SEARCHES FOR BSM PHYSICS USING CHALLENGING AND LONG-LIVED SIGNATURES WITH THE ATLAS DETECTOR

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on behalf of the ATLAS collaboration

12 January 2022

The ‘new’ dimension

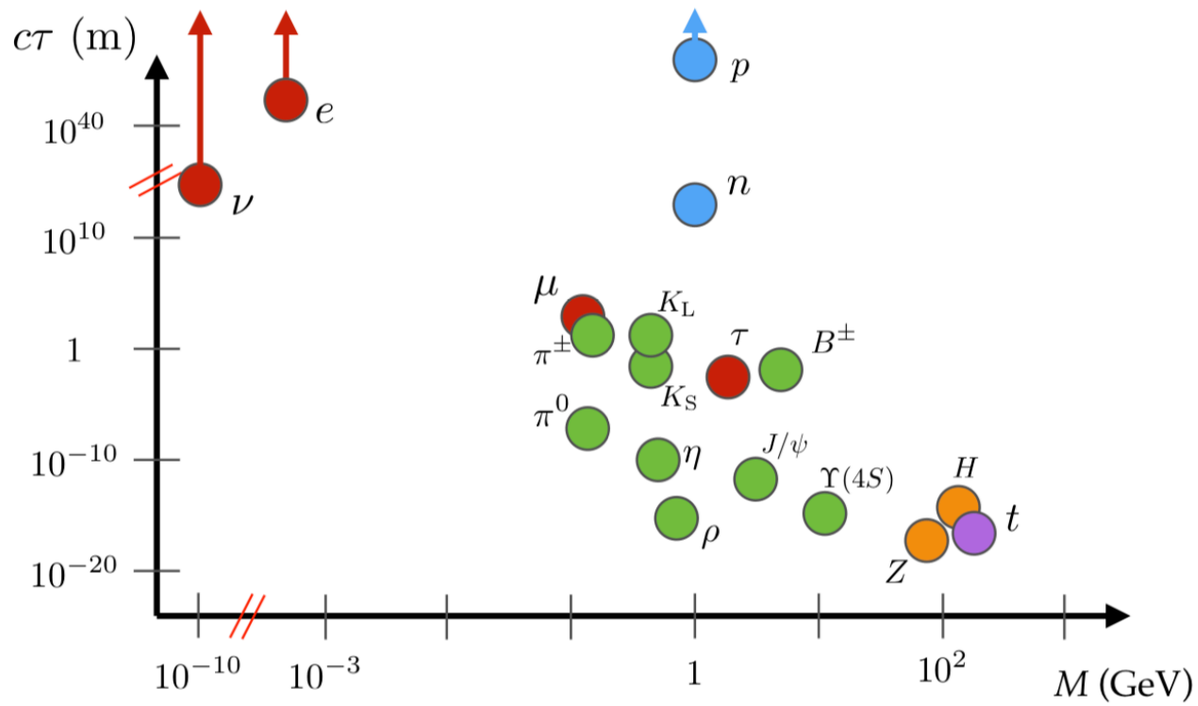
LHC experiments have extensively searched for New Physics in the prompt regime or ‘invisible’ final states.

* detectors ideal to look for prompt signatures
  - higgs boson discovery

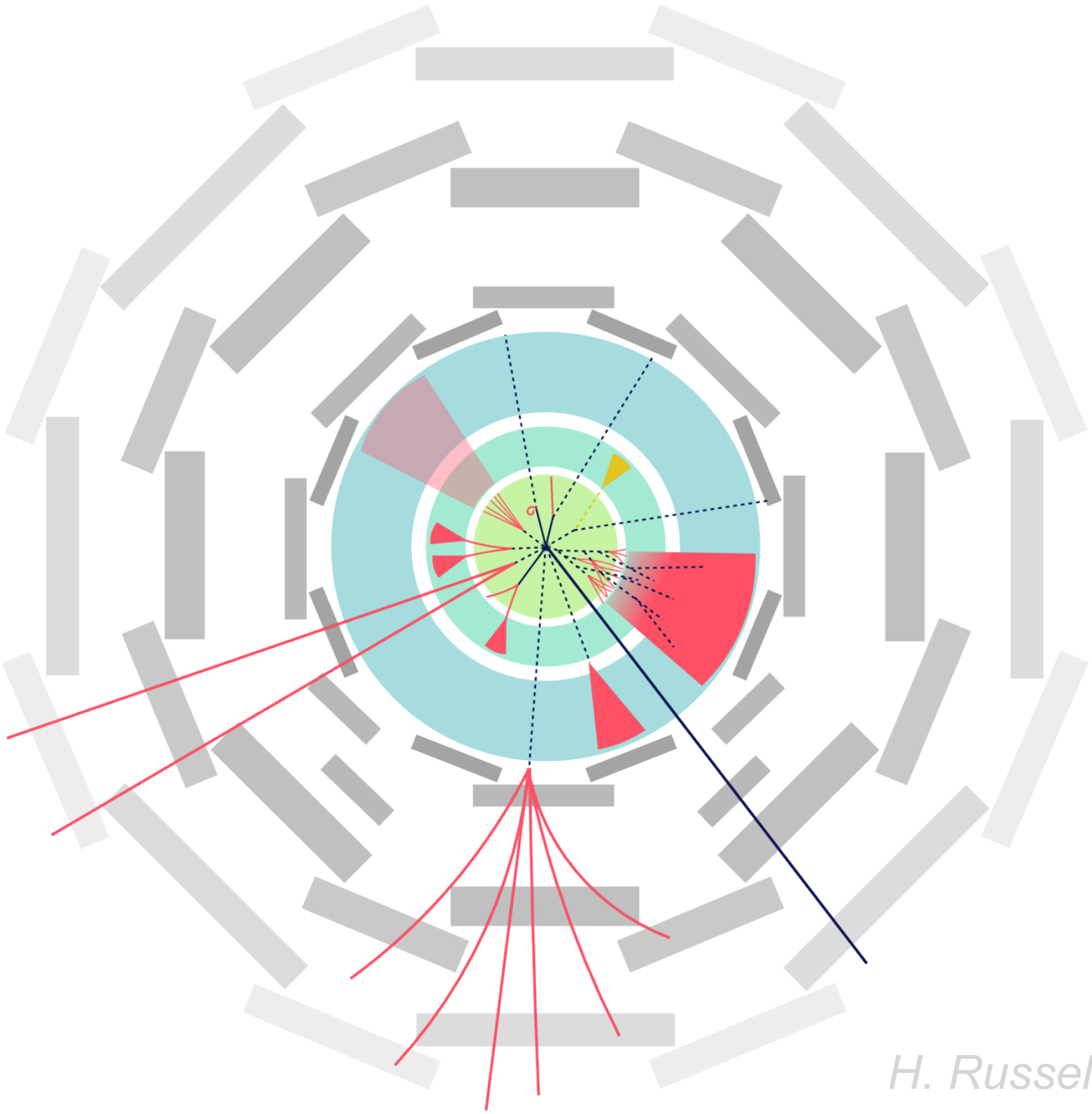
More and more BSM theories motivates displaced signatures

* (nearly) mass-degenerate spectra
* small couplings
* highly virtual intermediate states

White Paper
to define benchmark signals
J. Phys. G 47 (2020) no.9, 090501



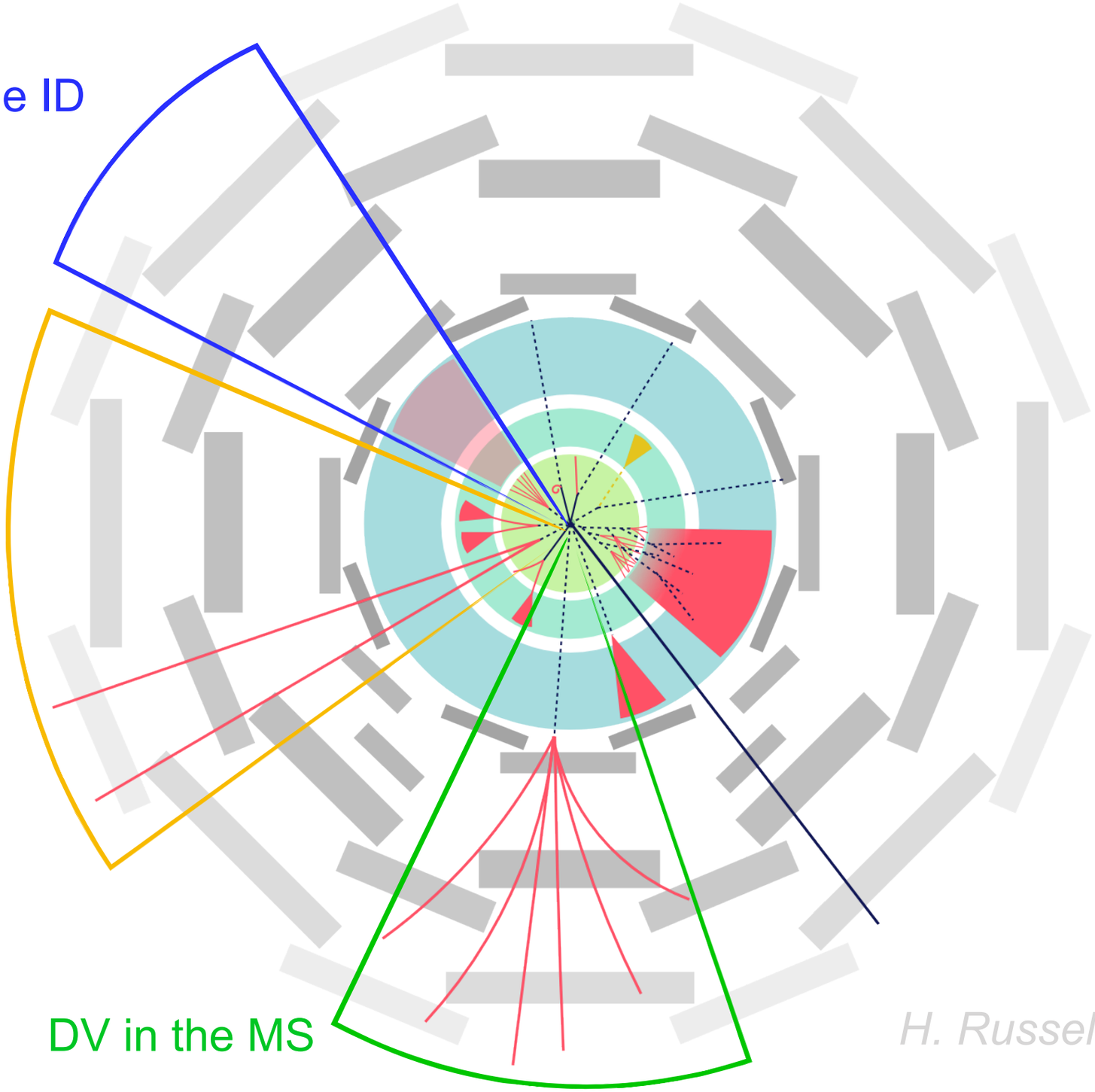
A vast LLP search program



A vast LLP search program

DV in the ID

lepton-jets



DV in the MS

H. Russell

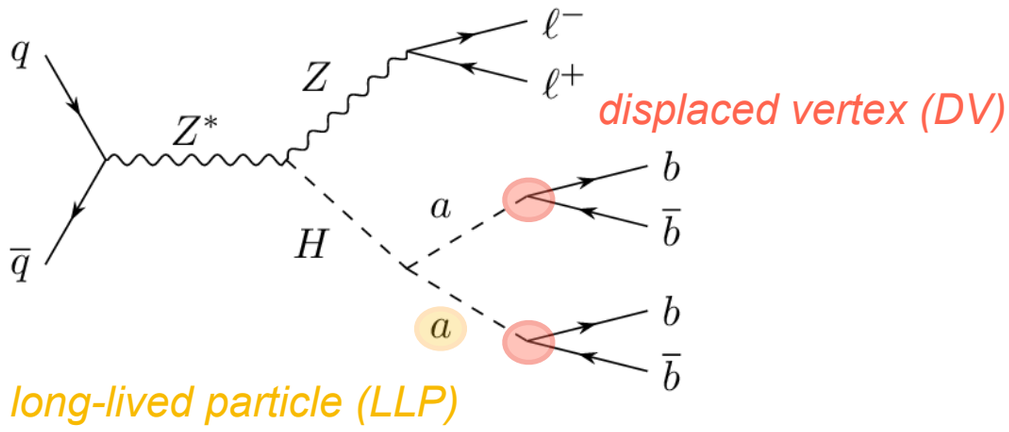
*Here just focusing on some of the most **RECENT** results!*

LLPs - in the tracker

JHEP 11 (2021) 229

Search of DVs in ZH channel:

* take advantage of associated production!
  - use promptly produced leptons to trigger



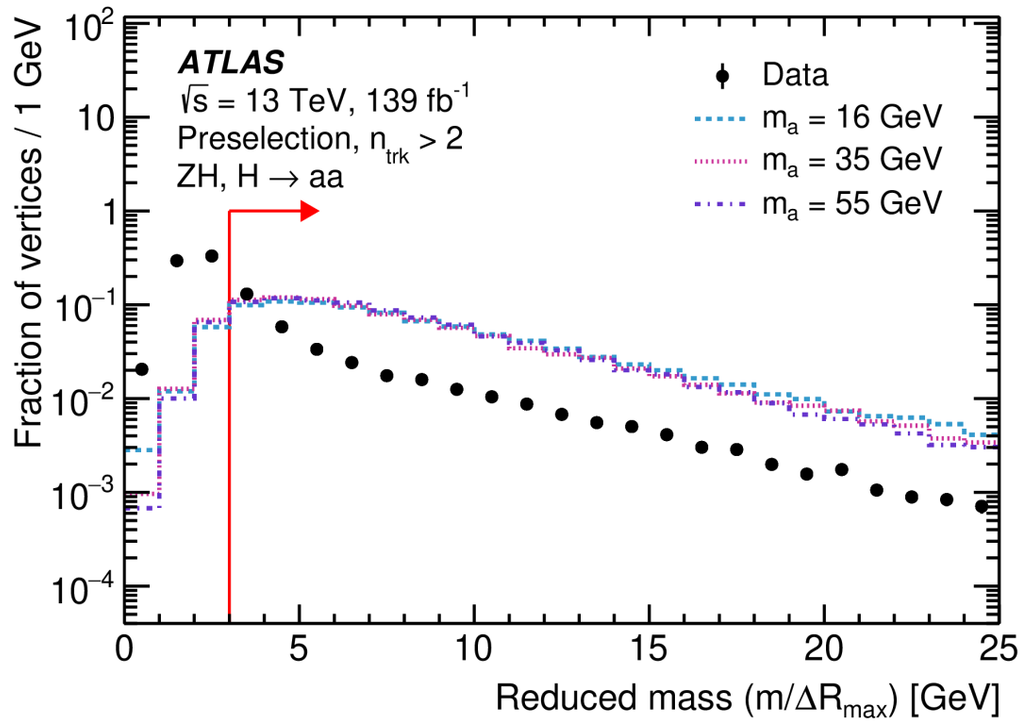
1. select events with displaced jet candidates:
   * low charged hadron fraction
   * few tracks matched to primary vertex

2. use Large Radius Tracking (LRT) algorithm:
   * to select high d0 tracks

3. reconstruct 2 displaced vertices in the ID:
   * matched to jets

Key selection variables:

* n_{trk} per vertex
* $m/\Delta R_{max}$ reduced mass
  - ratio of reco vertex invariant mass and ΔR_{max}(track, DV)



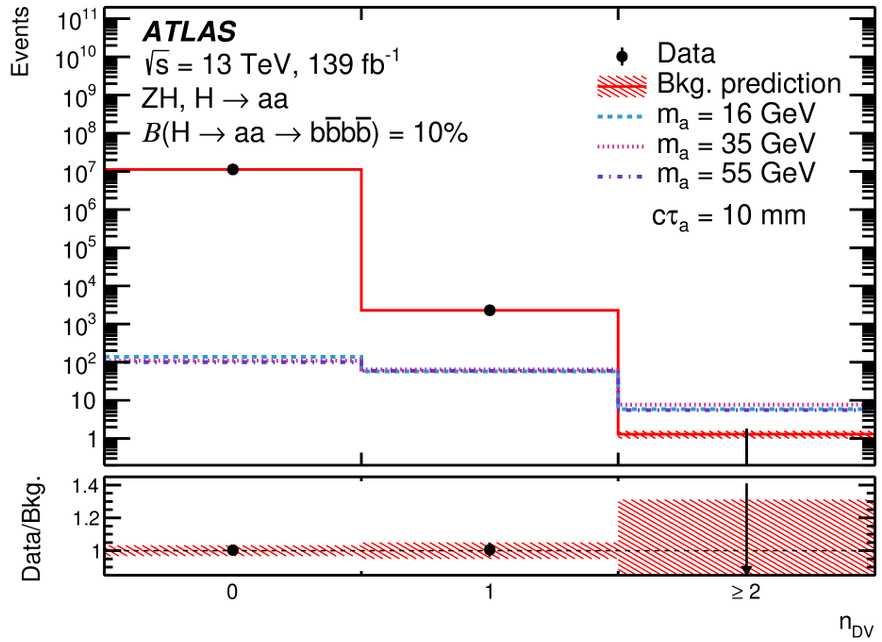
LLPs - in the tracker (2)

JHEP 11 (2021) 229

Data-driven bkg estimate

- per-jet probability of DVs in CR
  - in p_T vs b-tag discriminant plane
- B = 1.30 ± 0.08 ± 0.27

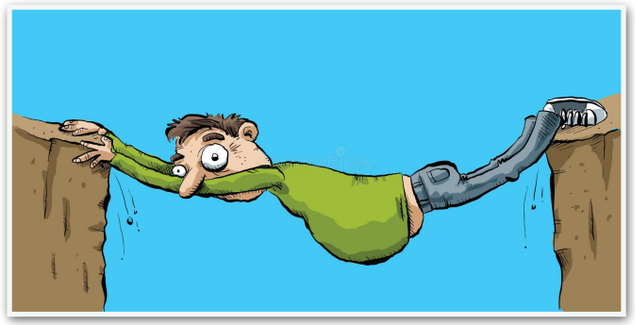
No events observed in the signal region

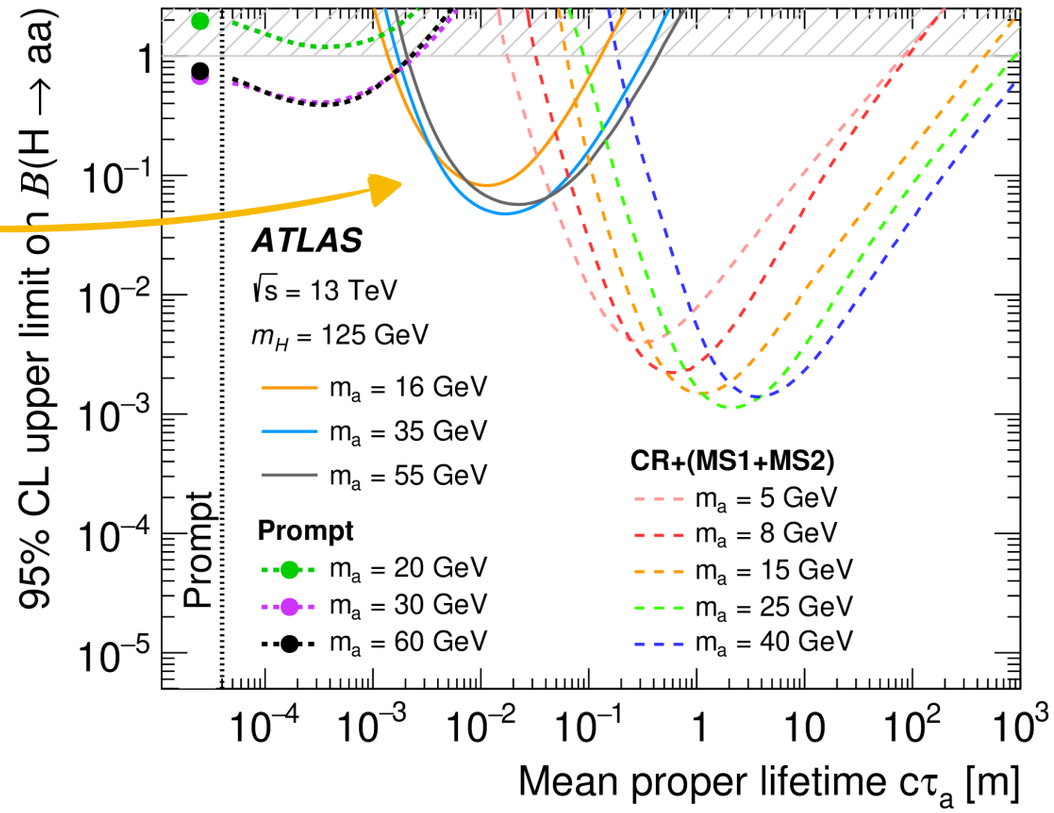


Set limits of B(H→aa) < 10%

for **$10 \lesssim c\tau_a \lesssim 100$ mm**

closing the gap between prompt and LLP searches in ATLAS



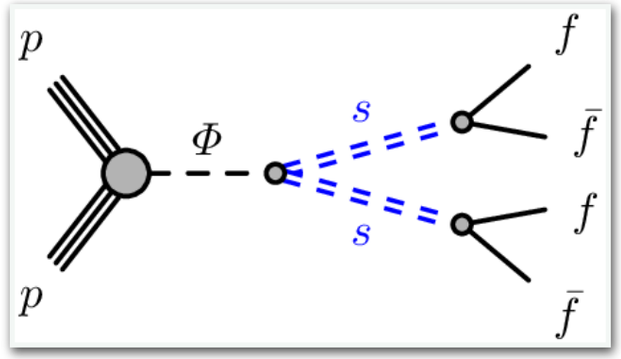


LLPs - in the spectrometer

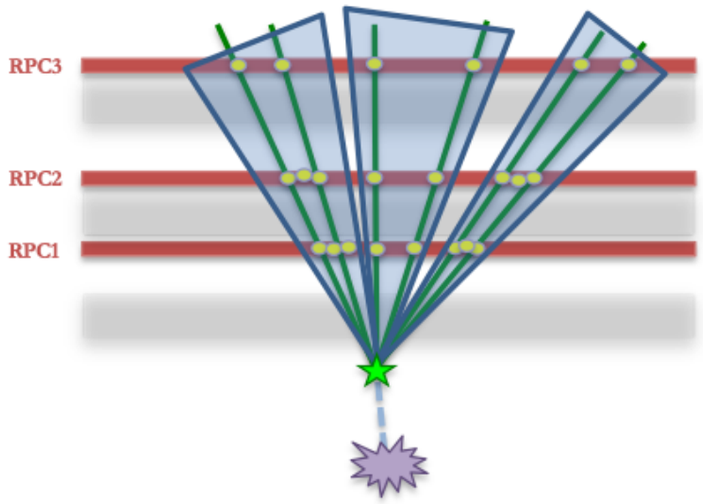
ATLAS-CONF-2021-032

Searching for narrow, high multiplicity hadron showers in muon detector

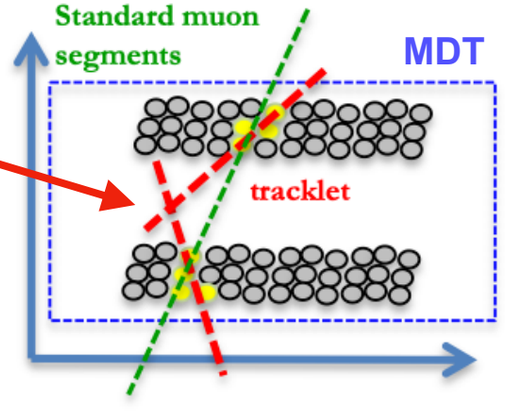
➡ no matched tracks in the ID

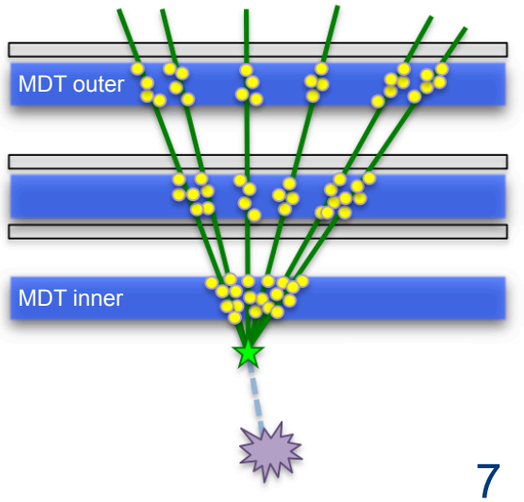


* Dedicated **Trigger**
  - selecting events with a **cluster of at least 3 (4) "region of interest"** in the barrel (endcaps) in a ΔR cone of 0.4 around L1_2MU10
  - JINST 8 (2013) P07015



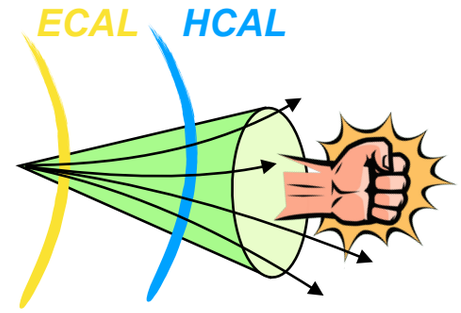
* Dedicated **vertex algorithm**
  - reco vertices with at least 3 (4) **tracklets** in the barrel (endcaps)
    - exploiting multilayer separation in MDT chambers
  - JINST 9 (2014) P02001



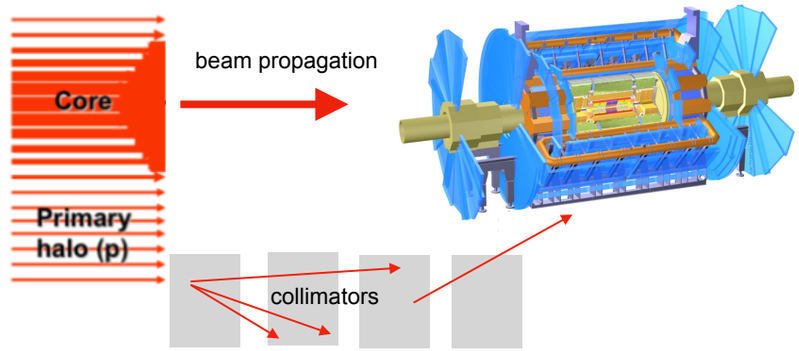


LLPs - in the spectrometer (2)

ATLAS-CONF-2021-032



* Primary bkgs come from
  - punch-through jets
  - beam induced bkg (BIB)



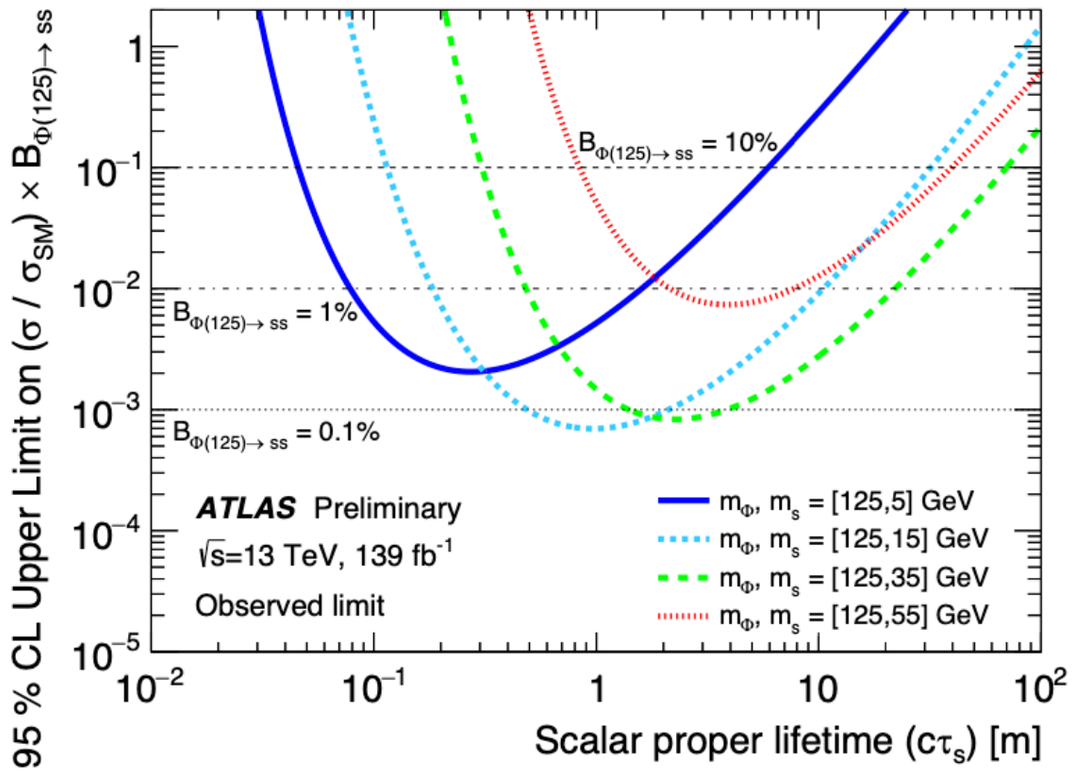
* Data-driven bkg estimation
  - based on main and zero bias streams

$$N_{2Vx} = 0.32 \pm 0.05$$

zero waste

No events observed in SR

* Limits set to less than 0.1% BR level in the SM higgs scenario

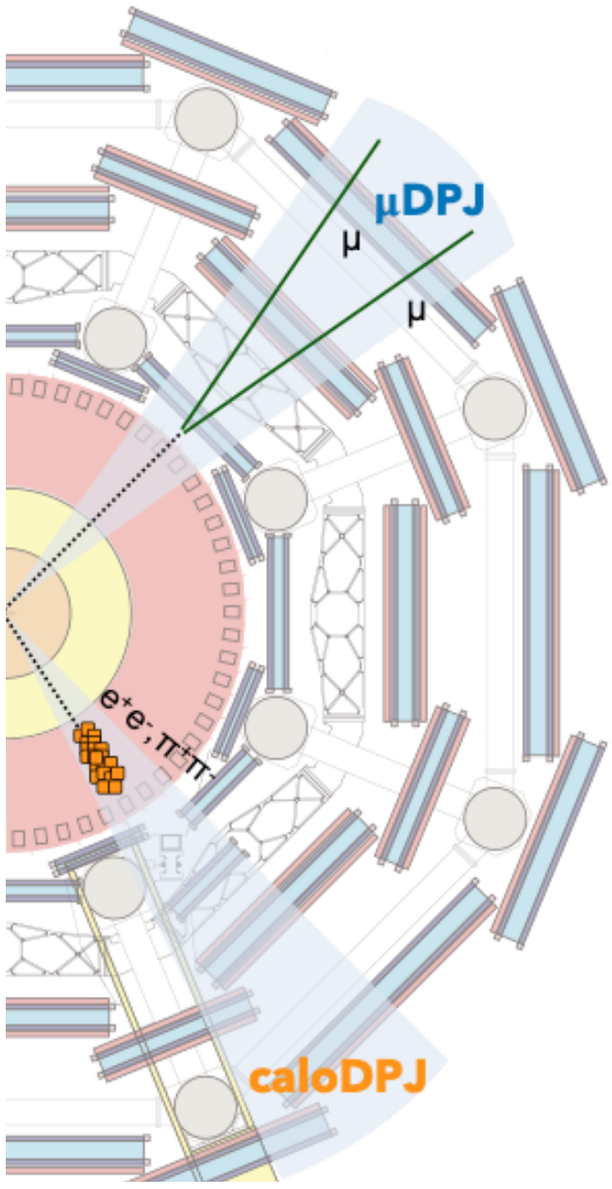


LLPs - lepton-jets

NEW!

ATLAS-CONF-2022-001

Search for light LLPs decaying into
collimated jet structures of leptons or light hadrons

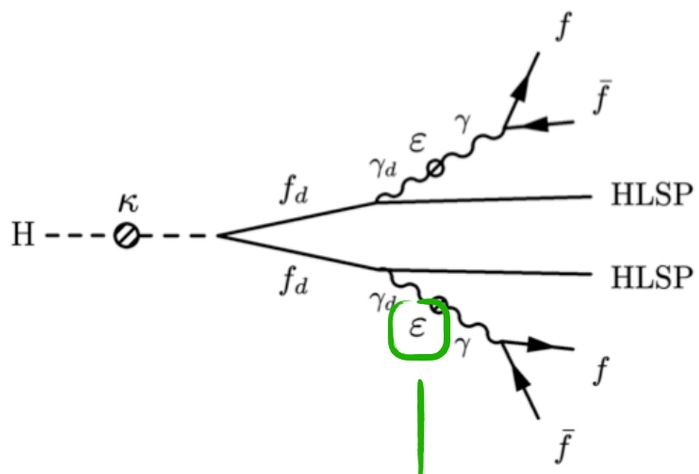


Collimated bunch of muons w/o tracks in the ID

- Low-p_T muons hard to trigger
- Cosmic-ray muons bkg

Displaced jet with most of energy deposit in the HCAL

- High bkg from QCD events



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

small couplings → displaced decays

More details on Alessandro's poster

LLPs - lepton-jets (2)

NEW!

ATLAS-CONF-2022-001

Two production modes

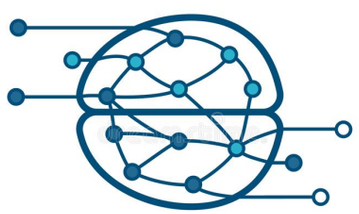
ggH
- dedicated NarrowScan (μ) and CaloRatio (had) triggers
- ✦ QCD, cosmics, BIB

WH
- single lepton triggers
- ✦ V+jets bkg

6 channels defined:

μ-μ (ggH), μ-calo (ggH & WH), 1-calo (WH), calo-calo (ggH & WH)

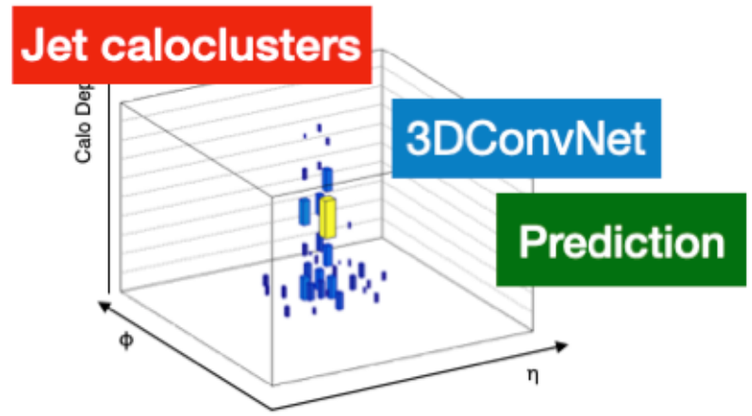
NN taggers

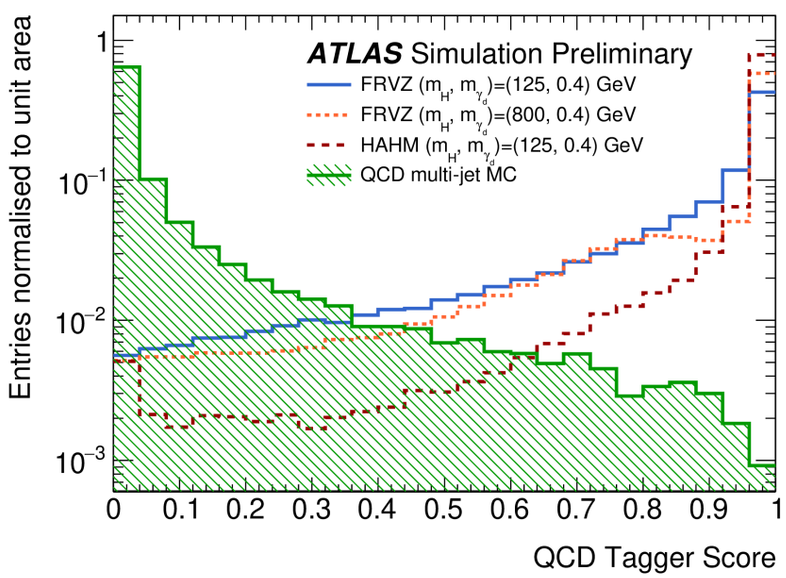


Dense NN-based (per track)
tagger in **μ-channels**
to reject cosmics (90%)

Convolutional NN-based taggers
in **calo-channels**
to reject QCD (94%) and BIB (68%)

trained on low-level inputs
(3D jet images from calorimetric clusters)





LLPs - lepton-jets (3)

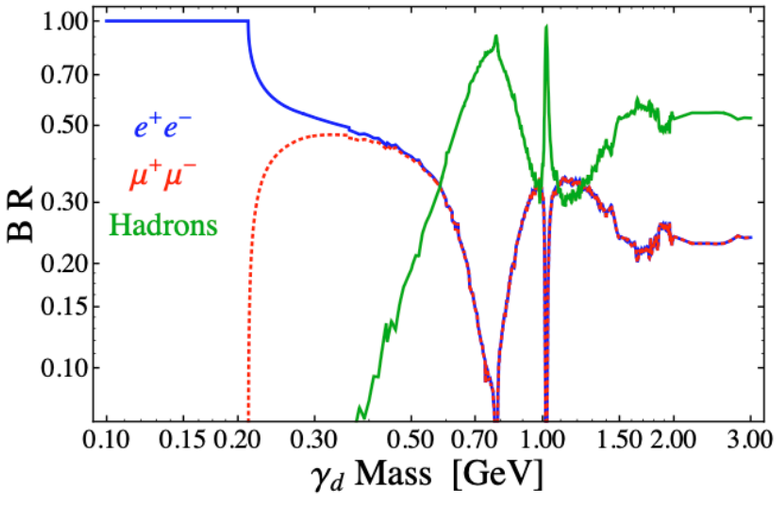
NEW!

ATLAS-CONF-2022-001

Data-driven ABCD method to estimate the residual bkg in the signal regions

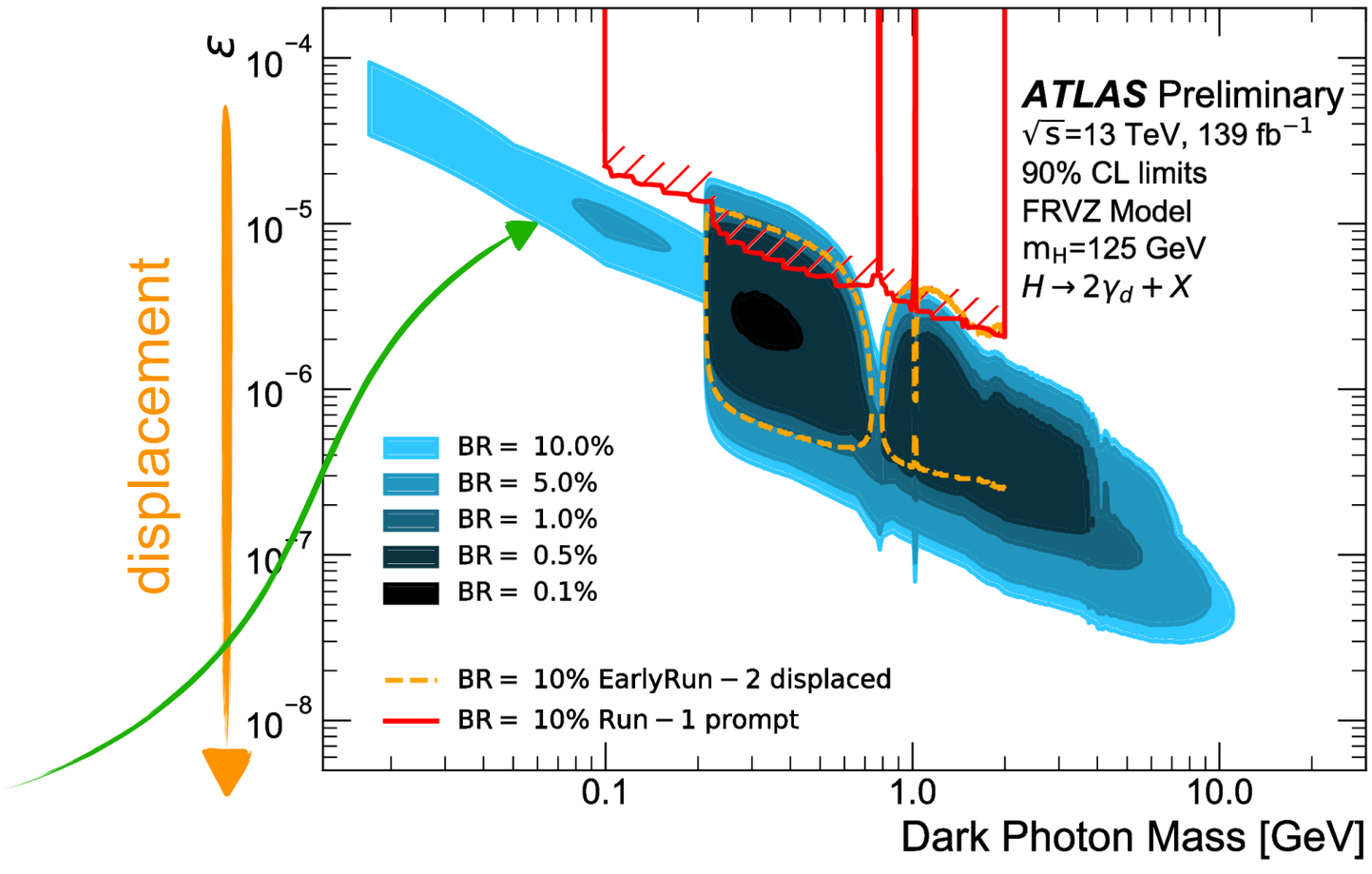
No data excess is found

Selection	Search channel	CRB	CRC	CRD	SR expected	SR observed
ggF	2μ	55	61	389	357 ± 67	269
	c+μ	169	471	301	108 ± 12	110
	2c	97	1113	12146	1065 ± 112	1045
WH	c	1850	3011	155	95 ± 13	103
	c+μ	30	49	31	19 ± 7	20
	2c	79	155	27	14 ± 5	15



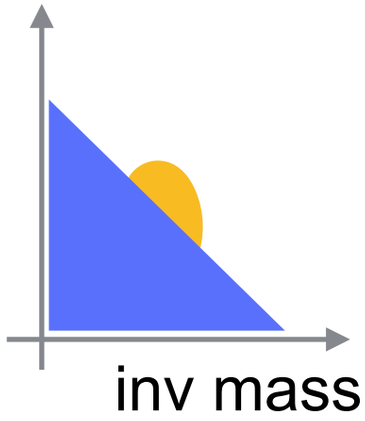
μ-exclusion of B(h→$f_d f_d$) down to 0.1% (~B(h→4v))

First time exclusion in the fully electron channel



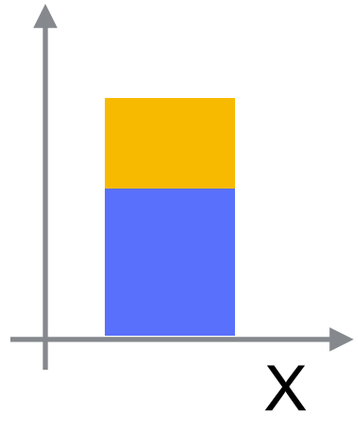
LLPs - everywhere

Resonant searches



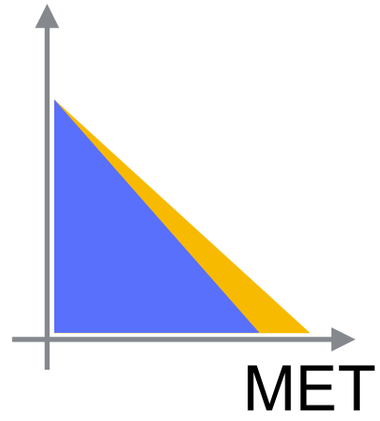
Prompt resonances can be reinterpreted. b-tagging algorithms can be performant for sizeable lifetimes!

LLP searches

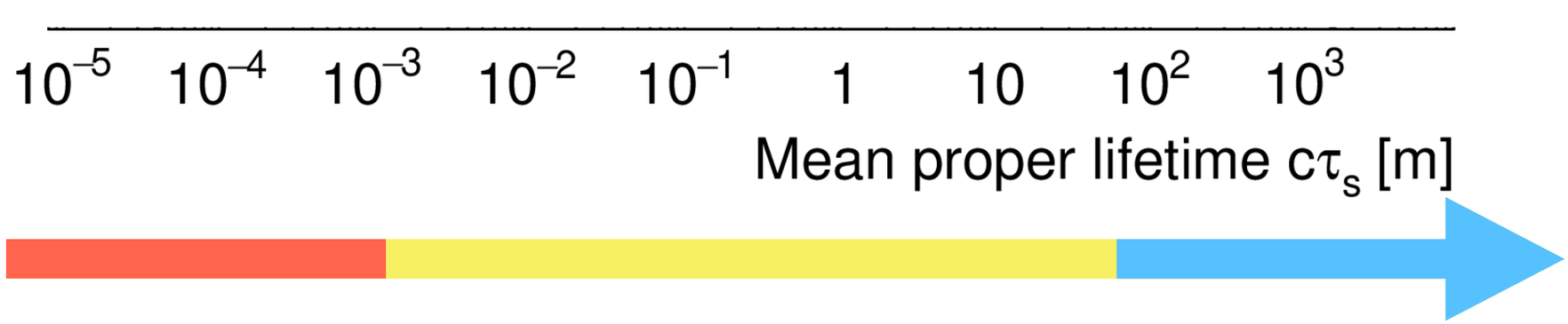


Unique signatures helps to strongly reduce bkg:
→ bkg-zero channel

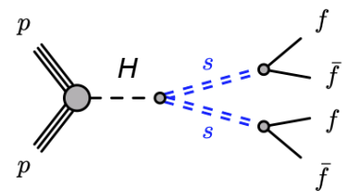
MET+X searches

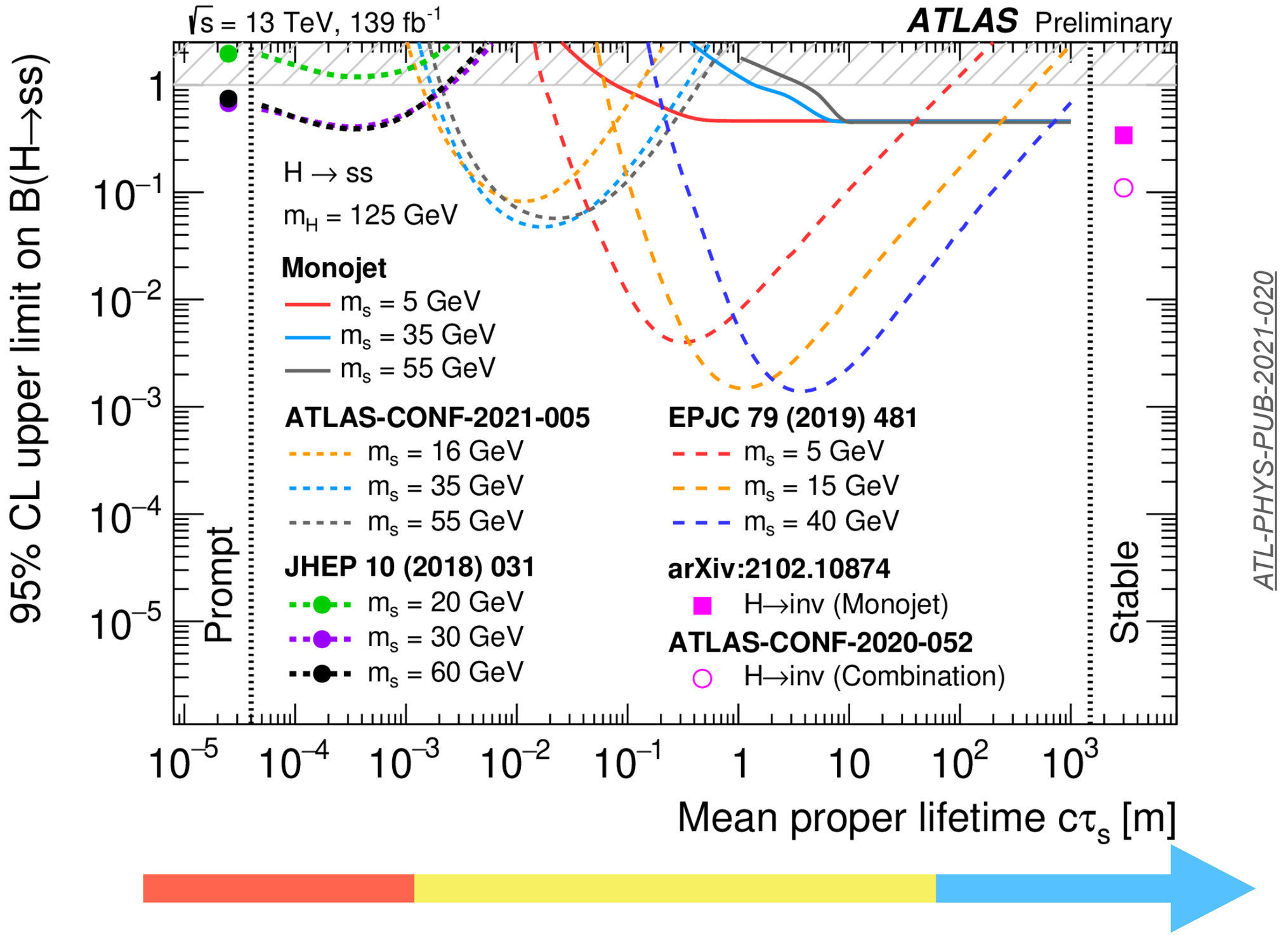


Displaced jet can contribute with further fake-MET!

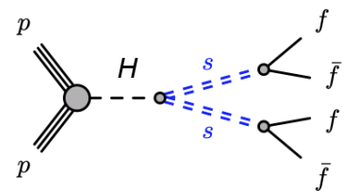


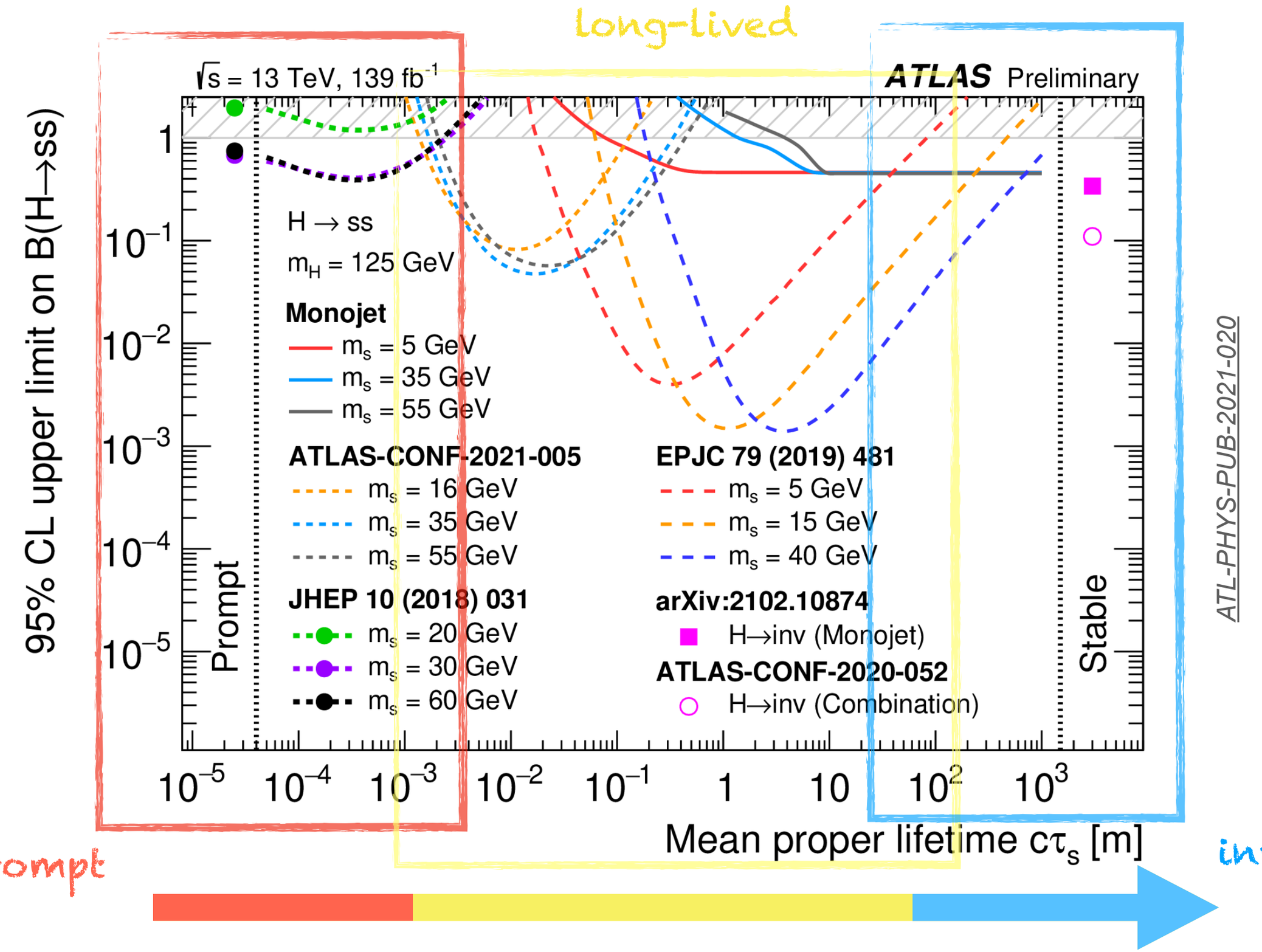
LLPs - everywhere (2)





LLPs - everywhere (2)



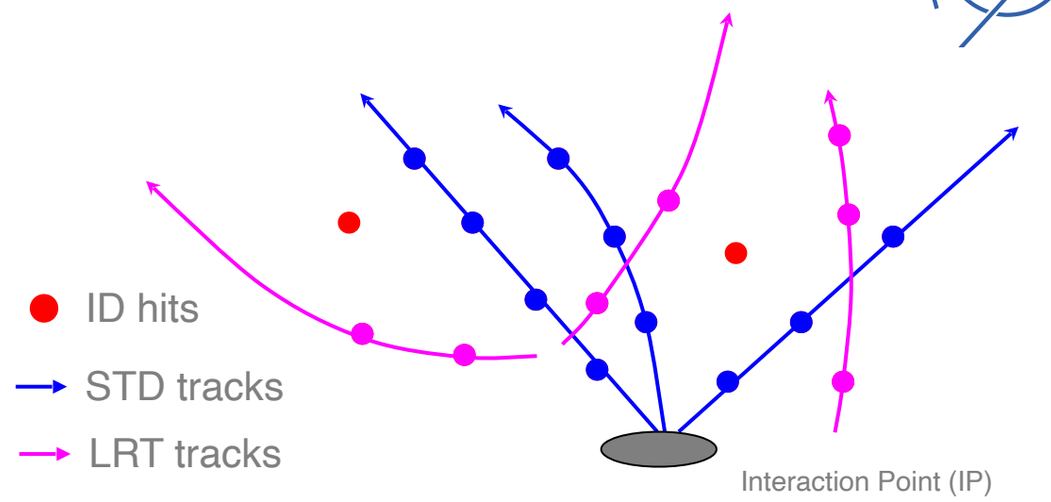


LLPs - future

IDTR-2021-003

LRT is an additional ID tracking algorithm that is run after standard tracking

➡ Run on leftover hits with relaxed tracking cuts

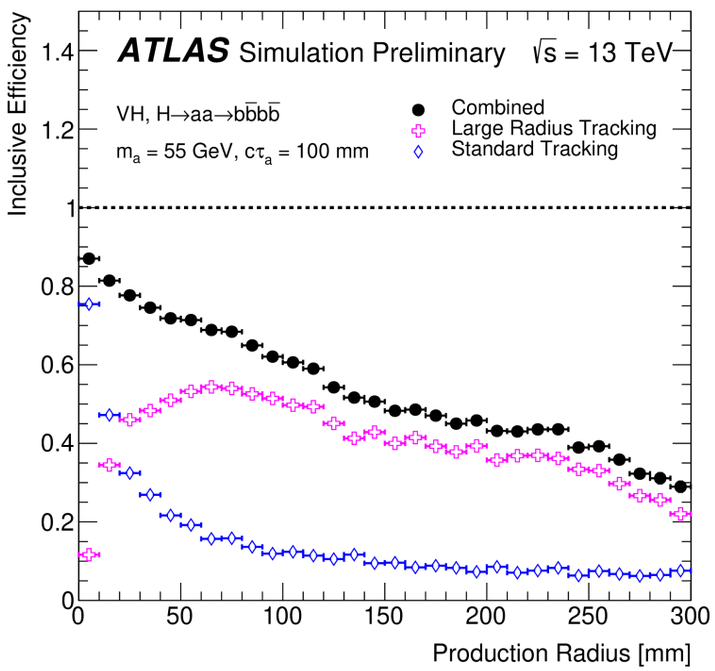


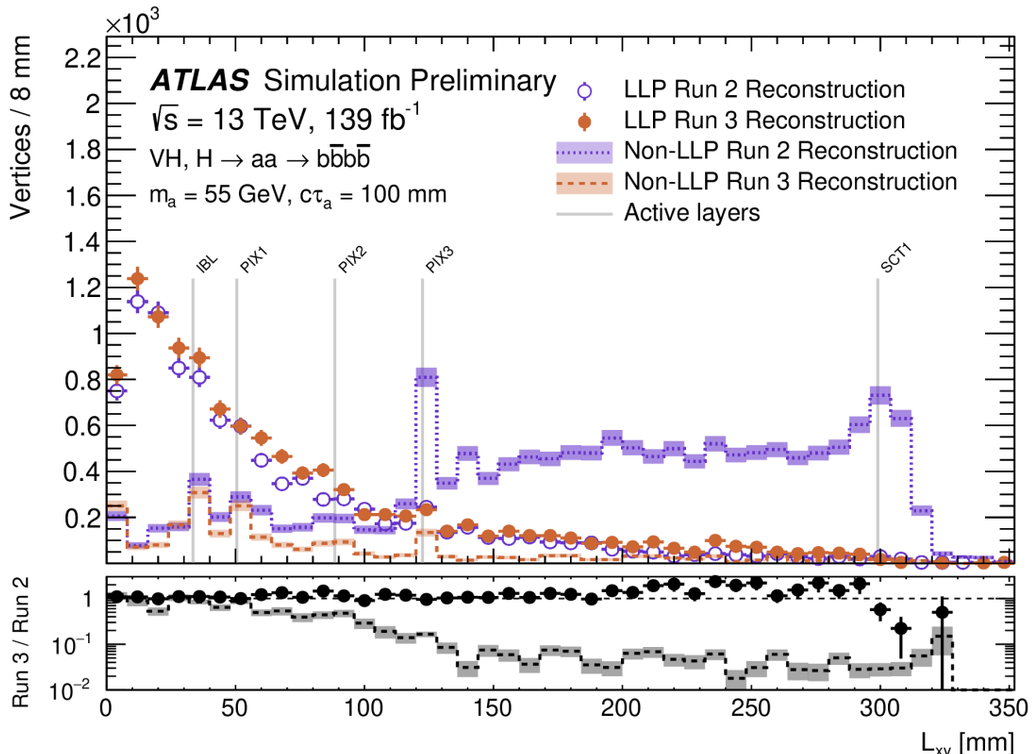
New implementation optimised for fake reduction

- factor **x20** reduction in fakes
- run together w/ standard ATLAS reco chain
  - no filters needed anymore!

DV algorithm hugely benefits from LRT overhaul!

- dramatic reduction of fake vertices
  - particularly outside of pixel detector





see also Julian's talk

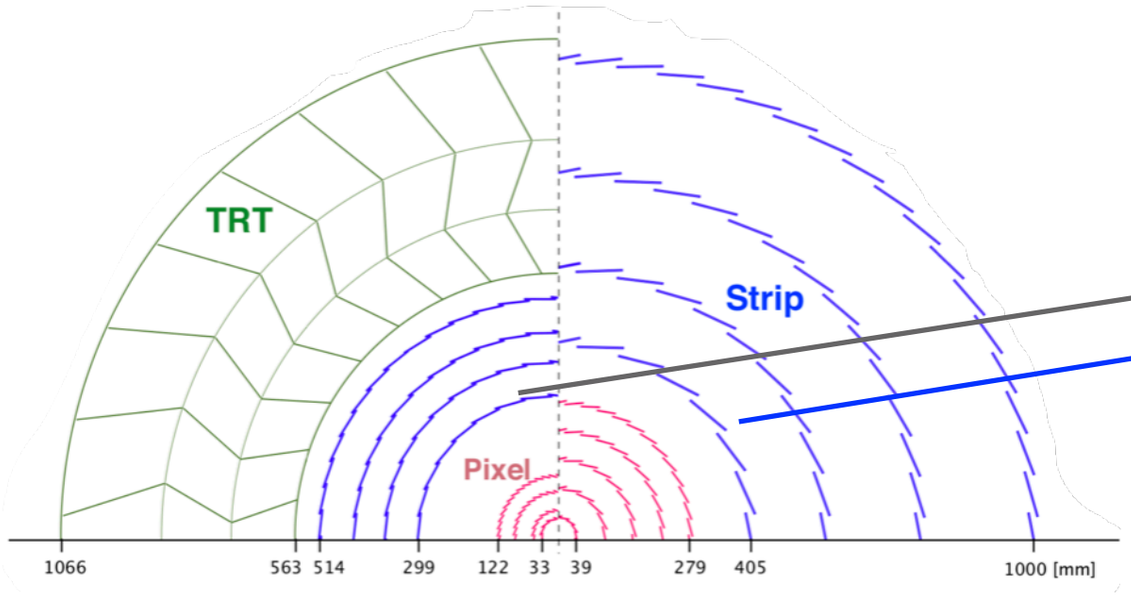
LLPs - future future

ITK

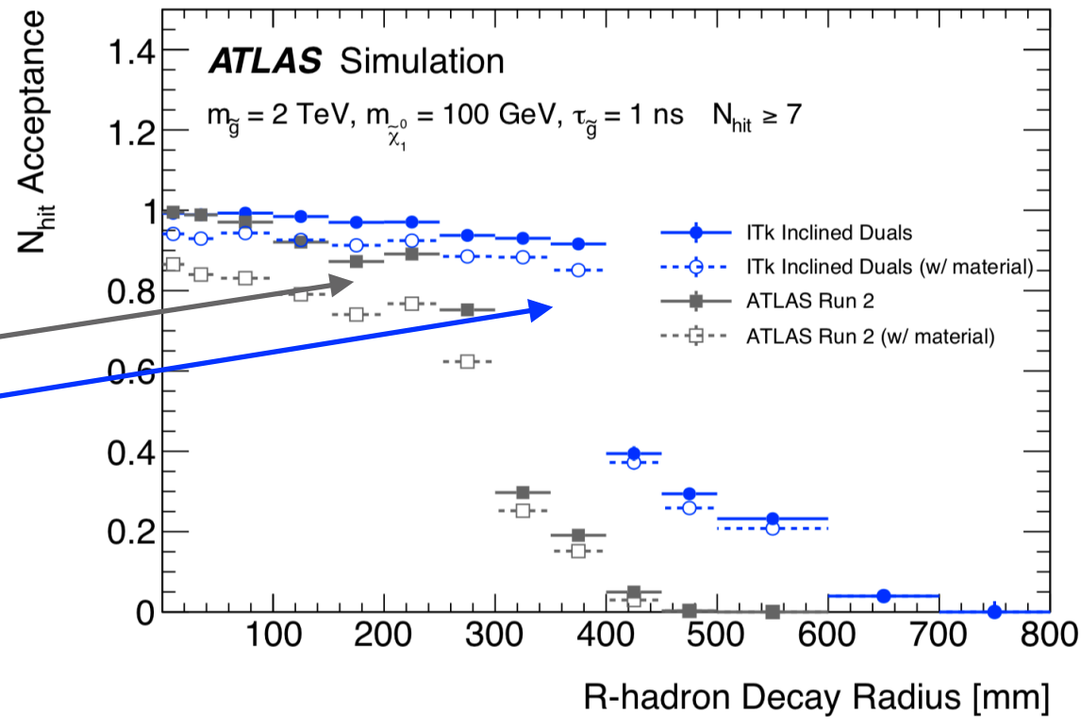
Higher reco efficiency:

* improved geometry
* larger silicon volume
* lower material budget

- more hits-on-track with higher resolution
- minimum number of hits after decay
- tracker-based triggers can further boost sensitivity



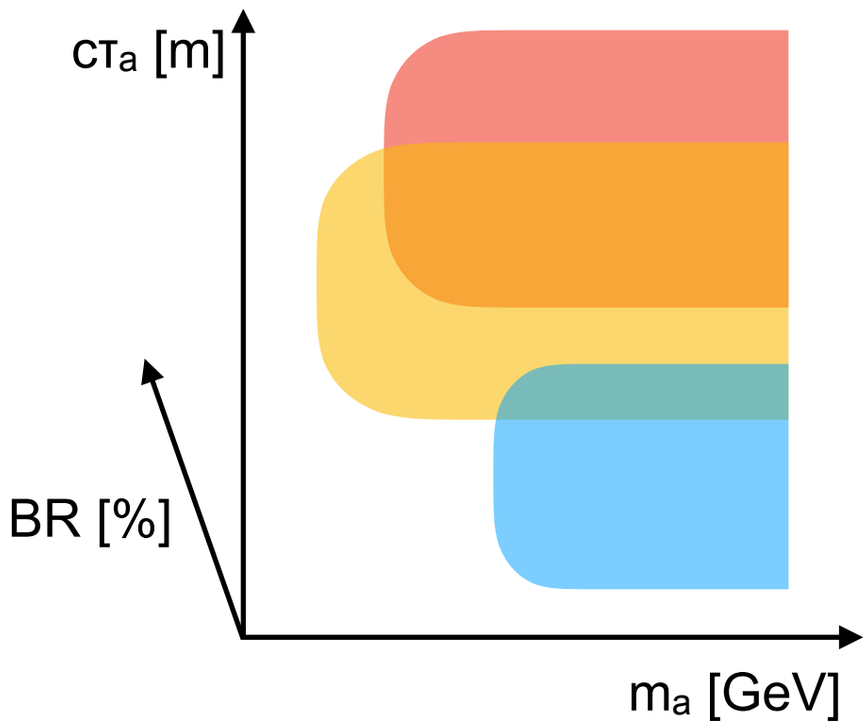
ATL-PHYS-PUB-2018-033



Conclusions

Vast search program in ATLAS focused on

- extending the reaches and fill the gaps!
  - reinterpretations
  - new developments (e.g. LRT)
  - new technologies
  - new triggers for Run-3 and beyond
  - creativity



- Many LLP searches are statistically limited!
- Background-zero searches sensitivity $\propto \mathscr{L}$
- Gain by exploiting new detector technologies

Run-3 is fast approaching…the best still needs to come!

BACK UP

LLPs - in the tracker

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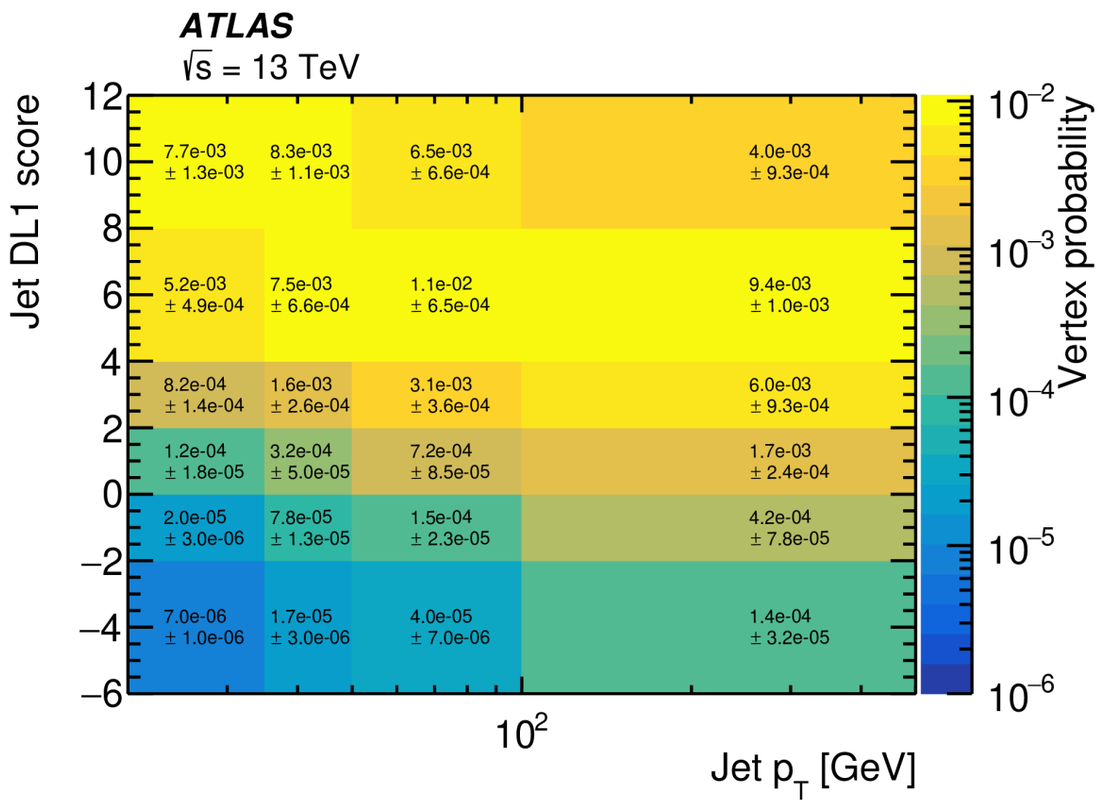

$$P_1 = \sum_{i=1}^{4} P_{\mathrm{DV}}(j_i) \times \prod_{k \neq i} (1 - P_{\mathrm{DV}}(j_k))$$

$$P_{\geq 2} = 1 - P_0 - P_1$$

Selection type	Requirement
Track pruning	$\lvert d_0^{\mathrm{DV}} \rvert < 0.8$ mm
	$\lvert z_0^{\mathrm{DV}} \rvert < 1.2$ mm
	$\sigma(d_0^{\mathrm{DV}}) < 0.1$ mm
	$\sigma(z_0^{\mathrm{DV}}) < 0.2$ mm
Vertex preselection	$\chi^2/n_{\mathrm{DoF}} < 5$
	$r < 300$ mm
	$\lvert z \rvert < 300$ mm
	pass material veto
Vertex selection	$n_{\mathrm{trk}} > 2$
	$m/\Delta R_{\mathrm{max}} > 3$ GeV
	$r/\sigma(r) > 100$
	$\max(\lvert d_0 \rvert) > 3$ mm
	$\Delta R_{\mathrm{jet}} < 0.6$

Source	Uncertainty [%]
Theory	4.7
Luminosity	1.7
Pile-up reweighting	2.6
Electron identification	1.6
Electron calibration	0.4
Muon reconstruction	0.8
Muon calibration	0.4
Electron trigger	0.7
Muon trigger	1.3
Jet energy scale	1.4
Jet energy resolution	1.3
Filter	2.8–3.8
LRT	2.4–12
Total	7.4–14

LLPs - in the tracker

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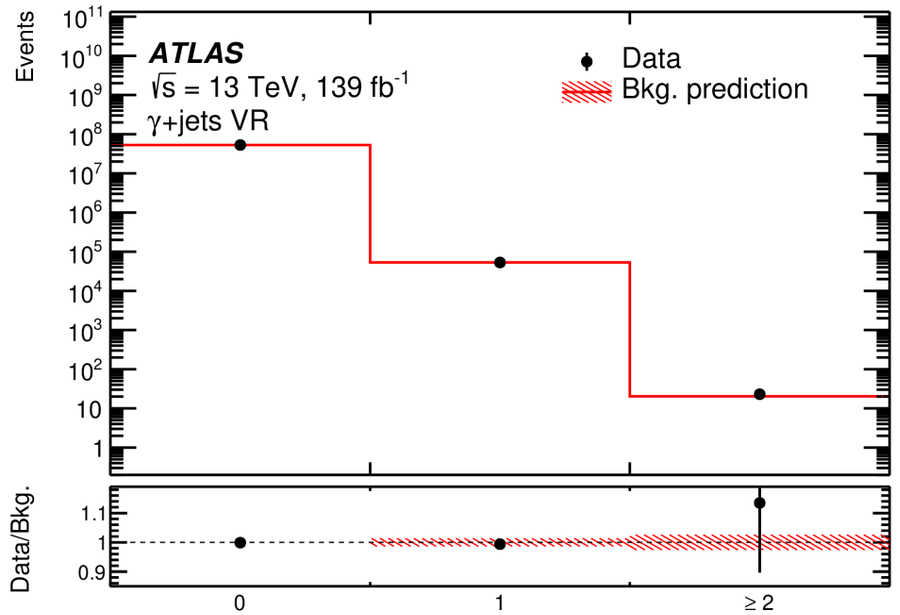
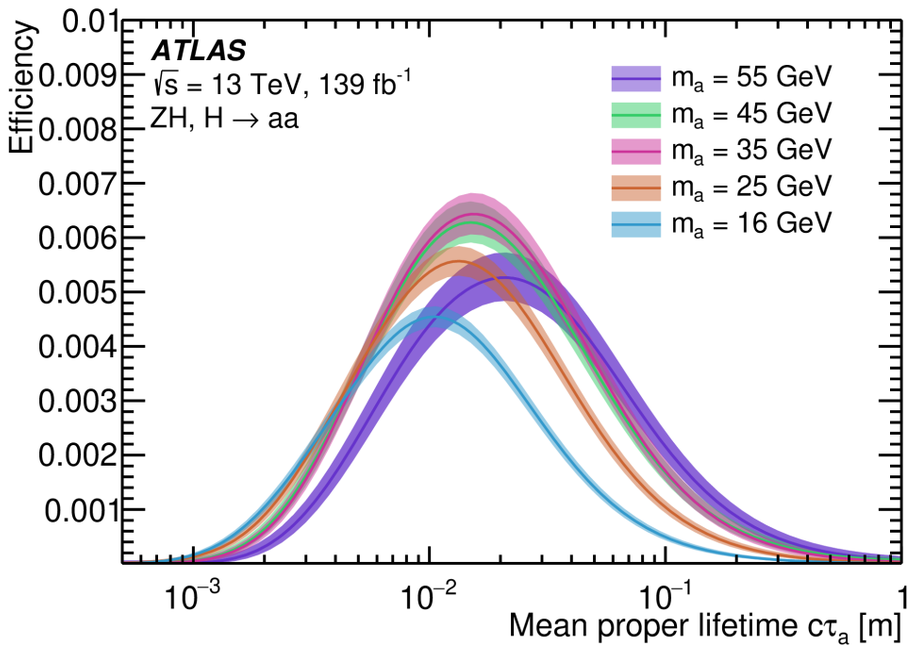
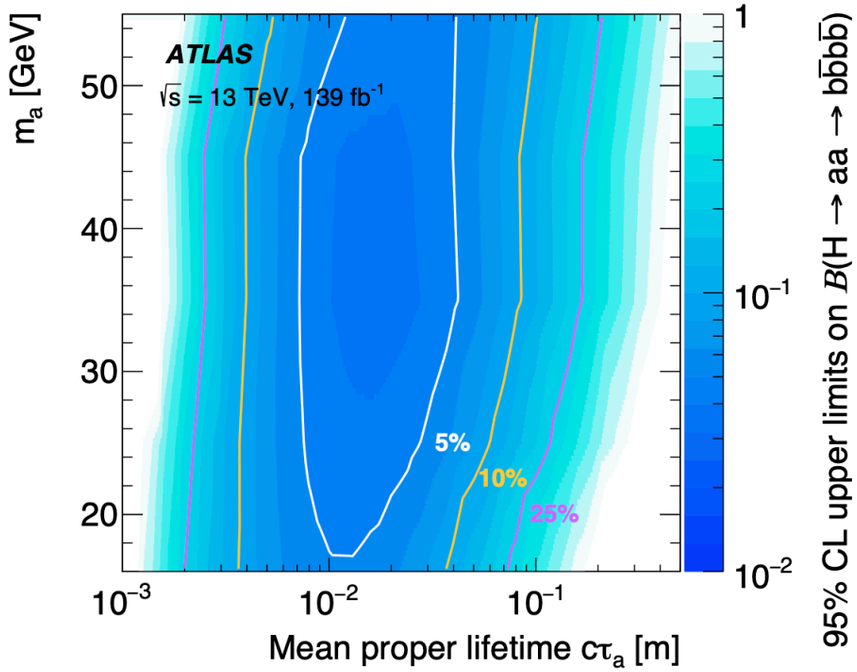






LLPs - in the spectrometer

ATLAS-CONF-2021-032

Event passes Muon RoI Cluster trigger
Event has a PV with at least two tracks with $p_{\mathrm{T}} > 500$ MeV
Event has at least one MS DV
MS DV matched to the triggering muon-RoI cluster ($\Delta R(\mathrm{DV}, \mathrm{RoI\ cluster}) < 0.4$). In the case of two muon-RoI clusters, the second vertex should be matched to the second cluster.
$300 \leq n_{\mathrm{MDT}} < 3000$

Barrel	*Endcaps*
MS DV with $\lvert\eta_{\mathrm{vx}}\rvert < 0.7$ MS DV with $3\,\mathrm{m} < L_{xy} < 8\,\mathrm{m}$ $n_{\mathrm{RPC}} \geq 250$	MS DV with $1.3 < \lvert\eta_{\mathrm{vx}}\rvert < 2.5$ MS DV with $L_{xy} < 10\,\mathrm{m}$ and $5\,\mathrm{m} < \lvert L_z\rvert < 15\,\mathrm{m}$ $n_{\mathrm{TGC}} \geq 250$

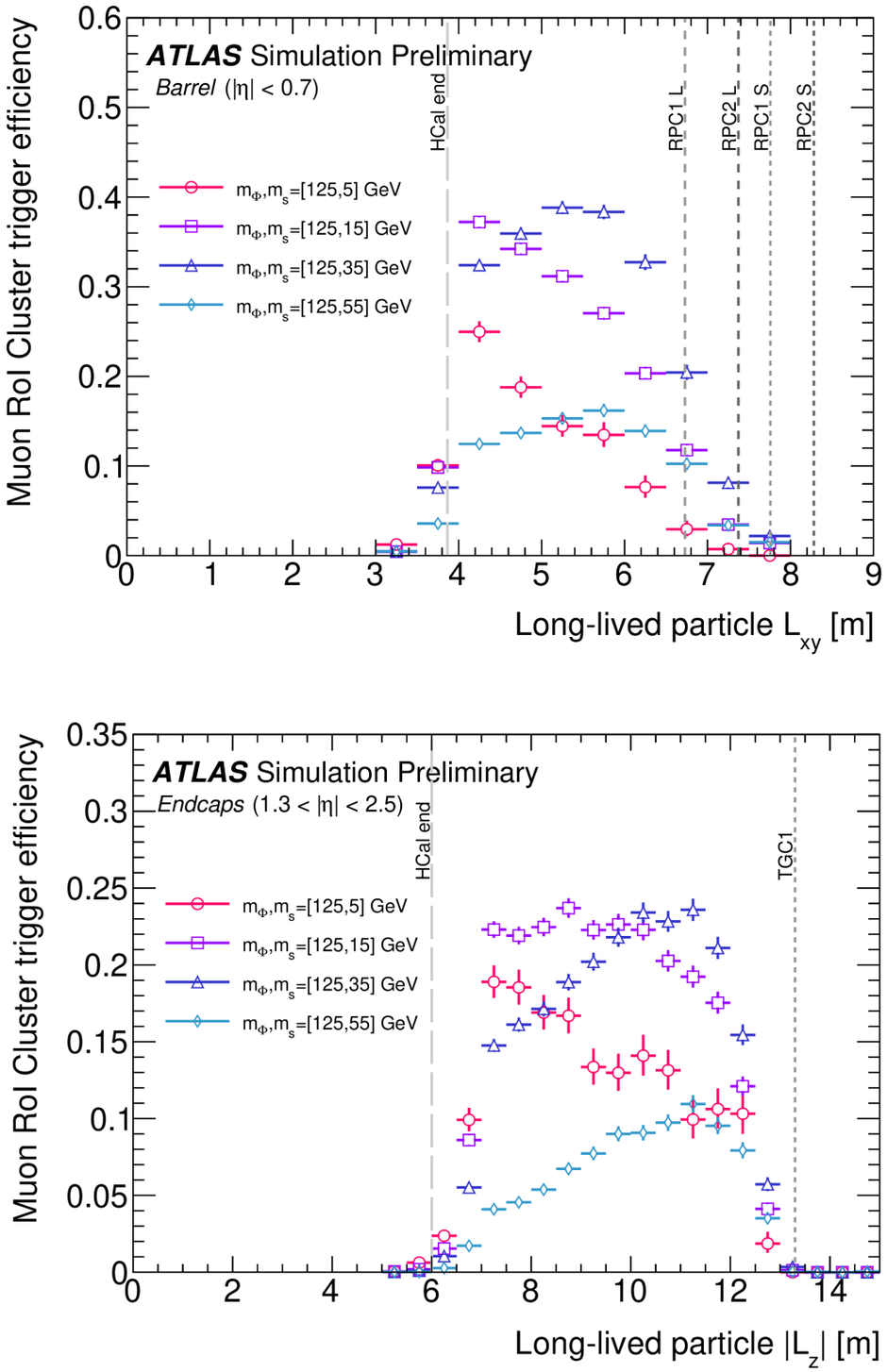
$$N_{2Vx} = N^{1cl} \times P^{2cl}_{noMStrig} + N^{2cl}_{1UMBcl} \times P^{Vx}_{Bcl} + N^{2cl}_{1UMEcl} \times P^{Vx}_{Ecl} = 0.32 \pm 0.05$$

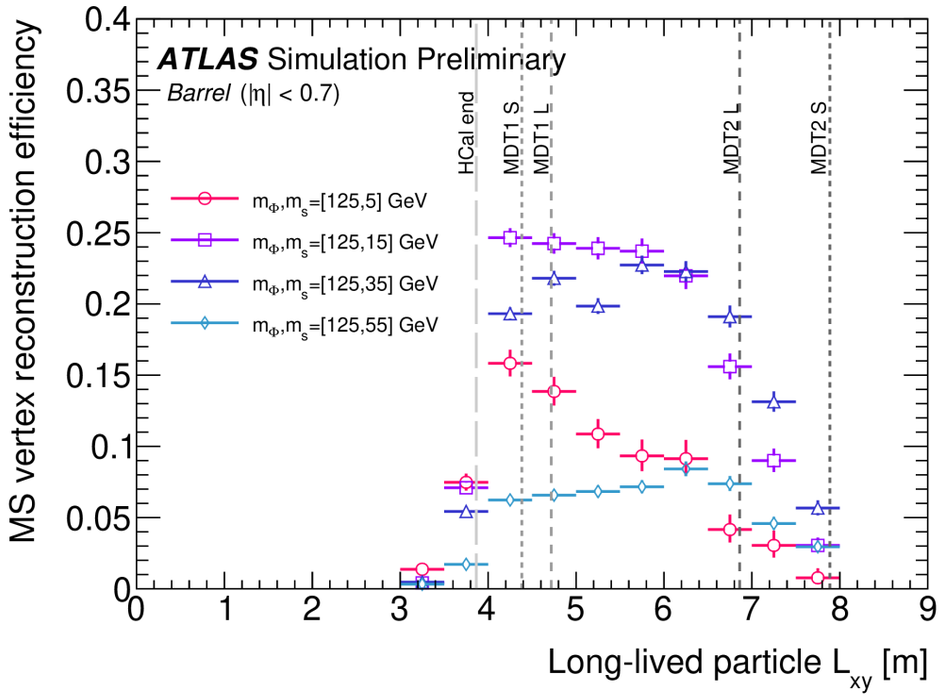
non-signal events
w/ 1 cluster in fiducial region
and 2 vertices

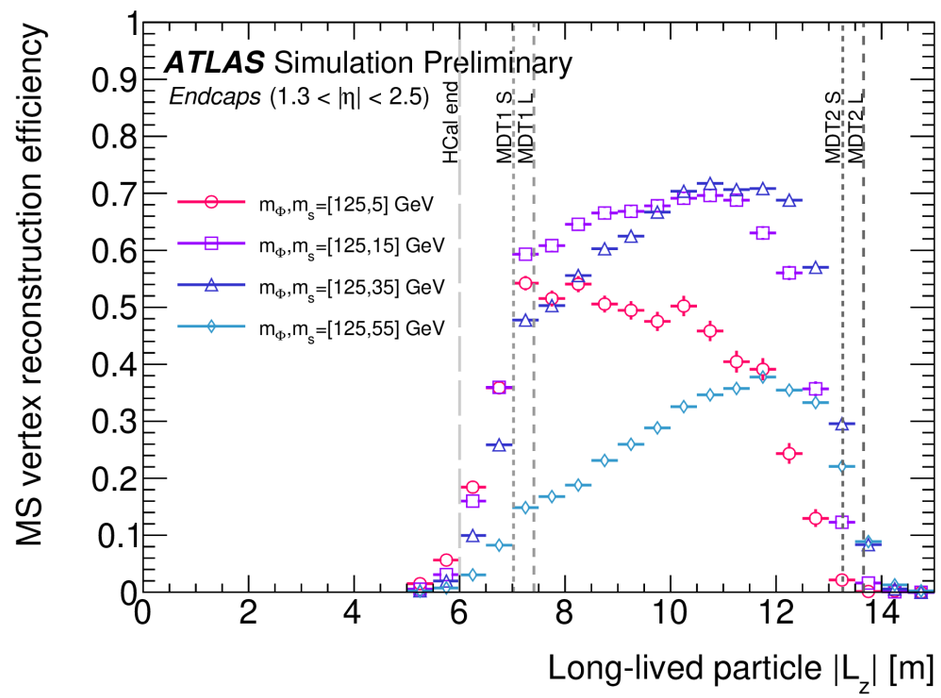
non-signal events
w/ 2 clusters in fiducial region
and 2 vertices

LLPs - in the spectrometer

ATLAS-CONF-2021-032







LLPs - lepton-jets

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ggH

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

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

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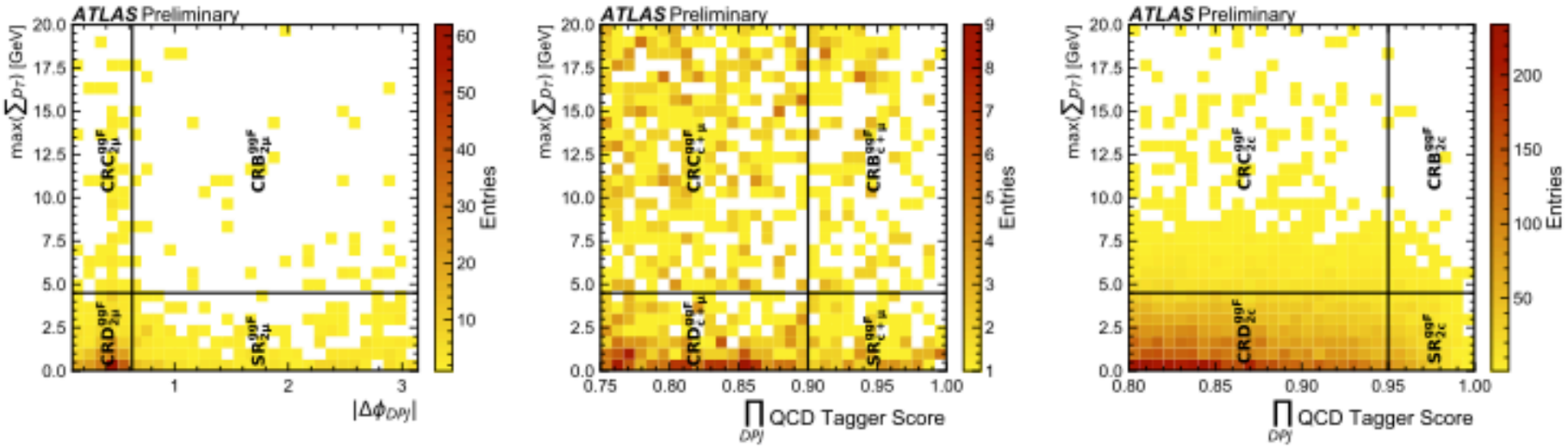
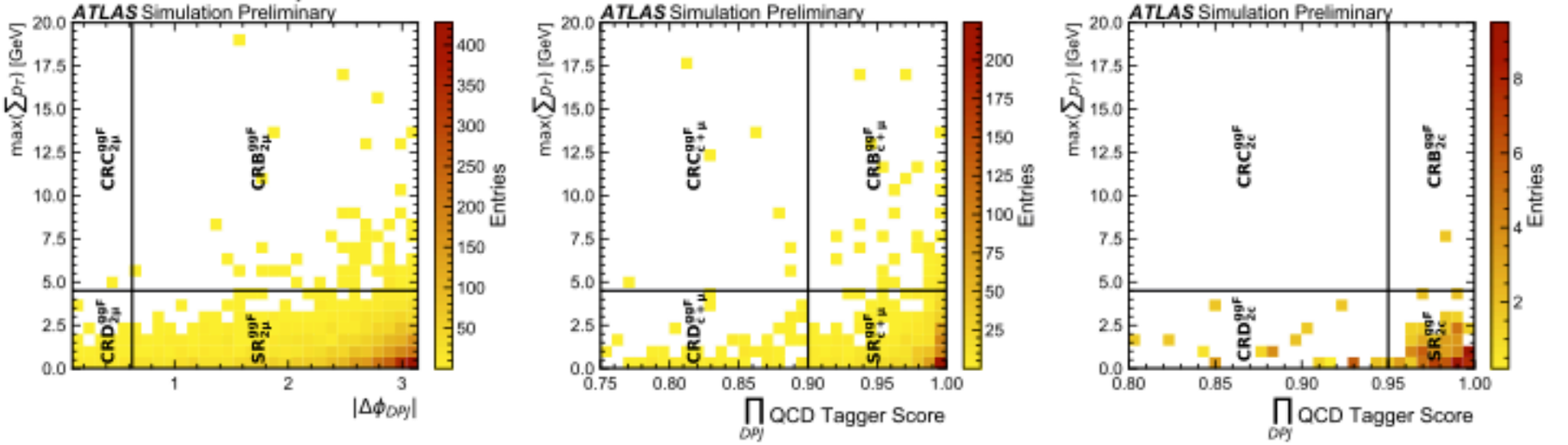
ggH



(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.

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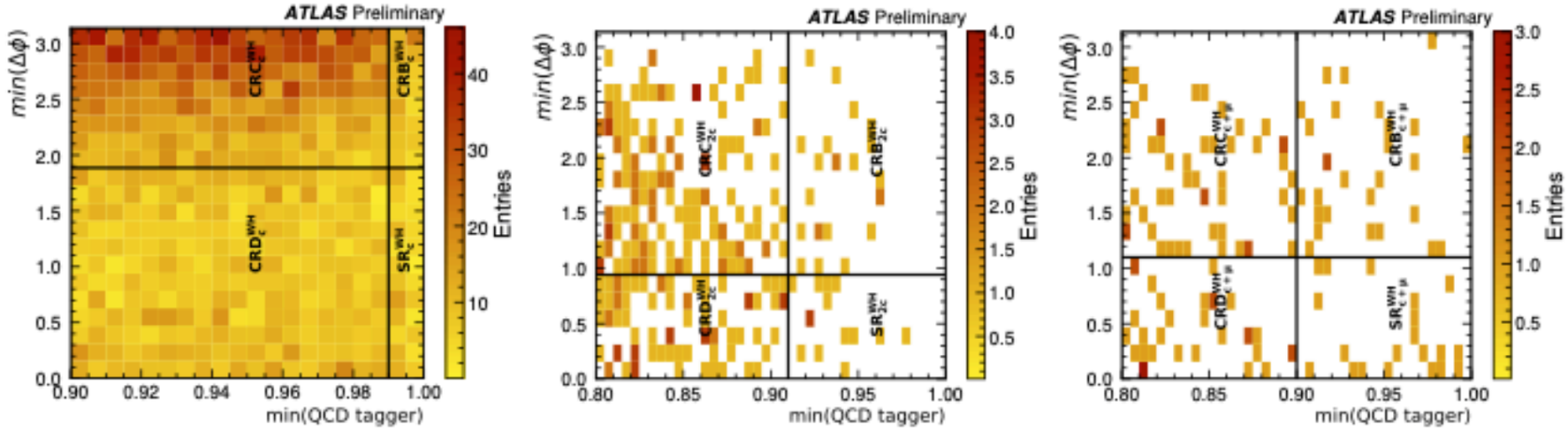
WH



(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 $SR_{c+\mu}^{WH}$.

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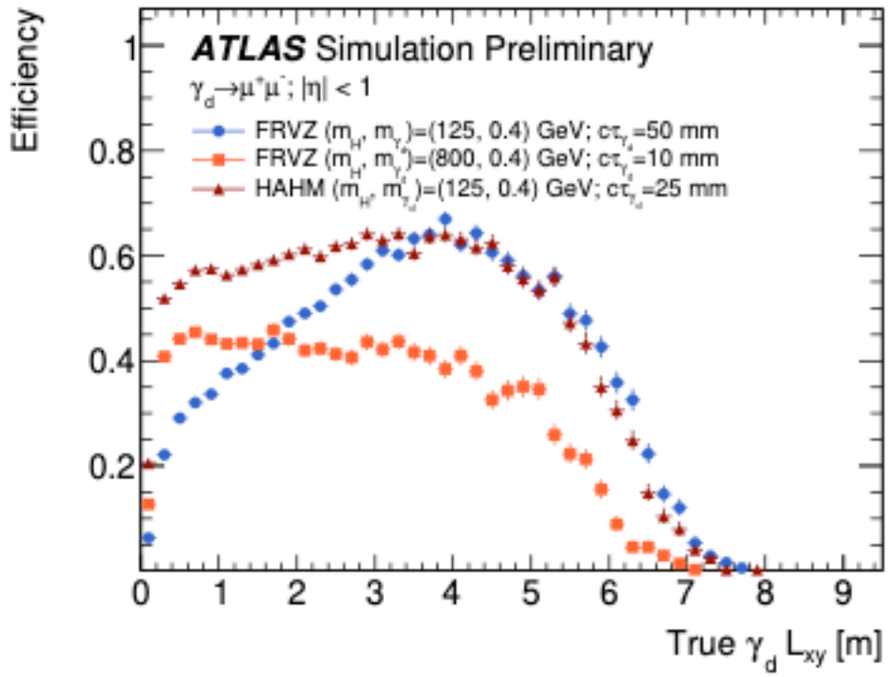
ggH



WH