconstruct vertex position as point (r,z) that uses highest number of tracklets to make vertex with χ^2 *probability > 5.0 %*





EVENT SELECTION AND BACKGROUND

- **Reconstructed Vertices are required to have**
  - at least three tracklets
  - point back to IP
  - be in range $|\eta| < 2.2$
  - be separated from high p_T tracks and jets

- **Final event selection requires**
  - 2 vertices/event and separated by $\Delta R > 2.0$

- **Background Estimation**
  - From 2-jets punch through calorimeter is *negligible*
  - Random background from cosmic showers, beam halo or detector noise -calculated from data driven method

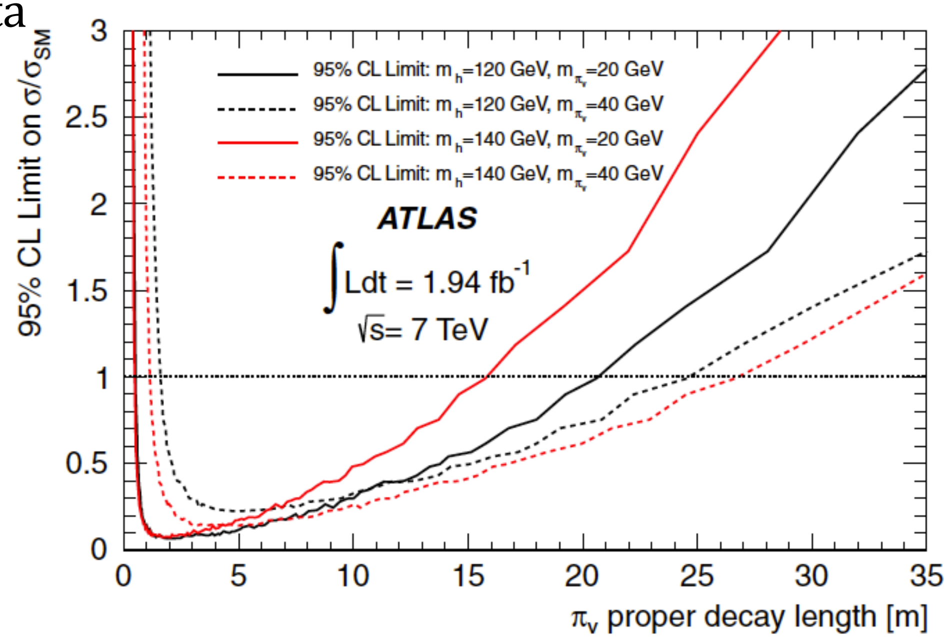
Total background estimation is (0.03 ± 0.02) events

Results and Interpretation

"ZERO" events in the signal region in $1.9 fb^{-1}$ data

Exclusion Limit set for σ_{h0} X BR($h^0 \rightarrow \pi_v \pi_v$)
by rejecting the signal hypothesis at 95% C.L. using CLs procedure
(assuming 100% $h \rightarrow \pi_v \pi_v$)

"As expected the Higgs boson and π_v mass combinations with largest boost to have larger $\beta\gamma c\tau$ have smallest exclusion limits"



These limits are also applicable to Models where higgs decays into weekly interacting scalars that in turns decay into the heavy quark pairs

Phys. Rev. Lett 108 (2013) 251801

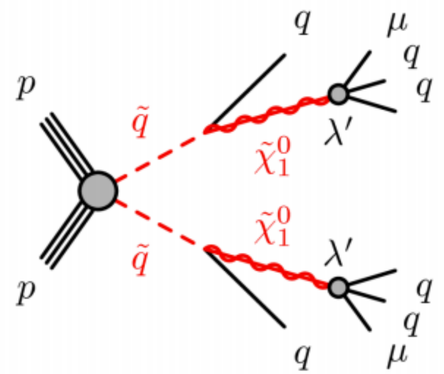
m_{h^0}(GeV)	m_{π_v}(GeV)	Excluded region
120	20	$0.50 < c\tau < 20.65$ m
120	40	$1.60 < c\tau < 24.65$ m
140	20	$0.45 < c\tau < 15.8$ m
140	40	$1.10 < c\tau < 26.75$ m

in TODAY'S TALK

1) Search a Muon and multitrack displaced vertices from heavy particle such as neutralino

Null Results and interpretation in RPV scenario

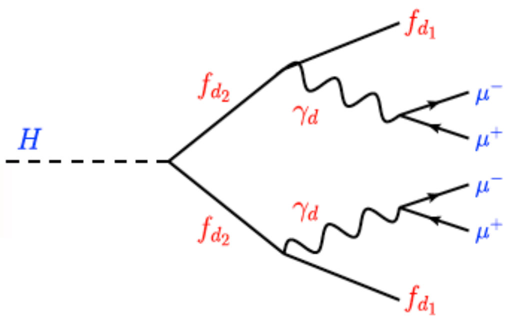
……. experimental challenges and latest results



2) Search for the displaced lepton muonic jets from light higgs boson decay

Null Results and interpretation in higgs → hidden sector.

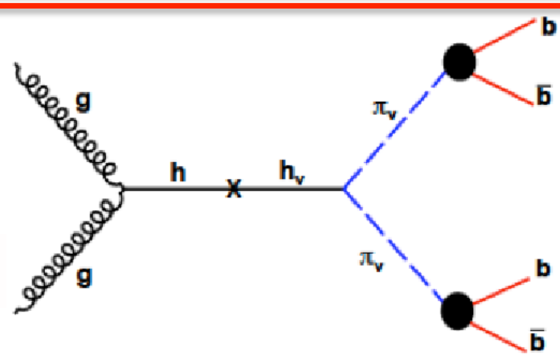
…. almost similar to 1) but some special techniques



3) Search for displaced hadronic jets from light-higgs boson decay into long-lived weakly interacting particle

Null Results and interpretation in higgs → hidden sector.

….. almost similar to 1) and 2) and additional details

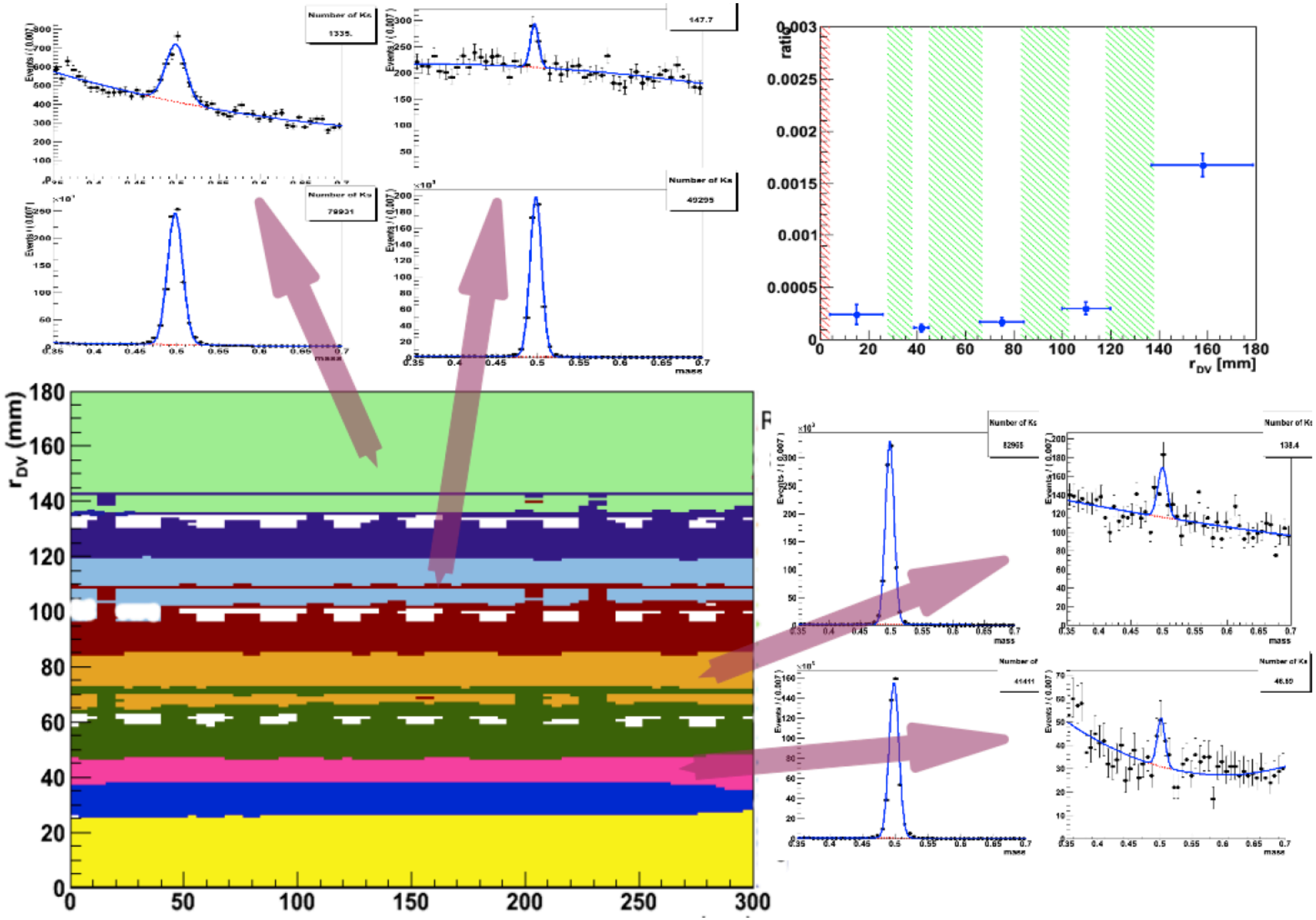


Concluding Remarks

- *No excess* is seen in the displaced vertices searches
- But these analyses are very challenging and require
  - Dedicated triggers
  - Special techniques for track and vertex reconstruction
  - and special procedure for background evaluation although backgrounds are very small
- All these results would be updated soon with full 8TeV data set
- ……and who knows we may find some exciting stuff after all we are hunting for New physics at every corner and every possible way

EXTRA SLIDES

Background Estimation



INCOMPATIBILITY-GRAPH APPROACH

- S. R. Das, "On a new approach for finding all the modified cut-sets in an incompatibility graph", IEEE Transactions on Computers v22(2) (1973) 187.

Abstract—The compatibility relation occurs in many different disciplines in science and engineering. When a compatibility relation exists between pairs of elements in a set, an important problem is to derive the collection of all those elements that form maximal compatibles. If the set of elements with the compatibility relation can be visualized as a compatibility graph of which the different nodes represent the elements of the set, the only edges of the graph being the nonoriented lines joining pairs of elements with the compatibility relation, then the problem of deriving the maximal compatibles becomes identical to the graph theory problem of finding all the maximal complete subgraphs in a symmetric graph. Recently, in connection with simplifying incompletely specified sequential machines, where a kind of compatibility relation also exists between pairs of internal states, Das and Sheng proposed a method for deriving the different maximal compatibles through finding all of the modified cut-sets of the incompatibility graph of the machine. This paper, without confining itself to only incompletely specified machines, considers the problem involving the compatibility relation in a broader perspective and suggests a new approach for finding all the modified cut-sets of the incompatibility graph of a set having a compatibility relation between its different pairs of elements.

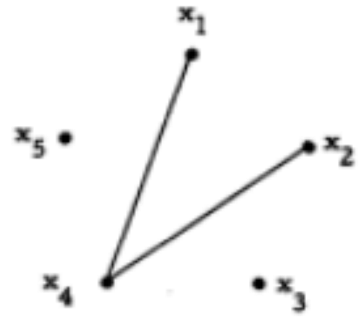


Fig. 1. Compatibility graph of five elements.

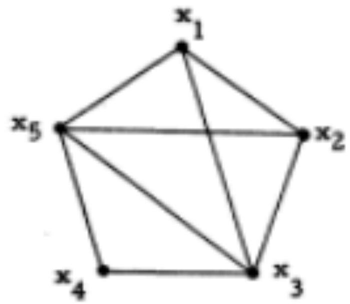
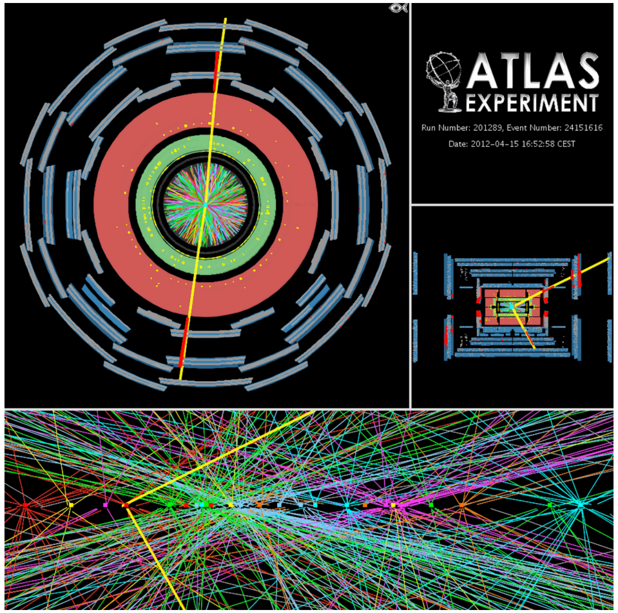


Fig. 2. Incompatibility graph of five elements.

VERTEX RECONSTRUCTION

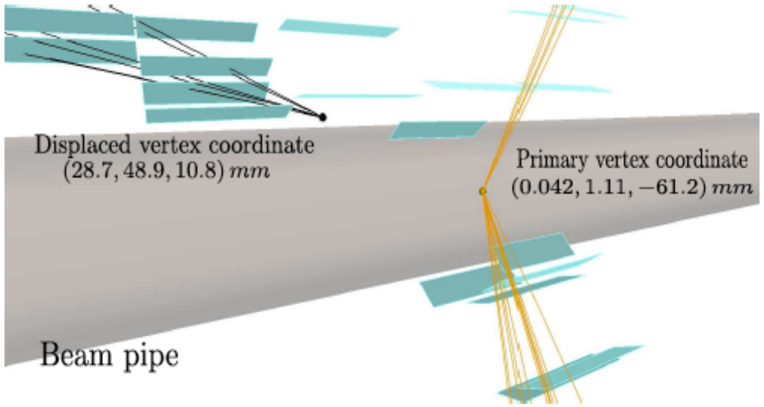
- Trigger
  - Events with muon candidate with high pT > 40GeV in muon spectrometer (MS) and No Inner Detector (ID) track requirement
- Primary Vertex:
  - Should have at least 5-tracks
  - $|z| < 200$ mm
- To deal with pile-up
  - The highest scalar sum of the pT of its tracks are used
- To reduce cosmic ray backgrounds
  - For two muons appears back-to-back$\sqrt{[\pi - (\varphi_1 - \varphi_2)^2 - (\eta_1 + \eta_2)^2]} > 0.1$



SIGNAL MC

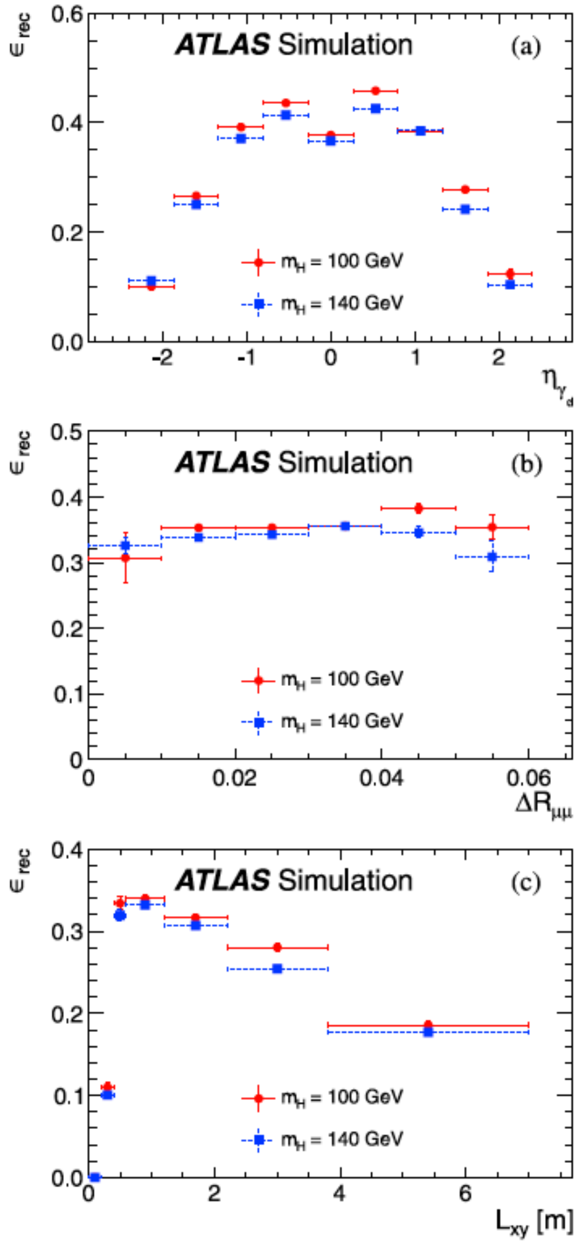
- Signal MC samples generated with Pythia6
- Processes are simulated in which squark squark, anti-squark anti-squark or squark anti-squark pair is produced in pp-collisions
  - Degeneracy of the first and second generations and for the left handed and right-handed squark is assumed
  - The masses of gluinos, sleptons and third generation squarks are set at such a high value ~5TeV that they are not directly produced in SUSY scenario considered here
  - RPV couplings other than λ'_{211} are set zero

Sample	$m_{\tilde{q}}$ [GeV]	σ [fb]	$m_{\tilde{\chi}_1^0}$ [GeV]	$\langle\gamma\beta\rangle_{\tilde{\chi}_1^0}$	$c\tau_{MC}$ [mm]	$\lambda'_{211} \times 10^{-5}$
MH	700	66.4	494	1.0	78	0.3
ML	700	66.4	108	3.1	101	1.5
HH	1500	0.2	494	1.9	82	1.5



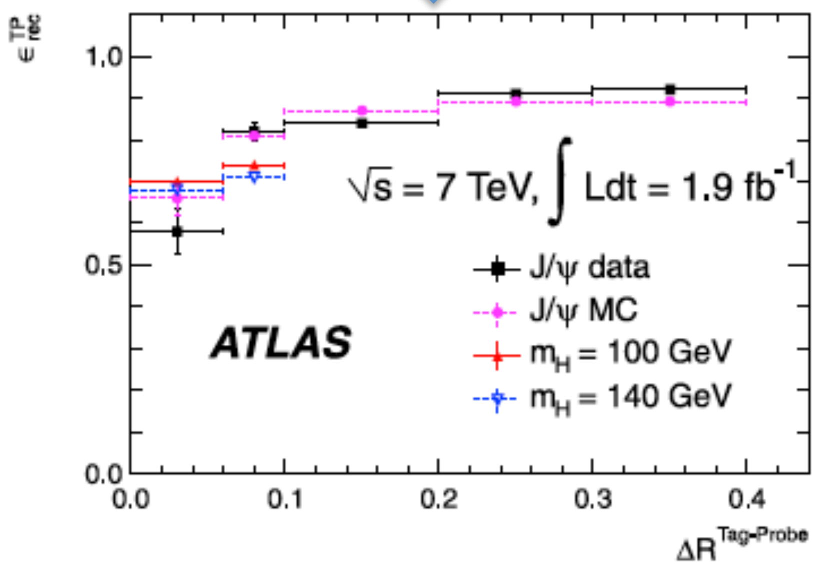
Example of MC signal events (ML)

Displaced muonic lepton Jets



Reconstruction Efficiency

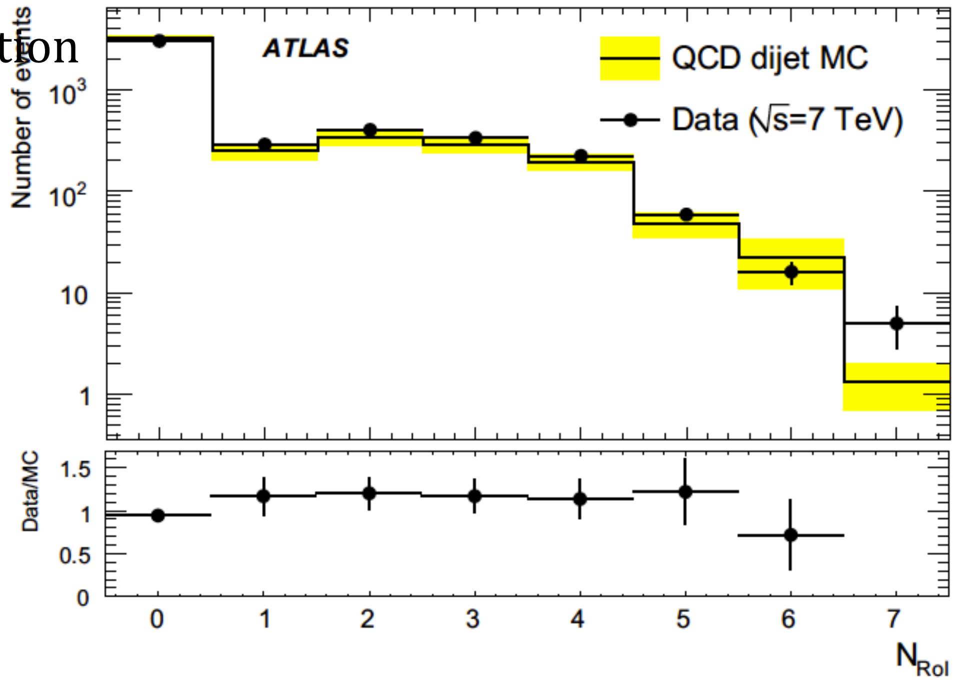
validation using J/psi sample
data and MC



HIDDEN VALLEY

to Check the validation of MC description of photon and jets

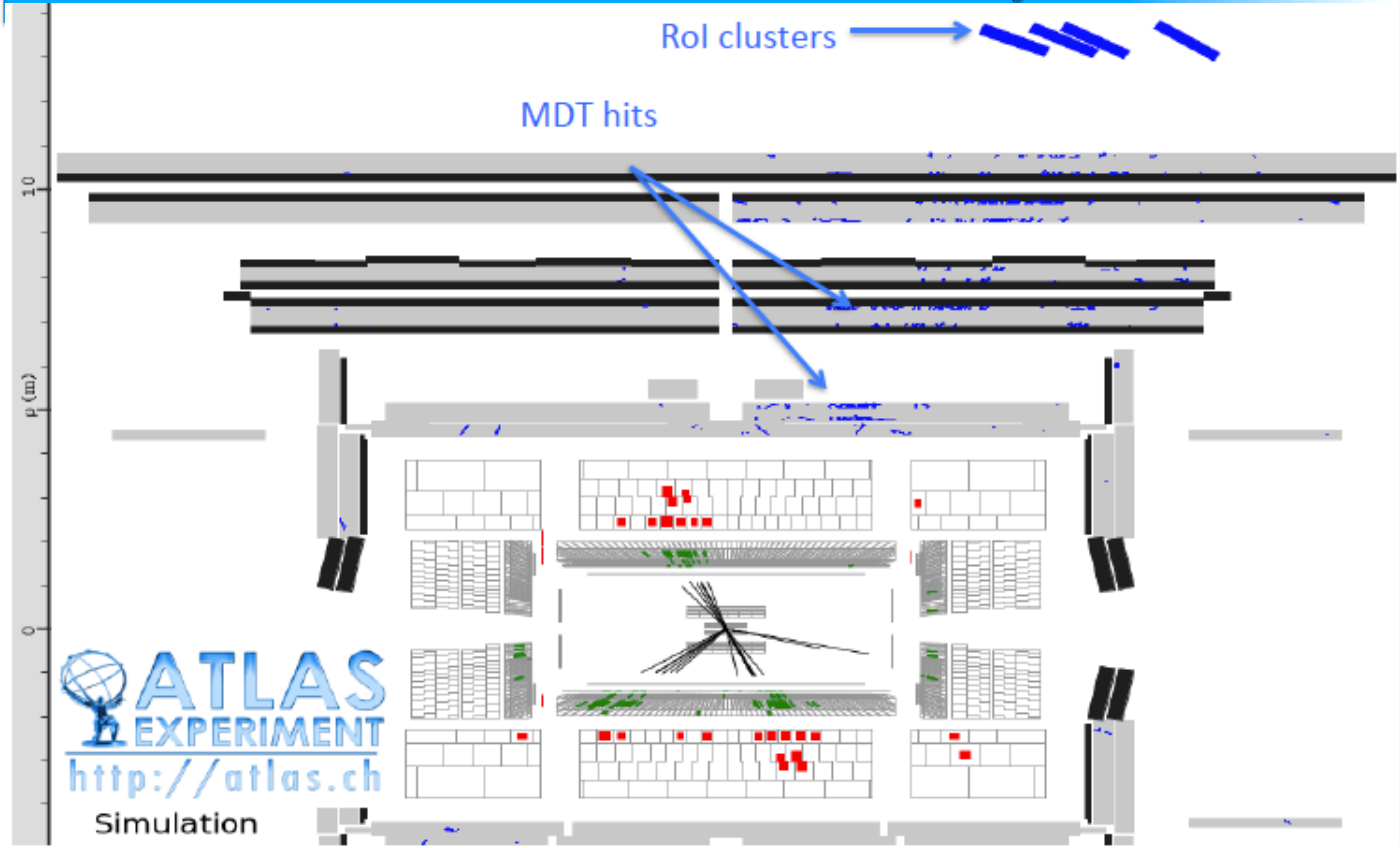
- Data to MC fit is flat



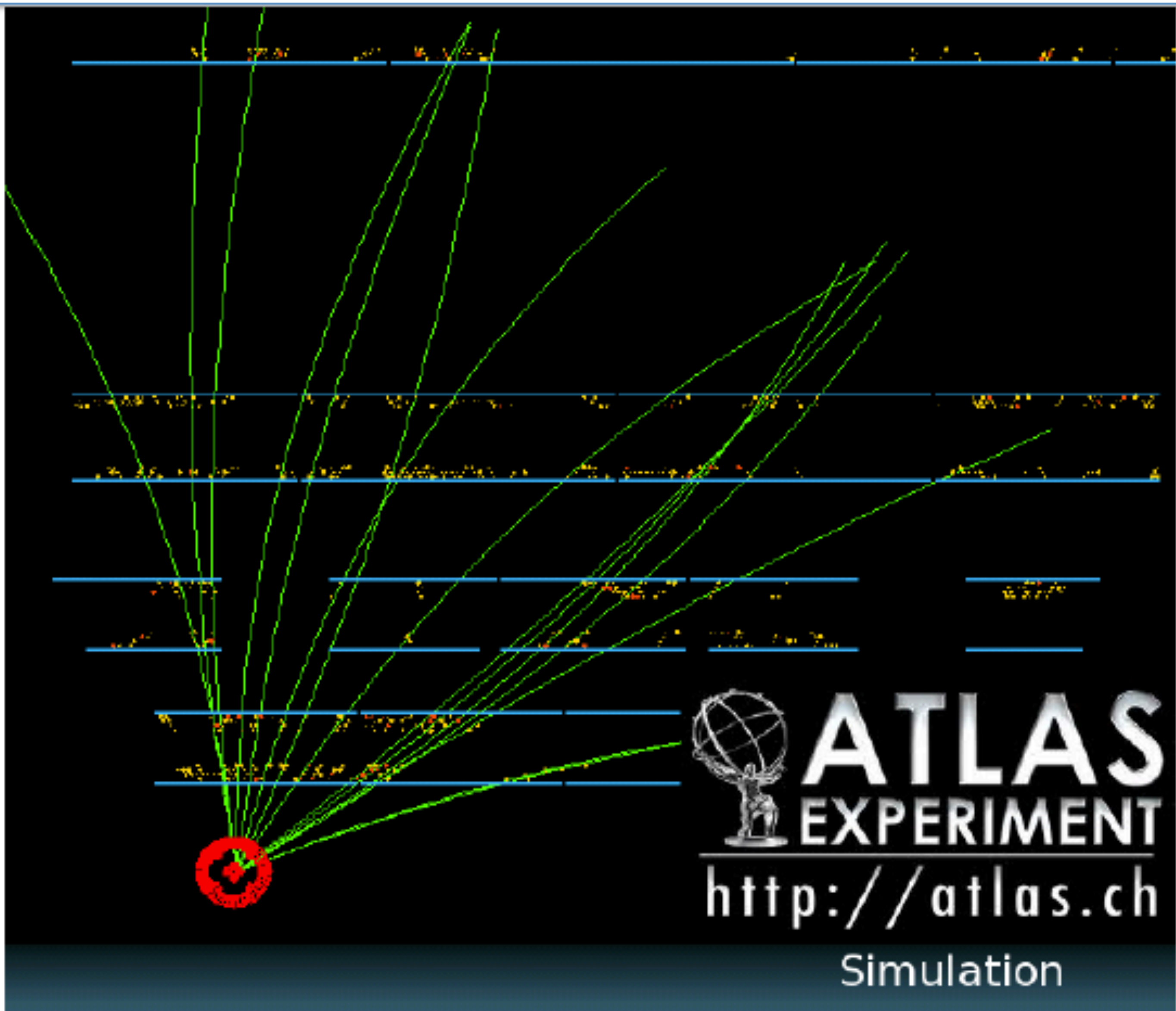
- Final event selection requires
    - two vertices in MS with ΔR >2.0

Number of MDT hits	QCD dijet Monte Carlo	Data
$300 \leq N_{\mathrm{MDT}} < 400$	$10.1 \pm 2.2\%$	$9.1 \pm 0.5\%$
$400 \leq N_{\mathrm{MDT}} < 500$	$9.2 \pm 2.8\%$	$10.5 \pm 0.7\%$
$500 \leq N_{\mathrm{MDT}} < 600$	$13.1 \pm 5.4\%$	$13.0 \pm 0.9\%$
$N_{\mathrm{MDT}} \geq 600$	$16.5 \pm 4.5\%$	$16.7 \pm 0.7\%$

Hidden Valley: Displaced Jets



HIDDEN VALLEY: DISPLACED JETS



Truth tracks

HIDDEN VALLEY : DISPLACED JETS