Light Dark Matter 2017

24-28 May 2017 *La Biodola - Isola d'Elba*

Low Mass Dark Sector Searches at ATLAS and at CMS

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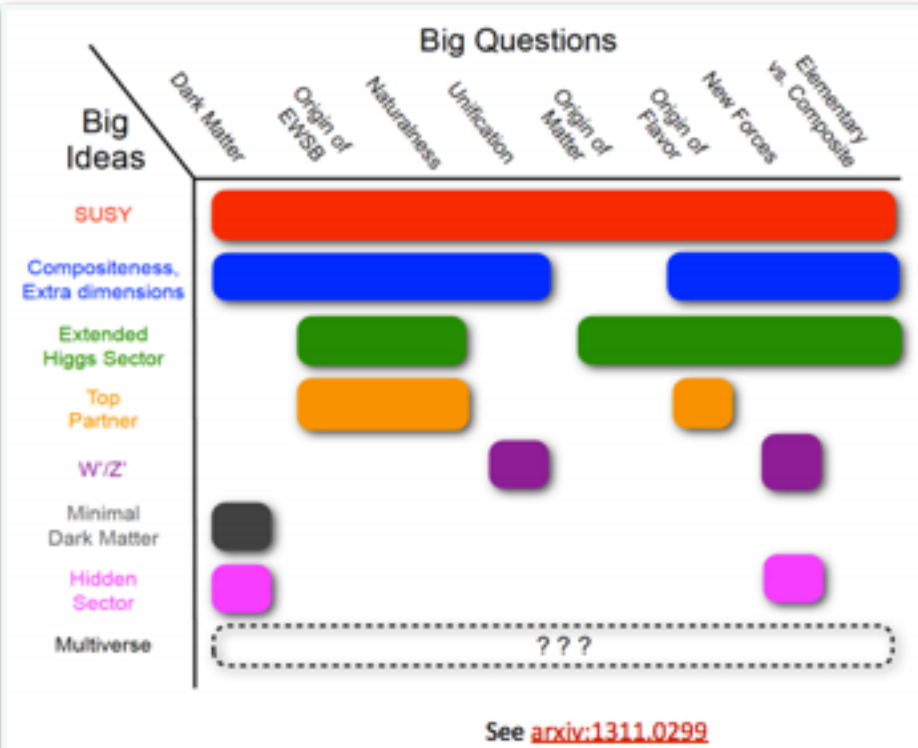
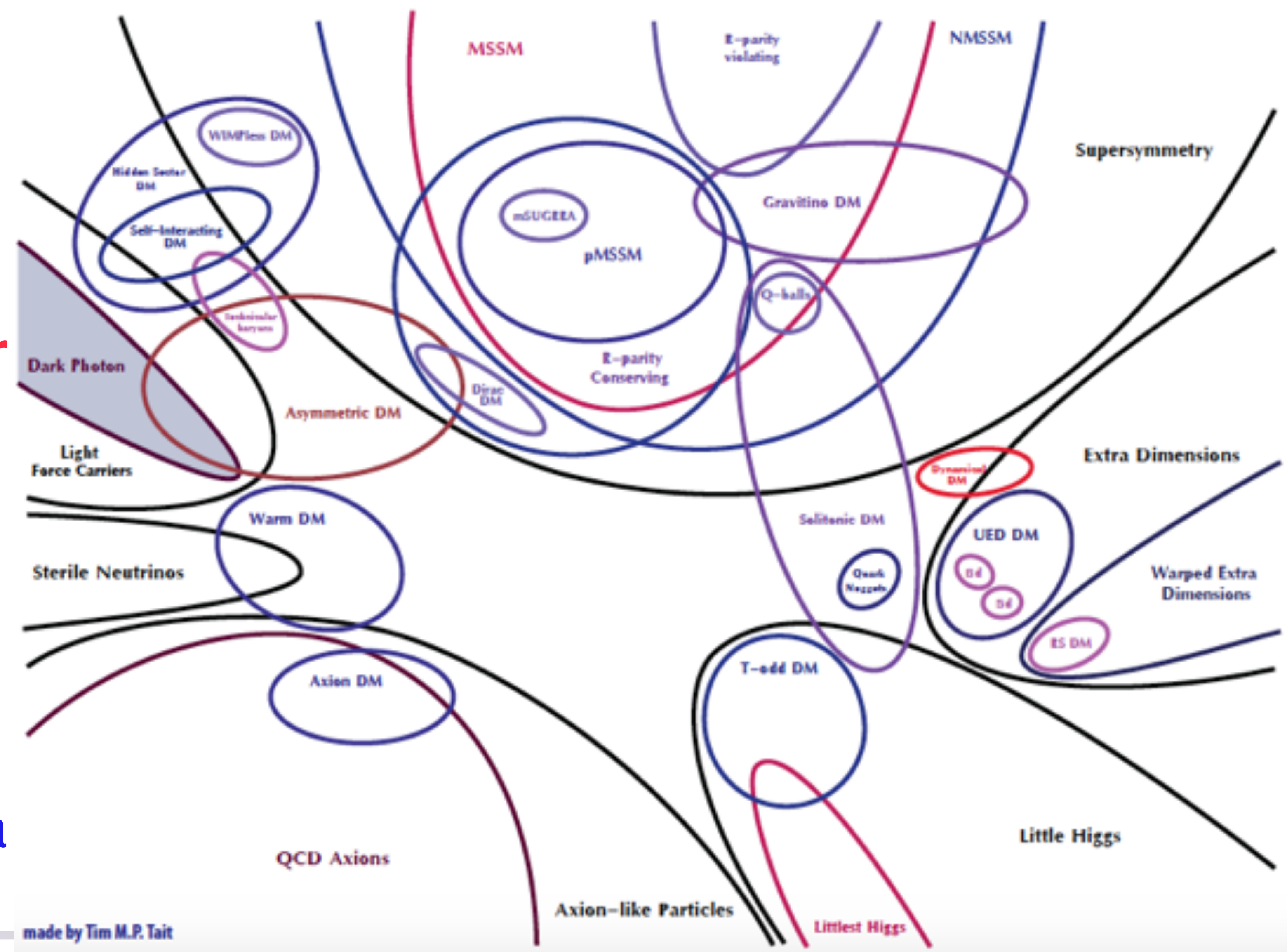
Introduction



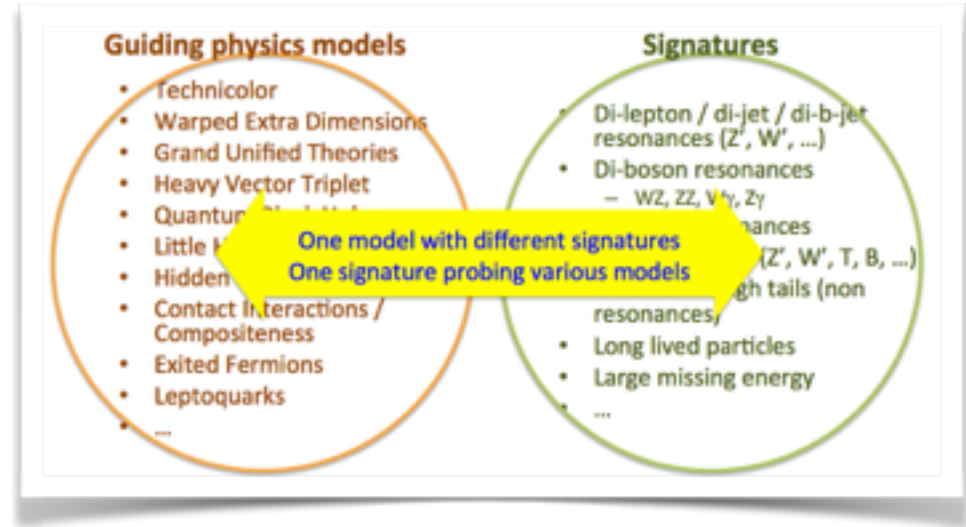
- The experimental results beautiful fit in Standard Model (SM) framework…
- …but some mysteries are still opened and need physics beyond the SM to be solved!



- This talk will highlight the latest results on **`light' hidden sector (dark sector)**, present in many models of new physics.
- These models contain new particles, which give rise to unique signatures at colliders when the mass scale in the hidden sector could be below a TeV.

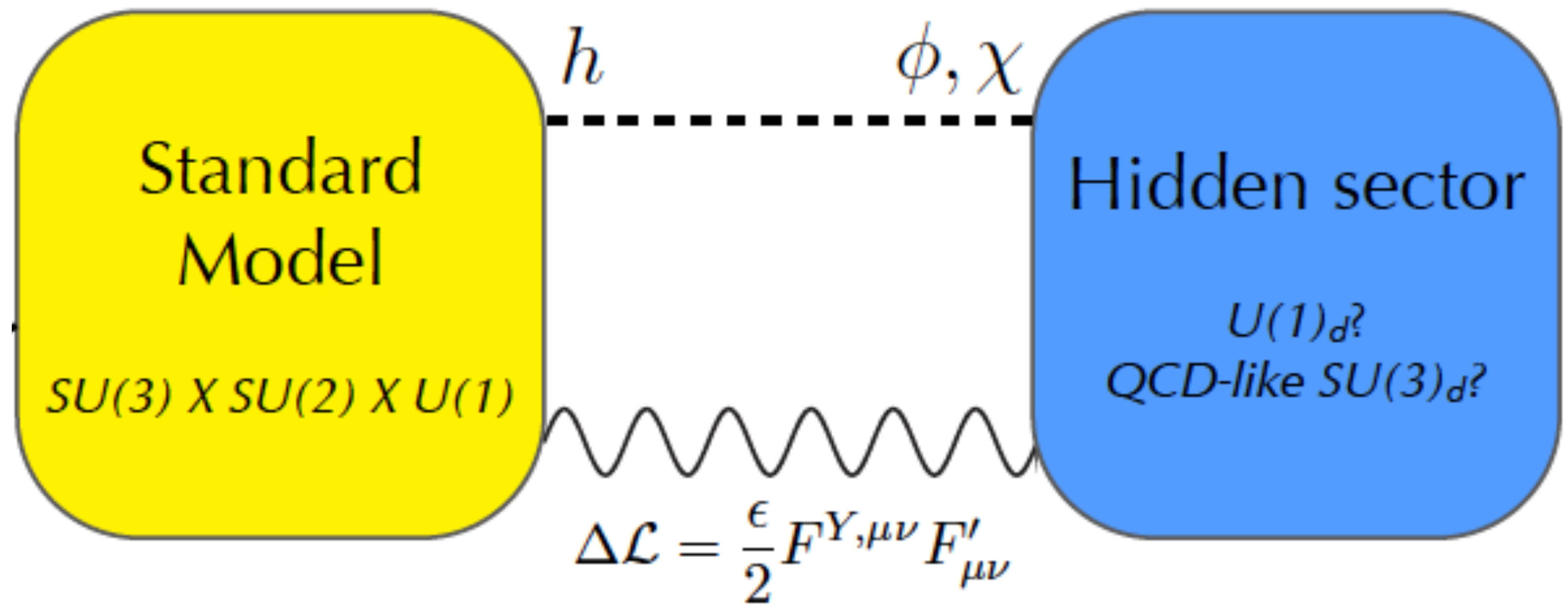
Light Dark Candidate Search

- The final topologies are very challenging! Base ingredients are required to perform the analysis and get a result:
  - **Well performing collider + efficient & precise multi-purpose detectors** (ATLAS & CMS).
  - **A choice of a search topology** (several topologies for one phenomenon are possible and vice versa: several phenomena could be searched for in a given topology).
  - **Trigger**: Triggers (L1 and HLT) developed ad-hoc for many signatures.
  - **Physics objects**: definition, performance, validation, time stability etc. It is done for all analyses, but **some searches need custom objects** (long-lived, monopoles …).



- **Claim discovery if statistically significant excess is found or, if not, interpret the result in term of constraints on selected models.**

Dark / Hidden Sector Example



- The hidden sector can be simple (e.g., a single U(1)dark) or more complicated, involving dark QCD sector / dark hadronization, dark matter candidates, etc.
- Only a few allowed ways the hidden sector and the SM can talk to each other, and many of them yield rich, unconventional signatures at the LHC
- But unconventional means significant customization and non-standard methods

This involves inspiring the detector to do things it wasn't designed to do

ATLAS

ATLAS-CONF-2016-042

Dark Photons in Lepton Jets (LJ)

Low-mass dark photons can be produced via cascade decays of heavier states

Benchmark models predicting Higgs boson or heavy scalar particle decays to neutral long-lived particles (dark photons $\gamma_d \gamma_d$ of 0.4 GeV Mass each), which in turn produce:

- **collimated jets of light leptons and mesons, so-called "lepton-jets"**

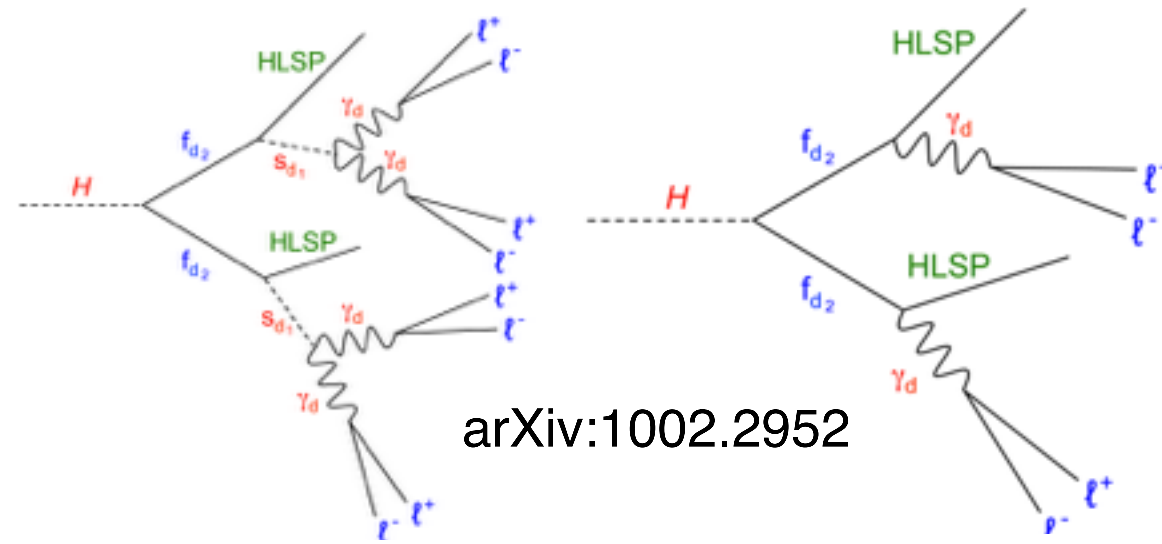
The Low-mass of the Dark Photon produces:

—> large boost

—> collimated decay products

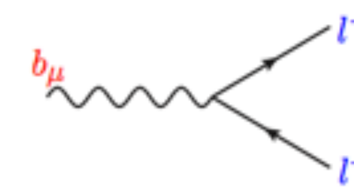
Dark photon lifetime depends on the size of kinetic mixing ε: small ε → displaced decays

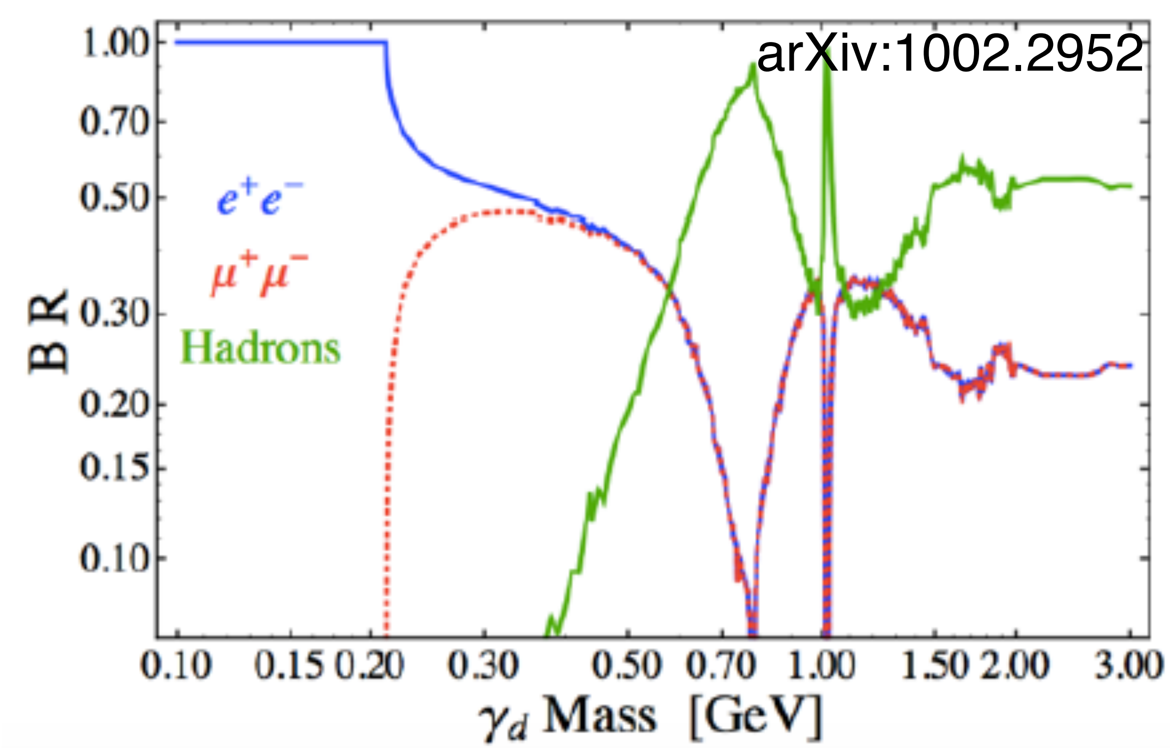
Leptonic decays prominent over wide (low) mass range. The dark photons and two LJs are expected to be produced back-to-back in the azimuthal plane.



arXiv:1002.2952

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

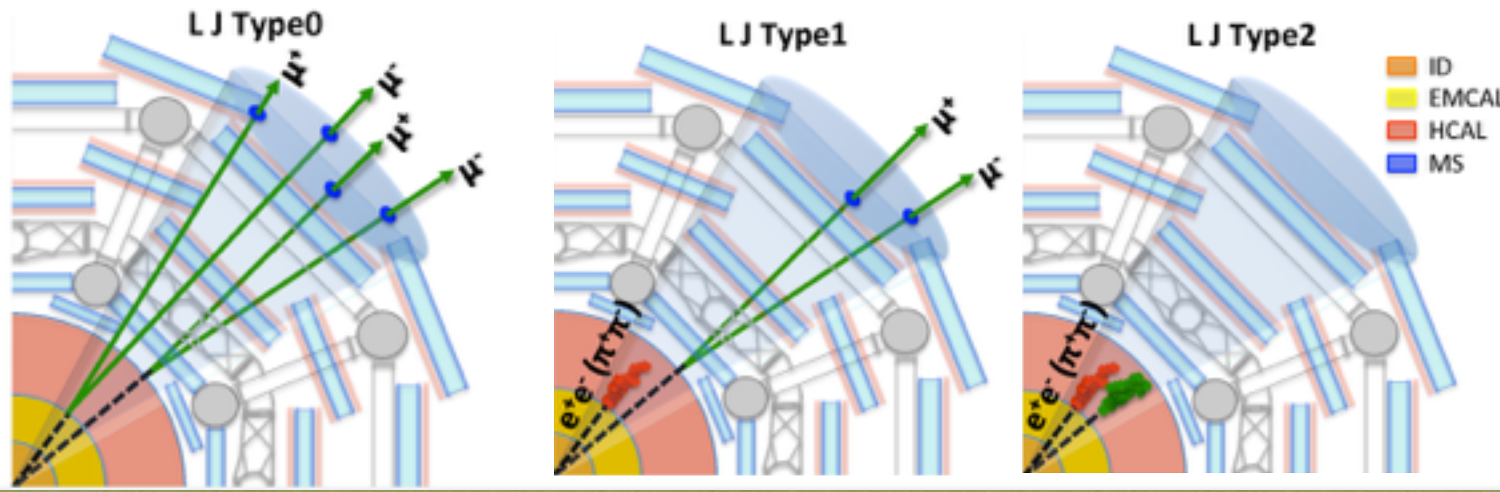




ATLAS

ATLAS-CONF-2016-042

Displaced Lepton Jets (LJ)



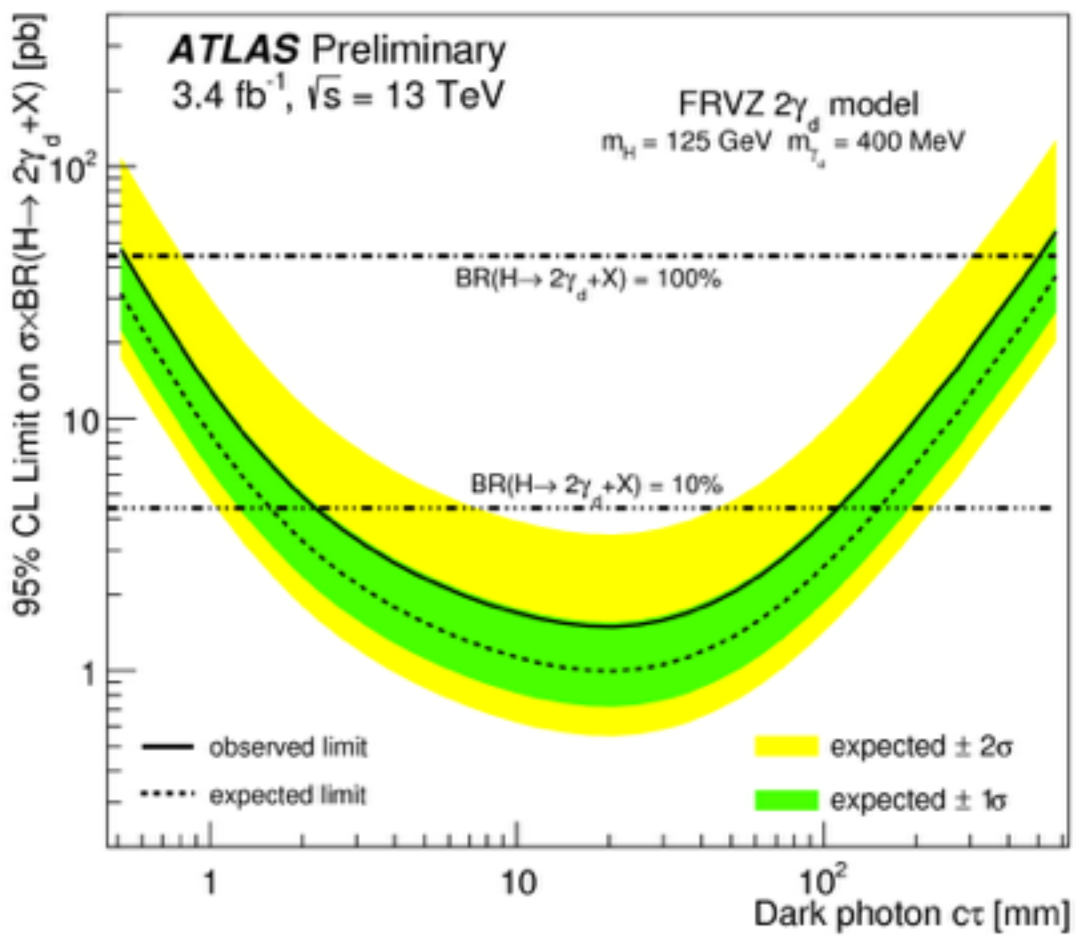
Three Topologies:
Type0 LJ is composed of multi-muons non-combined in a cone 0.5.
Type1 LJ is composed of muons and a standard jet.
Type2 LJ is composed of jets with low electromagnetic energy (i.e. assumes a decay inside the hadronic calorimeter).

- **Selection**: dedicated trigger to select these states. Different selections depending on the LJ type.
  - **Collimated final-state particles difficult to reconstruct** (detector granularity)
  - **Tracks with displaced decay vertices difficult to reconstruct** (no primary vertex constraint)
- **Background**: Cosmics events (impact parameter and timing as discriminating variables), machine background, multi-jets (ABCD method)
- **Main Uncertainty**:Trigger, reconstruction efficiency

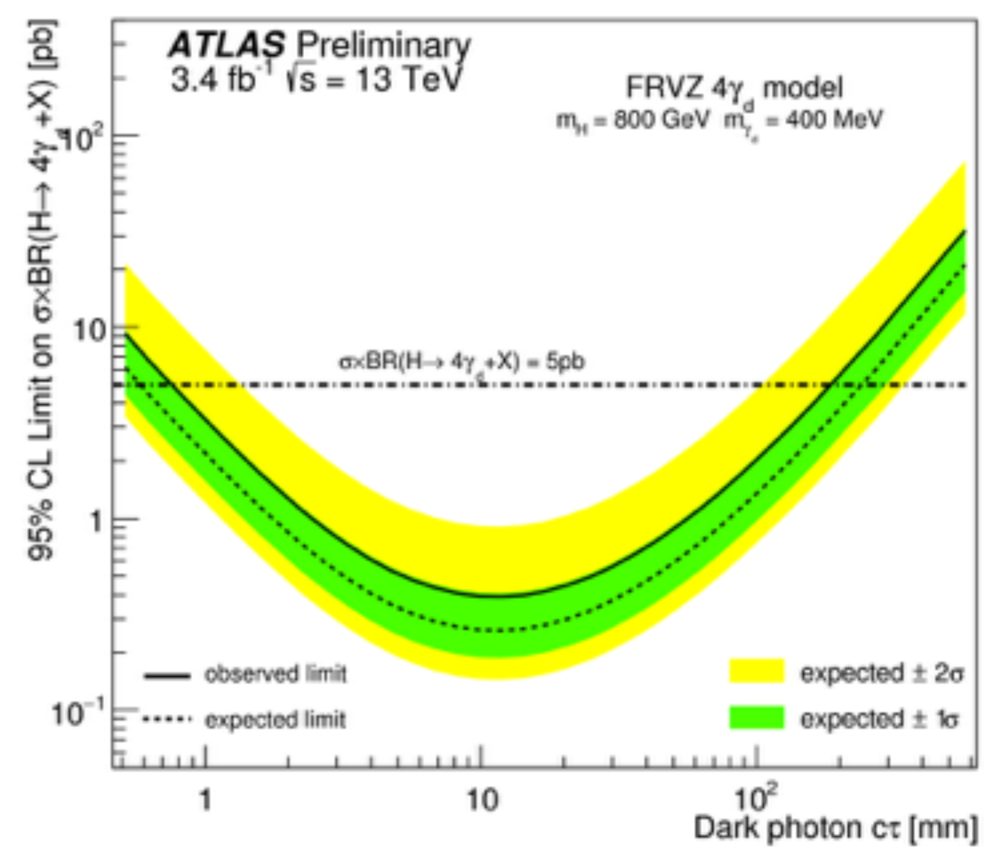
ATLAS

Limits on LJ searches

- The 95% upper limits on the σ×BR for the FRVZ 125 GeV Higgs and heavy scalar of 800 GeV.
  - Higgs → 2γd+X and Higgs → 4γd+X benchmark models as a function of the γ_d lifetime (c τ).
  - Results on prompt-lepton jet on 13 TeV will be released soon.

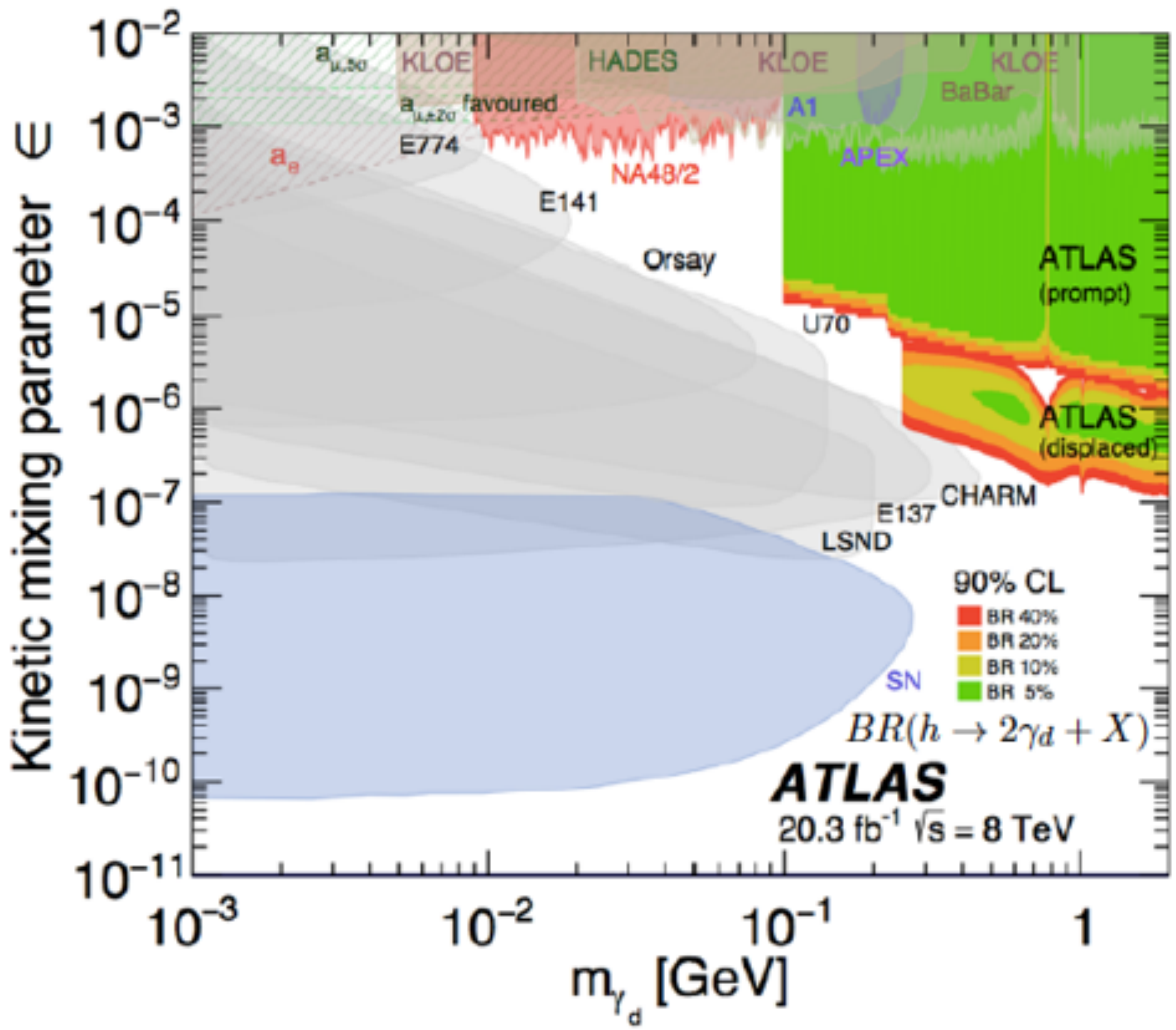


FRVZ model	m_H (GeV)	Excluded $c\tau$ [mm]
Higgs $\rightarrow$ $2\gamma_d + X$	125	$2.2 \leq c\tau \leq 111.3$
Higgs $\rightarrow$ $4\gamma_d + X$	800	$3.8 \leq c\tau \leq 163.0$
Higgs $\rightarrow$ $2\gamma_d + X$	125	$0.6 \leq c\tau \leq 63$
Higgs $\rightarrow$ $4\gamma_d + X$	800	$0.8 \leq c\tau \leq 186$



Dark Matter Interpretation

Run 1: JHEP 11 (2014) 088
JHEP 1602 (2016) 062



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

Key variables

Determine decay composition and lifetime

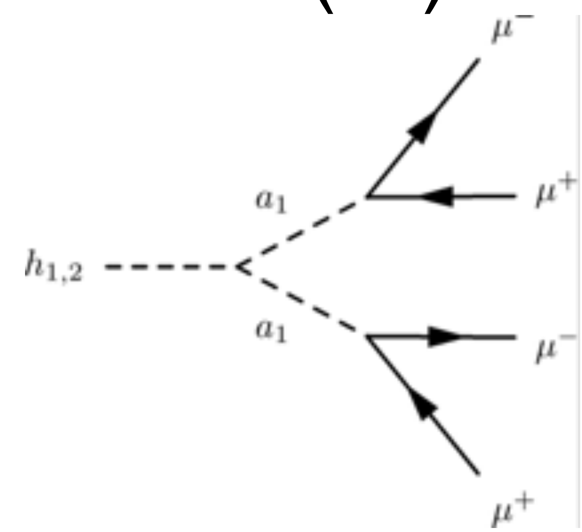
$$(\epsilon, m_{\gamma_d})$$

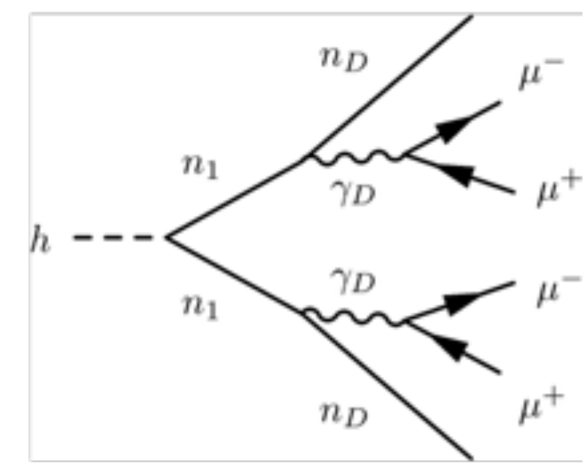
$$\Gamma = \frac{1}{3} \alpha\, \epsilon^2\, m_{\gamma_d} \sqrt{1 - \frac{4m_l^2}{m^2_{\gamma_d}}} \left(1 + \frac{2m_l^2}{m_{\gamma_d}}\right)$$

Light Bosons Decaying into Muon Pairs

- **This analysis searches for new light bosons with a mass in the range 0.25-8.5 GeV/c^2 decaying into muon pairs.**
- The results are interpreted in the context of two benchmark models, namely, the next-to-minimal supersymmetric standard model, and dark SUSY models including those predicting a non-negligible light boson lifetime.

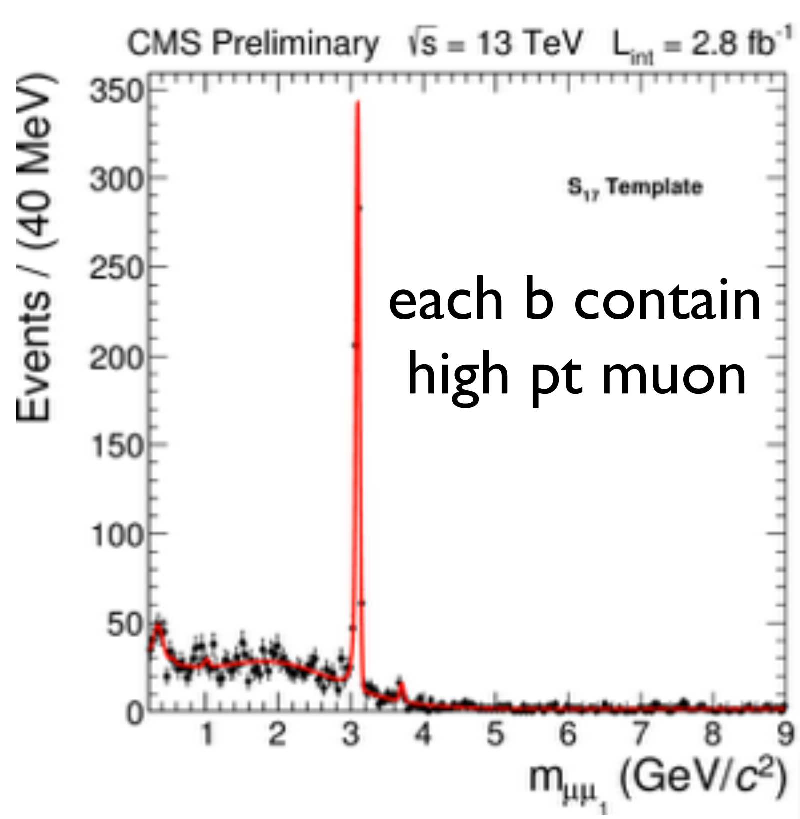
H ->aa(ss)-> 4SM (or 2SM+X)

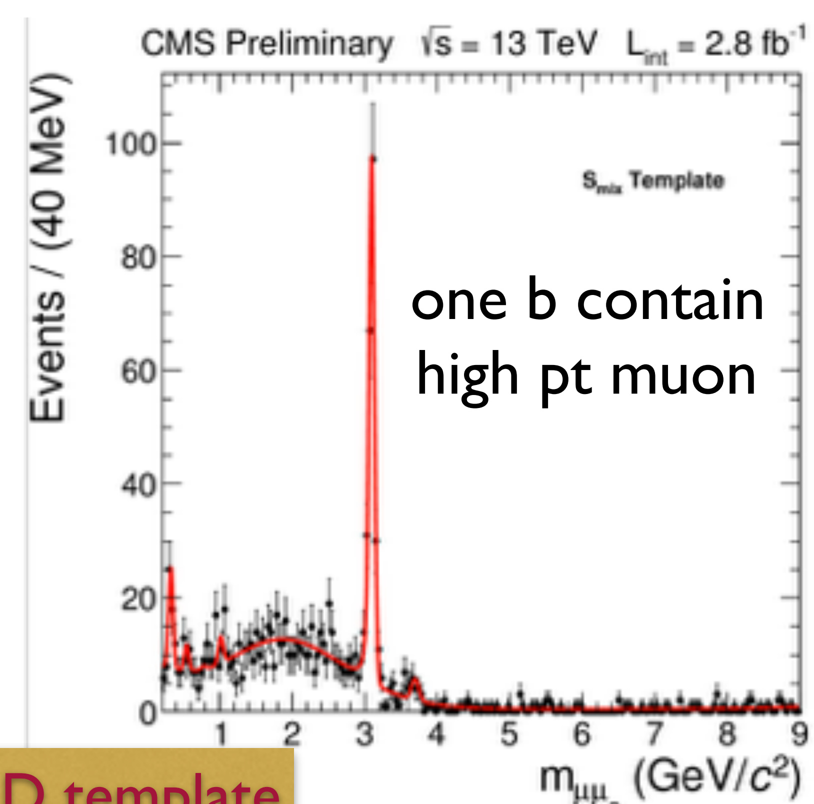




Event Identification:

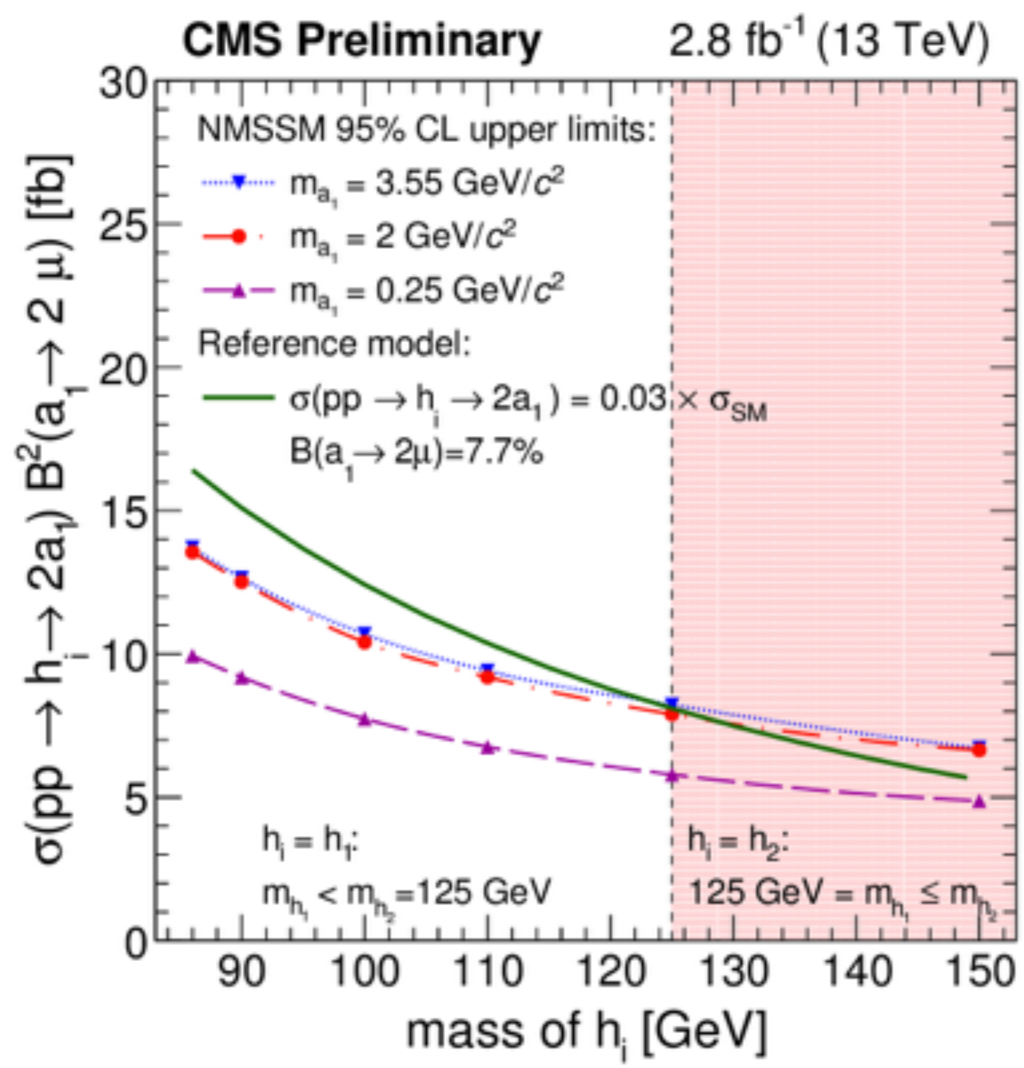
main background is bb events. Background is modelled as a two dimensional (2D) template bb (m1, m2) in the plane of the invariant masses of the two di-muons in the selected events, where (1) always refers to the dimuon containing a muon with pT > 17 GeV/c and |η| < 0.9.

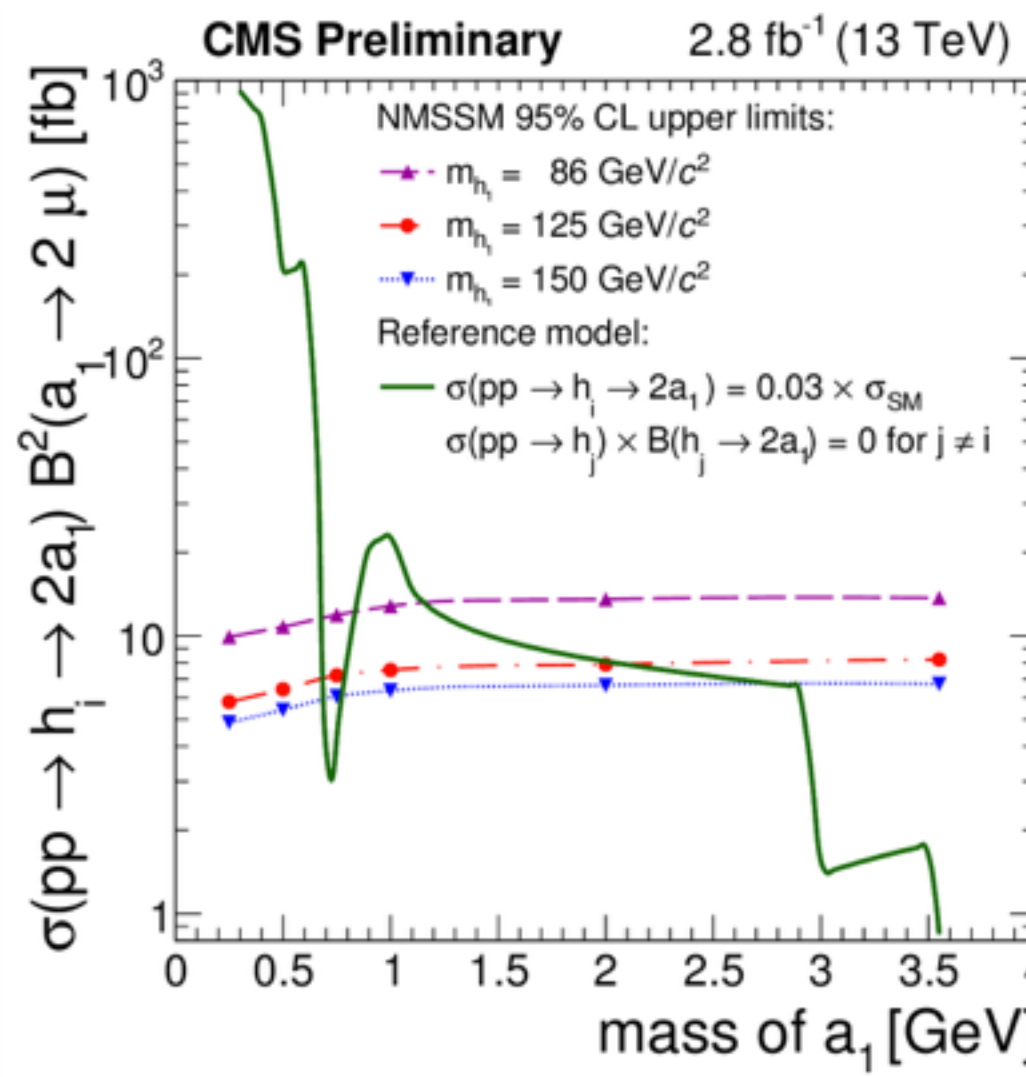




1D template

Multi-Muons Limits



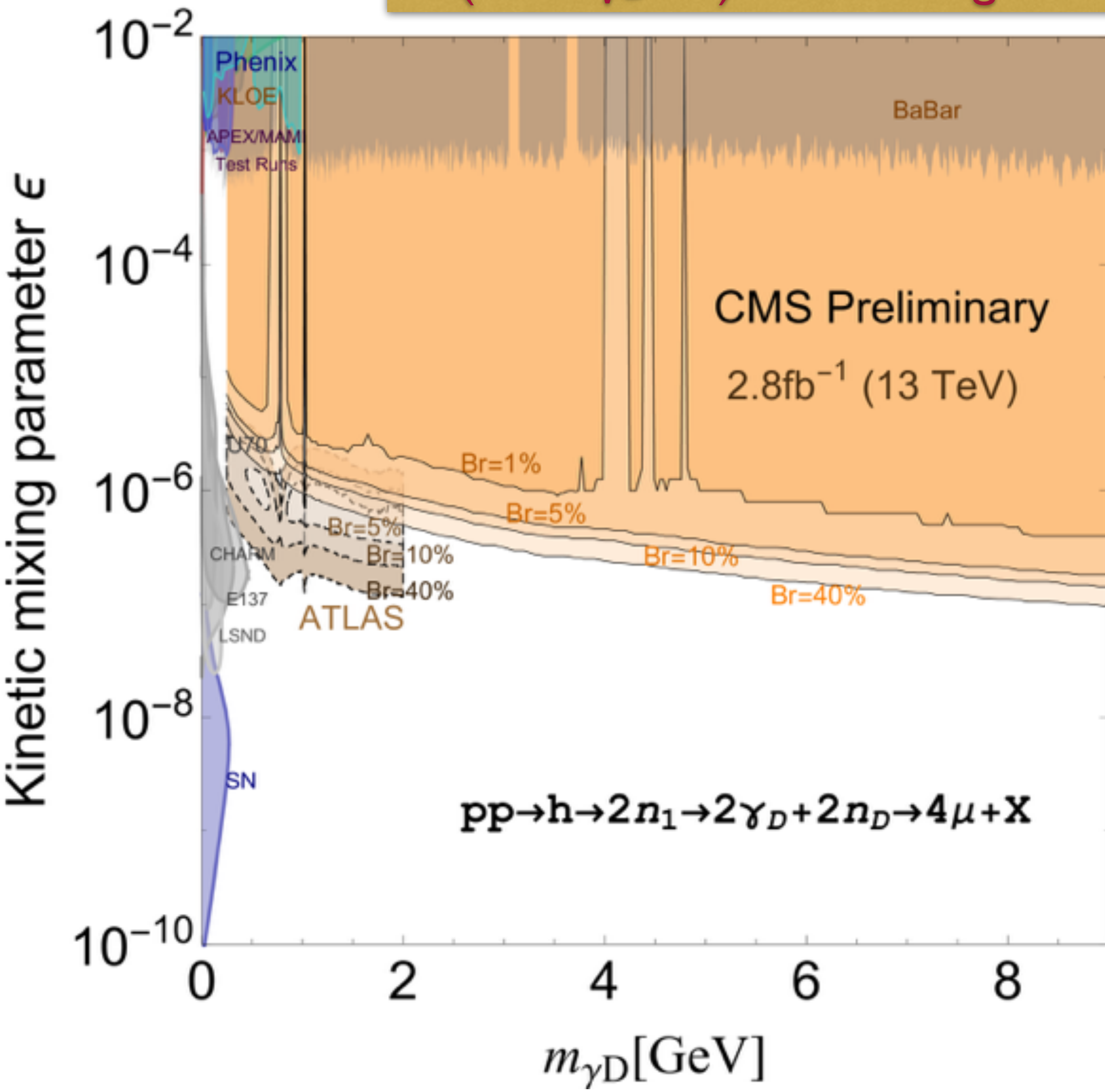


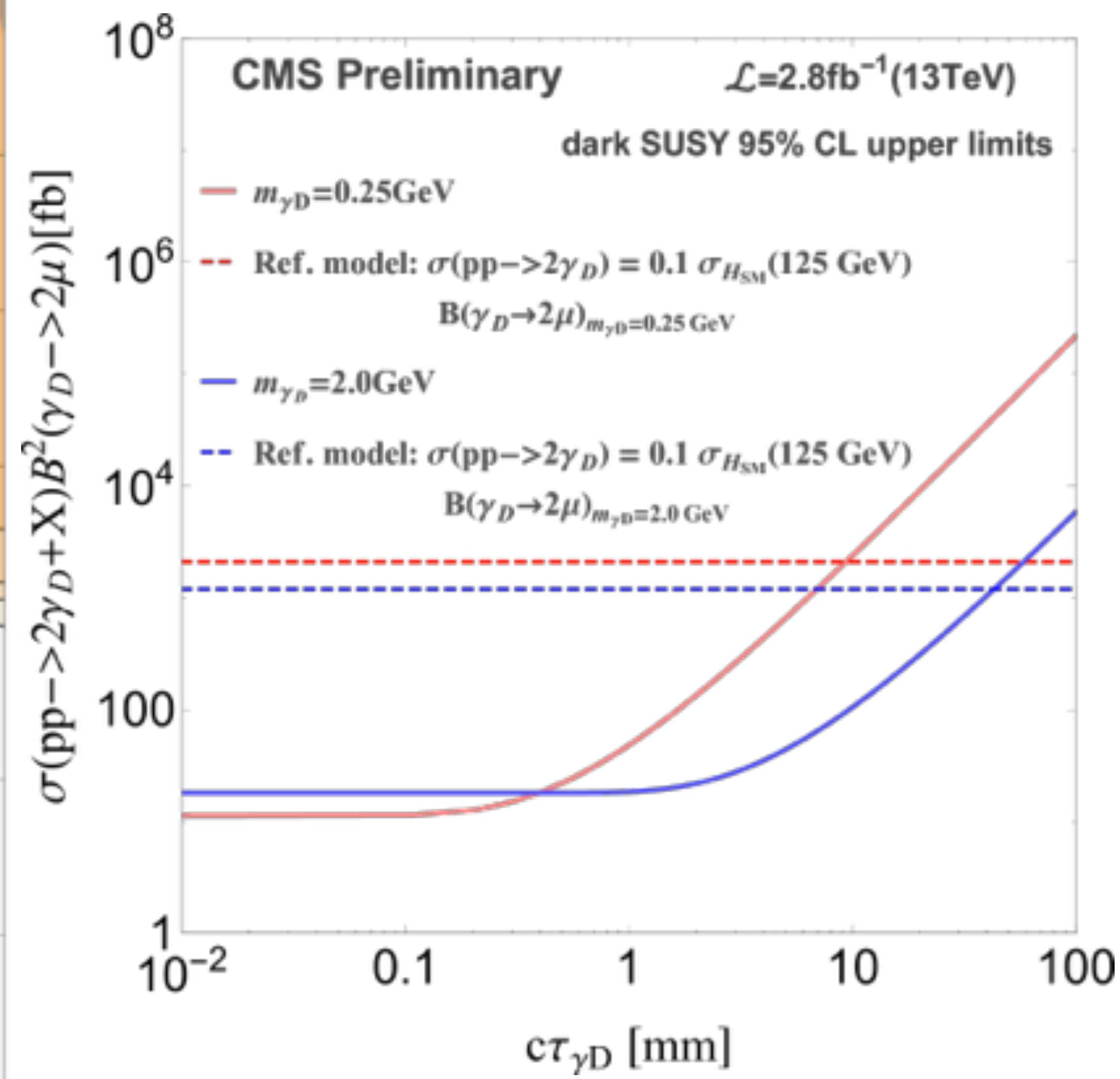
- The 95% CL upper limits as functions of mh_1 and ma_1 for the NMSSM case with $\sigma(pp \to 2a + X) \times BR^2(a \to 2\mu)$.

CMS

Multi-Muons Limits

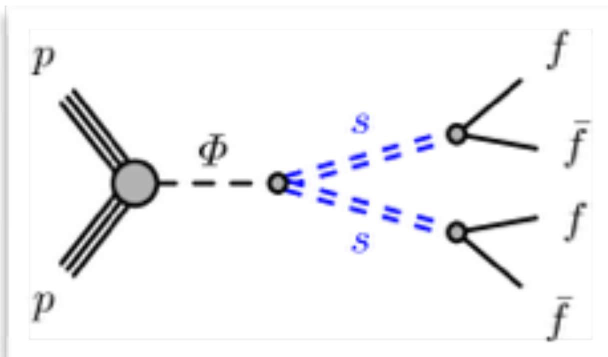
BR($H \rightarrow 2\gamma_D + X$) in the range 1-40%.



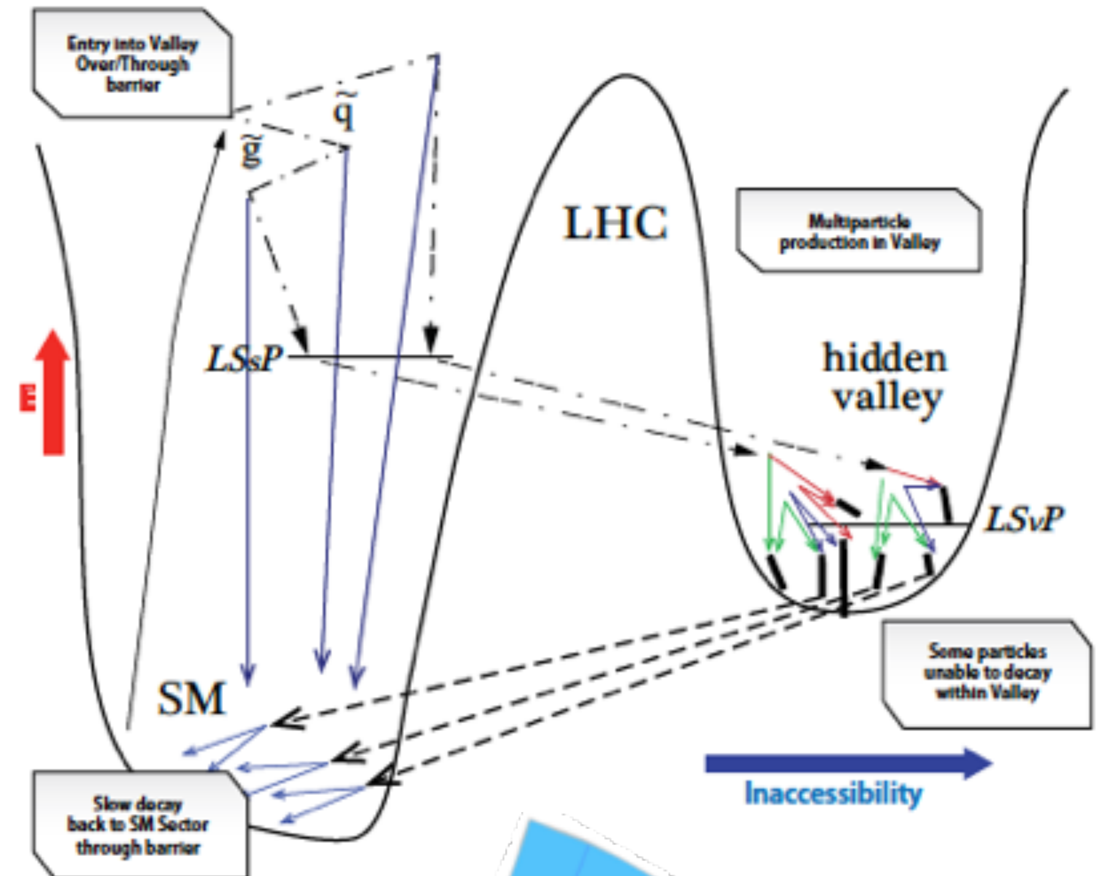


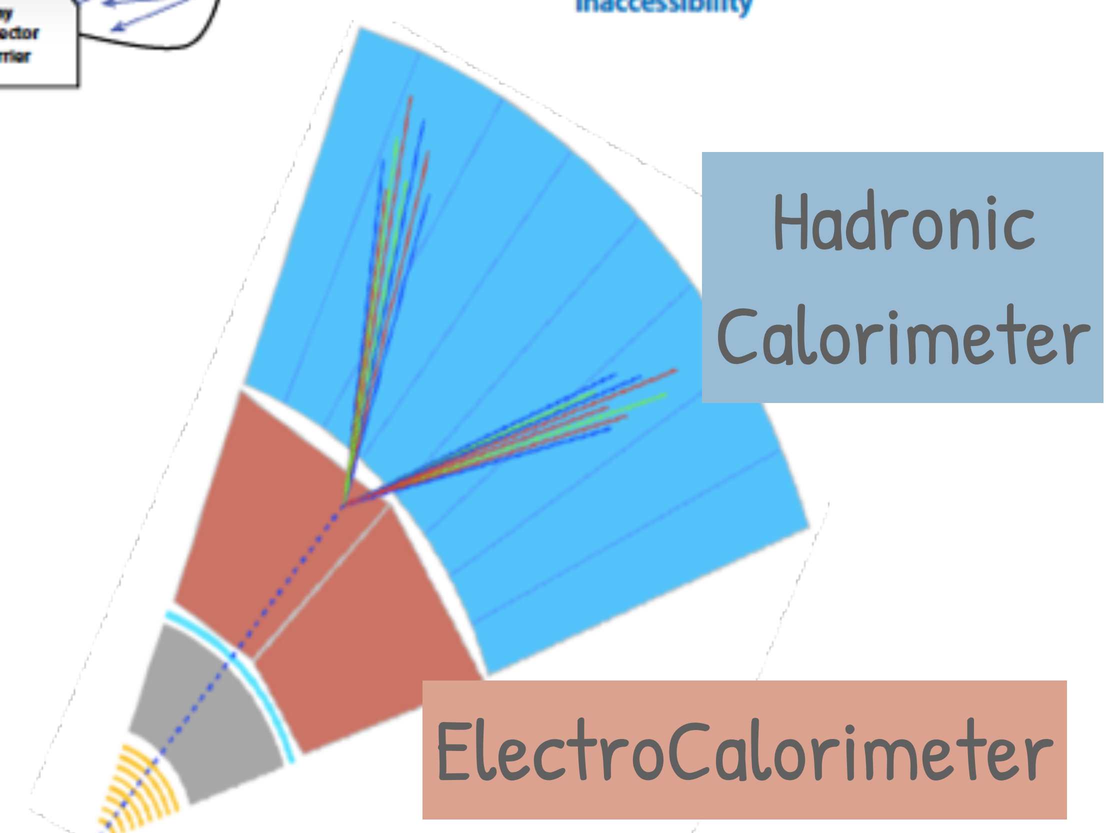
ATLAS-CONF-2016-103

Hidden Valley Models: Displaced Jets



- **Search for neutral, long-lived particles produced from heavy-scalar decays decaying into displaced fermions.**
- A schematic showing the $\Phi \rightarrow ss$ decay used as the benchmark model. Due to their Yukawa coupling with the Φ, the s decay primarily to heavy fermion pairs (Hidden Valley Models).
- This analysis explores signature, where **a neutral LLP decays in the hadronic calorimeter.** This would yield to an atypical jet with no tracks in the inner tracker and would deposit little or no energy in the electromagnetic calorimeter.
- There are searches for decays in the ID and/or MS, in ATLAS (under review 13 TeV analysis).

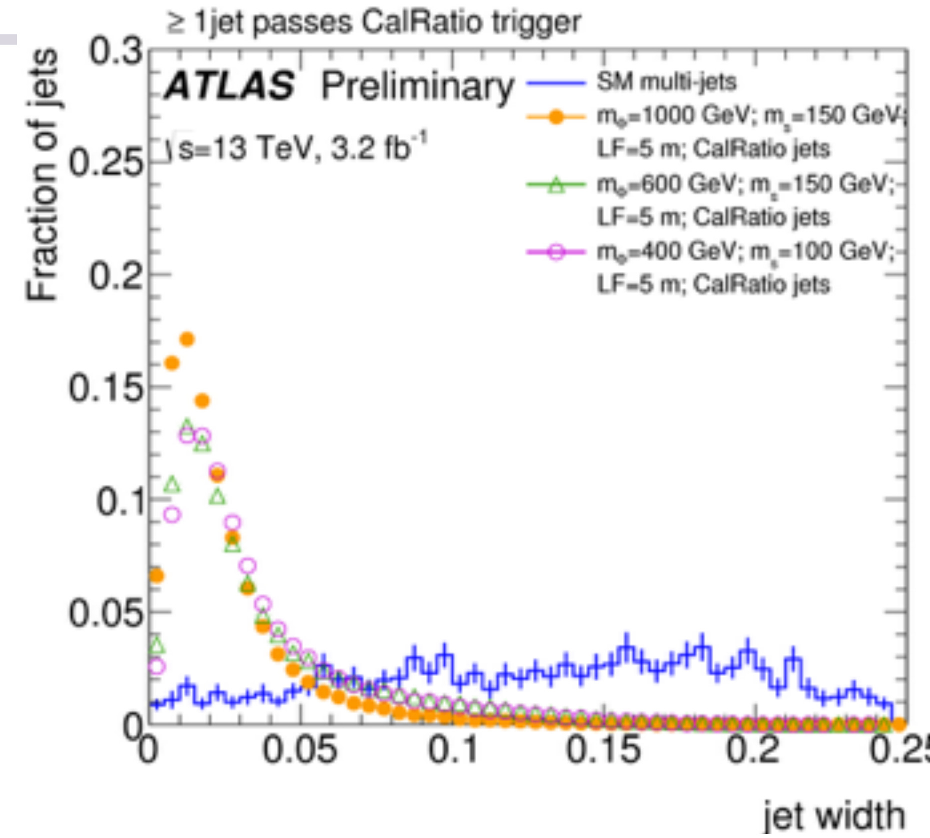


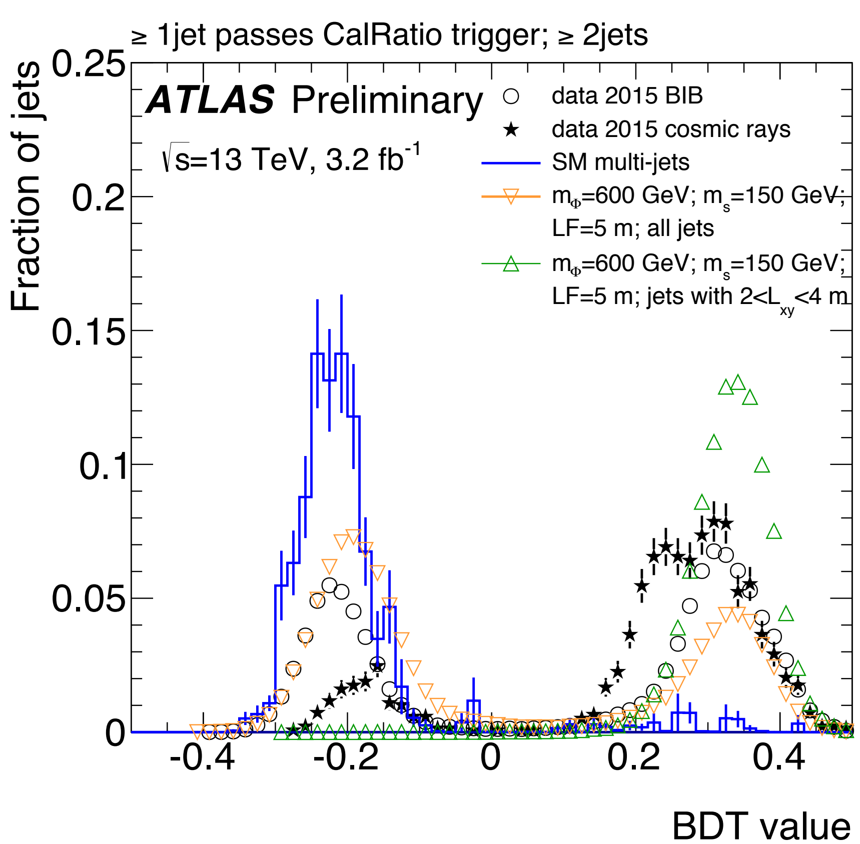


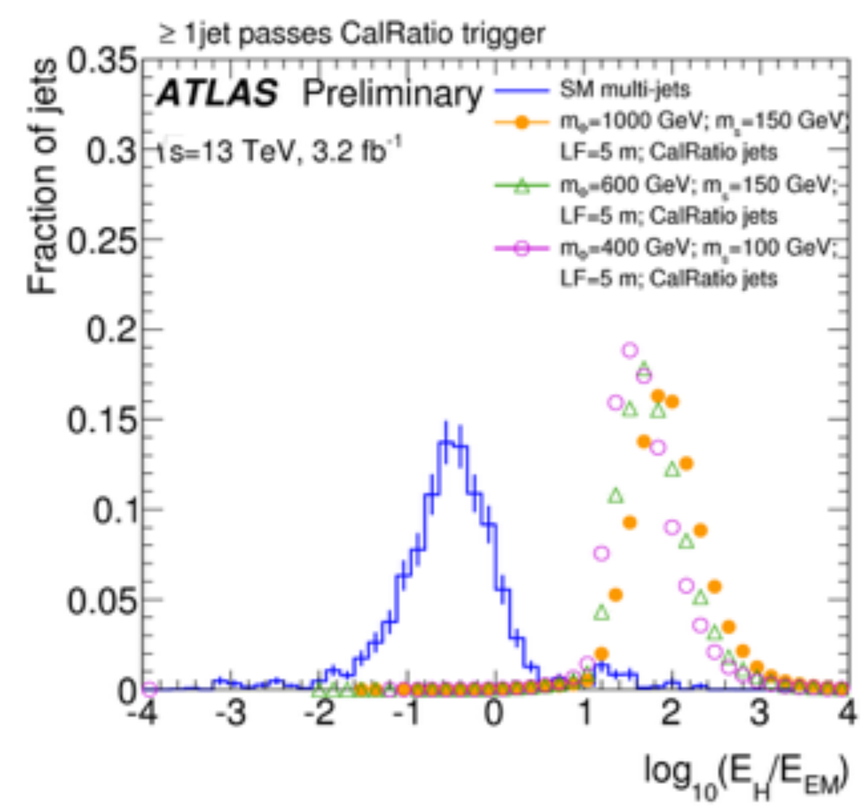
ATLAS-CONF-2016-103

Event Selection

- **Selection**: dedicated trigger to select displaced decays.
  - Cut on $Log_{10}(E_{Had}/E_{Em})$
  - Isolation wrt inner tracks
  - Cuts on Jet pt
- BDT to improve the identification of the two displaced jets.
- **Background**: Cosmics events (timing and event variables such as MHT/HT and dPhi between the two calRatio jet as discriminating variables), machine background BIB, QCD jets (ABCD method)
- **Main Uncertainty**: ABCD method estimate

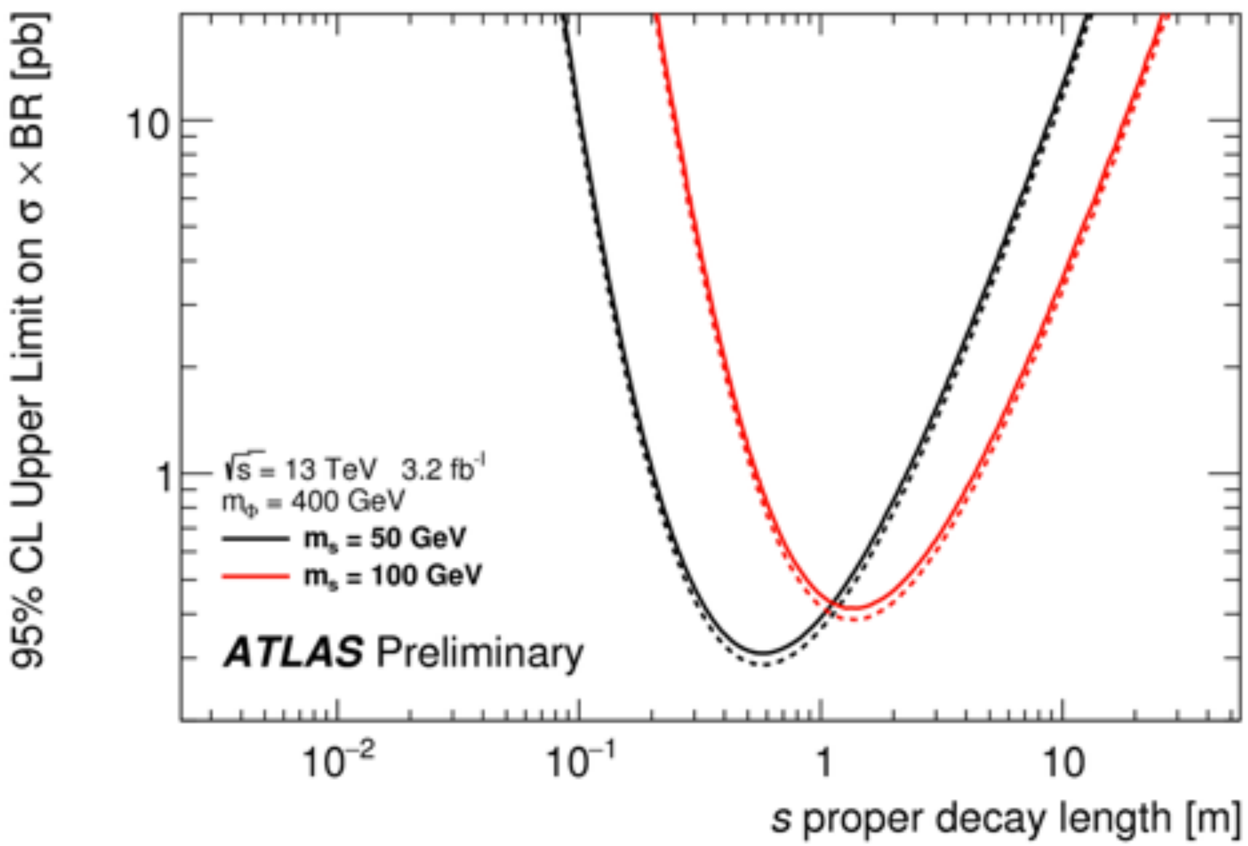


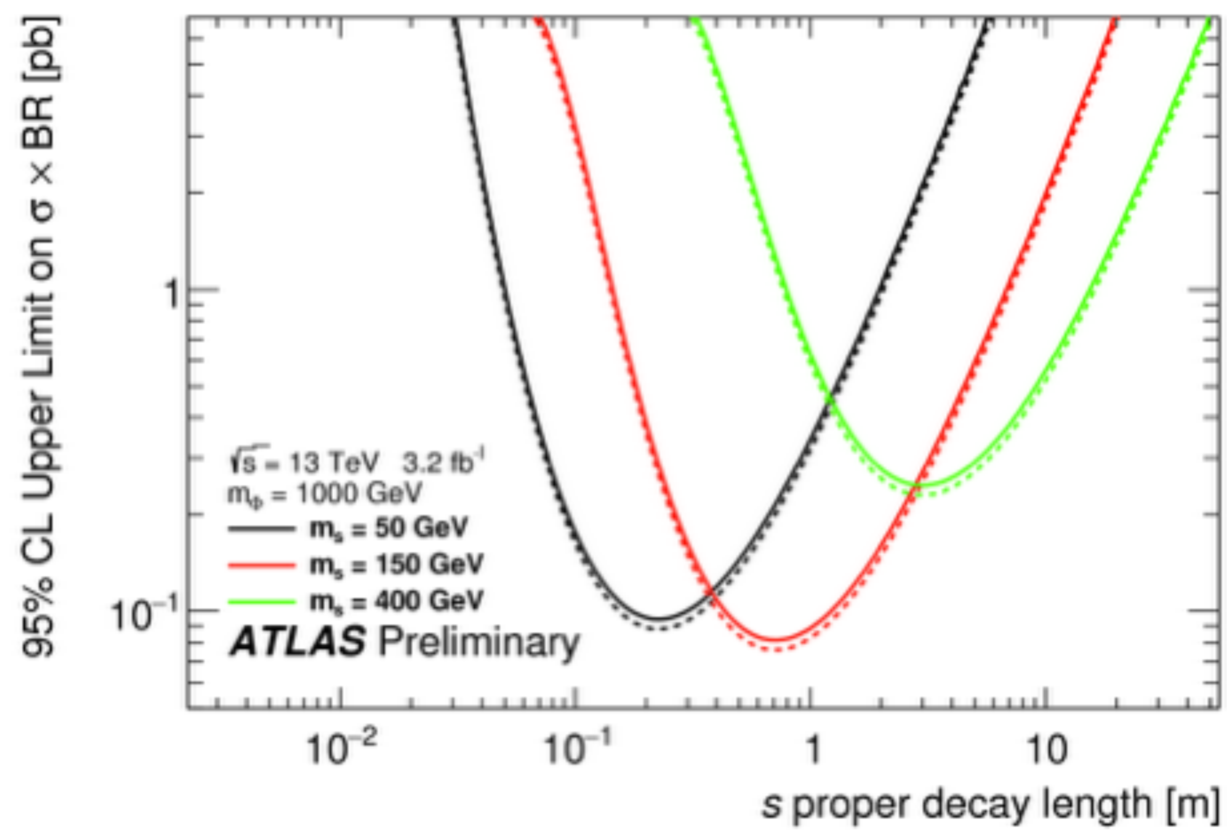




Excluding Limits

- The observed 95% CL upper limits on the σ × BR for the signal samples with different ϕ and s masses





	$m_s = 50\ GeV$	$m_s = 100\ GeV$	$m_s = 150\ GeV$	$m_s = 400\ GeV$
	Decay length range excluded at 95% CL for $\sigma\times$ BR = 1 pb			
$m_\Phi = 400\ GeV$	(0.20, 2.4) m	(0.52, 4.6) m	–	–
$m_\Phi = 600\ GeV$	(0.09, 2.7) m	–	(0.38, 8.2) m	–
$m_\Phi = 1$ TeV	(0.05, 2.0) m	–	(0.14, 7.2) m	(0.78, 16) m

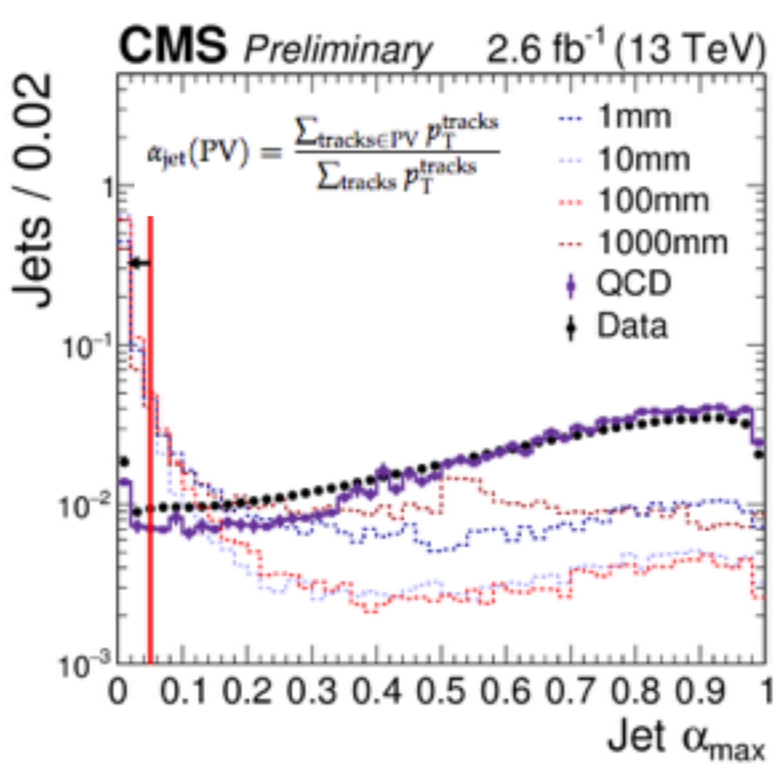
PAS EXO-16-003

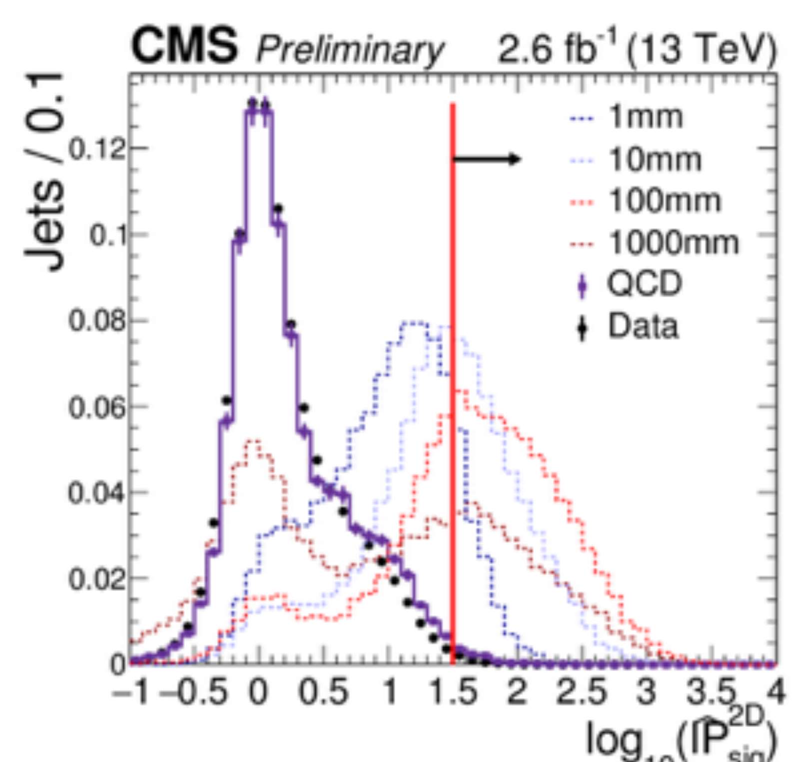
Search for new particles decaying to displaced jets

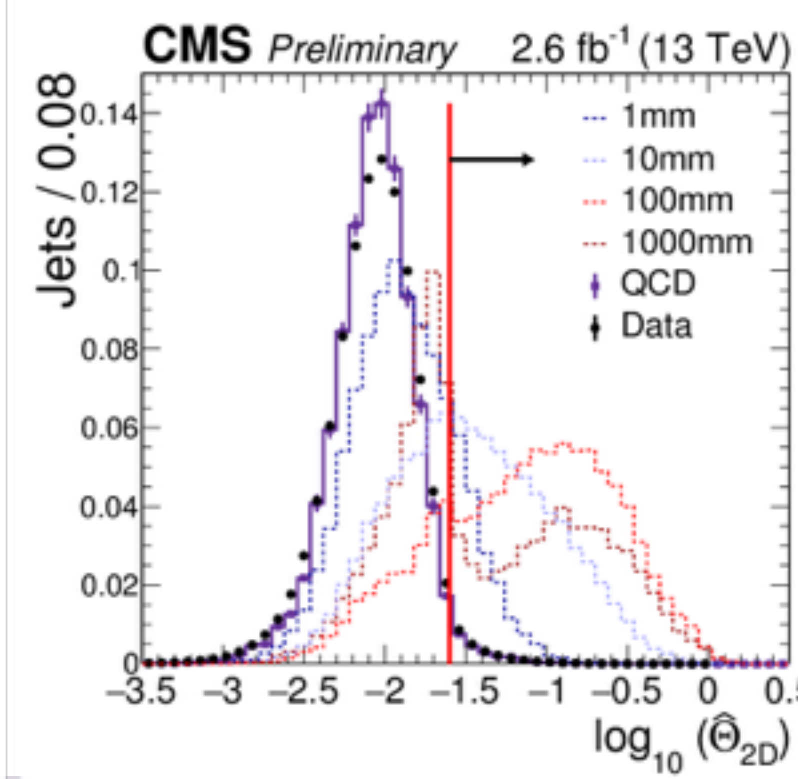
- An **inclusive search for long-lived particles decaying to various combinations of jets and leptons.** The analysis exploits the information about jets with the information from reconstructed tracks, in particular the transverse impact parameter (discriminate the displaced-jets signal from the background of ordinary multijet).
- The analysis exploits two customised topological trigger algorithms and an offline displaced-jet tagging algorithm.
- **The multiplicity of displaced jets is used to search for the presence of a signal with a proper lifetime between 1 mm and 1000 mm.**

Jet-Jet: X0, a neutral scalar particle of 50-1500 GeV, decays in qq.

BLepton: squarks pairs, each decays in b quark and lepton (each flavour identified)





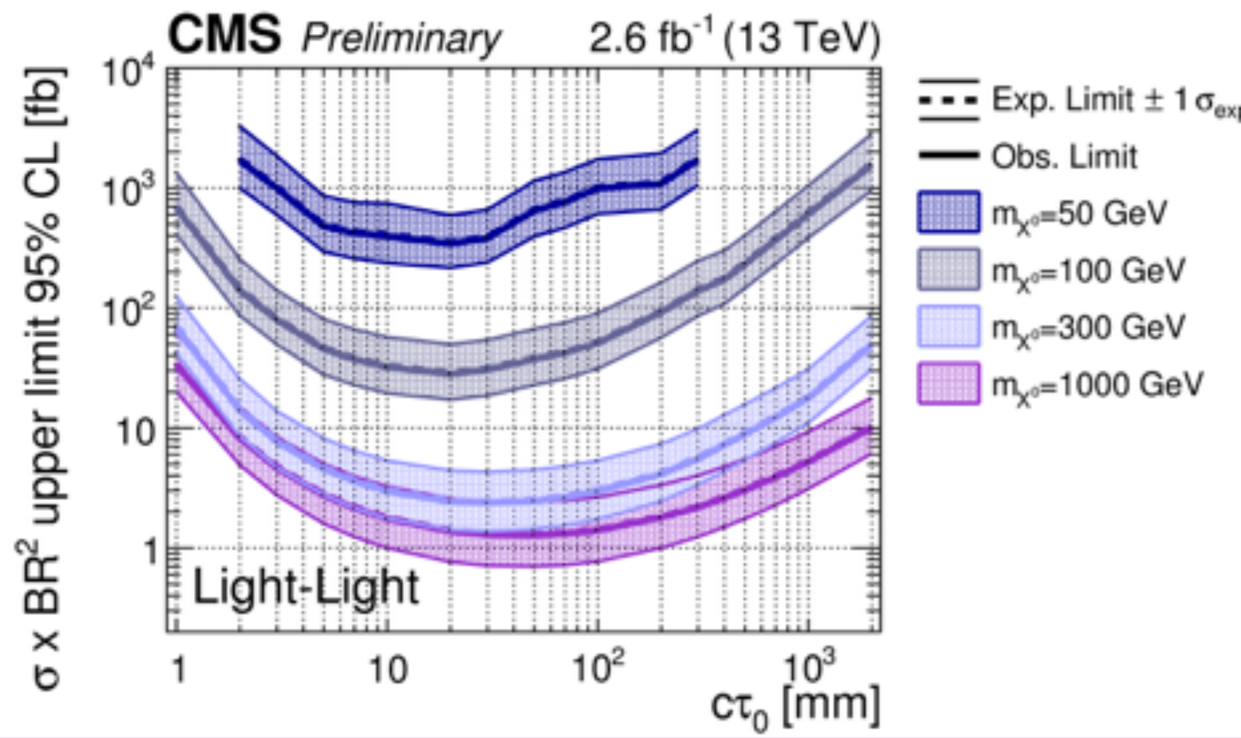


PAS EXO-16-003

Final Limits on Different Jet Flavour

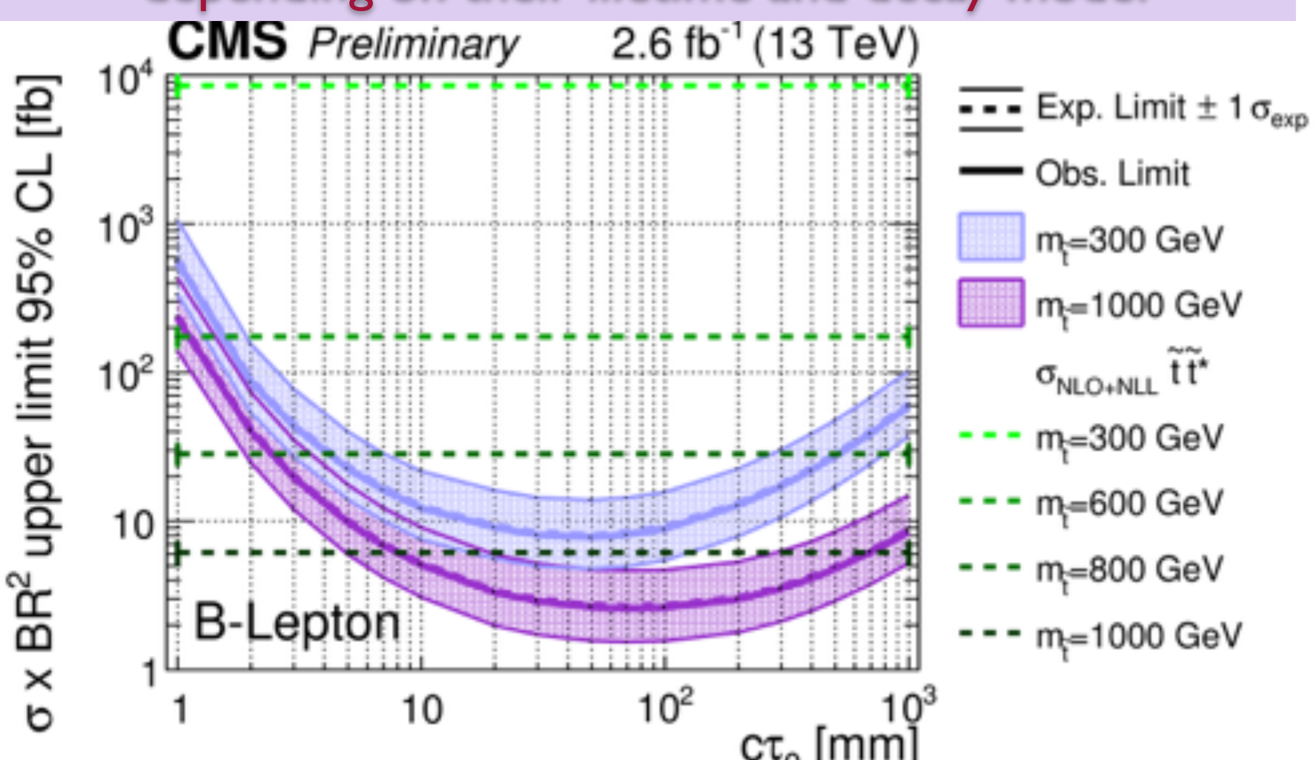
- No excess above the predicted background is found, upper limits are set at 95% confidence level on the production cross section for resonances decaying to two jets or to a lepton and b quark.

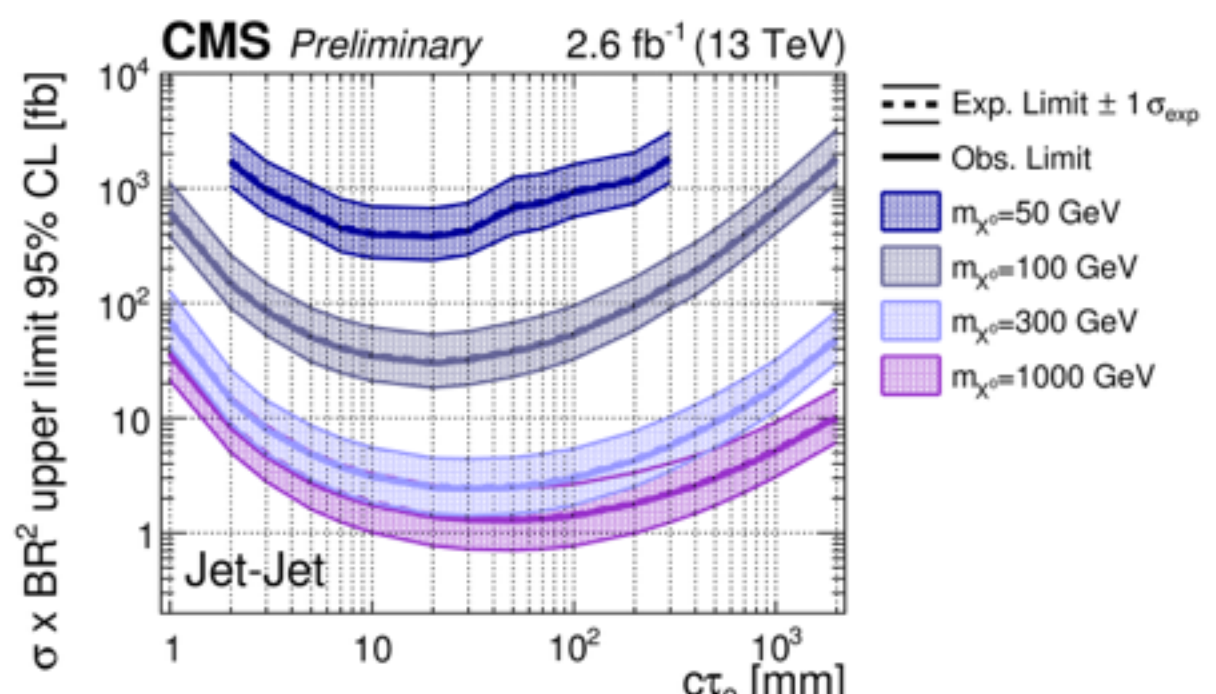
N_{tags}	Expected	Observed
2	1.09 ± 0.16	1
≥ 3	$(4.9 \pm 1.0) \times 10^{-4}$	0



BLepton: Pair-produced long-lived R-parity violating top squarks lighter than 550-1130 GeV are excluded, depending on their lifetime and decay mode.

JET-JET: cross sections larger than 1.2 fb (2.5 fb) are excluded for proper lifetimes of 50 mm (70-100 mm).





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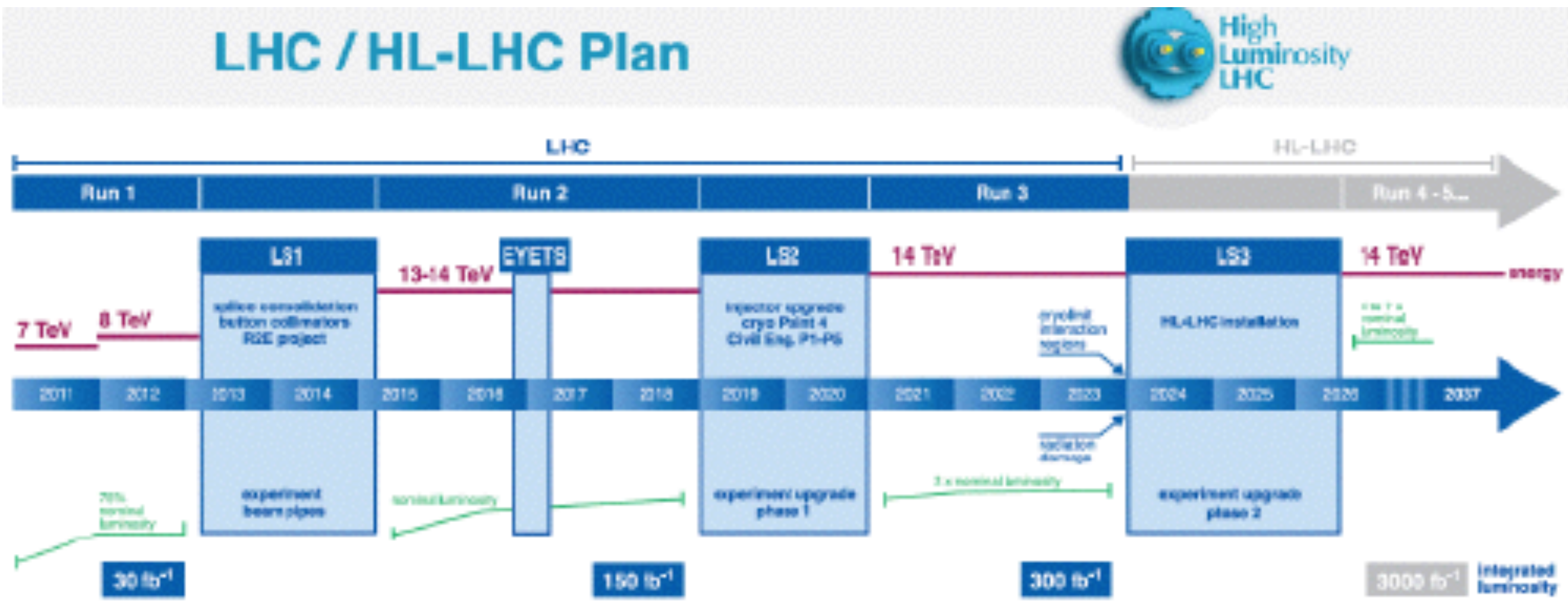
Conclusions

LHC joins the DM pursuit, pushing high energy physics into new territory and presenting an unprecedented opportunity to probe the realm of new physics in the TeV region.

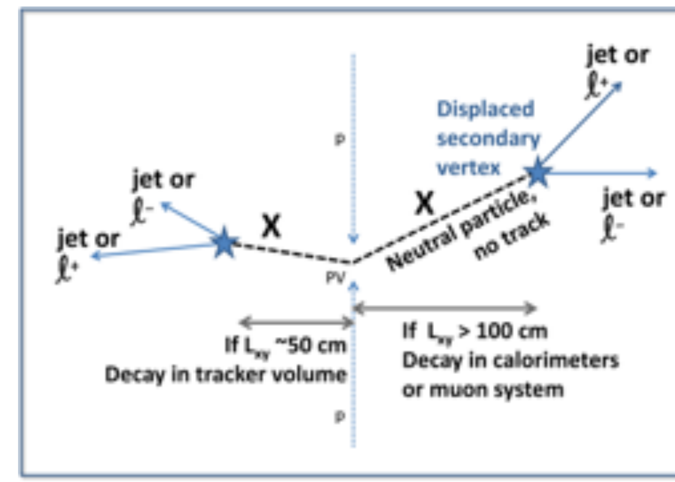
- **Presented new results using 13 TeV dataset collected so far by ATLAS and CMS**
  - Large increase in sensitivity from the Run 1 results
  - But no significant deviation observed yet

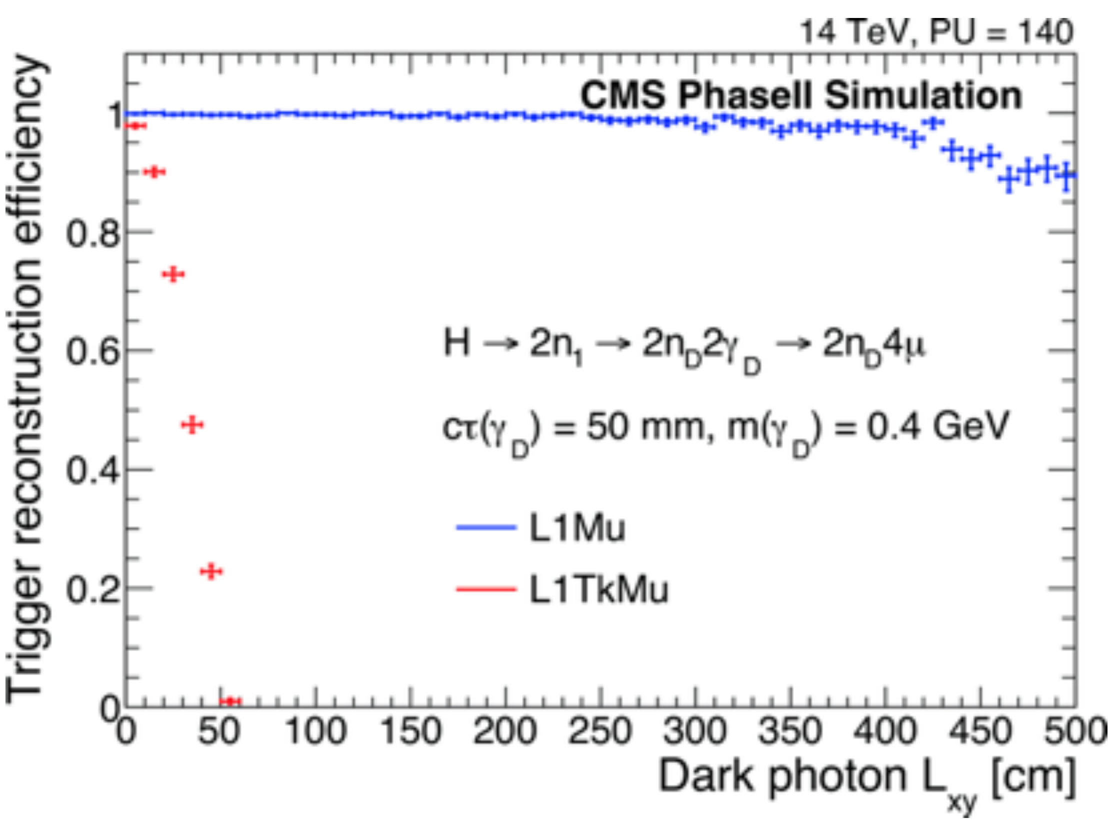
- **Exploitation of the 13 TeV dataset has just started, can still hope for surprises.**
- **Taking in mind that there will be HL-LHC where the possibilities to discover new DM candidates will increase a lot!**

A Look to the Future: HL-LHC

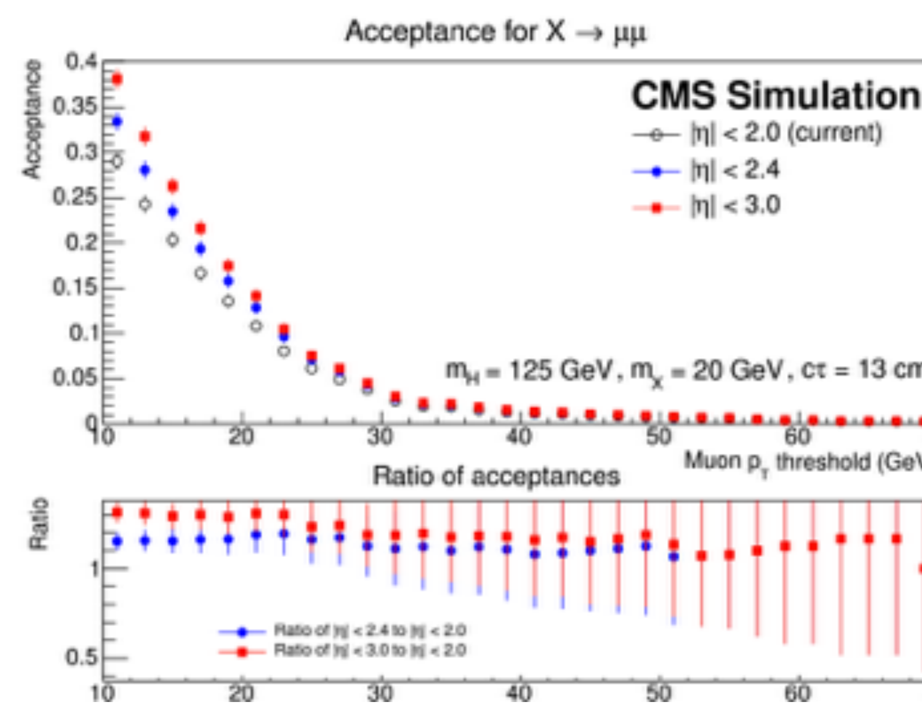


The target integrated luminosity for the HL-LHC program is about 3000 fb^{-1}. An ultimate performance of the accelerator along with upgrade on the detector layout.





Promising future for DM searches in the HL-LHC era!



BACKUP

Light Bosons Decaying in Multi Leptons

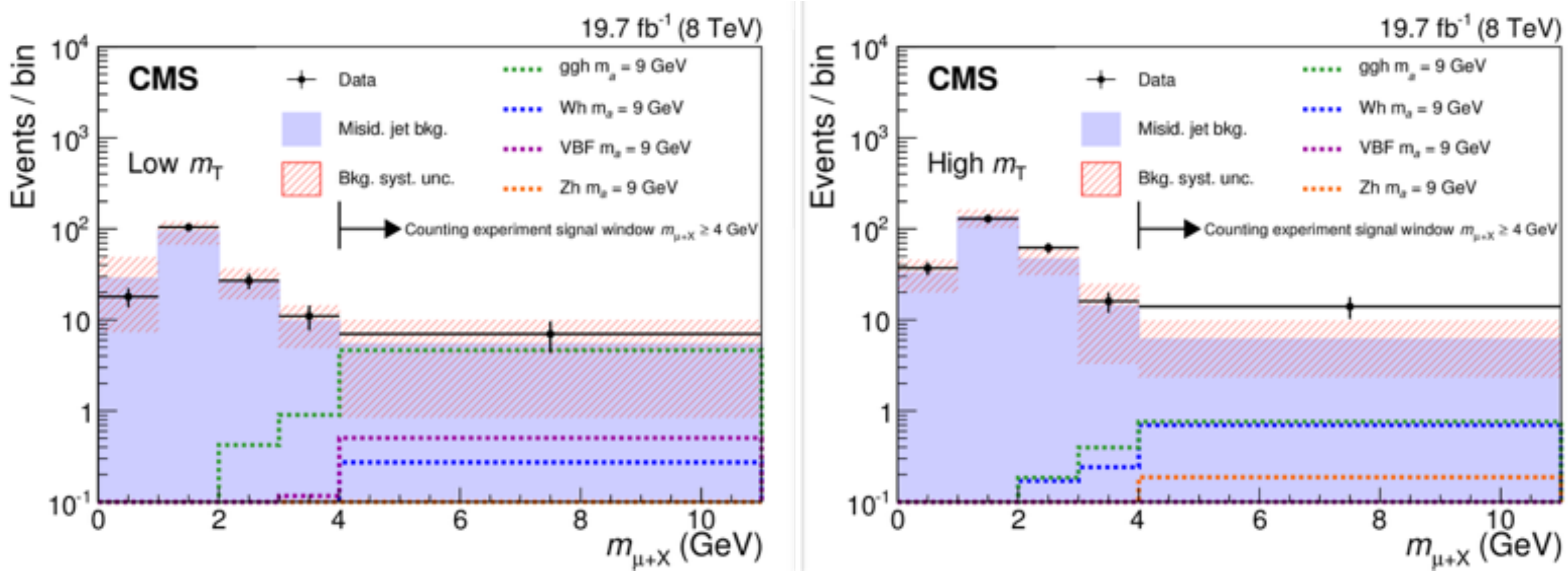
- **Three searches for decays of the 125 GeV Higgs boson to pairs of lighter scalars or pseudoscalars.**

$$h \to aa \to 4\tau,$$
$$h \to aa \to 2\mu 2b,$$
$$h \to aa \to 2\mu 2\tau.$$

- Two other analyses focus on masses large enough that the decay products are well separated from each other, and below half of the Higgs boson mass. **The results of these searches are interpreted in the 2HDM and 2HDM+S contexts.**

$$h \to aa \to 4\mu$$
$$h \to aa \to 4\tau$$

Only at 8 TeV



The event selection is performed by using the transverse mass :

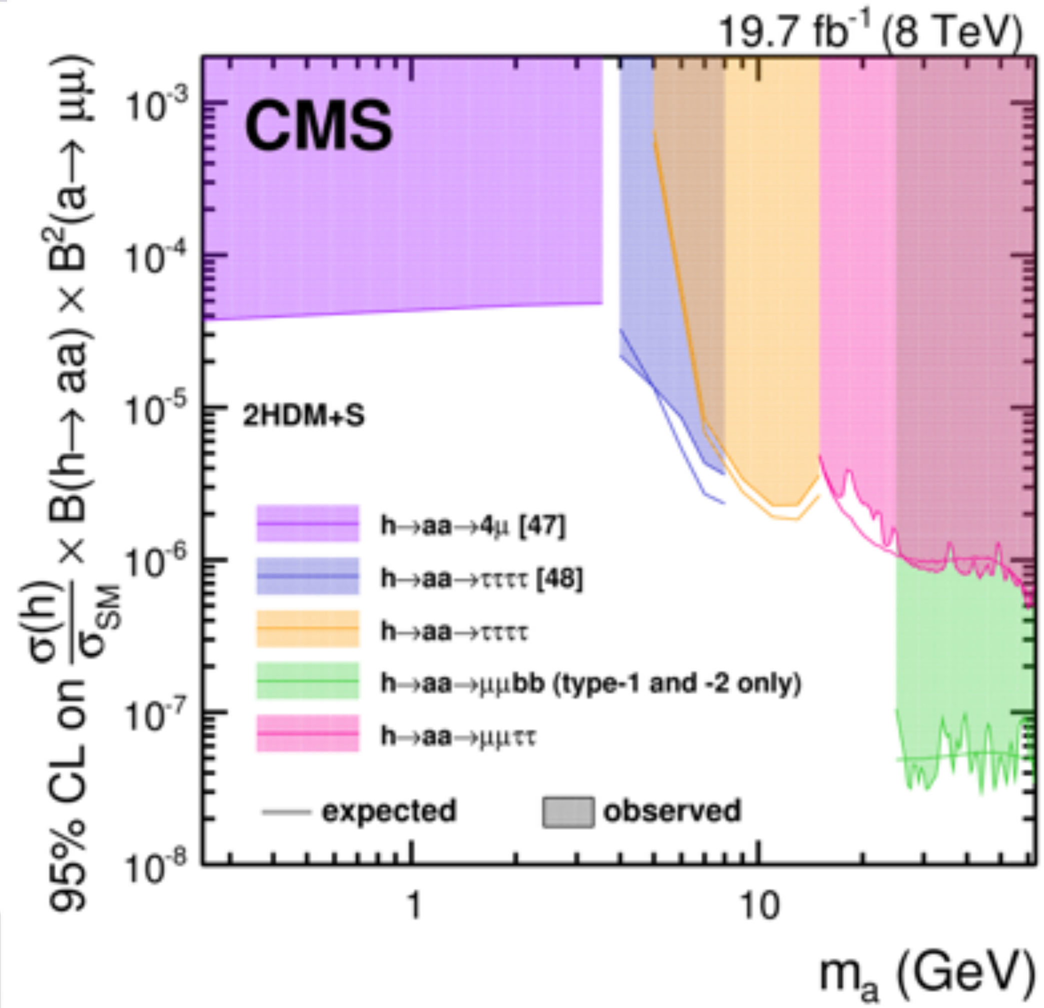
$$m_T = \sqrt{2 p_T^{\mu_{trg}} E_T^{miss} [1 - \cos \Delta\phi(\mu_{trg}, \vec{p}_T^{\,miss})]}.$$

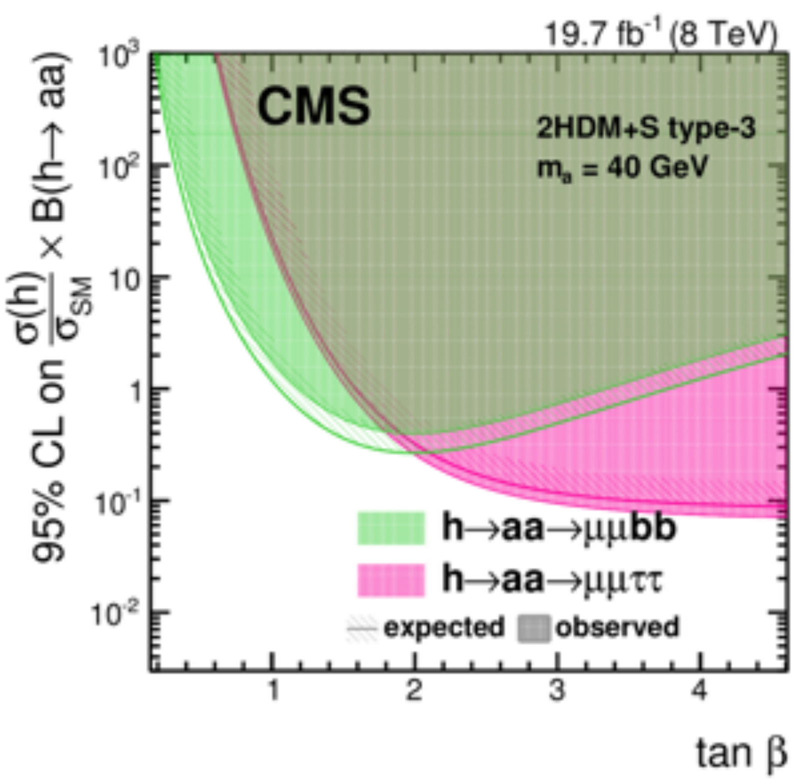
Final Limits on Different Topologies

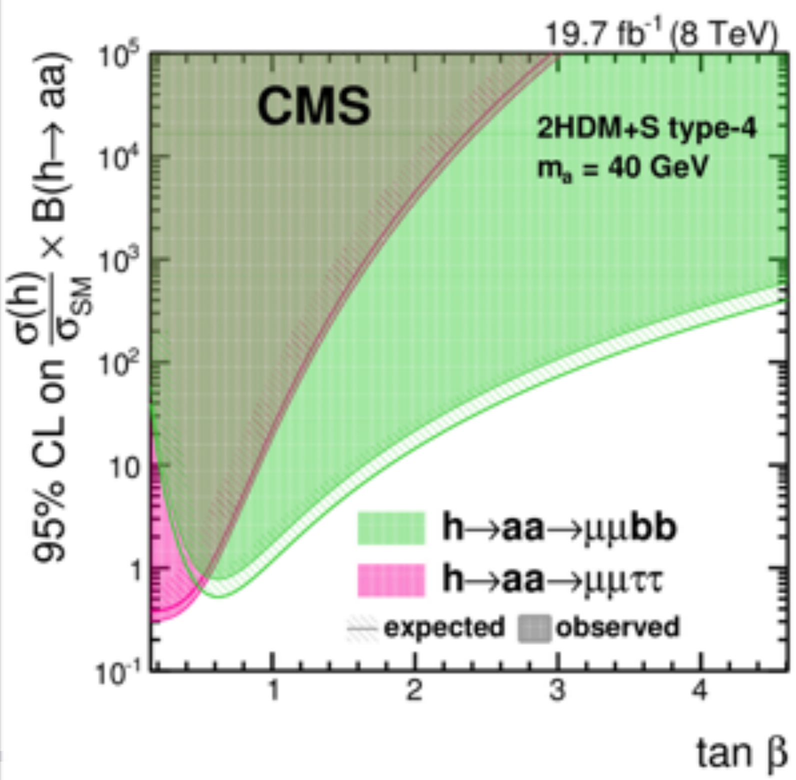
- Expected and observed 95% CL exclusion limits or various exotic h boson decay searches performed with data collected at 8 TeV.
- The branching fractions of the pseudoscalar boson to muons, ττ leptons and b quarks follow:

$$\frac{\Gamma(\mathrm{a} \to \mu^+\mu^-)}{\Gamma(\mathrm{a} \to \tau^+\tau^-)} = \frac{m_\mu^2\sqrt{1-(2m_\mu/m_\mathrm{a})^2}}{m_\tau^2\sqrt{1-(2m_\tau/m_\mathrm{a})^2}}.$$

$$\frac{\Gamma(\mathrm{a} \to \mu^+\mu^-)}{\Gamma(\mathrm{a} \to \mathrm{b}\overline{\mathrm{b}})} = \frac{m_\mu^2\sqrt{1-(2m_\mu/m_\mathrm{a})^2}}{3m_\mathrm{b}^2\sqrt{1-(2m_\mathrm{b}/m_\mathrm{a})^2}\,(1+\text{QCD corrections})}.$$







Only at 8 TeV

U(1) Models

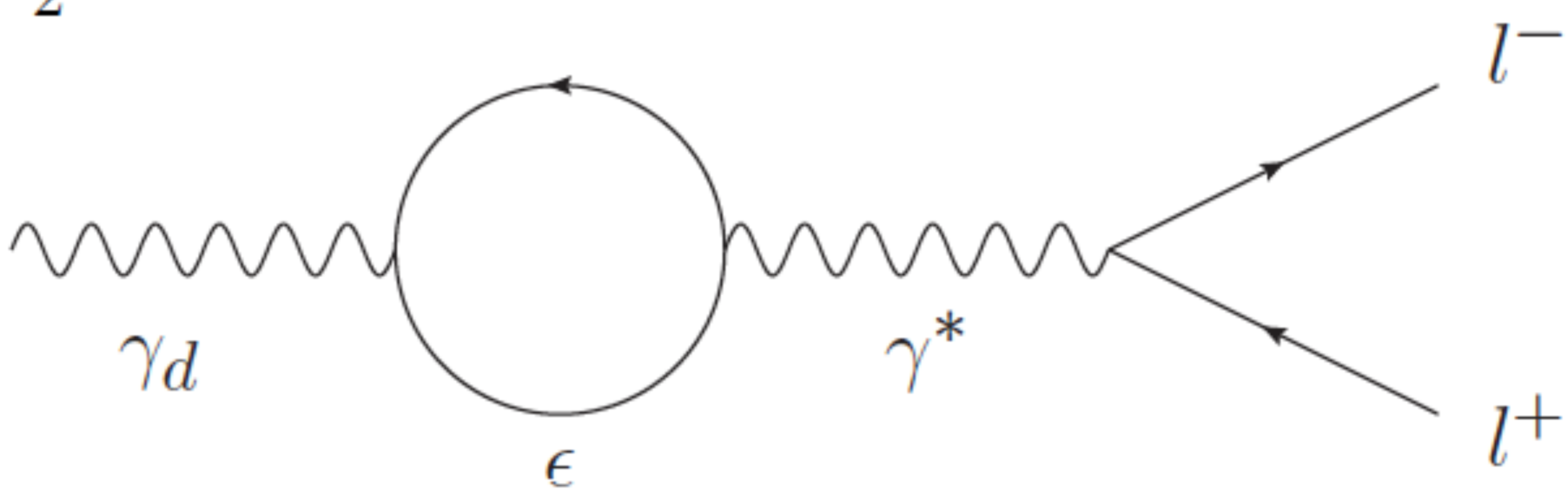
Many U(1) extensions of the Standard Model
- Holdom, Phys.Lett. B166 (1986) 196
- Galison, Phys.Lett. B136 (1984); Manohar

γd

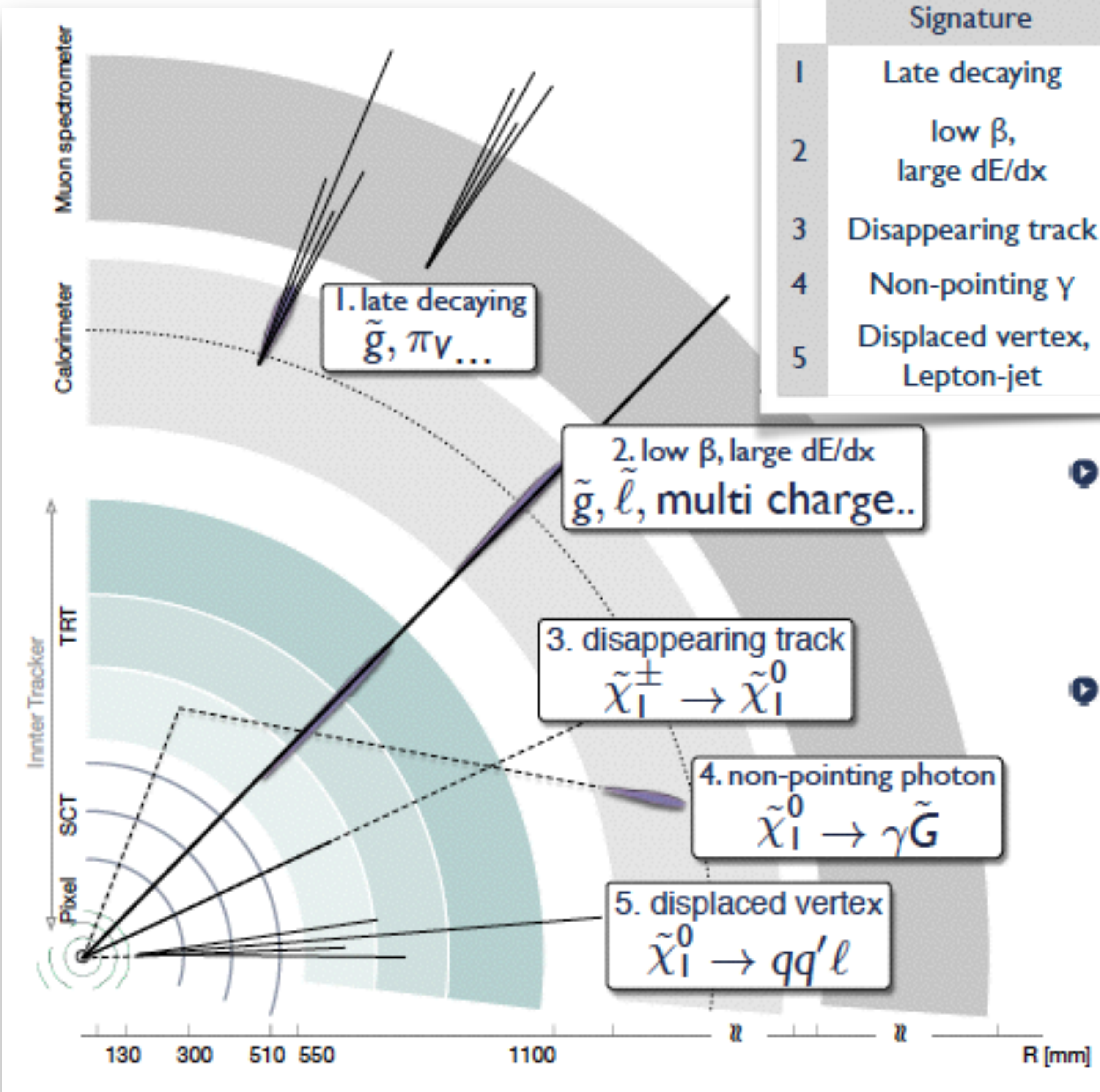
Dark photon
A′
Heavy photon
Z_{dark}
Hidden photon
U-boson
etc.

Kinetic mixing
- **Lagrangian contains a term**

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$



Long-Lived Particle
Displaced objects



	Signature	Scenario	decay-length sensitivity
1	Late decaying	split SUSY, Hidden Valley	—
2	low β, large dE/dx	GMSB, Split-SUSY, Stealth SUSY, Multi-charged	>1000mm
3	Disappearing track	AMSB (wino-LSP)	O(100-1000)mm
4	Non-pointing γ	GMSB	O(100-1000)mm
5	Displaced vertex, Lepton-jet	RPV, GMSB, Hidden Valley	O(10-100)mm

ATLAS-CONF-2016-042

CMS-EXO-15-010 ; CERN-EP/2016-204

ATLAS-CONF-2016-103

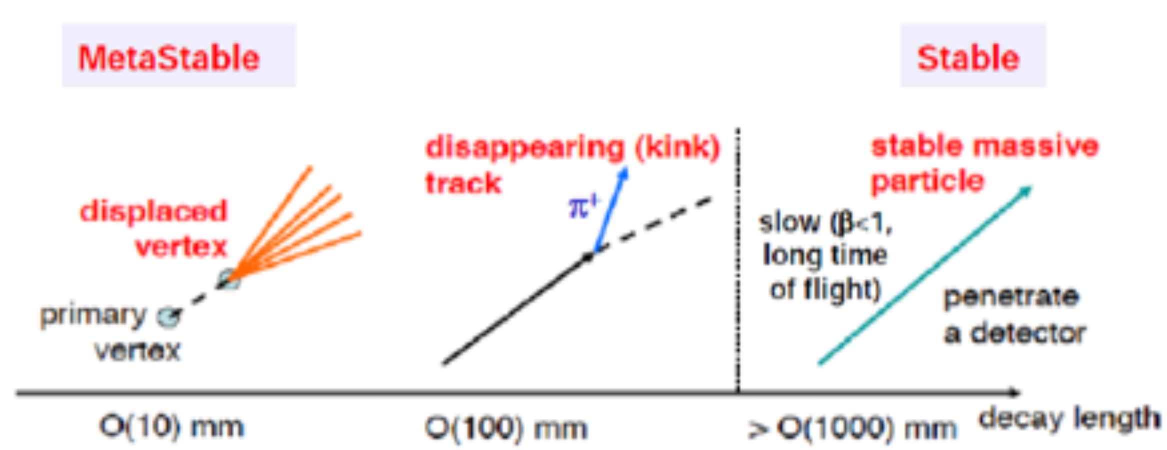
Long-Lived Particles

Several new physics models could give raise to new, massive particles with long-lifetime.

- **Long-lived charginos** in AMSB model: disappearing tracks
- If very heavy squarks mediate gluinos decay (strong virtuality): **Long-lived gluinos , R-hadrons** (eg. Split SUSY)
- If NLSP-gravitino GMSB couplings are weak: **long-lived sleptons**
- **R-Parity Violation (RPV) LSP decay:** Displaced vertex
- **Higgs decay to hidden-sector neutral particles:** lepton-jets and displaced vertex

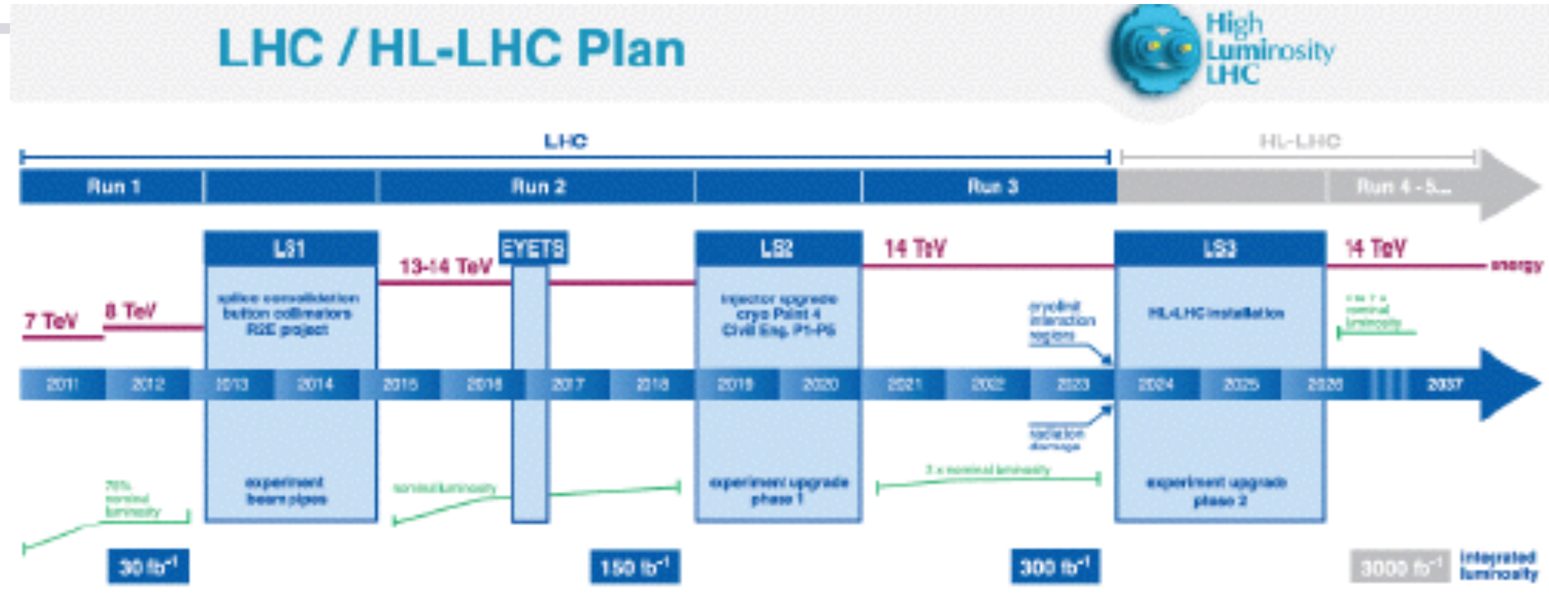
Experimentally very diverse, depending on particles' properties:

- Life time, charge, decays
- Highly ionising (dE/dx)
- Slow (Time-of-flight)
- Out-of-Time (wrt collision) decay
- Highly displaced vertices
- Kinked tracks
- Disappearing tracks
- High lepton multiplicity (lepton-jets)



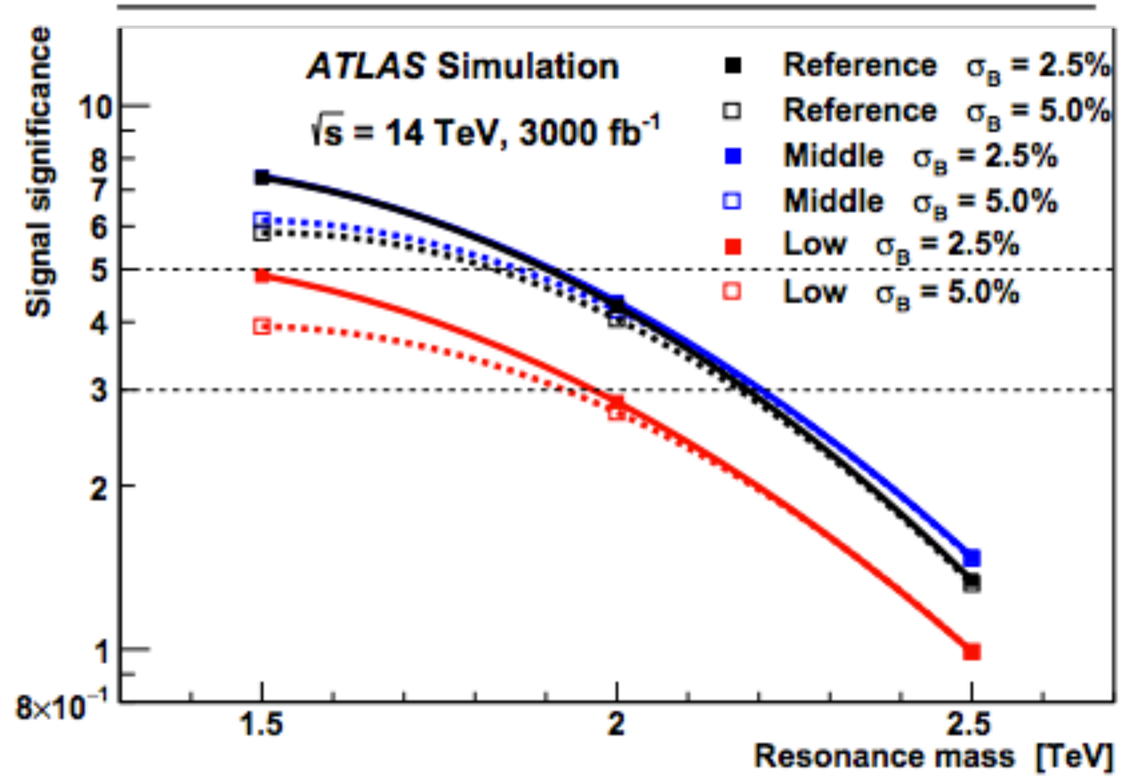
A window to the Future: HL-LHC

The target integrated luminosity for the HL-LHC program is about 3000 fb^{-1}. An ultimate performance of the accelerator along with upgrade on the detector layout.



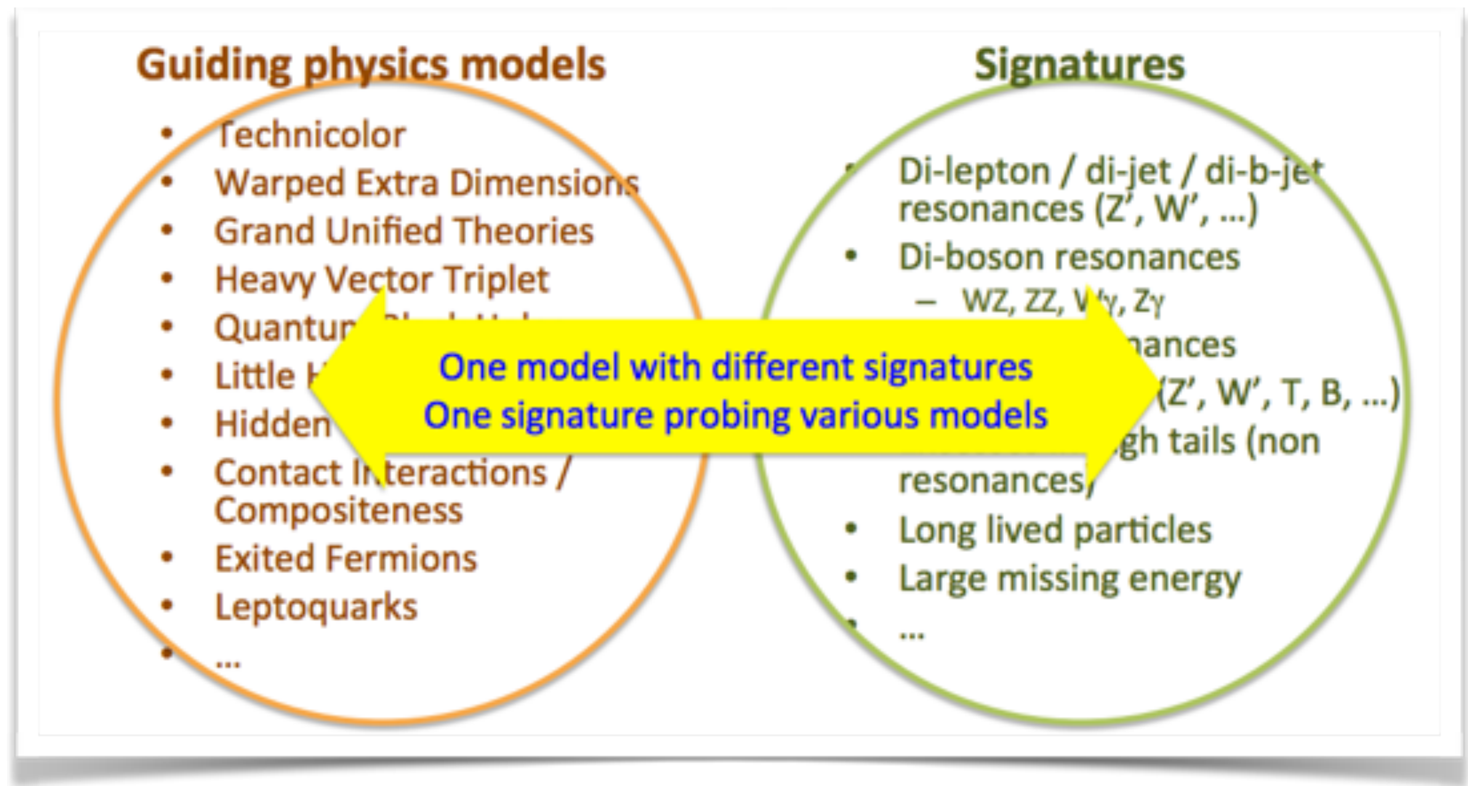
- **Scoping Document**: few BSM studies have been already explored at HL-LHC.
  - Search for **charginos and neutralinos** in final states with one lepton and two b-jets.
  - **Resonant Higgs boson pair** production in the $b\bar{b}b\bar{b}$ final state. Cross-section limit increased by a factor 2.
  - **Dijet resonance** searches:
    - q* from 4 TeV to 8 TeV
    - QBH from 5 TeV to 10 TeV
  - Soon long-lived particles results.

Scenario	Significance ($M_{G^*_{KK}}$=2.0 TeV)
Reference scenario	4.4
Middle scenario	4.5
Low scenario	3.1



Exploring New Physics

- **Strategy for new physics searches** (for example, in the case of Higgs boson):
    - **Indirectly**, ***by looking for non-standard properties*** of light Higgs (spin, CP, couplings…)
    - **Directly**, ***by explicit search for BSM objects***
        - additional Higgs bosons (neutral and charged, decays to SM particles,..)
        - Higgs boson decays to BSM states (light scalar resonances, invisible decays,..)
- **In the case of direct searches, define selection based on signal signatures/ acceptance and background kinematics**
- **Comparisons provided for specific models, but usually possible to constrain additional models**



Displaced Jets: Full Cut Flow

Requirement	Data main	SM multi-jets MC	$m_\phi = 600\ GeV$; $m_s = 150\ GeV$	Data BIB	Data cosmic rays
Events passing the trigger	548600 ± 740	404000 ± 27000	25.7%	100%	100%
≥ 2 clean jets	421800 ± 650	197000 ± 19000	22.1%	38.3%	21%
$\mathrm{jet}_{1,2}^{\mathrm{CalRatio}}$ clean	23860 ± 150	900 ± 440	7.21%	6.67%	7.28%
$\Delta\phi > 0.75$	17590 ± 130	600 ± 350	6.85%	0.86%	3.38%
$-3 <$ time < 15	16180 ± 130	600 ± 350	6.84%	0.35%	1.10%
$H_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}} < 0.3$	14880 ± 120	600 ± 350	6.09%	0.30%	0.25%
$\sum \Delta\mathrm{R_{min}} > 0.5$	9500 ± 97	500 ± 330	6.08%	0.14%	0.25%
BDT value($\mathrm{jet}_1^{\mathrm{CalRatio}}$) > 0.2	8190 ± 91	500 ± 330	5.95%	0.09%	0.25%
BDT value($\mathrm{jet}_2^{\mathrm{CalRatio}}$) > -0.2	4890 ± 70	300 ± 260	5.93%	0.06%	0.25%
$p_{\mathrm{T},1} > 150\ GeV$	330 ± 18	0 ± 0	5.31%	0.005%	0%
$p_{\mathrm{T},2} > 120\ GeV$	110 ± 10	0 ± 0	4.27%	0.001%	0%
region A:					
$\sum \Delta\mathrm{R_{min}} > 1.5$	60 ± 8.0	0 ± 0	3.73%	0%	0%
$\sum \mathrm{BDT} > 0.15$	24 ± 4.9	0 ± 0	3.57%	0%	0%

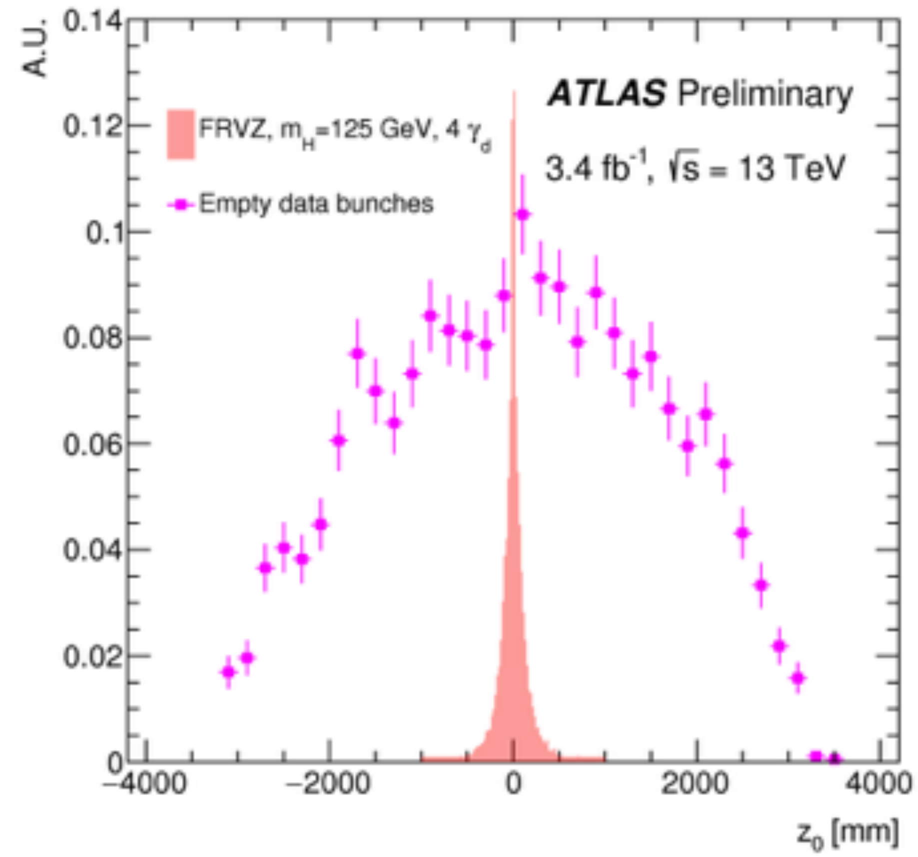
Mass Point (GeV, GeV)	JES (%)	JES EMF (%)	JER (%)	Trigger (%)	Pile-up (%)	Luminosity (%)
(400,150)	3.3	14	0.43	2.3	4.0	2.1
(600,150)	1.5	5.4	0.40	1.5	0.56	2.1
(1000,150)	0.51	1.8	0.05	1.0	2.0	2.1

ATLAS

ATLAS-CONF-2016-042

Signal Event: topology and selection

- **Selection**: dedicated trigger to select these states. Different selections depending on the LJ type.
  - **Collimated final-state particles difficult to reconstruct** (detector granularity)
  - **Tracks with displaced decay vertices difficult to reconstruct** (no primary vertex constraint)



- **Background**: Cosmics events (impact parameter and timing as discriminating variables), machine background, QCD jets (ABCD method)

- **Main Uncertainty**:Trigger, reconstruction efficiency

LJ type	Selection requirement	Requirement description
Type 0/1	z_0 limits	an impact parameter $\|z_0\| < 280$ mm for both muons of the LJ
Type 1/2	jet timing Δt_{Calo}	remove jets outside the $\pm$ 4 ns time window
Type2	tile-gap scint.	max energy in tile-gap scintillators $\leq$ 10% of the jet energy
Type2	EM fraction	EM fraction of the jet < 0.1
Type2	jet width	$W < 0.058$
Type2	JVT	JVT variable ≤ 0.56
Type2	BIB	use BIB tagging to remove fake jets from beam-halo muons
Type 0/1	no-CB	all muons of the LJ to be non-combined ("no-CB")