Ricerca di LeptoJets prodotti dal decadimento di particelle neutre a lunga vita in 20.3 fb^{-1} di collisioni p-p a $\sqrt{s}$ = 8 TeV con l'esperimento ATLAS al LHC

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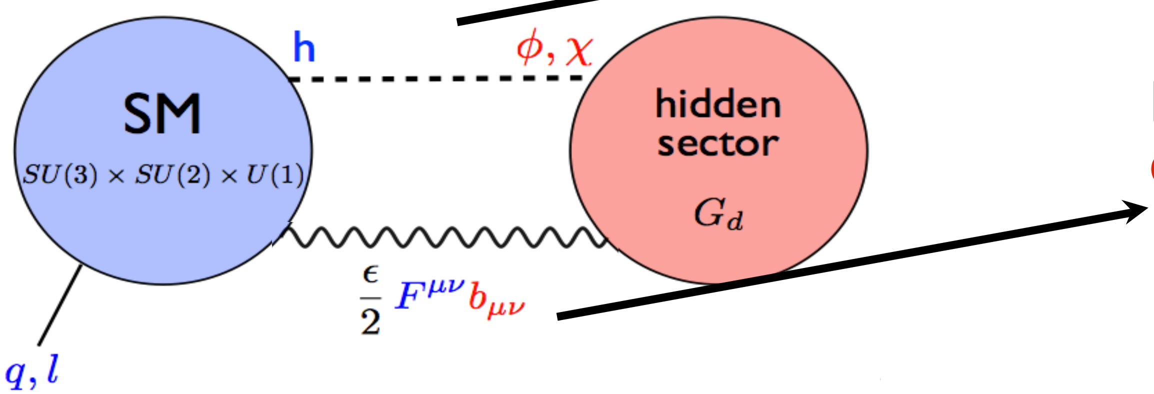
LeptonJets

Several BSM models predict final states containing LeptonJets

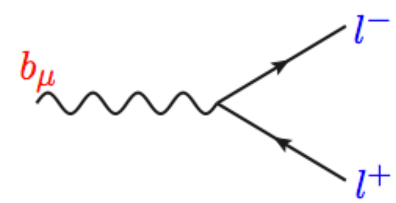


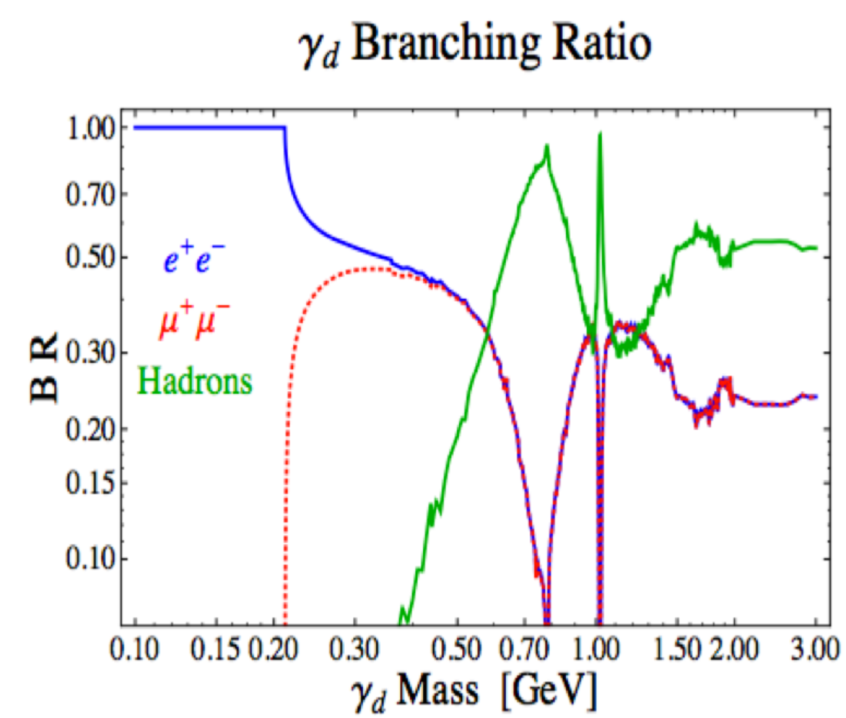
Portal to hidden sector: ex. Higgs or supersymmetric particles

Hidden particles decay back to SM: e.g. **dark-photons (γ_d)** → collimated pair of leptons (**LeptonJets**)

kinetic mixing

$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} b_{\mu\nu} + m^2_{\gamma_d} b^2$$



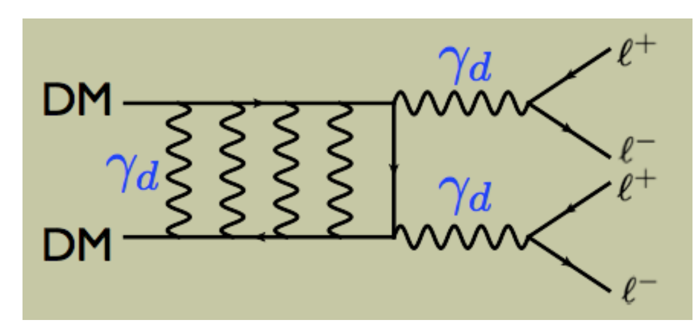


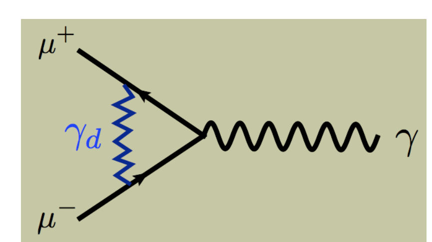
Dark photon lifetime depends on the size of kinetic mixing **ε**

small ε → displaced decays

LeptonJets can be prompt or displaced

- (Some) motivations
  - Excess of positron flux in cosmic rays (not anti-proton) → if DM annihilates to a hidden sector it would produce leptons
  - $(g_s\text{-}2)_\mu$ anomaly: comparing theory to experiment there is a 3.2σ discrepancy → anomaly can be explained including corrections from an hidden photon





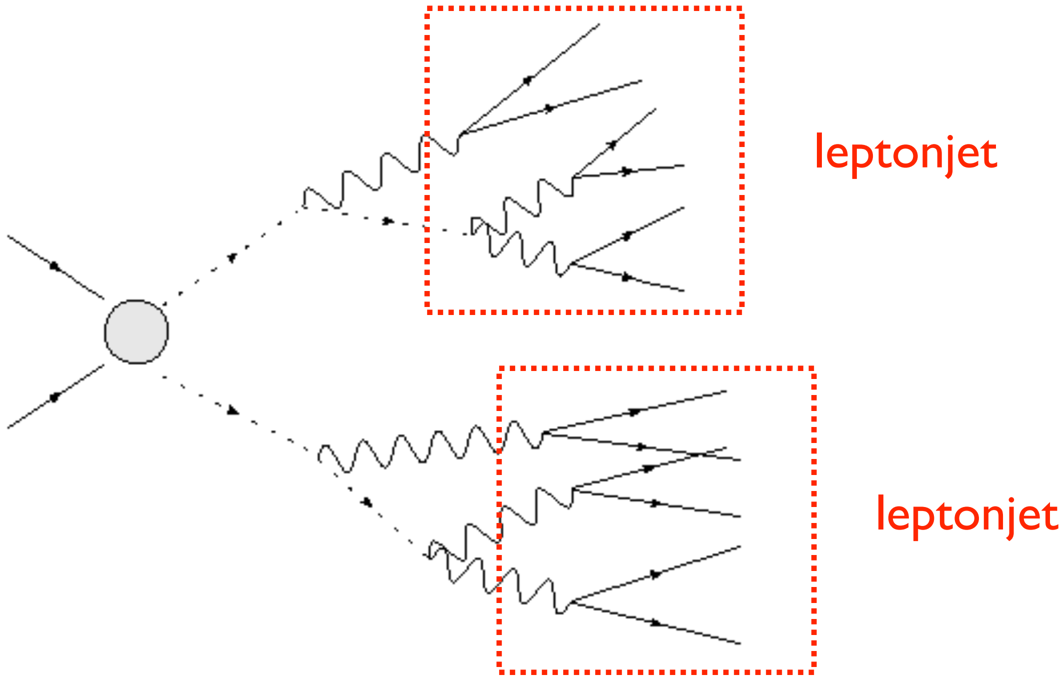
Displaced LeptonJets

When studying LJ's, it is better to avoid focusing on one specific model (that can be more or less motivated), and try instead to use as much as possible an experimental definition that reproduces a set of signatures.

Model independent search strategy for non-prompt LJs: start from a general non-prompt LJ definitio

LeptonJets: N neutral light dark photons in a narrow cone (ΔR) decaying to pairs of electrons/muons/pions → **lepton/hadron pairs in a narrow cone ΔR**

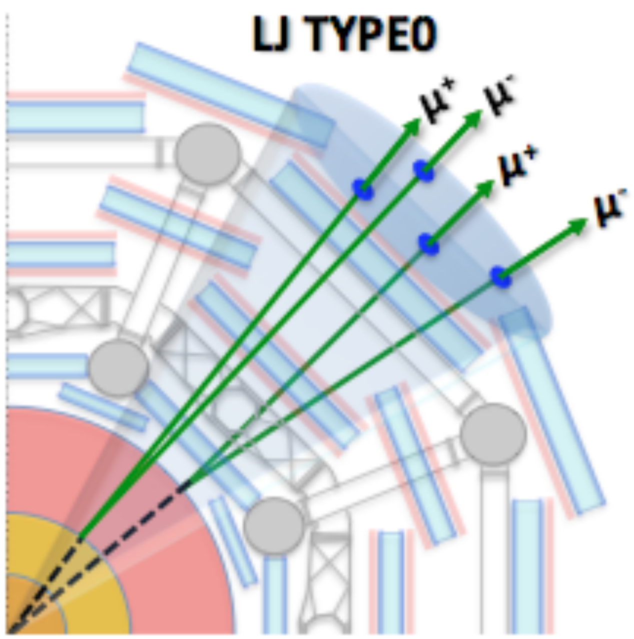
Non-prompt leptonjets: leptonjets with long-lived γ_d's (small ε) → **displaced decays highly isolated in ID**

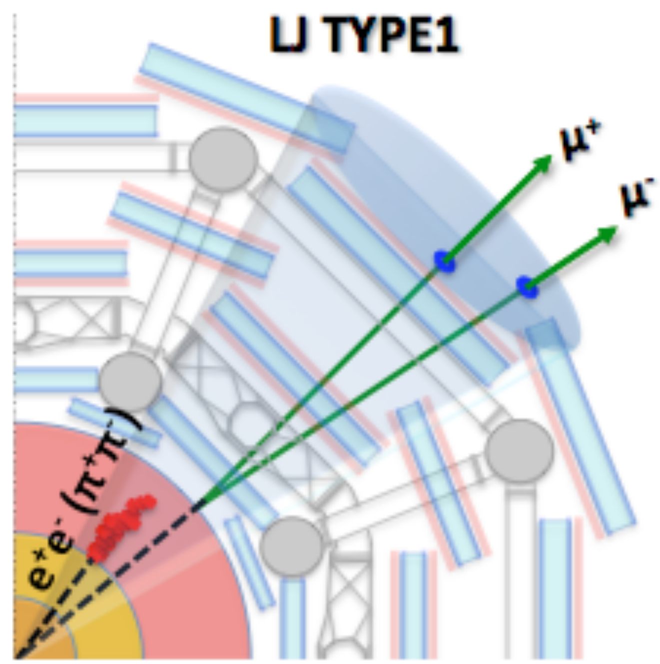


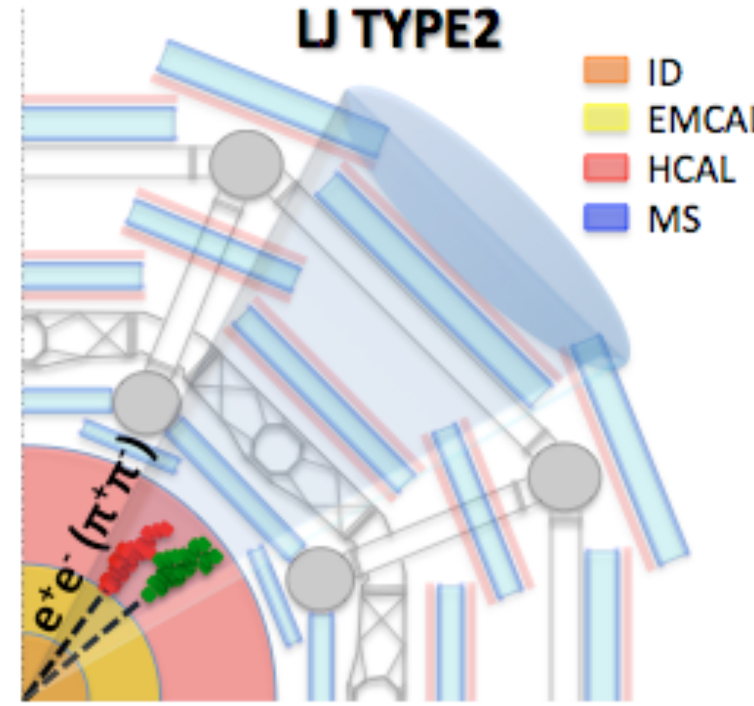
Non-prompt LeptonJet definition

Non-prompt leptonjet general definition: use

- standalone muons
- anti-kt 0.4 jets with p_T >20 GeV







TYPE 0: ≥2 "good" muons clustered in a cone opening ΔR=0.5 and NO jets in the cone

- selection of non-prompt LJs with only muons

TYPE 1: ≥2 "good" muons + "good" jets clustered in a cone opening ΔR=0.5

- selection of non-prompt LJs with muons and electrons/pions

TYPE 2: "good" jets with low EM fraction and narrow width and no muons in a cone opening ΔR=0.5 around jet direction

- selection of non-prompt LJs with only electrons/pions in HCAL

LeptonJet gun MC generator:
- generate LeptonJets made up to two dark photons varying boost and masses in the LeptonJets parameter space
- used to optimize search criteria and to produce detection efficiency curves to constrain theory models predicting LeptonJet production

Selection of events with non-prompt LJs

Triggers for non prompt-leptonjets (unprescaled during 2012 data taking)

- muon trigger: requires ≥3 standalone muons with p_T>6GeV → selects displaced leptonjets with muonic content; MSonly to allow for non-prompt decays
- calorimeter trigger: a 35 GeV (EM scale) jet with EM fraction < 0.07 → selects displaced leptonjets containing only electrons/pions decaying in the HCAL

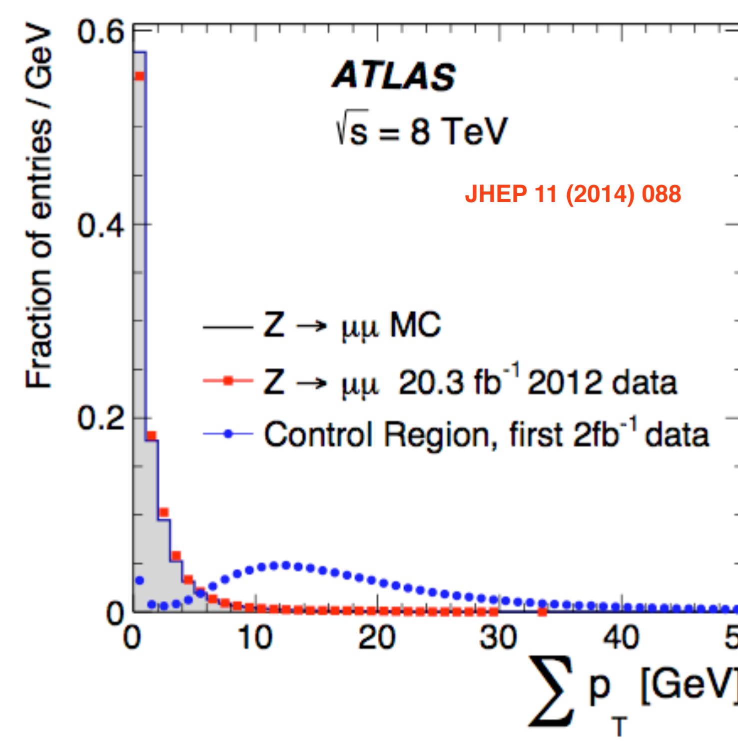
Main variables for background rejection

- Main background expected from QCD multijets and cosmic rays

    → use isolation variable and jet EM fraction/width to reduce QCD multijet background

    → use jet timing to remove cosmic ray events

- Isolation in inner tracker to reduce pile-up dependence
- $\sum P_T$ variable: sum of the p_T of the ID tracks associated to the primary vertex in a cone ΔR=0.5 around the LJ line of flight (p_T tracks > 0.5 GeV)
- Use real Z→μμ to validate the isolation variable
- Full 2012 statistics; standard Z selection



Cut flow for event selection

Requirement	Description
Two reconstructed LJs	select events with at least two reconstructed LJs
η range (TYPE1)	remove jets with $\|\eta\| > 2.5$
η range (TYPE2)	remove jets with $\|\eta\| > 2.5$ and $1.0 < \|\eta\| < 1.4$
EM fraction (TYPE2)	require EM fraction of the jet < 0.1
Jet width W (TYPE2)	require width of the jet < 0.1
Jet timing (TYPE1/TYPE2)	require jets with timing -1 ns $< t < 5$ ns
NC muons (TYPE0/TYPE1)	require muons without ID track match
ID isolation	require $\max\{\Sigma p_{\mathrm{T}}\} \leq 3$ GeV
$\Delta\phi$	require $\|\Delta\phi\| \geq 1$ rad between the two LJs

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20.34 fb^{-1} 2012 data

LJ pair types	0-0	0-1	0-2	1-1	1-2	2-2	All
Trigger selection	9.226×10^6						
Good primary vertex	9.212×10^6						
Two reconstructed LJs	946	1771	16676	1382	19629	82653	123057
η range (TYPE1/TYPE2)	946	1269	5063	701	3838	25885	37702
EM fraction (TYPE2)	946	1269	393	701	172	4713	8194
Jet width W (TYPE2)	946	1269	350	701	148	3740	7154
Jet timing (TYPE1/TYPE2)	946	1054	216	547	92	578	3433
NC muons (TYPE0/TYPE1)	27	3	42	5	5	578	660
ID isolation	12	0	19	4	3	160	198
$\|\Delta\phi\|$	11	0	11	4	3	90	119

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Backgrounds

- No events surviving the cut flow running on MC background samples:
  - QCD jet samples but equivalent integrated luminosity too low
    - Use data-drive matrix method for QCD di-jet background evaluation
  - W/Z+jet and W/Z+jet+gamma samples (~10fb^{-1}, already negligible at trigger level)
  - Di-photons and Di-bosons samples (>20fb^{-1} , already negligible at trigger level)
  - single top samples (~20fb^{-1}, already negligible at trigger level)
  - t-tbar sample (~20fb^{-1}, no events after the request of ≥2 LJs in the events)
- Use triggers in empty bunches of 2012 data for cosmic-ray contribution

LJ pair types	0-0	0-1	0-2	1-1	1-2	2-2	All
Trigger selection	161951						
Good primary vertex	not applicable						
Two reconstructed LJs	6	0	42	0	36	3744	3838
η range (TYPE1/TYPE2)	6	0	29	0	17	2243	2295
EM fraction (TYPE2)	6	0	29	0	17	2190	2242
Jet width W (TYPE2)	6	0	22	0	6	1632	1666
Jet timing (TYPE1/TYPE2)	6	0	6	0	0	24	36
NC muons (TYPE0/TYPE1)	6	0	6	0	0	24	36
ID isolation	6	0	6	0	0	24	36
$\lvert\Delta\phi\rvert$	6	0	5	0	0	4	15
Rescaled to interactions	15 ± 6	$0^{+3.1}_{-0}$	14 ± 6	$0^{+3.1}_{-0}$	$0^{+3.1}_{-0}$	11 ± 7	40 ± 10

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Cosmic-ray background rescaled to the number of collision bunches using the scale factor:

$$SF = \frac{Number\ of\ Filled\ Bunch\ Crossings}{Number\ of\ Empty\ Bunch\ Crossings}$$

QCD di-jet background evaluation: ABCD method

- Use |Δφ| and max(∑ p_T) as uncorrelated variables
- Define the signal region at |Δφ|>1 rad and max(∑ p_T)< 3 GeV

Look at the expected background in the signal region using ABCD $N_A=N_B x N_D/N_C$

(assuming no signal leakage in control regions)

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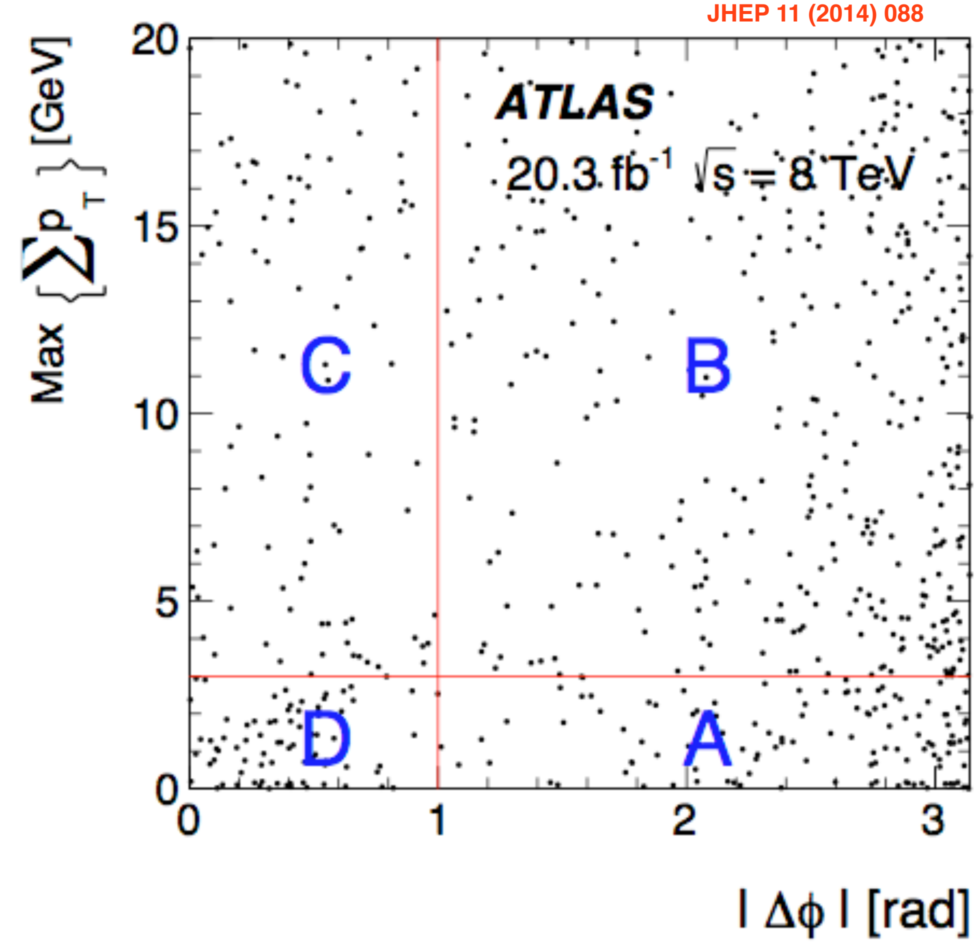

- All LJ pair TYPES

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

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- QCD background is expected to give the maximum contribution to TYPE2 - TYPE2 events: depending on the LJ models they can be removed or not
- TYPE2-TYPE2 removed:

Data Type	Events in B	Events in C	Events in D	Expected events in A
Cosmic-ray data	0	0	3 ± 3	29 ± 9
Data (cosmic rays subtracted)	29 ± 5	15 ± 4	6 ± 4	12 ± 9

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Summary

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	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	$110 \pm 59 \pm 14$	$41 \pm 12 \pm 29$

The observed number of events is fully compatible with the expected background events

↓

No excess of events observed over the estimated background → put exclusion limits on specific LJ models

↓

BSM Higgs boson decay to LJ

deviations in the 125 GeV Higgs boson decay rates to final states predicted by the SM

LeptonJet models: Higgs → 2γ_d + X and Higgs → 4γ_d + X

(Falkowsky-Ruderman-Volansky-Zupan)

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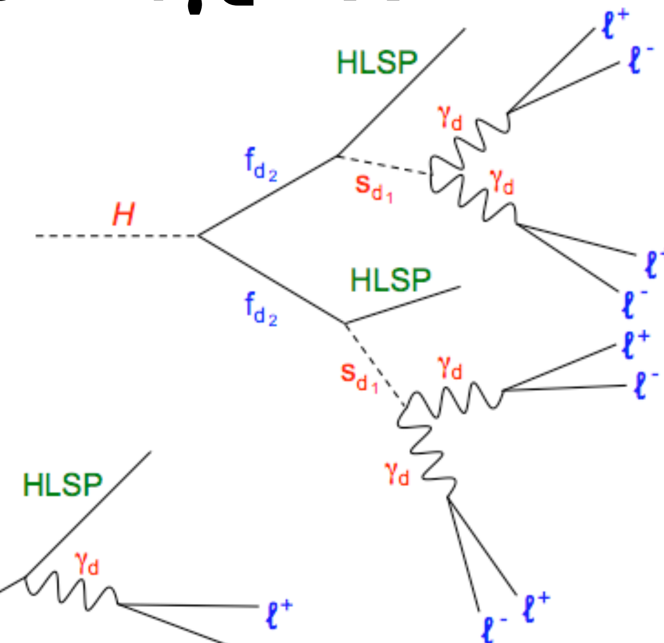
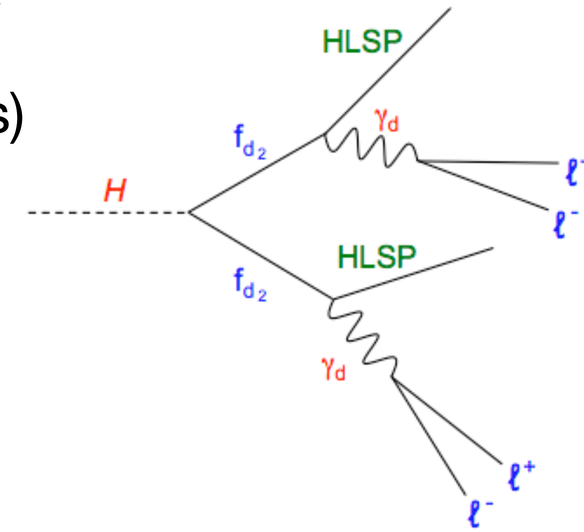
model	events	m_H [GeV]	$m_{f_{d_2}}$ [GeV]	$m_{f_{d_1}/LSP}$ [GeV]	$m_{s_{d_1}}$ [GeV]	m_{γ_d} [GeV]	$c\tau_{\gamma_d}$ [mm]	BR $\gamma_d \to ee$	BR $\gamma_d \to \mu\mu$	BR $\gamma_d \to \pi\pi$
2 dark photons	150k	125	5.0	2.0	-	0.4	47	0.45	0.45	0.10
4 dark photons	150k	125	5.0	2.0	2.0	0.4	47	0.45	0.45	0.10



100k events for each sample. Lifetime chosen in order to have enough decays in all the regions of the ATLAS detectors; (all parameters consistent with current experimental constraints)

Cut flow

(gluon-gluon fusion Higgs production σ, 10% Higgs BR to hidden sector - rescaled to 20.3 fb^{-1})



4 dark photons

LJ pair types	0-0	0-1	0-2	1-1	1-2	2-2	All
Total number of events	39730 ± 100						
Trigger selection	2518 ± 42						
Good primary vertex	2518 ± 42						
Two reconstructed LJs	196	121	71	23	24	14	448 ± 11
η range (TYPE1/TYPE2)	196	83	32	13	9	5	337 ± 10
EM fraction (TYPE2)	196	83	11	13	6	1	308 ± 9
Jet width W (TYPE2)	196	83	11	13	6	1	308 ± 9
Jet timing (TYPE1/TYPE2)	196	80	11	11	5	1	304 ± 9
NC muons (TYPE0/TYPE1)	101	39	8	5	4	1	158 ± 6
ID isolation	72	24	6	3	2	1	107 ± 5
$\|\Delta\phi\|$	70 ± 4	23 ± 2	5 ± 1	3 ± 1	2 ± 1	$0^{+0.6}_{-0}$	104 ± 5

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Results depend on the lifetime used in the model simulation

↓

2 dark photons

LJ pair types	0-0	0-1	0-2	1-1	1-2	2-2	All
Total number of events	39730 ± 100						
Trigger selection	1330 ± 30						
Good primary vertex	1330 ± 30						
Two reconstructed LJs	86	9	40	0	1	39	175 ± 7
η range (TYPE1/TYPE2)	86	8	27	0	1	23	145 ± 6
EM fraction (TYPE2)	86	8	23	0	1	12	130 ± 6
Jet width W (TYPE2)	86	8	23	0	1	12	130 ± 6
Jet timing (TYPE1/TYPE2)	86	6	23	0	1	11	128 ± 6
NC muons (TYPE0/TYPE1)	50	4	17	0	0	11	82 ± 5
ID isolation	37	2	13	0	0	10	63 ± 4
$\|\Delta\phi\|$	35 ± 3	2 ± 1	12 ± 2	$0^{+0.6}_{-0}$	$0^{+0.6}_{-0}$	10 ± 2	60 ± 4

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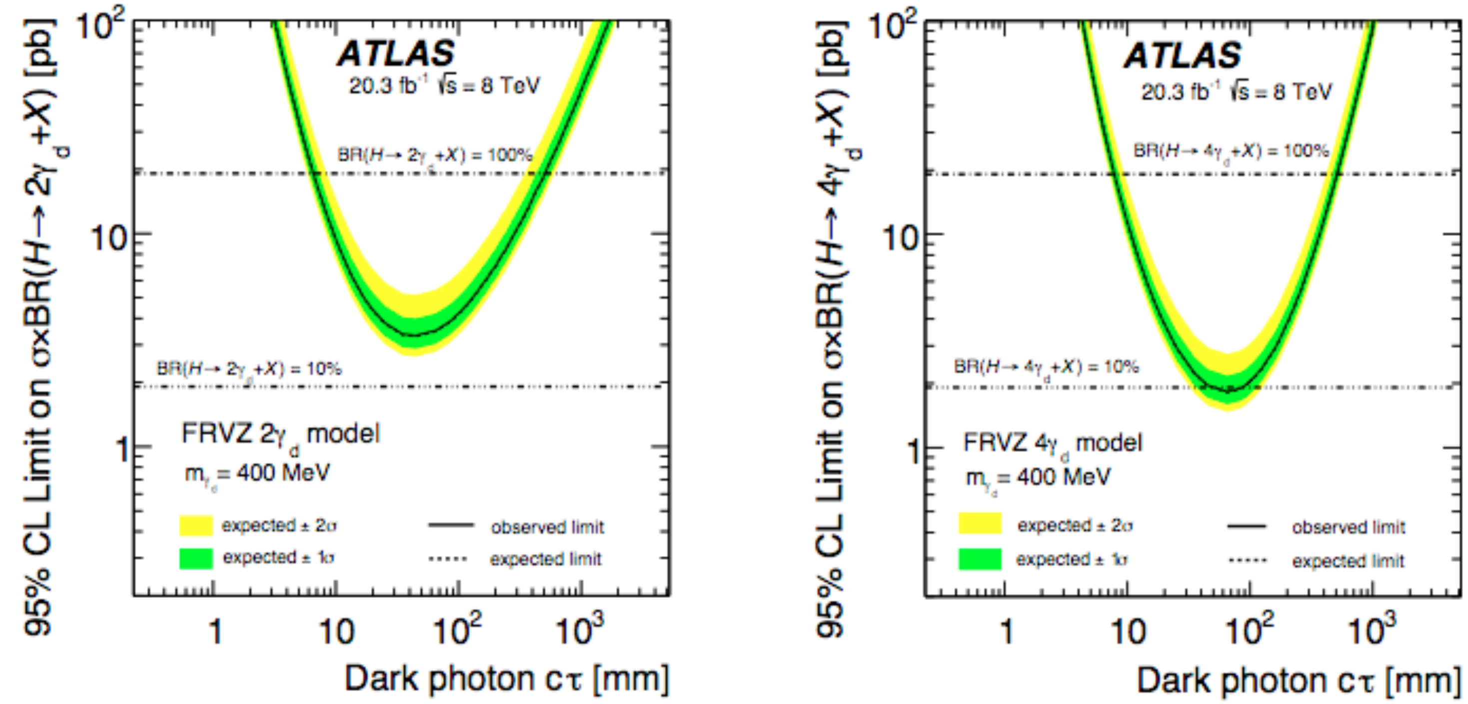
From the detection efficiency of the LJs in the various part of the detector the expected signals as a function of the lifetime can be evaluated

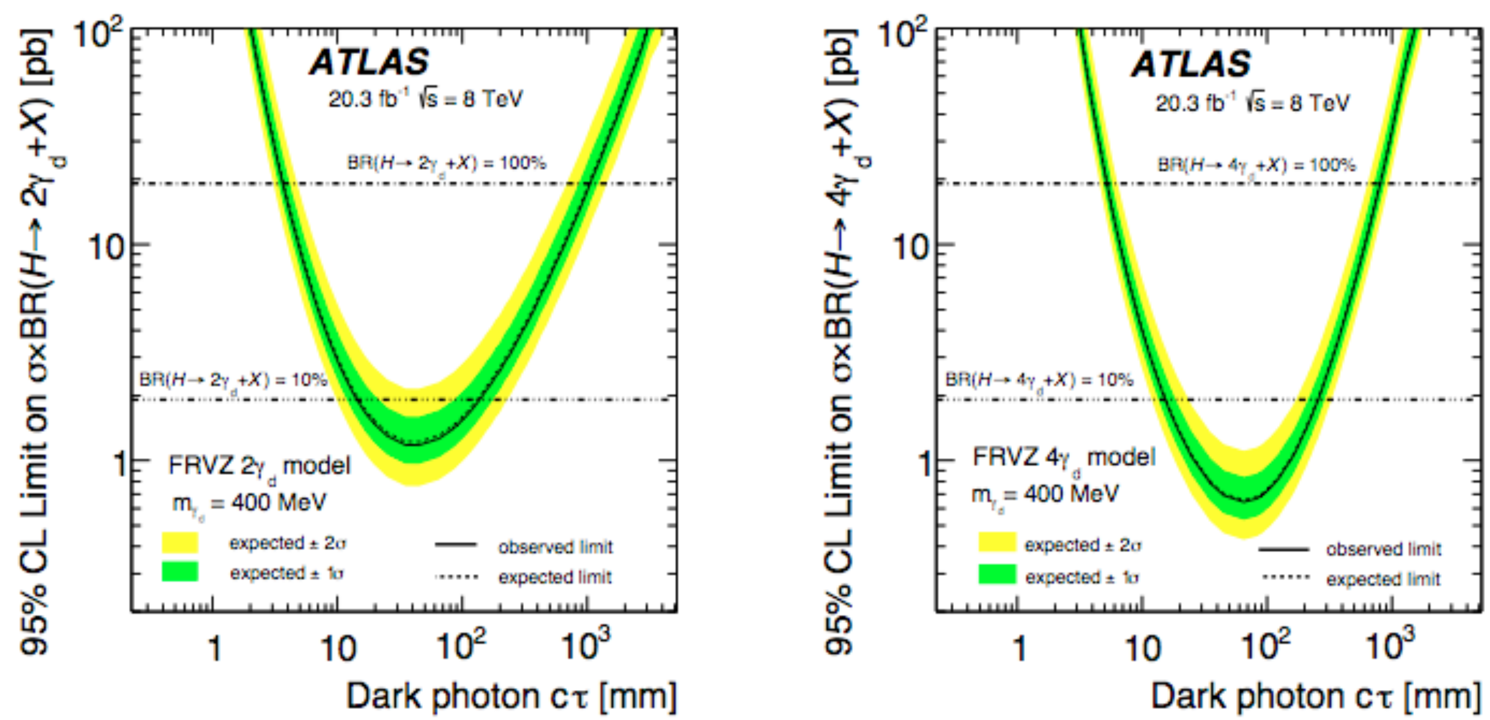
95% upper limits on σxBR for FRVZ models

- **Statistical method:**
  - likelihood-based ABCD:
    - simultaneous fit for signal and multijet BKG in the signal and CRs
    - other BKGs + all systematics included via nuisance parameters
- **Limits as function of γ_d lifetime:**
  - yields(cτ) obtained by pseudo experiments using detector efficiencies function of the decay length of the dark-photons and p_T distributions of the dark-photons
- **$\sigma \times BR(H \rightarrow \gamma d\text{'s})$:**
  - assuming SM gg-H x-section (19.2 pb)

All LJ pair TYPES



TYPE2-TYPE2 removed



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

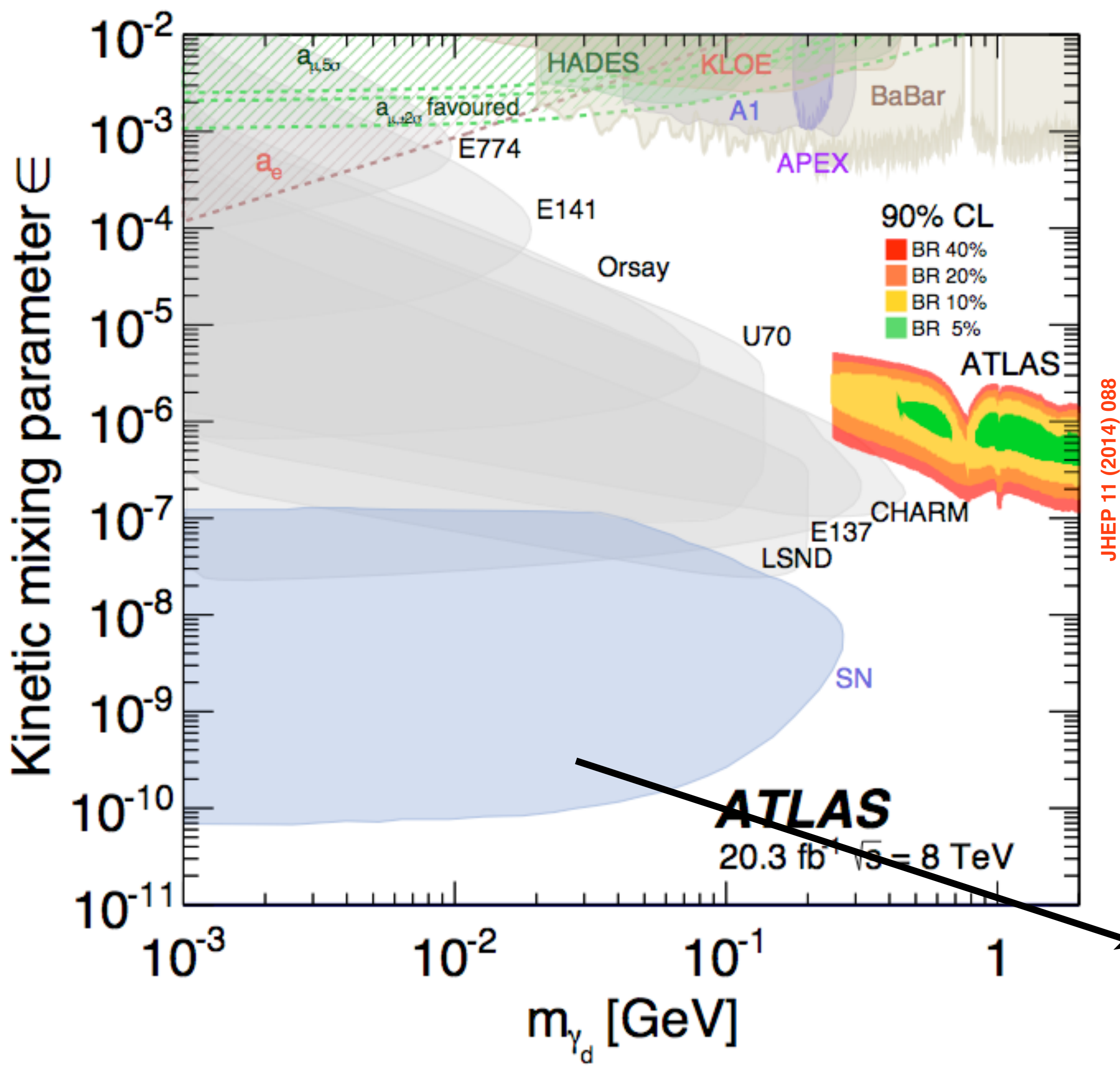
Dark matter exclusion plot

Way to unify lepton-Jets limits from various experiments and from different searches in the same experiment

Key variables → (ϵ, m_{γ_d}) ← Determine decay composition and lifetime

$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} b_{\mu\nu} + m_{\gamma_d}^2 b^2$$

$$\Gamma = \frac{1}{3}\alpha\,\epsilon^2\, m_{\gamma_d} \sqrt{1 - \frac{4m_l^2}{m_{\gamma_d}^2}} \left(1 + \frac{2m_l^2}{m_{\gamma_d}}\right)$$



- present the ATLAS results in the (ε,m) plane as σ×BR limits
- use only the model Higgs → $2\gamma_d$ + X
- detection efficiency as a function of m_{γ_d} from LJ gun
- color pallet shows the dependence on BR(H→$2\gamma_d$+X)

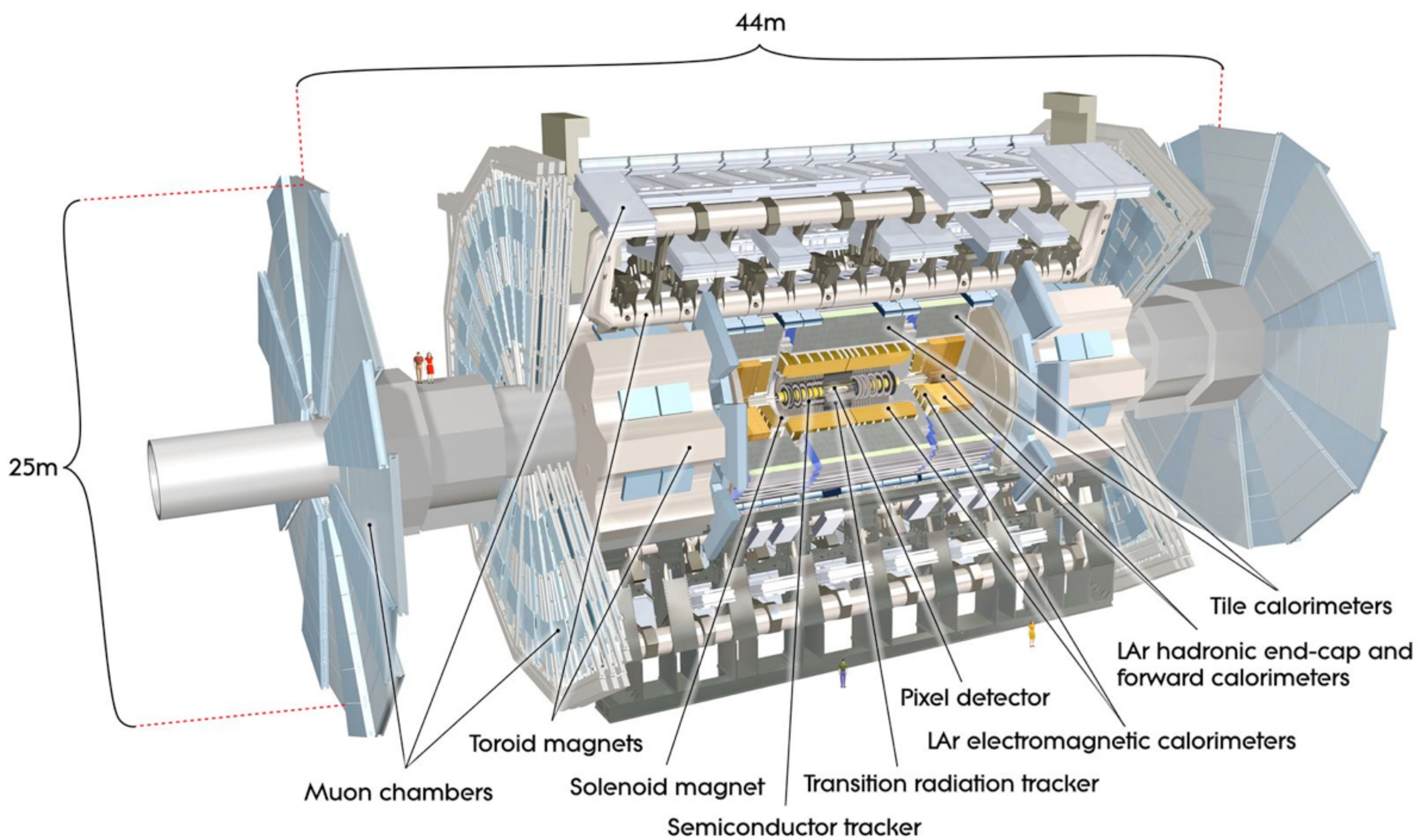
Experimental constraints on ϵ versus gauge boson mass. Enclosed regions are excluded by anomalous magnetic moments, beam and astrophysics data.

Conclusions and plans for 13 TeV data taking

- Model-independent search for non-prompt LJs
- No excess of events observed
- CLs used to set upper limits on the $\sigma \times$ BR as function of the dark photon lifetime
- Results presented on the kinetics mixing (ε) and γ_d mass plane to unify with other experimental results
- Efficiency curves/tables using LJ gun have been produced and can be used to constrain more theoretical models: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2013-22/#auxstuff
- Continue and extend the search in Run2 to take advantage of the augmented discover potential of the LHC
  - more efficient triggers for signal selection
  - include displaced electronjets (reconstructed as converted photons)
  - include associated production of leptonjets with standard objects (high p_T muons, electrons or jets) to cover more production mechanisms

BACKUP

The ATLAS detector



- Inner Detector (ID) tracking: semiconductors (pixel and SCT) and transition radiation tracker (TRT)

  Sampling-based calorimetry: lead+liquid argon for EM energy (ECAL), steel+scintillator for Hadronic energy (HCAL), copper/tungsten +liquid argon in the forward calorimeter (FCAL)

  2 T magnetic field by a solenoid just enclosing the ID

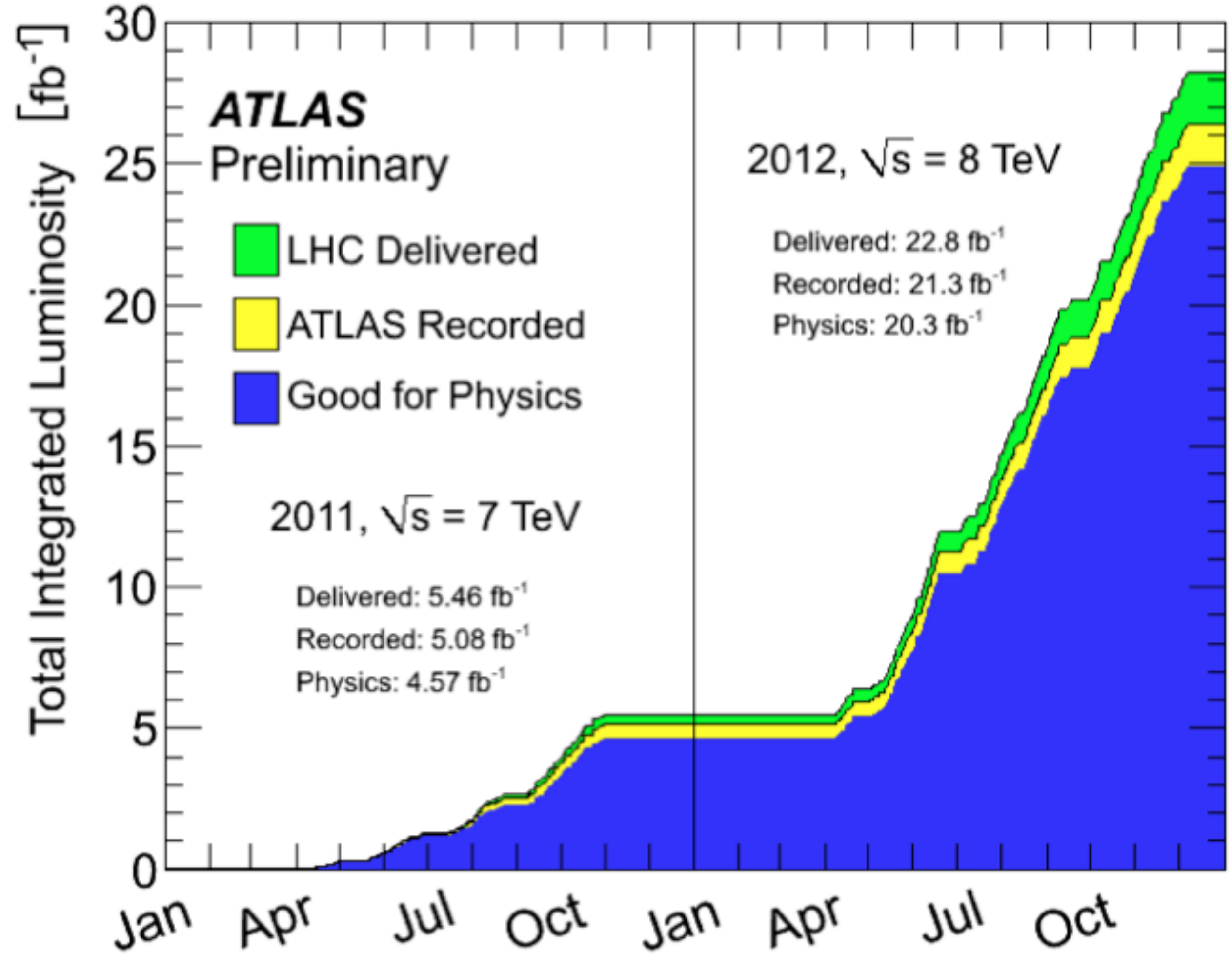
  One barrel and 2 end-cap 4 T toroids in the air-core muon spectrometer provide fields to bend muon tracks in η

PERFORMANCE (E, p_T in GeV)

Detector component	**Required resolution**	**η coverage**	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \|\eta\| < 4.9$	$3.1 < \|\eta\| < 4.9$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV	± 2.7	± 2.4

Data-taking conditions

- ATLAS results shown in this talk based on 7+8 TeV collisions recorded in 2011-2012
- collisions at $\sqrt{s}$ = 8 TeV
  - ~20 interactions per crossing
  - 20.3 fb^{-1} collected good for physics
- collisions at $\sqrt{s}$ = 7 TeV
  - ~9 interactions per crossing
  - 4.6 fb^{-1} collected good for physics



Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.5%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.3 fb^{-1} of recorded data.

ATLAS performance close to or exceeding design specs in all compartments

Systematics

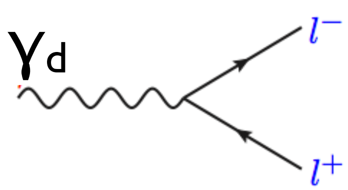
- Systematics on the calorimetric trigger on 2012 data: 11% (see ATL-COM-PHYS-2013-113)
- Systematics on the muon trigger using 2012 J/ψ data: 5.8%
- Systematics on muon reconstruction efficiency using J/ψ data: 5.4%
- Systematics from ABCD method: 15%
- Effect of the pile-up on the isolation in ID: 4.1%
- Systematics on luminosity: 2.8% official value
- Statistics of the detection efficiency (L_{xy}) tables:10%
- JES: 1.9%
- Higgs production cross section (gluon fusion production): 8%

LeptonJet Gun: a tool for LJ search optimization

- A Monte Carlo generator to generate LeptonJets made of up to 2 γ_d's decaying to ee, μμ, ππ
- Explore the mass and boost parameter space of the LJs
- Study the LJ characteristics and optimize search criteria
- Study the reconstruction and trigger efficiency as function of the most relevant LJ parameters

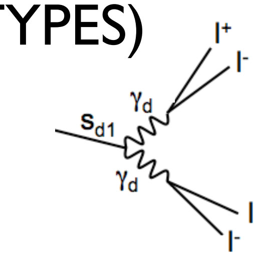
LJ gun MC samples

- LJ's with one dark photon (only TYPE0 and TYPE2)



- **γ_d masses: 50, 150, 400, 900, 1500 MeV**
- γ_d parameters used in the simulation
  - p_T = 5÷100 GeV, flat
  - φ = -3.14÷3.14 rad, flat
  - η = -2.5÷2.5, flat
  - transverse and longitudinal polarization
  - dark photon lifetime computed, depending on its boost , so that the decay occur inside the detector volume
- 100k events for each γ_d mass value

- LJs with two dark photons coming from an hidden scalar s_{d1} (ALL LJ TYPES)



- **s_{d1} masses: 1, 2, 5, 10 GeV**
- s_{d1} parameters used in the simulation
  - p_T = 5÷100 GeV, flat
  - φ = -3.14÷3.14 rad, flat
  - η = -2.5÷2.5, flat
- γ_d masses: 50, 150, 400, 900, 1500 MeV
- γ_d parameters used in the simulation
  - no polarization
  - dark photon lifetime computed, depending on its boost , so that the decay occur inside the detector volume
- 100k events for each sample

2012 pile-up added