Search for **Long-Lived Particles** in **ATLAS** with **Displaced Vertex** Signatures in Multi-**Jet-Triggered** Events (DV+Jets)

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EDSU2022

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Outline

All results and plots in **ATLAS-CONF-2022-054**

- What on earth does this long title mean? (i.e. what is DV+Jets?)
- Physics Motivation and Signal Models
- Analysis Overview and Selections
- Backgrounds
- Unblinded Results
- Conclusion

What is DV+Jets?

- If BSM particle doesn't couple well with SM, has small mass splitting, or decays through off-shell mediator
  → **long-lived (LLP)**

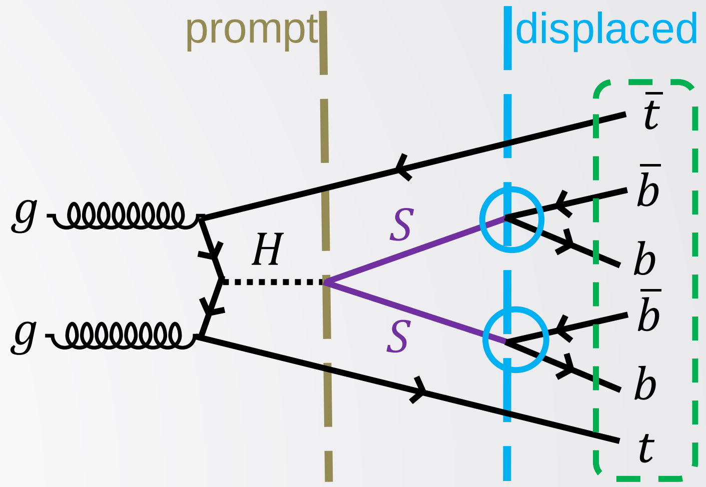
- If **decays into quarks** or several charged products
  →LLP gives **displaced vertex (DV)**

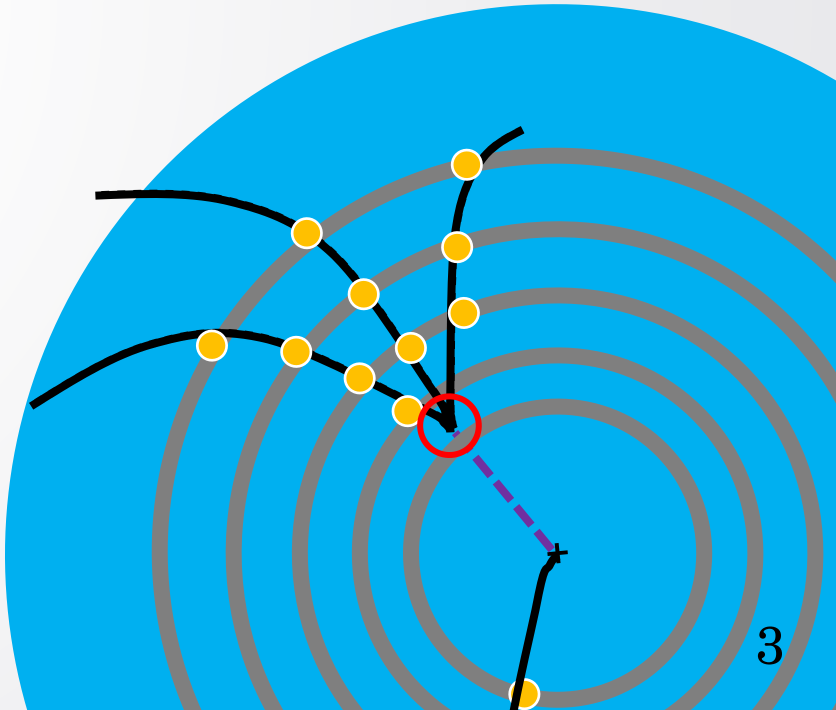
- Techniques for **reconstructing** long-lived BSM particles **improved** dramatically since Run 1.

- Triggering: **jets** can come from **initial or final state**

→ **DV+Jets searches for LLPs with DV signatures in events triggered by multi-jets**

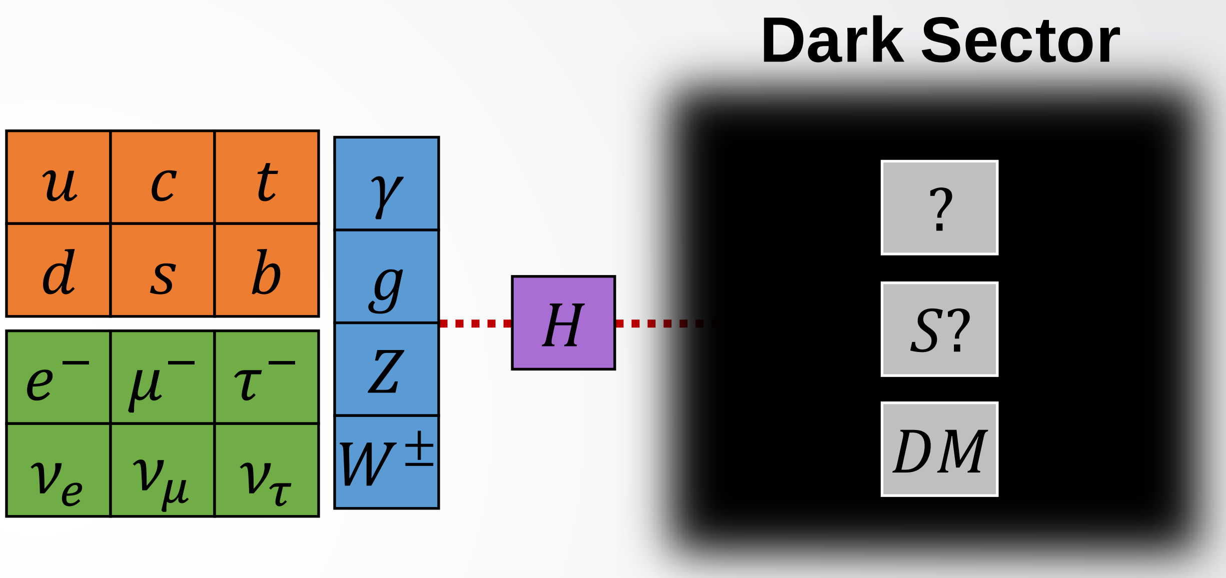
Be **inclusive** to as many models as possible:
Higgs portal & **RPV SUSY**



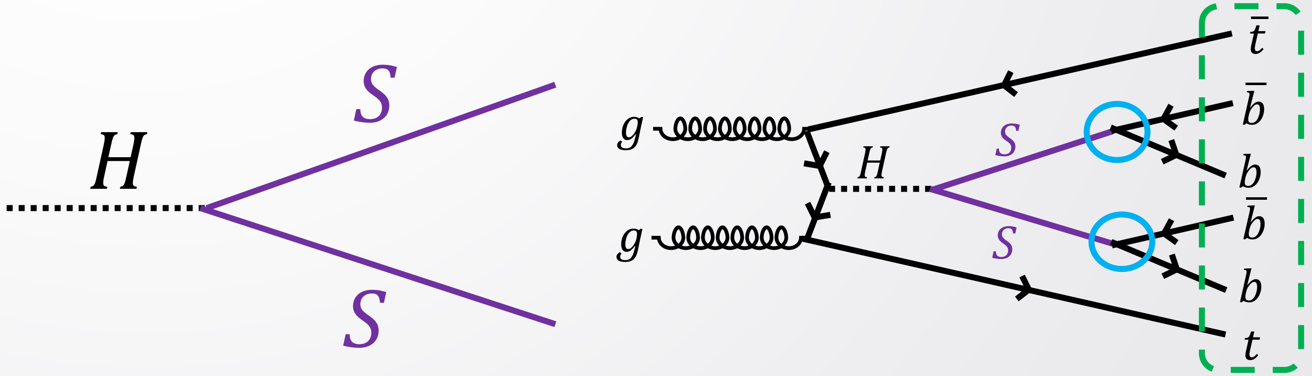


Higgs Portal Models

- Dark matter (DM) could have **higher generation particles**
- This "**dark sector**" (DS) should couple with the SM via the **Higgs** (i.e. a Higgs portal) if they have mass
- Therefore Higgs should be able to **decay into dark sector particle pairs**
- **Jets** from Higgs **production** process **and** DS particle **decay**



Higgs Portal



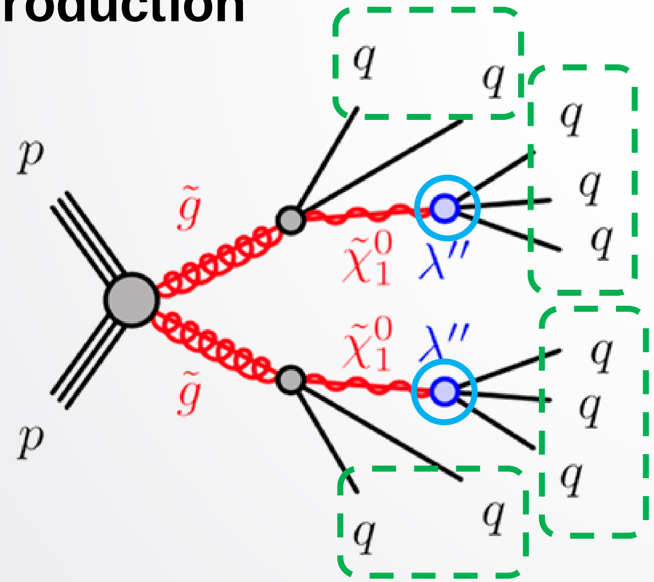
RPV SUSY Signal Models

- We are also sensitive to many models that predict LLPs with jets
- Particularly **R-Parity Violating SUSY**
- **Small RPV coupling → long-lived $\tilde{\chi}_1^0$**

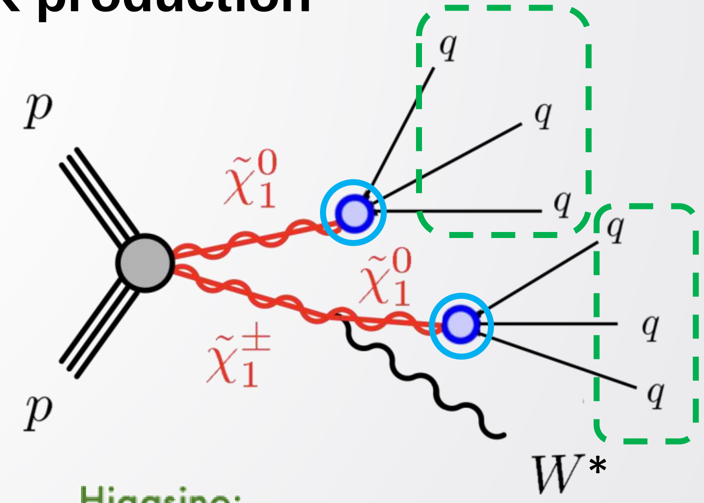
Strong production

Gluino:
$m_{\tilde{g}}$ = 1.6 - 2.6 TeV

Neutralino:
$m_{\tilde{\chi}_1^0}$ = 10 - 2550 GeV
$\tau_{\tilde{\chi}_1^0}$ = 0.01 - 10 ns



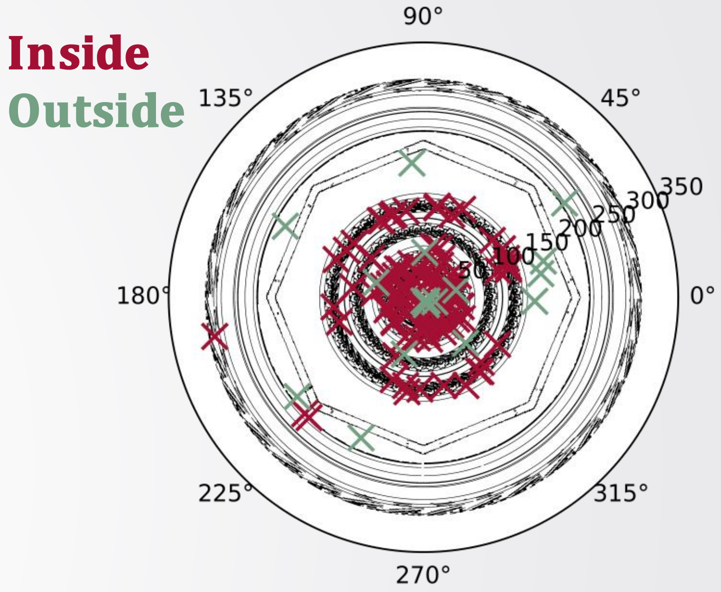
EWK production

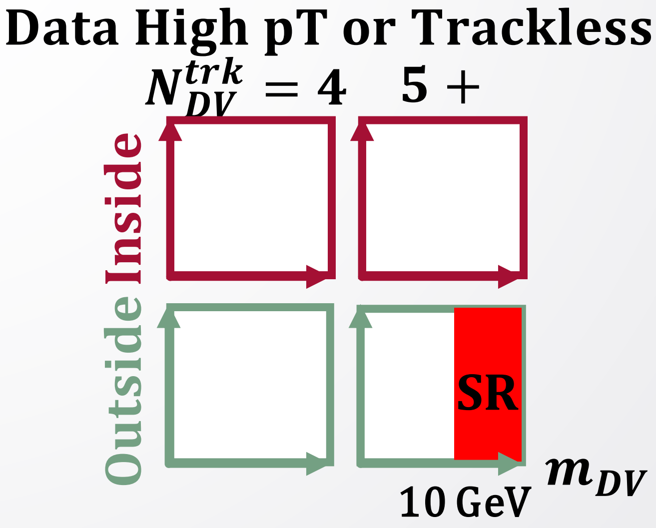


Higgsino:
$m_{\tilde{\chi}_1^0}$ = 100 GeV – 1700 GeV
$\tau_{\tilde{\chi}_1^0}$ = 0.01 - 10 ns

Analysis Overview and Selections

- **Full Run-2** dataset: 139 /fb
- **Multi-jet trigger**
- 2 SRs: **High pT** Jet and **Trackless** Jet signal regions [SR] (if jet is trackless, can lower jet pT req.)
- DVs must:
  - lie **outside** of detector material,
  - have **5+ tracks**,
  - invariant mass $m_{DV} > 10\ \mathrm{GeV}$





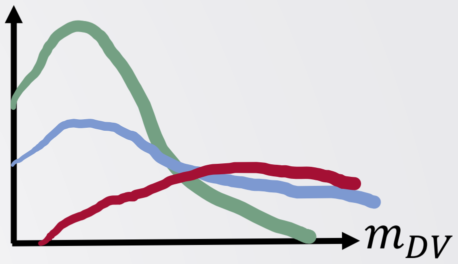
Combined Background Estimate

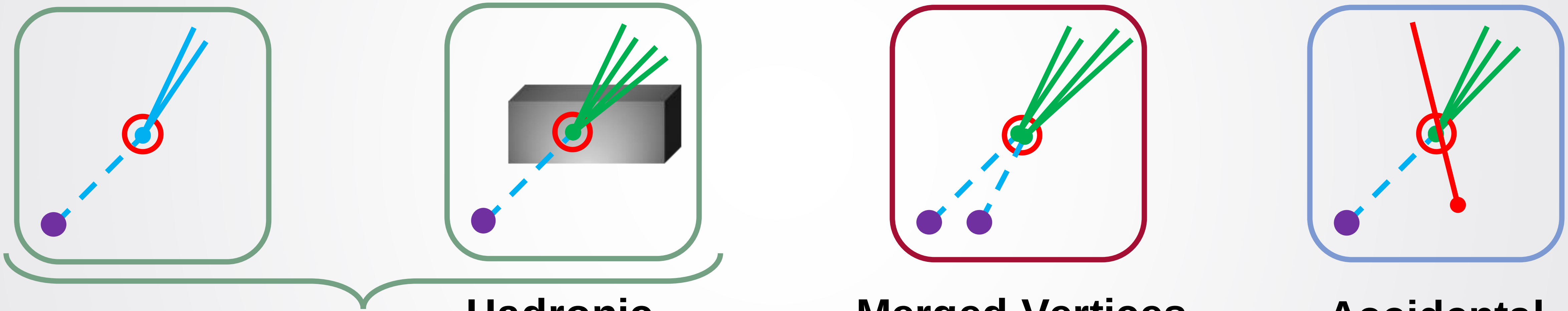
Generator Tracks

GEANT4 Tracks

True-Pileup Tracks

Fakes-Pileup Tracks





SM Decays

None in SR
(high mass,
high # tracks)

Hadronic Interactions (HI)

Dominates
low mass,
inside material

Merged Vertices (MV)

Primary in
high mass

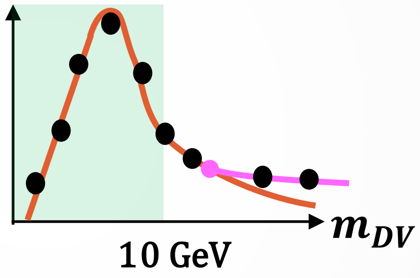
Accidental Crossings (AX)

Secondary in SR

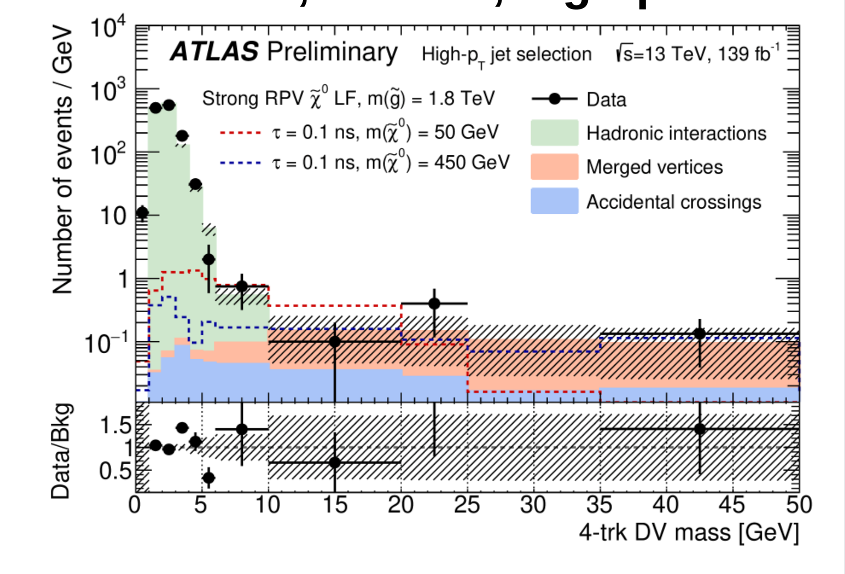
Combined Background Estimate – Cross-Check

Estimate three main sources of background individually and combine

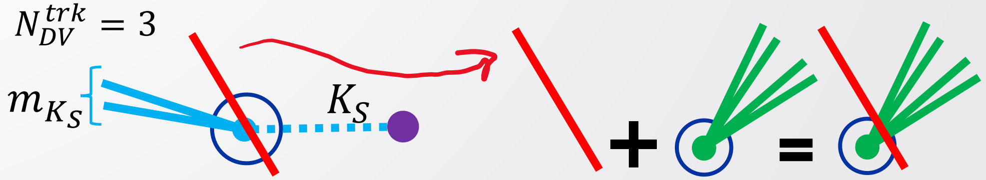
- **Hadronic Interactions (HI):** [normalisation data-driven]
  - Functional fit to $m_{DV} < 10$ GeV
  - Extrapolate with MC-based correction to $m_{DV} > 10$ GeV



Outside, N-trk=4, High pT SR



- **Merged Vertices (MV):** [fully data-driven]
  - Look at deficit of distance significance between pairs of DVs in same event vs different events
- **Accidental Crossings (AX):** [fully data-driven]
  - Add crossed tracks to DVs
  - Get rate from $K_S^0 \to \pi^+\pi^-$ decays with extra track



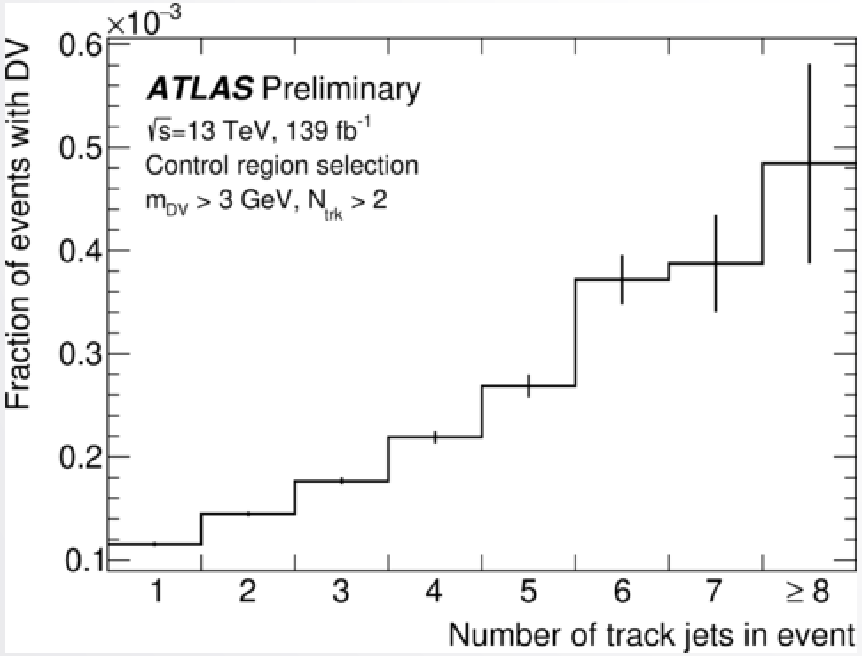
Inclusive Background Estimate

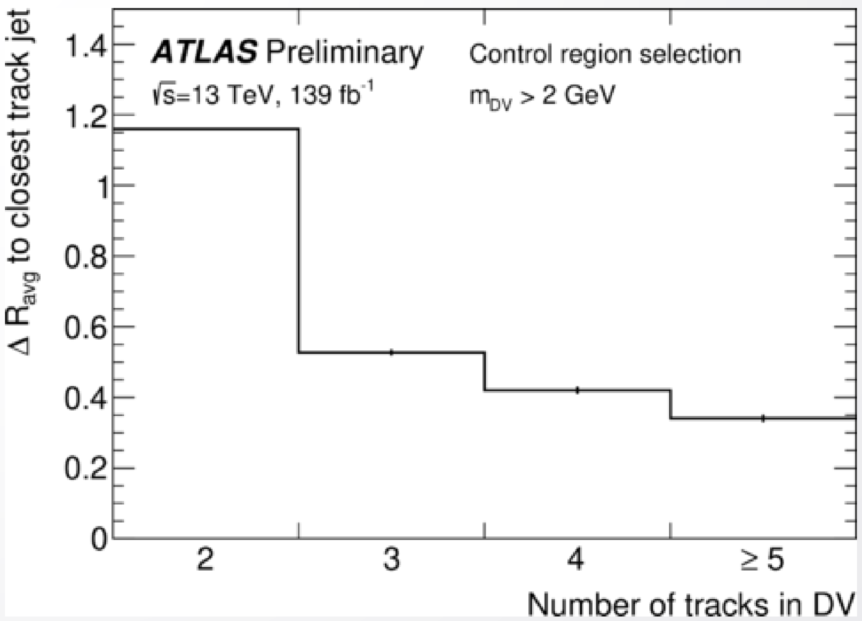
Alternative method. Combined and inclusive estimates cross-check each other.

- All sources of background correlated with prompt jets

→If know **# DVs per jet in control region** [CR], can take **# SR jets and estimate # DVs**

- Use **single photon trigger as CR** (no contamination from jetty signal)

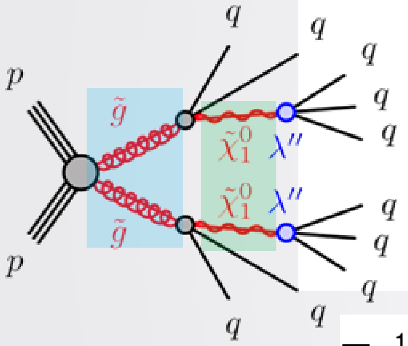


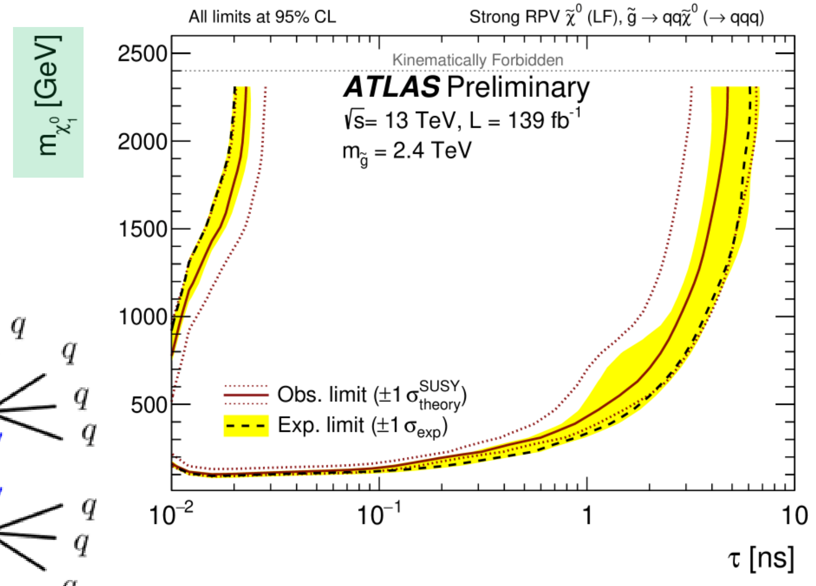


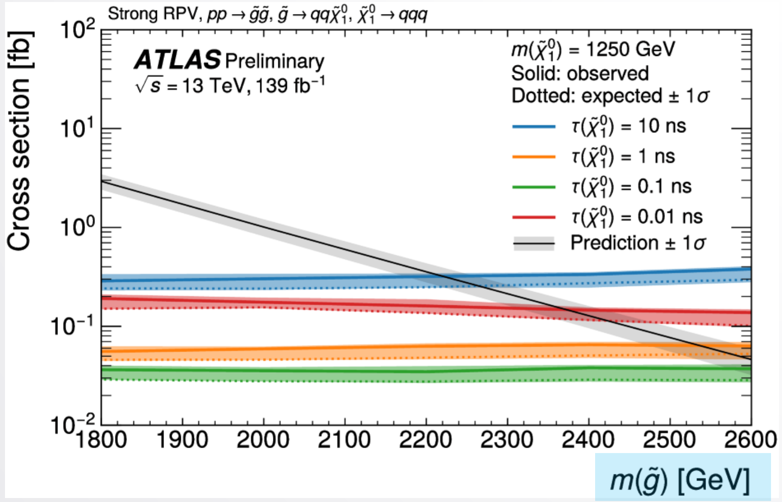
Results

Signal Region	Combined	Inclusive	Observed
High pT	1.08 ± 0.69	$0.46^{+0.27}_{-0.30}$	
Trackless	2.1 ± 1.1	$0.83^{+0.51}_{-0.53}$	

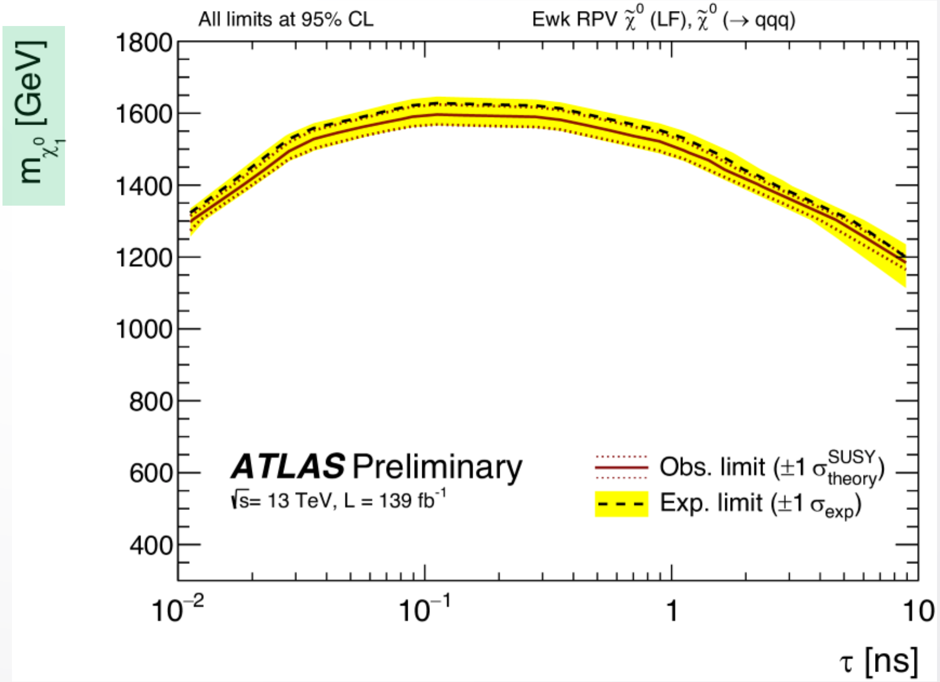
Results

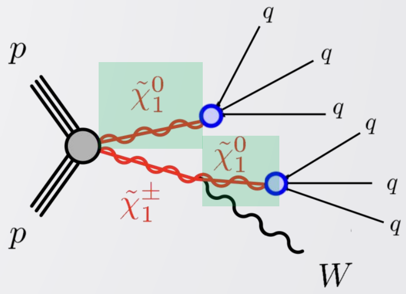






Signal Region	Combined	Inclusive	Observed
High pT	1.08 ± 0.69	$0.46^{+0.27}_{-0.30}$	1
Trackless	2.1 ± 1.1	$0.83^{+0.51}_{-0.53}$	0





Conclusions

- We searched for hadronically-decaying long-lived particles in the presence of many jets
- No significant excess observed
- Strict limits placed on the existence of such particles under two SUSY models
- Higgs portal interpretation still in progress
- Current public results here: **ATLAS-CONF-2022-054**

CERN

ATLAS EXPERIMENT

Thank You

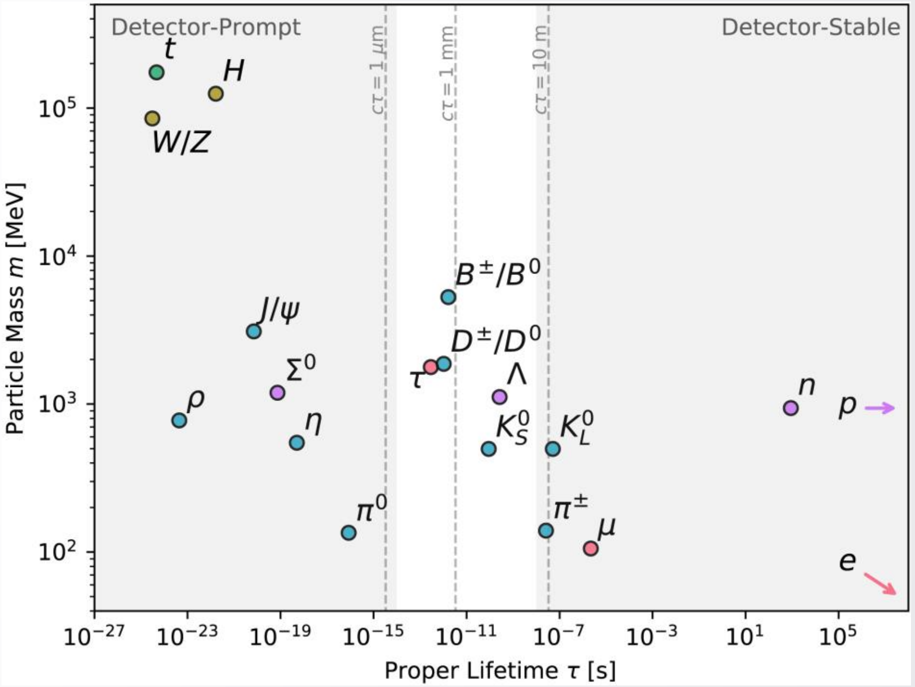
GATES Cambridge

UNIVERSITY OF CAMBRIDGE

Backup Concepts

Why long-lived particles?

- There are likely **undiscovered particles beyond the standard model** (BSM)
  - Hierarchy problem
  - Dark matter
- **No particular reason** for BSM particles to be restricted to lifetimes $\tau < \sim 10^{-14}\ s$ **["decaying promptly"]**
  - Assumption built into most regular collider searches (usually reconstruction or cleanings)
  - Many SM particles don't satisfy this
- → **We should check** the possibility that BSM particles we are looking for could be **"long-lived"**



https://doi.org/10.1016/j.ppnp.2019.02.006

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

1) Fewer possible decay modes

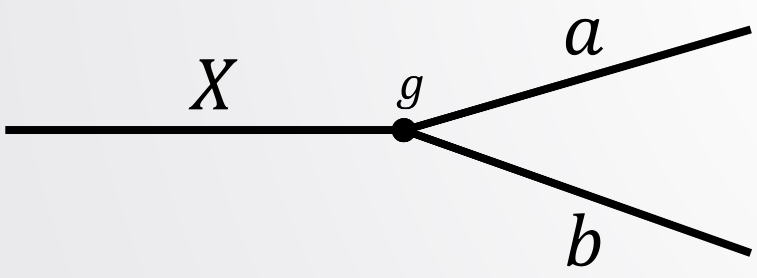
2) Less phase space (small mass-splitting)

3) Small coupling between particles

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

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

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



$$M \propto g$$

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

1) Fewer possible decay modes

2) Less phase space (small mass-splitting)

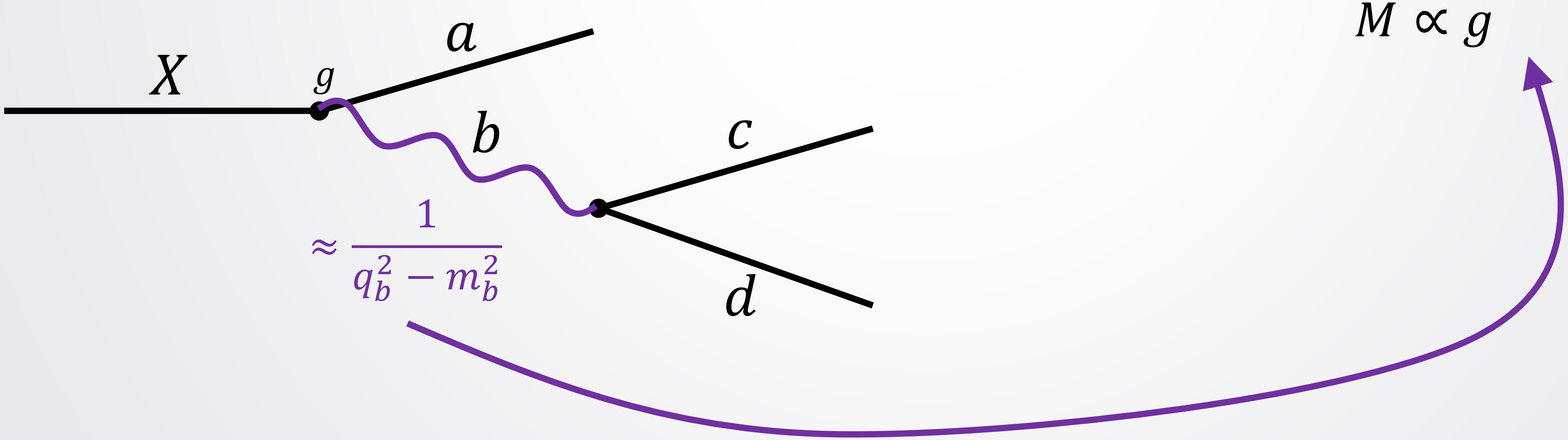
3) Small coupling between particles

4) Very off-shell intermediary

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

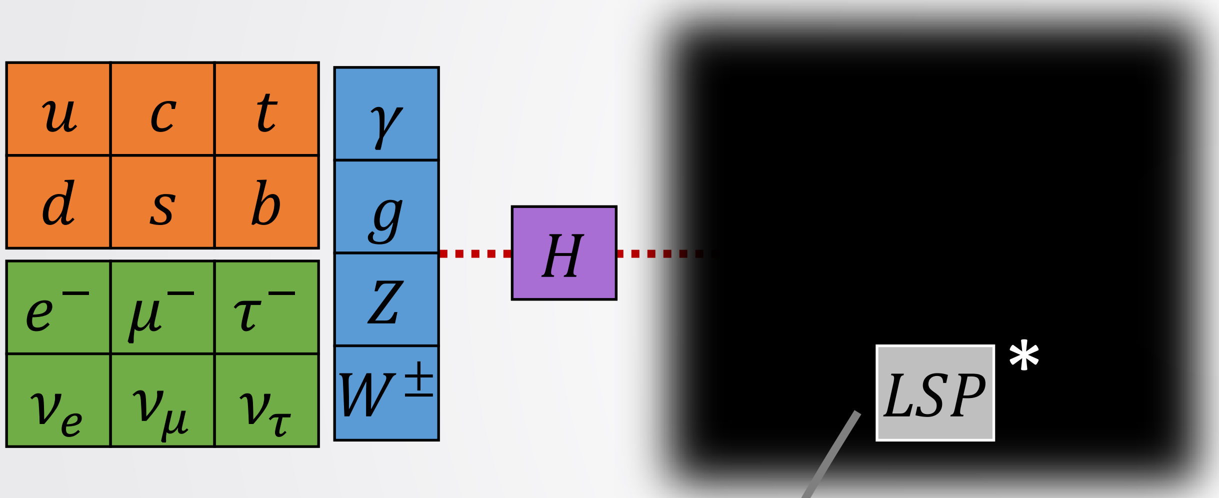
$$\Gamma_{\text{decay mode}} \propto |M|^2$$

$$M \propto g$$

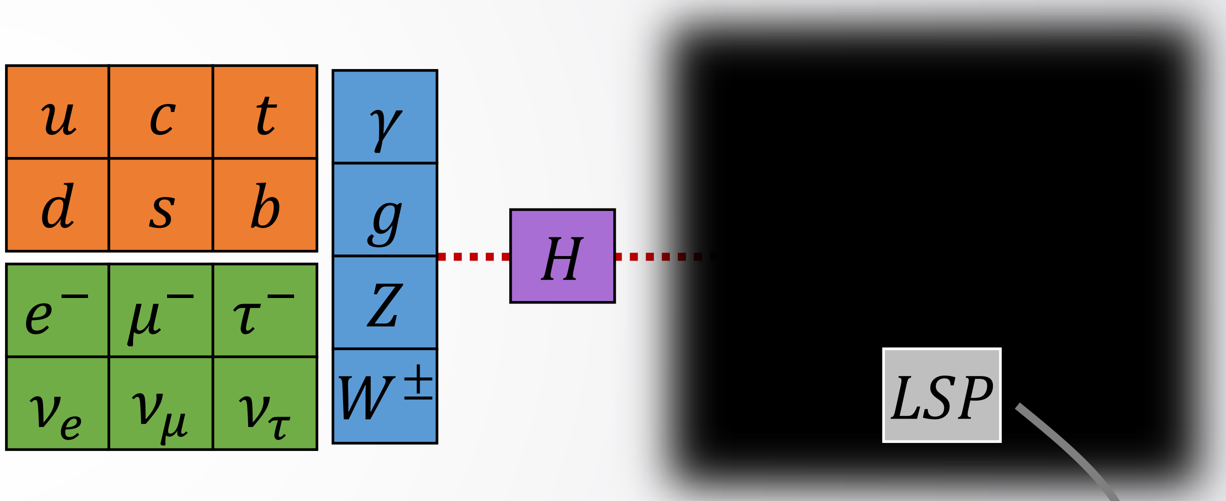


Benchmark Models: SUSY vs. Scalar Portal

SUSY



Scalar Portal

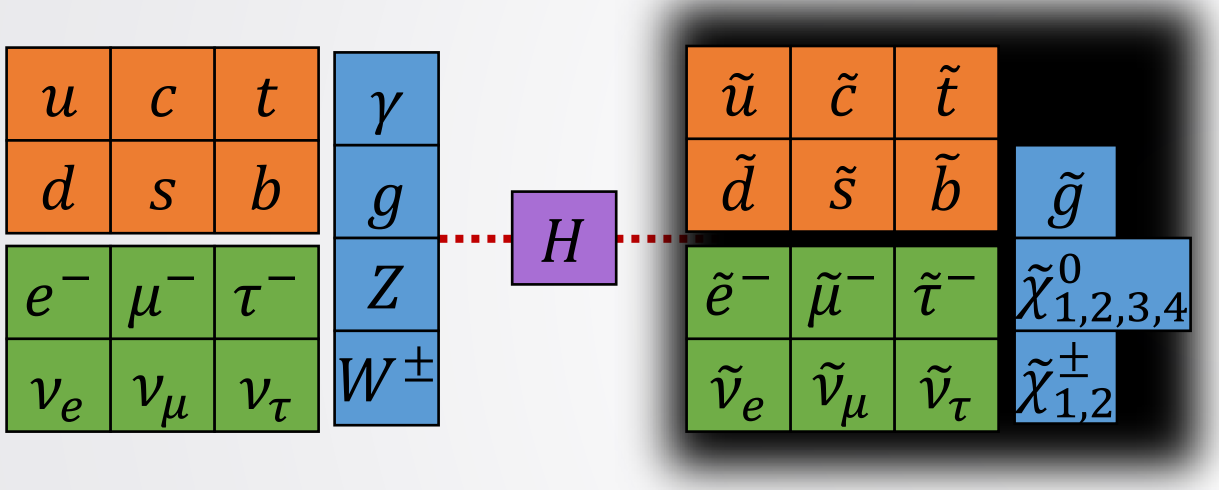


Lightest Stable Particle
=
Dark Matter Candidate

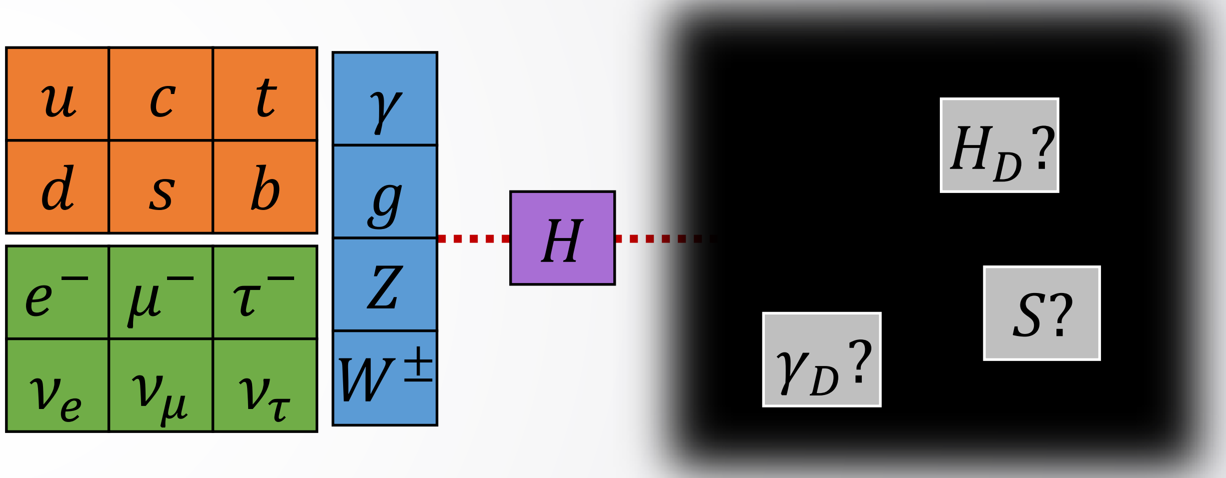
*Except R-parity violating SUSY

Benchmark Models: SUSY vs. Scalar Portal

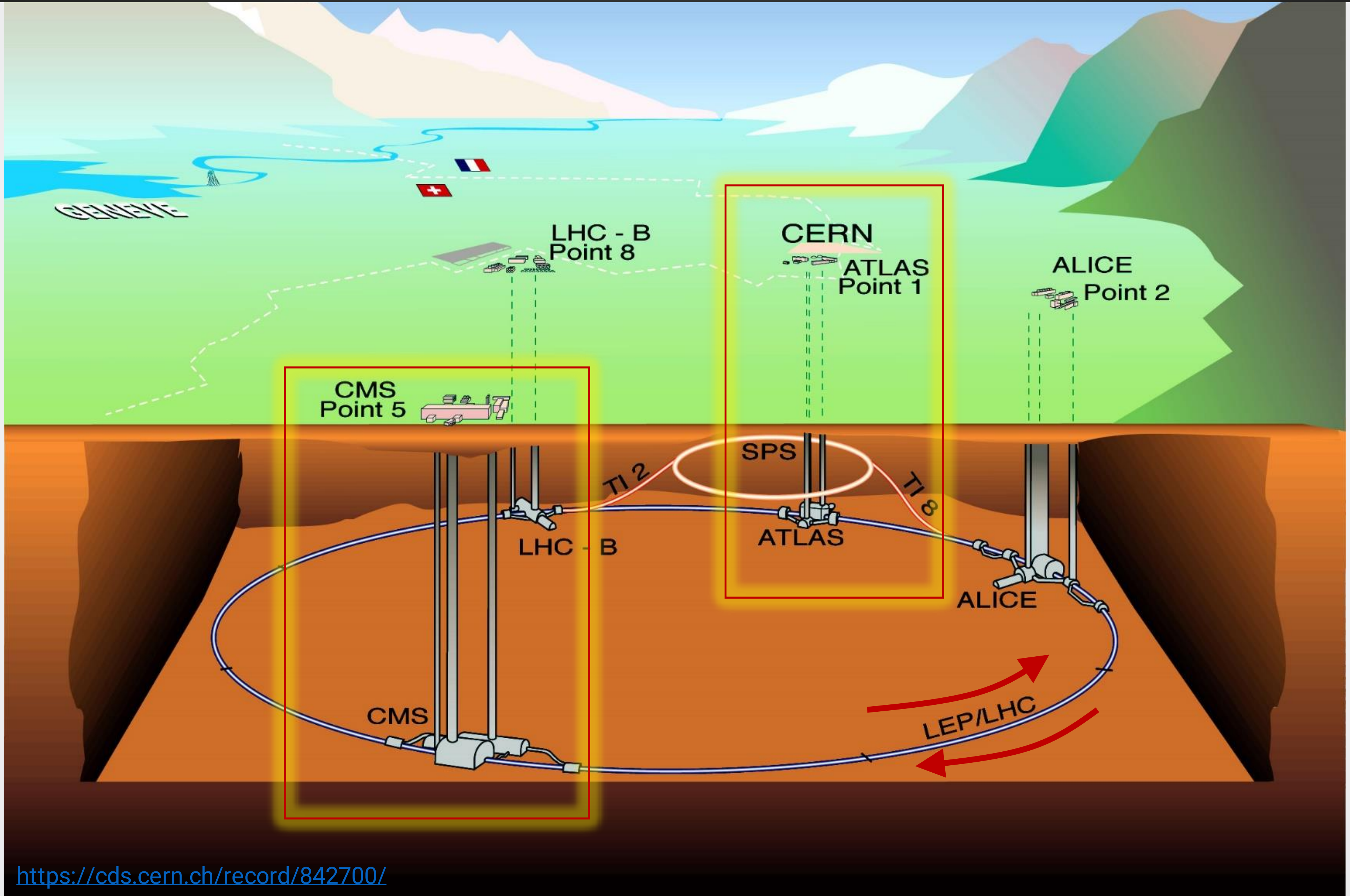
SUSY



Scalar Portal

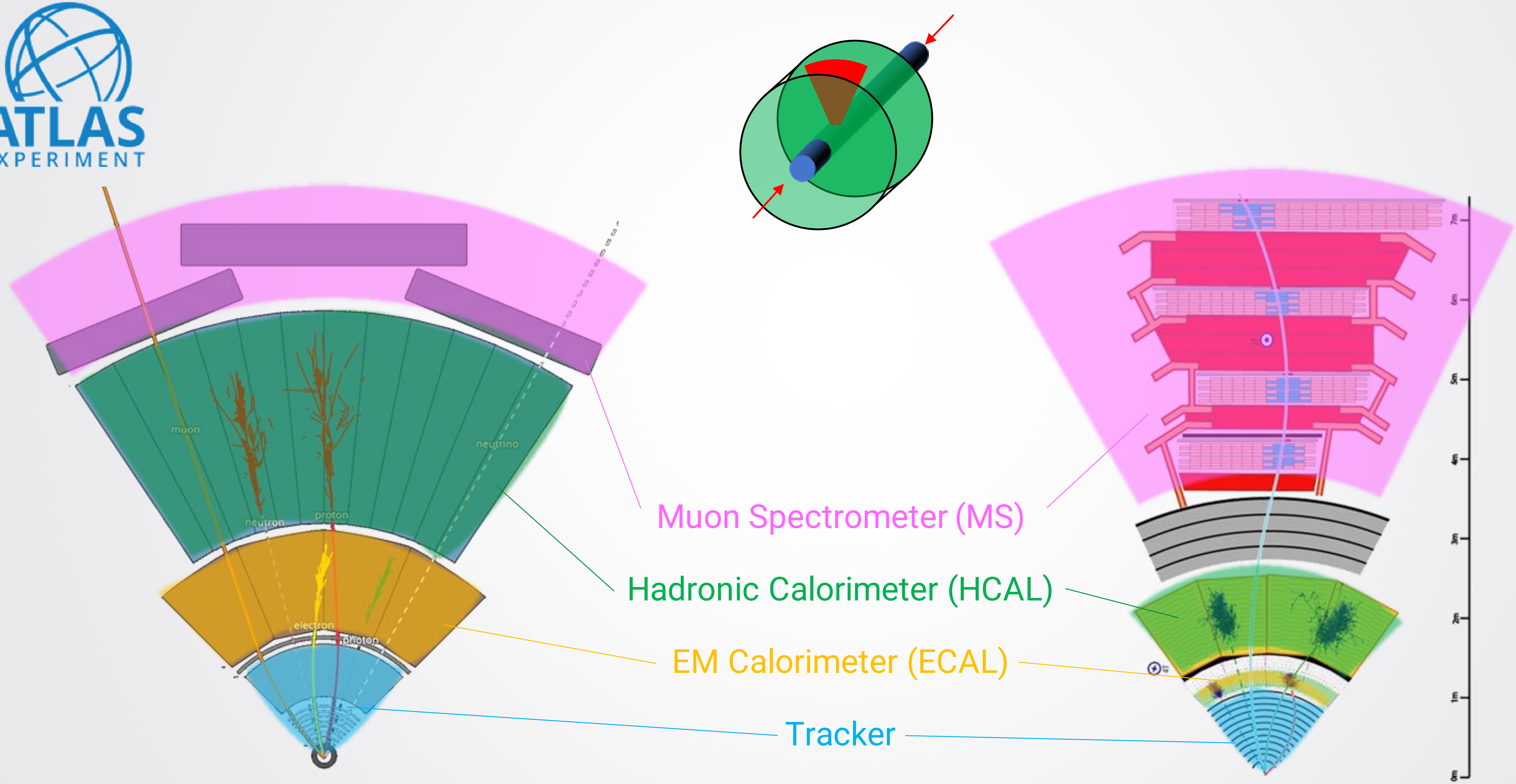


Context on the LHC Experiments



https://cds.cern.ch/record/842700/

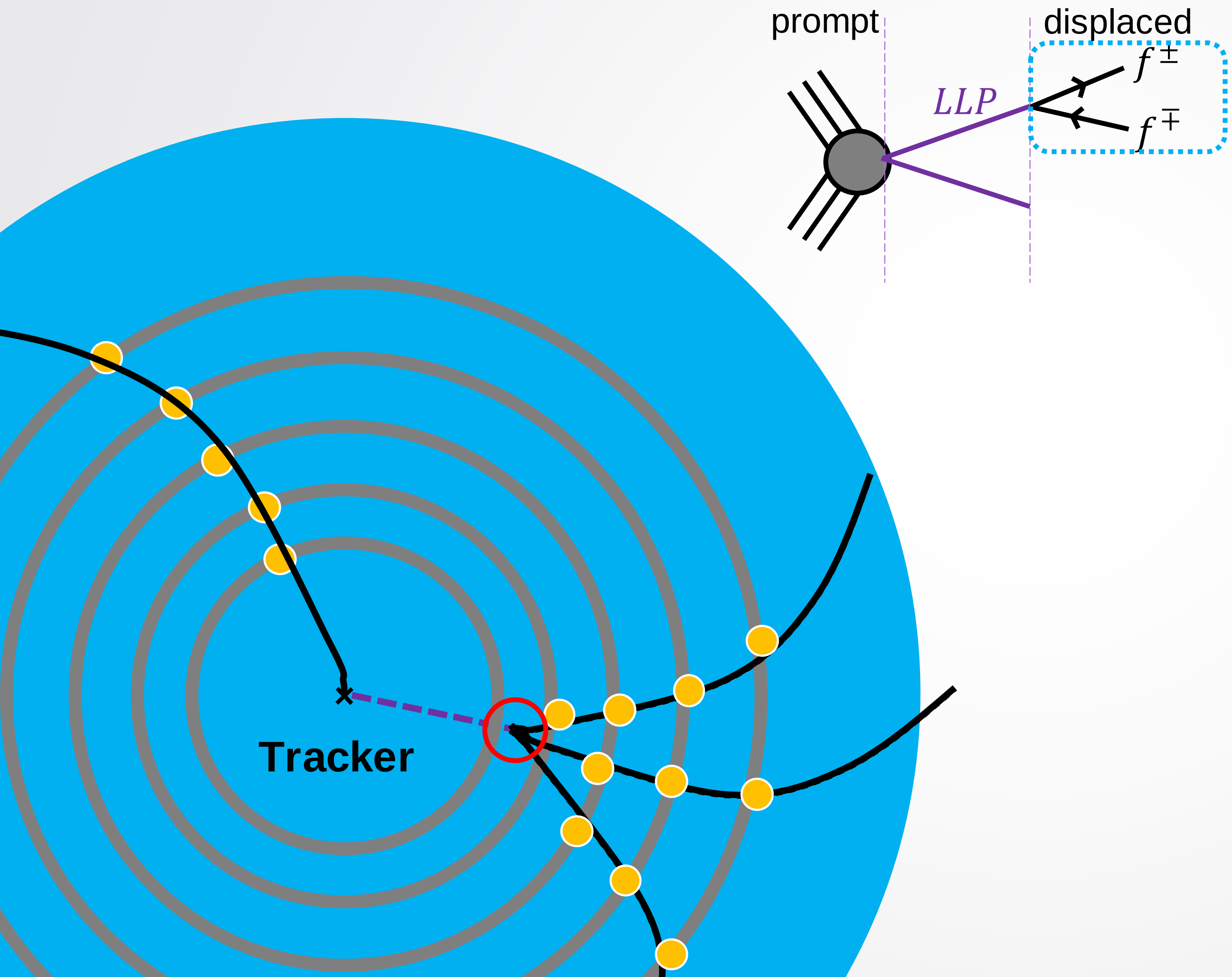
Context on ATLAS and CMS



https://cds.cern.ch/record/1505342

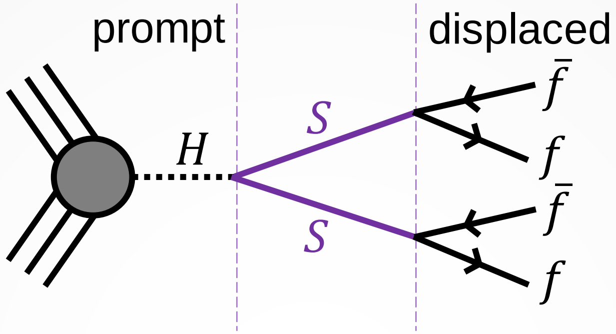
https://cds.cern.ch/record/2204863/

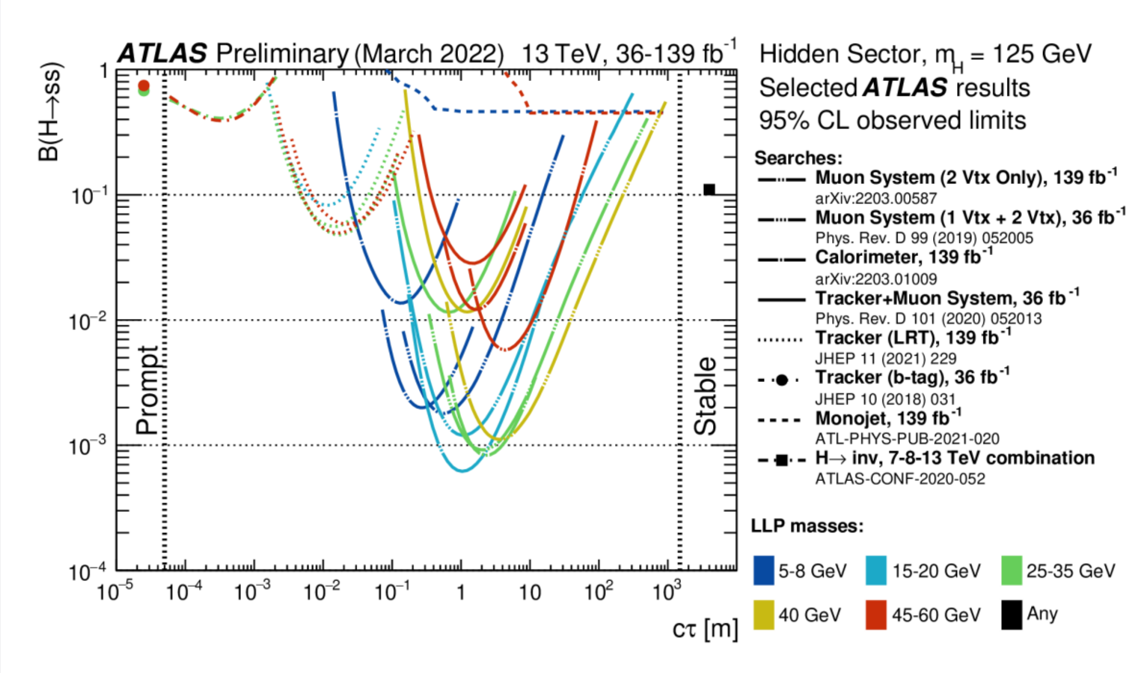
LLP Signatures in the Tracker

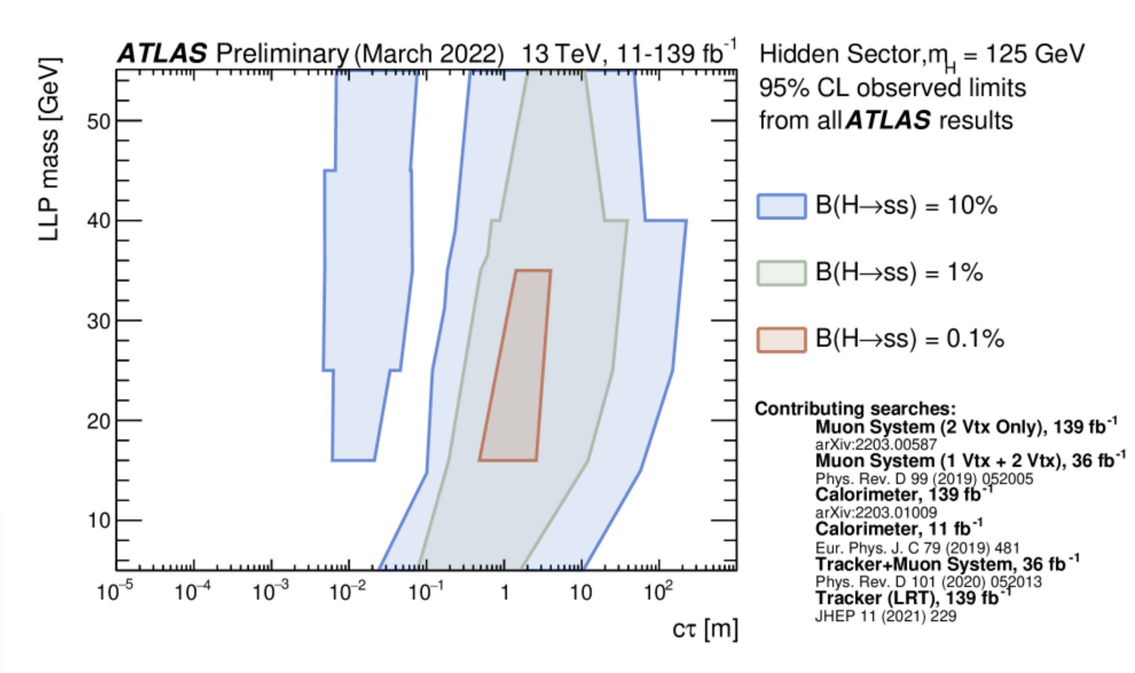


- Can target:
  - **LLP itself** (disappearing track [ATLAS, CMS])
  - or **decay products**
- LLPs decaying to charged particles:
  - Don't see anything: need to run **large radius tracking (LRT)**!
  - **Displaced vertex** (#trks, inv. mass, location)
- Backgrounds include:
  - SM decays
  - Hadronic interaction of SM particle with material (HI)
  - Accidentally crossed tracks
  - Vertices accidentally merged together can affect analysis

Some Existing Results [Higgs Portal]







https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-007/

Backup Analysis Info and Plots

Special Reconstruction for DVs

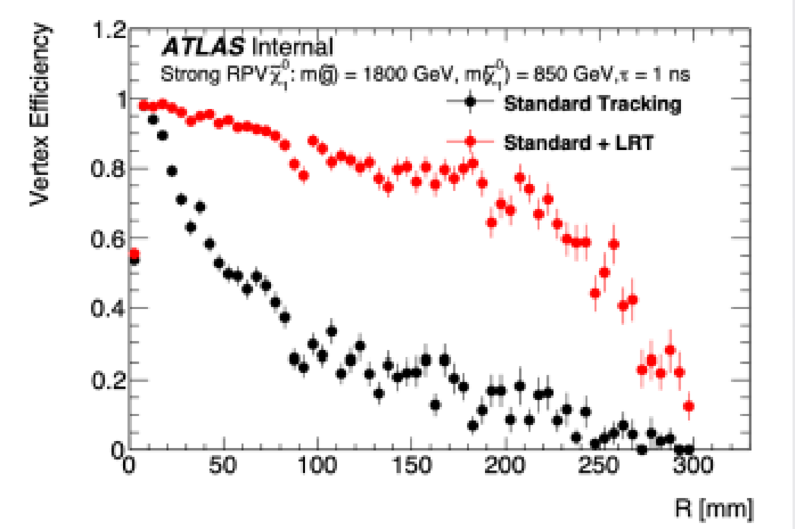
We use 2 special reconstruction algorithms

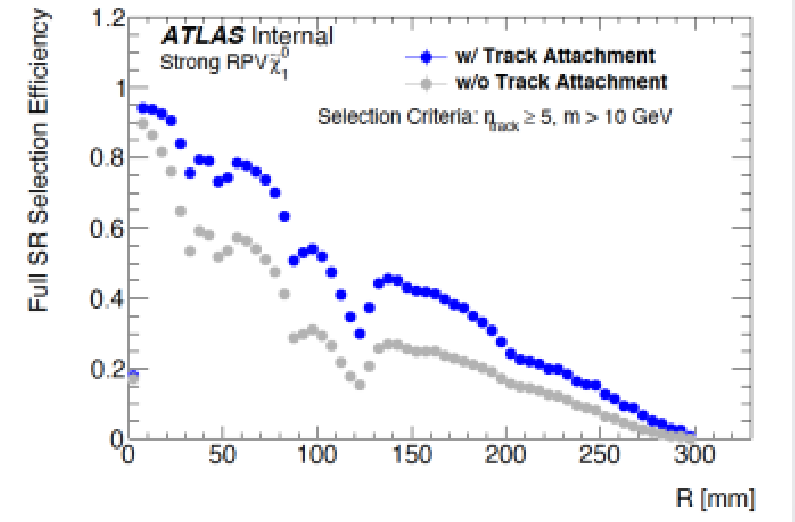
1) Large radius tracking (LRT) [ATL-PHYS-PUB-2017-014]

- Similar to standard tracking, but loosen requirements on impact parameters
- Computationally expensive, run in reco step (DRAW)

2) Secondary vertexing [ATL-PHYS-PUB-2019-013]

- Run in derivation step (SUSY15)
- Input: standard AND LRT tracks
- Algorithm:
  1) Form 2-trk seed vertices with high-quality tracks
  2) Merge to form N-trk vertices
  3) Lower-quality tracks **attached** to vertices





SRs and Event Selections

Two cut-and-count signal regions:

- **High pT SR:** Events must
  - Pass High-pT baseline jet selection
  - Contain ≥1 DV passing the DV selection
- **Trackless SR:** Events must
  - Pass Trackless baseline jet selection
  - Fail the High-pT baseline jet selection
  - Contain ≥1 DV passing the DV selection

Apply jet selections to offline-calibrated jets that are ~98% efficient wrt. Trigger and DRAW filters

$$\text{High-pT} = \begin{cases} 4j250 \\ 5j195 \\ 6j116 \\ 7j90 \end{cases}$$

$$\text{Trackless} = \begin{cases} 4j137 \\ 5j101 \\ 6j83 \\ 7j55 \end{cases} \quad \& \quad \begin{cases} 1(\text{trackless jet})78 \\ 2(\text{trackless jets})56 \end{cases}$$

$$\sum_{trks\ assc.w.jet} p_T < 5\ \text{GeV}$$

DV and Track Selections

No SM process produces a **high-mass DV**

Final DV selection: m_{DV}>10 GeV, N_{trk}≥ 5, N_{trk}^{sel}≥ 2

N_{trk}: # all tracks; N_{trk}^{sel}: #non-attached tracks

Baseline DV selections:

- χ^2/N_{dof}< 5 → (good quality)
- R_{DV} < 300 mm and $|z_{DV}|$ < 300 mm → (fiducial volume)
- > 4 mm from any PV in the event → (displaced)
- Pass strict material veto → (not in detector material [removes 48% of fiducial volume])

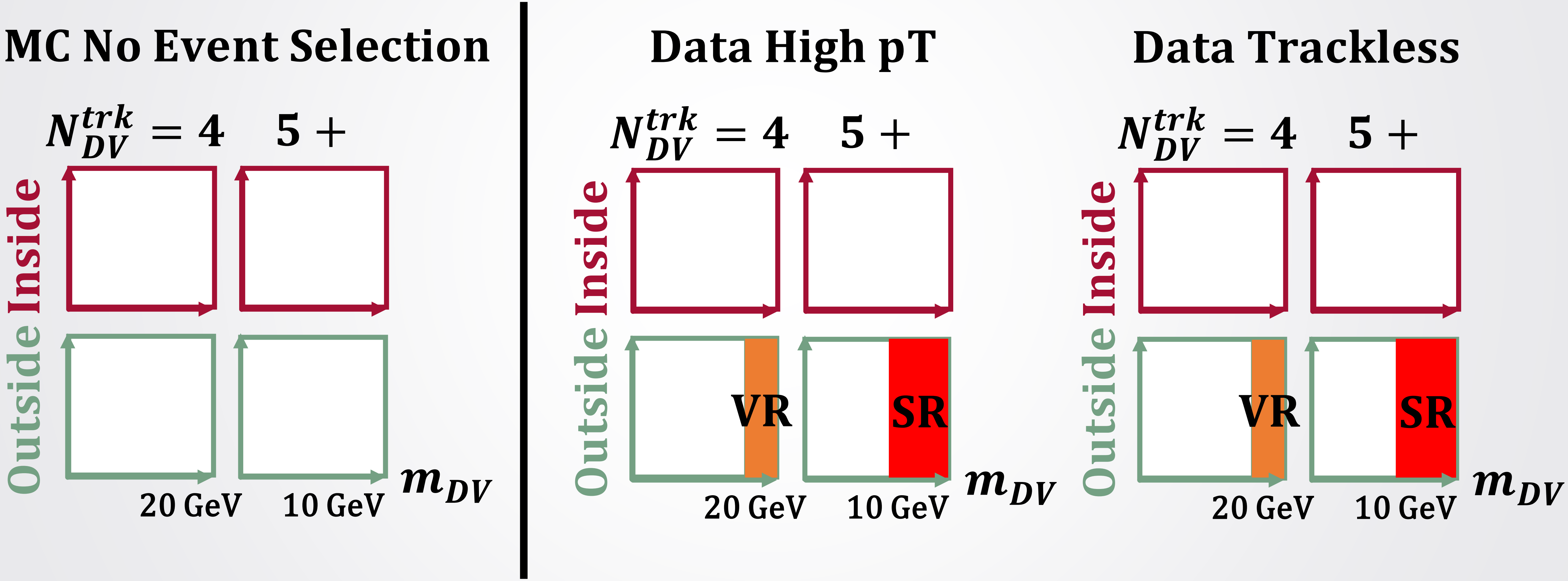
DV-trks must pass a track cleaning to be counted at all:

Depends on r_{DV} and whether or not track is attached

- p_T > 2-4 GeV
- d_0-significance > 10-15
- Angular requirements
- Hit pattern requirements

Chosen to reduce background to ~1 event in each SR

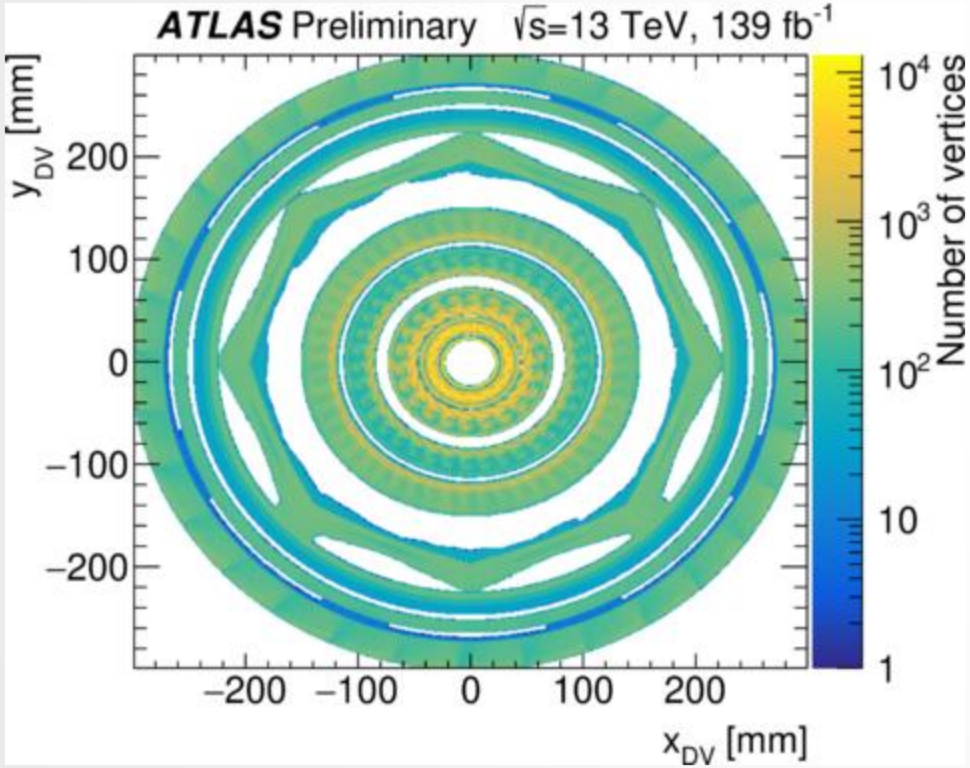
Summary of Regions

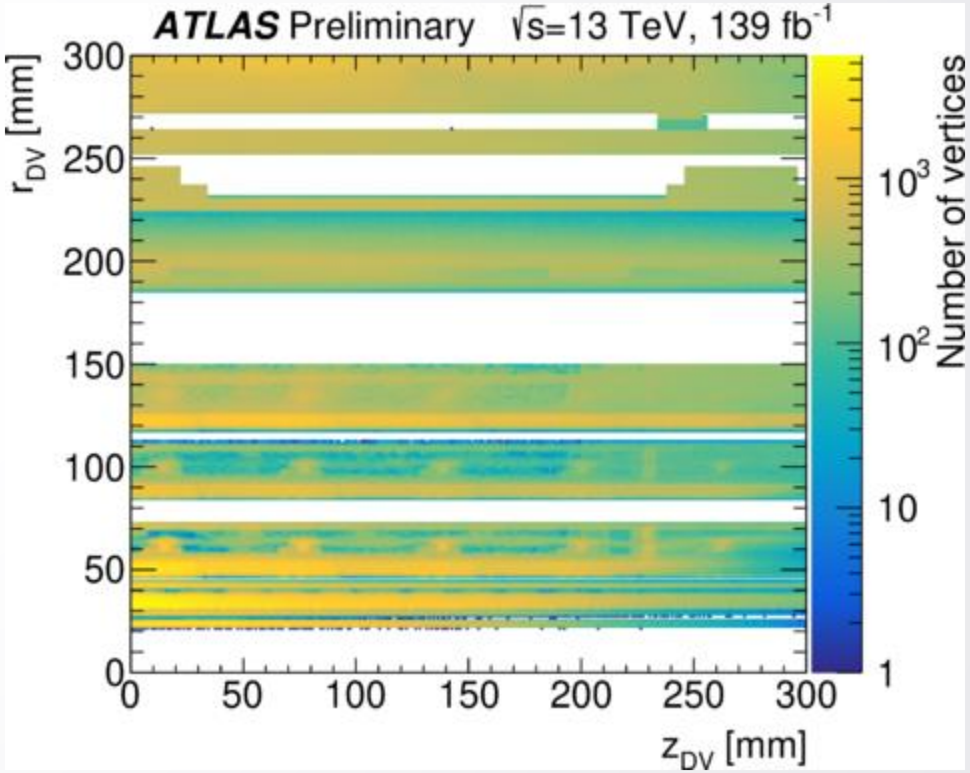


(Inside/outside refers to inside/outside detector material according to a material map veto)
(VR shown is only the blinded VR. Various other regions used as unblinded VRs)

Material Map

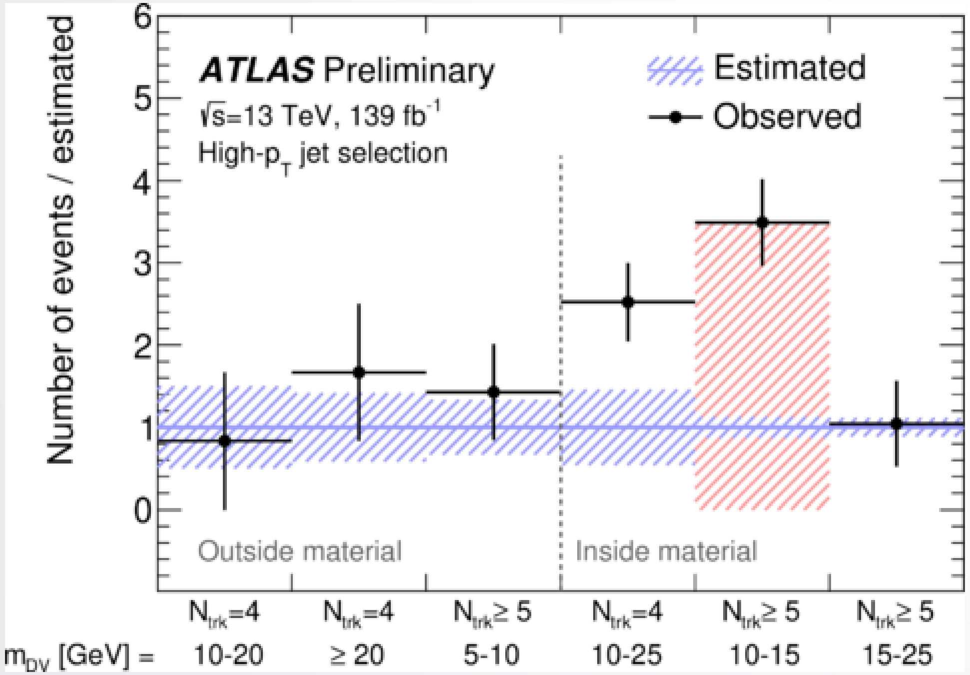
- This shows DVs vetoes by the map

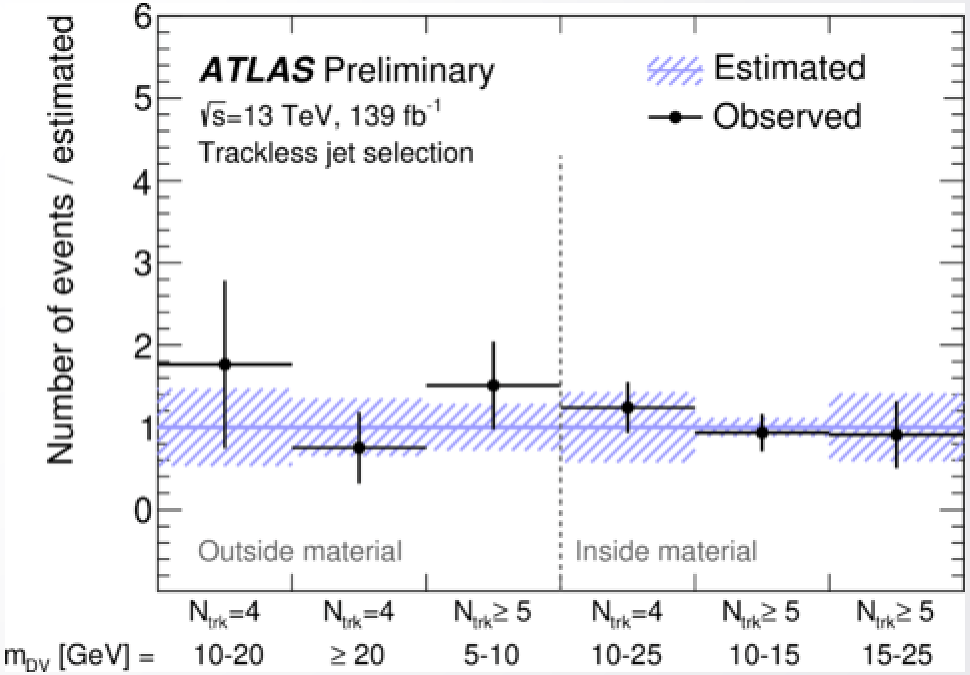




Inclusive Background Estimation Validation

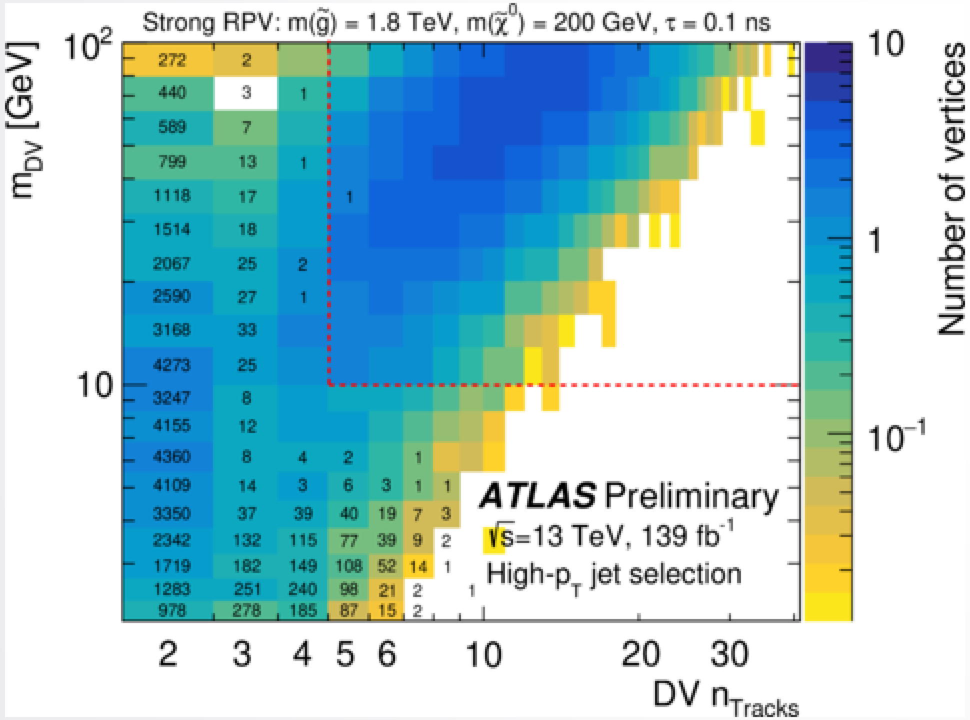
- The blue error bands includes all systematic uncertainties.
- The uncertainty based on observed non-closure in the Inside material VR is separately shown in red.

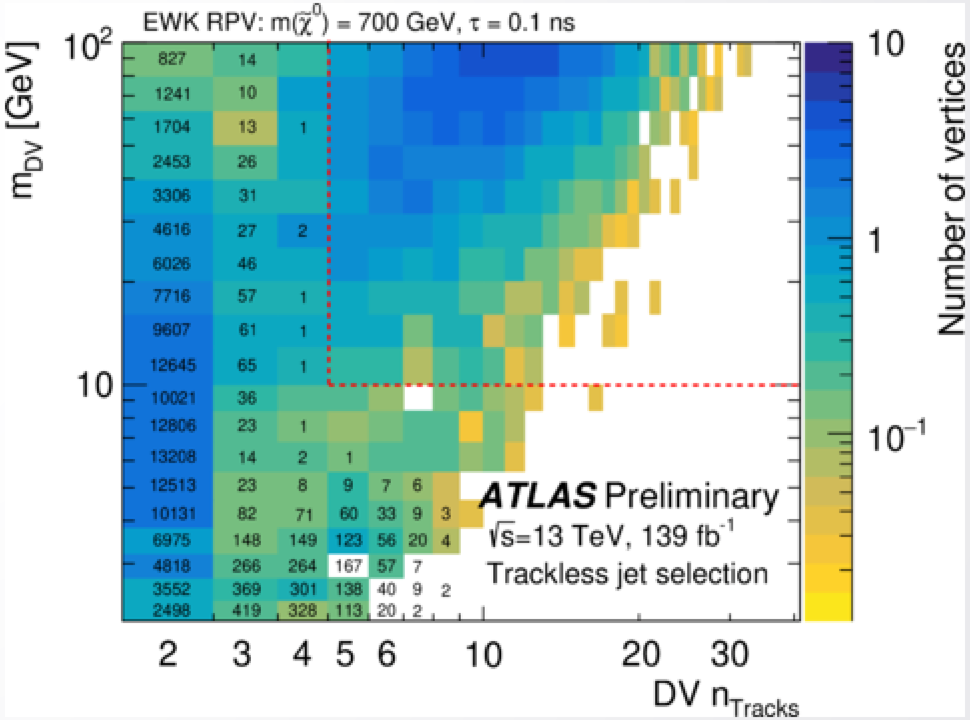




Results

- Colour is signal yield, number is actual data number





Cleanings and Selections

	Region	$0 < R_{DV} < 25$ mm	$25 < R_{DV} < 145$ mm	$R_{DV} > 145$ mm
Attached tracks	Track p_T [GeV]	> 2	$> 3^{\dagger}$	> 4
	Track d_0-significance	> 10	> 15	-
	$\Delta\phi_{PV-DV}$	$< \pi/2$		
	Upstream veto	No hits allowed with $R < R_{DV}$		
Selected tracks	Track p_T [GeV]	> 2	$> 2^{\dagger}$	> 2
	Track d_0-significance	> 10	-	> 10
	Upstream veto	No hits allowed with $R < R_{DV}$		

†: the requirement is tightened to $p_T > 4$ GeV for tracks with $\Delta\phi_{PV-DV} < 0.2$

Signal Region	High-p_T jet SR	Trackless jet SR
Jet selection	$n_{jet}^{250} \geq 4$ or $n_{jet}^{195} \geq 5$ or $n_{jet}^{116} \geq 6$ or $n_{jet}^{90} \geq 7$	Fail high-p_T jet selection, $n_{jet}^{137} \geq 4$ or $n_{jet}^{101} \geq 5$ or $n_{jet}^{83} \geq 6$ or $n_{jet}^{55} \geq 7$, $n_{trackless\ jet}^{70} \geq 1$ or $n_{trackless\ jet}^{50} \geq 2$
DV pre-selection	$R_{DV} < 300$ mm, $\lvert z_{DV} \rvert < 300$ mm, $\min(\lvert \vec{r}_{DV} - \vec{r}_{PV} \rvert) > 4$ mm, $\chi^2/n_{DoF} < 5$, $n_{Selected\ tracks}^{DV} \geq 2$, pass material map veto	
n_{Tracks}^{DV}	≥ 5	
m_{DV}	>10 GeV	

Background Estimates

Signal Region	Observed	Expected	S^{95}_{obs}	S^{95}_{exp}	$\langle\sigma_{\text{vis}}\rangle^{95}_{\text{obs}}$ [fb]
High-p_{T} jet SR	1	$0.46^{+0.27}_{-0.30}$	4.5	$4.0^{+0.7}_{-1.4}$	0.032
Trackless jet SR	0	$0.83^{+0.51}_{-0.53}$	3.3	$4.4^{+0.6}_{-0.4}$	0.024

Region	Merged vertices	Hadronic interactions	Accidental crossings	Combined
High-p_{T} jet SR	0.79 ± 0.66	0.006 ± 0.018	0.28 ± 0.21	1.08 ± 0.69
Trackless jet SR	1.5 ± 1.1	0.248 ± 0.077	0.32 ± 0.24	2.1 ± 1.1

Background Uncertainties

- "CR statistical“: propagation of statistical variations from CR->SR
- "Non-linearity“: residual dependence of jet-DV probability on amount of jet activity in event
- "VR non-closure“: from inside of material validation regions.
- "Pileup": reweighting events in CR to match SR pileup distribution

Region	Uncertainty source			
	CR statistical	Non-linearity	VR non-closure	Pileup
High-p_T jet SR	$\pm$ 58%	$^{+10\%}_{-27\%}$	$\pm$ 4%	$\pm$ 5.9%
Trackless jet SR	$\pm$ 58%	$^{+6.3\%}_{-17\%}$	-	$\pm$ 20%

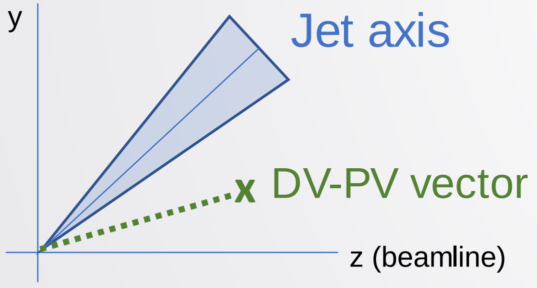
Source of uncertainty	Relative impact signal yield [%]	
	Gluino pairs	Electroweakino pairs
Total	17–20	20–31
Tracking and vertex reconstruction	14–17	
ISR modeling in MC simulation	< 1	1–24
Jet energy scale and resolution	1	10
Integrated luminosity of dataset	1.7	

Inclusive Estimate Procedure (1)

1. Measure jet-DV correlations in low n-jet control region of data (single photon trigger, fail jet requirements of SR)

In control region of data, match each DV to closest track jet:

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



Calculate Prob(DV | track jet) as a function of track jet properties

Number of jets matched to a DV

$$P = \frac{N_{DV}}{N_j}$$

Number of jets

Inclusive Estimate Procedure (2)

1. Measure jet-DV correlations in low n-jet control region of data (single photon trigger, fail jet requirements of SR)

2. Use track jets in events passing SR jet requirements to estimate expected background:

$$N_{DV}^{SR} = f \cdot \sum_{bins} P(DV|jet) \cdot N_{jets,bin}$$

Prob (DV | jet) × Events passing SR jet selection

$$f = \frac{N_{\text{Event}}(m > 10\text{ GeV}, N_{\text{track}} > 4)}{N_{\text{Event}}(m > 5\text{ GeV}, N_{\text{track}} > 3)} \text{ in CR}$$

Inclusive Estimate Uncertainties

Sources of systematic uncertainty:

1. Statistical variations of jet-DV probability and f-factor (58%)
2. **Non-linear dependence of jet-DV probability on amount of jet activity in event (+10-27% High pT / +6.3-17% Trackless)**
3. Non-closure inside material regions (4% in High-p_T SR only)
4. **Pileup difference in control and signal regions (5.9% High pT / 20% Trackless)**
   - Obtained from difference in jet-DV probability when reweighting to match pileup distribution
   - Reweighted is taken as nominal background estimate, difference is taken as uncertainty

Inclusive Estimate Uncertainties

Sources of systematic uncertainty:

2. Non-linear dependence of jet-DV probability on amount of jet activity in event (+10-27% High pT / +6.3-17% Trackless)

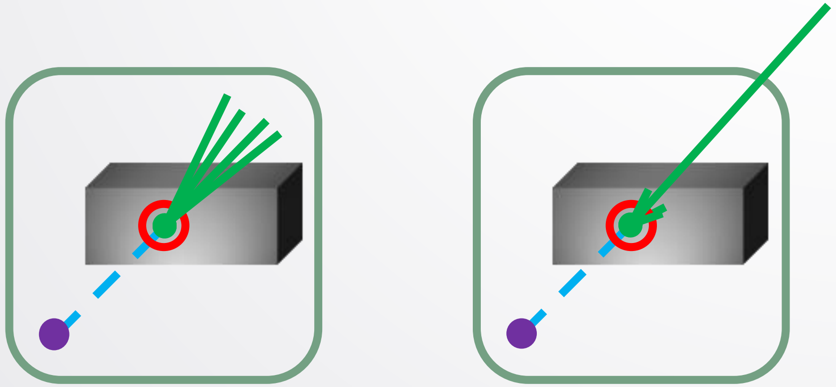
- Fraction of CR jets matched to SR-like DV vs # track jets in event
- Value of fit at each bin is used to create an alternate jet-DV probability and multiplied by normalized # of track jets in that bin in CR and SR -> difference is uncertainty
- Repeated with variations of fit where anti-correlated params varied within 1 σ, largest difference becomes asymmetric uncertainty

Updated HI Estimate

- HI generally follows the shape (start with straight ascending line at low mass, exponential decay in high mass after peak)

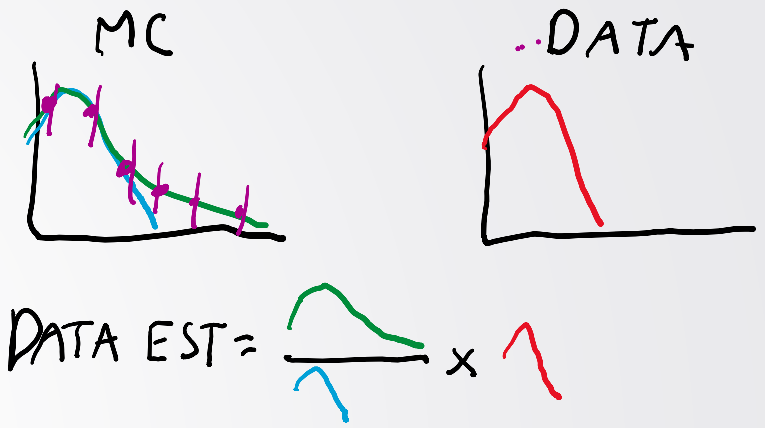
$$\#\text{DVs} = \frac{1}{\frac{1}{C(x-b)} + \frac{1}{e^{-\frac{(x-B)}{l}}}}$$

- Fit in $m_{DV} < 10\ \text{GeV}$ and extrapolate to $m_{DV} > 10\ \text{GeV}$
- However there is a secondary component of HI with a shallower exponential tail present
- This is due to "elastic" HI where most of the mass comes from a single high-momentum track collinear with the PV-DV vector
- There are unfortunately too few stats for us to properly characterize this component



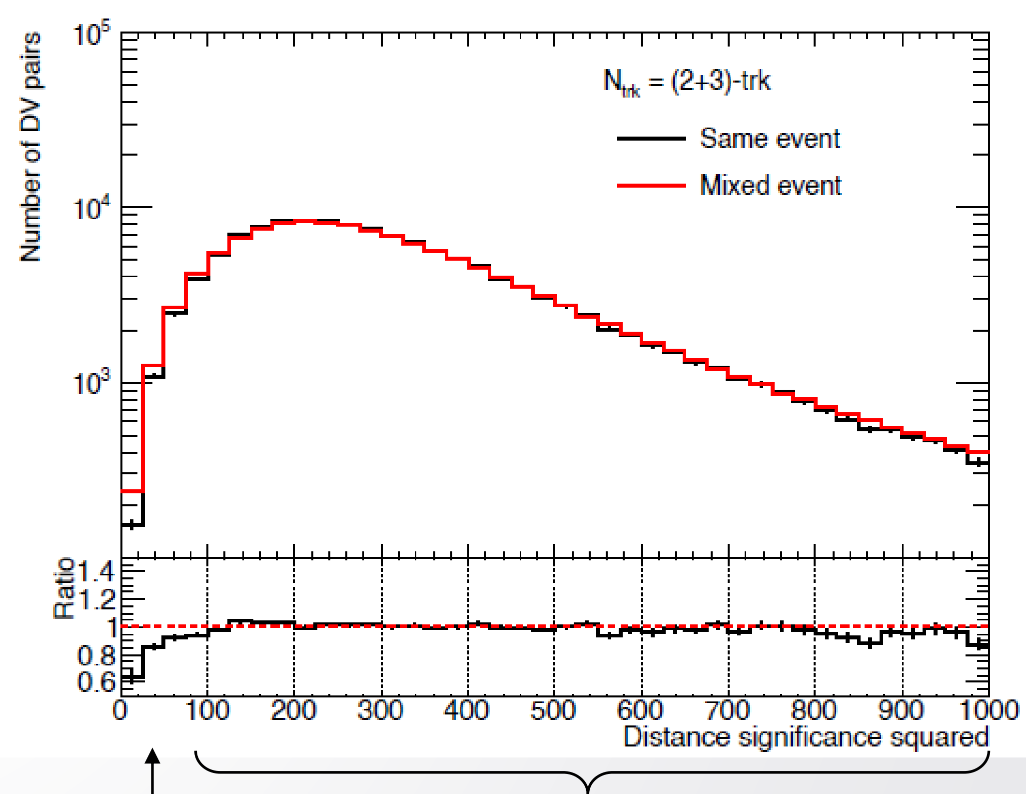
Updated HI Estimate

- Assuming effect of MC->data and event selections are similar with primary and secondary components:
  - Fit secondary exponential in MC full range
  - Propagate ratio between components from MC to data
- We do not have enough stats to prove/disprove these assumptions
- Uncertainties on our knowledge of secondary component behaviour (i.e. MC) propagated to final template
- “Fixed” templates close within uncertainties



MV Estimate

- Merging in vertexing algorithm is only possible if pairs of DVs have distance significance (S) < 10 σ
- Get mass template shape by merging pairs of DVs
- Get merging rate from comparing S of same-event pairs and different-event pairs
- Uncertainties:
  - 7-13%/30-50% (trackless/high pT) from statistical uncertainty on merging rate
  - 70% from MC non-closure

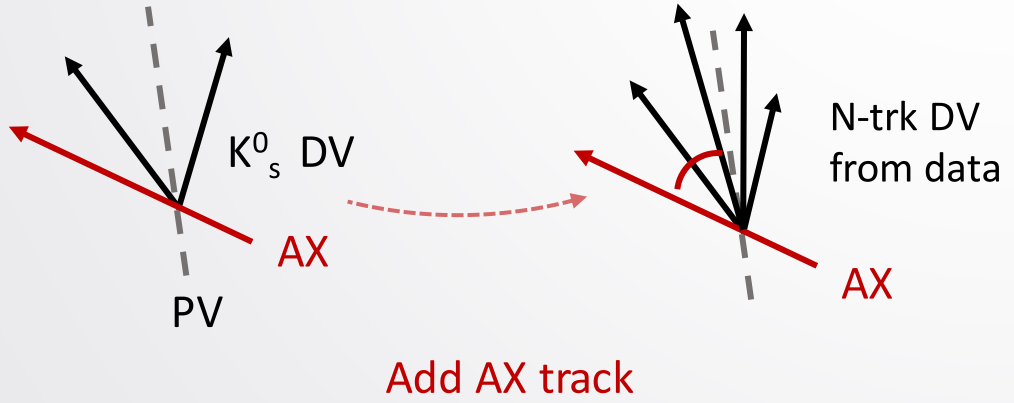


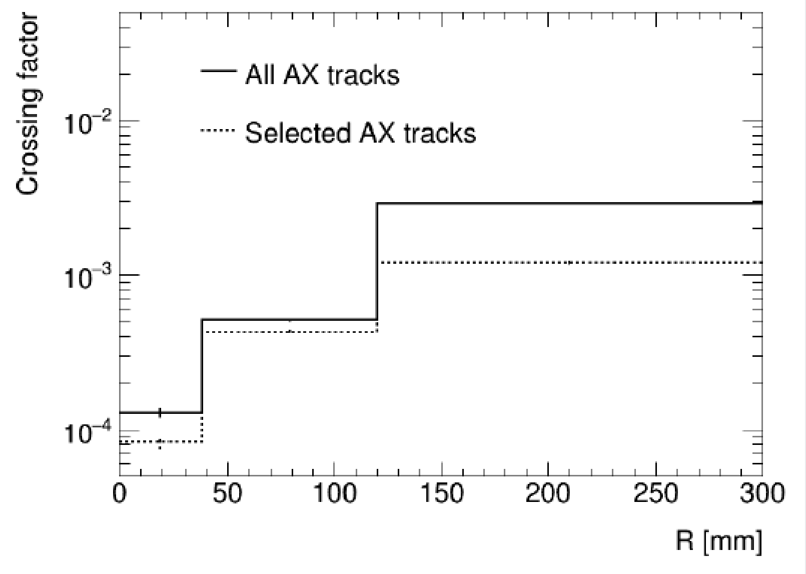
Merging in S < 10 σ region

Shape of distributions match in S > 10 σ region – good!

AX Estimate

- Get mass template shape by randomly attaching tracks to DVs in data
- Get crossing rate from fraction of $K_s^0 \to \pi^+\pi^-$ decays reconstructed with extra track
- Uncertainties:
  - 25% from crossing rate
  - 70% from MC non-closure





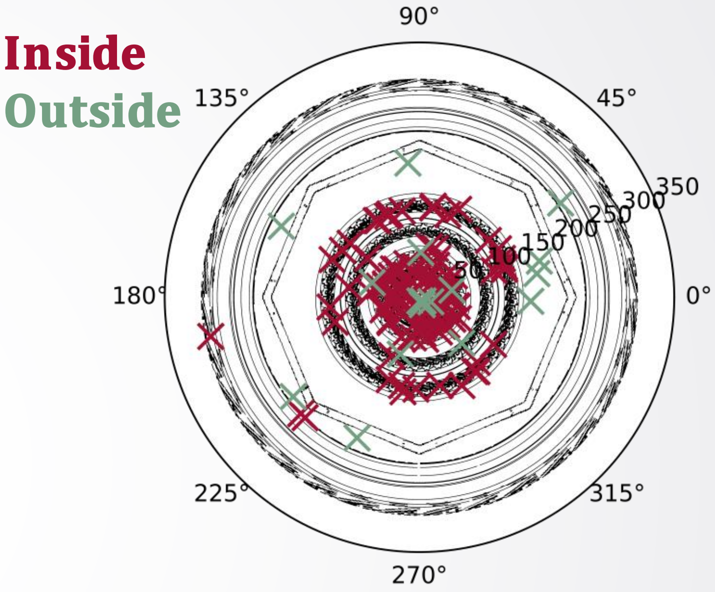
MC Signal Uncertainties

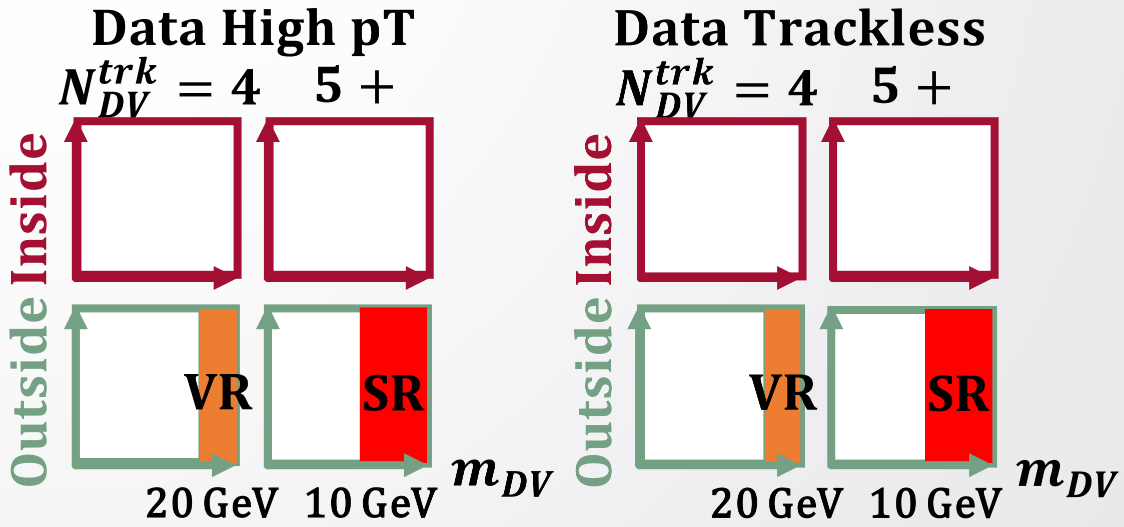
- Standard:
  - JES/JER → negligible for Strong RPV (set 1% flat), $\lesssim$ 10% for EWK RPV
- Custom:
  - JES/JER vs. displacement (we checked for trackless jets)→ negligible
  - Large radius tracking / secondary vertexing → up to 15% for low m_χ , long lifetime
    - Compare number of reconstructed K_S^0 in data vs dijet MC
    - Calculate per-track uncorrelated uncertainty
    - Translate to signal efficiency by seeing difference when randomly killing tracks in a DV
  - **Pileup reweighting → insignificant compared to statistical uncertainty**
    - Apply pileup reweighting by hand from MC/data distribution difference
    - Currently being finalized

Extra Stuff

Analysis Overview and Selections

- **Full Run-2** dataset: 139 /fb
- **Multi-jet trigger**
- 2 SRs: **High pT** Jet and **Trackless** Jet SRs (if jet is trackless, can lower jet pT req.)
- DVs must:
  - lie **outside** of detector material,
  - have **5+ tracks**,
  - invariant mass $m_{DV} > 10\ \text{GeV}$





Reminder of Toy Model and Method

	No Evsel (MC)	With Evsel (Data)
Inside	$e^{-\frac{x-c}{m_1}} + e^{-\frac{x-t}{m_2}}$	$Se^{-\frac{x}{s}}e^{-\frac{x-c}{m_1}} + Se^{-\frac{x}{s}}e^{-\frac{x-t}{m_2}}$
Outside	$Ae^{-\frac{x-c}{m_1}} + Ae^{-\frac{x-t}{m_2}}$	$ASe^{-\frac{x}{s}}e^{-\frac{x-c}{m_1}} + ASe^{-\frac{x}{s}}e^{-\frac{x-t}{m_2}}$

Nominal data

$$\left[ASe^{-\frac{x}{s}}e^{-\frac{x-c}{m_1}} + ASe^{-\frac{x}{s}}e^{-\frac{x-t}{m_2}}\right] = \frac{\left[ASe^{-\frac{x}{s}}e^{-\frac{x-c}{m_1}}\right]}{\left[e^{-\frac{x-c}{m_1}}\right]}\left[e^{-\frac{x-c}{m_1}} + e^{-\frac{x-t}{m_2}}\right]$$

Nominal HI MC Inside

Full HI MC inside

Fitted in Estimate + Could Fit for non-closure + Can be fitted + Could be fitted if we took dRMax cut

Reminder of Toy Model and Method

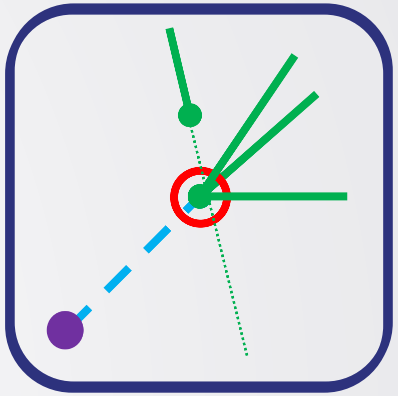
- Since errors would be dominated by bad stats in MC:
- Errors will be maximum of:
  - Data nominal propagated statistical errors
  - HI MC Inside poissonian errors scaled by the new data estimate divided by the full HI MC inside fit.
    - 0 bins instead of HI MC Inside poissonian errors will be 1.832 times the average HI MC weight inside

Name	Selection	Region	DV track type
Transverse momentum	$p_T > 2$ GeV $p_T > 3$ GeV $p_T > 4$ GeV	all outside beampipe outside last pixel layer	both attached only attached only
d_0-significance $= \|d_0\|/\sigma(d_0)$	d_0-sig > 10 d_0-sig > 15 d_0-sig > 10	within beampipe within last pixel layer outside last pixel layer	both attached only core only
Small angle, low-p_T	$\Delta\alpha(\text{track}, r_{\text{DV-PV}}) > 0.2$ or $p_T > 4$ GeV	outside beampipe	both
Backwards-going tracks	$\Delta\alpha(\text{track}, r_{\text{DV-PV}}) < \pi/2$	all	attached only
Upstream hit veto	Cannot have hits on tracking layers at $r < r_{\text{DV}}$	all	both

Table 6.3: Summary of DV-track cleaning.

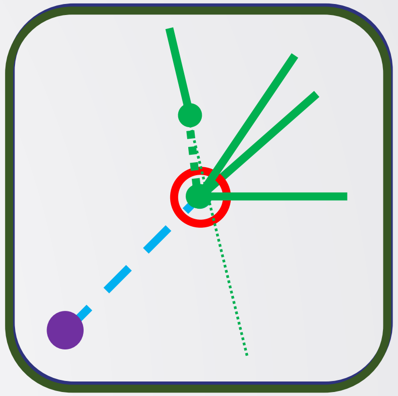
Motivation for Deeper Truth Studies

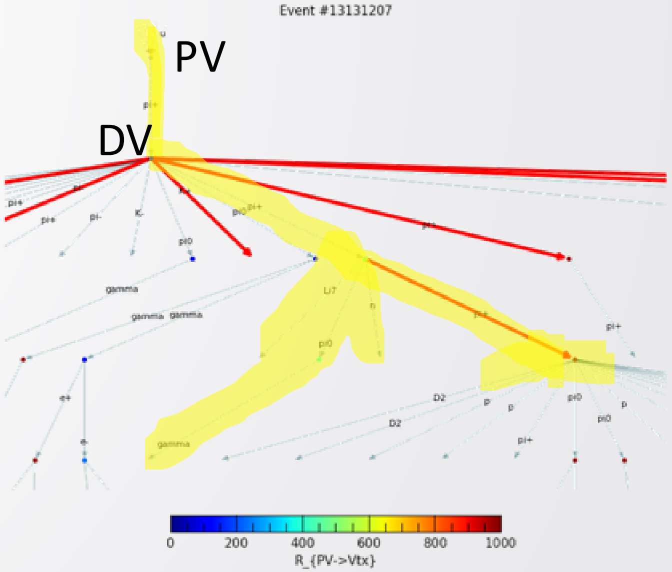
- Is this an AX? Using only info in NTUP we might naively think so!



Motivation for Deeper Truth Studies

- Is this an AX? Using only info in NTUP we might naively think so!
- Digging into the DAOD and looking at the decay tree:
  → more accurate to call this HI
- Tracks can undergo decays or HI later in the detector
- Any of these descendant tracks (that point back to the DV) can be reconstructed as “the track”
  →distance between truth origins not what we think!
- Therefore it is essential that we know the truth parentage history of the tracks in order to determine what our categories should look like in MC truth!

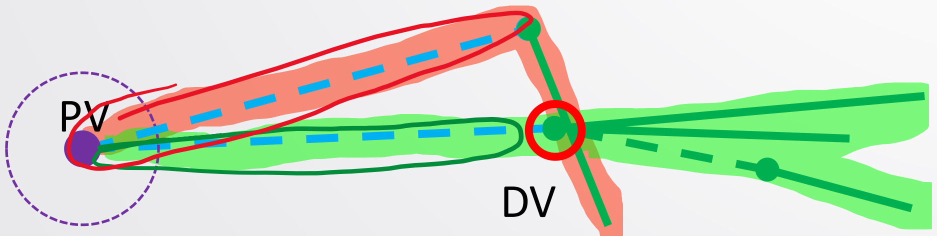




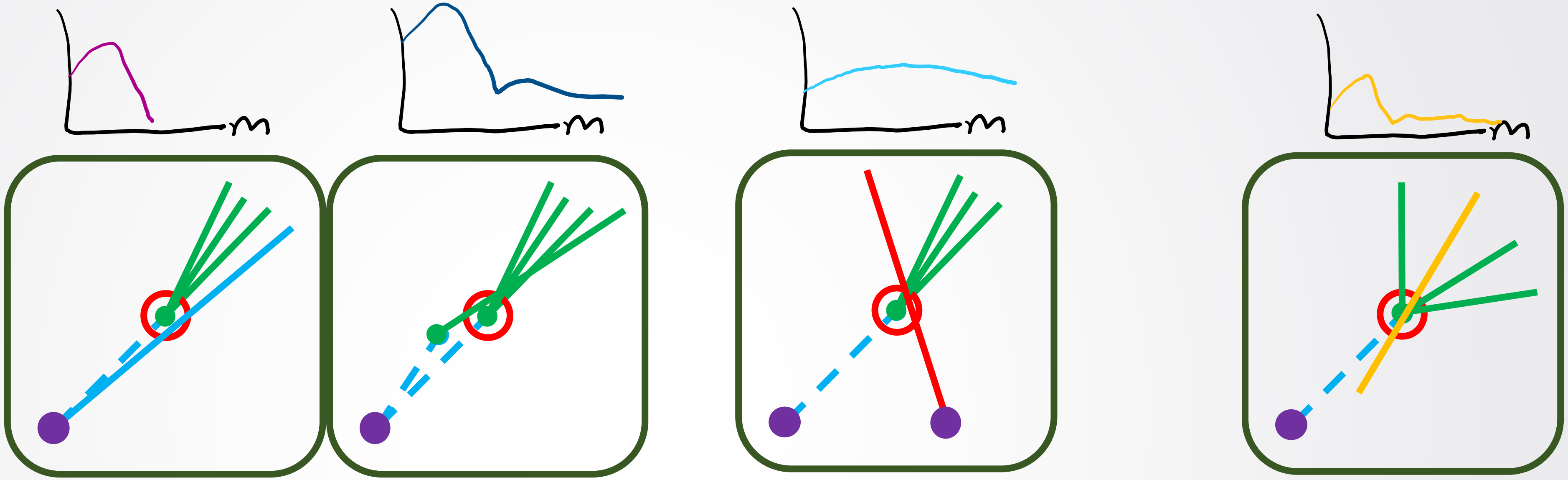
Defining the “Originating SM LLP” (OSMLLP)

- Motivated by distinguishing “real process” DVs (like SM or HI) from DVs that involve tracking (AX) or vertexing (MV) effects
- Trace ancestry or reconstructed tracks back to the originating particle that begun at the PV and the travelled out into the detector displaced
- Allows us to categorize background in truth as:

  - Single-Process DVs (SM or HI)
  - Single-Process DVs + Other Track (AX, or MV*)
  - Possible MV
  - Other



Turns out there are **4 types of AX with distinct behaviours**



Crossed by track from same pp-interaction

- Collimated with DV tracks
- Dominant in **low m**

Crossed by track from other pp-interaction (True-PU)

- Distribution of angle with DV tracks is more broad
- Tends to have a much broader tail **extending to high m**

Crossed by fake track? (Fake-PU)