Displaced lepton jets in ATLAS

Run-2 & comments on Run-3

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on behalf of the ATLAS Collaboration

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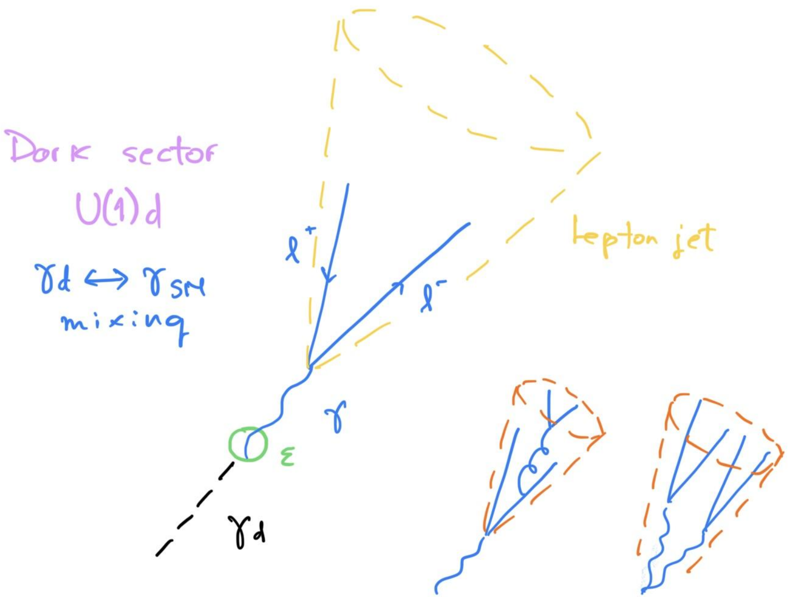
Why lepton jets?

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

- **Today:**
  - Searches for **displaced LJ-like signatures** in Run-2 data
  - Different **Higgs production modes:**
    - ggF+WH production (2022)
    - VBF production (2023)
  - **A few comments on Run-3**

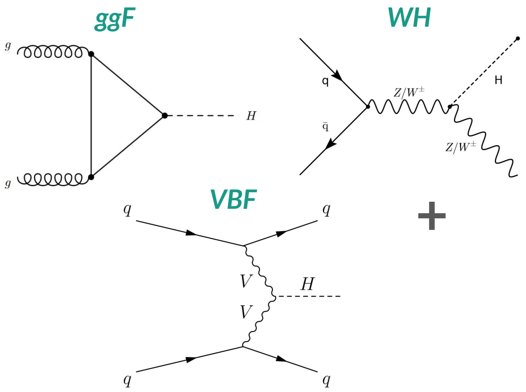
Lepton jet (LJ) = cluster of collimated light charged particles (e^+e^-, $\mu^+\mu^-$, qq')



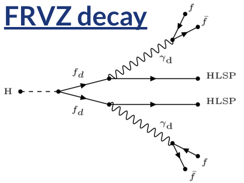
Search overview

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

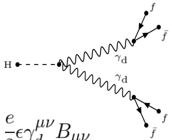
Production modes



FRVZ decay



HAHM decay



$\mathcal{L} \propto \frac{e}{2}\epsilon\gamma_d^{\mu\nu}B_{\mu\nu}$

Exploit signature of different production modes

Final state:

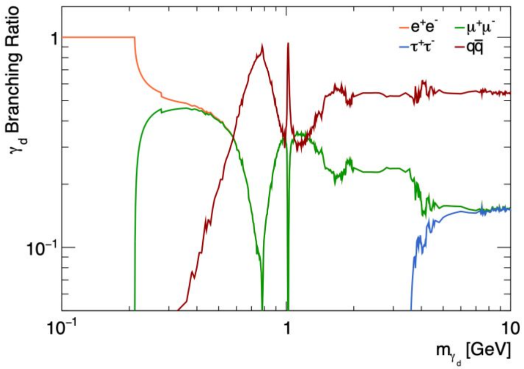
Displaced LJs (+ E_T^{miss})

- 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 (pub. 2022)
  - VBF search & full combination (pub. 2023)

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

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

γ_d decay length



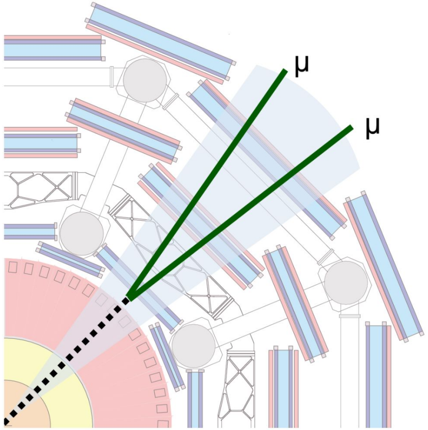
Displaced LJ signatures

Custom reconstructed objects:

Dark Photon Jets (DPJ)

Sensitive to γ_d decays after pixel detector

Background signatures	Collisional	Non-collisional	
	Hadronic jets (e.g., QCD MJ, V+jets)	Cosmic rays (μDPJ)	Beam-induced (caloDPJ)



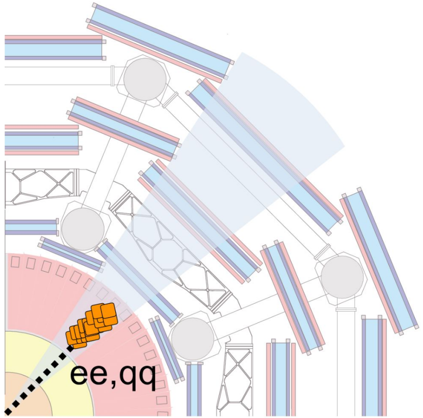
muonic DPJ

μDPJ

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

Decays outside ID acceptance

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



calorimeter DPJ

caloDPJ

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

Targeting decays in HCAL

Low EM fraction jets with no matching MS tracks

NN-based taggers for DPJ quality

Cosmic-ray tagger (μDPJ)

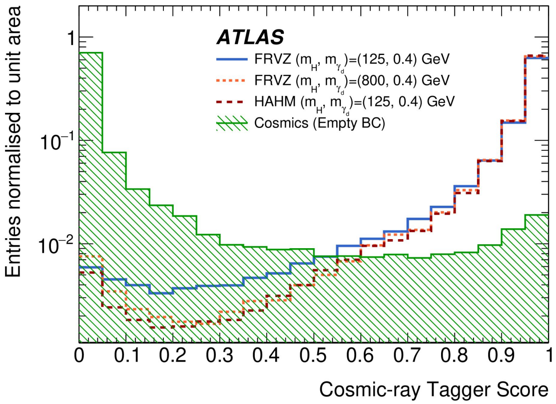
- Based on track parameters and RPC timing information
- Per-track tagging classifying **cosmic background against tracks originated by collision products**

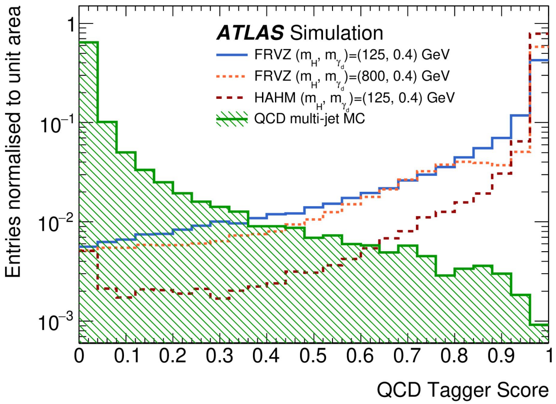
QCD tagger (cDPJ)

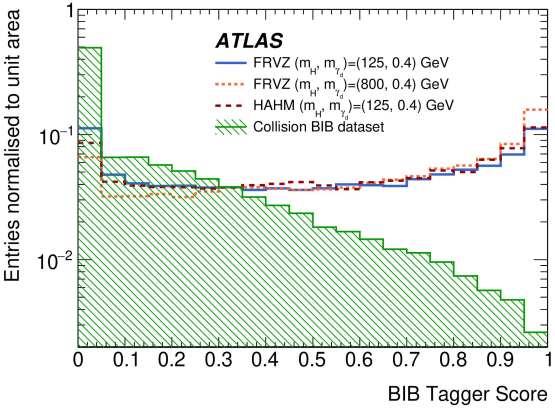
- 3D representations of jet energy built with calo-clusters
- Using energy deposit, Φ and η in each calorimeter sampling
- CNN trained to **classify QCD MJ from signal-like jets**

BIB tagger (cDPJ)

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







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

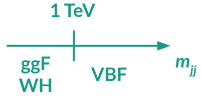
Useful when triggering on the DPJ itself becomes difficult

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

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

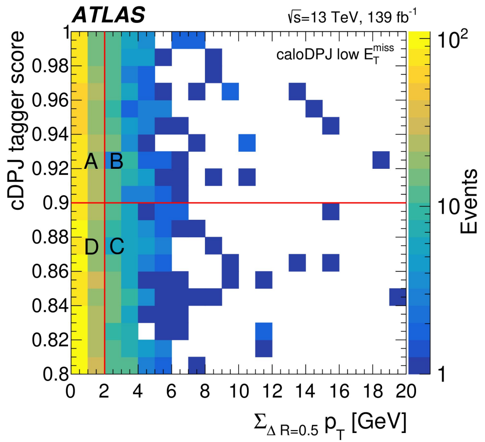
- Define plane using two uncorrelated variables
- Split plane in A, B, C & D regions:
  - A = Signal-enriched
  - B,C,D = Background-enriched
- Estimate N_A as:

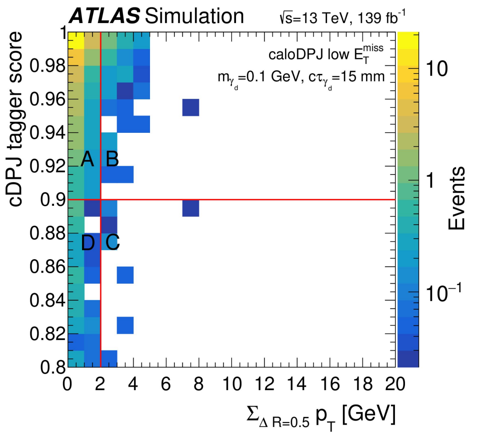
$$N_A = \frac{N_B \times N_D}{N_C}$$

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

Variables

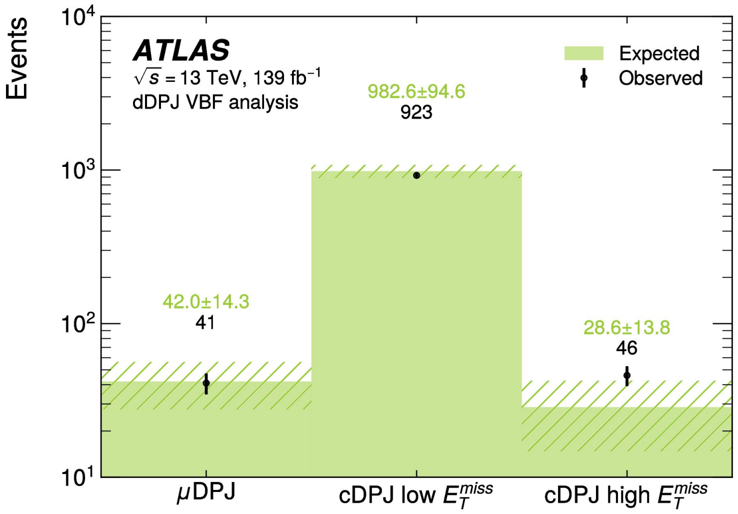
1. caloDPJ ID isolation
   Sum of p_T of tracks inside cone with R=0.5 around leading DPJ ID track
2. caloDPJ QCD tagger score





Unblinded results: anything new?

- **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

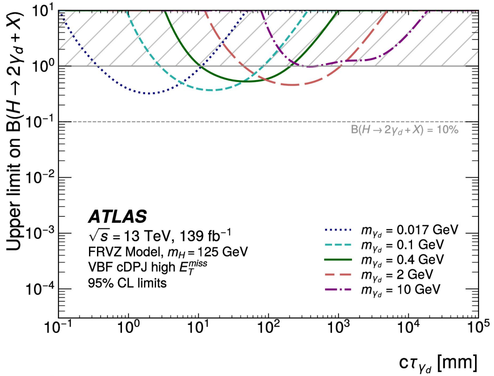
Selection	CRB	CRC	CRD	SR expected	SR observed
SR_{μ}	44	22	21	42 ± 14	41
SR_c^L	224	256	1123	983 ± 95	923
SR_c^H	9	11	35	29 ± 14	46

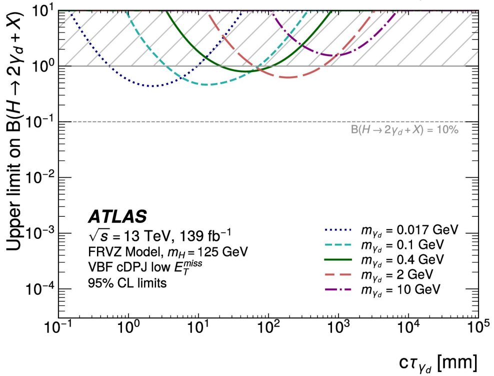
Upper limits on BR(H⟶2γ$_d$+X): e.g., VBF

Limits on single *cτ* are extrapolated via lifetime reweighting to other *cτ* values **(backup)**

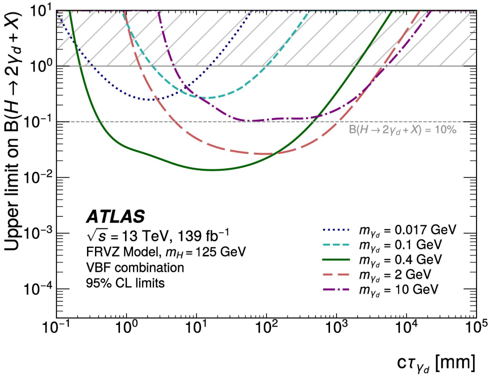
- Single ABCD limits for each channel and mass point
- Observed upper limits on *BR(H⟶2γ$_d$+X)* for each SR and overall VBF combination
- Limits available for ggF & WH allow for full combination!

caloDPJ

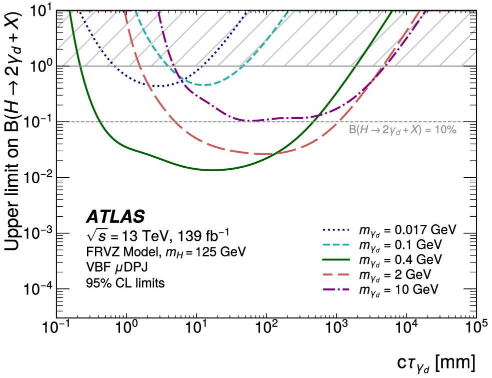




VBF combination

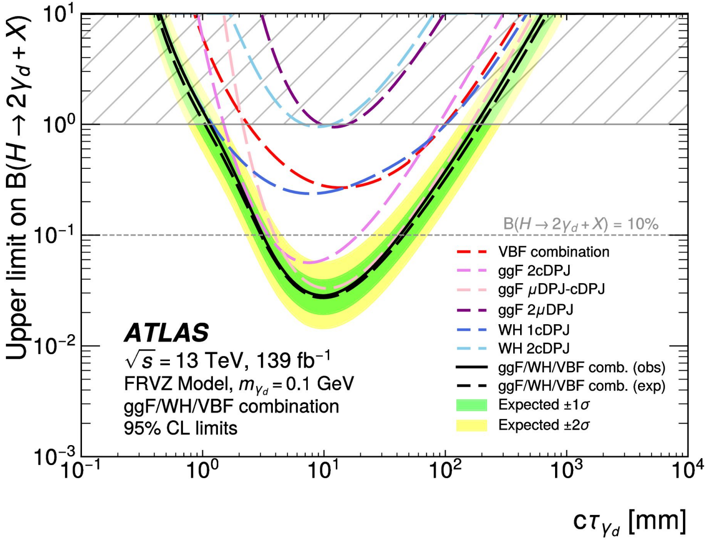


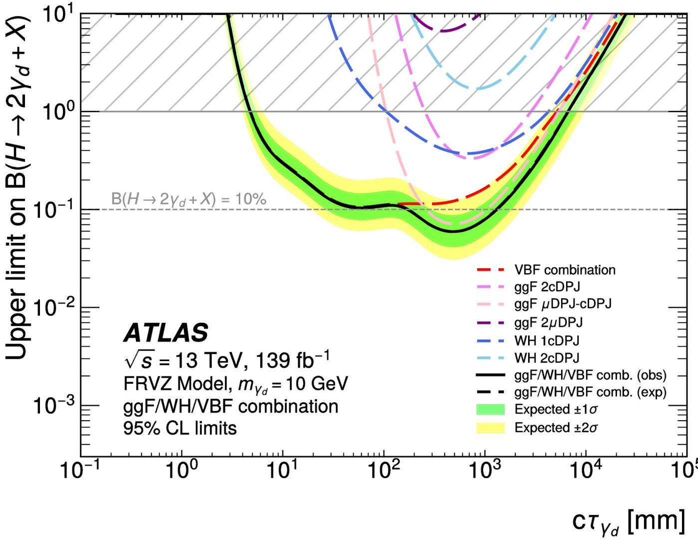
μDPJ



Combined limits on BR(H⟶2γ_d+X): ggF+WH+VBF

- Limits on $BR(H \longrightarrow 2\gamma_d+X)$ 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



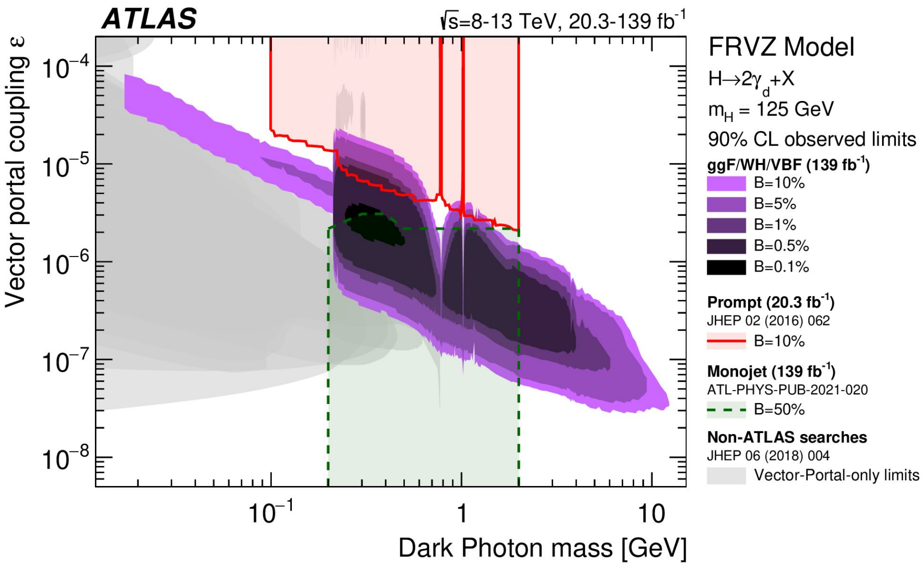


- Higher sensitivity obtained from ggF channels
- VBF offers competitive sensitivity at low and high $c\tau_{\gamma d}$, particularly at high $m_{\gamma d}$ values

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+VBF
Full FRVZ combination



Status and some comments on Run-3

Run-2

- **No new physics - for now!**
- [ε, $m_{\gamma d}$] limits for full combination → Strongest ATLAS exclusion for displaced LJ searches!
- Tentative future combination with prompt LJ Run-2 search (expected for ICHEP)

Run-3: Preliminary studies

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

Improved trigger strategy

Exploring NarrowScan+VBF for μDPJ signatures

CalRatio+VBF for caloDPJ signatures

Implement updated taggers

NN taggers trained in newest release for performance improval

Displaced vertexing in MS

Further constrain μDPJ channel

Improved background estimation

Tentative bump hunt background estimation in μDPJ channel

Mono-LJ signature

e.g., E_T^{miss}/jet + pLJ/dLJ
Sensitive also to inelastic DM models

Backup

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

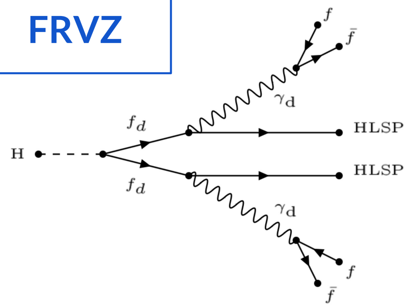
- **Run-2 VBF:** E_T^{miss} trigger forces offline cut that reduces sensitivity to models with low intrinsic E_T^{miss} (e.g., HAHM)

- **Run-3 wishlist:**

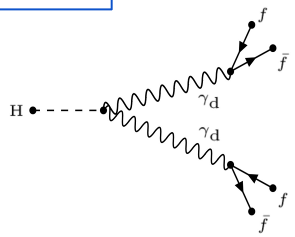
  - **µDPJ:** VBF + NarrowScan MS-only
  - Inclusive NS ready for stable beam this year

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

FRVZ



HAHM



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	-
$\lvert\Delta t_{\text{caloDPJs}}\rvert$ [ns]	-	< 2.5	-
caloDPJ JVT	-	< 0.4	-
$\Delta\phi_{\text{DPJ}}$	$> \pi/5$	$> \pi/5$	$> \pi/5$
BIB tagger score	-	> 0.2	> 0.2
$\max(\sum p_T)$ [GeV]	< 4.5	< 4.5	< 4.5
$\prod$ QCD tagger	-	> 0.95	> 0.9

WH

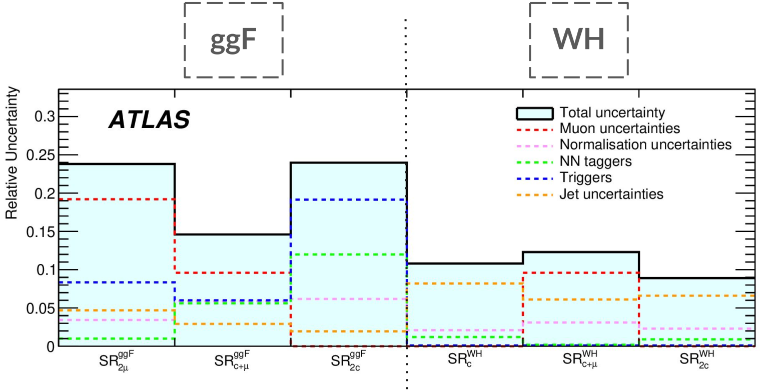
Requirement / Region	SR^{WH}_{c}	SR^{WH}_{2c}	$SR^{WH}_{c+\mu}$
Number of μDPJs	0	0	1
Number of caloDPJs	1	2	1
Single-lepton trigger (μ, e)	yes	yes	yes
m_T [GeV]	> 120	-	-
$\lvert t_{\text{caloDPJ}}\rvert$ [ns]	< 4	< 4	< 4
Leading (far) caloDPJ width	< 0.08	< 0.10 (0.15)	< 0.1
caloDPJ p_T [GeV]	> 30	-	-
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

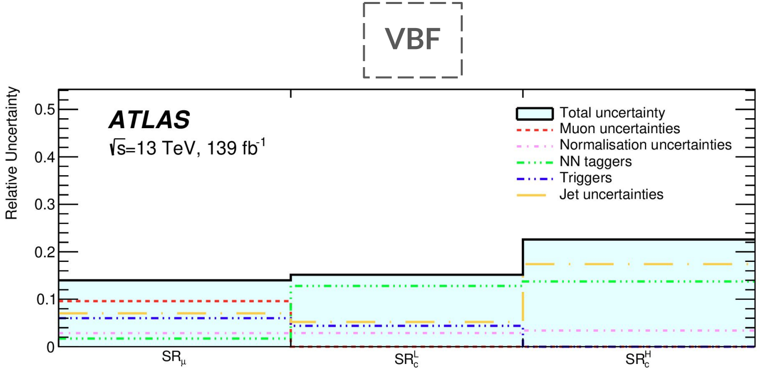
VBF

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

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





Displaced LJs VBF

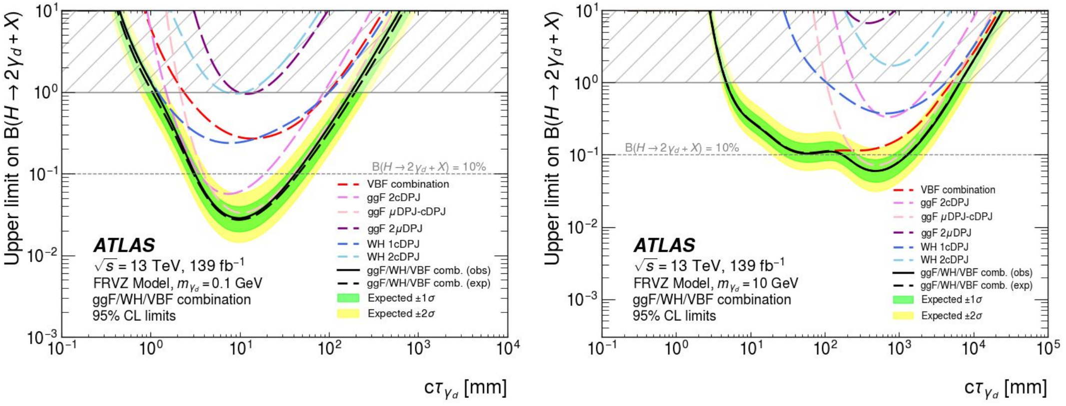
- First ATLAS search using VBF production
- Analysis performed for combination with previous ggF/WH iteration

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!

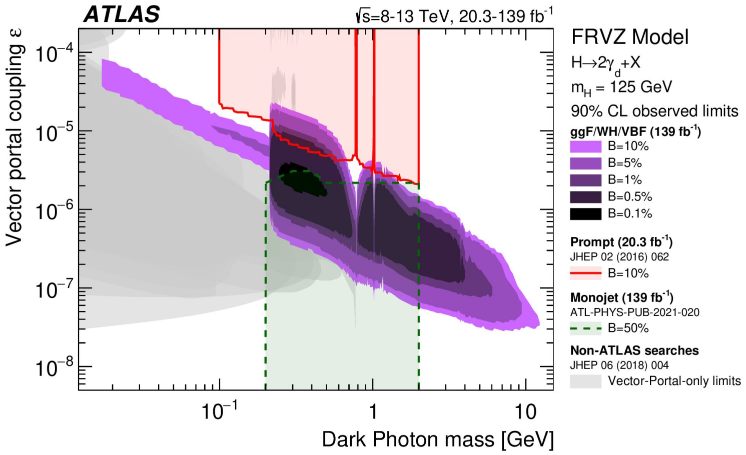
Combination with observed ggF/WH limits



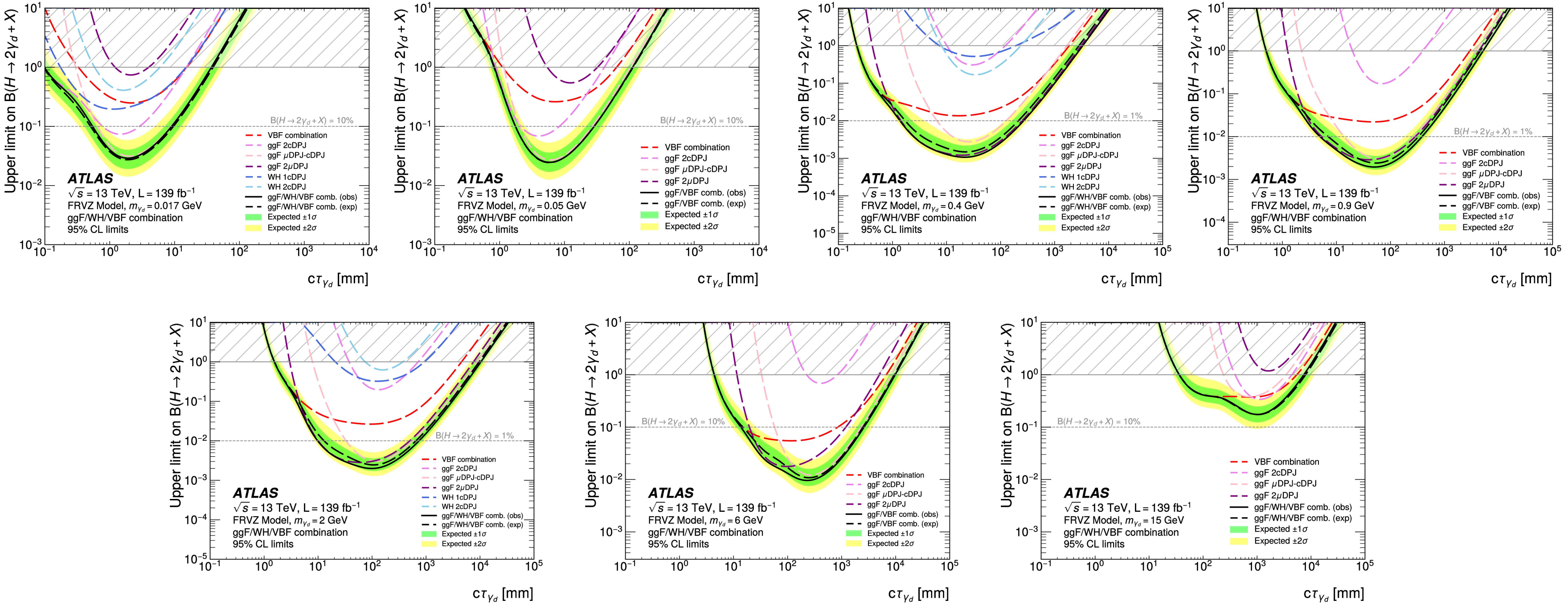
Combined limits are interpolated in the full mass range

⇩

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



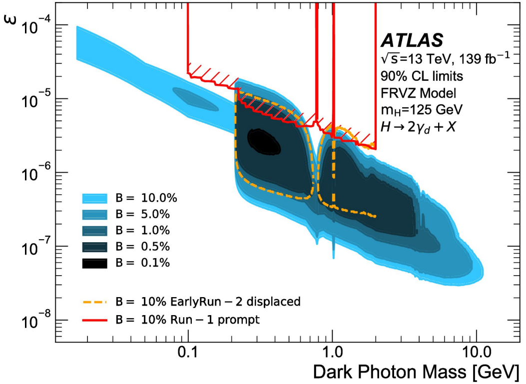
BR(H⟶2γ$_d$+X) combined limits: ggF+WH+VBF



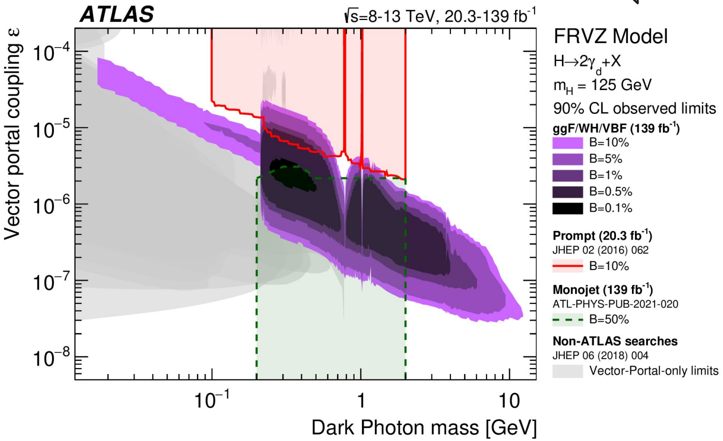
FRVZ vector portal interpretation: (ε, $m_{\gamma d}$) limits

- 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



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		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 $Z \to \mu\mu$ 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 $Z \to \mu\mu$ 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

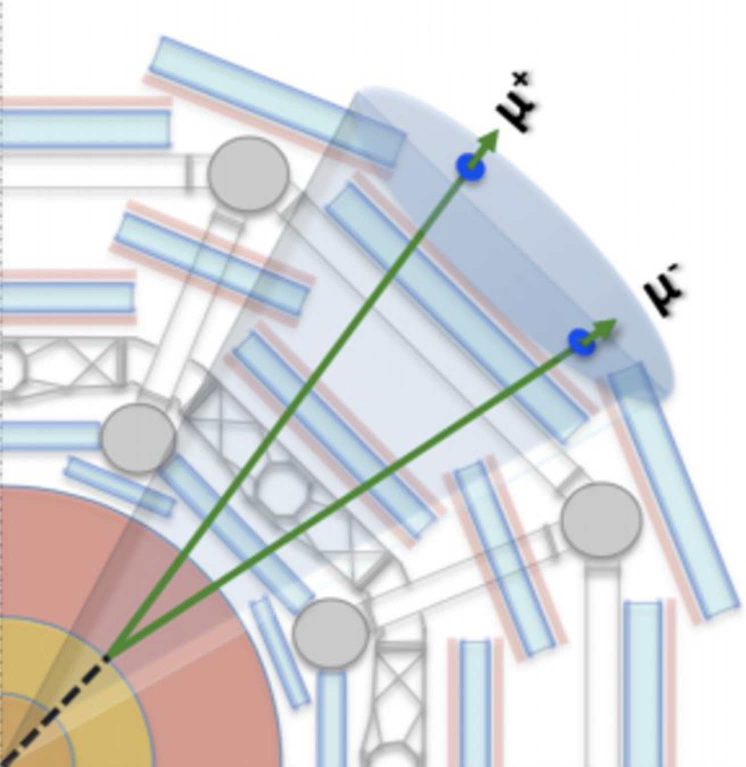
Trigger type	Lowest Unprescaled Chain	Year
E_T^{miss}	HLT_xe70 HLT_xe90_mht_L1XE50 HLT_xe110_mht_L1XE50 HLT_xe110_pufit_L1XE55 HLT_xe110_pufit_xe70_L1XE50	2015 2016 2016 2017 2018
Single Muon	HLT_mu20_iloose_L1MU15 HLT_mu26_ivarmedium	2015 2016-2018

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

no SF applied for 2015

VBF μDPJ channel

VBF μDPJ channel selection



(1) Trigger strategy

- **NarrowScan** targets **μ**DPJs
- **Trimuon** helpful for $H \to 4\gamma_d + X$
- **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

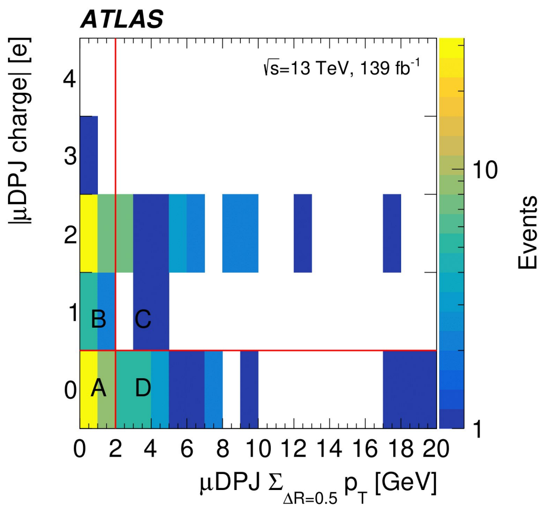
(3) Further cuts

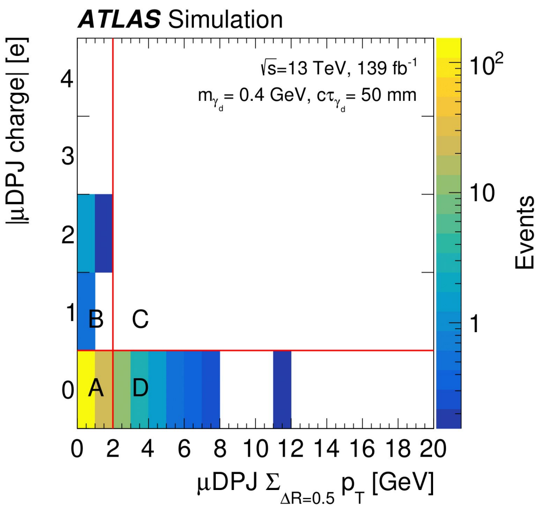
- DPJ centrality (wrt. VBF jets) > 0.7
- $E_T^{miss} > 100$ GeV

(4) ABCD SR definition

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

μDPJ ABCD plane





Variables

1. Leading μDPJ isoID
   Sum of p_T of tracks inside cone with R=0.5 around leading μDPJ ID track
2. Leading μDPJ net charge

Region	isoID [GeV]	Charge [e]
A	0 - 2	0
B	0 - 2	≥ 1
C	2 - 20	≥ 1
D	2 - 20	0

ABCD Yield	$m(\gamma_d) = 0.017$GeV $c\tau = 2$mm	$m(\gamma_d) = 0.05$GeV $c\tau = 7$mm	$m(\gamma_d) = 0.9$GeV $c\tau = 115$mm	$m(\gamma_d) = 2$GeV $c\tau = 175$mm	$m(\gamma_d) = 6$GeV $c\tau = 600$mm	$m(\gamma_d) = 25$GeV $c\tau = 1200$mm	$m(\gamma_d) = 40$GeV $c\tau = 1400$mm
nA	7.0±0.5	7.0±0.5	119.1±2.1	107.4±1.9	38.0±1.1	4.0±0.4	1.5±0.2
nB	0.9±0.2	0.8±0.2	2.3±0.3	3.0±0.3	2.6±0.3	1.7±0.3	1.5±0.2
nC	0.1±0.1	0.1±0.0	0.2±0.1	0.2±0.1	0.2±0.1	0.2±0.1	0.1±0.1
nD	0.6±0.1	0.6±0.1	10.1±0.6	9.3±0.6	3.2±0.3	0.4±0.1	0.1±0.0
nA estimate							

ABCD Yield	$m(\gamma_d) = 0.4$GeV $c\tau = 50$mm	$m(\gamma_d) = 0.4$GeV $c\tau = 5$mm	$m(\gamma_d) = 0.4$GeV $c\tau = 500$mm	$m(\gamma_d) = 10$GeV $c\tau = 900$mm	$m(\gamma_d) = 15$GeV $c\tau = 1000$mm	Run 2 Data
nA	178.7±3.6	168.3±3.4	33.8±1.5	19.3±1.7	8.8±1.1	41
nB	2.2±0.4	1.6±0.3	0.4±0.2	1.9±0.7	4.5±3.0	44
nC	0.3±0.1	0.2±0.1	0.1±0.1	0.2±0.1	0.3±0.1	22
nD	16.4±1.1	15.4±1.0	3.2±0.6	1.6±0.3	0.6±0.2	21
nA estimate						42.0±14.3

$BR(H \rightarrow 2\gamma_d + X) = 10\%$

ABCD validation: subplane BC

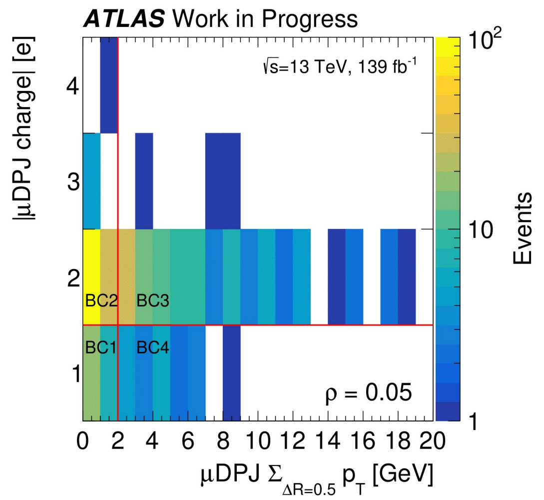
- Due to lack of statistics in ABCD subplanes, cut is relaxed to E_T^{miss}*>20 GeV* to allow more events to enter BC & DC

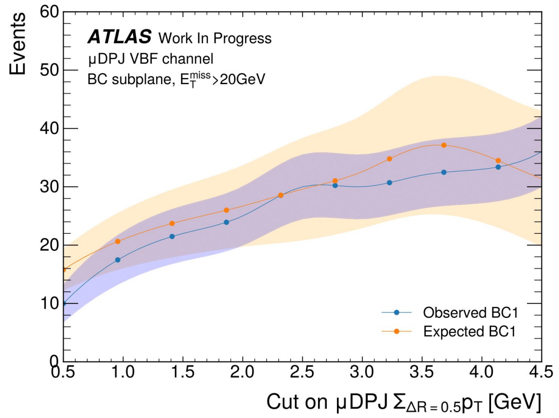
- Prediction closes with default cuts
- Correlation ~5%
- Good agreement when sliding threshold in μDPJ ID isolation

ABCD Yield	$m(\gamma_d) = 0.017$GeV $c\tau = 2$mm	$m(\gamma_d) = 0.05$GeV $c\tau = 7$mm	$m(\gamma_d) = 0.9$GeV $c\tau = 115$mm	$m(\gamma_d) = 2$GeV $c\tau = 175$mm	$m(\gamma_d) = 6$GeV $c\tau = 600$mm	$m(\gamma_d) = 25$GeV $c\tau = 1200$mm	$m(\gamma_d) = 40$GeV $c\tau = 1400$mm
nA	0.3±0.1	0.2±0.1	1.1±0.2	1.7±0.2	1.8±0.2	0.7±0.2	0.5±0.1
nB	1.0±0.2	1.3±0.2	2.1±0.3	2.9±0.3	1.9±0.2	2.0±0.3	2.0±0.3
nC	0.1±0.1	0.1±0.0	0.2±0.1	0.3±0.1	0.3±0.1	0.3±0.1	0.2±0.1
nD	0.1±0.0	0.0±0.0	0.1±0.1	0.1±0.1	0.1±0.1	0.0±0.0	0.0±0.0
nA estimate							

ABCD Yield	$m(\gamma_d) = 0.4$GeV $c\tau = 50$mm	$m(\gamma_d) = 0.4$GeV $c\tau = 5$mm	$m(\gamma_d) = 0.4$GeV $c\tau = 500$mm	$m(\gamma_d) = 10$GeV $c\tau = 900$mm	$m(\gamma_d) = 15$GeV $c\tau = 1000$mm	Run 2 Data
nBC1	1.7±0.3	0.4±0.2	0.4±0.3	1.9±0.8	3.7±3.0	25
nBC2	2.2±0.4	2.8±0.4	0.3±0.2	0.8±0.2	2.4±1.0	136
nBC3	0.3±0.1	0.8±0.4	0.1±0.1	0.2±0.1	0.1±0.1	102
nBC1	0.1±0.1	0.1±0.1	0.1±0.1	0.0±0.0	0.1±0.1	20
nBC1 estimate						26.7±6.9

BR($H \rightarrow 2\gamma_d$+X)=10%

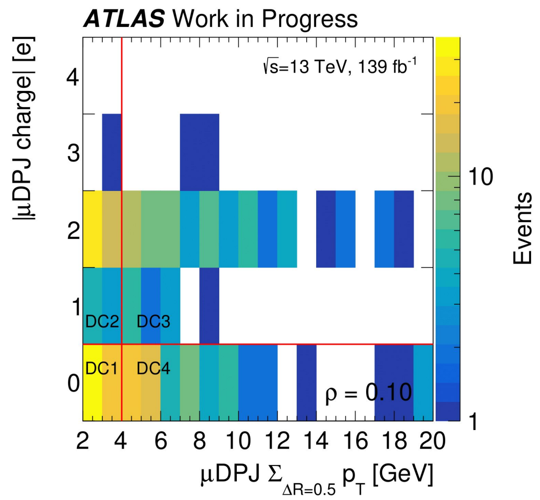




ABCD validation: subplane DC

- Due to lack of statistics in ABCD subplanes, cut is relaxed to *E_T^{miss}>20 GeV* to allow more events to enter BC & DC

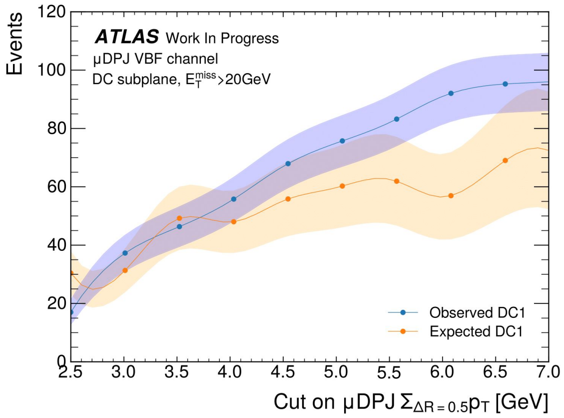
- Prediction closes with default cuts
- Correlation ~10%
- Good agreement when sliding threshold in μDPJ ID isolation



ABCD Yield	$m(\gamma_d)$ = 0.017GeV $c\tau$ = 2mm	$m(\gamma_d)$ = 0.05GeV $c\tau$ = 7mm	$m(\gamma_d)$ = 0.9GeV $c\tau$ = 115mm	$m(\gamma_d)$ = 2GeV $c\tau$ = 175mm	$m(\gamma_d)$ = 6GeV $c\tau$ = 600mm	$m(\gamma_d)$ = 25GeV $c\tau$ = 1200mm	$m(\gamma_d)$ = 40GeV $c\tau$ = 1400mm
nA	<0.1	0.1±0.02	1.6±<0.1	1.5±0.07	0.5±0.04	<0.1	<0.1
nB	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
nC	<0.1	0	<0.1	0.2±0.1	<0.1	<0.1	0
nD	<0.1	<0.1	0.3±0.03	0.3±0.03	0.2±0.02	0	0
nA estimate							

ABCD Yield	$m(\gamma_d)$ = 0.4GeV $c\tau$ = 50mm	$m(\gamma_d)$ = 0.4GeV $c\tau$ = 5mm	$m(\gamma_d)$ = 0.4GeV $c\tau$ = 500mm	$m(\gamma_d)$ = 10GeV $c\tau$ = 900mm	$m(\gamma_d)$ = 15GeV $c\tau$ = 1000mm	Run 2 Data
nDC1	2.4±0.13	2.6±0.14	4.6±0.6	<0.1	<0.1	55
nDC2	<0.1	<0.1	<0.1	<0.1	<0.1	50
nDC3	<0.1	<0.1	0	<0.1	<0.1	72
nDC4	0.6±<0.1	0.6±<0.1	0.9±0.3	<0.1	<0.1	69
nDC1 estimate						47.9±10.5

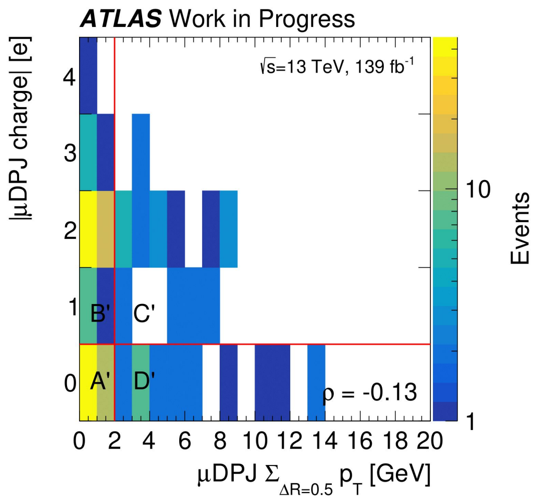
$BR(H \to 2\gamma_d + X) = 1\%$



ABCD validation: orthogonal plane

- Inverted $|\Delta\Phi_{jj}|$ cut
- Remove μDPJ centrality cut

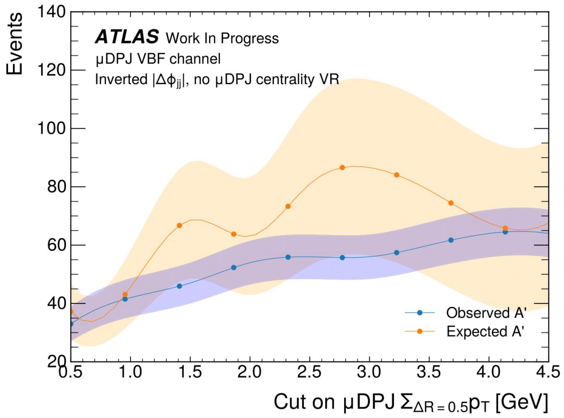
- Prediction closes with default cuts
- Correlation ~13%
- Good agreement when sliding threshold in μDPJ ID isolation



ABCD Yield	$m(\gamma_d)$ = 0.017GeV $c\tau$ = 2mm	$m(\gamma_d)$ = 0.05GeV $c\tau$ = 7mm	$m(\gamma_d)$ = 0.9GeV $c\tau$ = 115mm	$m(\gamma_d)$ = 2GeV $c\tau$ = 175mm	$m(\gamma_d)$ = 6GeV $c\tau$ = 600mm	$m(\gamma_d)$ = 25GeV $c\tau$ = 1200mm	$m(\gamma_d)$ = 40GeV $c\tau$ = 1400mm
nA	0.1±0.02	0.1±0.02	0.2±0.08	1.9±0.08	0.6±0.04	<0.1	<0.1
nB	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
nC	0	0	0	0	<0.1	0	0
nD	<0.1	0	0.1±0.02	0.1±0.02	<0.1	0	0
nA estimate							

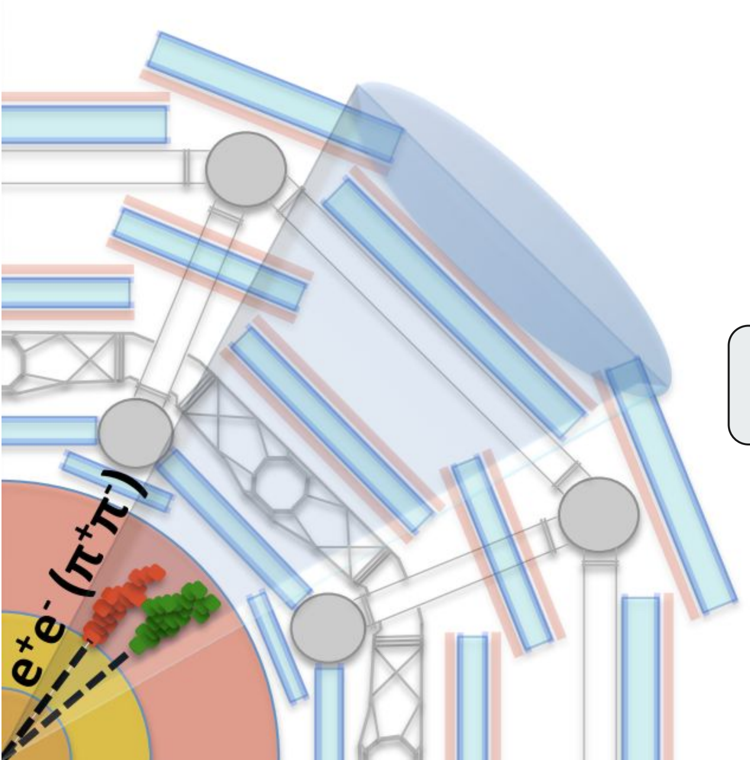
ABCD Yield	$m(\gamma_d)$ = 0.4GeV $c\tau$ = 50mm	$m(\gamma_d)$ = 0.4GeV $c\tau$ = 5mm	$m(\gamma_d)$ = 0.4GeV $c\tau$ = 500mm	$m(\gamma_d)$ = 10GeV $c\tau$ = 900mm	$m(\gamma_d)$ = 15GeV $c\tau$ = 1000mm	Run 2 Data
nA'	2.68±0.14	2.58±0.14	0.54±<0.1	0.37±0.1	0.11±<0.1	54
nB'	<0.1	<0.1	0	<0.1	<0.1	75
nC'	<0.1	<0.1	0	0	0	21
nD'	0.21±<0.1	0.23±<0.1	<0.1	<0.1	0	20
nA' estimate						63±20

BR(H→2γ_d+X)=1%



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

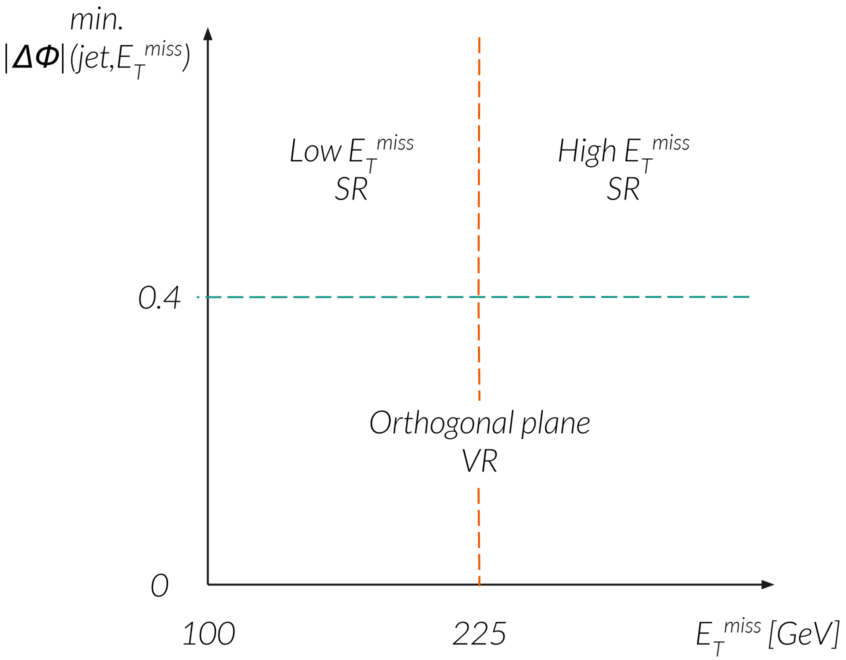
(3) Further cuts

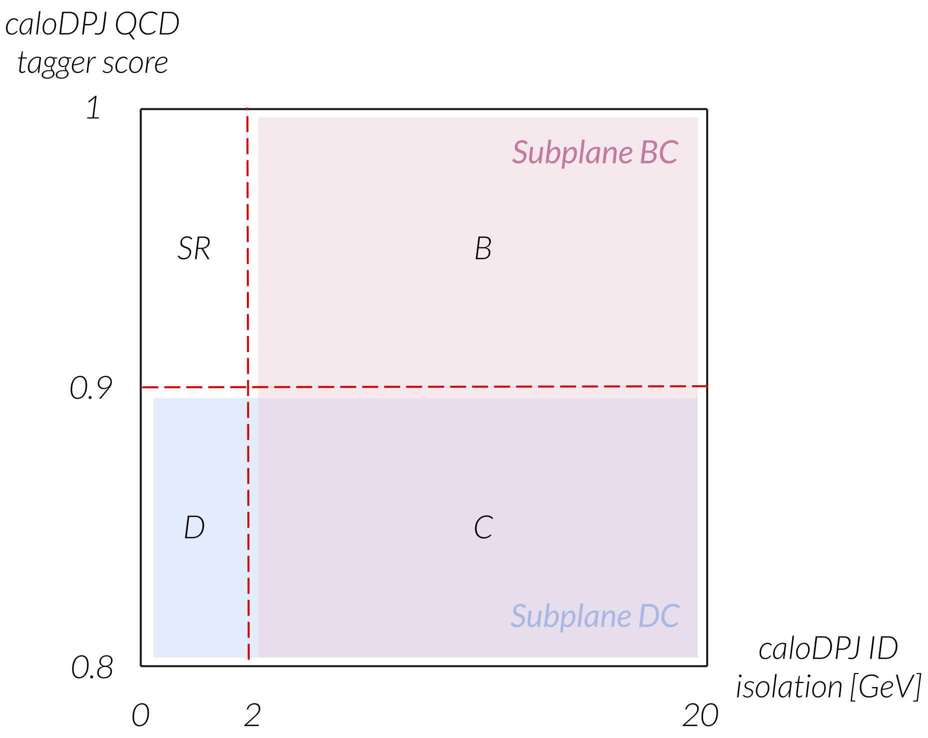
- $100 < E_T^{miss} < 225$ GeV || $E_T^{miss} > 225$ GeV
- Minimum $|\Delta\Phi|(jet, E_T^{miss}) > 0.4$

(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} → [100, 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]

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]

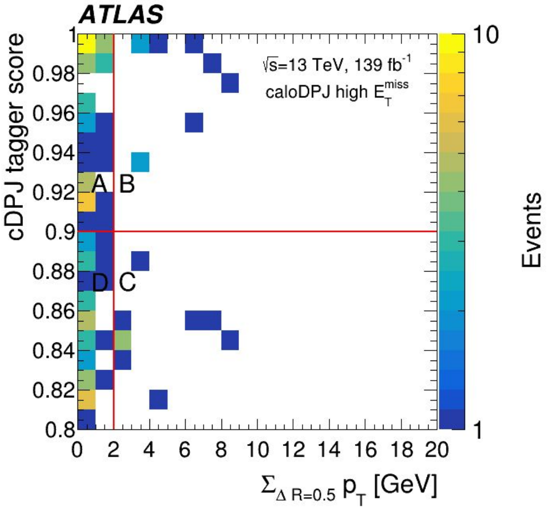
DC
caloDPJ ID isolation → [0, 20] GeV
caloDPJ QCD tagger score → [0.8,0.9]

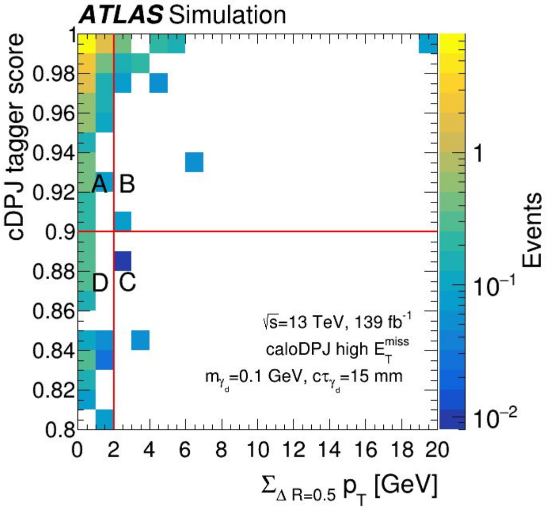
caloDPJ ABCD: $E_T^{miss} > 225$ GeV

Variables

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

Region	isoID [GeV]	QCD tagger score
A	0 - 2	0.9 - 1
B	0 - 2	0.9 - 1
C	2 - 20	0.8 - 0.9
D	2 - 20	0.8 - 0.9





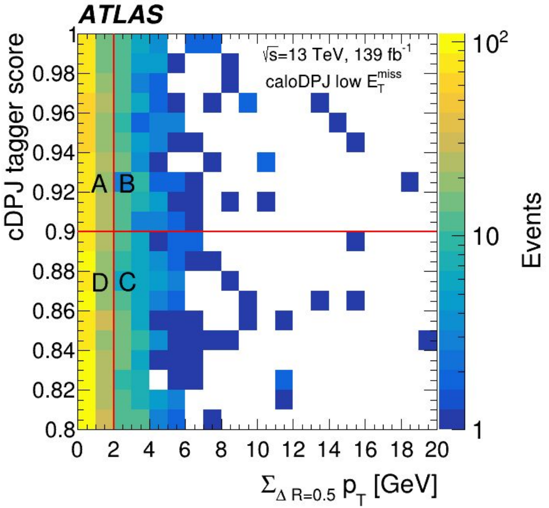
ABCD Yield	$m(\gamma_d)$ = 0.017GeV $c\tau$ = 2mm	$m(\gamma_d)$ = 0.05GeV $c\tau$ = 7mm	$m(\gamma_d)$ = 0.9GeV $c\tau$ = 115mm	$m(\gamma_d)$ = 2GeV $c\tau$ = 175mm	$m(\gamma_d)$ = 6GeV $c\tau$ = 600mm	$m(\gamma_d)$ = 25GeV $c\tau$ = 1200mm	$m(\gamma_d)$ = 40GeV $c\tau$ = 1400mm
nA	17.0±0.8	16.5±0.8	13.2±0.7	12.9±0.6	9.5±0.6	6.2±0.5	4.3±0.4
nB	1.2±0.2	1.4±0.2	1.4±0.2	1.0±0.2	1.2±0.2	0.6±0.1	0.6±0.1
nC	0.1±0.1	0.2±0.1	0.2±0.1	0.0±0.0	0.1±0.1	0.1±0.1	0.1±0.1
nD	1.3±0.2	1.5±0.2	1.9±0.2	2.2±0.3	1.3±0.2	0.6±0.2	0.3±0.1
nA estimate							

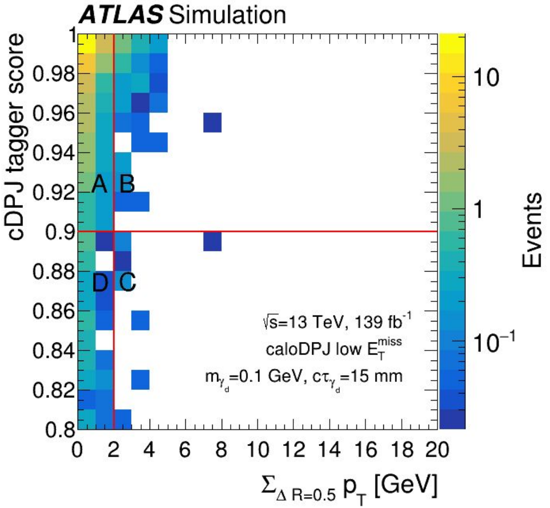
ABCD Yield	$m(\gamma_d)$ = 0.1GeV $c\tau$ = 15mm	$m(\gamma_d)$ = 0.4GeV $c\tau$ = 50mm	$m(\gamma_d)$ = 10GeV $c\tau$ = 900mm	$m(\gamma_d)$ = 15GeV $c\tau$ = 1000mm	Run 2 Data
nA	16.8±1.1	12.3±1.0	8.4±2.1	8.6±2.0	46.0
nB	1.5±0.3	0.7±0.2	2.2±1.3	0.5±0.2	9.0
nC	0.1±0.1	0.1±0.1	0.0±0.0	0.0±0.0	11.0
nD	1.6±0.3	1.1±0.4	0.3±0.1	0.3±0.2	35.0
nA estimate					28.6±13.8

$BR(H \rightarrow 2\gamma_d + X) = 10\%$

caloDPJ ABCD: $E_T^{miss} \in [100,225]$ GeV

- Using E_T^{miss} trigger SFs allows to explore low E_T^{miss} SR for statistical combination with high E_T^{miss} SR & μDPJ SR
- Other selections remain unchanged wrt. high E_T^{miss} SR
- Slightly worse sensitivity compared to high E_T^{miss} SR





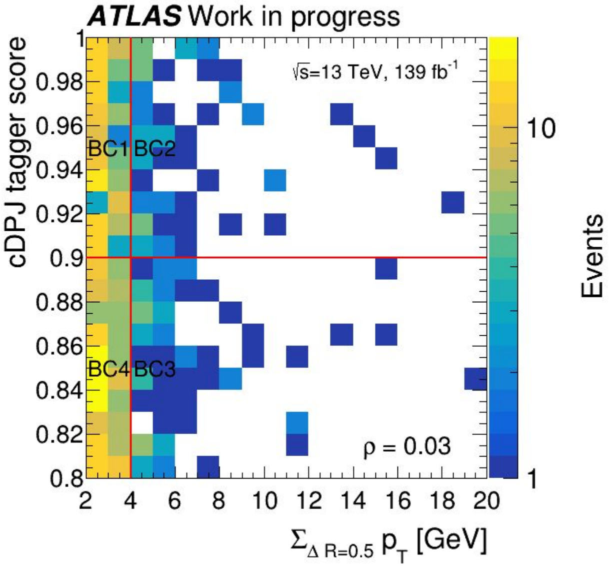
ABCD Yield	$m(\gamma_d)$ = 0.017GeV $c\tau$ = 2mm	$m(\gamma_d)$ = 0.05GeV $c\tau$ = 7mm	$m(\gamma_d)$ = 0.9GeV $c\tau$ = 115mm	$m(\gamma_d)$ = 2GeV $c\tau$ = 175mm	$m(\gamma_d)$ = 6GeV $c\tau$ = 600mm	$m(\gamma_d)$ = 25GeV $c\tau$ = 1200mm	$m(\gamma_d)$ = 40GeV $c\tau$ = 1400mm
nA	52.3±1.2	53.2±1.2	44.3±1.1	41.0±1.0	32.6±0.9	22.2±0.8	16.4±0.7
nB	4.3±0.3	4.3±0.3	3.8±0.3	3.9±0.3	3.3±0.3	2.6±0.3	1.4±0.2
nC	0.4±0.1	0.5±0.1	0.8±0.2	0.6±0.1	0.5±0.1	0.4±0.1	0.3±0.1
nD	4.6±0.3	4.4±0.3	6.7±0.4	5.9±0.4	4.7±0.3	3.1±0.3	2.0±0.2
nA estimate							

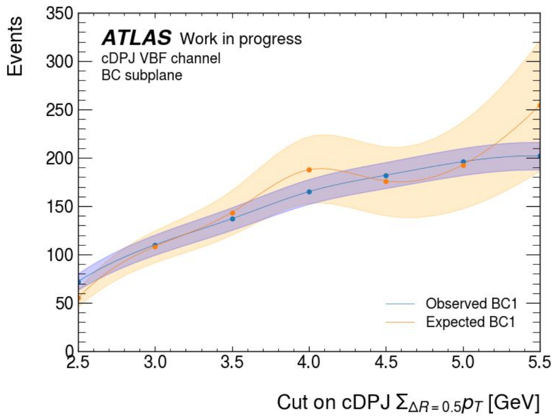
ABCD Yield	$m(\gamma_d)$ = 0.1GeV $c\tau$ = 15mm	$m(\gamma_d)$ = 0.4GeV $c\tau$ = 50mm	$m(\gamma_d)$ = 10GeV $c\tau$ = 900mm	$m(\gamma_d)$ = 15GeV $c\tau$ = 1000mm	Run 2 Data
nA	49.0±1.6	35.2±1.4	27.7±2.8	37.5±5.3	923.0
nB	4.1±0.4	3.7±0.4	4.0±1.4	2.2±0.6	224.0
nC	0.5±0.2	0.4±0.1	0.6±0.5	0.1±0.1	256.0
nD	4.2±0.4	5.2±0.5	4.8±1.7	4.2±1.1	1123.0
nA estimate					982.6±94.6

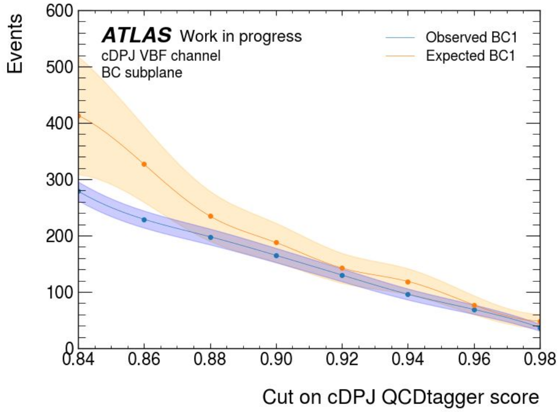
$BR(H \to 2\gamma_d + X) = 10\%$

ABCD validation: subplane BC

- Cut is relaxed to *E_T^{miss}>100 GeV* to allow more events to enter BC & DC
- Prediction closes with default cuts
- Correlation ~3%
- Good agreement when sliding threshold in both axes





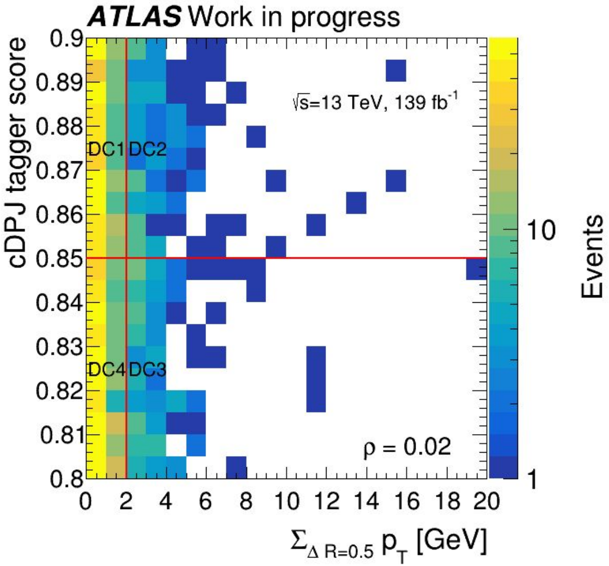


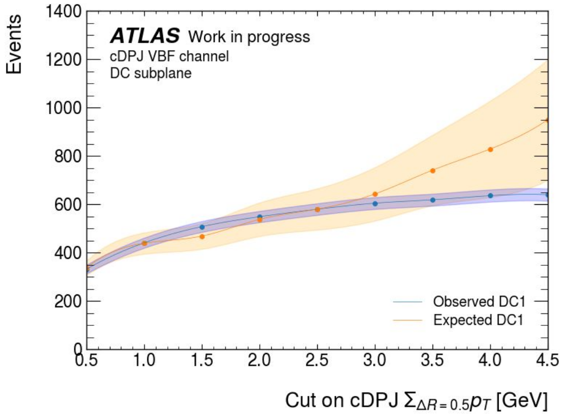
BC yield	$m(\gamma_d) = 0.1$GeV $c\tau = 15$mm	$m(\gamma_d) = 0.4$GeV $c\tau = 50$mm	$m(\gamma_d) = 10$GeV $c\tau = 900$mm	$m(\gamma_d) = 15$GeV $c\tau = 1000$mm	Run 2 Data
nBC1	4.6±0.5	3.7±0.4	4.3±1.5	2.1±0.6	165.0
nBC2	1.0±0.2	0.8±0.2	1.9±1.0	0.6±0.3	68.0
nBC3	0.0±0.0	0.1±0.1	0.5±0.5	0.0±0.0	71.0
nBC4	0.5±0.2	0.4±0.2	0.1±0.1	0.1±0.1	196.0
nBC1 estimate					187.7±34.6

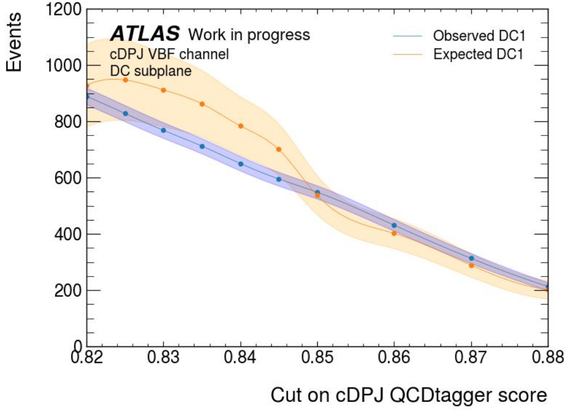
$BR(H\rightarrow 2\gamma_d+X)=10\%$

ABCD validation: subplane DC

- *E_T^{miss}>100 GeV* as mentioned before
- Prediction closes with default cuts
- Correlation ~2%
- Good agreement when sliding threshold in both axes







DC yield	$m(\gamma_d)$ = 0.1GeV $c\tau$ = 15mm	$m(\gamma_d)$ = 0.4GeV $c\tau$ = 50mm	$m(\gamma_d)$ = 10GeV $c\tau$ = 900mm	$m(\gamma_d)$ = 15GeV $c\tau$ = 1000mm	Run 2 Data
nDC1	3.4±0.4	3.7±0.5	3.0±1.4	3.4±1.1	548.0
nDC2	0.4±0.2	0.3±0.1	0.1±0.1	0.1±0.1	125.0
nDC3	0.2±0.1	0.2±0.1	0.6±0.5	0.0±0.0	142.0
nDC4	2.4±0.4	2.5±0.4	2.1±1.0	1.1±0.3	610.0
nDC1 estimate					537.0±69.4

$BR(H\rightarrow 2\gamma_d+X)$=10%

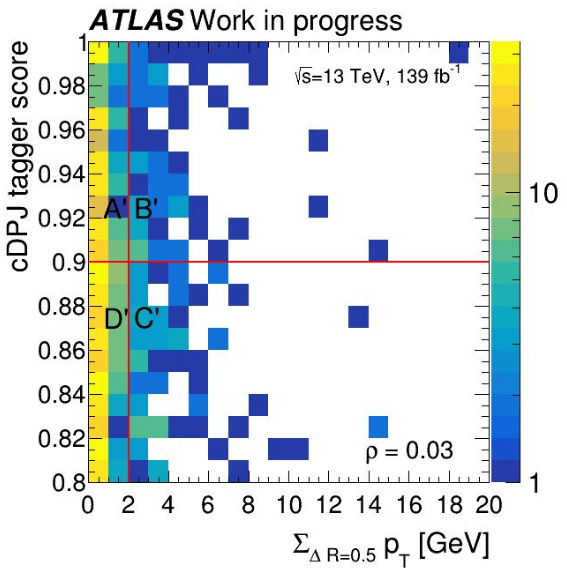
ABCD validation: orthogonal plane

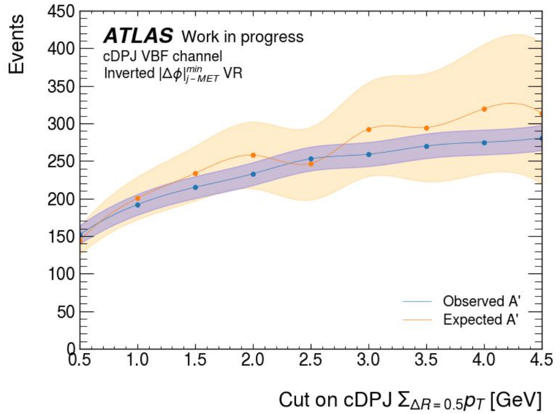
- Inverted $|\Delta\Phi|(jet, E_T^{miss})$ cut
- $E_T^{miss} > 100$ GeV as mentioned before

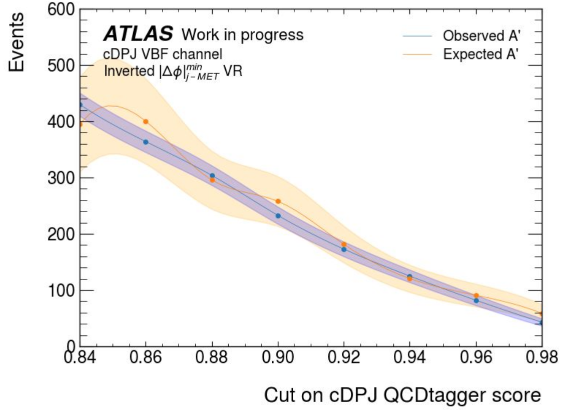
- Prediction closes with default cuts

- Correlation ~3%

- Good agreement when sliding threshold in both axes







(ABCD)' yield	$m(\gamma_d) = 0.1$GeV $c\tau = 15$mm	$m(\gamma_d) = 0.4$GeV $c\tau = 50$mm	$m(\gamma_d) = 10$GeV $c\tau = 900$mm	$m(\gamma_d) = 15$GeV $c\tau = 1000$mm	Run 2 Data
nA'	7.7±0.6	4.4±0.5	5.3±1.6	2.4±0.6	233.0
nB'	1.1±0.3	0.7±0.3	0.6±0.5	0.3±0.1	69.0
nC'	0.1±0.1	0.2±0.1	0.0±0.0	0.0±0.0	84.0
nD'	0.5±0.2	0.8±0.2	0.2±0.1	0.2±0.1	314.0
nA' estimate					257.9±44.4

$BR(H \rightarrow 2\gamma_d + X) = 10\%$

More on VBF analysis

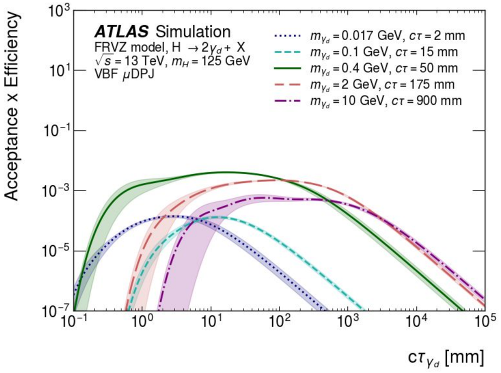
VBF - Lifetime reweighting

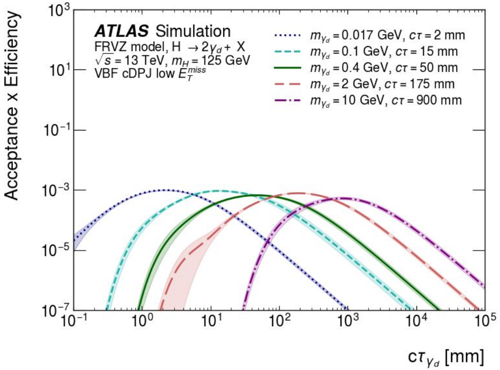
caloDPJ

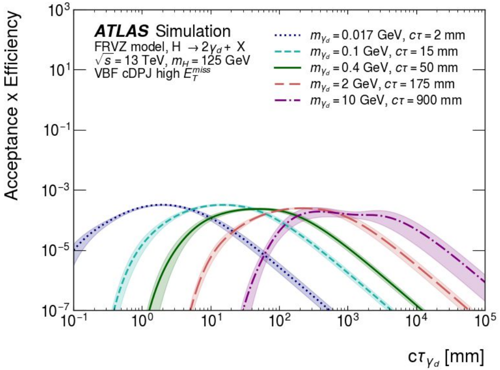
Validation

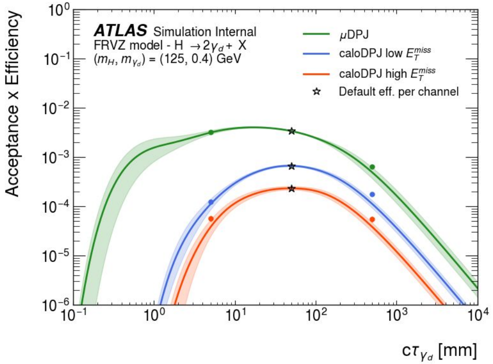
Using samples with $m_{\gamma d}$=0.4 GeV

μDPJ









- 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 $c\tau$ (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!