Search for light long-lived neutral particles produced in pp collisions at $\sqrt{s}$ = 13 TeV that decays to collimated pairs of leptons or light hadrons with the ATLAS detector

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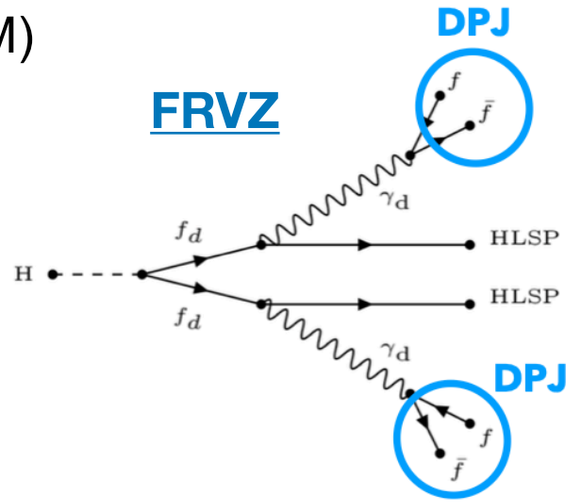
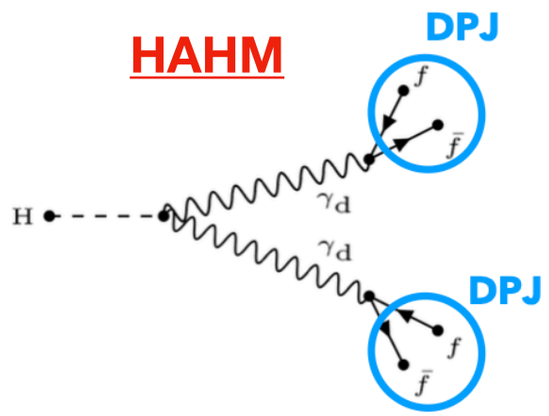
on behalf of the ATLAS collaboration

Theory introduction

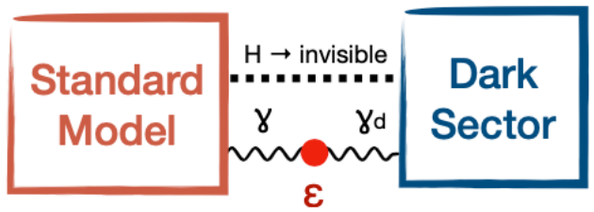
- Dark sector weakly coupled to the Standard Model (SM)
- Dark Photon (γ_D) from Higgs portal, decaying through vector portal to leptons or light hadrons
- Investigate gluon-gluon Fusion (ggF) and Higgs associated production with a W boson (WH)

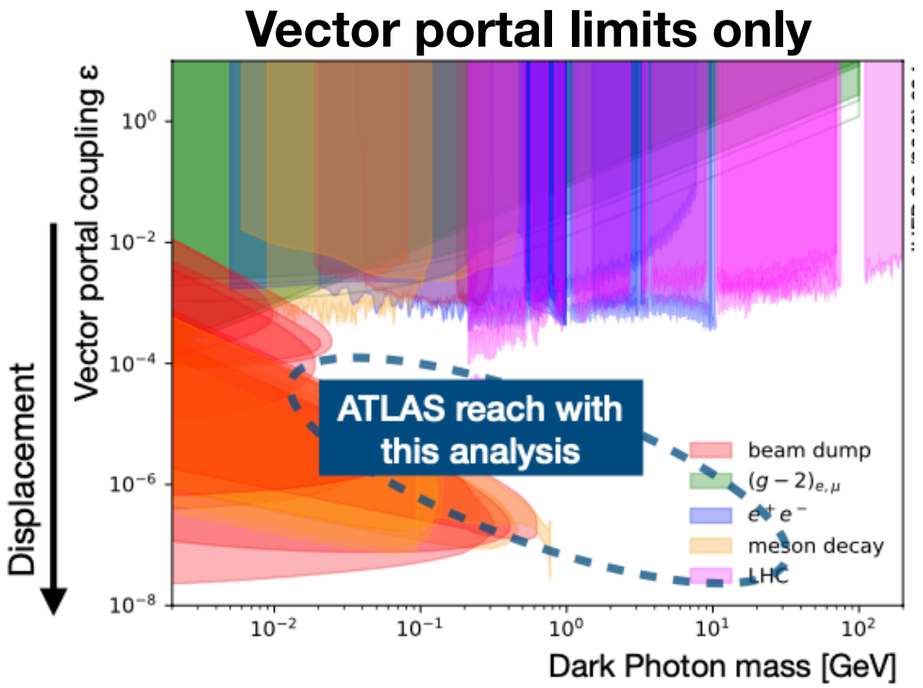




$$Dark - QED\ U(1)$$
$$\mathcal{L} \propto \epsilon e \gamma_d^{\mu} J_{\mu}^{em}$$

$$c\tau = \frac{1}{\Gamma_{\gamma_d}^{tot}} \propto \frac{1}{\epsilon^2 m_{\gamma_d}}$$

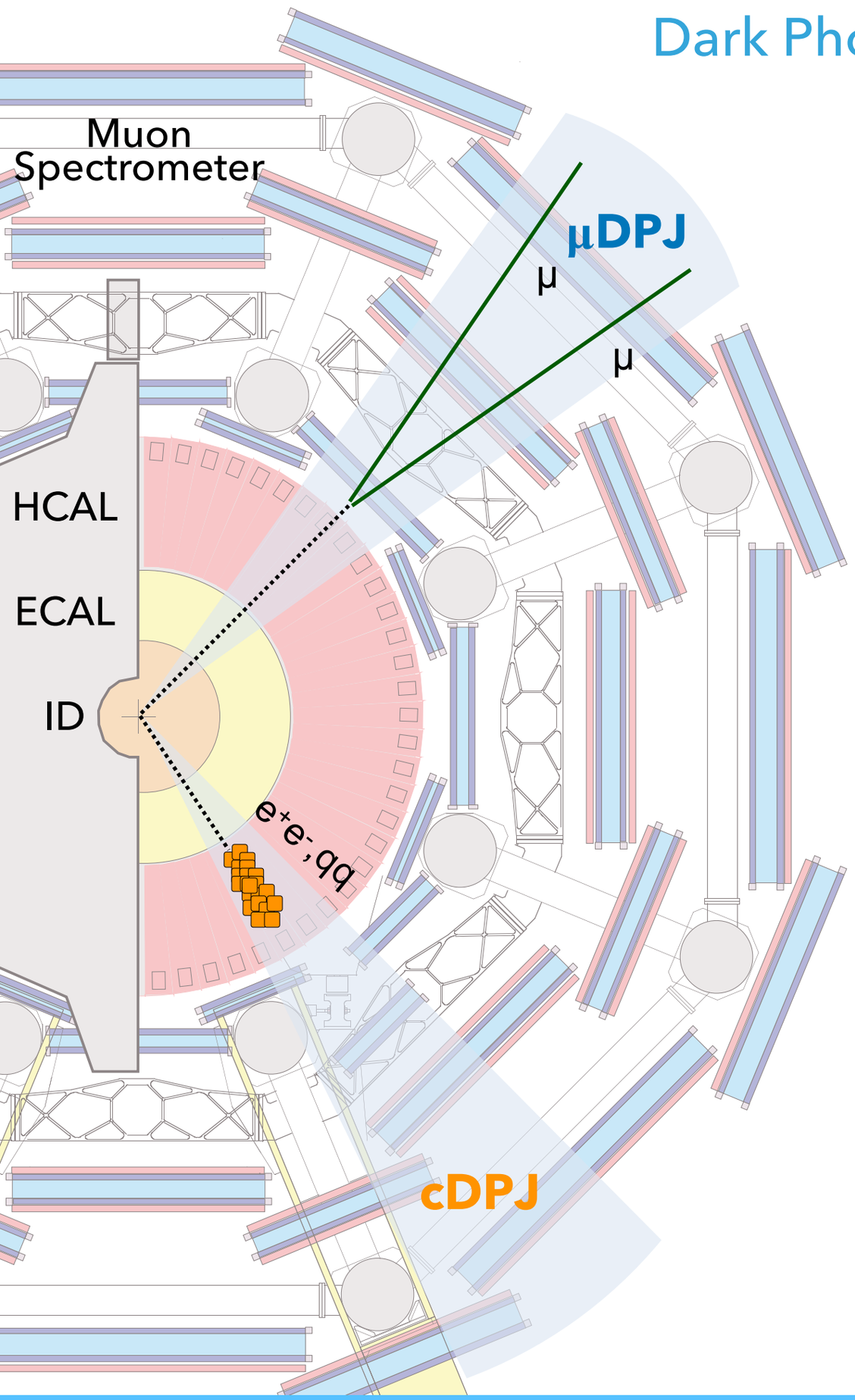


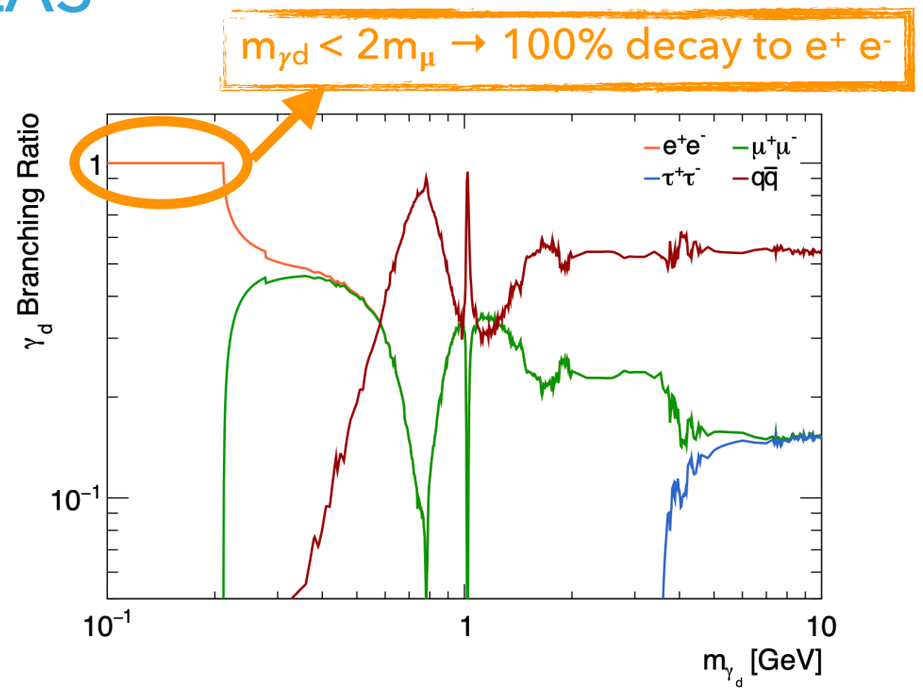


- ε = coupling parameter between SM and Hidden Sector
- **Small $\varepsilon \rightarrow$ long lived γ_d**
- **Light and boosted LLP → Collimated pair of leptons/ hadrons: "Dark Photon Jets" (DPJ)**
- 10 MeV ≲ m(γ_d) ≲ 10 GeV → collimated decay
- SM-like Higgs decaying to 2γ_d (H→ 2γ_d +X)
- Investigating also:
  - Heavy scalar ($m_{H'}$ = 800 GeV)
  - Decays involving more than two dark photons

ATLAS BR(H→undet) upper limit is 19% leaves room for Higgs exotics decays

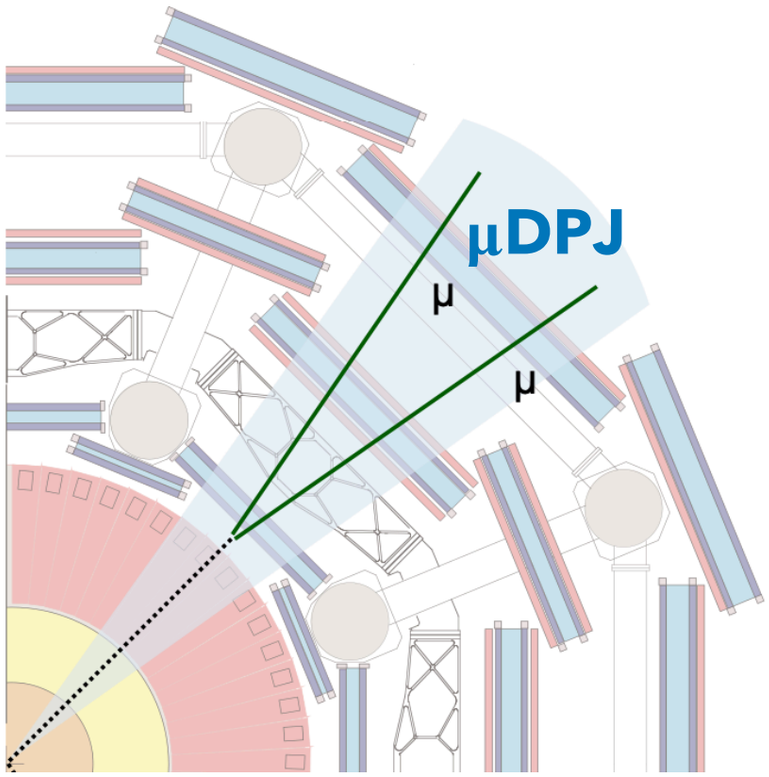
Dark Photon Jets in ATLAS



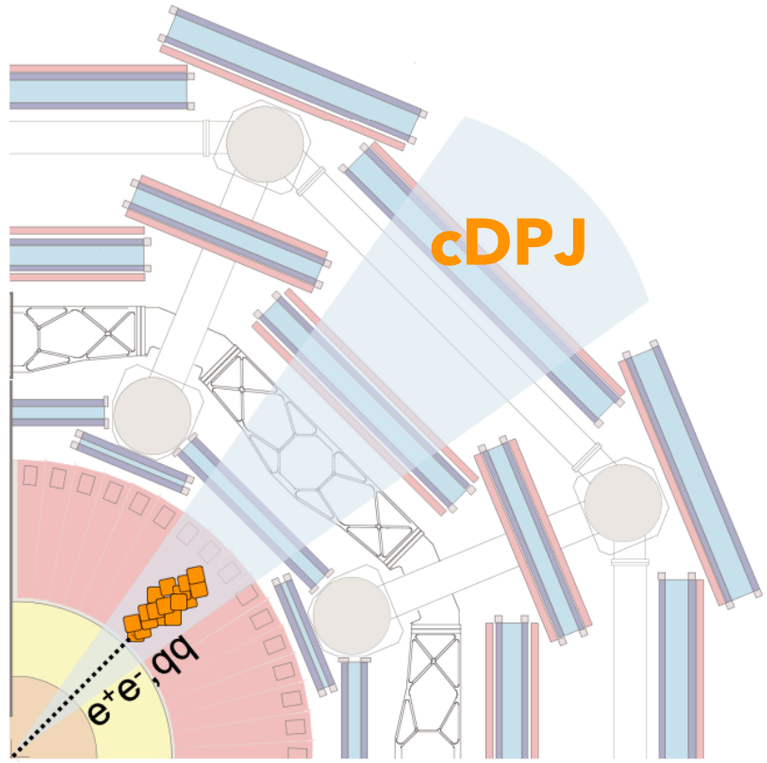


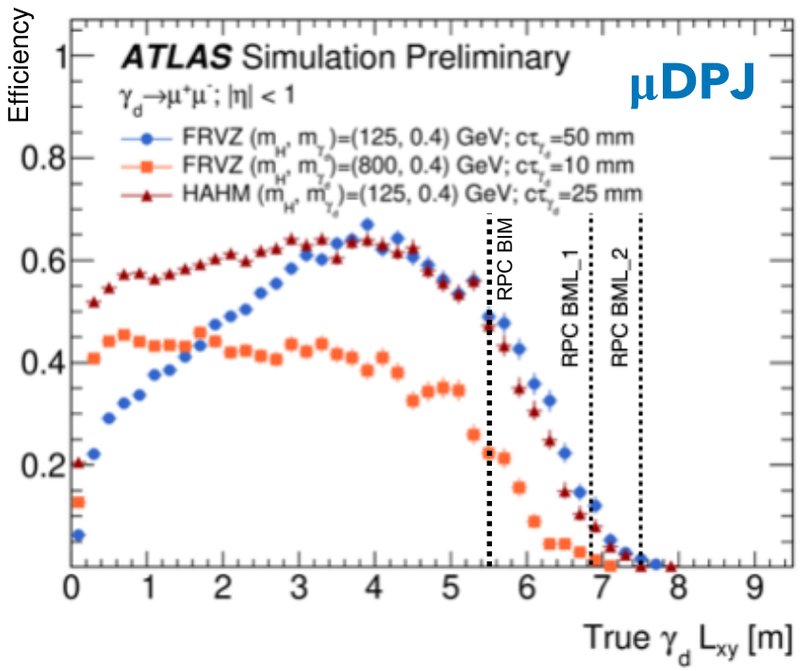
- **μDPJ**:
  - Collimated muon bundle in the Muon Spectrometer (MS) with no matching jets and tracks in the inner detector
  - Close-by muons, reconstructed using a Cambridge-Aachen clustering algorithm that combines all the muons lying within a $\Delta R = 0.4$ cone in (η, ϕ) space
  - Main background: cosmic-ray muons
- **cDPJ**:
  - Resulting from γ_d decaying to electrons or light hadrons
  - Low Electromagnetic Fraction jets, without associated tracks in the Inner Detector (ID) and narrower than ordinary jets
  - Targeting γ_d decaying in the HCAL: cDPJ reconstructed with anti-k_T R=0.4 algorithm
  - Main background: rare multijet events, LHC Beam losses

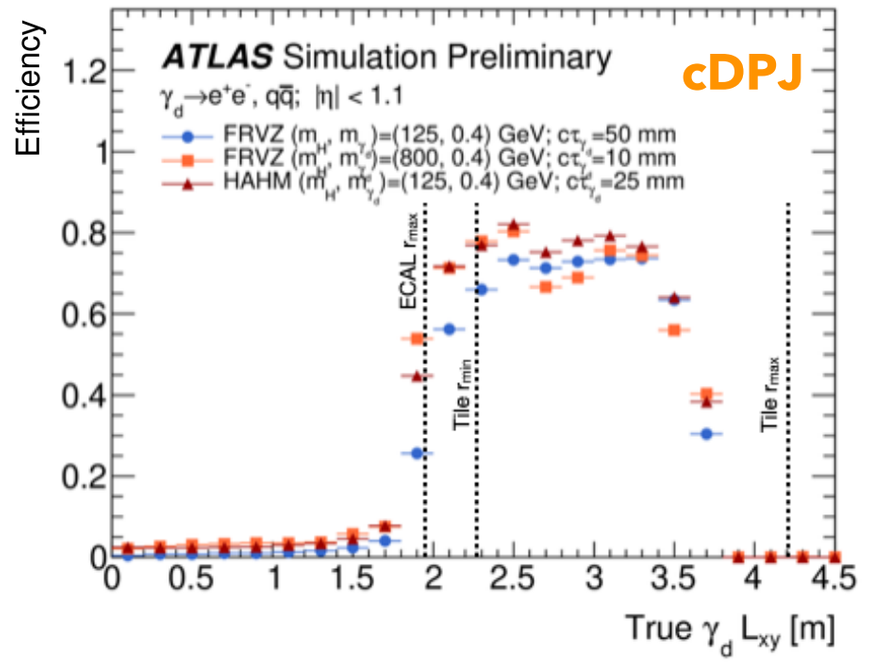
DPJ Reconstruction



- DPJ reconstruction efficiency in few benchmark signal scenarios
- **μ**DPJ:
  - Drop in efficiency expected for γ_d decaying after MS middle layer (~6m in Barrel region)
- cDPJ:
  - γ_d decaying to hadrons and electrons reconstructed within HCAL volume (2.2m-4.2m in Barrel region)



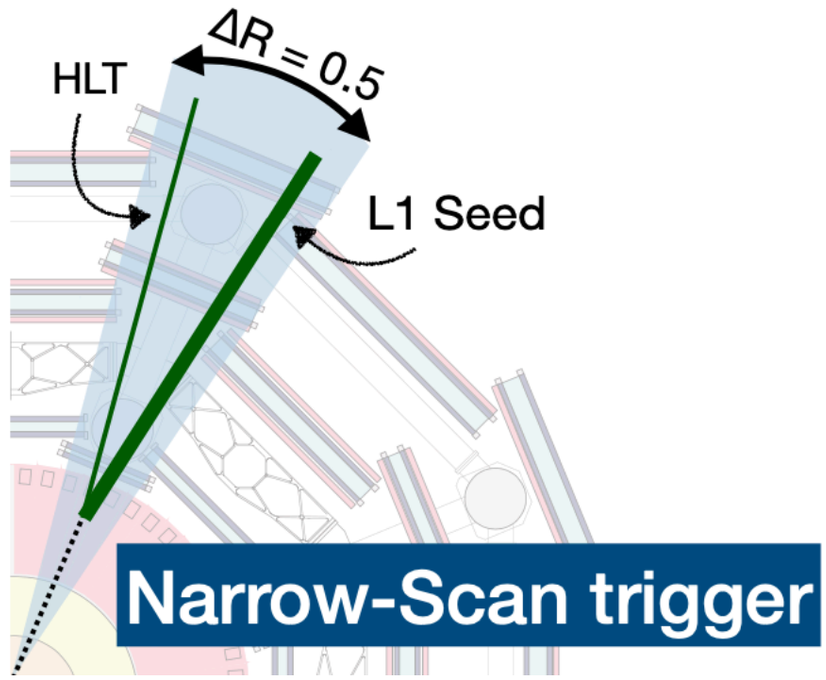


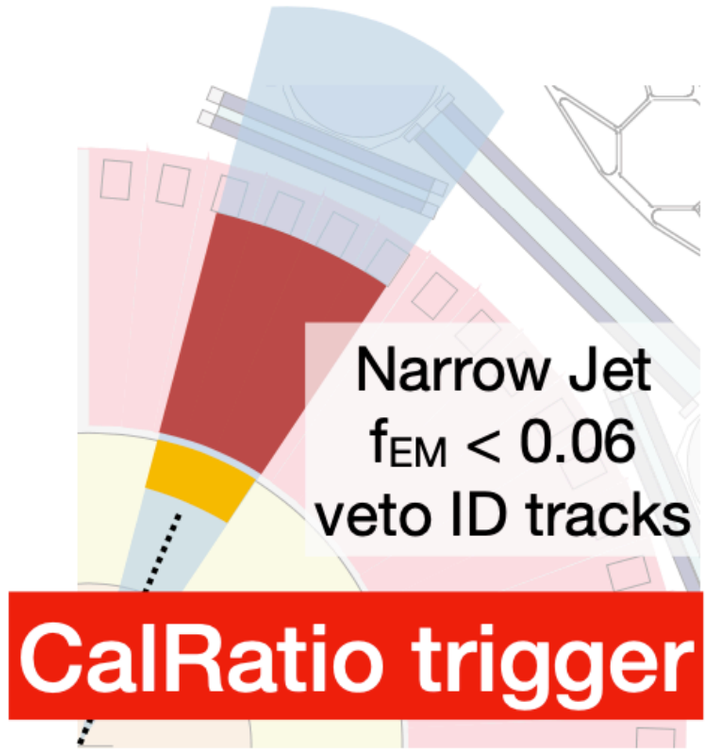


Analysis triggers

+ Multi-muon triggers

- Different triggers for WH and ggF categories:
- ggF: dedicated LLP triggers
  - Narrow-Scan trigger:
    - Based on MS informations, muon candidate at L1 trigger + HLT ‘scan’ for a second muon in $\Delta R = 0.5$ from the L1 muon
    - Both muons required to be not matched to any track in the ID
  - CalRatio:
    - Narrow jets from the HCAL
    - Cuts on transverse energy and jet isolation (veto on ID tracks around the jet axis)
    - Cut on Electromagnetic Fraction of jet energy: $f_{EM} = E_{Ecal}/E_{Hcal}$
- WH:
  - Trigger on lepton from W boson decay
  - “standard” single lepton triggers (e / μ)





Analysis strategy

- Two Higgs boson production channels:
- Per DPJ type & number selection involving specific cuts on DPJ constituents (**μ** / jets)
- **Six orthogonal channels:**
  - **ggF**: 2**μ**DPJ, **μ**DPJ-cDPJ, 2cDPJ
  - **WH:** 1cDPJ, **μ**DPJ-cDPJ, 2cDPJ
    - focus on decays involving cDPJs (competitive with ggF)

- **Neural Networs taggers for background rejection** →

- Main discriminant variables:
  - Taggers score
  - Angular distance between DPJs
  - DPJ isolation in the Inner Detector

- **Background estimate**:
  - Fully data-driven background estimate (ABCD method) →

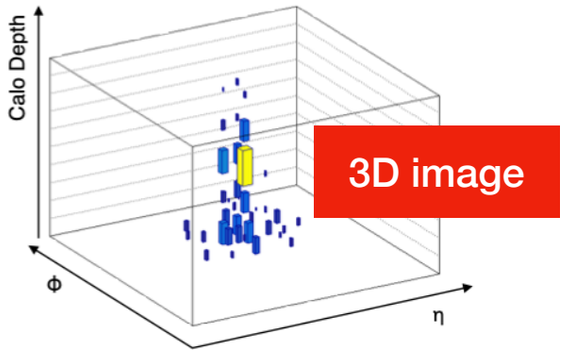
- **ggF category**:
  - Dedicated LLP triggers
  - Prompt lepton veto (ortogonality with WH)
- **WH category**:
  - Triggering on prompt lepton from *W* decay
  - Preselection with missing transverse energy (E_T^{miss}) and transverse mass (m_T) cuts

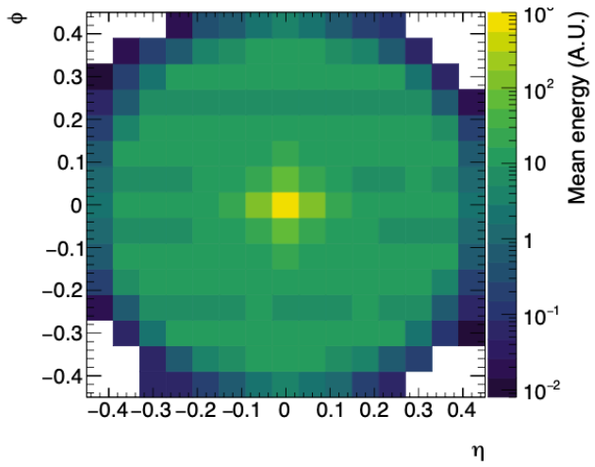
- Main background:
  - hadronic jets from multijet and V+Jets (punch through, rare events)
- Other backgrounds:
  - LHC beam losses: Beam Induced Background
  - Cosmic-ray muons

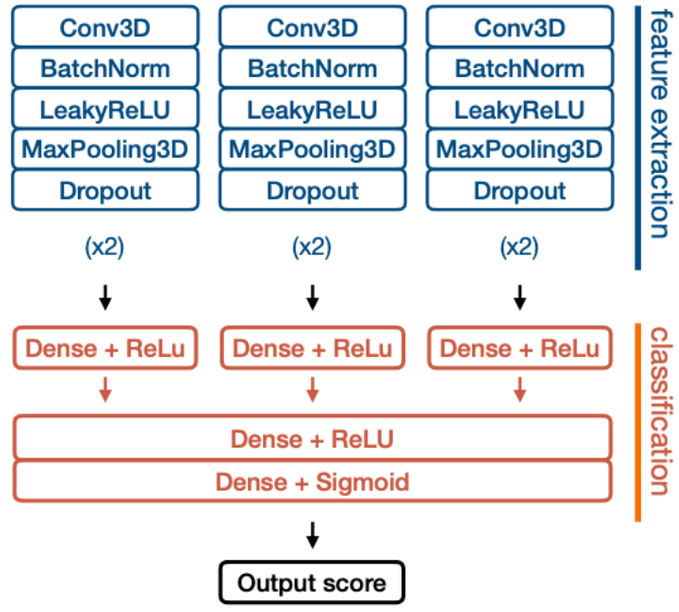
- Background events factorised in the plane of two uncorrelated variables
- Plane subdivided in four regions: A,B,C,D
- A = SR, $N_A = N_B \times N_D / N_C$

QCD Tagger

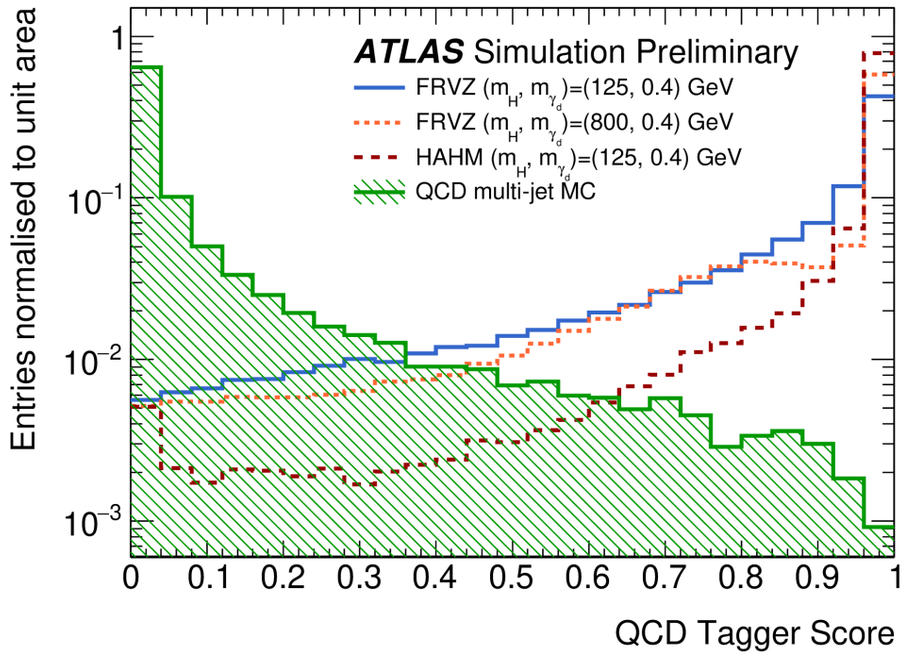
- Huge hadronic jets background (from multijet and V+Jets)
- **Per-Jet Convolutional Neural Network tagger exploiting 3D images**
  - Inputs: angular direction and calorimeter cluster information
  - One of the first use in ATLAS searches of a CNN based on low-level inputs





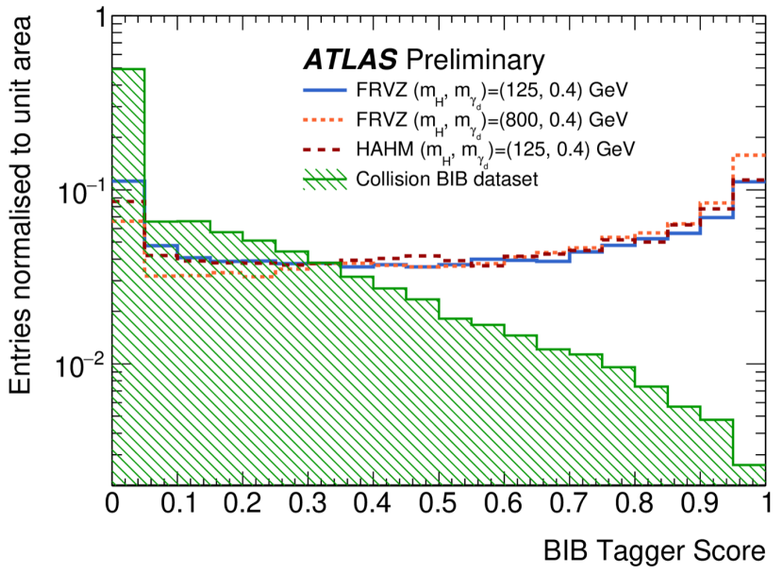


- Tagger trained on simulated SM hadronic jets and jets from dark photon decay
- Trained to output 1 for signal and 0 for backgorund jets

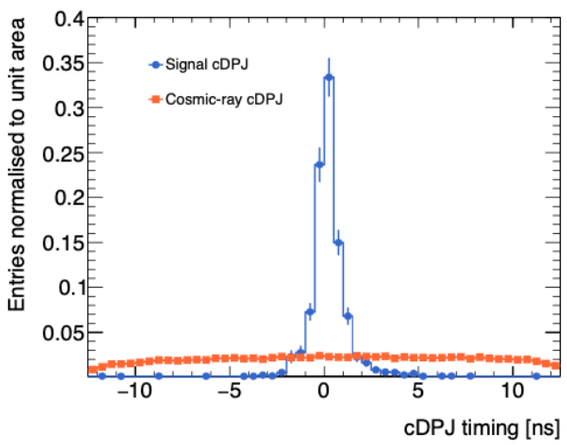


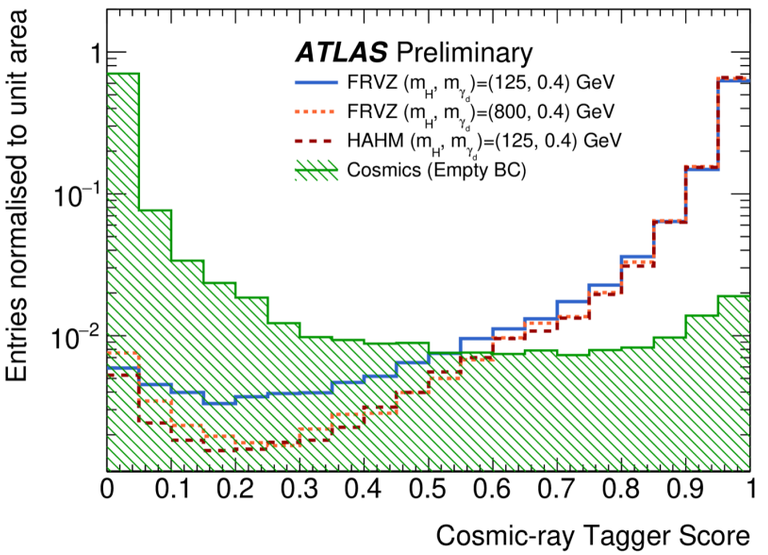
BIB tagger and Cosmic-ray muons tagger

- **Beam Induced Backgorund (BIB)**:
  - Highly penetrating particles from LHC beam losses → fake cDPJ
  - Can't use tight jet cleaning → poor signal efficiency
  - Instead use Jet images: training on signal samples and data-driven BIB sample
  - BIB rejection: BIB tagger score + timing & $|\Delta\phi_{\mathrm{DPJ}}|$ cuts



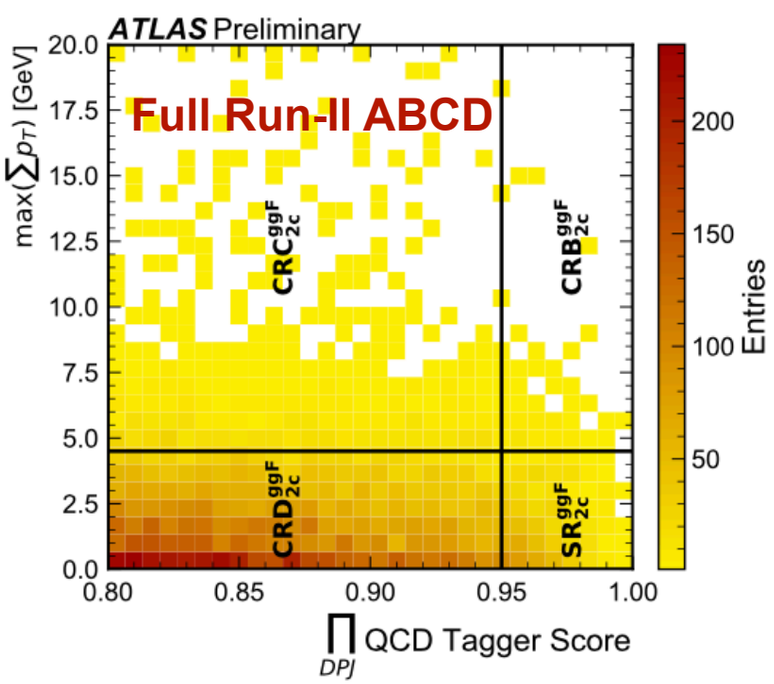
- **Cosmic-ray muons**:
  - Can yield both fake μDPJ and cDPJ
  - cPDJ: cut on jet timing
  - μDPJ: per-muon Deep Neural Network tagger
    - Inputs: timing, angular direction and impact parameter info
  - Residual cosmic-ray contribution subtracted in ABCD

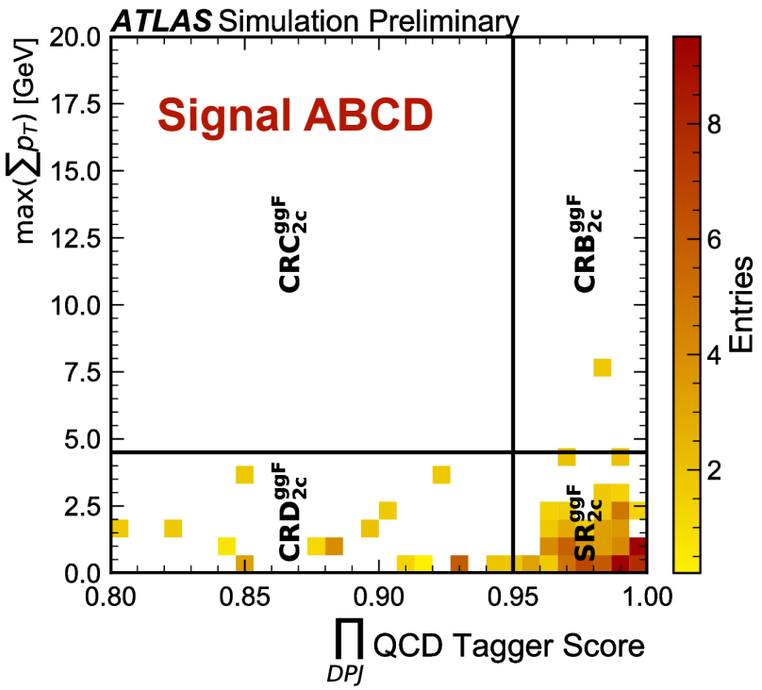




Background estimation

- ABCD method: the number of events in the signal region are estimated as: $N_A = N_B \times N_D / N_C$
- Possible signal leakage outside SR accounted for: simultaneous fit of signal and background events
- No significant contribution from beam induced background
- Minor residual contribution from cosmic-ray background → subtracted
- Multiple validation regions show nice closure of the ABCD method
- ABCD plane variables:
  - max(Σp_T): defined as the maximum, between DPJs, of the scalar-sum of the inner detector tracks in a $\Delta R=0.4$ cone around the DPJ
  - Π(QCD Tagger) is computed among all caloDPJ in the event
  - min($\Delta\phi$) is the minimum distance between DPJ and E_T^{miss} method
  - min(QCD Tagger) is computed between the caloDPJ considered for the selection





Signal regions selection

ggF category

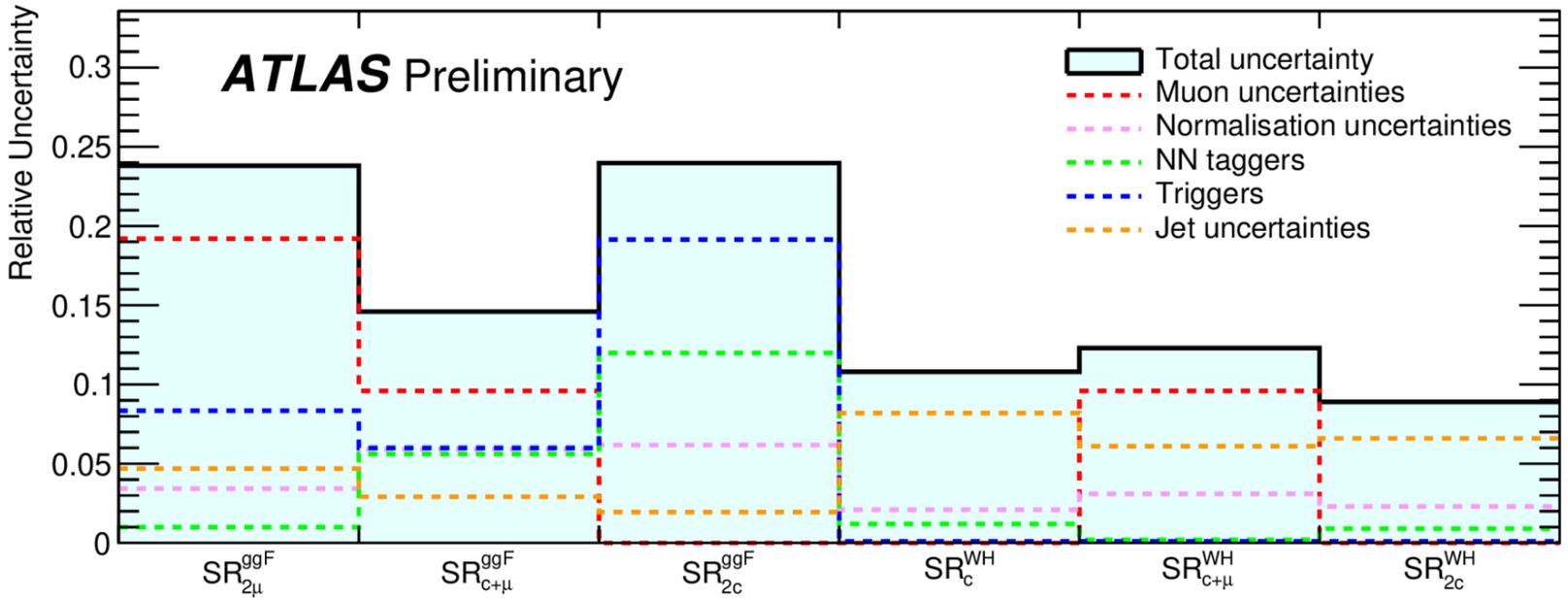
Requirement / Region	$SR_{2\mu}^{ggF}$	SR_{2c}^{ggF}	$SR_{c+\mu}^{ggF}$
Number of μDPJs	2	0	1
Number of caloDPJs	0	2	1
Tri-muon MS-only trigger	yes	-	-
Muon narrow-scan trigger	yes	-	yes
CalRatio trigger	-	yes	-
$\lvert\Delta t_{\text{caloDPJs}}\rvert$ [ns]	-	< 2.5	-
caloDPJ JVT	-	< 0.4	-
$\Delta\phi_{\text{DPJ}}$	$> \pi/5$	$> \pi/5$	$> \pi/5$
BIB tagger score	-	> 0.2	> 0.2
$\max(\sum p_{\text{T}})$ [GeV]	< 4.5	< 4.5	< 4.5
$\prod$ QCD tagger	-	> 0.95	> 0.9

WH category

Requirement / Region	SR_{c}^{WH}	SR_{2c}^{WH}	$SR_{c+\mu}^{WH}$
Number of μDPJs	0	0	1
Number of caloDPJs	1	2	1
Single-lepton trigger (μ, e)	yes	yes	yes
m_{T} [GeV]	> 120	-	-
$\lvert t_{\text{caloDPJ}}\rvert$ [ns]	< 4	< 4	< 4
Leading (far) caloDPJ width	< 0.08	< 0.10 (0.15)	< 0.1
caloDPJ p_{T} [GeV]	> 30	-	-
JVT	< 0.6	< 0.6	< 0.6
$\min(\Delta\phi)$	$< 3\pi/5$	$< 3\pi/10$	$< 7\pi/20$
min(QCD tagger)	> 0.99	> 0.91	> 0.9

Uncertaintites

- Data-driven background estimation: systematic uncertainty on the ABCD method, obtained by propagating the stat uncertainties of CRs
- Leading experimental systematics:
  - ggF: Muon and Trigger uncertainties
  - WH: Muon and Jet uncertainties
- The overall uncertainty in the SR yields is dominated by the statistical uncertainty



Residual background estimation: post fit

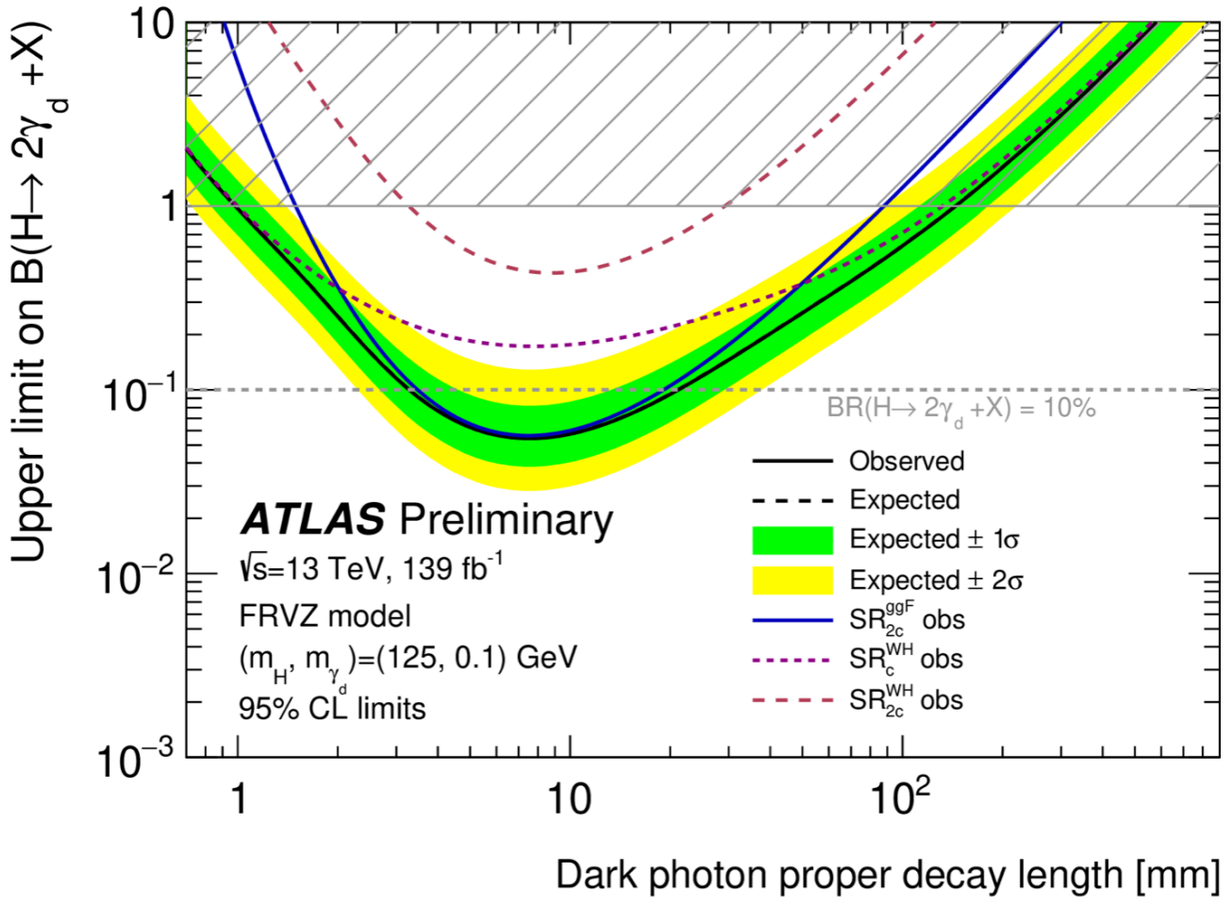
- Simultaneous SR+CR fit of the ABCD plane, including the ABCD ansatz with nuisance parameters
- Pre-fit estimates well compatible within 1σ
- Unblinded result show no excess with respect to the expected background, limits are set for the FRVZ and HAHM models

Selection	Search channel	CRB	CRC	CRD	SR expected	SR observed
ggF	2μ	55	61	389	317 ± 47	269
	c+μ	169	471	301	108 ± 13	110
	2c	97	1113	12146	1055 ± 82	1045
WH	c	1850	3011	155	93 ± 12	103
	c+μ	30	49	31	19 ± 8	20
	2c	79	155	27	14 ± 5	15

Exclusion limits I

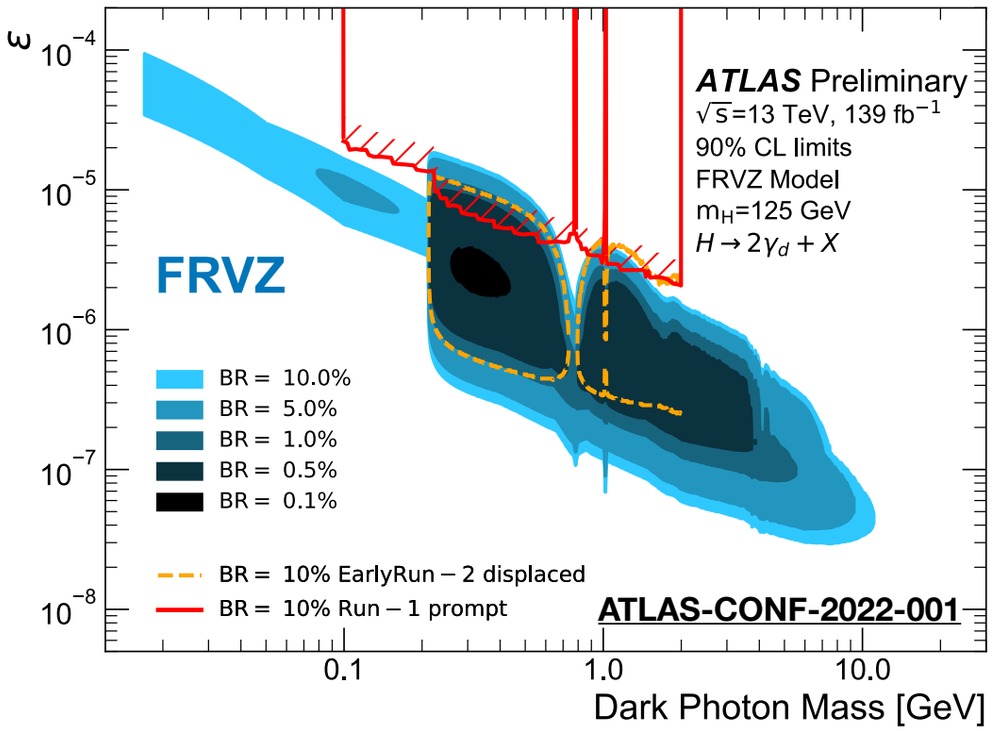
- Upper limit on the signal strength are obtained with the CL_s method using the asymptotic calculator
- Limits obtained for a given dark-photon $c\tau$ are extrapolated to other $c\tau$ with a lifetime reweighting method
- Limits as function of the dark photon mass are obtained interpolating between the available signal mass points, following the SM photon BR.
- Limits are computed for the various signal scenarios considered in the analysis

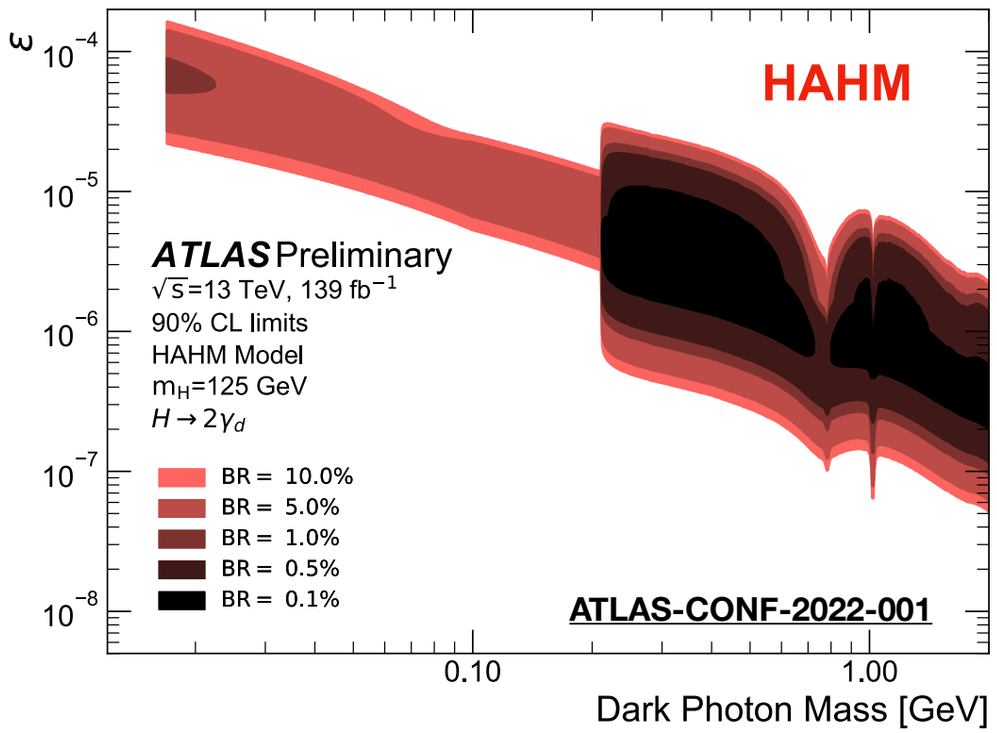
- **ggF+WH** combination:
  - Simultaneous fit of different ABCD planes with common signal strength
  - First search for light long-lived neutral particles deacying to collimated pairs of fermions at ATLAS exploiting the associated production mode
  - ggF dominating for $5 \lesssim c\tau \lesssim 20$ mm, complementarity with WH at smaller and higher $c\tau$



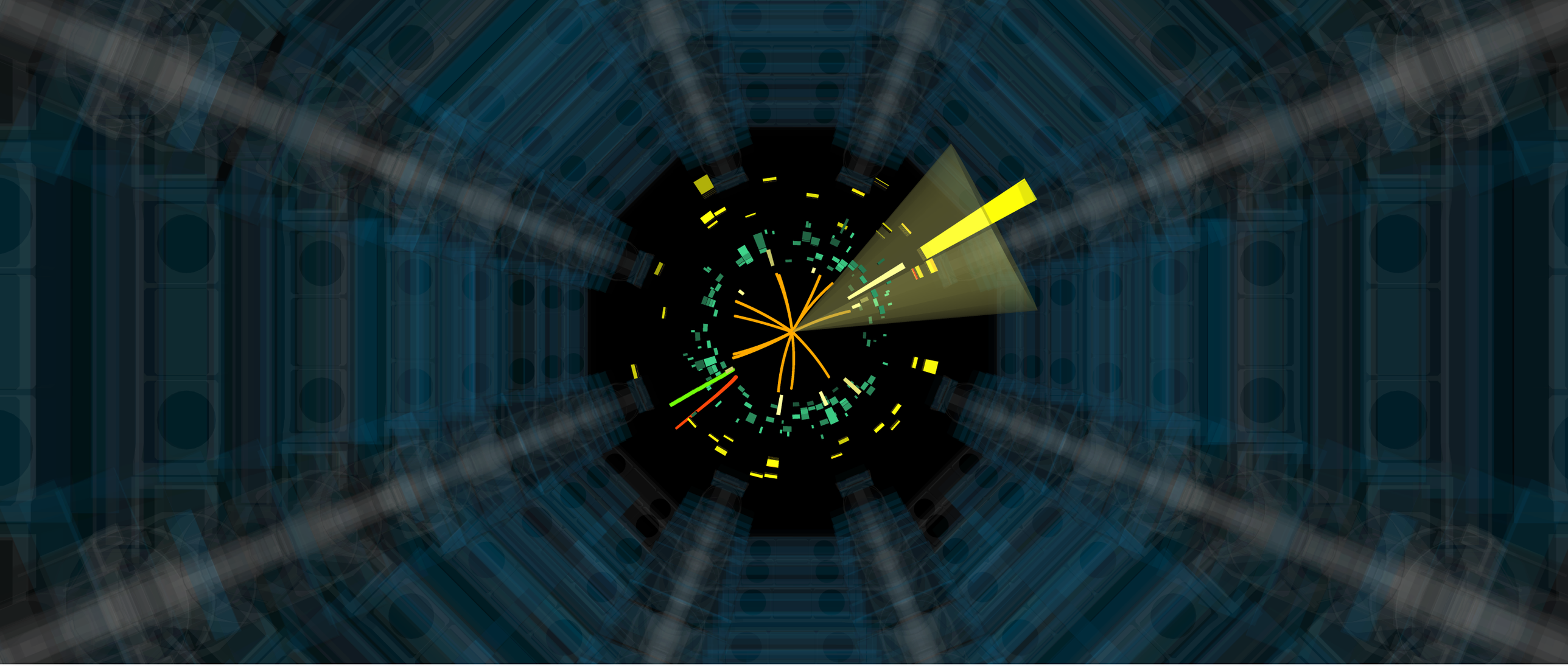
Exclusion limits II

- Significant analysis improvements (NN taggers) and new production modes (WH) exploited
- **First exclusion of fully electronic decays of the γ_d** allowing to probe previously uncovered regions of the phase space: $m_{\gamma d} < 2m_{\mu}$
- Muonic channel exclusion down do BR ~ 0.1%
- First interpretation into HAHM models





ATLAS LLP summary plot



Conclusions:

- Results were presented at Lepton-Photon as a CONF note
- Converting into a paper: soon to be submitted for JHEP
- Analysis team:
  - Working on a Full Run-II VBF analysis to be later combined with ggF+WH
  - Full Run-II prompt search recently started (last result from Run-I)

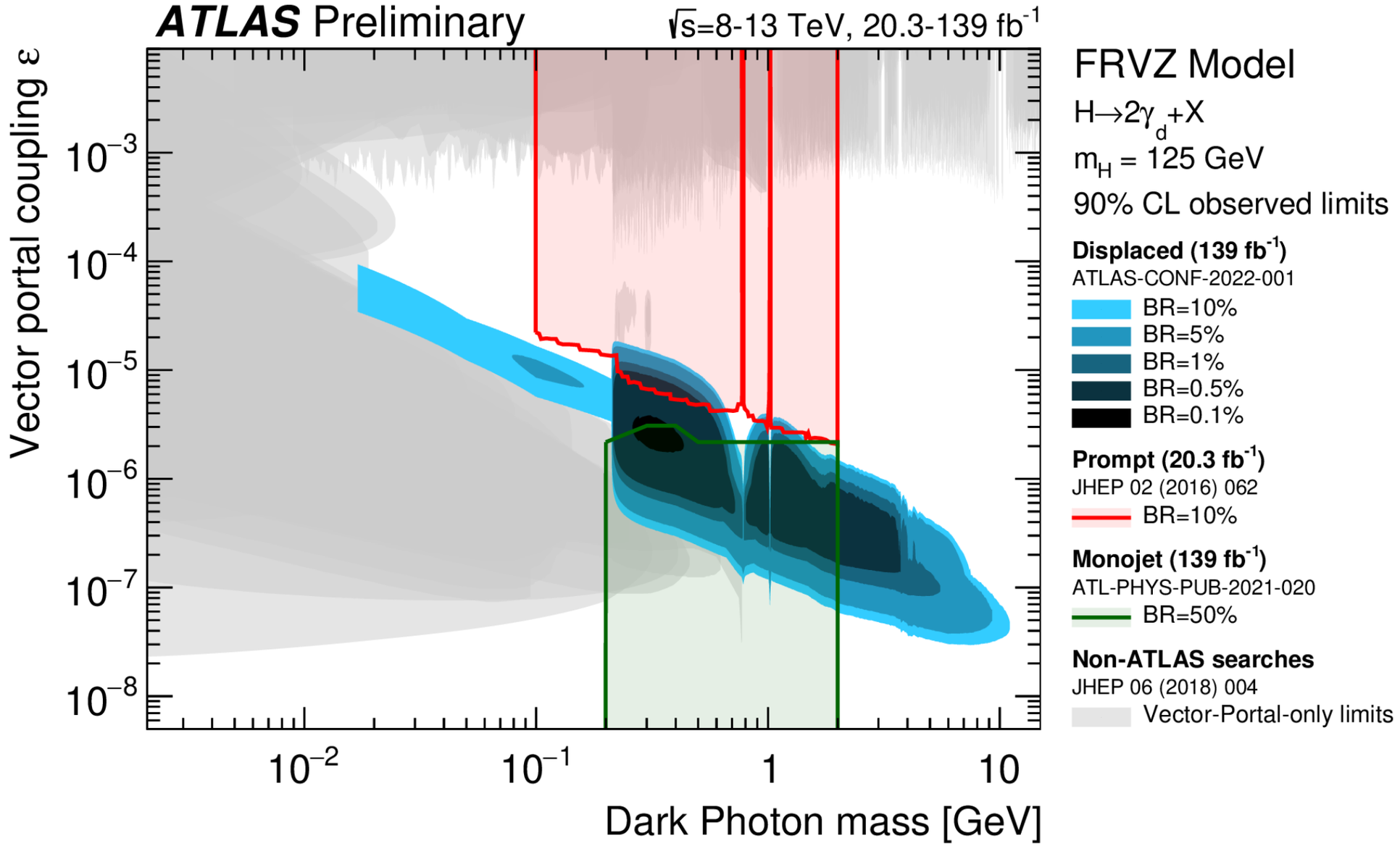
Public page

THANK YOU!

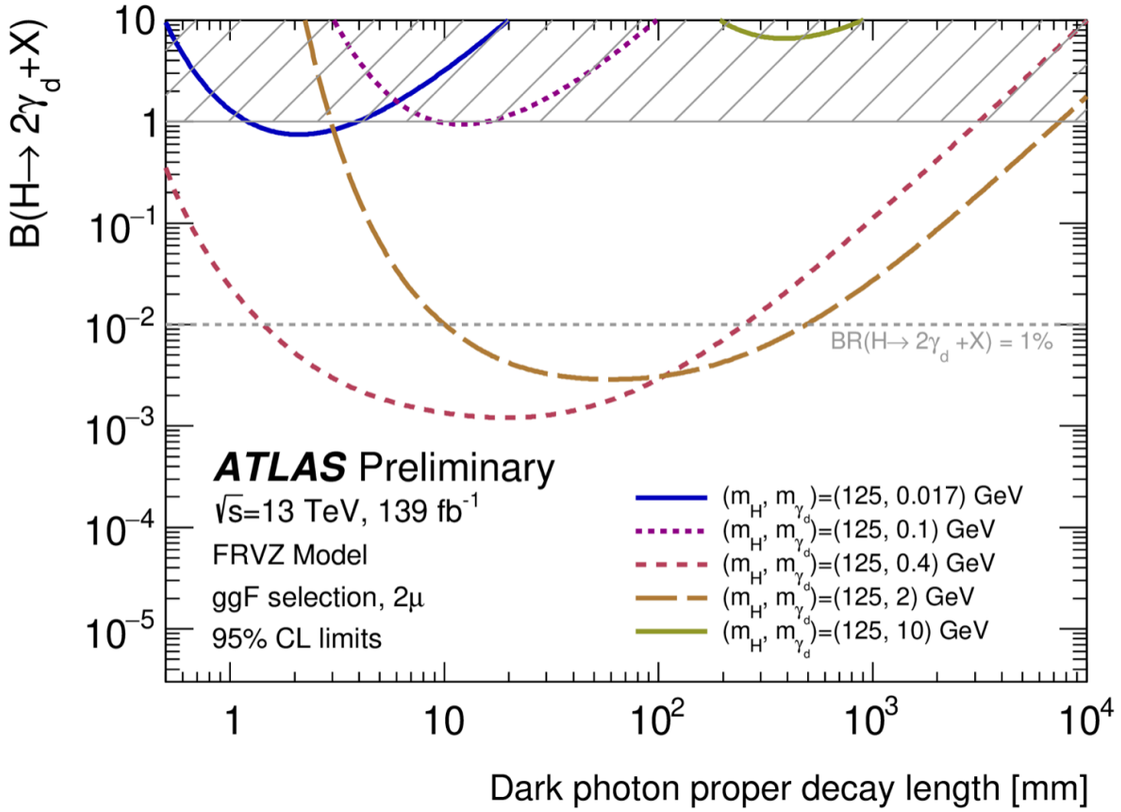
QUESTIONS?

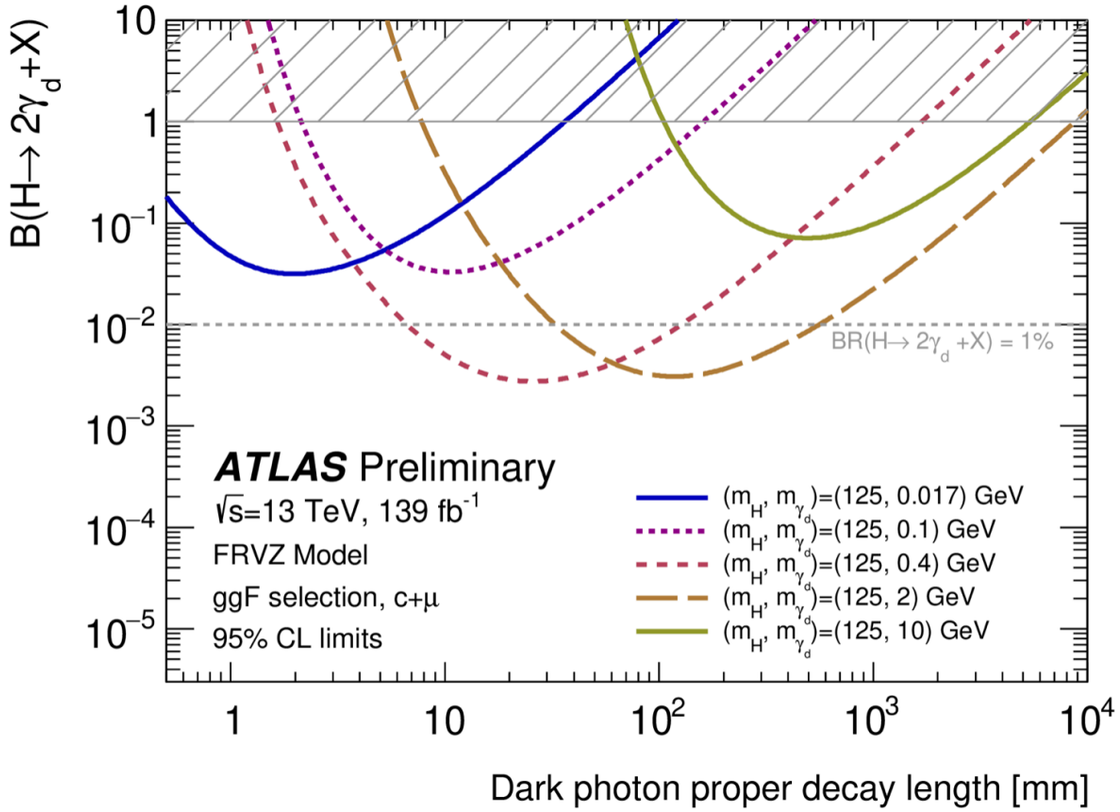
BACKUP

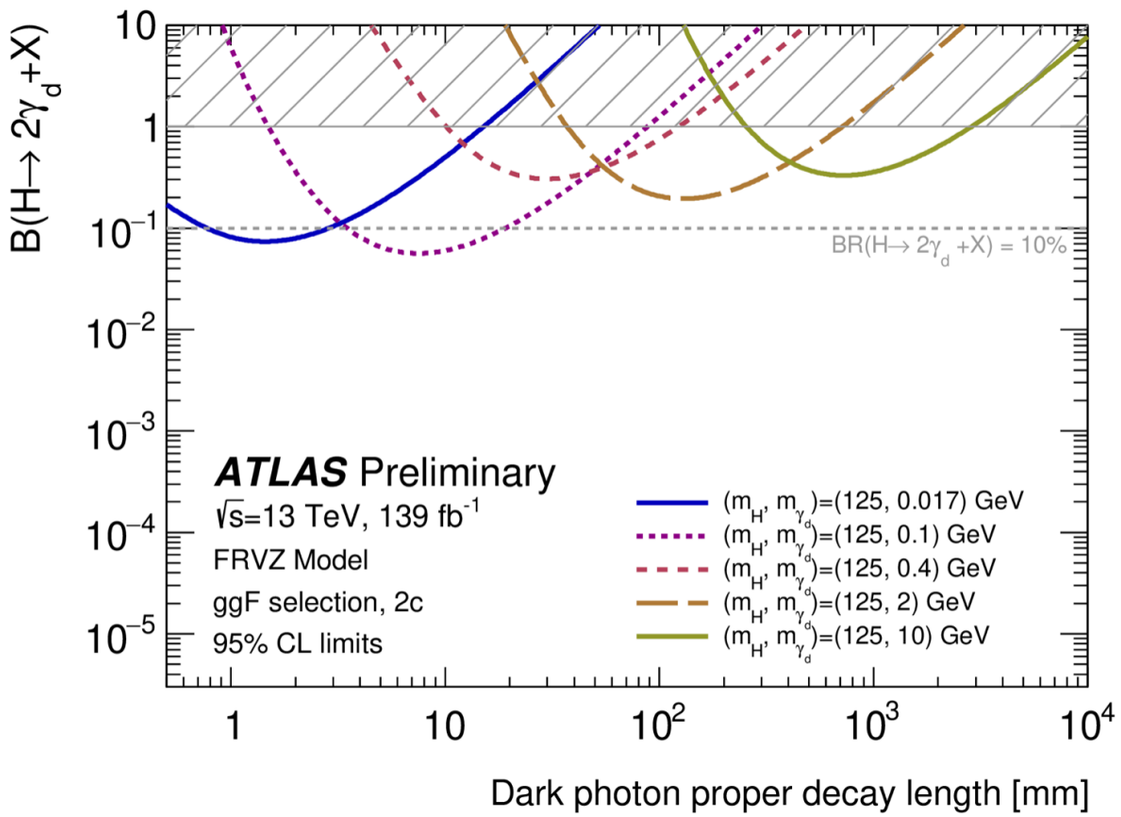
Summary plot



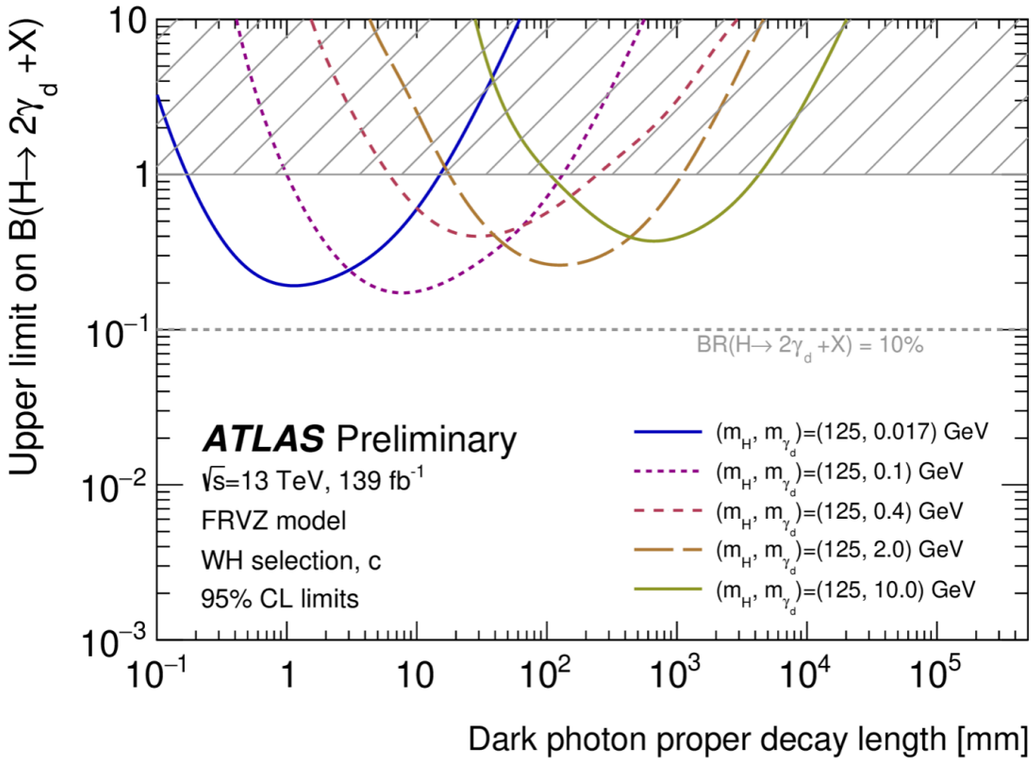
1D Limits: FRVZ ggF H125

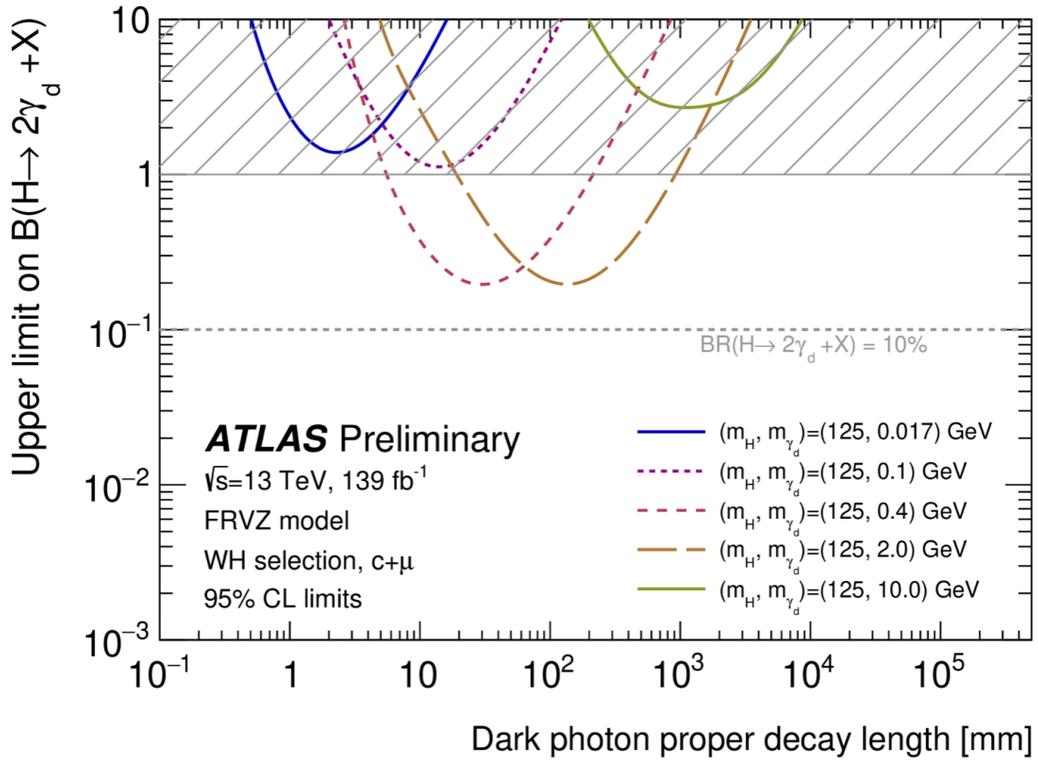


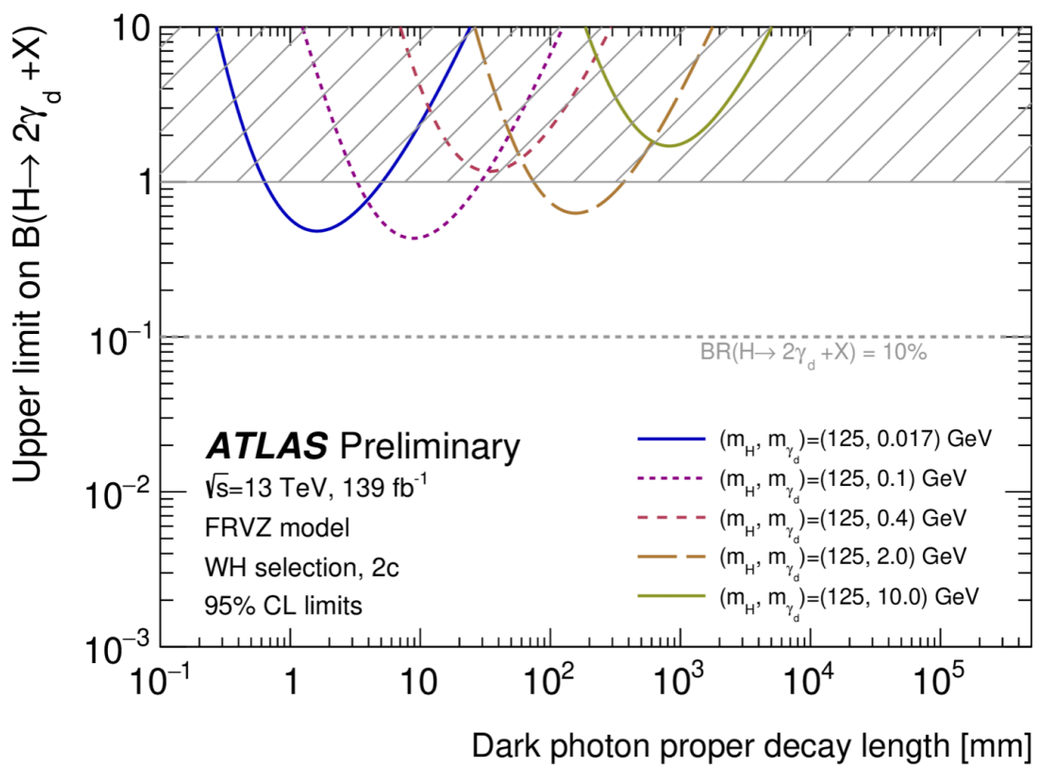




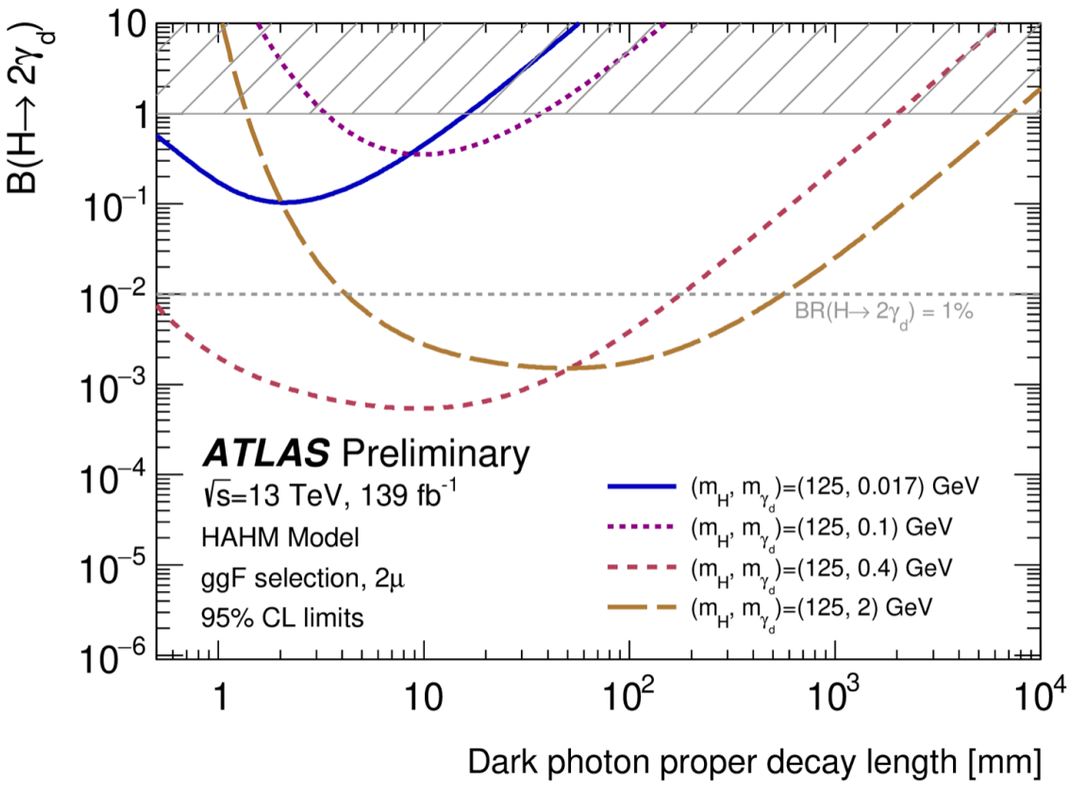
1D Limits: FRVZ WH H125

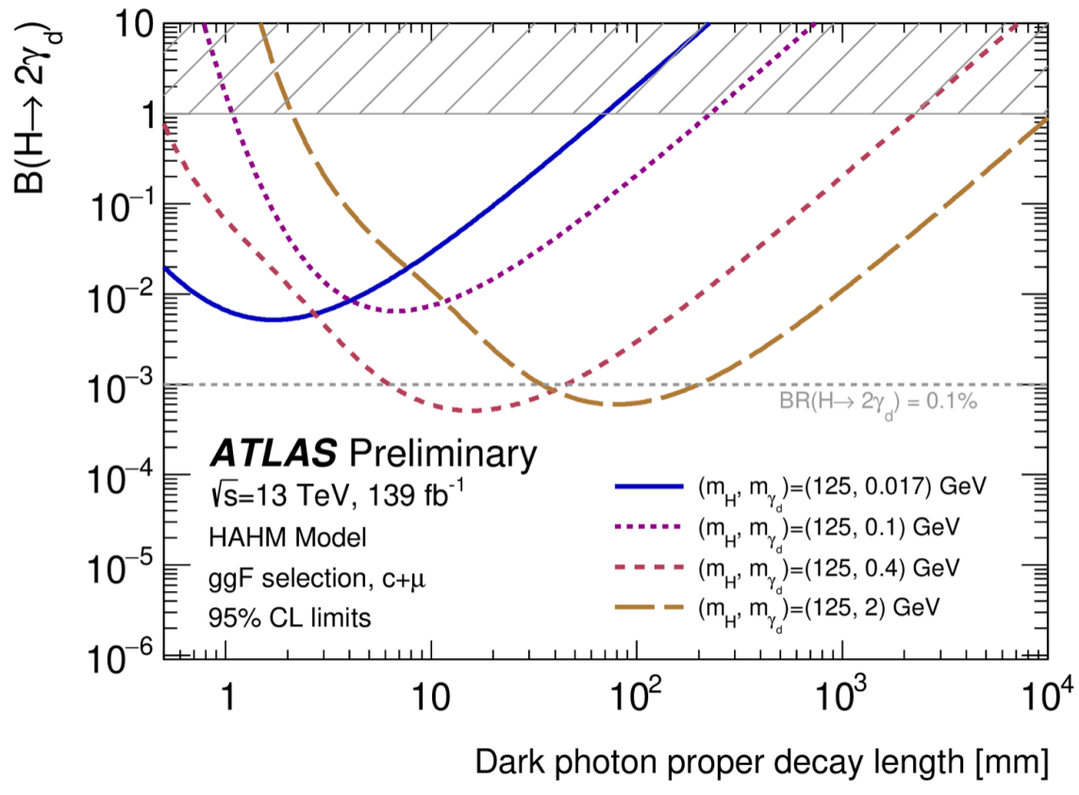


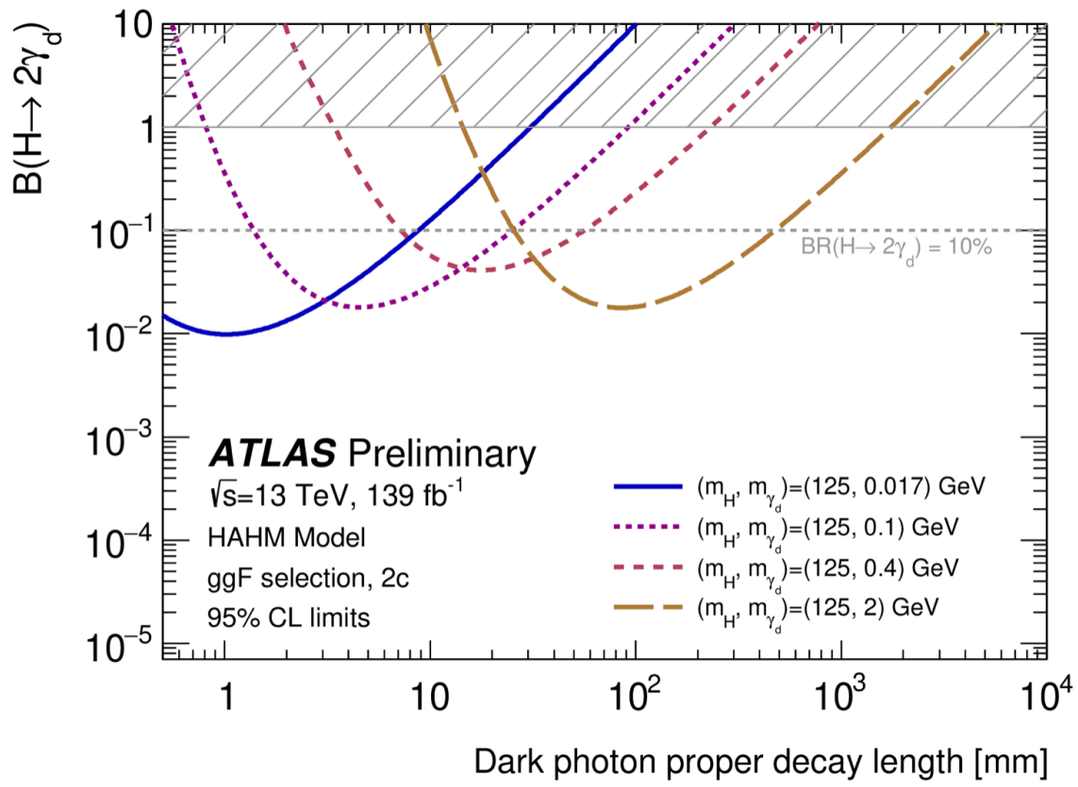




1D Limits: HAHM ggF H125







ABCD plane CRs (B,C,D)

Requirement / Region	$CRB_{2\mu}^{ggF}$	$CRC_{2\mu}^{ggF}$	$CRD_{2\mu}^{ggF}$
$\Delta\phi_{DPJ}$	$> \pi/5$	$(0.1, \pi/5]$	$(0.1, \pi/5]$
$\max(\sum p_T)$ [GeV]	$[4.5, 20)$	$[4.5, 20)$	< 4.5

Requirement / Region	CRB_{2c}^{ggF}	CRC_{2c}^{ggF}	CRD_{2c}^{ggF}
$\prod$ QCD tagger	> 0.95	$(0.8, 0.95]$	$(0.8, 0.95]$
$\max(\sum p_T)$ [GeV]	$[4.5, 20)$	$[4.5, 20)$	< 4.5

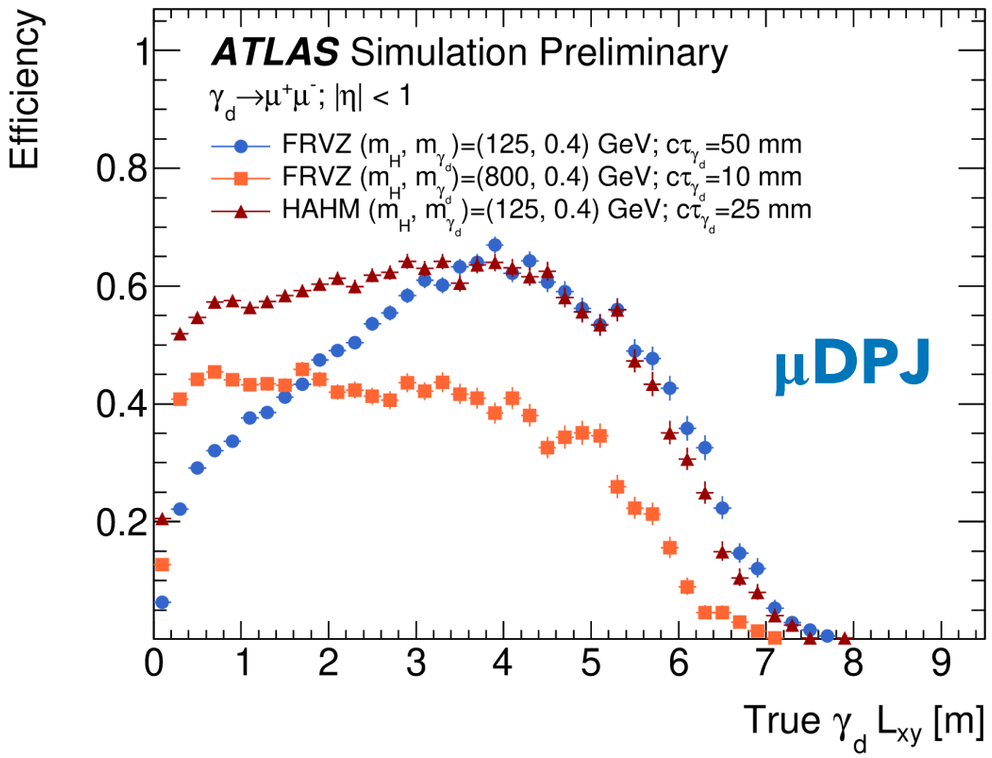
Requirement / Region	$CRB_{c+\mu}^{ggF}$	$CRC_{c+\mu}^{ggF}$	$CRD_{c+\mu}^{ggF}$
$\prod$ QCD tagger	> 0.9	$(0.75, 0.9]$	$(0.75, 0.9]$
$\max(\sum p_T)$ [GeV]	$[4.5, 20)$	$[4.5, 20)$	< 4.5

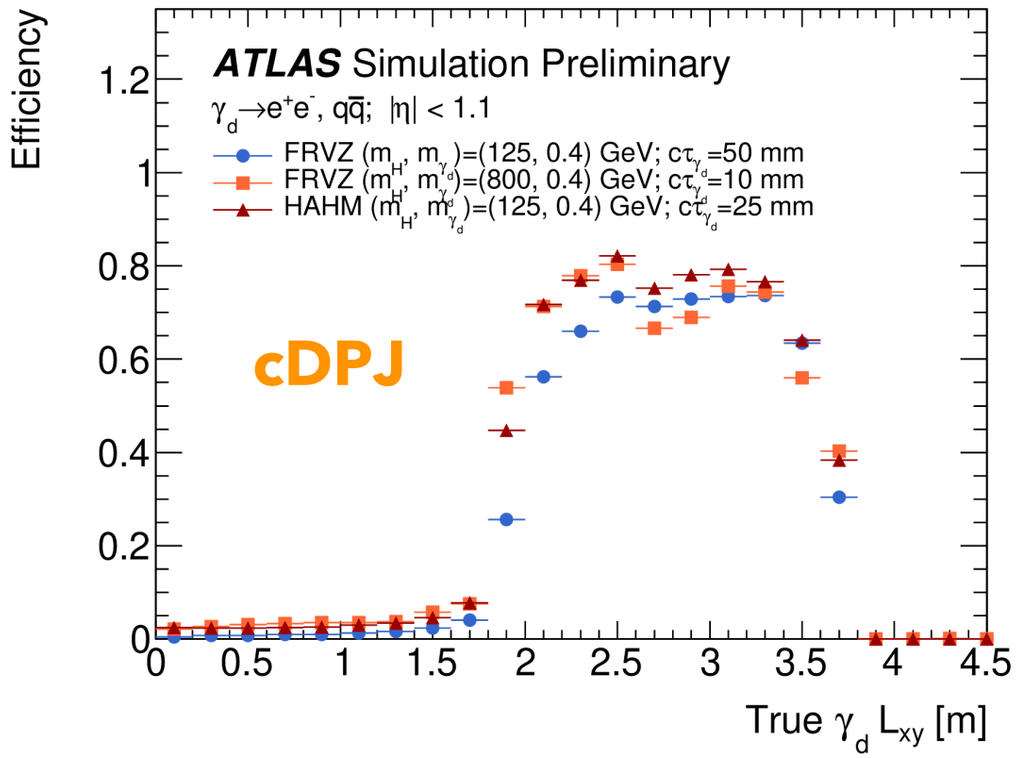
Requirement / Region	CRB_{c}^{WH}	CRC_{c}^{WH}	CRD_{c}^{WH}
$\min(\Delta\phi)$	$< 3\pi/5$	$> 3\pi/5$	$> 3\pi/5$
min(QCD tagger)	$[0.9, 0.99)$	$[0.9, 0.99)$	> 0.99

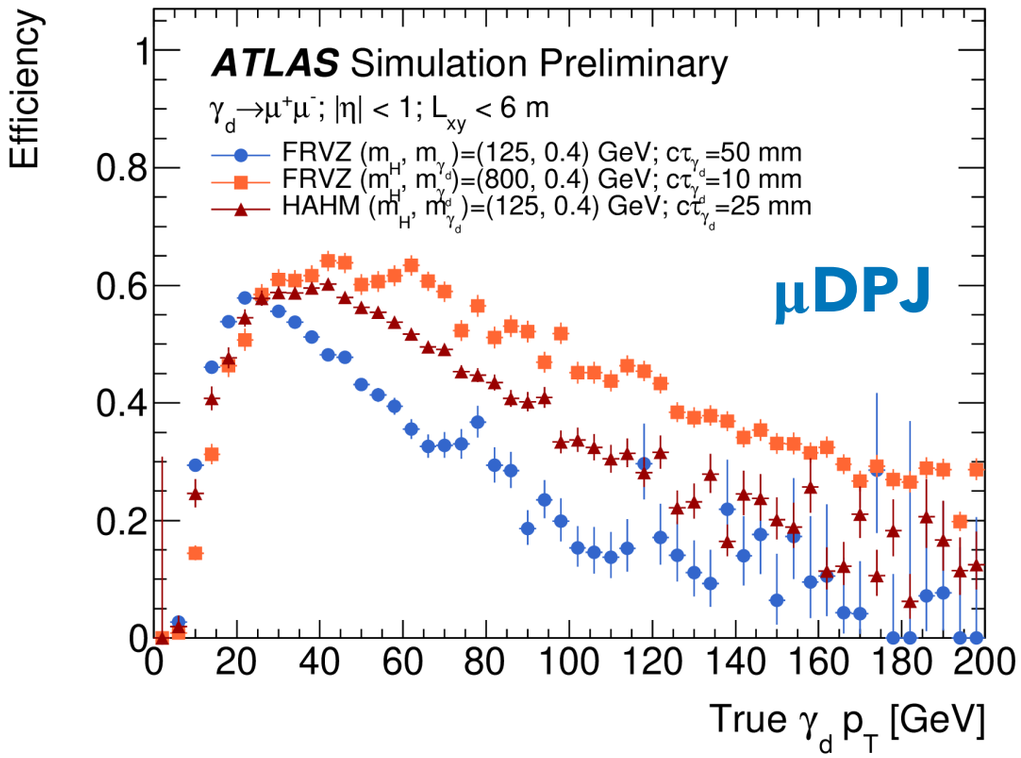
Requirement / Region	CRB_{2c}^{WH}	CRC_{2c}^{WH}	CRD_{2c}^{WH}
$\min(\Delta\phi)$	$< 3\pi/10$	$> 3\pi/10$	$> 3\pi/10$
min(QCD tagger)	$[0.8, 0.91)$	$[0.8, 0.91)$	> 0.91

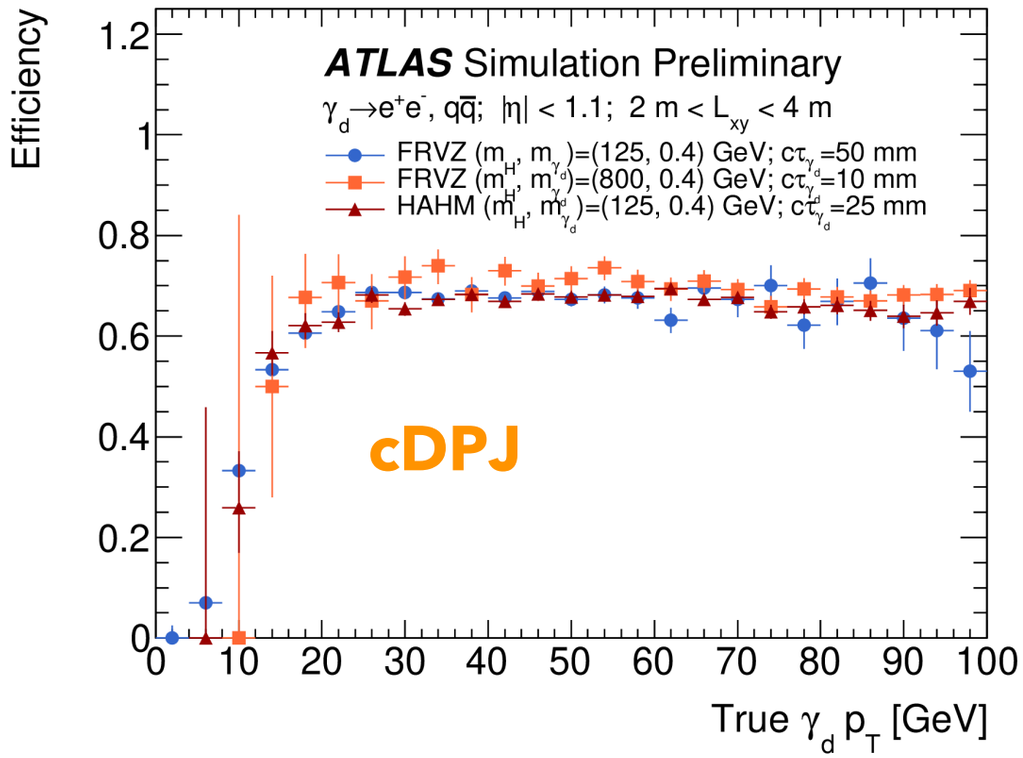
Requirement / Region	$CRB_{c+\mu}^{WH}$	$CRC_{c+\mu}^{WH}$	$CRD_{c+\mu}^{WH}$
$\min(\Delta\phi)$	$< 7\pi/20$	$> 7\pi/20$	$> 7\pi/20$
min(QCD tagger)	$[0.8, 0.9)$	$[0.8, 0.9)$	> 0.9

DPJ Reco

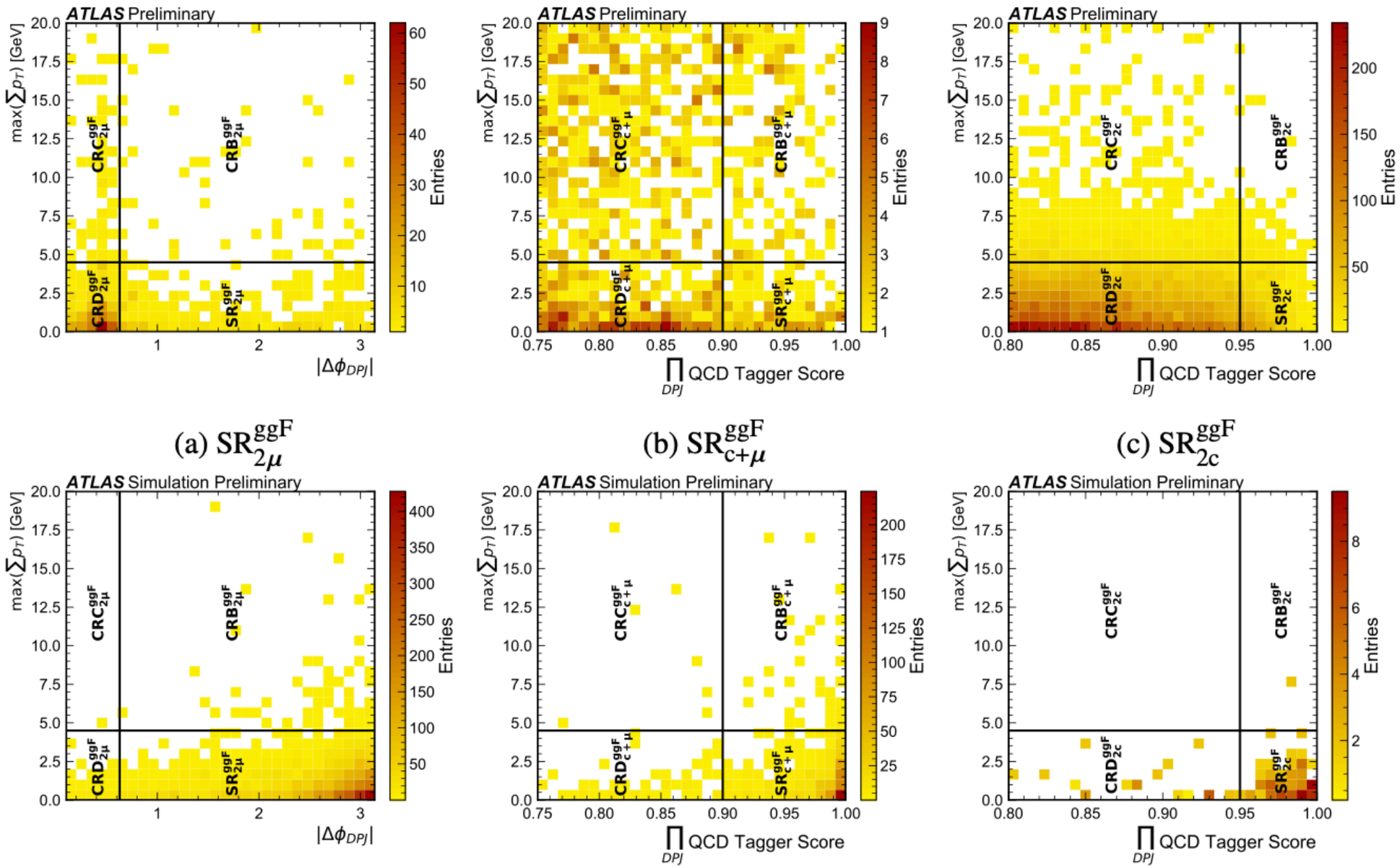

ATLAS Simulation Preliminary
γd→μ+μ-; |η| < 1
FRVZ (mH, mγd)=(125, 0.4) GeV; cτγd=50 mm
FRVZ (mH, mγd)=(800, 0.4) GeV; cτγd=10 mm
HAHM (mH, mγd)=(125, 0.4) GeV; cτγd=25 mm
μDPJ
Efficiency
True γd Lxy [m]


ATLAS Simulation Preliminary
γd→e+e-, qq̄; |η| < 1.1
FRVZ (mH, mγd)=(125, 0.4) GeV; cτγd=50 mm
FRVZ (mH, mγd)=(800, 0.4) GeV; cτγd=10 mm
HAHM (mH, mγd)=(125, 0.4) GeV; cτγd=25 mm
cDPJ
Efficiency
True γd Lxy [m]


ATLAS Simulation Preliminary
γd→μ+μ-; |η| < 1; Lxy < 6 m
FRVZ (mH, mγd)=(125, 0.4) GeV; cτγd=50 mm
FRVZ (mH, mγd)=(800, 0.4) GeV; cτγd=10 mm
HAHM (mH, mγd)=(125, 0.4) GeV; cτγd=25 mm
μDPJ
Efficiency
True γd pT [GeV]


ATLAS Simulation Preliminary
γd→e+e-, qq̄; |η| < 1.1; 2 m < Lxy < 4 m
FRVZ (mH, mγd)=(125, 0.4) GeV; cτγd=50 mm
FRVZ (mH, mγd)=(800, 0.4) GeV; cτγd=10 mm
HAHM (mH, mγd)=(125, 0.4) GeV; cτγd=25 mm
cDPJ
Efficiency
True γd pT [GeV]

ABCD Planes: ggF

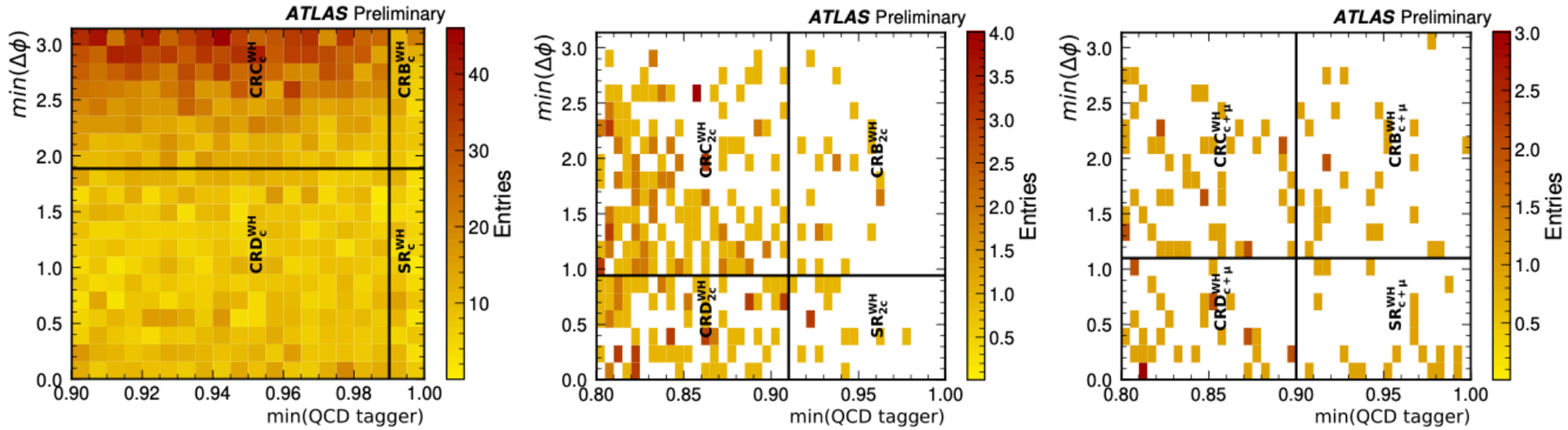


(a) $SR^{ggF}_{2\mu}$ (b) $SR^{ggF}_{c+\mu}$ (c) SR^{ggF}_{2c}

(d) $SR^{ggF}_{2\mu}$ (e) $SR^{ggF}_{c+\mu}$ (f) SR^{ggF}_{2c}

Figure 6: The per-event distributions in the ABCD planes defined for the ggF search channels. Figures (a, b, c) show data, while Figures (d, e, f) show simulated signal events. FRVZ signal samples with a SM Higgs boson and a γ_d mass of 400 MeV are shown.

ABCD Planes: WH



(a) SR_c^{WH} (b) SR_{2c}^{WH} (c) $SR_{c+\mu}^{WH}$

(d) SR_c^{WH} (e) SR_{2c}^{WH} (f) $SR_{c+\mu}^{WH}$

Figure 7: The per-event min($\Delta\phi$) vs. min(QCD tagger) distributions for the WH search channels. Figures (a, b, c) show data, while Figures (d, e, f) show simulated signal events. FRVZ signal samples with a SM Higgs boson and a γ_d mass of 100 MeV are shown for the SR_c^{WH} and SR_{2c}^{WH} search regions, while a γ_d mass of 400 MeV is shown for $SR_{c+\mu}^{WH}$.