Dark photon production in Higgs decays at FCC-ee

Expression of interest

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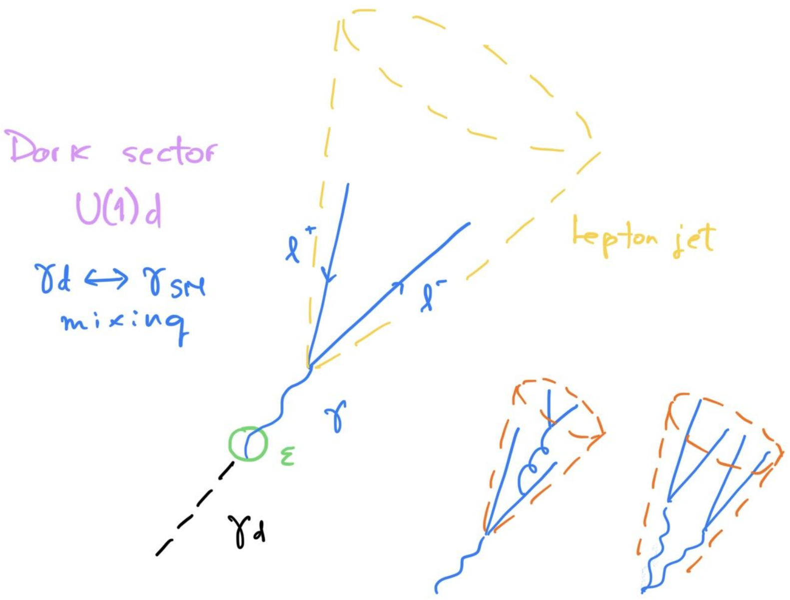
Dark sectors signatures

- Light dark sectors as general possibility in colliders (minimal extensions, DM candidates, various exotic signatures)
- At the LHC, **light dark particles** would be produced **with large boosts, causing their decay products to form** jet-like structures
- LJ-like signatures arise in models with a **dark sector** composed of unstable particles with *MeV-GeV* masses decaying to SM particles

- **Studies in ATLAS:**
  - Searches for **displaced LJ-like signatures** in Run-2 data
  - Different **Higgs production modes:**
    - ggF+WH production
    - VBF production
  - **Run-3 analysis ongoing**

Lepton jet (LJ) = cluster of collimated light charged particles (e^+e^-, $\mu^+\mu^-$, qq')



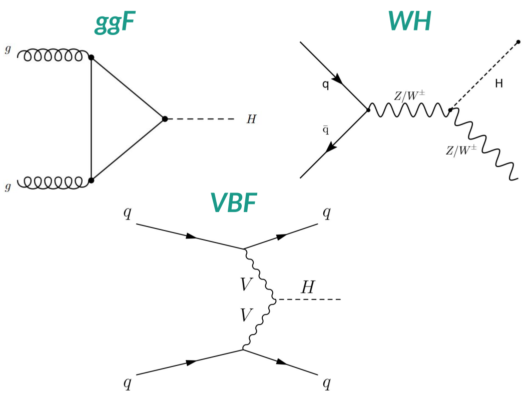
ATLAS Run-2 searches

- $H \rightarrow 2\gamma_d$ (+ X) via **Higgs & vector portals**
- SM final states ($\gamma_d \rightarrow \ell^+\ell^-/qq$) (+ E_T^{miss} signature in FRVZ decay)

- Small coupling ε: long-lived γ_d
  - $10^{-7} < \varepsilon < 10^{-5}$
- With $m_{\gamma d} << m_H$: collimated decay
  - $m_{\gamma d} \sim O(10\ \text{MeV})$-$O(10\ \text{GeV})$

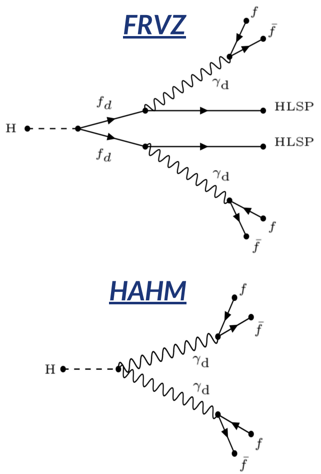
- Two searches using full Run-2 dataset:
  - ggF+WH search (2022)
  - VBF search & full combination (2023)

Production modes



Exploit signature of different production modes

Decay modes

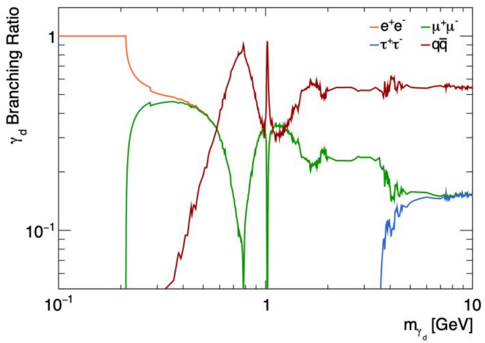


Final state: Displaced LJs (+ E_T^{miss})

LJ composition changes based on $m_{\gamma d}$

$$c\tau_{\gamma_d} \propto \frac{1}{\epsilon^2 m_{\gamma_d}}$$

γ_d decay length



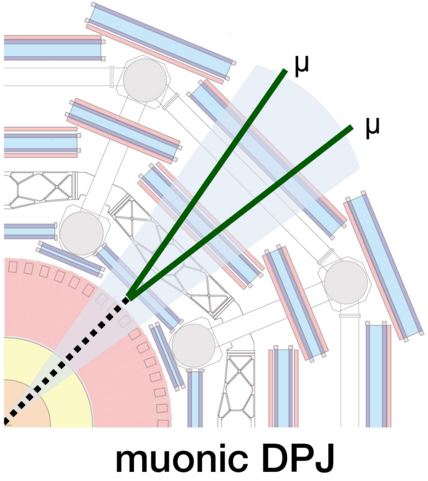
Displaced LJ signatures

Custom reconstructed objects:

Dark Photon Jets (DPJ)

Sensitive to γ_d decays after pixel detector

Backgrounds	Collisional	Non-collisional	
	Multi-jet (e.g., QCD MJ, V+jets)	Cosmic rays (μDPJ)	Beam-induced (caloDPJ)

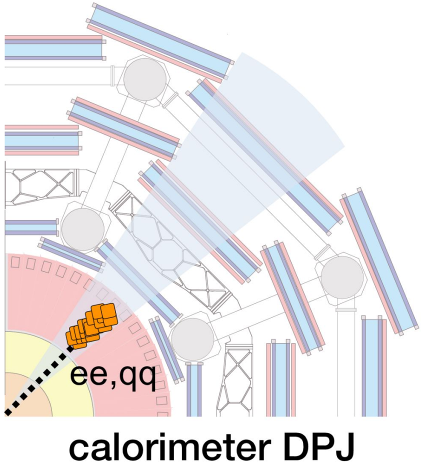


μDPJ

$\gamma_d \rightarrow \mu^+\mu^-$

Decays outside ID acceptance

Pair of close-by MS tracks with no matching jets/tracks in the ID



caloDPJ

$\gamma_d \rightarrow e^+e^-/qq$

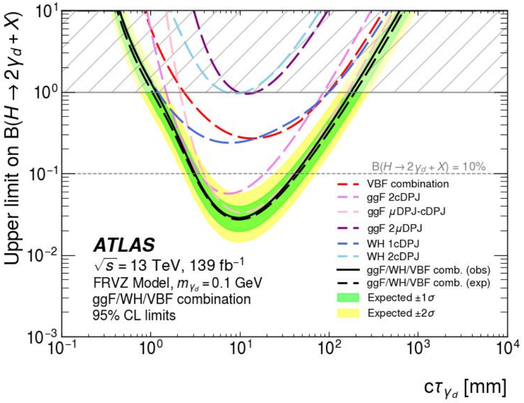
Targeting decays in HCAL

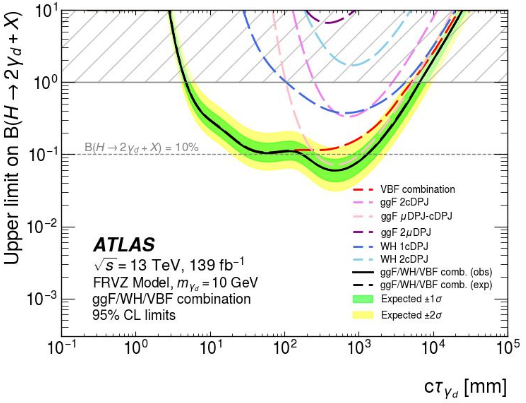
Low EM fraction jets with no matching MS tracks

Run-2 results

- Explored γ_d masses ∈ [0.017, 15] GeV
- Explored lifetimes translating in $c\tau_{\gamma d}$ ∈ [2, 1000] mm
- Interpretation of results:
  - Exotic Higgs decays to LLPs
  - Dark sector models (FRVZ, HAHM)
  - Caveat:
    - Full combination is FRVZ
    - Not commonly used compared to minimal models studied by other facilities

Combination with observed ggF/WH limits





Combined limits are interpolated in the full mass range

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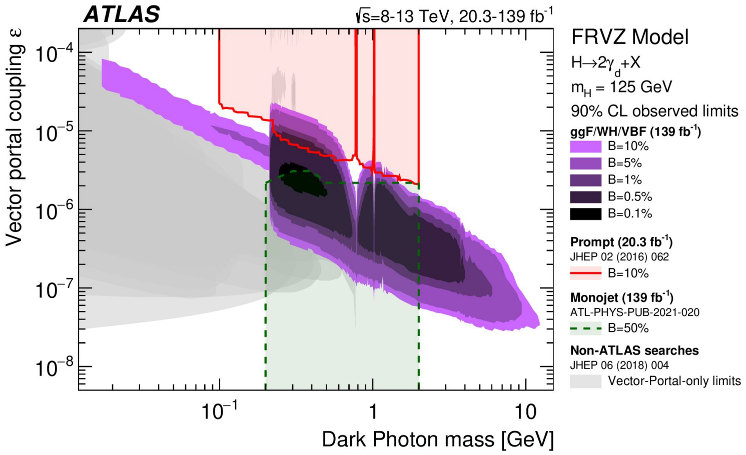
2D limits obtained as function of $m_{\gamma d}$ & kinetic mixing parameter ε



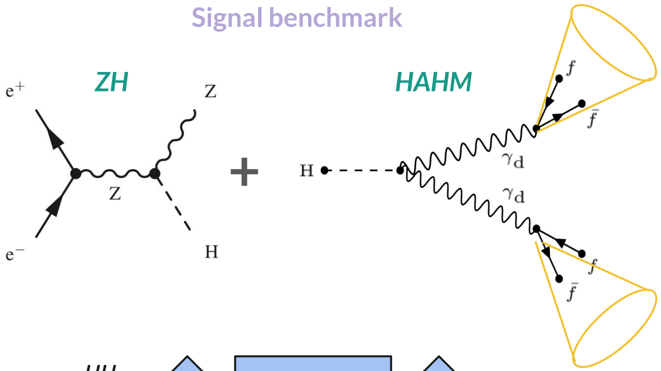
What about a similar thing at FCC-ee?

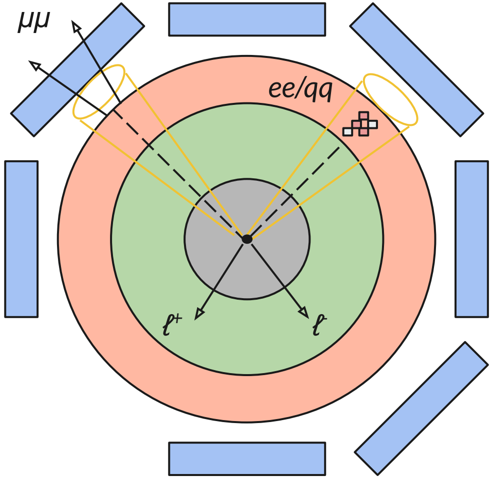
- First look into dark photon production in Higgs decays at FCC-ee
- Good complementarity with ongoing FCC LLP searches:
  - Similarity with displaced signatures from ALPs
  - Additional exotic Higgs decay scenario

- Targeting FCC-ee ZH production & HAHM Higgs decay
  - $e^+e^- \longrightarrow Z(\ell^+\ell^-)H(2\gamma_d)$ @ ecm 240 GeV

- Experimental signature:
  - A reconstructed Z boson from $\ell^+\ell^-$ pair
  - A displaced DPJ from each long-lived γ_d

Signal benchmark





Signal MC and future plans

- Signal simulated using [MadGraph5 HAHM UFO model]
  - 100k events per sample
  - MG5_aMC v3.5.4 for LHE production
  - Pythia8 + Delphes using IDEA Delphes card

- Backgrounds:
  - Candidates: ZH, ZZ, Zqq, etc
  - Checking existing samples in winter2023 camp.

- Future plans:
  - Generator level studies (LHE level kinematics)
  - FCCAnalyses framework to study reco-level info
    - Explore low-level detector response; e.g.,
      - Calocluster and muon information (including timing)

$m_{\gamma d}$= 0.1 GeV
$c\tau_{\gamma d}$= 15 mm

$BR(\gamma_d \rightarrow e^+e^-)=100\%$

Useful for caloDPJ signatures

$m_{\gamma d}$= 2-6 GeV
$c\tau_{\gamma d}$= 100-1000 mm

Allow $\gamma_d \rightarrow \mu^+\mu^-$ since $m_{\gamma d} > 2m_\mu$

Useful for μDPJ signatures

Displaced DPJ considerations

- μDPJ final states as "safe option" since easier to reconstruct (collimated muons in narrow cone or resolved dimuons with simple vertexing)
- Explore ATLAS-like NN taggers to distinguish displaced caloDPJs from prompt jets

Backup

Trigger strategy

γ_d decaying to muons

Narrow Scan

Find muon in MS with p_T>20 GeV

Scan for a second muon in narrow cone (ΔR=0.5) with lower p_T threshold

Trimuon (3μ) MS-only

Find 3 muons in the MS with p_T>6 GeV

Useful when two γ_d decay into muons

Events with single prompt leptons

Single lepton

Only used for WH production

Events with single prompt leptons coming from W decay

γ_d leaving hits in the calorimeter

CalRatio

Narrow jets with E_T>30 GeV

No matching tracks in the ID

94% of jet energy deposited in HCAL

Events with sizable E_T^{miss} signature

E_T^{miss}

Only used for VBF production

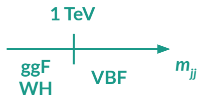
Useful when triggering on the DPJ itself becomes difficult

Used with offline cut E_T^{miss}>100 GeV

Analysis strategy

Orthogonality between production modes achieved via:

- Dijet invariant mass (m_{jj}) selection
- Vetoing prompt leptons (ggF, VBF)



(1) Pre-selection

Ensure orthogonality

Trigger choice

Further cuts at event and DPJ-level

→

(2) Channel definition

Orthogonal selections based on DPJ number and type

→

(3) NN taggers

DPJ quality cuts

Rejection of cosmic contamination, BIB & QCD multi-jet

→

(3) Data-driven background estimate

ABCD method

Rejection of cosmic contamination, BIB & QCD multi-jet

	ggF			WH			VBF		
# of DPJs	≥2						≥1		
Channel	2μ	2c	c+μ	1c	2c	c+μ	μDPJ	caloDPJ low E_T^{miss}	caloDPJ high E_T^{miss}
Trigger	Narrow Scan/3μ/ CalRatio			Single lepton			NS/3μ/ E_T^{miss}	E_T^{miss}	

Some VBF differences wrt. ggF/WH:

- Additional characterisation from VBF jets
- Lower DPJ multiplicity requirement for higher signal eff.
- E_T^{miss} triggers for both DPJ signatures & no CalRatio

NN-based taggers for DPJ quality

Cosmic-ray tagger (µDPJ)

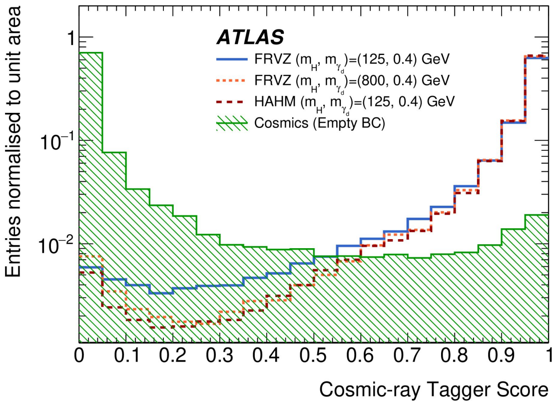
- Based on track parameters and RPC timing information
- Per-track tagging classifying **cosmic background against tracks originated by collision products**

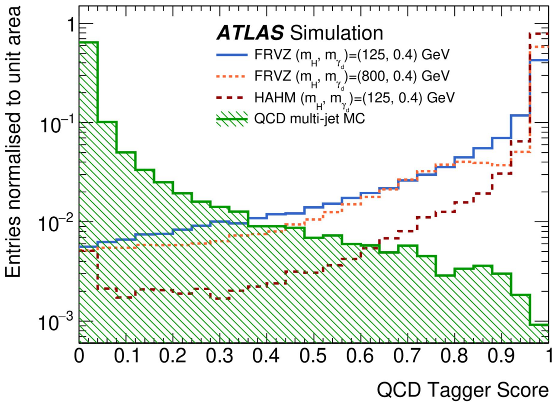
QCD tagger (cDPJ)

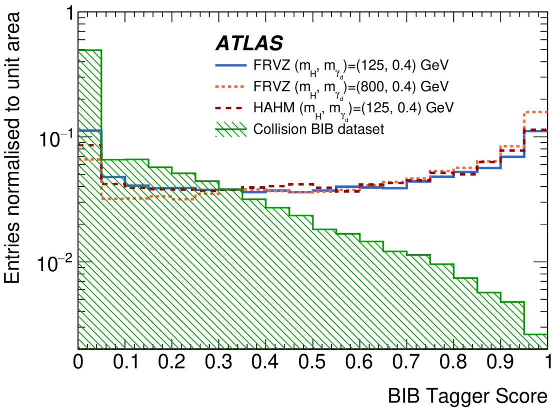
- 3D representations of jet energy built with calo-clusters
- Using energy deposit, Φ and η in each calorimeter sampling
- CNN trained to **classify QCD MJ from signal-like jets**

BIB tagger (cDPJ)

- Using same information than QCD tagger
- CNN trained to **classify Beam-Induced Background jets from signal-like jets**







Signal region definitions

ggF

Requirement / Region	$SR^{ggF}_{2\mu}$	SR^{ggF}_{2c}	$SR^{ggF}_{c+\mu}$
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	-
$\lvert\Delta t_{caloDPJs}\rvert$ [ns]	-	< 2.5	-
caloDPJ JVT	-	< 0.4	-
$\Delta\phi_{DPJ}$	$> \pi/5$	$> \pi/5$	$> \pi/5$
BIB tagger score	-	> 0.2	> 0.2
$\max(\sum p_T)$ [GeV]	< 4.5	< 4.5	< 4.5
$\prod$ QCD tagger	-	> 0.95	> 0.9

WH

Requirement / Region	SR^{WH}_{c}	SR^{WH}_{2c}	$SR^{WH}_{c+\mu}$
Number of μDPJs	0	0	1
Number of caloDPJs	1	2	1
Single-lepton trigger (μ, e)	yes	yes	yes
m_T [GeV]	> 120	-	-
$\lvert t_{caloDPJ}\rvert$ [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

VBF

Requirement / Region	SR_{μ}	$SR^{L/H}_{c}$
Number of DPJs	≥ 1	≥ 1
Leading DPJ type	μDPJ	caloDPJ
Trigger	E_T^{miss} Tri-muon MS-only Muon narrow-scan	E_T^{miss}
p_T(jet) [GeV]	> 30	> 30
N_{jet}	≥ 2	≥ 2
m_{jj} [GeV]	≥ 1000	≥ 1000
$\lvert\Delta\eta_{jj}\rvert$	> 3	> 3
$\lvert\Delta\phi_{jj}\rvert$	< 2.5	< 2.5
N_{ℓ}	0	0
$N_{b\text{-jet}}$	0	0
C_{DPJ}	> 0.7	-
$\Delta\phi_{min}$	-	> 0.4
E_T^{miss} [GeV]	> 100	SR^{L}_{c}: $[100, 225]$ SR^{H}_{c}: > 225
—μDPJ charge—	0	-
caloDPJ tagger	-	> 0.9
$\sum_{\Delta R=0.5} p_T$ [GeV]	< 2	< 2

Data-driven background estimation: ABCD method

- Estimate expected QCD multi-jet background in each SR
  - Non-collisional backgrounds (CR, BIB) are suppressed before populating ABCD planes
  - Validations performed in BC & DC subplanes + additional validation regions **(backup)**

Estimation using ABCD

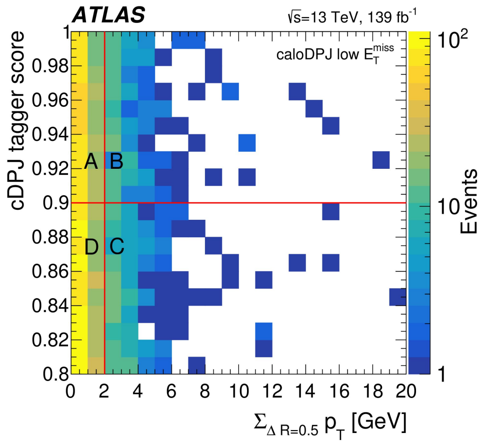
- Define plane using two uncorrelated variables
- Split plane in A, B, C & D regions:
  - A = Signal-enriched
  - B,C,D = Background-enriched
- Estimate N_A as:

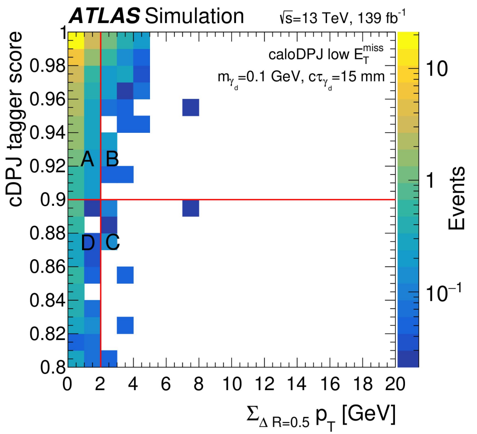
$$N_A = \frac{N_B \times N_D}{N_C}$$

- e.g., **ABCD planes for VBF low E_T^{miss} channel:**

Variables

1. caloDPJ ID isolation
   Sum of p_T of tracks inside cone with R=0.5 around leading DPJ ID track
2. caloDPJ QCD tagger score





Unblinded results: anything new?

Unblinding
Populate signal regions with real data and check if we have found something new!

- **Before unblinding:**
  - Estimate expected exclusion limits on observable of interest $BR(H \to 2\gamma_d + X)$
- **After unblinding:**
  - No new physics found!
  - All predictions in good agreement with observations
  - Estimate observed exclusion limits on observable of interest $BR(H \to 2\gamma_d + X)$

ggF & WH

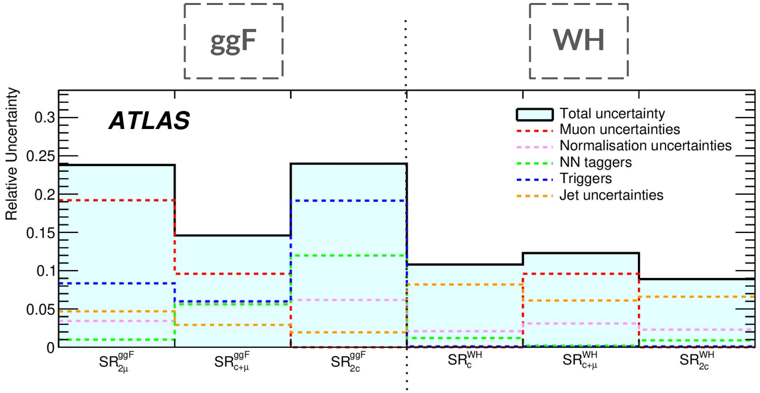
Selection	Search channel	CRB	CRC	CRD	SR expected	SR observed
ggF	2μ	55	61	389	317 ± 47	269
	c+μ	169	471	301	108 ± 13	110
	2c	97	1113	12146	1055 ± 82	1045
WH	c	1850	3011	155	93 ± 12	103
	c+μ	30	49	31	19 ± 8	20
	2c	79	155	27	14 ± 5	15

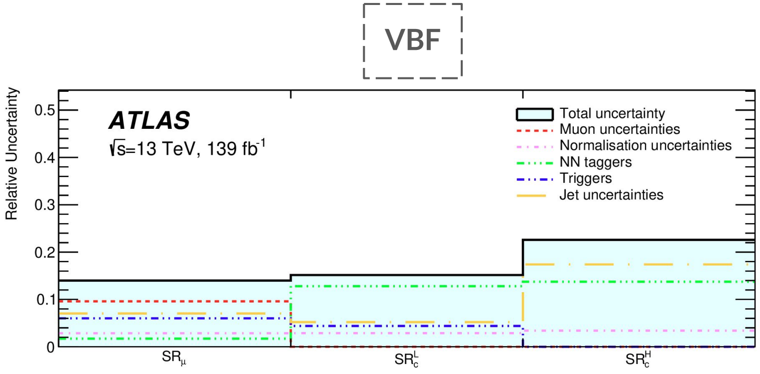
VBF

Selection	CRB	CRC	CRD	SR expected	SR observed
SR_{μ}	44	22	21	42 ± 14	41
SR_{c}^{L}	224	256	1123	983 ± 95	923
SR_{c}^{H}	9	11	35	29 ± 14	46

Systematic uncertainties

- **ABCD method syst. uncertainty** obtained by propagating the stat. uncertainty in the CRs
- **Experimental uncerts.** are evaluated from **data/MC differences** in the DPJ reconstruction and **NN taggers**
  - **Muon uncertainties:** Reconstruction of close-by muon, evaluated using a tag-and-probe method on $J/\Psi \rightarrow \mu\mu$ as function of $\Delta R_{\mu\mu}$
  - **Normalisation uncerts.:** Luminosity and pile-up reweighting
  - **NN taggers:** Set of weights is extracted from $Z \rightarrow \mu\mu$ or dijet samples and propagated to signal samples to cover MC/data differences
  - **Triggers:** Same close-by muon tag-and-probe approach is adapted to *trimuon* and *NarrowScan* triggers. *MET trigger* uncertainty obtained by propagating 100% of scale factors uncertainty
  - **Jet energy resolution** and **energy scale** are considered, plus additional jet energy scale uncert. for low EM fraction jets



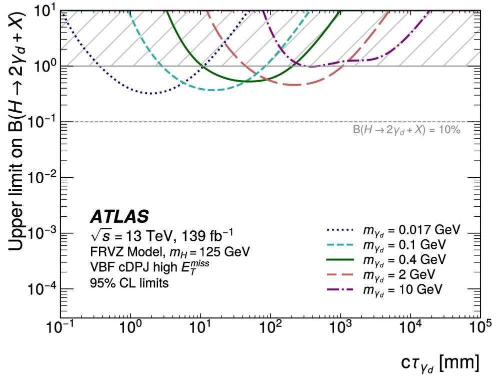


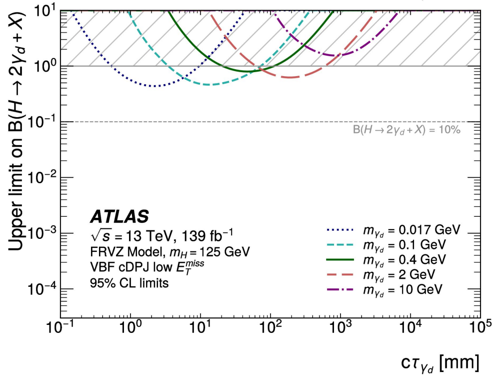
Upper limits on BR($H \to 2\gamma_d + X$): e.g., VBF

Limits on single $c\tau$ are extrapolated via lifetime reweighting to other $c\tau$ values **(backup)**

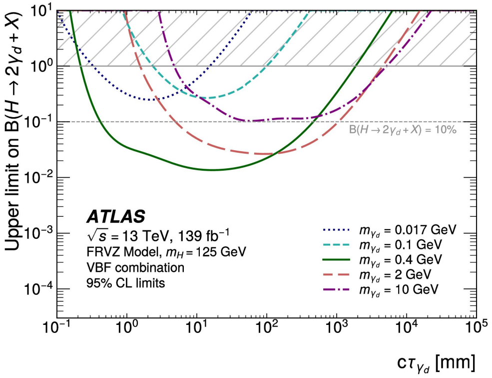
- Single ABCD limits for each channel and mass point
- Observed upper limits on *BR($H \to 2\gamma_d + X$)* for each SR and overall VBF combination
- Limits available for ggF & WH allow for full combination!

caloDPJ

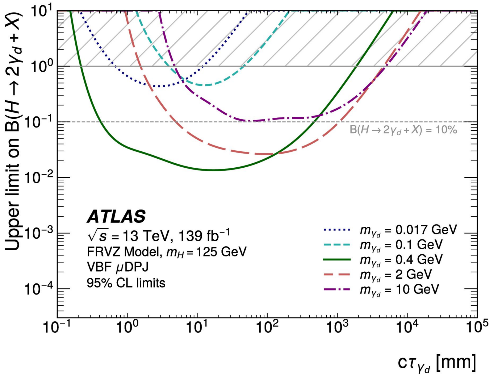




VBF combination

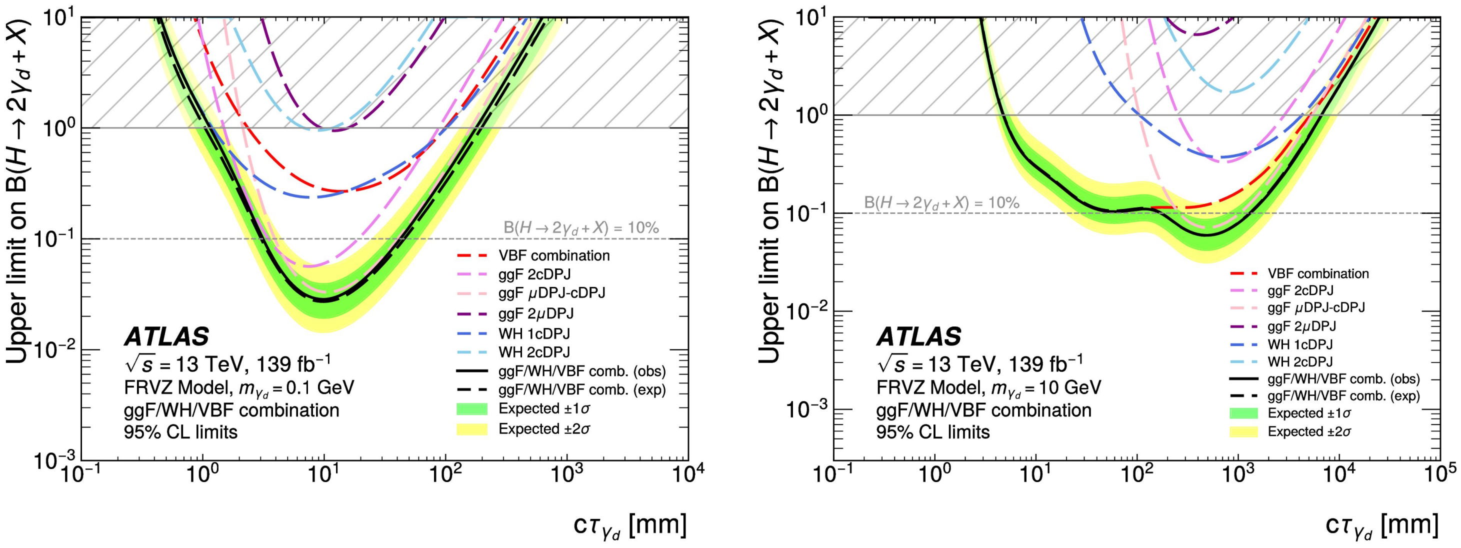


µDPJ



Combined limits on BR($H \rightarrow 2\gamma_d$+X): ggF+WH+VBF

- Limits on $BR(H \rightarrow 2\gamma_d+X)$ combining all ggF/WH/VBF SRs per γ_d mass point
- Combination of observed limits obtained for $m_{\gamma d} \in [0.017, 15]$ GeV



- Higher sensitivity obtained from ggF channels
- VBF offers competitive sensitivity at low and high $c\tau_{\gamma d}$, particularly at high $m_{\gamma d}$ values

Displaced LJs VBF

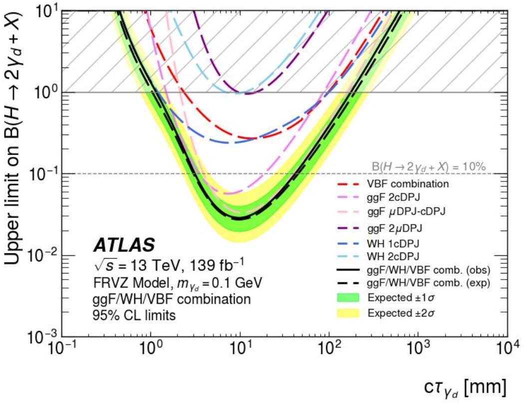
- First ATLAS search using VBF production
- Analysis performed for combination with previous [ggF/WH iteration]

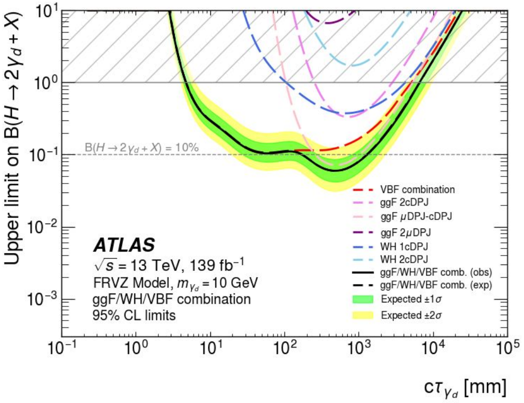
1	Event selection	• VBF jets cuts, triggers, etc. • Per-DPJ object selection • µDPJ/caloDPJ signal regions
2	Background estim. & signal efficiency extrapol.	• Data-driven background estimate per SR (ABCD) • Signal acceptance x efficiency extrapol. as function of $c\tau_{\gamma d}$
3	Exclusion limits on $B(H\to 2\gamma_d+X)$	• Expected & observed ULs on $B(H\to 2\gamma_d+X)$ from VBF • Full combination with ggF/WH limits

- Combination renders **strongest limits up-to-date for displaced LJs searches in ATLAS**
- Analysis presented in EPS-HEP 2023
- Paper submitted to EPJC on Nov/2023

- Inclusive production study for Run-3 is on the way!

Combination with observed ggF/WH limits





Combined limits are interpolated in the full mass range

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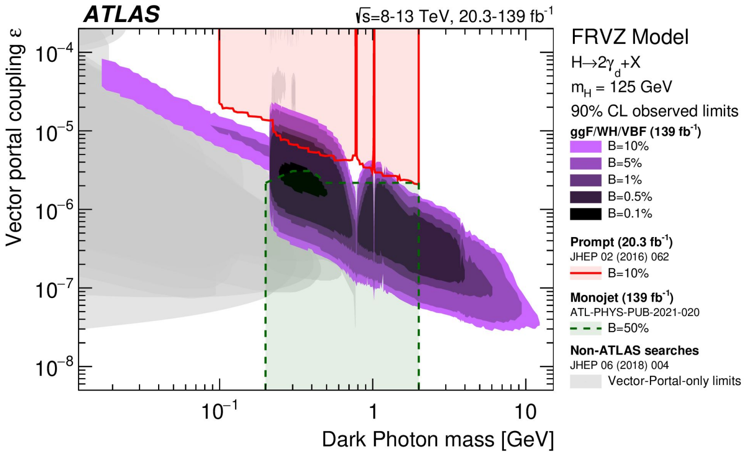
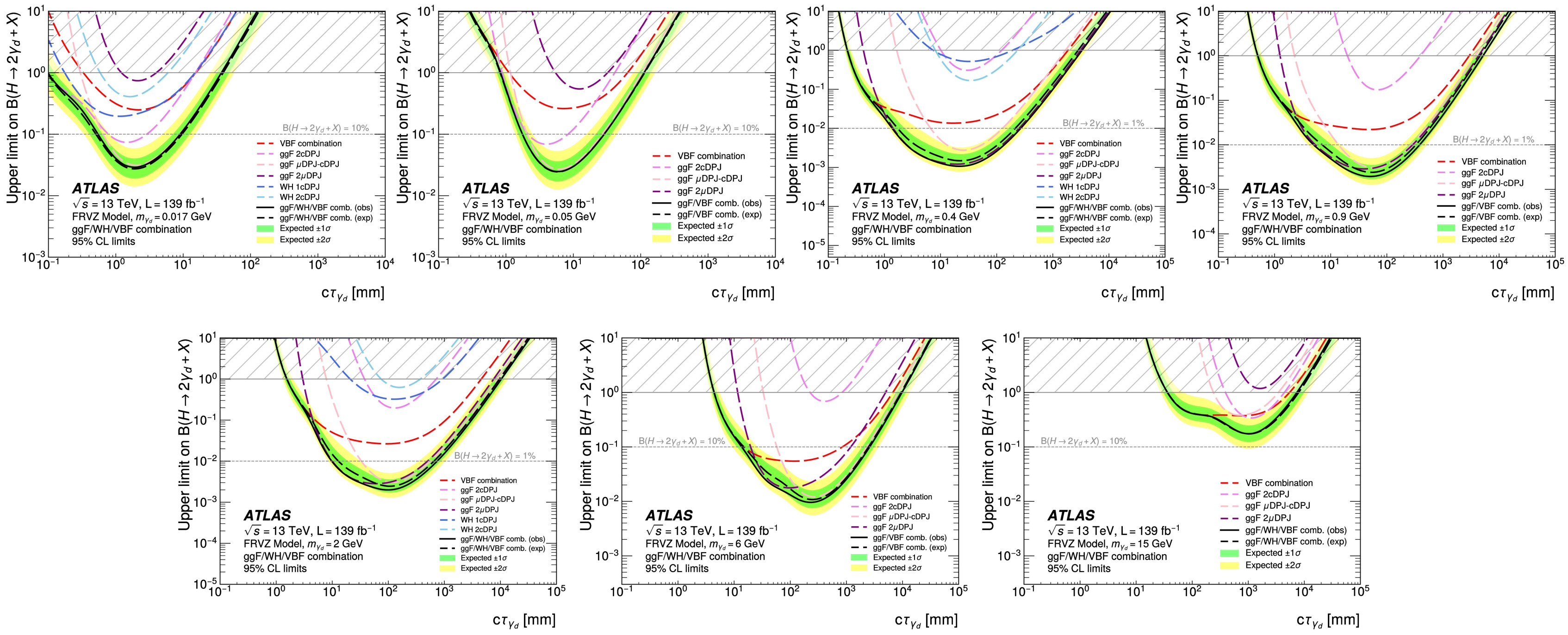
2D limits obtained as function of $m_{\gamma d}$ & kinetic mixing parameter ε



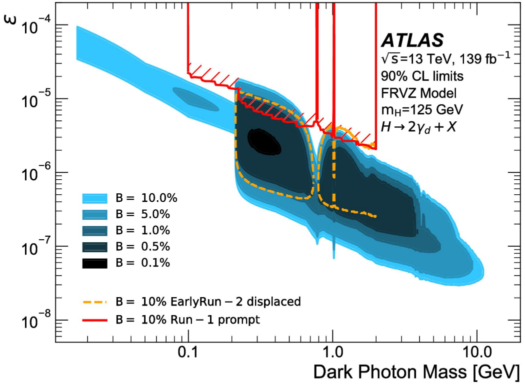
BR(H⟶2γ$_d$+X) combined limits: ggF+WH+VBF



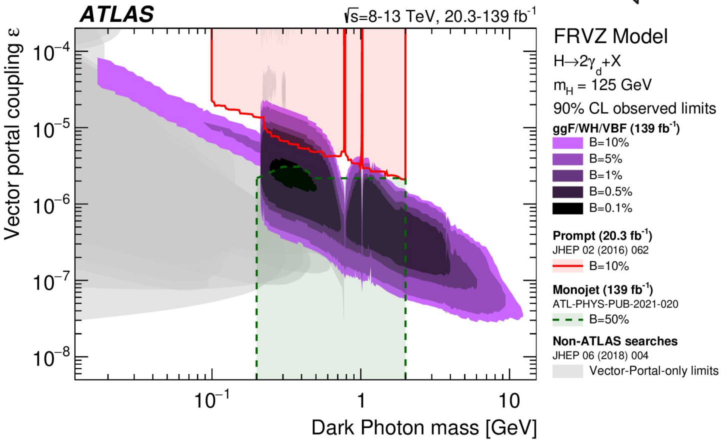
FRVZ vector portal interpretation: (ε, $m_{\gamma d}$) limits

- 2D limits obtained as a function of $m_{\gamma d}$ & kinetic mixing parameter ε
- For **each generated ($m_{\gamma d}$, $c\tau_{\gamma d}$) pair**, the **analysis efficiency is extrapolated to the 2D plane:**
  - Along ε using the lifetime reweighting curves
  - Along $m_{\gamma d}$ according to γ_d branching ratio
- Combination renders **strongest limits up-to-date for displaced LJ searches in ATLAS**

ggF+WH



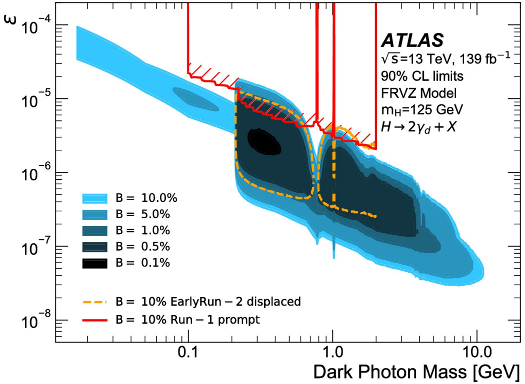
ggF+WH +VBF



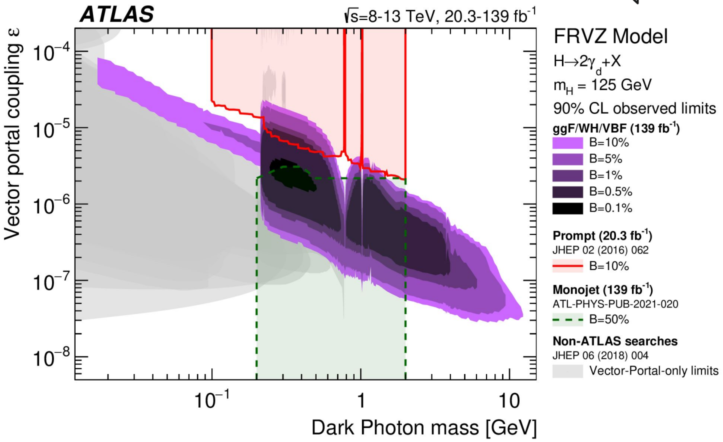
FRVZ vector portal interpretation: (ε, $m_{\gamma d}$) limits

- For **each generated ($m_{\gamma d}$, $c\tau_{\gamma d}$) pair**, the **analysis efficiency is extrapolated to the 2D plane:**
  - Along **ε** using the lifetime reweighting curves
  - Along $m_{\gamma d}$ according to γ_d branching ratio
- **2D limits are obtained doing a simultaneous fit of the available ggF/WH/VBF analysis channels** in a ($m_{\gamma d}$, $c\tau_{\gamma d}$) grid
- The **final limit is obtained by running a linear interpolation** between the results from each simultaneous fit

ggF+WH



ggF+WH +VBF



Status and current work

Run-2

- **No new physics - for now!**
- Observed limits obtained for all mass points in each signal region
- Full ggF+WH+VBF combined limits on $BR(H \rightarrow 2\gamma_d + X)$ at 95% CL
- $[\varepsilon, m_{\gamma d}]$ limits for full combination → Strongest ATLAS exclusion for displaced LJ searches!

Run-3: Preliminary studies

- **Inclusive production analysis is ongoing!**
- Several opportunities for improvement:

Explore HAHM signals

Study additional signal benchmark with low E_T^{miss} signature

Improved trigger strategy

Exploring NS+VBF for µDPJ signatures

CalRatio+VBF for caloDPJ signatures

Implement updated taggers

NN taggers trained in newest release for performance improval

Optimised SR definitions

Explore further observables for background rejection/prediction

Run-3: Trigger studies for VBF

- Three signatures crucially related to trigger selections:
  - Production mode (VBF jets)
  - Displaced reconstruction (LLPs)
  - Missing transverse energy

- VBF & LLP: Low trigger efficiency on their own

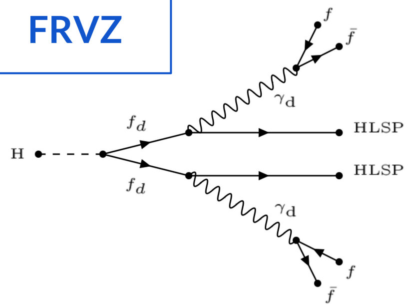
- **Run-2 VBF:** E_T^{miss} trigger forces offline cut that reduces sensitivity to models with low intrinsic E_T^{miss} (e.g., HAHM)

- **Run-3 wishlist:**

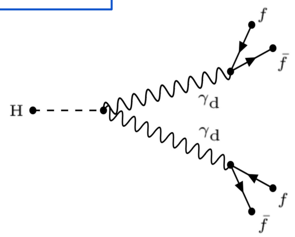
  - **μDPJ:** VBF + NarrowScan MS-only
  - Inclusive NS ready for stable beam this year

  - **caloDPJ:** VBF + CalRatio
  - Studying low m_{jj} L1 threshold
  - CalRatio development ongoing

FRVZ



HAHM



VBF analysis

VBF analysis strategy

(1) Pre-selection

- VBF jets selection:

At least two jets with p_T>30 GeV
m_{jj} > 1 TeV $|\Delta\eta_{jj}|>3$ $|\Delta\Phi_{jj}|<2.5$

- Trigger:

μDPJ channel ⟶ NarrowScan || Trimuon || E_T^{miss}
caloDPJ channel ⟶ E_T^{miss}

- Lepton veto (orthogonal to WH)
- *b*-jet veto (targeting *t*-quark decays)

- Further channel-specific cuts:
  - Reduce background
  - Trigger-related
  - DPJ quality cuts

(2) Per-DPJ type selection

- Inclusive DPJ selection:

μDPJ channel ⟶ Leading DPJ is μDPJ
caloDPJ channel ⟶ Leading DPJ is caloDPJ

(3) NN tagger cuts

- Taggers implemented in ggF/WH public analysis:

μDPJ channel ⟶ Reject cosmic ray muons
caloDPJ channel ⟶ Reject QCD & BIB jets

(4) Data-driven background estimate

- ABCD method to estimate multijet background in signal regions

VBF - Trigger strategy

Chain	Triggering on	Final state	Name	Year
Narrow Scan	Long-lived particles	μDPJ	HLT_mu20_msonly_mu6noL1_msonly_nscan05 HLT_mu20_msonly_mu10noL1_msonly_nscan05_noComb HLT_mu20_msonly_mu15noL1_msonly_nscan05_noComb HLT_mu20_msonly_iloosems_mu6noL1_msonly_nscan05_L1MU20_J40 HLT_mu20_msonly_iloosems_mu6noL1_msonly_nscan05_L1MU20_XE30 HLT_mu6_dRl1_mu20_msonly_iloosems_mu6noL1_dRl1_msonly	2015 2016 2016 2017/18 2017/18 2017/18
Trimuon	MS-only muons	μDPJ	HLT_3mu6_msonly	2015 2016 2017 2018
MET	E_T^{miss}	μDPJ & caloDPJ	HLT_xe70 HLT_xe90_mht_L1XE50 HLT_xe110_mht_L1XE50 HLT_xe110_pufit_L1XE55 HLT_xe110_pufit_xe70_L1XE50	2015 2016 2016 2017 2018

VBF - Scale factors estimation for E_T^{miss} trigger

- In order to trigger on E_T^{miss} below the efficiency plateau, scale factors (SFs) are estimated for each data period by studying the data/MC ratio in $Z \rightarrow \mu\mu$ events

- All events required to pass:
  - VBF selection: $N_{jets}(p_T>30\ GeV) > 1$, $|\Delta\eta_{jj}|>3$, $m_{jj}>1\ TeV$
  - Standard ATLAS $Z \rightarrow \mu\mu$ selection
  - Lowest unprescaled single lepton trigger
- Events in numerator also required to pass lowest unprescaled E_T^{miss} trigger
- Per data period:
  - Turn-on curves plotted as a function of proxy offline $E_T^{miss} = E_T^{miss} + p_T^{\mu\mu}$
  - Data/MC ratio fitted with error function to obtain final SFs

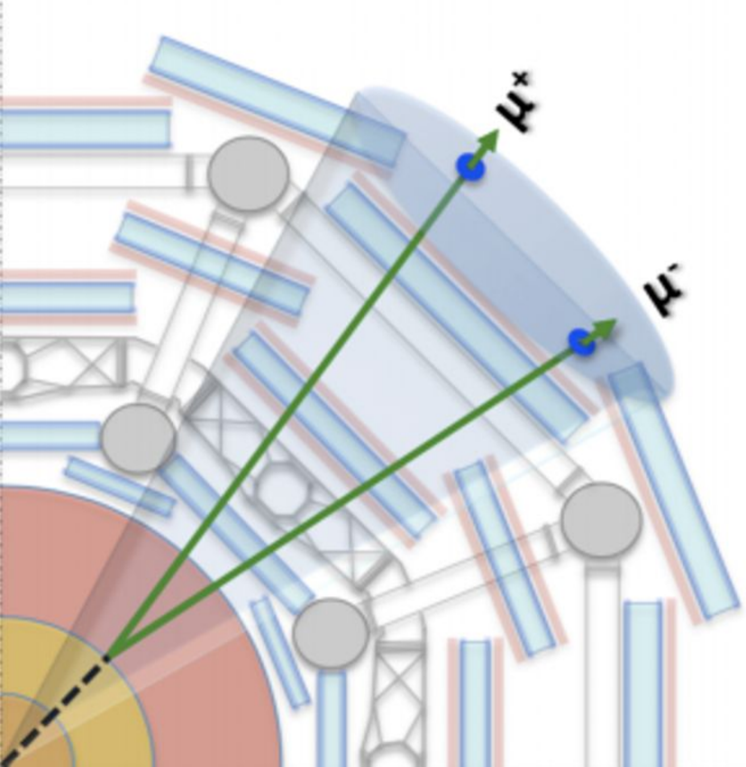
Trigger type	Lowest Unprescaled Chain	Year
E_T^{miss}	HLT_xe70 HLT_xe90_mht_L1XE50 HLT_xe110_mht_L1XE50 HLT_xe110_pufit_L1XE55 HLT_xe110_pufit_xe70_L1XE50	2015 2016 2016 2017 2018
Single Muon	HLT_mu20_iloose_L1MU15 HLT_mu26_ivarmedium	2015 2016-2018

$Z \rightarrow \mu\mu$ MC vs. Run 2 Data

*no SF applied for 2015

VBF μDPJ channel

VBF µDPJ channel selection



(1) Trigger strategy

- **NarrowScan** targets µDPJs
- **Trimuon** helpful for $H \rightarrow 4\gamma_d + X$
- **MET** to gain sensitivity below 225 GeV

(2) DPJ quality cuts

- Cosmic ray tagger score greater than 0.5
- Veto MS crack region: $1.0 \leq \eta \leq 1.1$
- Veto combined muons

(3) Further cuts

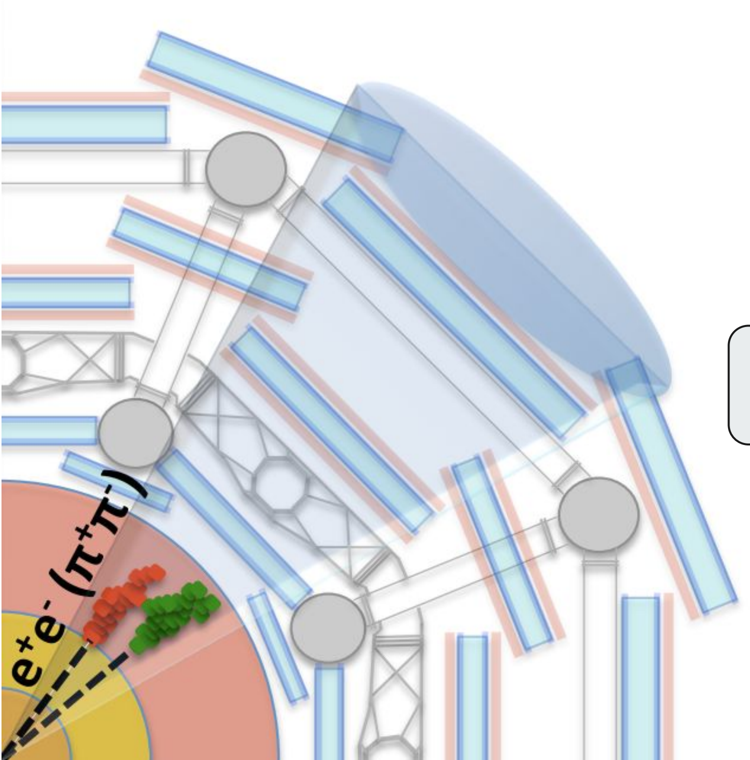
- DPJ centrality (wrt. VBF jets) > 0.7
- E_T^{miss} > 100 GeV

(4) ABCD SR definition

- µDPJ net charge = 0
- µDPJ ID track isolation (isoID) < 2 GeV

VBF caloDPJ channel

VBF caloDPJ channel selection



Two SRs with different E_T^{miss} range

(1) Trigger strategy

- E_T^{miss} trigger plus further cut offers ~100% efficiency

(2) DPJ quality cuts

- Exclude calorimeter overlap region
- caloDPJ |timing| < 4 ns
- BIB tagger score > 0.2
- Jet Vertex tagger (JVT) score < 0.4
- QCD tagger score > 0.5

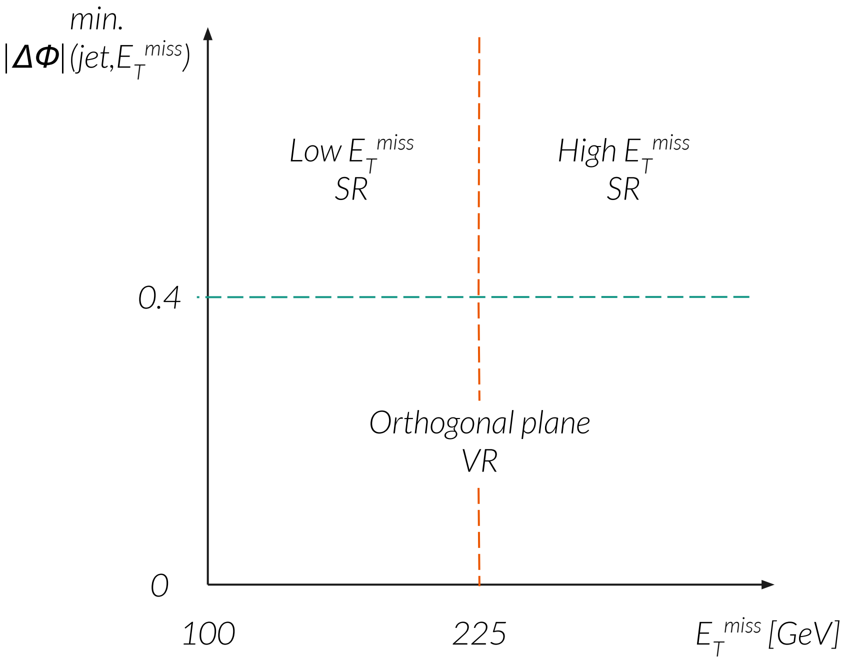
(3) Further cuts

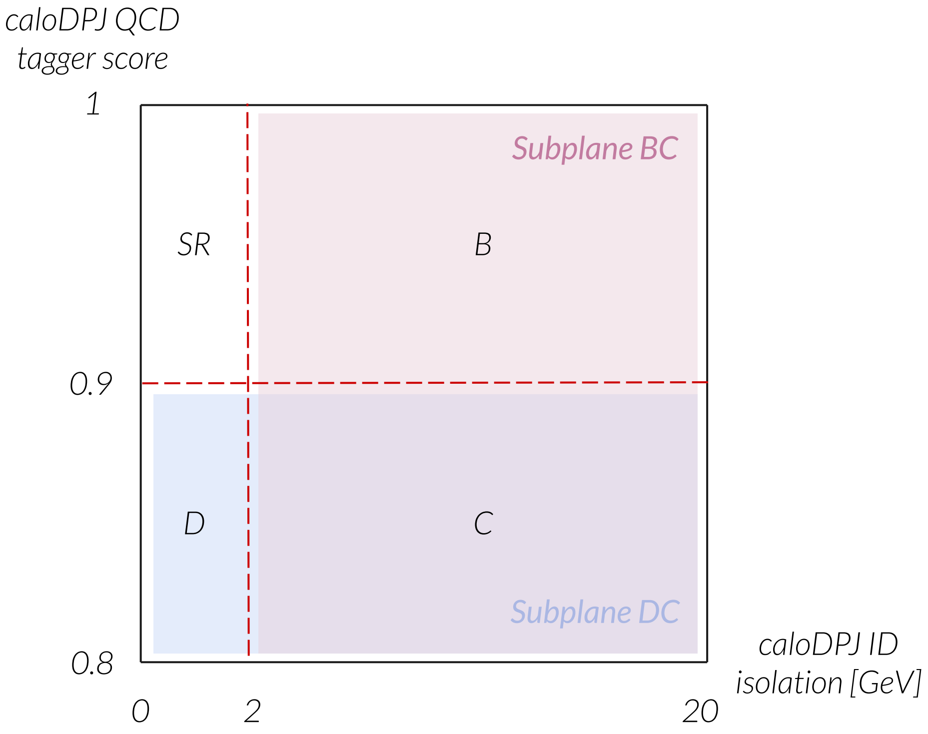
- $100 < E_T^{miss} < 225$ GeV || $E_T^{miss} > 225$ GeV
- Minimum $|\Delta\Phi|(jet, E_T^{miss}) > 0.4$

(4) ABCD SR definition

- cDPJ ID track isolation (isoID) < 2 GeV
- cDPJ QCD tagger score > 0.9

VBF caloDPJ channel breakdown





VBF caloDPJ channel breakdown

High MET SR

VBF jets cuts & $|\Delta\Phi_{jj}|<2.5$
Lepton & *b*-jet vetos
E_T^{miss} trigger
$E_T^{miss}>225$ GeV
$\Delta\Phi(\text{jet},E_T^{miss})>0.4$

Leading DPJ is caloDPJ
caloDPJ gapRatio >0.9
caloDPJ BIBtagger score >0.2
caloDPJ |timing| <4 ns
caloDPJ JVT score <0.4
caloDPJ QCD tagger score >0.5

caloDPJ ID isolation → [0, 2] GeV
caloDPJ QCD tagger score → [0.9,1]

Low MET SR

VBF jets cuts & $|\Delta\Phi_{jj}|<2.5$
Lepton & *b*-jet vetos
E_T^{miss} trigger
$E_T^{miss}\rightarrow$ [100, 225] GeV
$\Delta\Phi(\text{jet},E_T^{miss})>0.4$

Leading DPJ is caloDPJ
caloDPJ gapRatio >0.9
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caloDPJ |timing| <4 ns
caloDPJ JVT score <0.4
caloDPJ QCD tagger score >0.5

caloDPJ ID isolation → [0, 2] GeV
caloDPJ QCD tagger score → [0.9,1]

Orthogonal plane VR

VBF jets cuts & $|\Delta\Phi_{jj}|<2.5$
Lepton & *b*-jet vetos
E_T^{miss} trigger
$E_T^{miss}>100$ GeV
$\Delta\Phi(\text{jet},E_T^{miss})<0.4$

Leading DPJ is caloDPJ
caloDPJ gapRatio >0.9
caloDPJ BIBtagger score >0.2
caloDPJ |timing| <4 ns
caloDPJ JVT score <0.4
caloDPJ QCD tagger score >0.5

caloDPJ ID isolation → [0, 20] GeV
caloDPJ QCD tagger score → [0.8,1]

Subplanes VR

VBF jets cuts & $|\Delta\Phi_{jj}|<2.5$
Lepton & *b*-jet vetos
E_T^{miss} trigger
$E_T^{miss}>100$ GeV
$\Delta\Phi(\text{jet},E_T^{miss})>0.4$

Leading DPJ is caloDPJ
caloDPJ gapRatio >0.9
caloDPJ BIBtagger score >0.2
caloDPJ |timing| <4 ns
caloDPJ JVT score <0.4
caloDPJ QCD tagger score >0.5

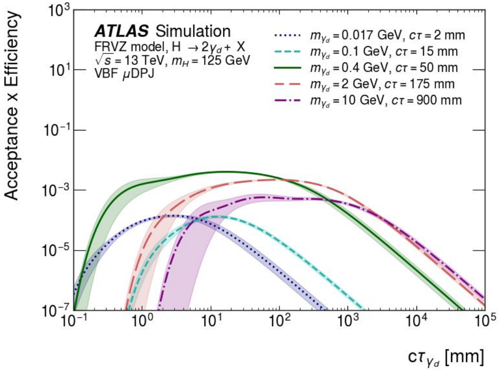
BC
caloDPJ ID isolation → [2, 20] GeV
caloDPJ QCD tagger score → [0.8,1]

DC
caloDPJ ID isolation → [0, 20] GeV
caloDPJ QCD tagger score → [0.8,0.9]

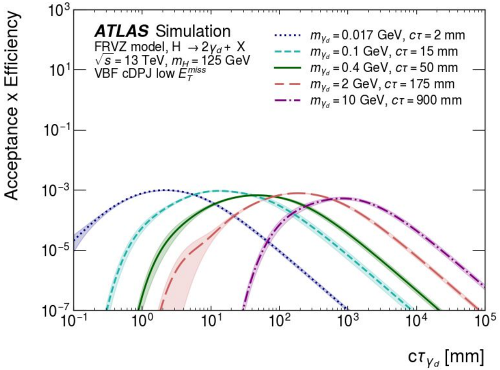
More on VBF analysis

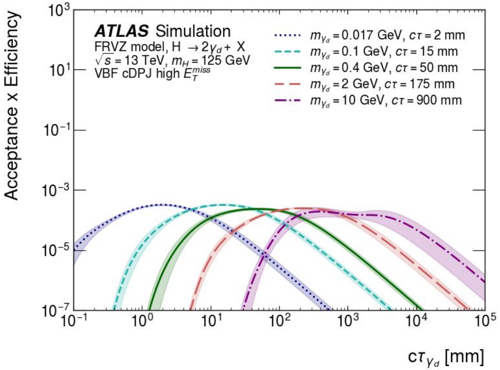
VBF - Lifetime reweighting

μDPJ



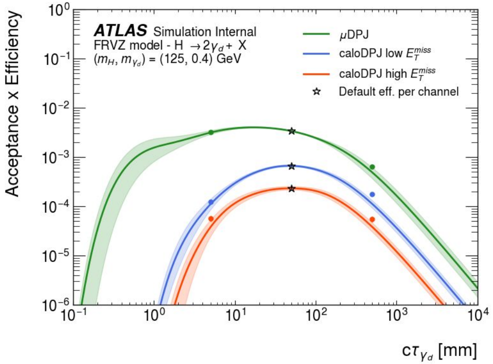
caloDPJ





Validation

Using samples with $m_{\gamma d}$=0.4 GeV



- Validation points agree with extrapolated curve for $m_{\gamma d}$ = 0.4 GeV within uncertainty
  - Disagreement in cDPJ low E_T^{miss}
  - Extra syst. uncert. considered in low E_T^{miss} SR for *cτ>50 mm* to take into account non-closure

FRVZ vector portal interpretation: (ε, $m_{\gamma d}$) limits

1. For each generated ($m_{\gamma d}$, $c\tau_{\gamma d}$) pair, the analysis efficiency is extrapolated to the 2D plane:
   a. Along cτ (ε) using the lifetime reweighting curves
   b. Along $m_{\gamma d}$ according to γ_d branching ratio
2. 2D limits are obtained doing a simultaneous fit of the available ggF/WH/VBF analysis channels in a 100x100 grid in ($m_{\gamma d}$, $c\tau_{\gamma d}$)
   a. Contaminations from $\gamma_d \to e^+e^-$ in the μDPJ channels are not considered here
   b. This step runs for each generated mass point
3. The final limit is obtained by running a linear interpolation between the results that are obtained in step (2)

- "Wobbly" contour due to low resolution used when running the fit framework. This was done with about 13K fits!