Long-lived Particles:

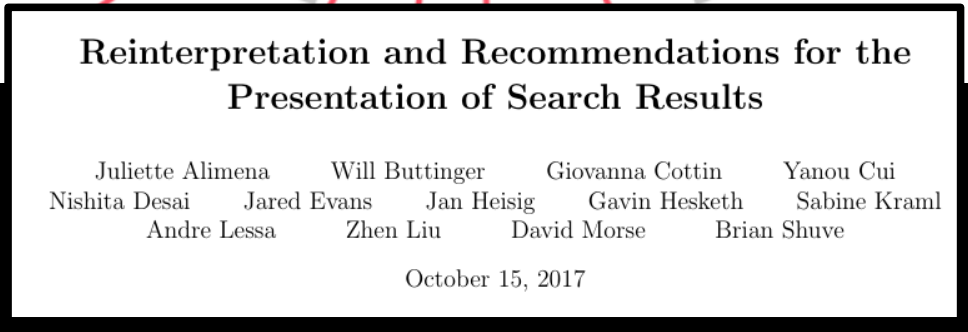
some experimental perspective

1) Experimental challenges
2) Ways to present results
   - efficiencies
   - fastsim?
   - RECAST

This is a workshop, we are here to discuss!

Gavin Hesketh, UCL

Based on LLP Whitepaper Chapter 5 draft



Reinterpretation and Recommendations for the Presentation of Search Results

Juliette Alimena Will Buttinger Giovanna Cottin Yanou Cui
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October 15, 2017

For details of experimental results, see:

Carlos Sierra, Albert de Roeck, Karri di Petrillo

https://indico.cern.ch/event/649760/timetable/

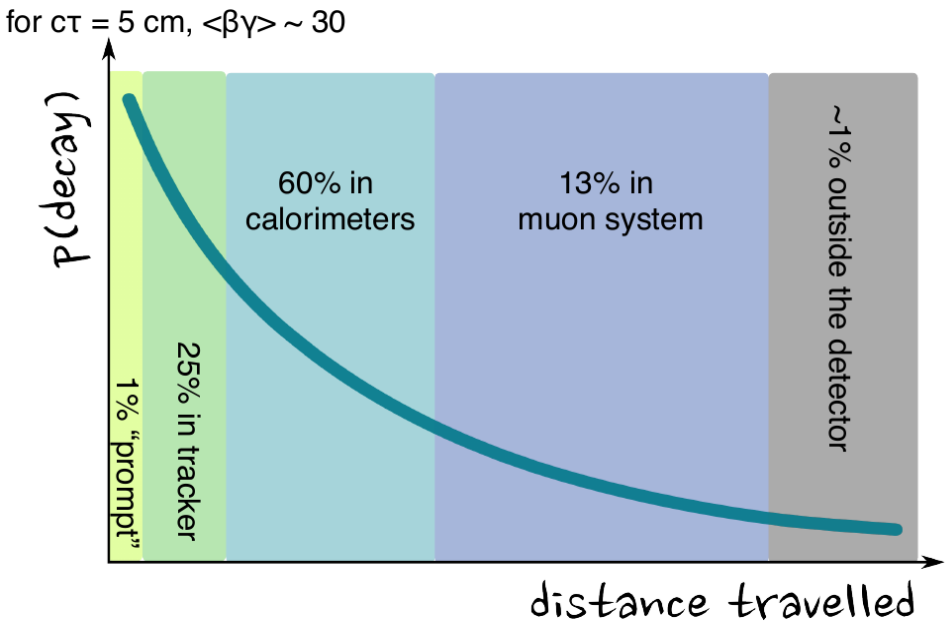
Experimentally, long-lived particles are an interesting challenge

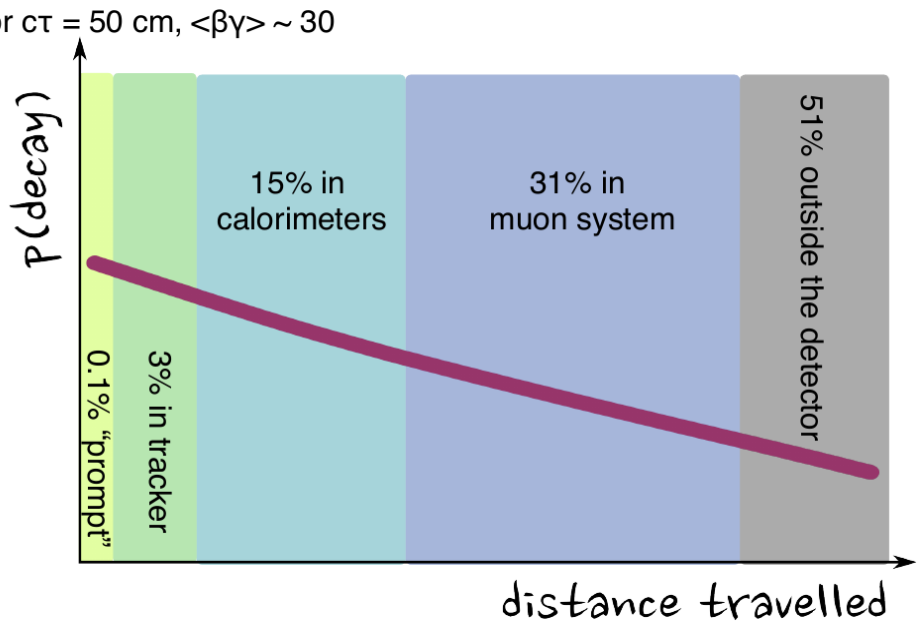
- use all parts of the detector

…in ways they were not necessarily designed to be used!

- requires different triggers, reconstruction, background estimates

...depending on where the signal may appear





images from Heather Russell

LLPs: Experiment

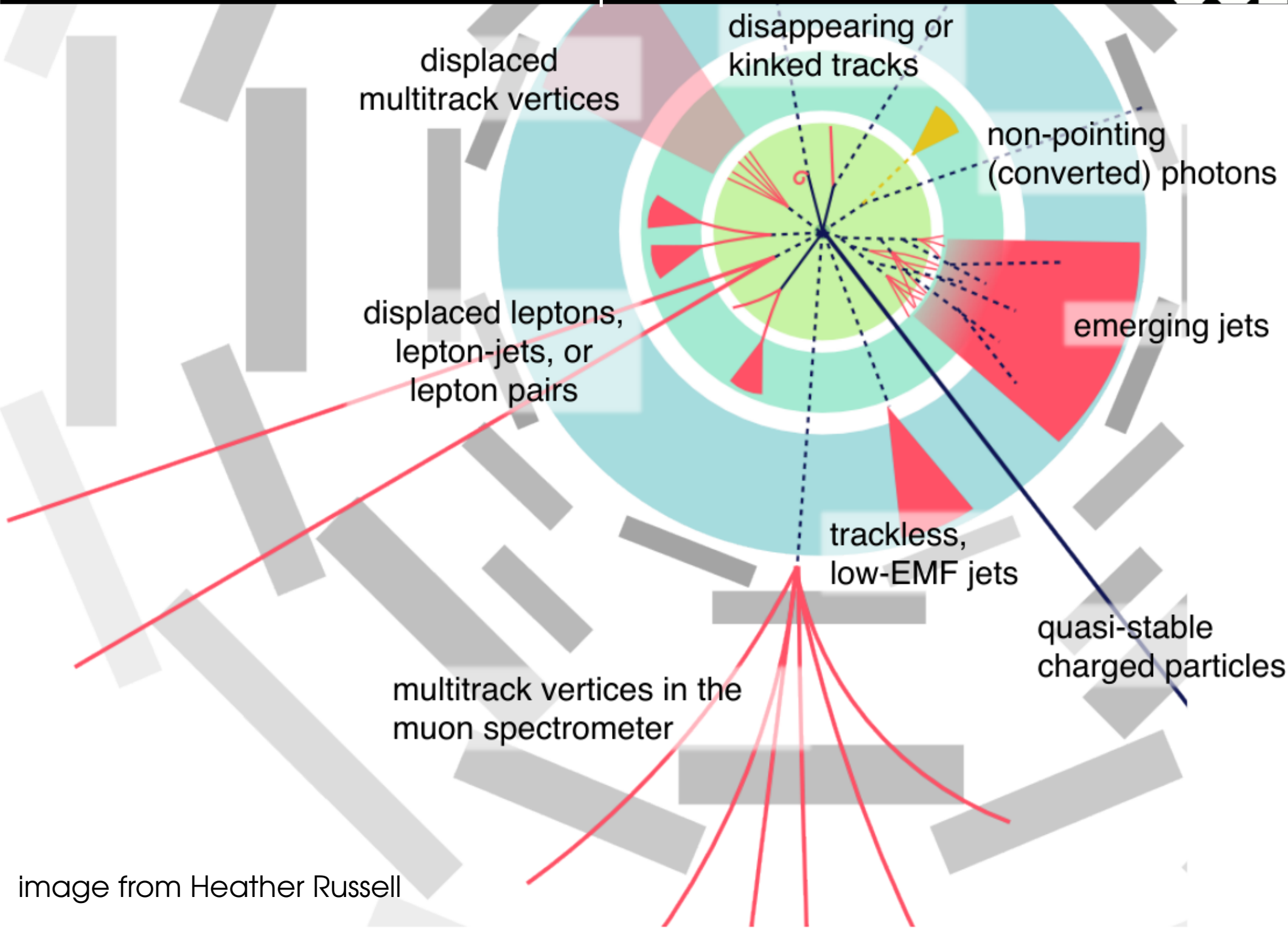
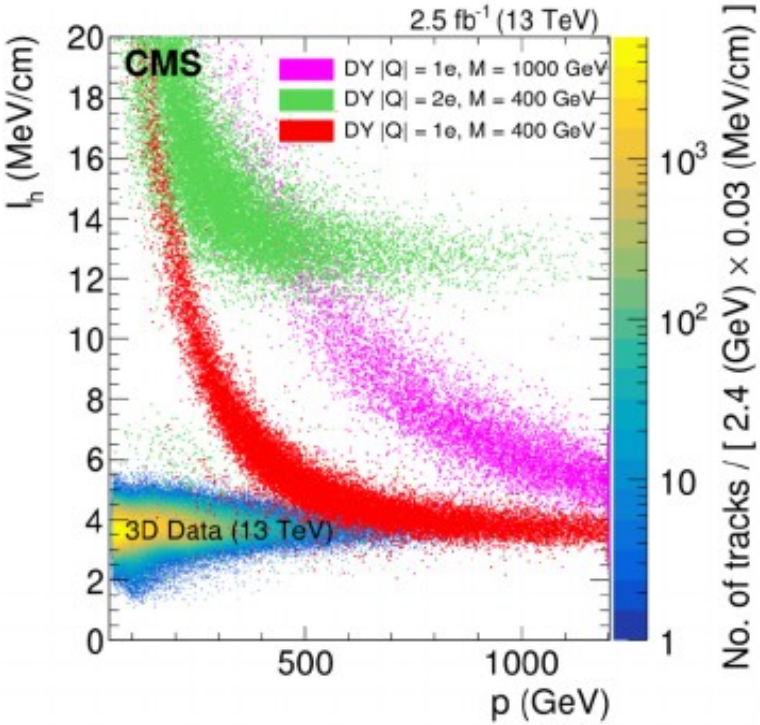


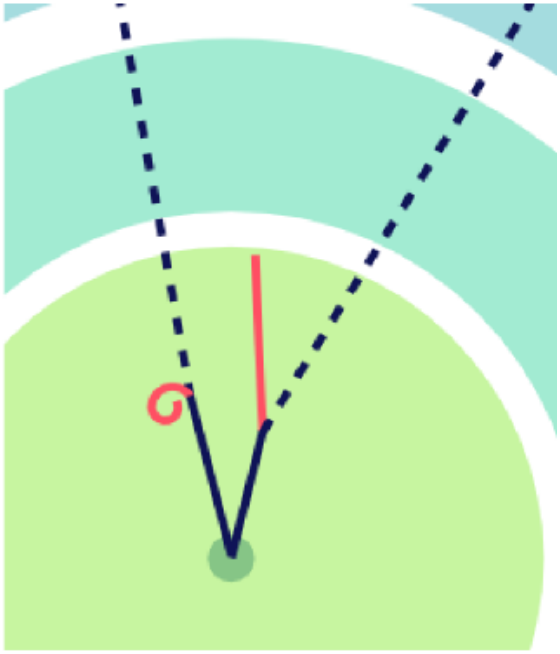
image from Heather Russell

Charged LLPs, decaying outside detector:

- signature similar to muons

Can use **dE/dx** in muon system (ATLAS)
or silicon (ATLAS & CMS)
or **cherenkov radiation** in RICH (LHCb)





Neutral LLPs, decaying outside the detector:

- MET! Similar to dark matter searches

Charged LLPs, decaying inside detector:

- disappearing or kinked track
- requires dedicated tracking

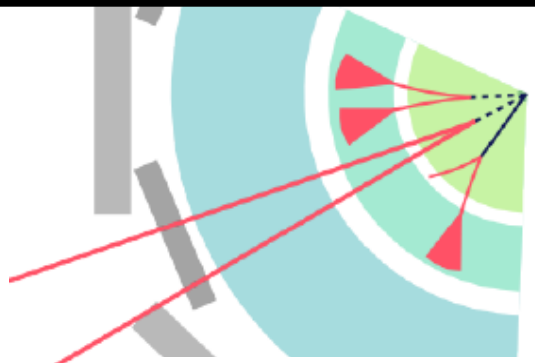
In both cases, triggering is the challenge:

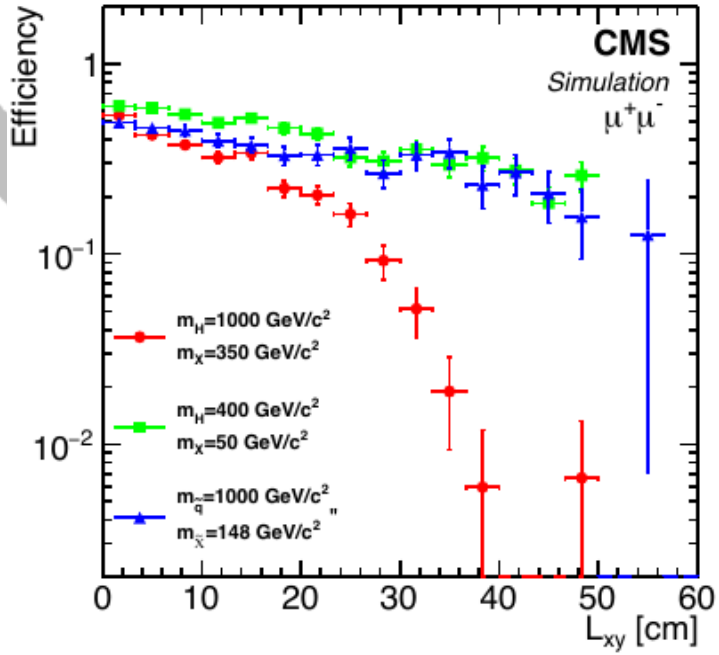
- need additional activity in the event
  mono-X style searches.

LLPs decaying to leptons in the tracker:

displaces vertices or kinked tracks

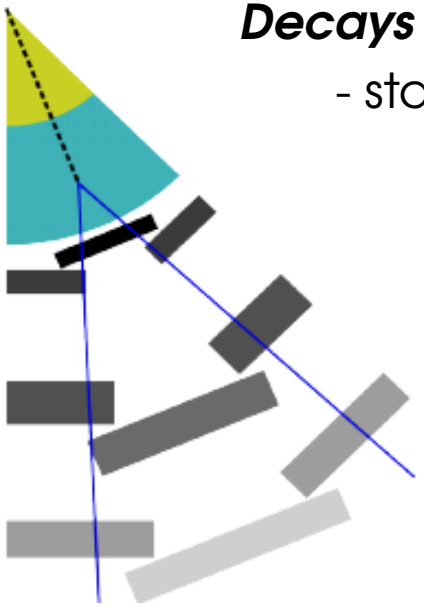
- CMS can identify large IP muons by default
- retracking + Ecal/MS at ALTAS





Decays outside the tracker:

- stand-alone muons, possibly + calo



Signatures can be resolved or boosted

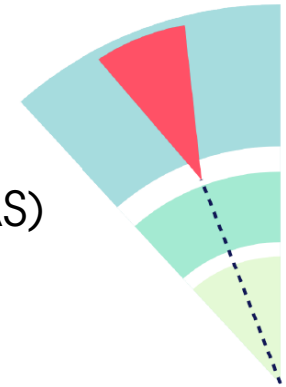
→ "lepton jets"

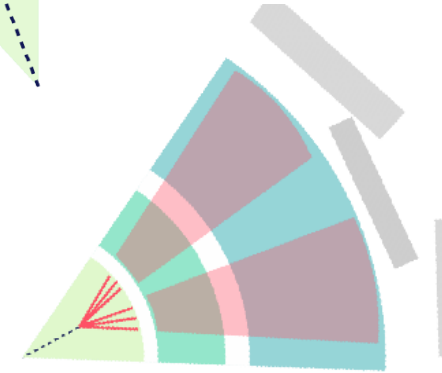
Triggering again an issue:

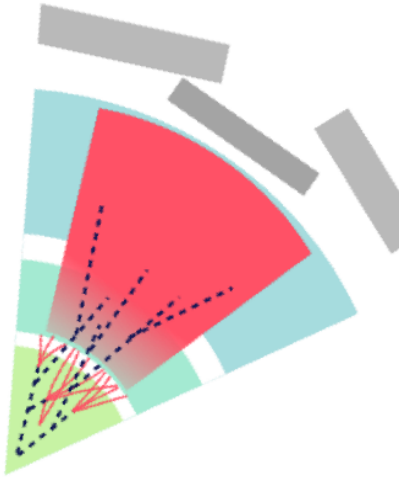
- IP requirements generally stricter in the trigger
- specialised triggers needed if decay outside tracker

LLPs decaying to hadrons:

- signature could be displaced multi-track vertex
  + resolved jets (CMS, LHCb), or single boosted jet (ATLAS)
- a jet with no tracks & low EMF
  - ATLAS can trigger on this signature
- multi-track vertex in the muon system

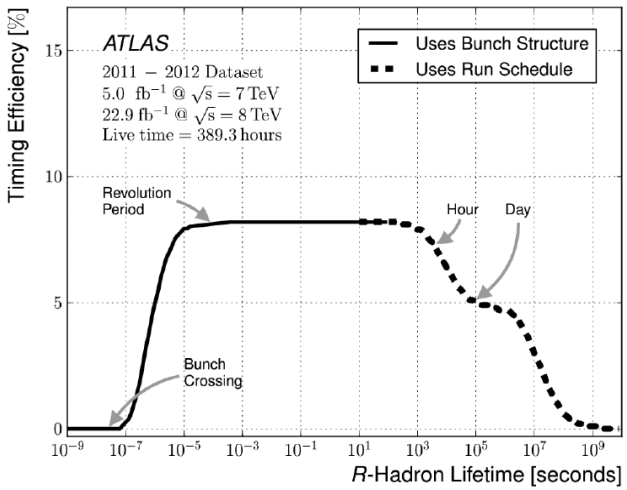






Emerging jets

- multiple displaced vertices



(very) late decays in the calorimeter

- ATLAS and CMS look for jets in empty bunch crossings (neither beam in the detector)

LLPs: Backgrounds

G. Hesketh

LLPs also come with a different mix of backgrounds

beam-induced background

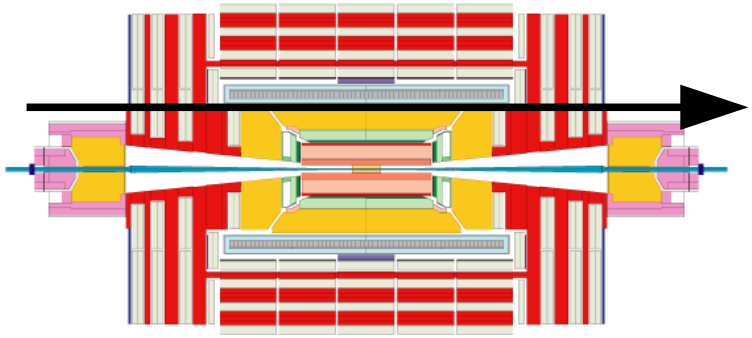
cosmics

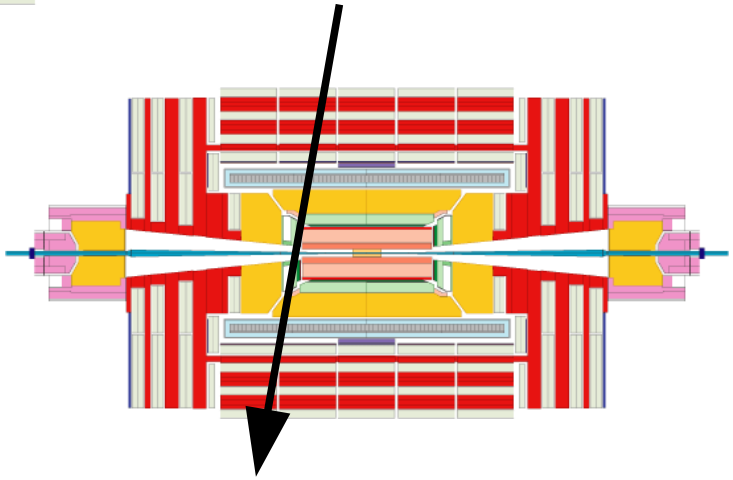
displaced vertices from material interaction

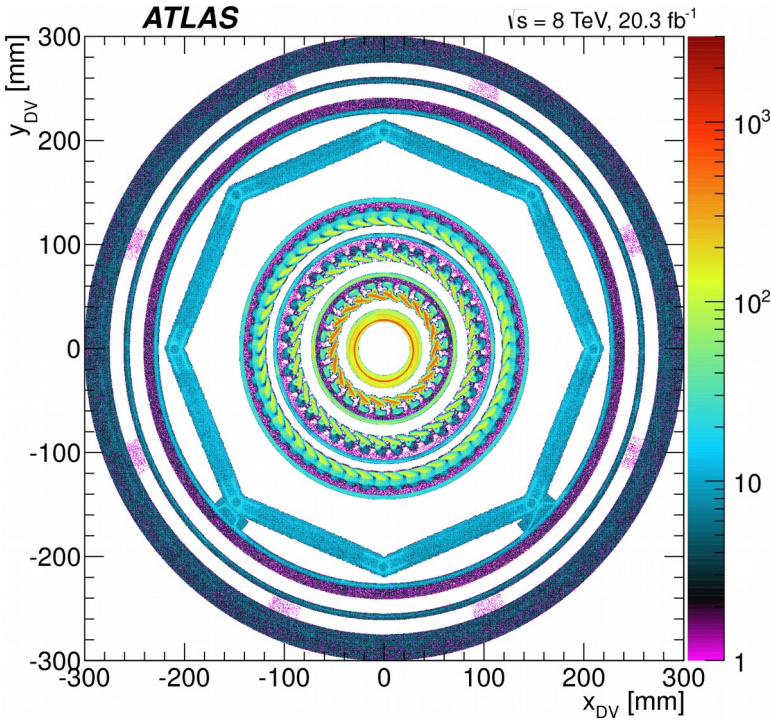
etc…

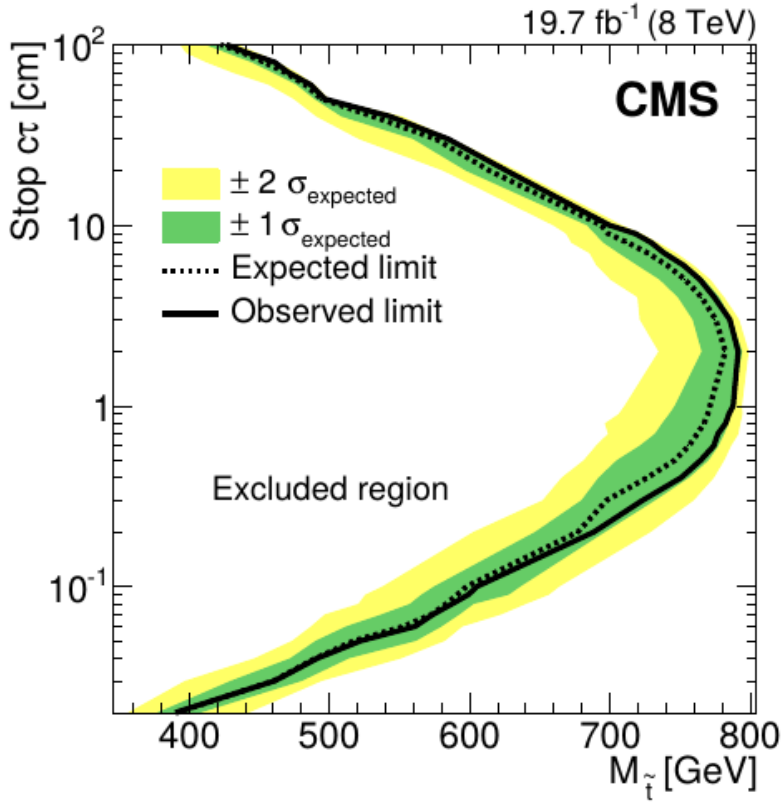
Can lead to non-trivial event selection

→ and efficiencies that are not so trivial to parametrise









From limits…

…to reinterpretation:

1) the event selection defining the signal region
2) the event yield in the SR
3) the background yields in the SR (+uncertainties)

Provided by experiments

4) the signal yield in the SR, for which you need a model of the detector...
   - a parameterisation of the efficiency (in terms of..?)
   - fast-sim (possible for LLPs?)
   - full sim (see RECAST)

To discuss!

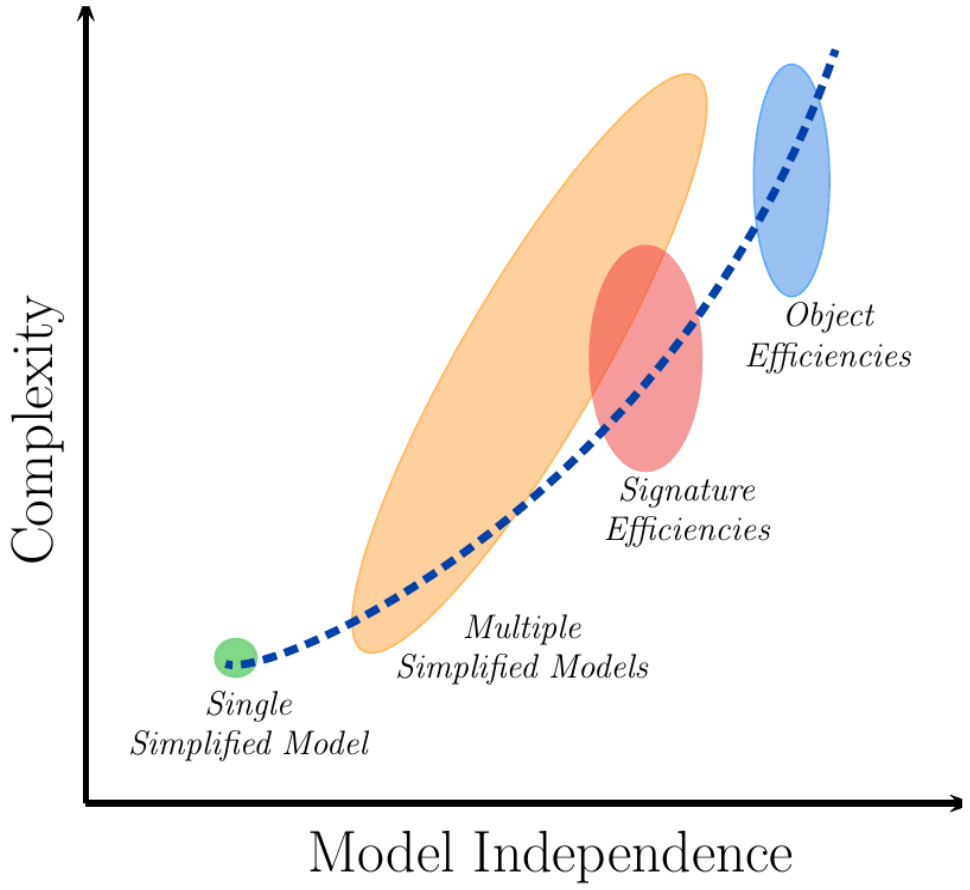
Searches usually focus on a particular signature, in a specific part of the detector

- displaced muon tracks, displaced vertex in tracker, jet with no tracks, …etc

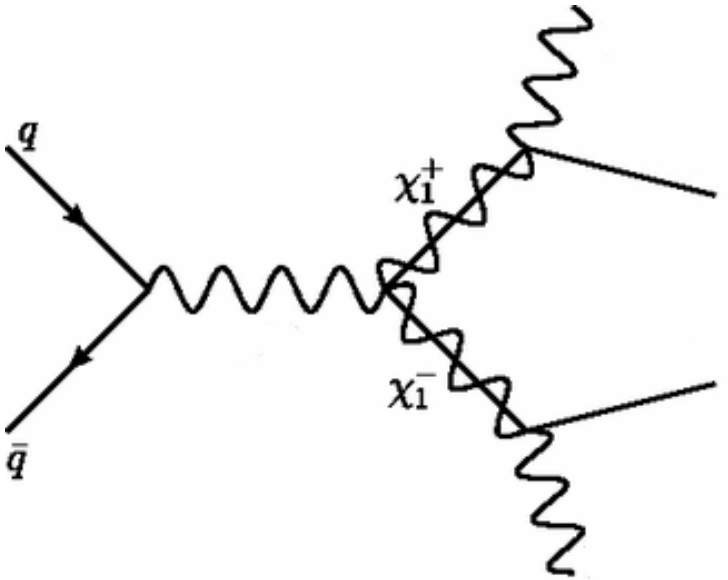
Changing the model can completely change the analysis!

- different lifetime, decay model → different experimental signature

So how to enable reinterpretation?



Provide efficiencies for a simplified model



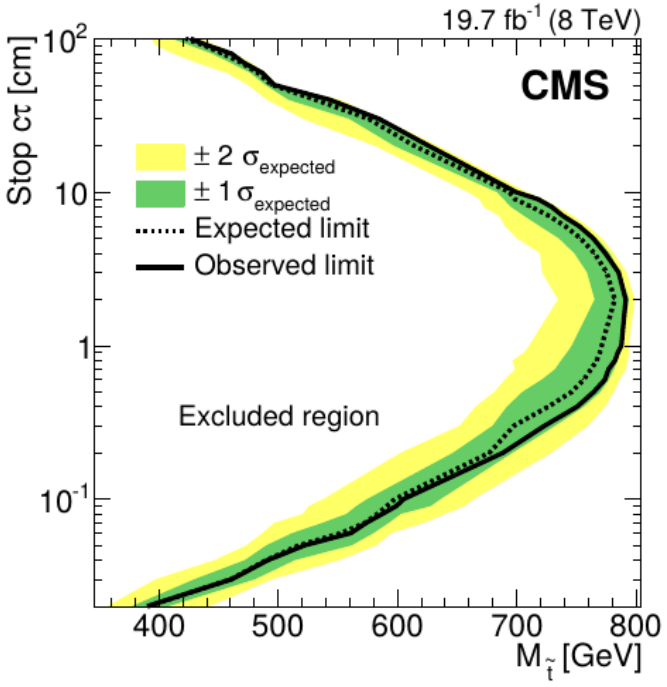
Model may depend on the analysis
- eg decay mode of χ

Limits ***& efficiencies*** as a function of
- mass & lifetime of LLP

Provides a single calibration point for reinterpretation
- using the efficiencies, anyone can run the same model, and get the same limits
  - within the limits of the parametrisation…

Reinterpreting the same model is not very interesting…

Fairly high-level efficiencies
- may not capture dependencies of efficiencies
- hard/impossible to interpolate between different models
  … and between analyses



Provide efficiencies for multiple simplified models?

- allows testing of interpolation
- and confidence in extrapolation

Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair		SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$		SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$		SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX + \text{inv.}$	Higgs, DM*		Higgs, DM*		Higgs, DM*	
HIG: $h \to X + \text{inv.}$	DM*		DM*		DM*	
ZP: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*		Z', DM*		Z', DM*	
ZP: $Z(Z') \to X + \text{inv.}$	DM		DM		DM	
CC: $W(W') \to \ell X$			RHν*	RHν	RHν*	RHν*

Production \ Decay	$\ell + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell\gamma$
DPP: chargino pair or slepton pair	SUSY	SUSY	SUSY	
HP: $\tilde{q} \to jX$	SUSY	SUSY	SUSY	
ZP: $Z' \to XX$	Z', DM*	Z', DM*	Z'	
CC: $W' \to X + \text{inv.}$	DM*	DM*		

Production \ Decay	$j + \text{inv.}$	$jj(+\text{inv.})$	$j\ell$	$j\gamma$
DPP: squark pair or gluino pair	SUSY	SUSY	SUSY	

Problem: generating samples,

calculating & parametrising efficiencies on many models not simple...

Simplified models and reinterpretation quite closely connected

More discussion on simplified models to follow in Jared's talk

Next step:

- rather than the efficiency to select a given model...

...provide efficiencies to select the experimental objects

Example 1: CMS displaced electron + muon search

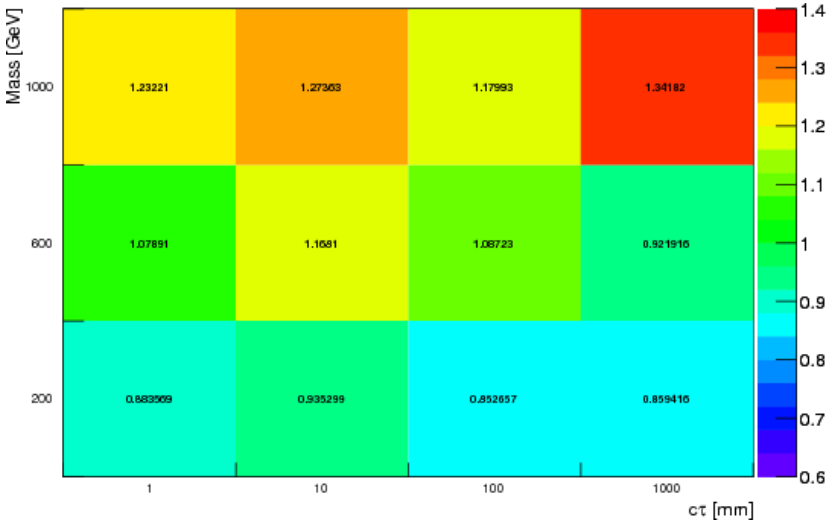
- search for top squark pair production, decay to lepton+b-jet (only leptons used)
- squark cτ in range 1mm → 1m

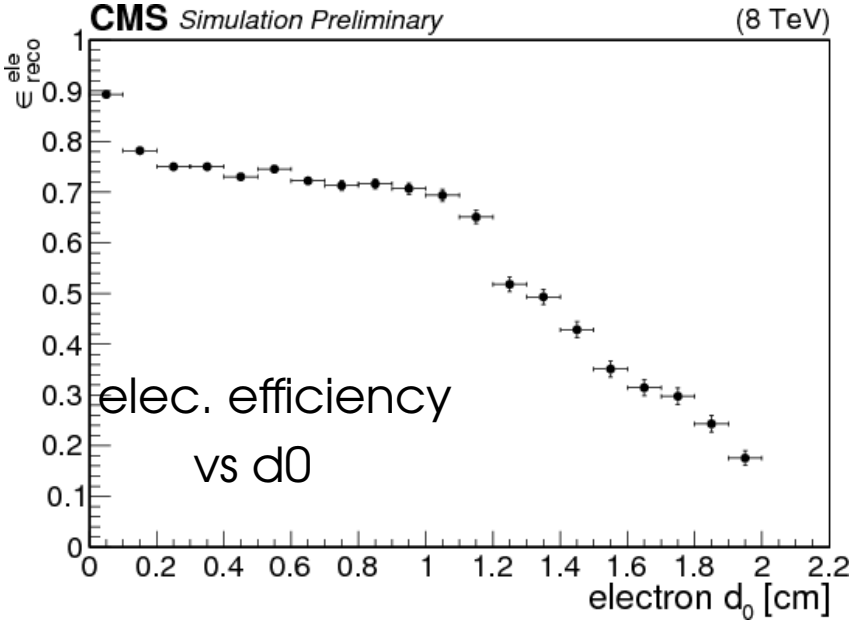
Provided electron and muon efficiencies vs d0 or pT

arXiv:1409.4789 (8 TeV)
CMS-PS-EXO-16-022 (13 TeV)

Cut Summary of CMS displaced $e\mu$

Preselection
1 OS $e^{\pm}\mu^{\mp}$ pair
$d_\ell > 100\,\mu$m
$p_{T,\ell} > 25$ GeV, $\lvert\eta_\ell\rvert < 2.5$
Reject $1.44 < \lvert\eta_e\rvert < 1.56$
$I^{calo,e}_{\Delta R<0.3} < 0.10$, $I^{calo,\mu}_{\Delta R<0.4} < 0.12$
$\Delta R_{\ell j} > 0.5$ $\forall$ jets with $p_T > 10$ GeV
$\Delta R_{e\mu} > 0.5$
$v_{T,\ell} < 4$ cm, $v_{Z,\ell} < 30$ cm
Veto additional leptons





Closure test vs full analysis

for various mass / lifetime benchmarks

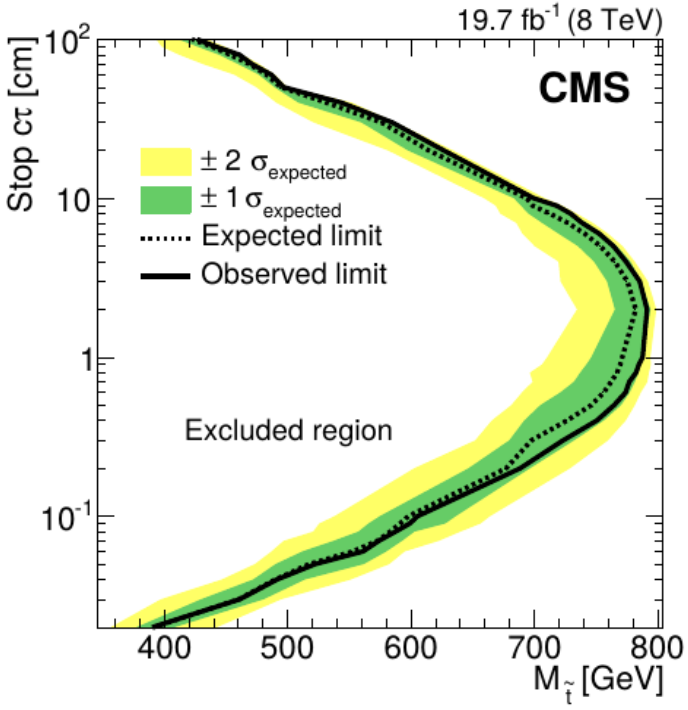
- closure at ~20% level

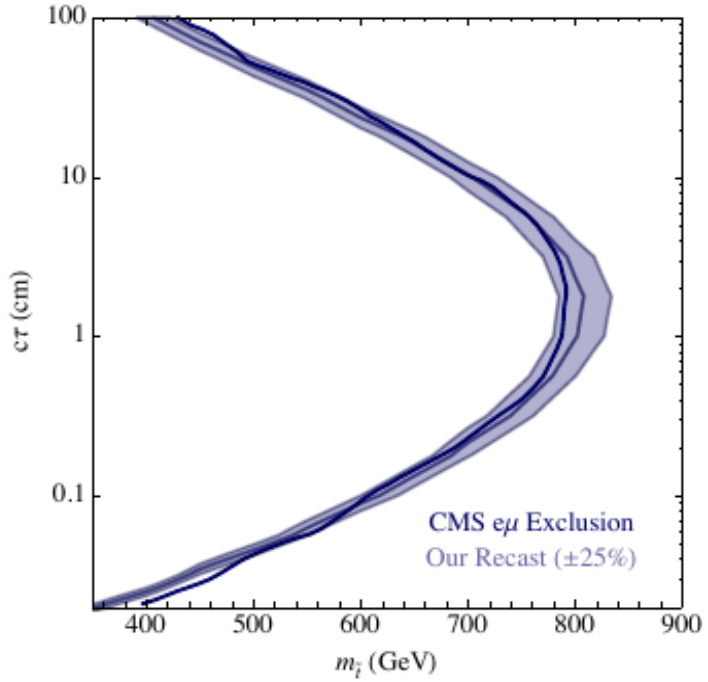
https://twiki.cern.ch/twiki/bin/view/CMSPublic/DisplacedSusyParametrisationStudyForUser

arXiv:1409.4789 (8 TeV)
CMS-PS-EXO-16-022 (13 TeV)

Reinterpretation (arXiv:1601.01326)

- successful! Agrees within 25%





Numbers for benchmark points agree well

- though 8 TeV efficiencies may not be valid at 13 TeV

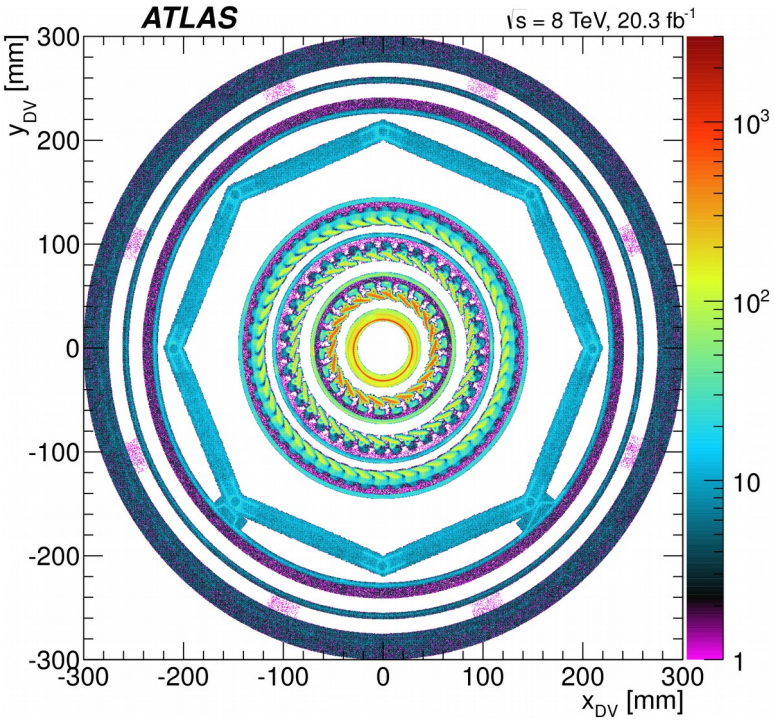
Lifetime	1 mm	10 mm	100 mm	1000 mm
8 TeV				
SR1	34.4 (30 ± 5)	28.3 (35 ± 7)	4.83 (4 ± 1)	–
SR2	8.76 (6.5 ± 1)	24.6 (30 ± 5)	5.73 (5 ± 1)	–
SR3	1.69 (1.3 ± 0.3)	53.6 (51 ± 10)	24.6 (26 ± 5)	–
13 TeV				
SR1	1.63 (3.8 ± 0.2)	4.39 (5.2 ± 0.4)	0.80 (0.8 ± 0.1)	0.0349 (0.009 ± 0.005)
SR2	0.312 (0.94 ± 0.06)	3.77 (4.1 ± 0.3)	1.53 (1.0 ± 0.1)	0.0700 (0.03 ± 0.01)
SR3	0.070 (0.16 ±0.02)	5.30 (7.0 ± 0.3)	7.74 (5.8 ± 0.2)	0.523 (0.27 ± 0.03)

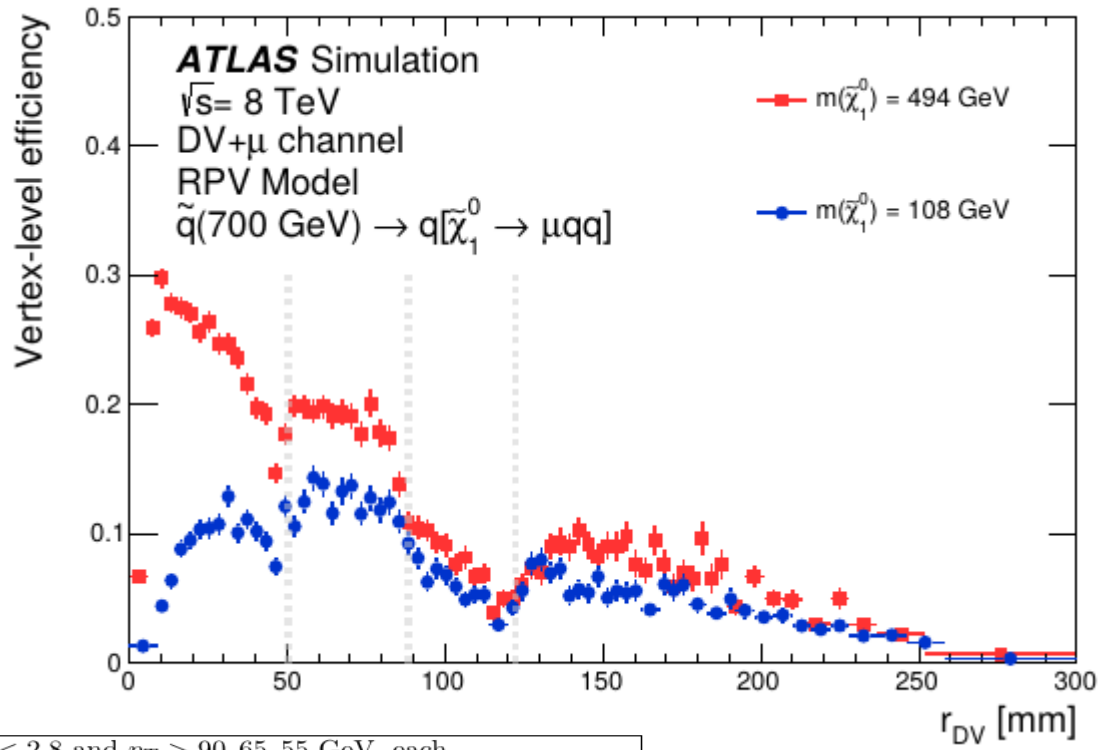
ATLAS search for displaced vertex or displaced lepton pair

arXiv:1504.05162

- RPV or GGM (l+jets, dilepton+MET, jets+MET, ...)

For efficiencies, displaced vertex is a much more complex object!

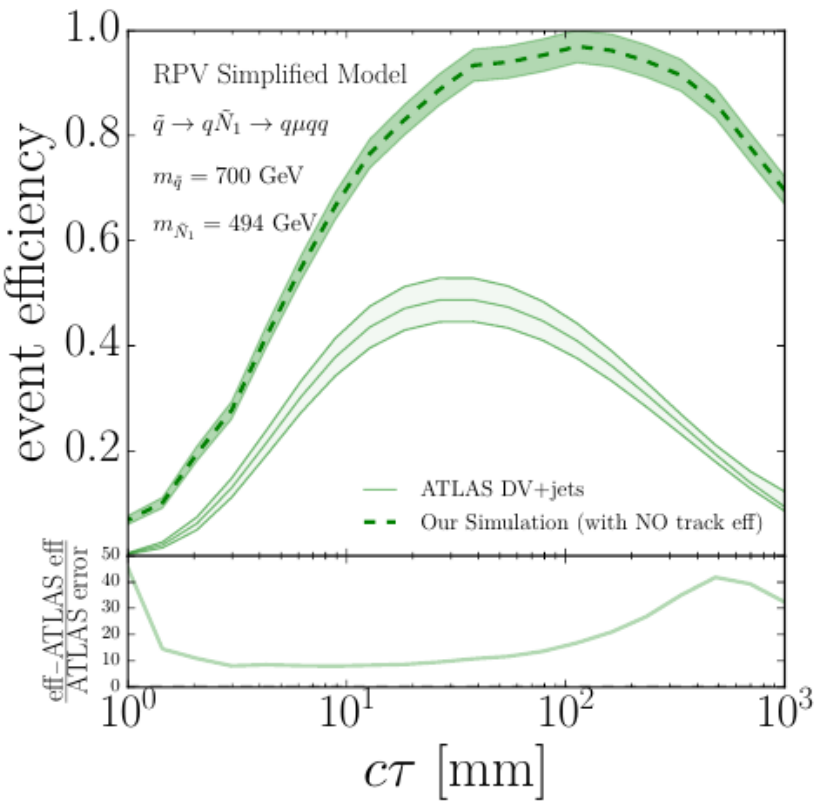


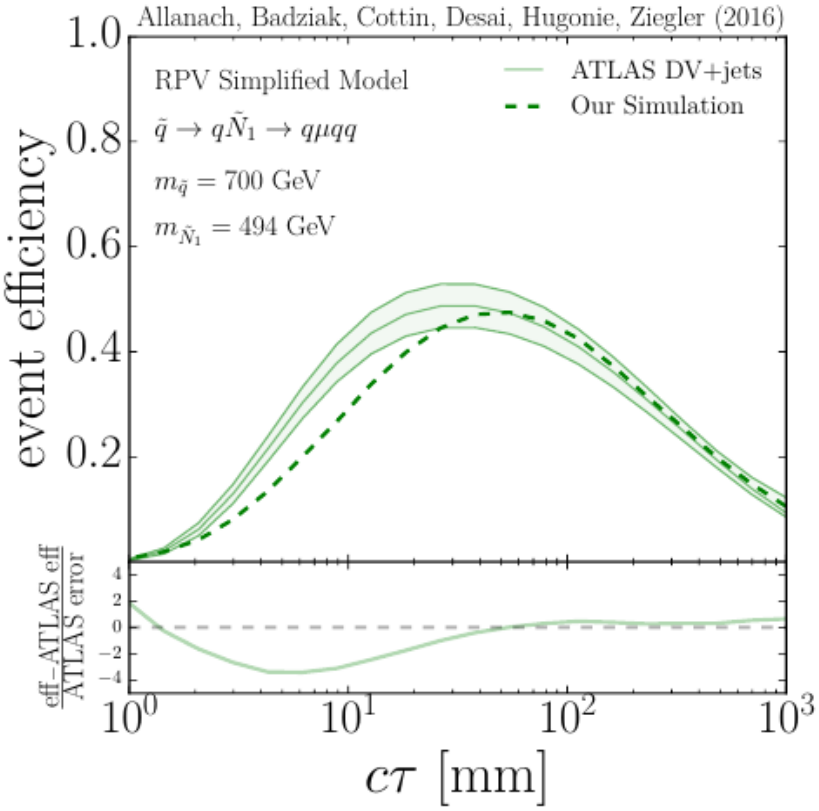


DV jets	4 or 5 or 6 jets with $\|\eta\| < 2.8$ and $p_T > 90, 65, 55$ GeV, each.
DV reconstruction*	DV made from tracks with $p_T > 1$ GeV, $\|\eta\| < 2.5$ and $\|d_0\| > 2$ mm, vertices within 1 mm are merged. Note: a tracking efficiency needed here; we assume a functional form given by equation 1.
DV fiducial	DV within 4 mm $< r_{DV} <$ 300 mm and $\|z_{DV}\| <$ 300 mm.
DV material*	No DV in regions near beampipe or within pixel layers: Discard tracks with $r_{DV}/\text{mm} \in \{[25, 38], [45, 60], [85, 95], [120, 130]\}$.
N_{trk}	DV track multiplicity ≥ 5.
m_{DV}	DV mass > 10 GeV.

Reinterpretation (arXiv1606.03099) with some success

arXiv:1504.05162





Needed to implement an approximate tracking efficiency:

$$\varepsilon_{\text{trk}} = 0.5 \times \left(1 - \exp\left(\frac{-p_T}{4.0\ \text{GeV}}\right)\right) \times \exp\left(\frac{-z_{\text{DV}}}{270\ \text{mm}}\right) \times \max(-0.0022 \times \frac{r_{\text{DV}}}{1\ \text{mm}} + 0.8, 0)$$

Vertex efficiency provided for one benchmark model (D.V. + muon)

- did not extrapolate very well to other benchmark models in paper.
  - DV+MET, dilepton

A vertex efficiency may not be enough:

It "would be useful if ATLAS could provide three-dimensional interpolated efficiencies for tracks for different types of particles, possibly with an additional efficiency factor for the vertex depending upon the numbers and types of particles coming from it"

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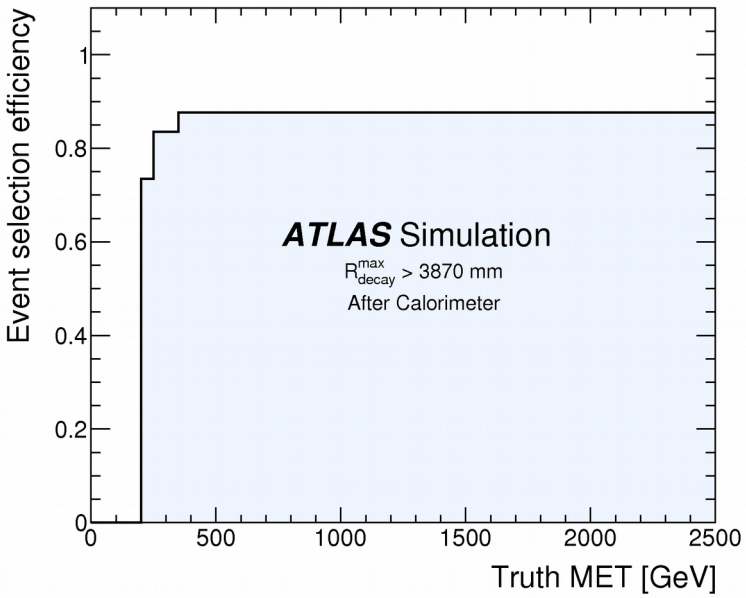
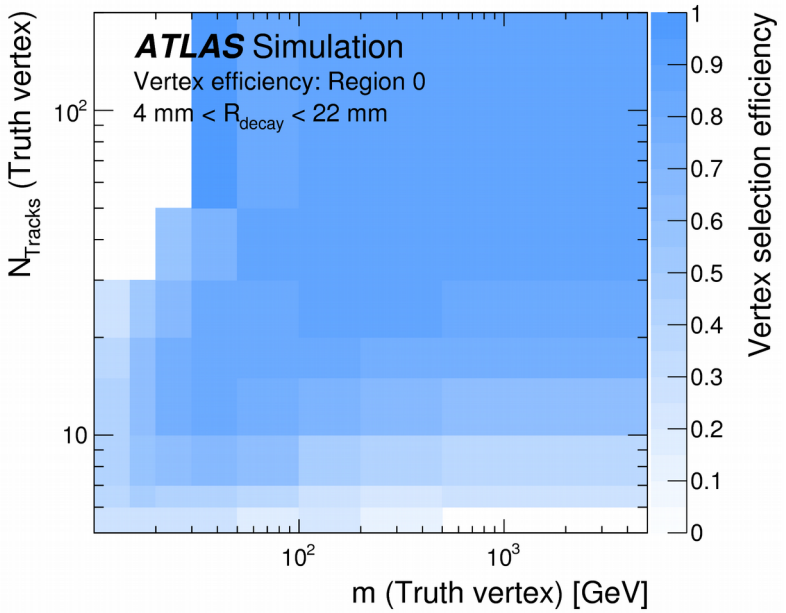
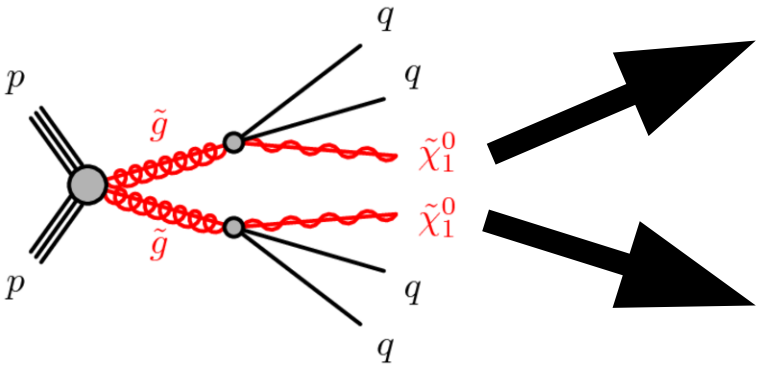




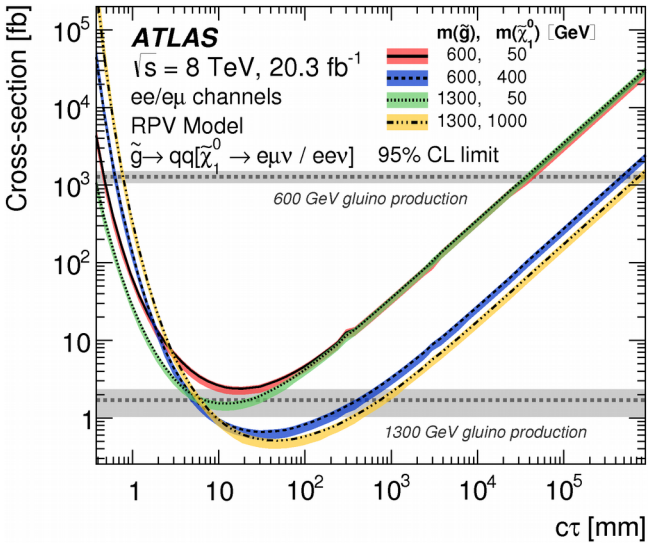
Since Monday:
arXiv:1710.04901

($m_{\tilde{g}}$ [GeV], $m_{\tilde{\chi}^0_1}$ [GeV], τ [ns])	(1400, 100, 1)	(2000, 100, 1)	(2000, 1800, 1)	(1400, 100, 0.1)
Initial Events	827	32	32	827
Trigger-based data reduction	826	32	27	827
Event cleaning	826	32	27	827
Good Runs List	826	32	27	827
Primary vertex	826	32	27	827
NCB veto	823	32	26	824
$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger	791	31	24	803
$E_{\mathrm{T}}^{\mathrm{miss}}$ filter	760	31	17	717
Offline $E_{\mathrm{T}}^{\mathrm{miss}}$	671	29	7	641
DV fiducial acceptance	620	28	6	625
DV fit quality	615	27	6	621
DV displacement	613	27	6	608
Material veto	493	22	5	544
Disabled module veto	480	22	5	541
DV track multiplicity	331	15	3	455
DV mass	305	14	2	442

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-08/



DELPHES
fast simulation



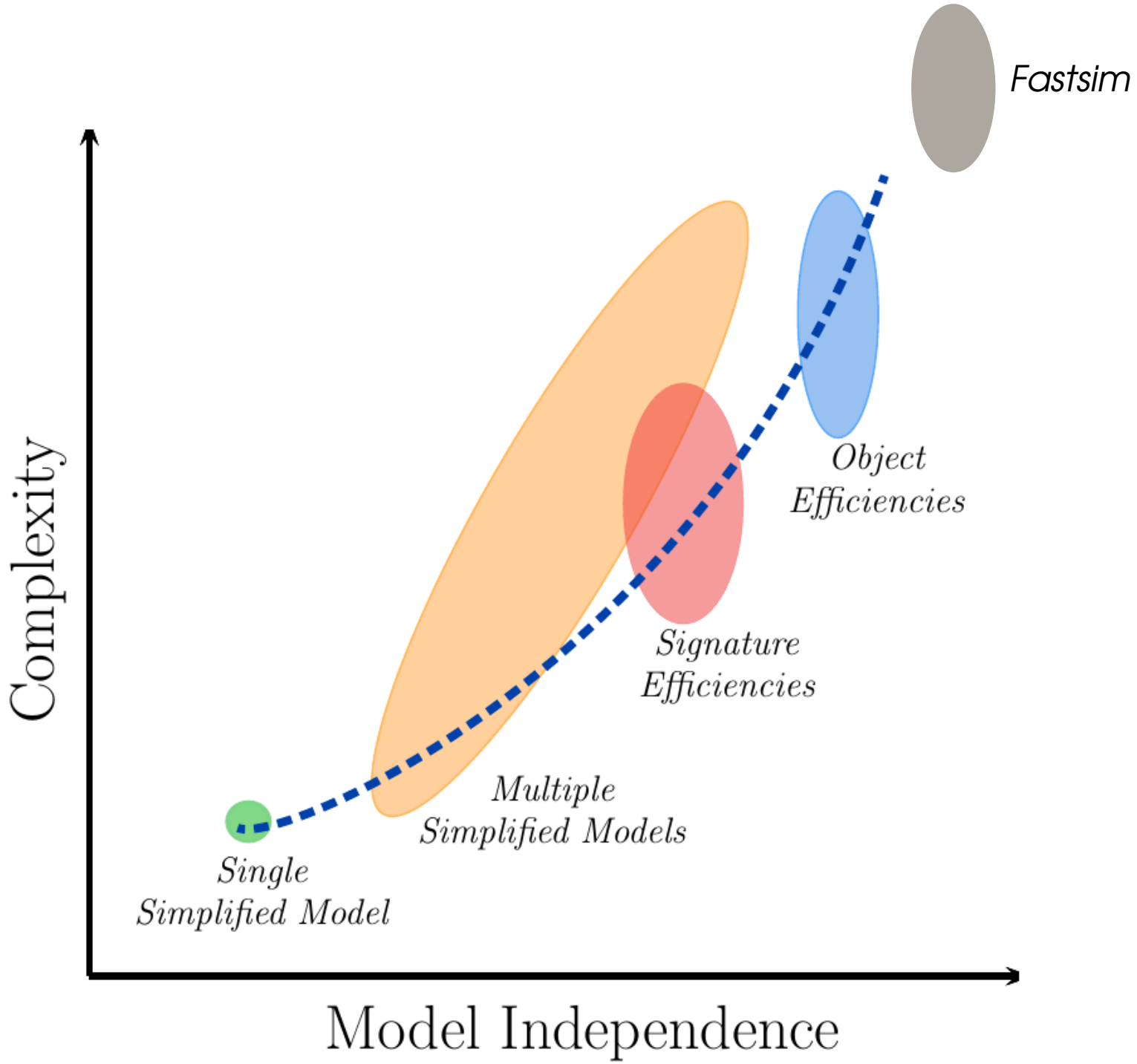
As provided efficiencies become more general...

Is fast sim for LLPs possible?

eg a particle decaying to electron (+ MET) looks very different if the decay is in the tracker… the hadronic calorimeter… the muon system…

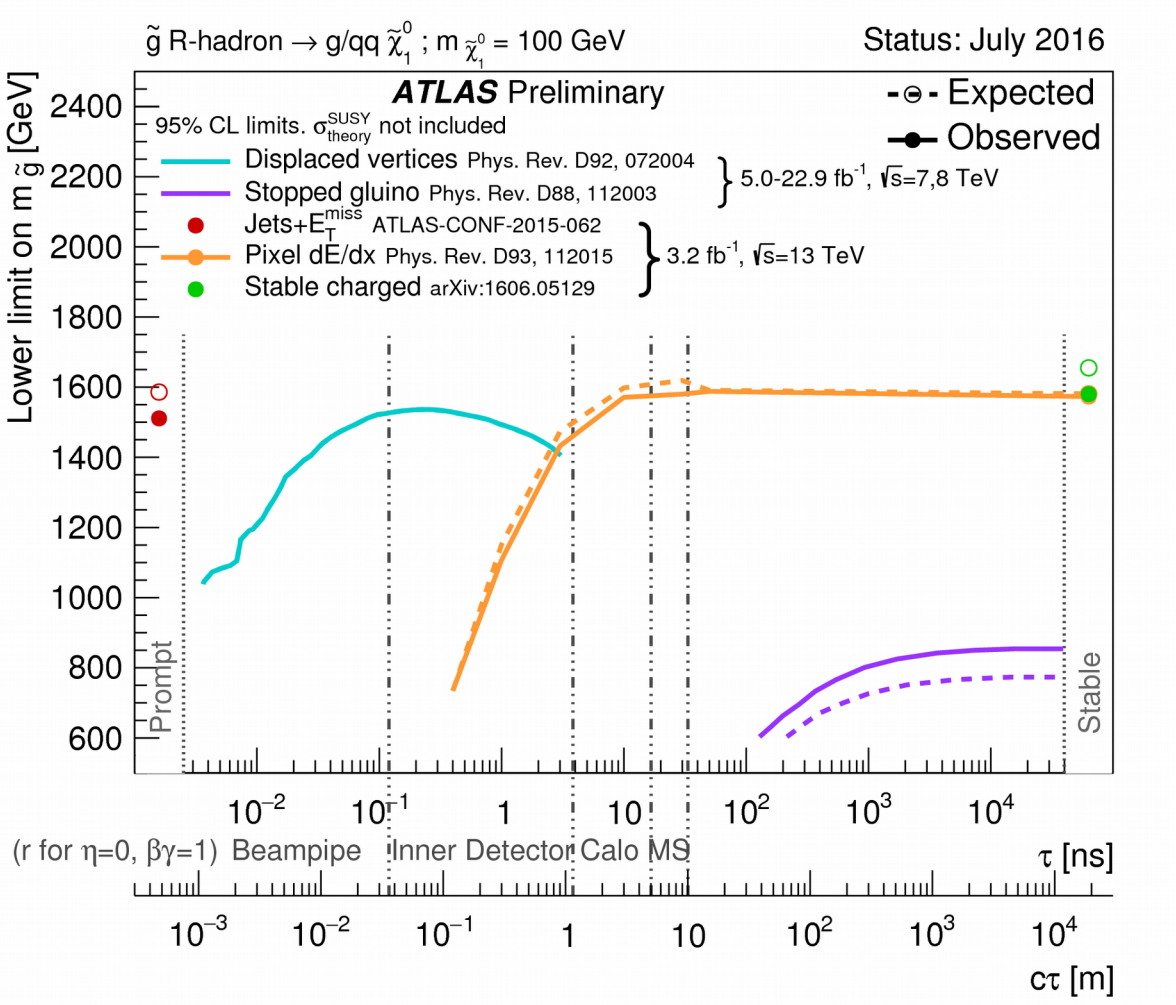
- will need input from many analyses
- and be used with caution...

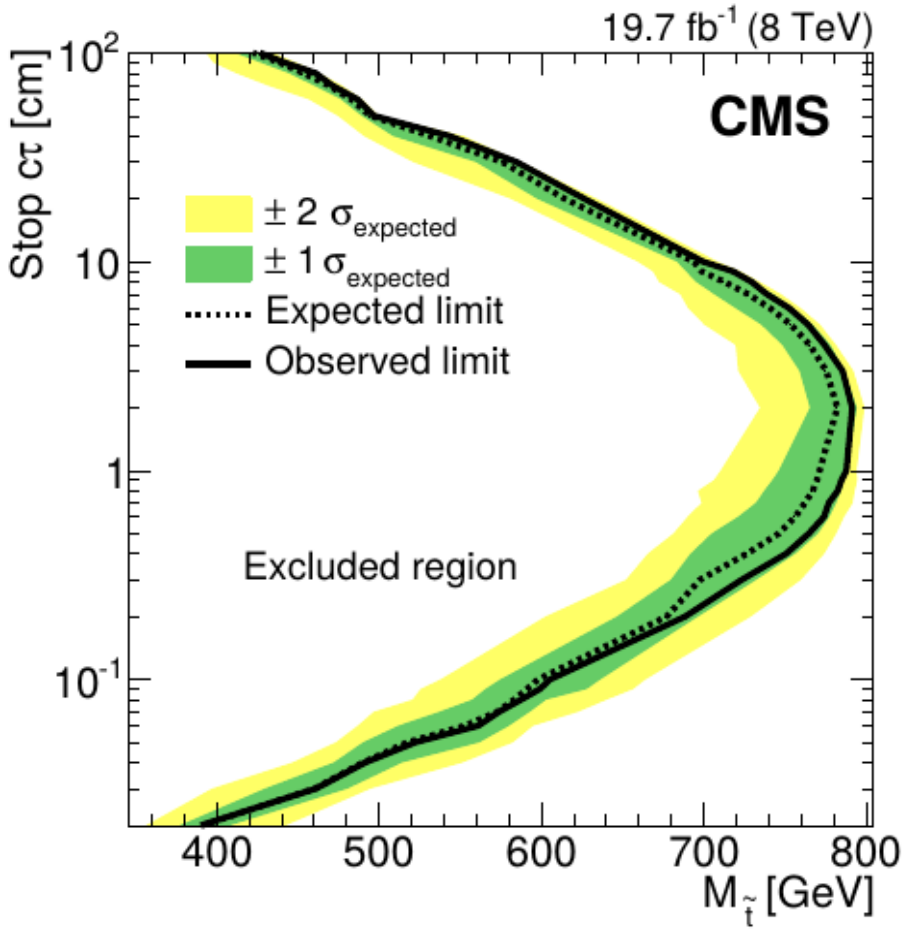
Finding the right point



It would also be very interesting to reinterpret prompt searches for LLPs

- prompt searches have implicit constraints on lifetime
- only really possible to reinterpret by rerunning the prompt analysis?
  - done by the prompt analysers, …or with RECAST ?





CMS displaced di-lepton search (13 TeV)

- top squark pairs → lepton pair (+2 b-jets)

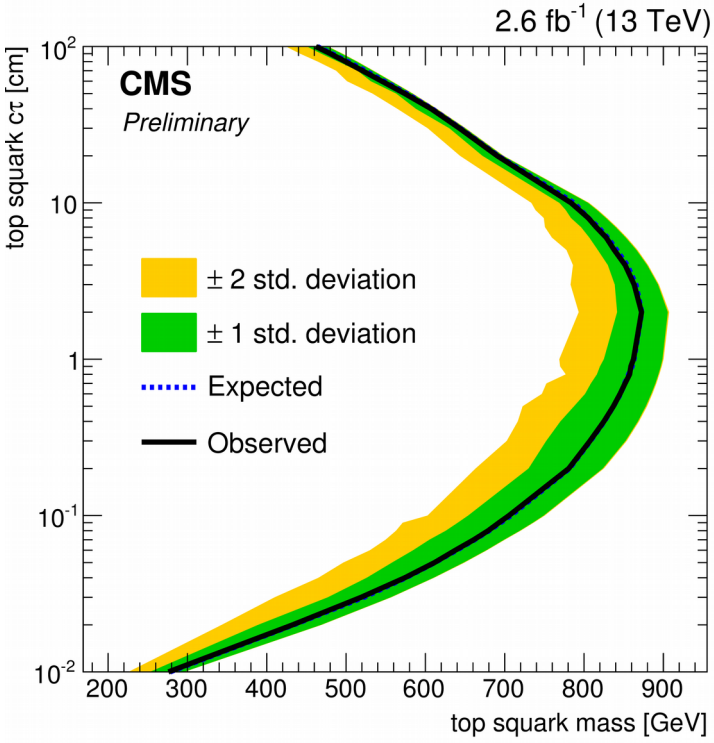
CMS-PAS-EXO-16-022
CMS-PAS-EXO-16-007

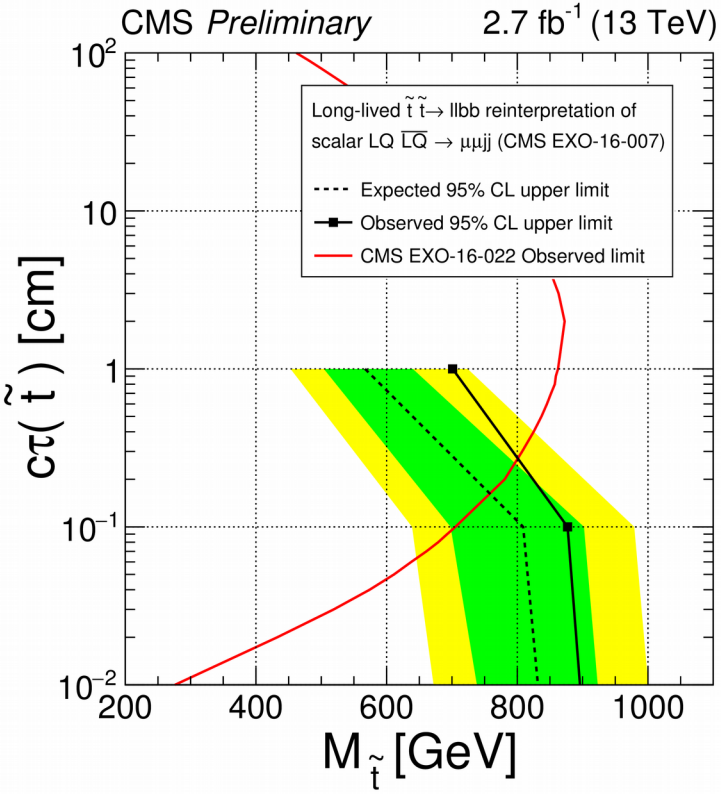
compared to search for (prompt) scalar leptoquarks

- leptoquark pairs → 2 muons + 2 jets

Running LLP signal sample through prompt search

→ prompt search sets tighter limits for $c\tau$ < ~3mm





Some benchmark models could be run through any prompt analysis…

- otherwise, getting relevant prompt analyses in RECAST may be the best option

Conclusion

LLP searches tend to focus on experimental signatures rather than specific models

- and reinterpretation is central to this idea

Experiments recognise the importance, and want to provide useful information

- already very active on reinterpretation, simplified models, ...
- material for reinterpretation should be published & put on HEPData
  - though not generally provided for preliminary results

LLP searches are a special case …

- very different experimental signatures, more challenging to parametrise

  ...but of course people will do it anyway!

In the white-paper, collect experience trying to reinterpret:

- Displaced leptons, jets, vertices, lepton-jets
- Disappearing tracks, Heavy Stable Charged Particles, Non-pointing Photons
- Prompt searches to set limits on LLPs
- Developing fast-sim

  → discussion on white-paper chapter tomorrow (in Trieste)

What should the experiments provide?

This is probably a trade-off between what people want and what is realistic

- ideally, efficiency maps for LLPs, vs mass/lifetime/decay mode of LLP
  - ie something approaching a fastsim for LLPs ...is not realistic in all cases
- how is the provided information used, and what precision is needed?
- this conversation needs to happen as early as possible...

Simplified models are closely related

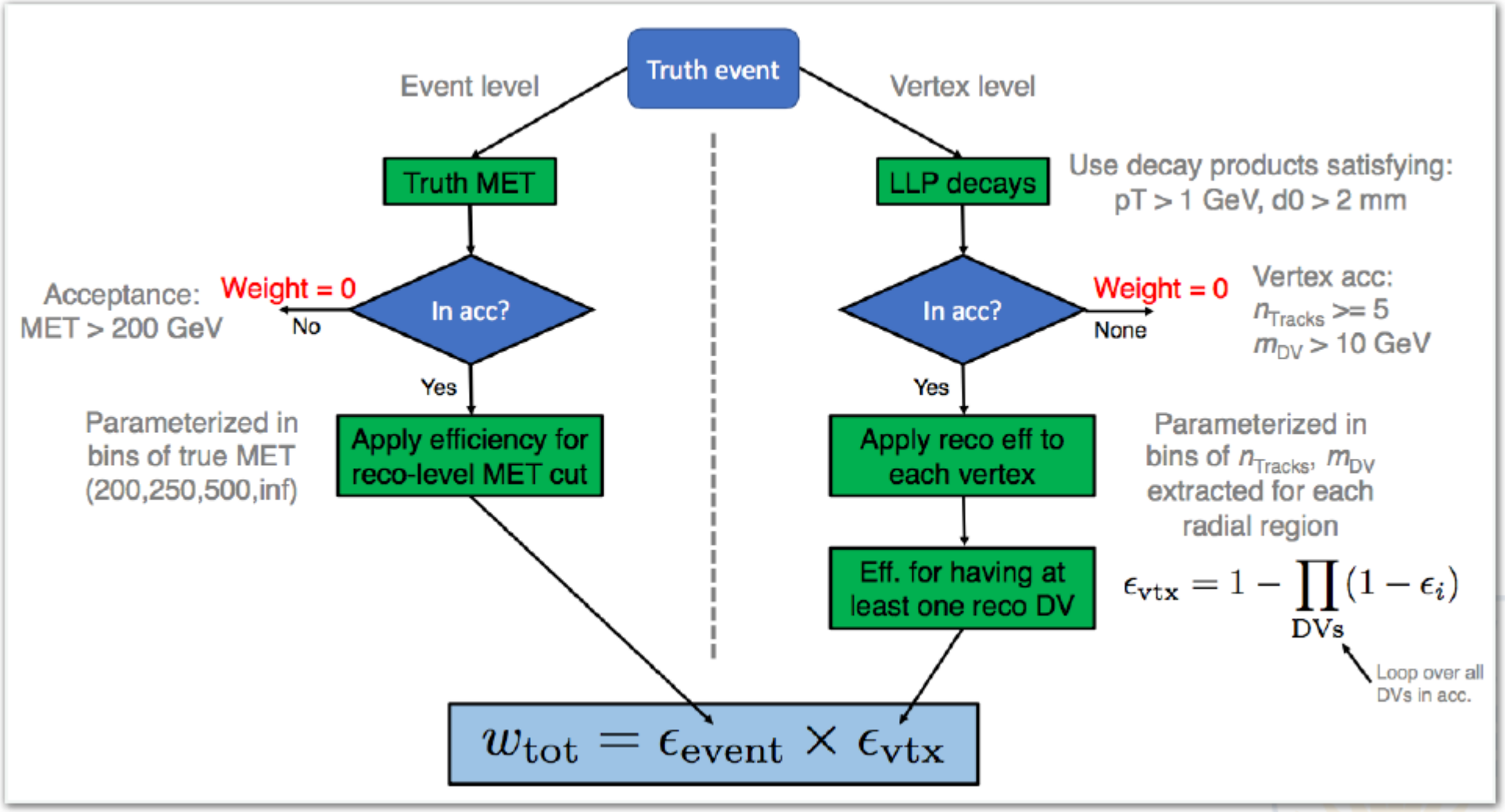
- efficiencies for a single model, as a function of mass/lifetime (which model?)
  - with cutflows / yields for a couple of benchmark reference points?
- efficiencies for a handful of models would allow easier interpolation
- comparing several models may motivate a new analysis, trigger, ….

In some cases, the object-based efficiencies are probably more useful

- eg the ATLAS displaced vertex provides a vertex efficiency vs mass, #tracks
- again, efficiencies for some simplified models/benchmarks needed?

Reinterpreting prompt searches for LLPs:

- benchmark simplified models to be tested with any relevant prompt searches?
- priority list of prompt searches to include in RECAST?


Truth event
Event level
Vertex level
Truth MET
LLP decays
Use decay products satisfying:
pT > 1 GeV, d0 > 2 mm
Acceptance:
MET > 200 GeV
Weight = 0
No
In acc?
In acc?
Weight = 0
None
Vertex acc:
n_{Tracks} >= 5
m_{DV} > 10 GeV
Yes
Yes
Parameterized in
bins of true MET
(200,250,500,inf)
Apply efficiency for
reco-level MET cut
Apply reco eff to
each vertex
Parameterized in
bins of n_{Tracks}, m_{DV}
extracted for each
radial region
Eff. for having at
least one reco DV
$\epsilon_{vtx} = 1 - \prod_{DVs}(1 - \epsilon_i)$
Loop over all
DVs in acc.
$w_{tot} = \epsilon_{event} \times \epsilon_{vtx}$