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SIMON FRASER UNIVERSITY

Search for light long-lived particles in pp collisions at $\sqrt{s} = 13$ TeV using displaced vertices in the ATLAS inner detector

arxiv:2403.15332

Hamza Hanif

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LLP 2024

ATLAS EXPERIMENT

Motivation

Search for long-lived scalar particles in the ATLAS Inner Detector (ID)

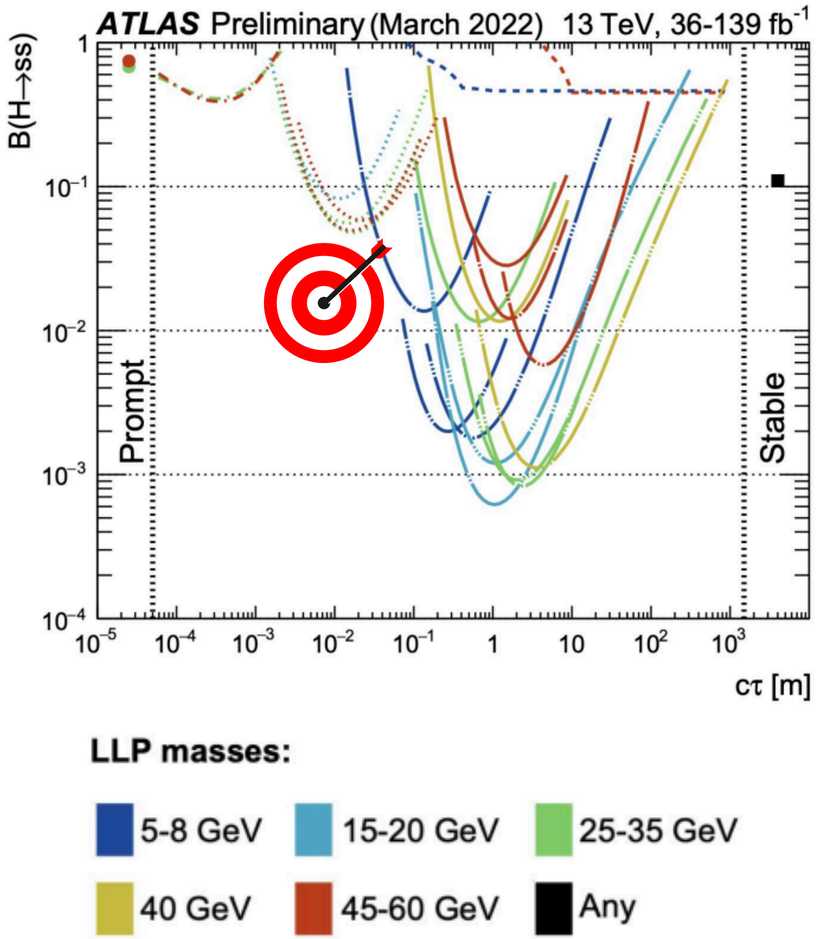
Many BSM models predict exotic Higgs decays to LLPs

- top down: Neutral Naturalness (Folded SUSY, Quirky Little Higgs)
- bottom up: Hidden Valleys, SM+scalar, 2HDM+a

For scalar masses above 5 GeV, LLPs expected to decay hadronically

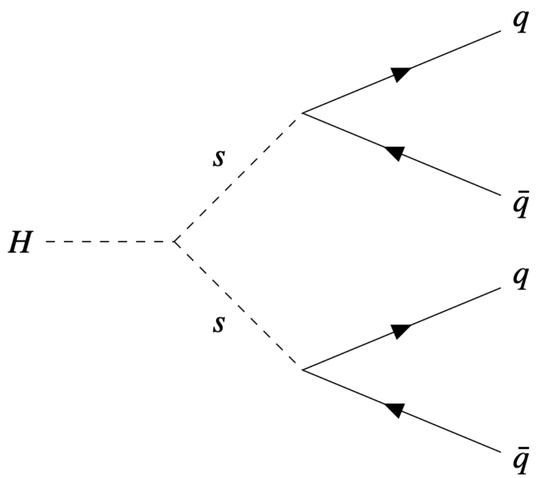
- gives rise to signature of pairs of displaced jets/vertices

Additional interpretations in terms of models with Axion-like particles (ALPs) are also considered



Benchmark Models

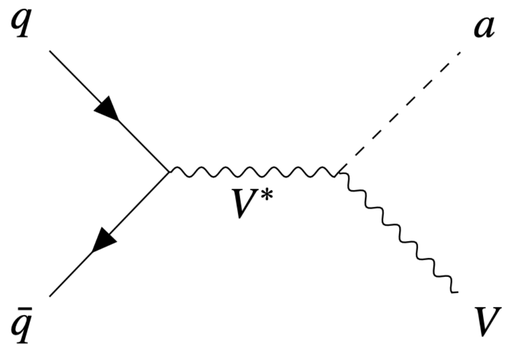
Higgs Portal



H mediates interactions with dark sector through coupling to neutral scalar *s*

Search regions: 1-lepton, 2-lepton and VBF enriched

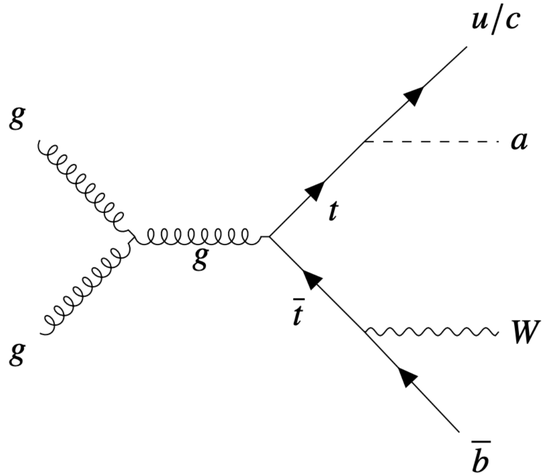
ALP Model # 1



photophobic a couples to W/Z bosons

Search regions: 1-lepton and 2-lepton

ALP Model # 2



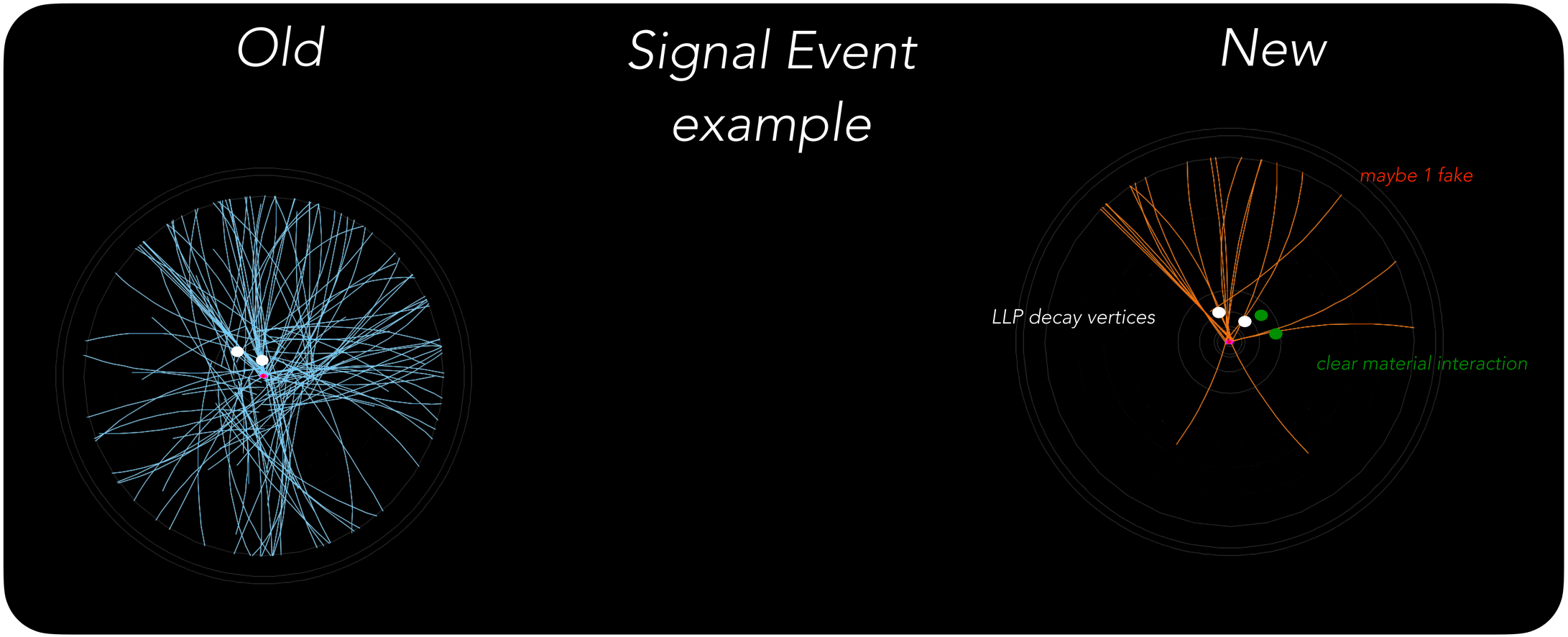
photophobic a couples to up-type quarks

Search region: 1-lepton

Reconstruction

Analysis using the updated larger radius tracking (LRT) reconstruction algorithm to reconstruct displaced tracks

- LRT: Using left-over hits from the primary pass, is used to increase tracking acceptance up to $|d_0| < 300$ mm.



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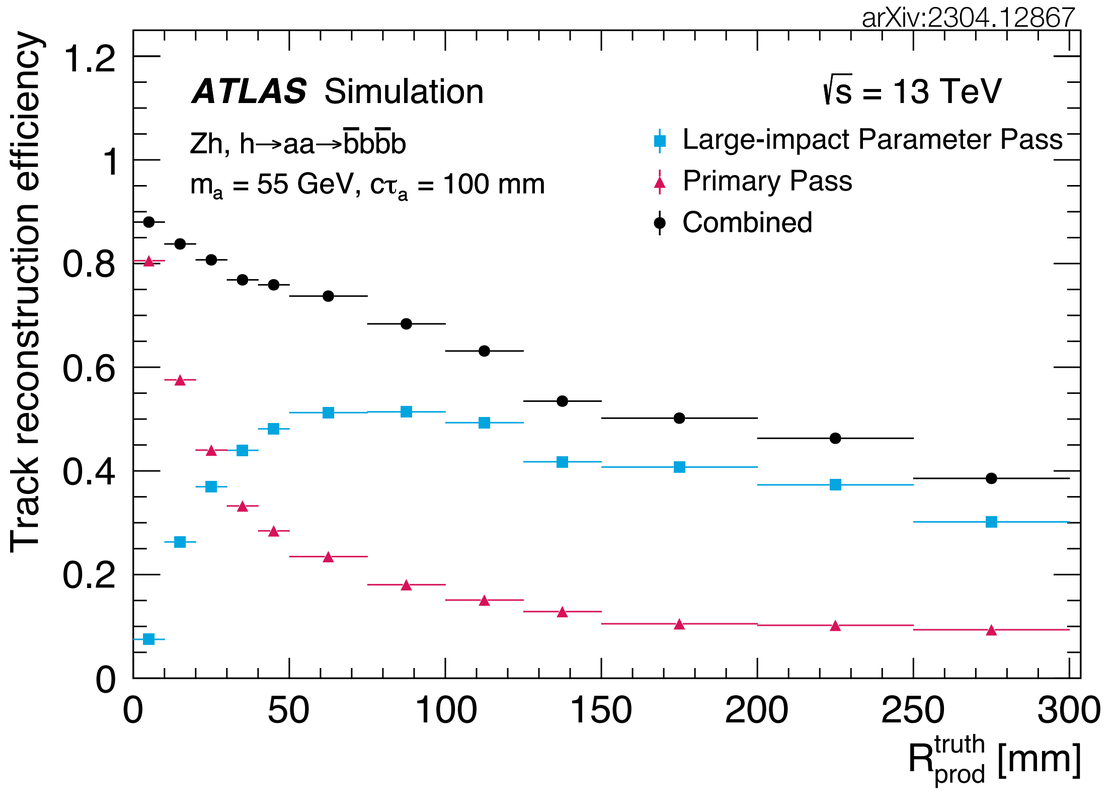
Reconstruction

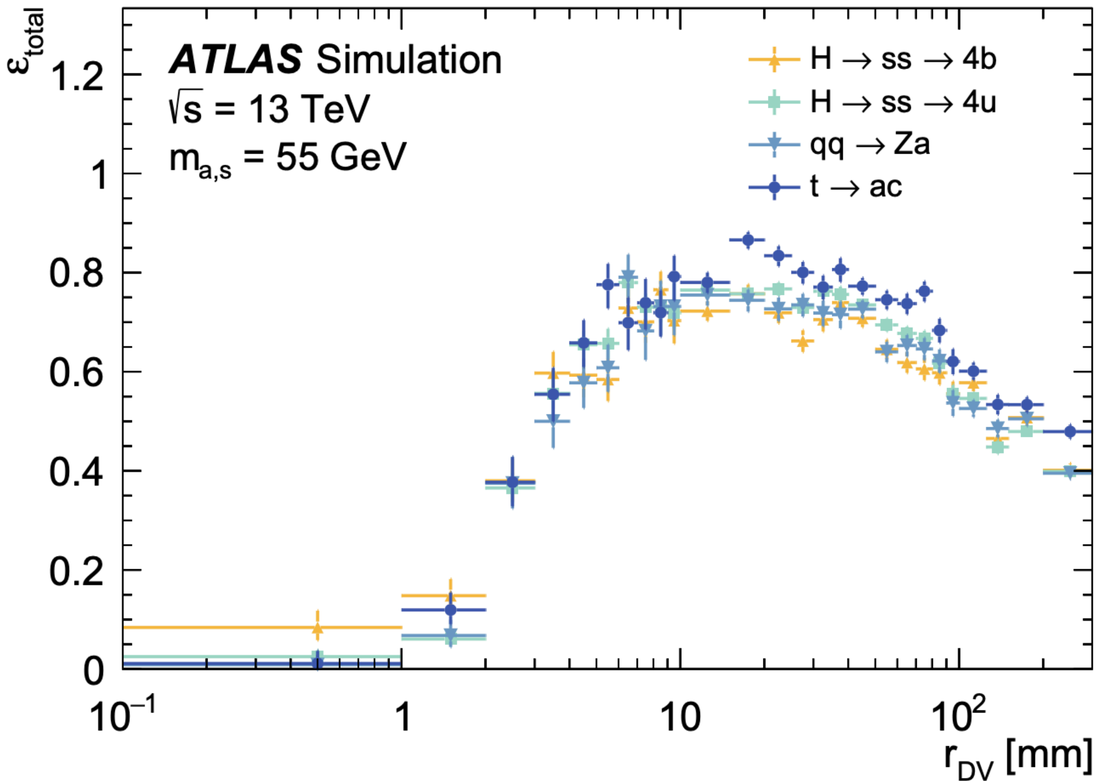
Analysis using the updated larger radius tracking (LRT) reconstruction algorithm to reconstruct displaced tracks

- Maintains signal efficiency while reducing fake reconstruction by a factor of 20

Displaced vertices (DVs) are reconstructed from a combination of prompt and displaced tracks

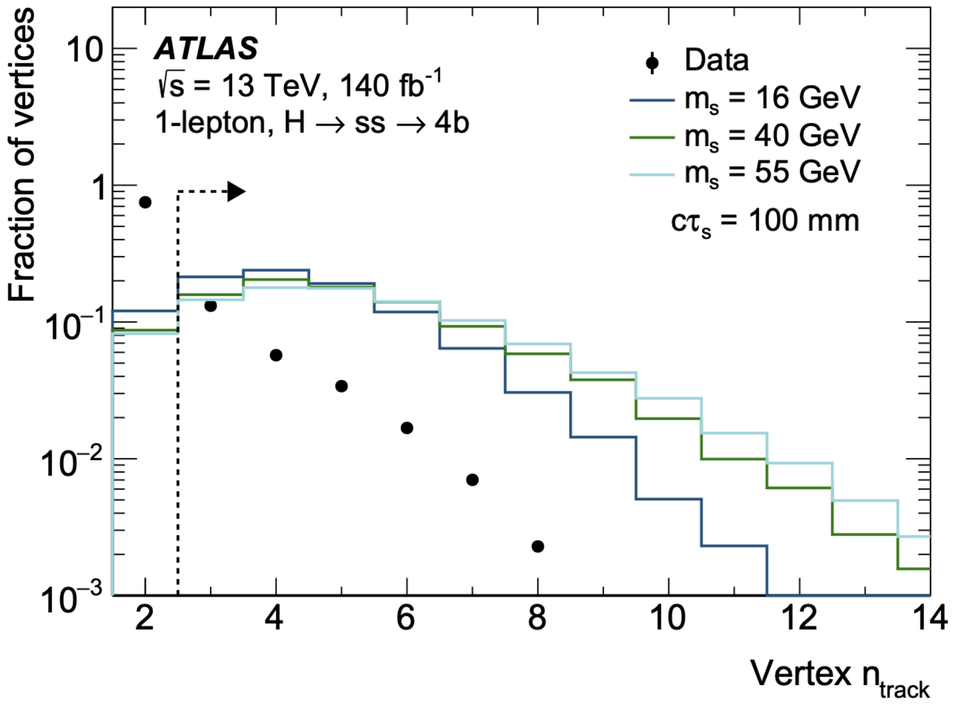
- Efficiencies of up to 80% for 55 GeV LLPs

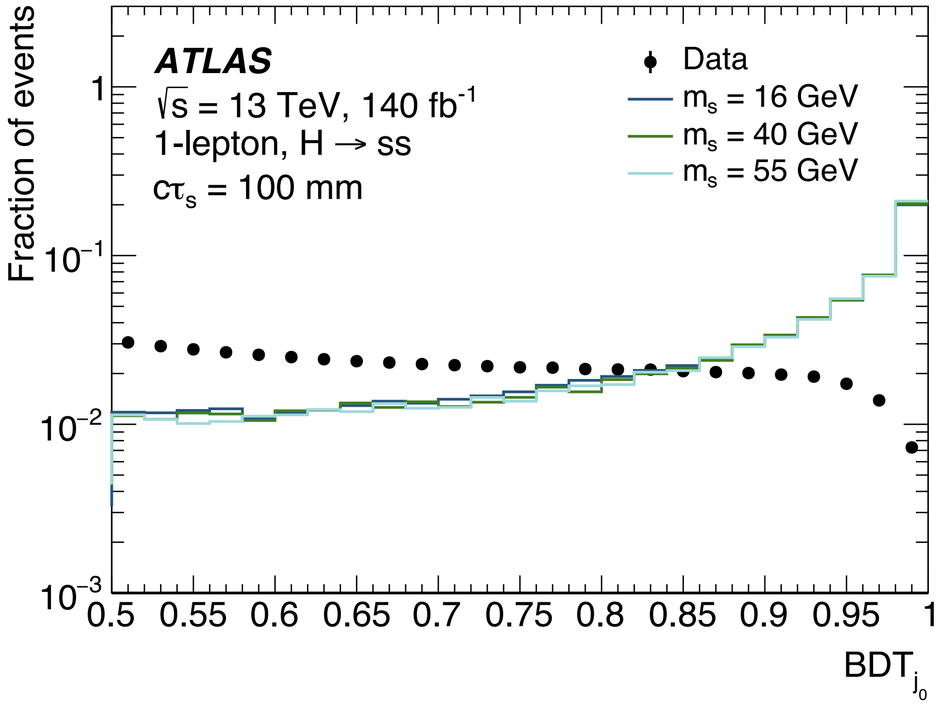




Displaced Vertices & Displaced Jets

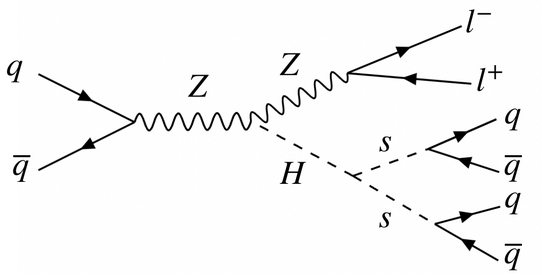
- Selections are placed on the reconstructed vertices to reject DVs from SM processes and random combinations of tracks
- BDT displaced jet tagger are built to distinguish from prompt jets to displaced jets





DVs that satisfy all of the selections and are matched to a displaced jet are used to count the DV multiplicity in the event (n_{DV})

What can we expect?



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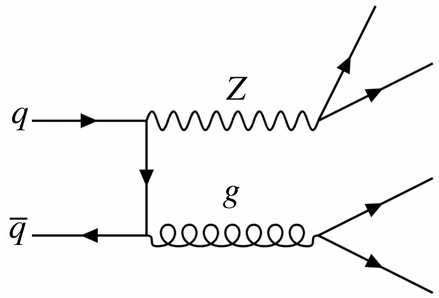

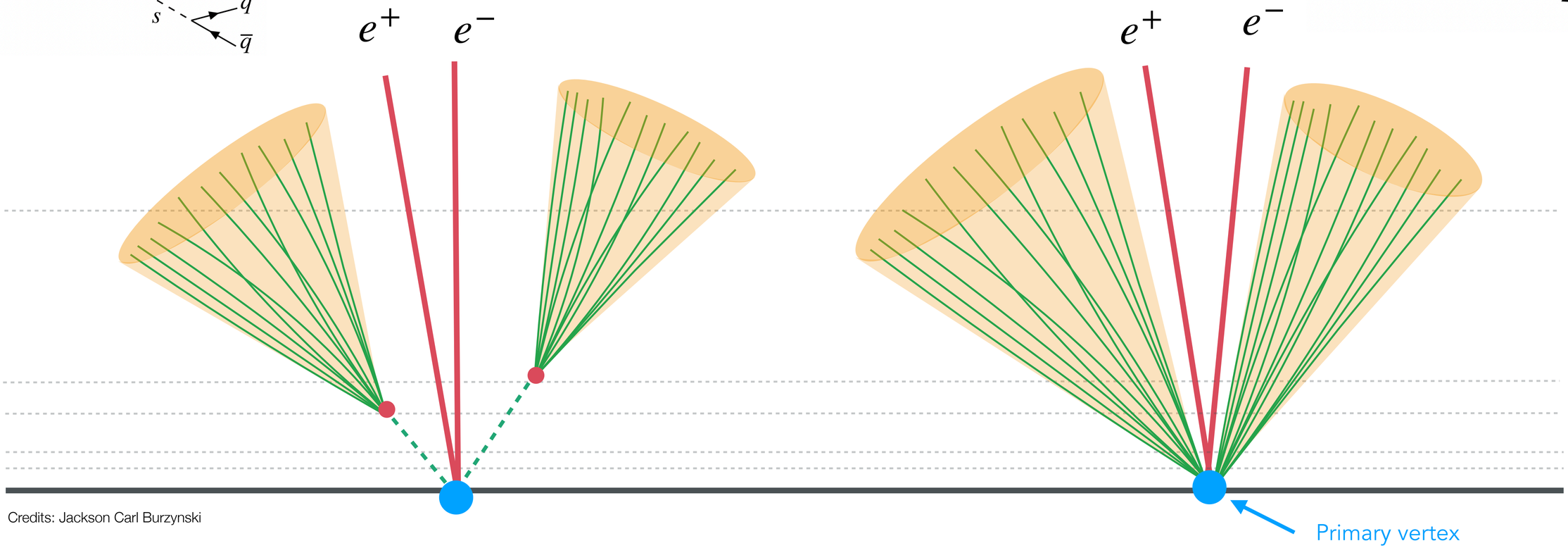

Credits: Jackson Carl Burzynski

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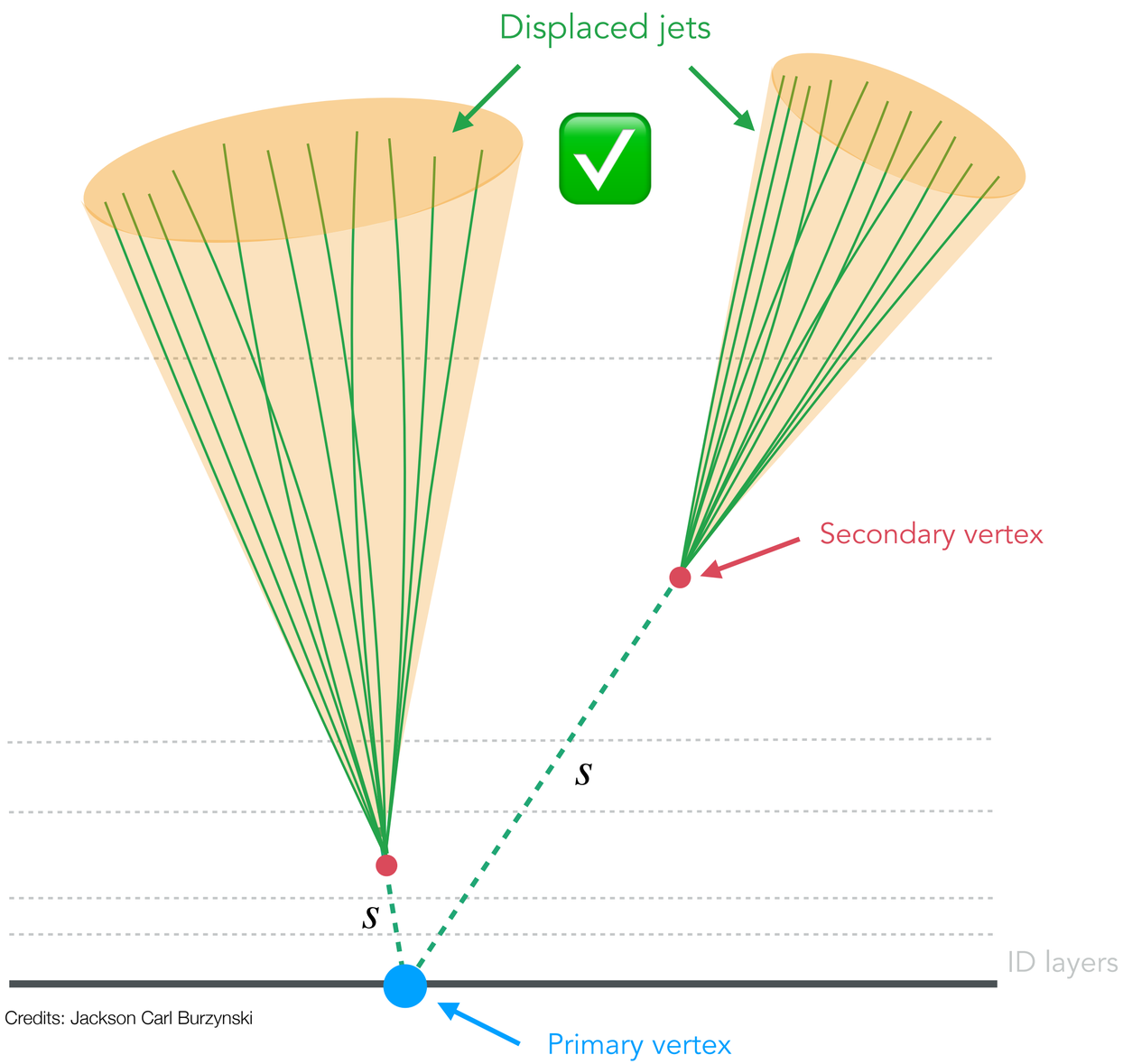
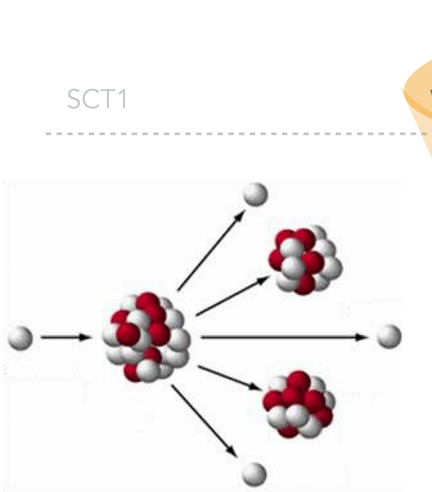


Credits: Jackson Carl Burzynski

Material Interactions



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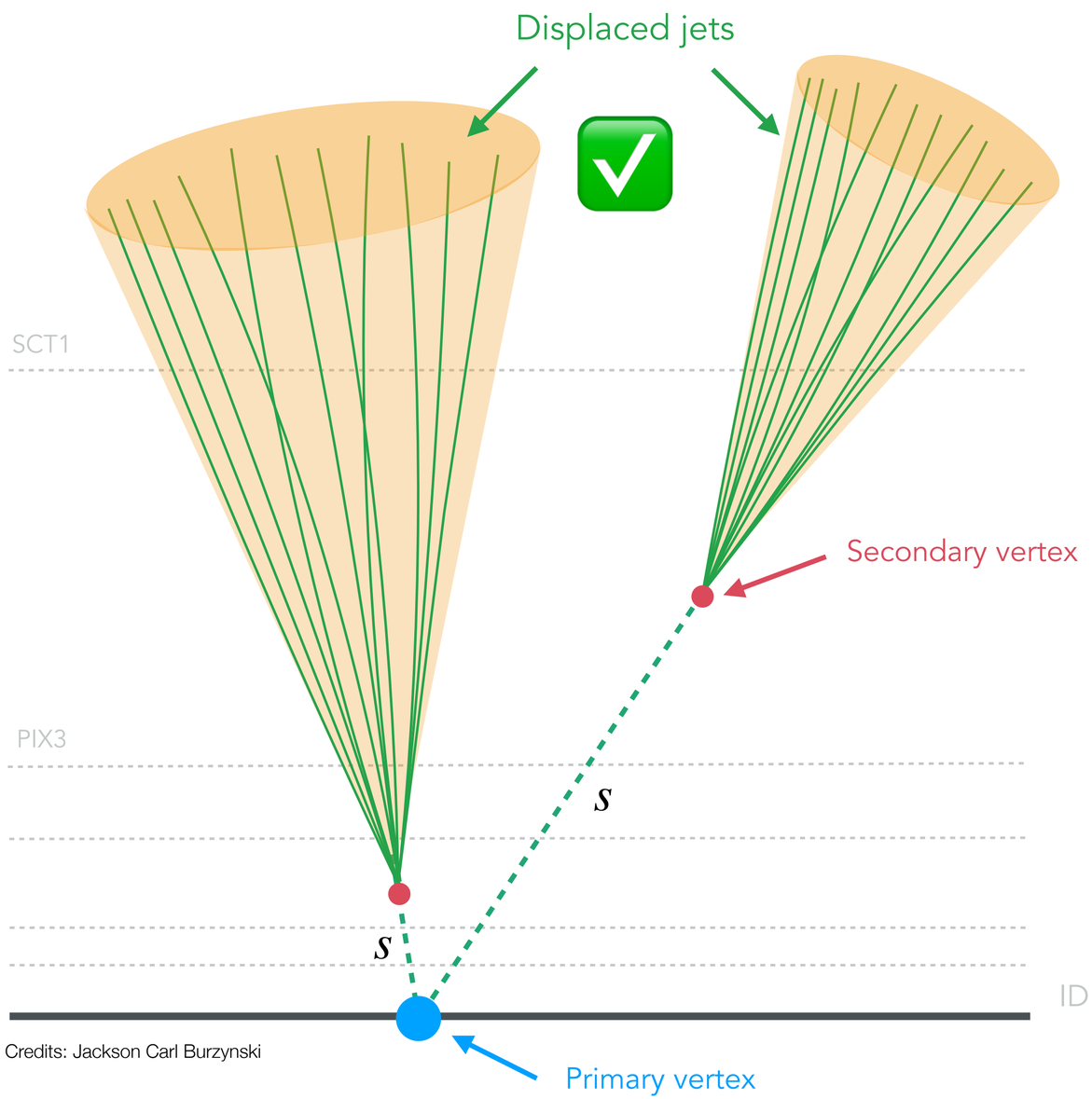

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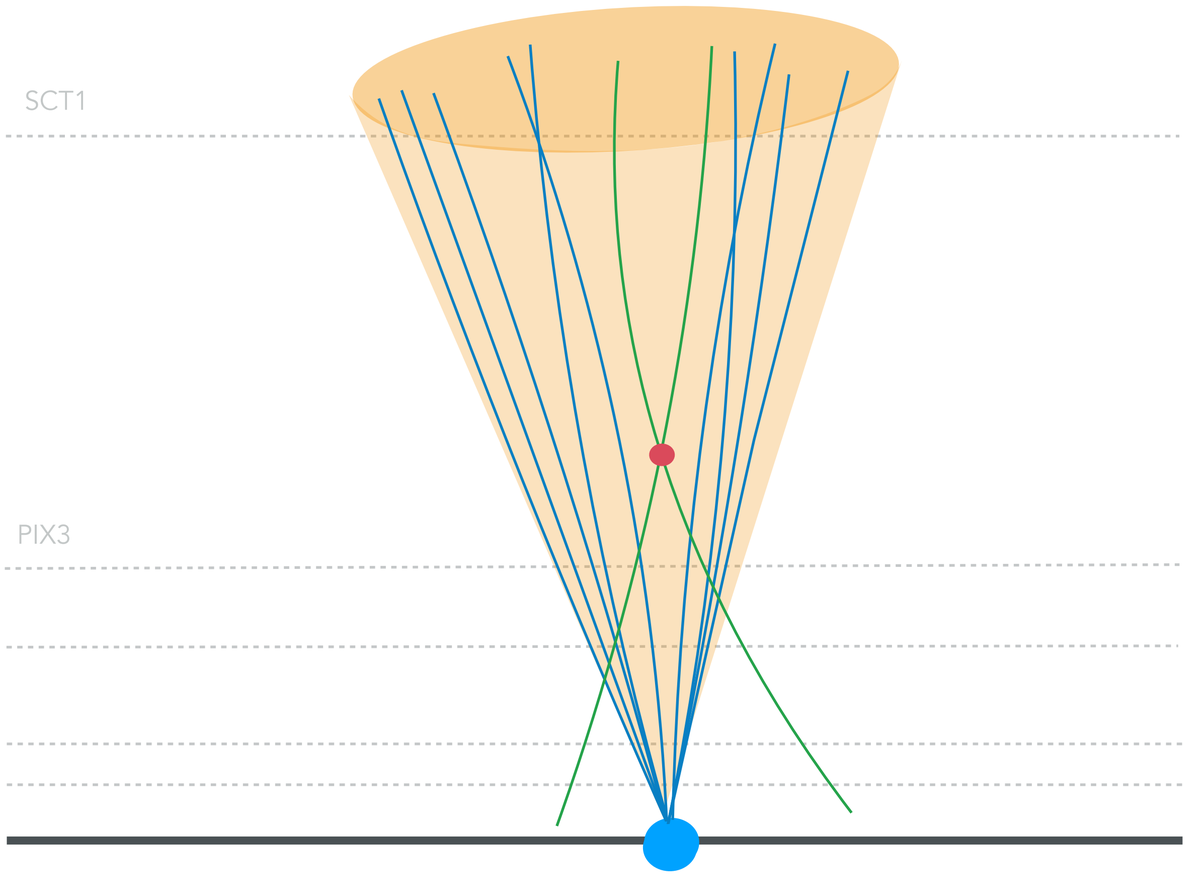
Random Combinations



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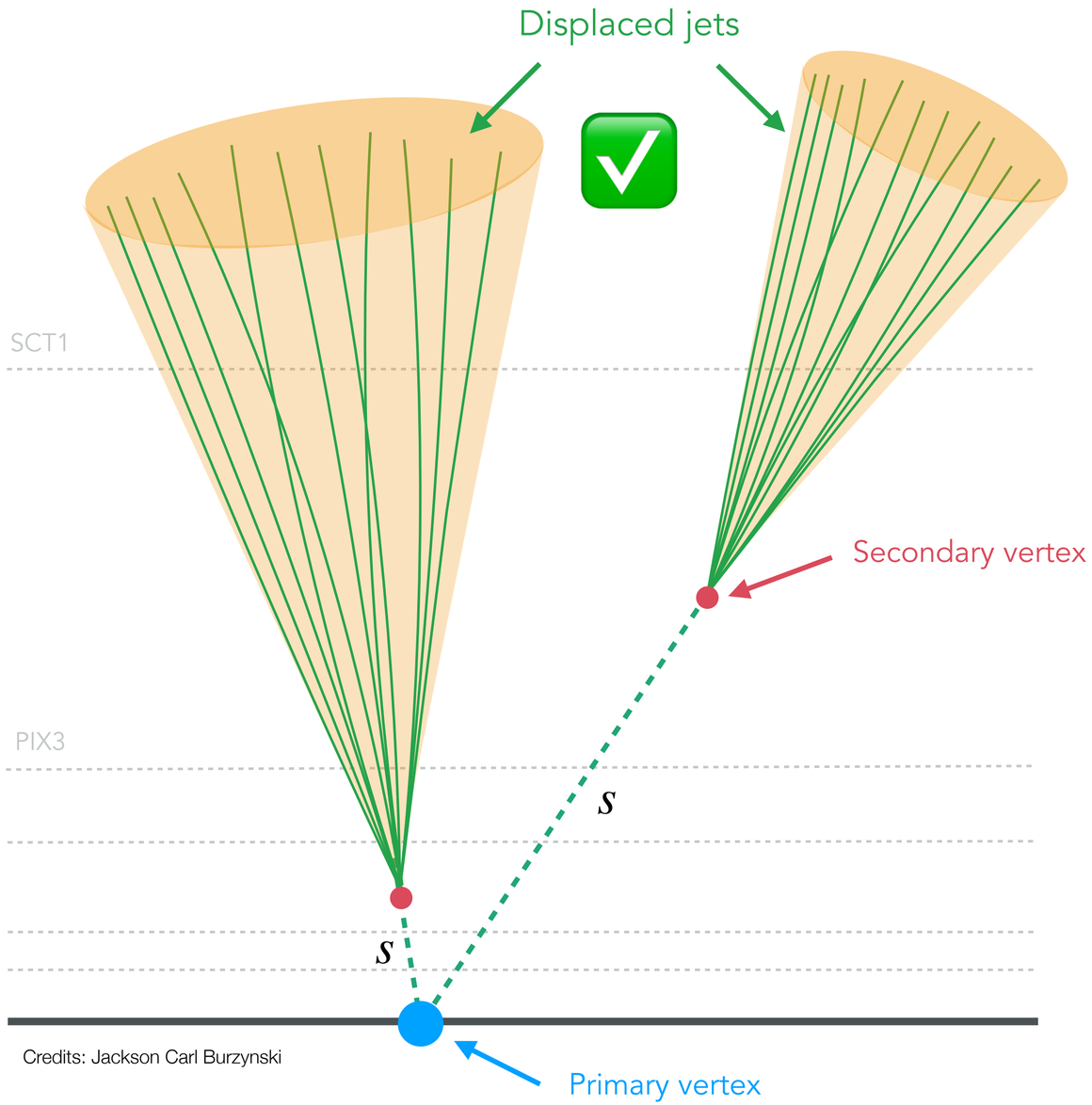
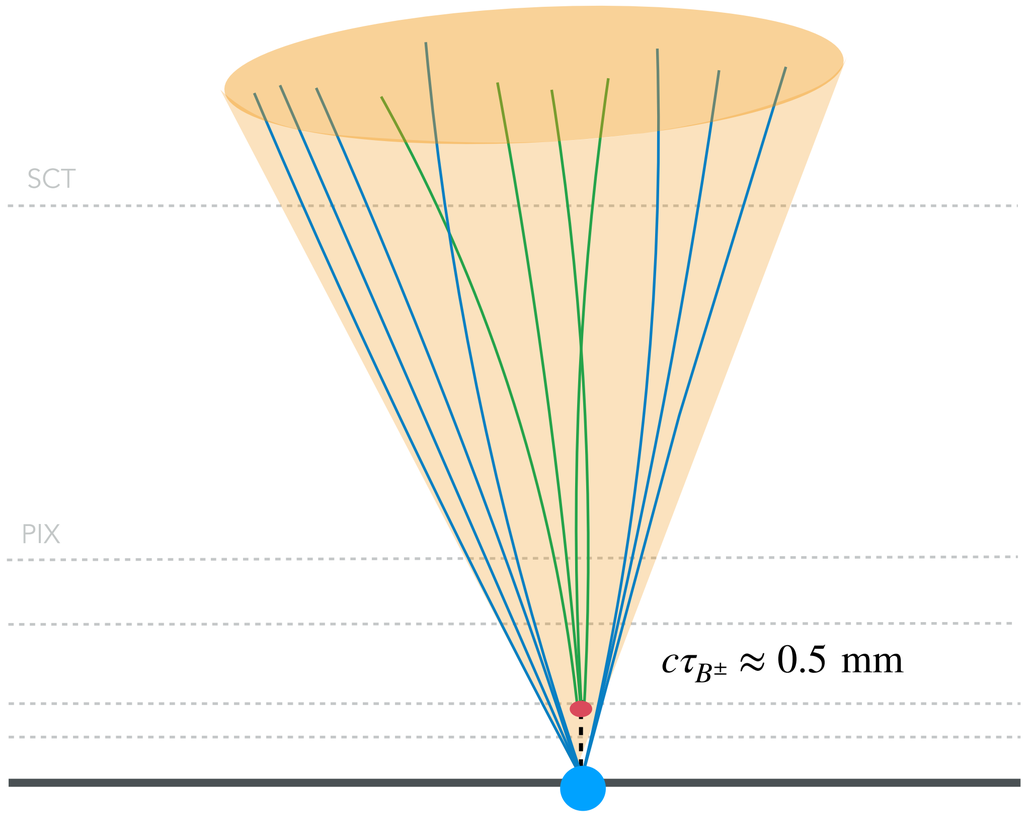


Credits: Jackson Carl Burzynski

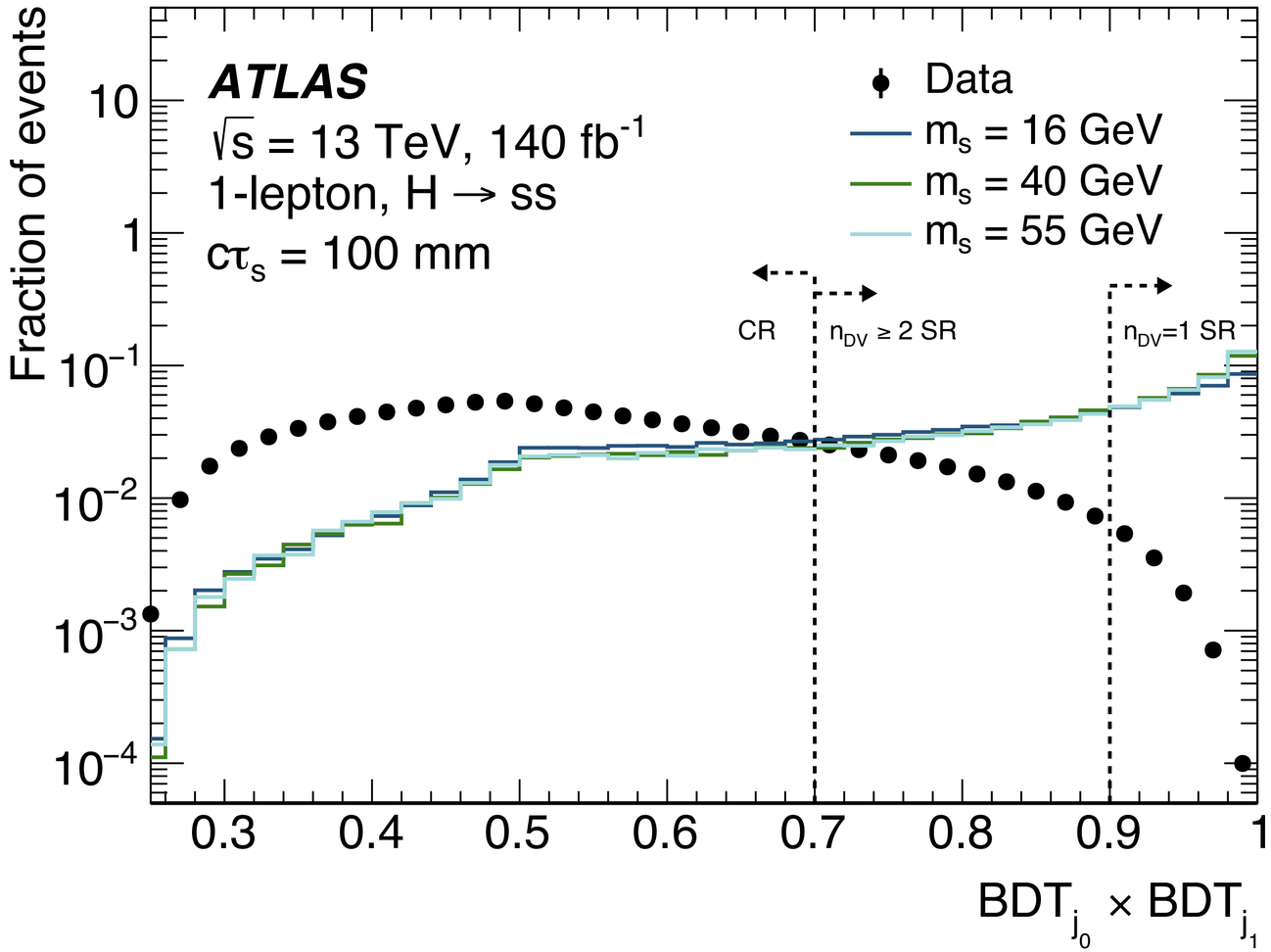
Jets containing B-hadrons



ID

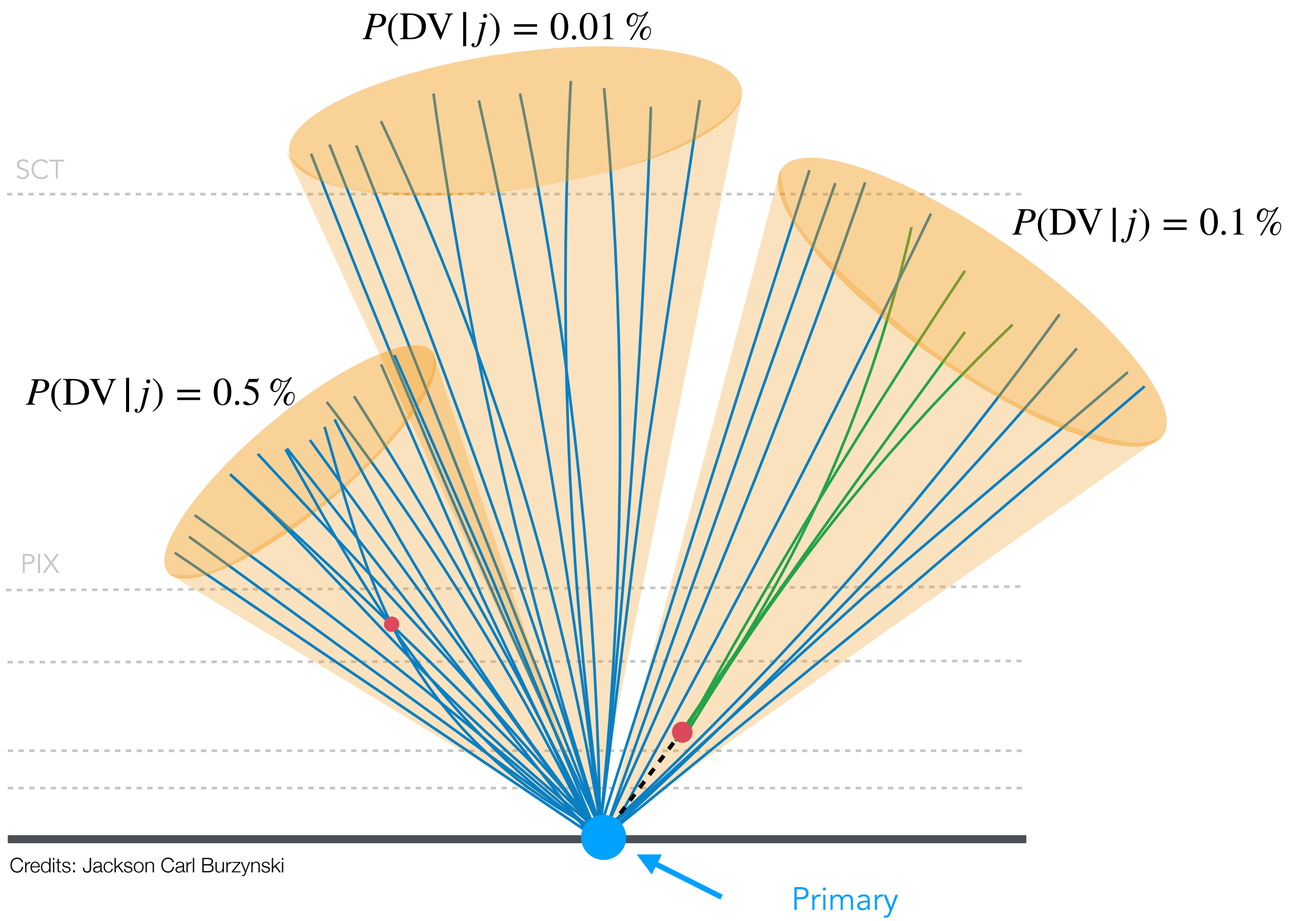
Event-level Discriminant

- Event-level discriminant ($BDT_{j_0} \times BDT_{j_1}$) computed by taking product of jet BDT scores
- Six signal regions (SRs) are defined based on production modes and vertex multiplicity (n_{DV})



Background Estimation

- Due to vertex modeling issues in background simulation → need a data-driven approach
- Strategy: measure the probability in data for a given jet to be matched to a displaced vertex



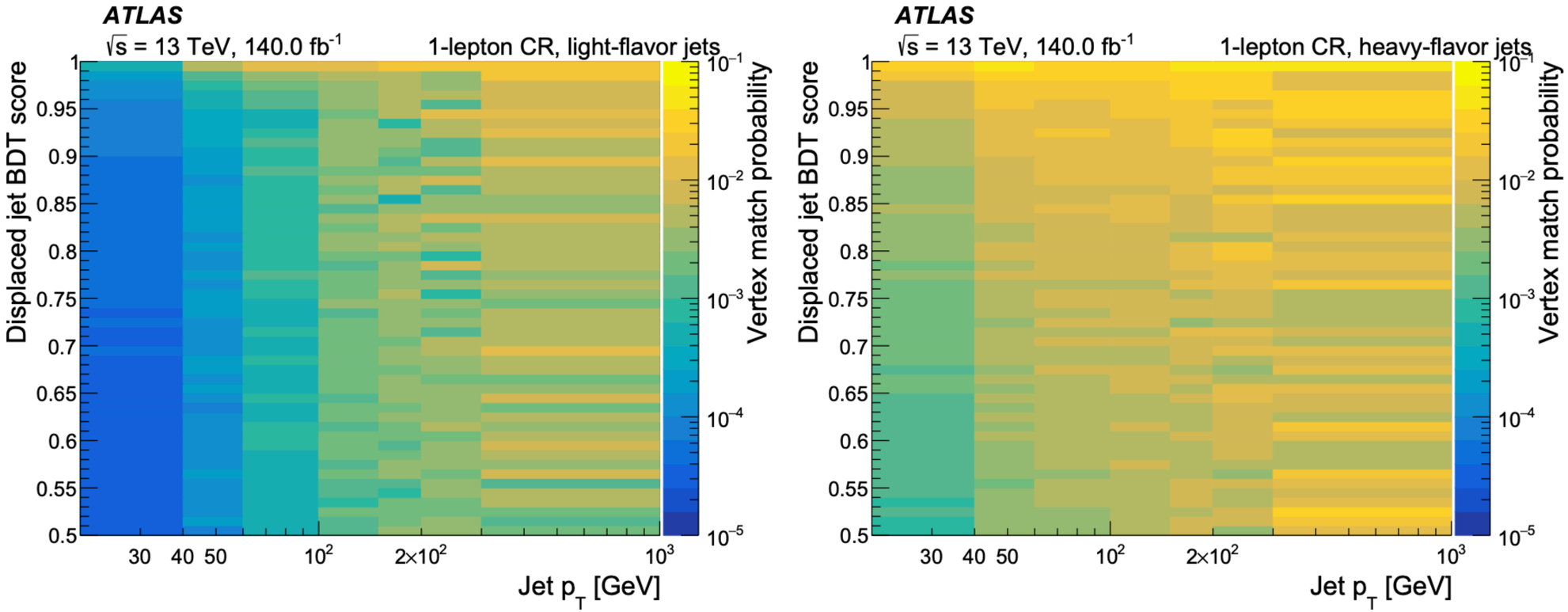
3-dimensional parameterization:

- LLP jet classification (BDT Score)
- b-jet classification (flavour tagging score; dL1r)
- Jet Momentum

Background Estimation

Strategy: measure the probability in data for a given jet to be matched to a displaced vertex

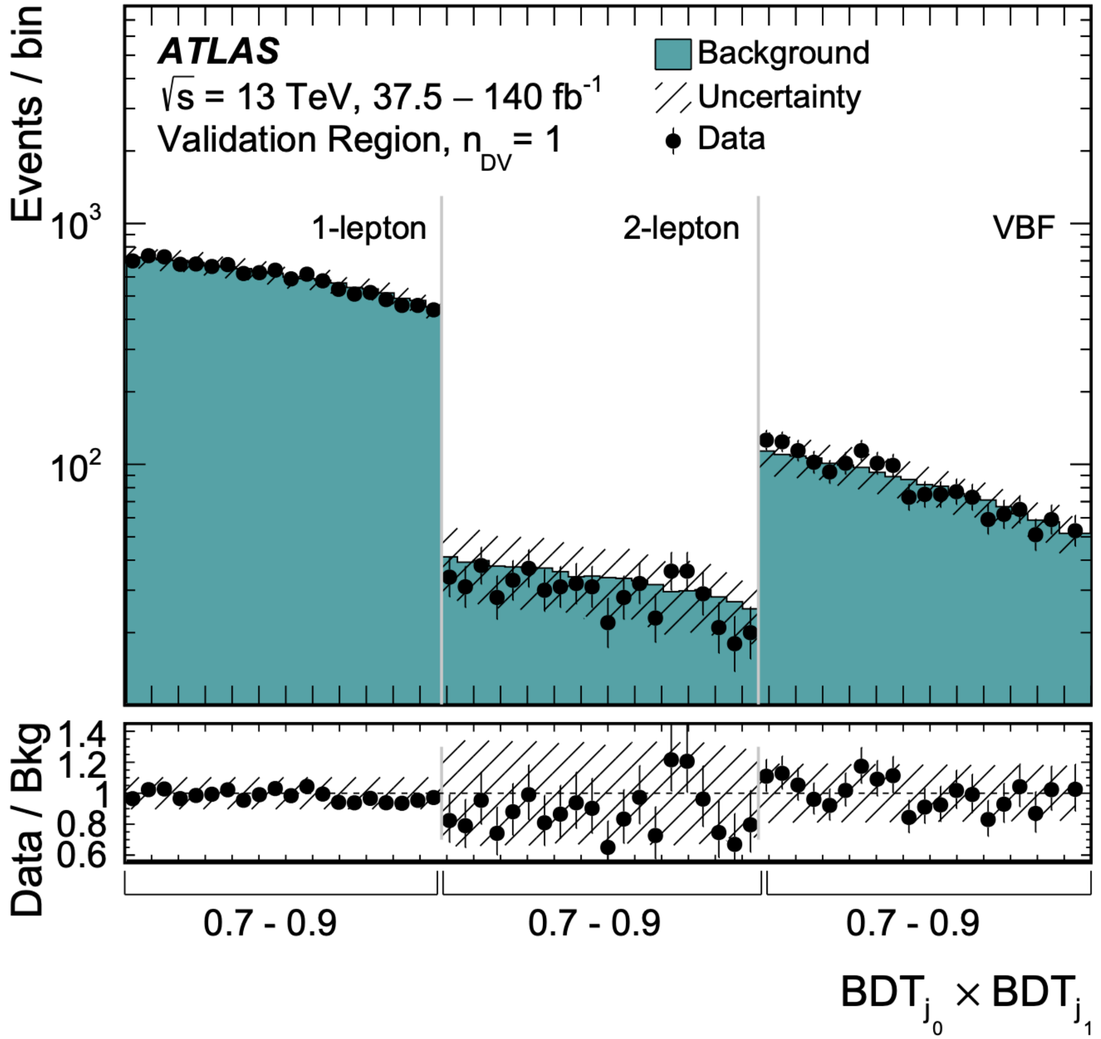
- A per-jet probability map is derived from each Control Region
- Per-jet vertex match probability to estimate background in 6 SR



The three-dimensional per-jet probability maps are shown as two two-dimensional projections for light-flavor (low-level) jets and heavy-flavor (high-level0 jets.

Validation of Background Estimate

The observed data in validation regions are found to agree with the predicted background.



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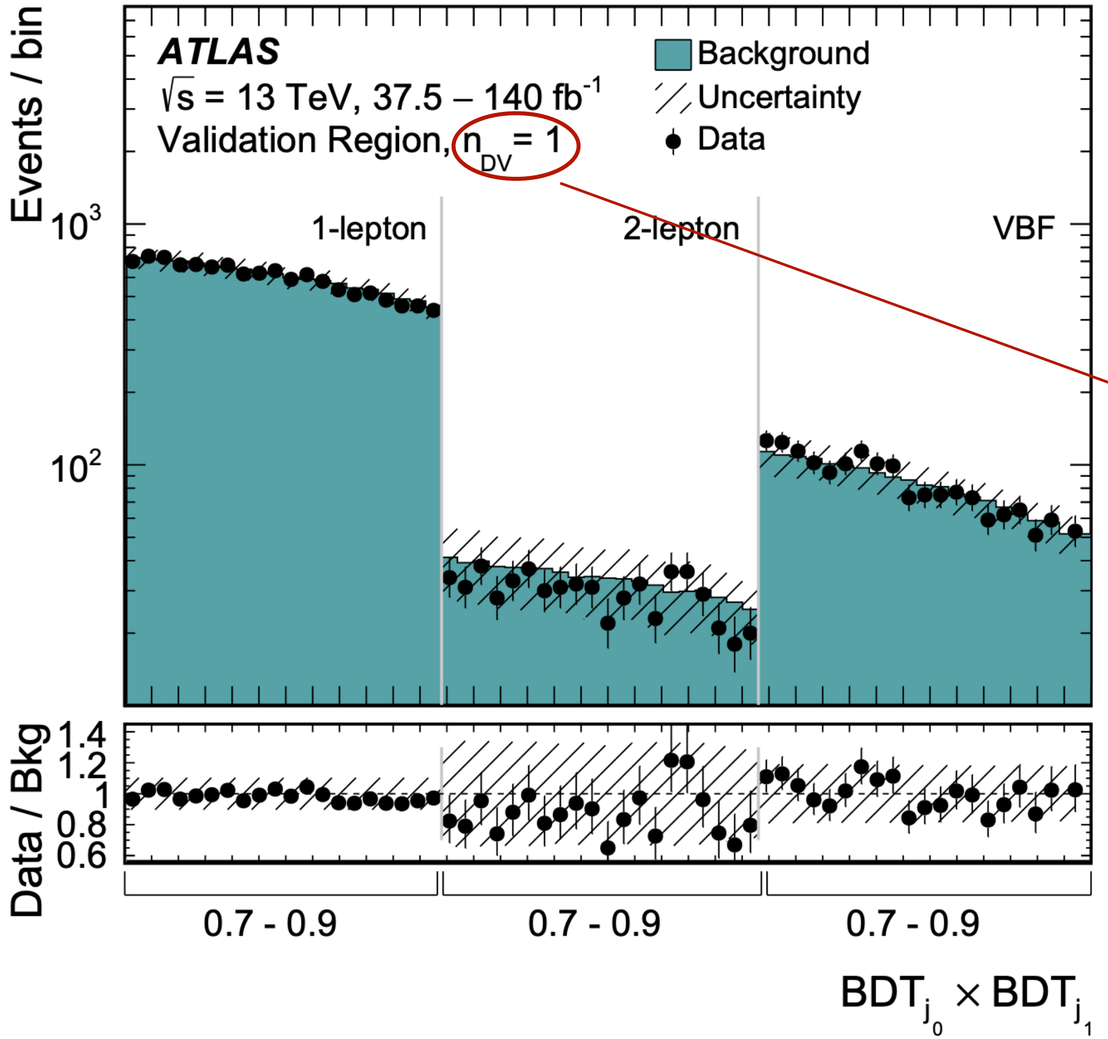
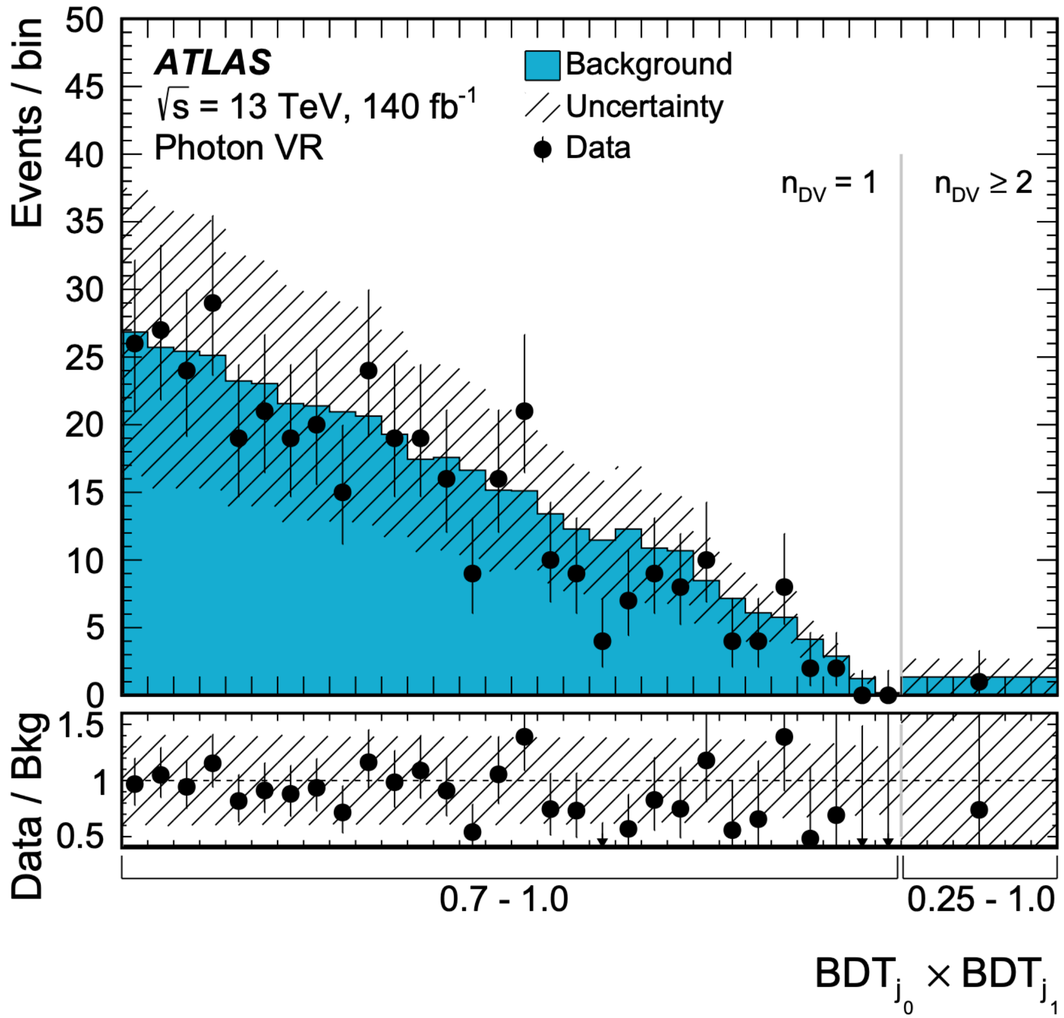


What about validation in $n_{DV} \geq 2$?

Photon validation region

Photon region is used to apply identical background estimation strategy to a signal-free region

- Excellent agreement observed in both 1DV and 2DV regions



Maximum-likelihood Fit

A binned maximum-likelihood fit to is performed in the SRs.

Higgs Portal

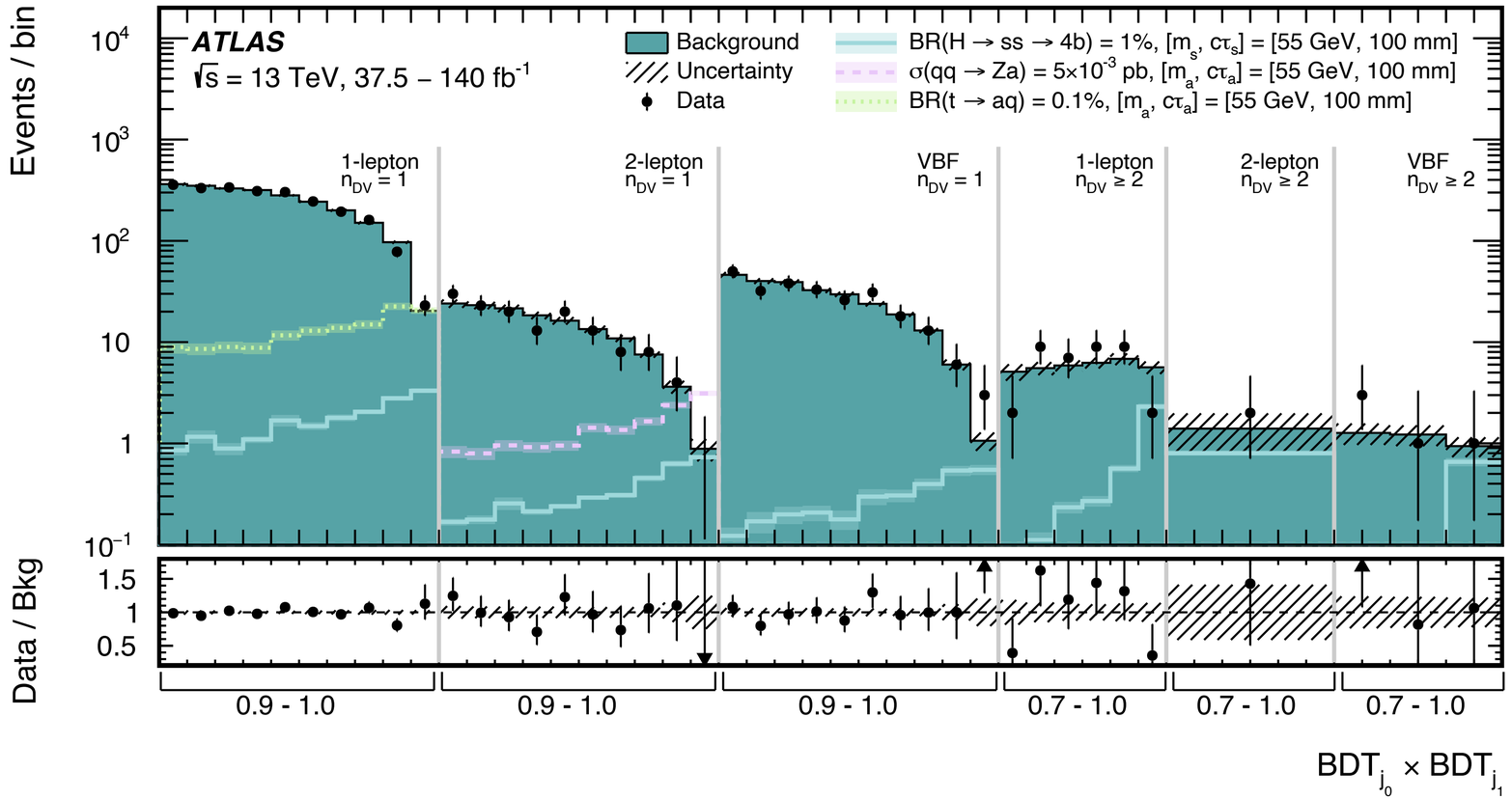
All six SRs are fitted simultaneously

ALP Za model

Only 2-lepton $n_{DV} = 1$ considered

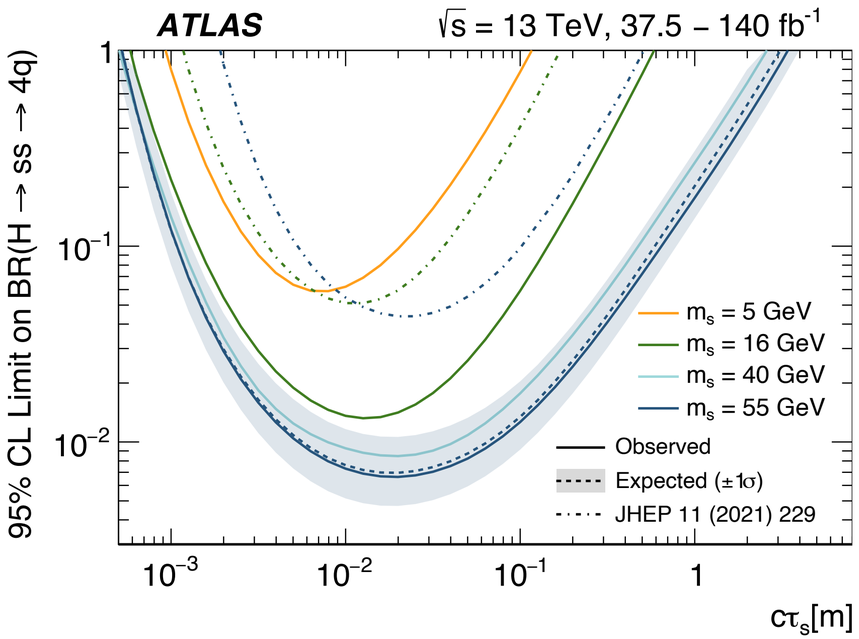
ALP Wa and $t \rightarrow aq$ models

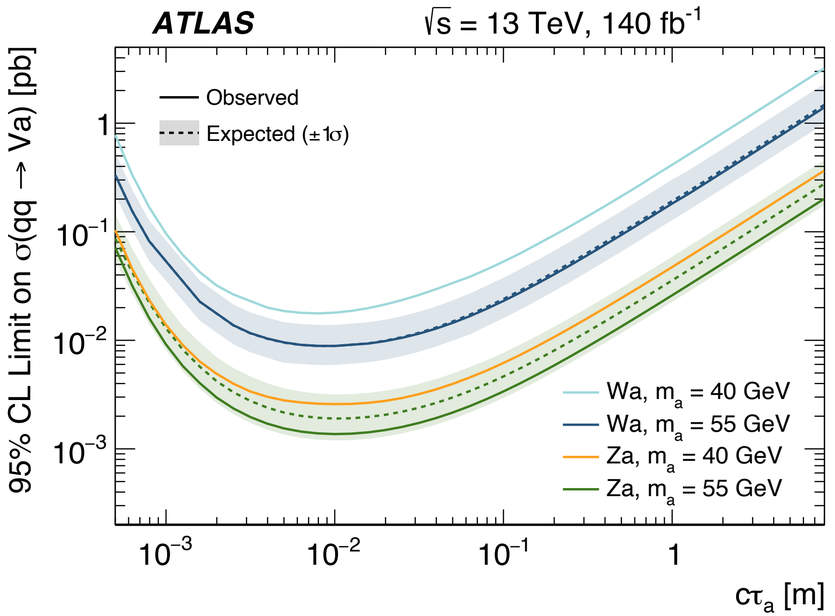
1-lepton $n_{DV} = 1$ SR is considered

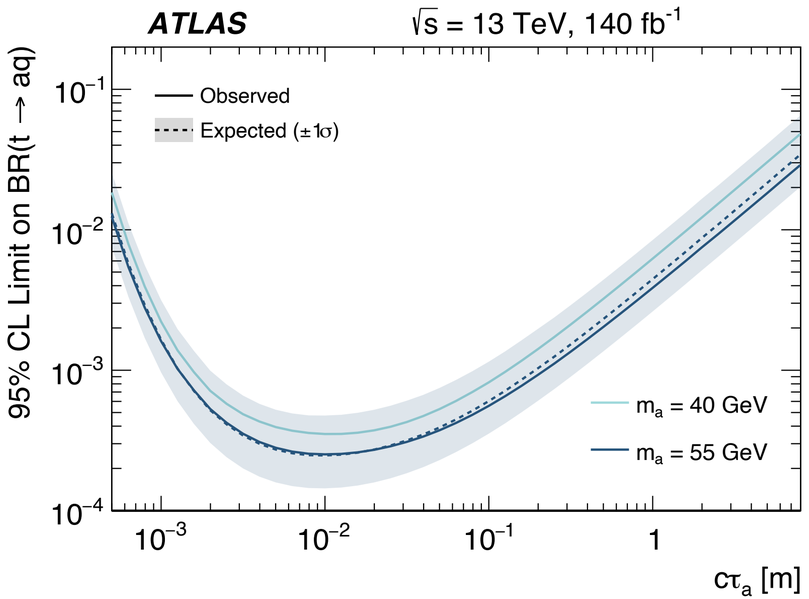


Limits

- For the Higgs portal benchmark, stronger limits than previous ATLAS results using the same dataset.
  - Improvements due to updated large-impact parameter track reconstruction, the addition of the 1-lepton and VBF search regions, and the inclusion of $n_{DV} = 1$ SRs

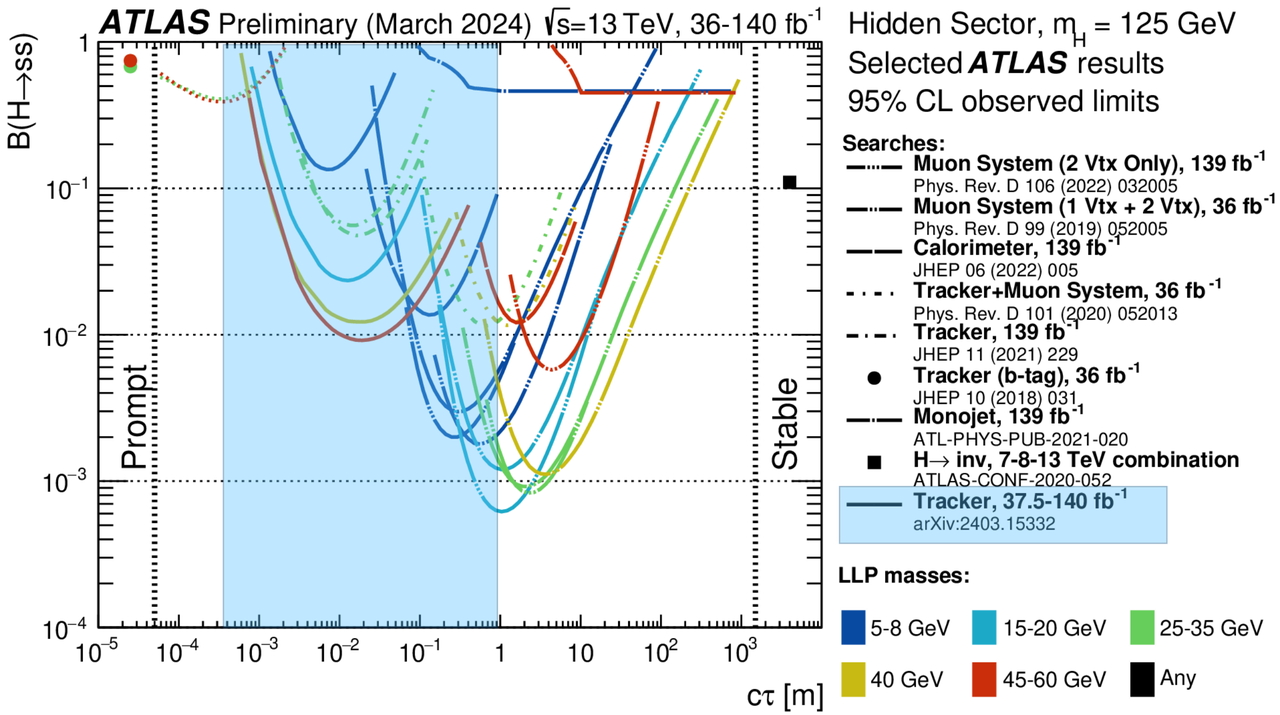






Conclusion

- No excess observed
- Provides 10-100x improvement over previous ATLAS results for Higgs portal **using the same dataset!**
- First LLP results for the $V' \to Va$ and $t\bar{t}, t \to aq$ ALP model



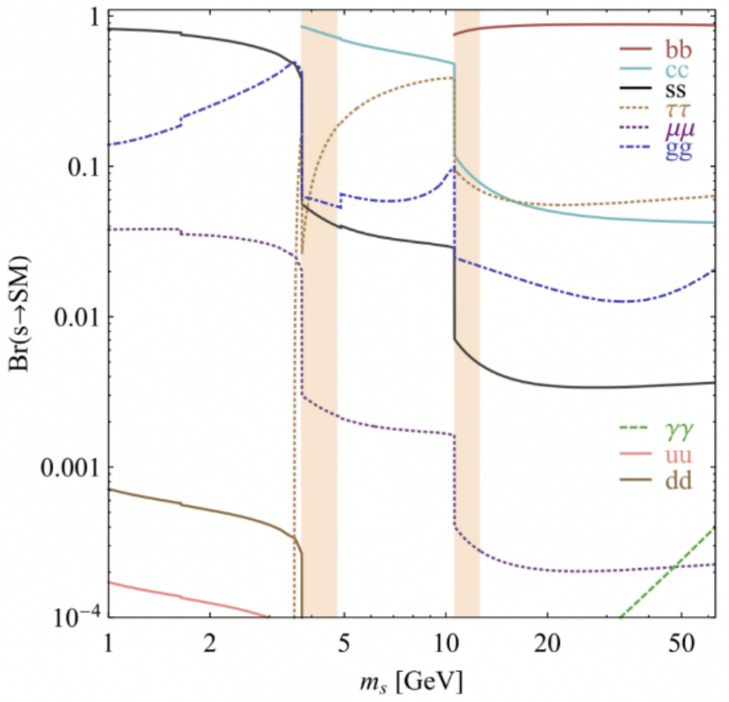
Thank you for listening!!!

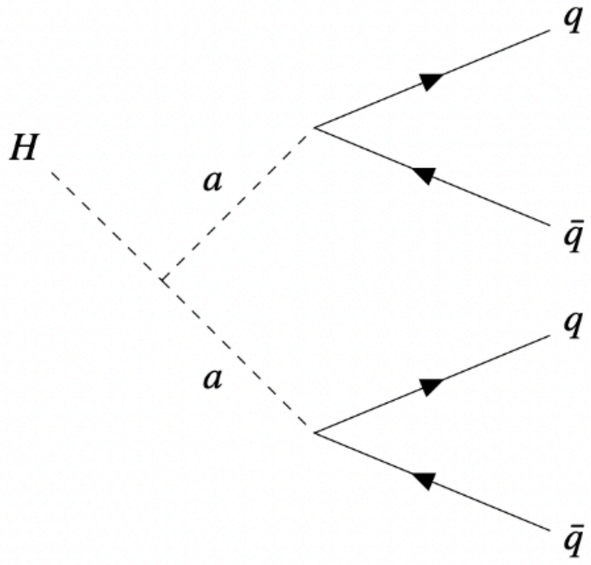
Backup Slides

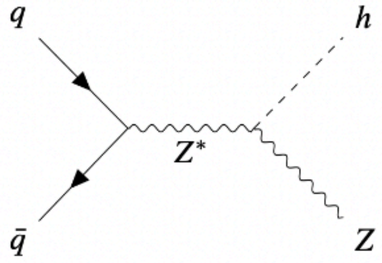
Signal Models

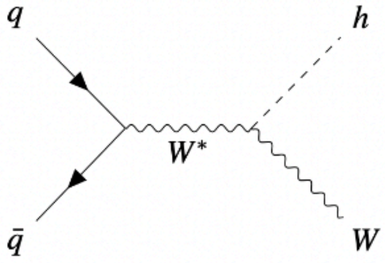
Primary benchmark is the exotic Higgs decay

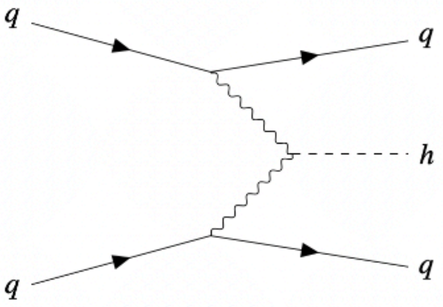
- Masses considered: 5, 16, 40, 55 GeV
- Lifetimes considered: 1, 10, 100, 1000 mm
- Final states: 4*u*, 4*b* (4*c* for 5 GeV)
- Production modes considered: ZH, WH, VBF











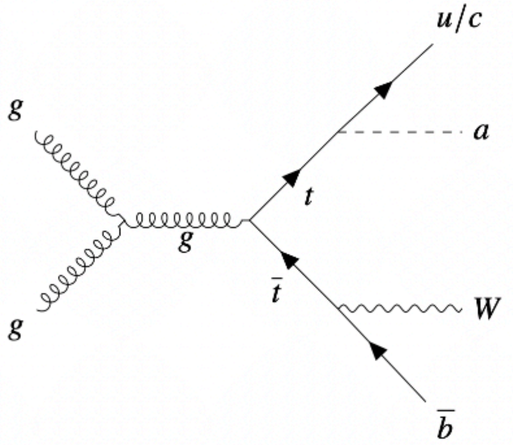
Signal Models

Additional models considered with an Axion-like particle (ALP) produced in association with a SM vector boson

- Masses considered: 40, 55 GeV
- Lifetimes considered: 10, 100, 1000 mm
- Final states: *gg*
- Production modes considered: *Za*, *Wa*

Investigating additional signal of exotic top decay

- Masses considered: 40, 55 GeV
- Lifetimes considered: 10, 100, 1000 mm
- Final states: *cc*, *gg*
- Production modes considered: $t\bar{t}$



Note: lower ALP masses not considered as the analysis strategy requires two displaced jets

- For ALP masses below 40 GeV, the decay products tend to merge into a single jet

Displaced jet observables

The signal is characterized by the presence of two or more displaced jets that do not originate at the PV

- 5 jet-level observables are computed which discriminate between prompt and displaced jets

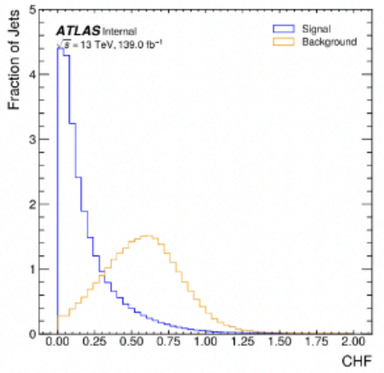
1. Charged Hadron Fraction (CHF)
   - Fraction of jet p_T carried by tracks with $|d_0| < 0.5$ mm
2. Displaced Charged Hadron Fraction (dCHF)
   - Fraction of jet p_T carried by tracks with $|d_0| > 0.5$ mm
3. α_{max} : Maximum value of jet track momenta matched to a given PV

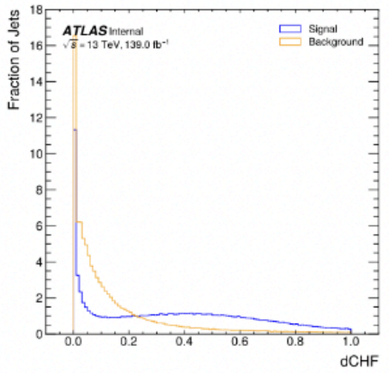
$$\alpha_i = \frac{(\sum_{\text{tracks matched to } PV_i} \vec{p})_T}{(\sum_{\text{tracks in jet}} \vec{p})_T}$$

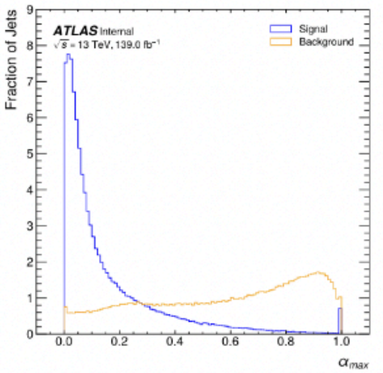
4. Impact parameter significance (IPSIG)
   - (log) median transverse impact parameter significance of tracks associated to the jet

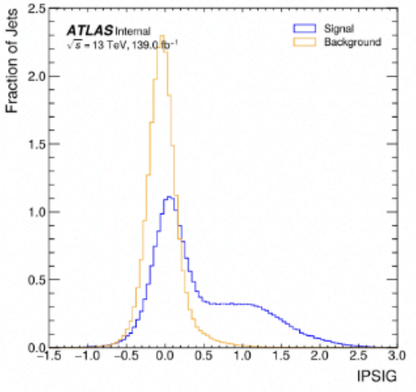
$$\text{IPSIG} = \text{median}[\log_{10}\left(\frac{d_0^{\text{track}}}{\sigma(d_0^{\text{track}})}\right)]$$

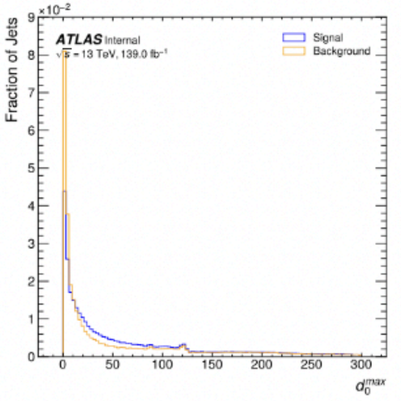
5. d_0^{max} : Maximum $|d_0|$ among tracks associated to the jet







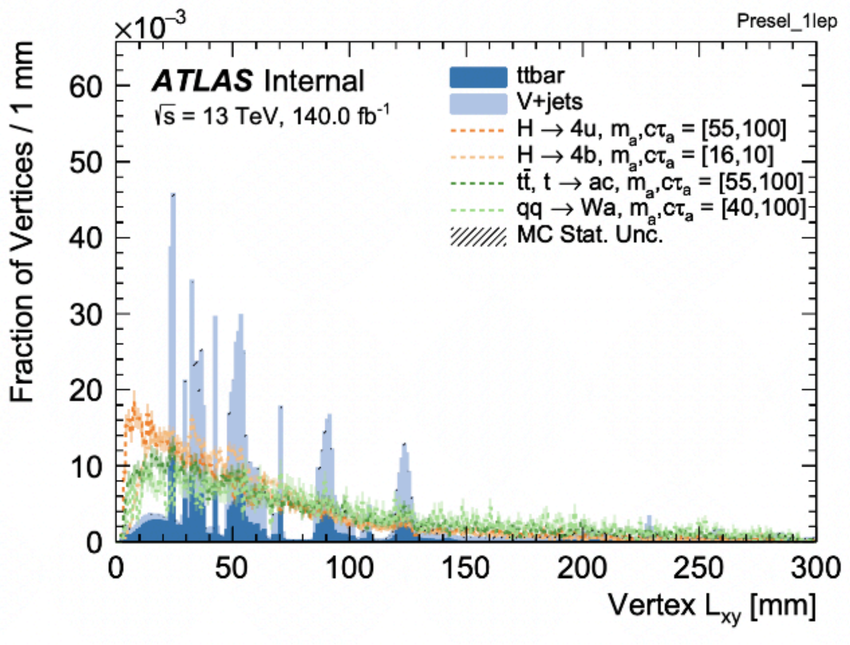




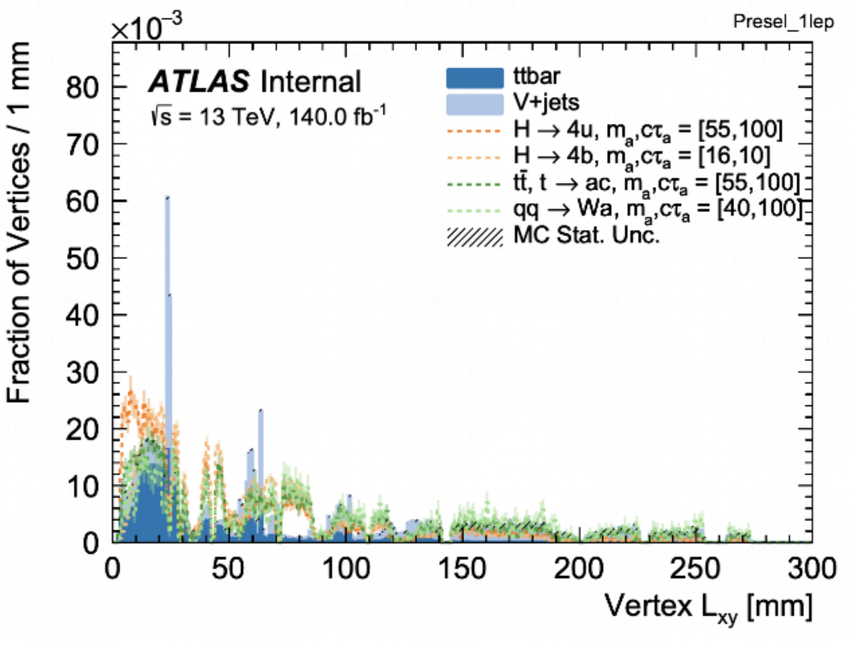
Material Veto

Material veto used to reject secondary vertices from material interactions

- Same data-driven map used in R21 analysis



No material veto



With material veto

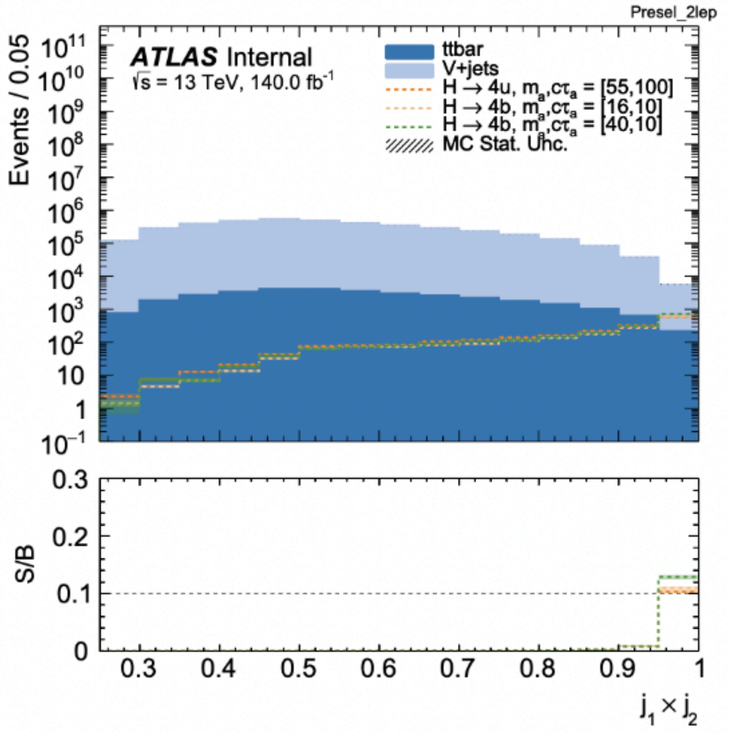
Note: material veto is inefficient when applied to background MC

- Main factor behind decision to pursue a data-driven background estimate

Event selection

From the preselected regions, we define search regions by requiring that the events contain at least two jets with BDT score > 0.5

- The product of the BDT scores of the two most signal-like jets used as final event-level discriminant: "$j_1 j_2$"



	Search_2lep	Search_1lep	Search_VBF	Valid_Photon
nLeptons	2 (SFOS)	1	0	0
Central Jets	≥ 2			
Displaced Jets	≥ 2			
Forward Jets	-		2	-
nPhotons	-			≥1
MET (GeV)	-	> 30 GeV	-	-
Trigger	Single + Di Lepton		VBF incl.	Photon

Search regions are further subdivided into control, validation, and signal regions based on $j_1 j_2$ score and n_{DV}

Background Estimation

The analysis uses a data-driven background estimate

- Derived from the three control regions with $0.25 < j_1 j_2 < 0.7$ and 1DV

Strategy: parameterize background by deriving a per-jet probability map which quantifies the likelihood that a given jet is matched to a DV as a function of:

1. BDT score
2. p_T
3. DL1r *b*-tagging score

Per-event probability is then computed from a multinomial distribution based on the jets in the event:

$$P(1\ \mathrm{DV})_{\mathrm{event}} = \sum_{i=1}^{n_{\mathrm{jet}}} P(1\ \mathrm{DV}|j_i)_{\mathrm{jet}} \times \prod_{k \neq i} \left(1 - P(1\ \mathrm{DV}|j_k)_{\mathrm{jet}}\right) \qquad P(2\ \mathrm{DV})_{\mathrm{event}} = 1 - P(1\ \mathrm{DV})_{\mathrm{event}} - P(0\ \mathrm{DV})_{\mathrm{event}}$$

Per-event probability is applied as a weight to data events to obtain the predicted background distributions in the SRs

- Can be used to predict shapes of $j_1 j_2$ distributions in events with $n_{\mathrm{DV}} = 1$ and $n_{\mathrm{DV}} \geq 2$

Per-jet efficiency Map

The per-jet maps are derived using events from the three control regions

- Three total maps are used, one for each search region

Binning:

1lep:

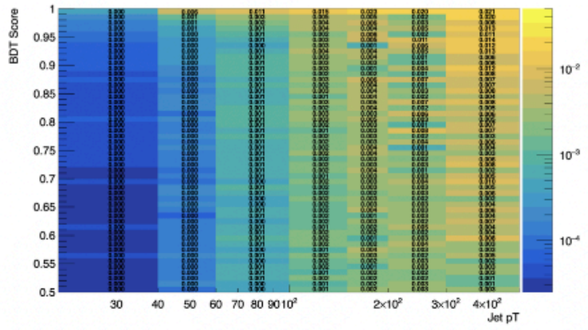
Jet observable	Bin edges
p_{T}	[20, 40, 60, 100, 150, 200, 300, 500]
DL1r	[−6, 2, 12]
BDT score	[0.5, 0.51, 0.52, 0.53, . . . , 0.97, 0.98, 0.99, 1.0]

2lep/VBF:

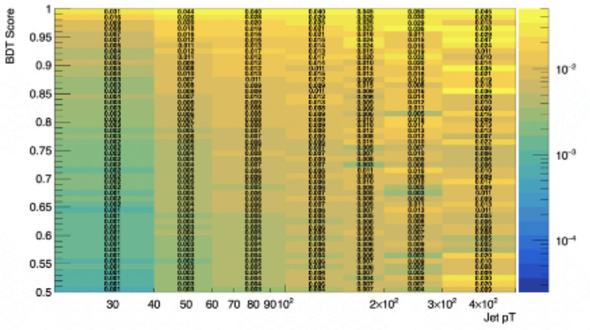
Jet observable	Bin edges
p_{T}	[20, 40, 60, 100, 150, 200, 300, 500]
DL1r	[−6, 2, 12]
BDT score	[0.5, 0.525, 0.55, 0.575, . . . , 0.925, 0.95, 0.975, 1.0]

Interpolation procedure is used to fill empty bins, in which neighbouring bins are averaged

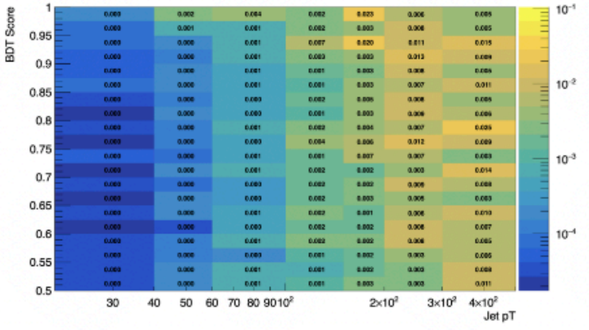
- Uncertainty computed by taking ±1σ variation of all neighbouring bins before taking average



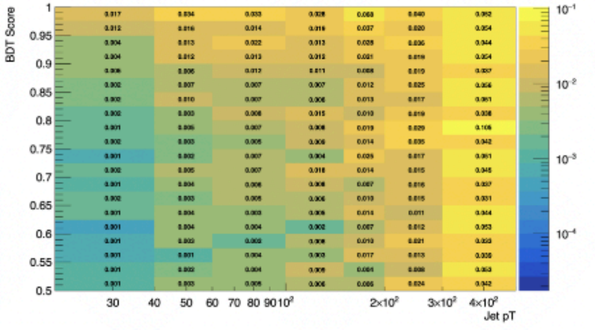
(a) Efficiency map for −6 < DL1r < 2



(b) Efficiency map for 2 < DL1r < 12



(a) Efficiency map for −6 < DL1r < 2



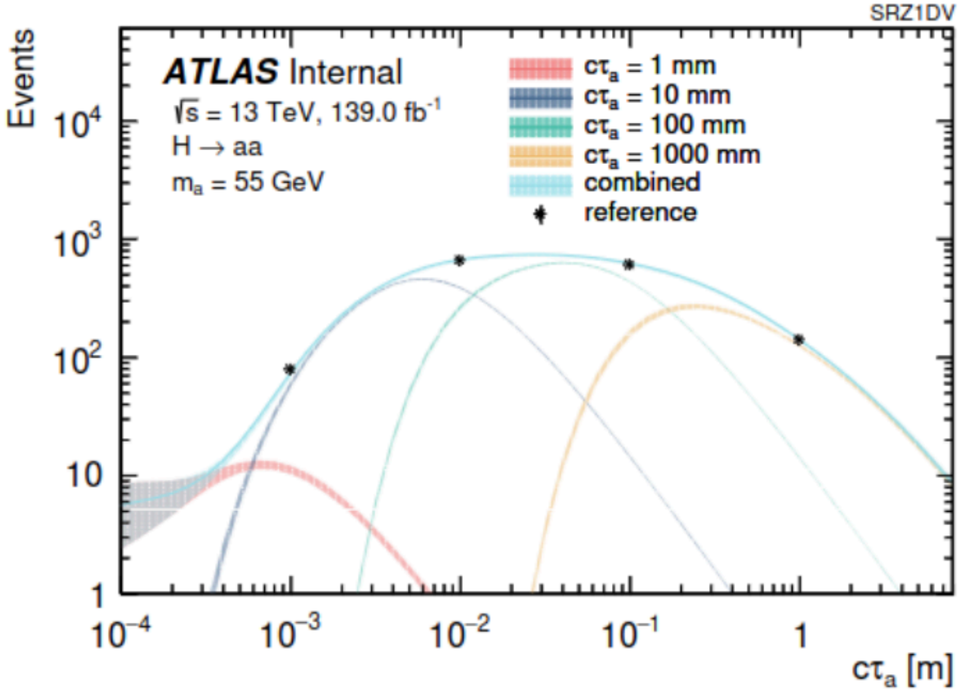
(b) Efficiency map for 2 < DL1r < 12

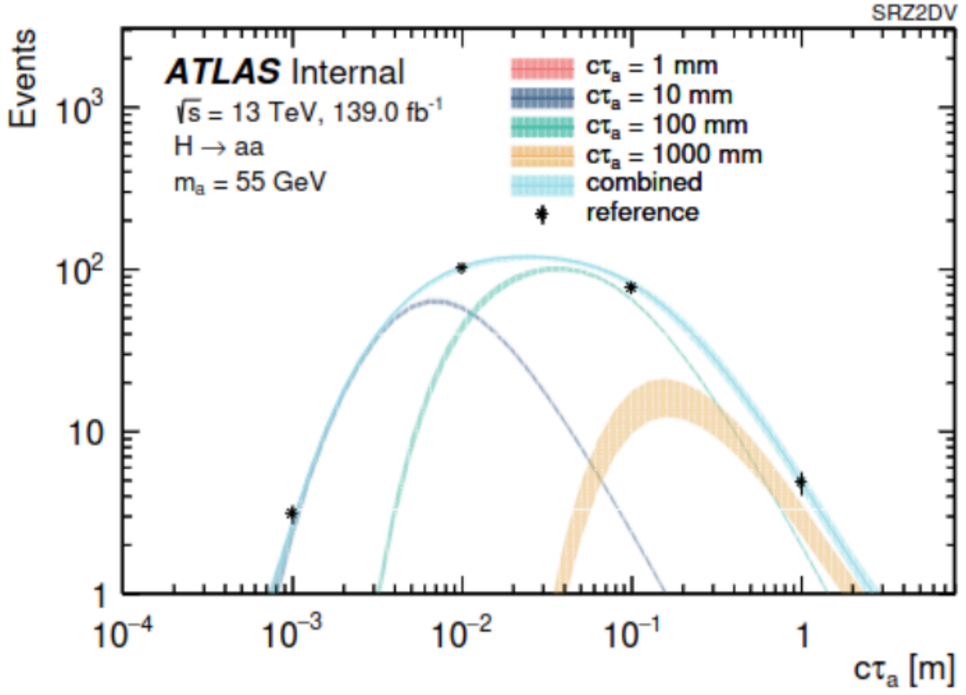
Lifetime reweighting

The analysis uses a *multi-sample* lifetime reweighting

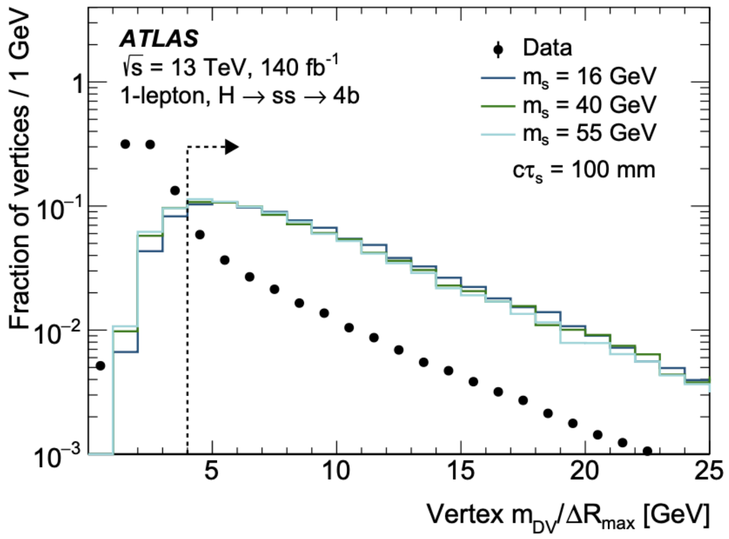
- Events from all generated lifetimes are combined to maximize statistical power
- "Critical lifetime" determines point at which one sample becomes dominant over the others

$$w_i = \frac{\tau_1}{\tau_2} e^{-\left(\frac{1}{\tau_2} - \frac{1}{\tau_1}\right) t_i}$$

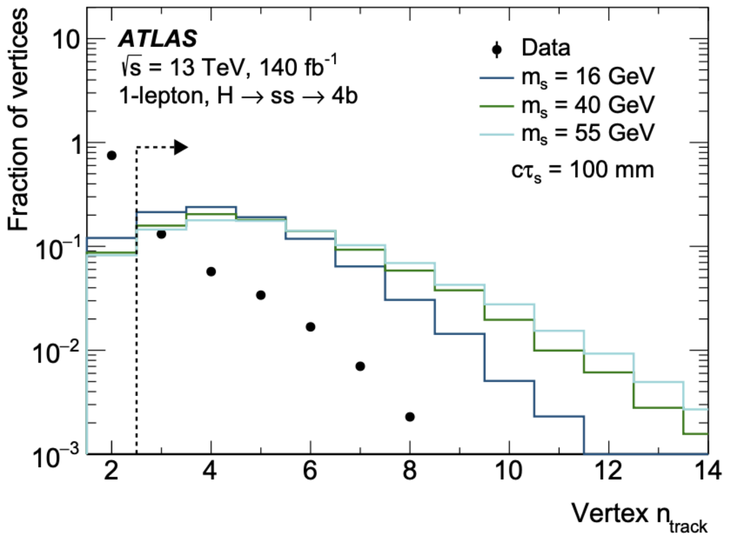




$$t_c = \frac{2 \ln\left(\frac{\tau_3}{\tau_1}\right)}{\left(\frac{1}{\tau_1} - \frac{1}{\tau_3}\right)}$$



(a)



(b)

Selection type	Parameter	Value
Vertex preselection	Material veto	True
	Max. χ^2/n_{DoF}	5
	Max. $\lvert z_{\mathrm{DV}}\rvert$	300 mm
Signal selection	Min. n_{trk}	3
	Min. $m/\Delta R_{\mathrm{max}}$	4 GeV
	Min. H_{T}	10 GeV
	Min. $d_{0,\mathrm{max}}$	3 mm
	Min. $d_{0,\mathrm{min}}$	0.1 mm
	Min. ΔR_{jet}	0.6

Figure 10: The distributions of (a) $m_{\mathrm{DV}}/\Delta R_{\mathrm{max}}$, and (b) n_{track}, in selected Higgs portal signal samples with $H \to ss \to 4b$ (solid lines) and in data (black points). DVs in events satisfying the 1-lepton control region selection are considered. The DVs are required to satisfy all selections described in the text, except the selection on the observable shown in each Figure. An arrow indicates the selection requirement that is applied to the observable. The distributions are normalized to unit area.