Search for Long-Lived Particles and Lepton-Jets with the ATLAS detector

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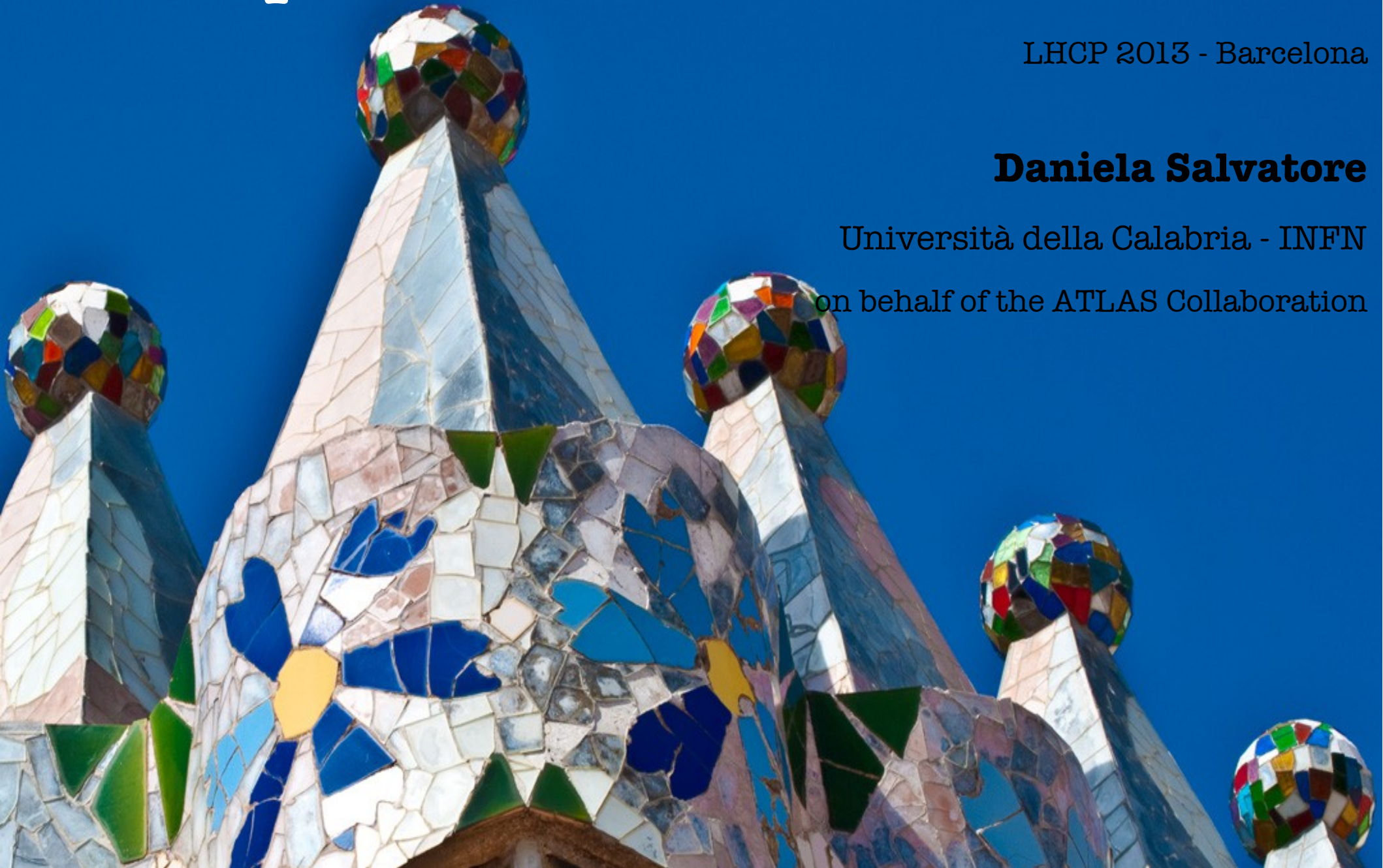
on behalf of the ATLAS Collaboration



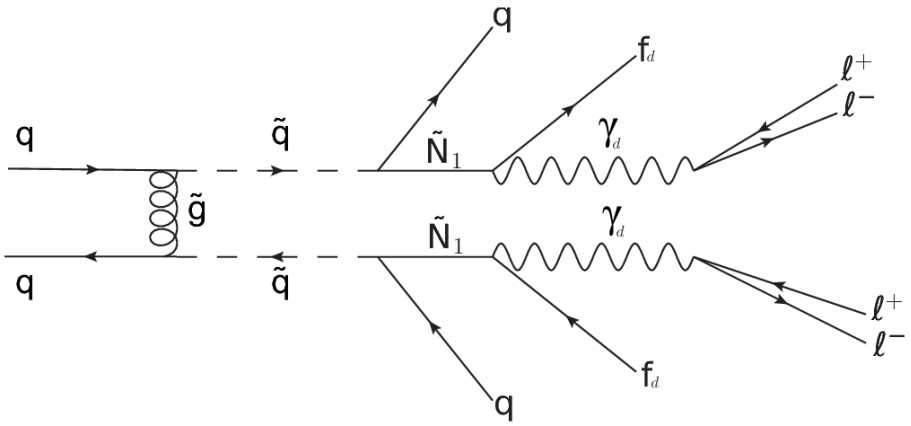
Overview

- Different models predict the existence of long-lived particles
- Hidden Valley models have been proposed to explain several observed anomalies in cosmic-rays and dark matter detection experiments
  - final states with lepton-jets or displaced vertices

- Review of ATLAS public results, from the analysis of 2011 collision data at 7 TeV
  1. ***Prompt lepton-jets***
  2. ***Prompt electron jets in association with a W boson***
  3. ***Displaced muon-jets***
  4. ***Displaced vertices***

1. Prompt lepton-jets

- Models with SM + SUSY + dark sector
  - dark sector particles can mediate decays between SUSY and SM
  - the LSP (N_1) can decay into dark photons γ_d
  - γ_d decays into pairs of collimated leptons



- Parameters:
  - dark sector gauge coupling α_d (0.0, 0.1, 0.3) determines the amount of final leptons
  - dark photon mass $m_{\gamma d}$ (150, 300, 500 MeV)

- Final states:
  - pairs of electron jets (>= 2 e)
  - single muon jet (>= 4 μ)
  - pairs of muon jets (>= 2 μ)

- Triggers:
  - electron-jet channel: single electron p_T > 20 (22) GeV
  - single muon jet: single muon p_T > 18 GeV
  - double muon jet: single muon p_T > 18 GeV OR 3 muons p_T > 6 GeV

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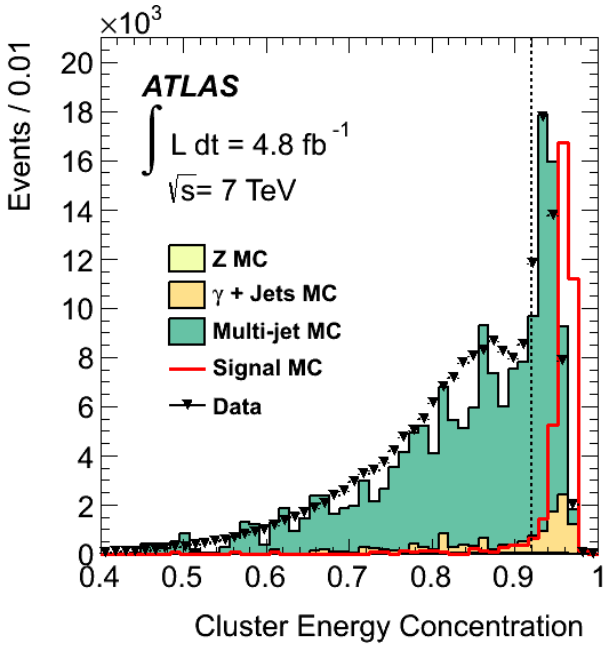
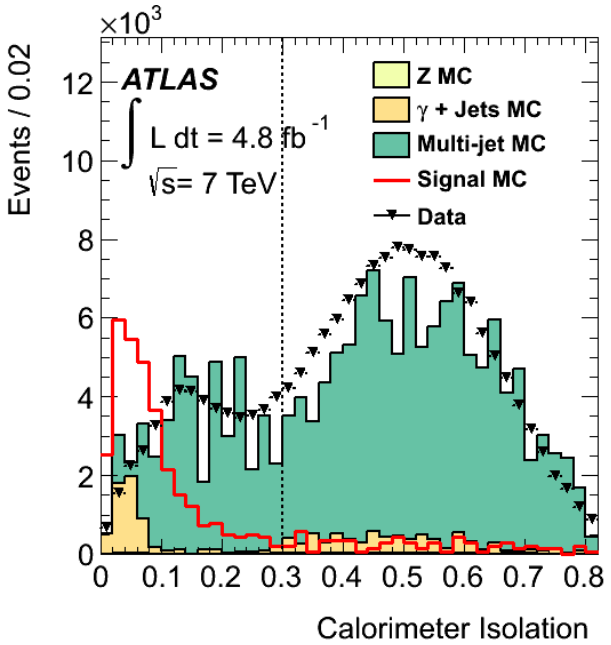
Prompt lepton-jets:
selection criteria

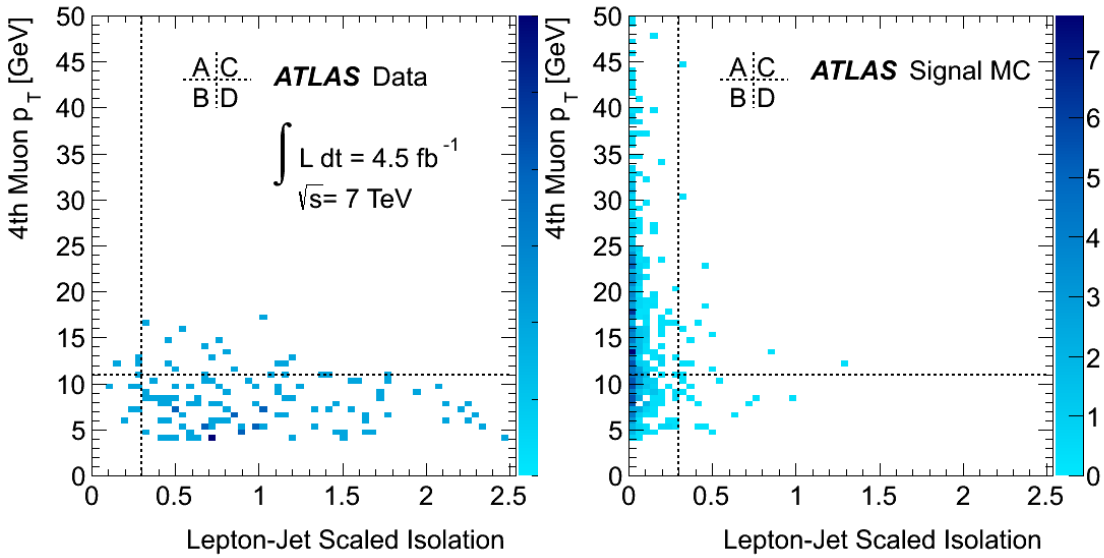
- ***Electron-jet***
  - at least one reconstructed electron with $p_T > 35$ GeV
  - invariant mass < 2 GeV for the 2 highest-p_T tracks associated with each e-jet
  - 2 e-jet candidates per event
- ***Muon-jet***
  - composed of all muons in $\Delta R < 0.1$ around highest-p_T muon
  - muon candidates reconstructed in MS and ID
  - invariant mass < 2 GeV for the the 2 muons closest in p_T
- background from multi-jet events
  - shower shape in the EM calorimeter and track quality cuts are applied for the electron-jet analysis
  - calorimeter isolation (fraction of E_T for all cells around any muon)





Prompt lepton-jets:
results from 4.5 fb^{-1} at 7 TeV

- ABCD method for background estimation
  - electron-jet analysis: electron cluster concentration and EM fraction for the 2nd highest-p$_T$ electron-jet
  - single (double) muon-jet analysis: scaled isolation variable p$_T$ cut on 3rd (4th) muon



Selected events

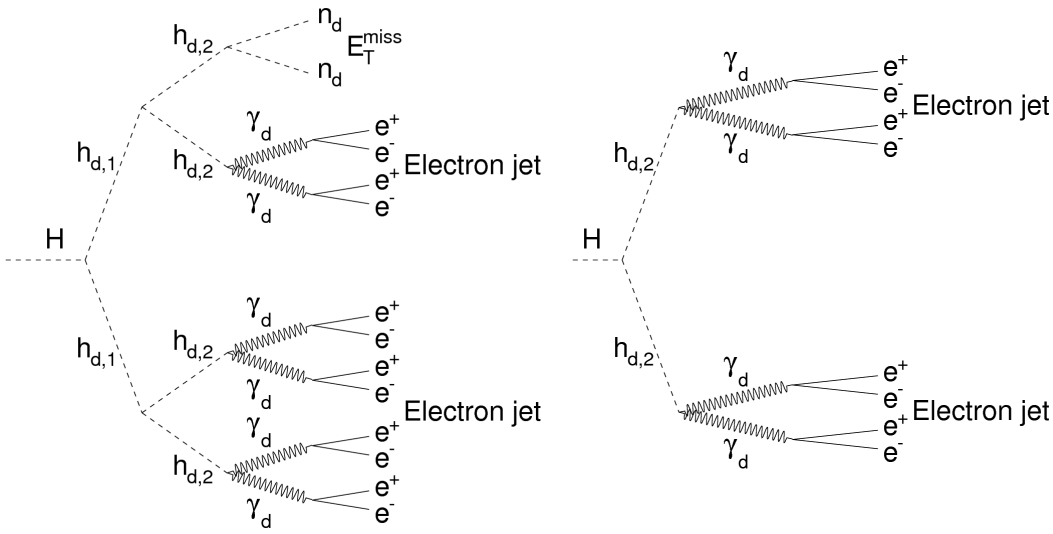
	Electron LJ	1 Muon LJ	2 Muon LJ
Data	15	7	3
All background	15.2±2.7	3.0 ± 1.0	0.5 ± 0.3

- ***No significant excess of events found in any channel on 4.5 fb^{-1} at 7 TeV collected in 2011***
  - Observed upper limits for σ × BR range from 0.017 to 1.2 pb
  - limits in the muon-channel slightly higher than expected but within 2σ of the SM expectations

Signal Parameters α_d	m_{γ_D}[MeV]	Electron LJ Obs (Exp) pb	1 Muon LJ Obs (Exp) pb	2 Muon LJ Obs (Exp) pb
0.0	150	0.082 (0.082)	-	-
0.0	300	0.11 (0.11)	0.060 (0.035)	0.017 (0.011)
0.0	500	0.20 (0.21)	0.15 (0.090)	0.019 (0.012)
0.10	150	0.096 (0.10)	-	-
0.10	300	0.37 (0.37)	0.064 (0.036)	0.018 (0.011)
0.10	500	0.39 (0.39)	0.053 (0.035)	0.018 (0.011)
0.30	150	0.11 (0.11)	-	-
0.30	300	0.40 (0.40)	0.099 (0.055)	0.020 (0.012)
0.30	500	1.2 (1.2)	0.066 (0.043)	0.022 (0.015)

2. W + prompt electron jets

- WH production
- light Higgs boson *(100 to 140 GeV)* decays via a two (three) steps cascade to hidden sector particles
  - two hidden scalars $h_{d,1}$ and $h_{d,2}$
  - a neutral weakly interacting stable scalar n_d
  - dark photons γ_d < 200 MeV decay exclusively to collimated e^+e^- pairs
- W reconstructed both in electron / muon channels
- Signal topology:
  - ***an isolated high p_T lepton + E_T^{miss} + >= 2 electron-jets*** (>= 4 e per jet)
- Triggers:
  - reconstructed electron > 22 GeV
  - reconstructed muon in ID + MS > 18 GeV



Parameter	
$m_{h_{d,1}}$	10 GeV
$m_{h_{d,2}}$	4 GeV
m_{n_d}	90 MeV
m_{γ_d}	100, 200 MeV
Three-step model	
BR($h_{d,1} \to h_{d,2}h_{d,2}$)	1
BR($h_{d,2} \to \gamma_d\gamma_d$)	0.8
BR($h_{d,2} \to n_d n_d$)	0.2
Two-step model	
BR($h_{d,2} \to \gamma_d\gamma_d$)	1
BR($h_{d,2} \to n_d n_d$)	0

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W + prompt electron jets: selection criteria

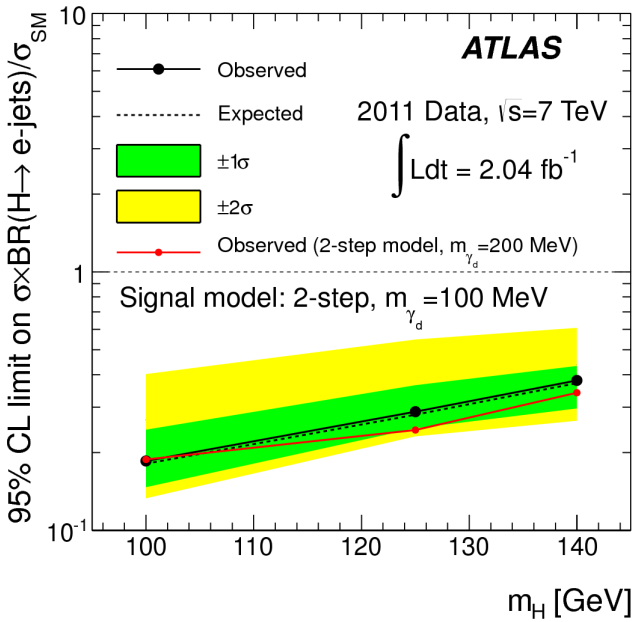
- ***W boson decay***
  - both electron and muon channel considered
  - isolation criterion on both electron and muon, to reduce background from multi-jet events
  - E_T^{miss} >= 25 GeV
  - W is required to originate from the primary vertex

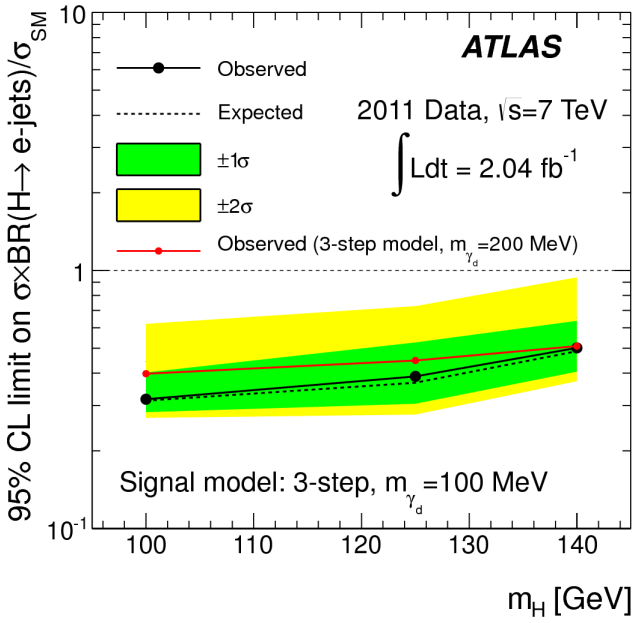
- ***Electron-jet pairs***
  - at least 4 electrons per jet
  - jet p_T >= 30 GeV
  - electrons are very collimated ---> reconstructed jets
  - reject hadronic jets by requiring high EM fraction >= 0.99
  - reject photons from neutral pions by requiring jet charged particle fraction >= 0.66
  - At least 2 tracks associated with jets in a cone $\Delta R < 0.4$
    - quality cut on silicon detectors hits
    - fraction of TRT high threshold hits

W + prompt electron jets: results from 2.04 fb^{-1} at 7 TeV

- ***No significant excess of events found in any channel on 2.04 fb^{-1} at 7 TeV collected in 2011***
  - Event yield in the signal region consistent with background only hypothesis
  - 1 event in the W muon channel
  - 0 events in the W electron channel
  - Limits at m_{γ_d} = 100 and 200 MeV compatible within the statistical uncertainties
  - Assuming WH SM cross section, Higgs BR to electron-jets between 24 and 45% excluded at 95% CL for m_H = 125 GeV

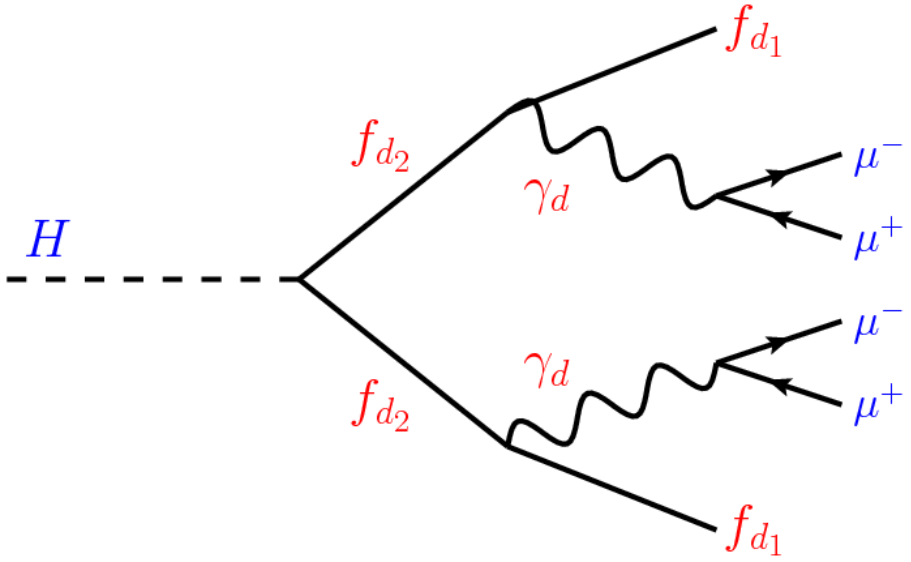
Signal	Three-step model		Two-step model	
m_H (GeV)	$m_{\gamma_d} = 100$ MeV	$m_{\gamma_d} = 200$ MeV	$m_{\gamma_d} = 100$ MeV	$m_{\gamma_d} = 200$ MeV
100	$14.3 \pm 1.7 \pm 0.8$	$12.4 \pm 1.6 \pm 0.7$	$22.6 \pm 2.1 \pm 1.2$	$23.5 \pm 2.1 \pm 1.2$
125	$11.3 \pm 1.0 \pm 0.6$	$10.7 \pm 1.1 \pm 0.6$	$16.2 \pm 1.2 \pm 0.9$	$18.1 \pm 1.4 \pm 1.0$
140	$9.6 \pm 0.8 \pm 0.5$	$9.0 \pm 0.8 \pm 0.4$	$13.7 \pm 0.9 \pm 0.8$	$13.9 \pm 0.9 \pm 0.8$
Background	$0.41 \pm 0.29 \pm 0.12$			
Data	1			





3. Displaced muon-jets

- Higgs boson decays to a pair of neutral hidden fermions (f_{d2})
  - each f_{d2} decays to one **long-lived** γ_d and one stable neutral hidden fermion (f_{d1})
- γ_d to two **collimated lepton jets**
  - γ_d p_T > 20 GeV; ΔR_{ll} < 0.1
  - for mass = 400 MeV 45% e^+e^-, **45% $\mu^+\mu^-$** , 10% $\pi^+\pi^-$
- γ_d pair emitted back-to-back
- trigger: 3 muons reconstructed only in the MS with p_T >= 6 GeV
- expected background
  - multi-jet processes, cosmic rays



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

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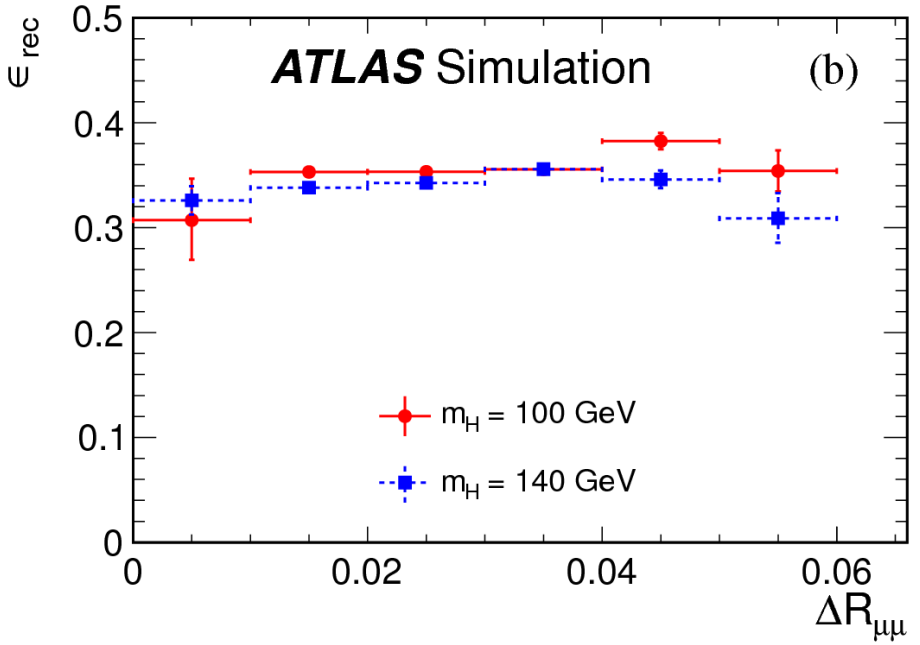
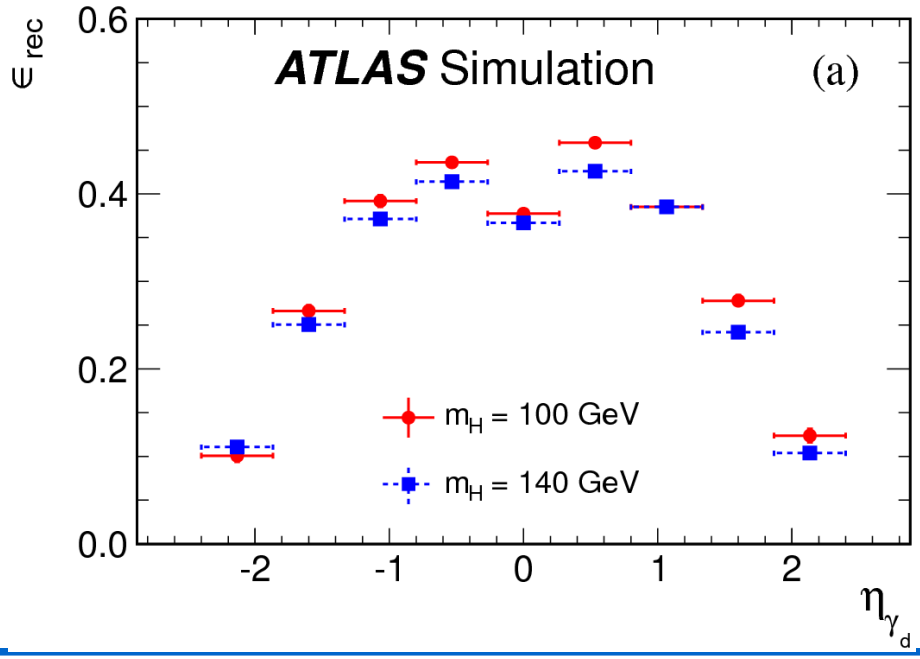
Displaced muon-jets: selection criteria

Muon-jet

- reconstructed from the highest p_T muon and associating all muons in a $\Delta R = 0.2$ cone
- At least 2 muons per MJ
- 2 back-to-back MJs per event
  - $|\Delta\Phi| > 2$
- Calorimetric isolation variable (E_T^{isol}) <= 5 GeV
  - difference of E_T in a $\Delta R = 0.4$ cone around the highest p_T muon and E_T in $\Delta R = 0.2$
- Sum of track p_T < 3 GeV
  - scalar sum of p_T of the tracks in a $\Delta R = 0.4$ cone around the direction of the MJ
- γ_d reconstruction efficiency tested on $J/\psi \rightarrow \mu^+\mu^-$

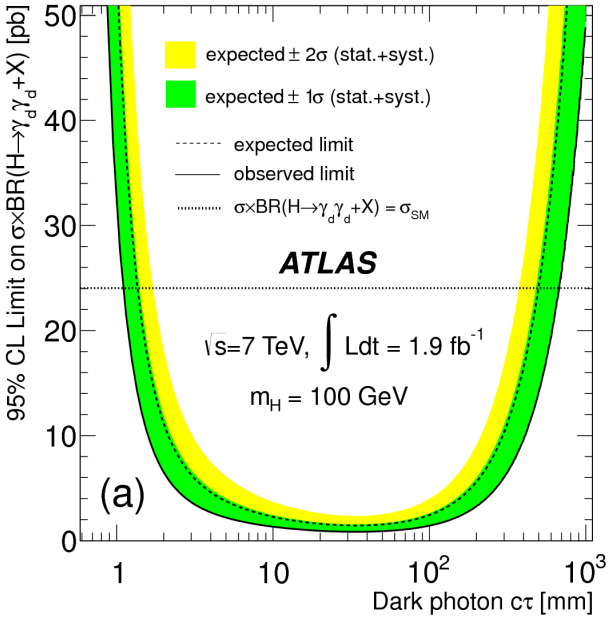


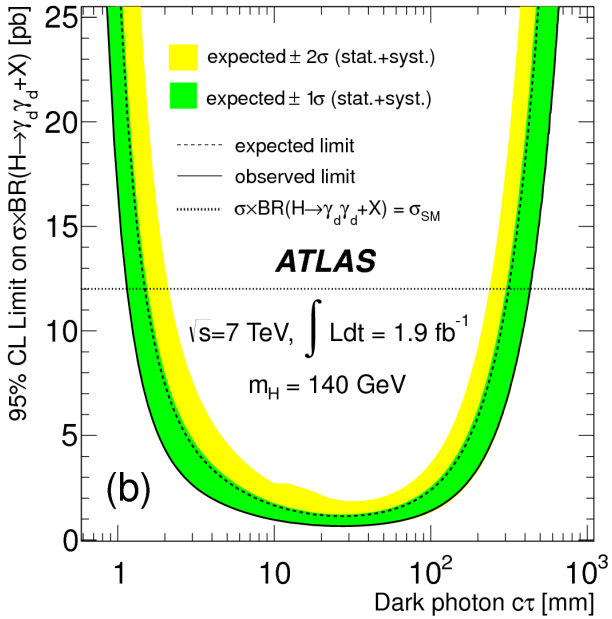


Displaced muon-jets
results from 1.94 fb^{-1} at 7 TeV

- multi-jet background estimation through ABCD method
  - E_T^{isol} - $|\Delta\Phi|$ plane
  - expected 0.06 events
- ***No excess of events observed in 1.94 fb^{-1} at 7 TeV***
  - Assuming BR (H--->$\gamma_d\gamma_d$ + X) = 10% γ_d proper lifetimes excluded
    - from 5 to 159 mm for m_H = 100 GeV
    - from 7 to 82 mm for m_H = 140 GeV

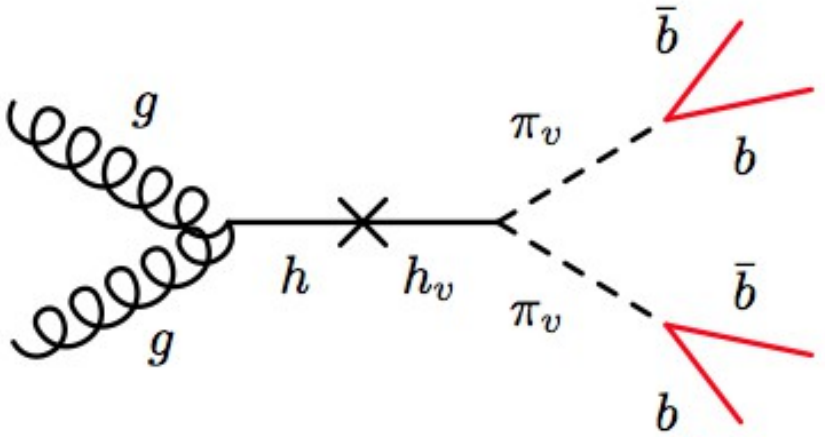
cut	cosmic-rays	multi-jet	total background	m_H = 100 GeV	m_H = 140 GeV	data
$N_{MJ} = 2$	3.0 ± 2.1	N/A	N/A	$135\pm11^{+29}_{-21}$	$90\pm9^{+17}_{-13}$	871
$E_T^{isol} \leq 5$ GeV	3.0 ± 2.1	N/A	N/A	$132\pm11^{+28}_{-21}$	$88\pm9^{+17}_{-13}$	219
$\|\Delta\phi\| \geq 2$	1.5 ± 1.5	153 ± 18 ± 9	155 ± 18 ± 9	$123\pm11^{+26}_{-19}$	$81\pm9^{+15}_{-12}$	104
$Q_{MJ} = 0$	1.5 ± 1.5	57 ±15±22	59 ± 15 ± 22	$121\pm11^{+26}_{-19}$	$79\pm8^{+15}_{-12}$	80
$\|d_0\|, \|z_0\|$	$0^{+1.64}_{-0}$	111±39±63	111±39±63	$105\pm10^{+22}_{-16}$	$66\pm8^{+12}_{-10}$	70
$\Sigma p_T^{ID} < 3$ GeV	$0^{+1.64}_{-0}$	$0.06\pm0.02^{+0.66}_{-0.06}$	$0.06^{+1.64+0.66}_{-0.02-0.06}$	$75\pm9^{+16}_{-12}$	$48\pm7^{+9}_{-7}$	0

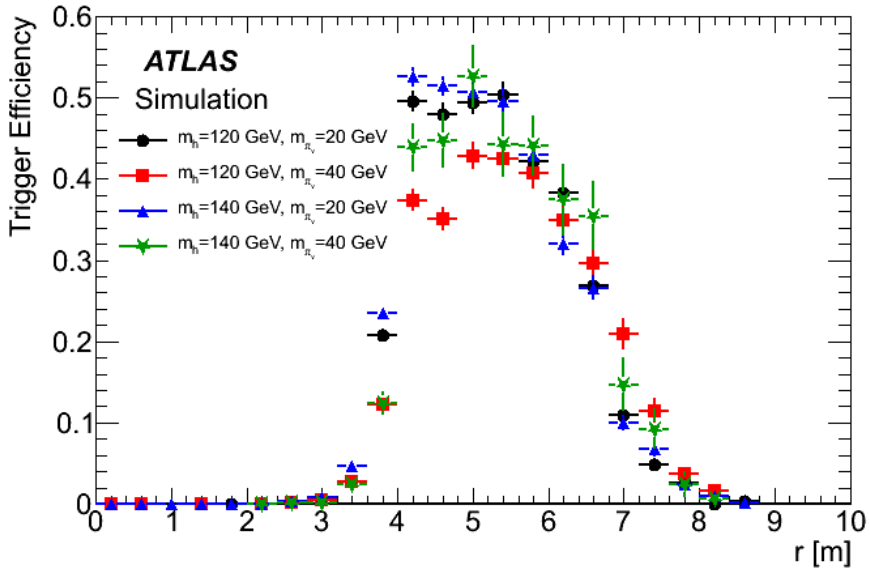




4. Displaced vertices

- Higgs boson decays to two hidden sector **long-lived neutral** v-pion (π_v)
  - π_v pairs emitted back-to-back
- Each π_v decays into heavy-fermion pairs
  - mainly $b\bar{b}$
- search for decays near the outer radius of hadronic calorimeter or in the muon spectrometer (MS)
- dedicated trigger
  - MuonRoICluster trigger selects events with a cluster of >= 3 muon RoIs in a $\Delta R = 0.4$ cone in the MS barrel chambers
- dedicated vertex reconstruction
- background rejection
  - punch-through jets and muon bremsstrahlung suppressed by requiring isolation in calorimeters and ID



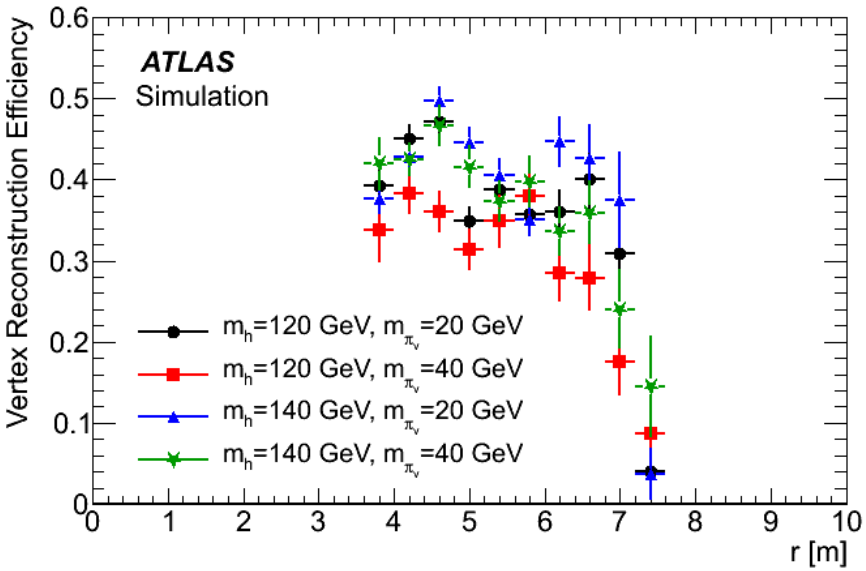


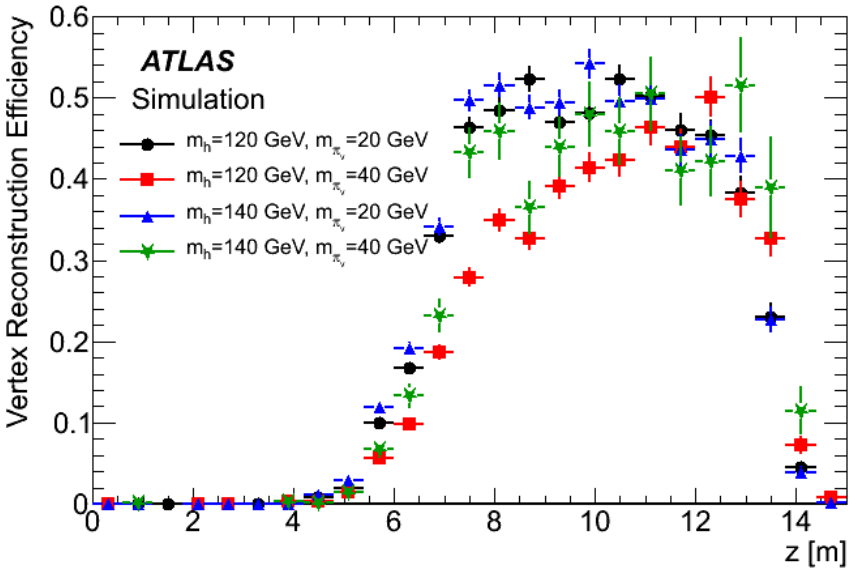
Physical Review Letters, 108, 251801 (2012)

Displaced vertices: selection criteria

Vertices in the MS

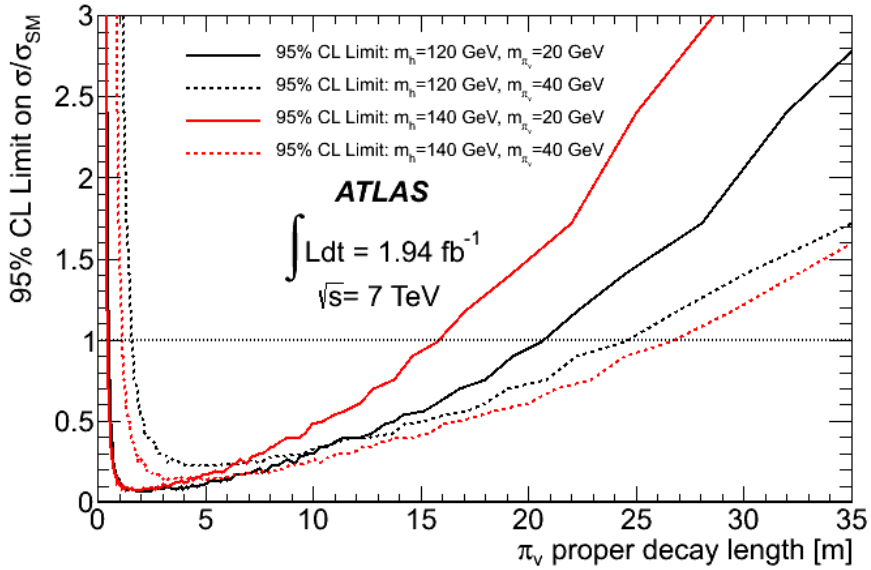
- Specialized tracking and vertex reconstruction algorithm
  - π_v decays in the MS characterized by low p_T particles (~10 charged particles and ~5 π^0 clustered in a small region)
  - detectable vertices between the outer radius of HCAL and the middle station of the MS
  - high occupancy in MDTs
- Requirement for a vertex
  - At least 3 tracklets grouped in $\Delta R = 0.6$
  - point back to IP
  - Separated from ID tracks and jets
- Reconstruction efficiency
  - 40% in barrel region (4-7.5 m)
  - 40% in endcaps (8-14 m)
- two good vertices per event, $\Delta R > 2$





Displaced vertices:
results from 1.94 fb^{-1} at 7 TeV

- Background estimated from a fully data-driven method based on:
  - probability for a random event to contain a MS vertex
  - probability to reconstruct a vertex in an event which passed the RoI cluster trigger
  - **estimated 0.03 ± 0.02 events**



- ***No data pass the selection criteria in 1.94 fb^{-1} at 7 TeV***
  - Assuming a 100% BR for H--->$\pi_v\pi_v$ a wide range of proper lifetimes is escluded at 95% CL

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

Conclusions

- Long-lived particles and lepton-jets are predicted by a number of theories beyond the Standard Model
- Challenging detector signatures requiring detailed work on dedicated trigger and reconstruction algorithms
- Extensive search program conducted by the ATLAS Collaboration on the 2011 7 TeV dataset
- Analysis teams are now actively working on the 2012 8 TeV dataset and first results will be public soon
- Analysis techniques are being improved
- More statistics but also more final states

BACKUP

Prompt lepton-jets: selection criteria

Electron-jet

- at least a p_T > 35 GeV reconstructed electron (trigger efficiency constant)
- candidates built from EM clusters
  - E_T > 10 GeV in calorimeter fiducial region
  - at least two PV tracks with p_T > 10 GeV, $|d_0|$ < 1 mm, ΔR < 0.1 wrt cluster in the second sampling layer of ECAL
- invariant mass < 2 GeV for the 2 highest-p_T tracks associated with each e-jet

- 2 e-jet candidates per event
  - one matches the electron reconstructed in the trigger system
- main background from multi-jet events
  - cuts on the electron cluster concentration and lateral shower, high-threshold hits, electromagnetic fraction and fraction of E_T in 0.1 < ΔR < 0.4 around the cluster

Muon-jet

- all muons in ΔR < 0.1 around highest-p_T muon
- muon candidates reconstructed in MS and ID
- $|d_0|$< 1 mm cut on the tracks
- invariant mass < 2 GeV for the the 2 muons closest in p_T

- Single muon-jet analysis
  - 4 muons with p_T > 19, 16, 14 GeV + additional muons > 4 GeV
- Double muon-jet analysis
  - 2 muons with p_T > 11 GeV per jet
- Scaled isolation variable
  (to suppress muons from hadronic jets)
  - sum of E_T for all cells with 0.05 < ΔR < 0.3 around any muon divided by muon-jet p_T
  - less than 0.15 (0.3) for single (double) muon-jet analysis

W + prompt electron jets: selection criteria

- ***W boson decay***
  - both electron and muon channel considered
  - sum of the p_T of all tracks in $\Delta R < 0.4$ around the electron (muon) divided by electron (muon) $p_T < 0.3$ (0.2)
- $E_T^{miss} >= 25$ GeV
- Trigger matching
  - $\Delta R < 0.1$ between the trigger object and the reconstructed lepton
- W is required to originate from the primary vertex
  - vertex with largest sum of p_T^2 for all tracks
  - track longitudinal and transverse impact parameters wrt PV < 10 mm and 0.1 mm respectively

- ***Electron-jet pairs***
  - at least 4 electron per jet
  - electron very collimated ---> reconstructed jets
  - $p_T >= 30$ GeV
- Rejection of hadronic jets
  - high EM fraction (>= 0.99)
- Rejection of photons from neutral pions
  - jet charged particle fraction
    - fraction of the jet energy deposited in cells that are associated to tracks within the jet
  - At least 2 tracks associated with jets in a cone $\Delta R < 0.4$
    - $p_T >= 5$ GeV
    - cut on silicon detectors hits
    - fraction of TRT high threshold hits