

Searching for long-lived particles at the LHC:
Fourth workshop of the LHC LLP Community



23-25 October 2018
Amsterdam Science Park
Europe/Zurich timezone

DISPLACED DIMUONS AND DARK PHOTONS: EXPERIMENTAL PERSPECTIVE



Antonio Policicchio
Sapienza U. and INFN Roma

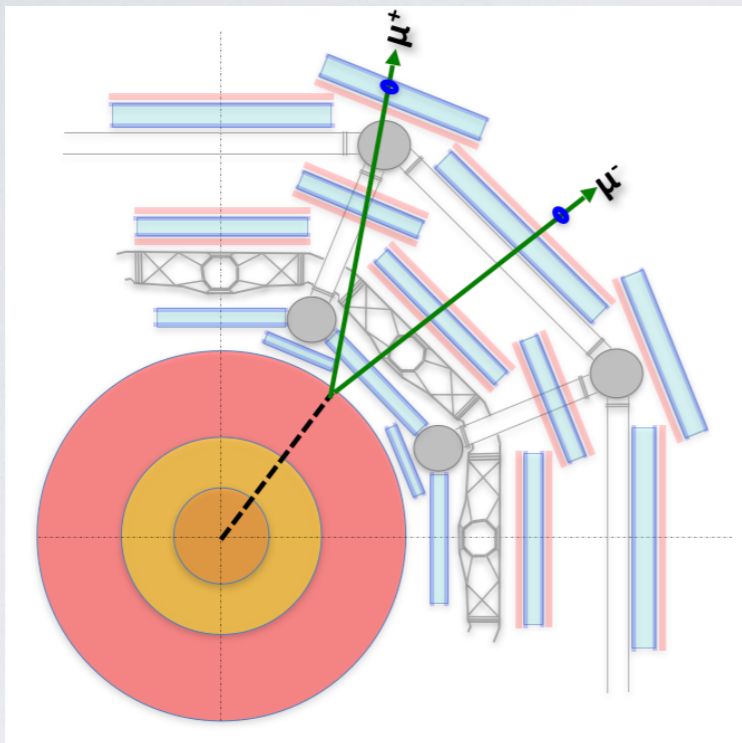


OUTLINE

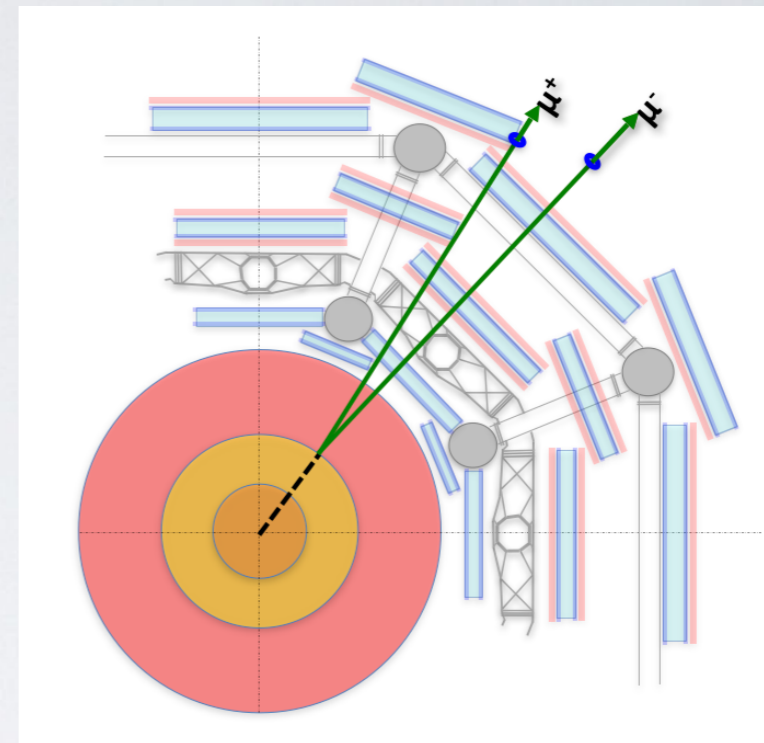
- Experimental signatures of dark photon decays at LHC
- Searches at ATLAS, CMS and LHCb
 - focus on Run2 13 TeV searches
 - benchmark models
 - triggers
 - results
 - prospects for upgrade and HL-LHC - **more in Simone's talk**
- New detectors - **more in dedicated talks**

SIGNATURES OF LONG-LIVED DARK PHOTON DECAYS IN LHC DETECTORS

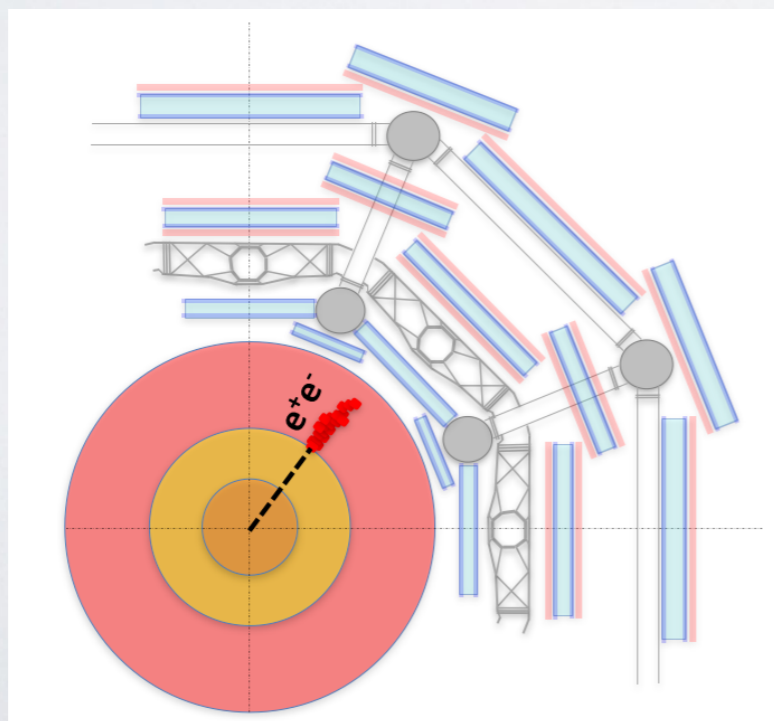
non-collimated muon pairs
vertex reconstruction



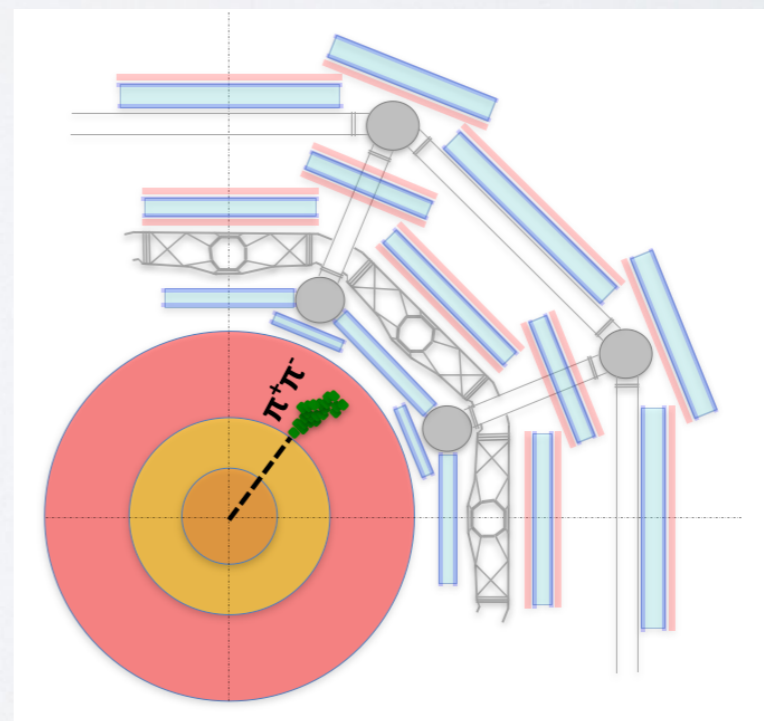
collimated muon pairs
no vertex reconstruction



displaced electron pairs
low em fraction jets



displaced light hadron pairs
low em fraction jets



CHALLENGES IN LONG-LIVED DARK PHOTON SEARCHES

- **Trigger**: combination of hardware + software → make sure that interesting events are saved
 - Design and develop a new trigger. need to keep trigger rates under control and within budget, not an easy task at low masses
- **Object identification** algorithms assume prompt particles → need to adapt them
- **Backgrounds**: SM backgrounds usually small but instrumental background such as mis-identified leptons and non-collision backgrounds have to be taken into account
- **Systematic** uncertainties: cannot use standard recommendations for object reconstruction nor trigger

Small teams engaged with analysis for a long time

NON-COLLIMATED MUON PAIR SEARCH IN ATLAS (I)

13 TeV, 32.9/fb: EXOT-2017-03

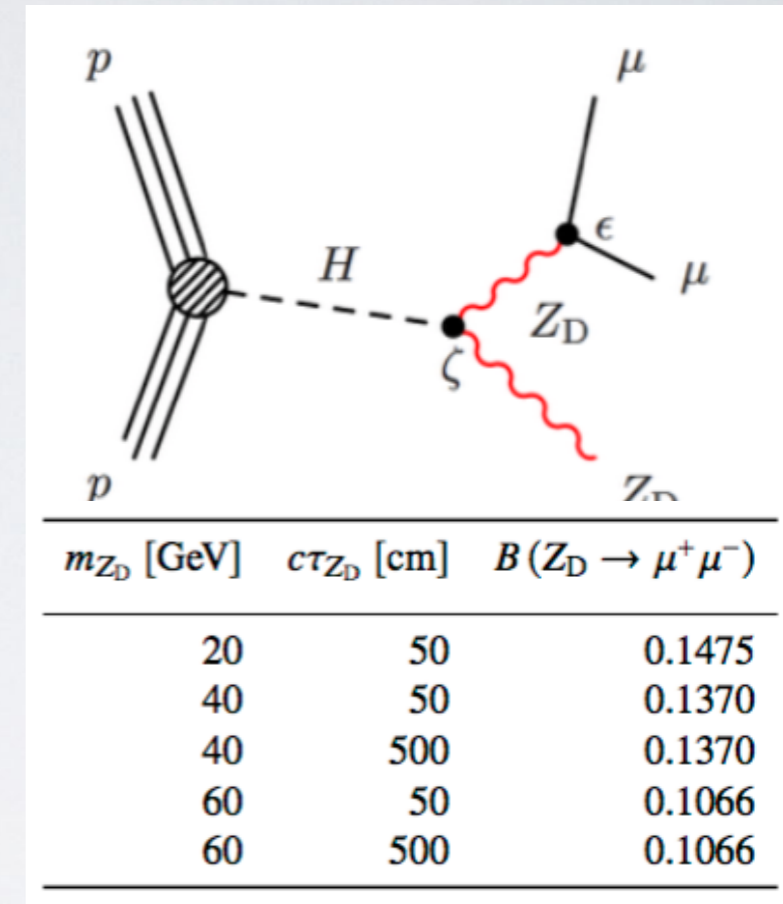
- Search for pairs of dimuons with opposite-sign electric charge not originating at IP

- Benchmark models

- Higgs portal model

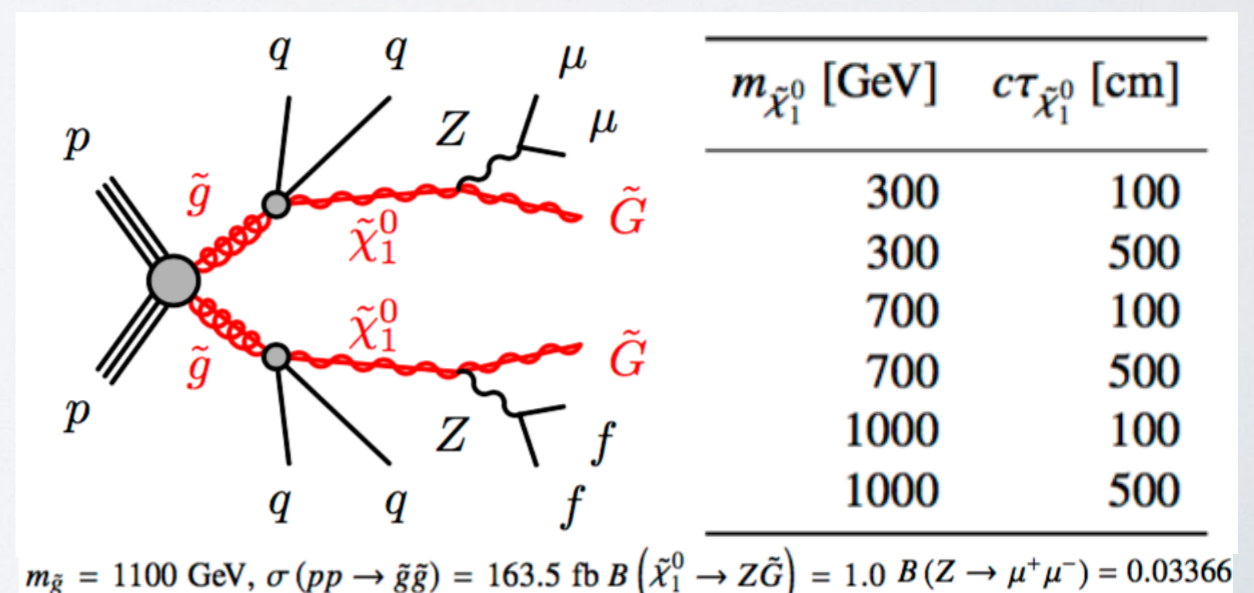
- $U(1)$ symmetry in the dark sector

- the dark photon Z_D assumes mass via a singlet scalar field H_D , analogous to the Higgs field H in the visible SM sector



- SUSY GGM model

- the lightest neutralino is the next-to-lightest supersymmetric particle, with a relatively long lifetime due to its weak coupling to the gravitino, the lightest supersymmetric particle



NON-COLLIMATED MUONS SEARCH IN ATLAS (II)

13 TeV, 32.9/fb: EXOT-2017-03

- Selection

- Trigger on MOnly muons, measurement based on information from muon spectrometer only

Signal type	Trigger	Description	Thresholds
High mass	E_T^{miss} single muon	missing transverse momentum single muon restricted to the barrel region	$E_T^{\text{miss}} > 110$ GeV muon $ \eta < 1.05$ and $p_T > 60$ GeV
Low mass	collimated dimuon trimuon	two muons with small angular separation three muons	p_T of muons > 15 and 20 GeV and $\Delta R_{\mu\mu} < 0.5$ $p_T > 6$ GeV for all three muons

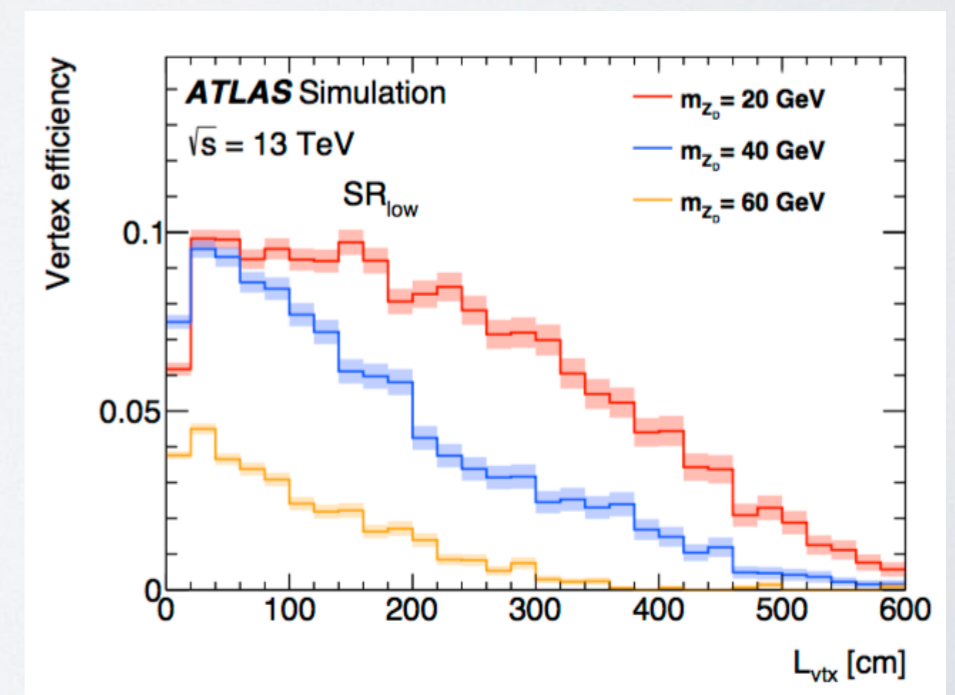
- Muon reconstruction

- “standard” muons: matching between inner tracker track and muon spectrometer track
- muons from long-lived particle: track in the muon spectrometer without matching in inner tracker (MSonly muons)

- the analysis searches for pairs of MSonly muons

- Vertexing

- for every pair of MSonly muons, extrapolate tracks to interaction point and find point of closest approach
- efficiency decreases with decay position

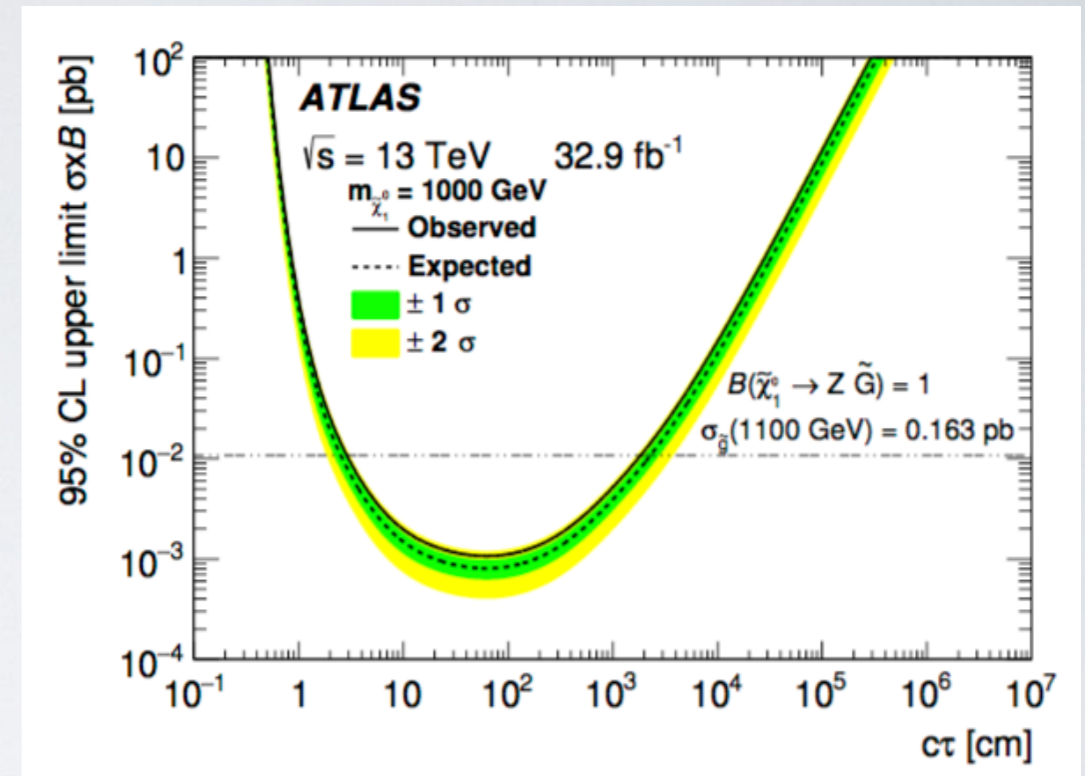


NON-COLLIMATED MUONS SEARCH IN ATLAS (III)

13 TeV, 32.9/fb: EXOT-2017-03

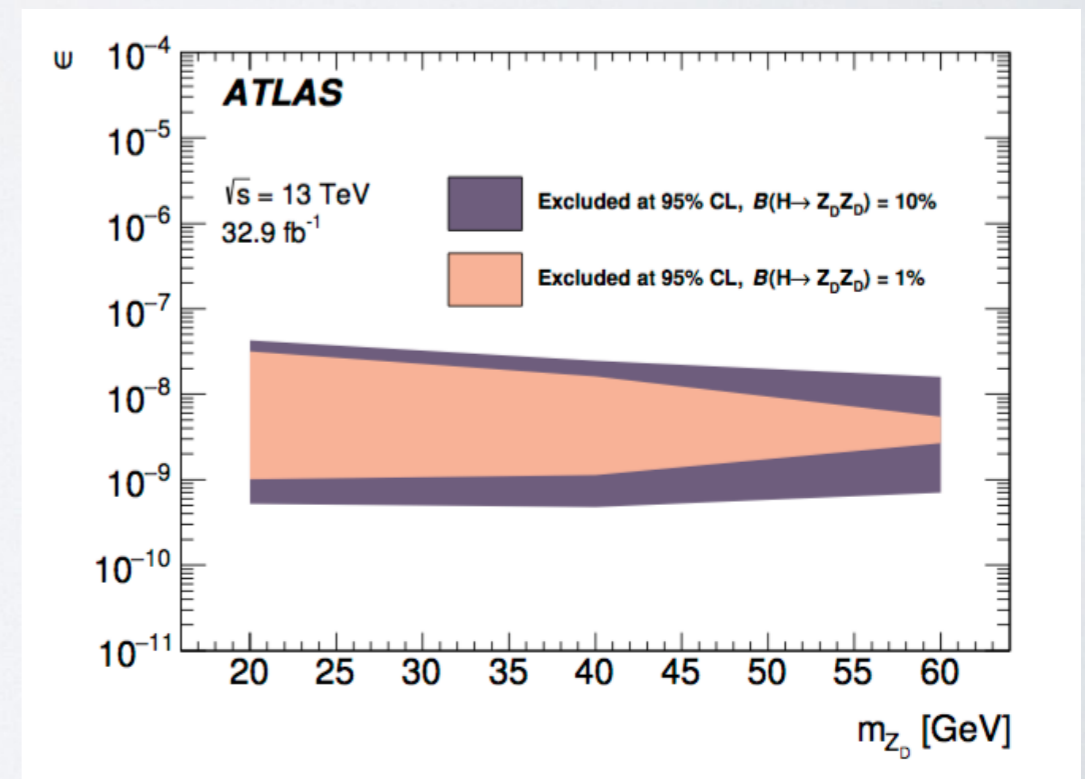
• Backgrounds

- non-prompt: cosmics muons, beam induced, pion and kaons
 - leave signal in the MS only and can be reconstructed as MS only muons
 - estimated using a control region with same sign muons
- prompt: from SM processes (DY, Z+jets, jets)
 - jets are misidentified as muons and jet punch-through
 - reduced by requiring muon isolation from jets and tracks and requiring $m_{\mu\mu} > 15$ GeV to avoid low-mass resonances
 - estimated with data-driven method



• Results

- background estimation in agreement with observation
- Exclusion limits on $\sigma \times BR$ versus $c\tau$
- In the dark photon model, the lifetime limits are interpreted as exclusion contours in the plane of the coupling between the Z_D and the Standard Model Z boson versus the Z_D mass for various assumptions for the $H \rightarrow Z_D Z_D$ branching fraction

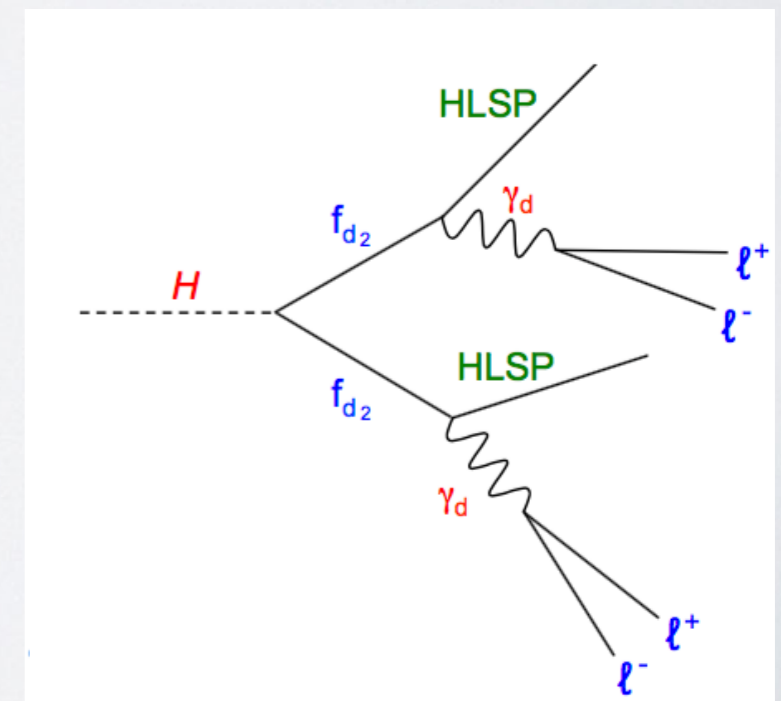


DISPLACED LEPTON-JETS SEARCH IN ATLAS (I)

13 TeV, 3.2/fb: ATLAS-CONF-2016-042

- Search for pairs of collimated muons or low em fraction jets
- Benchmark model
 - Falkowsky-Ruderman-Volansky-Zupan (FRVZ) model
 - Higgs boson decays to a pair of hidden fermions f_{d2} which produce γ_d 's and stable particles in final state
 - the low-mass dark photon mixing kinetically with the standard photon and decays to leptons/light mesons
 - the γ_d decay lifetime, controlled by the kinetic mixing parameter ϵ , is a free parameter
 - γ_d are produced with large boost \rightarrow collimated decay products \rightarrow leptonjets

Benchmark model	m_H [GeV]	$m_{f_{d2}}$ [GeV]	m_{HLSP} [GeV]	$m_{S_{d1}}$ [GeV]	m_{γ_d} [GeV]	$c\tau_{\gamma_d}$ [mm]
2 γ_d	125	5.0	2.0	-	0.4	47.0
4 γ_d	125	5.0	2.0	2.0	0.4	82.40
2 γ_d	800	5.0	2.0	-	0.4	11.76
4 γ_d	800	5.0	2.0	2.0	0.4	21.04



DISPLACED LEPTON-JETS SEARCH IN ATLAS (II)

13 TeV, 3.2/fb: ATLAS-CONF-2016-042

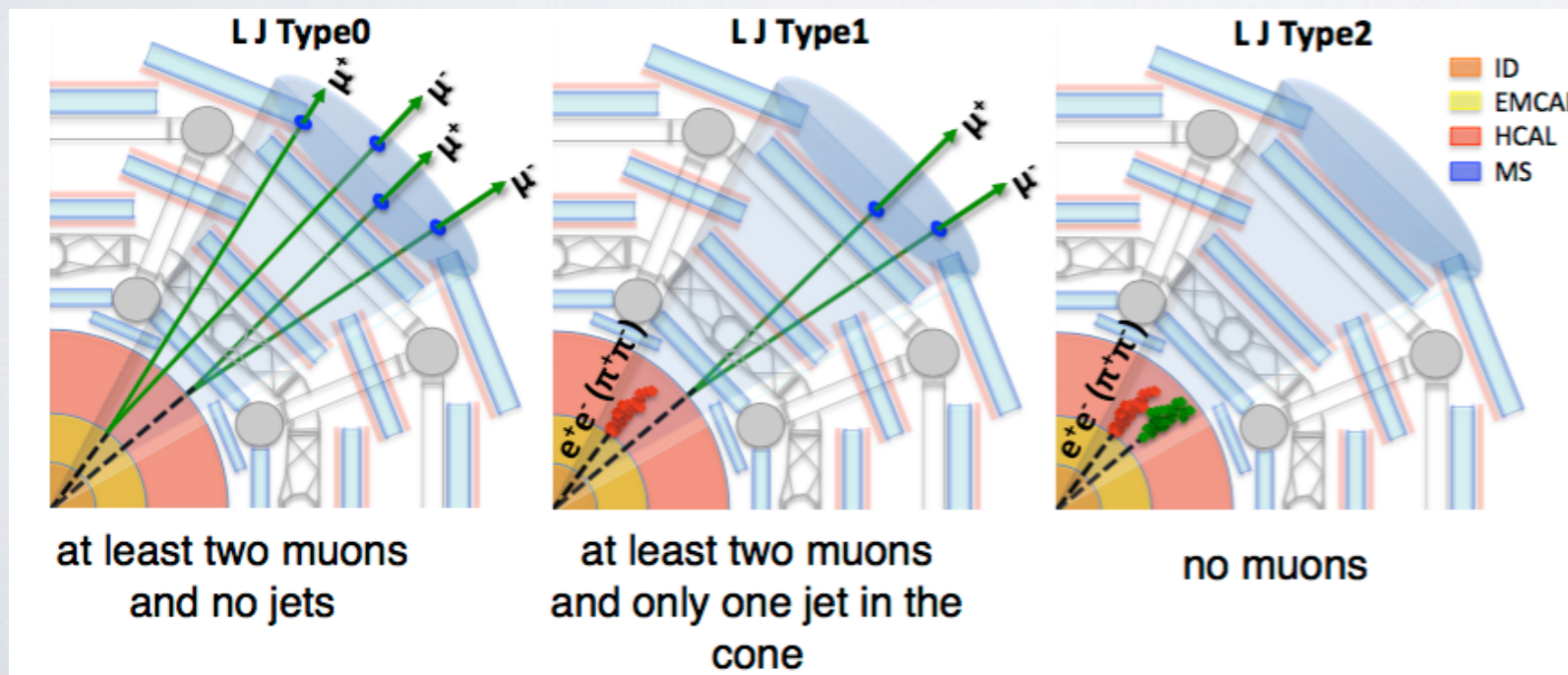
- Selection

- triggering difficult at low masses

Trigger	Higgs $\rightarrow 2\gamma_d + X$ $m_H = 125$ GeV	Higgs $\rightarrow 2\gamma_d + X$ $m_H = 800$ GeV	Higgs $\rightarrow 4\gamma_d + X$ $m_H = 125$ GeV	Higgs $\rightarrow 4\gamma_d + X$ $m_H = 800$ GeV
Tri-muon MS-only	2.0	2.4	4.9	7.8
Narrow-Scan	10.6	23.0	8.3	38.4
CalRatio	0.3	9.7	0.1	7.4
OR of all	11.9	32.0	11.8	44.8

same as in the non-collimated muons search
trackless low-EMF jets

- reconstruction: Leptonjets are divided in categories based on the constituents



- muon reconstruction
 - MSonly muons
 - clustering algorithm to combine all muons in a cone
- jet reconstruction
 - electron/meson pairs reconstructed as a single jet due to the high boost
 - standard jets with low em fraction to reduce QCD background

DISPLACED LEPTON-JETS SEARCH IN ATLAS (III)

13 TeV, 3.2/fb: ATLAS-CONF-2016-042

• Backgrounds

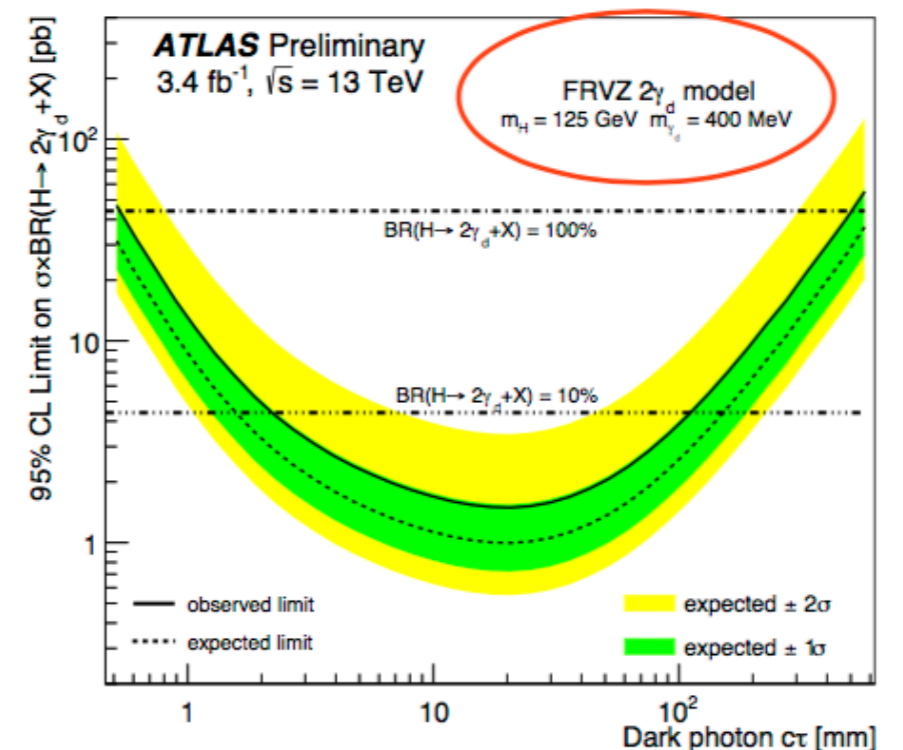
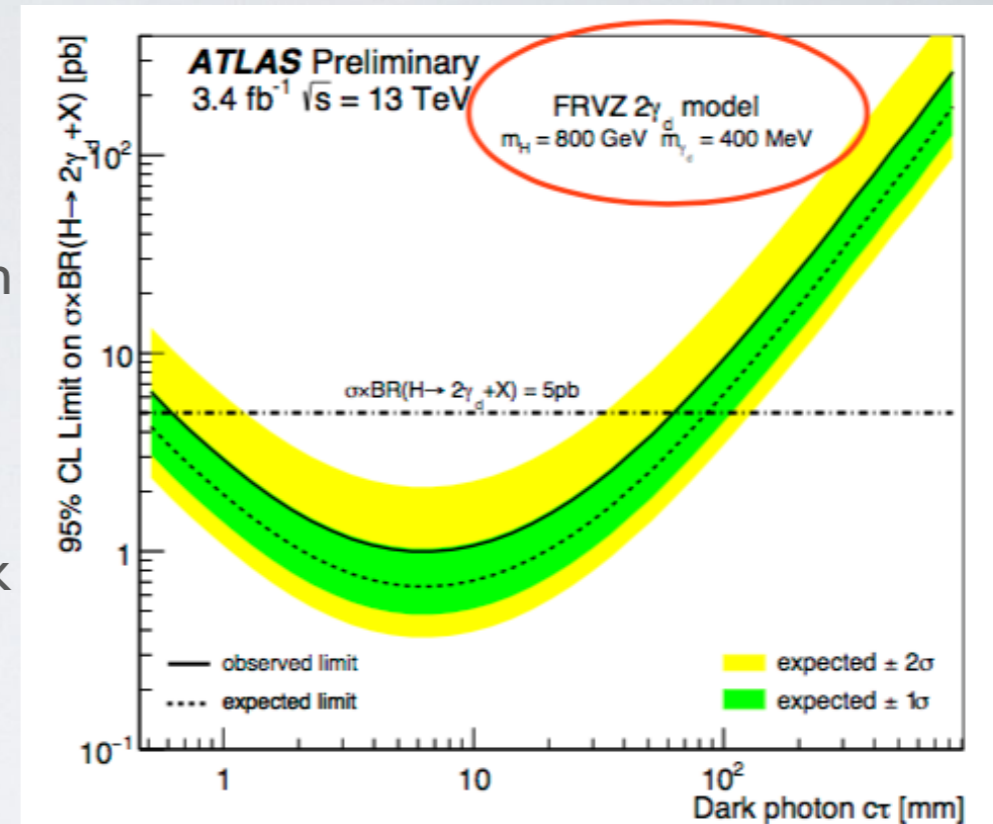
- non-prompt: cosmics muons, beam induced
 - reduced with cuts on muon/jet timing and impact parameter of muon tracks, and BIB-tagging using low em fraction jets and muon spectrometer end-cap information
 - data driven final estimation using triggers in EMPTY/UNPAIRED bunch crossing
- prompt: multijet QCD production
 - reduced with cuts on jet em fraction and width, and track isolation of the LJ
 - final estimation with data driven method

• Results

- background estimation in agreement with observation
- exclusion limits on $\sigma \times \text{BR}$ versus $c\tau$

• Ongoing analysis and plans

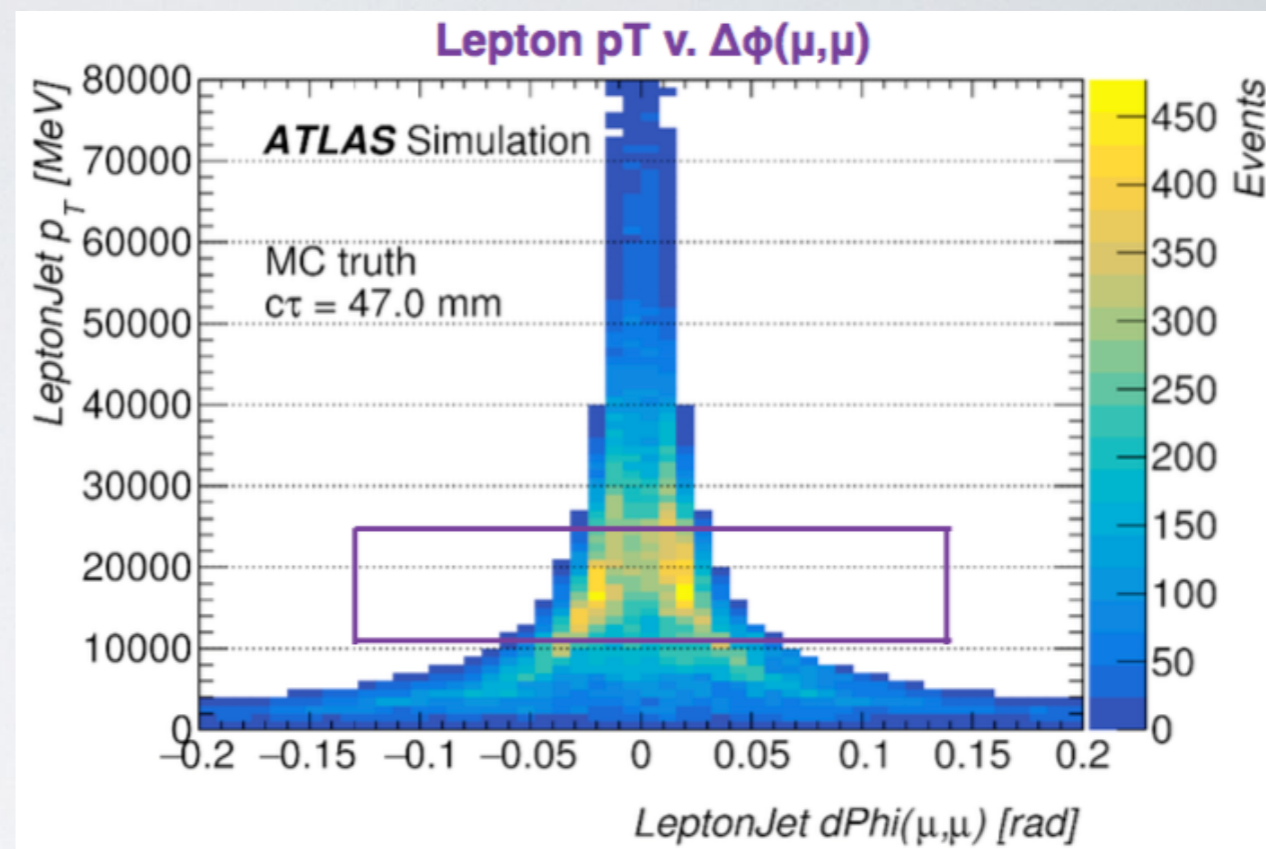
- updated triggers for the muon channel
- ML techniques to identify LJs
- plans to include other production modes (dark photon production with W/Z) and search for mono-LJ + X
- prompt dark photon search ongoing



ATLAS - UPGRADE/HL-LHC STUDIES

ATLAS-TDR-029

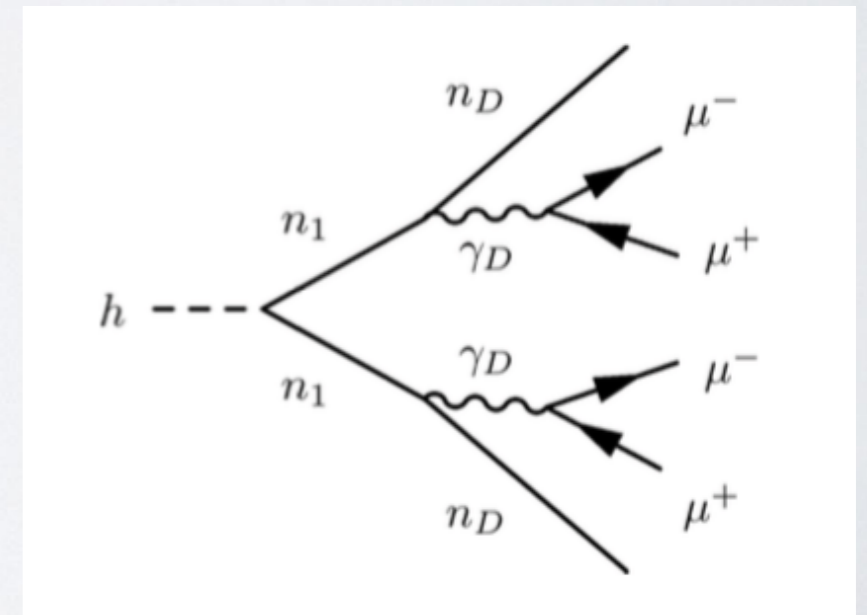
- Large inefficiencies at trigger level
 - the selection of close-by muon candidates, requires a separation of $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ between the two muon candidates
 - single muon p_T threshold ~ 20 GeV
 - most of the signal is between 10 and 20 GeV and fall in the same Region of Interest
- Phase II trigger
 - new muon sector logic and New Small Wheel and MDT trigger processors allow development of di-muon trigger within Region-of-Interest
 - reduce threshold to ~ 10 GeV
 - significant ($>10\%$) gain in trigger efficiency for close muons
- Investigating the possibility to use ML techniques at the trigger level
- Exploiting DNN capabilities to improve selection of dark photon decay to electrons/hadrons in hadronic calorimeter - [see Cristiano's talk](#)
- Sensitivity projections for HL-LHC will come soon



SEARCH FOR DIMUON PAIRS IN CMS (I)

13 TeV, 39.5/fb: CMS PAS HIG-18-003

- Search for pairs of muons with opposite-sign electric charge, dimuon production vertexes are allowed to be displaced
- **Benchmark models**
 - Next-to-Minimal Supersymmetric Standard Model (NMSSM)
 - neutral Higgs bosons $h_{1,2}$ decay to light boson a_1 ; the light boson a_1 subsequently decays to a pair of oppositely charged muons
 - Higgs mass between 90 and 150 GeV are simulated
 - light boson mass are simulated between 0.25 GeV and 3.55 GeV
 - Dark SUSY
 - the breaking of a new $U(1)$ symmetry gives rise to a massive dark photon γ_D that can couple to Standard Model particles via a small kinetic mixing ϵ with standard photons
 - Higgs boson mass and n_1 mass are fixed to 125 GeV and 10 GeV
 - dark photon masses are simulated between 0.25 GeV and 8.5 GeV



SEARCH FOR DIMUON PAIRS IN CMS (II)

13 TeV, 39.5/fb: CMS PAS HIG-18-003

• Selection

- trigger requires at least three reconstructed muons, one with $p_T > 15\text{GeV}$ and the other two with $p_T > 5\text{GeV}$
- reconstruction
 - based on Particle-Flow (PF) algorithm, which reconstructs the final-state particles using a global fit that combines the information from each subdetector
 - require exactly two dimuons constructed from pairs of oppositely charged muons that share a common vertex reconstructed using a Kalman Filtering technique
 - dimuon must have an invariant mass less than 9 GeV and masses should be consistent to within five times the detector resolution \rightarrow carve out a signal region in the two dimensional plane of the dimuon invariant masses

$$|m_{(\mu\mu)_1} - m_{(\mu\mu)_2}| < 0.13 + 0.065(m_{(\mu\mu)_1} + m_{(\mu\mu)_2})/2$$
 - require track isolation and at least one hit in pixel for each dimuon pair
- model independent search: ensured by verifying that the ratio of the full reconstruction efficiency over the generator level acceptance is independent of the signal model

m_{h_1} [GeV]	90	100	110	125	150
m_{a_1} [GeV]	2	0.5	3	1	0.75
ϵ_{Full} [%]	8.85 ± 0.06	13.23 ± 0.08	11.96 ± 0.07	14.68 ± 0.08	18.48 ± 0.09
α_{Gen} [%]	13.93 ± 0.08	20.47 ± 0.09	19.24 ± 0.09	23.59 ± 0.10	29.93 ± 0.10
$\epsilon_{\text{Full}}/\alpha_{\text{Gen}}$ [%]	63.52 ± 0.29	64.62 ± 0.24	62.19 ± 0.25	62.23 ± 0.22	61.73 ± 0.20

m_{γ_D} [GeV]	0.25			8.5		
$c\tau_{\gamma_D}$ [mm]	0	1	5	0	2	20
ϵ_{Full} [%]	9.12 ± 0.21	1.72 ± 0.06	0.12 ± 0.01	12.78 ± 0.12	12.25 ± 0.06	3.61 ± 0.02
α_{Gen} [%]	13.52 ± 0.25	2.85 ± 0.07	0.20 ± 0.01	20.49 ± 0.14	20.05 ± 0.08	6.16 ± 0.03
$\epsilon_{\text{Full}}/\alpha_{\text{Gen}}$ [%]	67.47 ± 0.91	60.2 ± 1.3	58.39 ± 2.0	62.36 ± 0.38	61.10 ± 0.21	58.70 ± 0.24

SEARCH FOR DIMUON PAIRS IN CMS (III)

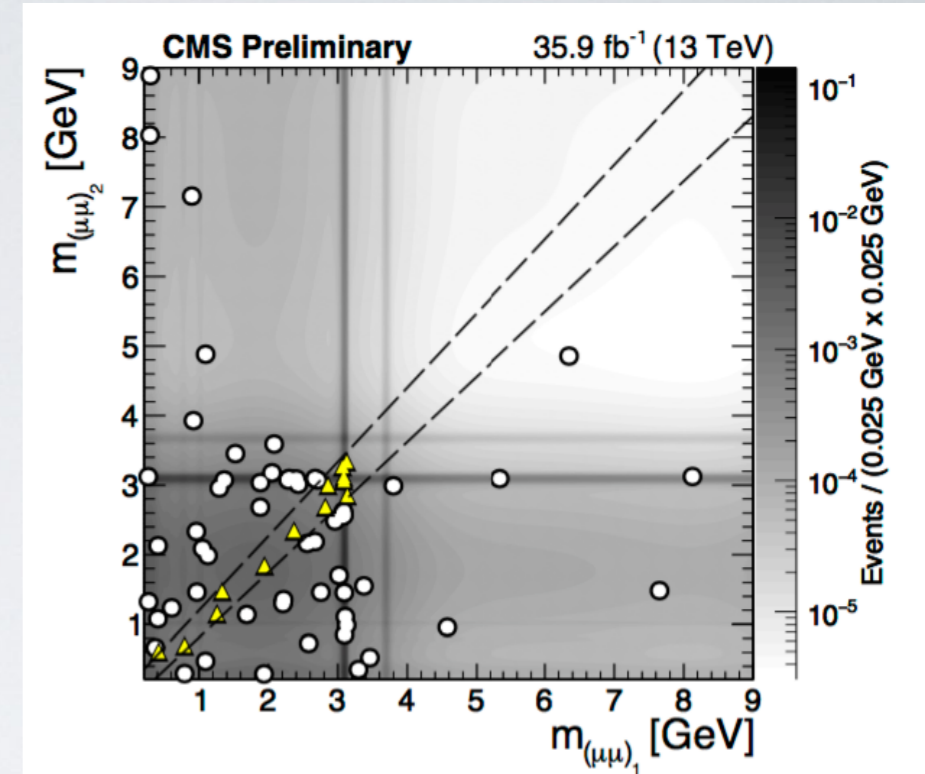
- Backgrounds

- SM background
 - b-quark pair production
 - estimated with data driven templates
 - prompt double J/ψ production
 - estimated from simulation

13 TeV, 39.5/fb: CMS PAS HIG-18-003

- Results

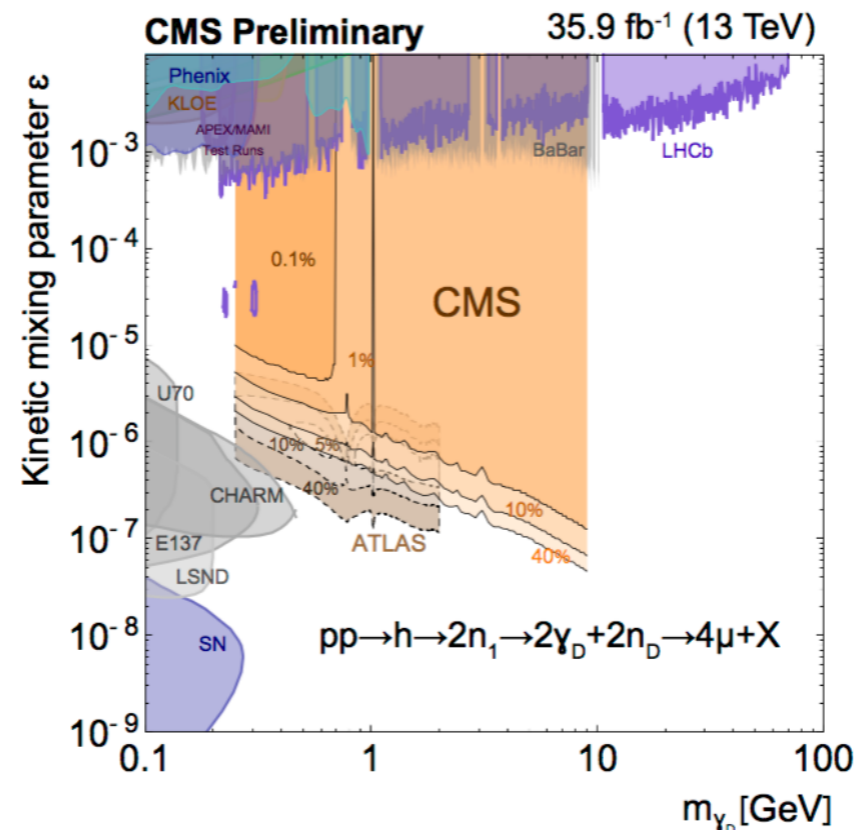
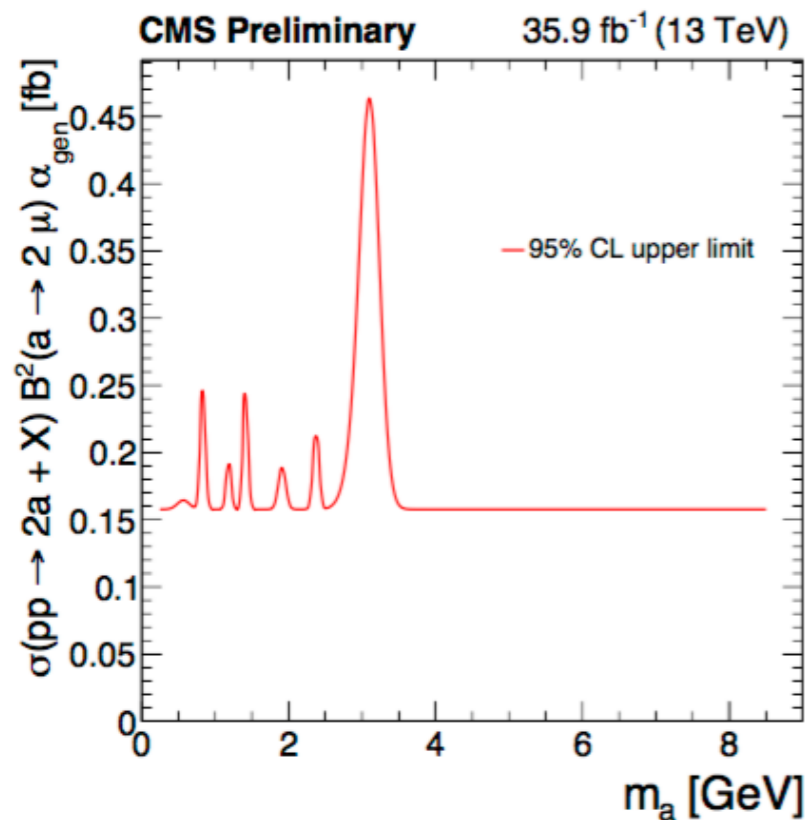
- background estimation in agreement with observation
- a model independent 95% CL upper limit on the product of the cross section, branching fraction, and acceptance is set over the mass range $0.25 < m_a < 8.5$ GeV.
- this model independent limit is then interpreted in the context of dark SUSY with non-negligible light boson lifetime and the NMSSM



- Plans

- Muon scouting: record data using muon triggers with much lower thresholds
- very limited amount of event information is recorded
- potential to improve reach for low mass dimuon resonances

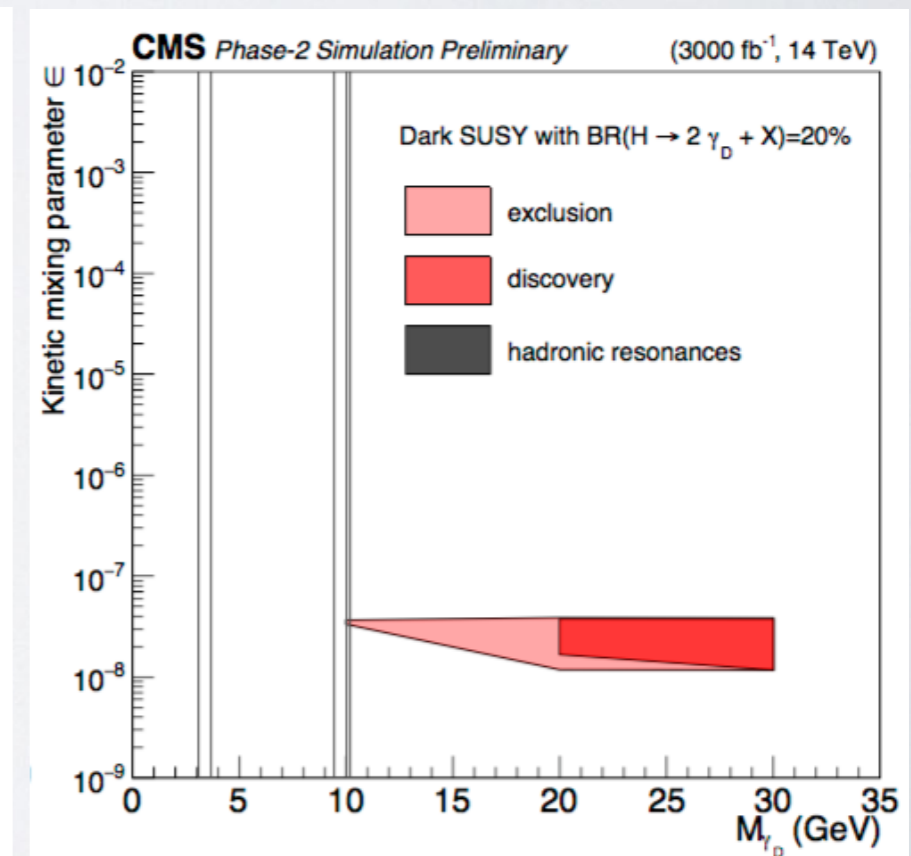
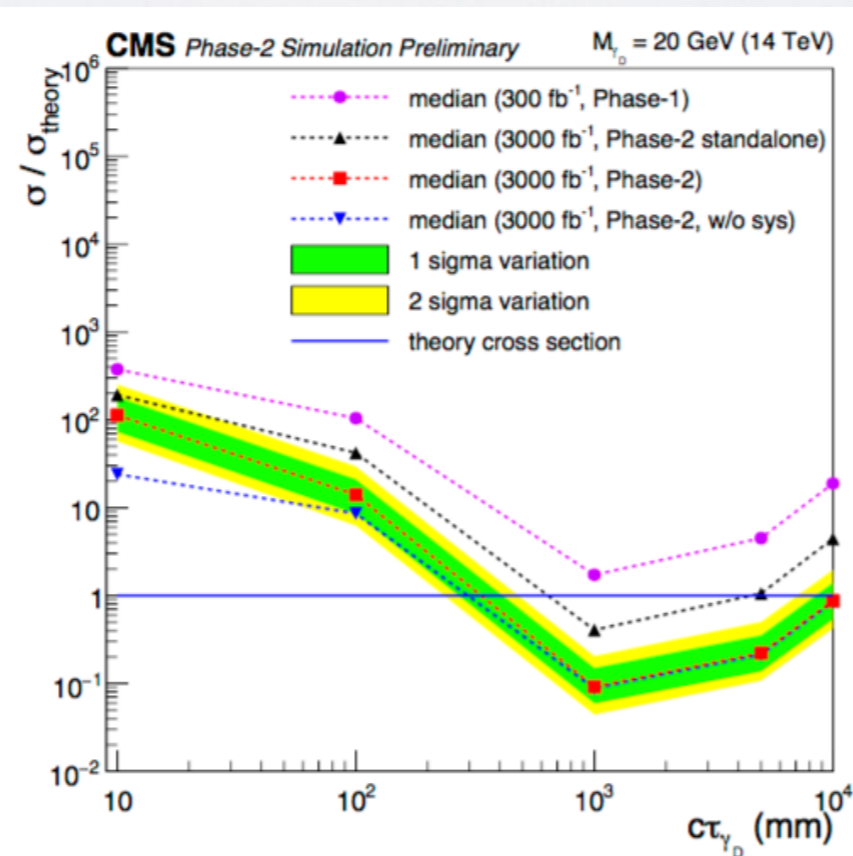
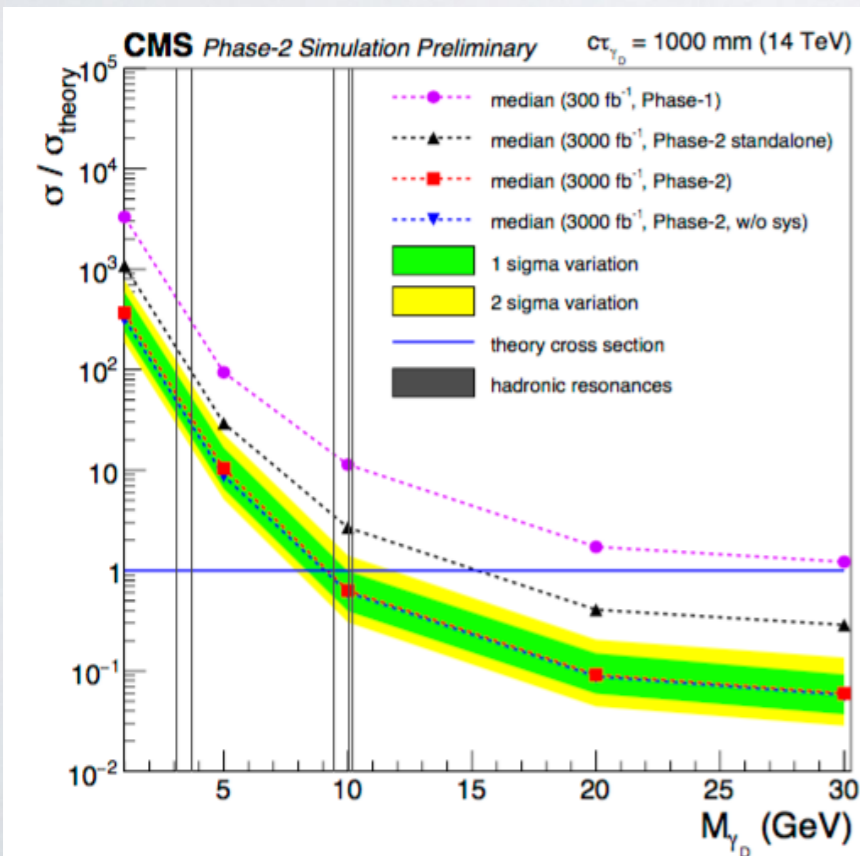
See Swagata's talk



CMS - UPGRADE/HL-LHC STUDIES

CMS PAS FTR-18-002

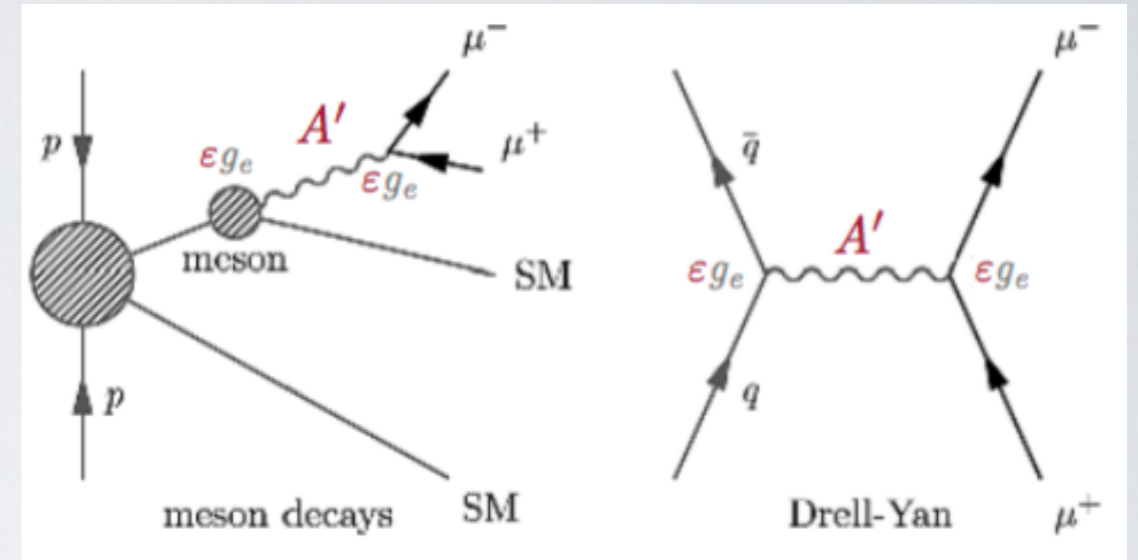
- New forward muon detectors to improve trigger
 - Trigger efficiency of 90% at LI for displaced muons up to 50 cm radial decay distance
- New tracking algorithms for displaced muons
 - Higher reconstruction efficiency for displaced algorithm (no vertex constraint)
- In the context of Dark SUSY model assuming 20% BR of Standard Model Higgs boson decay
 - 95% CL upper limits on production cross section $\sigma/\sigma_{\text{theory}}$ for various dark photon mass hypotheses and a fixed decay length of $c\tau = 1000$ mm and a fixed mass of 20 GeV as a function of the dark photon decay length
 - Ranges with exclusion and discovery sensitivity shown in light and dark red color in the m_{γ_D} - ϵ plane



SEARCH FOR DARK PHOTONS AT LHCb (I)

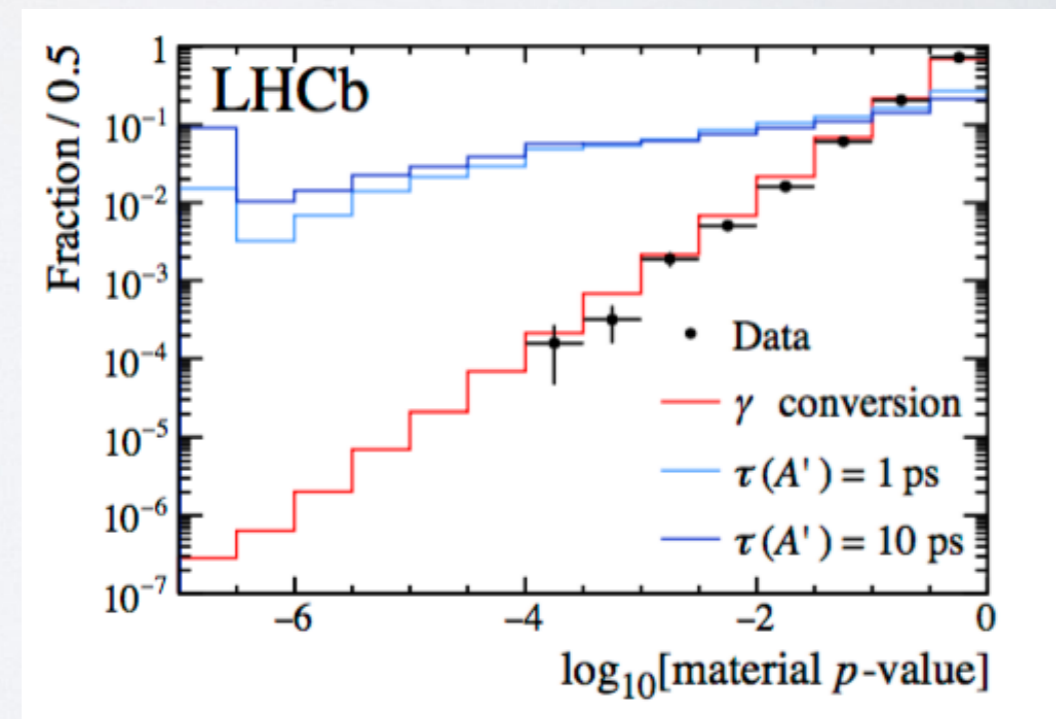
13 TeV, 1.6/fb: Phys. Rev. Lett. 120, 061801

- Inclusive search for $pp \rightarrow XA' \rightarrow \mu\mu$, muon pair production vertexes are allowed to be displaced
- Massive dark photon A' can couple to Standard Model particles via a small kinetic mixing ϵ with standard photon
- Selection
 - trigger
 - require two oppositely charged tracks that form a good quality vertex and satisfy stringent muon-identification criteria
 - muons are required to have $2 < \eta < 4.5$, $p_T > 0.5$ GeV, and be inconsistent (consistent) with originating from the PV in the long-lived (promptlike) A' search



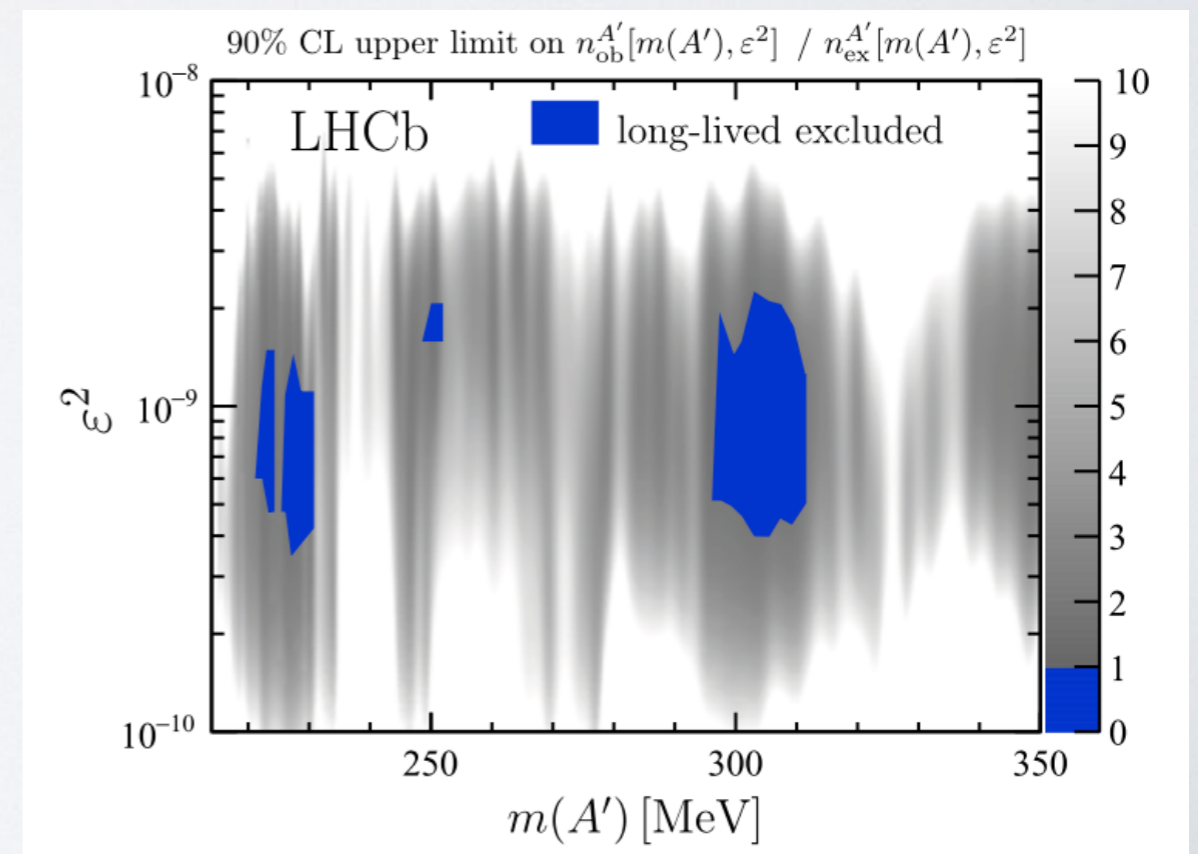
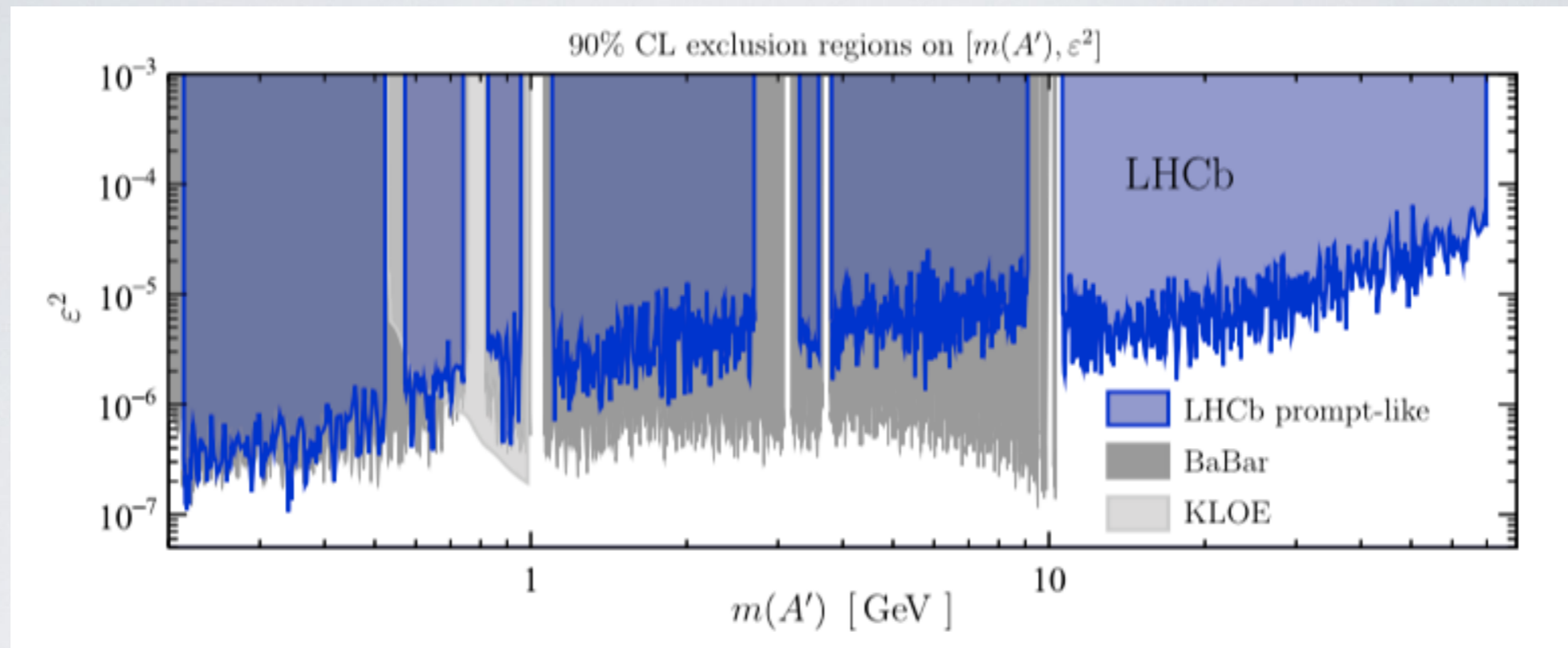
Background

- photon conversions in VELO material
 - a high-precision three-dimensional material map used to assign a p value to the photon-conversion hypothesis for each long-lived A' candidate
- 2 semileptonic b hadrons decays
 - isolation BDTs (from $B_s \rightarrow \mu\mu$)
- double misID $K \rightarrow \pi\pi$ decays
 - modelled from PID sideband



SEARCH FOR DARK PHOTONS AT LHCb (II)

13 TeV, 1.6/fb: Phys. Rev. Lett. 120, 061801



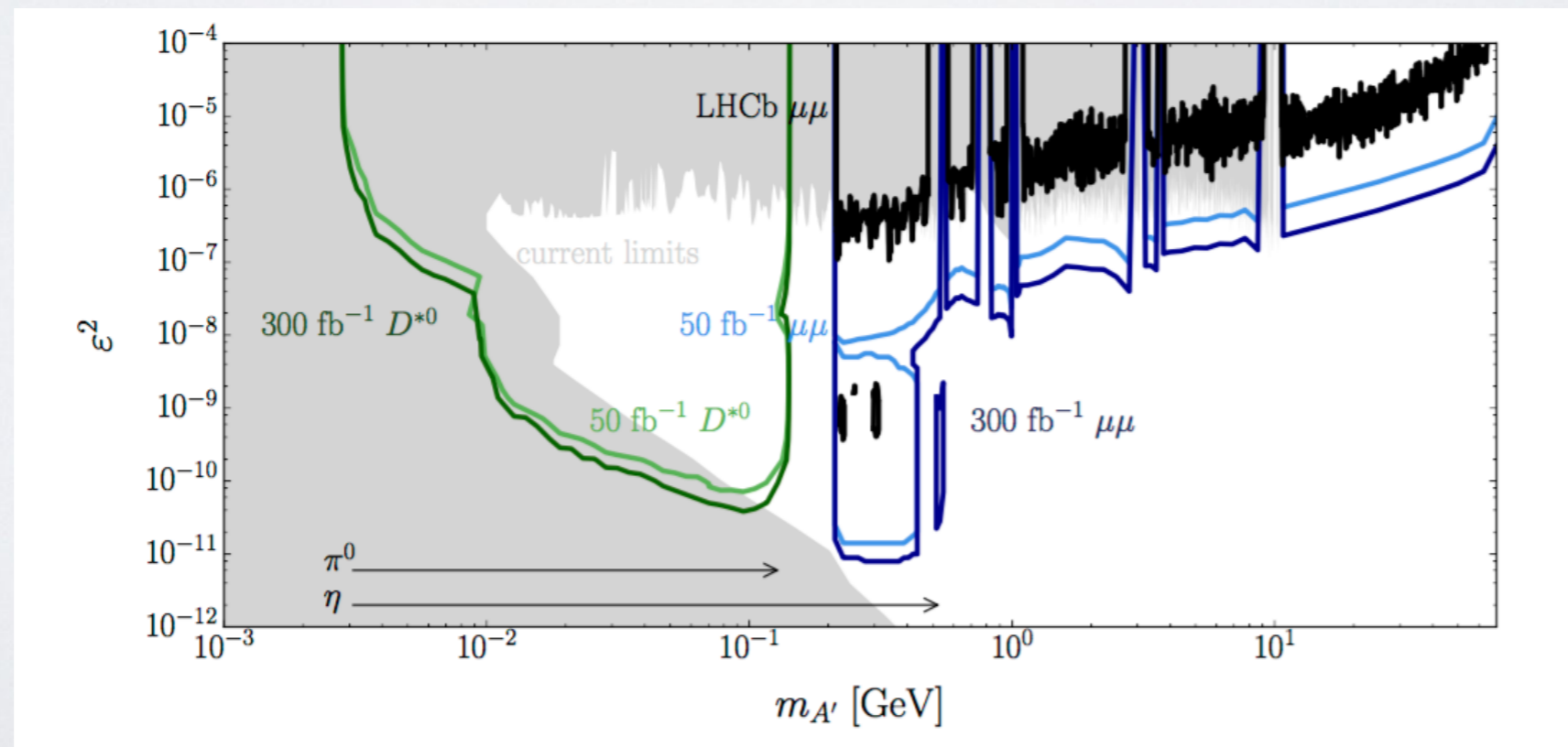
• Results and plans

- scan of dimuon invariant mass
- fit to the mass distribution to get long-lived A' signal yield
- no significant excess found
- sensitivity to long lived A'
 - small region excluded but large region (a factor 100 to 1000) is within reach in Run 3

LHCb - UPGRADE/HL-LHC STUDIES

ArXiv:1808.08865

- Upgraded trigger, tracker and VELO
- Fully software L0 trigger
 - Huge improvements expected for low mass searches
 - Develop dedicated lines for displaced jets, di-muons and di-electrons
- Exploit tracking capabilities
 - Trigger on **downstream tracks** → better for light LLP signatures
 - New tracker for **upstream tracks (UT)** – high granularity, closer to beam pipe
 - Proposal to add magnet stations (MS) inside the magnet → improve low p acceptance
- Phase 2 VERtex Locator
 - Access to shorter lifetimes, better PV and IP resolution, and real-time alignment
 - Better knowledge of material interactions (dedicated material veto map)



NEW DETECTORS FOR LHC (I)

Not a complete list!

- LLP searches that will be difficult at main LHC detectors
- Proposed detectors show some complementarity, covering a wide mass range and different physics scales

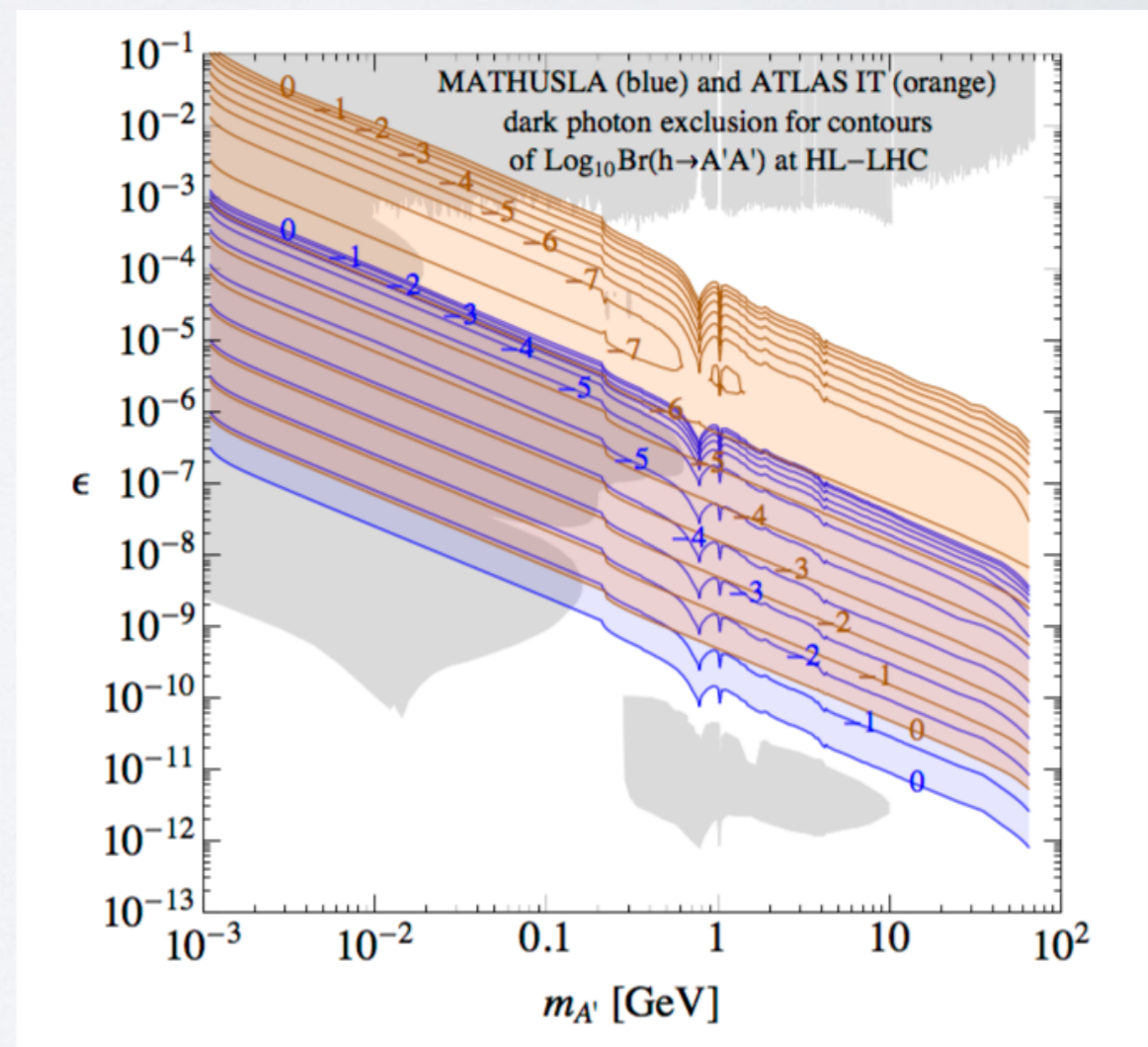
Dark photons
from exotic Higgs decays

- **MATHUSLA**

- surface detector

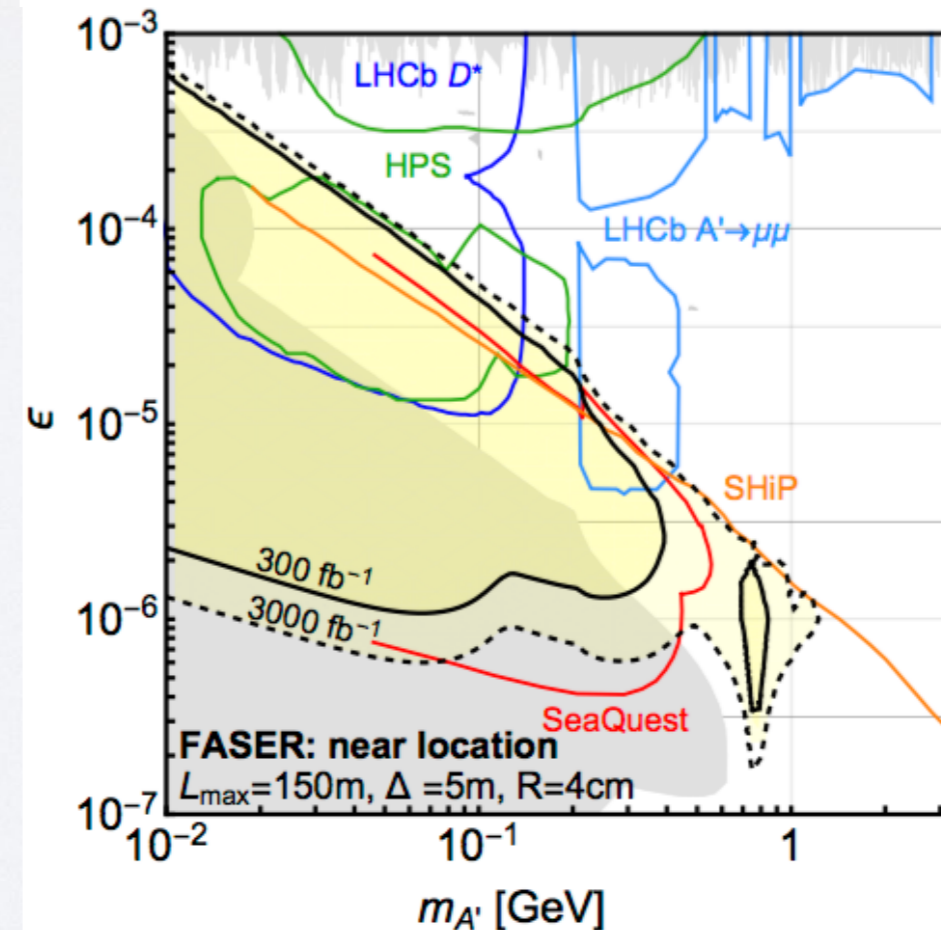
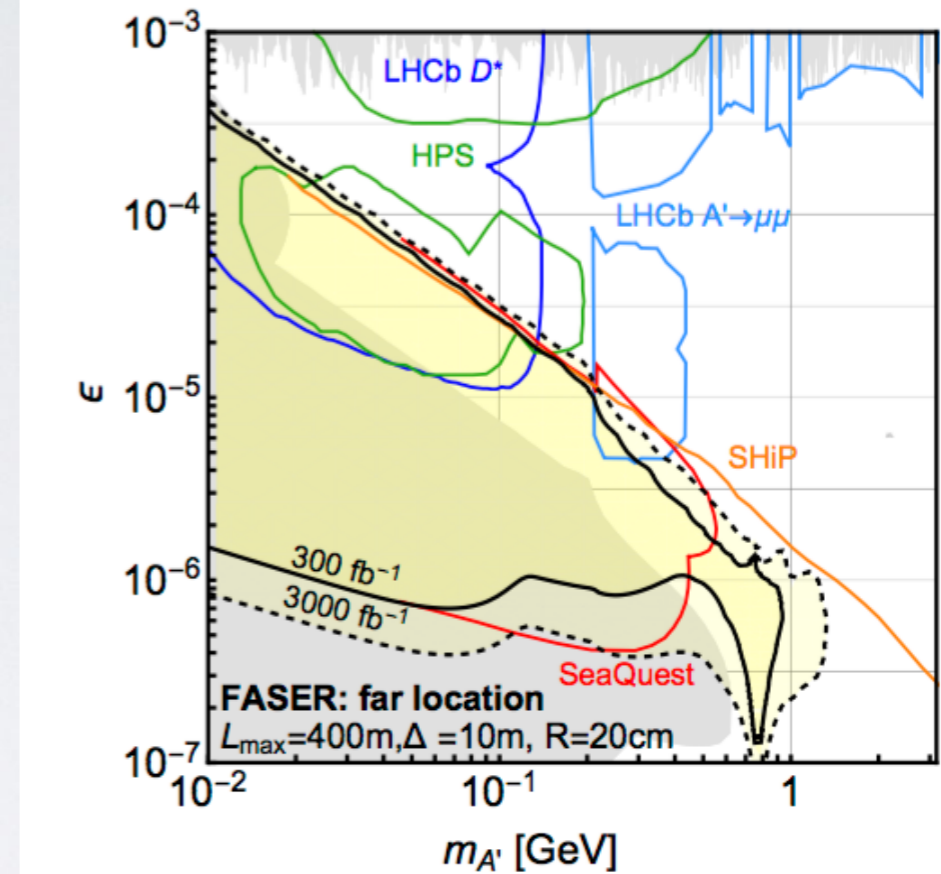
- **FASER**

- On-axis, 150 and 400 m from IP



NEW DETECTORS FOR LHC (II)

- MATHUSLA
 - surface detector
- **FASER**
 - On-axis, 150 and 400 m from IP
 - Rapid timescale



SUMMARY

- Lack of evidence of new physics in “standard” searches at LHC → unconventional signatures are gaining in interest
- Dark photons are an intriguing possibility to discover new physics
- Several searches carried out at the main LHC detectors
 - very challenging (trigger and reconstruction), pushing the detectors for searches not accounted at the moment of their design
- Not discovery so far, but 2017+2018 data are waiting to be analysed and analysis teams are working on improvements developing new analysis techniques to cover as much phase space as possible, and already looking forward to upgrade and HL-LHC phases
- New proposed detectors for LHC aim to cover LLP searches that are difficult at LHC main detectors exploring as much phase space as possible
- Very interesting possibilities in non-LHC experiments

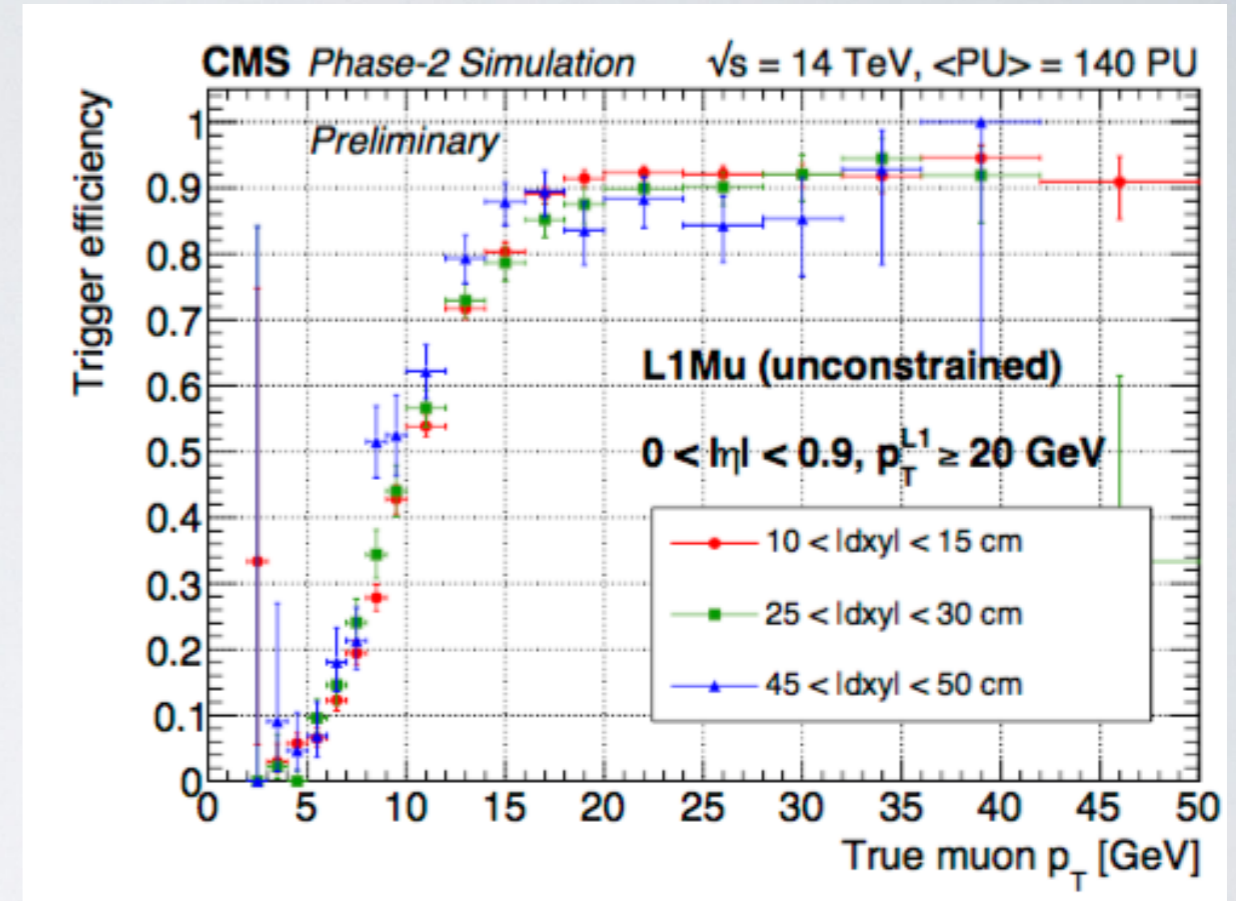


**Nice review
in Gaia's talk**

BACKUP

CMS - UPGRADE/HL-LHC STUDIES

- New forward muon detectors to improve trigger
 - Trigger efficiency of 90% at L1 for displaced muons



- New tracking algorithms for displaced muons
 - Higher reconstruction efficiency for displaced algorithm (no vertex constraint)

