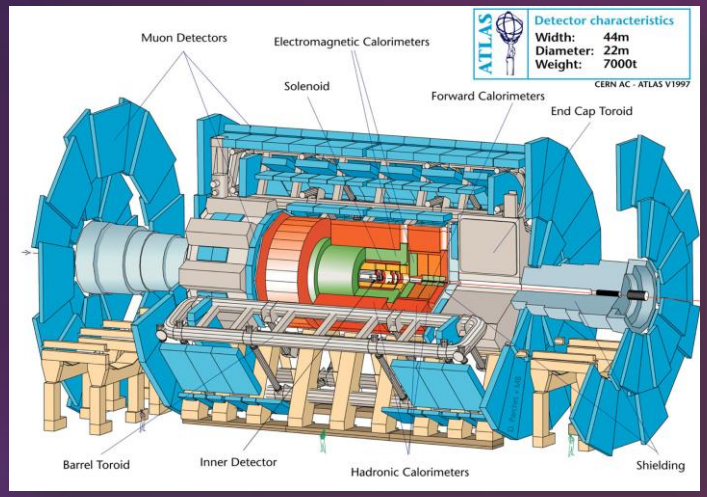


Living Long At the LHC

G. WATTS (UW/SEATTLE/MARSEILLE)

WG3: EXOTIC HIGGS DECAYS @ FERMILAB

MAY 21, 2015

What is long lived?

For me, started with the worry we'd miss the Standard Model Higgs

SM couplings still allow a lot of room for something new… But what!?

Can't be too driven by a model… but can't ignore them completely!

Be as final state and model independent as possible

Jets

Flavor
Further Displaced Vertices

Lepton Jets

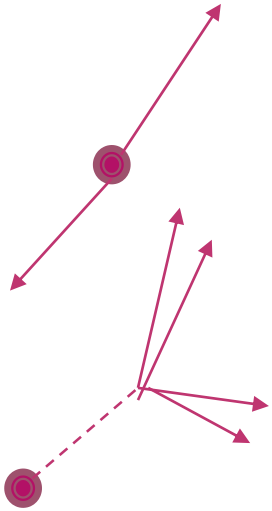
# of leptons
Lepton Flavor(s)

L_{xy} p_T

How are we going to look for it?

Topologies

Two jet decays



Single jet decays

Final States

Jets

Lepton Jets ⇒ Where did it decay?

Additional cuts as needed to reduce background…


Reality
Dream

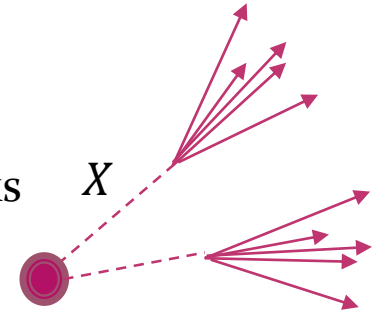
- Hadronic Signatures
- Lepton Jets
- Miscellaneous
- Comments & Conclusions

Hadronic Jets

ATLAS Displaced Jets

Numerous models generate a Displaced Jet signature:

- Requires decays to SM quarks from a hidden sector
- HV, Stealth SUSY, HV Z', etc. are examples used as benchmarks



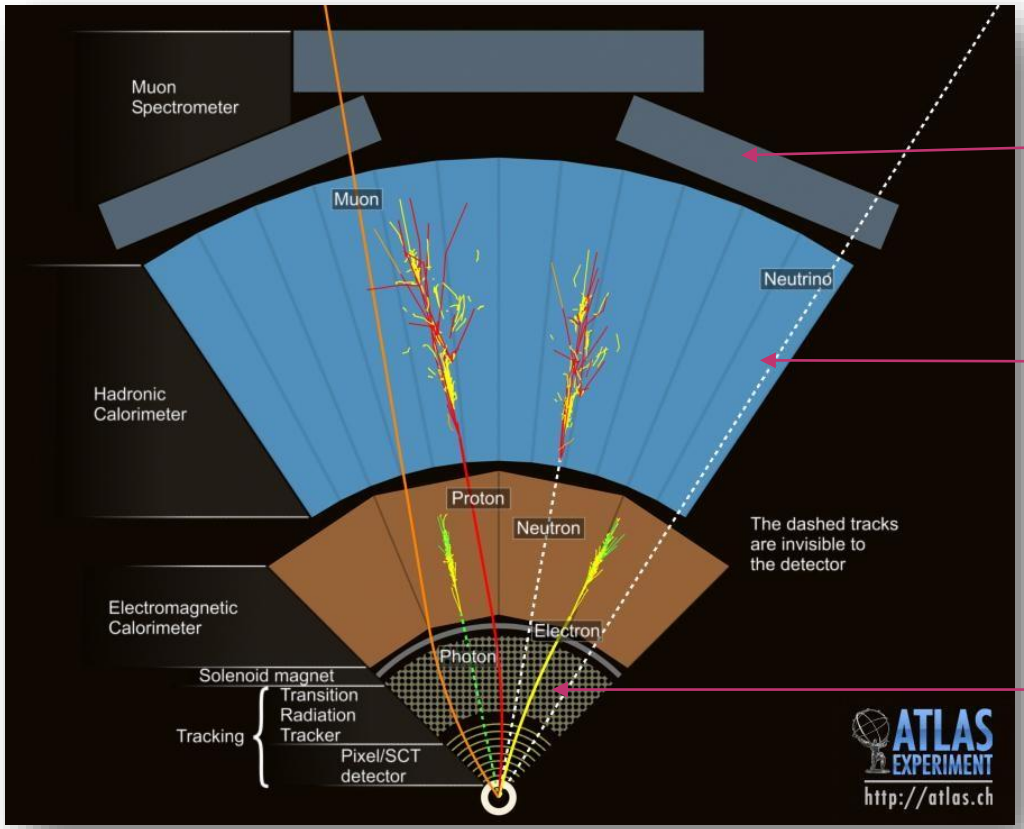
Require evidence of two displaced jets

- Keep backgrounds under control

Detector signature evolves with decay length

- Decay in each sub-detector is a new analysis

ATLAS Displaced Jets



Jet of particles in the Muon Spectrometer

Trackless, low EMF Jet

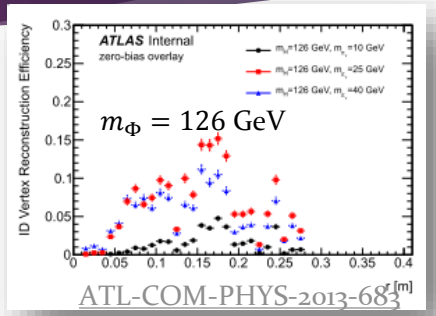
Displaced Vertex

ATLAS Displaced Jets

Inner detector

Vertexing, looser track impact parameter cuts than normal vertexing

Sensitivity: 4 cm – 27 cm

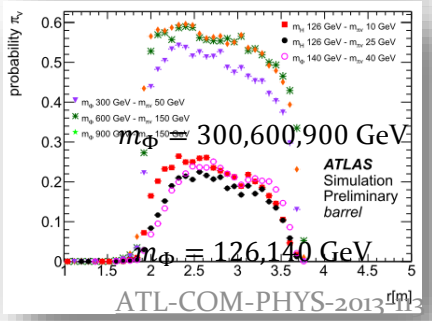


ATL-COM-PHYS-2013-683

Calorimeter

Tracking veto, late calorimeter development ($\log_{10} E_H/E_M$)

Sensitivity: 1.75 m - 3.75 m

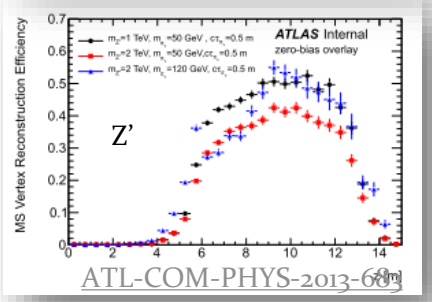


ATL-COM-PHYS-2013-[illegible]

Muon Spectrometer

Tracking & Jet veto, vertexing in the MS

Sensitivity: 4.5 m – 14 m



ATL-COM-PHYS-2013-683

http://arxiv.org/abs/1305.2284

ATLAS Displaced Jets

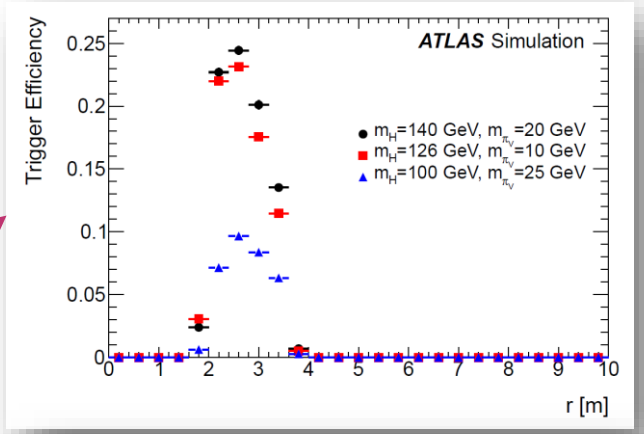
Look for associated production

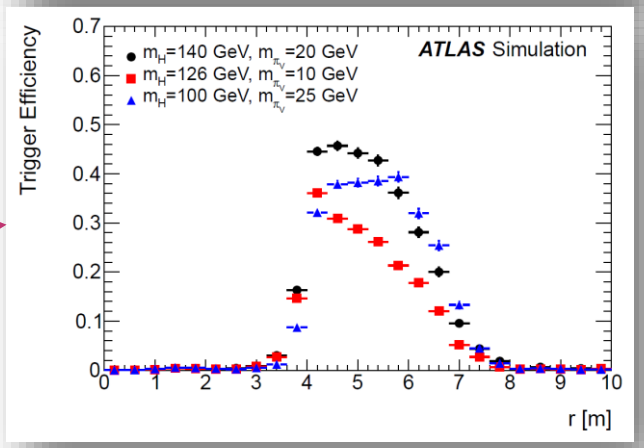
Can use standard triggers
Take a hit in cross section!

Custom **trigger** to look for the signal

- Jet that decays late in the calorimeter (little or no EM calorimeter energy deposit)
- No tracks with $p_T > 1$ GeV before it

- Three or more muon hit clusters (RoI's)
- No tracks with $p_T > 5$ GeV
- No EM jets with $E_T > 30$ GeV

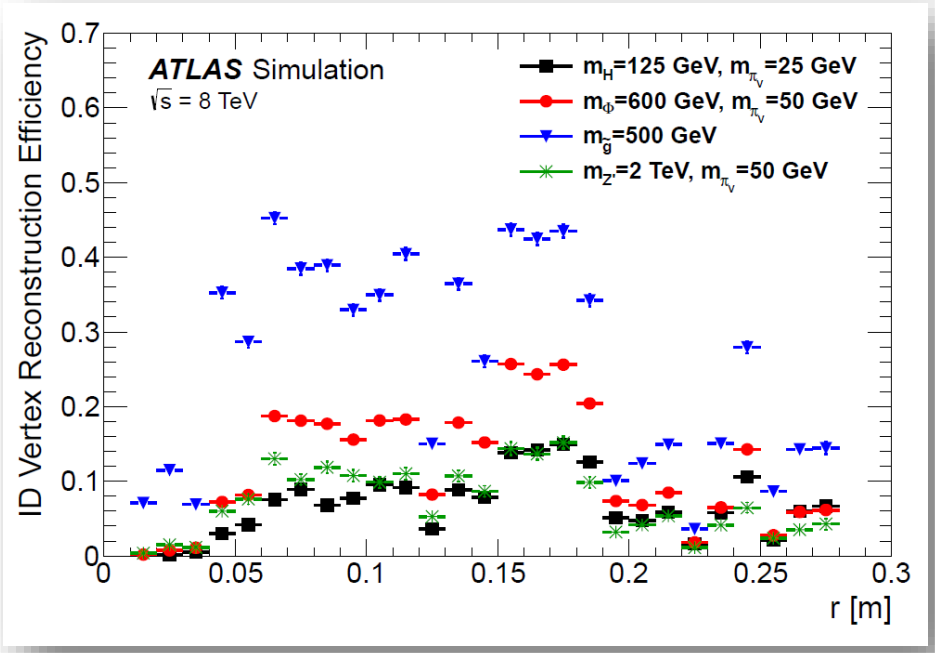




ATLAS Displaced Jets

Inner Detector Vertex Reconstruction

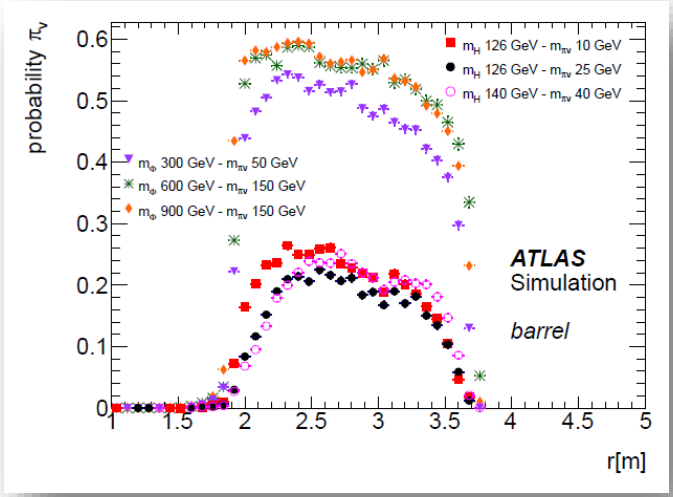
- A high d_0 optimized tracking algorithm is run, picking up hits unused by default track finding algorithm.
- Only tracks with $d_0 > 10$ mm considered.
- Material veto to reduce detector interactions
- At least 5 or 7 tracks in vertex, depending on search channel



ATLAS Displaced Jets

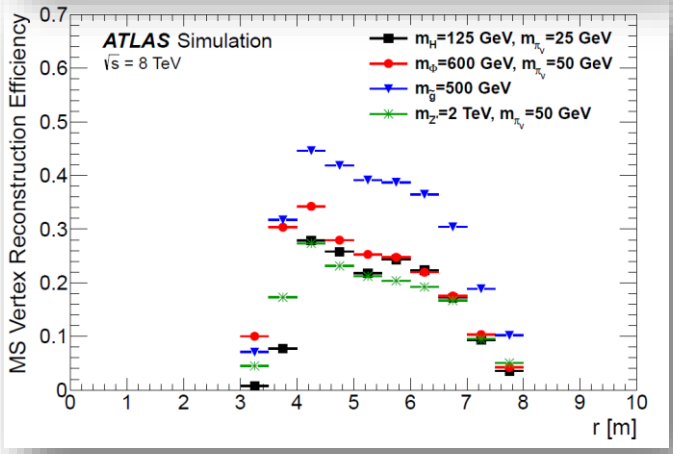
CalRatio Jet Finding

- Jets $E_T > 40/60$ GeV
- $\log\left(\frac{E_{HAD}}{E_{EM}}\right) > 1.2$
- No tracks near by with $p_T > 1$ GeV



Muon Spectrometer Vertexing

- Custom vertex finding algorithm
- Tracklets formed from MS hits
- Tracklets are fit to a vertex using a custom vertex finding algorithm
- Track and jet isolation similar to trigger level cuts

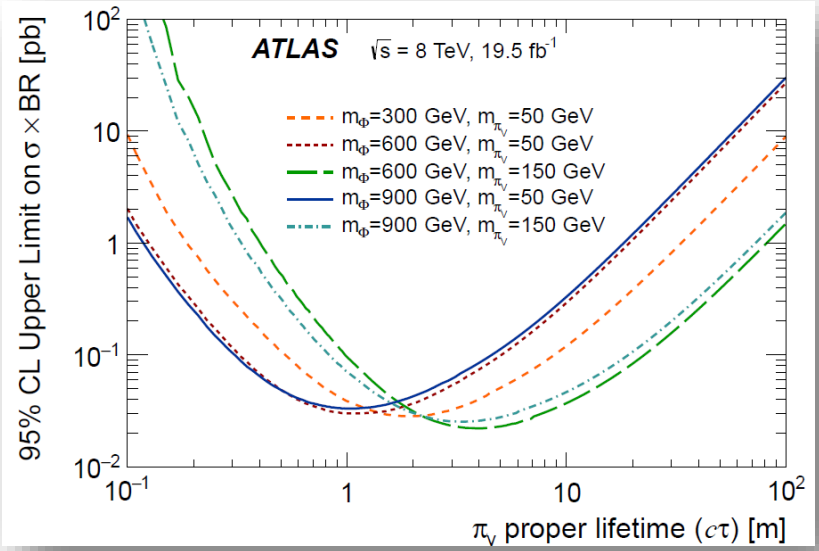


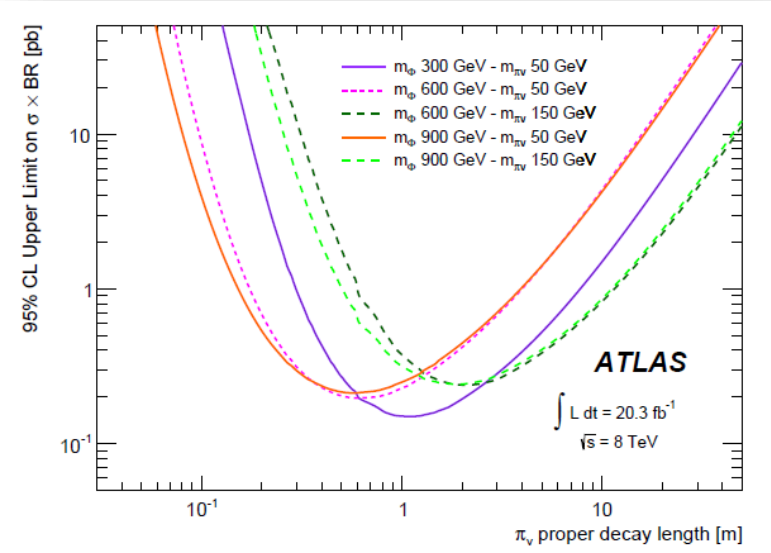
ATLAS Displaced Jets

Jet (>110 GeV) + missing E_T > 75 GeV	Displaced Trigger	Topology (Vertex Locations)	
Yes	-	2 ID	Combined
Yes	MS	ID + MS	
Yes	MS	2 MS	
-	CalRatio	2 CalRatio	

Limits are derived for each of the various senarios

ATLAS Displaced Jets





http://arxiv.org/abs/1504.05162

ATLAS DV and 2 Lepton Search

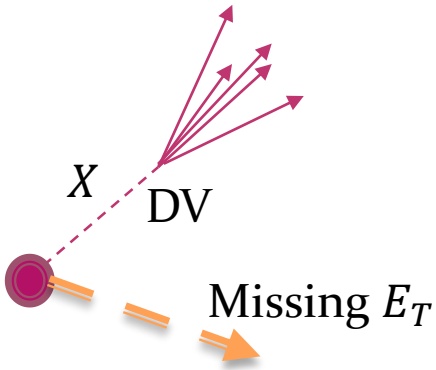
Searches optimized for for RPV SUSY, split SUSY, GMSB

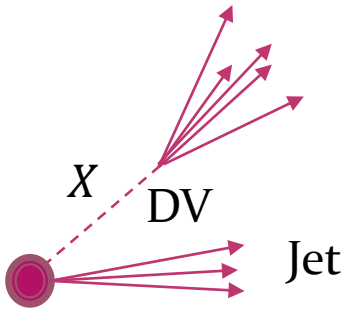
⇒ Long lived: both decays to leptons and to jets!

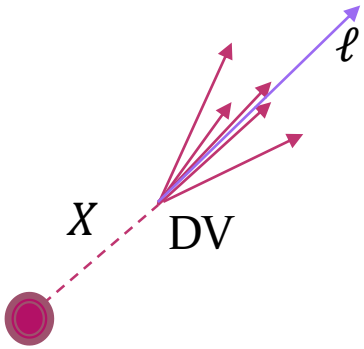
2μ → Single Muon $p_T > 50$ GeV

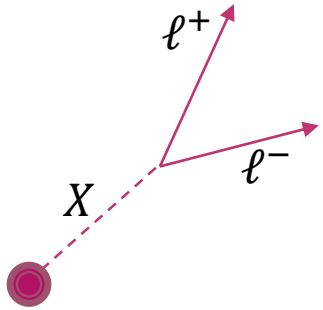
$2e$ → Single Photon $E_T > 120$ GeV or 2 photons $E_T > 40$ GeV

DV+
- High p_T lepton → Same as 2ℓ triggers
- Missing E_T → Missing $E_T > 80$ GeV
- Jet → 4j80, 5j55, 6j45





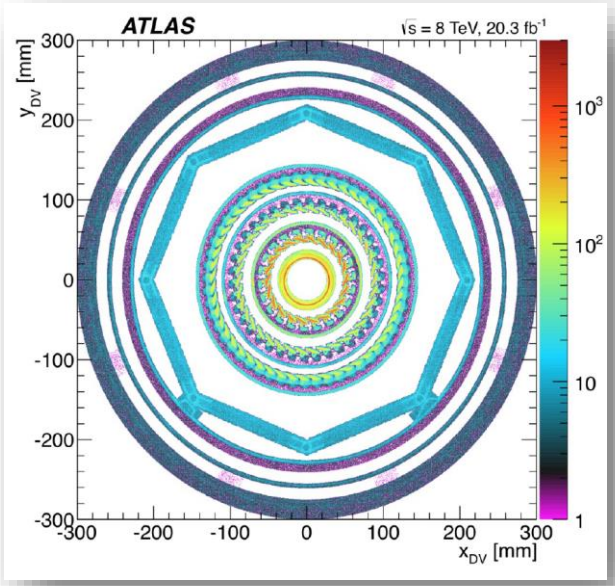




ATLAS DV and 2 Lepton Search

Displaced Vertex

- ≥ 5 tracks
- $m_{DV} > 10$ GeV
- Material Veto
- Track's have no hits inside vertex position



+ 1 e $p_T > 125$ GeV

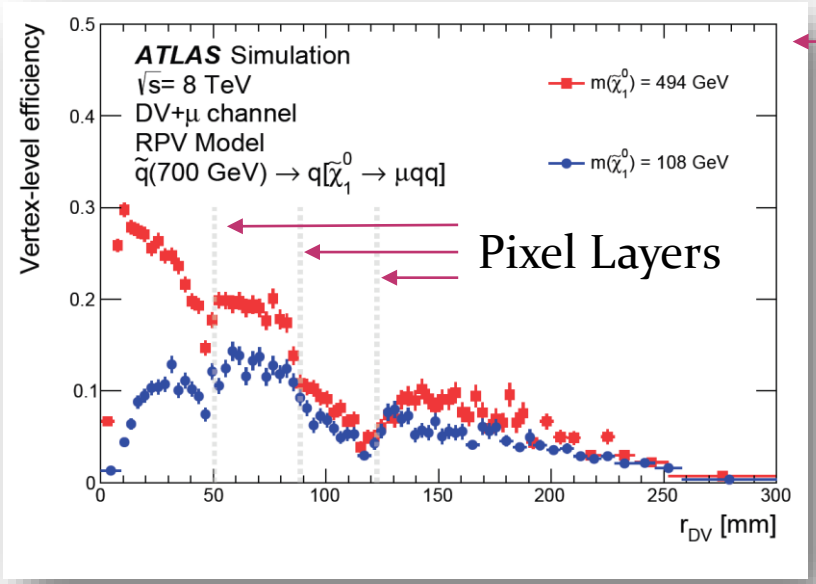
+ 1 μ $p_T > 55$ GeV

+ 4j90, 5j65, or 6j55

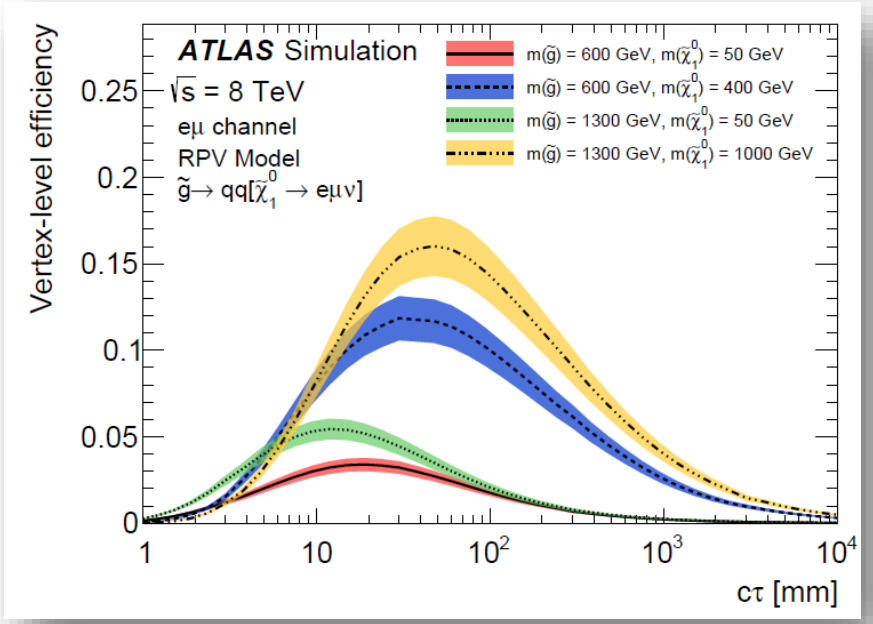
+ missing $E_T > 180$ GeV

Or $\ell^+\ell^-$ each with $p_T > 10$ GeV
And form a displaced vertex

ATLAS DV and 2 Lepton Search

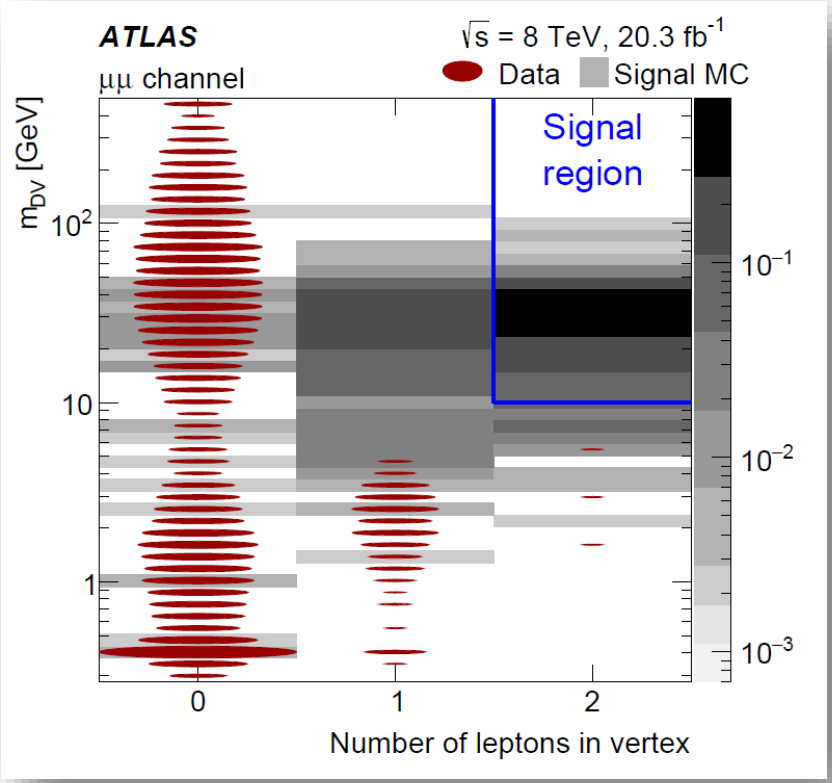


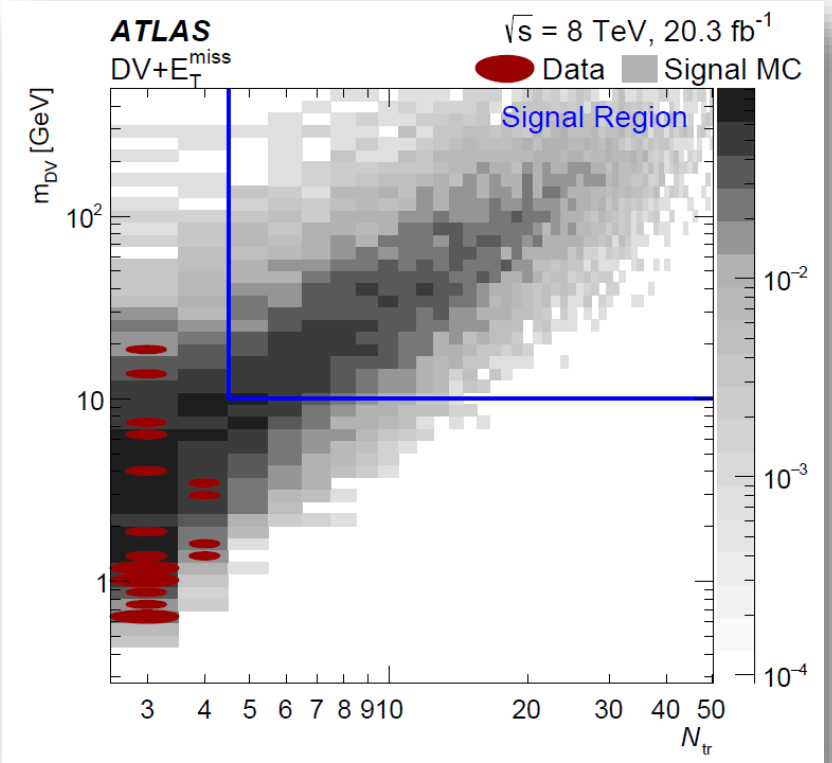
The vertex reconstruction efficiency



Vertex efficiency for $e\mu$ events (extrapolated to different $c\tau$)

ATLAS DV and 2 Lepton Search

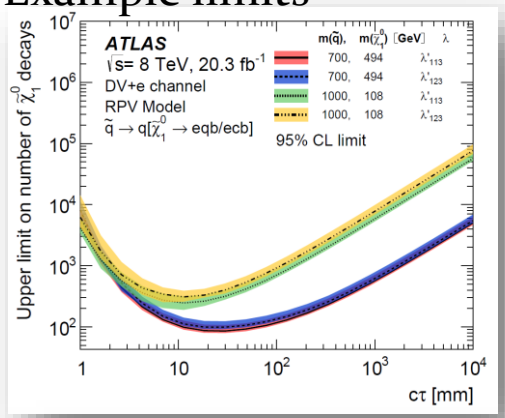


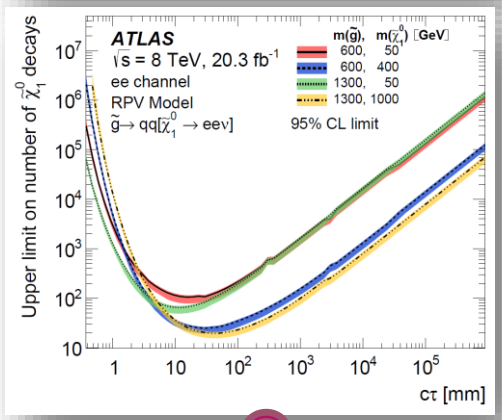


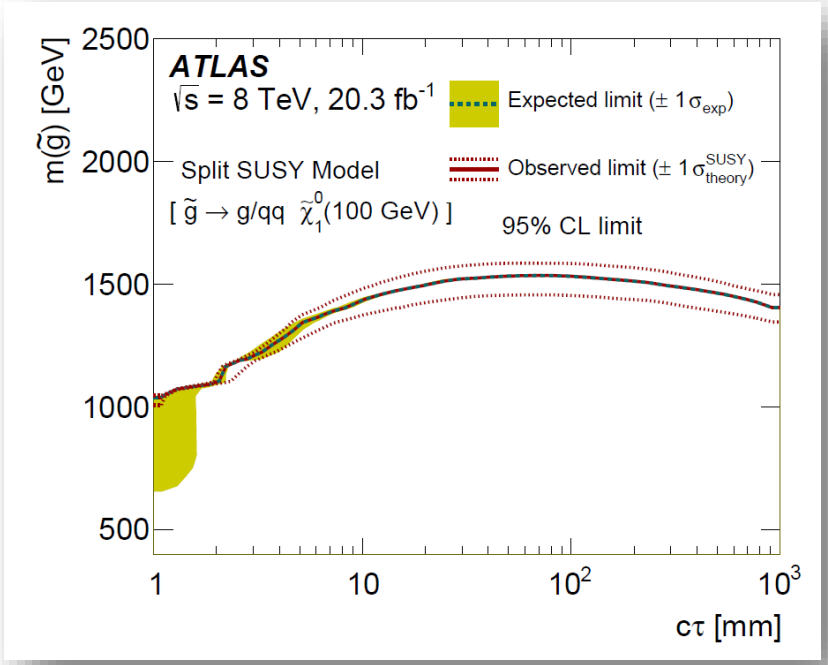
Complex background model (Control Regions simultaniously fit)

ATLAS DV and 2 Lepton Search

Example limits







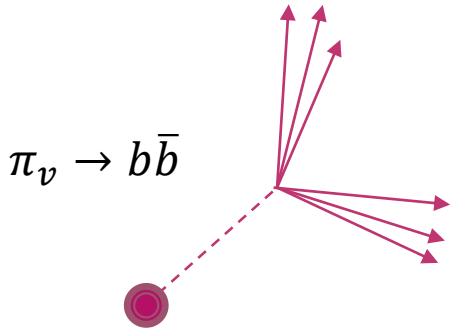
Combine by taking channel with most stringent limit at each $c\tau$

2 Jets from one Vertex

Two jets coming from a single vertex

- Only requires a single LLP
- Mass cut possible in a way it isn't in other search topologies

- The longer L_{xy} the harder it is to separate jets
  - Detector resolution
  - Opening angle



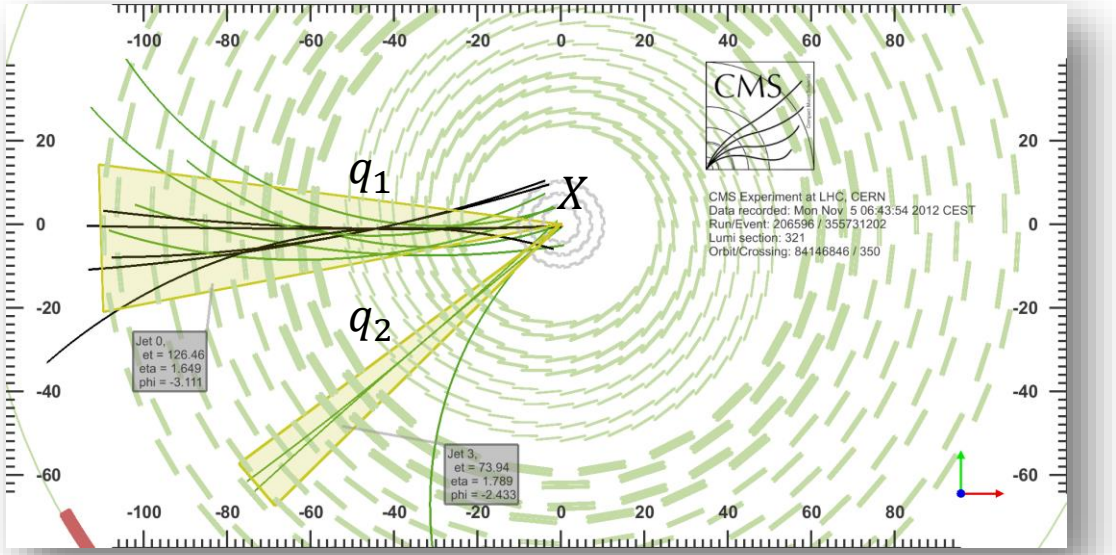
Pro: Can do a mass cut

http://arxiv.org/abs/1411.6530

CMS 2-Jet Vertex Search

$H \rightarrow XX \rightarrow q_1\overline{q_2}q_3\overline{q_4}$

Only interested in one $X \rightarrow q_1\overline{q_2}$



All the models in the paper expect two of these displaced vertices

The trigger is a hybrid

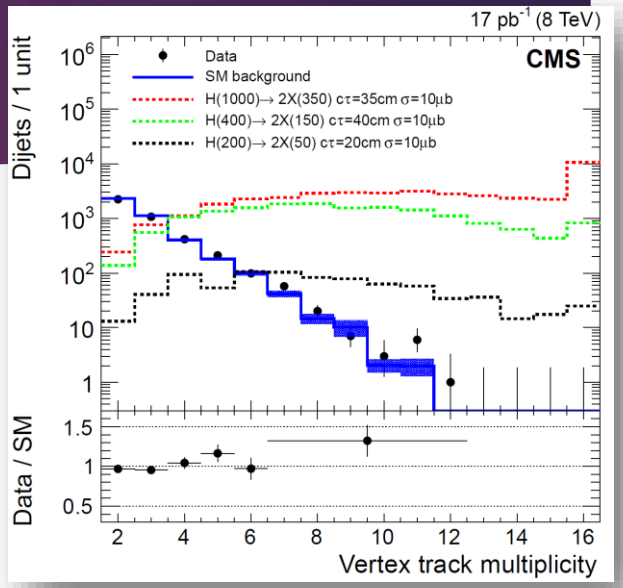
- $H_T > 300$ GeV
- At least two jets $p_T > 60$ GeV
- 2 tracks or less with $d_0 < 300\ \mu$m
- 15% or less of energy of tracks near jets with $d_0 < 500\ \mu$m

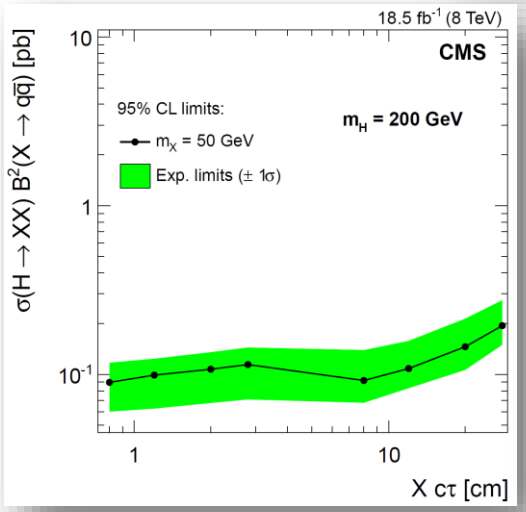
"Nothing but b-tag"

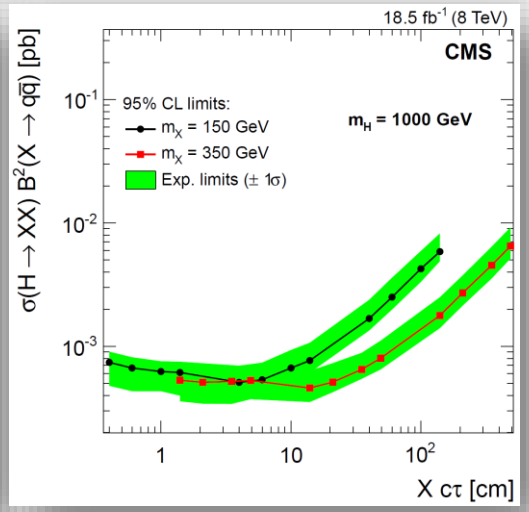
CMS 2-Jet Vertex Search

The Secondary Vertex:

- Displaced tracks from 2 jets ($d_0 > 500\mu$m).
- Vertex fit using adaptive method
- Various quality cuts (e.g. mass, etc.) to reduce background
- Likelihood:
  - # of tracks in vertex
  - Sign of impact parameter of tracks
  - Track-cluster consistency (L_{xy} vs L_{xy}^{track})







http://arxiv.org/abs/1412.3021

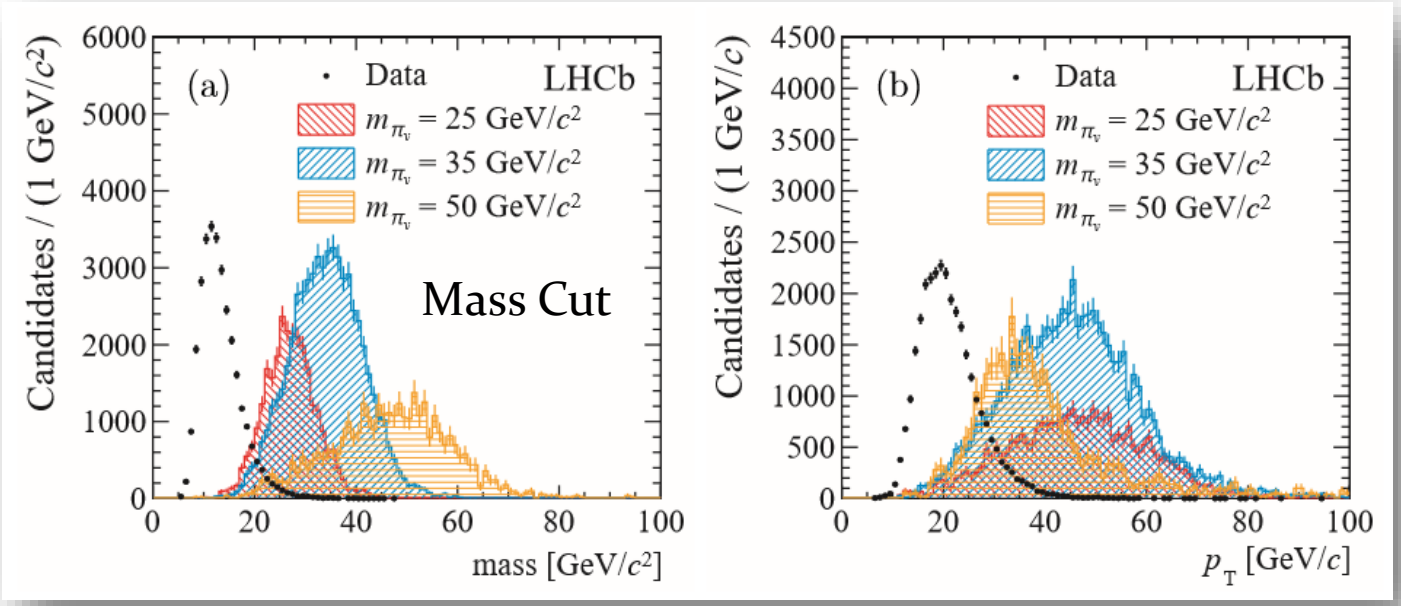
LHCb 2-Jet Vertex Search

7 TeV Result

Use Particle Flow (Jet Reco)

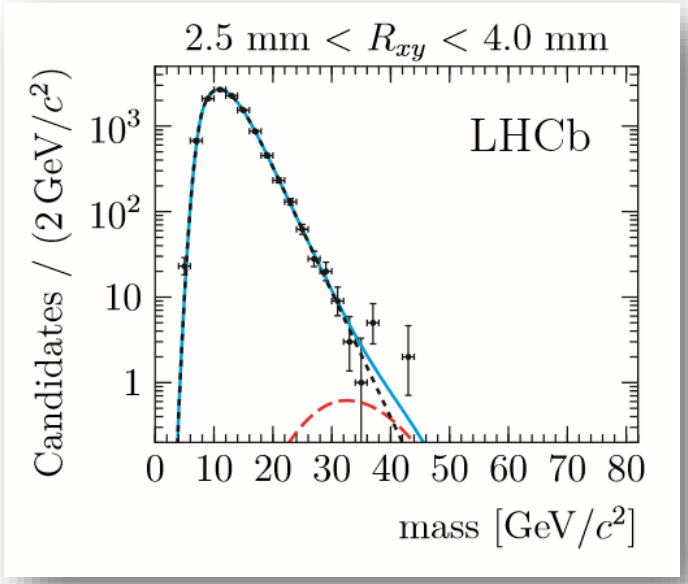
- Differentiate between energy from neutrals and charged particles
- Association gives energy that comes from only displaced tracks/vertex
- Require > 10% of jet's energy from tracks that are displaced.

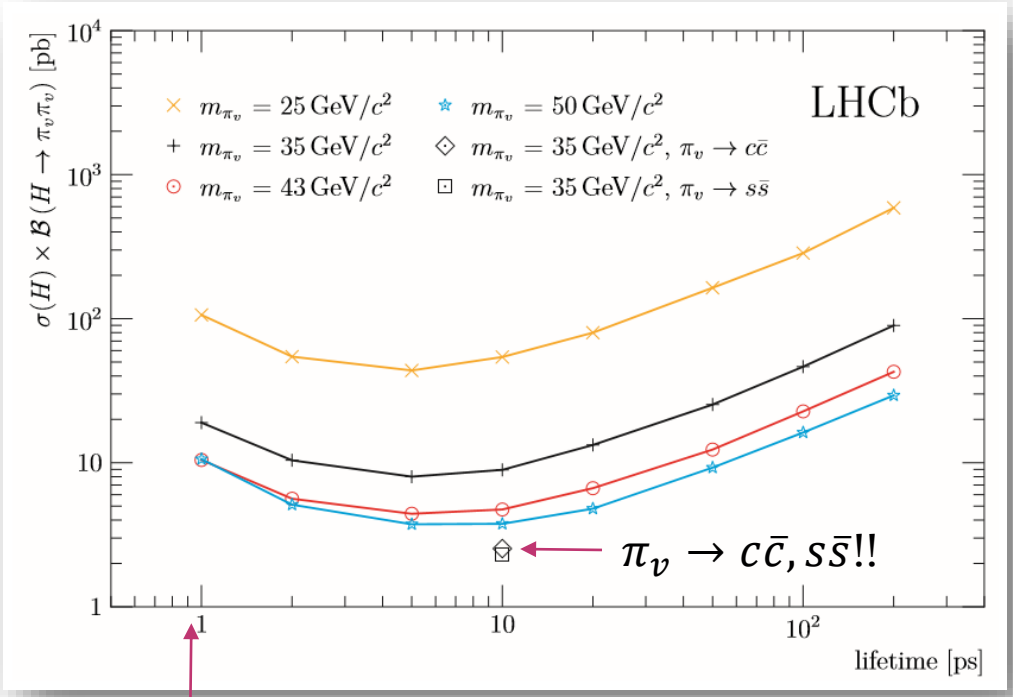
$m_H = 120$ GeV



LHCb 2-Jet Vertex Search

Use the m_{jj} spectrum to determine background (extrapolation)





Down to $c\tau$~0.1

Lepton Jets

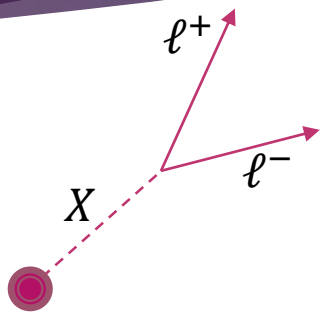
CMS Displaced 2-Lepton Jets

Look for two leptons originating from a displaced vertex

$H \to XX \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$
$\tilde{q} \to \tilde{\chi}^0, \tilde{\chi}^0 \to \ell^+\ell^-\nu$

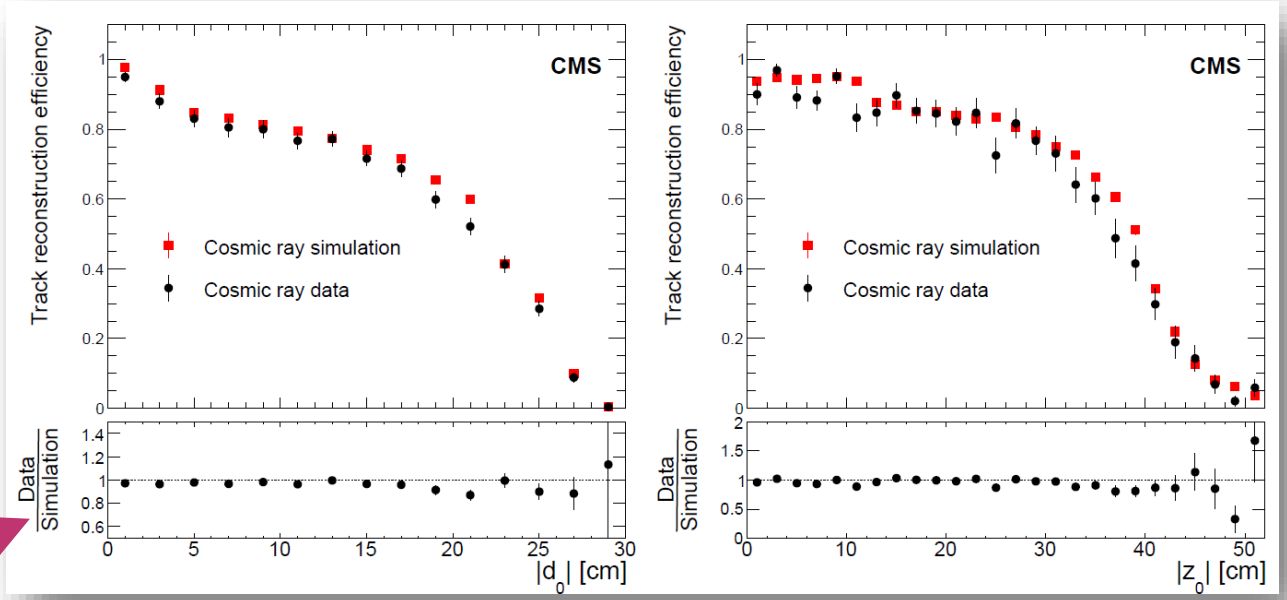
} Both predict two displaced vertices

↳ But only one required



Two track vertex fit

- Large d_0 tracks!!
- With no more than one hit along the track's trajectory before the vertex
- Vertex must be approximately inline with PV
- Use Cosmics to study



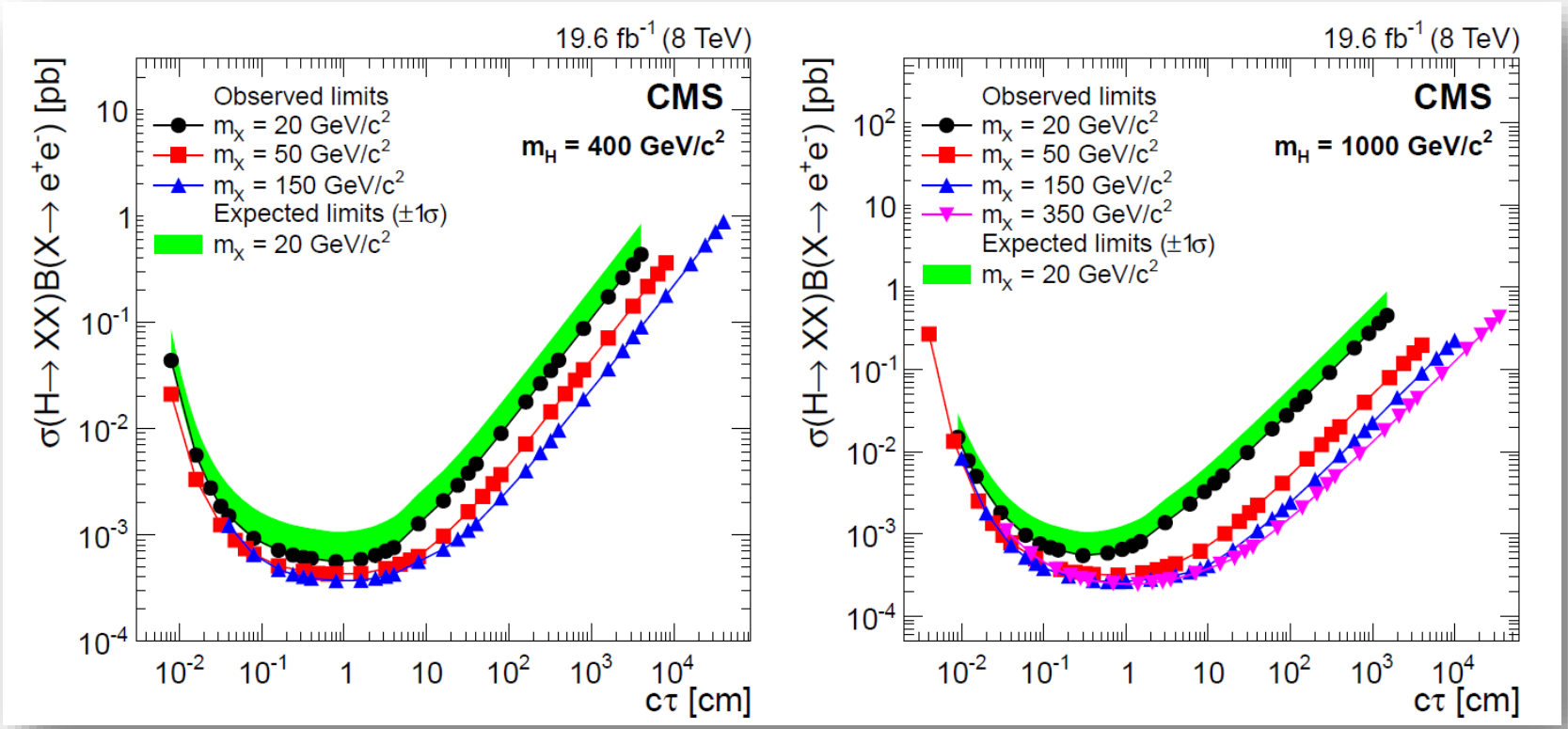
CMS Displaced 2-Lepton Jets

Trigger:

- μ: $p_T > 23$ GeV (di-muon)
- e: $E_T^1 > 36, E_T^2 > 22$ GeV (di-electron)

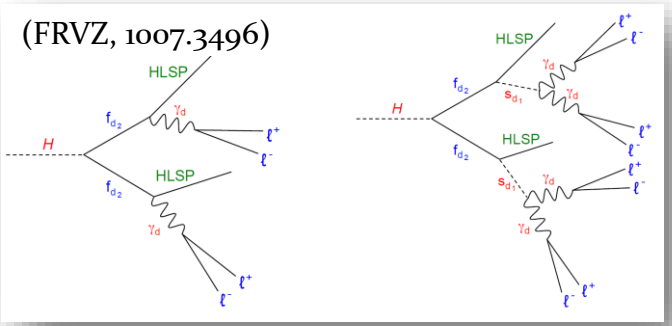
Reject electrons that brem by comparing E_T and p_T.

- Impact parameter measurement is poor



http://arxiv.org/abs/1409.0746

ATLAS Displaced Lepton Jets



Dark photon decays to standard model leptons if it's mass is MeV-GeV

4-8 leptons in these models

Search optimized for 1 or 2 γ_d in a lepton-jet

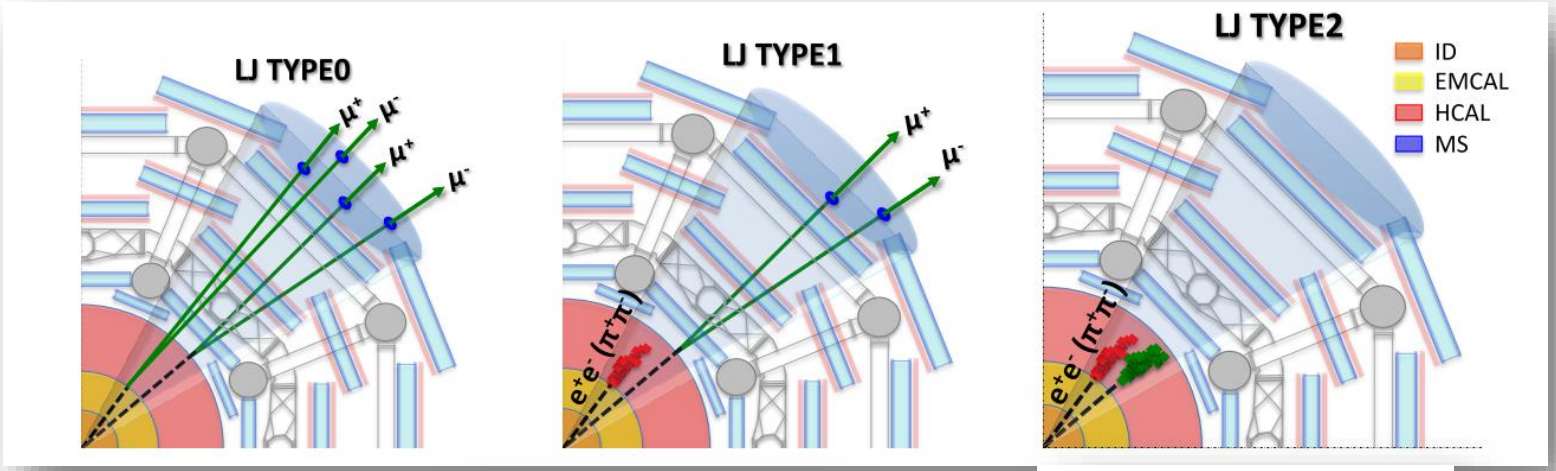
An attempt to be as inclusive as possible:

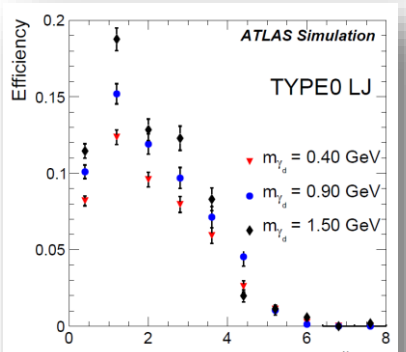
- Possible Decays: $\gamma_d \rightarrow ee, \mu\mu, \pi\pi$
- Signature depends on L_{xy} and number of γ_d

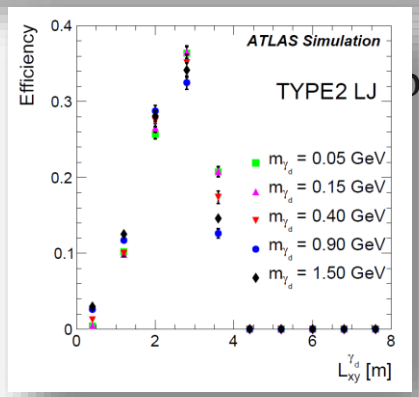
μ: a stand-alone muon (no evidence in the inner tracker or calorimeter)
e, π: A late decaying jet in the calorimeter (low EMF)

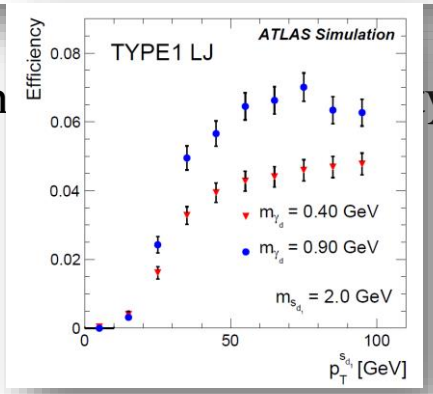
ATLAS Displaced Lepton Jets

Use # of high p_T muons to categorize:





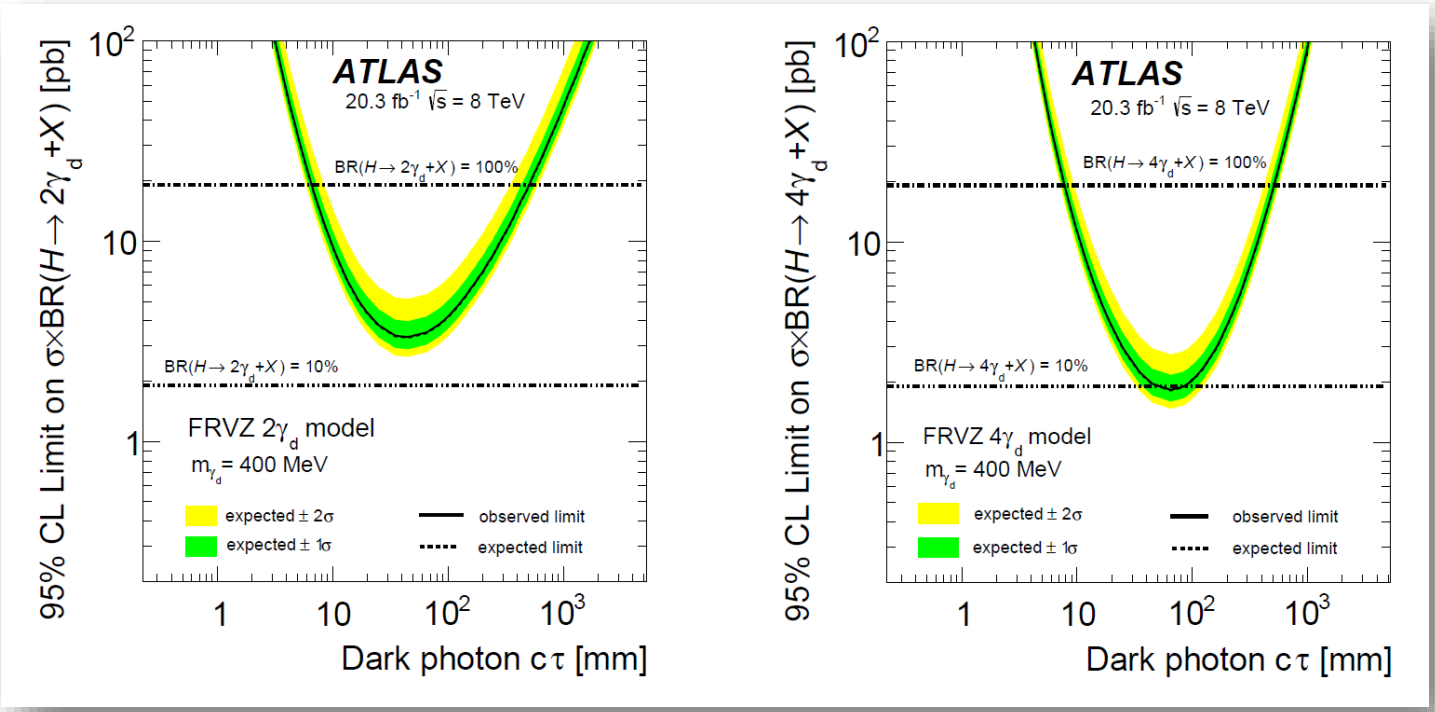




background ype!

ATLAS Displaced Lepton Jets

Trigger: 3μ with $p_T > 6$ GeV and no mating inner track
Or a CalRatio trigger (LJ Type 2)

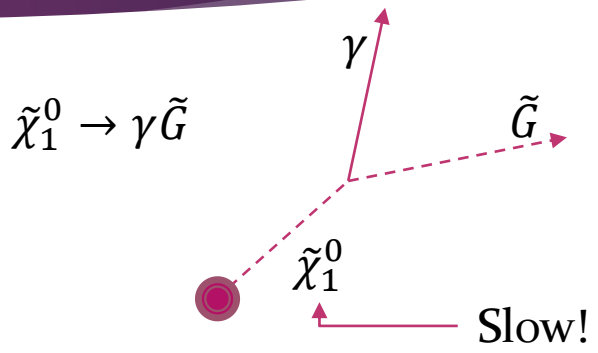


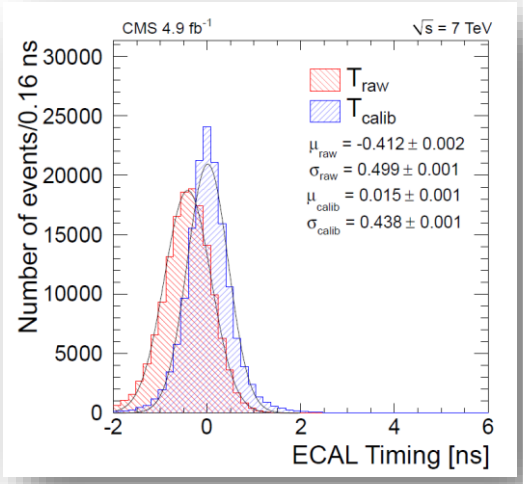
Miscellaneous

http://lanl.arxiv.org/abs/1212.1838

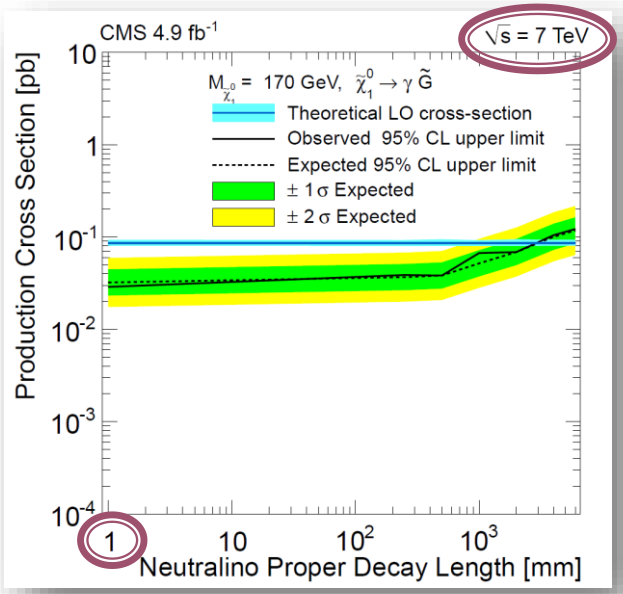
CMS LL Slow Particles Decaying to Photons

SUSY Production
- GMSB (Snowmass Points/Slopes 8)
- R Parity Conservation, Neutralino production, gravatino is LSP, $\tilde{\chi}_1^0$ long lived
- Photon's not always produced in pairs
  - (Other decay channels)





- ±1 ns timing resolution
- Segmentation in EM Cal to look at shape of deposit
  - Non prompt γ shape is different



http://arxiv.org/abs/1411.6795

ATLAS Long Lived Charged Particle Search

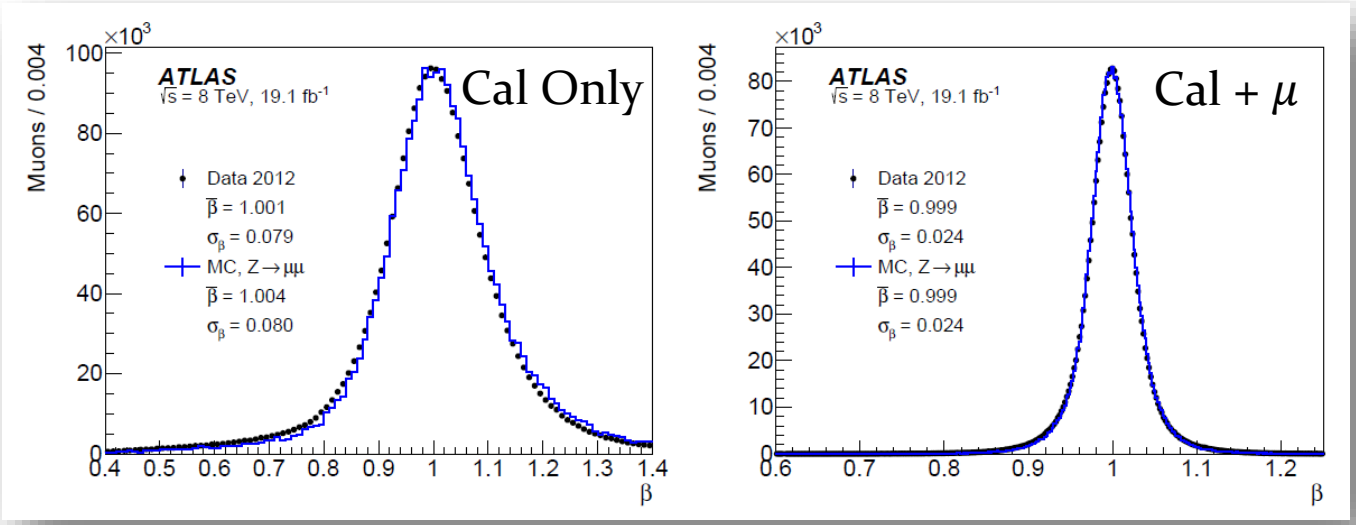
SUSY search, looking for long lived $\tilde{q}$, $\tilde{\ell}$, $\tilde{g}$ (traverse the detector)

⇒ They are heavy and they are slow

$$m = p/\beta\gamma$$

Two techniques:

- β – Time of Flight (muon system)
- dE/dx – Pixel system



Ignored

- Looking at inactive crossings:
  - CMS stopped long-lived particles: http://arxiv.org/abs/1501.05603
  - ATLAS Long Lived Stopped Hadrons: http://arxiv.org/abs/1310.6584
- ATLAS disappearing track analysis ($\tilde{\chi}^{+} \rightarrow \tilde{\chi}^{0} X$): http://arxiv.org/abs/1310.3675
- ATLAS Heavy long lived charged particles: http://arxiv.org/abs/1411.6795

Conclusions

WHY HAVE ONLY ONE SLIDE?

Detectors Are Different

CMS has amazing tracking

- Can find tracks with a d_0 up to 25 cm from the production vertex
- Can find tracks from a secondary decay as far away as 50 cm from the production vertex
- Also works with prompt tracks…

ATLAS' Muon Spectrometer can be used stand-alone

- Multiple layers allows for high-impact parameter local track finding
- Vertexing possible as well, allowing for real, but crude, vertex detection at L_{xy} of meters
- Also very good at prompt 4ℓ channel.

$c\tau$ extrapolation is non-trivial

Side comment:

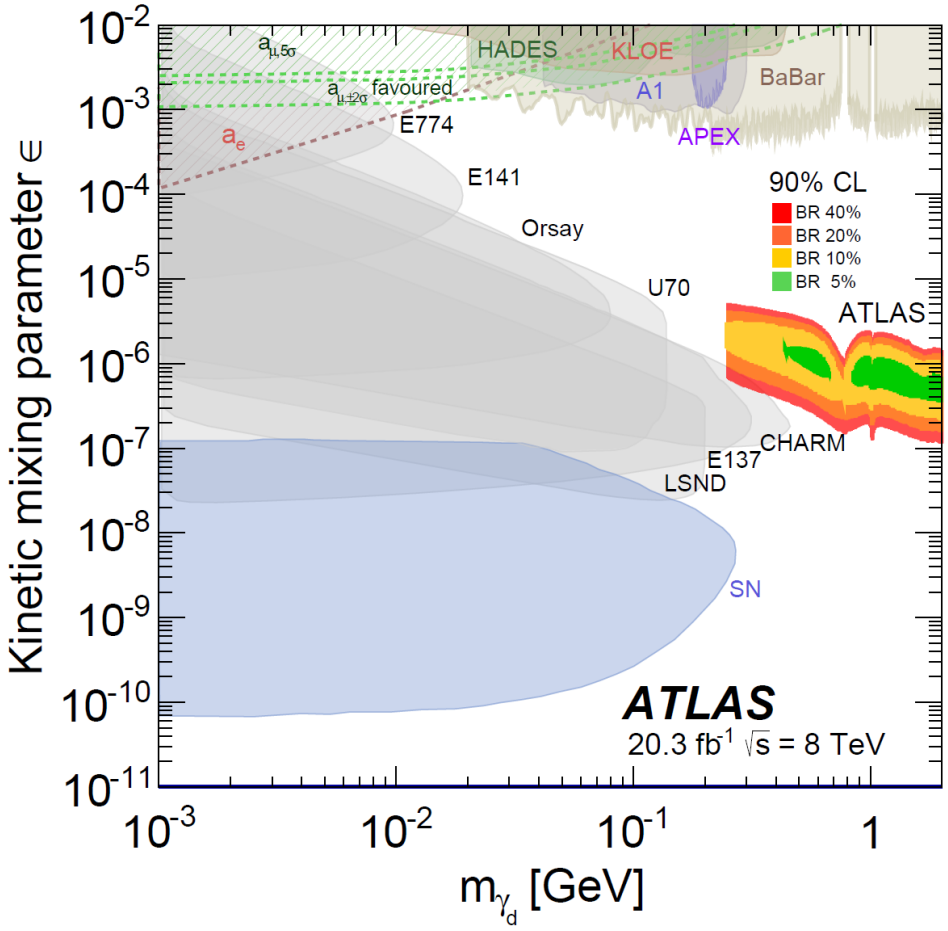
Timing cuts exist:
- Explicit in the measurement, or
- The timing window for the experiment trigger

Combinitorics:
- More than one LL particle in each event

Start With:
- A limit at a single proper lifetime
- Range of actual lifetimes may be limited for distribution expected for long proper lifetimes!

⇨ Toy-MC often used to extrapolate

Summary Plots

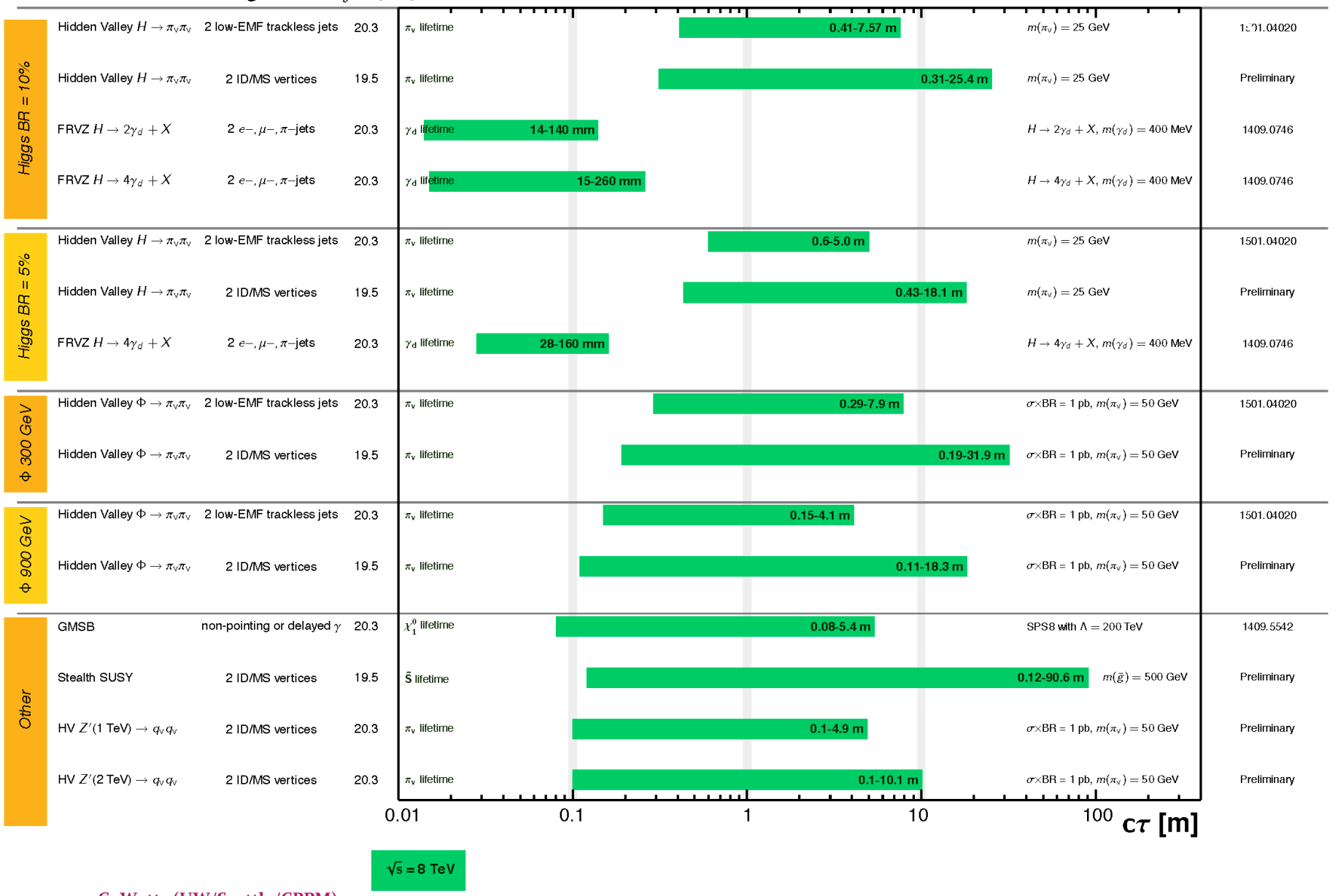


ATLAS Exotics Long-lived Particle Searches* - 95% CL Exclusion

Status: March 2015

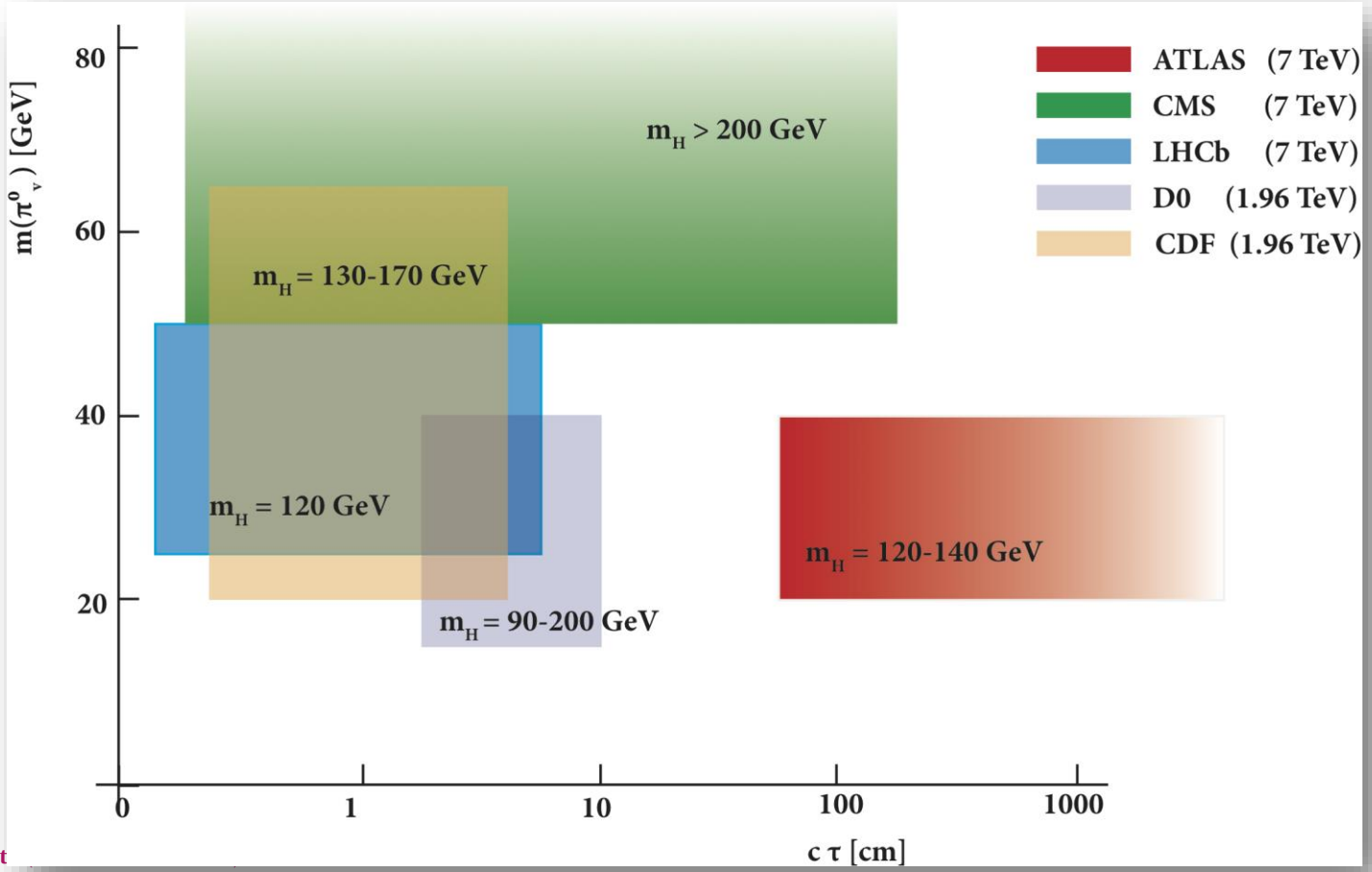
ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (19.5 - 20.3) fb^{-1} $\sqrt{s}$ = 8 TeV



*Only a selection of the available lifetime limits on new states is shown.

The Reach of the experiments



(old)

Run 2

$\sqrt{s}$ and Luminosity Upgrade

Run 2 has enough luminosity we can really look at WH finally?

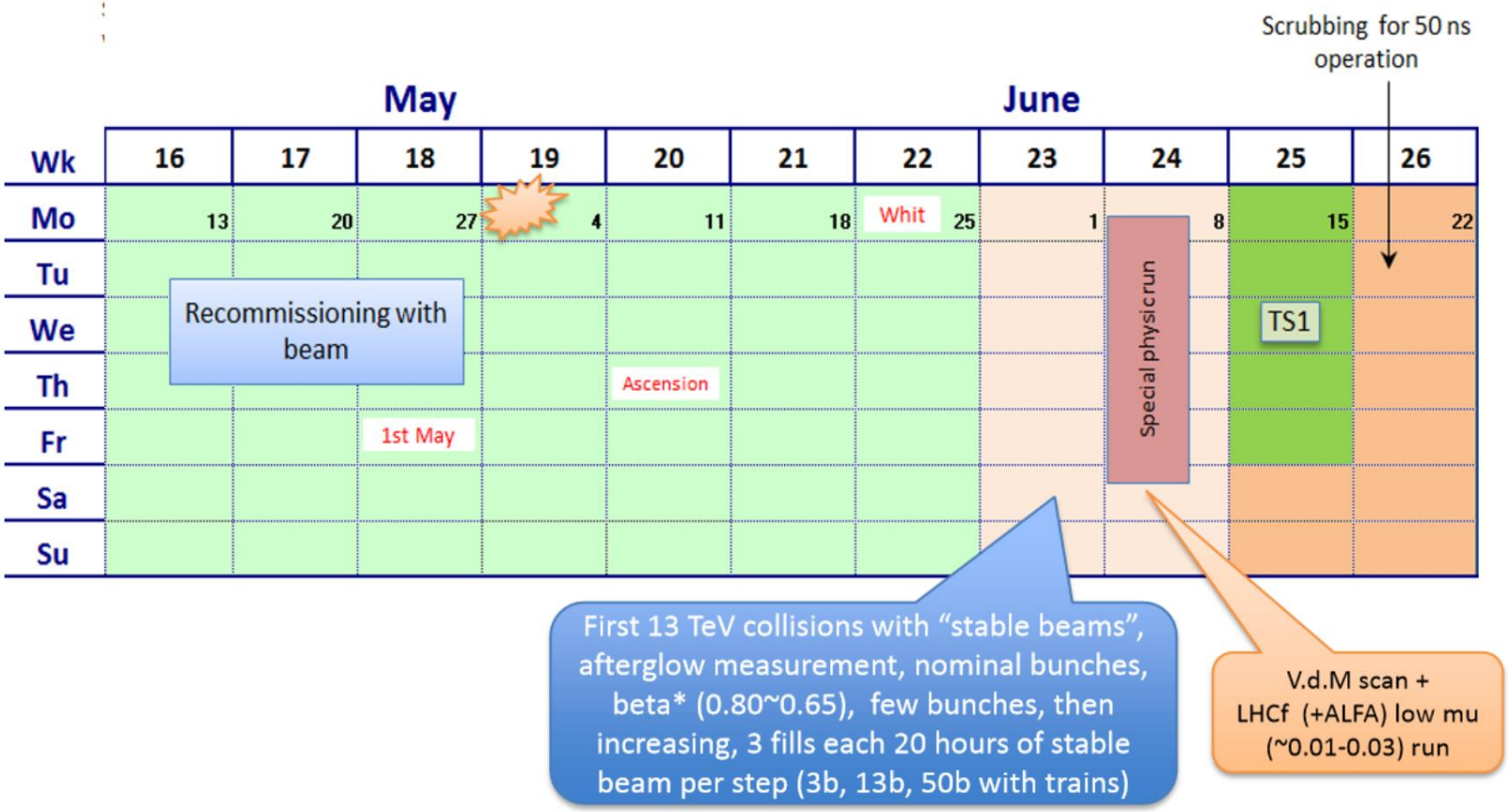
Most LL analyses are not threshold analyses

Will have to wait until equivalent luminosity is × 2 of Run 1's ~20 fb^{-1}

Detector Upgrades

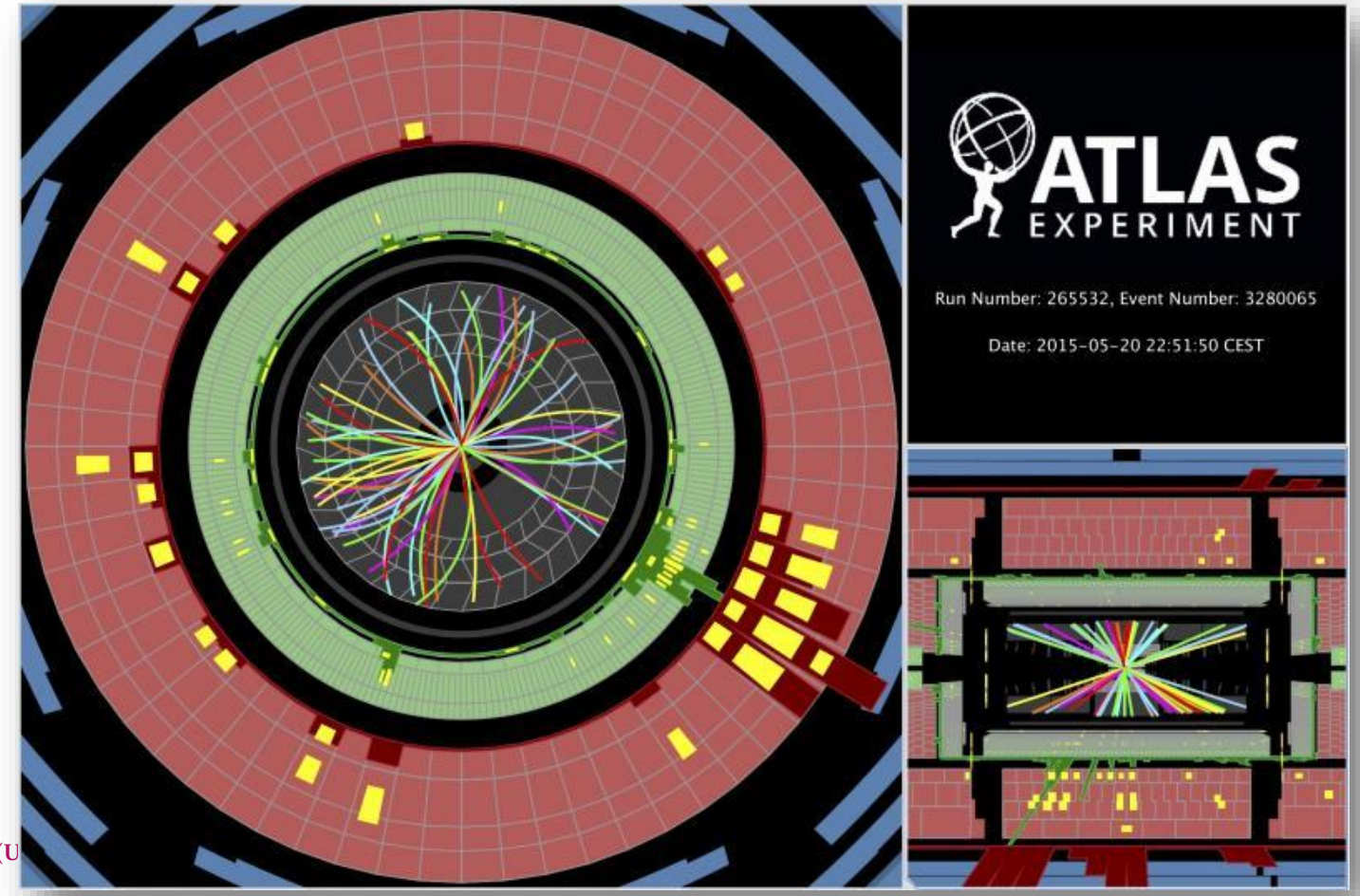
New sub-detectors have been added to both experiments
New triggering capabilities

LHC Schedule



13 TeV From Last Night!!!

With new inner detector!!



Experiment's Physics Schedule

Conference

LHC

→ Results

Threshold Search analyses (e.g. Z')

Perhaps need 1-2 fb^{-1}

50 ns to 25 ns transition

First preliminary results for everything else at ~5 fb^{-1}

But, data will pour in until Winter Conference Cut off

Conclusions

- Thanks to everyone that has started to use these measurements
  - We are aware of the comments, and please keep them coming
  - We are designing the Run 2 versions of these analyses as we speak (well, already moving past that stage).
- Detector design differences can make a real difference
- The program is strong
  - Lots of current measurements. A huge amount of work by both theorists and experimentalists to get to this point!
  - We are still missing quite a bit… input on what is important to first fill out is always helpful (for Run 2 and beyond)