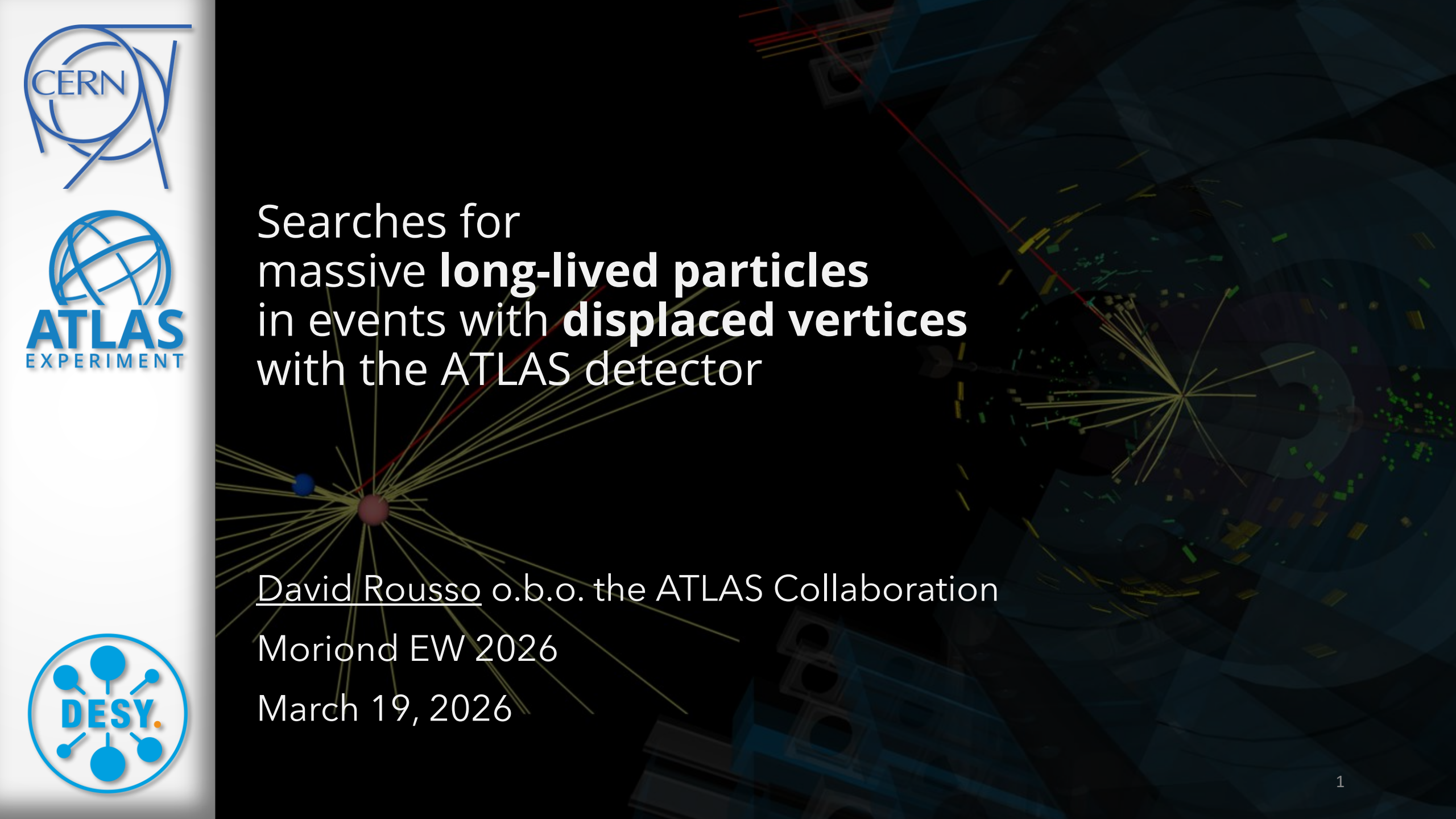

Searches for massive **long-lived particles** in events with **displaced vertices** with the ATLAS detector

David Rousso o.b.o. the ATLAS Collaboration

Moriond EW 2026

March 19, 2026

What are long-lived particles (“LLP”s)?

New particles we search for can either:

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New Particle
Decay Products
Detector

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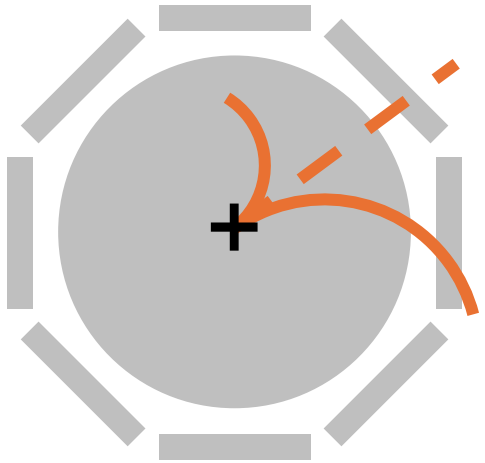
decay immediately



Lifetime: <≈ 0.0033 ns / 1 mm

“Prompt”

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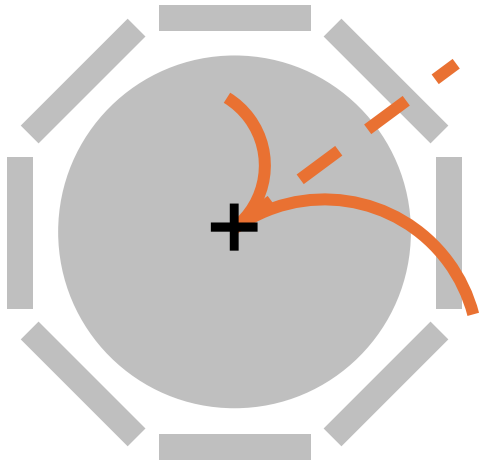
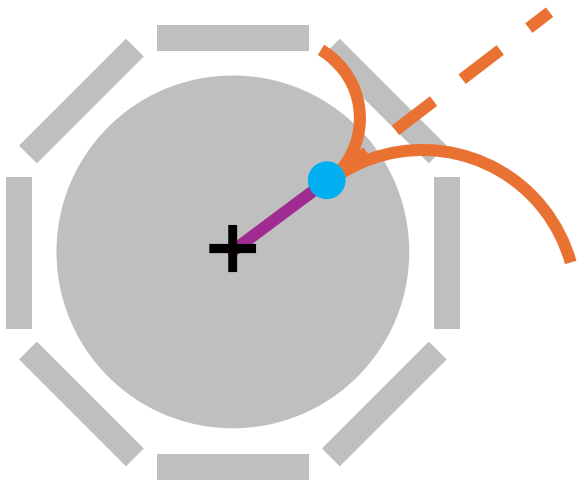


decay while travelling through detector



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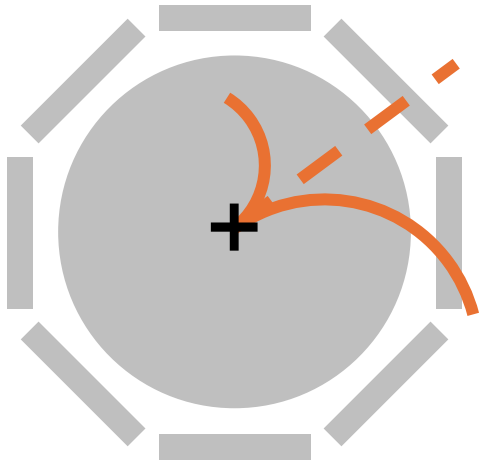

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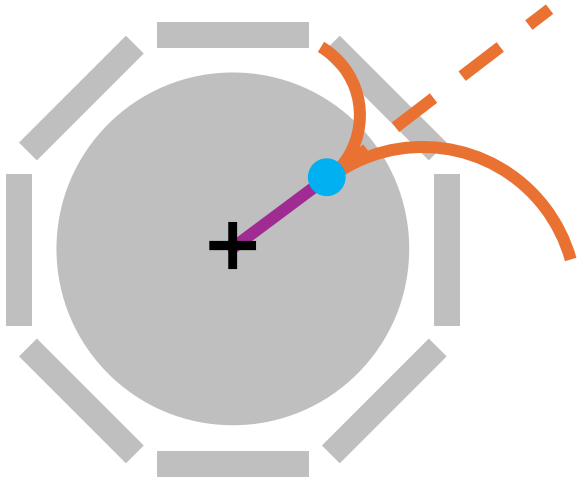
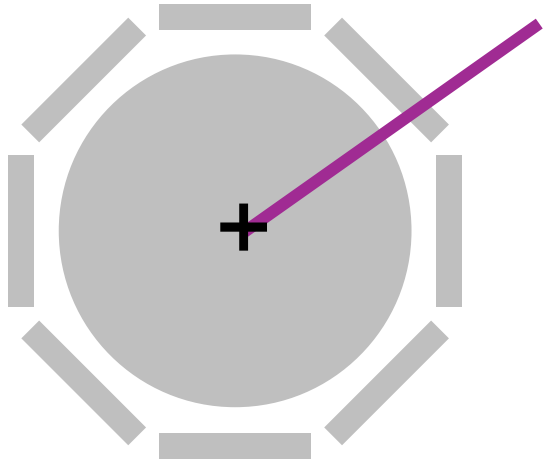


"LLP"

not decay/ decay after detector



>≈ 33 ns / 10 m

"Stable"

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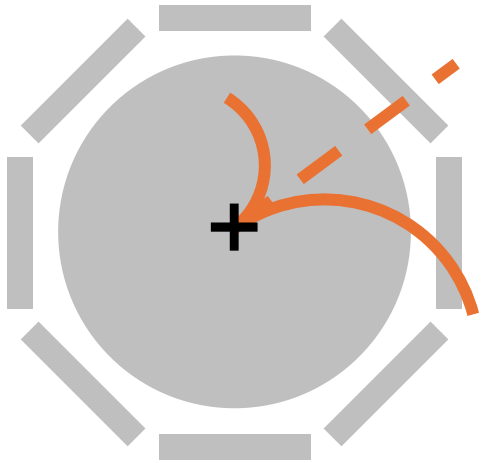

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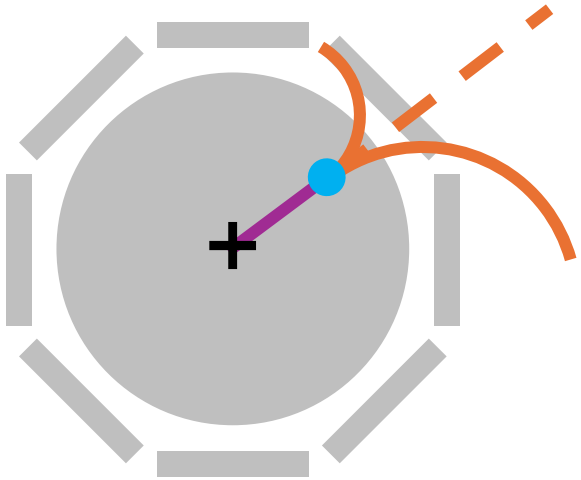

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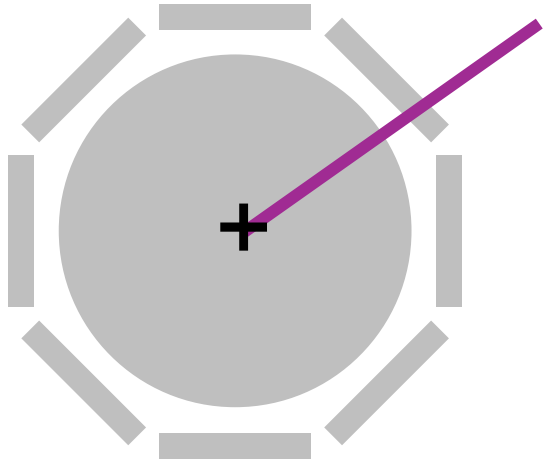

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"LLP"

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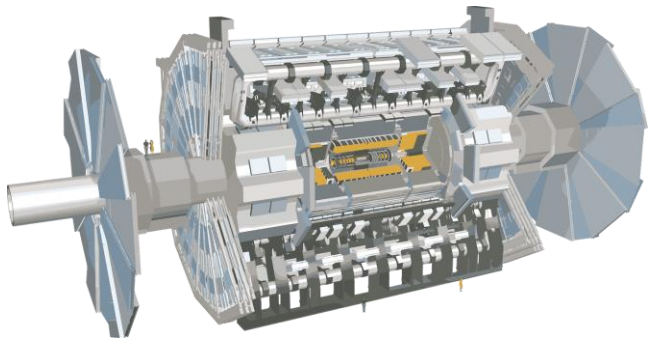
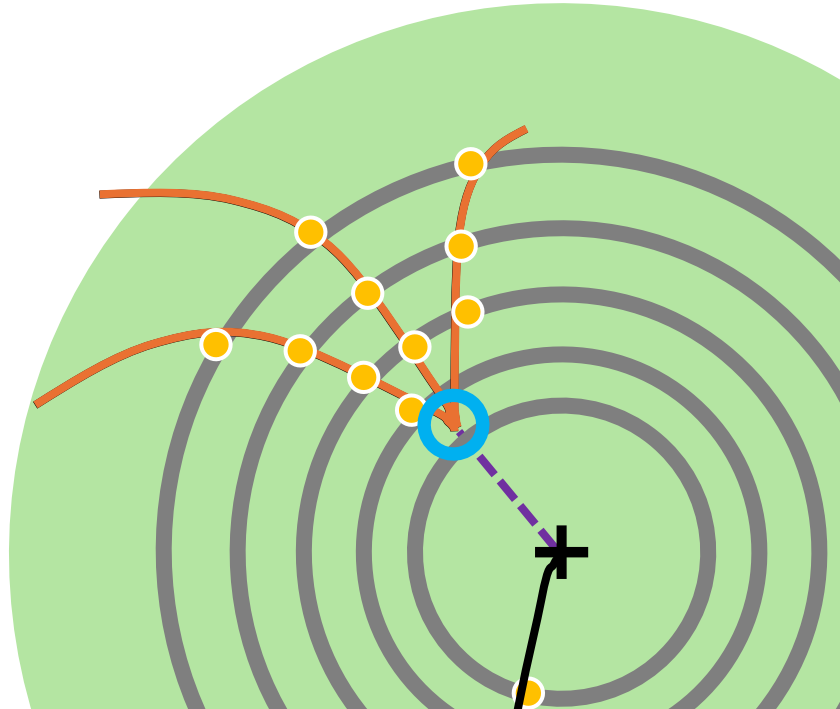
Many possible LLP signatures to search for → see John Anders' talk for more!

What are displaced vertices (“DV”s)?





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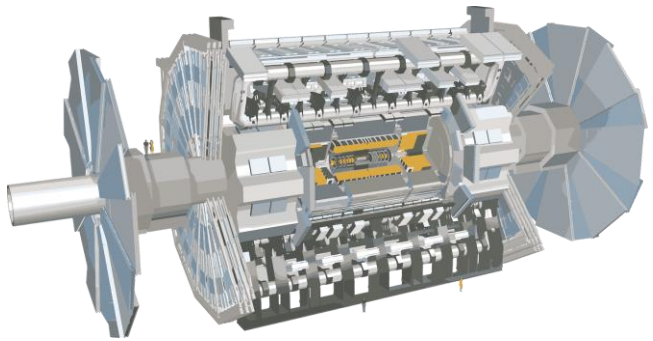

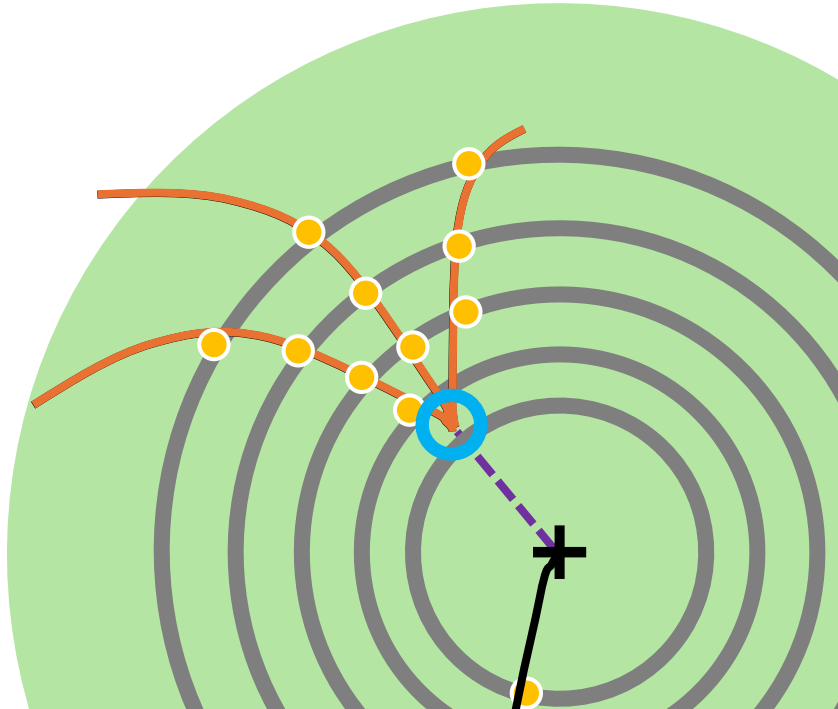

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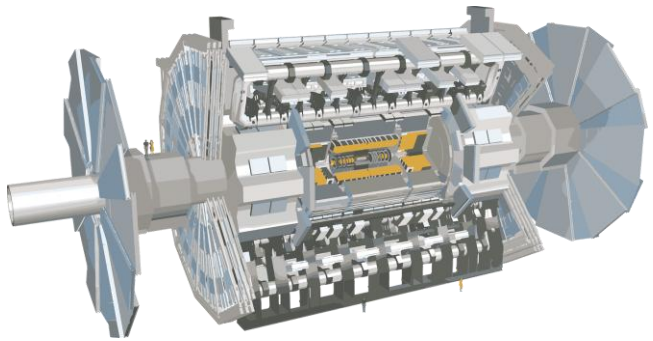

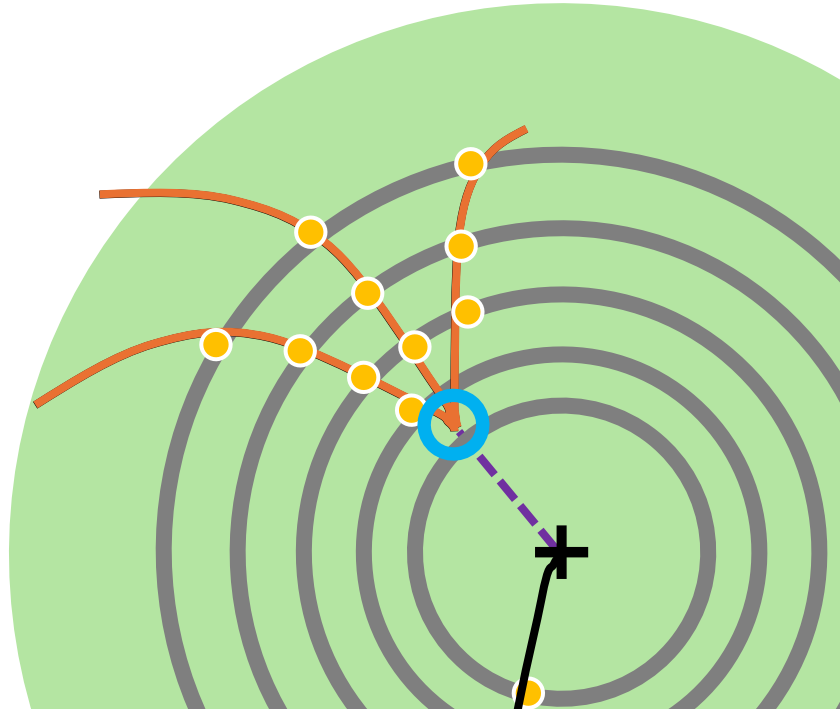

ATLAS EXPERIMENT

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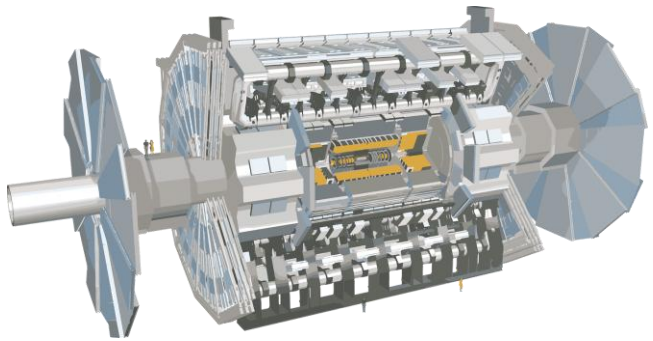

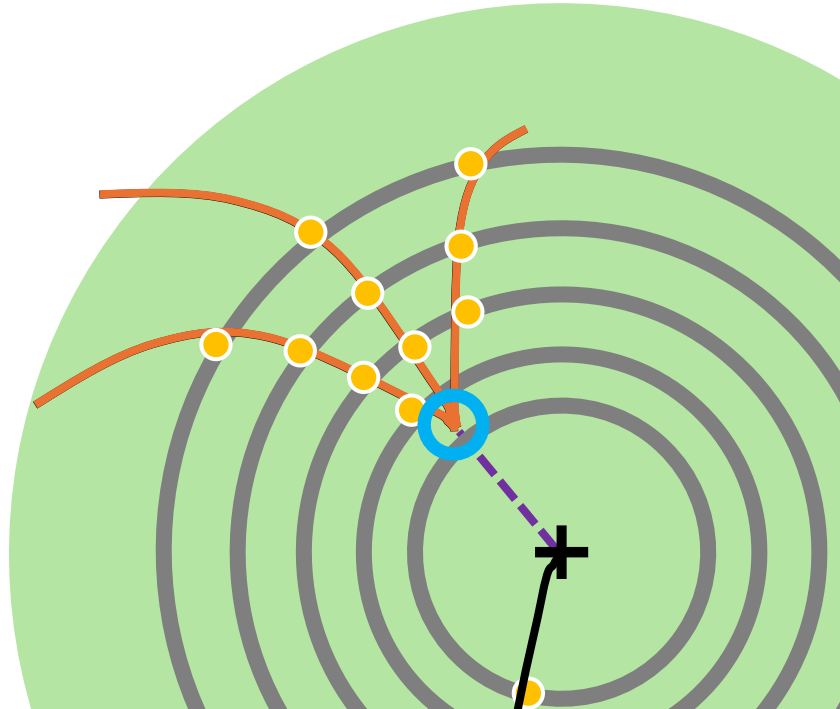

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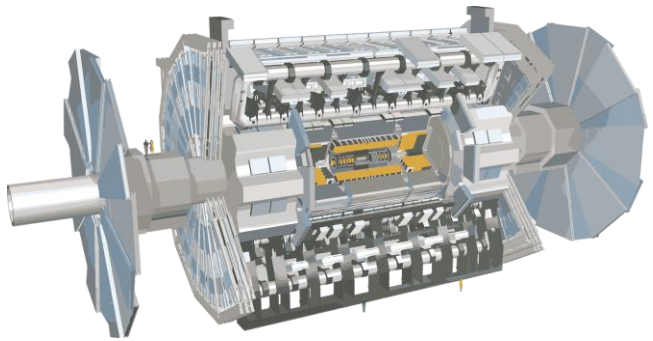
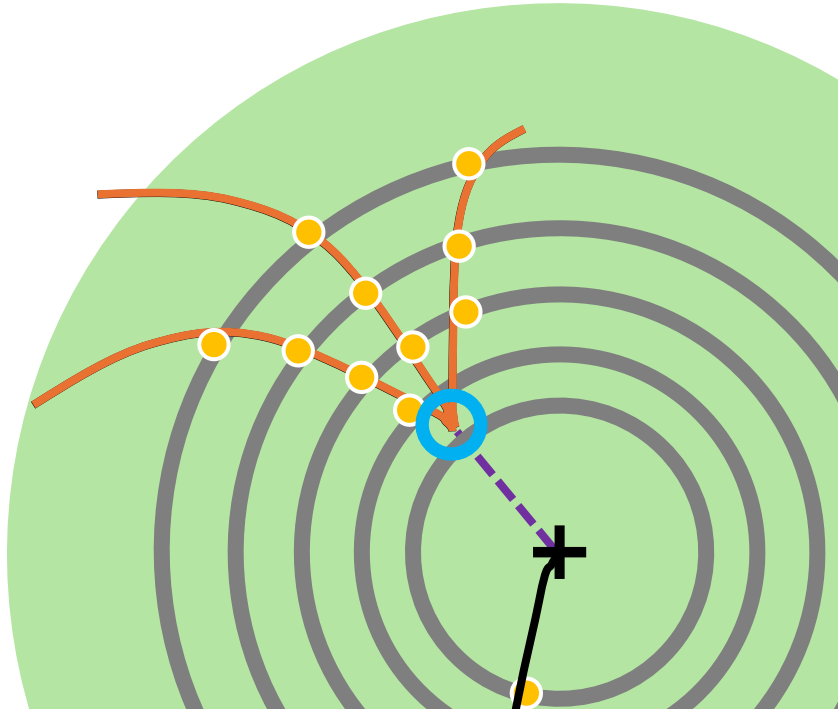


DVs characterized by:

- Number of tracks
- Invariant mass of tracks (m_{DV})
- Vertex position ($\mathrm{DV}_{rxy/x/y/z}$)



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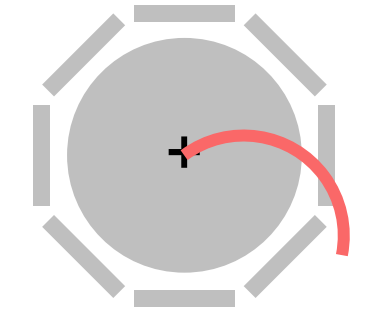

muons

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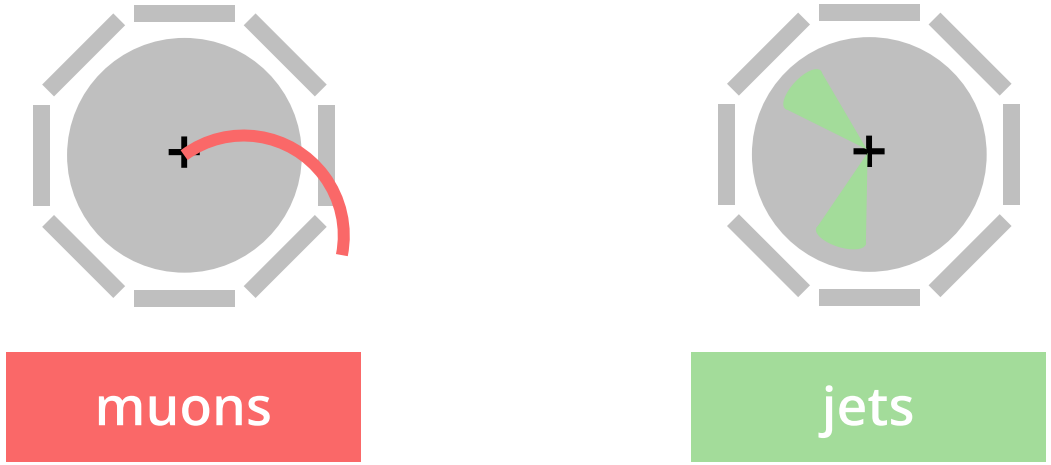

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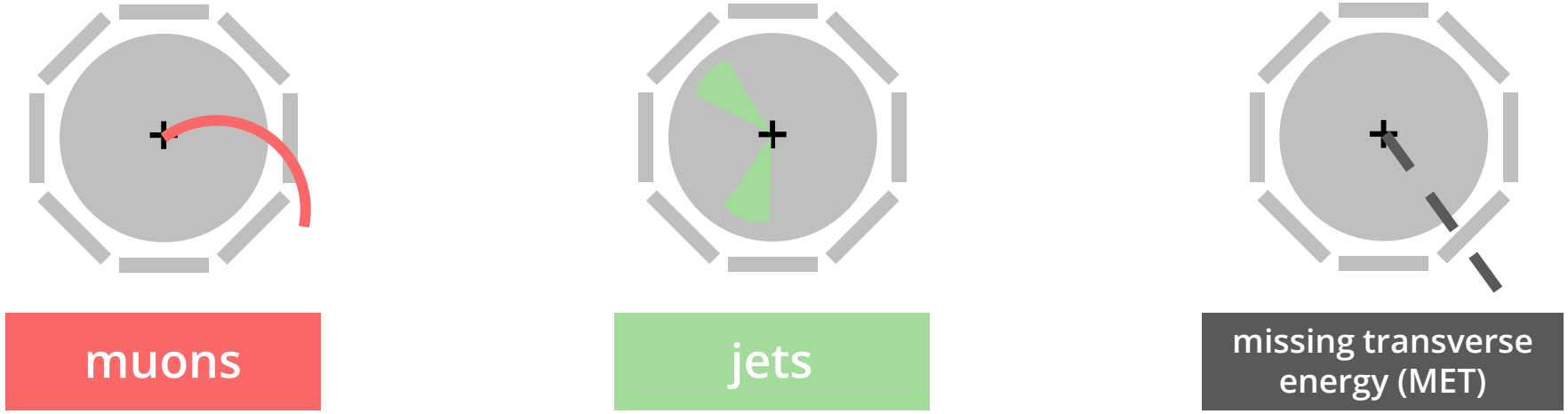

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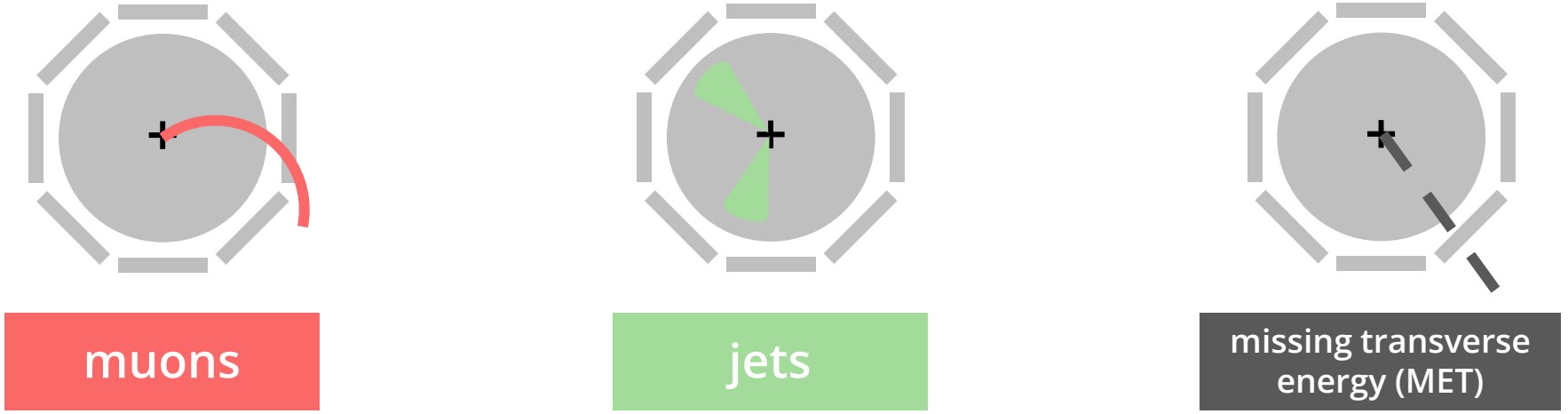


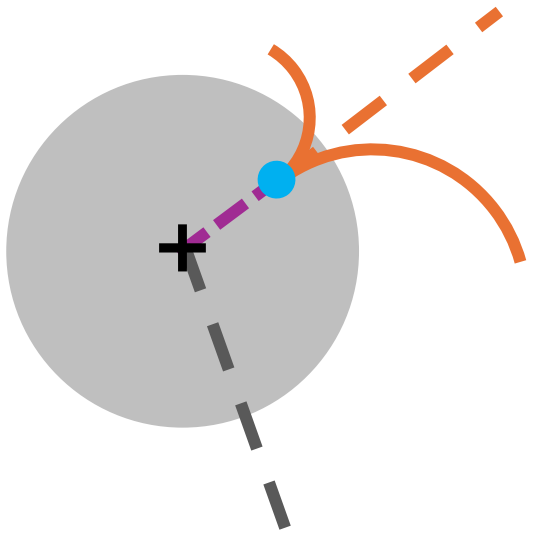
- Therefore, analyses typically search for “DV+*something*”

Which searches will we learn about today?

DV+*MET* ❤️

(Full Run 2 2016-2018)

arXiv:2603.12051



Both Hot Off the Press Last Week!

follow-up of:
Partial Run 2 2016-only search

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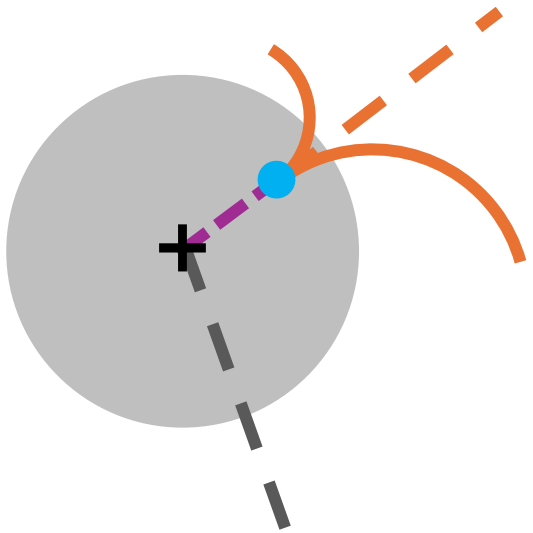

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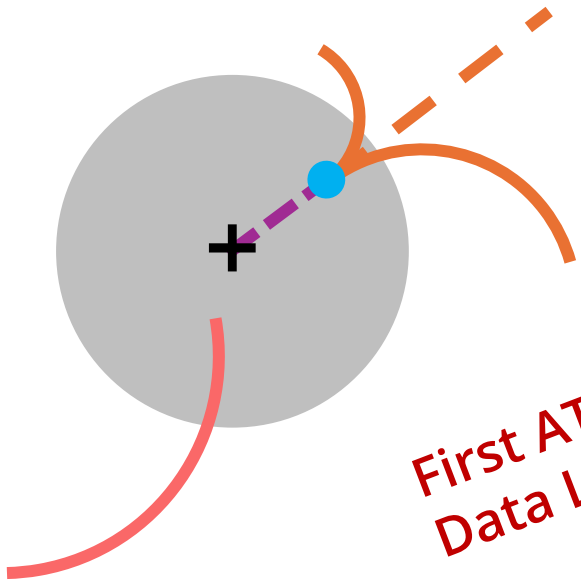

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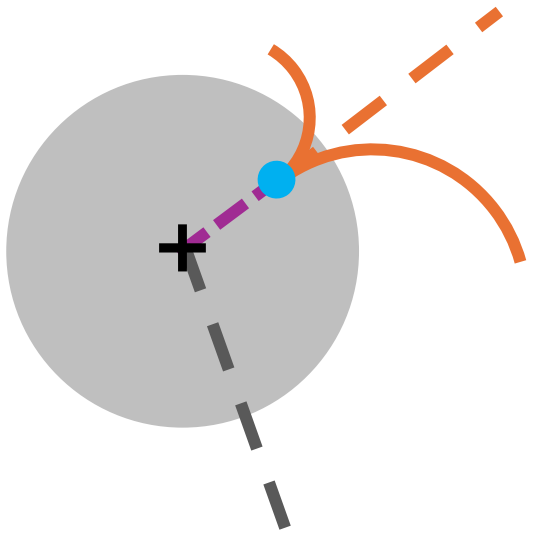

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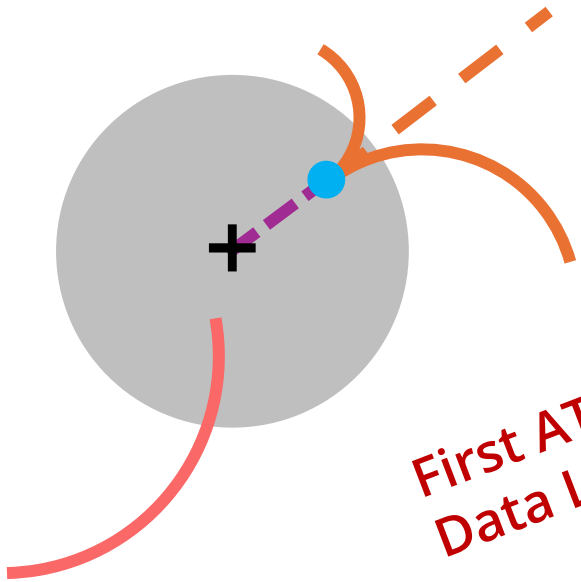

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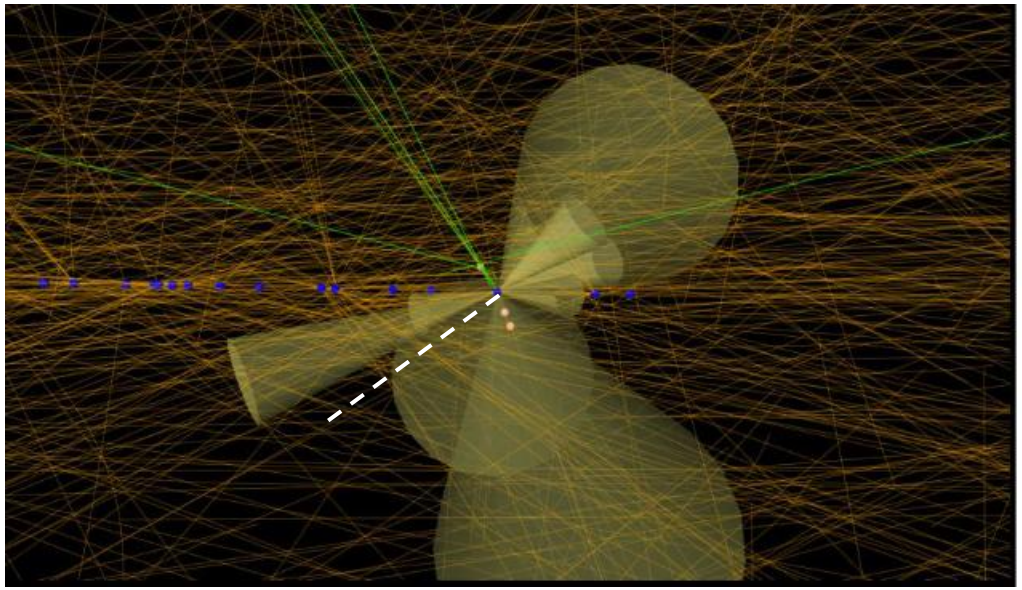

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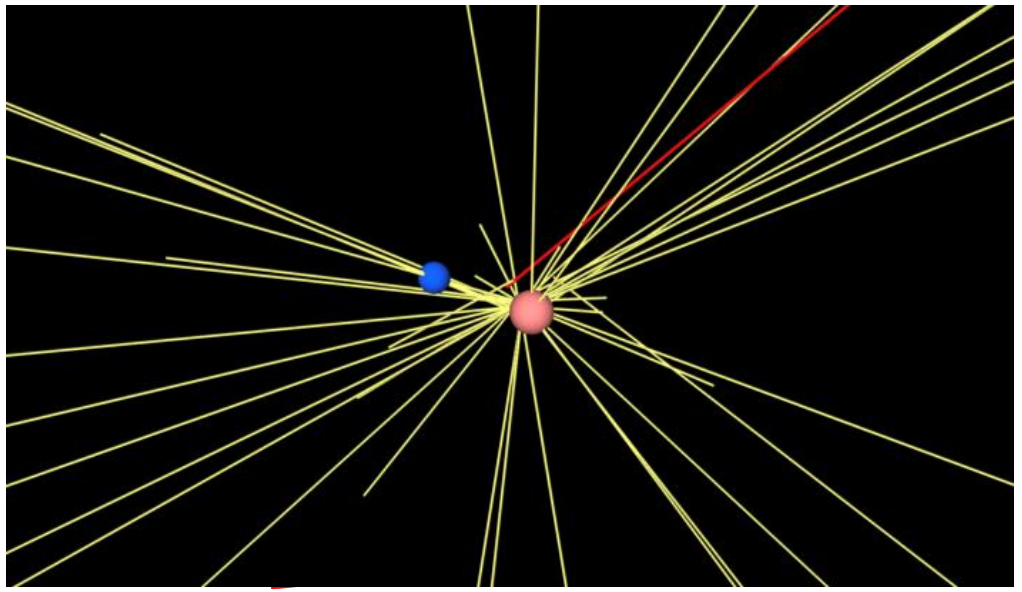

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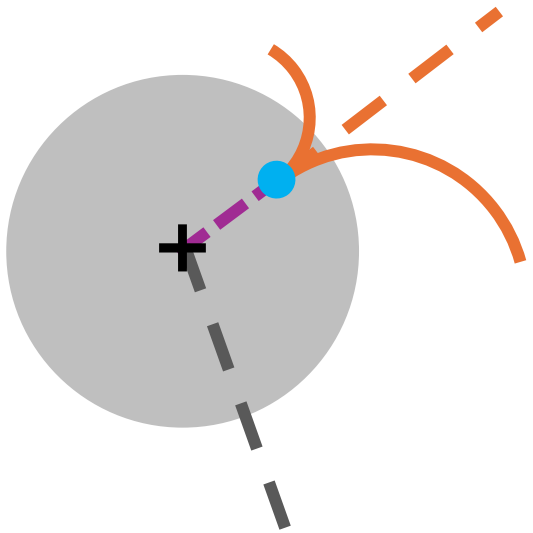

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DV+MET: What's new this time?

More Data

$\geq$ 2 DV Events

Fuzzy Vertexing

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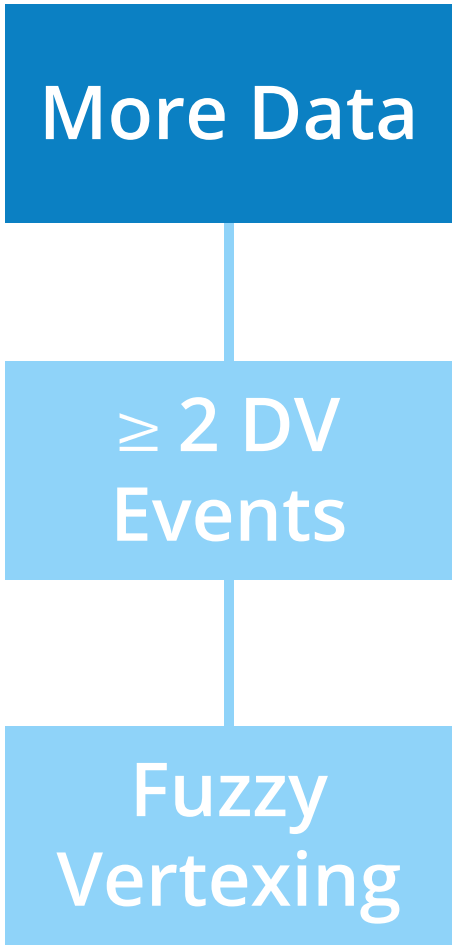


$137\ fb^{-1}$

2016-2018

vs.

$32.8\ fb^{-1}$

2016 only

DV+MET: What's new this time?

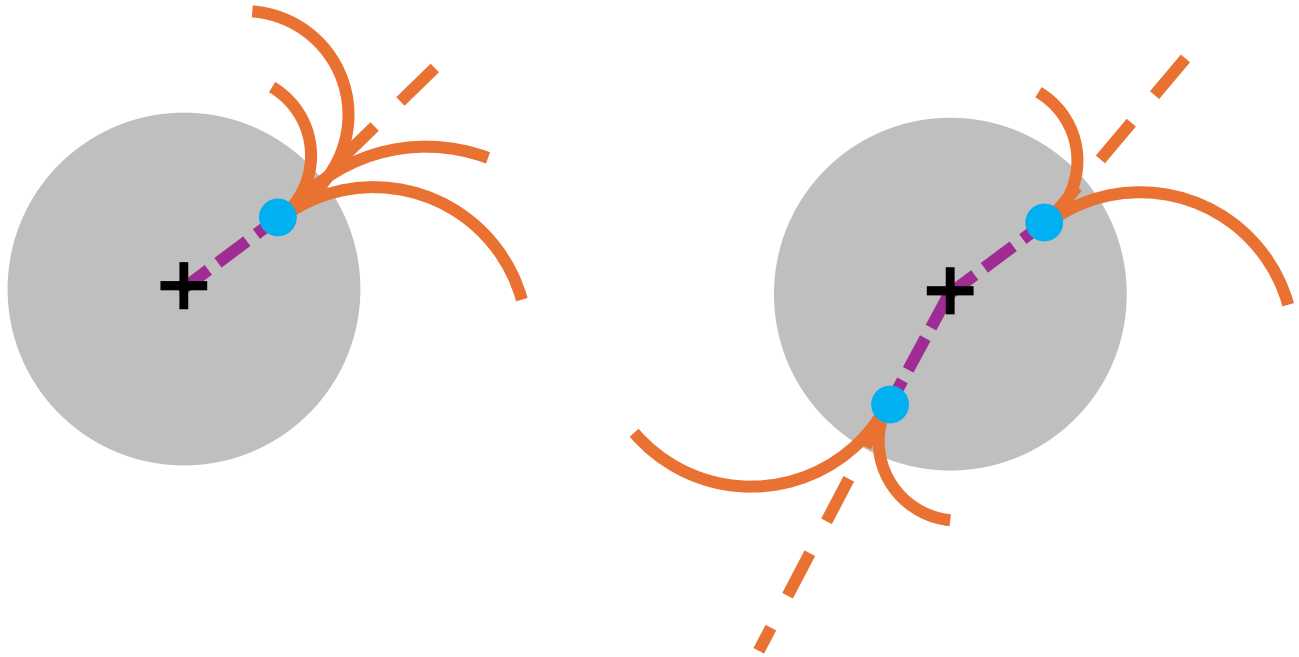
More Data

≥ 2 DV Events

Fuzzy Vertexing

- Requiring 2 DVs in the event allows us to search for lighter and fewer-track DVs

  →lighter LLPs!



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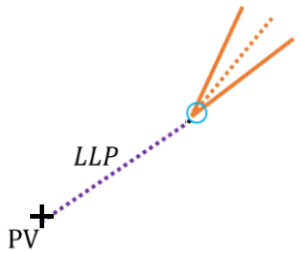

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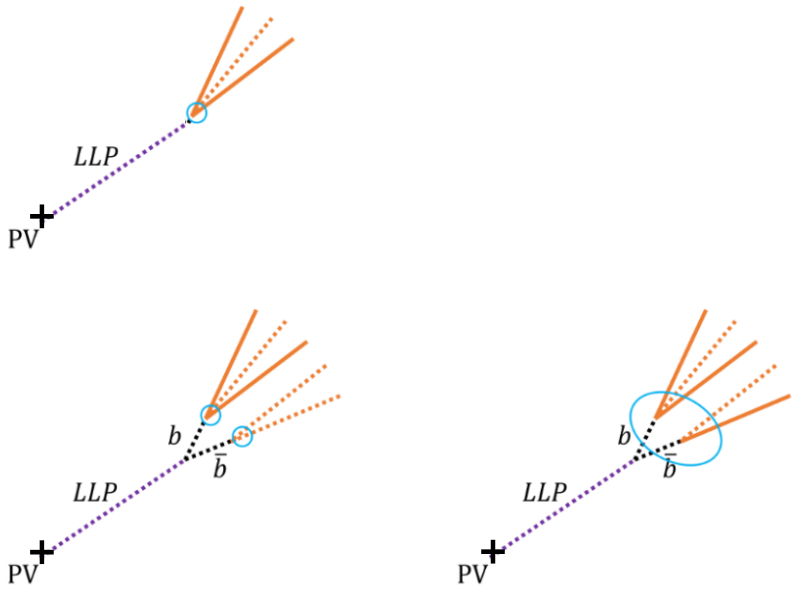

Standard Vertexing (SDV)

Fuzzy Vertexing (FDV)

DV+MET: What's new this time?

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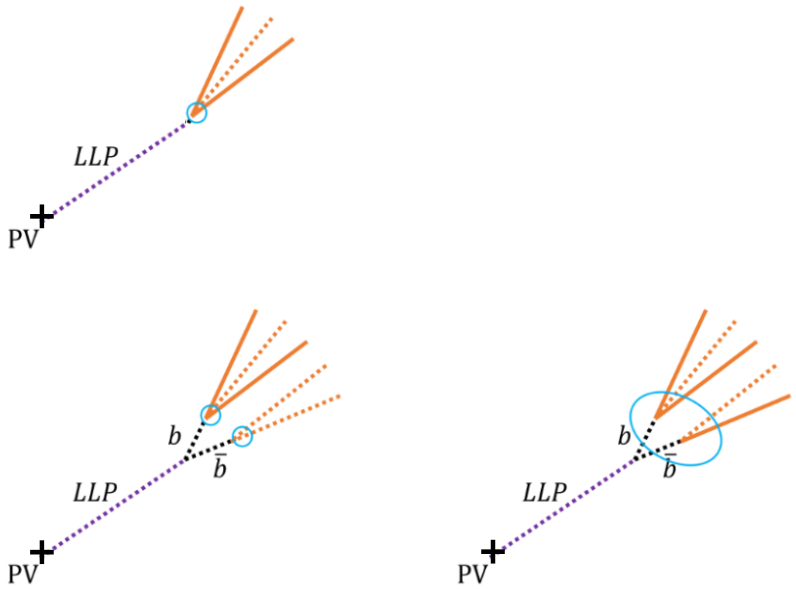

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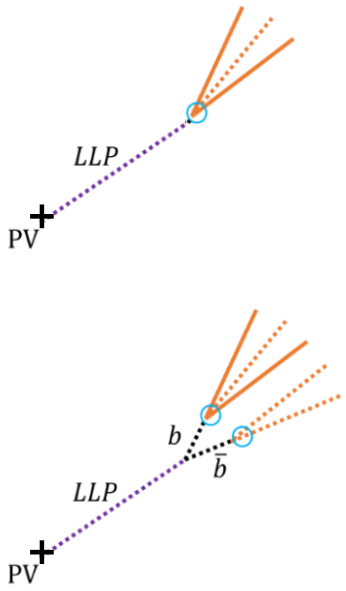

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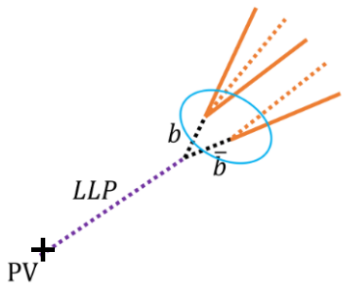

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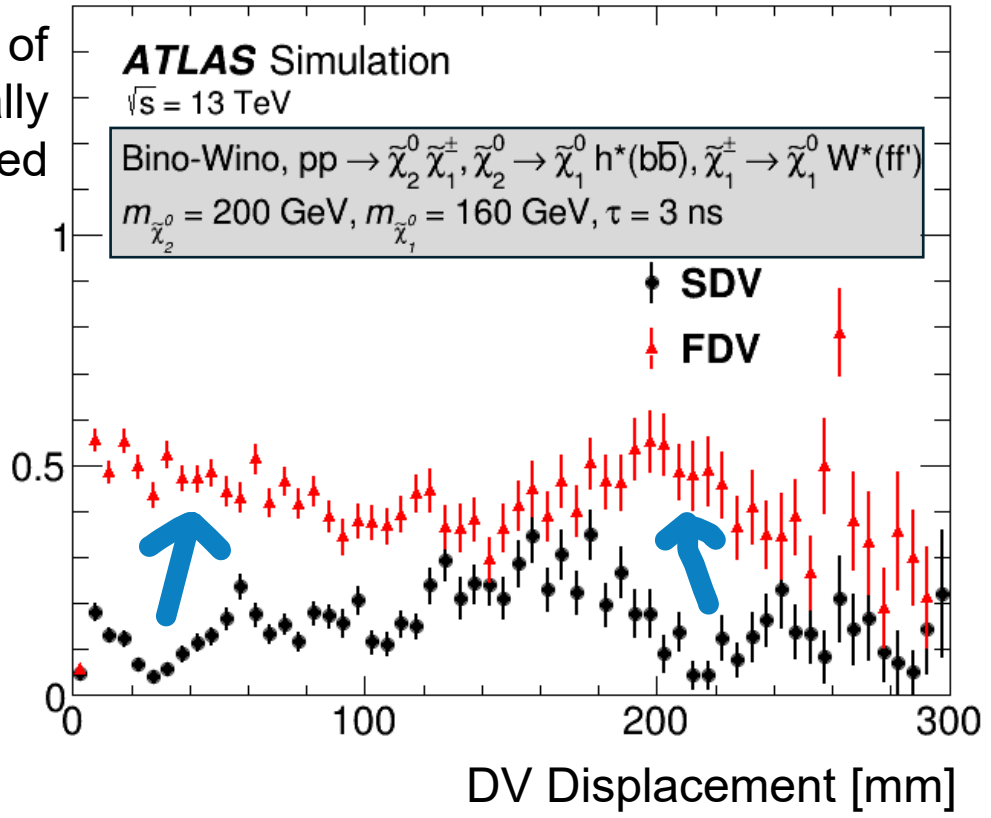

DV+MET: Signal Regions

DV + MET

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DV + MET

1+ Standard DV

≥ 5 tracks

$m_{\mathrm{DV}} \geq 10\ \mathrm{GeV}$

DV+MET: Signal Regions

DV + MET

1+ Standard DV
≥ 5 tracks
$m_{\mathrm{DV}} \geq 10$ GeV

1 Fuzzy DV
≥ 5 tracks
$m_{\mathrm{DV}} \geq 10$ GeV

ATLAS EXPERIMENT

DV+MET: Signal Regions

DV + MET

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≥ 5 tracks
$m_{\mathrm{DV}} \geq 10$ GeV

1 Fuzzy DV
≥ 5 tracks
$m_{\mathrm{DV}} \geq 10$ GeV

2+ Fuzzy DVs
≥ 4 tracks
$m_{\mathrm{DV}} \geq 1.5$ GeV

ATLAS EXPERIMENT

DV+MET: Signal Regions

DV + MET

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$m_{\mathrm{DV}} \geq 10$ GeV

2+ Fuzzy DVs
≥ 4 tracks
$m_{\mathrm{DV}} \geq 1.5$ GeV

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- All DVs must lie within $|\mathrm{DV}_{rxy}| \leq 300$ mm, $|\mathrm{DV}_z| \leq 300$ mm
- All DVs must have transverse distance at least 4 mm away from any collision vertex

ATLAS EXPERIMENT

DV+MET: Signal Regions

DV + MET

1+ Standard DV
≥ 5 tracks
$m_{\mathrm{DV}} \geq 10\ \mathrm{GeV}$

1 Fuzzy DV
≥ 5 tracks
$m_{\mathrm{DV}} \geq 10\ \mathrm{GeV}$

2+ Fuzzy DVs
≥ 4 tracks
$m_{\mathrm{DV}} \geq 1.5\ \mathrm{GeV}$

All events must:
Pass MET triggers
MET≥150 GeV

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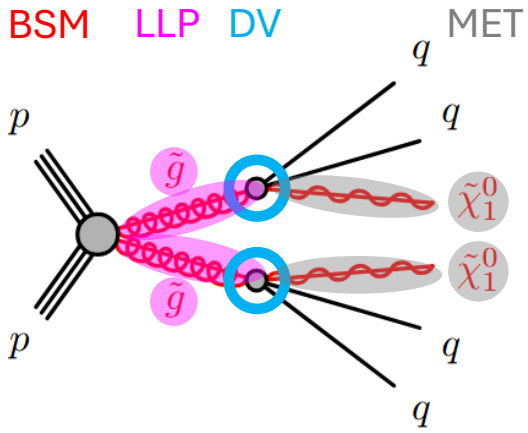
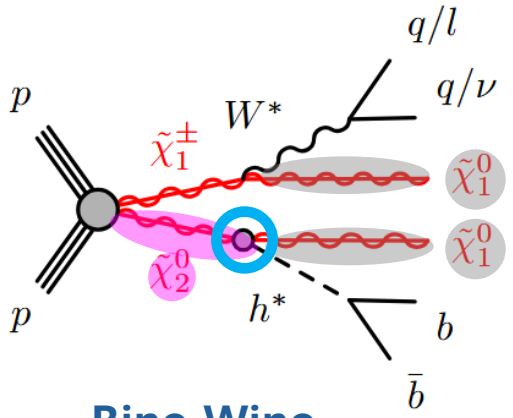
ATLAS EXPERIMENT

DV+MET: Benchmark Models

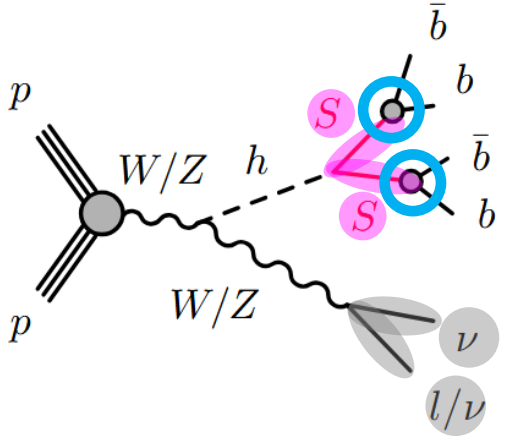
1+ Standard DV
1 Fuzzy DV
2+ Fuzzy DV



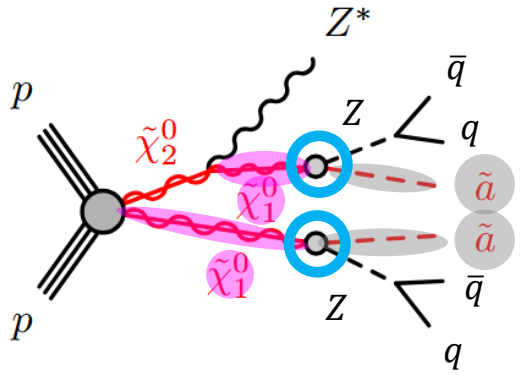
Gluino R-hadron



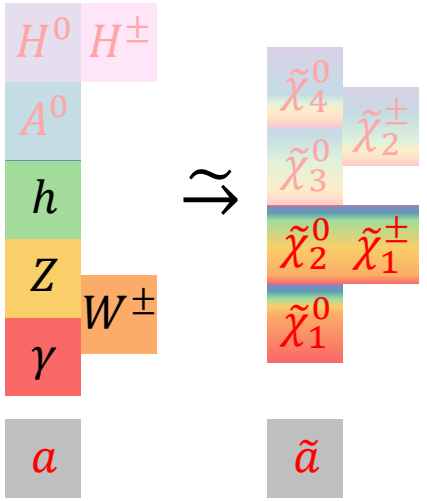
Bino-Wino Coannihilation



Higgs Portal



DFSZ Axino



Note:
If model has **2 LLPs** where **1 lives long enough** to be reco'd as MET
Don't need neutrinos or any other MET-producing objects in diagram!

(We do not require leptons)

DV+MET: Backgrounds

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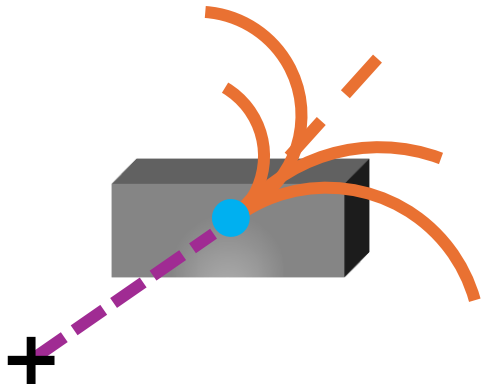
What non-new-physics processes also produce DVs?

DV+MET: Backgrounds

What non-new-physics processes also produce DVs?

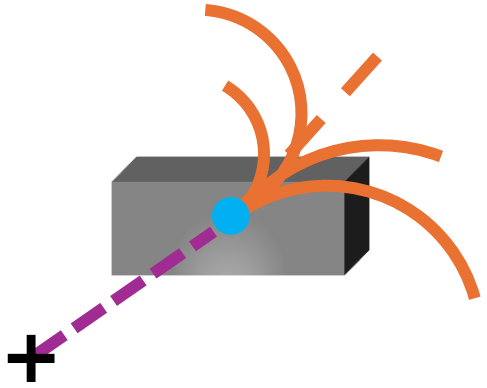
- Normal particles interacting hadronically with detector material

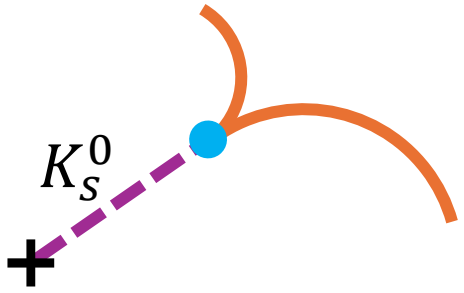


DV+MET: Backgrounds

What non-new-physics processes also produce DVs?

- Normal particles interacting hadronically with detector material
- K-short and some other b-decays





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→These are correlated to the number of tracks and jets in the event

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- Normal particles interacting hadronically with detector material
- K-short and some other b-decays

→These are correlated to the number of tracks and jets in the event

→ Note that they are completely independent from MET, muons, photons, etc. in the event

DV+MET: Data-Driven Background Estimate

Background DVs originate from event tracks and jets

Irrelevant

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Background DVs originate from event tracks and jets

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Same SR selections made across. Only selections change is related to trigger/MET/photon

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DV+photon

1) Determine fraction of events that have DVs

$$\left(\frac{\#\text{Events w. DVs}_{\text{photon}}}{\#\text{Total Events}_{\text{photon}}}\right)$$

DV+MET: Data-Driven Background Estimate

Background DVs originate from event tracks and jets

Irrelevant

2) Determine #events total $(\#\text{Total Events}_{MET})$

Same SR selections made across. Only selections change is related to trigger/MET/photon

DV+photon

1) Determine fraction of events that have DVs

$$\left(\frac{\#\text{Events w. DVs}_{\text{photon}}}{\#\text{Total Events}_{\text{photon}}}\right)$$

DV+MET: Data-Driven Background Estimate

Background DVs originate from event tracks and jets

Irrelevant

DV+MET

Same SR selections made across. Only selections change is related to trigger/MET/photon

DV+photon

1) Determine fraction of events that have DVs

$$\left(\frac{\#\text{Events w. DVs}_{\text{photon}}}{\#\text{Total Events}_{\text{photon}}}\right)$$

2) Determine #events total

$$(\#\text{Total Events}_{\text{MET}})$$

3)

$$(\#\text{Events w. DVs}_{\text{MET}}) = (\#\text{Total Events}_{\text{MET}})\left(\frac{\#\text{Events w. DVs}_{\text{photon}}}{\#\text{Total Events}_{\text{photon}}}\right)$$

Validation Regions are made by inverting the SR # tracks, mDV, # seed, or material veto SR requirements

DV+MET: Results

Region	Estimated Background	Uncertainties		
		Statistical	Pileup	Non-closure
1+ Standard DV	0.6 ± 0.4	$\pm 70\%$	$\pm 5\%$	–
1 Fuzzy DV	0.8 ± 0.5	$\pm 57\%$	$\pm 2\%$	$\pm 22\%$
2+ Fuzzy DV	1.3 ± 0.6	$\pm 45\%$	$\pm 4\%$	$\pm 20\%$

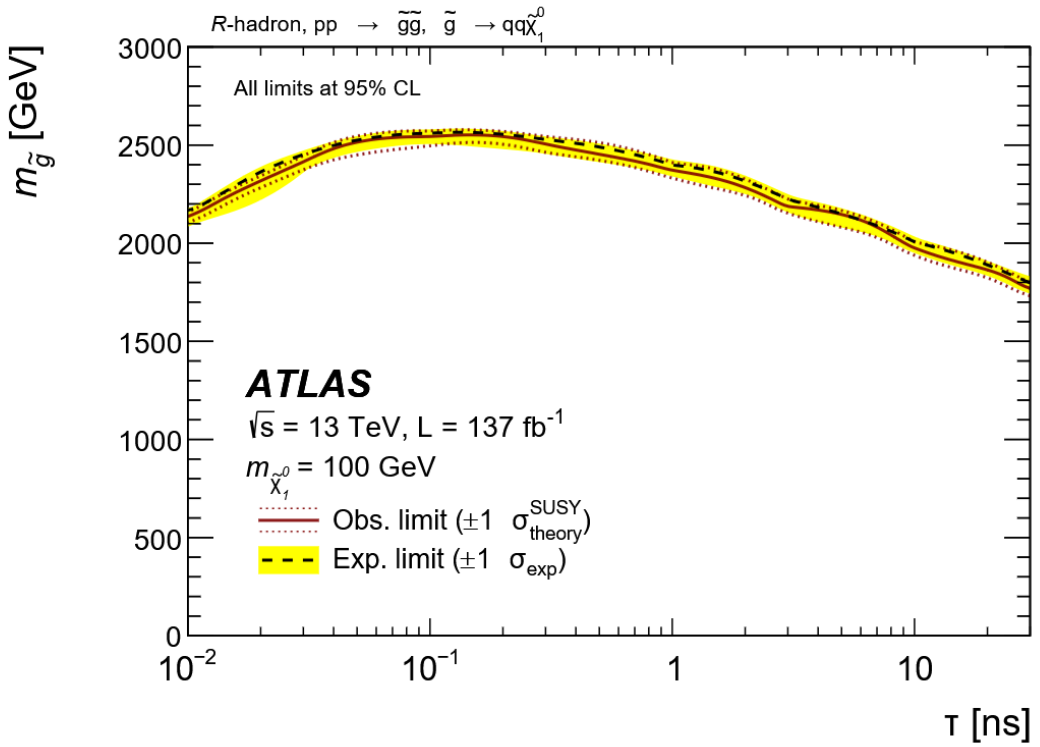
DV+MET: Results

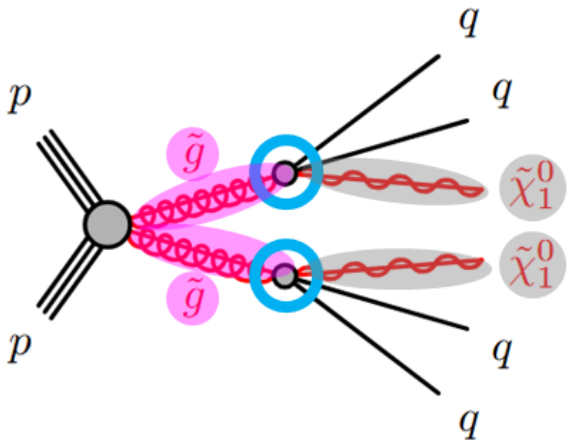
Region	Estimated Background	Obs.
1+ Standard DV	0.6 ± 0.4	1
1 Fuzzy DV	0.8 ± 0.5	3
2+ Fuzzy DV	1.3 ± 0.6	2

No significant excess found

DV+MET: Exclusion Limits

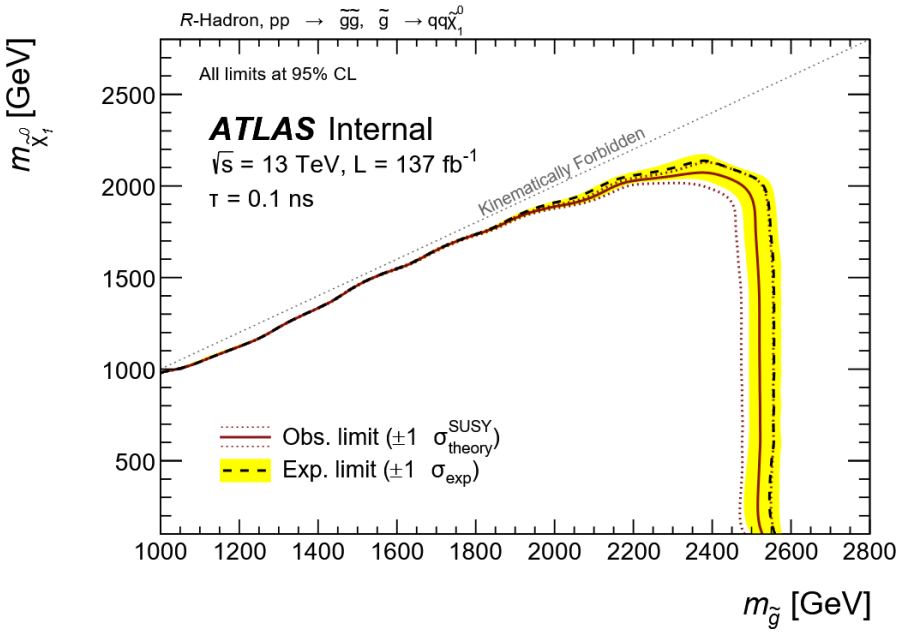
- **Gluino R-hadron**
- Higgs Portal
- Bino-Wino
- DFSZ Axino





Gluino R-hadron

→Improvement on the 2016-only search!



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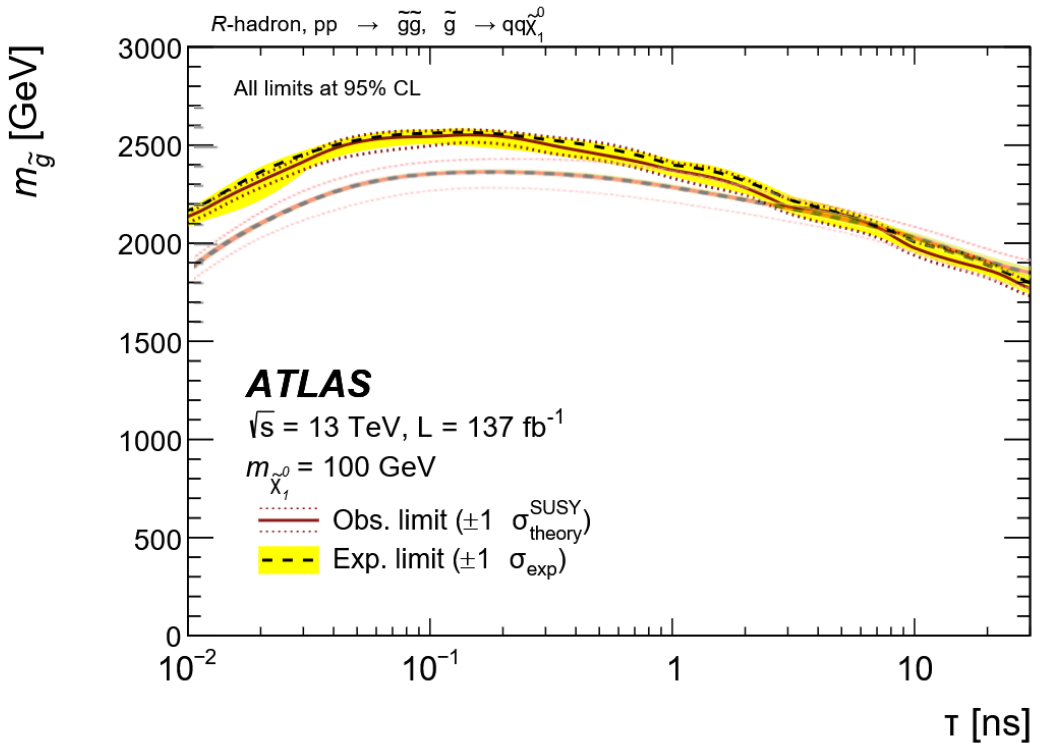

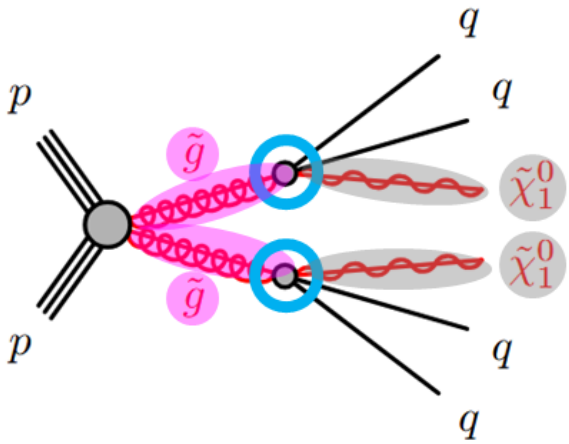

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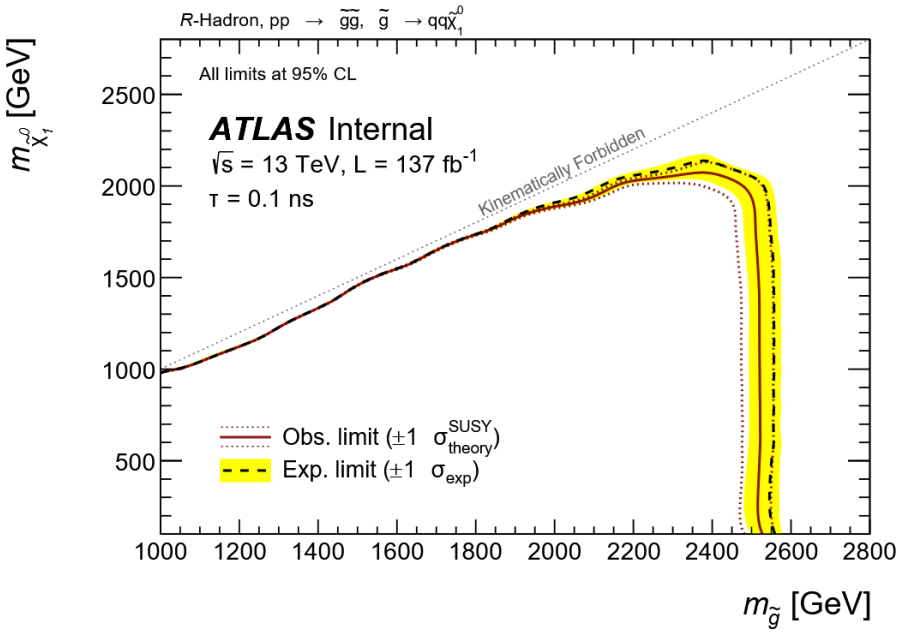

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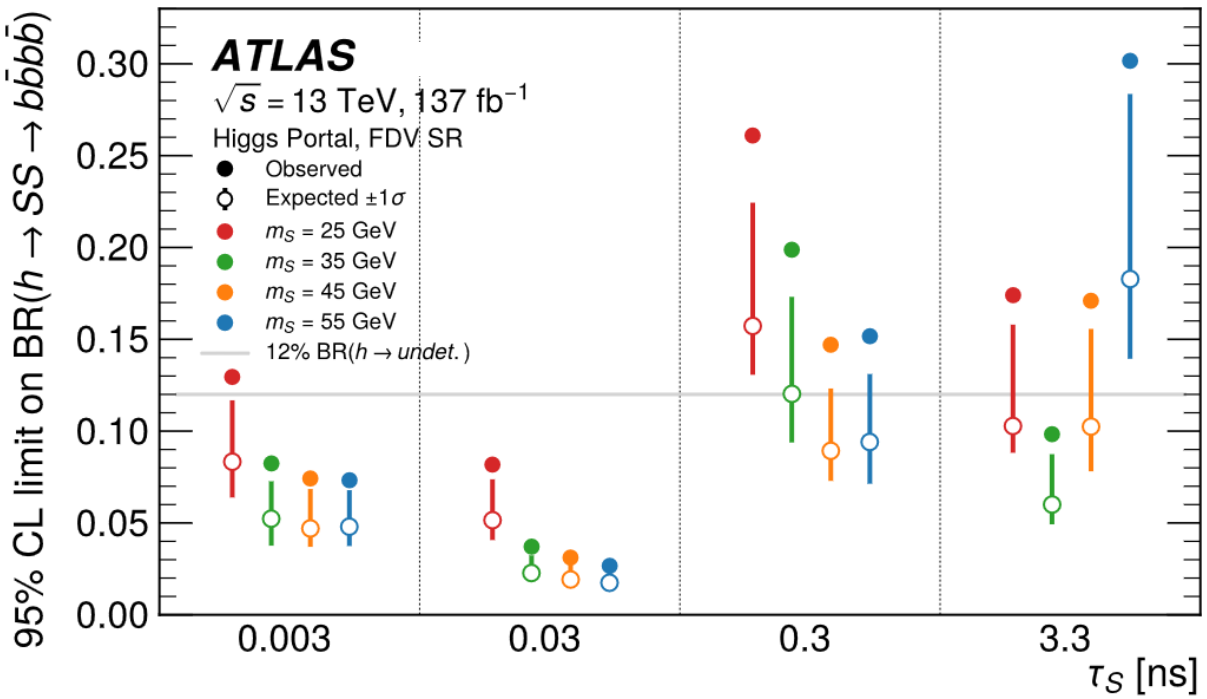

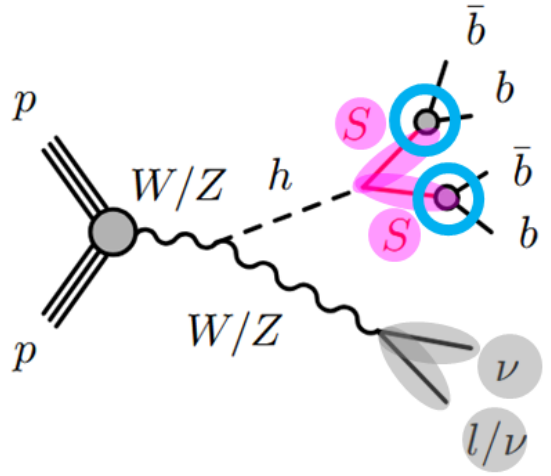

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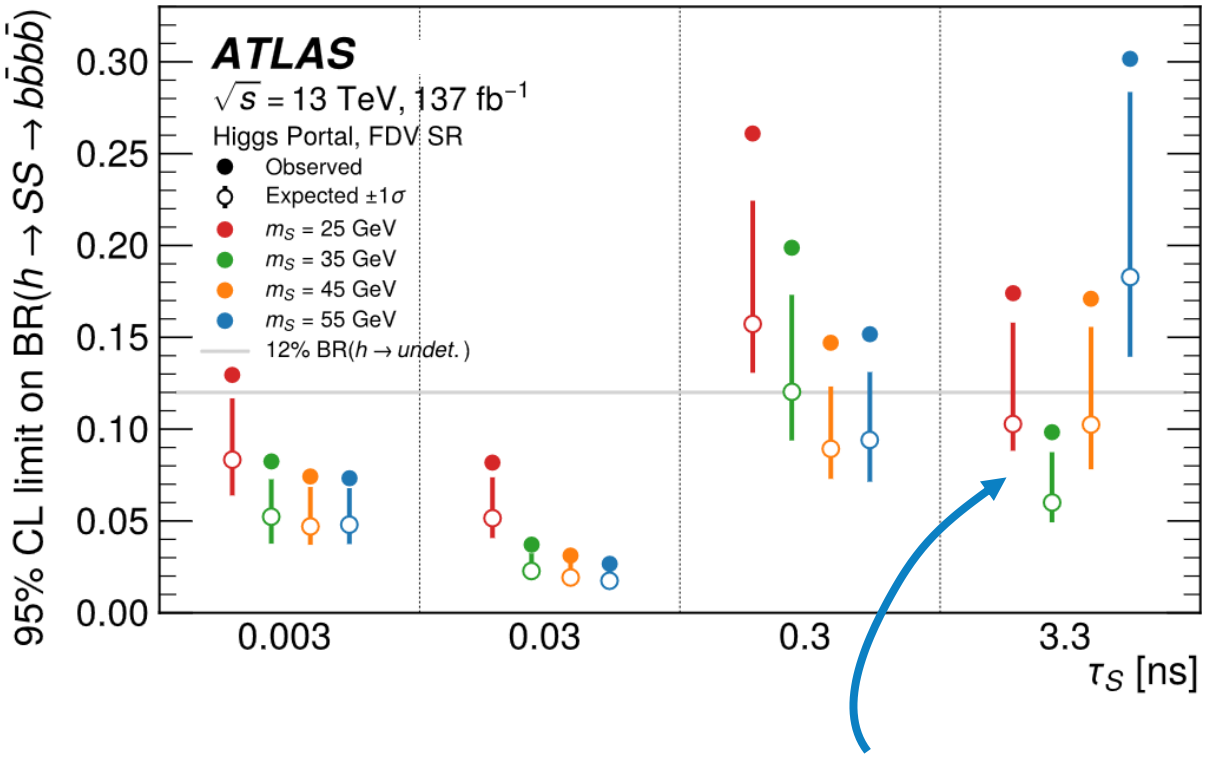

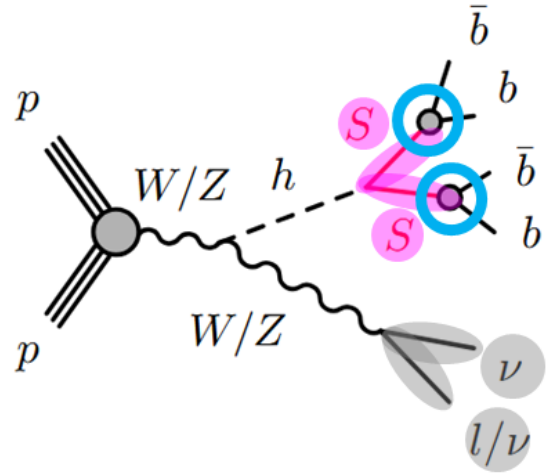

Higgs Portal

Sensitivity at high lifetime from high xs ggH where 1 LLP is reco'd as MET!

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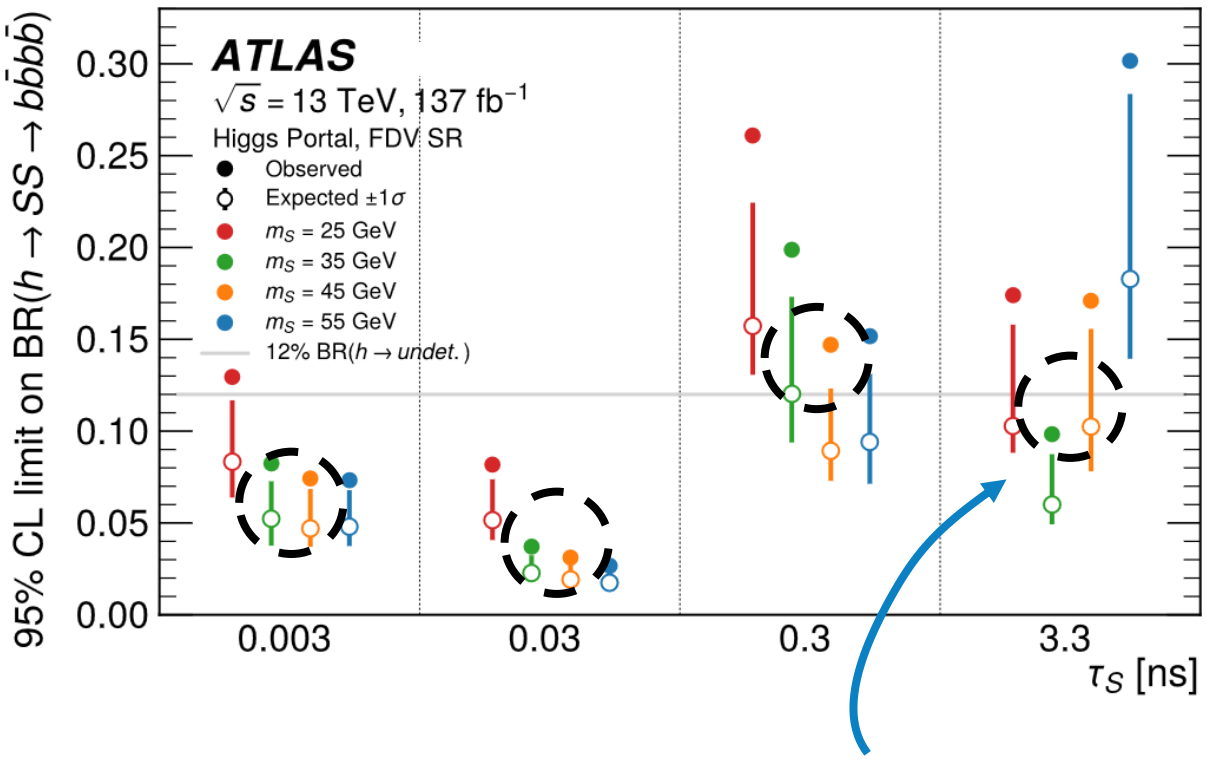

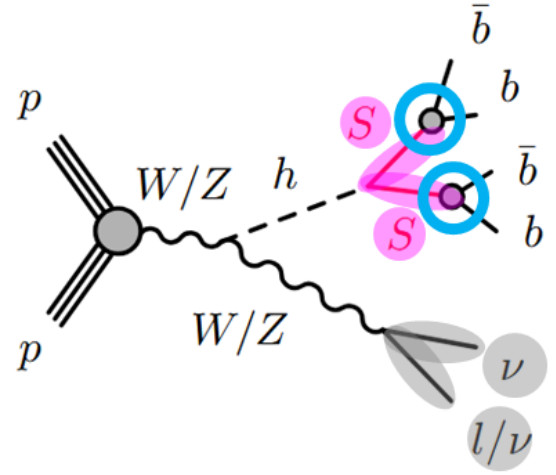

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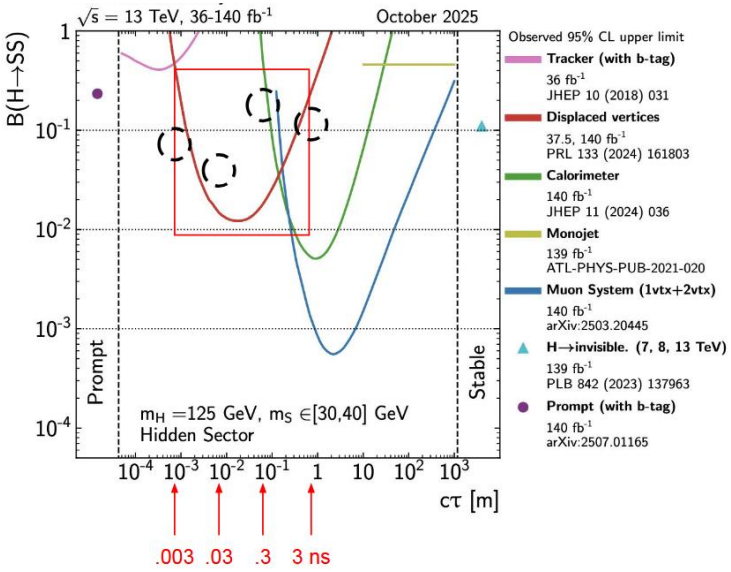
LLP Summary Plot



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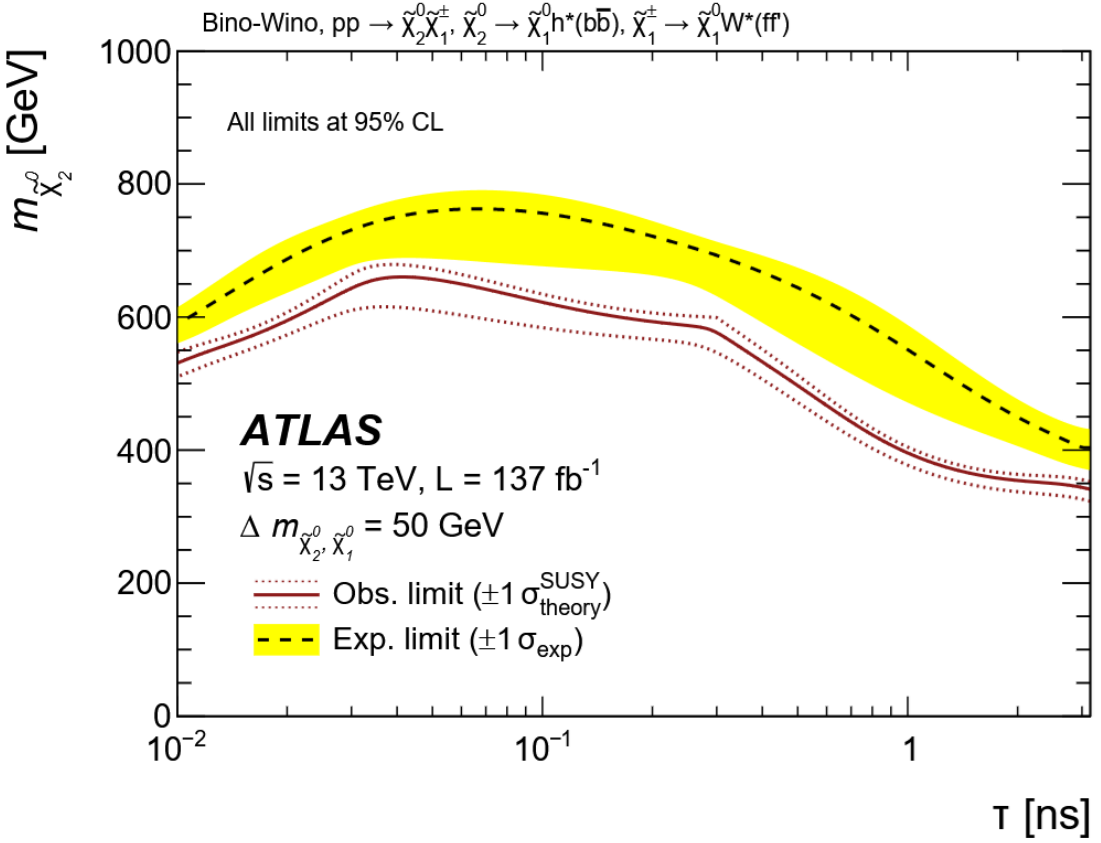
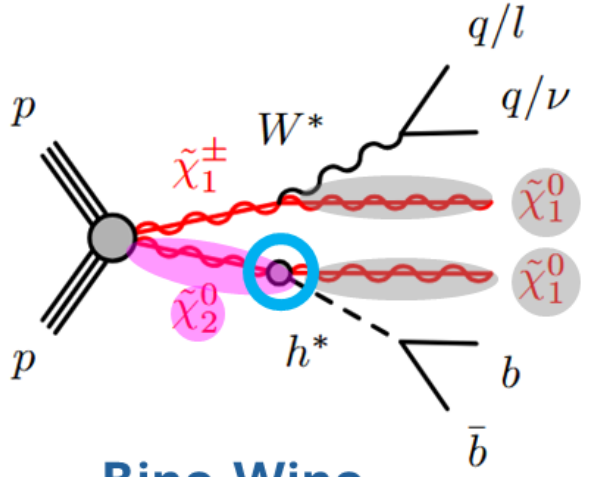
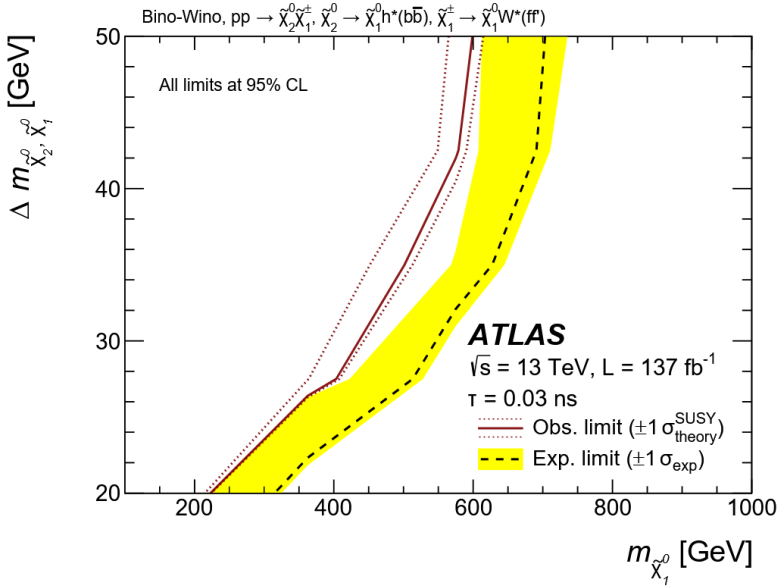




Bino-Wino Coannihilation

→Now included in SUSY Summary Plots!



ATLAS EXPERIMENT

DV+MET: Exclusion Limits

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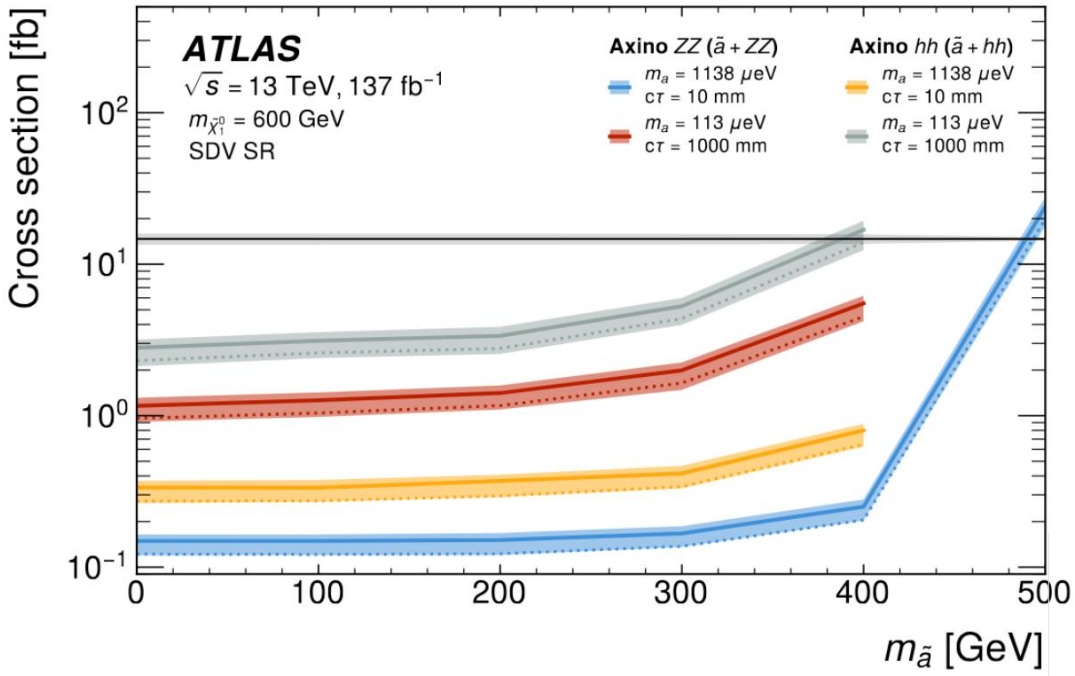
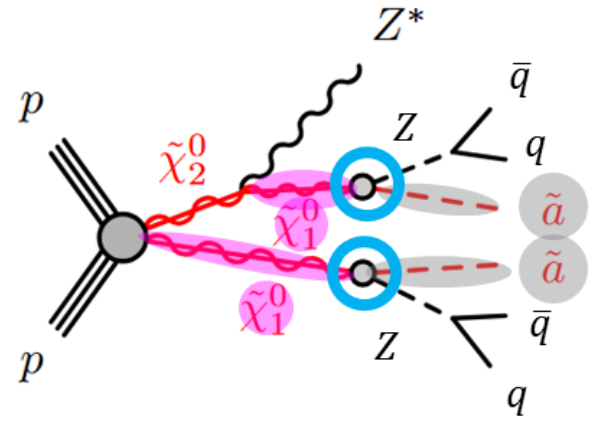
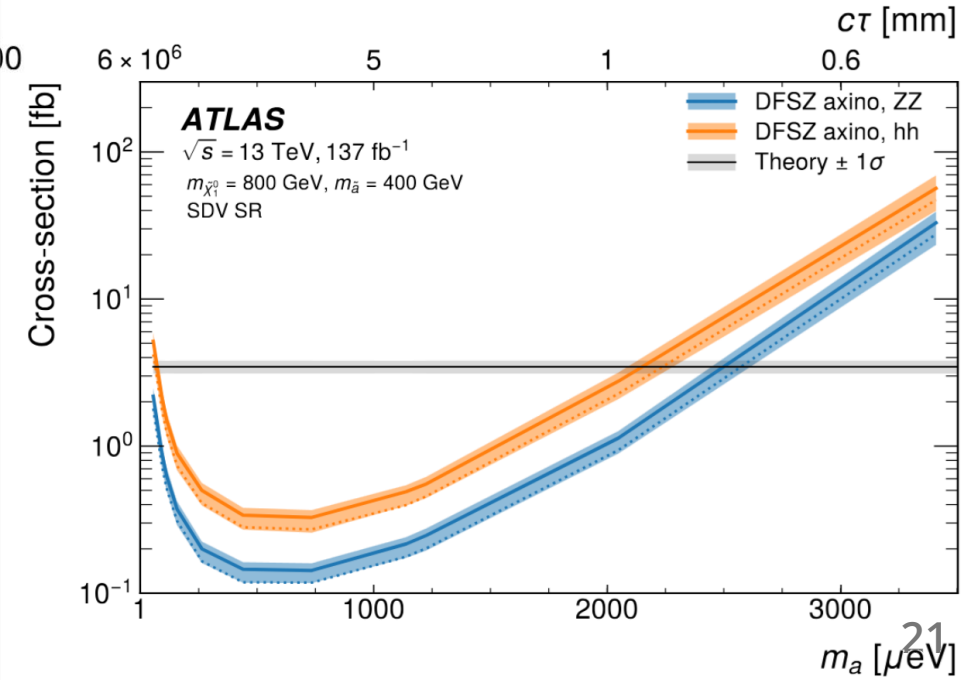




DFSZ Axino

→ First explicit limits on this scenario!



Which searches will we learn about today?

DV+*MET*

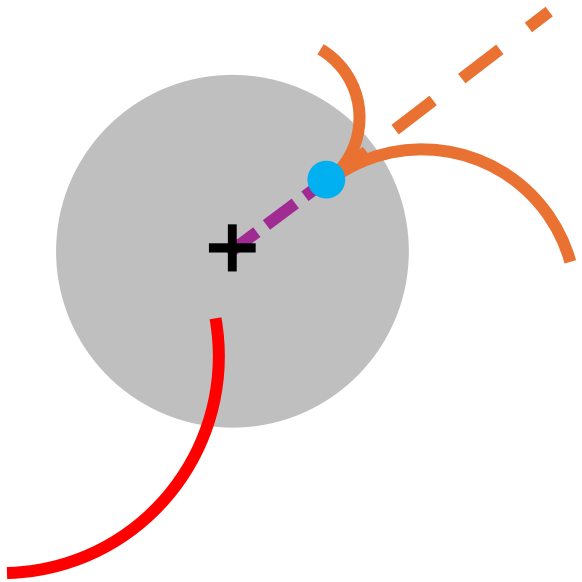
(Full Run 2 2016-2018)

arXiv:2603.12051

DV+*muon*

(Partial Run 3 2022-2024)

arXiv:2603.01991



DV+muon: What's new this time?

More Data

Displaced Muon Trigger

DV+muon: What's new this time?

More Data

Displaced Muon Trigger

$164\ fb^{-1}$

2022-2024

vs.

$137\ fb^{-1}$

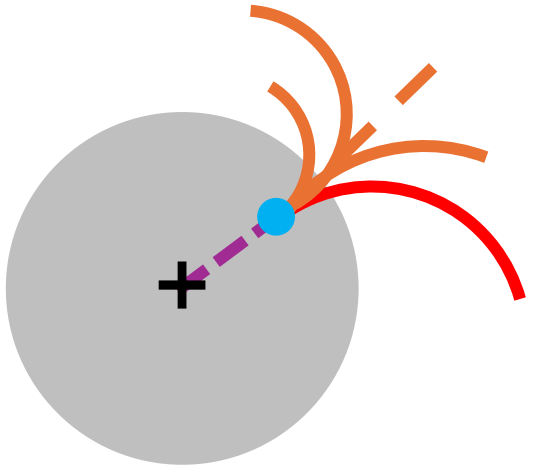
2016-2018

DV+muon: What's new this time?

More Data

Displaced Muon Trigger

- New displaced muon trigger based on trigger Large Radius Tracking implementation!
  (in addition to normal muon spectrometer-only muon triggers)



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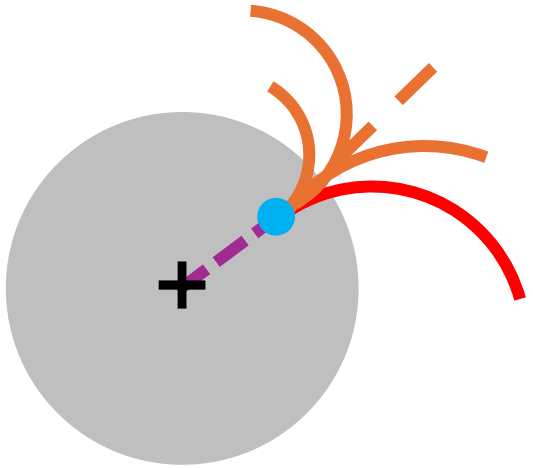
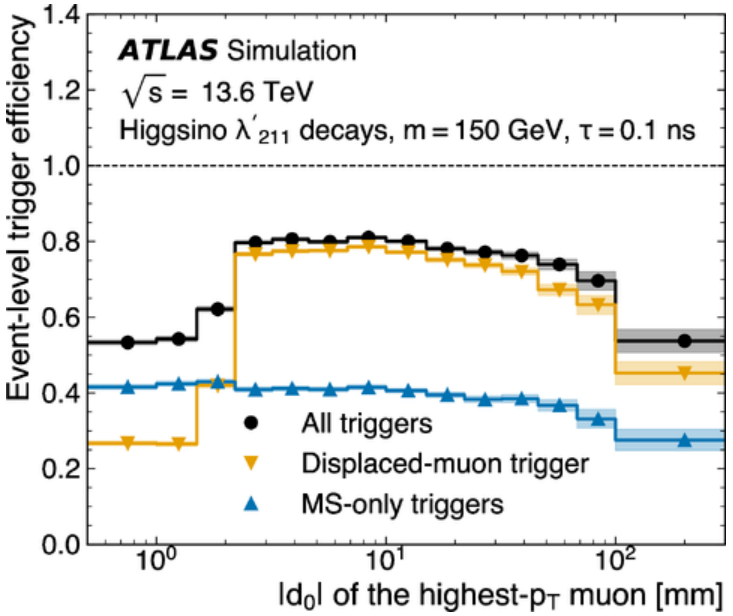
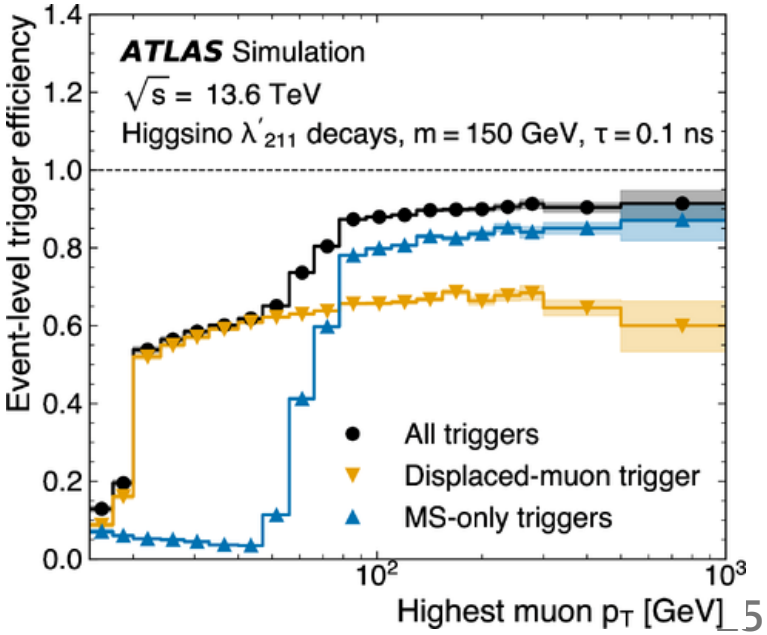
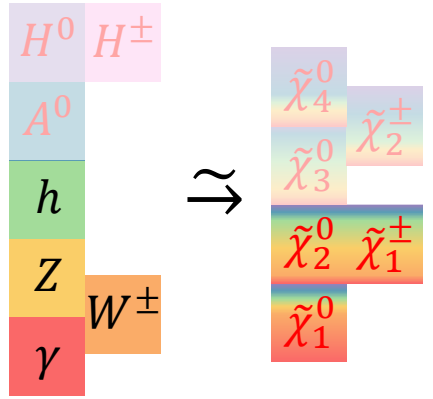






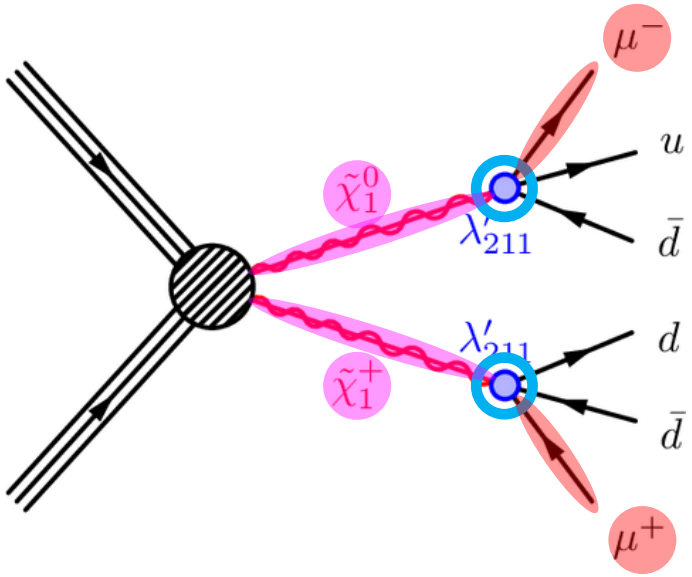
DV+muon: Benchmark Models (RPV SUSY)

- $\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ Higgsinos within 1 GeV of each other. Others decoupled
- Small R-Parity Violating couplings make $\tilde{\chi}$ long-lived and decay to muon & hadrons (DVs!)

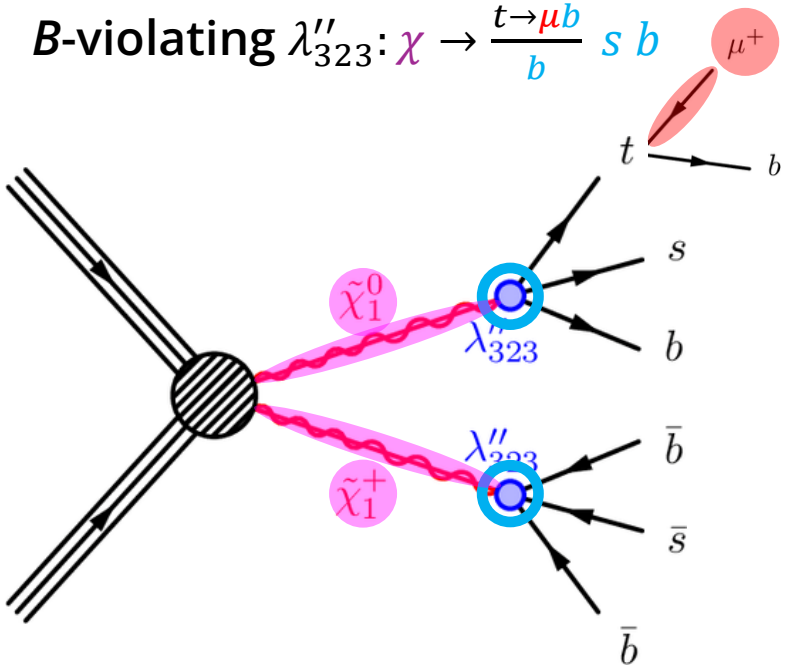


DV
LLP
muon

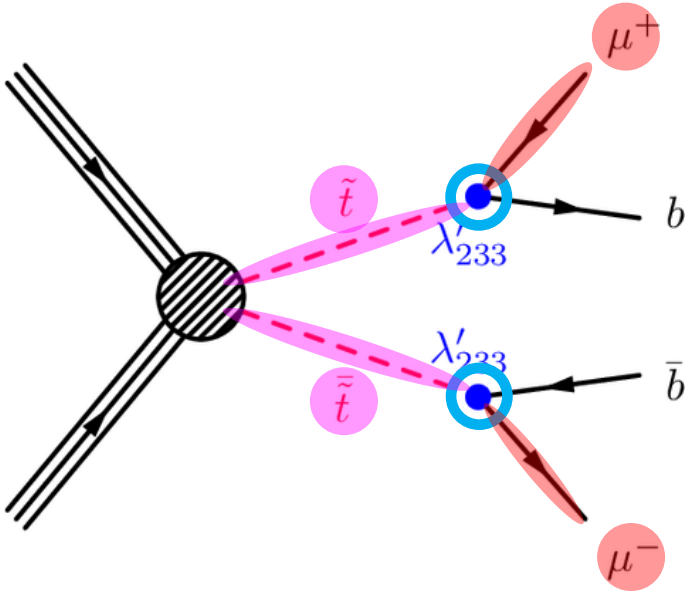
***L*-violating λ'_{211}:** $\chi \to \mu \frac{u}{d} d$



***B*-violating λ''_{323}:** $\chi \to \frac{t \to \mu b}{b} s\, b$



***L*-violating λ'_{211}:** $\tilde{t} \to \mu\, b$



DV+muon: Signal Regions

DV + muon

“displacement”= proton-proton vertex to DV transverse distance

DV+muon: Signal Regions

DV + muon

1+ "Near" DVs

$1\ \text{mm} < \text{displ.} < 4\ \text{mm}$

≥ 4 tracks

$m_{\text{DV}} \geq 40\ \text{GeV}$

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displacement $\geq 4\ \text{mm}$

≥ 4 tracks

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"displacement"= proton-proton vertex to DV transverse distance

- All DVs must not be inside detector material
- All DVs must lie within $|\text{DV}_{rxy}| \leq 300\ \text{mm}, |\text{DV}_z| \leq 300\ \text{mm}$

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Events must pass vetoes for the following backgrounds:

-Heavy-Flavour

-Cosmic Rays

-Algorithmic Fakes

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Events must pass vetoes for the following backgrounds:

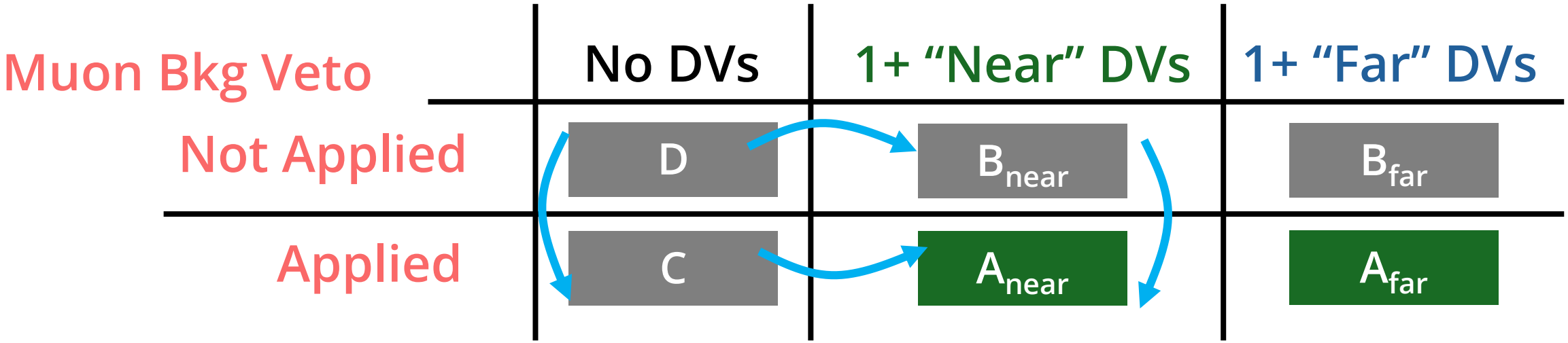
- -Heavy-Flavour
- -Cosmic Rays
- -Algorithmic Fakes

- Events must pass 1 of 2 normal muon triggers or new displaced muon trigger
- Muon must have pT $\geq$ 1.05x normal trigger threshold (63, 84 GeV), or be what new displaced muon trigger triggered on
- $p_{\text{T}} \geq 25\ \text{GeV}, |z_0| < 300\ \text{mm}$, $2\ \text{mm} < |\text{d}_0| < 300\ \text{mm}, \ |\text{d}_0|/\sigma_{d_0} > 150$

ATLAS EXPERIMENT

DV+muon: Data-Driven Background Estimate

- Muon and DVs independent
- Estimate number of events with muons slipping through veto through ratios



$$\frac{D}{C} = \frac{B}{A}$$

DV+muon: Results

Category	1+ "Near" DVs	1+ "Far" DVs
Heavy flavour	2.3 ± 0.8	1.2 ± 1.0
Cosmic rays	0.23 ± 0.13	0.18 ± 0.10
Algorithmic fakes barrel	0.31 ± 0.15	0.31 ± 0.15
Algorithmic fakes endcap	0.06 ± 0.04	0.11 ± 0.06
Total predicted	2.9 ± 0.8	1.8 ± 1.1

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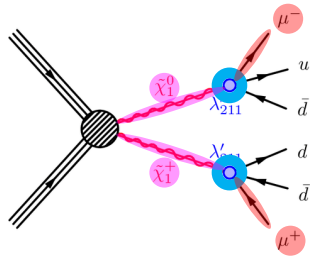
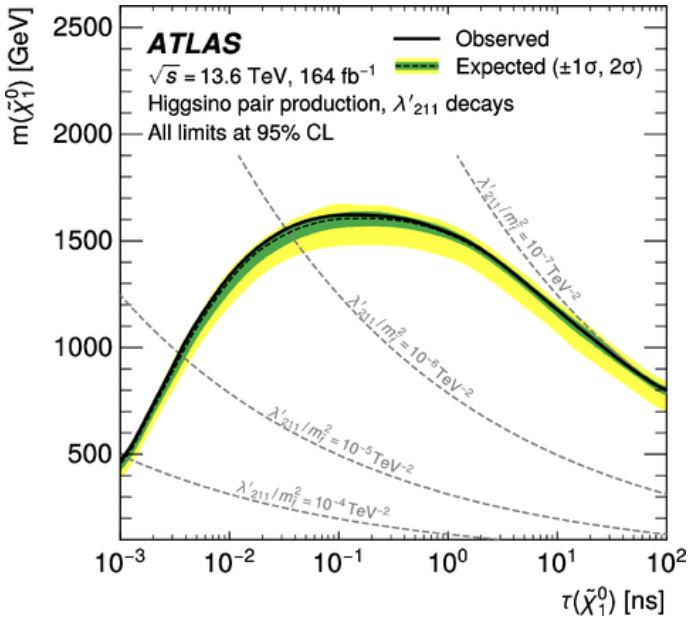
Algorithmic fakes endcap	0.06 ± 0.04	0.11 ± 0.06
Total predicted	2.9 ± 0.8	1.8 ± 1.1
Observed	1	3

No significant excess found

DV+muon: Exclusion Limits

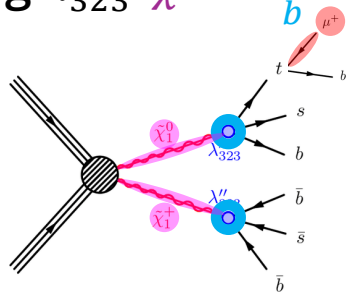
***L*-violating λ'_{211}: $\chi \to \mu \frac{u}{d} d$**

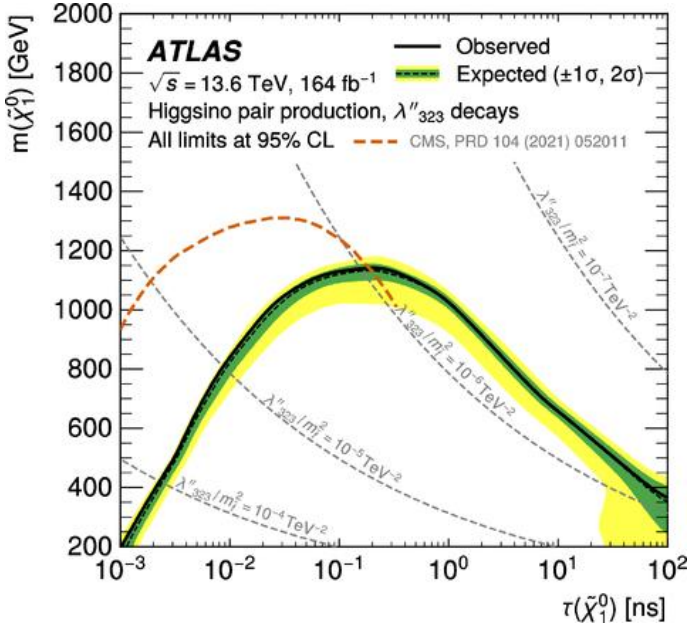




Improvement on [ATLAS Run 1 Higgsino-like Neutralinos search]!

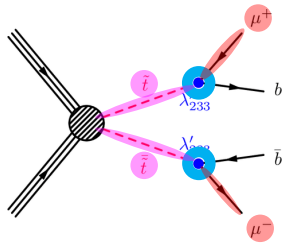
***B*-violating λ''_{323}: $\chi \to \frac{t \to \mu b}{b} s\, b$**

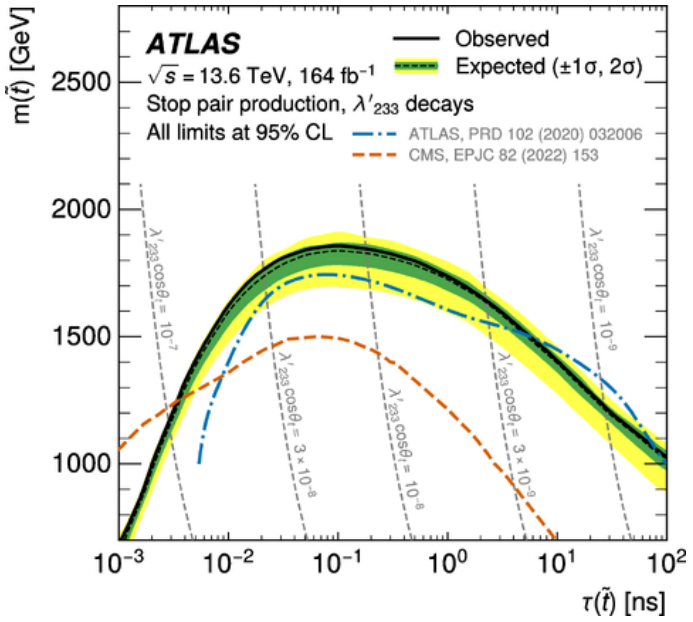




Complementary to [CMS Run 2 Hadronic DV Pairs search]!

***L*-violating λ'_{211}: $\tilde{t} \to \mu\, b$**

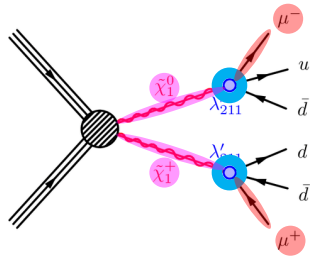


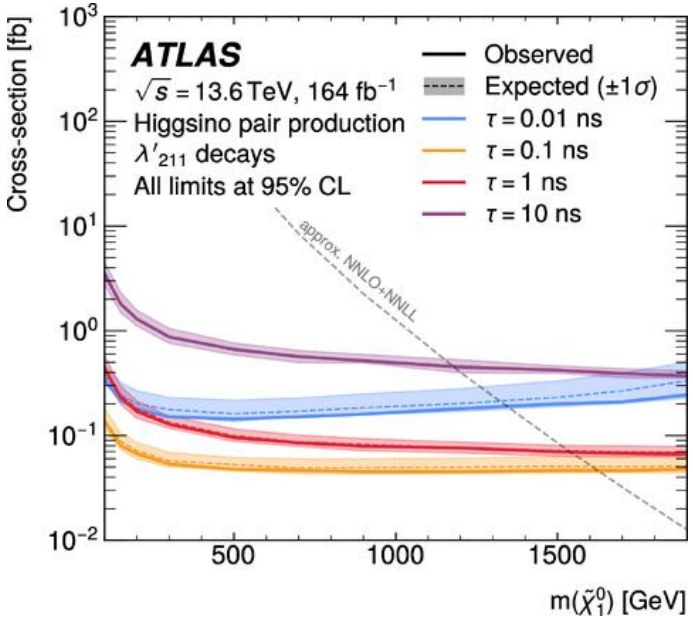


Improvement on [ATLAS Run 2 DV+muon search]!

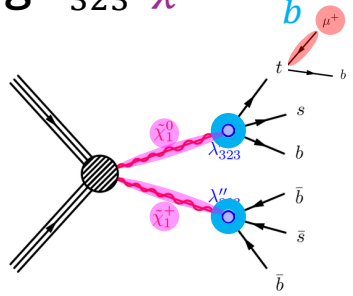
DV+muon: Cross-Section Limits

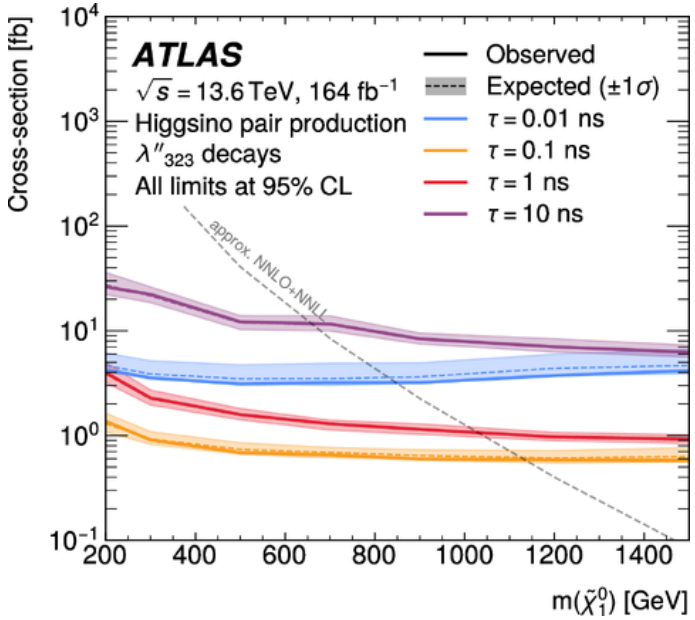
L-violating λ'_{211}: $\chi \to \mu \frac{u}{d} d$



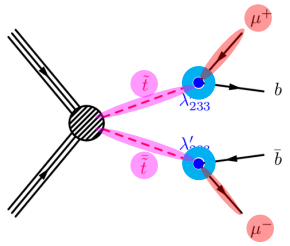


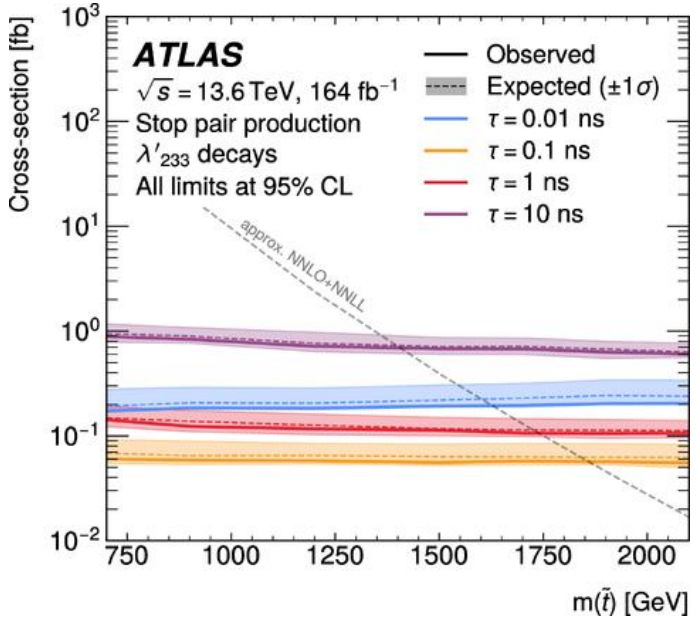
B-violating λ''_{323}: $\chi \to \frac{t \to \mu b}{b} s\, b$





L-violating λ'_{211}: $\tilde{t} \to \mu\, b$





Conclusion

- We searched for **long-lived particles** using **displaced vertex signatures** in the ATLAS detector, with events triggered by:
  - **Missing Transverse Energy**
  - **Muons**
- DV+MET had introduced an exciting **new fuzzy vertexing algorithm** to better reconstruct LLPs decaying into heavy quarks
- DV+muon had introduced a **new displaced muon trigger** to better trigger on LLPs decaying into muons
- No significant excess found, but great new limits set!

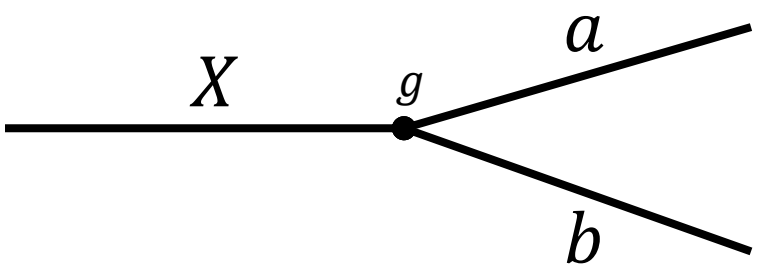
Thank You

Backup

What could cause a BSM particle to be long-lived?

1) Fewer possible decay modes
2) Less phase space (small mass-splitting)
3) Small coupling between particles

$$\tau = \frac{1}{\sum_{\text{decay modes}} \Gamma_{\text{decay mode}}}$$



$$\Gamma_{\text{decay mode}} \propto \frac{|\vec{p}^*|}{m_X}|M|^2$$

$$\propto \frac{\sqrt{(m_X^2 - m_a^2 - m_b^2)^2 - 4m_a^2 m_b^2}}{m_X^2}|M|^2$$

$$M \propto g$$

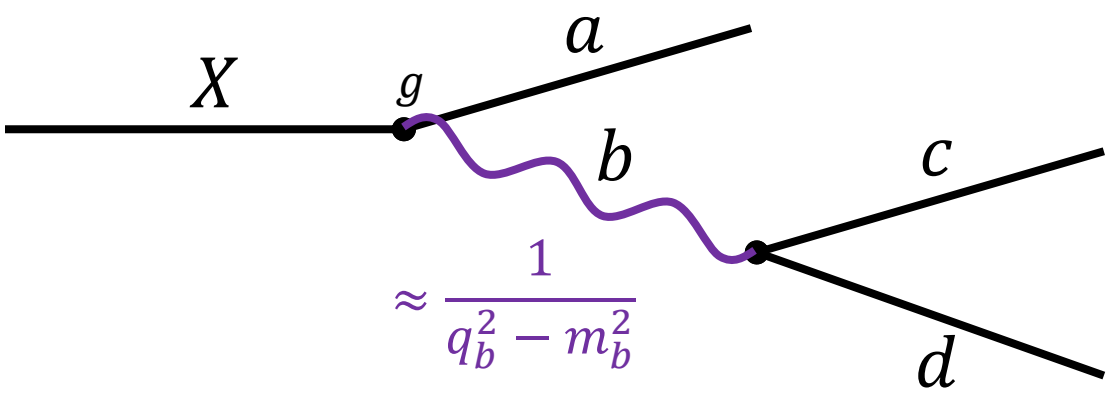
What could cause a BSM particle to be long-lived?

1) Fewer possible decay modes
2) Less phase space (small mass-splitting)
3) Small coupling between particles
4) Very off-shell intermediary

$$\tau = \frac{1}{\sum_{\text{decay modes}} \Gamma_{\text{decay mode}}}$$

$$\Gamma_{\text{decay mode}} \propto |M|^2$$

$$M \propto g$$



DV+MET: Data-Driven Background Estimate (1SDV/1FDV SRs)

Same SR selections made across. Only selections change is related to trigger/MET/photon

DV+photon

1) Determine fraction of events of a certain number of tracks and jets that have DVs

$$\left(\frac{\#\text{Events w. DVs}_{\text{photon}}}{\#\text{Total Events}_{\text{photon}}}\right)$$

Background DVs originate from event tracks and jets

Irrelevant

DV+MET

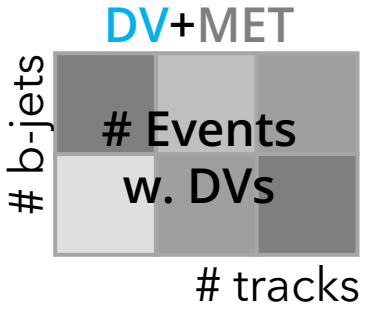
2) Determine #events with certain number of tracks and jets

$$(\#\text{Total Events}_{\text{MET}})$$

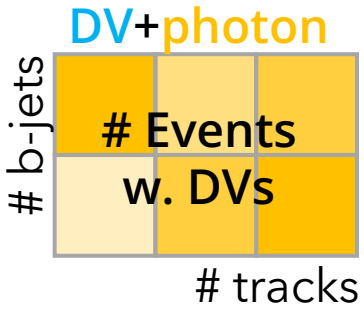
3) $$(\#\text{Events w. DVs}_{\text{MET}}) = \left(\frac{\#\text{Events w. DVs}_{\text{photon}}}{\#\text{Total Events}_{\text{photon}}}\right)(\#\text{Total Events}_{\text{MET}})$$

Validation Regions are made by inverting the SR # tracks, mDV, # seed, or material veto SR requirements

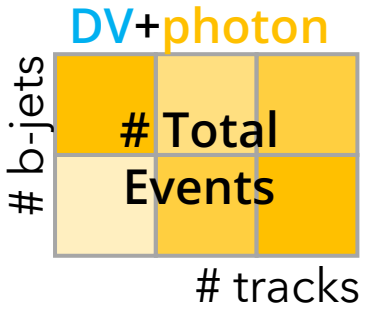
$$\#\text{Events w. DVs}_{\text{MET}} = \sum$$



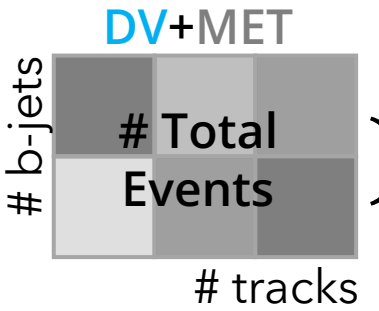
$$= \sum($$



$$/$$



$$*$$

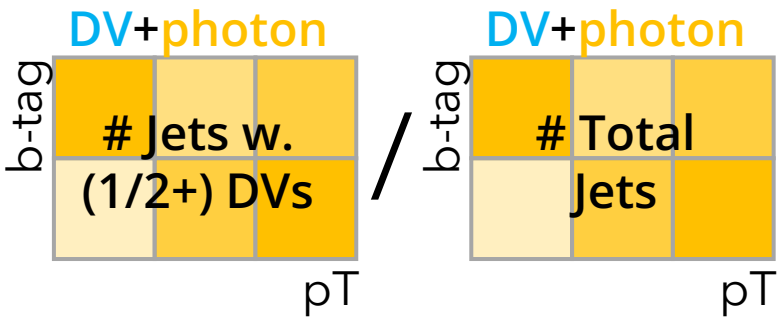


$$)$$

DV+MET: Data-Driven Background Estimate (2FDV SRs)

- Similar to 1SDV and 1FDV SRs, except tracks are not as important, so focus on jets
  → Do procedure using jets instead of events:

$$\text{Jet-(1/2+)DV Prob.} =$$



$$\#\text{Evts w. 2DVs}_{\text{MET}} = \#\text{Total Evts}_{\text{MET}} - \#\text{Evts w. 1 DV}_{\text{MET}} - \#\text{Evts w. 0 DVs}_{\text{MET}}$$

$$\#\text{Evts w. 0 DVs}_{\text{MET}} = \sum_{\text{Evts } E} \prod_{\text{jets } j \text{ in } E} (1 - \text{J1DP} - \text{J2DP})$$

$$\#\text{Evts w. 1 DVs}_{\text{MET}} = \sum_{\text{Evts } E} \prod_{\text{jets } j_E \text{ in } E} \text{J1DP} \left(\prod_{\text{jets } j \neq j_E \text{ in } E} (1 - \text{J1DP} - \text{J2DP}) \right)$$

DV+MET: Results

upper limits on

visible cross-section

signal events

Region	Estimated Background	Obs.	$\langle A\epsilon\sigma \rangle^{95}_{\text{obs}}$ [fb]	S^{95}_{obs}
1+ Standard DV	0.6 ± 0.4	1	0.0280	3.84
1 Fuzzy DV	0.8 ± 0.5	3	0.0469	6.42
2+ Fuzzy DV	1.3 ± 0.6	2	0.0353	4.83

(All Limits at 95% Confidence Level)

No significant excess found

DV+muon: Results

Category	SR_{far}	SR_{near}
Heavy flavour	1.2 ± 1.0	2.3 ± 0.8
Cosmic rays	0.18 ± 0.10	0.23 ± 0.13
Algorithmic fakes barrel	0.31 ± 0.15	0.31 ± 0.15
Algorithmic fakes endcap	0.11 ± 0.06	0.06 ± 0.04
Total predicted	1.8 ± 1.1	2.9 ± 0.8

SRs divided into bins of $m_{\mathrm{DV}}^{\mathrm{red}} = m_{\mathrm{DV}}/\Delta R_{\mathrm{max}}$
Where ΔR_{max} is max angular separation between tracks

upper limits on

visible cross-section

signal events

	Total predicted	Observed	$\langle \sigma A \epsilon \rangle_{\mathrm{obs}}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}
SR_{far}, m_{DV}^{red} inclusive	1.8 ± 1.1	3	0.038	6.2	4.9
SR_{far}, $m_{DV}^{red} \geq 10$ GeV	0.37 ± 0.20	1	0.023	3.8	3.1
SR_{far}, $m_{DV}^{red} \geq 13$ GeV	0.17 ± 0.09	0	0.018	3.0	3.0
SR_{near}, m_{DV}^{red} inclusive	2.9 ± 0.8	1	0.021	3.5	4.7
SR_{near}, $m_{DV}^{red} \geq 15$ GeV	0.73 ± 0.20	0	0.018	3.0	3.0

(All Limits at 95% Confidence Level)

No significant excess found

DV+muon: Selections and Signal Regions

$d_T(PV, DV)$ = PV-DV transverse distance

Muon Selection

$p_T \geq 25$ GeV* $\quad |z_0| < 300$ mm

2 mm $< |d_0| < 300$ mm, $\quad |d_0|/\sigma_{d_0} > 150$

Heavy-Flavour Veto:
Muon must be isolated (Tight_VarRad)

Cosmic Ray Veto:
No muon segment opposite side of detector

Algorithmic Fake Veto:
$\chi^2 < 3$ of combined ID/MS tracks fit
3 precision layer hits

SRs

1+ "Far" DVs	1+ "Near" DVs
$d_T(PV, DV) \geq 4$ mm	1 mm $< d_T(PV, DV) < 4$ mm
≥ 4 tracks	≥ 4 tracks
$m_{DV} \geq 20$ GeV	$m_{DV} \geq 40$ GeV

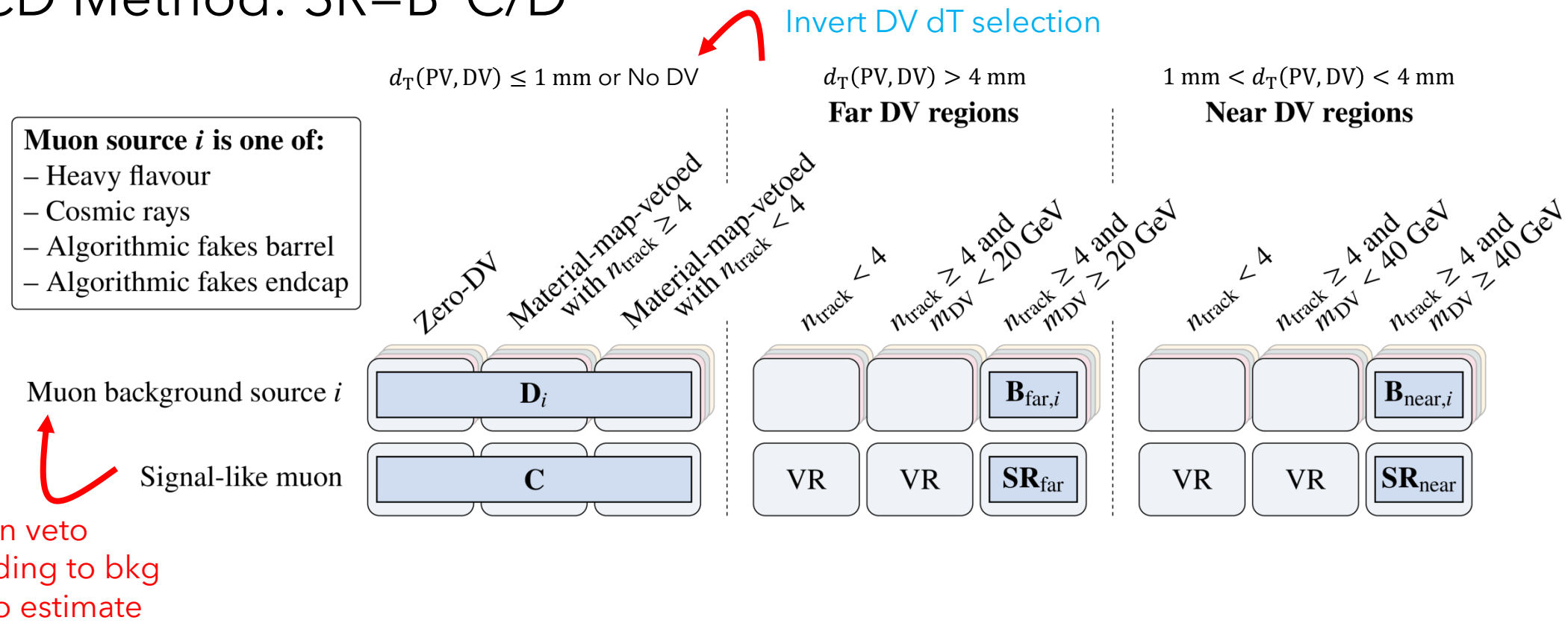
orthogonal

- All events must pass 1 of 2 MS-only triggers or the new displaced muon trigger
- *Muon must have pT ≥ 1.05x MS trigger threshold (63, 84 GeV), or be what new displaced muon trigger triggered on
- All DVs must not be inside detector material
- All DVs must lie within $|DV_{rxy}| \leq 300$ mm, $|DV_z| \leq 300$ mm (i.e. decays before first strips detector barrel layer)

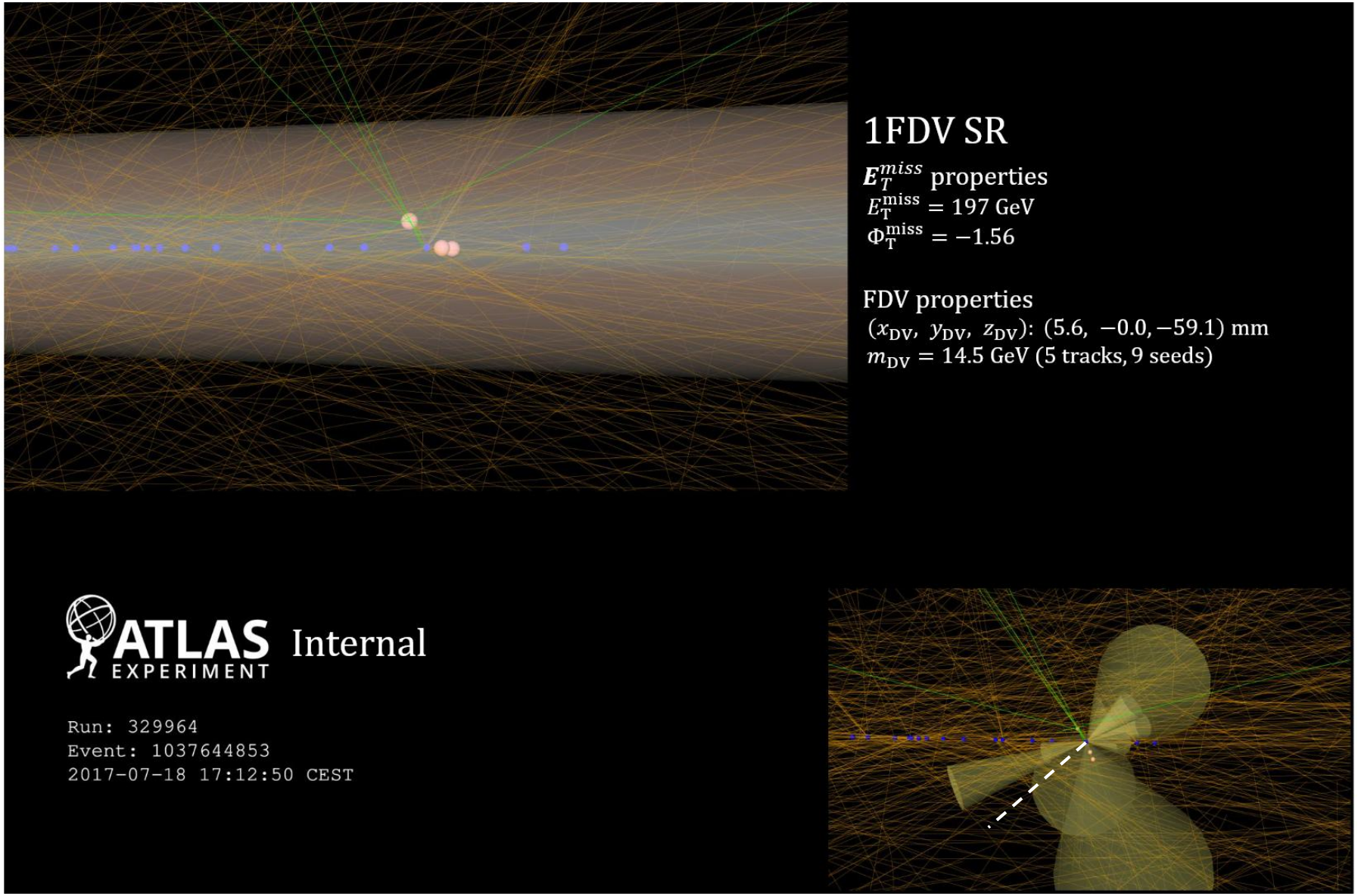
ATLAS EXPERIMENT

DV+muon: Data-Driven Background Estimate

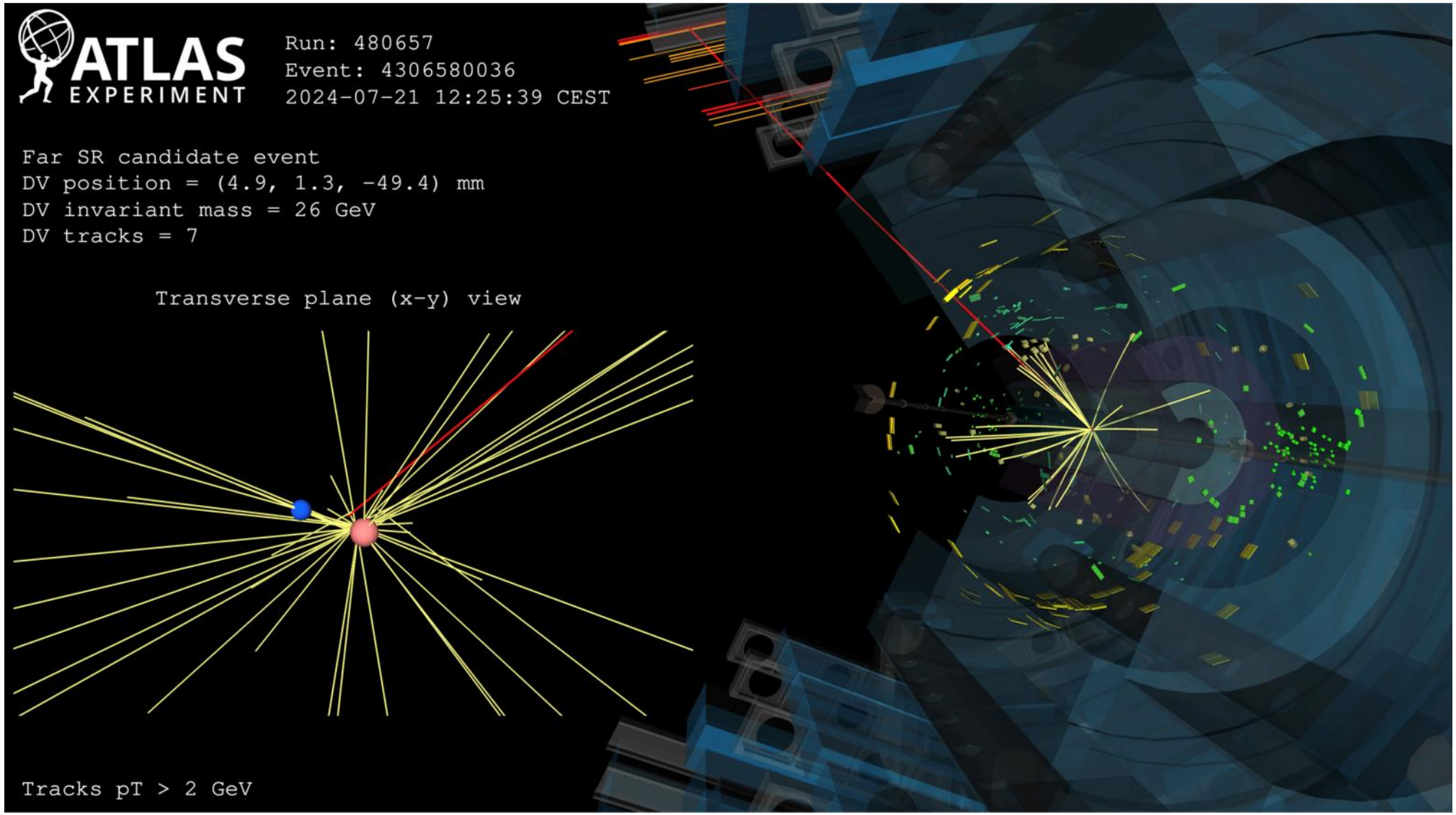
- Estimate done per individual muon bkg
- ABCD Method: SR=B*C/D



DV+MET: Example Event Display

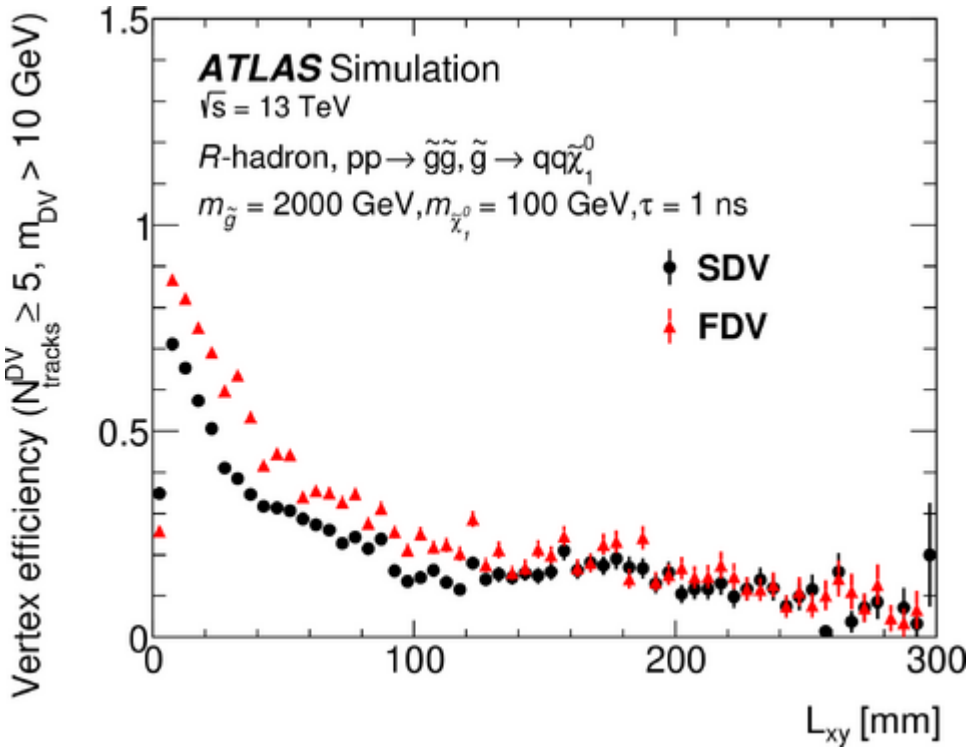


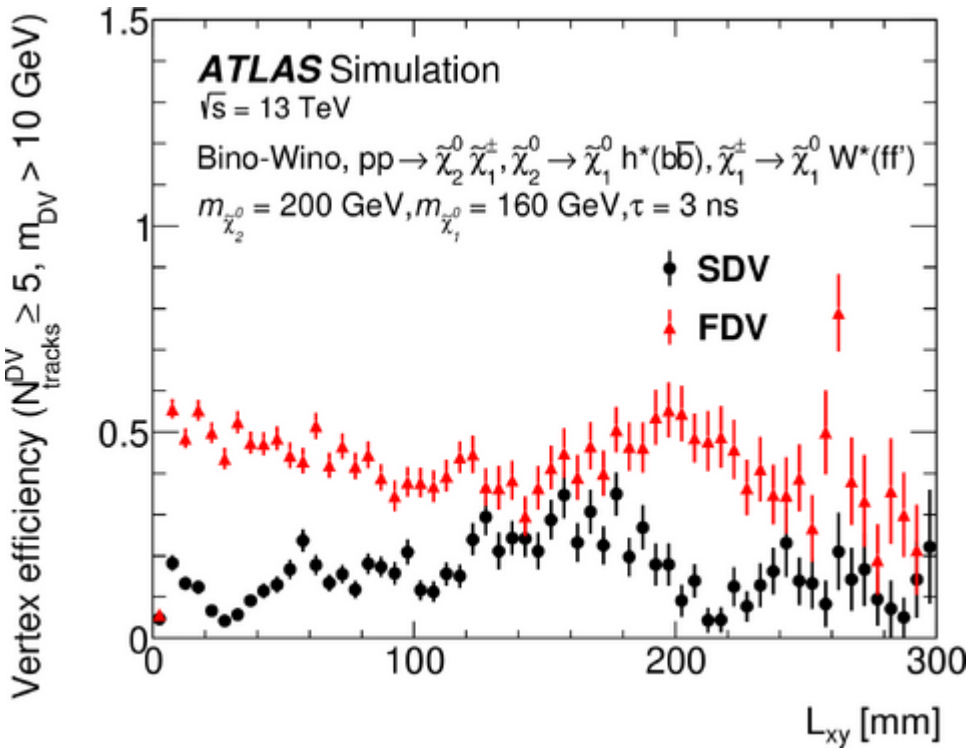
DV+muon: Event Display



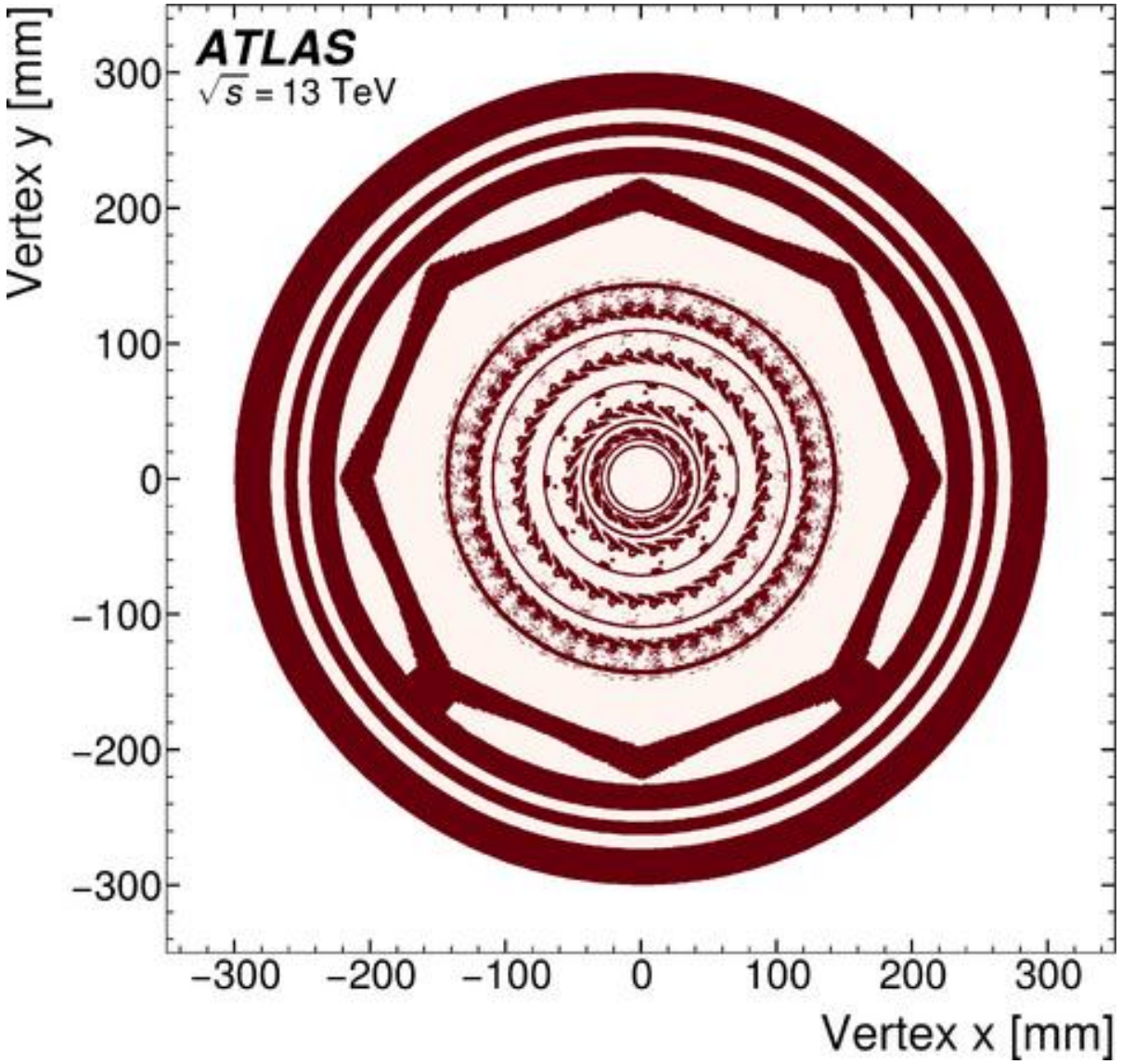
DV+MET

Fuzzy Vertexing Efficiencies

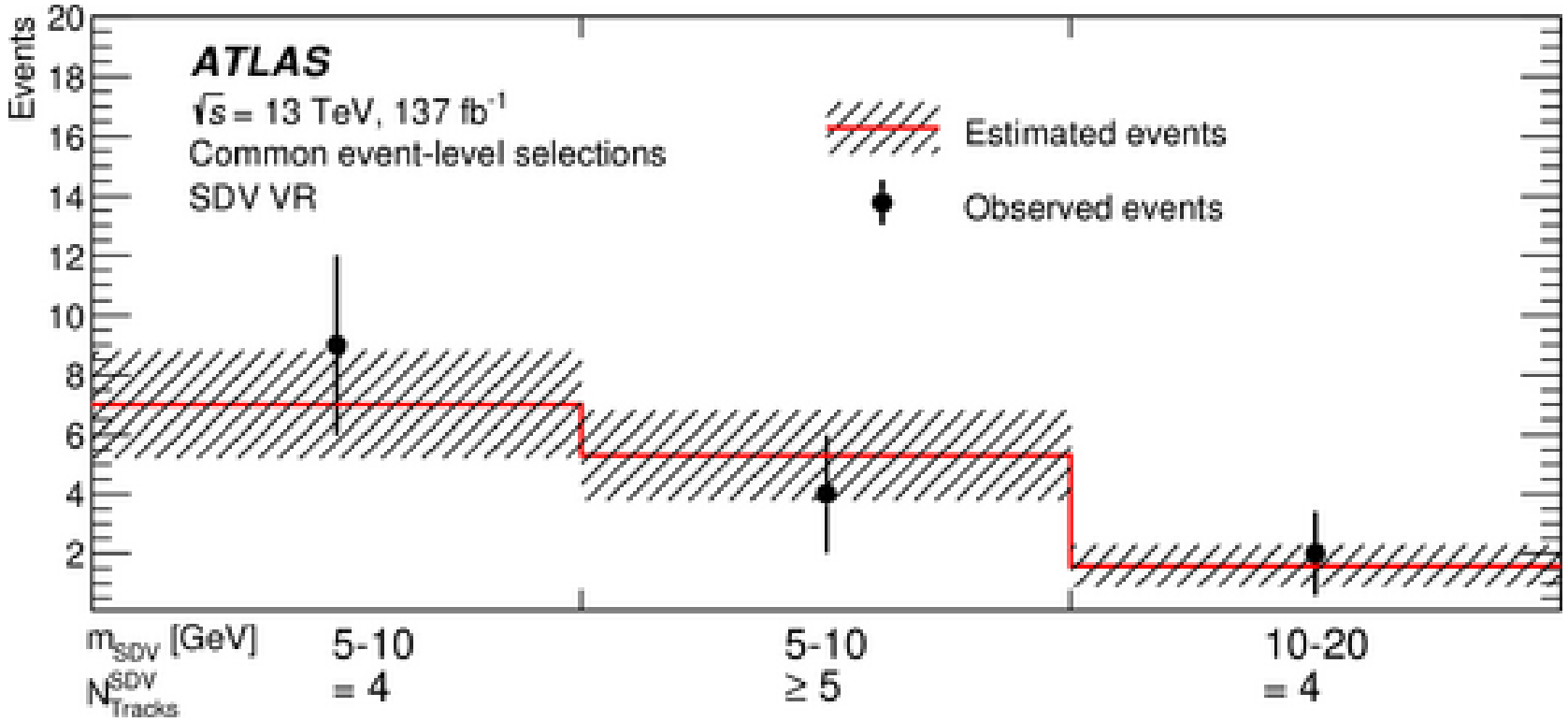




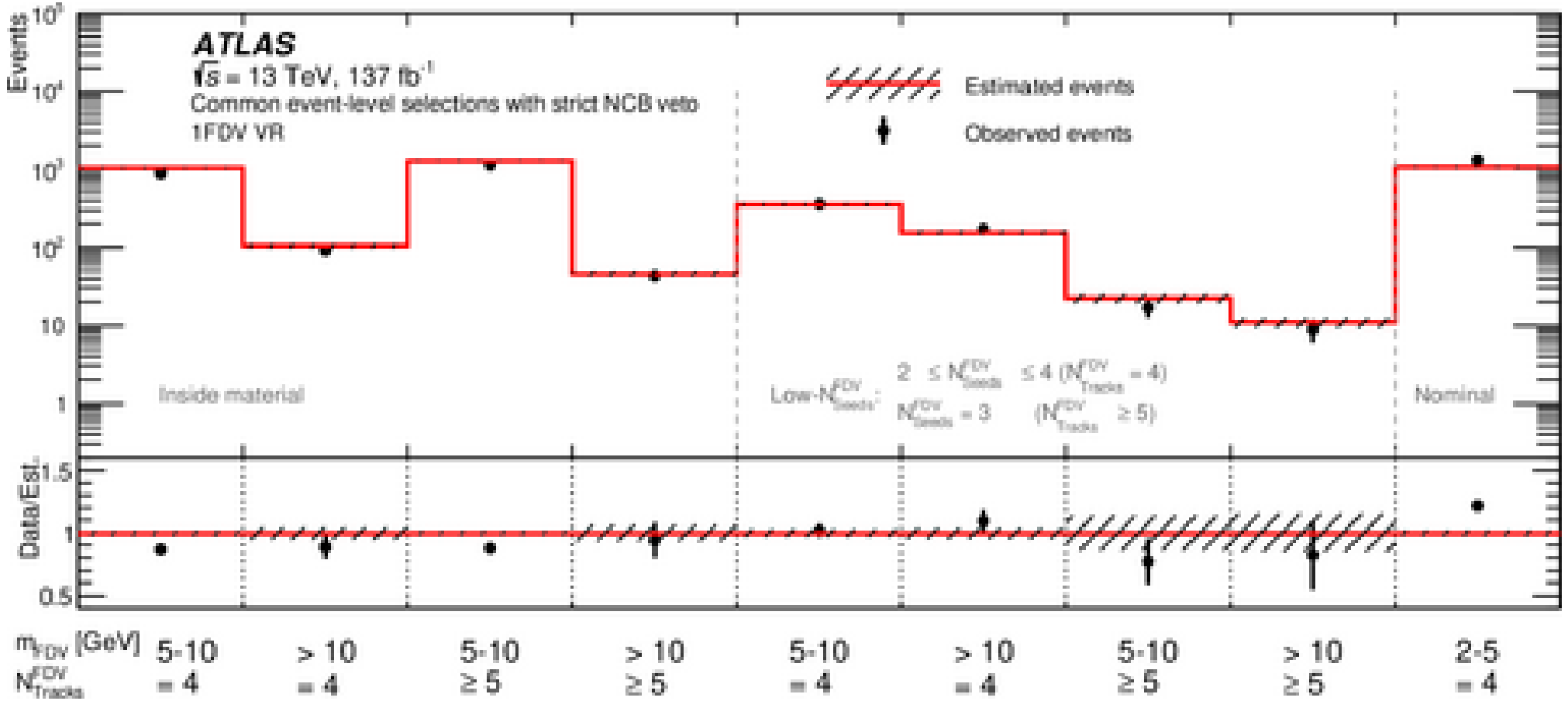
Material Map Veto



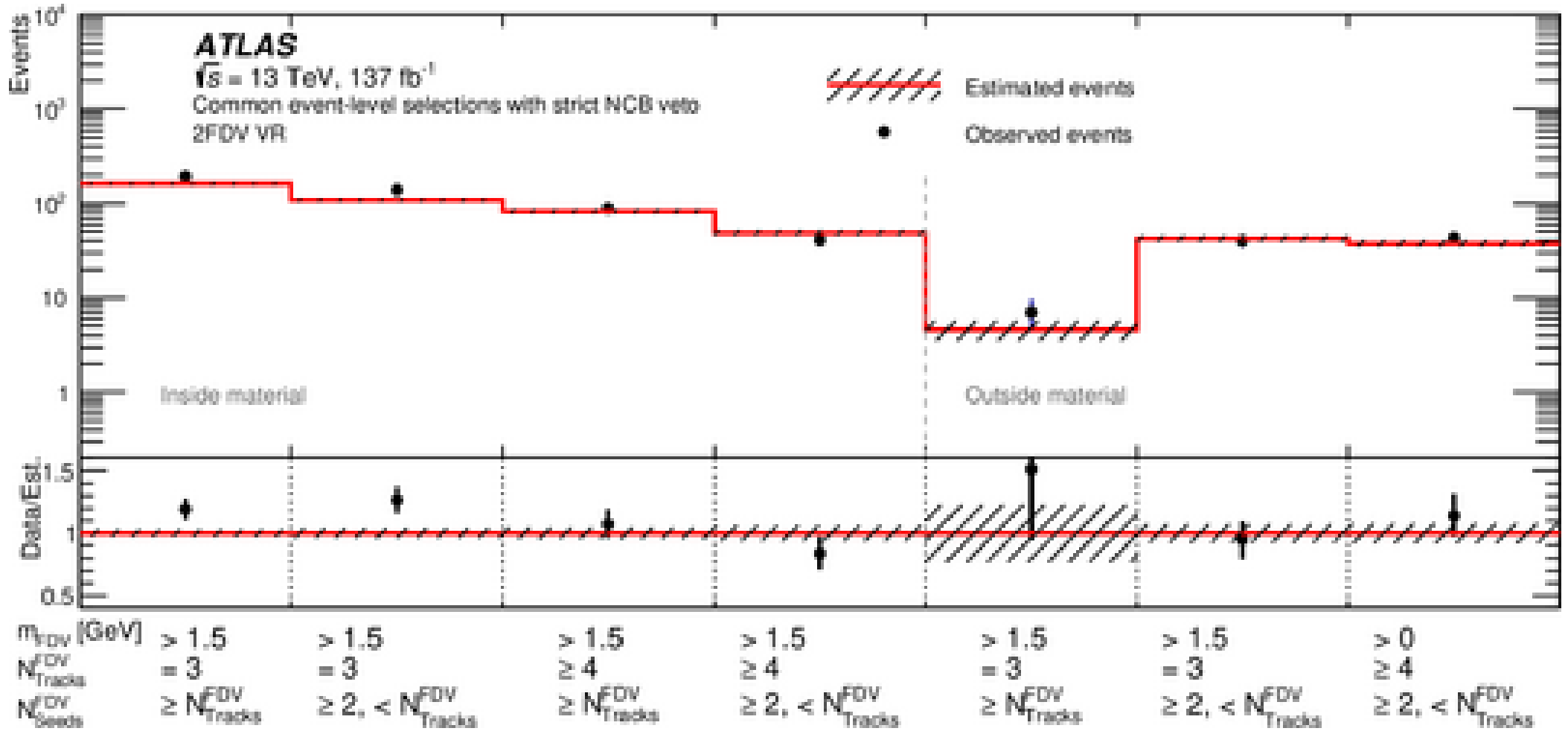
SDV VRs


ATLAS
√s = 13 TeV, 137 fb-1
Common event-level selections
SDV VR
Estimated events
Observed events
Events
20
18
16
14
12
10
8
6
4
2
m_SDV [GeV]
N_Tracks^SDV
5-10
= 4
5-10
≥ 5
10-20
= 4

1FDV VRs


ATLAS
√s = 13 TeV, 137 fb⁻¹
Common event-level selections with strict NCB veto
1FDV VR
Estimated events
Observed events
Events
Data/Est.
Inside material
Low-N^FDV_Seeds
2 ≤ N^FDV_Seeds ≤ 4 (N^FDV_Tracks = 4)
N^FDV_Seeds = 3 (N^FDV_Tracks ≥ 5)
Nominal
m_FDV [GeV]
N^FDV_Tracks
5-10 = 4
> 10 = 4
5-10 ≥ 5
> 10 ≥ 5
5-10 = 4
> 10 = 4
5-10 ≥ 5
> 10 ≥ 5
2-5 = 4

2FDV VRs


ATLAS
√s = 13 TeV, 137 fb-1
Common event-level selections with strict NCB veto
2FDV VR
Estimated events
Observed events
Inside material
Outside material
Events
Data/Est.
m_fDV [GeV] > 1.5 > 1.5 > 1.5 > 1.5 > 1.5 > 1.5 > 0
N_Tracks^fDV = 3 = 3 ≥ 4 ≥ 4 = 3 = 3 ≥ 4
N_Seeds^fDV ≥ N_Tracks^fDV ≥ 2, < N_Tracks^fDV ≥ N_Tracks^fDV ≥ 2, < N_Tracks^fDV ≥ N_Tracks^fDV ≥ 2, < N_Tracks^fDV ≥ 2, < N_Tracks^fDV

Variables used for Fuzzy Vertex Optimization

Variables	Description
$\eta^{(1)}, \eta^{(2)}$	η direction of tracks #1 and #2
$d_0^{(1)}, d_0^{(2)}$	Transverse impact parameter of tracks #1 and #2
$S(d_0^{(1)}), S(d_0^{(2)})$	$\lvert d_0\rvert/\sigma(d_0)$ of tracks #1 and #2, where $\sigma(d_0)$ is d_0 uncertainty of tracks #1 and #2
$z_0^{(1)}, z_0^{(2)}$	Longitudinal impact parameter of tracks #1 and #2
$z_0^{\mathrm{BS},1}, z_0^{\mathrm{BS},2}$	Longitudinal impact parameter with respect to the beam spot of tracks #1 and #2
$S(z_0^{(1)}), S(z_0^{(2)})$	$\lvert z_0\rvert/\sigma(z_0)$, where $\sigma(z_0)$ is z_0 uncertainty
$\mathcal{HC}^{(1)}, \mathcal{HC}^{(2)}$	Category indicating the innermost hit layer of tracks #1 and #2 (0: First Pixel layer, 1: Second Pixel layer, 2: Third or fourth Pixel layers, 3: SCT layers)
$\Delta\eta$	Angular separation in η direction between tracks #1 and #2
$\Delta\phi$	Angular separation in ϕ direction between tracks #1 and #2
$p_{\mathrm{T}}^{\mathrm{asym}}$	p_{T} asymmetry between tracks #1 and #2 ($= (p_{\mathrm{T}}^{(1)} - p_{\mathrm{T}}^{(2)})/(p_{\mathrm{T}}^{(1)} + p_{\mathrm{T}}^{(2)})$)
$\Delta\mathcal{HC}$	Difference of $\mathcal{HC}$ between tracks #1 and #2

Selections

Full SR vertex selection	SDV SR	FDV SR	
		1FDV	2FDV
Vertices	SDV		FDV
m_{DV} [GeV]	> 10	> 10	> 1.5
$N^{\mathrm{DV}}_{\text{Sel. Tracks}}$	≥ 2	–	–
$N^{\mathrm{DV}}_{\text{Seeds}}$	–	$\geq \binom{N^{\mathrm{DV}}_{\text{Tracks}}}{2} - 1$	$\geq N^{\mathrm{DV}}_{\text{Tracks}}$
$\Delta R_{\mathrm{DV,jet}}$	–	–	< 0.4
$\lvert\eta_{\mathrm{PV-DV}}\rvert$	–	–	< 2.5
$\max_i \left[\Delta\eta(\vec{p}_{\mathrm{track},i}, \sum_j \vec{p}_{\mathrm{track},j} - \vec{p}_{\mathrm{track},i})\right]$	–	< 3.5	–
$N_{\mathrm{DV_{sat}}}$	≥ 1	$\geq 1^{\dagger}$	≥ 2

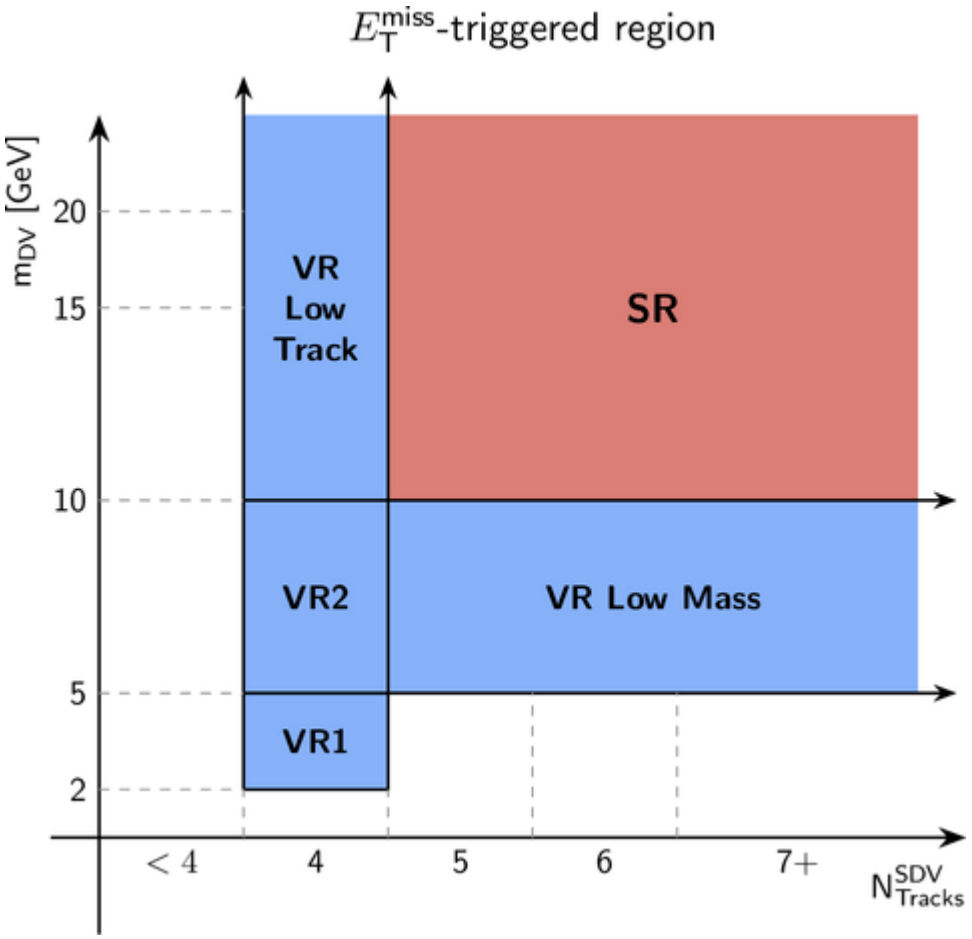
† The event must not have any additional FDVs satisfying the 2FDV selections.

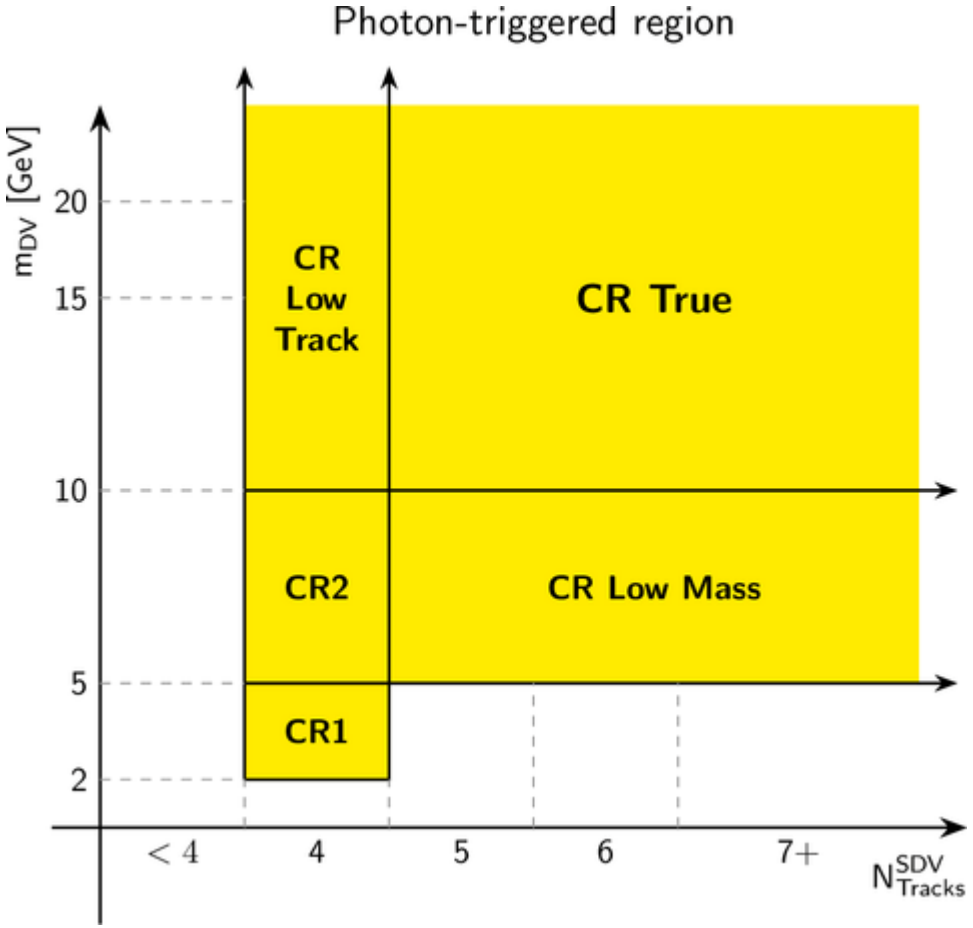
Baseline vertex selections	SDV SR	FDV SR
Vertexing algorithm	Standard DV algorithm (SDV)	Fuzzy DV algorithm (FDV)
Vertex position	$r_{\mathrm{DV}} < 300$ mm,	$\lvert z_{\mathrm{DV}}\rvert < 300$ mm
$\Delta r_{xy}(\mathrm{DV}, \mathrm{CV})$	> 4 mm for any CV	
Material map veto	Strict veto required (Section ??)	
$\Delta R(\mathrm{DV}, \gamma)$	> 0.1, for photons with $p_{\mathrm{T}}(\gamma) > 60$ GeV	
$\max(p_{\mathrm{T}}^{\mathrm{track}})/(\text{scalar sum } p_{\mathrm{T}}^{\mathrm{track}})$	< 0.95	< 0.9
χ^2/N_{DoF}	< 5	–

Model Efficiencies

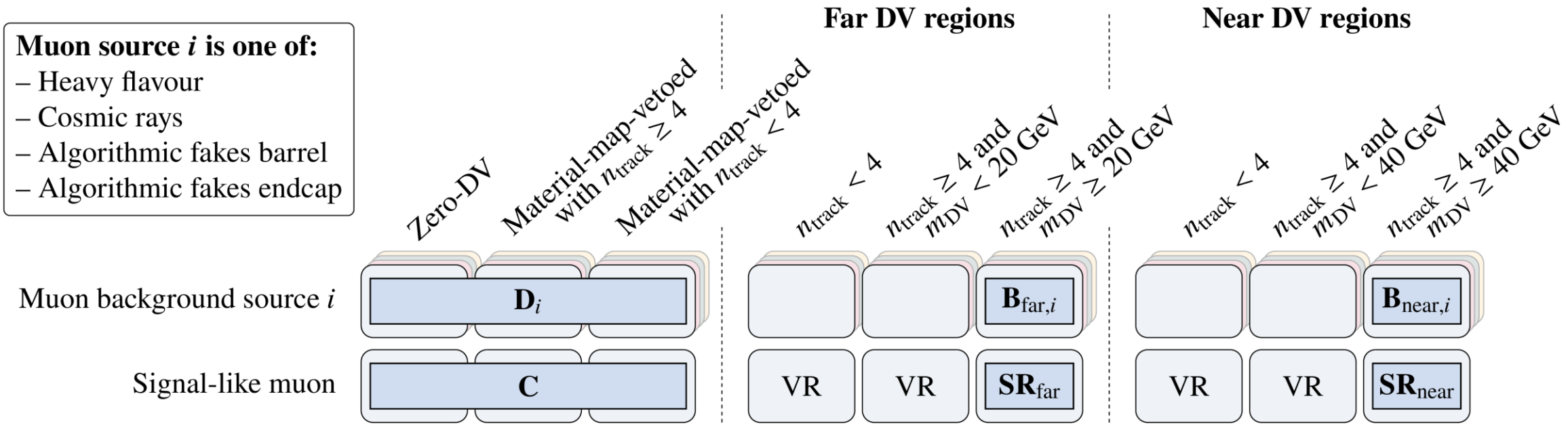
Model	Lifetime τ [ns]	Efficiency [%] SDV SR	1FDV SR	2FDV SR
Gluino R-hadron $m_{\tilde{g}} = 1600\,\text{GeV}$ $m_{\tilde{\chi}_1^0} = 100\,\text{GeV}$	0.01	6.4	0.29	0.084
	0.1	41	1.1	0.36
	3.0	6.9	0.09	0.0029
DFSZ axino (ZZ) $m_{\tilde{a}} = 400\,\text{GeV}$ $m_{\tilde{\chi}_1^0} = 800\,\text{GeV}$	0.0045	9.26	0.48	0.012
	0.097	40.19	0.1	0.30
	1.5	5.15	0.99	0.11
Bino-Wino coannihilation $m_{\tilde{\chi}_1^0} = 650\,\text{GeV}$ $m_{\tilde{\chi}_2^0} = 700\,\text{GeV}$	0.03	0.13	0.37	0.055
	0.3	0.10	0.20	0.024
	3.0	0.014	0.037	0.006
Higgs portal $m_S = 55\,\text{GeV}$	0.0033	0.007	0.007	0.022
	0.033	0.026	0.023	0.057
	3.3	0.0003	0.0003	0.0002

SDV Regions


E_T^{miss}-triggered region
m_{DV} [GeV]
20
15
10
5
2
VR Low Track
SR
VR2
VR Low Mass
VR1
< 4
4
5
6
7+
N_{Tracks}^{SDV}


Photon-triggered region
m_{DV} [GeV]
20
15
10
5
2
CR Low Track
CR True
CR2
CR Low Mass
CR1
< 4
4
5
6
7+
N_{Tracks}^{SDV}

DV+muon


Muon source i is one of:
– Heavy flavour
– Cosmic rays
– Algorithmic fakes barrel
– Algorithmic fakes endcap
Far DV regions
Near DV regions
Zero-DV
Material-map-vetoed with $n_{track} \geq 4$
Material-map-vetoed with $n_{track} < 4$
$n_{track} < 4$
$n_{track} \geq 4$ and $m_{DV} < 20$ GeV
$n_{track} \geq 4$ and $m_{DV} \geq 20$ GeV
$n_{track} < 4$
$n_{track} \geq 4$ and $m_{DV} < 40$ GeV
$n_{track} \geq 4$ and $m_{DV} \geq 40$ GeV
Muon background source i
Signal-like muon
$\mathbf{D}_i$
$\mathbf{B}_{far,i}$
$\mathbf{B}_{near,i}$
C
VR
VR
$\mathbf{SR}_{far}$
VR
VR
$\mathbf{SR}_{near}$

Validation Regions

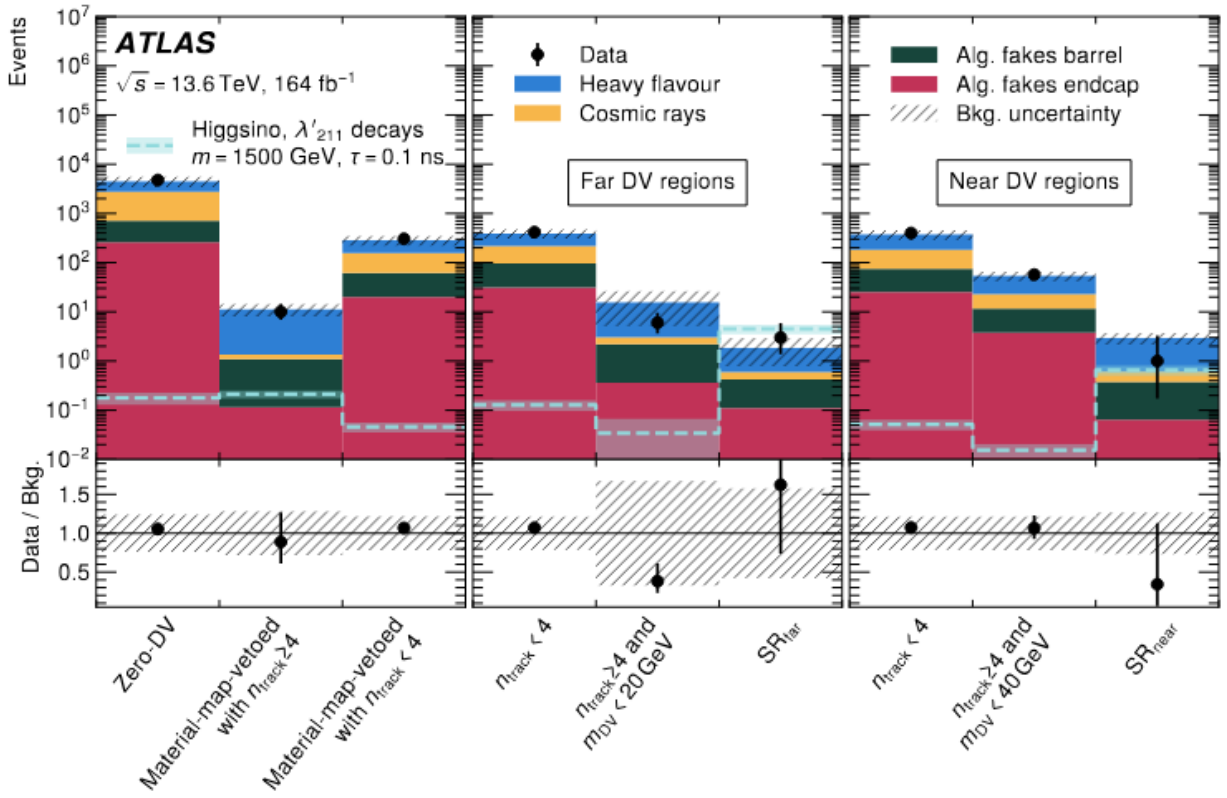


Figure 4: Overview of the analysis regions with varying displaced vertex (DV) selection criteria. The predicted background yields are obtained via the transfer factor method from the zero-DV and material-map-vetoed DV selections, with additional muon selection criteria to enhance the purity for each background. Good agreement is observed in all validation regions, except the far $n_{\text{track}} \geq 4, m_{\text{DV}} < 20\,\text{GeV}$ region. An additional non-closure uncertainty is applied to the heavy-flavour estimate in that region and in SR_{far}. The hatched band represents the total uncertainty in the prediction. The predictions are overlaid with one representative higgsino pair production benchmark model, with $m = 1500\,\text{GeV}$ and $\tau = 0.1\,\text{ns}$, and lepton-number-violating decays via the λ'_{211} coupling. The uncertainty in the signal prediction includes statistical and systematic uncertainties.

Distributions

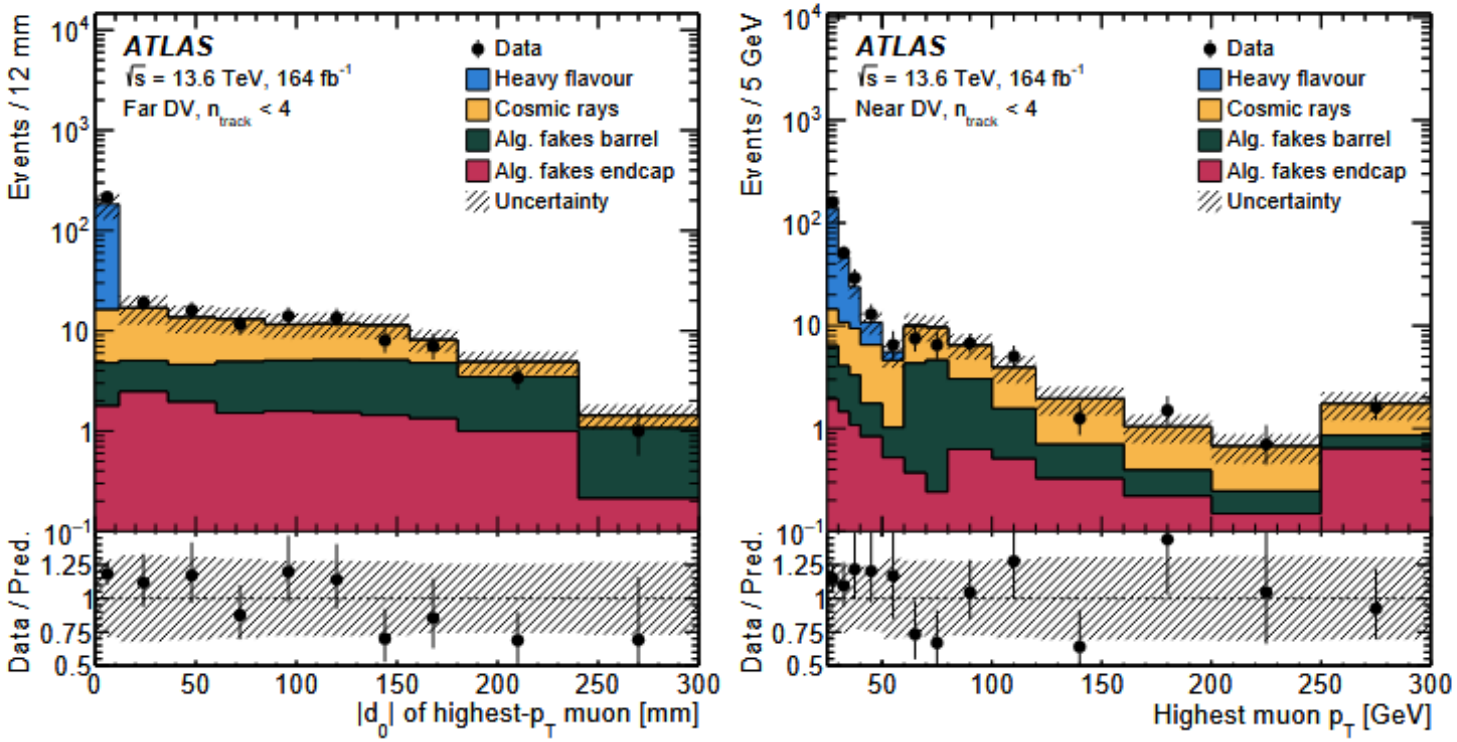


Figure 5: Distributions of the predicted background yields and the observed data for events with (a) a far displaced vertex (DV) with a transverse distance from the primary vertex larger than 4 mm and $n_{\text{track}} < 4$ as a function of the $|d_0|$ of the highest-p_{T} muon, and (b) a near DV with a transverse distance from the primary vertex between 1 mm and 4 mm and $n_{\text{track}} < 4$ as a function of the p_{T} of the highest-p_{T} muon. The hatched band represents the total uncertainty in the prediction. Overflow events are included in the last bins. Good agreement is observed in both regions.

Signal Region Distributions

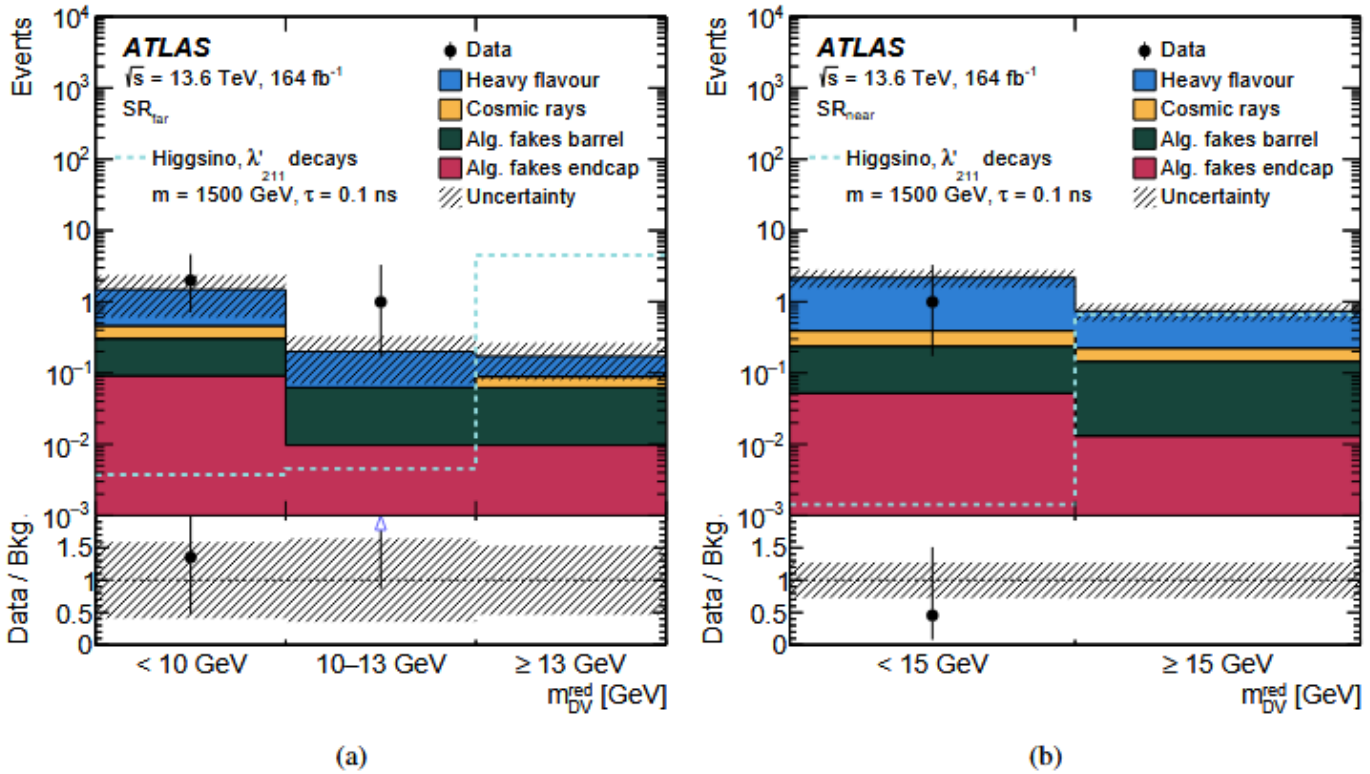


Figure 6: Distributions of the largest reduced invariant mass of any displaced vertex, $m_{\mathrm{DV}}^{\mathrm{red}}$, in the two signal regions: (a) $\mathrm{SR_{far}}$ and (b) $\mathrm{SR_{near}}$. In both signal regions, no events are observed in data in the two highest $m_{\mathrm{DV}}^{\mathrm{red}}$ bins. The background predictions derived using the data-driven transfer factor method are shown, along with an example signal benchmark (higgsino pair production with λ'_{211} decays, $m = 1500\,\mathrm{GeV}$ and $\tau = 0.1\,\mathrm{ns}$) overlaid for illustration. The lower panels show the ratio of observed data to the total background prediction.

Results

Table 2: Model-independent upper limits at 95% confidence level on the visible cross-section, $\langle \sigma A \epsilon \rangle^{95}_{\text{obs}}$, in the two signal regions. The limits are derived using the CL_s method [72, 73] and include the effect of systematic uncertainties as nuisance parameters in the statistical analysis. The limits are given for three different minimum requirements on the reduced invariant mass of the displaced vertex, $m^{\text{red}}_{\text{DV}}$, in SR_{far} and two different minimum requirements in SR_{near}. *Total predicted* lists the total background prediction in each selection, with uncertainties including both statistical and systematic components. *Observed* lists the number of events observed in data for each selection. The $\langle \sigma A \epsilon \rangle^{95}_{\text{obs}}$ column lists the observed upper limits on the visible cross-section; the S^{95}_{obs} and S^{95}_{exp} columns list the observed and expected upper limits on the number of signal events, respectively.

	Total predicted	Observed	$\langle \sigma A \epsilon \rangle^{95}_{\text{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}
SR_{far}, $m^{\text{red}}_{\text{DV}}$ inclusive	1.8 ± 1.1	3	0.038	6.2	4.9
SR_{far}, $m^{\text{red}}_{\text{DV}} \geq 10\,\text{GeV}$	0.37 ± 0.20	1	0.023	3.8	3.1
SR_{far}, $m^{\text{red}}_{\text{DV}} \geq 13\,\text{GeV}$	0.17 ± 0.09	0	0.018	3.0	3.0
SR_{near}, $m^{\text{red}}_{\text{DV}}$ inclusive	2.9 ± 0.8	1	0.021	3.5	4.7
SR_{near}, $m^{\text{red}}_{\text{DV}} \geq 15\,\text{GeV}$	0.73 ± 0.20	0	0.018	3.0	3.0

ATLAS EXPERIMENT