Long lived particles at LHC (not HNL)

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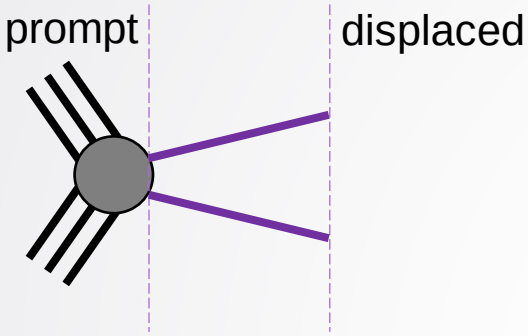
UNIVERSITY OF CAMBRIDGE

Outline

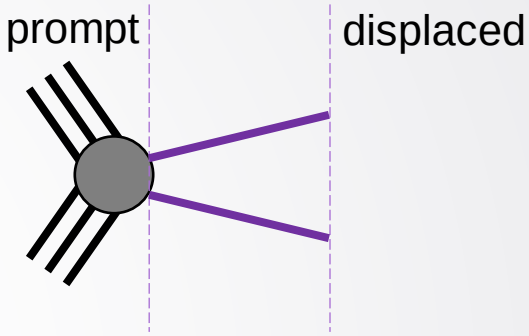
- Benchmark models
- Some existing results
- Context of the LHC and the detectors
- Signatures and search results
  - MS displaced leptons and HCAL displaced jets
  - ECAL displaced photons or electrons
  - Tracker displaced vertices
  - dE/dx ionisation loss
- Conclusion

Benchmark Models: Long-Lived Particles (LLPs)

SUSY



Scalar Portal



Benchmark Models: Long-Lived Particles (LLPs)

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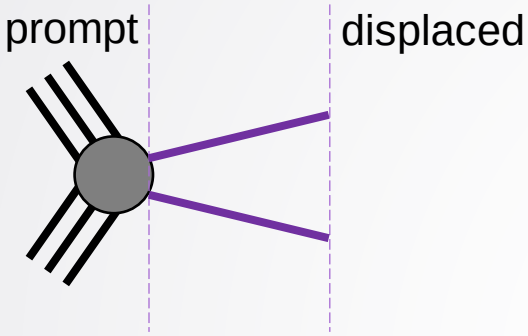

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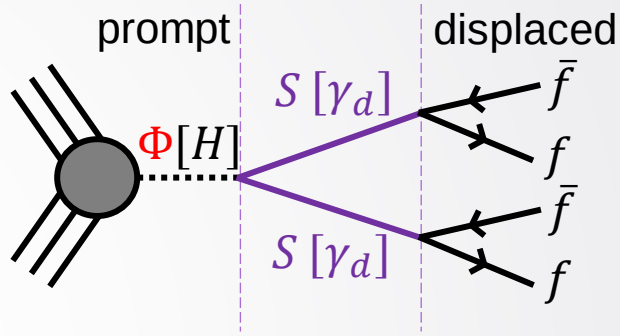
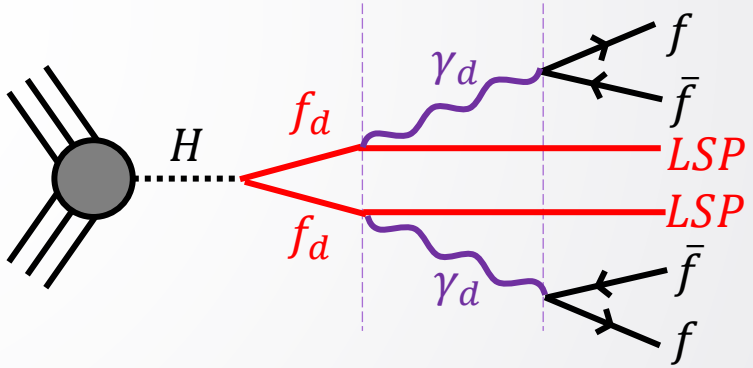


[Hidden Abelian Higgs Model (HAHM)]

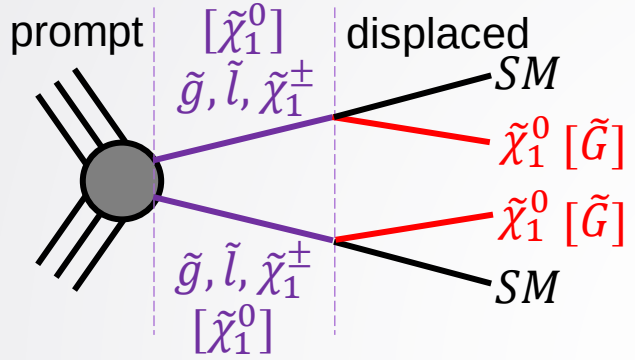


Falkowski-Ruderman-Volanksy-Zupan (FRVZ) model

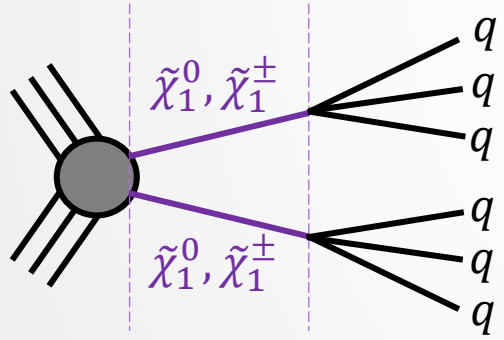
Benchmark Models: Long-Lived Particles (LLPs)

SUSY

[Gauge-Mediated SUSY Breaking (GMSB)]



R-Parity Violating SUSY (RPV)



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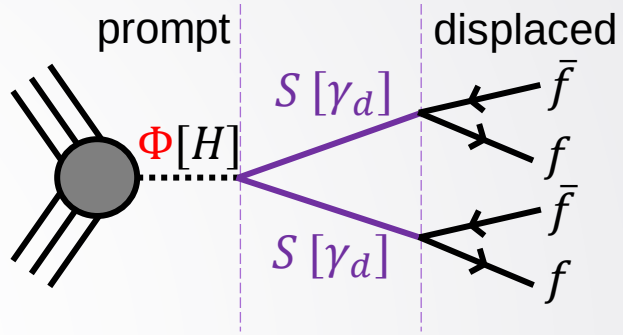

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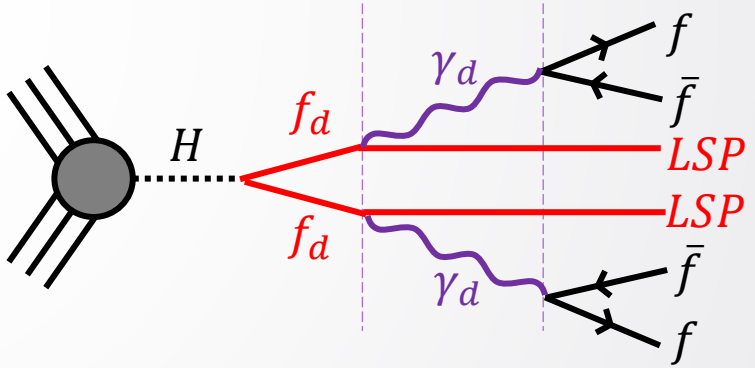
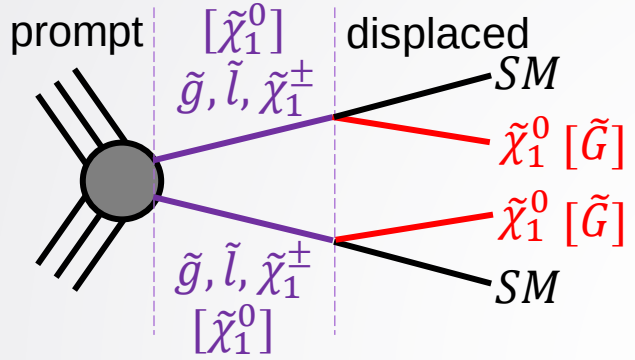


Falkowski-Ruderman-Volanksy-Zupan (FRVZ) model

Benchmark Models: Long-Lived Particles (LLPs)

SUSY

[Gauge-Mediated SUSY Breaking (GMSB)]



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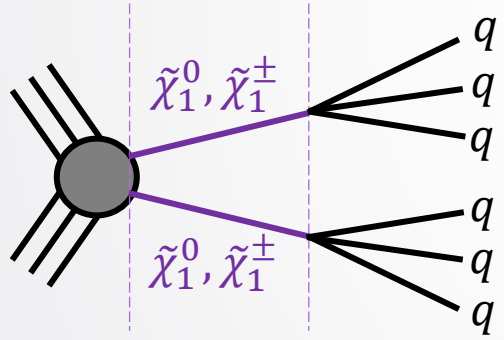

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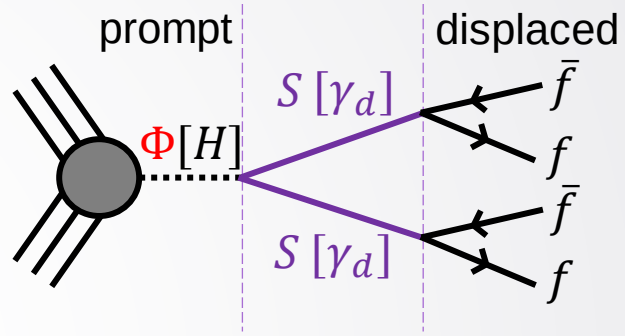

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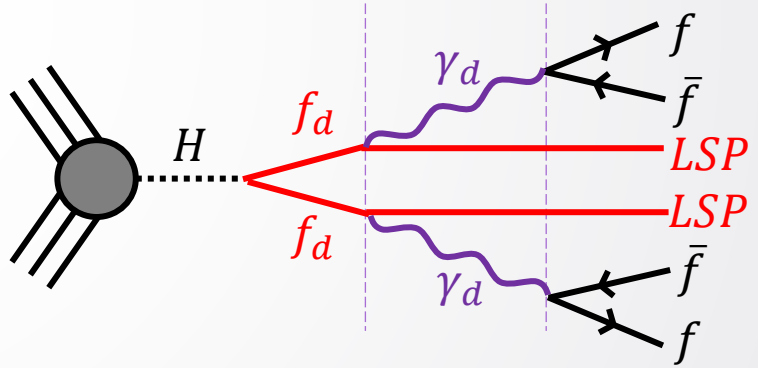
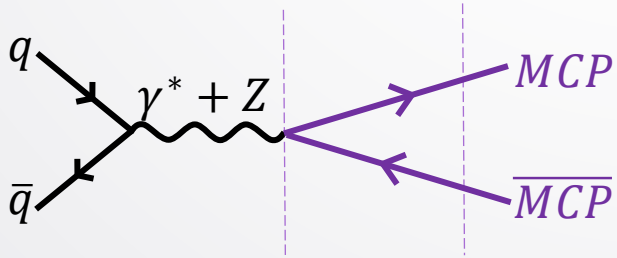
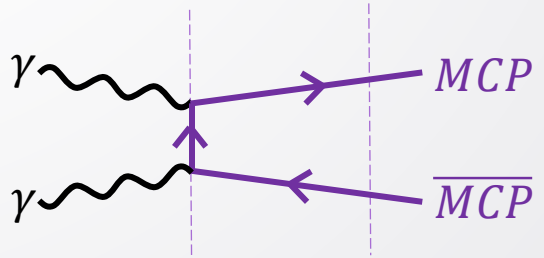


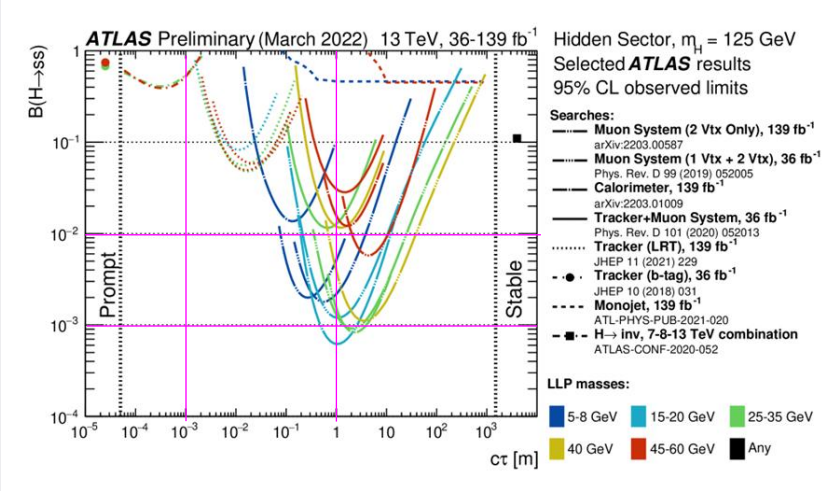
Falkowski-Ruderman-Volanksy-Zupan (FRVZ) model

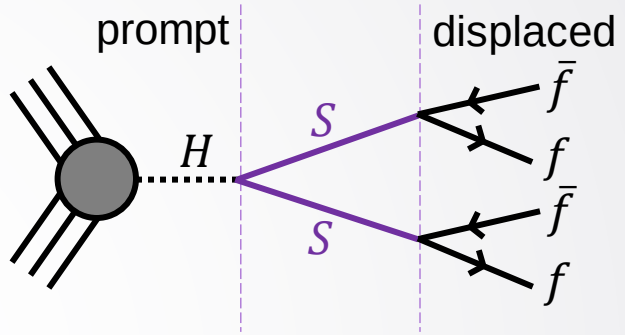
Multi-Charged Particles (MCP)

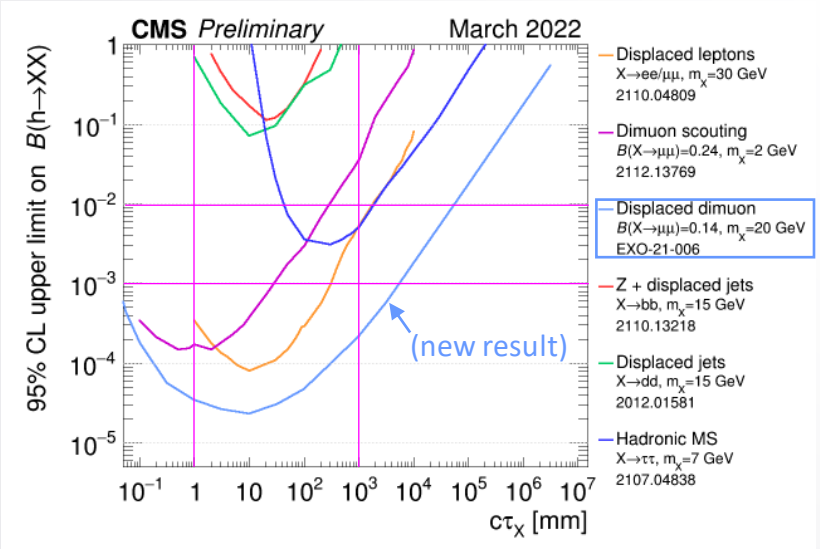


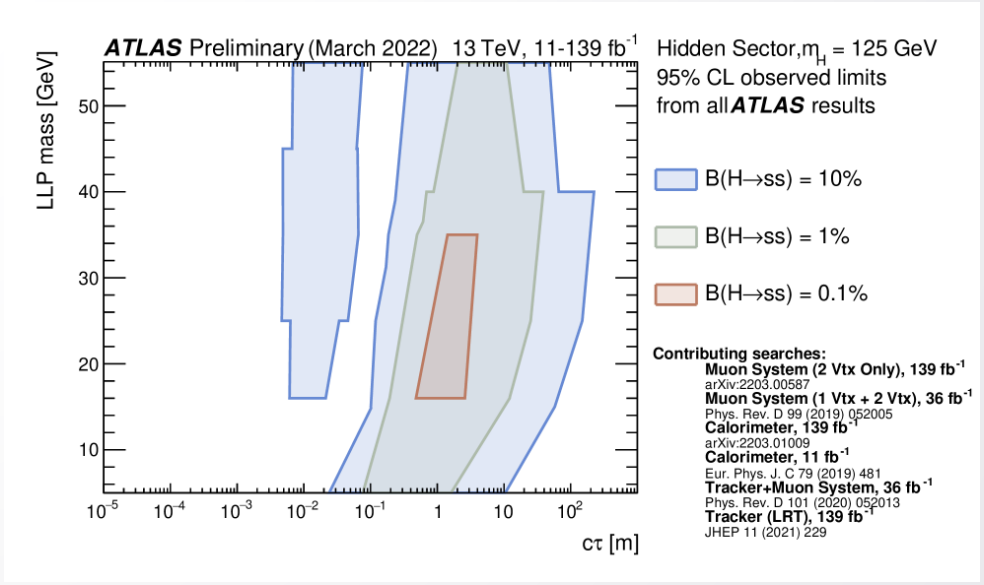


Some Existing Results [Higgs Portal]



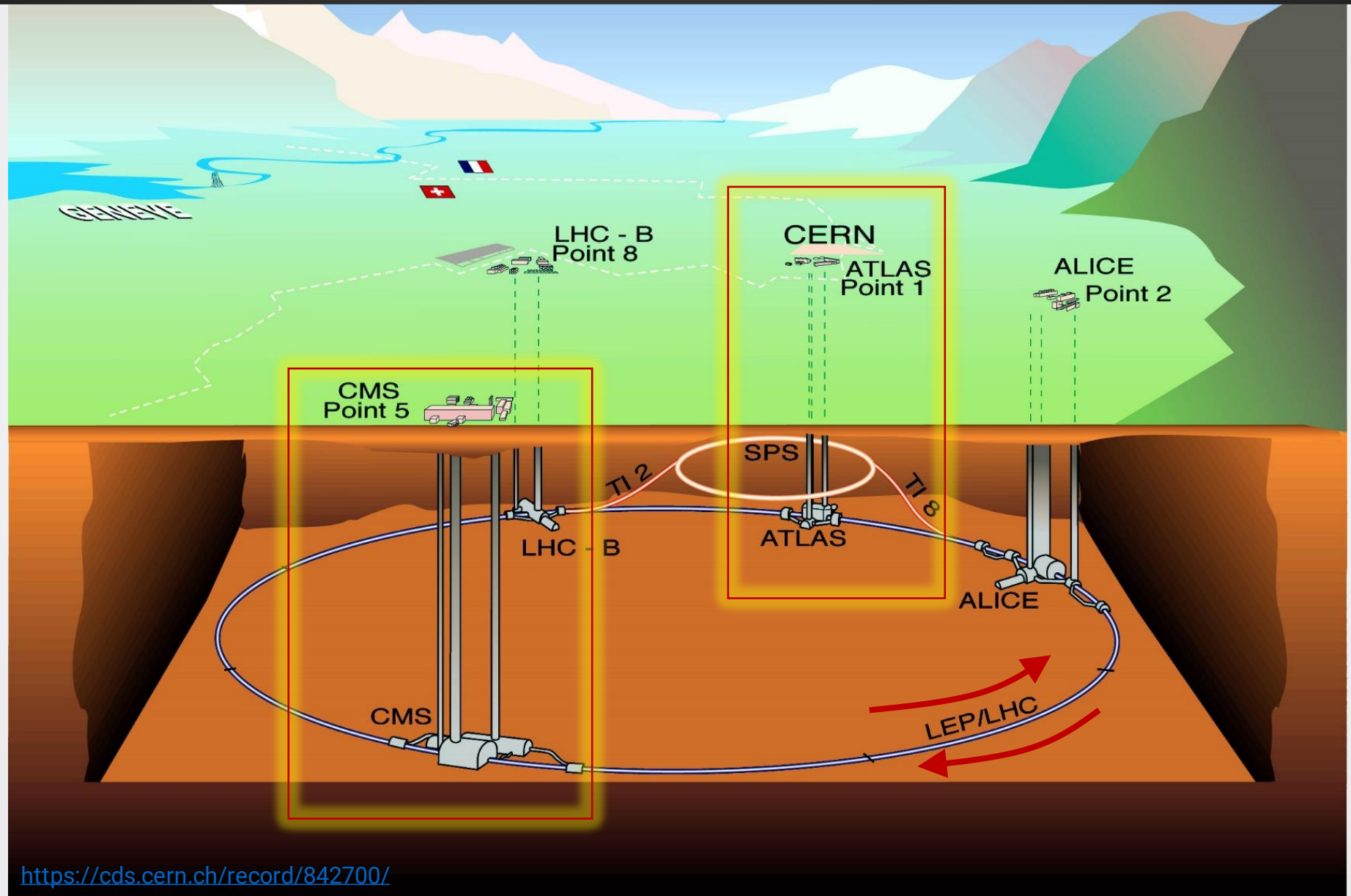






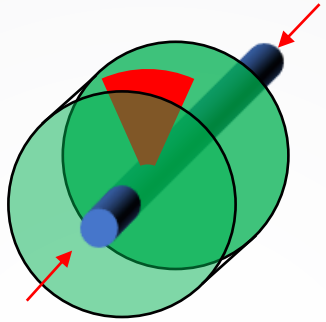
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-007/
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#ICHEP_2022

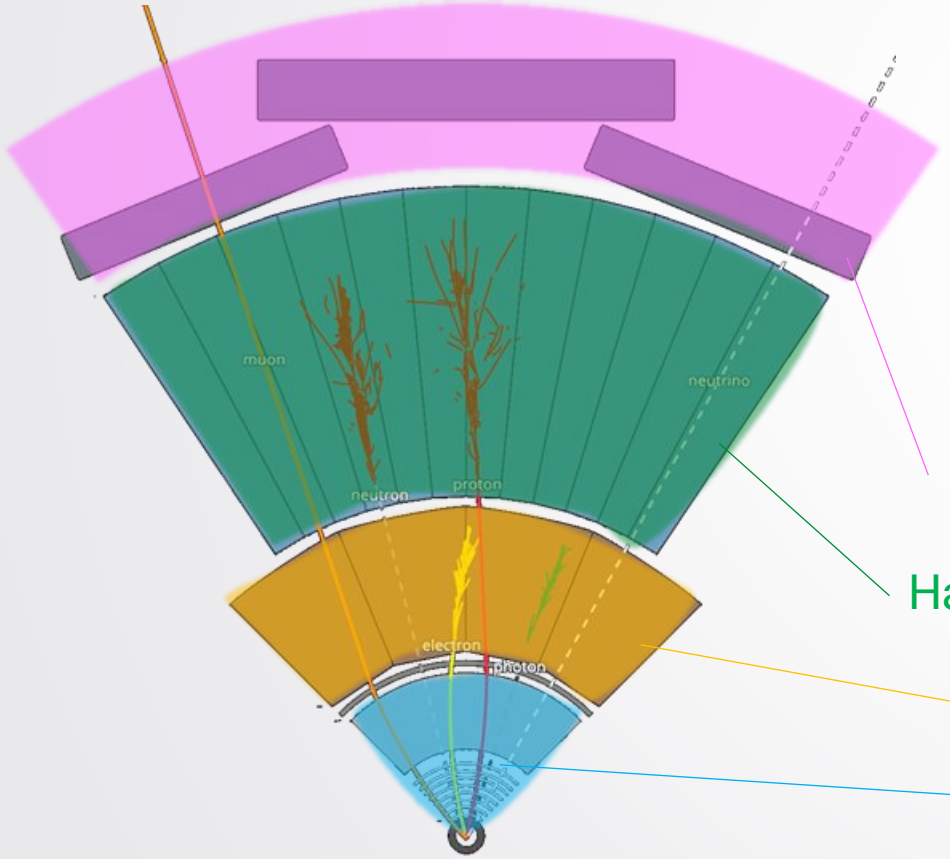
Context on the LHC Experiments



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

Context on ATLAS and CMS



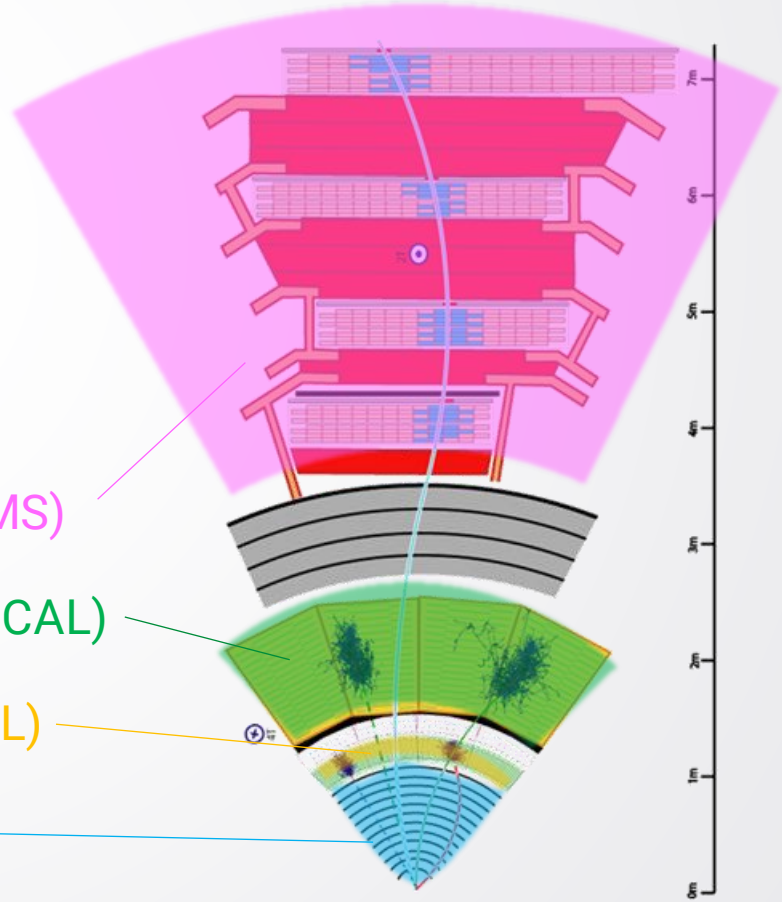


Muon Spectrometer (MS)

Hadronic Calorimeter (HCAL)

EM Calorimeter (ECAL)

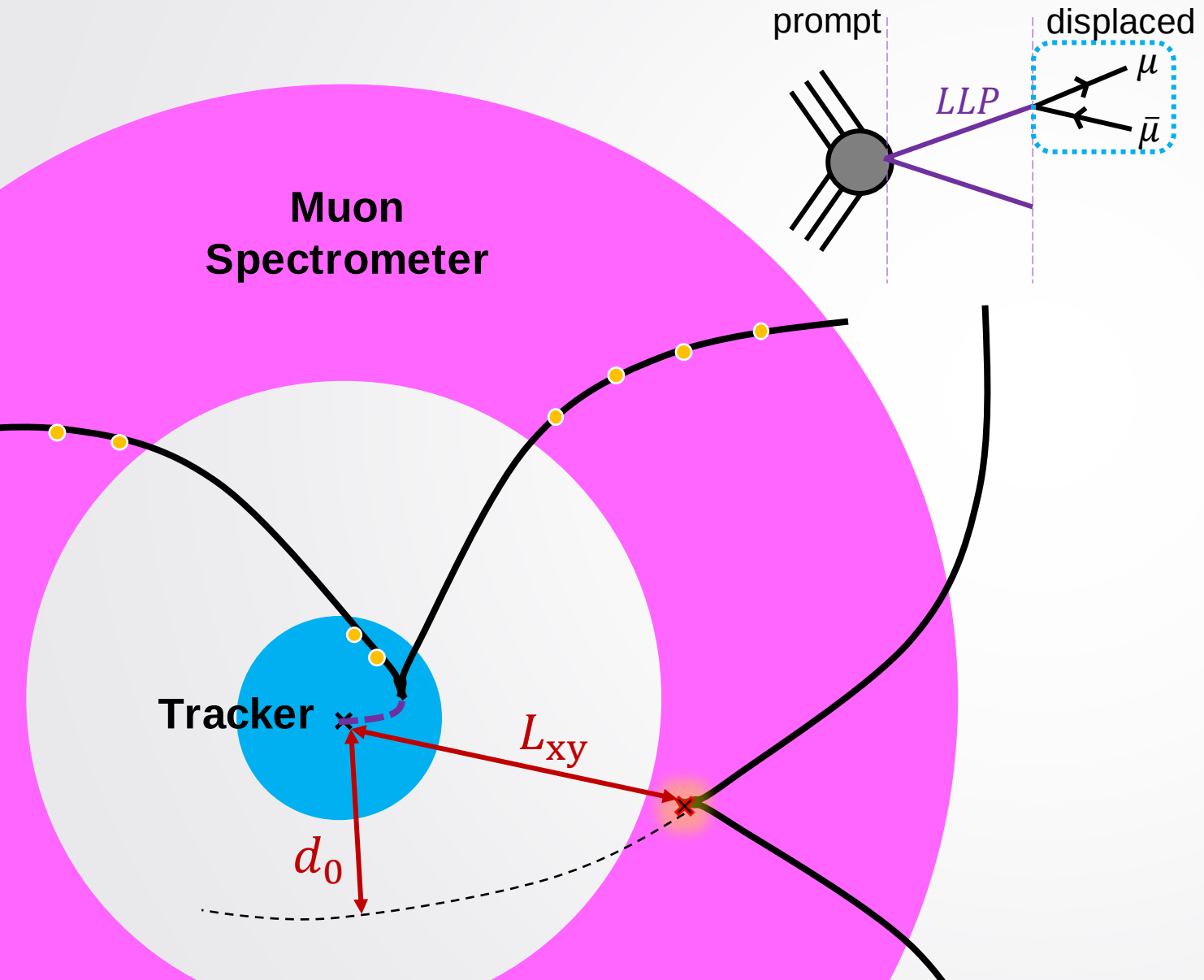
Tracker



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

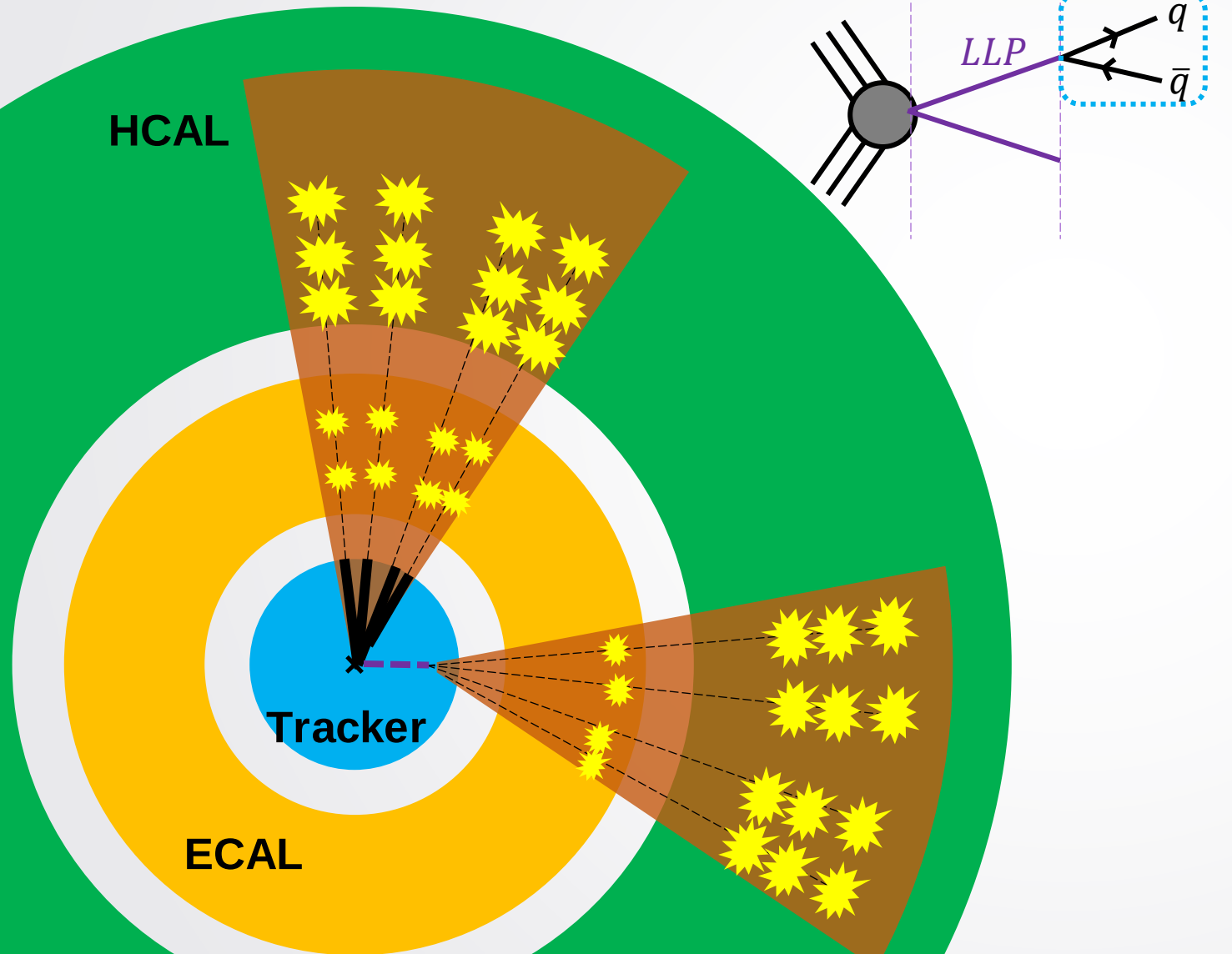
https://cds.cern.ch/record/2204863/

LLP Signatures in the MS



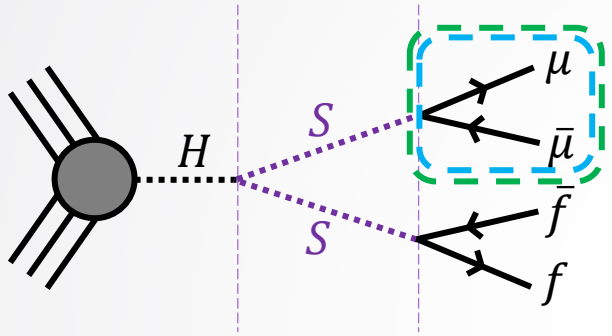
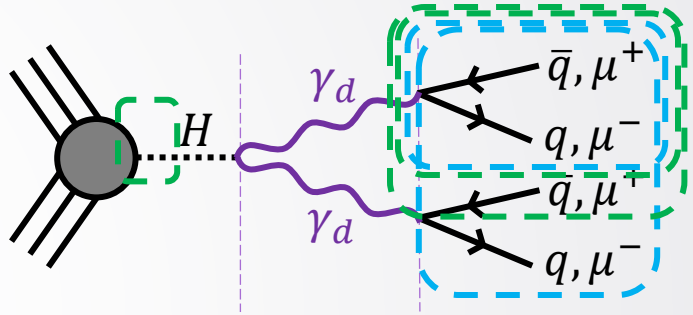
- LLPs decaying to muons make them **displaced (i.e. don't point back to PV [pp-interaction])**
- Backgrounds include:
  - Badly reconstructed prompt muons
  - Some SM decays
  - Crossings of unrelated displaced muons
  - Cosmics
  - Beam-induced background (BIB)

LLP Signatures in the HCAL



- Quarks hadronized into a collimated jet of hadrons
- LLPs decaying to quarks have **both quark products in single jet** with:
  - **Little to no standard tracker tracks**
  - **Higher CalRatio**=E_{HCAL}/E_{ECAL}
- Backgrounds include:
  - SM multi-jets
  - Cosmics and beam-induced background (BIB)
- Can also identify displaced jets with “tagging variables” [CMS]

Searches for LLPs in the MS and HCAL

	CMS-EXO-21-006 [Similar CMS scouted dimuon search]	arXiv:2206.12181 [Similar ATLAS CalRatio jet search]
	$H \rightarrow LLP^0 \rightarrow$ Displ. 2μ	$H \rightarrow LLP^0 \rightarrow$ Displ. Collim. 2l or 2q
Simplest Targeted Model:		
Trigger:	• **Dedicated MS dimuon trigger** w/o beamspot constraint	• **WH: lepton trigger. ggF: 3muon, muon-scan, CalRatio triggers**
Signal Region:	• Separate **SRs** for **[STA-STA, STA-LMS, LMS-LMS]** • $\frac{L_{xy}}{\sigma_{L_{xy}}} > [6,3,6]$ (**is displaced**) • Dimuons not back-to-back (**not cosmics**) • $m_{\mu\mu} > 10$ GeV (**not SM decay or random crossing**) • Angle between $\vec{p}_{\mu\mu}$ and $\vec{L}_{xy}$ is $\lvert\Delta\Phi\rvert < \pi/4$ (**not prompt misreconstructed**)	• Separate **SRs** for **ggF**$[2\mu, c+\mu, 2c]$, **WH**$[c, c+\mu, 2c]$ • **CNN to discriminate multi-jet** • $\sum p_{T,tracks\ within\ \Delta R=0.5} < 4.5$ (**jets are trackless**) • Many things abstracted out in definitions of muon and calojets

Searches for LLPs in the MS and HCAL

Bkg Estimate:

CMS-EXO-21-006

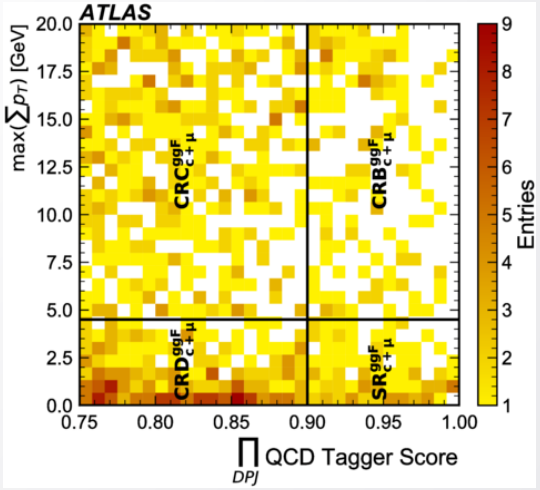
$$H \rightarrow LLP^0 \rightarrow \text{Displ. } 2\mu$$

- **Cosmics:**
  - # events passing all criteria except back-to-back is **already negligible, so ignore**
- **Misreconstructed Prompt:**
  - Will have symmetric $|\Delta\Phi|$
  - **Predict $|\Delta\Phi| < \pi/4$ from $|\Delta\Phi| > 3\pi/4$**
- **SM Decays and Random Crossings:**
  - Correlated with jet activity
  - Get **ratio of opposite-sign to same-sign** in **jet-embedded muon CR** and extrapolate to SR

arXiv:2206.12181

$$H \rightarrow LLP^0 \rightarrow \text{Displ. Collim. 2l or 2q}$$

- Cosmics estimated from cosmic dataset and subtracted for ggF, negligible for WH
- BIB negligible
- **ABCD method** using:
  - **Azimuthal angle between object from pTmiss** for WH SRs
  - **Tracklessness of jets variable** for ggF SRs
  - **Multi-jet rejection CNN score** for Calojet SRs
  - **Azimuthal angle between both muon jets** for that SR



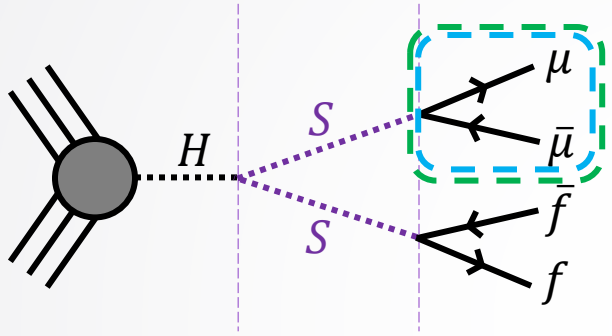
Searches for LLPs in the MS and HCAL

Simplest Targeted Model:

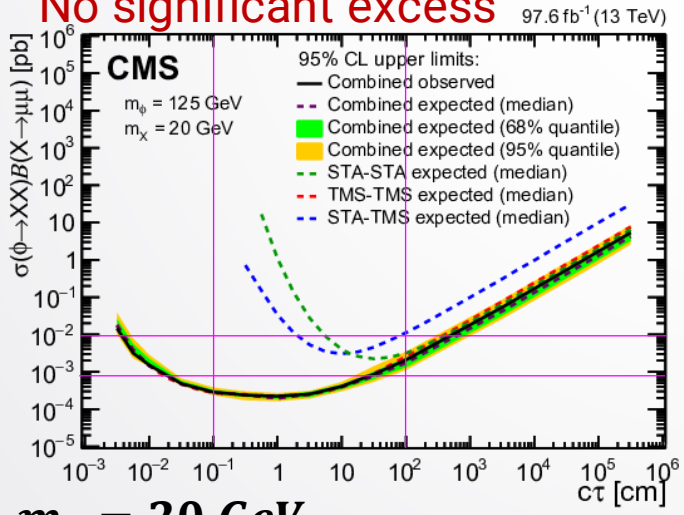
Results:

CMS-EXO-21-006

$\mathbf{H \rightarrow LLP^0 \rightarrow Displ.\ 2\mu}$



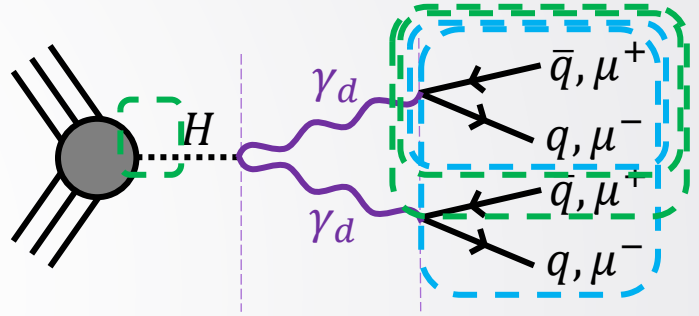
No significant excess



$m_S = 20\ GeV$

arXiv:2206.12181

$\mathbf{H \rightarrow LLP^0 \rightarrow Displ.\ Collim.\ 2l\ or\ 2q}$



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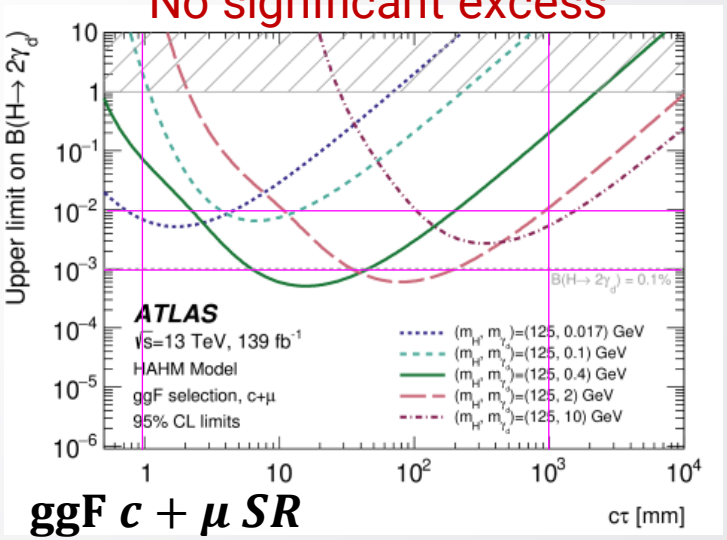
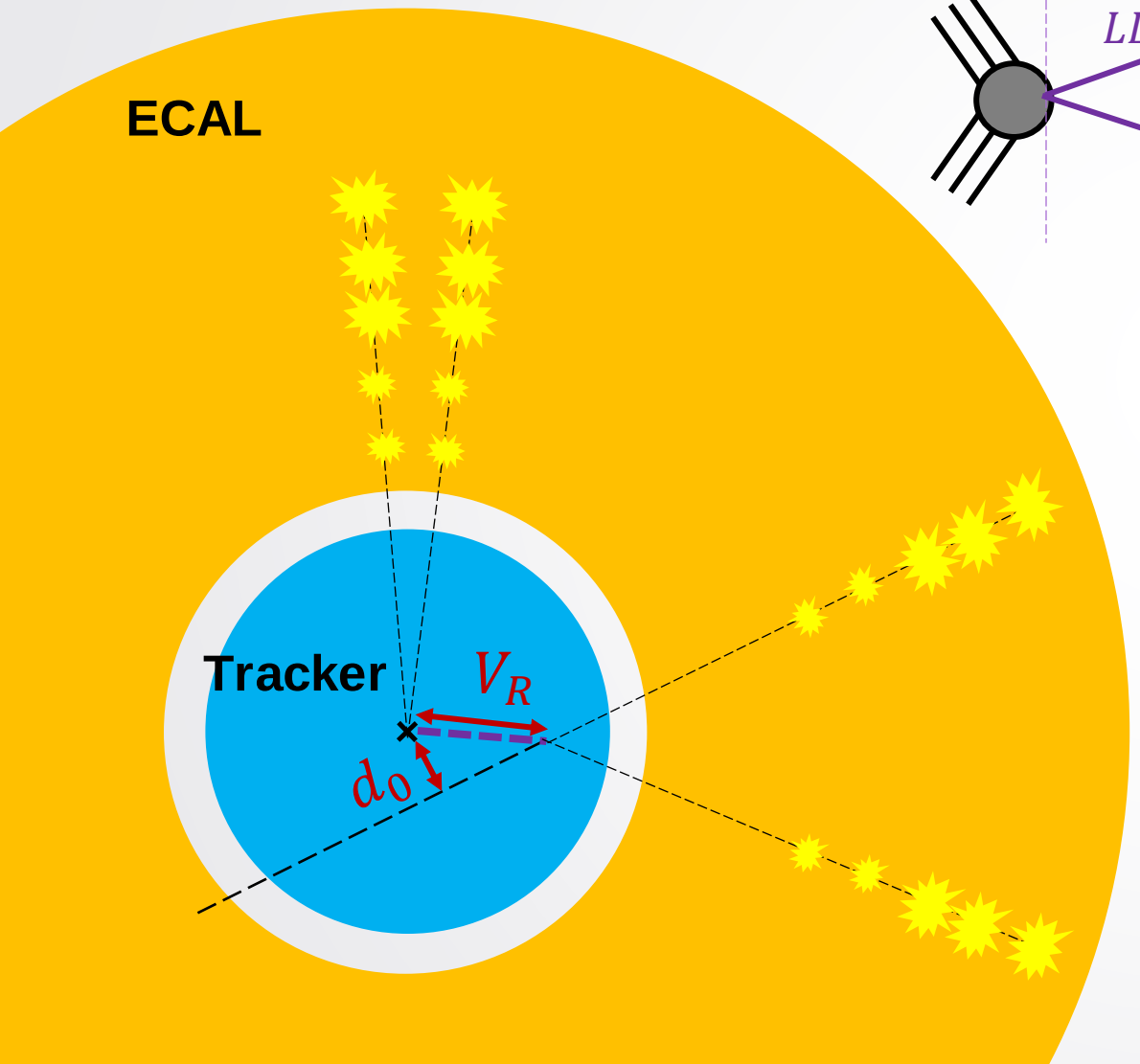
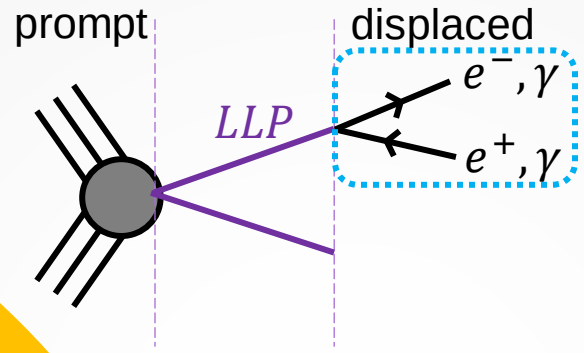


ggF $c + \mu$ SR

LLP Signatures in the ECAL





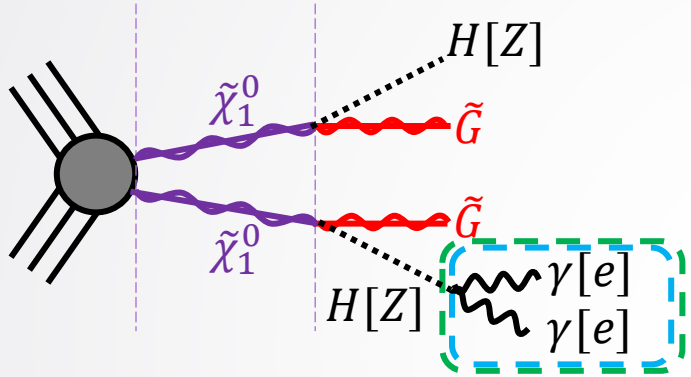
- ATLAS LAr ECAL **has timing capabilities** and **unique pointing abilities**
- Photons or electrons from LLP decays will differ by:
  - **Not pointing back to the PV**
  - **A timing delay**
- Backgrounds include:
  - Misidentification of other objects
  - Misreconstructed prompt photons or electrons

Searches for LLPs in the ECAL

[ATL-COM-PHYS-2022-474](#) [Similar ATLAS displ. γ search]

$$\textbf{LLP} \rightarrow \textbf{Displ. H} \rightarrow \gamma\gamma / \; Z \rightarrow e^{+}e^{-}$$

Simplest Targeted Model:



Trigger:

- **2 high-pT photon triggers**

Signal Region:

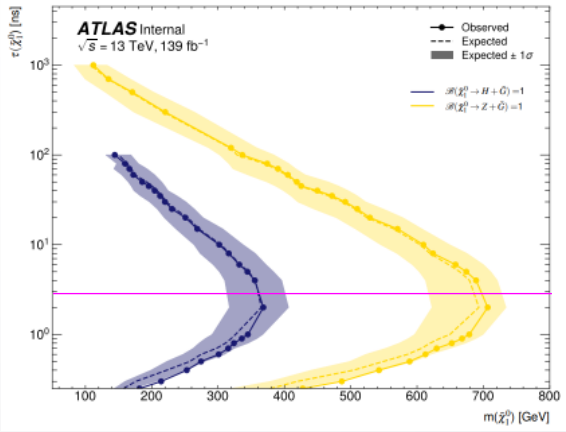
- Require **time delay > 0**
- Require **MET > 30 GeV**
- **Displacement and timing are binned**
- $m_{\gamma\gamma} \in [60, 135]$ **GeV** (i.e. from Z or H)

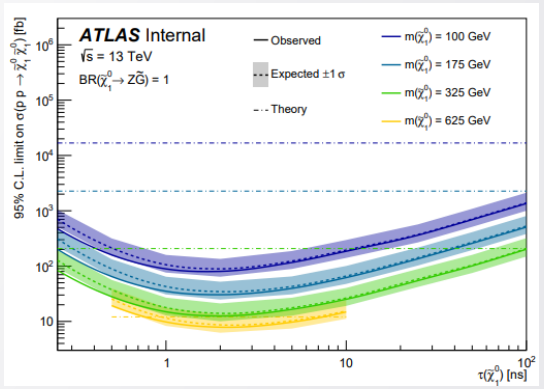
Bkg Estimate:

- **Background fakes or misreconstructed**. Non-collision negligible.

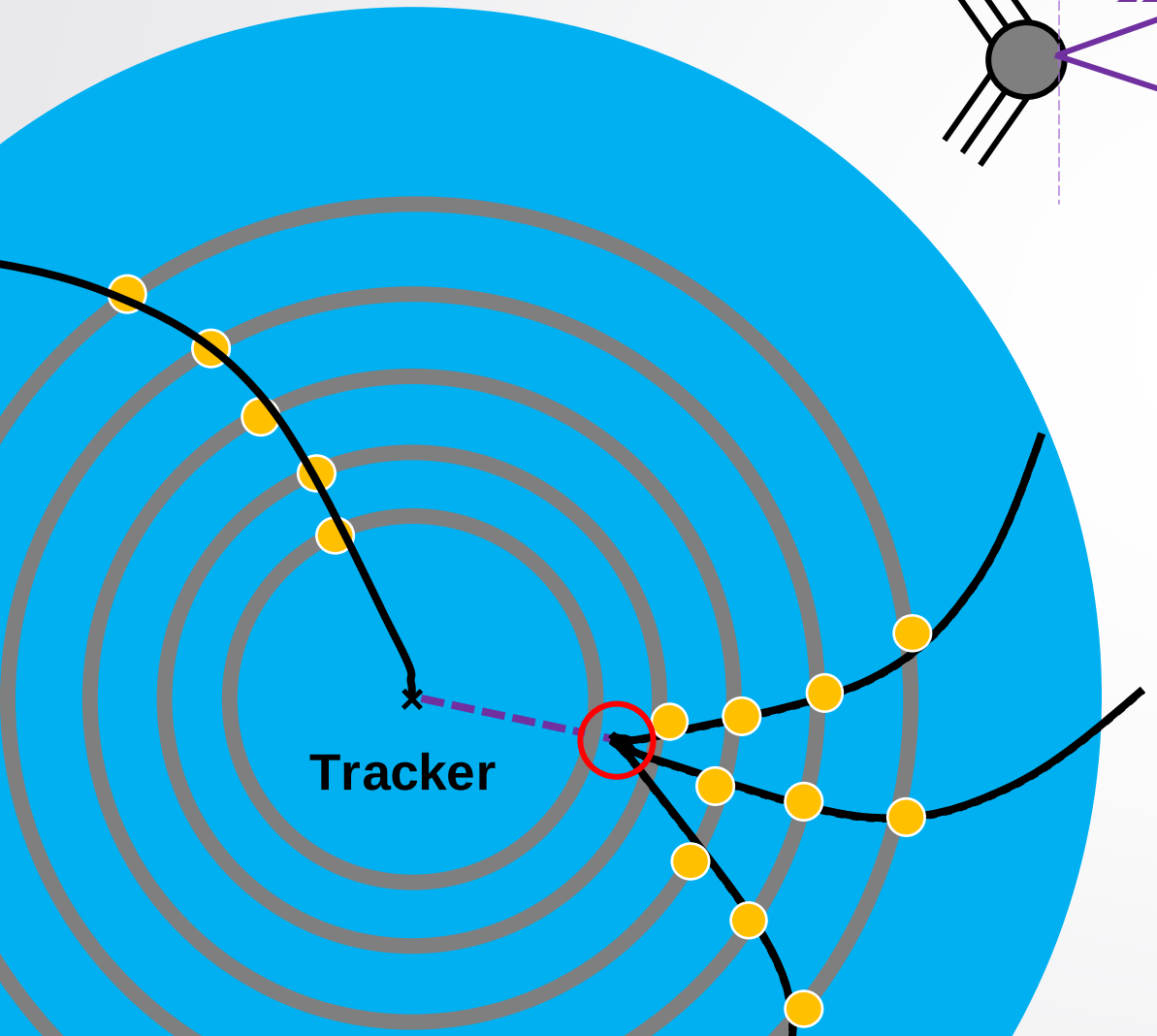
- Define CR with low MET, **form fake-photon-enriched and genuine-photon enriched templates** in timing and pointing bins from identification requirements
- **Normalize templates in SR** using overall fraction of "genuine" to "fake" in SR

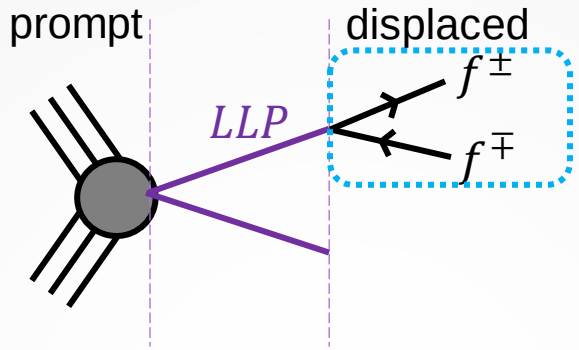
No significant excess





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

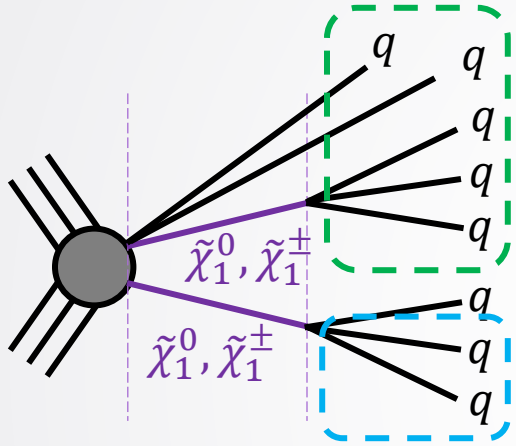
Searches for LLPs in the Tracker

ATLAS-CONF-2022-054

[Similar CMS jets with DVs search]

Jets + LLP → Displ. Vertex

Simplest Targeted Model:



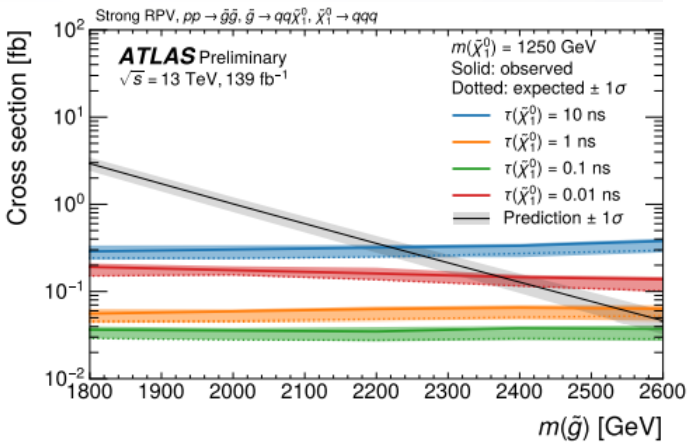
Trigger:

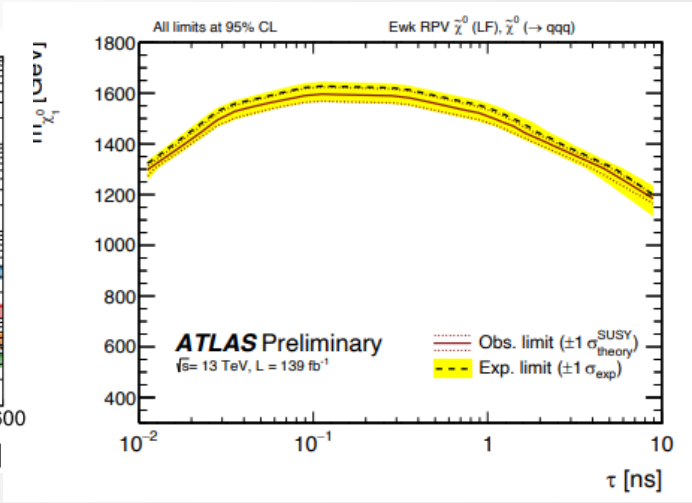
- **Multi-jet trigger**

Signal Region:

- **High pT Jet and Trackless Jet SRs** (if jet is trackless, can lower jet pT req.)
- **Outside detector material** (cut out HI)
- $m_{DV} > 10$ **GeV** (cut out HI)
- **# tracks >=5** (cut out SM decays & HI)

- All **backgrounds correlated** with **prompt jets**
- Use single-photon trigger as CR with same prompt jet properties but no signal contamination
- From **number of jets,** estimate **number of DVs**
- Cross-checked by estimating each component of background individually

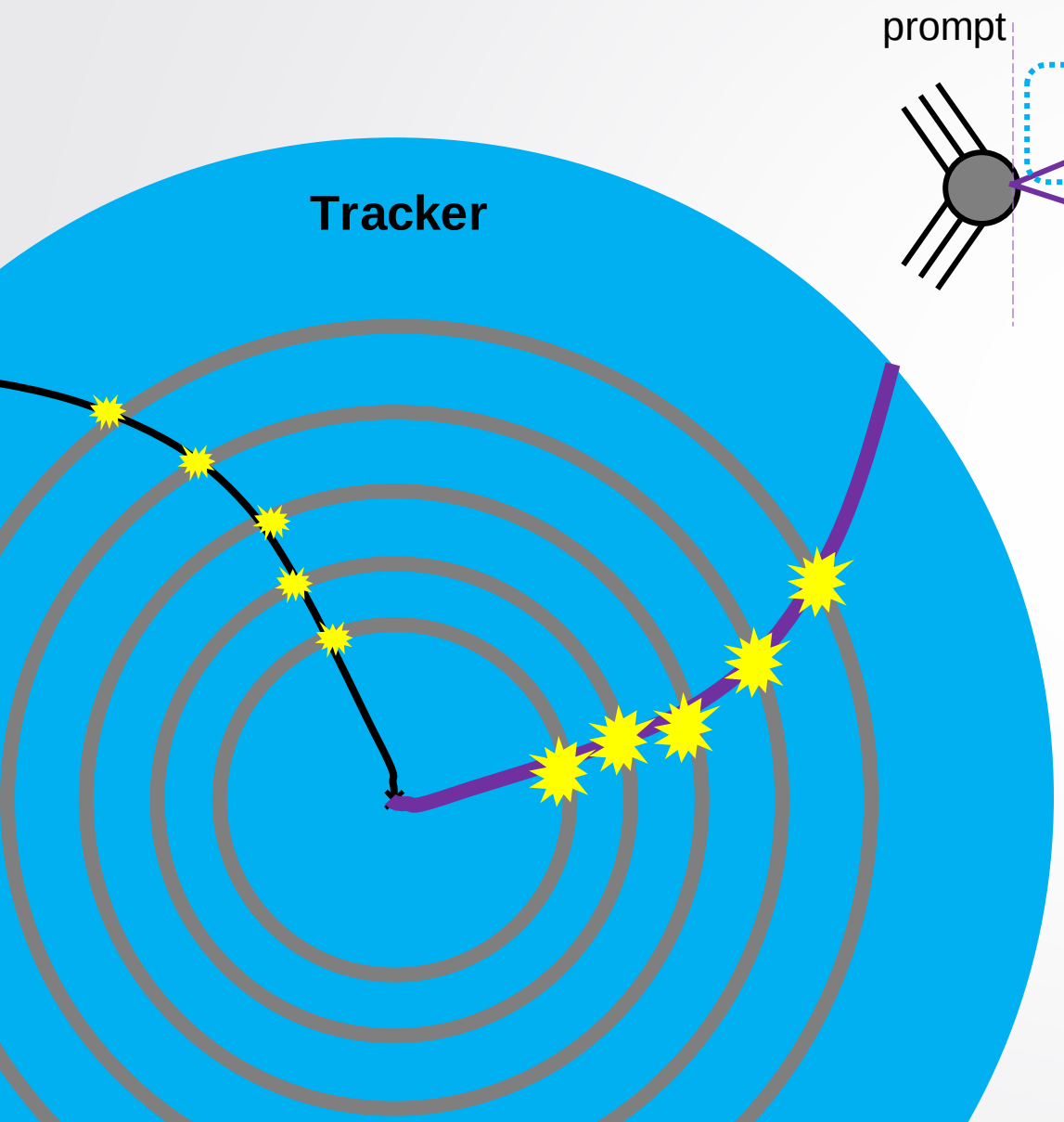


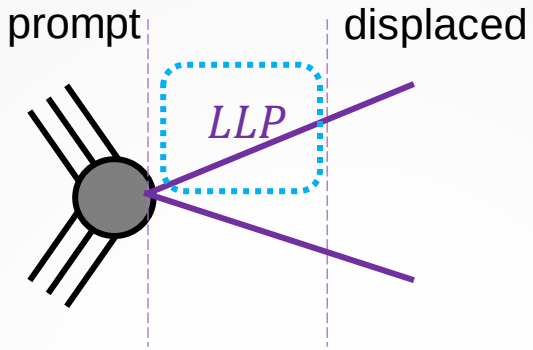


High pT SR: expected **0.46**, observed **1**

Trackless SR: expected **0.83**, observed **0**

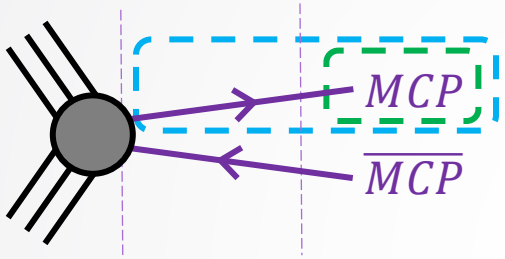
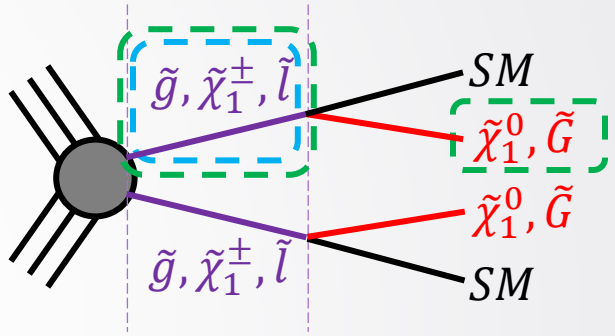
The Ionization Loss LLP Signature (dE/dx)





- Normally, **average charge released at each hit** is ~20000e.
- Usually **don't care, set threshold** at ~3500e for hit.
- **Time over threshold (ToT) is recorded**, approx. propr. to ionization charge, so can **calculate dE/dx**
- **Heavy (slow) charged LLPs or MCPs themselves** have **higher dE/dx**
- If **very stable,** might even **also see track in the MS**
- Backgrounds include:
  - Random SM tracks
  - Multiple particles hitting same area
  - Radiation background and noise

Searches for LLPs with dE/dx

	[ATLAS-CONF-2022-034](#)	[arXiv:2205.06013](#)
	LL – MCP	**Pixel dE/dx**
Simplest Targeted Model:		
Trigger:	• **Single muon** trigger, **CAL MET** trigger, **"late-muon"** trigger (muon in bunch-crossing after jet)	• Calorimeter missing transverse energy (**CAL MET**) trigger
Signal Region:	• **z=2 and z>2 SRs** • Track **must** have segments **in tracker AND MS** • **Significance of dE/dx in (pixel, TRT, MDT)** $[S\left(\frac{dE}{dx}\right) = \left(\frac{dE}{dx} - \left\langle\frac{dE}{dx}\right\rangle_{\mu}\right) / \sigma\left(\frac{dE}{dx}\right)_{\mu}]$ must be above threshold • Fraction of TRT hits above high threshold for z>2	• **Low and high dE/dx SRs** as well as another region to deal with edge case of dynamic range. • **SRs** divided into **[only tracker, tracker + MS]** • Require **MET>170 GeV** • **dE/dx** measured in **pixel only**

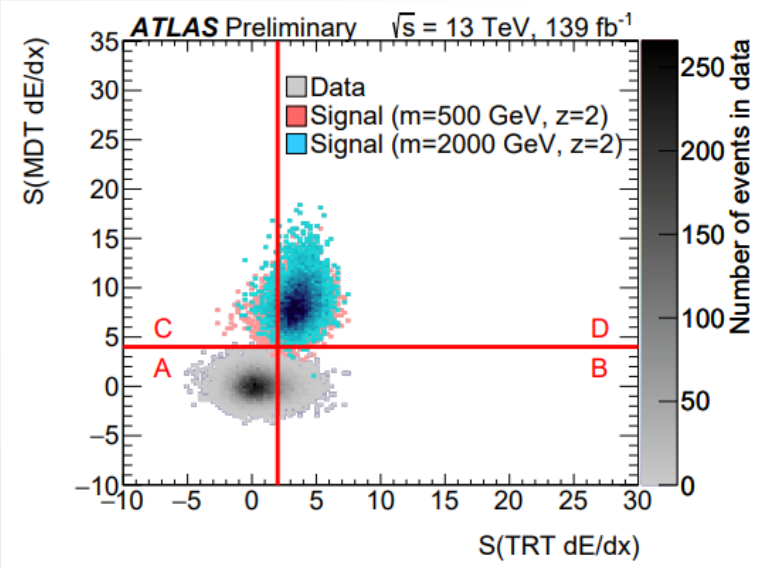
Searches for LLPs with dE/dx

Bkg Estimate:

ATLAS-CONF-2022-034

LL – MCP

- Background is **detector occupancy and noise**
- **ABCD Method:**
  - z=2: **S(TRT dE/dx)>2** and **S(MDT dE/dx)>4**
  - z>2:
    fraction of high threshold TRT hits > 0.7
    and **S(MDT dE/dx)>7**



arXiv:2205.06013

Pixel dE/dx

- Background is **SM processes in pixel** (dominates low dE/dx and low MET)
- We **want #events** binned in **m** (need **pT and dE/dx)**
- For narrow $|\eta|$ **bin**, expect:
  pT uncorrelated with dE/dx and
  dE/dx uncorrelated with MET
- Get $|\eta|$ **vs pT** distribution from **low dE/dx region**
  Get $|\eta|$ **vs dE/dx** distribution from **low MET region**
- **Sample $|\eta|$, sample pT and dE/dx -> calculate m**

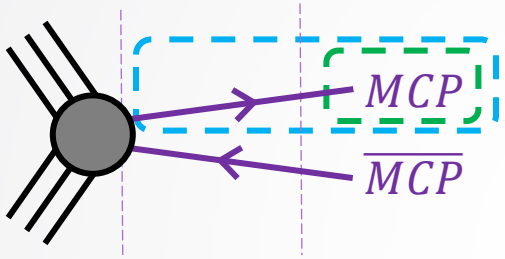
Searches for LLPs with dE/dx

Simplest Targeted Model:

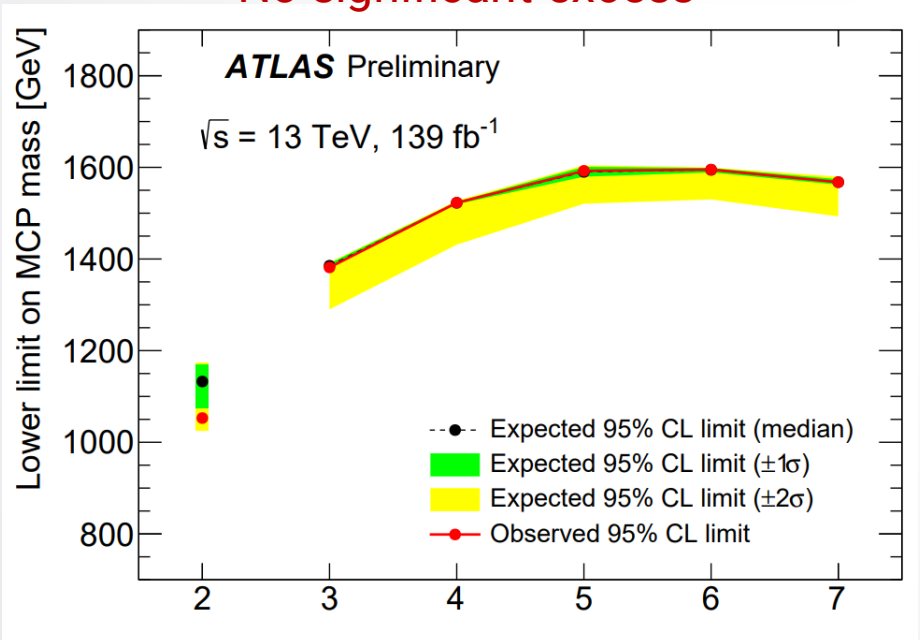
Results:

ATLAS-CONF-2022-034

LL – MCP

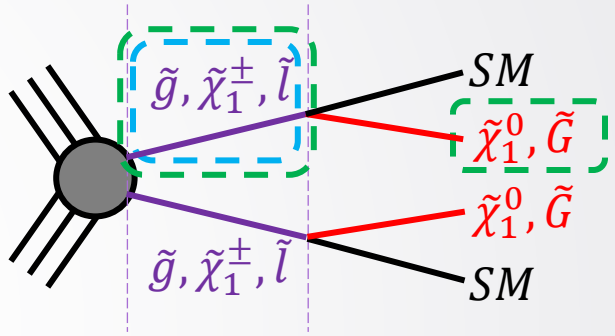


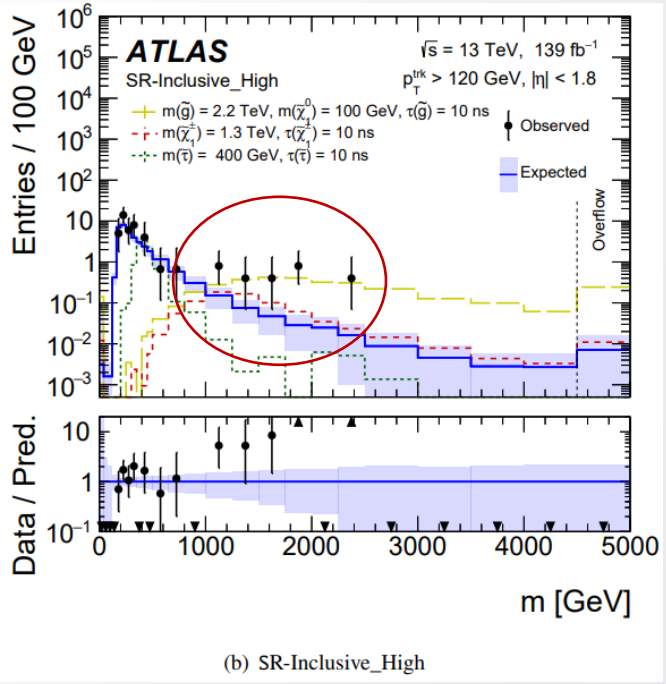
No significant excess



arXiv:2205.06013

Pixel dE/dx





(b) SR-Inclusive_High

Notes about the excess in the pixel dE/dx analysis

- **7 events observed** in [1100,2800] GeV bin where **0.7±0.4 were expected** [local **3.6σ**, global **3.3σ**]
- **4/5 matched with muon in MS**, with **consistent momentum** information from tracker and MS.
- **MCP analysis sees 2** of these events as having **good enough dE/dx in pixel**, but does not see excess since **not sufficient dE/dx in TRT or MDT**
- No obvious pathologies found with these events
- $\frac{dE}{dx} \in [2.42, 3.72]\,\mathrm{MeV\,g^{-1}cm^2} \rightarrow \boldsymbol{\beta} \in [\mathbf{0.62 - 0.52}]$, so particles have longer time-of-flight than SM
- However **directly measuring β from calorimeter and MS consistent with 1**, so low particle speed is not consistent.
- Local 2.4σ excess at 600 GeV observed in [36 fb^{-1} version of this analysis] is not confirmed.

Conclusions

- **Long-lived particles** are an **important direction for BSM searches** with **many possible signatures** to exploit
- We are able to **set new limits** on **Scalar Portal, SUSY, and MCP** models
- Many more results on the way for both Run 2 and early Run 3 datasets
- Links to updated recent public results:
  - ATLAS SUSY
  - ATLAS Exotics
  - CMS Exotica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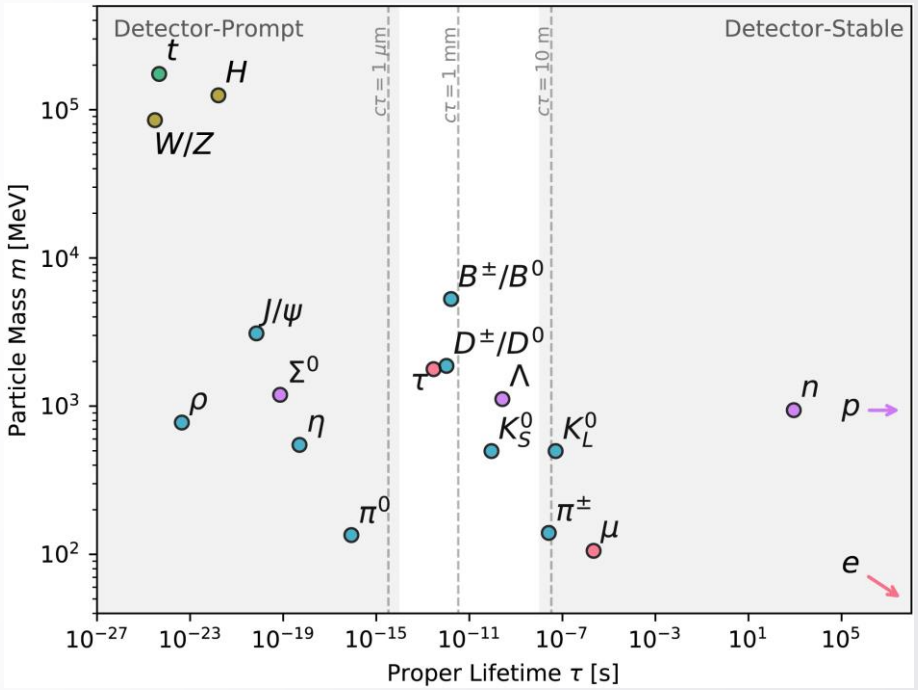
Thank You

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

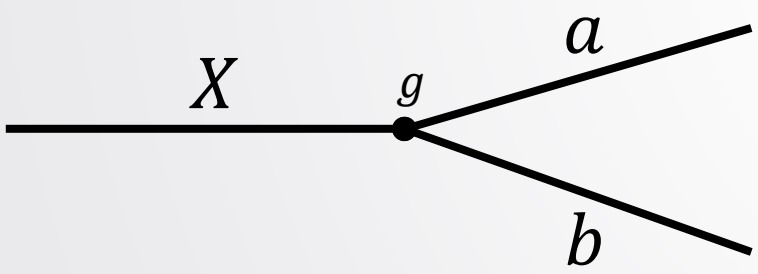
What could cause a BSM particle to be long-lived?

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

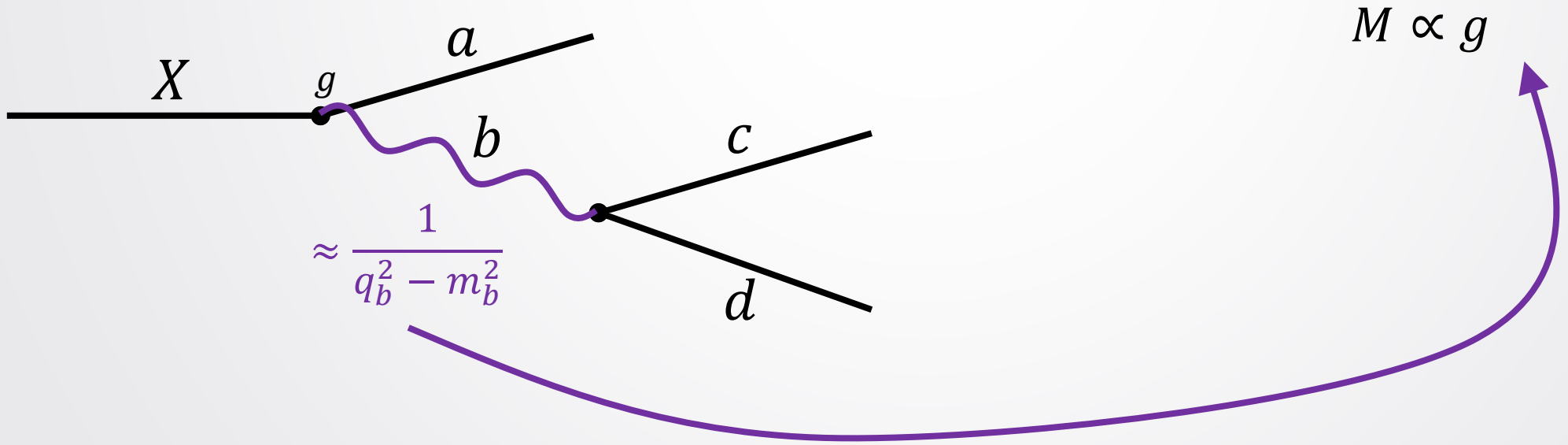
2) Less phase space (small mass-splitting)

3) Small coupling between particles

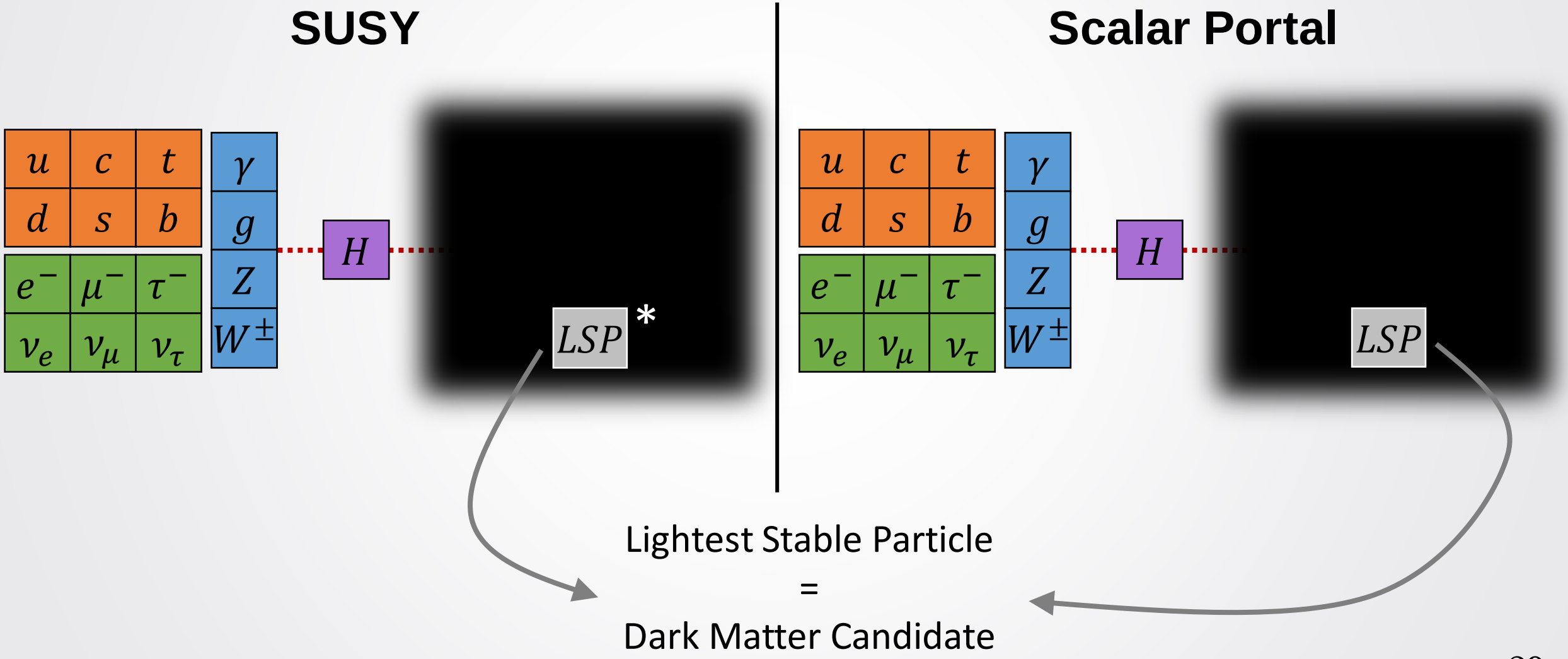
4) Very off-shell intermediary

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

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

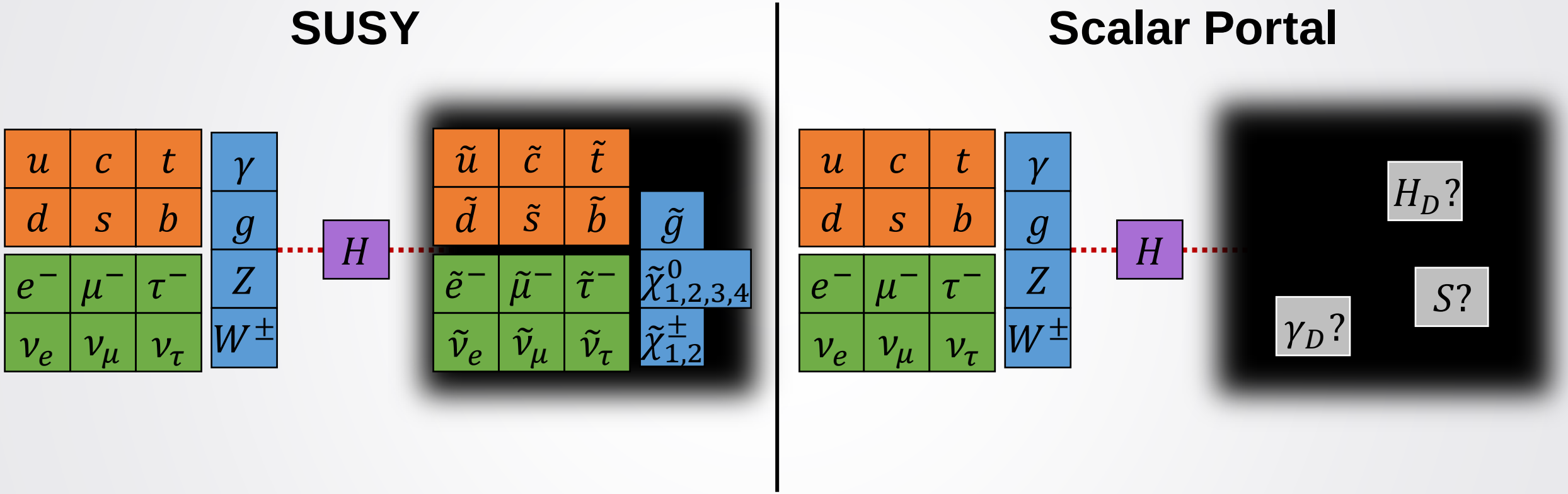


Benchmark Models: SUSY vs. Scalar Portal

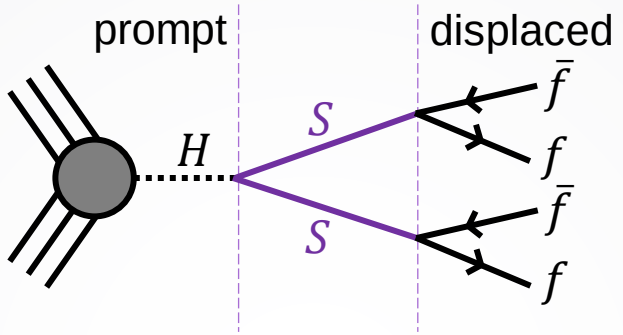


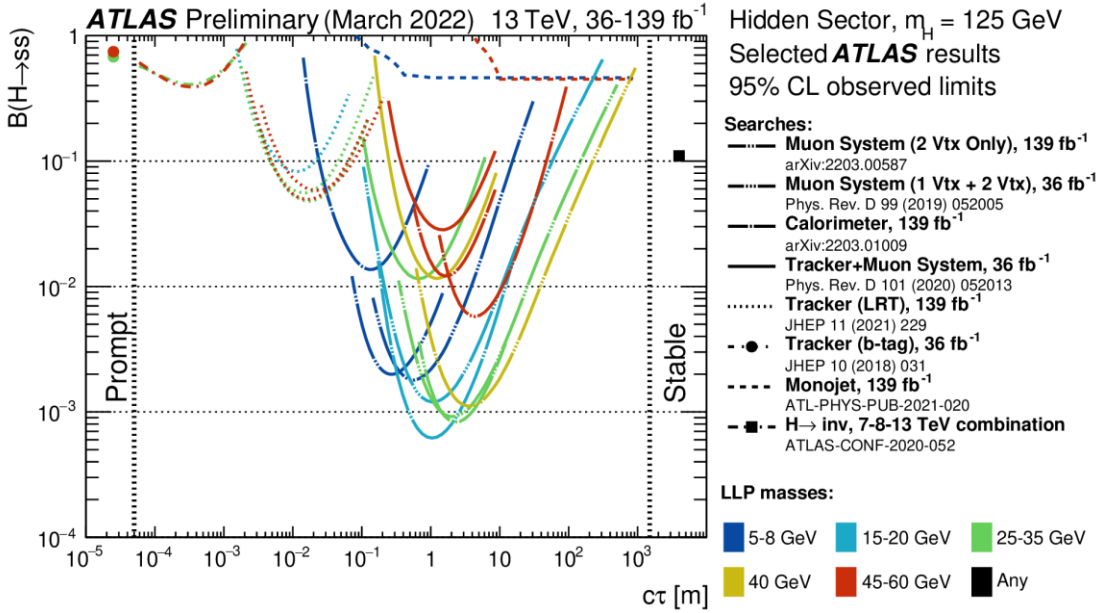
*Except R-parity violating SUSY

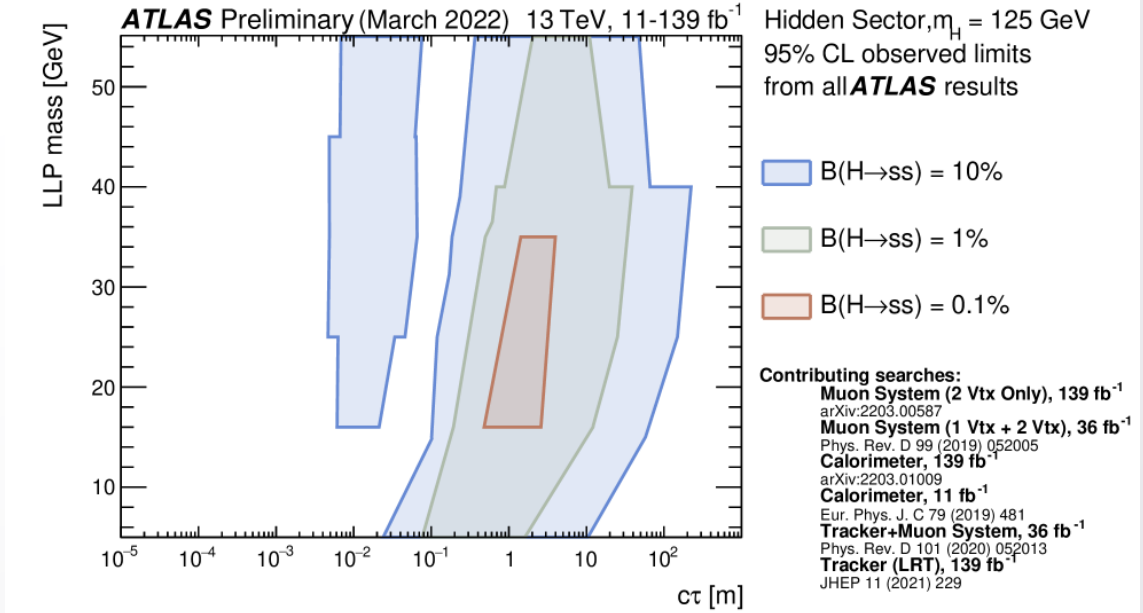
Benchmark Models: SUSY vs. Scalar Portal



Some Existing Results [Higgs Portal]

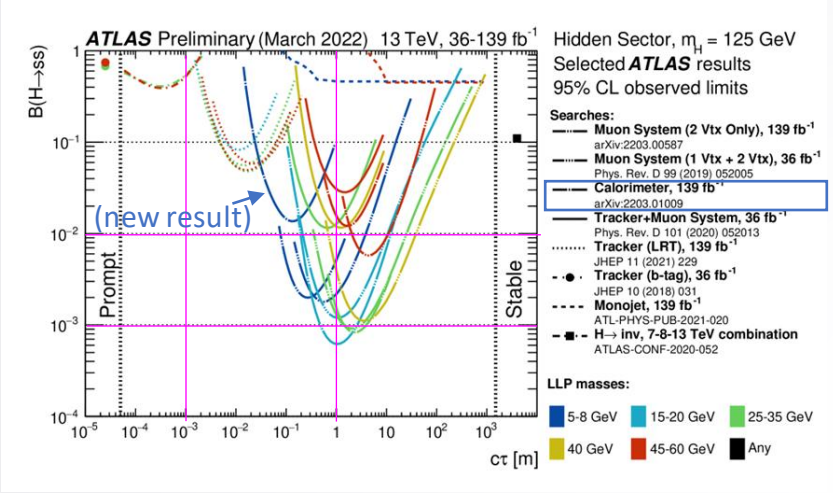


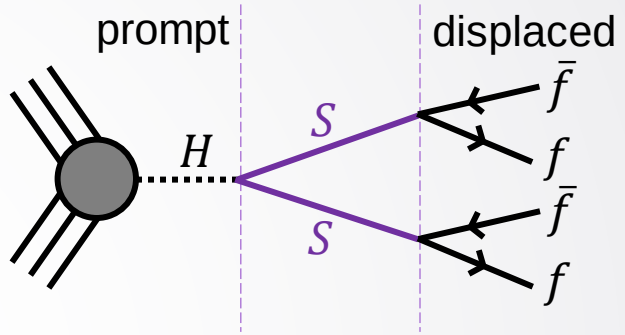


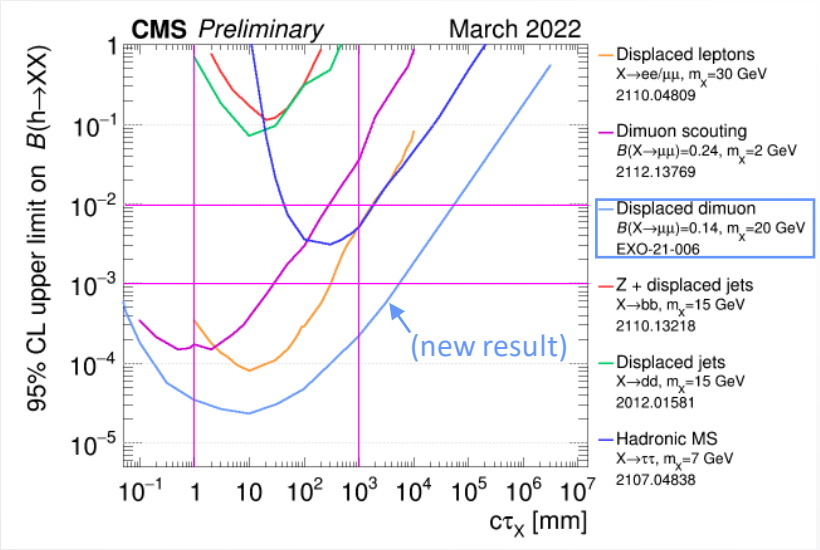


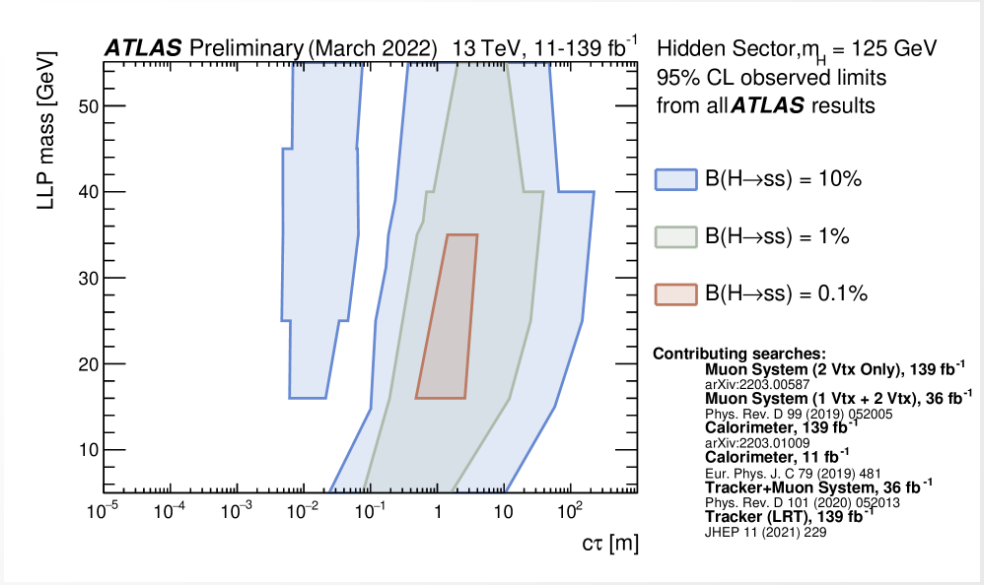
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-007/

Some Existing Results [Higgs Portal]



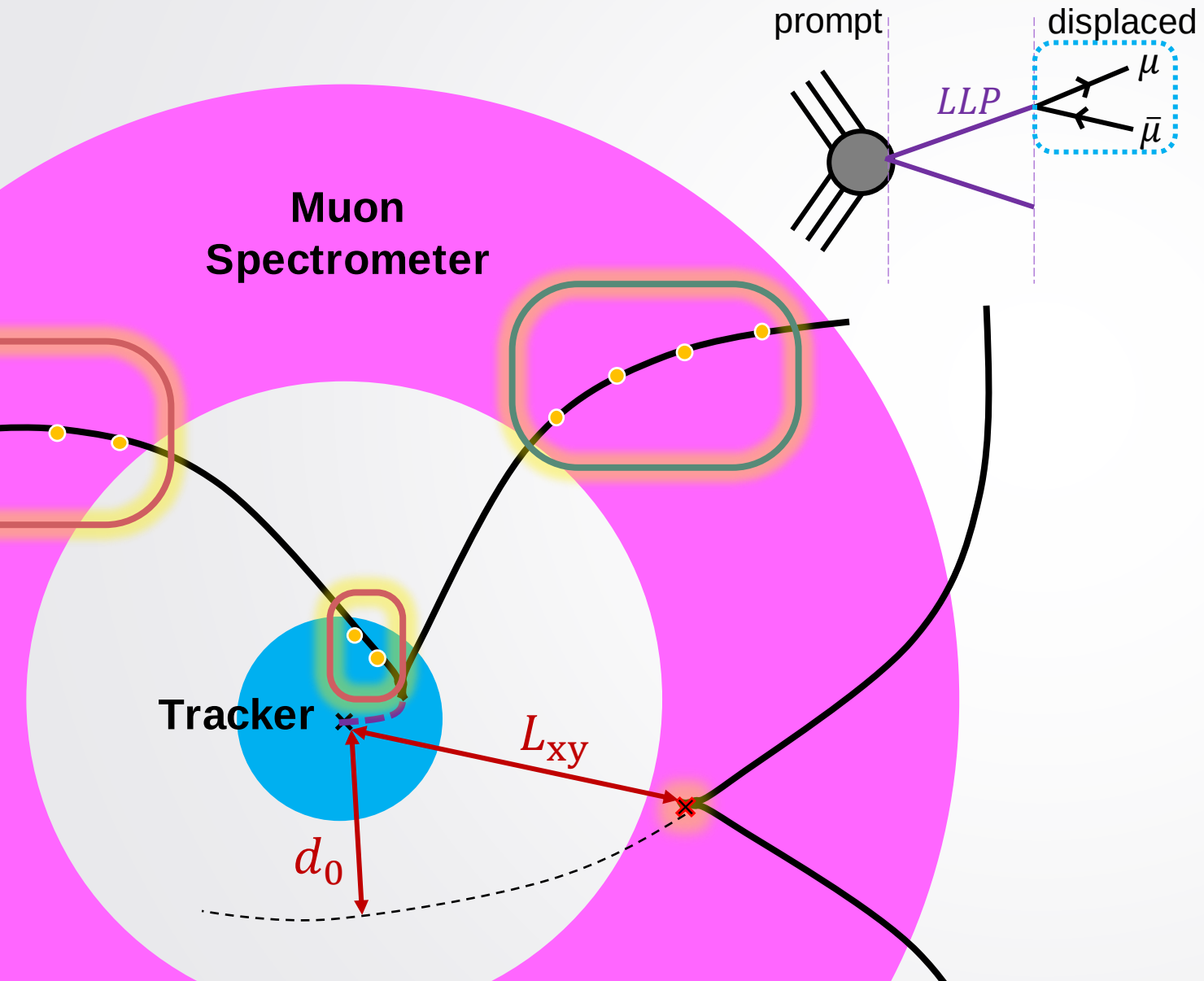






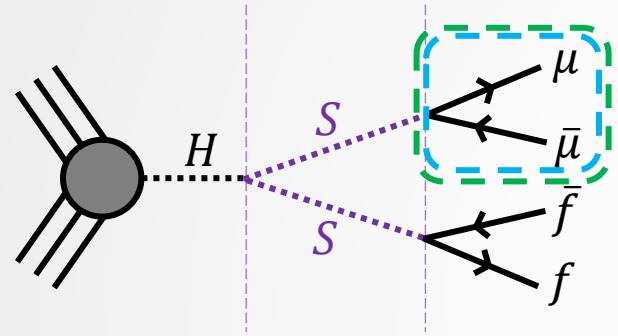
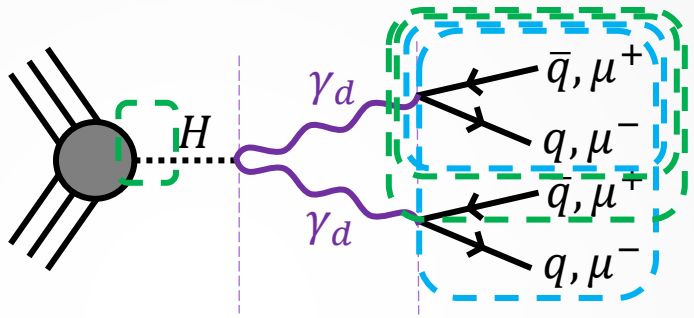
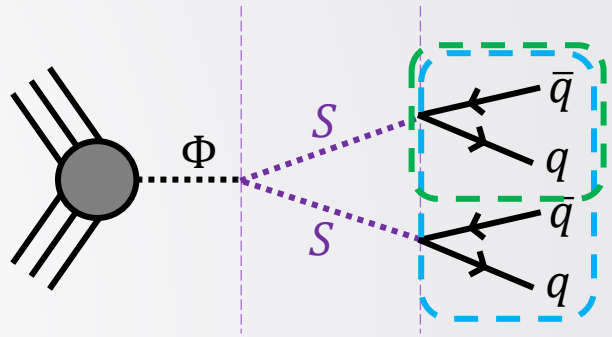
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-007/
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#ICHEP_2022

LLP Signatures in the MS



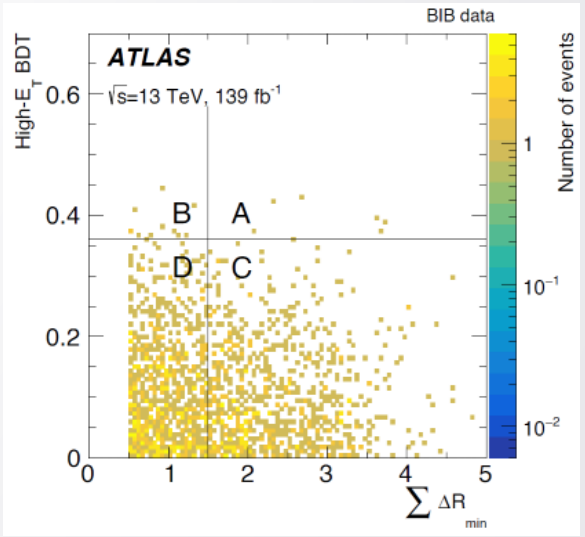
- LLPs decaying to muons make them **displaced (i.e. don't point back to PV [pp-interaction])**
- **Info to reconstruct** displaced muon can come:
  - **From both MS and tracker (TMS)**
  - **Solely from MS (STA)**
- Backgrounds include:
  - Badly reconstructed prompt muons
  - Some SM decays
  - Crossings of unrelated displaced muons
  - Cosmics
  - Beam-induced background (BIB)

Searches for LLPs in the MS and HCAL

	[CMS-EXO-21-006](#)	[arXiv:2206.12181](#)	[JHEP 06 (2022) 005](#)
	$H \rightarrow LLP^0 \rightarrow$ Displ. 2μ	$H \rightarrow LLP^0 \rightarrow$ Displ. Collim. 2l or 2q	$\Phi \rightarrow LLP^0 \rightarrow$ Displ. CalRatio Jets
Simplest Targeted Model:			
Trigger:	• **Dedicated MS dimuon trigger** w/o beamspot constraint	• **WH: lepton trigger. ggF: 3muon, muon-scan, CalRatio triggers**	• Low and high E_T **CalRatio triggers**
Signal Region:	• Separate **SRs** for **[STA-STA, STA-LMS, LMS-LMS]** • $\frac{L_{xy}}{\sigma_{L_{xy}}} > [6,3,6]$ (**is displaced**) • Dimuons not back-to-back (**not cosmic**) • $m_{\mu\mu} > 10$ GeV (**not SM decay or random crossing**) • Angle between $\vec{p}_{\mu\mu}$ and $\vec{L}_{xy}$ is $\lvert\Delta\Phi\rvert < \pi/4$ (**not prompt misreconstructed**)	• Separate **SRs** for **ggF[$2\mu, c+\mu, 2c$], WH[$c, c+\mu, 2c$]** • **CNN to discriminate multi-jet** • $\sum p_{T,tracks\ within\ \Delta R=0.5} < 4.5$ (**jets are trackless**) • Many things are abstracted out in the definitions of the muon and calojets	• Separate **SRs for [$m_\Phi \leq 200$ GeV, > 200 GeV]** [Low and high E_T] • Require **2 clean displaced jets in event** with $p_T > 80$ GeV* • **NN** separates **signal, multi-jet and BIB/cosmics by jet, BDT** takes **NN score per jet in event** and other info • BDT score $> [0.27,0.36]$ (**is signal**) • $\sum \Delta R_{min}(jet, tracks) \geq [1.0,1.5]$ (**jets are trackless**)

Searches for LLPs in the MS and HCAL

	CMS-EXO-21-006	arXiv:2206.12181	JHEP 06 (2022) 005
	$H \rightarrow LLP^0 \rightarrow$ Displ. 2μ	$H \rightarrow LLP^0 \rightarrow$ Displ. Collim. 2l or 2q	$\Phi \rightarrow LLP^0 \rightarrow$ Displ. CalRatio Jets

Bkg Estimate:	• **Cosmics:**
	  • # events passing all criteria except back-to-back is **already negligible, so ignore**
	• **Misreconstructed Prompt:**
	  • Will have symmetric $\lvert\Delta\Phi\rvert$
	  • **Predict $\lvert\Delta\Phi\rvert < \pi/4$ from $\lvert\Delta\Phi\rvert > 3\pi/4$**
	• **SM Decays and Random Crossings:**
	  • Correlated with jet activity
	  • Get **ratio of opposite-sign to same-sign** in **jet-embedded muon CR** and extrapolate to SR
		•Cosmics estimated from cosmic dataset and subtracted for ggF, negligible for WH
		•BIB is negligible
		•**ABCD method** using:
		  • **Azimuthal angle between object from pTmiss** for WH SRs
		  • **Tracklessness of jets variable** for ggF SRs
		  • **Multi-jet rejection CNN score** for Calojet SRs
		  • **Azimuthal angle between both muon jets** for that SR
			• Per-Event **BDT score** mainly **rejects BIB**
			• $\sum \Delta R_{min}(jet, tracks)$ **trackless requirement** mainly **rejects prompt multi-jets:**
			• **ABCD method:**
			 

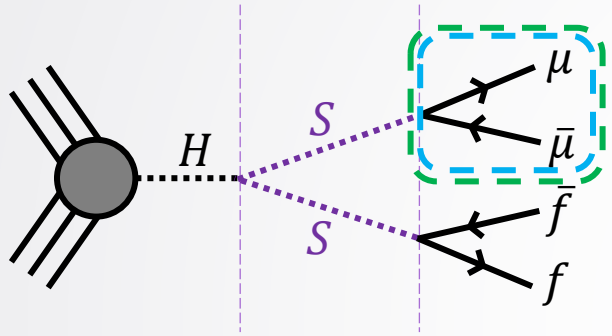
Searches for LLPs in the MS and HCAL

Simplest Targeted Model:

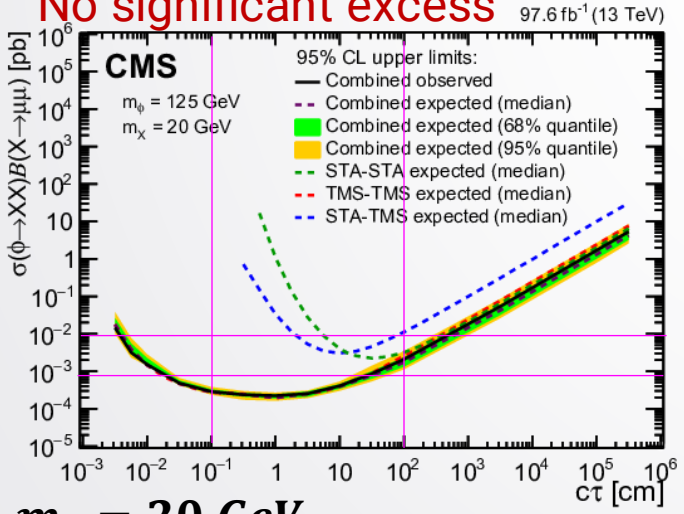
Results:

CMS-EXO-21-006

$H \rightarrow LLP^0 \rightarrow$ Displ. 2μ



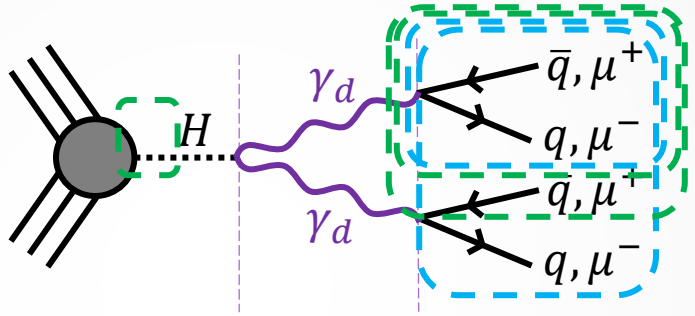
No significant excess



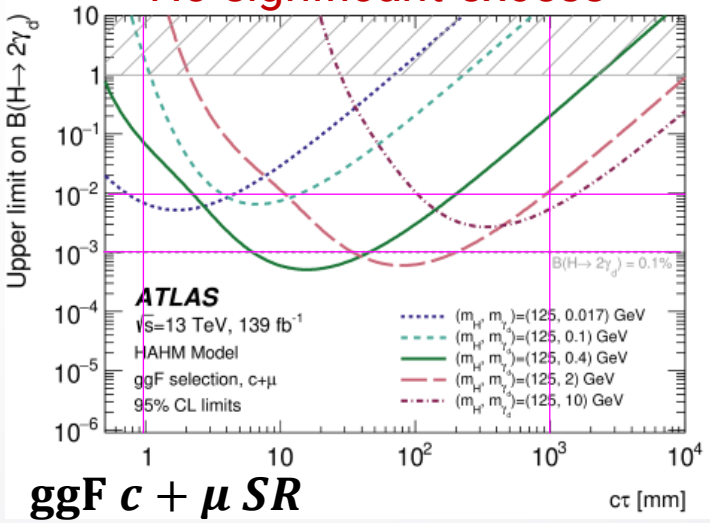
$m_S = 20\ GeV$

arXiv:2206.12181

$H \rightarrow LLP^0 \rightarrow$ Displ. Collim. 2l or 2q



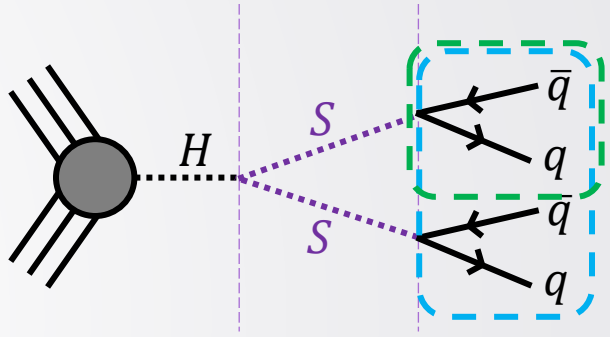
No significant excess



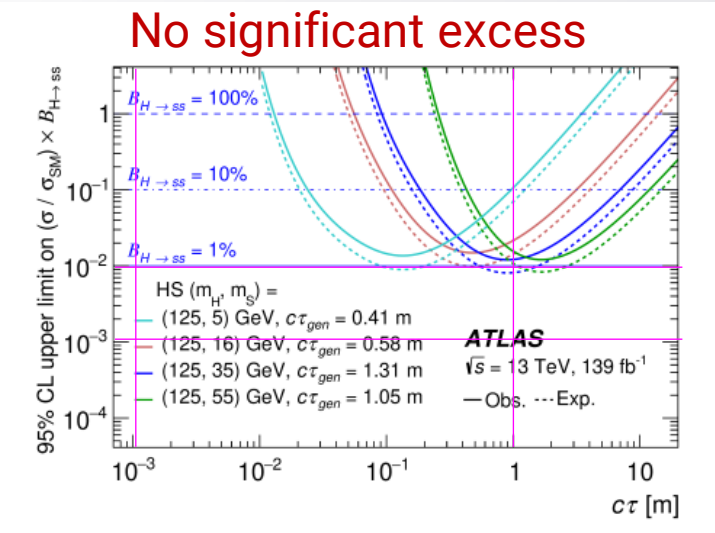
ggF $c + \mu$ SR

JHEP 06 (2022) 005

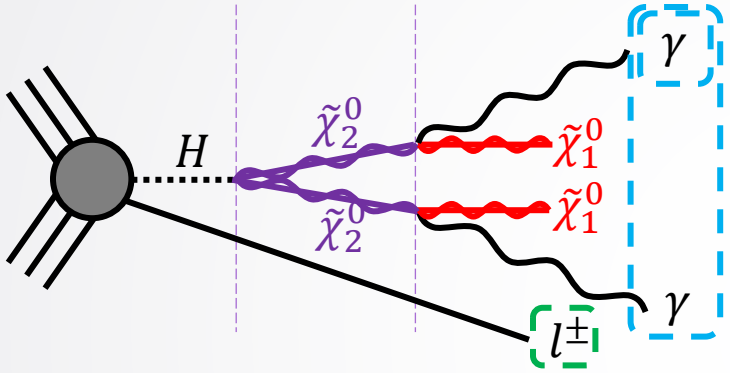
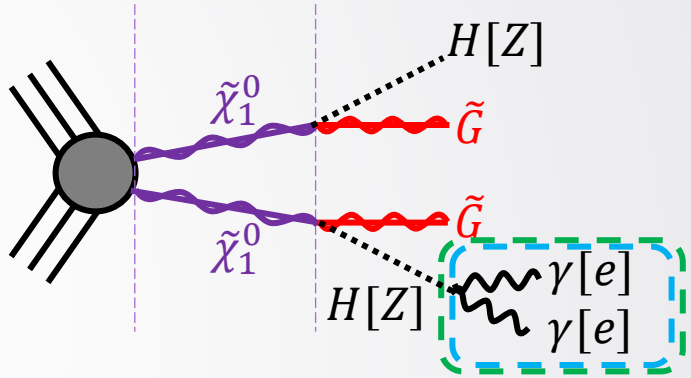
$\Phi \rightarrow LLP^0 \rightarrow$ Displ. CalRatio Jets



No significant excess



Searches for LLPs in the ECAL

	[ATL-COM-PHYS-2022-076](#)	[ATL-COM-PHYS-2022-474](#)
	$\mathbf{H \rightarrow LLP^0 \rightarrow Displ.\gamma}$	$\mathbf{LLP \rightarrow Displ.H \rightarrow \gamma\gamma / Z \rightarrow e^+e^-}$
Simplest Targeted Model:		
Trigger:	• **Single lepton trigger** from Higgs production process (WH, ZH, ttbar)	• **2 high-pT photon triggers**
Signal Region:	• Separate **SRs** for **[low,high]** $\Delta m_{NLSP,LSP}$ (as well as for $(1\gamma, 2\gamma)$) • Require **time delay > 0** • Require **MET > [50, 80] GeV** • **Displacement and timing are binned**	• Require **time delay > 0** • Require **MET > 30 GeV** • **Displacement and timing are binned** • $m_{\gamma\gamma} \in [60, 135]$ **GeV** (i.e. from Z or H)

Searches for LLPs in the ECAL

ATL-COM-PHYS-2022-076

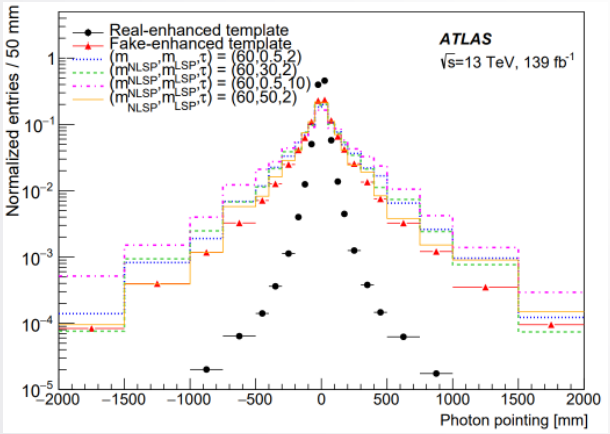
$\mathbf{H \rightarrow LLP^0 \rightarrow Displ.}\,\boldsymbol{\gamma}$

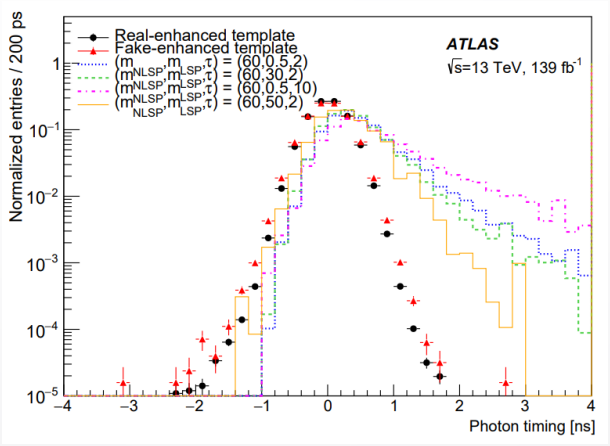
ATL-COM-PHYS-2022-474

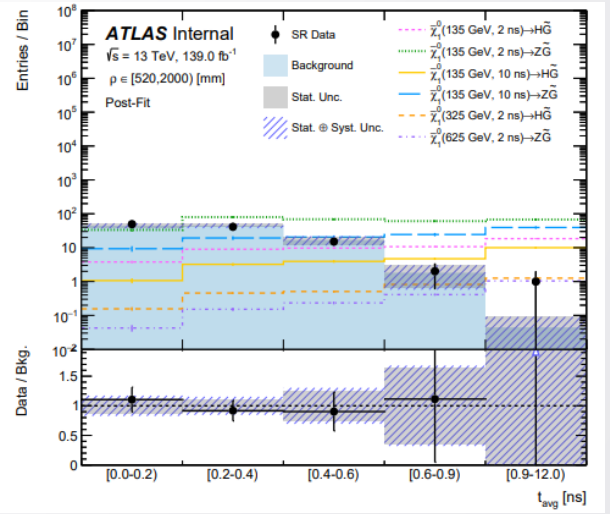
$\mathbf{LLP \rightarrow Displ.\,H \rightarrow}\,\boldsymbol{\gamma\gamma / Z \rightarrow e^+e^-}$

Bkg Estimate:

- **Background is fakes or misreconstructed**. Non-collision negligible.
- Define CR with low MET**, form fake-photon-enriched and genuine-photon enriched templates** in timing and pointing bins from identification requirements
- **Fit relative fractions of templates to data** and **extrapolate to SR**
  - Genuine-photon template multiplied by fraction of SR events where both photons are deemed “genuine”
  - Fake-photon template multiplied by 1 minus that fraction







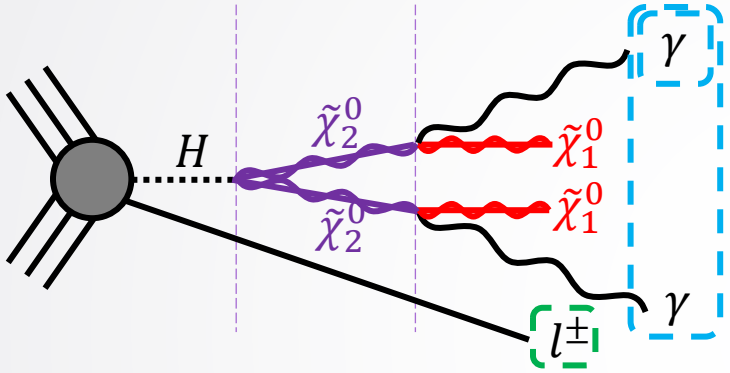
Searches for LLPs in the ECAL

Simplest Targeted Model:

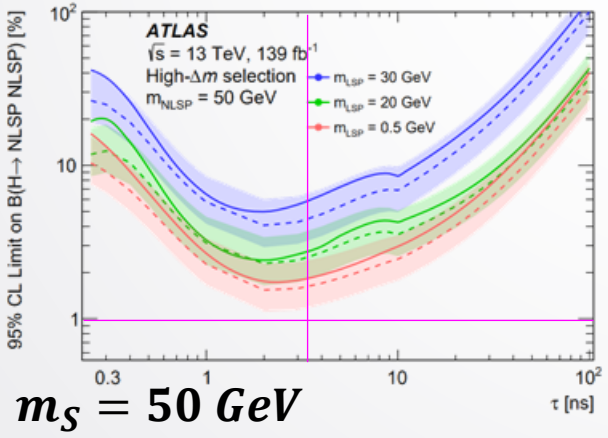
Results:

ATL-COM-PHYS-2022-076

$\mathbf{H \rightarrow LLP^0 \rightarrow Displ.\gamma}$

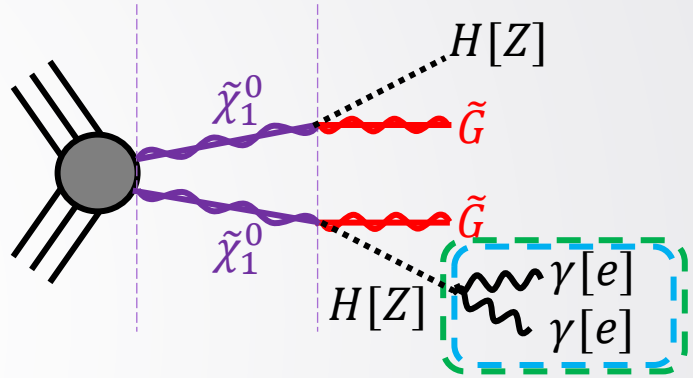


No significant excess

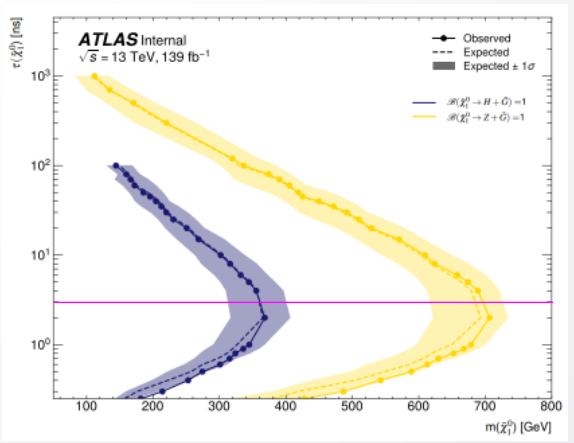


ATL-COM-PHYS-2022-474

$\mathbf{LLP \rightarrow Displ.\,H \rightarrow \gamma\gamma / \,Z \rightarrow e^+e^-}$



No significant excess



CMS1
LLP->2 mu

EXO-21-006

- HAHM or heavy scalar model. H->2ZD (dark photons)->2mu 2f and Phi->2X->2mu 2f
- 3 SRs: both muons recon’d using both ID and MS, both only recon’d by MS, one only in MS, other is both tracker and MS
- Dedicated triggers for dimuons inside and outside trackers. Therefore require 2 muons reconstructed in MS alone without info from tracker
- No excess

(EXOT1) LLNP→Collimated 2l or 2(Light Hadrons)

EXOT-2019-05

Summary

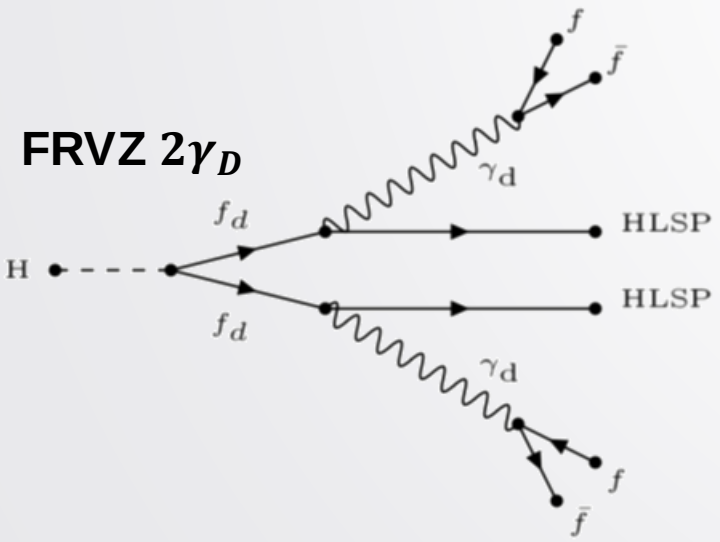
- Look for ggF/WH Higgs->dark photons -> 2 collimated muons or light quarks
- Triggers:
  - ggF: 1+/3 dedicated triggers targeting displaced objects
    - Tri-muon MS-only: Require 3+ muons with pT>=6 GeV in MS
    - Muon narrow-scan MS-only: Require pT>=20 GeV muon candidate from L1, confirmed by HLT which then scans $\Delta R = 0.5$ around looking for second muon. Both muons must not match to ID tracks.
    - CalRatio L1Calo: Select narrow jets in HCAL
  - WH: single-electron or single-muon triggers
- Signal Regions:
  - ggF: 2mu, 2c, c+mu [use max(sum pT) [low] vs prod QCD tagger (delta phi DBJ for 2mu) [high] as ABCD]??
  - WH: c, 2c, c+mu [use min(delta phi) and min(QCD tagger) as ABCD]??
- Backgrounds:
  - ggF:
    - ggF2mu:punch-through jets from rare multi-jet events
    - ggF2c, ggFcmu: multijet production
    - Second leading for all ggF is cosmic muons
  - WH:

Results

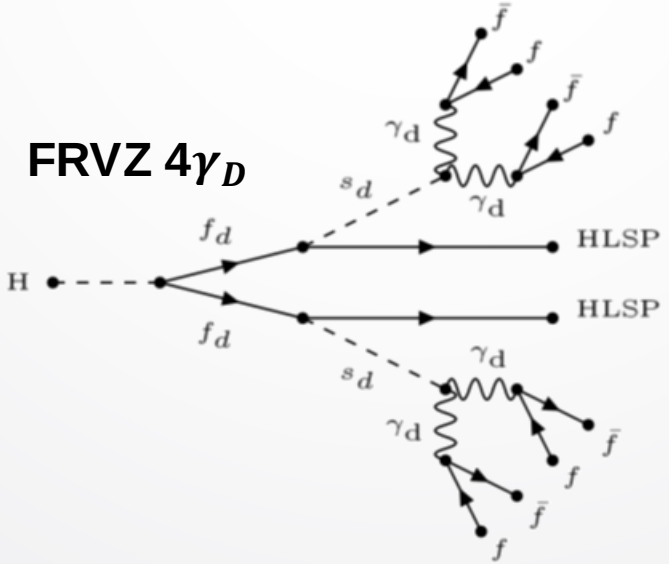
Targeted Models

- Investigate case where SM and DS couple via Higgs portal for BSM production, vector portal for decay to SM
- Assume γ_D mixes kinetically via parameter ϵ with SM photon and decay into leptons or light quarks
- Focus on $m_{\gamma_D} \sim O(\mathrm{MeV} - \mathrm{GeV})$ and $\epsilon < 10^{-5}$ (so long-lived)
- Due to small mass, expect large Lorentz boosts → collimated fermions [dark-photon jets (DPJs)]
- Target ggF and WH production of the Higgs, then Falkowski-Ruderman-Volansky-Zupan (FRVZ) and Hidden Abelian Higgs Model (HAHM) for dark photon production

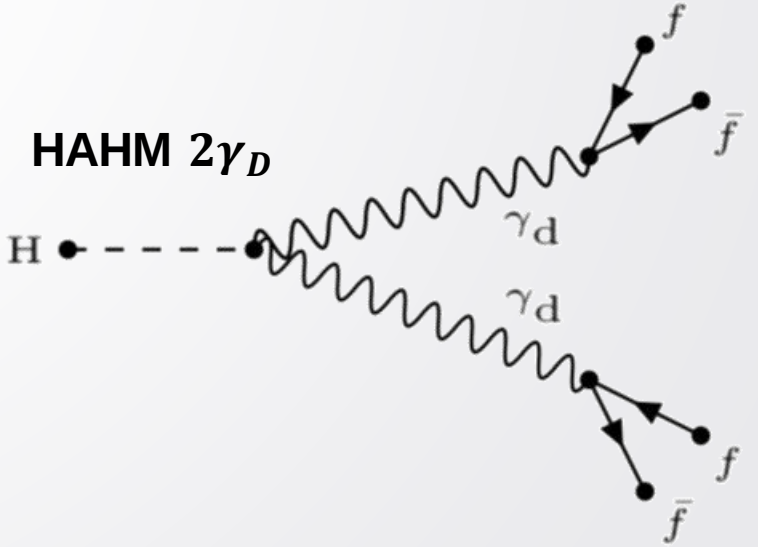
FRVZ $2\gamma_D$



FRVZ $4\gamma_D$



HAHM $2\gamma_D$



Data and MC Information

- Full Run 2 data
- MC signal done with both a 125 GeV Higgs and a 800 GeV Higgs-like scalar
- Branching fractions of γ_D depends on its mass [for example $m_{\gamma_D} = 0.4\ \mathrm{GeV}$ gives 45% e^+e^-, 45% $\mu^+\mu^-$, 10% q^+q^-]
- Sensitive part of ATLAS for this context is up to 7 m in radius and 13 m along beampipe.
- For FRVZ, mass of f_d chosen to be small wrt Higgs mass and far from kinematic threshold of $m_{HLSP} + m_{\gamma_d} = m_{f_d}$
- SM background estimate is data-driven, but uses MC multi-jet; W+jets, Z+jets, WW, WZ, ZZ; ttbar and single-top-quark for validation, uncertainties, and training classifiers
- $J/\psi \to \mu\mu$ MC for muon trigger uncertainties and reconstruction efficiency

Event Reconstruction 1

- Candidate events must have a reconstructed vertex (PV) with 2+ assc. tracks with $p_T > 500\ \mathrm{MeV}$ consistent with coming from collision
- PV is vertex with highest sum of squared p_T of assc. tracks
- Electron candidates from isolated ECAL deposits matched with ID tracks.
  - Require: $|\eta| < 2.47, p_T > 20\ \mathrm{GeV}$, "TightLHElectron" (cleaning based on shower shapes and track properties)
  - Veto candidates in transition region between barrel and endcap ECAL $1.37 < |\eta| < 1.52$
- Muon candidates from MS tracks matching ID tracks
  - Require: $|\eta| < 2.5, p_T > 20\ \mathrm{GeV}$, "medium" (cleaning based on # hits, q/p measured in ID and MS divided by uncertainties)
- [Electrons, muons] need $\frac{|d_0|}{\sigma(d_0)} < [5, 3]$ and $|z_0 \sin\theta| < 0.5\ \mathrm{mm}$ to count as displaced
- Isolation criteria: [why is this needed?]
  - Scalar sum of p_T of tracks within cone of $\Delta R = \min(\ 10\ \mathrm{GeV}/p_\mathrm{T}\ ,\ [0.2,0.3])$ of lepton must be less than 15% of lepton p_T (excluding lepton track).
  - Sum of transverse energy of calo cell clusters in $\Delta R = 0.2$ must be less than [20%, 30%] lepton p_T (excluding lepton itself)

Event Reconstruction 2

- Jets from 3D energy clusters in calo using anti-kt algo with $R = 0.4$
  - Require: $|\eta| < 4.9$, $p_T > 20$ GeV
  - To remove jets from pileup, jets with $|\eta| < 2.5$, $p_T < 120$ GeV require significant fraction of tracks coming from PV (using JVT)
  - B-tagged jets (usi

Triggers

EXOT-2019-05 – LLNP->collim. 2l or 2(light hadrons)

- Targets LLP dark photon from H via ggH or WH
  - Which models? Higgs Portal
  - SM and DS through Higgs Portal for BSM prod, and vector portal for decay.
  - gammaD assumed to mix kinetically (epsilon) with gamma->leptons & light quarks.
  - Focus on m=O(MeV-GeV) and eps<1e-5 (small) [justified since need this for m>10 MeV for some reason] so gamma decays are long-lived
  - Models: FRVZ (H->2DF->2/4DP->4/8f) and HAHM (H->2DF->4f)

- Displaced collimated SM fermions in Calo or MS, 139 fb-1
  - Small mass compared to large pp hard scatter energy: Large Lorentz boost. So collimated.
  - Collimated groups of fermions in jet-like structure: dark photon jets
  - ggF and WH mutually exclusive
  - Candidate events must have reconstructed vertex**(PV?) with 2+ ass. Tracks with pT>500MeV, consistent with coming from collision.
  - Electron candidates recon from isolated ecal deposits matched to ID tracks
  - Muons from MS tracks matching ID tracks

- SM and instrumental backgrounds estimated from data
  - Which backgrounds?

- Observed consistent with background

- Limits on prod xs x BF vs tau, or vs m and kinetic mixing param.

- Higgs BR >1% excluded for H->2gammaD 10mm-250mm, 0.4-2 GeV

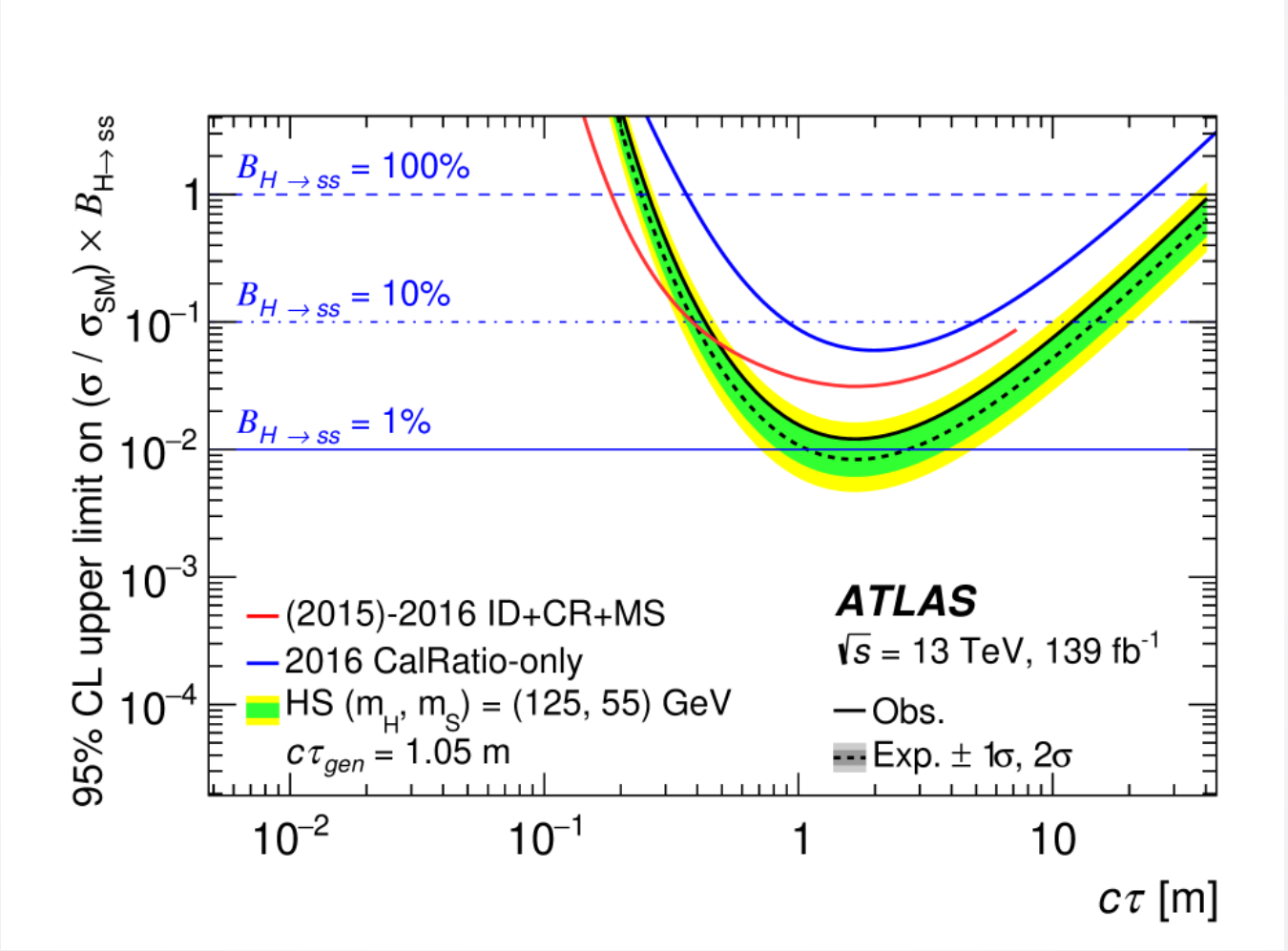
(EXOT3) LLNP-> displaced CalRatio Jets

EXOT-2019-23

Summary

- Scalar portal models
- Ff->single trackless narrow jet with abnormally high proportion of energy in HCAL
- Require 2 jets
- Two SRs, specialized for models with mPortal<>200 GeV (low/high ET models)
- (Why would jets be narrow If scalar is heavy?)
- Dominant background is SM multijet. Others are noncollision background like cosmics and BIB (LHC beam-gas and beam-halo interactions with upstream collimators-> muons parallel to beam pipe)

ATLAS EXOT-2019-23 $LLP^0 \rightarrow$ Displ. CalRatio Jets



(SUSY2) – LLNP to Displaced photons

SUSY-2019-14

- In gauge-mediated SUSY breaking (GMSB) models, gravitino is LSP usually, and weak coupling of NLSP to LSP could make NSLP LLP, while LSP leaves detector undetected
- Neutral NLSP would avoid detection, and decay into photon plus LSP (delay, nonpointing to PV)
- Use Lar ECAL to make precise pointing measurements and time of arrival to search. Size of ATLAS restricts sensitivity to O(ns)
- Specifically ZH, WH, ttH Higgs->2NSLP->2gamma+2LSP
- Trigger on single leptons, require 1+ photon candidate
- Exploits expectation of MET due to LSP and neutrinos from leptons
- No excess

(SUSY3)-displaced H/Z->2gamma/e

SUSY-2020-28

- Also GMSB. LSP is gravitino. NLSP is usually N1. N1 is mixture of higgino so most likely decay is N1->H/Z+G. The
- Lar ECAL to target H->2gamma and Z->2e. Signature is two ECAL objects originating from a displaced diphoton vertex. No attempt is made to distinguish between them in the ECAL, and only use ECAL info. Sensitivity limited to O(ns) by ATLAS. Some delay wrt prompt.
- SR is 2+ photons, high MET (due to LSP)
- Use 2 high pT photon triggers
- No excess

(DVJETS) LLP→DV [triggered by Jets]

SUSY-2018-13

- Look for any LLP that goes to charged fermions, in the presence of jets
- High mass, high number of tracks
- Use jet correlations to predict background, as well as a combined background estimate

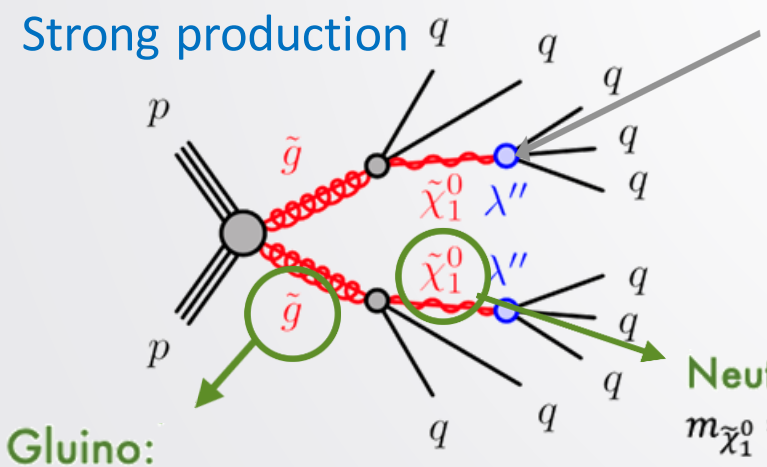
Outline

- Summary of Major Updates
- Analysis Overview
  - Strategy
  - Event selection
  - Background estimation + uncertainty
  - Signal MC uncertainties
  - Unblinded results
- Discussion and Future Steps

Analysis Overview

- Search for LLPs decaying inside the ID creating displaced vertices (DVs) with high mass and large track multiplicity
- Search conducted in multijet final state, using multi-jet triggers
- Full Run-2 dataset: 139 /fb
- Benchmark models:

Strong production

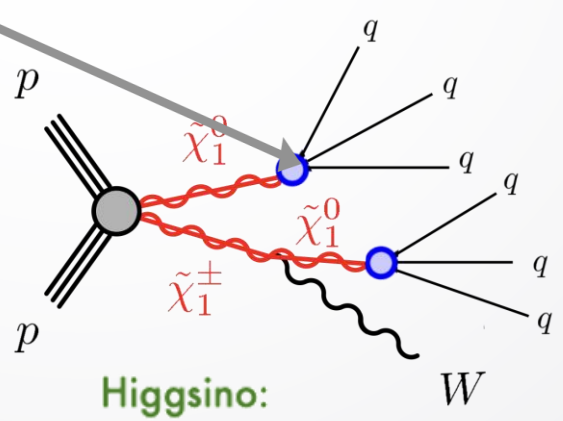


Gluino:
$m_{\tilde{g}}$ = 1.6 - 2.6 TeV

Small RPV coupling → long-lived N1 → DV

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

Also considering for interpretation:

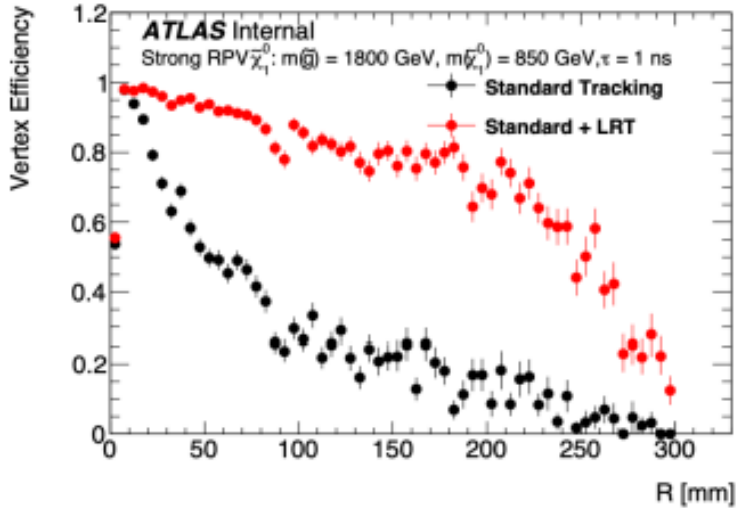
- R-hadrons
- Higgs to long-lived scalars
- Emerging jets

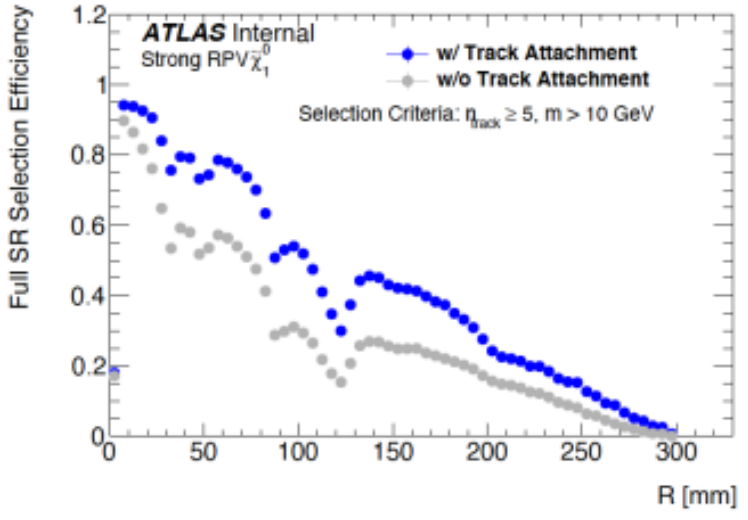
Special Reconstruction for DVs

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

$$\text{High-pT} = \begin{cases} 4\text{j}250 \\ 5\text{j}195 \\ 6\text{j}116 \\ 7\text{j}90 \end{cases}$$

$$\text{Trackless} = \begin{cases} 4\text{j}137 \\ 5\text{j}101 \\ 6\text{j}83 \\ 7\text{j}55 \end{cases} \quad \& \quad \begin{cases} 1(\text{trackless jet})78 \\ 2(\text{trackless jets})56 \end{cases}$$

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

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

all tracks #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:

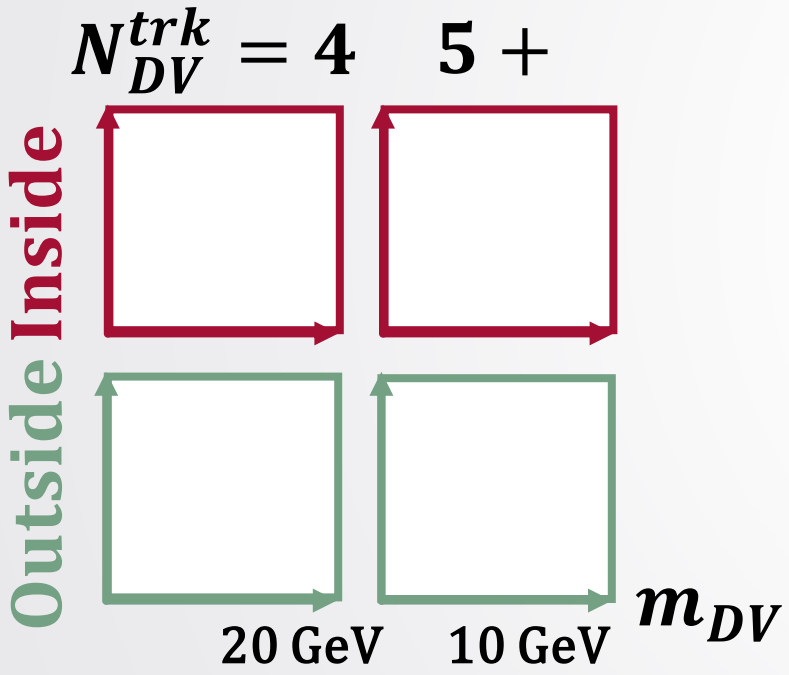
Depends on r_{DV} and whether or not track is attached

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

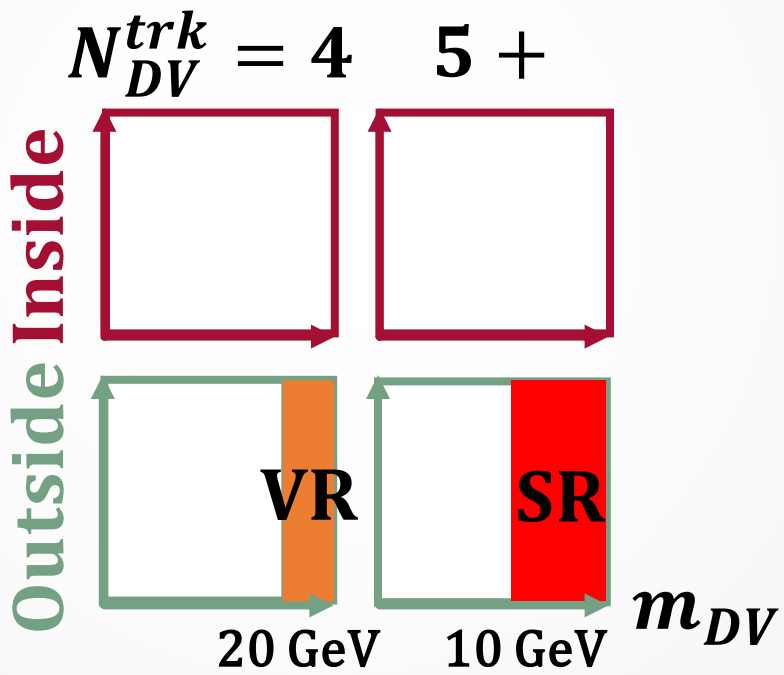
Chosen to reduce background to ~1 event in each SR

Summary of Regions

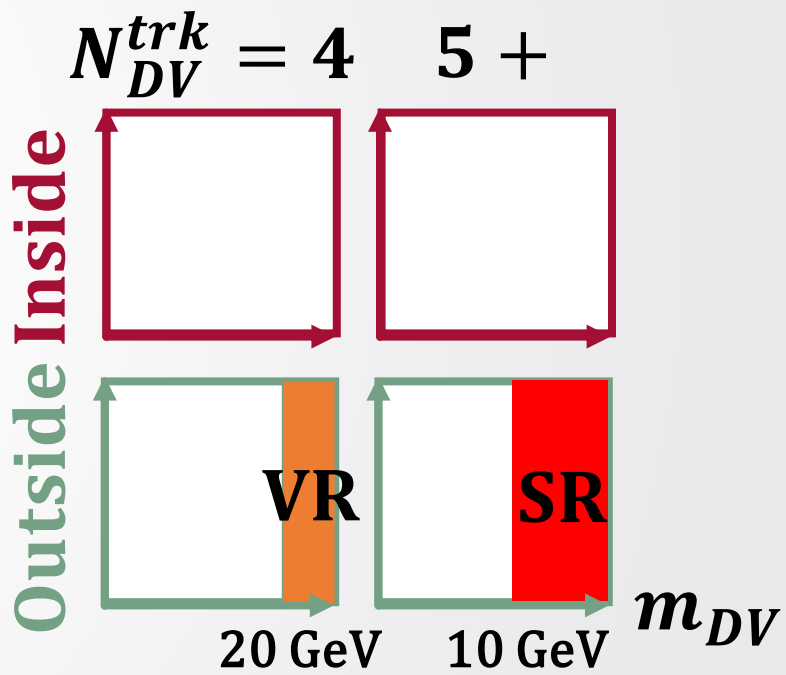
MC No Event Selection



Data High pT



Data Trackless



(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)

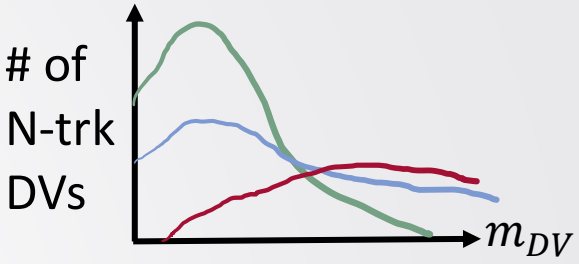
Backgrounds

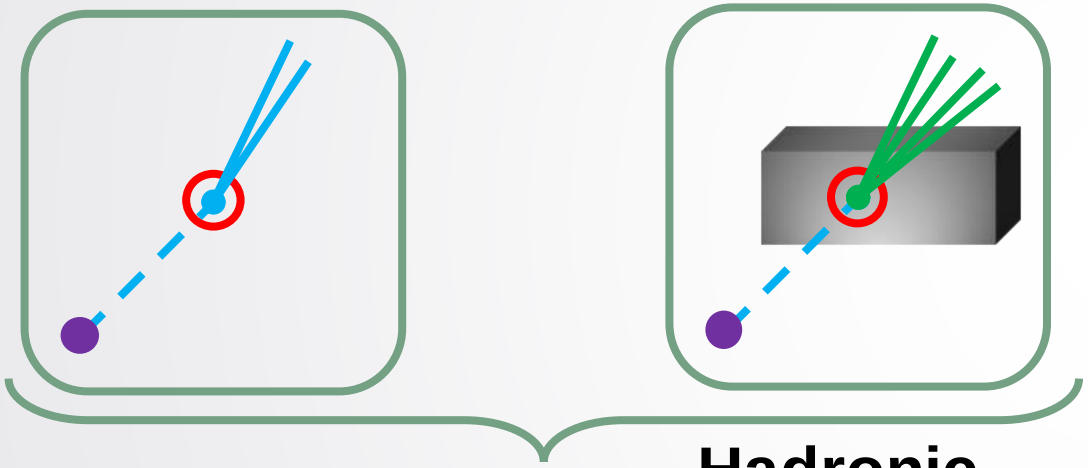
Generator Tracks

GEANT4 Tracks

True-Pileup Tracks

Fakes-Pileup Tracks



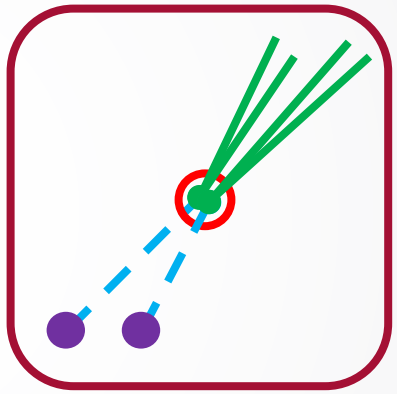


SM Decays

- SM LLP just decays naturally in flight

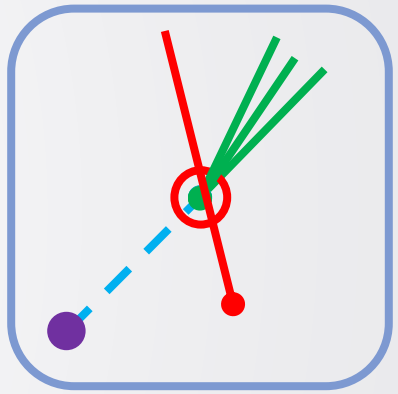
Hadronic Interactions (HI)

- SM LLP hits and interacts with detector material



Merged Vertices (MV)

- Two DVs close together get reconstructed as a higher N, higher m DV



Accidental Crossings (AX)

- Random track crossing DV makes it appear higher N and higher m

(Dijet MC used for studies, closure, and part of HI shape. Everything else and normalizations are data-driven*)